TRACKING THE HISTORY OF RADAR

THE IEEE-RUTGERS CENTER FOR THE HISTORY OF ELECTRICAL ENGINEERING

&

THE DEUTSCHES MUSEUM

TRACKING THE HISTORY OF RADAR

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ISBN Number: 0-7803-9987-0

IEEE Order Number: JP2593-2

A Publication of the IEEE-Rutgers Center for the History of Electrical Engineering
and
the Deutsches Museum

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PREFACE

The objective of this volume is to track the current state of research and stimulate further work in the history of radar -- a subject that the editors and contributors believe has received far less attention than it deserves. The essays in this volume either describe the development of radar in a particular period or in a particular country, present the military and political contexts of that development, investigate the science-technology relationship on varying institutional and cultural conditions, or raise some historiographic questions by making use of a particular approach to radar history. Together with the essays on primary and secondary sources of radar history, this volume attempts to give a fair representation of the current state of scholarship and to suggest some avenues for further study.

Most of the essays are based on papers given at a workshop held at the Deutsches Museum in Munich in December 1992, organized by the editors. The workshop was made possible by a generous grant from the Deutsche Forschungsgemeinschaft, which enabled some forty leading historians and radar professionals from the United States, Great Britain, and Germany to assemble. This may have been the first time that radar experts interested in history and historians interested in the development of radar came together for discussion. This kind of interchange is extremely important if writing in the history of radar is to progress.

The workshop originated through the efforts of the IEEE Center for the History of Electrical Engineering in 1989 to cooperate with the Smithsonian Institution, the MIT Museum, the Science Museum of London, and the Deutsches Museum München to organize an international exhibit on the history of radar. Representatives of these organizations determined that further historical research was desirable before planning an exhibit. The Deutsches Museum took the next step of organizing this workshop, with some assistance from the IEEE Center.

Oskar Blumtritt, Hartmut Petzold and William Aspray

INTRODUCTION

Radar is "the art of detecting by means of radio echoes the presence of objects, determining their direction and ranges, recognizing their character and employing data thus obtained in the performance of military, naval or other operations."[1] Robert Watson-Watt, in his autobiography, has quoted this classic definition of "radar" which appeared in "The Principles of Radar" edited by staff members of the MIT Radar School in 1944. Watson-Watt then used this definition in an effort to legitimate his claim to "have been the first and true inventor of radar" -- in 1935.[2] Robert Page, on the other hand, has claimed that he was the first to develop pulse radar for the detection of aircraft -- in 1934.[3] It seems, at first glance, as if technical (and operational) definitions are the basis for determining questions of priority in the history of radar and, furthermore, that the contemporary witnesses are those who should be able to answer historical questions. There is, however, consent among historians that definitions, questions of priority, and statements of witnesses are themselves all subjects of historical research. The discourses of technical experts as well as their particular social context are, for this very reason, the basis for historical work. In other words, historical research depends, among other things, on the technical knowledge of experts, knowledge of their personal careers, and the development of their particular work. In order to advance research in radar history, engineers and historians working on this subject must find ways of talking to each other at a deeper level. This volume includes essays written by radar experts as well as by historians, essays which are based partly on intensive discussions during a workshop on radar history held at the Deutsches Museum in Munich in December 1992. Looking into the literature on radar history will enable us to understand the necessity of these efforts more precisely.

In the present literature on radar history one can find many details about the technical development of radar[4] and its institutional and military context[5] -- particularly in the period up to 1945. The proceedings of the conference on "Radar

Development to 1945," held in London in 1985, reflect the state of the art in radar historiography at that time: "Most of the chapters have been written by former/present radar experts. However to ensure a degree of integration of the numerous topics covered, several chapters have been composed by professional historians. Some color has been added to the text by the inclusion of personal reminiscences."[6] But the gap between the literature written by experts and that written by historians has not yet been overcome. Radar has also often been neglected in more general books on the history of technology. For example, in Thomas Hughes' American Genesis[7] radar is not mentioned, and Technology in America, edited by Carroll Pursell, only notes that radar was "developed in Great Britain."[8]

Besides the gaps in the literature, especially concerning the development of radar in the post-war era, we are also confronted with different national styles in the historiography of radar and with different situations concerning material and written sources. For instance, most of the British books are personal memoirs by engineers or physicists who were active in radar technology during the Second World War, beginning with the autobiography by Watson-Watt in 1959 and ending with the story of H_2S radar by Bernard Lovell in 1991.[9] Most of the American literature on radar history is closely related to a particular institution, whether the authors are historians or radar experts. One of its best-known and most frequently cited books is unquestionably Henry Guerlac's RADAR in World War II.[10] This kind of "official history" -- or "applied history" -- of a particular institution seldom appears in other countries.[11] In summary, we have to be aware that the national differences in the technological development have superimposed upon them heterogeneous national styles of historiography.

If one takes into account that only a small part of Guerlac's manuscript has been published, the 28 volumes of the Radiation Laboratory Series might be considered as a supplement to his contribution. The fluid transition from historical books to archival material shows, however, that general historical questions have not yet been elaborated. That is not only true of questions arising from the comparison of the development of radar across countries; radar, primarily developed in the face of an impending war, also has particular characteristics that need to be investigated in that context. These characteristics include the secrecy of its development, the development of countermeasures, and -- especially after the Second World War -- the cooperation of allied countries.

The post-war radar historiography also includes unsolved problems such as the difference between and identity of military and civilian technological developments, the genesis of the science-technology relationship, the assessment of technological changes related to the emergence of the computer and microelectronics industry, and the evaluation of the social impact of radar in view of its diversity. Historians of technology have developed tools in order to investigate these problems; the study of radar history might also help to reflect upon these tools, such as the contextual approach, the semiotic approach, or the so-called social construction of technology. The deficiencies and problems in the study of radar history, which we could expound upon even more, belies the importance of radar technology. For example, radar has often been called the decisive weapon in the Second World War and one of the essential components of modern traffic systems.

The present volume tries modestly to fill some of the gaps in radar history and formulate some of the remaining questions as precisely as possible in order to motivate further historical research. The first section deals with the development of radar technologies from their very beginning up to the present time. The essays, written by active and retired radar experts, are mostly based on an implicit evolutionary model. They provide the reader with a detailed step-by-step sequence of radar artifacts and systems -- while the historical contexts, however, appear to be more or less arbitrary. The different divisions into periods, including the different categories the authors use, is one of the presuppositions which reflects the development of radar in a broader historical context. The "Generations of Radar," described by John Bryant, gives a general overview on radar development from the mid thirties up to the present. Herbert Kümmritz's essay concentrates on the achievements of radar technology in Germany up to 1945. Werner Gerlitzki, in presenting the main periods of the international radar development after the Second World War, argues that military needs and requirements continued to be the driving force behind radar up to 1990s. The "Development of Monopulse Radar in the U.S." by David Barton gives more detailed insight into particular techniques. One of its applications can be found in the secondary surveillance radar -- the topic of Richard Trim's story.

The second section gives both a review and some recent investigations of the military and institutional contexts of radar development. Louis Brown's way of looking at the problem of whether radar was a decisive weapon in the Second World War, livens up an old, but until now, rather spontaneous discussion with new arguments and materials. The more detailed case study by Tony Devereux compares the aggressive use of American submarine radar in the Battle of the Pacific with the role of the airborne ASV radar in the Battle of the Atlantic. While these essays concentrate on the significance of radar in the Second World War, Ulrich Kern's paper analyzes the political and institutional background of German radar development in the course of that war. "The Military Context of Early American Radar" by David van Keuren leads up to the next section by drawing a line from the scientific and technological work in the military laboratories established in World War I to the strong linkage between science, technology, and the military in the post-World War II period.

The science-technology relationship, partly embedded into a broader cultural context, is the concern of the third section. Sean Swords argues that radio wave propagation studies have been significant in the evolution of radar. This approach is contrasted by that of Arthur Norberg and Robert Seidel who describe the development of the klystron in its scientific and cultural web in the United States and in the United Kingdom. The interaction of physics and technology, explained through a comparison of the development of electron tubes across nations, is the topic of Walter Kaiser's essay.

Based on the achievements of the radar historiography presented so far in this volume, some historiographical questions are developed in section four. Charles Süsskind demonstrates that the history of radar presents us with an typical exemplar of a simultaneous invention, which, however, still needs to be studied more systematically. Hartmut Petzold's central question is that of the place of radar systems and radar history within the history of electronic information technology. He draws an impressionistic picture of different aspects relating to material and immaterial artifacts. The distinction of "technical change," "operational change," and "technological change" serves Alan Beyerchen as a tool for expressing the history of radar in its different contexts: the military, the scientific, and the technical. Michael Dennis discusses the role of Henry Guerlac as an official historian at the MIT Radiation Laboratory.

The fifth and last section gives an overview on material and written sources in Great Britain and the U.S. as well as on the current historical literature. The lack of an article concerning the German situation is due to the (near) absence of sources, as described in Kern's essay in section two. The contributions by John Becklake and Andrew Goldstein, combined with the annotated bibliography compiled by Louis Brown, provide a good reference to the reader who wants to investigate the history of radar.

Oskar Blumtritt

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11 See also the essay by Michael Dennis in this volume.

John H. Bryant

GENERATIONS OF RADAR

1. Introduction

Technology and its uses evolve in stages. No sharp line separates these -- or any other -- historical periods. The activities begun in one era continue throughout all subsequent periods, almost always on a continually expanding basis.[1] The history of radar and related technologies provides copious examples of this principle. I see three major generations of radar to date, based on the capability to extract information and use it: the basic pulse radar, the radio-frequency (rf) coherent radar, and the digital-computer-embedded radar. I shall outline some of the generic events and advances in radar development and use, and include some illustrative details. The term radar refers to a system or technique for determining the position, motion, and characteristics of a remote object by radio waves reflected from that object. The term also applies to the operating equipment.

As with any human activity, there are social, political, organizational, and economic issues and conflicts, but the technical history is central to the story. Let us start before the technology relevant to radar even appeared. Figure 1 illustrates the vast extent of the electromagnetic spectrum, with no limit to the higher frequency at the top, to DC below. On the left are notations of various bands as commonly used now, from low frequency (LF) through the visible and into the ultraviolet range.

Prior to the work of Heinrich Hertz, just over one hundred years ago, the only knowledgeable use of the electromagnetic spectrum except DC was a band in the visible and the near infrared portions, where radiation is detectable by human senses. The remaining portions of the spectrum were alive with nature's manifold activities, but no one knew about that. In Germany, in 1886-90, Hertz carried out fundamental research at 6 m and 3 m wavelength in the VHF portion of the spectrum, at 60 cm in

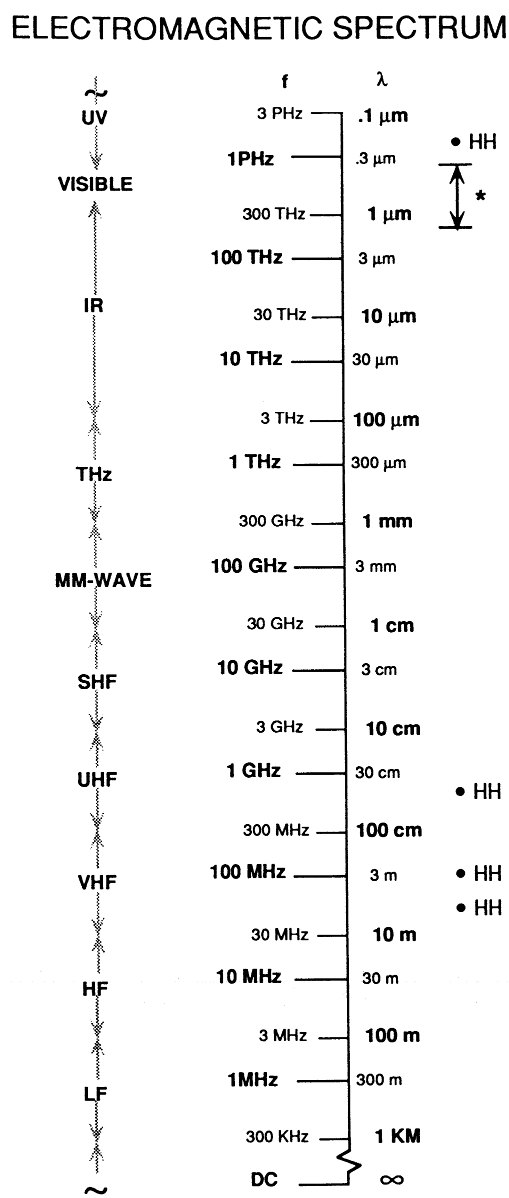


Figure 1. The only knowledgeable use of electromagnetic spectrum prior to 1886, except DC, was in the band comprising the visible and near infrared regions (marked by the asterisk) where radiation is detectable by human senses. Hertz conducted electromagnetic experiments in four specific wavelength regions, noted by "•HH".

UHF, and somewhere in the ultraviolet range.[2] He demonstrated for the first time the generation and detection of radio waves. He went on to demonstrate their optics-like properties of reflection, refraction, and rectilinear propagation. Hertz also showed that these waves travel at a velocity equal to the velocity of light. These observations are relevant to radar, but five decades of technological development stood between Hertz's demonstrations and practical radar.

Hertz, the scientist, took no steps beyond scientific research, but others started almost immediately into scientific and practical investigations. The first practical uses of radio waves included wireless telegraphy, diathermy, radio communications and broadcasting, and radio direction finding. Practical uses were at low frequency, due to the limitations of technology as well as the lack of appreciation that frequencies of VHF and higher were usable. Radio amateurs helped to discover these frequencies' usefulness. Radar and communications needs gave the urgent incentive, and fostered support to exploit the higher frequencies.

2. Radar Prior to 1940

In Great Britain in 1934, the Committee for the Scientific Study of Air Defense was formed "to consider how far recent advances in scientific and technical knowledge can be used to strengthen the present method of defense against hostile aircraft."[3] Headed by Henry Tizard, with two other scientists and H. E. Wimperes of the Air Ministry, this committee and its supporters have been duly credited with crucial accomplishments. Most importantly, the Fighter Command of the Air Force was an active and essential participant.[4] (see chapter by Beyerchen)

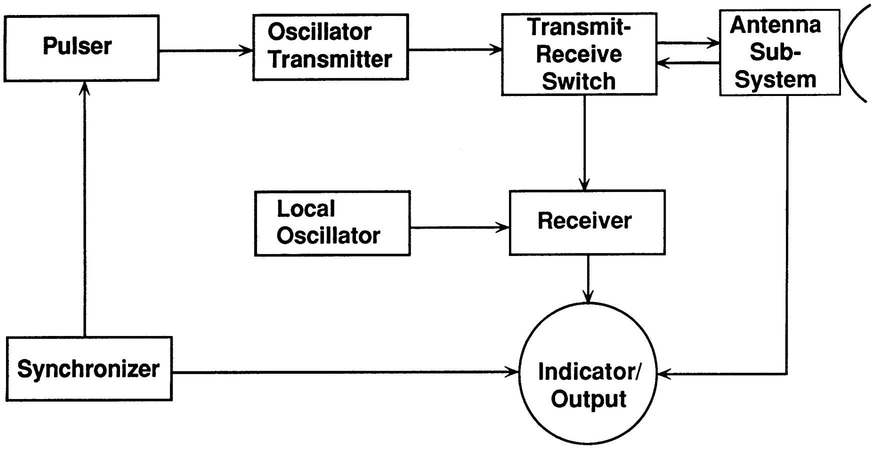
The development of basic radars was initiated in several countries in the mid-1930s, but only those of Germany, the United Kingdom, and the United States had major operational impact. Radar development at that time required no major technical breakthrough. Instead, it entailed the widespread adaptation and extension of existing technology plus the development of a few new components peculiar to radar.

Every country ended up with about the same basic system. With many refinements, and in many adaptations, the simple radar system shown schematically in Figure 2 found widespread use. This can be called the first generation of radar. The information on targets obtained by such radars is limited to one parameter: position. Range is obtained by measuring the time between occurrence of the transmitted pulse and receipt of the return echo, and direction from the angular direction of the antenna. In addition to the display as an output, there might also have been a weapon controlled by the radar. Certain radars were equipped for rudimentary height finding. Target tracking, to estimate speed and direction, was done by manual plotting of periodic position information. Because of the military applications, each country did its development independently. The literature in the field shows no successful efforts at espionage. On the contrary, it appears that workers in each country tended to believe themselves ahead of others in radar development.

Electron tubes were very often the pacing item, especially (1) to produce high peak power in very short pulses, and (2) to move higher and higher in frequency. With all other parameters constant, the maximum range of a radar is dependent on the average power transmitted. Reducing the minimum detectable range and increasing range resolution each require shortening the transmitted pulse. Without pulse compression (a technology of two decades in the future), the tendency was to increase peak power to maintain average power as pulse length was made shorter.

Some radars that came into use prior to 1940 are listed in Figure 3. The British home chain (CH) radar was the first radar in extensive operational use. This, and succeeding British achievements, are especially a tribute to the successful initiative of British scientists, starting in 1935, to apply science and technology to national defense; and also a tribute to the cooperation of certain officers of the armed services.

Noted also are three developments in technology in the United States in 1936-37 which were destined to extend the usable portion of the radio spectrum into the region we now term microwave[5]: the resonant cavity circuit, the klystron electron tube, and



RADARS PRIOR TO 1940

- **HF Radar. UK: CH radar, 1937**
- **VHF Radar. Ger: Freya (GEMA), 1938**
- **UHF Radar. Ger: Seetakt (GEMA), 1938**

Particularly Significant Developments:

- **The plan position indicator (PPI)**
- **Identification of friend or foe (IFF)**
- **Microwave technology**
  - **The resonant cavity circuit**
  - **The klystron**
  - **Coaxial and waveguide transmission lines and components**

Figure 2 (top). Basic pulse radar system block diagram. With this system, the receiver detects the presence of, and yields amplitude information on, a remote object using radio waves reflected from the object. Range to the object is obtained by measuring the round-trip time of the radio waves, and the direction is obtained from the antenna pointing position.

Figure 3 (bottom). Radars, and some particularly significant developments affecting radar, prior to 1940.

coaxial and waveguide transmission lines and components. These technologies found their way to Great Britain in early 1939, and aided in the successful search for the main missing component for microwave radar: the cavity magnetron.[6]

A major factor in the scientists' effectiveness in the United Kingdom was the "old-boy network" that transcended organizational boundaries. It very likely transcended military security at times, but with no leaks. It must be a tribute to certain high-ranking individuals that funds were awarded to start the civilian establishment under Robert A. Watson-Watt to develop radar. That support continued in succeeding phases, even when progress may not have been too evident.

The work of Watson-Watt, his successor, A. P. Rowe, and their colleagues is characterized by their recognition that a radar set is part of a system. They planned and built an operational CH station on the Bawdsey Manor site (on the east coast of Suffolk) where radar was being developed. That station was turned over to the RAF for operation in 1937. A radar school to train operators and technicians was established at Bawdsey, and development work on identification of friend or foe (IFF) and airborne radar was undertaken at an early date. Operational research programs grew out of studies in Fighter Command on use of radar-derived information for optimum use of fighter aircraft for defense.

Meanwhile, in the United States in the 1930s, much public sentiment was isolationist. Pulsed radar development took place in two military laboratories: the Naval Research Laboratory (NRL) in Washington, D.C., starting in 1934, and the Signal Corps' laboratory for ground equipment at Fort Monmouth, New Jersey, in 1936. Both programs were chronically short of money. In contrast with Great Britain, U. S. work on radar development was initiated by engineers in government laboratories rather than having been instigated by government officials and senior scientists. Contact was not established at high levels of government and the military, nor was there consultation with senior scientists. No airborne radar development was initiated. Contacts with officers in the operating commands of the armed services was minimal.

3. 1940

1940 was a watershed year for radar, as illustrated in Figure 4. Additional VHF and UHF radars came into use. The cavity magnetron was perfected in the United Kingdom, quickly placed in production, and used in experimental microwave airborne and shipboard radars.

In 1940 in the United States, scientists started a successful initiative with the formation of the National Defense Research Committee (NDRC), dedicated to bringing the principles of science to bear on problems of warfare. A year later it became the Office of Scientific Research and Development (OSRD).

In Germany, as I understand it, a similar initiative by scientists was not possible because National Socialists, who took control in 1933, distrusted the scientists. Neither a network of scientists nor any other such group could have existed in Germany. Radio amateur activity was essentially banned at the same time. Enrollment in technical universities declined sharply. At the beginning of the war, German engineers and scientists were drafted into the armed services (see chapter by Kern). Even so, excellent radars were designed and developed in Germany by industrial companies.

The timing of establishing the NDRC was excellent for this organization to host the British Scientific Mission to the United States and Canada, led by Henry Tizard and better known as the Tizard Mission. Great Britain had urgent needs for greater engineering and production capability and capacity to make use of proprietary technologies in ordnance, chemistry, mechanics, materials, and electronics, which included radar, communications, and navigation.

Arriving in September 1940, the Tizard Mission members brought their knowledge and showed how to use it. They brought manufacturing drawings, equipment, operations manuals, and reports, along with details of their newest research results, including the cavity magnetron. They recommended the formation of a civilian organization dedicated to the development and application of radar,

NEW RADARS IN 1940

- **VHF Radar**
  - **Ground**
    US: CSAM (NRL), SCR-268, 270, 271 (SIG C)
    UK: CHL (RAF), GL2 (Army), Type 79 (Navy)
  - **Airborne**
    UK: AI MK IV (RAF)
- **UHF Radar**
  - **Ground**
    G: Würzburg, 55cm (Telefunken)
    US: CXAS, 60 cm (BTL)*
- **Centimeter-wave radar**
  UK: Experimental, 10 cm, Airborne and Shipboard

* Adapted to 40 cm in substituting a magnetron transmitter, designated FA or MK 1 by the Navy.

Figure 4. New radars in 1940

patterned on the British experience. The establishment of the Radiation Laboratory at the Massachusetts Institute of Technology (MIT) was one result. This became a focus of microwave radar design, development and application, as did the Bell Telephone Laboratories.

Thus, the British radar program was successfully transplanted to the United States and Canada. From then on the program was a combined effort by these three countries. Since the American engineering and production capacity was much larger than that of the United Kingdom, use of the British knowledge and experience was greatly expanded. What could not be transferred to the United States was an understanding on the part of operating commands of the armed forces of the potential of radar, or even the need for it. A major task of the OSRD and the MIT Radiation Laboratory staff members was to try to remedy that problem. By mid-1940, American industry executives were in the process of converting and expanding their operations to supply wartime material to Great Britain, and were able to take on new war-related work with little problem.

4. 1941-45

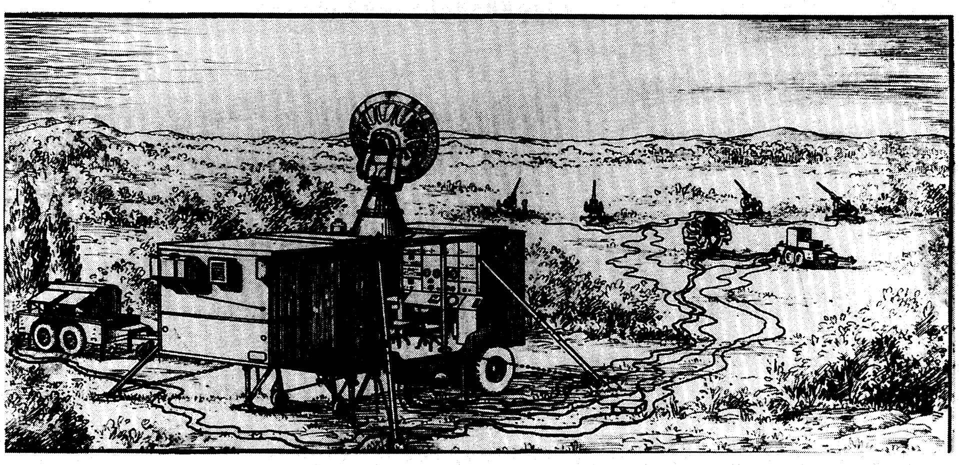
Intensive Radar Development and Applications

The development and application of radar moved rapidly in this time period. Literature in the field is extensive (See bibliography chapter by Brown). Most of the basic features of radar were discovered, and many were exploited. A wide variety of systems and uses evolved. The types of radars included early warning, gunlaying, airborne interception (AI), ground control of intercept (GCI), air to surface vessel (ASV), ground control of approach (GCA), blind bombing, navigation, fire-control, and weather monitoring. These included a wide range of specific radars used on land, sea, and in the air. We shall sample just a few items.

Two Specific Radars

Consider two specific radars, each representative of the state of the art in their class. The SCR-584 radar is illustrated in Figure 5, with a gun battery. Designed for gunlaying, this radar does automatic tracking with high accuracy: plus or minus .06 degrees in angle, and plus or minus 25 yards (23 m) in range. Such high accuracy reflects great strides in analog control system design and implementation: conical scan angle tracking and leading-edge range tracking, for example. The SCR-584 radar also found many applications other than gunlaying.

The Microwave Early Warning (MEW) AN/CPS-1A radar, the antenna assembly and pedestal of which is shown in Figure 6, was first operational in 1944. It had several uses including early warning, ground controlled intercept (GCI), and air traffic control (ATC). It comprises two complete radar sets, with back-to-back antennas. The low-beam antenna shown on the right gives a high-gain beam for long range; the high-beam antenna on the left gives a shorter range, higher altitude beam. The antennas are 25 feet (8 m) wide, giving a beamwidth of about 8/10 of a degree. Note the smaller antenna on top, for IFF, which we now call secondary surveillance radar (SSR) (see chapter by Trim). The transmitter and receiver units are mounted in the enclosures below the high-beam antenna. In an adjacent control center there were multiple displays of two types, each giving map-like presentations: (1) plan position indicator (PPI), using polar coordinates (range and azimuth), and (2) B-scan using rectangular coordinates. The azimuth could be read to an accuracy of about 1/4 of a degree. The range resolution is about 300 feet (100 m), corresponding to one-half the pulse length (about one microsecond.) Target plotting was manual, with three or four plotters working behind a large translucent screen. A separate radar was required for height finding. At most, 15 or 20 targets could be plotted at any one time[7], in contrast with present day surveillance and tracking radars that can automatically acquire and track hundreds of targets simultaneously--and display the identification, heading, speed, and altitude.



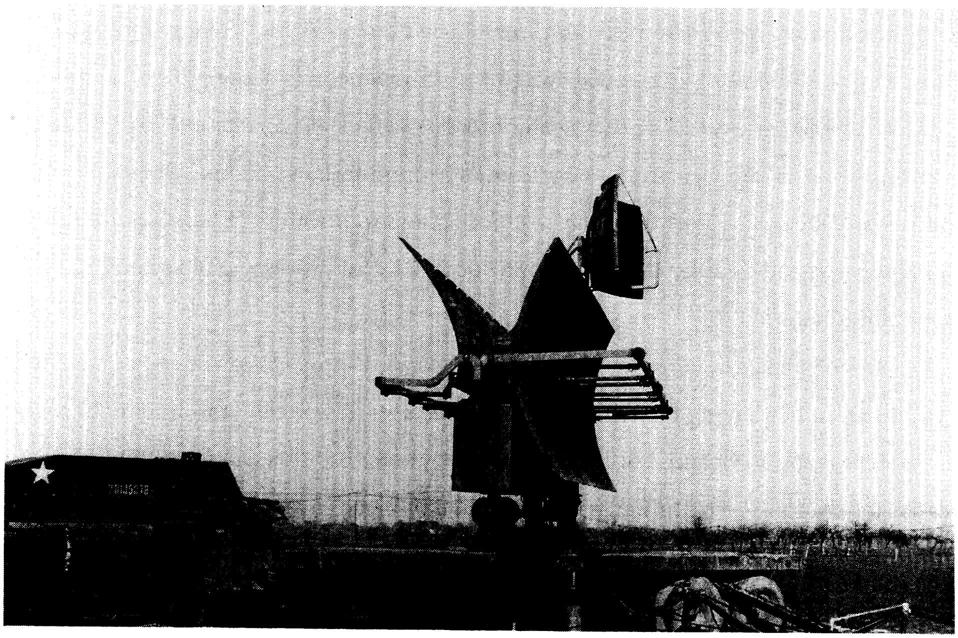


Figure 5 (top). SCR-584 radar, shown with a gun battery (MIT Museum).

Figure 6 (bottom). Microwave early warning (MEW), AN/CPS-1A, radar antenna assembly and pedestal (MIT Museum).

Moving Target Indication (MTI)

The full potential for certain applications had to wait for missing technology to evolve in the post-war period. An urgent requirement was to separate targets from clutter, that is, from strong echoes from the ground and stationary objects. This was a severe problem, since the signal return from clutter is typically orders of magnitude greater than from an aircraft. Very late in the war, useful methods were developed which substantially reduced the effects of clutter. The full potential of MTI came only with RF coherent radar, however, which was a technology of the 1950s and 1960s.

Propagation

A knowledge of propagation of radio waves is essential to overall success in radar applications. As technology was pushed to shorter wavelengths, the radar equipment often represented the first instrumentation available. When long-range 10 cm radar was first used, it was discovered that thunderstorms show nicely on the display, due to backscattering from water droplets. Pilots were surprised and pleased when controllers directed them away from or around thunderstorms. Radar information became a part of weather reporting and forecasting. The full potential, however, awaited doppler radar and sophisticated signal processing of second generation radar.

In one instance, radar development got ahead of propagation studies. No harm was done for not having carried out propagation tests at wavelengths around 10 cm in S-band, or 3 cm in X-band, but a limiting problem--atmospheric attenuation by water vapor for the long distance transmissions of radar--came to attention for radar at 1.25 cm in K-band.[8] Prior tests could not have readily been made at any of these respective cm wavelength bands because the radar sources, receivers, and test equipment being developed represented the first instruments suitable for the tests. These tools, and other wartime radar developments repaid radar's debt to basic science (see chapter by Forman).

Even with the remarkable progress in the 1935-1945 decade of intense military development, the full potential of radar had not been exploited. Advances had merely set the stage for decades of dramatic change that we have witnessed since then.

5. 1945-50

Readjustment, and Fallout Benefits

Legacies of World War II include new and improved products and services, new and expanded industries, new patterns for the organization of research, new professions, and notable changes in engineering education. After the war, in the United States, there was a trained labor force, new and enlarged industrial resources, and pent-up demands for consumer products, and markets for commercial exploitation of new technologies developed during wartime.

In the United States, the OSRD with its several laboratories quickly shut down. Most of the scientists returned to universities, some to industries. There was a scramble to fund research at universities, initially by the Armed Forces agencies and the Office of Naval Research, followed by other government agencies. This was a major factor in the United States' becoming the leader in science. By contrast, in Great Britain, funds went to strengthen government-sponsored laboratories while universities needed more support. In the United States, laboratories patterned on the MIT Radiation Laboratory were established at universities, including the Lincoln Laboratory at MIT, and laboratories at Columbia, the California Institute of Technology, and the Universities of Michigan and Illinois. Rosters of committees advising the military agencies read like a Who's Who of key members of wartime research laboratory experience. New "think tanks" were formed to engage in study of strategic and operational problems of defense and offense. At the same time, however, the operational effectiveness of radar declined compared to that at the end of World War II. Neither the advanced equipment nor a roster of trained and experienced manpower and organization was preserved. With the beginning of the Korean war (1950), these neglected needs became evident.

Civil and Commercial Applications of Radar

One application that had urgent need for radar, but did not require a very sophisticated system, was marine navigation. Soon after 1945 several manufacturers introduced small, lightweight commercial radars which pleasure boaters and fishing boat owners could afford. These initially made use of low-cost magnetrons and other radar components from large-volume military production. Similar radars were soon standard on ships, both local and ocean-going, for navigation and anti collision purposes. Rather conventional weather-avoidance radars appeared on commercial airliners, enabling them to fly around thunderstorms.

New Crises

On the international scene, several events gave rise to urgent new demands on operational capabilities involving radar which helped ensure that radar development would continue being carried out primarily on military programs. The Berlin blockade (1948) and other events signaled the onset of the Cold War. An atomic bomb test by the Soviet Union (1949) brought into sharp focus the fact that North American continental air defense was practically nonexistent in the face of intercontinental jet bomber aircraft carrying atomic weapons.

6. After 1950

A new generation of radar was in the making, deriving from much new technology, and from new engineering and scientific advances. The evolution of technology, including the transistor, the digital computer, fully coherent RF systems, and revolutionary advances in circuits and devices leading to drastic reduction in weight, size, and power consumption of electronic equipment has largely paced radar development over four decades of change. Added to this has been the development of communications theory, statistical methods, and extensive analytical work which could not have been done without powerful digital computers and their programmable software. Two books are recommended for their comprehensive descriptions of radars and radar systems from the 1950s into the 1980s.[9]

Radio Frequency Coherent Radar

A coherent radar utilizes both signal phase and amplitude to determine target location and characteristics. A stable (phase) relationship from pulse to pulse is maintained over many pulses so that their echoes can be compared in detail. Either the extraction of doppler information or pulse coding requires a high degree of coherence, for example. A major step in the 1950s (Figure 7) was to replace the transmitter magnetron oscillator with an amplifier--either a high-power pulsed klystron or a traveling-wave tube--as the final stage, and incorporating a highly stable oscillator for use in generating the transmitter signal, while also acting as the local oscillator. By this arrangement, phase coherence between transmitted and received signals is maintained, a major step in signal processing capability and the start of being able to use the 99 plus percent of information that is lost in the basic system. I term this the second major generation of radar. In addition to the location of a remote object, the detection and measurement of motion and other characteristics of the target became feasible with this new technology. This opened up a totally new world of options for radar design.

The tracking of moving targets among clutter, both moving-target-indication (MTI) and airborne moving-target-indication (AMTI), became practical and highly effective. The term "pulse doppler" was initially used to describe an MTI approach especially applicable to airborne radar to distinguish targets from severe background clutter and provide a vastly improved "downlook" capability. Such radars initially were analog (generation 2), and later in the 1960s they were digital (generation 3). Even from a moving platform such as an airplane, with strong signals from ground

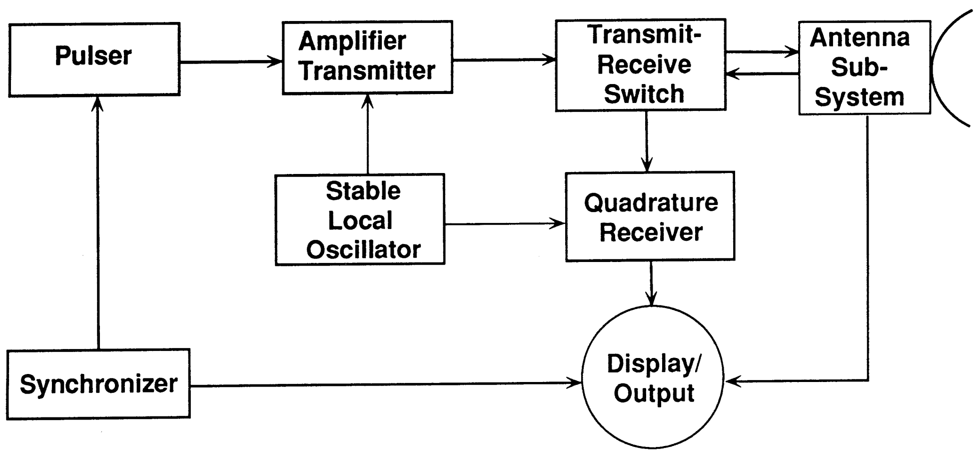


Figure 7. Radio-frequency coherent radar system block diagram. This system allows use of a quadrature receiver which yields both amplitude and phase information.

reflection, targets moving with respect to the ground can still be detected and tracked. Early pulse doppler radars extracted the velocity information using banks of filters. Later, this function was synthesized by digital processing (fast fourier transforms).

Great improvement in range resolution also became feasible and practical with coherent radar, while using moderate values of both pulse length and peak transmitted power. In one method, termed pulse compression or "chirp," the transmitted signal is linearly frequency modulated during the pulse, and the receiver is provided with a dispersive delay line that causes the returned signal for each pulse to be compressed into a much shorter pulse (this does require use of greater bandwidth).

Digital Radar Systems

In the United States in the early 1950s, the Semiautomatic Ground System (SAGE) used a digital computer to control the system. By 1960, a typical radar fire-control weapon system had a radar and a closely associated fire-control computer, but with development of each by separate contractors. Before long, the fire-control radar incorporated the computer functions. Progressively, digital technology replaced analog technology, with digitization of system control functions as well as signal processing (see Figure 8). Mathematical enhancement of weak or cluttered signals enables better detection and tracking abilities. Off-the-shelf components such as analog-to-digital converters, signal processing hardware, central processing, and memory and graphics processors may often be used and thus reduce radar systems' cost. Computer functions may control the rendering of output information in the different formats required by the various customers, as well as communications and data transfer. I call this the third major generation of radar. The line of demarcation between this and the previous generation is blurred in time, since the changes have generally taken place on an evolutionary basis. At the same time, numerous radars from generation 2, and even a few from generation 1 continue in use.

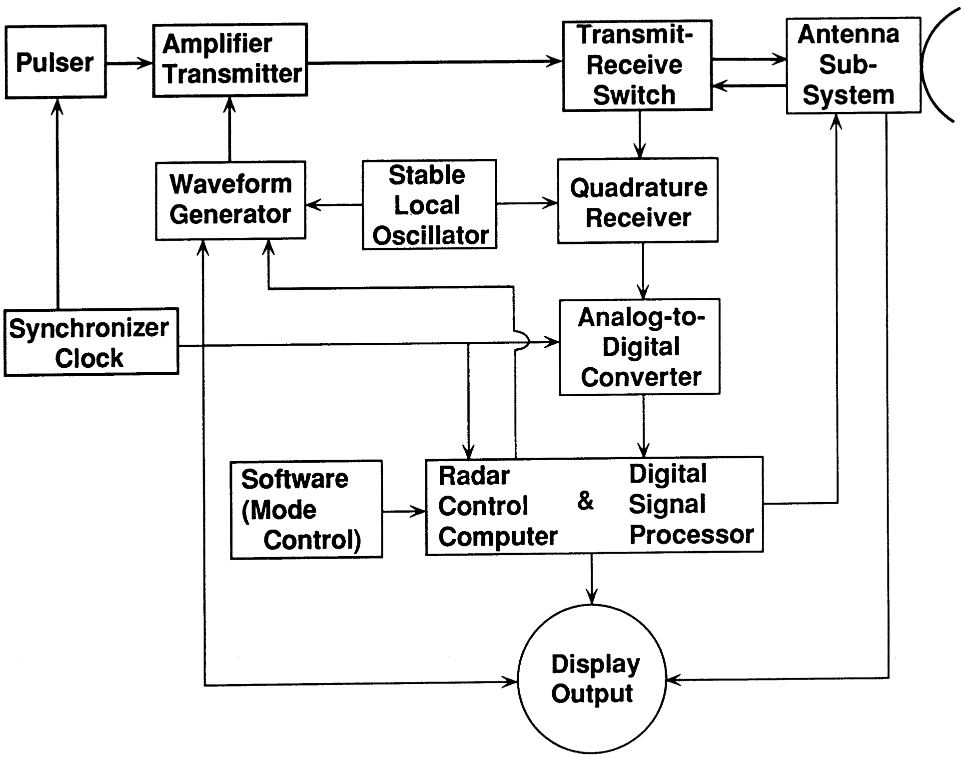


Figure 8 Digital-computer-embedded-radar system block diagram. This system affords enhanced detection, signal processing, control, and networking capability as compared to that shown in figure 7.

A Specific Radar System

One of the most successful and well-known examples of airborne pulse doppler radar is found in the Airborne Warning and Control System (AWACS), illustrated in Figure 9. AWACS development spanned the 1965-75 period. The reduction in size, weight, and power consumption of radars in three decades is dramatically illustrated by comparing physically the AWACS and MEW radar systems. The transportable MEW required eight trucks to move the equipment alone. The antennas are comparable in size. For AWACS, the complete radar with displays, maintenance staff and operators, command and control staff, and prime power are all accommodated in one large airplane.

Radar Meteorology

Radar meteorology is now 50 years old. Radar has played a prominent role in instrumentation for weather reporting, forecasting, and research. The use of radar took on new meaning with advanced technology, especially pulse doppler and digital signal processing. A comprehensive coverage of meteorological radar and its uses is given in a compendium of articles in Atlas (1990).[10]

Air Traffic Control

Since the early 1950s, the United States Federal Aviation Agency has made use of two series of primary radar sets: Airport Surveillance Radar (ASR) and Air Route Surveillance Radar (ARSR). The ASR is currently in the ninth generation, and the ARSR in the fourth. These radars have much greater utility than the MEW radar had, and operation requires considerably less manpower. The ASR and ARSR radars in fact operate unattended.

The ASR radars, with their displays remoted to the control tower for controllers to use, are highly automated. Each ASR radar operates in conjunction with a secondary surveillance radar (SSR) (see chapter by Trim). The antennas of these two radars share

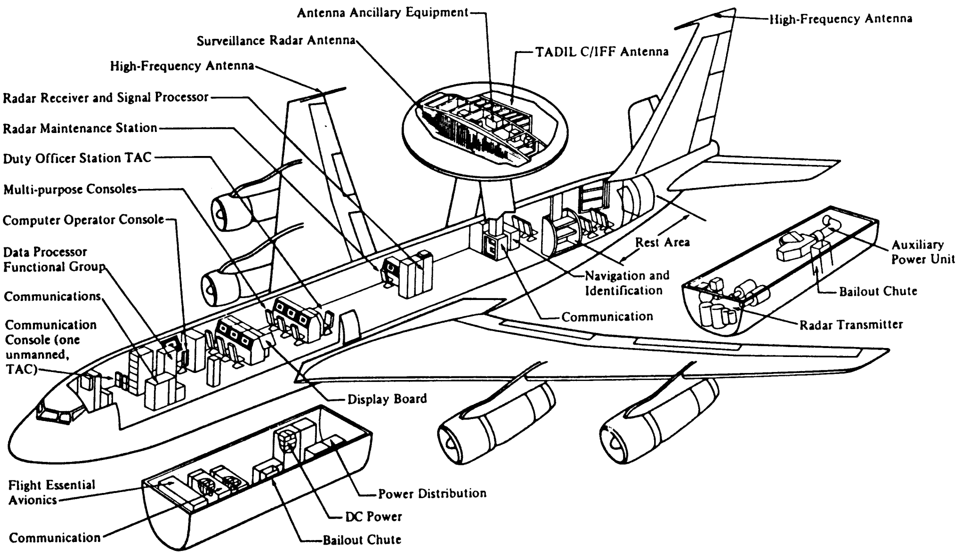


Figure 9 Schematic of the Airborne Warning and Control System (AWACS).

the same pedestal, and rotate together. The function of the SSR radar is to interrogate each aircraft in the vicinity, and receive that aircraft's identifying code and barometric altitude. These appear on the controller's display alongside the blip for each aircraft being tracked. The ASR-9 radar also has a weather reporting function. The more recent Terminal Doppler Weather Project, using the very sophisticated XRAD radar, is addressing a very urgent need: to detect wind shear conditions that may cause an aircraft to lose lift on a landing approach, and cause it to crash.

<u>Imaging Radar</u>[11]

Radar imaging also took on new meaning with advanced signal processing. By imaging, I refer to making a three-dimensional (3-D) image of a topographic surface, or of a physical object. Imaging radars take different forms, according to the mission. These forms include synthetic aperture radars (SAR), with the radar carried on a moving platform--an aircraft or a satellite--for imaging terrain features of the earth or planets, for example. Stationary radars may be used for imaging objects that move. These are known as inverse synthetic aperture radars (ISAR). The moving object can be an aircraft, a missile, an earth-orbiting object, or celestial objects such as the moon or planets or a passing comet. These are coherent radars that use range and doppler information to obtain the desired image resolution. Conventional pulse-compression techniques are used to obtain the desired range resolution, while the doppler frequency gradient generated by the rotation of the object field relative to the radar is used to obtain a cross-range angular resolution that is much finer than that obtainable by the radar's beamwidth.

<u>Over The Horizon Radar</u>

Although in development since the 1940s, long-range over the horizon (OTH) or sky-wave radars made their appearance relatively recently in the United States. The operating frequency is low, in the range of 5 to 30 MHz, making use of refraction of radio waves around the earth by the ionized layers of the stratosphere at these frequencies. The main attraction is long range, up to 4,000 km, and typically 800 to 3,000 km.

Low Visibility or Stealth[12]

Stealth for aircraft relates to six disciplines: radar, IR, visual, acoustic, smoke, and contrail. Shape is by far the biggest feature in reducing the radar cross section (RCS). This entails the design of outer surfaces to cause as much as possible of the incident radar signal to be scattered in directions other than back to the radar. This is a trade-off between electromagnetic scattering and aerodynamic design. Radar absorbent material (RAM) may be applied to the surfaces, and around seams, doors, and other access areas including engine inlets.

Laser Radar

In Figure 1, moving up on the frequency spectrum to the near infrared, laser radars have characteristics similar to microwave radars, except that the much shorter wavelength and shorter pulses allow greater accuracy, more precise resolution, and enhanced definition of target characteristics. Laser radars may be susceptible to instabilities of the atmosphere, and targets may be obscured by smoke, dust, or fog. Laser radars have been in use for about 25 years. Technological fallout for civilian benefit includes highly precise surveying. An indication that low-cost technology has reached this field is the recent appearance of laser radars used by police.

7. Conclusions

I see three major generations of radar, based on the capability to extract information and use it: (1) the basic pulse radar, capable of determining the position of a remote object, using radio waves reflected from the object; (2) the radio-frequency coherent radar, capable of detecting and measuring motion and other characteristics of the object, and (3) the digital-computer-embedded radar. No sharp line separates the generations in time. Features introduced in one era continue in use in subsequent periods, usually with continuing technological improvement and enhancement in performance and utility.

Generic examples of events and advances in radar and its uses have been sampled. Not mentioned are: radar astronomy, ultra-wideband, including impulse radar, and many other types of radar, or antennas and antenna systems; or electronic countermeasures, communications, and other ancillary systems and equipment, or work in the millimeter-wave and terahertz (THz) frequency ranges.

Radar systems are essential in air traffic control, weather forecasting and storm warning, remote sensing of the environment, and the safe navigation of aircraft and ships. Radar developed from the needs of the military, and military expenditure has financed a large part of the technology that we find in all radars today. The rate of advance since 1945 has been at least as great as in the 1935-45 decade of intense pressure, if measured by the utility of radar, the expanded applications of radar, and its cost effectiveness.

I wish to especially thank H. B. Smith and V. V. Liepa for consultation, F. T. Ulaby for support, and Bonnie Kidd for help with the illustrations.

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4. Including especially Air Vice Marshal Sir Hugh Dowding, Air Member for Research and Development at the Air Ministry, and Commander-in-Chief of Fighter Command during the Battle of Britain.

5. Referring to Figure 1, the microwave region, based on technology employed, includes approximately the top half of UHF, all of SHF, and most of the MM-Wave band.

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7. This was not an absolute limit, since each controller had a PPI display, and could select any desired target.

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Herbert Kümmritz

ON THE DEVELOPMENT OF RADAR TECHNOLOGIES IN GERMANY UP TO 1945

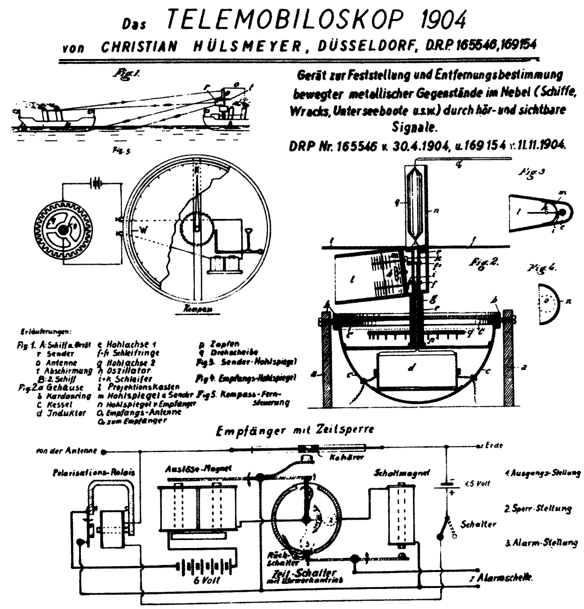
Introduction

The physical origin of radar can be found in the reflection principle. Thus, German scientists spoke first of reflection technology and only later of radio measurement technique (Funkmeß).

The reflection principle was first applied practically in Germany by Christian Hülsmeyer, who attempted to prevent ship collisions by means of his "Telemobiloskop" patented in 1904. (See Fig. 1) Although he could prove ranges up to 3km in his demonstrations reflecting off of ships in Rotterdam harbor, he generated no interest in his idea in technical circles.

1. Preliminary experiments

The fast development of radio engineering, including tube development, prepared the way for radar. Parallel to experiments with microwaves in other countries, Rudolf Kühnhold of the NVA (Nachrichtenmittel-Versuchsabteilung der Marine) undertook experiments with electrical waves in 1930, following encouraging experiments with ultrasound. He studied the propagation, reflection, and detection of electrical waves. Kühnhold carried out experiments on 13.5cm waves in cooperation with Julius Pintsch AG, but the lack of suitable transmitting tubes proved to be a constant handicap. However, once they procured magnetrons from Philips in Holland, they could achieve ranges up to 2km against ships using 4000mW continuous wave (CW) output. The lack of suitable tubes and measurement instruments for cm-waves led to an early change to lower frequencies (i.e., longer wavelengths) and to a growing disregard for and long-term neglect of cm-waves in Germany. Work on the cm-wave was not resumed until the discovery of the British H_2S radar in 1943.



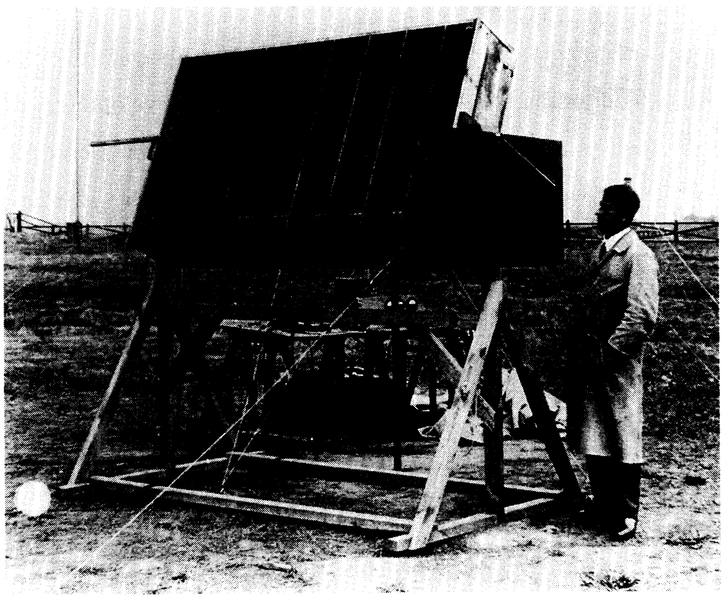


Figure 1 (top). "Telemobiloskop" by Christian Hülsmeyer.

Figure 2 (bottom). Wilhelm Runge with his first antenna for reflection measurements.

The company GEMA, which was established by Kühnhold's initiative, as well as Telefunken GmbH and C. Lorenz AG, commenced radar experiments in the 50cm band during 1935. The latter two companies sought to take advantage of their long-term experience in radio-link technology in this work. Fig. 2 gives the results of these first experiments at Telefunken. Using an antenna laid flat on the ground they could detect a Junkers 52 at an altitude of 5000m. In other words, they found that in addition to ships, they could also detect aircraft. The importance of this discovery increased with time.

By 1935 it was obvious that operation with pulse transmitters was essential. The NVA and other military sections agreed to develop radar sets according to the following parameters:

1. pulse operation of the transmitter;
2. receiver blocking during transmission periods;
3. range measurement by means of signal travel time measurement;
4. sensing by switching over the directional antenna patterns;
5. development of new tubes (magnetrons and decimeter-wave; and, triode valves)
6. 50cm wave.

Under the conditions of these parameters, radar development commenced in Germany, although without any clearly defined goals by the potential military customers. Lack of coordination and secrecy regulations constantly impeded development work. Thus it is scarcely surprising, that war-time radar developed in parallel in several places. Fig. 3 shows the parallel course of development by listing the most important families of radars in Germany. The five main fields, which will be explained below, are ground-based radar for air surveillance, fire control radar, tracking radar, airborne radar, and ship-based radar.

Significant German Radars 1938 – 1945

Year	Ground-based radar for air surveillance	Tracking radar (GAF)	Fire-control radar (Flak)	Airborne radar (GAF)	Ship-based radar
1938					SEETAKT (G) λ = 82cm, P = 1...8KW r = 20km later 91cm and 70cm
1939	A1, FREYA (G) λ = 2,4m, P = 8KW r = 130km		A2, KURFÜRST (L) λ = 62,4cm, P = 1KW r = 10...15km A3, DARMSTADT (T) λ ~ 50cm, P = ? r = 5...8km		
1940	WASSERMANN (G/S) λ = 2,4m, P > 100KW r ~ 300km		KURPFALZ / KURMARK (L) λ = 53,6cm, P = 50KW r = 25...40km WÜRZBURG A-D (T) λ = 53cm, P = 8KW r = 20...30km	experimental radars for ship-hunting e. g. NEPTUN (FFO) ROSTOCK (G) λ = 2,4m	
1941	MAMMUT (G/NVA/S) λ = 2,4m, P = 200KW r ~ 300km	WÜRZBURG RIESE (T) λ = 53cm, P = 8KW r ~ 70km	WÜRZBURG E (T) MAINZ (T) MANNHEIM (T) λ = 53cm, P = 16KW r = 25...30km	LICHTENSTEIN BC and C (T) (for night fighters) λ = 61cm, P = 1,5KW r = 4...5km	
1942	SEETAKT (G) (for coastal area) λ = 82cm, P = ? r = 40km			HOHENTWIEL (L) (for ship-hunting) λ = 54,5cm, P = 30KW r ~ 80km	
1943 July	Düppel/Window Panorama Radars JAGDSCHLOSS (S) λ = 1,2...2,4m, P = 30/150KW r = 80...200km			NEPTUN R (FFO) λ = 1,8m, P = 2KW r ~ 3,5km LICHTENSTEIN SN2 (T) λ = 3,7/4,1m, P = ? r = 4...6km	
1944	JAGDHAUS (L) λ = 1,4...1,8m, P ~ 300KW r ~ 150km JAGDWAGEN (L)			NEPTUN V2 (S) λ = 1,8m, P = 1,5...2KW r ~ 5km BERLIN A (T) (for bombers) BERLIN N (for night fighters) λ = 9cm, P = 15KW r ~ 5km	
1945	FORSTHAUS Z (T) λ = 9cm JAGDSCHLOSS Z (S) λ = 9cm, P = 100KW		MARBACH (T) λ = 9cm, P = 15KW r = ?		

Abbrevations: FFO = Flugfunk-Forschungsinstitut, G = GEMA, L = LORENZ, NVA = Nachrichtenmittel-Versuchsanstalt der Kriegsmarine, S = SIEMENS, T = TELEFUNKEN

Figure 3. Overview referring five radar families for five main applications.

2. Ground-based radar for air surveillance

Encouraged by the NVA, wanting to lose as little time as possible, and not anticipating success in the cm-wave field due to the lack of tubes, GEMA presented the surveillance radar A1 with the code name "Freya" in 1939. This radar was intended for aircraft reporting service. (See Fig. 4) The data of Freya, designed for azimuth and range measurement, is:

wavelength	2.4m
power output	8kW
max. range	130km
range accuracy	±150m
angle accuracy	±0.8°

Its first operational use was with an experimental set on the island of Wangerooge. It detected an approaching formation of British aircraft over the German Bight; German fighters were alerted and decimated the British fleet. (See Fig. 5) This was the first German air force action supported by radar. Freya gained importance as search and vectoring radar for German night fighters until it was jammed increasingly beginning in 1942. But it remained serviceable until the end of the war. Changes were made to Freya because its range was not adequate for actual aircraft reporting service. The transmitter power output and the antenna area of the Freya were increased, resulting in the long-range radar Wassermann (1940) and Mammut (1941-42), which operated on the same wavelength of 2.4m. Their data are:

wavelength	2.4m
power output	100kW and 200kW
max. range	300 km
range accuracy	±1000m and ±300m
angle accuracy	±0.3° and ±0.5°

Fig. 6 gives an impression of Wassermann's dimensions. Wasserman now made it possible to scan the air space from the channel coast to the midlands of England.

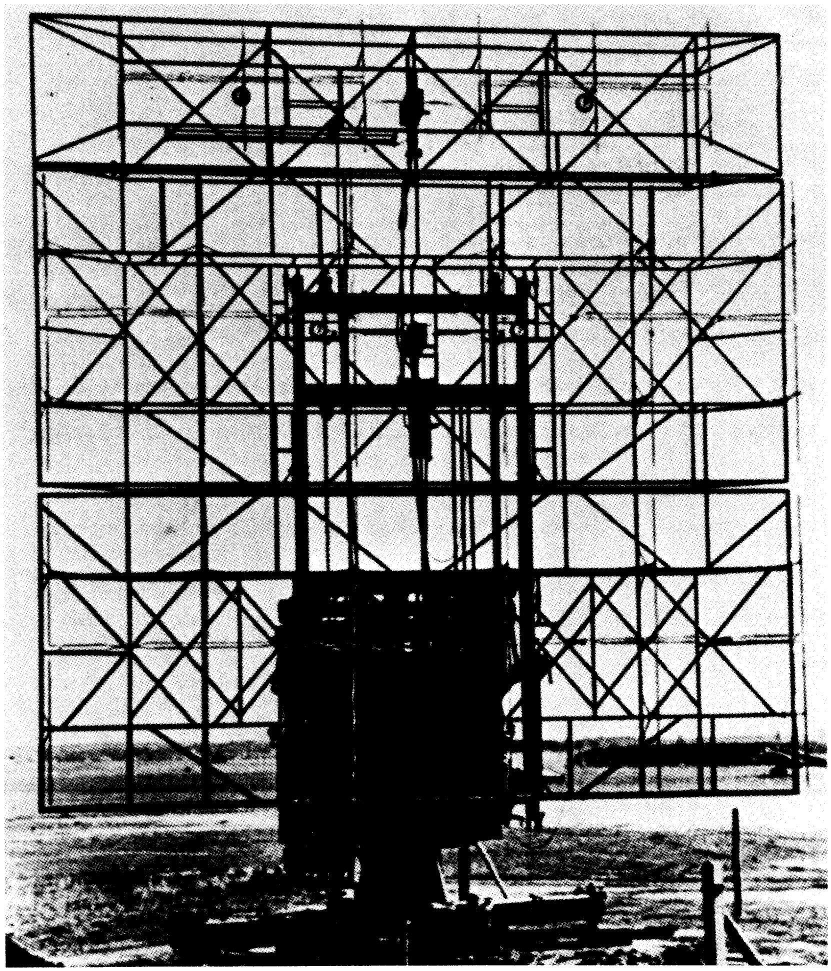
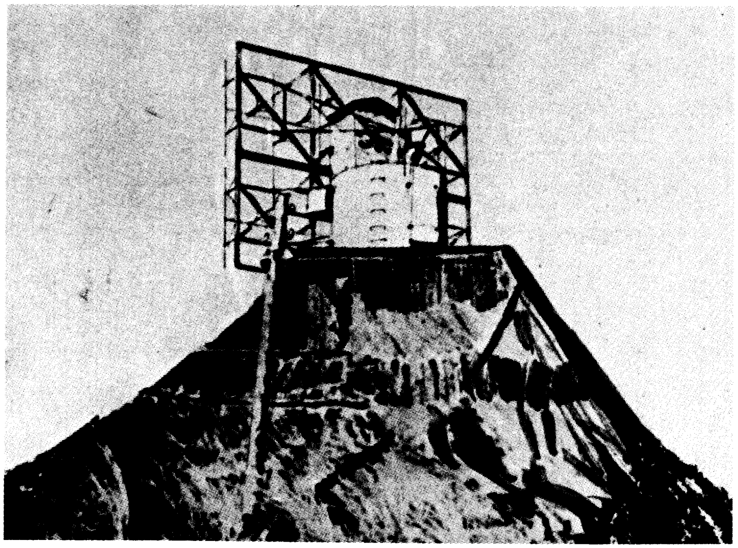


Figure 4. Freya Antenna.



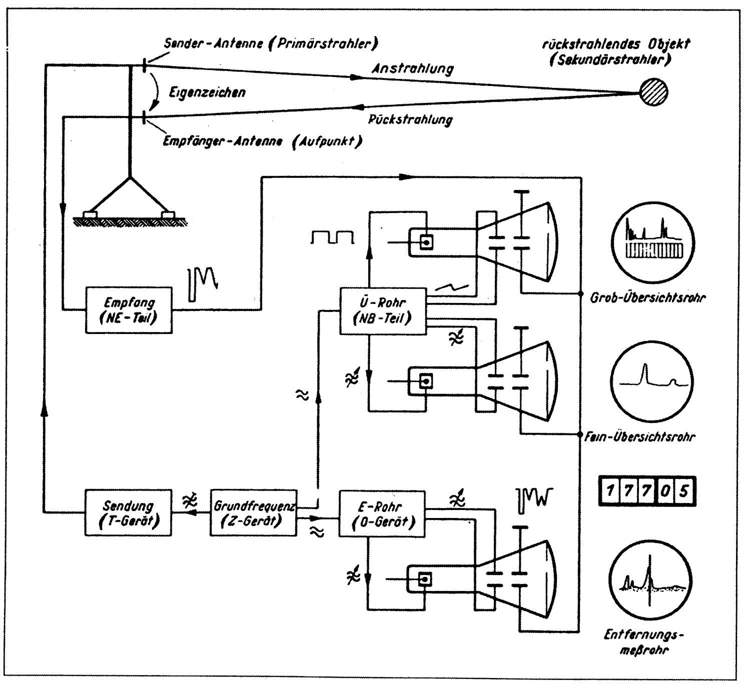


Figure 5. Freya; first experimental set on Wangerooge.

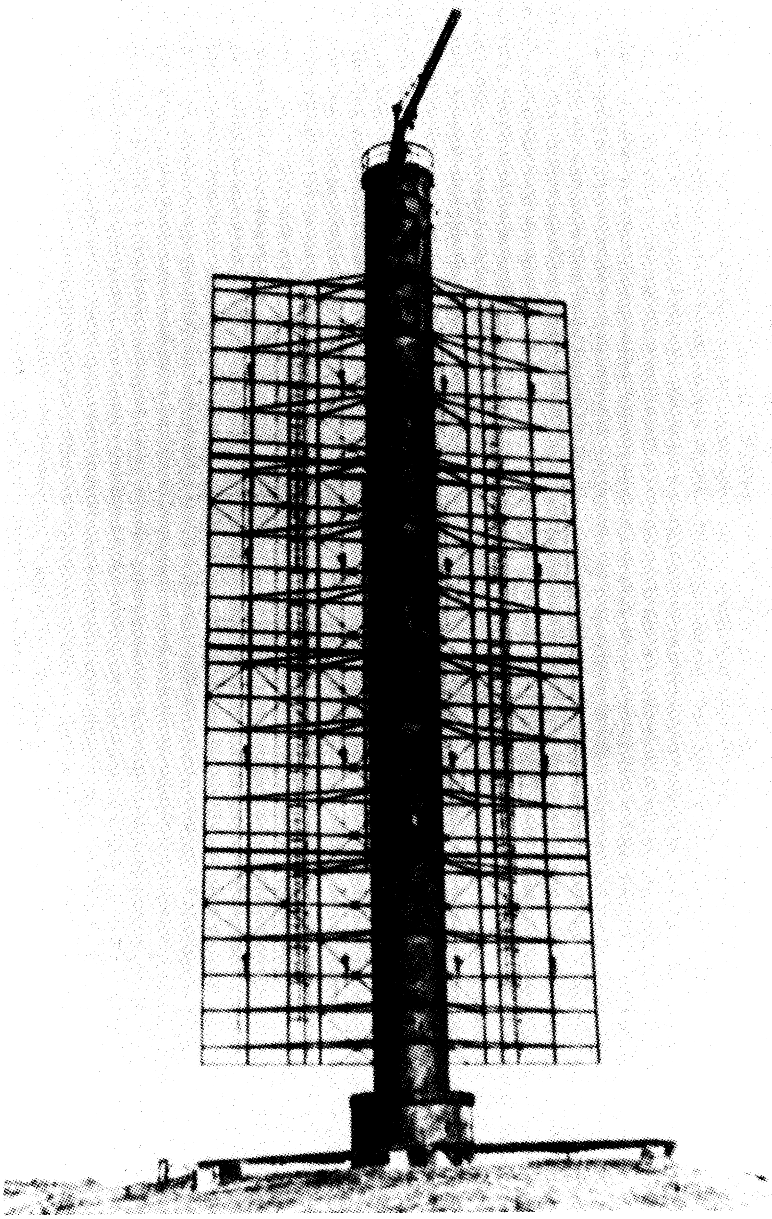


Figure 6. Wassermann S, beam swiveling by electronic means; height: 60m.

Aircraft taking off there could be detected in realtime. Seetakt, which completed the group of surveillance radars developed up to 1943, was derived from a naval radar also named Seetakt:

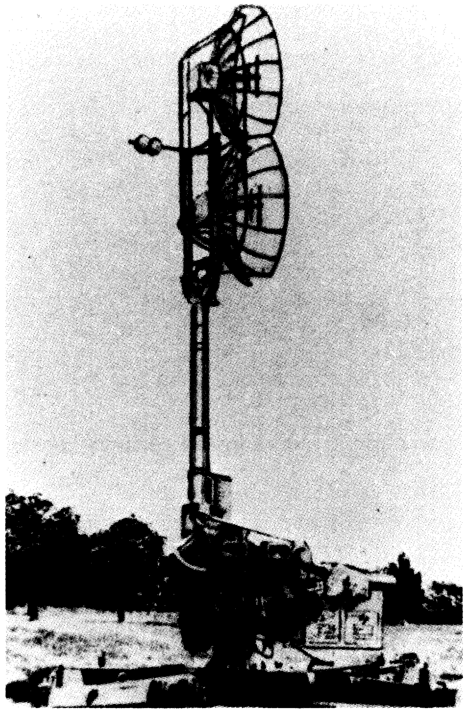
wavelength	82cm
power output	7kW
range	40km
range accuracy	±100m
angle accuracy	$\pm 1^{o}$

These stationary radars were employed along the German coasts and in occupied countries from 1942 onward.

3. Fire control radars

Lack of foresight and coordination combined with interservice rivalries and unsurpassed secrecy prevented the specification of clear objectives for fire control radar. The result was typified by the parallel development of fire control radars at Lorenz and Telefunken. The fundamental radar development pursued by Lorenz from 1935 onwards led to a series of sets called A2 (with code names Kurfürst, Kurpfalz, and Kurmark). These sets complied with all the specified requirements then discovered, but were inferior to those built on the Telefunken concept. Fig. 7 shows Kurfürst. At Telefunken Wilhelm Runge developed a very good design based on the "Spinner" dipole rotating about the focal point of the parabolic reflector. Using the Spinner, Runge had created not only a single-reflector unit for simultaneous operation but also the prerequisites for A/N-bearings (i.e. bearings by switching the two halves of an antenna array in succession) which were a considerable improvement on the customary way of taking bearings based upon maximum signal.

When Runge presented his set to Ernst Udet, the Luftwaffen Quatermaster General, in 1938, Udet indignantly replied that, "if you introduce that thing you'll take all the pleasure out of flying." (Pritchard, 1989, p64) This was the response from all the



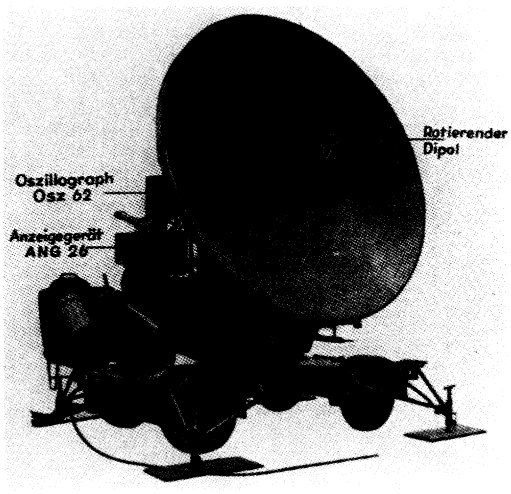


Figure 7 (top). First AA fire control set kurfürst with two antennas.

Figure 8 (bottom). Würzburg C with "Spinner" (Quirl) (rotating defocused dipole).

World-War I pilots, who did not anticipate the possibilities of electronics and RF technology for air warfare. This attitude was held at even the highest military and political levels.

Once Hans Rukop of Telefunken succeeded in developing a tube (LS180) in only four weeks with a peak output of 10kW at 0.5m, Runge was able to interest new customers with the range of 40km and the much smaller and mobile construction, than the Freya's. In the spring of 1939 the Luftwaffen procurement department ordered a small aircraft warning unit, which was demonstrated in April 1940 after a rapid development process at Telefunken. This was known as the Würzburg A radar (without Spinner). More stringent requirements by the antiaircraft artillery (AA) led to the fitting of the Spinner and more sophisticated signal processing circuitry. Würzburg C (Fig. 8), which later became the standard AA radar. Its data is:

wavelength	53cm
power output	8kW
max. range	25km
range accuracy	±50 to ±100m
angle accuracy	$\pm 0.5^{o}$

The Bruneval raid in February 1942 was the turning point for Würzburg A. After excellent reconnaissance, the British raiders were able to capture the frequency-determining parts of the radar which were needed for jamming. Fig. 9 shows Würzburg A in Bruneval, photographed by an English hunter. Later, during 1942, the Mainz and Mannheim radars followed as derivatives of the Würzburg. The Mannheim had considerably improved accuracy.

4. Tracking radar Würzburg Riese (Würzburg Giant)

One important derivative of the Würzburg was the Würzburg Riese. It was conceived as a fire control radar with increased range (70km) but was used for night

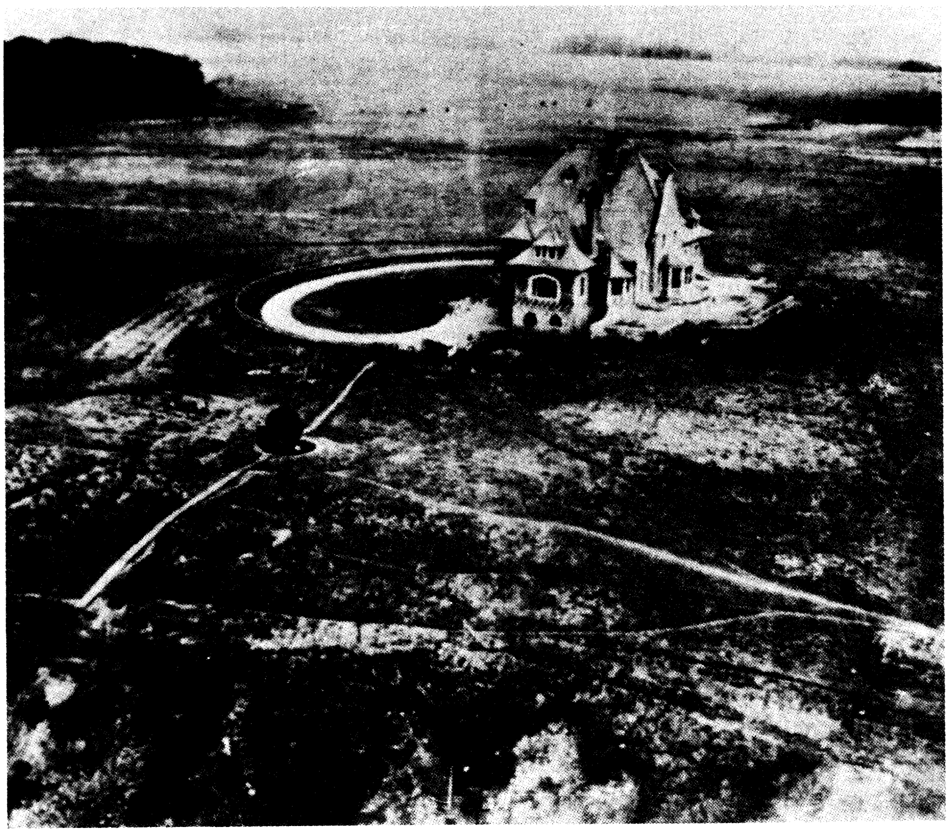


Figure 9. Würzburg A radar at Bruneval.

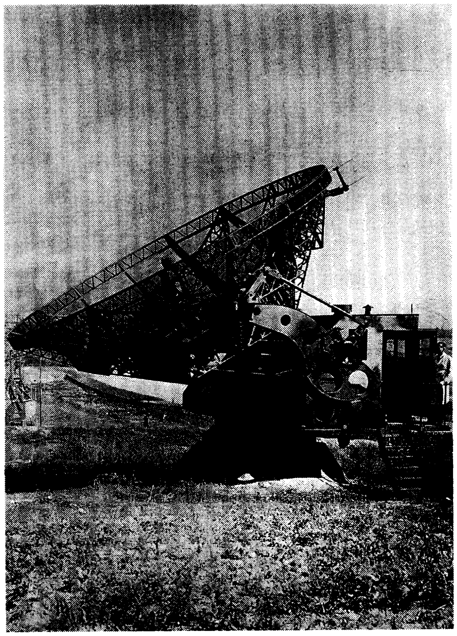
fighter control, as organized by Josef Kammhuber during 1941. (See Fig. 10) As a tracking radar, it quickly became the heart of the German night air defense. One set was used for the guidance of the night fighters, and a second set was employed for target tracking after vectoring by a Freya. Originally a stationary radar, it was installed on railway wagons and on the night fighter control ship Togo. (see Fig. 11) The data of Würzburg Riese is:

wavelength	53cm
power output	8kW
range	70km
range accuracy	±35m
angle accuracy	±0.15°

With its 7m reflector diameter, the Würzburg Riese remained an effective tool until 1943, when it was severely disturbed by jamming transmitters and windows (Düppel).

5. Airborne radars

Even before the war Runge had been working on an airborne radar to pull dive bombers out of dives automatically. In response to an request from General Wolfgang Martini for an airborne aircraft detector, Runge took this set as the design for the Lichtenstein family of radars, which was developed by Telefunken. They encountered unexpected difficulties with the slewed antenna pattern. The "Spinner" was replaced by an antenna consisting of four groups of dipoles with a rotating phase shifter. The pilots rejected this arrangement because it reduced speed and maneuverability. They demanded instead an antenna integrated in the fuselage. The conflict and the accompanying constant experimentation lasted almost a year until the sets could finally be supplied with the originally planned antenna -- very much to the annoyance of the night fighter pilots, who preferred to fly without the "mattress," as they called it, and who sometime simply sawed it off. Not until the end of 1942 were the sets accepted;



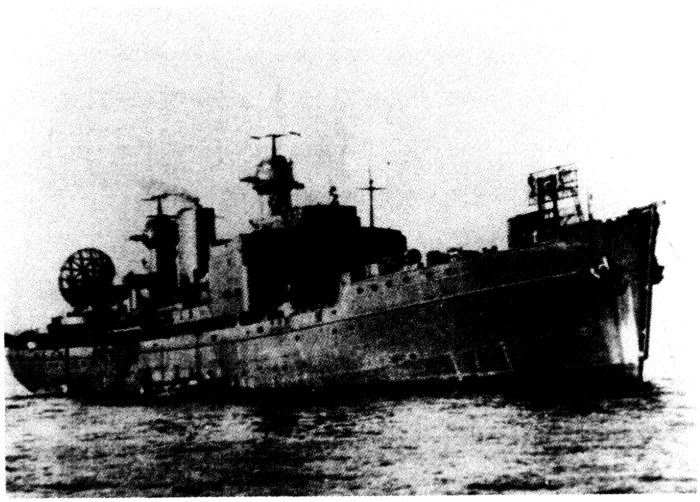


Figure 10 (top). 3D-radar set Würzburg Riese for night fighter guidance, 7.5 m reflector diameter.

Figure 11 (bottom). Würzburg Riese and Freya on hunter-guidance ship Togo.

then they were employed against hostile aircraft with growing success. The data of the Lichtenstein C is:

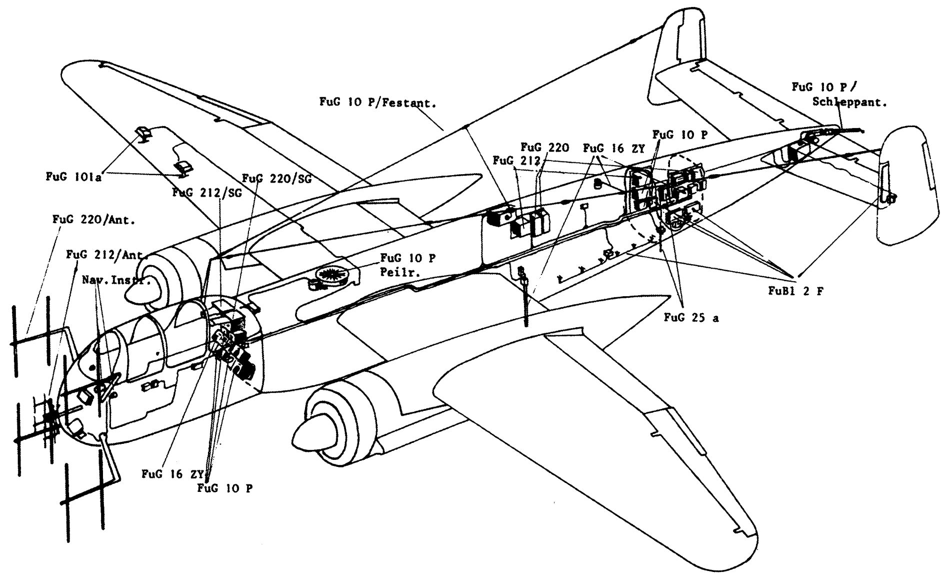
wavelength	61cm
power output	1.5kW
range	4 to 5km
range accuracy	±100m
angle accuracy	$\pm 2^{\circ}$

The elevation and azimuth deviation of the target with respect to the fighter were shown relatively by means of pulses on the cathode ray tube. The range was dependent on the altitude of the fighter because the ground clutter reduced the distance measurement, thus limiting the range to a distance corresponding to the altitude.

Starting in July 1943, the British, using windows, increased their jamming. As a result, the Germans developed new airborne radar sets with the ability to change frequencies, and especially with much longer wavelengths. The Lichtenstein SN2, for example, operated at wavelengths between 3.7 and 4.1m; and the Neptun set, developed at the same time by the Siemens AG, operated on a wavelength of 1.8m. The antenna dimensions are shown in Fig. 12 (Heinkel 219 with SN2 and LI C) and Fig. 13 (Me 262 with Neptun V2). Fig. 14 shows a rare and interesting representation of the planned night fighter Dornier 335 equipped with Neptun V1. Lorenz then began designing airborne radars for the detection of vessels. After more or less successful experiments with 2.4m radars, supplied by GEMA and Flugfunk-Forschungsinstitut (FFO) -- namely, Rostock and Neptun 1 -- Lorenz developed the extremely successful vessel search radar Hohentwiel.

6. Ship-based radars

The Seetakt radar, mentioned earlier in connection with coastal defense, originated from a naval radar of the same name developed by GEMA. It was the first serviceable radar set in Germany; it operated according to the prevailing opinion in



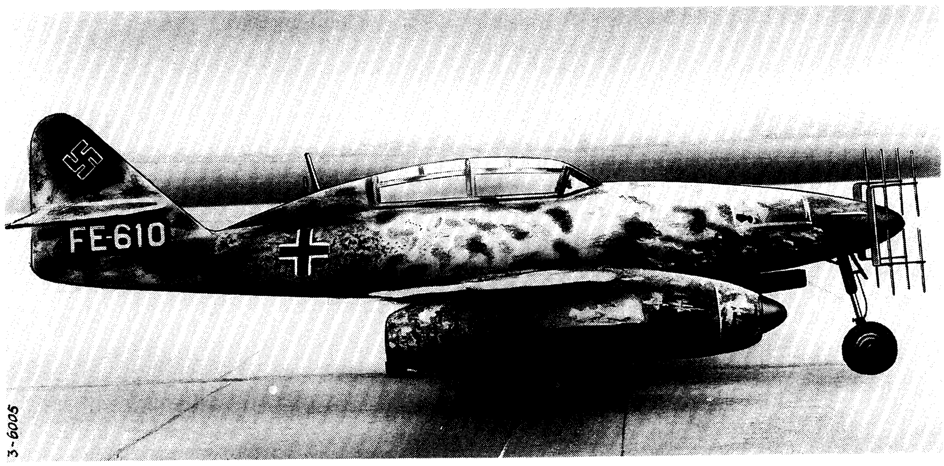


Figure 12 (top). Night fighter He 219 with two radar equipments.

Figure 13 (bottom). Night fighter Me 262 with radar set Neptune.

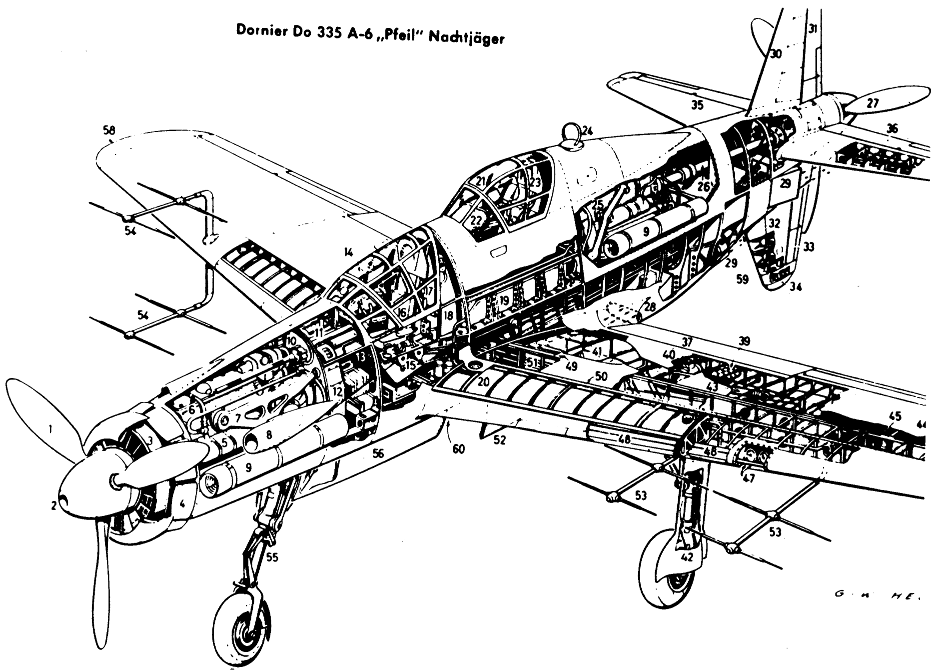


Figure 14. Planned night fighter Do 335 with Radar set Neptune V1.

Germany that radar must be employed first against ships. It therefore seemed logical to first equip both large and small ships. The first ship to be equipped with the Seetakt was the pocket battleship Admiral Graf Spee. Installation occurred during 1938-39. (see Fig. 15) The antenna arrangement was particularly interesting -- it was mounted in the plane of the optical rangefinder and moved with it. The data of this radar is:

wavelength	82cm (later 91cm and 70cm)
power output	1 to 8kW
range	15 to 20km
range accuracy	±70m
angle accuracy	$\pm 5^{\circ}$

7. Rotating surveillance radars

The situation in the air over Germany, which became more and more critical with the continuation of the war, compelled those responsible to call for new radar methods. Improvements could only be achieved with plan position indicators (PPI). Their method of operation was clear and simple; they scanned the entire air space by means of a constantly rotating radio beam. The PPI was relatively new, although an initial approach was available in form of the star writer (Sternschreiber). After preliminary work by GEMA, Siemens was able to produce the PPI radar Jadgschloss relatively quickly (1943/44):

wavelength	1.2 to 2.4m (switchable)
power output	30 to 150kW
range	80 to 200km

Especially because of its low susceptibility to jamming, it operated successfully and enabled the German military to keep the large-area air situation over Germany under control.

Lorenz introduced similar radar equipment under the name Jagdhaus in 1944-45. It was an improvement over the Jadgschloss, but it fell into the hands of the Russians

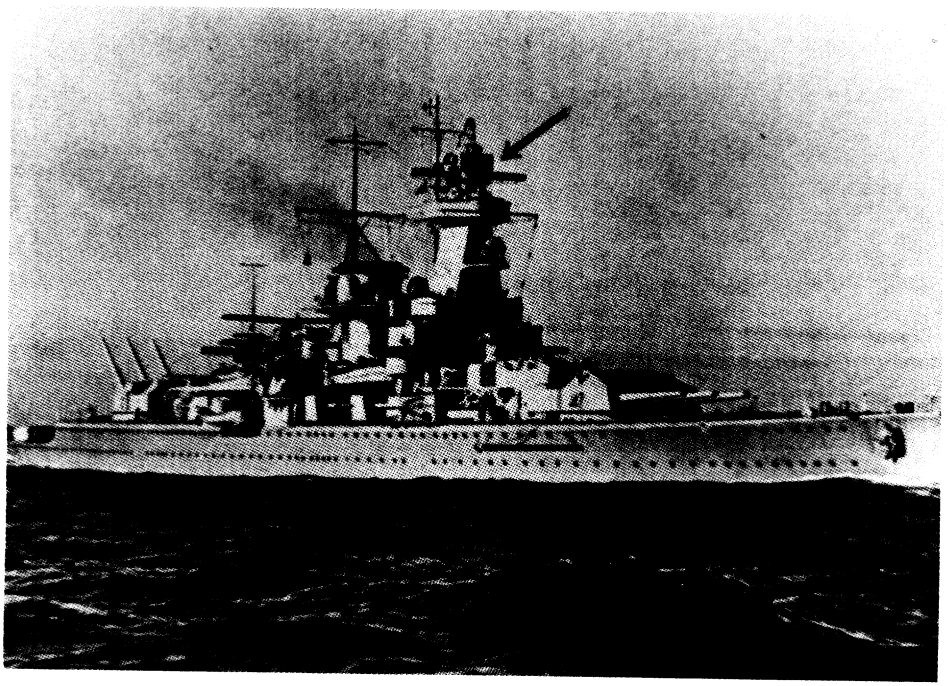


Figure 15. Pocket battleship Admiral Graf Spee with antenna of Seetakti radar.

in May 1945. Lorenz also developed the Jadgwagen for mobile operation. It achieved ranges up to 70km, using a wavelength of approximate 50cm. The third one of these produced also fell into the hands of the Russians.

8. cm-wave radars

The H_2S airborne radar, which was salvaged from a crashed RAF bomber near Rotterdam in February 1943 and reassembled by Telefunken, gave the German technical leadership such a shock that they allocated the highest priority to cm-wave technology. They pushed reproduction and development forward in the 9-cm range at maximum speed. The radar set Berlin was the German version of the H_2S. Developed originally as a ground surveillance set, like the H_2S, Berlin was modified (version N) to be an airborne search radar for night fighters when German bombing operations ceased; it was never used in operations.

The hectic pace that prevailed in the field of cm-wave development was transferred to other radar for other uses. The PPI radars, for example, were modified for a 9cm wavelength (Forsthaus Z and Jagdschloss Z) and operated experimentally with a pulse power of 100kW, until they were blown up by a German corps in April 1945. The 9cm radar Kulmbach was similarly designed as a PPI radar, but it was used for AA purposes. In combination with the fire control radar Marbach, which also operated at 9cm, Kulmbach formed the fire control system Egerland. (see Fig. 16) The end of the war in 1945 meant the end of all radar activities in Germany by fiat of the Allied Forces until 1953.

Conclusion

The goal of this essay has been to describe the technical development of radar sets in Germany until 1945. It has been shown that this technical development depended not only on the scientific and technical knowledge available in that period but also on military and political aspects -- including the mentality of pilots. In the present volume

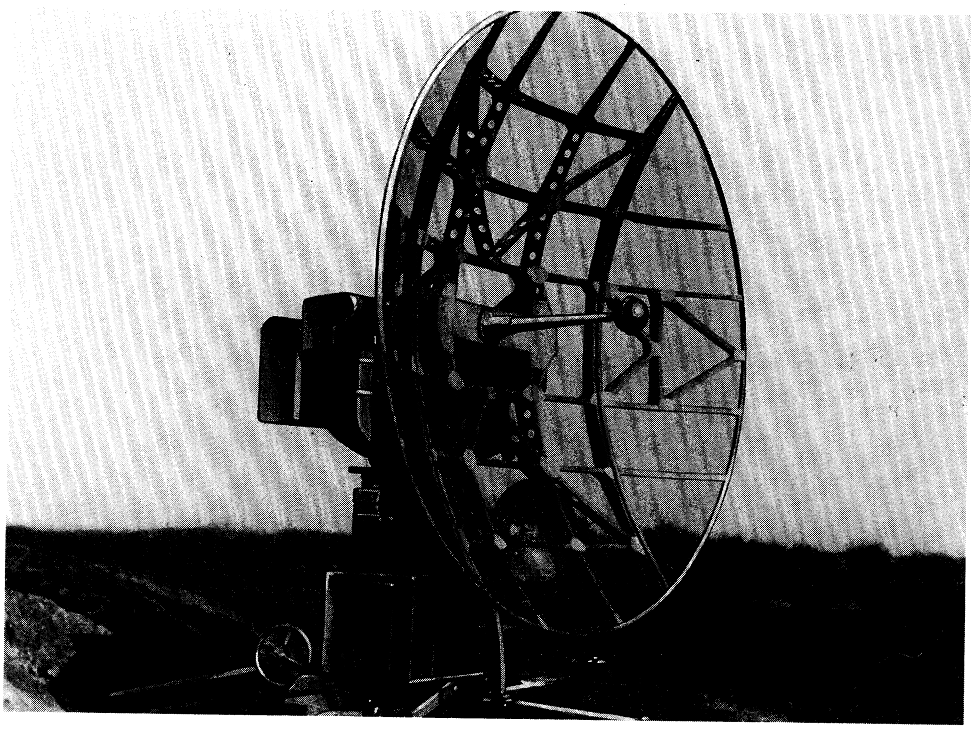


Figure 16. Fire control radar Marbach.

Ulrich Kern provides a more general historical reflection based upon the institutional and political background.

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Werner Gerlitzki

AN OVERVIEW OF RADAR DEVELOPMENT FROM 1950 TO 1990: TIME FRAME AND SOME COMMENTS ON DEVELOPMENTS IN GERMANY

1. Introduction

Driven by military needs, at the end of World War II radars and radar technology had reached a rather high status of maturity. The scientific and engineering work that was done from the 1930s to 1945 is well known and documented, and a summary of the German activities can be found in a number of publications.[1-3]

By 1945 the basic architecture of radar systems had been evaluated, the principles of pulse and CW radars from HF/UHF to X-Band frequencies and their applications for surveillance and target tracking on the ground and in the air were established and understood. However, due to the war effort, radar applications were primarily military.

In the decade following 1945 a rapid transition of this new technique into civilian fields followed. In particular, Airport and Air Route Surveillance by radar was established in ATC (Air Traffic Control), and GCA (Ground Controlled Approach) radar was introduced at all major airports to ensure safe approach and landing for commercial aircraft at night and under bad weather conditions. Further commercial applications were found as ship, weather, harbor and coastal radar was introduced. But during the decades of the cold war through the 1990s, military needs and requirements continued to provide the design drivers (and the funds) for new ideas, system designs and components.

Due to space constraints, my effort to trace the development of radar over these four decades (1950 - 1990), and to provide some outlook on the work done in Germany will only draw some basic lines and cover some of the essential highlights. Taking a look at the big trends in radar design over this time span, three different technological periods can be discerned:

- the time of the "analogue radar" from 1950 to the mid sixties
- a transition period far into the seventies, when digital components and the first computers were introduced into radar
- the time of the "digitized radar" up to this day.

2. The Post-war Era of the "Analogue Radar"

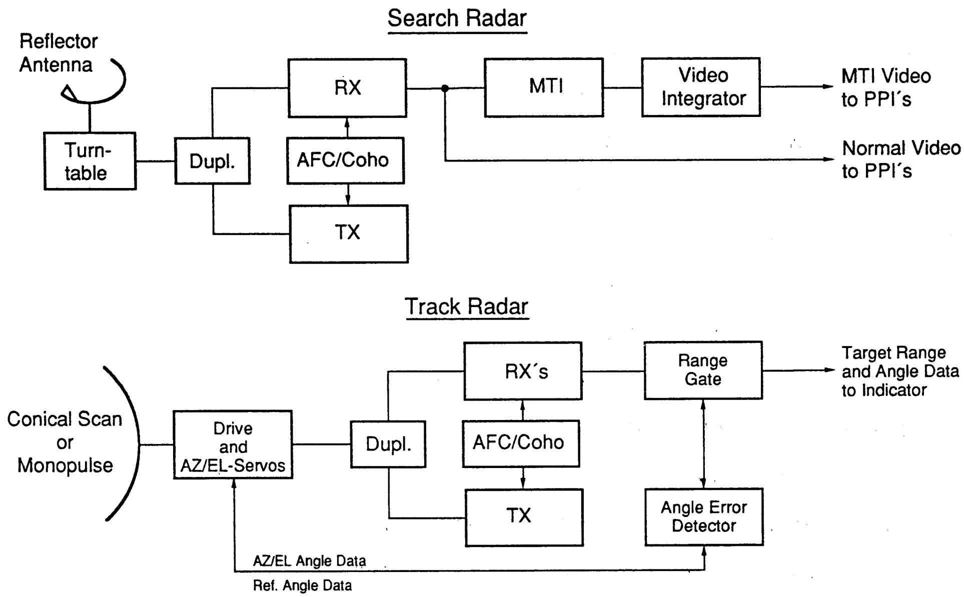
In the early 1950s some basic classes of radar had evolved:

- search radar for air and sea surveillance with ranges from 10 up to 200 NM. Frequencies used were in L and S-Band, but also in X-Band for short-range applications
- target track and fire control radar for short to medium ranges. Here, for reasons of antenna size and weight, accuracy etc. the X-Band frequencies were predominant
- airborne search and track radar.

The basic architecture for the first two classes of radar is shown in Figure 1. For searching, rotating reflector antennas with cosec^2-diagrams (for air and pencil beams for sea surveillance) were used. The transmitter tubes were predominantly pulsed magnetrons with peak power from some 10 KW up to 1 MW or more. In the receive path, coherent oscillators, holding the pulse phase over the receive time, provided the phase reference for the MTI (Moving Target Indication) system using acoustic delay lines. Subclutter visibilities for moving targets were in the order of 15 - 20 dB.

In some cases the MTI was followed by a delay-line video integrator. Normal video, also containing the ground returns, and MTI video, containing moving targets only, was fed via coaxial cables to plan position indicators (PPI's), their deflection coils rotated synchronously with the antenna. In the second or third generation of this radar, selectable circular polarization permitted the suppression of rain clutter. An example for a search radar of this time is shown in Figure 2.

Ground based track radar transmitters and receivers were very comparable to those in search radar. As the antenna had to follow a single target in azimuth and



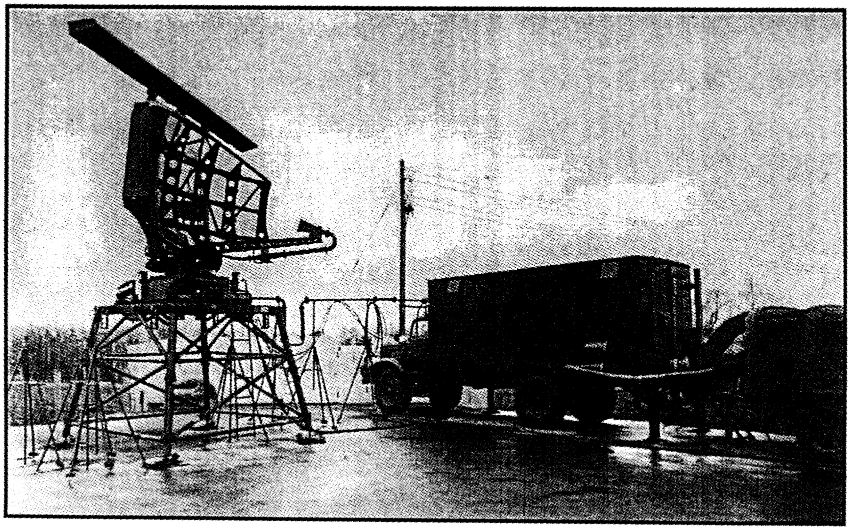


Figure 1 (top). Analogue radars.

Figure 2 (bottom). Telefunken S-Band surveillance radar ASR-B of the late 1950s.

elevation, angle and reference angle data were transferred by synchro systems to an angle error detector, and angle correction signals were fed back to the antenna azimuth/elevation-drive. For clutter suppression a narrow range gate following the target was in most cases sufficient. For exact on-boresight tracking either conical scan techniques were used, with a slightly offset pencil beam rotating around the boresight axis, but also monopulse antennas were used, with the boresight reference given by the null of the antenna difference pattern.

Airborne fire control radar was in principle not much different from its ground-based relatives, apart from some additional circuitry against sidelobe clutter effects, and the influence of much more stringent environmental conditions. For airborne search radar things were much more complicated. Here the ground clutter returns were modulated by the effects of aircraft motion and antenna rotation, and standard MTI procedures simply did not work. The problem, known already during World War II, was finally analyzed in the early fifties in the US by study groups between the Air Force, the Navy, and the MIT's Lincoln Laboratory. The General Electric Company then undertook industrial development. I can give only the rough outline for the technical solution here. It also influenced antenna design (DPCA, Displaced Phase Center Antenna on the basis of monopulse techniques) and receiver and processor design (TACCAR, Time Averaged Clutter Coherent Airborne Radar). This work of the early 1950s provided the basis for all later US-Airborne Early Warning Radar activities up to AWACS, and was distinguished in 1991 with the IEEE Pioneer Award. A detailed documentation is given in.[4] Further information on radar systems and techniques of this era can be found in the early edition of Skolnik's "Introduction to Radar Systems".[5]

3. Transition Period: "Sophisticated Radar" In The 1960s And 1970s

In the 1960s and into the 1970s, military needs and requirements still set the pace for the development of what was called "Sophisticated Radar" or "Advanced Radar Systems." But in civil ATC, 2D-surveillance radar[6] was considered operationally sufficient (which is true even today); beginning in the 1960s, the target height information was derived from Secondary Radar's Mode C.[7] In contrast, in the military, there was a strong drive for 3D-radar. 3D-target information was primarily needed for Intercept and Fighter-Control, and for the assignment of longer-range surface-to-air weapons. The military requirements for this radar generation may be summarized as follows:

- 3D-target detection and target tracking on a scan-to-scan (Track-while-scan, TWS) basis in the surveillance mode
- Fast switching between several targets in the tracking mode
- Resistance against ECM (Electronic Countermeasures)
- High resistance against natural clutter
- High resolution
- In some applications very long range performance for the detection of satellites and ICBM's (Intercontinental Ballistic Missiles).

Transformed into technical terms this meant:

- 3D-antennas, using either multiple receiving beams ("Stacked-Beam Radar"), frequency or phase scan for changing the beam position in azimuth or elevation, or Phased Array Antennas for beam positioning in both planes
- High power coherent transmitters, using either Klystrons or Traveling Wave Tubes for fast frequency agility
- Pulse Compression Techniques, first analogue, then digital
- Improved MTI-Systems, Doppler Filter Banks
- Digital Plot Extractors, to provide digitized target information for track algorithms.

The increase in the number and complexity of radar functions became possible because more and more digital components were available in the 1960s and 1970s. Mentioned here are A/D-converters (analogue-to-digital converters) able to quantize the phase and amplitude of a radar return in 8 to 10 bits in 1 μs or less, shift registers, arithmetic units, and above all ever bigger, faster, and cheaper memories.

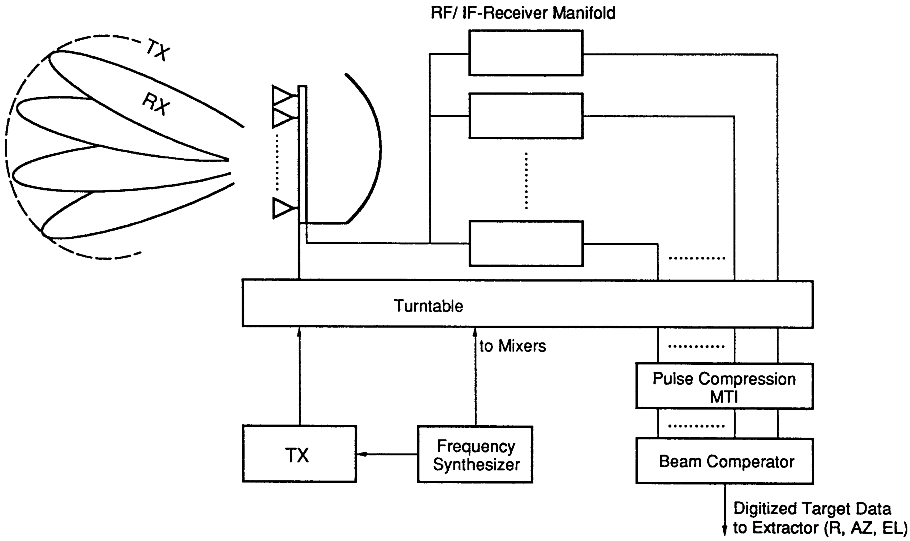
A deeper technical discussion of the topics mentioned here is far beyond the scope of this paper. For those interested, a good overview of the theoretical tools and the system know-how available to the radar engineer of the sixties can be found in Modern Radar.[8] The book contains the contributions of a number of scientists at special radar summer sessions of the University of Pennsylvania in 1960 and 1961.

Figures 3 and 4 show 3D-radar of this era in simplified block diagrams. In a typical Stacked Beam Radar a vertical linear array of radiators (up to 40 were sometimes used) feeds a reflector. On transmit a broad diagram in elevation is generated, whereas on receive the distribution is divided into a number of radiator subgroups, delivering separate receive diagrams. For each of these a separate receiving and signal processing path is required, ending in a beam comparator, where the fine elevation of the target is derived by comparison of target amplitude and/or phase between adjacent elevation beams. Typical representatives of this radar type are the Westinghouse TPS-43 or the Thomson-CSF "Palmier" - or Nadge MPR (Medium Power Radar).

A typical array radar configuration is shown in Figure 4. To make this principle more clear, only one-directional scanning is represented. Each radiator in an array line is fitted with a controllable phase-shifter. The phase shift commands to deflect the beam off-axis are delivered by a digital beam steering unit. The transmitter and receiver are connected to the distribution/ combiner network in much the same way as in a conventional radar. If each radiator is provided with its own transmit receive module, we arrive at the "Active Antenna" principle.

The theoretical principles of phased arrays were established in the sixties and early seventies. A summary can be found in the Electronic Scanning Radar Systems Design Handbook by Kahrilas.[9]

The stationary phased array face with a typical 60 - 90 degree scan sector gave the systems designer (and the user) many more degrees of freedom than a conventional radar with a mechanically moving antenna could. It was possible to control scan rates and scan sectors, the energy and time spent per beam position, and to set priorities for



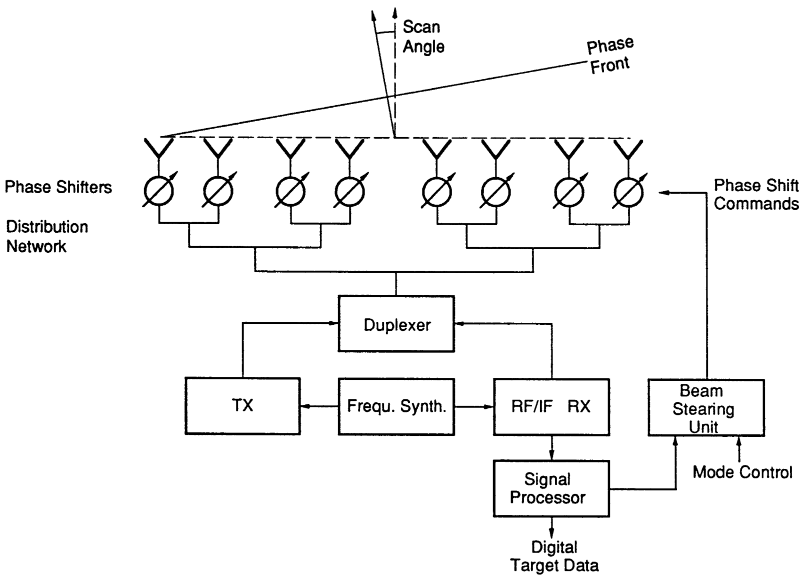


Figure 3 (top). Simplified block diagram of a stacked-beam radar.

Figure 4 (bottom). Simplified block diagram of a one-dimensional phased array radar.

targets to be tracked, as well as to use monopulse patterns, etc. On the other hand, this flexibility also led into a new dimension of cost for a radar, and thus production quantities of phased array radar remained low over the 1970s and 1980s.

The first developments for large stationary phased arrays were again triggered by US-military demands for the detection and tracking of space objects and ICBM's. Much pioneer work was done at Bendix with the design of the FPS-85 in the early sixties, whose separate transmit and receive antennas covered nearly the area of a football-field, due also to the low 420 MHz frequency.[10] General Electric undertook further development work for the PAR's (Perimeter Acquisition Radar) of the "Safeguard" System, having antenna diameters of about 30 m. The last generation of these long-range/high-resolution phased arrays are the FPS-108 ("Cobra Dane") in L-Band and FPS-115 ("Pave Paws") at 420 MHz developed by Raytheon. Some technical information on these can be found in Merrill Skolnik's, Radar Handbook.[11] This radar is really an "active antenna" with several thousands of transmit/receive-modules covering the antenna face.

Apart from this special application, where only a few systems are procured at a time, the only phased array radar produced in larger quantities is the battery radar in Raytheon's "Patriot" System. In this case, a space-fed lens-array is used instead of a corporate-feed antenna. The development of this system also started in the late 1960s-early 1970s.

For 360 degree surveillance radar, using planar antennas with phased scan in elevation and rotation in azimuth, applications were more widespread, as the cost was considerably less. In the seventies to eighties nearly all of the big radar companies came up with their own designs. An example is shown in Figure 5.

4. Digitized Radar Since The 1980s

In the eighties a number of new tasks, again mostly set by military demands, were tackled. I will mention only the most important ones:

Figure 5. Telefunken TRMS; a C-band phased array surveillance radar.

- Introduction of solid-state high-power transmitters at L and S-Band into civilian and military radar. Here higher reliability and ease of maintenance are the design drivers

- Application of the "Active Antenna Principle", first realized in the large long-range array radar described in the foregoing chapter, to small ground, ship and airborne radar, mostly in X-Band. Here some basic facts have to be taken into consideration: with a half-a-wavelength spacing between transmit/receive modules, the number of elements per m^2 of antenna face rises quadratically with frequency. Thus, for the 23 cm-wavelength 76 elements/m^2 are required, for 10 cm the number is approx. 400, for 3 cm already more than 3,500. The old experience, that the longer wavelength needs the bigger and costlier antenna, is not true here. The number of modules in an X-Band antenna of 1 m^2 is about the same as in an L-Band-antenna of about 46 m^2, and the cost for the small antenna becomes surprisingly high

- Design of conformal arrays following the hull curvature of a ship or aircraft;

- Target recognition by enhanced signal processing, using for example Doppler-Jet-Engine-Modulation or signatures in the polarization/frequency domain, or natural resonances

- New radar applications for mm-waves.

In order not to overstress the limits of this essay, these examples, though incomplete, may be representative. For those interested in today's state of the art in radar, detailed information can be found in the second edition of Skolnik's Radar Handbook.[11]

5. Some Comments On The Radar Development In Germany After 1945

Any work in radar was interrupted in Germany between 1945 and 1952. In the latter year Telefunken in Berlin reentered the field by starting a license production of small Decca ship radar. In 1955 all restrictions for radar activities in Germany were ended by the Paris Treaties, and the scope of work was widened by a license from Bendix for the ASR3/PAR2 GCA-equipment. In 1957 the Telefunken Radar Department was transferred from Berlin to Ulm, where soon after development work in radar began.

Looking at the development in Germany over the following 30 years or so, at least three different places and organizations must be mentioned, though some other companies like SEL (now Alcatel) or the German Philips were also active in some special fields. The three main players are: The "Forschungs-Institut für Funk und Mathematik" (FFM) of the FGAN (Fraunhofer-Gesellschaft für angewandte Naturwissenschaften), Siemens AG at Munich, and Telefunken at Ulm.

The "Forschungs-Institut für Funk und Mathematik" (FFM) of the FGAN (Fraunhofer-Gesellschaft für angewandte Naturwissenschaften) was established in the early 1960s at Wachtberg-Werthooven near Bonn. It can be considered a semi-governmental institution, where basic theoretical and experimental work on advanced radar systems is conducted. Already in the 1960s an experimental phased array, the ELRA (Electronic Radar) was implemented. It consists of separate side-by-side transmit/receive antennas in S-Band, and has been continuously modified over the years up to the present to follow the latest state in systems technology. A great number of theoretical and experimental studies were conducted here over the years.

Radar development and license productions were taken up in the early sixties at Siemens AG at Munich. The company concentrated on development and production of coherent short range surveillance and fire control radar for military applications, and also undertook some experimental work in phased arrays. Its main activities, however, were in the field of military IFF (Identification Friend or Foe) Systems, up to NIS (Nato Identification System). The division is now part of Siemens-Plessey.

The third organization, Telefunken at Ulm, is now Deutsche Aerospace, Radar and Radio Systems. The company covers the widest scope in radar development and production in Germany. Its activities over the years have included:

- Ground Radar Systems for civilian applications, such as ATC-Radar for Route Control and GCA, Secondary Radar, Coastal Radar

- Ground Radar Systems for military applications, such as military mobile GCA-Radar, 3D-Phased Array Surveillance Radar in C-Band (TRMS), 2D-Low Target Detection Radar with Helicopter Classification (TRML), 2-Band ship radar (X/C-Band), high-precision ship radar for mine-sweeping systems

- Airborne Radar, such as license-production for the F104- and Tornado Nose Radar, F4-Radar (APG-65), co-developer for EFA-Nose Radar
- Miniaturized Radar for warheads and fuzes.

The companies named here were able to contribute to the state of the art in a number of fields, and over the years a considerable quantity of radars were delivered to German and export customers.

6. Concluding Remark

Our fast tour through more than 35 years of radar ends here. With little space available, I was not able to mention some important fields such as sidelooking and synthetic aperture radar, Over-the-Horizon (OTH) systems, mm-wave radar for warheads and fuzes, and some others. But I hope that I have retraced the mainroads in radar development.

Appendix

Radar-Frequency Bands:

X-Band: 8.5 - 9.5 GHz
C-Band: 5.2 - 5.7 GHz
S-Band: 2.7 - 3.1 GHz
L-Band: 1.25 - 1.35 GHz

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5. Merrill I. Skolnik, "Introduction to Radar Systems", McGraw-Hill Inc., New York, 1962.

6. 2D-surveillance: (two-dimensional) measurement of target range and azimuth (but not of target height or elevation).

7. In Mode C of the Secondary Surveillance Radar (SSR) system the aircraft barometric height is transmitted to the ground station.

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David K. Barton

HISTORY OF MONOPULSE RADAR IN THE UNITED STATES

Introduction

The history of development of monopulse radar in the U.S. is reviewed. Significant techniques which permitted monopulse tracking radars to achieve accurate tracking with high efficiency are discussed, including sum-and-difference antenna feed networks, multihorn and multimode feeds, precision mechanical pedestals, and space-fed arrays. The discussion is concentrated on surface-based radars, but many of the techniques apply to airborne radars and missile seekers developed during the same periods.

1. First-Generation Monopulse Radars, 1940-1955

The evolution of monopulse radar in the U. S., from its inception in 1940 to systems deployed today, is shown in Figure 1. The earliest work appears to have been done at the Naval Research Laboratory (NRL) in 1940. Parallel efforts at the General Electric Company (GE) during the early 1940s were followed by developments at Radio Corporation of America (RCA) and Sperry Gyroscope Company. The Bell Telephone Laboratories (BTL) became involved by 1945, under the Nike missile program in 1945. Those organizations remained the principal centers of monopulse radar work into the late 1960s. NRL continued to support the field with theoretical studies, but was not directly responsible for radar development. GE did little work in tracking radar after about 1960. Sperry continued to support naval tracking radar, but had less success in new programs. BTL took themselves out of the military radar business in about 1970, and has played no role since that time.

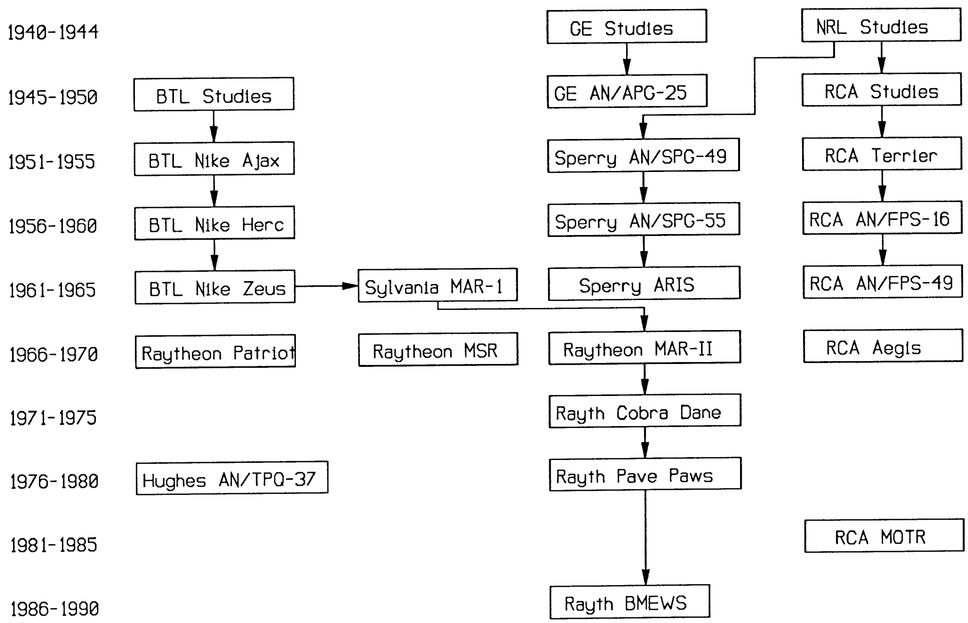


Figure 1. Evolution of monopulse radars, 1940-1990.

1.1 Naval Research Laboratory

Monopulse radar was first discussed in reports at NRL, one of which has been published in open literature.[1] In this report, R. M. Page mentions the previous use in radio direction finding of systems in which simultaneous comparison of signal energy in two lobes was used in order to eliminate the error caused by signal fading. However, a new idea expressed in the NRL report was the use of a central lobe for transmission and reception of a ranging signal, with four surrounding lobes providing difference signals for azimuth and elevation sensing. This was not the four-horn feed later used for generation of sum (Σ) and difference (Δ) patterns, but rather was to be a five-horn feed, similar to that eventually used by RCA in the AN/FPS-49 BMEWS (Ballistic Missile Early Warning System) search-track radar. The basic block diagram of the proposed system is shown in Figure 2. While some work had been done on monopulse radar at NRL as early as 1940, no operational equipment using this principle was produced during World War II.

1.2 Bell Telephone Laboratories: Nike Ajax

One of the earliest postwar developments in monopulse radar was carried out at BTL: the Nike Ajax command-guided surface-to-air missile system (Figure 3). Monopulse tracking was selected as the only technique which could provide the accuracy required for command guidance to maximum missile range. The study leading to this radar development was carried out in 1946, and the first test model was built in 1949.[2] The term monopulse was first proposed for this technique by H. T. Budenbom of BTL in 1946, and has since been accepted in preference to simultaneous lobing or the British term static split, even when continuous-wave signals are used as opposed to pulses. In the Nike system, two trackers were required, one tracking the incoming target and a second guiding the interceptor. Since the two radars were on separate trailers, problems of alignment were critical, as well as quality of tracking by

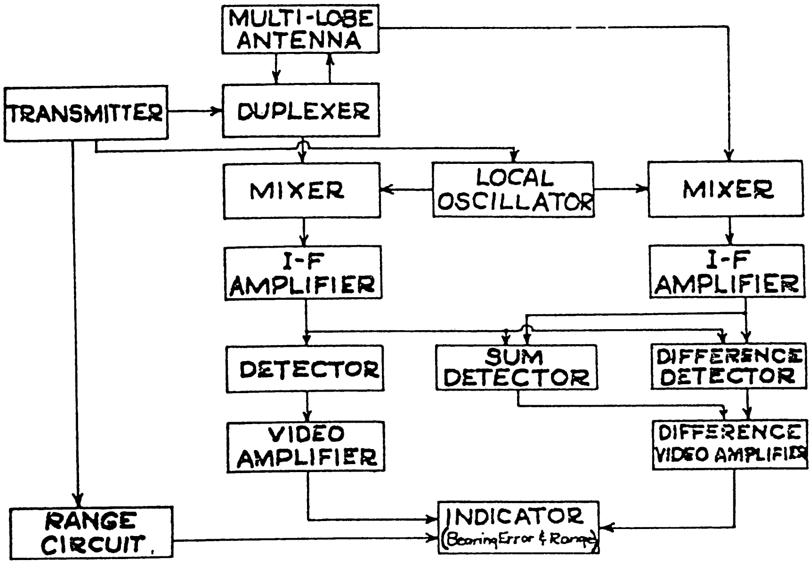


Figure 2 (top). Block diagram of NRL Modified Null System.

Figure 3 (bottom). Nike Ajax monopulse target tracking and search radars (photo courtesy of Bell Telephone Laboratories).

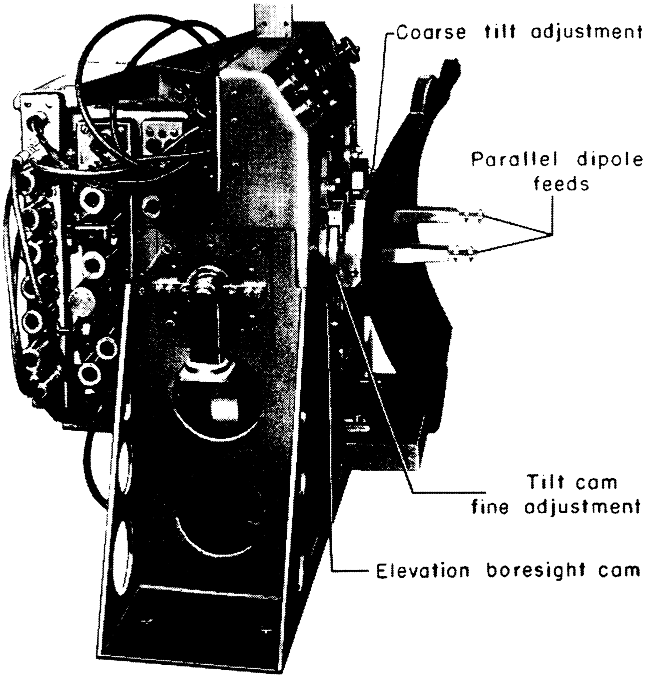
the individual radars. A discussion of performance issues of this radar is given in Sec. 2 of this paper.

1.3 General Electric Company: AN/TPQ-5 and AN/APG-25

The contributions of GE appeared primarily in the form of a classic study of monopulse theory by G. M. Kirkpatrick.[3] This report laid the theoretical basis for calculating potential precision of monopulse tracking, for comparing different antenna techniques, and for many other supporting techniques which have since appeared in practical equipment. Among these are the use of the electrical error signal to correct output data for servo lags, use of doppler filtering in Σ and Δ channels to extend tracking range in noise and avoid clutter errors, generation of Σ and Δ illumination by excitation of high-order modes within the feed horn, normalization of the error signal by limiting and phase detection of quadrature-combined sum-plus-difference signals, use of commutation at radio frequency or intermediate frequency to cancel detector bias errors, and use of off-axis tracking to improve low-elevation performance over reflective surfaces. One application of the GE work was the AN/APG-25 fire control radar for aircraft tail turrets (Figure 4). This is one of the few radars to use the phase-amplitude monopulse system, invented by W. Hausz of GE.[4] Less successful were the GE developments of a counter-battery radar, designated the AN/TPQ-5. This was one of a series of fruitless developments in this field, in which attempts we re made to replace the conical-scanning systems based on the World War II SCR-584. It was not until the success of the Firefinder phased array systems in the 1970s that significant progress was made in this area of tracking radar. The theoretical issues of amplitude and phase monopulse, not previously covered in professional literature, were explored in the early text by Rhodes, based on his doctoral dissertation.[5]

1.4 Sperry Gyroscope Company: AN/SPG-49

Sperry was active during the late 1940s and through the 1950s in development of naval fire control radar. Their initial entry into monopulse radar was the AN/SPG-49,



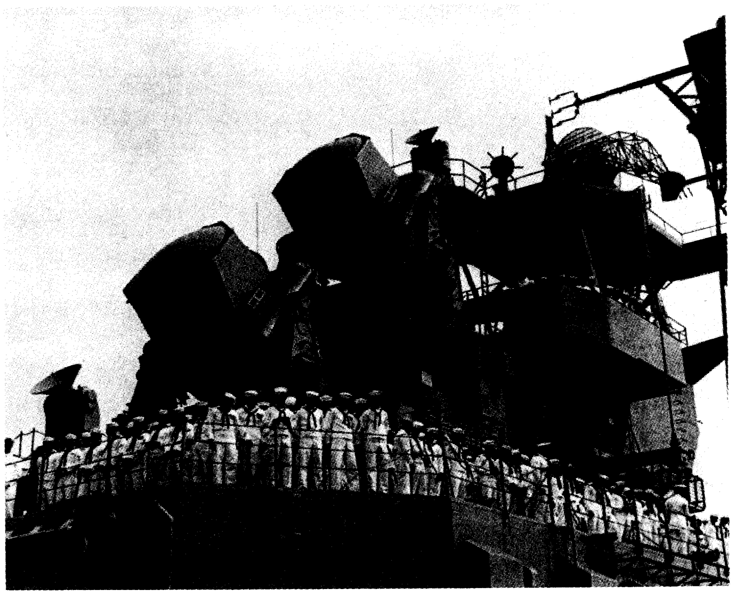


Figure 4 (top). AN/APG-25 tail turret fire control radar.

Figure 5 (bottom). AN/SPG-49 Talos tracking radar (photo courtesy of Sperry Gyroscope Co.).

a large, C-band (5600 MHz) monopulse tracker using a metallic lens antenna (Figure 5). This radar supported the Talos missile system. Because of its three-axis pedestal and shipboard installation, and the fact that the missile used homing guidance, high accuracy was neither required nor obtained.

1.5 Radio Corporation of America: Bumblebee Program, AN/FPS-16 and AN/FPQ-4

The first RCA efforts in tracking radar were carried out under the Bumblebee Program, a Navy-sponsored development of surface-to-air missile technology dating to the late 1940s, under direction of the John Hopkins University Applied Physics Laboratory. Little has been published on these efforts. In 1953, however, the RCA work led to their receiving an Army contract for development of a land-based version of the Terrier missile system. When the land-based Terrier was canceled, in 1954, the tracking radar developed for this system became the basis for the AN/FPS-16 precision instrumentation program. The requirements for the AN/FPS-16 instrumentation radar were developed in 1952, by Ozro M. Covington and this writer at the White Sands Proving Ground. A series of modifications to the conical-scanning SCR-584 had been developed to adapt this radar to range instrumentation functions, but it had become clear that accuracy requirements of the range could only be met by a modern, monopulse radar designed especially for instrumentation. The directors of the White Sands range failed to support the idea of precision radar, so the requirements were carried to the Army Signal Corps Laboratories at Ft. Monmouth, NJ, by this writer in 1953, where a study was undertaken to establish specifications for the new radar development. In 1954, RCA was awarded the development contract for a C-band system, based largely on their having successfully demonstrated a very precise pedestal and monopulse receiver for the X-band (9000 MHz) Terrier radar. The radar development under Army control was terminated early in the contract, on the basis of an unfavorable evaluation of project feasibility by defense department consultants. Transferred to Navy sponsorship, the AN/FPS-16 development became one of the

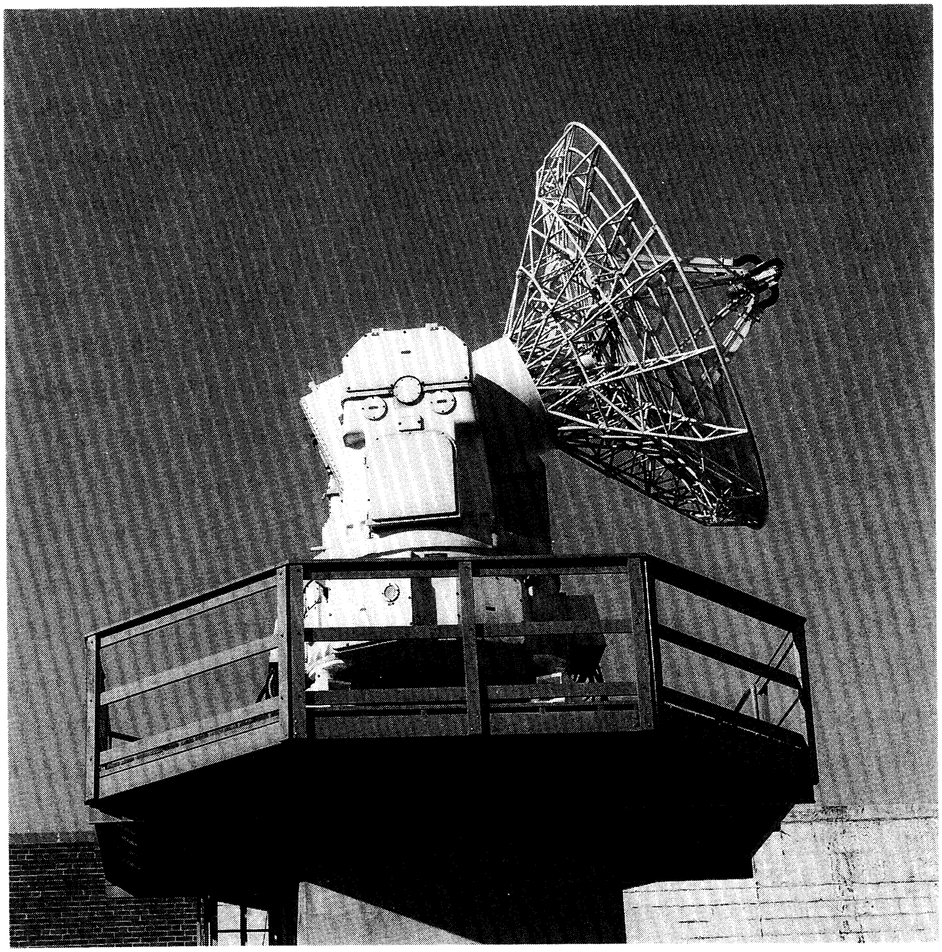


Figure 6. AN/FPS-16 instrumentation radar (photo courtesy of RCA).

most successful radar programs in post-war history. Additionally, since the radar was designed for instrumentation rather than as part of a weapon system, it was possible for this writer to describe its design and performance in the professional literature.[6,7] In 1957, after a successful flight test program, a production contract for twenty-five radars was issued, to equip the major U.S. missile test ranges. White Sands Proving Ground, although still dominated by engineers committed to optical and CW doppler instrumentation technology, received eight of the new radar systems, which have since become the basic instruments for trajectory measurement.

2. Monopulse Feed Horns for Reflector and Lens Antennas

Apart from precision mechanical pedestal technology, the key to design of accurate monopulse tracking radars was the technology of monopulse feed horns. Early workers considered the antenna in terms of multiple, independent horns (amplitude monopulse) or separate apertures (phase monopulse), which could be combined into Σ and Δ channels for the sake of boresight stability. This concept led to several difficulties in deployed radar systems, to be discussed below. Ultimately, it has become necessary to view the monopulse antenna in terms of its aperture illumination functions, and to design the feed system to produce an approximation of the desired function.

2.1 Amplitude-Comparison Monopulse

The conventional view of the amplitude monopulse antenna, Figure 7a, considers four squinted beams, formed by a cluster of four horns at the focal point of a reflector or lens. The relative amplitudes of signals received in these four beams provide the angle sensing information. When processed as Σ and Δ signals, microwave networks form the Σ channel as the in-phase sum of these four beams. The Δ channels for azimuth and elevation are formed in these same networks by placing pairs of horns in antiphase.

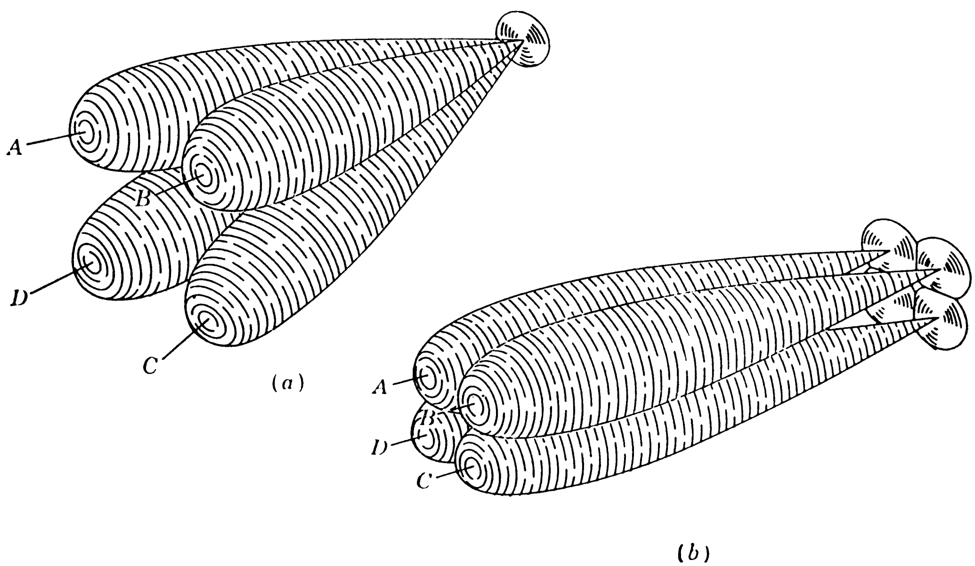


Figure 7. Simple view of monopulse antenna beams:
(a) amplitude monopulse
(b) phase monopulse

2.2 Phase-Comparison Monopulse

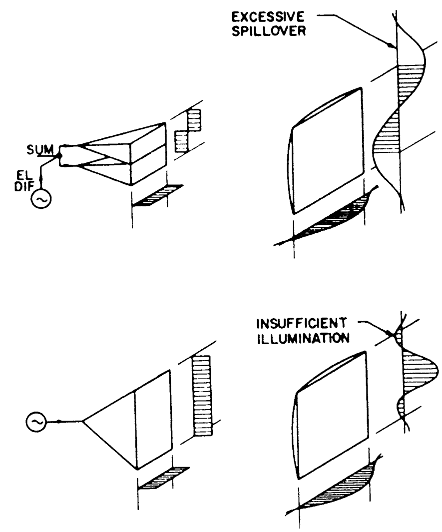
Phase monopulse is considered in terms of four parallel beams, Figure 7b, formed from four quadrants of an aperture displaced around a central axis. The relative phases of signals received in these four beams provide the angle sensing information. Sum-and-difference processing may be applied to this system, using microwave networks as in the case of amplitude monopulse.

2.3 Sum and Difference Illumination Functions

When the Nike Ajax test model was operated at White Sands Proving Ground, unexpectedly large errors appeared in the elevation data. After thorough mechanical testing had exonerated the pedestal and data output devices, it was discovered that large antenna sidelobes, responding to ground-reflected signals, were the source of error. The metallic lens was one source of these sidelobes, but the basic four-horn feed design was the major contributor. A study was commissioned by BTL and carried out by Peter Hannan at Wheeler Laboratories[8], which described the problem and its solution. The basic four-horn monopulse feed cannot simultaneously produce illuminations for efficient, low-sidelobe Σ and Δ patterns. If the total width of the horn cluster is adjusted for good Σ illumination, the Δ illumination will have high edge intensity and spillover (Figure 8a). If the total width is optimized for good Δ illumination, the Σ illumination will be concentrated in the center of the aperture, (Figure 8b), giving low efficiency.

2.4 Multihorn and Multimode Feeds

Hannan found the solution to the monopulse feed problem in the multihorn and multimode feeds designs of Figure 9. Through the use of additional couplers, the Δ channels can use horns at the periphery of the feed, confining illumination to the aperture while retaining also an efficient Σ illumination. A multimode feed was also evolved at RCA for the AN/FPS-16, providing reasonable sidelobe levels and efficiency but not fully exploiting the design features of the Hannan feed.



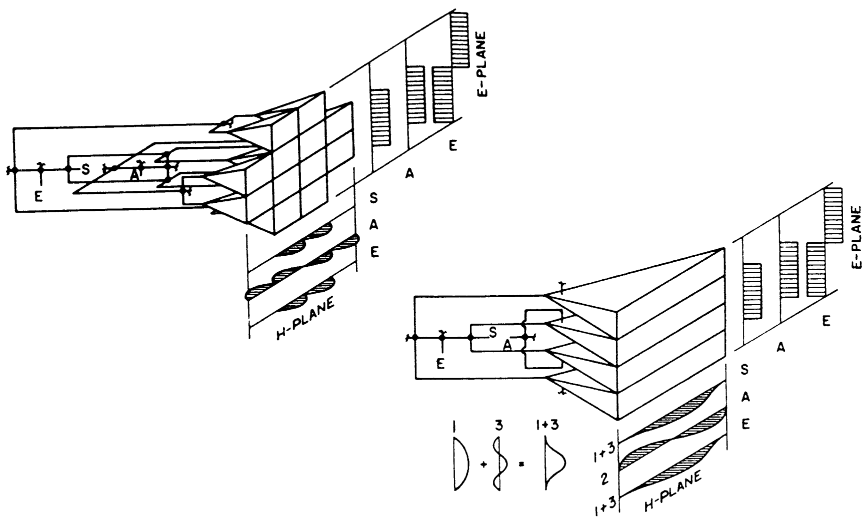


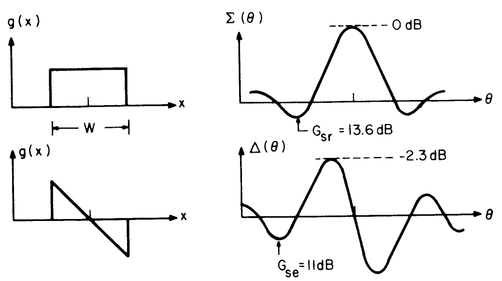
Figure 8 (top). Four-horn feed illumination limitations.
(a) difference illumination when horns are optimized for Σ channel
(b) sum illumination when horns are optimized for Δ channel

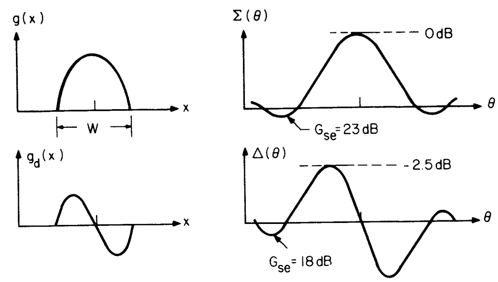
Figure 9 (bottom). Multihorn and multimode monopulse feeds.

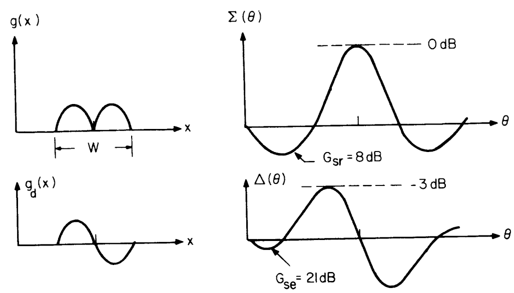
2.5 Monopulse Illumination Functions and Patterns

When considering the performance of different monopulse implementations, it is useful to return to Kirkpatrick's derivation of the optimum Σ and Δ illumination functions for the thermal noise environment, Figure 10. In this figure, g(x) is the illumination function across the aperture in the x coordinate, while $\Sigma(q)$ and $\Delta(q)$ are far-field voltage patterns in the angle coordinate, q. The first sidelobe levels are indicated as G_{sr} and G_{se}. The uniform Σ illumination gives maximum gain, while the linear-odd Δ illumination gives maximum measurement slope. However, the high sidelobe levels make these ideal functions unsuitable for use in the real radar environment.

Application of taper to both Σ and Δ illuminations produces practical functions of the type shown in Figure 11. Both gain and measurement slope are decreased, but sidelobe levels are greatly reduced. In constrained-feed phased arrays, the Σ illumination is often chosen from the Taylor family of low-sidelobe tapers, while the Δ illumination may be a Bayliss taper. Approximations to the illuminations shown in Figure 11 may be generated with feed horn clusters, as shown in Figure 9, as well as by array constrained feed net works. Whether these illuminations are called "amplitude monopulse" or "phase monopulse", with Σ-Δ processing, is an arbitrary choice: the two sides of the aperture will have Δ illuminations of opposite phase, while the Σ illumination will have uniform phase across the aperture. When the illumination functions of the conventional phase monopulse antenna approaches are compared, the results will appear as in Figures 12 and 13. In Figure 12, each of two side-by-side reflectors is illuminated with a cosine function, and the two outputs are added and subtracted in a hybrid junction. The resulting Δ pattern is good, but the Σ pattern has low gain and high sidelobes. In Figure 13, a phased-array aperture is illuminated with a cosine function, and a hybrid junction in the center produces the odd Δ illumination function. In this case the Δ pattern has unacceptable sidelobes. Neither of these types of antenna will provide adequate performance in the real radar environment.







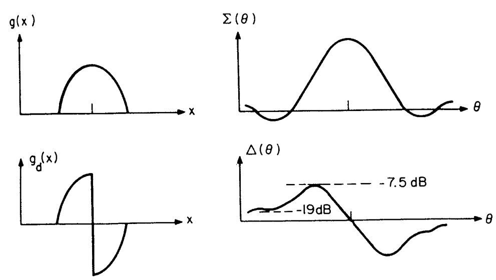


Figure 10 (top left). Ideal monopulse illumination functions for noise environment.

Figure 11 (top right). Practical monopulse illuminations for real environment.

Figure 12 (bottom left). Phase monopulse illuminations for a dual-reflector antenna.

Figure 13 (bottom right). Phase monopulse illuminations for a phased array.

3. Monopulse Radar Developments, 1955-1965

The second generation of monopulse tracking radars, using mechanical pedestals and reflector antennas with advanced feeds, became available during the late 1950s and early 1960s. These were produced primarily by the four organizations already mentioned as having developed the early systems.

3.1 RCA: AN/FPQ-4, AN/FPS-49, Tradex

Immediately after starting the AN/FPS-16 development, RCA received a contract for a land-based version of the Talos missile system. The AN/FPQ-4, developed to support this missile system, was almost identical to the AN/FPS-16, using the same pedestal, antenna, receiver system, and servos. A high-power klystron transmitter was included, based on the original AN/FPS-16 design. In 1957, requirements for a radar to provide long-range detection of intercontinental ballistic missiles (ICBMs) were formulated by the U.S. Air Force. RCA developed a 425-MHz triode transmitter for 300-kW average power, intended by the Air Force to be used with a huge toroidal parabolic antenna (later to become the AN/FPS-50 radar). However, by scaling the AN/FPS-16 parameters to the longer wavelength, it was found by RCA that a radar having 4000 km detection range on 1-m2 targets could be built as a monopulse tracker. The radar would search a narrow elevation sector just above the horizon, locking onto and tracking any target which penetrated the search sector. Positive discrimination of ballistic missiles from satellites and other false alarms could be obtained. The necessary 52 dB scaling produced the AN/FPS-49 (Figure 14), with a 25-m antenna diameter and five-horn feed (anticipated by Page in his 1944 report). The central Σ horn provided circular polarizations to overcome the effects of Faraday rotation in the ionosphere. Ultimately, AN/FPS-49 radars were installed at the British and Alaska BMEWS sites. The Tradex radar was an adaptation of the AN/FPS-49, used for instrumentation at the Kwajalein Atoll in the Pacific.[9] The paper describing Tradex is the only example in the professional literature of a monopulse tracking radar using pulsed doppler processing.

Figure 14. AN/FPS -49 BMEWS search-track radar (photo courtesy of RCA).

3.2 Bell Telephone Laboratories: Nike Hercules and Nike Zeus

The Army requirement for longer missile range, along with limited accuracy of the Nike Ajax radar at low elevation angles, led to development of the Nike Hercules system. The missile range was extended to 90 km, and radar tracking accuracy improvements were able to support this range with acceptable miss distance. The Hannan multimode feed design was used in the Nike Hercules tracking radar, Figure 15, with great success. Accuracy of this system approaches that of the AN/FPS-16 instrumentation radar. In addition to optimizing the feed, Wheeler Laboratories also designed the polarization-twist Cassegrain reflector system to replace the original lens. This type of reflector systems has been used in many subsequent radars, providing low blockage and excellent mechanical characteristics. During the late 1950s, development work was also done at BTL on radars for anti-ballistic-missile (ABM) systems. The Nike Zeus Target Tracking Radar (TTR) used a 6-m reflector antenna at C-band, achieving 1000 km tracking range against targets of 0.1 m2.[10] Many of the techniques developed for Hercules were applied to this radar.

3.3 General Electric Company: Atlas Guidance Radar

One of the successful applications of GE monopulse radar technology was in the guidance radar for the Atlas ICBM. Combining radar and inertial data, the guidance system was able to meet high accuracy requirements for long-range ballistic missiles. However, this mode of guidance was rapidly replaced by pure inertial guidance systems, requiring minimal ground support and having no vulnerability to electronic countermeasures.

3.4 Sperry Gyroscope Company: AN/SPG-55

The second generation of monopulse radar designed at Sperry was the AN/SPG-55, supporting the Navy's Terrier surface-to-air missile (Figure 16).

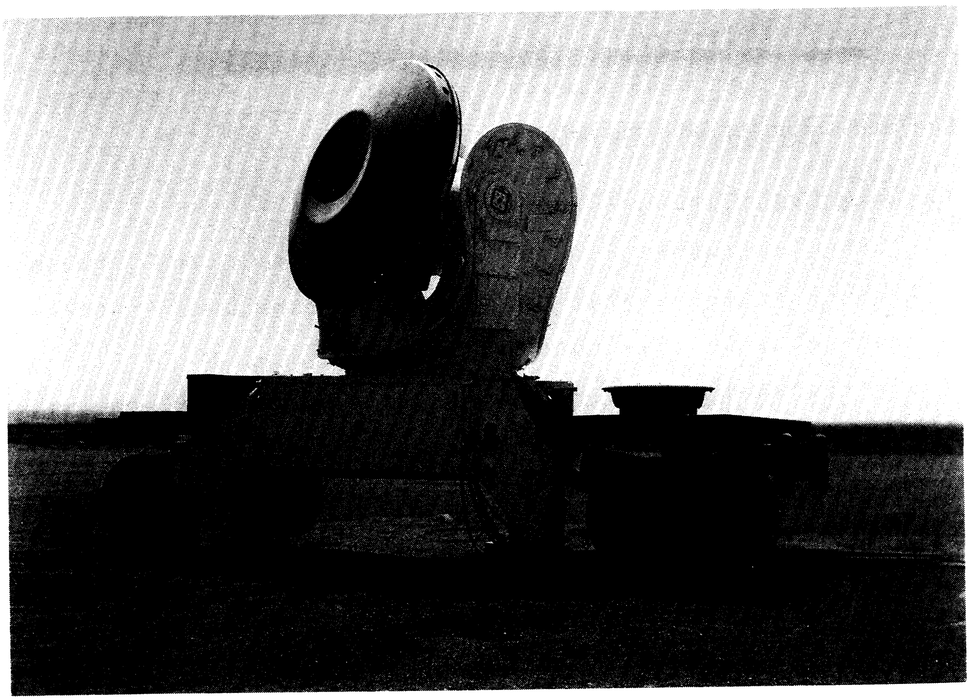


Figure 15. Nike Hercules tracking radar (photo courtesy of Bell Laboratories).

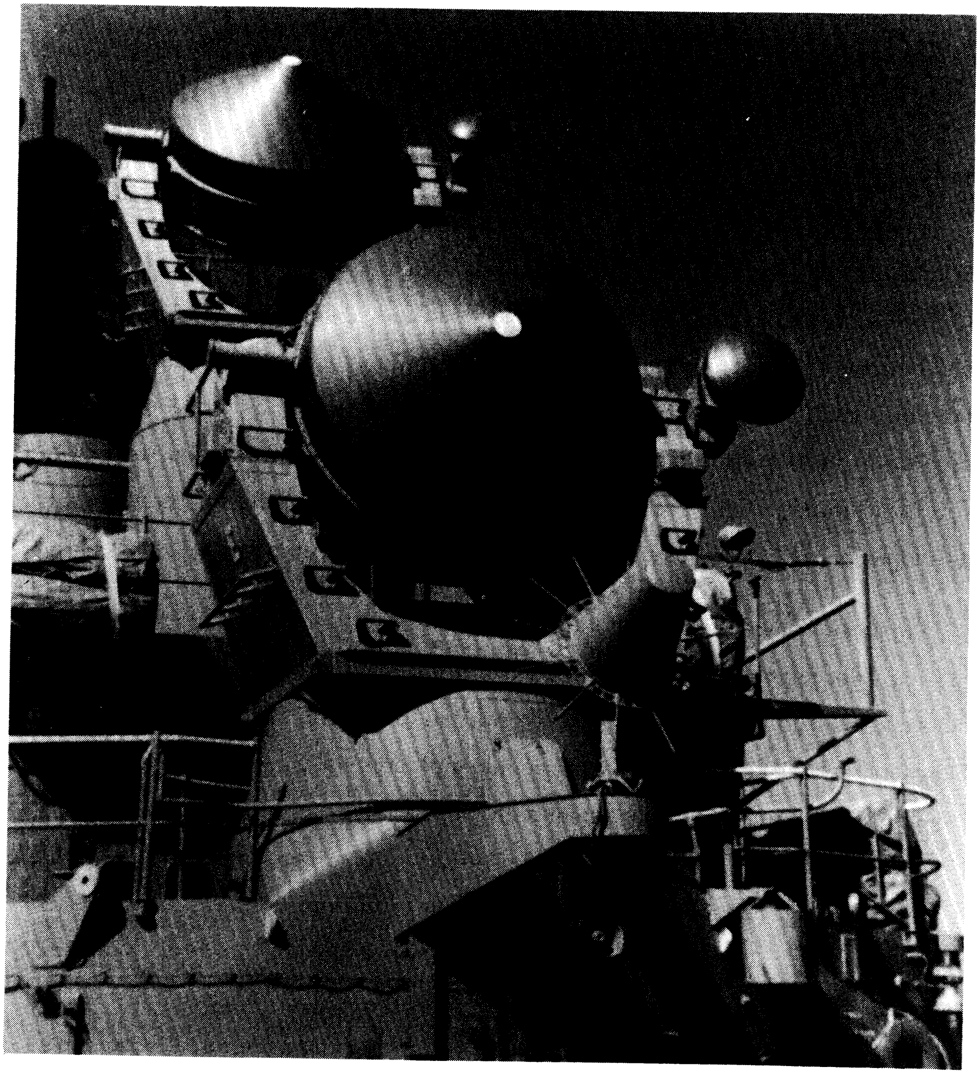


Figure 16. Sperry's AN/SPG-55 tracking radar (photo courtesy of Sperry Gyroscope Co.)

4. Monopulse Phased Array Radar, 1965-Present

Radar development efforts in the U.S. since 1965 have been primarily directed toward phased array systems. Successful as was the BTL Nike Hercules development, it turned out that the firepower of this command-guidance system fell far below what was desired. Radars having multiple-target capability were deemed essential. Defense against aircraft, tactical ballistics missiles (TBMs) and long-range ballistic missiles were included as requirements in a new generation of systems.

4.1 Sylvania Electronic Systems: MAR-I

As part of the Bell Telephone Laboratories Nike-X system, a contract was let to Sylvania in 1961, leading to development, installation at White Sands Missile Range (WSMR) and testing of the MAR-I (Multifunction Array Radar) during 1961-1965. This phased array system is shown in Figure 17. This multifunction radar was intended to provide search, discrimination, and precision tracking of targets. Separate arrays were used for transmitting and receiving. While there is disagreement as to the degree of success achieved in this development, there is no disagreement that subsequent development of MAR-II was assigned by BTL to Raytheon Company.

4.2 Raytheon Company: MAR-II, MSR

Patriot Raytheon had not been a major participant in monopulse radar development during the 1950s, concentrating instead on coherent doppler systems. Many engineers believed that the phase and amplitude matching requirements of monopulse receivers were inconsistent with the characteristics of doppler filters. However, in the class of large multifunction arrays, used in ABM applications, Raytheon established an important design capability which led to the award of the MAR-II contract. This radar was developed and installed on Kwajalein Atoll (Figure 18). It featured high peak and average power (100 MW, 3 MW), separate transmit and receive arrays, multiple simultaneous beamforming, and elaborate signal processing functions. Work on a common-aperture version of this radar (CAMAR) led to

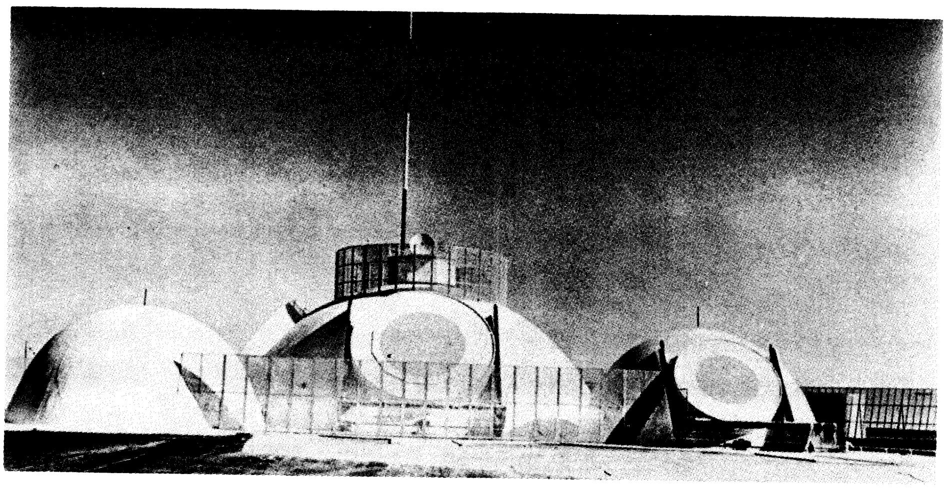


Figure 17. Sylvania MAR-1 at White Sands Missile Range.

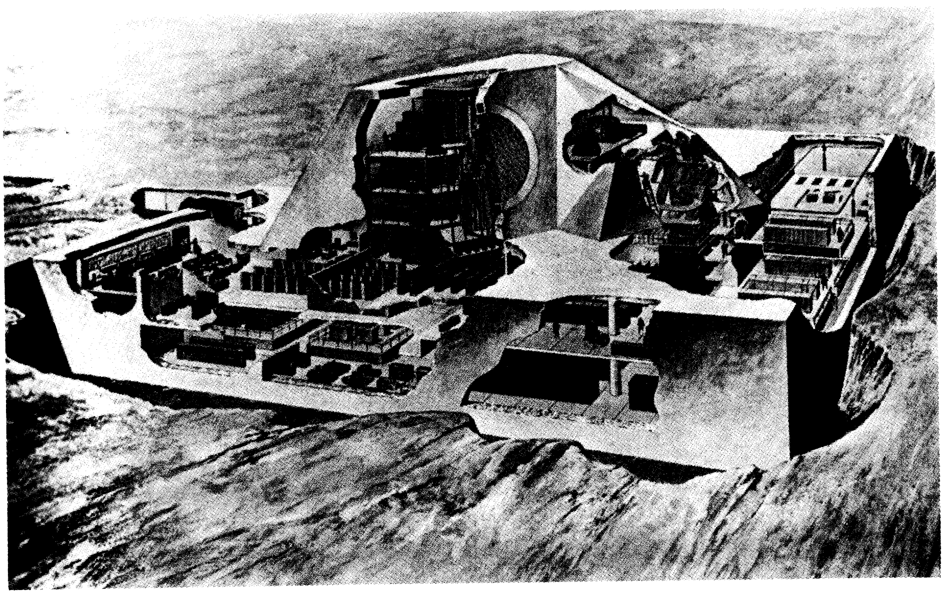


Figure 18. Raytheon MAR-II concept.

successful Raytheon development of radars such as Cobra Dane, Pave Paws, and more recently the phased-array replacements for the BME WS radars. All these systems use modular transmit-receive systems, the latter two implemented with solid-state transmitting sources. A second Raytheon development for the BTL ABM systems was the Missile Site Radar (MSR). This was a shorter-range system to control the actual intercept of reentry vehicles. After thorough study, BTL accepted the Raytheon recommendation for use of a space-fed array, in preference to corporate (or constrained) feed. The phase-shifting lens used 5000 diode phase shifters (Figure 19), and was illuminated by a high-power monopulse feed of the Hannan design (Figure 20). Two MSRs were built, one at the Kwajalein Atoll and one in Grand Forks, North Dakota. During this same period, Raytheon was engaged in competition with RCA and Hughes Aircraft for the Army Patriot system. This system originated as a Field Army Ballistic Missile Defense System (FABMDS) in about 1960, and changed to Army Air Defense System, 1970s (AADS-70) before being named SAM-D and, finally, Patriot. The multifunction radar concept owed much (both in advantages and limitations) to the previous studies of ballistic missile defense. Emphasis was placed on high-energy, single-pulse waveforms for most search and tracking actions. The limited time budget allowed for moving-target indication waveforms in both search and track, where needed. Illumination for the semiactive (target-via-missile, or TVM) seeker took the form of pulsed doppler bursts, not used in the radar itself. The space-fed lens array (Figure 21) consists of some 5000 nonreciprocal ferrite phase shifters, which must be switched before each received pulse. A major advantage of the space-fed array is the ability to exploit the excellent multimode feed designs, originated by Hannan for the Nike systems. The Σ and Δ illumination functions produced by this horn system are both near optimum for efficiency and low sidelobes. Spillover has been minimized, and it has been found unnecessary to place any special absorber around the antenna system.

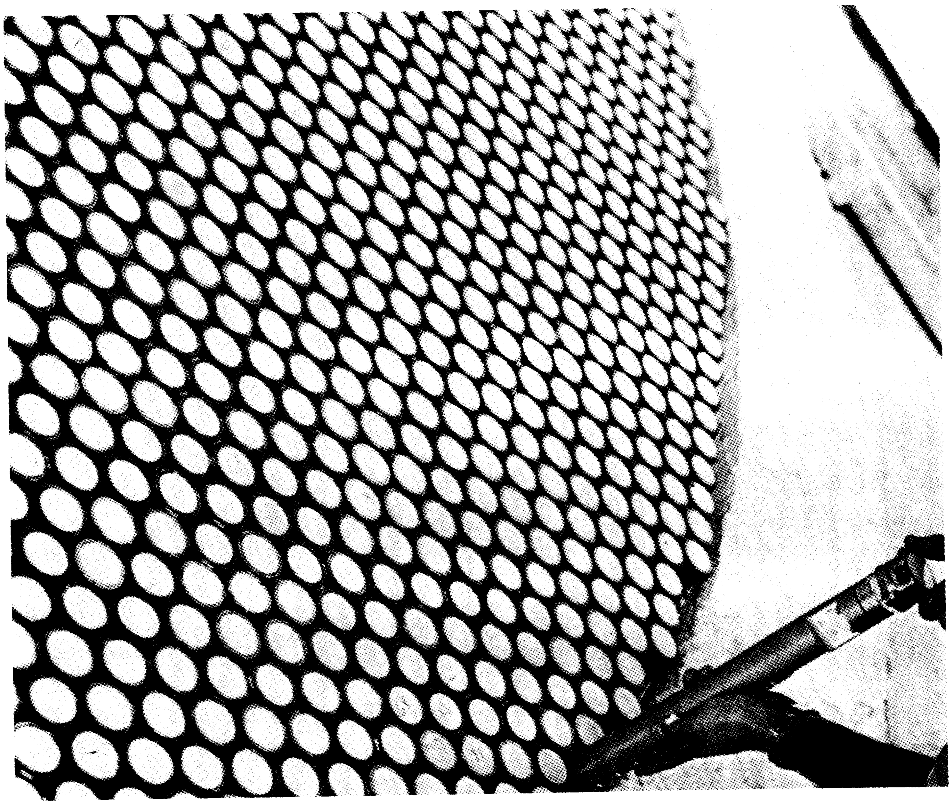


Figure 19. MSR array element installation

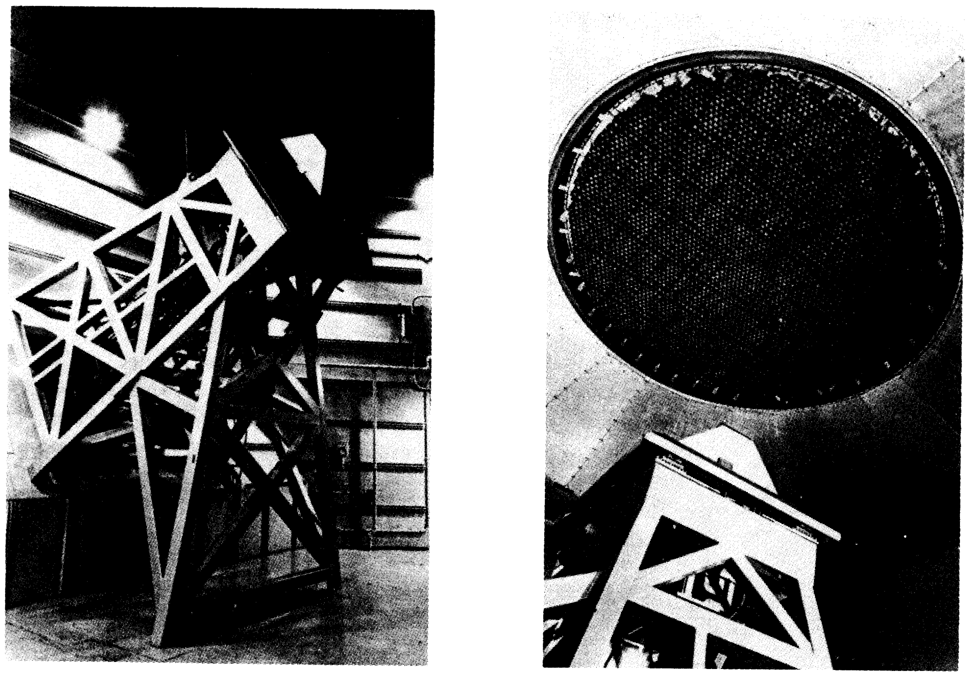


Figure 20. MSR feedhorn and chamber.

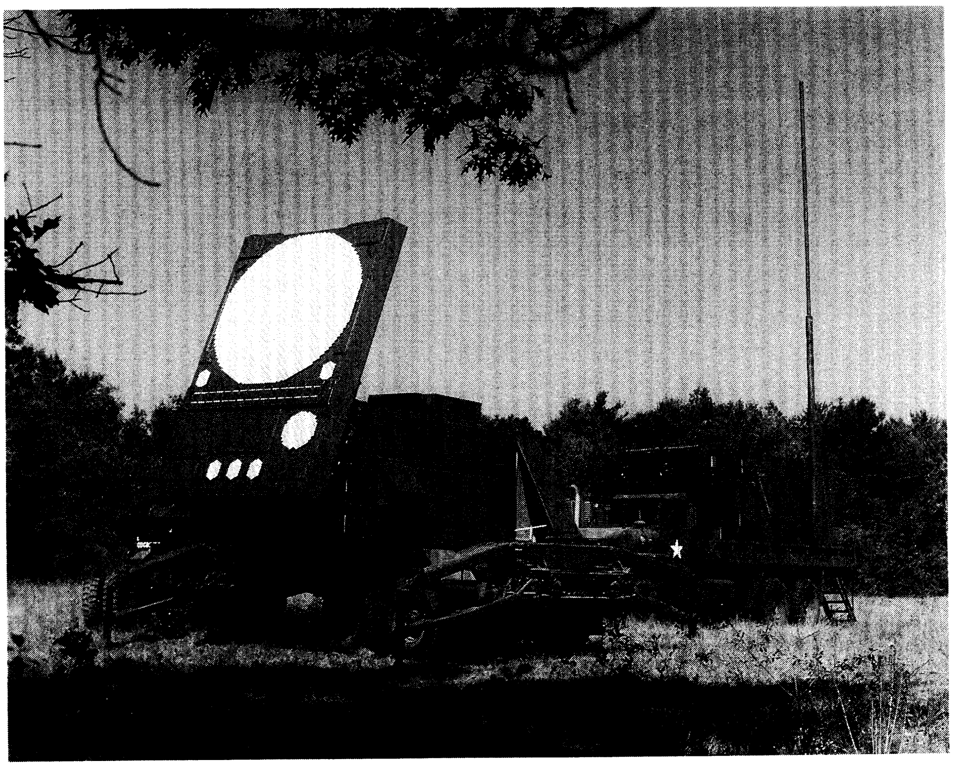


Figure 21. Patriot multifunction phased array (photo courtesy of Raytheon Company).

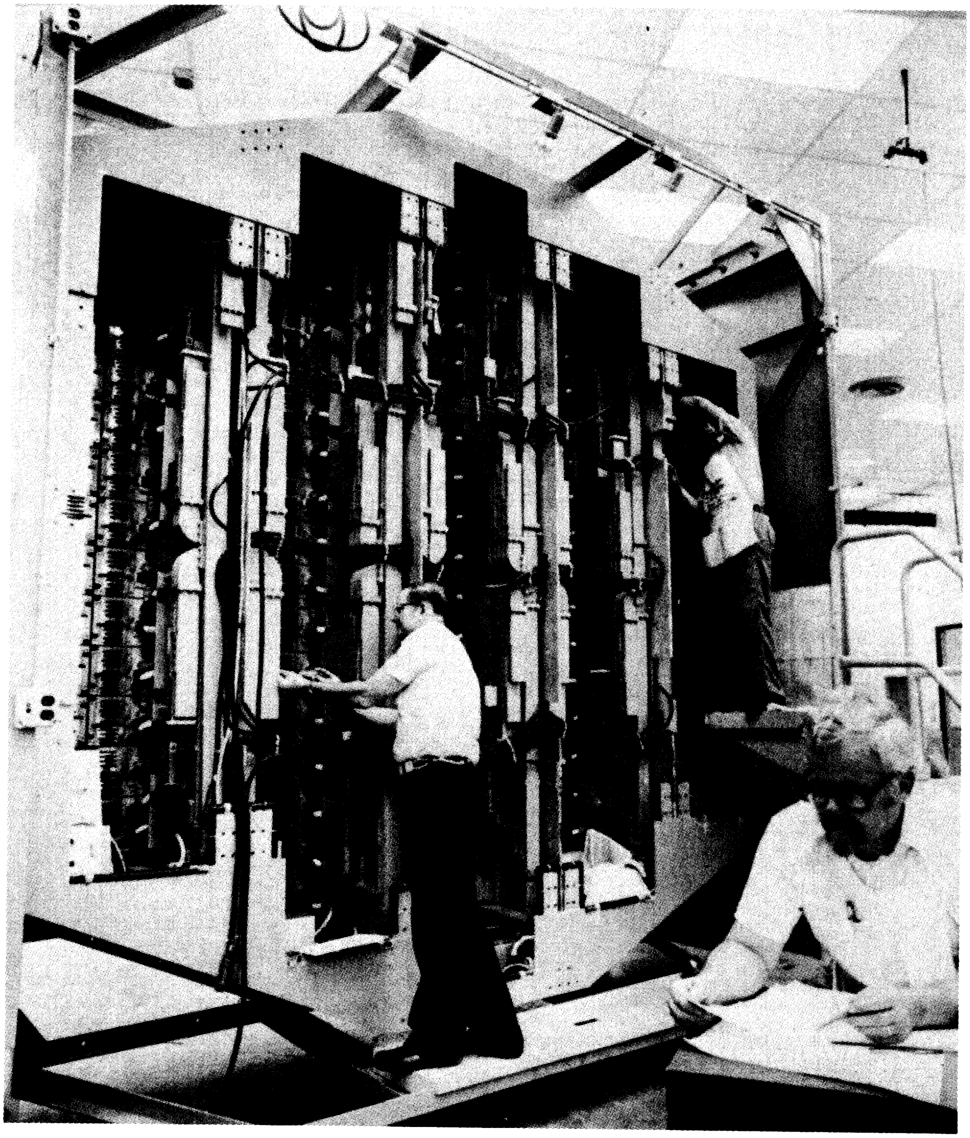


Figure 22. Aegis array viewed from the rear (photo courtesy of RCA).

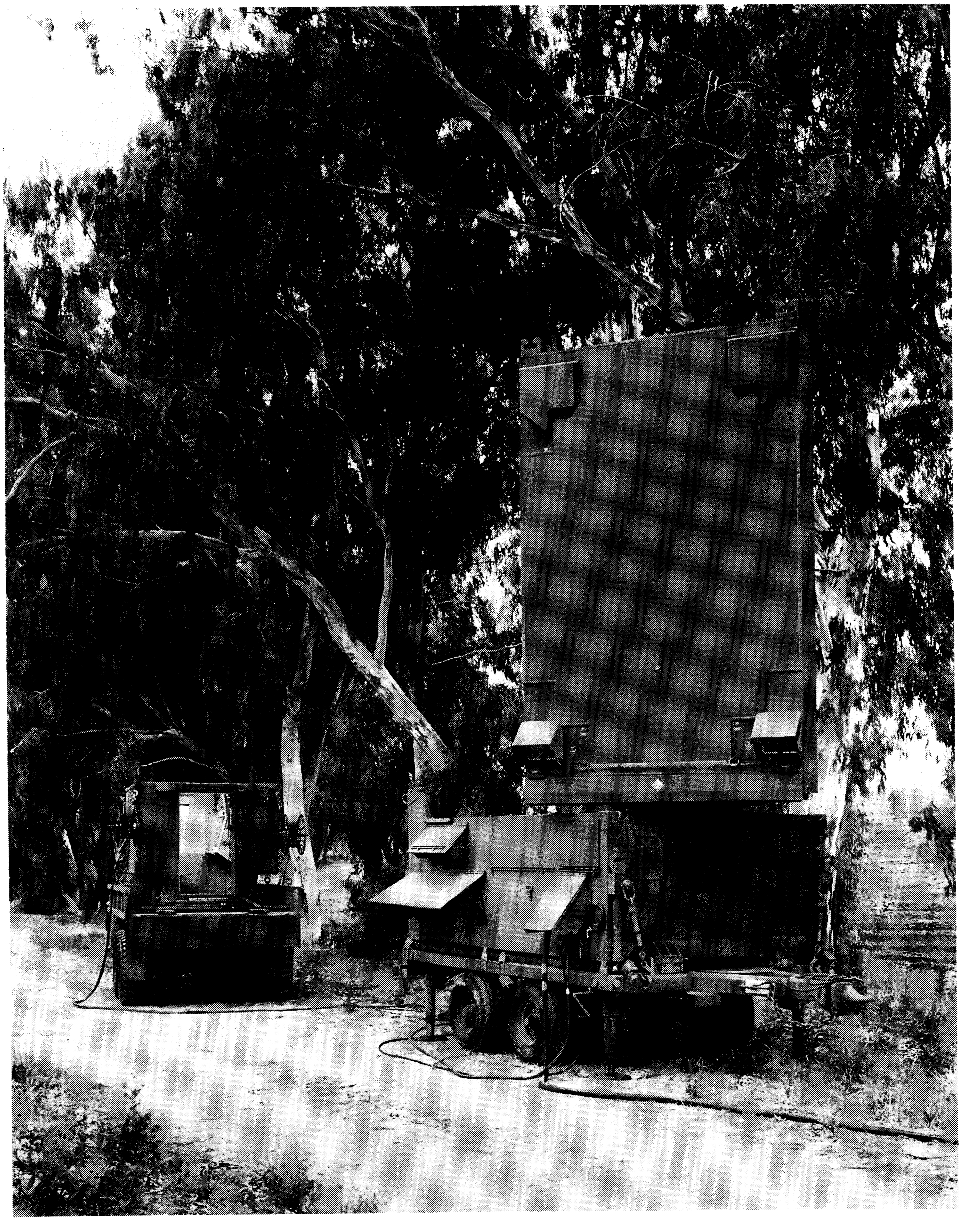


Figure 23. Hughes Aircraft Company AN/TPQ-37 counterbattery radar (photo courtesy of Hughes Aircraft Company).

4.3 RCA: Aegis

Soon after award of the SAM-D contract, another competition was sponsored by the U.S. Navy for ASMS (Advanced Shipboard Missile System), later to become Aegis. This was won by RCA (more recently incorporated into GE), with a constrained-feed subarray concept. Each subarray is fed from its own power amplifier, permitting very high peak and average powers to be radiated without problems of waveguide breakdown. However, the segmentation of the array presents difficulties in achieving low sidelobes. The monopulse network consists of a 40:3 microwave beamformer, coupling each of the 40 subarrays to each of the three monopulse channels (Figure 22). Attempts to convince the Navy that a space feed would be advantageous have not been successful. RCA/GE has developed a Multiple Object Tracking Radar (MOTR) for test range instrumentation, using a space-fed lens array.

4.4 Hughes Aircraft Company: Firefinder AN/TPQ-37

Hughes Aircraft, while unsuccessful in major competitions for ABM and SAM radar equipment, has developed many successful airborne radars using monopulse processing, and in the ground-based field has placed in production two types of counter-battery radar. The AN/ TPQ-37 (Figure 23) is an artillery location radar designed for about 30 km range. Diode phase shifters provide scanning over a 90° sector in azimuth and over a more limited elevation sector. Monopulse tracking is used to refine target trajectories.

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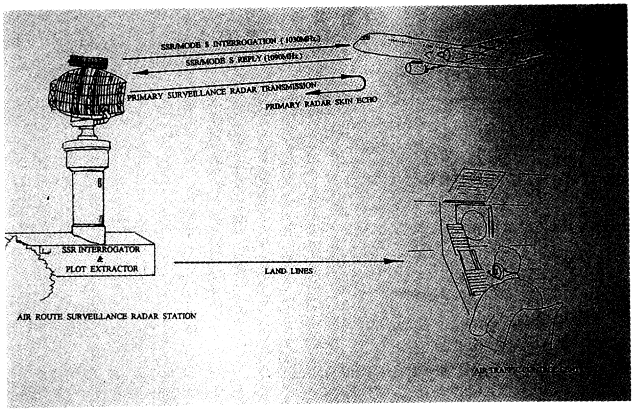
Richard M. Trim

SECONDARY SURVEILLANCE RADAR - PAST PRESENT AND FUTURE

1. Introduction

The number of passengers traveling by air has grown consistently since 1945, accelerating in recent years with the introduction into service of wide bodied aircraft and this growth is forecast to continue well into the next century.

This expansion has only been possible due to the availability of an efficient, radar-based system of air traffic control in which Secondary Surveillance Radar (SSR) has come to be the principal sensor (Fig.1). Secondary Radar differs from Primary Radar in that, instead of the "target" simply reflecting back passively to the observing radar a small part of the radio wave energy transmitted towards it, it is equipped with a radar receiver-transmitter, called a transponder, which receives a transmission, known as an interrogation, and replies with an active transmission which conveys not only the presence and position of the "target" but can also provide its identity and its pressure altitude. A particular advantage of secondary radar is that, whereas with primary radar, the strength of the echo signal received by the radar depends upon the reflectivity (Radar Cross Section) of the reflecting object ("Target") and varies as the inverse fourth power of the range, in the case of secondary radar, the signals are independent of target radar reflectivity and vary as the inverse square of range. As a result, very much lower transmitted powers are required for a given range performance in the case of secondary radar relative to primary radar. However, the system depends upon co-operating "targets", each equipped with a properly functioning transponder.[9,15,16]



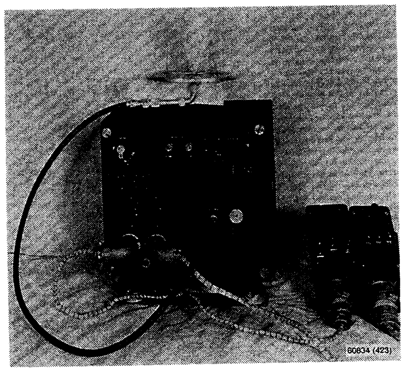


Figure 1 (top). SSR; principles of operation (source: author).

Figure 2 (bottom). IFF Mk V. (1944)-AN/APX-6 IFF transponder (source: *The Evolution of Naval Radio-Electronics and Contributions of the Naval Research Laboratory* , Louis Gebhard).

2. Development of SSR

2.1. Origins in World War II IFF

The present international system of Secondary Surveillance Radar for Air Traffic Control has its origins in the United Nations Beacon Project (IFF Mk V) of 1944/45 (Fig.2), although the origins of the technique of secondary radar go back further still to the mid-1930s.[1] The early development of the technique of secondary radar, first applied to target identification (Identification Friend or Foe - IFF) is a fascinating story in its own right. By 1943, the Allied IFF Mk III system was proving inadequate to meet the emerging military target identification requirement, as a result of which, a combined British, American and Canadian team of IFF specialists was assembled at the US Naval Research Laboratories (NRL) near Washington D.C. to develop a new IFF system to be known as the United Nations Beacon, or IFF Mk V. Although this project was canceled with the sudden end to World War II in 1945, the characteristics decided upon have had a profound effect upon both NATO IFF and the international system of Secondary Radar for Air Traffic Control up to the present day.

2.2. Early Days of SSR - The Problem of Sidelobe Interrogations.

With the end of the war, although the immediate pressure for a new IFF system was reduced, the need for a replacement for the IFF Mk III system remained, and NRL continued work on IFF Mk V. As a result of trials carried out in 1946, it was apparent that some characteristics of IFF Mk V as developed by 1945, should be changed: in particular, the slow code of the transponder reply was found to be impracticable for use with high speed aircraft targets and scanning ground radar antennas since the rotation of the IFF antenna had to be stopped for a period, in order to "searchlight" the target. Furthermore, pressure for the availability of some of the frequency spectrum allocated for the IFF Mk V system for use by other systems - especially TACAN - led to the abandoning of the use of multi-frequency operation, with single channels being allocated for interrogation and transponder reply - 1030 MHz. and 1090 MHz.

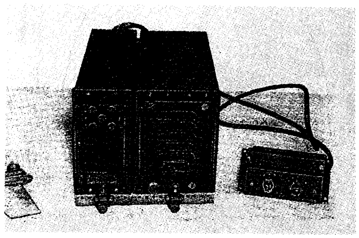
respectively. It seems likely that NRL had in mind improving the transponder reply code security by using some of the cryptographic techniques developed for the earlier NRL UHF IFF system.

The rapidly worsening relations with the Soviet Union, leading to the Berlin Airlift, resulted in pressure for a replacement for IFF Mk III with the result that the US development of IFF Mk V, designated IFF Mk X - the "X" denoting the fact that the system was still under development - was released for NATO use.

During the war, while at the Telecommunications Research Establishment, K.E.Harris had been aware of the work done on IFF, including the IFF Mk V project, and had become convinced of the advantages of secondary radar as a means of surveillance for radar-based Air Traffic Control. After a period with the Watson-Watt consultancy after World War II, he joined Cossor in 1950.

Cossor had played a prominent role in the design and manufacture of a wide range of radar and navigational equipment both before and during World War II, and Harris gained Cossor Main Board support to develop a secondary radar system for civil Air Traffic Control. Since the characteristics of IFF Mk X were still classified at that time, Harris used the frequencies for interrogation and reply which had been allocated for civil air navigation and which were close to those used by IFF. Also, he used interrogation and reply formats which were similar but not identical to IFF Mk X. In particular, he was convinced of the need for interrogation path side lobe suppression (ISLS), if the system was to be operationally acceptable for Air Traffic Control.

The need for ISLS had been recognised by those working on IFF Mk V during 1944-45, the British contingent being led by Vivian Bowden and including Robert Hanbury-Brown, but work on a technique for implementing it in IFF Mk V. had been stopped when the project was canceled in 1945. At Cossor, Harris set up a team of engineers led by Derek Levell, to develop a prototype system (Fig.3), supported by the British Ministry of Transport and Civil Aviation, in accordance with the concepts which he set out in Research Memorandum No.4, dated July 1951. The shoestring



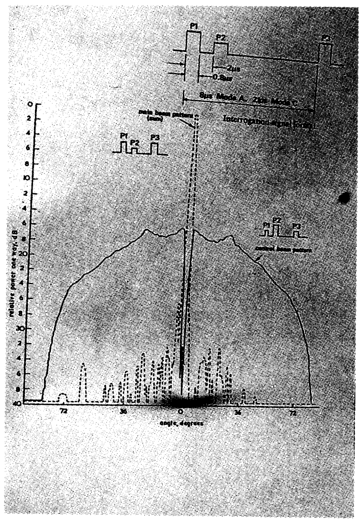


Figure 3 (top). First cossor SSR system installed at London Airport, Heathrow in 1951 (source: author).

Figure 4 (bottom). Interrogation path sidelobe supression (source: author).

circumstances of the project, when it was first set up, can be gauged from the fact that war surplus radios, bought at a local store, were used in the construction of early prototypes.

At this time, the US Civil Aviation Authorities were thinking in terms of a beacon system in which the interrogations would be provided by the primary surveillance radars, much like the earlier British Mk I and Mk II IFF.

The Cossor system employed a two pulse interrogation, Interrogation Path Sidelobe Suppression being incorporated, in which the first pulse of the two pulse interrogation transmission was radiated by means of an omni-directional antenna pattern to form the ISLS "Control" pulse, while the second pulse was transmitted via a directional antenna to form the "Interrogation" pulse (Fig.4). A crucial feature of the Cossor System was that the transponder was fitted with a logarithmic receiver of a wide dynamic range (50 dB), whereas contemporary IFF transponders, such as the AN/APX-6, had linear receivers of much more limited dynamic range. By 1952, a system was installed at Heathrow Airport, London, which was used for early demonstrations. The ground antenna consisted of a prime focus feed and reflector, but this was replaced by a broadside array of monopoles of the so-called "hogtrough" type which became the standard form of SSR interrogator antenna until quite recently. The reflector used for this first Cossor ground SSR system had a vertical aperture of about 4 ft. and was, as a consequence, a very early example of a Large Vertical Aperture (LVA) antenna. When it was replaced by a hogtrough antenna of much reduced vertical aperture, it was noticed that the loss of aircraft tracks in the vertical pattern lobing minima, was much more pronounced. The SSR interrogator antenna was co-mounted on top of the CPS-1 Microwave Early Warning (MEW) radar antenna which was used for surveillance.

Flight trials were carried out at London Heathrow, using this ground interrogator, in conjunction with an experimental airborne transponder. Demonstrations were given at London Heathrow, and later to the American Civil Aeronautics Administration and the Air Navigation Development Board (ANDB).[2]

Following these successful trials, an engineered version, known as SSR Mk 1 , was produced (Fig.5). SSR Mk 1 operated at frequencies of 1215 MHz. for the ground to air interrogation and at 1375 MHz. for the transponder reply.

As a result of these trials, two alternative forms of interrogation path sidelobe suppression were investigated, the first of which was the Two Pulse Method, referred to previously, and the second, the Three Pulse Method. A problem with the two pulse method was that the first pulse, radiated by means of a low gain, omni-directional antenna, had to be of high power in order for it to be received by airborne transponders at maximum range, whereas sidelobe interrogations only occurred at relatively short ranges.

Since one of the major advantages of secondary radar compared with primary radar was the much lower transmitter power required - and hence much lower equipment cost - Harris devised a three pulse method of sidelobe suppression. The advantage of the three pulse method was that the power of the omni-directional "Control" pulse had only to be great enough to exceed the sidelobes of the interrogation antenna by some 3 dB.

The SSR Mk 1, which was a production engineered version of the earlier prototype mentioned previously, was launched in 1953. In the same year, the US Joint Chiefs of Staff Joint Electronic Communications Committee proposed that all passenger carrying aircraft flying within US airspace be fitted with IFF Mk X - compatible SSR transponders. As a result, the technical parameters, but not the operational uses, of IFF Mk X (SIF) were made public. The US Air Navigation Development Board (ANDB) had placed a contract in March 1954 with the Stewart-Warner Company to modify an AN/APX-6 IFF transponder for use as an SSR beacon, compatible with IFF Mk X(SIF), the resulting transponder being known as the Radar Safety Beacon Type III. No provision was made for interrogation path sidelobe suppression. Based upon this work, a US National Standard was published and Aeronautical Radio Inc (ARINC) prepared Characteristic 532 for an airborne SSR transponder for use in civil airline

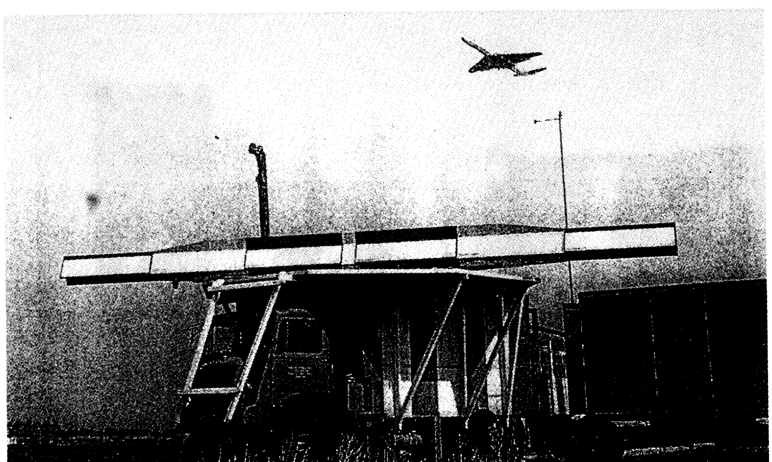


Figure 5. Cossor type 1 SSR mobile ground interrogator at London Airport, Heathrow (with Comet jet airliner) (source: author).

aircraft, being issued in July 1955. Again, no provision was made for interrogation path sidelobe suppression.

In 1954, at the International Civil Aviation Organization (ICAO) Communications Division meeting, the IFF Mk X interrogation and reply frequencies were adopted for common military and civil use for Air Traffic Control. In October 1955, in response to these developments, Cossor compiled specifications for SSR equipment compatible with the new US specifications but including interrogation path sidelobe suppression employing the two pulses of the standard IFF Mk X Mode 3 interrogation. The intention was to provide an interrogation format which would operate with airborne transponders, whether or not they had provision for ISLS, including existing IFF Mk X transponders. The control transmission was followed by the highly directional interrogation pulse transmission at a spacing of 8 microseconds, corresponding to Mode 3 of IFF Mk X (See Appendix A hereto). For use with the Type 3 interrogator, Cossor proposed two types of transponder, differing mainly in their reply coding. The Type 2 transponder was to provide a reply capacity of four codes consisting of one, two, three or four pulses, whereas the Type 3 transponder was to provide the 10 code, IFF Mk X (SIF) compatible reply capability called for in ARINC 532, these ten codes being those of the IFF Mk X (SIF) 64-code capacity system allocated for common military/civil use.

By 1956, the severe limitations imposed upon the utility of SSR for Air Traffic Control (ATC) due to interrogation antenna sidelobe interrogations, resulting in loss of target bearing and interference, were becoming apparent in the United States and interest in the Cossor methods of ISLS grew, as a result of which the Air Navigation Development Board (ANDB) placed a contract with Cossor via Melpar for the provision of a complete ground and airborne SSR system incorporating ISLS for evaluation at the US Navy Air Test Center at Patuxent River, Maryland. My task was to develop the airborne transponders while a colleague was responsible for the ground interrogator. This transponder incorporated silicon diodes for code selection together with a VHF transistor and may have been the first transponder to employ solid state techniques.

During the summer of 1957, the author provided engineering support to the US Navy at the USN Air Test Center in their successful evaluation of the Cossor system of side lobe suppression. The trials were observed by the US Civil and Military air traffic control authorities, with the result that, at the ICAO 7th. meeting of the Communications Division, held in Montreal in September/October 1957, the Standards and Recommended Practices (SARPS) for SSR, established in 1954, were extended to include provision for both two pulse and three pulse ISLS. The addition of ISLS had become more practicable with the development by Setrin, working at the USAF Rome Air Development Center, of the "Setrin Fix", which was a method of providing a limited degree of ISLS for current APX-6 transponders, of which there were some 17,000 in use, by means of their echo suppression ("Ditch Digger") facility. The Ditch Digger suppressed multipath echoes of interrogation pulses which could, otherwise, have caused false Mode 1 interrogations. In the Setrin method, the ISLS Control Pulse followed the first interrogation pulse at an interval of 1.5 µS, its amplitude being arranged to be equal to or greater than the interrogation pulses when they were radiated via the interrogator antenna sidelobes. Under these circumstances, a diode gate logic circuit in the transponder sensed the presence of the first interrogation pulse and the ISLS control pulse, with the result that the transponder was suppressed. When the transponder was within the main lobe of the highly directional interrogator antenna, the first interrogation pulse produced a desensitisation of the transponder receiver immediately following the first interrogation pulse by means of the transponder echo suppression, or "Ditch Digger" circuit. Under these circumstances, the weaker control pulse would fall into the suppression "ditch" and would not be of sufficient amplitude to operate the diode ISLS gate and the transponder would not then be suppressed. The advantages of the Setrin method relative to the Cossor technique was that the amplitude comparison for ISLS was made between the control and first interrogation pulses, whose spacing was fixed, irrespective of the mode of interrogation in use. During 1957, ARINC updated Characteristic 532A to 532B, to incorporate these improvements.

At this point, the UK favoured the two pulse method of ISLS, while the US preferred a three pulse technique, since it could be retrofitted into the large number of existing IFF transponders then in use, although it is doubtful whether, in the event, many were so modified, since the NATO Lockheed Starfighter Project made it necessary to develop a new generation of IFF transponder, the APX-46 into which provision for ISLS could be made, although still using the echo suppression facility and a linear receiver of limited dynamic range. Cossor work had shown that a receiver instantaneous dynamic range of at least 50 dB. was required for proper ISLS which could only be obtained by means of a logarithmic receiver, a technique which became standard in both IFF and SSR transponders from the mid 1960s onwards.[23] By late 1957, the possibility of a need for additional interrogation modes for civil ATC purposes was recognised and was reflected in ARINC Characteristic 532B, which specified the provision of a Mode B in addition to the original Mode A which, together with IFF Mode 3, provided the Common Military and Civil ATC mode of operation. Mode B was used in the UK, France and in Australia for some years afterwards since ISLS and transponder reply code capacity could be used without the need for compatibility with military IFF MK X, which applied to Mode 3/A. The use of Mode B in the UK was mainly in connection with technical flight trials. ARINC 532B also stated that the need might arise in the future for two further modes of operation, Mode C and Mode D, for "future system expansion" with spacings of up to 25 μS.

At this time, four methods of ISLS were under consideration by the ANDB, the Cossor Two Pulse and Three Pulse methods, the Rome ADC method (Setrin Fix) and the Stewart-Warner system. In addition to the Setrin-Fix and Cossor Two and Three Pulse methods of ISLS mentioned already, Stewart-Warner had proposed a three pulse method of ISLS in which the control pulse preceded the first interrogation pulse by 1.5

μS. This method also made use of the transponder echo suppression facility in that, for a sidelobe interrogation, the stronger control pulse suppressed the first interrogation pulse, as a result of which the transponder did not reply. However, as noted in a report by Battle and Ashby of Airborne Instrument Laboratory (AIL) in 1959 on behalf of the Federal Aviation Agency (FAA) on the effectiveness of the differing methods of ISLS proposed at the time, the Setrin and Stewart-Warner techniques were of limited use due to self-suppression of transponder replies at close ranges due to inadequate transponder receiver dynamic range. An advantage of the system proposed by Stewart-Warner was that, as with the Cossor System of ISLS, the interrogation and control patterns were produced by the same antenna array, so that problems with the matching of elevation patterns were avoided.

In 1956-57, papers by Vickers and Crippen in the US and by K.E.Harris in the UK, had described the technical limitations being experienced with the SSR system then coming into service and suggesting ways in which they might be alleviated or overcome.[3] In particular, attention was drawn to the problems of ground antenna sidelobe interrogations, loss of replies due to transponder capture, FRUIT, (False Replies Unsynchronised In Time), over-interrogation and also due to lobing of the ground and airborne antenna patterns.

In 1961, Cossor designed their SSR4G ground SSR interrogator, built to the ICAO standard, which was installed at London Heathrow and at Paris Orly. The corresponding airborne component was the SSR1251 ATC Transponder, which was an early example of hybrid vacuum tube and solid state technology. Following further revisions to the ICAO Specification in 1962, the SSR5G interrogator was developed and supplied to the UK Ministry of Civil Aviation. Also developed was the SSR1600 ATC Transponder which was entirely solid state apart from the high power transmitter which employed two Machlett 7815 ceramic triodes, the first as a master oscillator, and the second as a power amplifier/buffer.

In 1962, an SSR5G ground interrogator, serial number 001, was installed at London Heathrow, which, after being in continuous service at the airport for over twenty years, is now in the collection of the British Science Museum, housed in the Museum Annex at Wroughton, Wiltshire. In 1963 I became Manager of the Cossor Avionics Development Department and was responsible for the development of the first fully microminiaturised ATC transponder, the SSR2100 (Fig.6).[25] In 1967, ICAO expanded the transponder reply code capacity from ten to sixty four codes on Modes B and C and deleted the requirement for two-pulse ISLS.

During the late 1960s, Aeroflot carried out compatibility trials at London Heathrow with a Soviet "SSR CCP BPLC" SSR transponder, having compatibility with the ICAO standard, embodying some extra facilities, including air to ground transmission of identification, altitude, fuel state, in-flight emergency and identification of position (I/P).

2.3. ADSEL/DABS

By the mid-1960s, it was becoming apparent that, for the SSR system to achieve its potential as the main ground based radar sensor for ATC, the limitations affecting the system, as then implemented, would have to be overcome. Chris Ullyatt of the Royal Radar Establishment, in a paper of 1967, proposed the use of monopulse interrogations and of discrete addressing of transponders, suggesting the name ADSEL - Address Selective - for such a system. Independently, in the US, the Air Traffic Control Advisory Committee, under the chairmanship of Ben Alexander, proposed a Super Beacon system having characteristics in many ways similar to those recommended by Ullyatt, but also including a data link facility to reduce the load on the VHF Ground-Air Communications Link. A key element in the Ullyatt ADSEL Proposal was its compatibility with existing airborne transponders, including the use of a two pulse interrogation, corresponding to an ISLS pulse pair, which had the effect of suppressing standard transponders whilst enabling special transponders to receive and process discrete address interrogations.

At a meeting held on September 18th. 1969, during the United Kingdom Symposium on Electronics for Civil Aviation, chaired by Tom McWiggan, Chief of Telecommunications at the Board of Trade, at which those in the US and UK who were working on SSR improvements were present, it became apparent for the first time that the two projects, whilst different, were very complementary.

At Cossor, we were convinced of the potential of SSR Monopulse Working and we assembled a monopulse brassboard receiver, largely from existing SSR components, and gave a demonstration to the UK Department of Civil Aviation. We carried out a series of tests, the results being even better than expected. These trials were reported by the Cossor Project Engineer, Mike Stevens, in a paper published in the Proceedings of the Institution of Electrical Engineers in 1971. The result was the setting up of a programme of work, funded by the UK Civil Aviation Authority (CAA) and carried out by Cossor, on the development of ADSEL, including equipment definition, design and construction of experimental equipment and the carrying out of trials.

At much the same time, in the United States, the Federal Aviation Administration placed contracts with the Lincoln Laboratory of MIT for a system definition of the Super Beacon, now renamed the Discrete Address Beacon System (DABS). The DABS specification incorporated the Ullyatt ideas, together with an expanded data link which had not been present in the UK proposals.

In the US, the Air Traffic Control Advisory Committee considered that a target update rate of one every four seconds arising from the mechanically scanning antenna (15 rpm), would be inadequate, as a result of which Hazeltine designed and produced a toroidal, electronically scanning antenna, in which the interrogator main beam could be slewed rapidly, electronically, from target to target, once their presence and bearing had been determined (Fig.7). It was also possible for the beam to dwell on targets for long enough to ensure that a satisfactory interrogation and reply transaction had been completed. Although satisfactory from a technical performance point of view, the antenna was expensive and its operational use premature, as a result of which it did

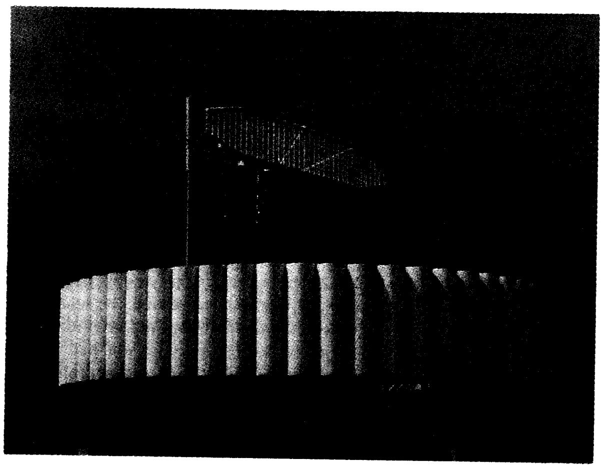


Figure 6 (top). Cossor SSR2100, 1965. Worlds first microminiature ATC transponder (source: author).

Figure 7 (bottom). Hazeltine E-Scan ground interrogator antenna (source: author).

not go into production. More recently, Allied Signal Bendix have supplied an E-Scan Antenna to the FAA for monitoring dual runway approach and landing.

In the UK ADSEL Project, most of the practical work was carried out by Cossor under the system design leadership of RSRE, the emphasis being on improving the surveillance function, while in the US, the interest included the development of the data link facility to enable routine ground-air message traffic to be off-loaded from the VHF voice communications channel, which was becoming overloaded in the busier terminal areas. A further interest was in the use of an SSR Data Link for Intermittent Positive Control (IPC), intended for ground based collision-avoidance. In the US, system responsibility rested with the Lincoln Laboratory under contract to the Federal Aviation Authority, building their own prototype equipment for evaluation before placing production contracts with Texas Instruments for three DABS ground stations for parallel trials with ADSEL. As part of their DABS project, the Lincoln Laboratory designed and built an experimental interrogator antenna having a large vertical aperture in order to reduce the mount of radio frequency energy reflected from the ground in front of the antenna. This had the effect of reducing the severity of the lobing of the antenna pattern in the vertical plane, the antenna measuring 20 ft. wide by 8 ft. high. This was followed by the development of the smaller Open Array Antenna, which still had a larger vertical aperture than the traditional "Hogtrough" and so greatly reduced vertical lobing, while retaining the wind resistance characteristics of the latter so that it could replace the hogtrough as part of a system upgrade programme. Initially, the Open Array Antennas had a vertical aperture of 4 ft. but later models had an aperture of 5 ft., giving reduced vertical lobing compared with the 4 ft. version, and incorporating sum and difference feed arrangements for monopulse working. This design of antenna has been built by several manufacturers world wide and has become standard for monopulse SSR (Fig.8).

Trials carried out by the Lincoln Laboratory team, including Paul Drouilhet and Vincent Orlando, confirmed that by using monopulse, bearing measurements made on

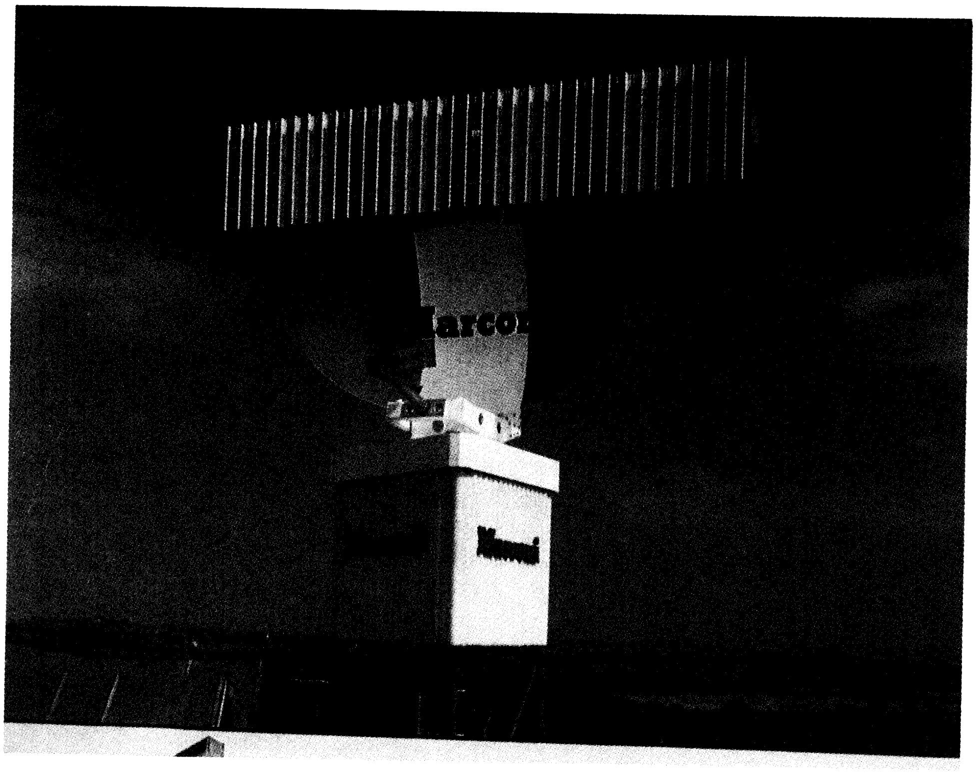


Figure 8. Marconi LVA ground SSR interrogator monopulse antenna (source: Marconi).

each SSR reply enabled overlapping SSR replies to be separated, thus overcoming the problem of garble which had been one of the most intractable of problems with non-monopulse SSR.[2] By the use of Large Vertical Aperture (LVA) interrogation antennas and monopulse, the main SSR system problems of lobing and garble had been solved without any changes to the current SSR system and, particularly important, without any changes to the airborne transponders.[21]

Late in 1974, a joint meeting was held at RSRE Great Malvern, between the FAA, the Lincoln Laboratory, UK MOD(PE) and the UK CAA, to discuss a collaborative future for ADSEL/DABS. The result of that meeting was a Memorandum of Understanding (MoU) between the USA and UK to harmonise the previously differing specifications of ADSEL and DABS. In 1976, at the ICAO 9th.Air Navigation Conference, a successful demonstration was given by the UK and the US to show that UK ADSEL and US DABS transponders were compatible with each other and that they were also compatible with the ICAO SSR System as laid down in ICAO Annex 10 SARPS. ICAO requirements for Mode B and D were dropped at this time.

2.4. Mode S

At the following MoU Technical Meetings held in London and Washington DC, ICAO Member States were enthusiastic, encouraging continuing effort to further the new system's development. Arising from queries from the 9th. Air Navigation Conference (ANC) and other presentations, efforts were concentrated on finding a suitable title for ADSEL/DABS. It had to be ICAO acceptable, yet descriptive of its capabilities. John Langley of the UK CAA found the answer - the new system was an extension of SSR with an addition to the then- known four interrogation modes A, B, C and D. The new system was selective in interrogating aircraft, so why not "Address Selective Mode", or to put it simply, "Mode S"? This suggestion was accepted and the term "Mode S" was officially adopted by ICAO.[4]

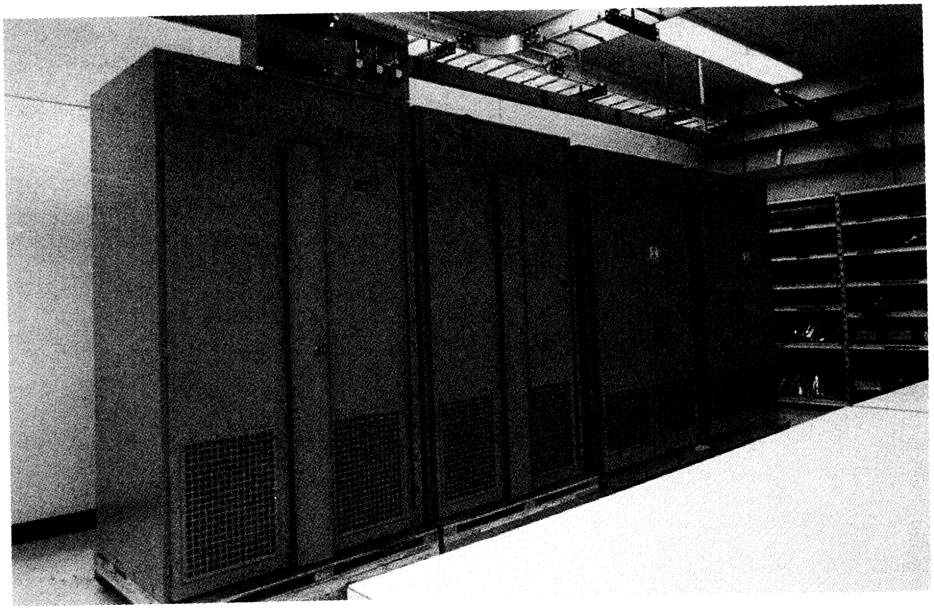
The fact that great benefits could be obtained by the use of LVA antennas with monopulse working, without any changes to the ICAO Standards and Recommended Practices, or to existing airborne equipment, led the UK to take the lead in implementing monopulse ground interrogators with LVA antennas, a lead since followed by other European States and by Canada (RAMP Program of 41 ground stations).[9-12, 24, 27, 28]

3. The Current Position

The UK Programme, in which LVA-Monopulse SSR ground stations have been installed at nineteen sites, was the result of pioneering work by a Government-Industry team in which John Shaw of RSRE, Tony Evans of the UK CAA and the Cossor team, led by Mike Stevens, played crucial roles. The success of this effort was recognised by a Queen's Award for Technological Achievement.[5-7, 26]

In the US, the need to transfer standard ATC and VOLMET (meteorological information for aircraft in flight) messages from VHF voice to data link has led to the placing of contracts with Westinghouse and Paramax for the supply of full Mode S ground interrogators. The current FAA contract with Westinghouse calls for the supply of 137 Mode S Ground Interrogator Stations (Fig.9). The first Interim Standard (Monopulse and LVA only) interrogator installation was made at the FAA Technical Center at Atlantic City in June 1991, followed by further Interim Standard installations at Orlando, Florida and at Denver, Colorado. The first full Mode S installation was due to be made at Washington International Airport in December 1992. This project has suffered some delays relative to the original rather ambitious programme, mainly due to difficulties with the software, as a result of which, Europe is ahead in the implementation of monopulse, although many US sites are equipped with LVA antennas.[13]

In Japan, the Civil Aviation Authorities have experimental trials programmes for Mode S and for Traffic Advisory and Collision Avoidance System (T-CAS). Toshiba



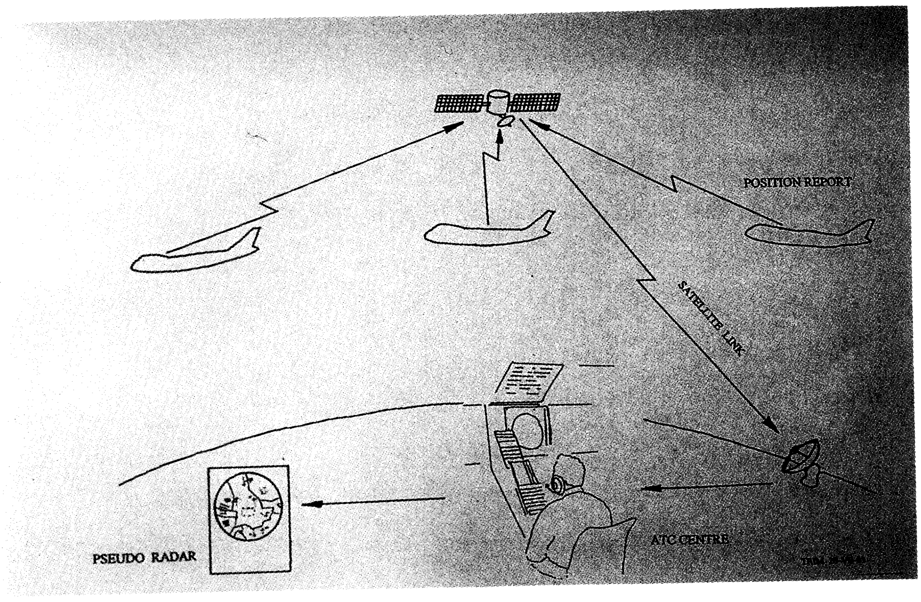


Figure 9 (top). Westinghouse SSR mode S interrogator (source: Westinghouse).

Figure 10 (bottom). Automatic dependent surveillance (source: author).

have produced an E-Scan antenna and Toyocom have supplied airborne Mode S and T-CAS equipment. In the UK, there are experimental Mode S interrogator ground stations at Gatwick Airport and at the Defence Research Agency at Great Malvern (better known by its former name of RSRE). In the United States, legislation requiring the carriage by passenger carrying aircraft of T-CAS has also led to the fitting of Mode S compatible ATC transponders, and recent UK trials show that some 25% of airline aircraft passing through UK airspace are fitted with Mode S Level II transponders and that, of these, some 25% are fitted with T-CAS. An important factor in the implementation of SSR Mode S is its inter-relationship with T-CAS (Airborne Collision Avoidance System - ACAS) in which aircraft in a potential collision situation will advise each other as to their manoeuvring intentions via the Mode S Data Link. While not strictly SSR, T-CAS is a secondary radar system making use of the SSR and Mode S transponders, having its origins in the Beacon Collision Avoidance and McDonnel Aircraft EROS systems of the mid-1960s, the latter being used to avoid collisions between F-4 aircraft on flight test.[14,18,19,20]

4. Future Developments

The implementation of the Global Positioning System (GPS) by the US Department of Defence (DoD) and the GLONASS Satellite Navigation System by the Russian Authorities, providing civilian users with an accuracy of position fixing worldwide sufficient for Air Traffic Control, has led to plans to move toward an ATC system in which aircraft determine their positions by means of GPS/GLONASS, reporting them via communications satellites to ground ATC, who then display them by means of "pseudo" radar displays. This system, known as Automatic Dependent Surveillance (Fig.10), is likely to augment SSR-based ATC, especially for trans-oceanic passages where the aircraft are out of range of SSR ground stations. In this connection, it is interesting to remember the proposals put forward by K.A.Wood of the UK CAA during the mid-1960s for a series of floating ocean platforms, moored at fixed locations across the Atlantic, on which would be mounted SSR interrogators so as to provide continuous SSR coverage for trans-Atlantic flights. The use of a satellite-based system will bring with it the need for improved monitoring and integrity of the satellite signals. Mode S datalink transactions between aircraft for the purpose of airborne collision avoidance, where they are out of range of terrestrial Mode S ground interrogators, could well be feasible as each equipped aircraft has a complete interrogator/transponder installation which is designed to be independent of the ground ATC system. Separation reduction will not depend upon Mode S as such, but rather on the SSR monopulse element with high accuracy direction finding. The UK is already using 5 nautical mile separation where monopulse is in operation. Improved altimetry will permit reduction from 2000 ft. to 1000 ft. separation above FL290 for sub-sonic flights. For Atlantic traffic, the present 60 nm. lateral/10 mins. longitudinal separation could be reduced once ADS has been fully accepted. At the present time, ADS flight trials are being carried out by British Airways, Quantas, American Airlines and Air Canada.

In October 1991, RSRE in the UK carried out flight trials of the Mode S Data Link, for ground-air communications - no voice communications were used. The trials, which lasted for three days, included two very successful demonstrations. In the meantime, several major programmes are in train in the US, Europe and elsewhere, to expand the capacity of the ATC system to cater for the greatly increased needs for commercial air travel foreseen for the coming century (Fig.11). As the international economic position improves, we are likely to see further rapid growth in air passenger transport in which Secondary Surveillance Radar will continue to play a vital central role.

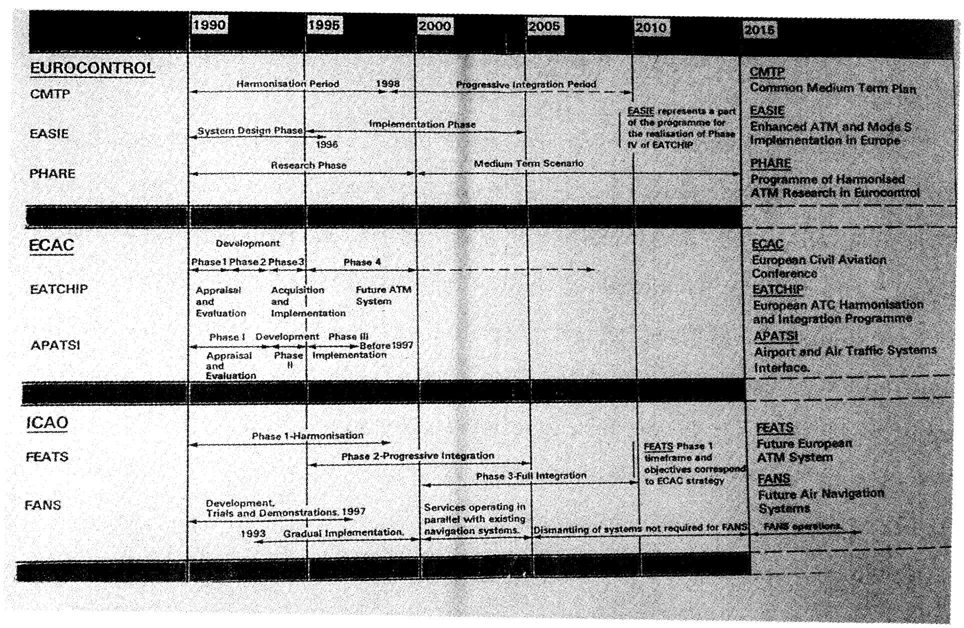


Figure 11 Current European air traffic management improvement programs (source: CAA).

5. Acknowledgments

In conclusion, I would like to thank those who have helped me in the preparation of this paper, especially Michael Stevens of Cossor Electronics Ltd. and John Langley of the UK National Air Traffic Services.

Appendix A

Interrogation Modes and Reply Codes.

When, in 1943/44, the operational requirement for IFF Mk V was being determined, experience with the limitations of IFF Mk III led to the recognition of the need, in addition to normal IFF operation, to be able to obtain IFF replies from formations of friendly aircraft free from mutual garble together with the necessity to identify particular aircraft (tail number), particularly in the context of ground based fighter direction.

These three "modes" of operation were implemented by the use of an interrogation consisting of two pulses whose mutual spacing could have one of three alternative values, 3 μS. for normal IFF, 5 μS. for specific aircraft identification (tail number) and 8 μS. for the identification of formations of friendly aircraft, being known as Mode 1, Mode 2 and Mode 3 respectively. In the case of Mode 3, the mutual garble which would occur if all aircraft in a friendly formation were to reply was avoided by arranging for the Flight Leader only to respond to friendly interrogations. These interrogation "modes" of IFF Mk V carried over into IFF Mk X and, most recently, into IFF Mk XII where they remain in current use.

When, in the early 1950s, it became US policy to require all civil airline aircraft entering and flying within US airspace to be identified by means of a system of secondary radar (SSR), compatible with IFF Mk X, it was decided that Mode 3 of IFF Mk X should also be used by the civil system of SSR as a common military/civil method of

Air Traffic Control (the "Common" ATC System), IFF Mode 3 being known as Mode A in the civil system.

The rather simple system of transponder reply coding developed for IFF Mk V was carried over into IFF Mk X (Basic) with the exception of the "Slow Code" which required the normally rotating interrogator antenna to be stopped so as to "searchlight" the friendly aircraft for long enough for the slow rate data to be transferred. In the event, as implemented, a Mode 1 interrogation elicited a reply consisting of one 2.5 μS. pulse, a Mode 2 interrogation resulted in two such reply pulses mutually spaced at 8 μS., while a Mode 3 interrogation resulted in a single pulse reply as in the case of Mode 1. For the indication of an in-flight emergency, four 2.5 μS. pulses were transmitted as the reply, mutually spaced at 8 μS.

By the mid-1950s, the limitations imposed by such a simple system of reply coding had become operationally unacceptable and a new form of reply coding was introduced, known as the Selective Identification Feature (SIF). In its initial form, the SIF reply coding consisted of two "framing" pulses, designated F1 and F2, each of 0.45 μS. duration and mutually spaced at 20.3 μS., between which code pulses of similar duration could be placed. In the case of a Mode 1 interrogation, the corresponding reply consisted of the two framing pulses together with up to five coding pulses, A1, A2, A4, B1 and B2 , spaced at 2.9, 5.8, 8.7, 11.6 and 14.5 μS. respectively after the leading edge of the first reply code framing pulse (F1). In the case of a Mode 2 interrogation (or "Challenge"), the reply consisted of up to twelve coding pulses in addition to the two framing pulses. The positions of these twelve pulses included the five positions of the Mode 1 reply pulses together with the addition of the B4 pulse position at 17.4 μS., the C1, C2 and C4 pulse positions and the D1, D2 and D4 positions at 1.45, 4.35, 7.25, 13.05, 15.95 and 18.85 μS. respectively. In fact, the technology available for high power modulation transformer design at the time made it impossible to use all of the available reply pulse positions for a Mode 2 interrogation, so that the reply code capacity available in practice was less than the 4096 theoretically available. The reply to a Mode

3 interrogation consisted of the two framing pulses together with coding pulses employing positions A1, A2, A4, B1, B2 and B4, providing a reply capacity of 64 codes. For each mode, it was possible to transmit on request from the ground controller, a pulse following the second framing pulse at a spacing of 4.35 µS., known as the Special Position Indication (SPI) or "Caboose" pulse. In an early implementation, the operation of the SPI pulse was linked to the pilot's VHF radio telephone microphone switch, being arranged to cause his IFF response to "Bloom" on the ground radar display when he made a radio transmission. In later versions, the pilot operated an "Ident" switch on his IFF control unit. For civil Air Traffic Control working on the common Mode 3/A, civil users were allocated 10 of the 64 codes available.

By the early 1960s, the operational limitations imposed by the limited reply coding of the current IFF Mk X/Civil SSR had become unacceptable. Fortunately, at this time the advent of high speed, high voltage transistors enabled transponders to provide replies consisting of all A, B, C and D pulses together with the Caboose (SPI) pulse on all modes, greatly increasing the military and civil reply code capacity. (The use of transistors for the modulation of the transponder reply transmitter was patented by Cossor Electronics Ltd., the author being cited as the inventor).

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Louis Brown

SIGNIFICANT EFFECTS OF RADAR ON THE SECOND WORLD WAR

In his essay "Walking" the historian George Macaulay Trevelyan[1] recommends that historians look at old battlefields and "... on looking, laugh at the 'science of history.' But for some honest soldier's pluck or luck round yon village spire, the lost cause would now be hailed as 'the tide of inevitable tendency' that nothing could turn aside!" Trevelyan wrote those words in 1913 when he could have scarcely imagined the scope of the land battles that were soon to come or have even dreamed of the struggles in the sky, transformations of scope that made his admonition in the strict sense pointless. Nevertheless, the Second World War had its own "honest soldier" who turned the tide, and his name was "radar". Such a statement must by the nature of scholarship generate learned dispute, but an investigation based on that assumption should prove useful. Historians of the war have often credited radar as having crucially affected the outcome of two engagements: the Battle of Britain and the Battle of the Atlantic, but the outcome of the war depended on Allied success at other times and places, so let us examine that dreadful conflict with a special eye for the decisiveness of this new technology and follow its tactical and strategic evolution.

Radar's effect on the outcome of the Second World War is a vast and complicated subject, and this paper is certainly no final judgment. On the contrary its purpose is to provoke renewed discussion of questions either not posed or for which answers have been tacitly accepted.

In September 1939 radar was barely ready for war, in many ways it paralleled aviation in 1914. It was being developed under extraordinarily secret circumstances in Britain, Germany, the United States, Japan, the Soviet Union, Italy, France and the Netherlands. It was unknown to all but a handful of engineers, physicists and military men and known by more than a dozen names. Its employment was an important part of the tactical doctrine only of the RAF Fighter Command. For a small fraction of the rest of the world's military it was an item of study and curiosity but even for those select groups it was not generally featured in their maneuvers, war games or thoughts.

Helgoland Bight.

Radar drew its first blood on 18 December 1939. Twenty-two Wellington bombers planned to attack German naval vessels at Wilhelmshaven by daylight; they did not release bombs because the ships were too near civilian targets, and neither side wanted to initiate the inevitable. A Lt. Hermann Diehl at a Freya station on the island of Wangerooge observed the approach and called a nearby Luftwaffe unit. The alert was ignored but the arrival of the bombers altered the attitude of the fliers, who took off and pursued the attackers from directions given by the radar operators.[2] Twelve of the bombers were shot down, and Bomber Command concluded that daylight attacks could not be sustained. They did not know of radar's part. Many who concerned themselves with such matters did not believe Germany had radar.

The Battle of Britain.

The success of Freya in December did not stir up much interest in the new technique of observation in the Luftwaffe. Lt. Diehl's proficiency was duly noted, but like RAF Bomber Command, the Luftwaffe looked on it as a defensive weapon for which they had little interest. In addition there was good reason to believe that Britain had no such skills. There was even solid intelligence data for believing this, for Col. Wolfgang Martini, the Luftwaffe signals chief, had used the new airship LZ-130 for electronic espionage.[3] It made a flight off the coast of England and Scotland in August 1939 with abundant equipment and technicians. Their flight was easily observed with Chain Home (CH), but they found no radar emissions, probably because they expected to find something similar to Freya. Unfortunately for them the first Chain Home Low

Cover station, which they would have certainly observed, did not make its appearance until December.

German forces found some portable British sets left behind after the evacuation from Dunkirk and soon observed the radiation from CH.[4] Although it had not been thought that Britain was that far advanced, the discovery did not alter Luftwaffe plans for their attack on the island. First, neither the captured sets nor the low frequencies of CH proved particularly impressive. Second, any employment of radar in the defense of France and the Low Countries had left few visible scars on the attackers. Third, outside of RAF Fighter Command few comprehended the power of conducting air defense by directing the defending fighters from the ground, based on accurate knowledge of the attackers positions. The result was only a half-hearted attempt to eliminate CH, which failed because the stations were more difficult to destroy than expected and the attacks on them were not pressed home. The outcome is too well known to repeat here.[5] The five years of effort by Watson Watt, Henry Tizard, Hugh Dowding and many others had succeeded.

The Blitz.

After a cataclysmic air battle on 15 September 1940 the German fliers no longer tried massive daylight attacks and shifted to night raids. Direct defense against the night attacks proved difficult. Interception by the defenders suffered from inaccurate ground direction and from airborne radar sets introduced prematurely with inadequate training and technical support.[6] The result for fall and winter of 1940-41 was a failure of radar night fighting. Using GL Mark II, a gun laying radar, the Army brought down some bombers with antiaircraft fire and by directing search lights for the fighters.[7] By May of 1941 airborne radar AI Mark IV with ground control using PPI (the plan position indicator) resulted in 102 night bombers brought down. The Blitz, as the night attacks were called, was reduced to sporadic raids as Germany attacked the Soviet Union.

Surface action in the Atlantic 1940-41.

The first warship to receive an operational radar set was the German pocket battleship "Graf Spee," which had a Seetakt set installed in January 1938. In October 1940 four German ships, the smallest being an 8-inch gun cruiser, began operation as commerce raiders. Their electronic capability allowed them to avoid the Royal Navy, which had little radar at the time, to detect ships for destruction and to locate their supply ships under adverse navigating conditions.[8] In May 1941 a similar action was instigated with the new super battleship "Bismark" participating. Although the first engagement quickly yielded a spectacular victory in the destruction of the "Hood" by radar directed gunfire, the "Bismark" encountered a radar equipped opponent who quickly turned the action into a hunt for the "Bismark." German surface warships never ventured into the open Atlantic again. They ended their service threatening the arctic route to Russia, requiring the Allies to keep capital ships on station that were needed elsewhere. They found their ends in actions in which radar always had a role to play.

The Mediterranean.

The importance of the control of these sea routes had led to a radar station having been established on Malta in March 1939.[9] The entrance of Italy into the war began a long struggle on, above and below the ocean surface. A few British radar-equipped capital ships arrived in September 1940, and their capabilities were quickly applied in a successful attack on the Italian fleet at Taranto on 11 November. The Italian reconnaissance planes protecting the port were destroyed by carrier planes after having been located by ship's radar, and surprise was complete. British radar superiority assured victory in the Battle of Matapan in March 1941, as crucial parts of the fight took place at night. This put an end to fleet actions by Italy.[10] Other engagements in the Greece-Crete actions appear not to have been influenced by radar to any extent by either side.

In 1941 Britain put every effort into preventing supplies from reaching the Italian and German forces in North Africa, and by July airborne radar became available, which gave a decided edge for attacks on convoys at night. In November an entire Italian convoy was destroyed.[11] By the end of the year the Axis powers realized that Malta must be eliminated as an air base and began the Malta Blitz during which the defenders relied on radar. The Axis forces broke off the attack without seizing the island, as the Luftwaffe squadrons joined Gen. Rommel's Afrika Korps, allowing the defenses to be strengthened. A renewed air attack from Sicily failed, owing to an influx of Spitfires commanded by Keith Park, who used radar instinctively. Suez was not captured, ending the possibility of a link with the Japanese in India, and the Axis forces in North Africa had to surrender with lack of supply the principal reason.

The Pacific War through 1942.

The war in the Pacific was fought with huge fleets in actions scattered over a third of the globe using strategies and tactics unlike any ever seen. For four years combat continued with pauses only for tending the awful wounds received and for preparing the next onslaught. At the start Japan had advantages in numbers and in an air arm that was both better equipped and better trained but bore the disadvantage of no operational radar despite technical competence. To offset this the United States had its capital ships equipped for early warning with the CXAM meter wave sets developed by the Naval Research Laboratory.[12]

The debacle at Pearl Harbor proved all the more humiliating when it was learned that the attacking planes had been accurately tracked by an Army SCR-270 but reported to an inactive control center. The sting of Pearl Harbor caused a response by carrier group attacks on Japanese bases in the Marshall Islands. These attacks were of no real military consequence and came about to satisfy the desire to hit the enemy somewhere, but they proved valuable for the first realistic use of radar to control the carrier planes and observe the enemy.[13] Fortunately the Navy had seen the importance of that manner of control and constructed special combat information centers around the radar screens.[14] The first engagement of carriers was fought on 6-8 May 1942 in the Coral Sea. Both sides suffered similar losses but the Japanese advance toward Port Moresby was stopped, and they retired to join a main thrust toward Hawaii with the island of Midway the initial target. In that decisive battle the Japanese planes were unable to attack with surprise, and their complete lack of this technology allowed them to be surprised by the arrival of the bombers that destroyed all four of their carriers and many of their valuable air crews.[15]

In the summer of 1942 the United States began an advance in the Solomon Islands that produced almost daily naval and aerial combat for months.[16] Warning of impending Japanese air raids may have spelled the difference between victory and defeat for Allied forces. Here radar helped the American ships to overcome the Japanese superiority in night engagements with gun fire directed from the Bell Labs Marks 3 and 4 40-cm sets.[17] By October 1942 a microwave radar, the SG, had been put into service. With its better resolution and plan position indicator it removed much of the confusion observed with longer wave equipment that resulted from the presence of many ships and nearby islands. The SG became greatly beloved by mariners. At about this time the Japanese deployed their first meter wave sets. In the first week of 1943 a Japanese bomber had been shot down with an antiaircraft gun using an industrially produced proximity-fuzed shell.[18] These events marked the opening of a completely new chapter in naval warfare.

Submarines and aircraft against merchant ships.

Despite the important effects of the submarine in World War I, none of the major powers gave serious thought to its use in their strategic planning of the 1930s. Germany built a U-boat fleet too small to be decisive initially, and Britain considered the threat more than matched by asdic, an underwater sound detection system. The U.S. Navy also developed the similar sonar yet never seems to have considered submarines a serious threat. Japan, dependent for the import of fuel and raw material as no other nation, seems to have given no real thought to the submarine as a commerce raider, either of her own or the enemy's vessels.[19]

The limited number of U-boats that Adm. Doenitz had at his disposal in 1940 were still enough for the first of the two "happy times" for submarine attacks on Allied shipping, but by late 1941 the introduction of the convoy system, the improvement of Royal Navy's anti-submarine techniques, and the entrance of the U.S. Navy as de facto belligerent in shepherding ships across the western part of their journeys reduced losses to tolerable rates. After war between Germany and the U.S. became official, U-boats began their second "happy time," in which they sank ships on the American East Coast and in the Caribbean almost unopposed through most of 1942. If the American fleet had learned anything during its 1941 apprenticeship on the North Atlantic, it was not apparent to merchant seamen. By the end of 1942 a significant number of RAF Coastal Command aircraft were equipped with ASV meter-wave sets and Leigh lights and made the U-boat passage through the Bay of Biscay dangerous. This was countered with radar receivers on the U-boats only to be made obsolete by ASV Mark III, the 10-cm airborne set for which the story of U-boat receivers became quite confusing for the submarine crews. At the same time however, airborne radar was matched by 10-cm sets on the vessels protecting the convoys, by shipboard radio direction finding, by airborne magnetometers, by escort carriers, by an adequate number of escort vessels, by continued de-coding of German signals and by the U.S. organizing its efforts efficiently. The sum of all this defeated the U-boats in mid 1943, although the grim struggle continued to the bitter end.[20] It is argued by some that the Battle of the Atlantic became critical for the Allies only because of the flawed policy of awarding priorities to Bomber Command for the destruction of German cities rather than to Coastal Command for protecting convoys.[21]

By 1945 Japan's merchant shipping had been essentially destroyed by U.S. submarine and aircraft attack, doing to the Island Kingdom what Doenitz had wished to do to Britain. The story in the Pacific is almost the inverse of the one in the Atlantic. Japanese anti-submarine efforts were as bad as the early American. By 1943 U.S. submarines began employing ever more sophisticated forms of radar to locate their prey and avoid enemy warships and planes. Neither Japanese aircraft nor surface ships deployed a significant amount of operational radar in defending their merchant shipping. Added to this the U.S. Army Air Force equipped B-24 bombers in August 1943 with a 3-cm set designed for low altitude bombing that allowed ships to be located and attacked at night.[22]

Preliminaries to the Great Radar War.

By 1942 it was obvious to all with responsibilities for technological policy that both sides possessed radar and that it had immediate and important effects. In that year it had become apparent that Germany had lost the lead in quality of equipment, which allowed Gen. Martini and Leo Brandt to secure the release of 8000 electronics technicians from military service. It was a time when Germany needed the radio amateurs, whose operations had been highly restricted since 1933. Martini had preceded this request with a strong demonstration of what a little radar cunning could accomplish. On 12 February the "Scharnhorst," "Gneisenau" and "Prinz Eugen" moved undetected until too late for decisive British action up the English Channel from Brest, where they had taken uneasy refuge after the sinking of the "Bismark." Martini had worked out techniques for jamming the British coastal radar that had allowed (with the help of a little bit of luck) these three ships and numerous escorts to escape the trap.[23] Sixteen days later in what proved to be the best executed commando raid of the war the important components of a German Würzburg were seized at Bruneval on the French coast.[24] Radar was no longer just a curiosity.

The Great Radar War.

With the end of the Blitz in June 1941 the RAF went primarily from defense to offense. Attacks on Germany's industry was a method of carrying on the war short of an invasion of the continent, a task for which Britain was clearly not ready. Bomber Command had ruled out daylight raids but lacked accurate means of locating targets at night. It also faced an enemy with excellent antiaircraft gun-laying radar and a rapidly improving radar-equipped night fighter capability. Great efforts went into countering German electronic defenses, matched by equally ardent efforts on the part of the defenders who were inspired by the knowledge that now they were defending their homes. German fliers responded with the same brand of courage and tenacity that had been found among Britain's "few" in 1940.

Navigation was first provided by Gee, a hyperbolic coordinate method that is the basis of modern civilian systems. Its limited accuracy was soon augmented with Oboe, which allowed the Ruhr to be bombed without visual sighting and with errors measured in hundreds of meters. The 10cm system H_2S, introduced in early 1943, allowed the fliers to see a crude picture of the ground that allowed targets to be attacked at ranges beyond the capabilities of Oboe and Gee, although with much less accuracy. Substantial radiant energy went into jamming Freya, and metal foil cut to the half wave length of the Würzburg gun-laying and the Lichtenstein airborne sets was introduced under the British code name of Window. Both H_2S and Window were considered sufficiently secret and important that their introduction was decided at cabinet level.[25]

But Bomber Command still had a hard fight. Oboe was jammed after the first months of operation, and H_2S became a beacon that guided night fighters to the bombers as did the radar sets in the tails of the bombers, designed to disclose the arrival of an attacker. Window, the technique for which so much had been hoped for by one side and almost pathologically feared by the other, proved indeed to be troublesome for the Würzburg. But target airplanes move fast and metal foils move slow, which allowed use of the Doppler effect to mitigate some of Window's bad effects for the antiaircraft gunners. The night fighters had already been converting from 60cm to 3.5m in order to gain range and found that this wavelength easily penetrated Window. The night fighters also altered their tactics with each change in the situation. Attempts to interfere with their radio communication links produced some confusion and a little humor but were not notably effective.[26]

Losses to Bomber Command grew from what was termed acceptable to substantial. The lightest losses of a major attack were in the attack on Hamburg with the introduction of Window; the worst were in the ill fated and ill planned attack on Nuremberg in March 1944, when the RAF reached the same point that the U.S. Army 8th Air Force had reached in October of the preceding year. The theories of penetration by evasion at night and by the self-defending bomber in daylight had been found illusory.[27] When the attacks on cities resumed after the invasion, Germany had lost command of the air, the result of the unexpected introduction of long range fighters. Bombers based in France, vanishing fuel supplies, insufficiently trained pilots and better radio discipline by the Allies brought Germany's air defense to the point where radar no longer counted.

The Invasion.

The radar deficiencies exposed in the practice invasion of Dieppe were meticulously avoided in the Normandie invasion.[28] Thorough radar cover for the ships and landing parties were matched in careful destruction of German sets and counter measures. Radar ruses, especially one to reinforce the suspicion that the real landing would take place at Calais, contributed much to the success of this enormous undertaking, which for a time hung in the balance. Radar navigation was so important that the action could not have taken place without it.

The End of the Pacific War.

In 1943 the American Navy was equipped with a wide variety of radars. When combined with the proximity fuze, which was widely distributed during that year in the Pacific (not in Europe until the V-1 attacks in mid 1944 for fear of one falling into enemy hands), the defense of a warship against air attack became extremely strong. Fighters were no longer considered vital for the defense of ships. Even without these new weapons the Japanese Navy was incapable of countering America's industrial output. A vital weakness, realized too late, was the limited training capacity for new carrier pilots. At the beginning Japanese fliers were simply the best in the world, the result of an intensive and highly selective training. When many of these fliers died at Midway there was no training program adequate to replace them. The United States had initiated in 1940 a very large training program for pilots, which began to supply all needs in 1943.

Japan's cities were systematically destroyed from the air in a manner quite different from what had been observed in Europe because the air defense of Japan was largely ineffectual. There was no radar war with Japan.

Epilogue.

What was the effect of radar on the outcome of the Second World War? Three critical engagements very likely were decided in favor of the Allies by their superiority in radar: the Battle of Britain, the interdiction of Axis shipping to North Africa in 1942 and probably the defeat of the Japanese Navy in 1942. In all three cases Allied forces were pressed to the limit and the outcomes had hung in the balance. Failure would have had grave consequences concerning which speculation is best left to long winter discussions at table.

The introduction of microwave radar is often cited as the weapon that decided the Battle of the Atlantic in 1943, a statement I find questionable. In 1943 the full weight of America's industry and manpower was being brought to bear in the Atlantic and radar was an important component, probably bringing the defeat of the U-boats a few months earlier, but their defeat was certain in 1943 -- with or without radar. By the middle of that year 17 escort carriers were available against only two twelve months earlier.

Radar navigation systems and radar countermeasures may well have made the difference at Normandie where Allied defeat was a real possibility, one that Allied industry and manpower might not have been able to make good.

Radar did not work exclusively to the advantage of the Allies, as the bomber crews will attest, but its effects tipped the scales in their favor without providing similar decisive battles to the Axis. To state, however, as it often has been, that radar won the war for the Allies ignores the nature of industrialized war, for the Industrial Age has made the single, decisive battle a rarity. The Battle of Britain was like Gettysburg, not Waterloo. Industrial age wars are fought to the exhaustion of the combatants.

Comprehending the significance of radar by commanders proved to be gradual with no side exempt from serious lapses in understanding. After achieving the first radar victory Germany let development slack and for a time gave little thought to the strategic ramifications of air defense. The United States, first to initiate a serious military program, had the electronic defense of its most important naval base on a training, not an operational basis and suffered a shameful defeat instead of the surprising victory that was possible. Britain, the leader in use of the new weapon, began bombing the enemy totally oblivious to its own radio navigation and countermeasures needs and landed at Dieppe a division onto a defended coast with planning that left out countering known radar defenses. By 1944 no more such lapses can be reported.

No mention has been made of the huge war between Germany and the Soviet Union. There is little evidence that radar had a critical effect on the outcome except as it was affected by the Battle of the Atlantic, but this may yet change as more information becomes available on Soviet radar. The gaps in our knowledge about radar's application on the eastern front and Soviet capabilities are substantial.

The mighty struggle between RAF Bomber Command at night over the German cities must rank as the greatest radar struggle, one in which the ingenuities of attacker and defender never slacked. It was also a most melancholy struggle, being for the young fliers an air equivalent of 1914-18 trench warfare. They went "over the top" twice a week. There is a bitter irony in this, because the enthusiasts of air power had promised the opposite. Trenchard, Mitchell and Douhet had seen mighty air armadas, against which there was no defense, quickly deciding future wars by first destroying the enemy air force and then the industry and cities; a short, decisive war would justify the regrettably high fraction of civilian casualties.[29] During the 1930s their extravagant pronouncements were taken seriously, indeed contributed to the urgency of British air defense planning. Fascinated by one new technology the air prophets had been unable to imagine a counter technology. Radar provided a creditable fighter defense, even at night; radar changed antiaircraft fire from a nuisance to a deadly danger; radar gave aircraft carriers their "armor plate"; radar transformed the writings of Mitchell and Douhet into comedies of the absurd.

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David K. van Keuren

THE MILITARY CONTEXT OF EARLY AMERICAN RADAR, 1930-1940

Introduction

In their studies of the First World War, historians have frequently made note of the important assistance provided to the combatants by contemporary science and engineering. Relatively new technologies, such as the airplane and the submarine, made their mark on the battle front, as did the products of war-related research and development in chemistry, ordnance, and applied optics. Indeed, the War has been repeatedly referred to by historians as the "Chemists' War," "The War of Invention," and their equivalents.[1]

Historians, in this regard, have simply followed in the footsteps of early twentieth century scientists and engineers themselves. Thus, John Fleming of University College, London, in 1915 described the on-going conflict as "a war of engineers and chemists."[2] Thomas Edison, the American inventor-entrepreneur, that same year declared the conflict to be a forerunner of struggles to come, which would become more and more "a matter of chemistry and electricity."[3] The latter sentiment was echoed by Fleming, who warned that, "... In addition to the concentration of engineering knowledge and skill on the problems of the war, we have to think as well of what will come after. What is required is not merely opinions on inventions already made, but the proper organisation of inventive power and scientific research to bring about new and useful results. This is only to be achieved by bringing to bear adequate combined inventive or scientific power on definite problems which are not too far removed from practical possibilities."[4]

Interest in hitching inventive and scientific power to military needs proved to be strong in the immediate postwar period, when the memory of science-based weaponry was still potent in the minds of the former protagonists. The British Admiralty Central Research Institution, predecessor to the Admiralty Research Laboratory, received administrative approval in 1918.[5] In the United States, the Naval Research Laboratory, first proposed in 1915 but delayed until after the war's conclusion, started construction in 1920 and opened in 1923.[6] The electrical and radio laboratories of the Army Signal Corps were combined in 1929 to create a central research and testing laboratory, the Fort Monmouth Signal Corps Laboratory.[7] Direct consequences of the "war of inventions," these new military laboratories had as their mission the creation of in-house centers of scientific and engineering expertise for the military services. The expectation was that, like corporate research laboratories, they would help provide their institutional masters with a critical scientific and engineering edge in future military competition. In the American case, the laboratories subsequently provided the research and development setting for the first operational U.S. radars.

Postwar Research in High Frequency Radio

The staffs of both the Naval Research Laboratory and, later, the Fort Monmouth Laboratory were created from pre-existing groups of researchers and engineers previously employed in war-related electronics work. The Naval Research Laboratory centralized all Navy Department sound and radio research into one facility.[8] Its personnel were drawn from radio research groups at the Bureau of Standards, the Naval Air Station at Anacostia, and the Washington Navy Yard radio test shop. The Laboratory's sound ranging group was brought from the Engineering Experiment Station at Annapolis, Maryland. Fort Monmouth amalgamated the Army Electrical and Research Laboratories in Washington, D.C., the Radio Laboratory at Fort Monmouth, and the Subaqueous Sound Ranging Laboratory at Fort H. G. Wright, N.Y.[9] The mission and impetus of the working groups, in turn, was set during the national emergency of 1917-18.

Section three of the United States Radio Act of 1912, passed in the wake of the Titanic disaster, authorized the American president to close down private radio stations or to place them under the control of the federal government, for the duration of the emergency.[10] Under authority of the act, on April 7, 1917, one day after the United States entered the First World War, the United States Navy Department seized control of private American radio stations, with the exception of those under War Department control. In addition to establishing governmental radio policy and overseeing operations of radio facilities, the Navy Department controlled the design, purchase, installation, and upkeep of government radio. As a consequence, the Department was able to exert considerable control over radio production and delivery rates by corporate suppliers. It encouraged companies such as General Electric, Western Electric, De Forest, and American Telephone and Telegraph (AT&T) to cooperate in the use of patents and in the production of products for use in the war effort. Additionally, the Navy encouraged increased corporate emphasis on radio R&D to advance the state of the art.

The war saw a greatly expanded use of radio for communications purposes in both the services. Radio was increasingly seen as a useful tool for command and control. Additionally, both the Navy and Army saw it as the best means for communicating with aviators and the Navy as a great advance in ship to ship and ship to shore communications. Control over national radio networks significantly expanded Navy oversight responsibilities in radio, while close work with corporate researchers and suppliers simultaneously increased Departmental awareness of current research interests and problems in radio R&D. Wartime contacts with private manufacturers would later prove useful to both the Navy and Army as they established their own postwar research and development programs in what had now become a critical military technology.

The postwar research and development programs at the consolidated military laboratories continued work that had been initiated during the war years. At the Naval Research Laboratory, Navy scientists and engineers set to work investigating means of increasing the power and sensitivity of radio receivers and transmitters; studying the design of new radio vacuum tubes; improving aircraft radio transmission and reception; reducing aircraft ignition interference; designing new loop, coil, and multiple transmission antennas; creating mechanisms for precise frequency control; and working on problems associated with radio compasses, aircraft height indicators, and aircraft landing field indicators.[11] The majority of the work was very applied in nature, closely tied to the current and near future needs of military communications.

However, a portion of lab time was directed to more basic studies, or what Laboratory officers defined as "real research."[12] An example of the latter was the research conducted by A. Hoyt Taylor and E. O. Hulburt at NRL in the mid-1920s into the transmission of high-frequency radio waves through the ionosphere. Although not of immediate utility, it dealt with questions that would need be answered when the military services eventually moved from low to high frequency communication systems. Researchers at NRL had begun to investigate the possibilities of just such communications in 1924, hoping to adapt the lower power needs and smaller antenna requirements of high frequency radio to Navy fleet and shore needs.[13] The application of high frequency radio waves to radio communications was quickly extended to radio direction finding, a topic of great interest to army and naval aeronautics. It was in the latter area that experimental observations soon led from radio direction to radio detection and ranging.

On June 24, 1930 two NRL Radio Division employees, Leo Young and Lawrence Hyland, were testing a high frequency direction finder designed by the Division.[14] The two men were transmitting a horizontally fixed beam at 32.8 megacycles in order to test directional reception obtained with a single-wire antenna attached along the fuselage of a plane on the ground at Anacostia Naval Air Station, a couple of miles to their north. During the course of the experiment Hyland noticed occasional augmented meter readings when he was expecting minimum signal strength on his receiver. Repeated observations showed that the unexpected fluctuations occurred when planes flying up and down the Potomac River crossed between Young and Hyland's receiving antennas and the transmitting station. It soon became clear to Hyland that the airplanes were

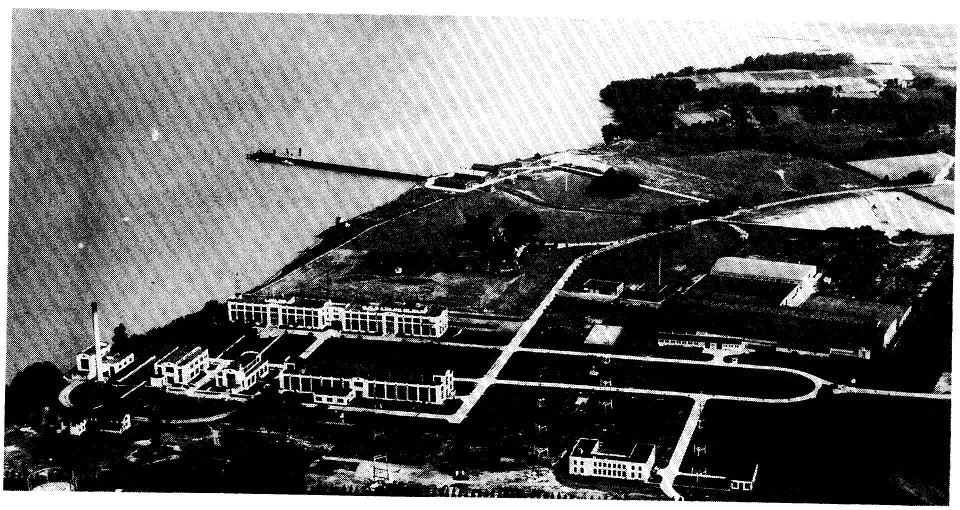

Figure 1. Aerial view of Naval Research Laboratory, Washington, D.C., ca. 1939.

reflecting the high frequency radio waves transmitted by the direction finder he and Young were testing.

Hyland's observations in many ways repeated and confirmed observations made by Leo Young and Albert Hoyt Taylor of the Naval Aircraft Radio Laboratory in 1922.[15] Young and Taylor, while studying experimental equipment using high-frequency waves, had situated a transmitter on one side of the Potomac and placed a superheterodyne receiver in a car which they drove around the base. At one point, they drove across the Potomac River and placed the receiver on the seawall across the river from the transmitter. A wooden steamer, the Dorchester, coming up the Potomac from Alexandria, produced interference patterns as it passed between the transmitter and receiver. Although Taylor and Young realized the potential of the discovery, they were unable to interest the Bureau of Engineering, their administrative superior, in supporting further research on the subject. By 1930, Young was a staff scientist at NRL and Taylor was head of the Laboratory's Radio Division.

Hyland excitedly reported his observations to C. B. Mirick, head of the Aircraft Radio Section, and to Commander E. D. Almy, the Laboratory's assistant director. Subsequent experiments confirmed Hyland's original observations. Over the next several months the observations were repeated using the same receiver, but varying the transmitter, antenna shapes, frequency (32.8 to 65 megahertz), and the location of the receiver. By November of that year, the Radio Division, under Taylor's leadership, had conducted enough experiments and collected sufficient data to request the Bureau of Engineering to establish an official research effort in the use of high or "super" frequencies to detect surface vessels or aircraft.[16] Bureau approval came, rather reluctantly, in mid-January of 1931. Radar research had been officially launched at the Naval Research Laboratory.

Radio Detection at the Naval Research Laboratory and the Signal Corps Laboratory: Continuous Wave Research

Early work on the "radio detection project" went slowly. The establishment by the Bureau of Engineering of an official research project in radio detection allowed NRL scientists and engineers to pursue the subject as time and other duties permitted. However, no extra funds were allotted to pay for the study and no new personnel appointments were made to help man it.[17] In the eyes of the Navy Department in general, and the Bureau of Engineering in particular, the primary utility of high frequency was in the area of secure communications, and the Laboratory was expected to focus its main attention there and in related engineering concerns.

Primary historical resources on the first years of the radar project at NRL are scarce. What they do indicate is that work on radio detection remained a part-time effort for a handful of researchers in the Radio Division's Aircraft Section, with Hyland remaining the most active worker on the project. Later reminiscences by A. Hoyt Taylor state that experiments were gradually expanded to cover frequencies up to 100 megacycles, using portable equipment which was transported to various locations in the metropolitan Washington area.[18] Photographic records of the receiver signals were made to help correlate the observed position and speed of airplanes with the radio detection observations.

By 1932 Laboratory personnel had designed a system using radio detection that had the potential of protecting a discrete area or facility, such as a city or military base.[19] The plan envisaged establishing a ring of directional transmitters around the periphery of a circle, with the transmitters sending out overlapping fan beams. An outer ring of receivers would be connected by wire to a central recording station. The system would detect and give advance warning of airplanes within fifty miles of the center of the protected area. Taylor notes that several of the component parts of the system were built and tested, although no complete operating prototype was ever attempted.

Nevertheless, early results were discouraging. As an early Laboratory report to the Bureau of Engineering declared, "Some scattered observations of great interest have been made between ship and ship and between ship and shore on superfrequencies," but on the whole "effects from moving objects in the air are much more pronounced than those on the surface or on the sea," although little work had been done on the latter end of the problem.[20] Early results, which required a fixed location for transmitters and receivers, appeared to be much more suitable to meeting Army, shore-based needs than those of the Navy. This was not a conclusion likely to produce increased support from an already cool and financially strapped Navy Department.

One consequence of this early assessment, however, was that the Navy Department decided to bring its Laboratory work on radio detection to the attention of the War Department. On January 9, 1932, the results of Navy research was summarized in letter from the Secretary of the Navy to the Secretary of War.[21] The letter pointed out the potential of radio detection for protecting defensive areas and expressed confidence that the observations upon which the system was based were as yet unknown outside the American military. The communication was a clear invitation to the Army to pick-up on a new technology that appeared so far to be better suited to ground-based defensive forces than to the Navy's ocean-going fleets.

The United States Army had been actively interested in developing detection systems for enemy aircraft since the First World War and continued to pursue such efforts in the postwar period.[22] Starting in 1926, its Ordnance Department, based in the Frankford Arsenal in Philadelphia, had studied the use of infra-red light for detection purposes. Responsibility for the project was handed over to the Signal Corps Laboratory in 1930, which attempted to develop means of tracking both one-way and two-way flows of infra-red radiation from airplanes. The project was abandoned in 1933, with research being shifted to the study of one-way heat radiation and to reflected radio waves.

By the time the Navy Department letter of 9 January reached the Signal Corps Laboratory, its commanding officer, Major William Blair, was already aware of the Navy experiments and the potential of reflected radio waves for detecting enemy aircraft.[23] He had proposed that the Signal Corps study the use of radio waves as a means of aircraft detection as early as 1926. However, his superior, Major General Charles Saltzman, had considered the idea impractical at the time and Blair was forced to shelve the idea. With the failure of the infra-red detection project and the continuing Navy efforts in radio detection, Blair felt it was finally time to establish a program in radio detection. Unlike the work at NRL, however, Signal Corps efforts, under Blair's direction, were focused on the use of microwaves.[24] Blair, who had studied physics under A. A. Michelson at the University of Chicago a quarter decade before, was convinced that microwaves had the potential of locating aircraft with far greater precision than did the longer waves used in the Navy experiments.

The meter wave research at the Naval Research Laboratory and the microwave research at the Signal Corps Laboratory were pursued simultaneously and independently during the next year and a half with equally unsatisfactory results. Because of the pressure that the Depression placed on the federal budget, funds at the Naval Research Laboratory from 1930 to 1934 were extremely limited and manpower was essentially frozen.[25] Additionally, in 1932 the Laboratory was transferred from the Office of the Secretary of the Navy to the Bureau of Engineering, an agency which under its current head, Stanford C. Hooper, was hostile to in-house government research. Hooper believed that research not connected to immediate operational needs ought to originate in the laboratories of private corporations.[26] The consequence was that NRL personnel were loaded down with product testing work and had only limited opportunity to spend time on the radio detection program.

What effort NRL researchers could spare on radio detection was spent attempting to increase the acuity and distance of system detection, on trying to damp down the reception of direct waves in the receiver so that the reflected radiation could be detected, and on establishing means of measuring the direction of the reflecting object.[27] Laboratory researchers by 1934 had still not produced a system that could be effectively used aboard ship.

The staff at the Signal Corps Laboratory were not encumbered with the same institutional constraints that were plaguing NRL and did not need to produce a system that could be used at sea. Nevertheless, they still faced problems in increasing the sensitivity and range of their equipment. More importantly, however, were the problems Signal Corps researchers faced in meeting the high power demands of microwave transmission.[28] This was a difficulty that would not be solved until the introduction of the cavity magnetron to the United States in 1940 by the Tizard Mission.

Radio Detection at the Naval Research Laboratory and Signal Corps Laboratory: Pulsed Wave Research

The critical breakthrough in prewar American radar came in 1934 when researchers at NRL began looking at pulse, as opposed to continuous wave, transmission. In February of that year, a group of Naval Appropriations Subcommittee members came to the Laboratory to visit the facilities and be briefed on on-going research projects. One of the projects that Subcommittee members were interested in was radio detection. It was at this time that Robert M. Page was brought into the undermanned project to help prepare a demonstration of continuous wave radio detection equipment.[29] After the visit, Page went back to his work on the decade frequency analyzer. When the latter project was canceled by the Bureau of Engineering at the end of March, he was reassigned to the radio detection project. However, there was to be a change of emphasis. Instead, of working on continuous wave equipment, Page was instructed by Leo Young to work on developing a system that would use radio pulses.[30]

Young was familiar with the work on the measurement of the ionosphere with radio pulses that had been done at the Laboratory in the mid-1920s. However, the

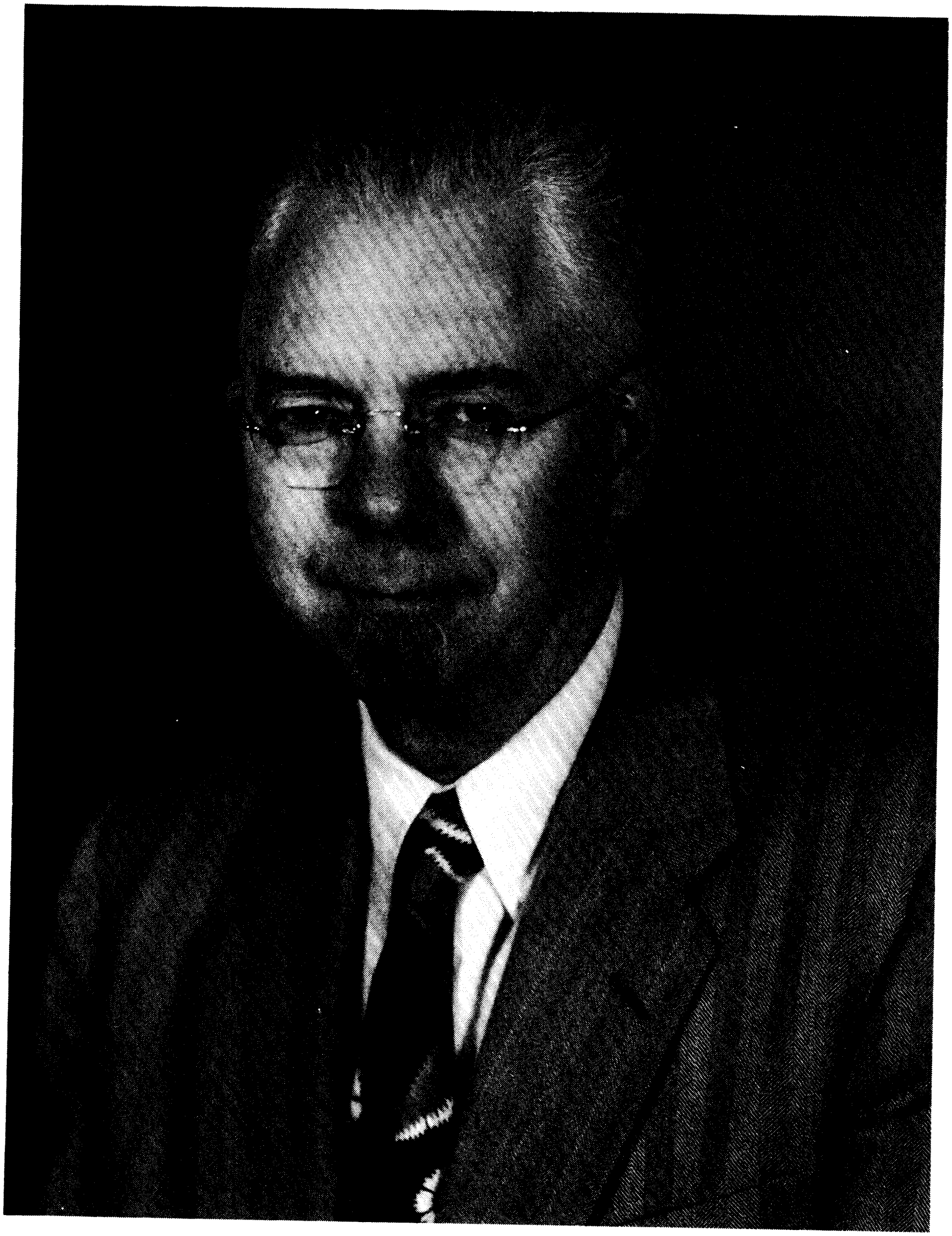

Figure 2. Robert M. Page, leader in development of pulse radar at Naval Research Laboratory.

pulses then used were very long and required large receiving antennas, characteristics which would have proven to be major drawbacks in creating an effective radio detection system.[31] Young's reconsideration of radio pulses came about in 1933, as a result of work he and colleagues were involved in on suppressing radio clicks produced in shipboard radio code transmissions.[32] As part of his efforts at eliminating the clicks, Young had devised a means of displaying the clicks on cathode ray tubes. When he produced the clicks on his cathode ray meter he was surprised at how strong and narrow the pulses were. With additional input from instrumentation produced by the Sound Division for supersonic depth finding, Young thought he saw the basis for a new approach to radio detection. He set Page on its trail.

Page quickly put together an indicator using a modified oscilloscope and then concentrated on building a signal generator and a high gain, high frequency transmitter with a cathode ray indicator.[33] He borrowed and modified a wide band communications receiver from elsewhere in the Laboratory. By mid-December, Page was ready to put his experimental system to the test. He placed the transmitter and keyer in one building, with a directive antenna on the roof.[34] The receiver and indicator were in an adjacent building with another directive antenna on the roof. The receiver picked up signals from the airplane while the transmitter was off between pulses. However, the receiver did not show distinct transmitted and received pulses. The test was successful enough to continue work, but the transmitter needed to be much improved and sensitivity and range of the overall system increased.

Page worked on the design of the receiver the rest of 1934 and the beginning of 1935. Samples of a new high frequency "acorn" tube just recently produced by RCA were worked into the receiver and extensive modifications were made to the overall design of circuitry, shielding, and filtering.[35] Additionally, because of scarcity of funds, the receiver was designed to cover a large frequency range so that work on it could be charged off to project funds for high-frequency communications.

During the course of 1935 the Laboratory received a supplementary appropriation from Congress, easing its financial situation. More funds became suddenly available for research personnel and materials. As a consequence, an additional researcher, Robert C. Guthrie, was added to the radio detection project later that year.[36] Page assigned Guthrie to work on improving the transmitter while he handled the receiver. By March of 1936, the redesigned equipment was ready for a practical test.

The first test came on April 28 with subsequent demonstrations to Laboratory personnel on May 6 and Bureau of Engineering officials on June 10.[37] All three went beautifully. On the April 28th test, planes were picked up at distances of 2.5 miles, and the received pulses were clearly defined. Plate voltage in the transmitter was gradually increased, and by May 6 clear echoes were received from airplanes at 17 miles. After the June 10 demonstration, the project was declared secret, and project personnel began directing themselves to producing a prototype appropriate for shipboard testing and use.[38]

Arthur Varela, an engineer, was assigned to the project in May of 1935 and was immediately given the task of designing a set to operate at 200 megahertz.[39] Page, under instruction from Taylor and Young, concentrated on producing a combined receiver and transmitter antenna. What became the radar duplexer is first mentioned in his notebook on 8 May 1936.[40] By July 22, both the 200 megahertz set and duplexer were ready for testing.

The success of the July test led to the first sea trial on board the U.S.S. Leary in April of 1937.[41] However, the Leary trial confirmed a continuing problem: pulse power remained too weak, limiting the effective scanning range of the system. Fortunately for the project, a new tube produced by Eitel-McCullough, the Eimac 100TH, was able to carry the high voltages the radar work required.[42] By early 1938, Page was using Eimac tubes in a reconfigured transmitter. The radio detection project constantly worked at the front edge of technological innovation. The "acorn" and then the "Eimac" tubes

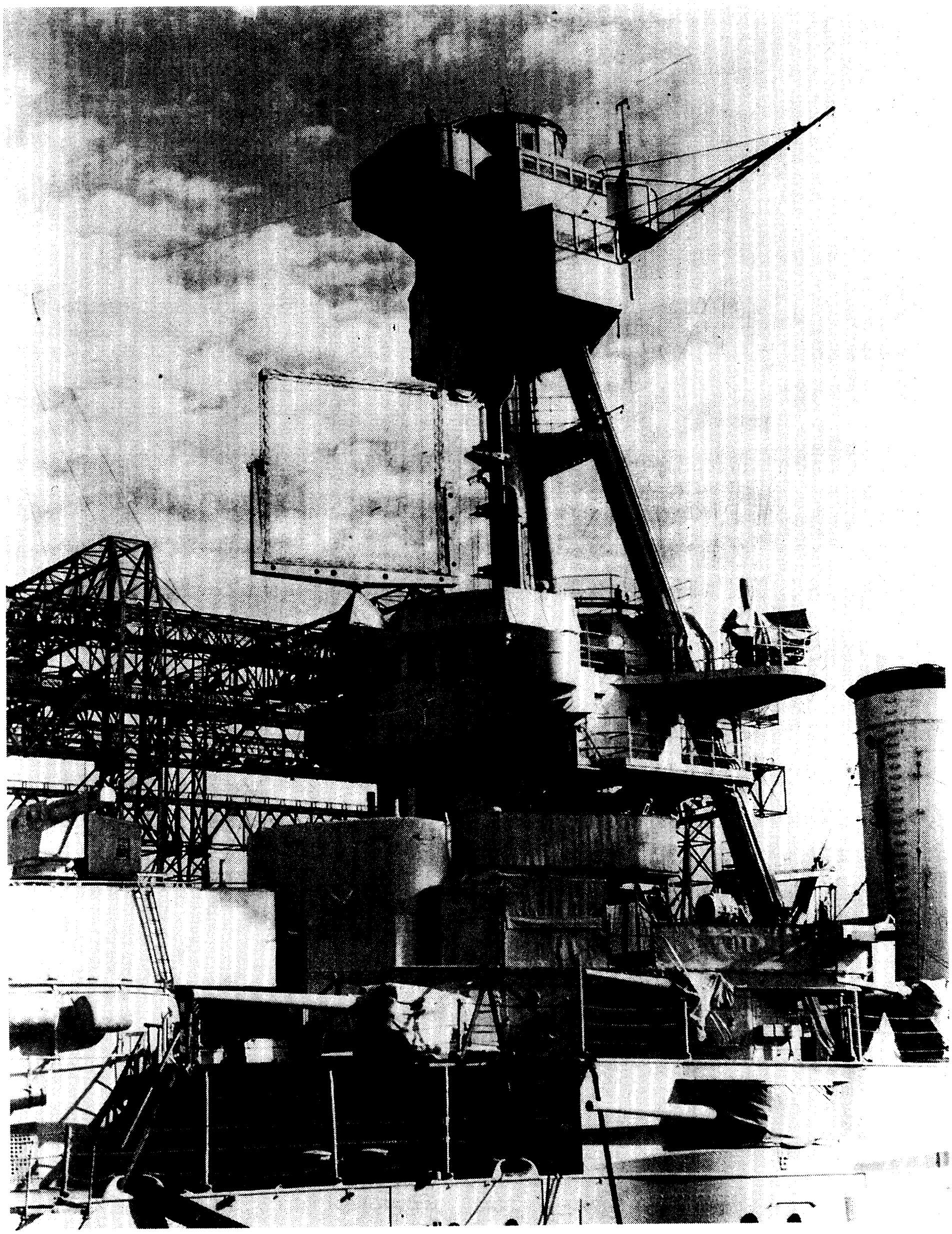

Figure 3. Model XAF radar installed on USS New York in 1939.

were absorbed into the system's component technology as quickly as they became available.

Subsequent development chronology includes the development of a radar prototype, the XAF radar, by December of 1938, and its testing at sea on the U.S.S. New York in January to March 1939.[43] Construction contracts were subsequently put up for bid by May of that year and awarded to RCA in October. The first of six initial production models of what became know as the CXAM was delivered in May of 1940.

Pulse radar work at the Signal Corps Lab closely paralleled the Navy work at NRL. W. D Hershberger, a physicist who went to the Signal Corps Laboratory from NRL's Sound Division in 1932, had proposed attempting radio detection by the pulse method as early as 1933.[44] However, the proposal languished until Hershberger returned to NRL on a visit in January of 1936, where he viewed the continuous wave detection equipment and was briefed on the early pulse work. On his return he mentioned both approaches to Major William Blair of the Office of the Chief Signal Officer, who directed that emphasis should be placed on the pulse method.[45] The work on microwave radio detection had so far failed to produce operational equipment, and the Army was interested in pursuing alternative approaches.

By the spring of 1936, Hershberger had begun building a pulse transmitter operating in the neighborhood of 100 MHz. When he left the Army in October, Paul Watson of the Laboratory Radio Section took over his work. The first successful tests of pulse radio detection equipment were made on December 14-15 and were followed up in early 1937 by efforts to design directive antenna systems for use with the transmitter and receiver.[46] By May of 1937, the Lab was ready to demonstrate 110 MHz and 240 MHz equipment. The sets, coupled with heat detectors and searchlights, were used to detect and illuminate airplanes in simulated combat before Army officials at Fort Monmouth.[47] The demonstration was repeated before the Secretary of the War, Chief of Staff, and Congressional observers a week later. The SCR-268, a pulse radar for use in conjunction with searchlights, and based on the 1937 prototype, began appearing in the

Army arsenal by 1940. Long range detectors, the SCR-270 and SCR-271, started coming off the production line in 1941. Both the Army and Navy radars, consequently, were available for the early period of American involvement in the war.

Conclusion

The question arises as to why American radar had its origins in fledging military institutions such as NRL and the Army Signal Corps Laboratory. Academic and industrial laboratories were both better funded and better staffed for the work. They also had greater freedom of research and wider discretion in terms of laboratory practice (how to pursue a topic and the means of pursuit). The answer may lie in the fact that whereas scientists and engineers in military labs were definitely interested in early warning systems, their peers in academic and industrial labs were not. Navy and Army scientists alike often possessed service experience dating back to World War I and were frequently concerned with countering the uncertainties posed by air launched attack. The earliest observation of the radar phenomenon occurred at the Naval Aircraft Radio Laboratory. Again, the later work by Lawrence Hyland at NRL appear to have been motivated by his concern for the dangers posed by that newest of military technologies, the airplane.[48]

To this must be added two additional factors. The first is the expertise and interest in high frequency radio that was to be found in the military labs in the aftermath of World War I. Military scientists were actively interested in high frequency for communication and radio direction finding purposes. They, consequently, were actively experimenting with it, working with it, and noting its unusual effects. Secondly, the great emphasis placed on the production of operational technologies in the military laboratories, meant that as soon as the potential of radio high frequency for detection purposes was recognized, efforts were made to expedite its transformation into a functional military tool. Radio detection and ranging was useful only when and if it make the leap from the laboratory to the battlefield.

In conclusion, Mendelsohn, Smith, and Weingart in the introduction to their volume on Science, Technology and the Military argue that the military has become more scientific and technological, science has become militarized, and that both institutions have been "changed profoundly because of their reciprocal relationship."[49] They then ask how this growing interpenetration of science and the military may be accounted for. Although the primary force of the authors' remarks is addressed to the recent postwar period, the roots of the historical connections they seek are at least partially to be found in the 1920s and 1930s -- the era when radar had its origins.

If the strong linkage between science, technology, and the military in the post-World War II period is directly linked to the military successes of science and technology during that war -- and, I think, this is an argument that in the American situation can be reasonably argued, -- then the background to this development is to be found in the earlier "War of Invention" and the military labs that were established in its wake. Radar by this judgment, then, may well be the first major fruit of that interpenetration of science and the military that Mendelsohn et. al. are concerned with.

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Tony Devereux

STRATEGIC ASPECTS OF RADAR AT SEA

Introduction

It is an accepted part of radar history that centimetric radar created a turning point in the Battle of the Atlantic. This was in mid-1943, when the German Navy was forced to withdraw submarines from the North Atlantic battlezone; needing to surface every twenty-four hours, they had become excessively vulnerable to detection and attack. Many people would agree this was the most significant influence exerted by radar on the course of the Second World War. However it does not by itself give a complete answer to the question what was radar's strategic impact on war at sea. This needs to be seen against a broader background of what happened before, what happened after, and what happened elsewhere.

In the early and middle 1930s, radar was being developed by the two countries which were the first to apply it, Germany and Britain. Significantly, it was as a naval initiative that radar began in Germany. The German Navy saw a twofold potential for it: guarding the coastal waters towards the North Sea, an area which had seen intensive conflict in the First World War, and controlling naval gunnery. The solutions which emerged to these requirements, the Freya and Seetakt radars, could be said to have been fully state-of-the-art, reflecting the high engineering competence of the German radio industry.

In Britain, the potential of radar was seen in 1935, slightly later than in Germany, by two branches of the armed forces independently, the Navy and the Air Force. Indeed the British Navy had studied the possibility of radar for some years, but taken no effective action to develop it. Now the Navy attempted to create simple radars which would serve the purpose of search and warning on warships whilst at sea, drawing on its own resources of radio technology.

The British Air Force saw the need for radar in the role of area defence against air attack, and having no existing technical competence of an appropriate kind, sponsored the development of the technology through an establishment specially set up for the purpose, at Bawdsey.

Bawdsey had the style of an academic institution, rather than of an engineering laboratory. This was good in some ways, not so good in others. Technically, it would be difficult to argue that Britain's Chain Home radar system was state-of-the-art, as Freya was. On the other hand, Bawdsey acted in a more general way as a centre for thought about radar. This helped appreciation of the wider role radar could play, and led to the application of radar to other purposes.

This was how Britain was led to attempt air interception radar, and as a development from air interception radar, airborne anti-surface vessel radar, ASV. Both projects were the responsibility of one airborne radar group. Air interception radar compelled the advance to higher frequency, about 200 megahertz, for the sake of airborne compactness.

Using this frequency, the anti-surface vessel application was easier to realise than airborne interception. This was because, while the installations were similar, with anti-surface vessel radar the target was massive, the target's altitude was always zero, and the contrast between the reflection from the target and reflection from the earth surface, i.e. the sea, was favourable.

First detection

The first successful detections of warships from the air were made early in September 1937, two years before the Second World War. For some years however the British strategic perception was such that airborne interception remained the priority of the airborne radar group. Nevertheless it was this early, prewar realisation of the value of ASV, and the corresponding demonstration of the technology, that should be regarded, in my view, as Britain's greatest contribution to radar history.

It came when the birth of centimetric technology, through the demonstration of a high-power magnetron, was still two years away. When these two achievements later came together, in 1943, as centimetric ASV, the results were striking, but I suggest a correction is needed to the perspective of radar history, because the contribution of ASV before this time has not received sufficient attention.

Let us turn to the aspect of the war in 1941, from the British and German standpoints. Both countries saw the strategic importance of the Atlantic, although the Battle of the Atlantic was still in an early phase.

Britain was attempting to improve her ability to patrol the Atlantic and offer convoy protection, and was beginning to utilise her ASV Mark II equipment, which worked on 1.5 metres. Maximum patrol effectiveness demanded that this equipment be mounted on an aircraft with long flight endurance, and this was provided by the Catalina flying boats which Britain was procuring from the United States and equipping with ASV radar. The Catalina had a flying endurance greater than 17 hours. We learn that by early June 1941, Britain had 25 radar-equipped Catalinas.

Germany was having some success with submarine attacks on convoys, and initially the introduction of ASV Mark II radar posed no serious threat to submarines from the aircraft themselves. The initial role of 1.5 metre radar was to enable aircraft sent out for escort purposes to find the convoy they were looking for. We are told on good authority that in poor visibility they had no hope of doing so without radar.[1] With radar they could find a convoy at 35 miles. The value of a patrolling aircraft was that its presence tended to deter submarine attacks, since the aircraft would pass sightings on to convoy escort vessels.

This type of radar had a vertical range display to which two optional distance scales could be assigned, either up to 9 or up to 36 miles. Thus a convoy was detectable at the radar's maximum operational range, which is not surprising in view of the massiveness of the target.

At this time we find reports of surfaced submarines being detected at 8 and 15 miles. There was at first no effective technique for attacking submarines; the first record of a submarine attacked and destroyed as a result of an ASV radar contact came in November 1941.

The ASV Mark II radar had antennas outboard on the wings, like today's familiar Yagi television antennas. These were directed outwards from the centre line at about 250. The outputs from left and right were applied alternately to the vertical time base, which showed deflection left and right correspondingly. Thus a stronger deflection to the right implied that the target was to the right of the centre line. In order to fly towards the target, the pilot steered so as to balance the deflections. This was the reality of the airborne ASV radar technology coming gradually into operational effectiveness for the first time during 1941.

Bismarck sortie

In the middle of that year, the German Navy planned to exploit the availability of the new battleship Bismarck with a two-warship sortie into the mid-Atlantic. From the strategic standpoint, this was an entirely valid concept and the most logical way to deploy the new warship, for the potential to disrupt transatlantic shipping was high, as had been demonstrated by earlier warship sorties. If successful, it might turn the Battle of the Atlantic in Germany's favour more quickly than submarines could.

The strategy turned upon a key point: the ability of the Bismarck force to disappear in the Atlantic, appear briefly for an attack, and disappear again. In other words, to remain unlocatable. It was fully understood that, during an extended sortie, the warships' operational capabilities had to be maintained at high level throughout. This dictated avoiding the chance of random combat damage when remote from base. Even minor damage could be critical. Hence the emphasis on continuing unlocatability

The German Navy studied the proposed operation with the greatest care. From previous experience, the chances of remaining unlocatable could be regarded as favourable. Any large ocean is a good hiding place, particularly the Atlantic with its frequent adverse weather.

Obviously, one factor to be included by the German Navy in its strategic assessment was that of radar. It was a new factor, not familiar from previous experience. The possibility of encountering British naval radar was doubtless realised, for Bismarck was equipped with the Metox radar warning receiver. But evidently the judgment was that naval radar would have relatively little effect in reducing the effective size of the Atlantic as a place of concealment.

It is a major question why the German Navy should down-rate the strategic significance of radar to the extent that it did. The judgment would have been based in part upon its own use of ship-borne naval radar, seen as a means of gunnery control rather than as a means of search and surveillance. It may also have been based on a technical estimate of British naval radar which underlined limited range. But certainly, a major factor missing from the German appreciation was airborne ASV radar, and this was hardly surprising since there was no German practical experience of such a development

History was undoubtedly in the making when Bismarck and Prinz Eugen left Gotenhafen on 19 May 1941. The ensuing events, marked by the highest courage, endurance and sacrifice on both sides, form one of the greatest naval sagas of all time. Yet it is a saga that, as generally told, climaxes with a final fight to a finish between battleships eight days later, on 27 May.

I believe this is false history. I believe the climax came before that. I believe the real history that was made was the debut of airborne radar in naval warfare, along with which I include the demonstration of the power of torpedo-carrying aircraft launched from a distant carrier. These aspects could be appropriately put together as the naval partnership of radar and aviation; it was this partnership which destroyed Bismarck, not the hostile battleships.

I will not go through the well-known details of the saga, except to highlight the involvement of radar and point out how the conventional account still fails to take this into proper consideration. Radar's involvement came first in the shadowing of the Bismarck and Prinz Eugen by British surface naval forces through the Denmark Straits between Iceland and Greenland, both before and after the engagement with the Prince of Wales and the Hood on the 24 May in which Hood was blown up.

Sonar

It is significant that the claim was subsequently made by the crew of the Prinz Eugen that the approach of the British capital ships had been detected by hydrophones before they appeared over the horizon. I think this indicates the importance accorded, on the German side, to what we now call sonar. German sonar, which was a passive technology, was then undoubtedly the world's best, and for the German navy it was an older and more tried and tested technology than radar.

Although there appears to be no definitive evidence on the subject, it would not be surprising if German naval judgment at the time ranked sonar, as a means of surveillance, higher than radar, as being less horizon-limited. Perhaps this was one additional reason why, in planning the Bismarck sortie, the German Navy down-rated the radar threat.

However, the German squadron found that it was apparently impossible to escape from constant shadowing by British warships, especially from the Suffolk which was equipped with the latest mark of British naval radar, the type 284 working at the hitherto unprecedented frequency of 600 megahertz.

It was at this stage that the German commanding officer, Admiral Luetjens, made a historic strategic reassessment. His radio reports make increasing mention of radar, and finally just after 09.00 on 25 May he signaled: "Presence of radar on enemy vessels, with a range of at least 35,000 meters, has a strong adverse effect on operations in Atlantic. Ships were located in Denmark Strait in thick fog and could never again break contact. Attempts to break contact unsuccessful despite most favourable weather conditions. Refueling in general no longer possible."

This is quoted from the English translation of Baron Burkard von Muellenheim-Rechberg's book "Battleship Bismarck".[2] The reference to favourable weather conditions means of course in this context the heavily-clouded and stormy conditions which prevailed throughout and gave the best chance of concealment.

Rather ironically, Admiral Luetjens' report came after Bismarck had, in fact, escaped from surveillance by naval radar, though this had not been realised. The Suffolk, whose radar range was considerably overstated by Admiral Luetjens, pursued a zigzagging course which led to periods of loss and recapture of the radar target. During one of the periods of loss the Bismarck turned away to starboard, the direction away from Suffolk. Consequently the radar target failed to reappear. This happened already some hours before Admiral Luetjens's signal, causing crisis on the British side.

From this point onwards it was airborne ASV radar that played the paramount role. There were two stages: firstly relocation of the Bismarck, and secondly attacks by Swordfish torpedo-bombers from the aircraft carrier Ark Royal.

In the available literature, the role of ASV radar in the second stage, that is its use by the attacking Swordfish, is always mentioned. In good visibility radar would not have been necessary, but in practice it was all but vital because of the heavily overcast weather and low cloud level, generally mentioned as about five or six hundred feet.

Also well recorded is the Swordfishes' mistake on one occasion of coming down out of cloud and attacking a radar target before visually verifying it; it turned out to be not Bismarck but the British cruiser Sheffield. This attack miscarried, not through any fault of the radar, but it is indicative of the psychological reliance which had built up on the ASV Mark II radar equipment.

Finally, as is well known, the Swordfish obtained a torpedo hit on Bismarck's stern, resulting from an attack guided by radar out of cloud down to the low level at which the Swordfish needed to deliver its torpedo. This disabled the Bismarck's steering and represented the case in which damage sustained in combat, although far from being catastrophic, eroded operational effectiveness to the point at which the mission collapsed. This point had now been reached with Bismarck, and the rest of the saga became inevitable.

Fundamental problem

But all this could only happen after the first stage had been completed, in which the fundamental problem of relocating Bismarck had to be solved. Here I am convinced ASV radar has not received the recognition due to it. If ASV radar was all but vital in the second stage, it was completely vital in the first.

The key role was played by Catalinas flying from Lough Erne in Northern Ireland. The accepted account of Bismarck's discovery by a Catalina remains to this day that which appeared in a British newspaper on the Sunday following the action, June 1 1941. According to this newspaper report, which was based on a journalist's visit to the Lough Erne base, the Catalina saw the Bismarck when the aircraft came out of cloud. The Bismarck was "so well camouflaged with light blue paint it was extremely difficult to follow with the eye even from a quarter-mile away".[3]

It must be clear that the chance of finding Bismarck by visual means alone in poor visibility when it was so difficult to discern even at such short range would have been exceedingly remote. However if we look at the search pattern set for the Catalinas, it becomes evident that this was based on the use of radar. The idea was to patrol a conceptual "gate' in the Atlantic about 340 miles across, oriented at an angle of 300 east of true north. Through this gate, it was calculated, Bismarck must pass on the way to France.

Only two Catalinas were detailed for the operation, which seemingly reflects considerable confidence. Their patrols were not along the actual baseline of the gate, but along two convergent lines which together with the baseline formed a triangular arrowhead pointing south east. Each Catalina patrolled one side of the arrowhead.

These sides were about 160 miles long. In the centre, at the point of the arrow, the sides did not come together; there was a gap of about 24 miles. Probably this was an anti-collision precaution made appropriate by heavy cloud.[4]

It would take either Catalina somewhat over an hour to make one transit along its patrol line, at probable cruising speed. The effective width of the patrol line, that is the strip within which Bismarck was liable to observation, was determined by the range on either side at which the battleship could be detected.

With visual search and recognition limited to a fraction of a mile, as it appears to have been, the effective width of the patrol line might be about a mile. The chances of a Catalina being close enough to see Bismarck in the few minutes the battleship would need to cross the effective width of the patrol line would be very small. Moreover with visual search the central gap would not be covered. But with ASV radar the effective width of the patrol line would be on the order of fifty miles, if not more, and Bismarck would need two hours to cross it. The central gap would also be covered.

Thus the patrol pattern set for the two aircraft corresponded to the operational requirement using ASV radar. Of course, the visual task of watching the radar display for a deflection would be much easier than the visual task of constantly searching a featureless grey waste of water. Fundamentally, the contrast which Bismarck made with its background was very much higher at radar wavelengths than at the wavelengths of light; in radar terms it was not camouflaged at all, but the reverse. Detection and recognition of Bismarck was reported at a point lying on the southern patrol line, not far from the apex of the arrowhead, at 10.30 on 26 May, by a Catalina which had left Lough Erne six and three-quarters hours earlier.

Making appropriate allowance for the time taken by the Catalina to reach its patrol line, it would have found Bismarck about an hour after commencing its search. The search began at about six in the morning local time, when there was sufficient light for the Catalina crew, by going beneath the cloud, to obtain visual confirmation of the identity of the radar target.

Thus I believe the relocation of Bismarck was a well-planned and executed operation made possible uniquely by ASV radar. Naturally, the journalist's article made no mention of radar. Apart from being top secret, radar would have been incomprehensible to the general public. But at the same time, a film newsreel company requested permission to visit the Catalina unit. This was granted, on condition no photographs were taken of the Catalina's "special equipment". .

In sum, I believe the Bismarck saga should be seen as the first and most impressive demonstration of the power of airborne radar to influence naval warfare, coming two years before the similar demonstration by centimetric radar. In it, the British ASV Mark II radar was matched against a target for which its capabilities were entirely adequate. I do not believe the Bismarck sortie would have been permitted by the German Navy if it had appreciated the power of radar.

That it lacked this appreciation I attribute to a number of factors: its own experience of naval surface radar, its previous tendency to rely on sonar for surveillance, and above all its absence of experience of airborne ASV radar. One lesson was the special significance of airborne search radar at sea.

Strategic lessons

The saga undoubtedly stimulated much thought. The German Navy abandoned the ambition of venturing into the Atlantic with surface warships. In fact, the next German surface warship operation was the passage of Scharnhorst and Gneisenau from Brest in France back to Germany through the Channel. This was successfully accomplished thanks to the choice of overcast weather in combination with radar jamming - a remarkable demonstration of a lesson well learnt, coming nine months after the loss of Bismarck.

The Battle of the Atlantic was subsequently fought on the German side exclusively with submarines, and this was a successful strategy until centimetric technology provided equipment which was as well matched against submarines as 1.5

metre equipment had been against the surface warship. Indeed 1.5 metre was probably preferable against the more massive target, as giving longer range with equivalent power.

The improvement which centimetric ASV gave against submarines was due in part to the strong radar reflection obtained from small parts of the submarine's superstructure. It was also due to the compact dimensions, which enabled a rotating antenna, a Plan Position Indicator display, and therefore all-round surveillance from the aircraft. All-round surveillance facilitated surprise attack, which was in turn assisted by the circumstance that German radar warning receivers did not at first respond to centimetric radiation.

On the British side the strategic lesson was not, surprisingly, learnt so well. Before the year was out, two battleships were sent to the Pacific region. Such an undertaking should have been studied beforehand in the light of what had happened to Bismarck. Two factors that should have been taken into account were the availability of radar to the Japanese and the availability of torpedo bombers. Both would have indicated against sending the ships, and both were ignored.

As is well known, the two battleships, Prince of Wales and Repulse, were promptly sunk by land-based torpedo bombers, the fatal hits in both cases being upon the steering. The action was in daylight and conditions of good visibility. This event signalised, along with the nearly simultaneous attack on the US fleet in Pearl Harbor, the beginning of what should be called the Battle of the Pacific.

Radar in the Pacific

For historians, the question is what new phase did the Battle of the Pacific herald in the story of radar. I only have time to give a brief outline. The conditions of the attack on the Prince of Wales and Repulse were typical in that good visibility during the day and fairly placid water tended to be characteristic of the Pacific, in contrast to the constantly stormy and obscured Atlantic. This determined both a different pattern of naval conflict and along with it, a different strategic role for naval radar.

Although engagements between surface fleets were a feature of the Battle of the Pacific, with large numbers of warships on both sides, the circumstances were such that target finding was not a primary problem and radar, although available to both sides, was not a crucial combat factor. This is not to deny that radar made a valuable contribution to many surface fleet operations.

American naval radar at that time had some similarities to both British and German developments. Japanese radar however was based on utilisation of a low-power magnetron. The combination of low power and centimetric wavelength was not favourable for naval surface radar. We recall that British surface centimetric naval radar was introduced towards the end of 1941 but, although based on higher power than Japanese, also failed to achieve specially memorable results.

However, the key role in the Battle of the Pacific was played by submarines. To the American submarine falls the ultimate responsibility for the defeat of Japan, in that it effectively and totally isolated the island country long before the war ended.

American submarines in the Pacific operated at great distances from their own bases and much nearer Japanese bases. They were large vessels and at particular risk from attack, when surfaced, by Japanese warships. Therefore they used different, longer-range methods of torpedo attack to those employed by German submarines in the Atlantic. They attacked both Japanese merchant shipping and naval ships, but operations tended to be solitary; although "wolf packs" were formed, group attacks on large convoys never resulted on the same scale as in the Atlantic.

Before the war began, American naval thinking placed great reliance on the use of passive sonar by submarines. This recalls the significance of passive sonar in the German Navy. In the American Navy, sonar was expected to enable successful attacks on surface ships by submarines remaining fully submerged throughout, even below periscope depth, which was seen as a necessary precaution against counter attack. The practice of sonar attack with long torpedo runs was worked out in detail by the American Navy.

However, the hopes placed on sonar were not borne out. This was one of the reasons for American submarines' initial lack of effectiveness, another being the "dudtorpedo" problem, as experienced by so many navies. It was into this blocked situation that radar made its main strategic impact on the Battle of the Pacific, as a submarine-borne equipment. It solved the attack problem.

It did this in two ways: it enabled the submarine, having found and trailed its quarry during daylight by sonar and periscope, to surface for attack under cover of darkness. It could then provide accurate range and direction of the target, and what was also vitally important in calculating the setting and firing of torpedoes, accurate estimation of the target's speed and course. Accurate range is where radar always scores; for direction, radar data would be refined if possible by optical observation through the periscope. This information was fed into the torpedo data computer.[5]

The first American submarine radar for this purpose was the centimetric 5-band SJ type, in use from June 1942. Later, in 1944, came the X-band ST, which was operable submerged, having an antenna only 6 inches by 2 inches, mounted directly below the periscope lens. At 3 feet above the water it could detect a surfaced submarine at 3 nautical miles.[6]

Radar's role in the Battle of the Pacific was thus in direct contrast to the Battle of the Atlantic. Fighting against submarines in the Atlantic it ensured their operational failure, fighting with submarines in the Pacific it enabled their operational success.

American submarine radar also included a surveillance type, mainly to provide warning of air attack. But for general surveillance against surface vessels, radar never supplanted sonar. This role remained with passive sonar, both because it operated all around the clock, including during daytime submergence, and because it had a greater range. Even when proceeding surfaced, American submarines would submerge for a short period to make use of sonar surveillance, which gave better results from a greater depth.

Radar was not confined to American submarines, of course; it came into use on German submarines in the later stages of the war for warning against air attack. But at this time it was not effective.

Conclusion

The conclusion must be that the aggressive use of American submarine radar deserves recognition for a role in the Battle of the Pacific comparable to that of airborne ASV radar, whether 1.5 metre or centimetric, in the Battle of the Atlantic. It contributed in similar measure to the fateful decisions of history made in the Second World War.

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Ulrich Kern

REVIEW CONCERNING THE HISTORY OF GERMAN RADAR TECHNOLOGY UP TO 1945

1. Introduction

I have subdivided this review concerning German radar technology until 1945 into four time periods. Despite the known difficulties of strictly chronological history, it is a useful way of looking at the history of German radar development. There are distinct features which characterize each of the phases of German radar development: only the precise break down of the time periods might be a matter of dispute.

The first section concerns the historical developments leading to what later was called radar. It refers to the early experiments with the technical use of the reflection effect and concerns roughly the period between 1900 and the 1920s. Despite their great number, the German developments of this period did not have significant influence on further developments. For this reason I will treat this section in brief.

The second section concerns the period from the beginning of German work with the goal of technical use of the reflection effect for position-finding, the successful realization of this purpose, and the development of the first ready-to-use apparatuses. This took place independently at different firms and institutions, at virtually the same time. This time period begins at the latest in 1933 and ends by 1938-39.

During the third period between 1938 and 1943, German radar development was determined essentially by physical knowledge from before the war and concentrated mainly on technical improvement of known methods. After 1943, an important technical change in radar technology was caused by the use of cm-waves in England. German work in this field, although done through the first period of the war, had suffered under very adverse conditions. From the moment British developments became known in Germany in 1943 - this date defined a change in the so-called high-frequency war - German thinking with respect to radar changed. They made efforts to reduce the advantage of the Allies on the field of radar.

The last time period defines itself - it begins 1943, deals with the German efforts on the field of cm-radar and the resulting technical development and ends in 1945. After this time, Germany was forbidden for many years to deal with radar technology; only in the mid-1950's did German industry recommence work on position locating.

2. Precursors of radar

For the period from 1900 until the early twenties we can identify in Germany almost twenty patent applications, some articles in popular science journals and some essays in technical literature (almost all in "Physikalische Zeitschrift") all with the same purpose: the technical exploitation of the effect of reflection of electromagnetic waves on metallic objects, discovered by Heinrich Hertz. But most of them functioned very poorly or did not function at all.[1] The first proposal I know of in the German-speaking world belongs to the Swedish mine engineer, O. Trüstedt, who presented a work concerning the application of reflection effect on the discovery of ore deposits on February 21, 1901, at Bergakademie Freiberg in Saxony. According to his own declarations, Trüstedt had done some fundamental experiments, but we do not know anything precisely about them.[2] Much better known is Christian Hülsmeyer, who in 1904 applied for a patent for his "Telemobiloskop". After his first experiments from the banks of Rhine at Cologne proved that his apparatuses fundamentally worked, Hülsmeyer improved them and presented them the same year at Rotterdam. The reports we know about all state that they could reach distances up to 3km. Despite his great popularity following these demonstrations, Hülsmeyer could not find investors for his project, so he eventually ceased working in this field.[3]

The apparatus Hans Dominik presented to the German navy in 1915 is known only from the brief information in his autobiography. Therefore I cannot consider it in detail. Nevertheless it seems that the "Strahlenzieler", as Dominik called his instrument, worked as an experimental model.[4]

It appears that the most intensive work on technical application of the reflection effect had been done at that time by Heinrich Löwy, who was born in Vienna. Furthermore, he had the best scientific education of all the men working in that field. He began to study under Boltzmann, moved to Göttingen to continue his studies under Hilbert, Minkowski and Abraham and took his degree in 1908 under Riecke. From 1910 on he published articles in connection with the technical exploitation of the reflection effect. Until 1919 he published at least eight articles, mostly in the "Physikalische Zeitschrift", some more in the "Elektrotechnische Zeitschrift", "Zentralblatt für Mineralogie" and "Gerlands Beiträge zur Physik". Almost exclusively they deal with the exploitation of the reflection effect for geological purposes. Löwy had done some fundamental experiments already in 1909 in the town swimming pool of Göttingen and later published the results of some more experiments.[5] The best known seem to be his considerations on the use of the impulse method on distance determination, for which he was granted a patent in 1922, with corresponding patents in foreign states.[6] His method became rather well-known among specialists, as Löwy repeatedly reported upon. In this way he called Jonathan Zenneck's attention to the impulse method; Zenneck later used this method for measurements in the ionosphere. Löwy had to emigrate during the Third Reich and we know nothing more about him, so we lack precise information about the instruments he used.

The few instruments that can be considered precursors of radar technology could be used only for demonstration purposes. Evidently, the technical background was lacking. Nevertheless, it is remarkable how much intensive work was done in Germany on the exploitation of the reflection effect. We don't yet have a complete presentation of these predecessors of radar technology in Germany. We only know individual presentations, mostly Hülsmeyer's. A lot of work still has to be done, firstly, an inventory of all German proposals of that time. Of course it would also be interesting to know if similar developments occurred in Great Britain, the United States and other countries, and if such developments were as numerous as in Germany, or if Germany was an exception.

3. The way to the successful realization

More or less independently, different firms and institutions started research on the application of the reflection of electromagnetic waves for position finding. 1929 is the earliest possible date we can say that this period began. It was then that physicist Karl Kohl of Erlangen and the Berlin firm of Julius Pintsch applied for a patent concerning a method of position finding based on the reflection of electromagnetic waves. Its importance resides primarily in the fact that later on both would play an important role in the development of German radar technology and prove that they already had worked in the field of radar during that time.[7]

But in general, 1933 is considered the beginning of successful realization in German radar historiography. At that time the experimental station for communication directed by Rudolf Kühnhold started work in this field. Before then it had worked mainly on active acoustic location. Based on the results of this research, and stimulated by publications in the foreign specialist press, Kühnhold decided to use very short electromagnetic waves for echo sounder in air. We do not know for certain which article stimulated Kühnhold, but I suspect it was the article of the three Bell engineers Englund, Crawford and Mumford, published in March 1933 under the title: "Some results of a study of ultra-short-wave transmission".[8] The importance of this report was both that it made theoretical proposals and it proved a measuring technique to determine the position of an airplane. A short time later Kühnhold started his work. Because a mutual misunderstanding led to a lack of cooperation with Telefunken, Kühnhold founded his own firm, whose actual purpose was the development of reflected wave location finding instruments (Rückstrahlortungsgeräte), but was given the misleading name, "Society for Electro-acoustic and Mechanic

Apparatuses (GEMA)", as camouflage. GEMA first conducted location experiments with a wave length of 13.5 cm, utilizing retarded field tubes (Bremsfeldröhren). In 1934 it succeeded in identifying without doubt reflected waves on an experimental boat. While the Pintsch firm delivered these instruments, GEMA ran experiments with magnetron transmitting stations based on a 48cm wave length. Because of the much greater power of the latter, the results were much better: a little experimental boat could be located up to a distance of 12 km, a randomly passing airplane at a distance of 700m. These experiments proved the applicability of reflected wave location finding in principle; it was in 1934 that the requirements for the further development of the apparatuses were set. Soon the first German radar apparatus ready for operation was developed. The so-called "Freya" apparatus with a wavelength of 2.4m could already locate flying targets up to a distance of 60km, and the locating distance improved in following years. As early as during the Sudeten crisis in 1938 it was used for military purposes and in the winter of 1938-39 serial production was started, although in small numbers at first. A great number of very different instruments constructed during the war were derived from the Freya apparatus. Independent of this development, the firm Telefunken had concentrated research since 1934 on the field of decimeter-waves. Telefunken successfully completed its first position finding experiments with a wavelength of 50cm using an airplane, and the following year it could submit its first patent applications.

At the end of 1935 Telefunken began its cooperation with military institutions. The Heereswaffenamt, which directed the Flakartillerie, asked it to examine the suitability of radio waves for flak artillery because the optical and acoustical methods did not seem sufficient any longer against the threats of modern air war. The leader of the Telefunken laboratory, Wilhelm Runge, delegated the further research work to his collaborator Wilhelm Stepp. By 1938 Stepp had developed an instrument with a concave mirror with 3m in diameter which needed a single antenna for transmission and reception. This antenna, comprising a dipole, rotated around the focus of the mirror. The beam produced this way was the premise for a very exactly position finding. Stepp called this laboratory model "Darmstadt", after his native town. He probably did not know he founded a tradition: German radar instruments from then on were named after German towns and landscapes. The Darmstadt apparatus became the precursor of the famous later "Würzburg" apparatuses.

The Freya apparatus had an unusual history. Initially the navy intended to use it for locating ships. When experiments showed that it could not be used for this purpose and after its ability to locate flying targets was discovered, the first models for coast control were used. After the navy ceded a few apparatuses to the air force, the latter recognized the usefulness of the apparatuses for her own purposes and the Freya apparatuses were thereafter mainly used for early warning. This development shows quite clearly what new fields the radar covered. This did not exactly meet the intentions of the navy. Parallel to the development of the Freya apparatus, research on an instrument was performed, which should have been suitable for war ships. From this research evolved the so-called "Seetakt" apparatus with a wavelength of 80cm. The first ship to be equipped with such an apparatus from a small model series was the armed cruiser (Panzerkreuzer) the "Graf Spee", in January 1938. When the Graf Spee sank on December 17, 1939 in the estuary of the Rio de la Plata, a Seetakt apparatus could be seen on the wreck, but the British did not draw the right conclusions. Furthermore, in Germany a few more independent developments occurred, for example, the Lorenz firm, started to work on radar apparatuses in 1935. This demonstrated that it was time for this invention; not only were there parallel developments in different countries, but also, at least with respect to Germany, within the same country as well. Thus, in 1939, Germany was able to begin the series production of apparatuses for the most important domains of radio location.

Sources are problematic for this period in the history of German radar technology because most of the documents concerning the apparatuses cannot be found and are probably destroyed. The most important source materials available for this period are the personal reminiscences of participants. Therefore one cannot give substantially more material than Fritz Trenkle cited in his work about "Die deutschen Funkmeßverfahren bis 1945".[9]

4. The most important German radar tools until 1943

The third section in the history of German radar began in 1939. The beginning of World War II coincided roughly with the start of series production and the delivery of the apparatuses. The series production of the Freya apparatus, which had already been started before the war was increased greatly after the breakout of war. During the war this apparatus was the most important link in the chain of German early warning; a total of 2000 were produced.

The first war mission of the Freya apparatus was on December 20, 1939, when an apparatus at Wangerooge located a British airplane formation, which the Germans then decimated. Germany also supported its allies with the development of radar control. Although Italy had made its own discoveries concerning radar, the Italians copied the Freya apparatus under the name of "Felino". German warships were first equipped with radar apparatuses in November 1939, while the first "Würzburg" apparatuses were delivered only in summer 1940. The Würzburg apparatus, which was repeatedly improved, was built in thousands of specimens. These installations became standard radio measuring tools of the German Flak artillery and continued until the end of the war. The Italian version of the apparatus was named "Volpe".[10] The Japanese version was called "Tachi-24". Plans for this apparatus and the major components were brought from Germany to Japan by a submarine blockade runner in January 1944.[11]

During the war more radar sets were developed, based on the above mentioned instruments. But many have criticized Germany for not having striven for fundamentally new developments during the war, especially with respect to the application of even shorter wavelengths, the advantages of which they knew in principle. In this respect a few remarks have to be made. For a long time the German Abwehr could not find the slightest evidence that the Allies had such apparatuses. Therefore, the Germans thought they had a great advantage in this field. In fact the German apparatuses had been superior to the British ones at the beginning of the war, and the selected wavelengths of 50, 80 and 240cm gave very good results in the corresponding domains of use. For this reason they felt no need for intensive research and development. Additionally, there was little possibility for new radar research due to political and military reasons. Specialists in industry and specialists in the technique of communication in the military domain began the initiative in the development of German radar apparatuses. The military command was scarcely concerned with such research, the political not at all. Furthermore all military planning was focused on the offensive. Hitler himself was completely disinterested in natural sciences, and his technical horizon ended with World War I.[12] His technical interests were limited to traditional domains. In some way the same applies to Hermann Göring, whose remarks on radar technology, as found in records, are sometimes quite grotesque. Out of the whole political command of the Third Reich, only army minister Albert Speer was capable of estimating the real importance of this new technology in the later course of the war. This is dramatically different than the attitude of the British. In Germany there never existed anything like the "Tizard Committee". Churchill's interest in natural science and technical subjects, and especially his readiness to be informed about them are in crass contradiction to Hitler's faculties on this domain.

But much graver than the consequences of the disinterest of the leading personalities of the Third Reich in radar technology were the consequences due to the loss of scientists Germany suffered because of racial and political persecution. These losses were especially great in the domain of physics, as it is well known. This applies not only to the leading scientists but also to physicists not so high in the hierarchy. Germany recognized the lack of industry physicists as a problem late in World War II, but by then the damage had become irreparable.[13] The direct neglect of engineering sciences was of great consequence too. The number of students matriculated at technical universities fell continuously. While greater than 20,000 before Hitler came to power, their number had fallen already by 1937 to under 10,000.[14] In electrical engineering the number of graduations fell from 1932 to 1939 by about half.[15] Because the consequences of this became apparent only after years passed, attempts were made too late to counterbalance them, and were mostly ineffective. The outbreak of the war aggravated the already tense situation within the engineering professions. The first calling-up wave reduced to half the number of students matriculated at technical universities. Electrical engineering, the field with the lowest number of students before World War II, suffered the biggest losses. 60 percent of all students had been already called up at the beginning of the war.[16] The consequences turned out to be irreparable too. Until 1943, according to official estimations, there was a shortage of 50,000 engineers.[17] Lastly, a further factor contributed to the hindrance of long-term research projects. At the beginning of the war, Germany estimated that the war would be very short, and therefore no or only very poor financial support could be obtained for such projects. Taking all this into account - the tense situation of the German electrical industry during the war, the problematic situation of the young generation, the military command's lack of interest in radar, a military situation which did not think of defensive measures, and finally, the perception that Germany already had excellent existing radar tools - we can understand why new developments, like those in the field of shortest wavelengths, were considered only of subordinate importance. This changed as the war progressed, when Germany was fighting a more defensive war and suffered more and more allied attacks. Now radar technology grew more important. Finally, the knowledge of British radar, especially the fact that the British had an enormous advantage in the field of shortest wavelengths, forced Germany to radically change its mind.

5. The turning point in the high-frequency war

At the latest the year 1943 can be considered a military turning-point in World War II. It also brought the turn in the so-called high-frequency war. German radar had already proved its efficiency for a long time, and had become a fundamental component of the German air defense. Unfortunately we only have the space here to give a suggestion of the very complex construction of this system, which repeatedly changed during the war. In 1942, the scientific, industrial and military authorities already began to collaborate on a program for the development of radar technology, for which about 15,000 engineers, constructors and electromechanical engineers were brought back from the front. Already in December 1941 the position of a special commissioner for high frequency technique had been created, which was occupied by Hans Plendl in November 1942. One year later Abraham Esau assumed this position. Esau was one of the pioneers of high-frequency technique, especially in the field of shortest wavelengths. His rapid rise during the Third Reich was due to his party membership. This enabled him to obtain a number of positions. Esau failed as authorized agent for nuclear physics, but got as compensation his new position. As an appreciated specialist for high frequencies and quite capable organizer and administrator, Esau mastered this position until the end of the war, as well as the circumstances allowed. At the beginning of 1942 his predecessor Plendl had convoked a conference at Wannsee, where responsible military and technical figures were present. Among other items, they discussed the possibility of employment of very short wavelengths for the German radar technique but dropped it on technical grounds. A few weeks later, in February 1943, a radar apparatus was found in a downed British airplane, which after a detailed examination proved to work with a wavelength of 9cm. This apparatus, which was called "Rotterdam" after the place it was found, had a great influence on the development of the German radar technology in the last two years of the war. The cavity magnetron (Hohlraummagnetron), a basic piece of this apparatus, was copied and used more and more in the German apparatuses, until the end of the war stopped the further development. The end of the war was also the end of the German activities on radar for many years.

6. Conclusions

The history of German radar technology has not been detailed so precisely as that of Great Britain and the United States. This is not least a consequence of the problematic source situation. As a survey there exist the already cited work of Fritz Trenkle and the presentation of Fritz Reuter concerning the development and application of radar technology in Germany until the end of World War II, published in 1971.[18] A number of special presentations exist on certain problems and aspects of German radar technology as well as the personal memories of some participants. It might be the time to comprise the history of German radar technology in a form which could be used as a basis for historians of our time and to confer to the radar the position it deserves in the history of World War II.

I do not want to judge the importance of German radar development, and I do not want to compare it with the British and the American developments. This was not the purpose of this essay. But nevertheless it should be taken into consideration under what difficult conditions the German performances in the field of radar technology were achieved. Yet the purpose, among others, should be to analyze the radar developments of the three most important countries working in this field in more detail, and to compare them. This is especially true because the parallels in the development of radar technology in these three places is somewhat unique; there is no other example in the history of technology of so many independent and similar developments.

References:

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11 R. I. Wilkinson, "Short Survey of Japanese Radar", Electrical Engineering, vol. 65, pp. 370-377, 455-463, Aug-Sept., Oct.1946.

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17 K. H. Ludwig, Technik und Ingenieure im Dritten Reich, Düsseldorf 1979, p. 298.

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S.S. Swords

THE SIGNIFICANCE OF RADIO WAVE PROPAGATION STUDIES IN THE EVOLUTION OF RADAR

1. Introduction

In virtually all of the countries in which radar emerged in the 1930s a very strong link can be seen between its emergence and existing quantitative studies of the propagation of radio waves.

During World War II, research into the tropospheric propagation of metric, decimetric and centimetric waves became an essential part of radar system evolution and indeed of the proper execution of overall radar programmes. The quality of radio propagation research is seen as a useful indicator when attempting comparative studies of radar and radar related progress from the pre-war years right through into the post-war era.

Workable radars were possible in the mid 1930s and effective microwave radars were possible after 1940 only because certain strands of electrical engineering had been developed: these strands were joined and formed into radar systems by astute radio-scientists.

R. L. Smith-Rose, writing in 1947 on radio-wave propagation research, expressed a truism that "The study of radio-wave propagation is thus seen to be fundamental to the whole of radio-engineering technique ...".[1] T. L. Eckersley in 1946 wrote that "It is the business of the theoretical man to advise the engineer, other things being equal, what wavelength to use for a given project, and to explain such phenomena as anomalous propagation ... . It is his function to provide a theoretical description of propagation, and it is his work that forms the basis for practical development".[2] It is contended here that propagation studies were not just one factor among many in the development of radar in the various countries, but that they constituted the very quintessence of its birth. Thereafter, propagation research solved problems that arose in radar's growth: in the case of any particular country its status might conceivably be used as an estimation of the level of maturity of radar programmes.

2. Pre-World War II

Guglielmo Marconi in his address to the American Institute of Electrical Engineers in 1922 referred to his own observation of the reflection of radio-waves by metallic objects.[3] Later, in 1931, he undertook a very comprehensive programme of experiments at 600MHz, in many cases using his floating laboratory, the steam yacht Elettra.[4] While setting up a 600MHz link between the Vatican City and Castel Gandolfo in 1932, he noticed a rhythmic disturbance of a transmitted test signal, which was being monitored by an adjacent receiving system. The observation of this disturbance, which was caused by a moving steam roller, led eventually to the manufacture in Marconi's laboratory of prototype radar sets for the Italian Army by August 1935.[5] It also led, through the influence of General Luigi Sacco, who was himself actively involved in propagation studies, to the initiation of the Italian Navy's pre-war radar programme.

In the United States, all those military and civilian organisations, that were important contributors in 1940 to their country's radar programme had a major involvement for many years in wave propagation studies.

The Naval Research Laboratory might arguably be considered the originators of American radar. Albert Hoyt Taylor, Superintendent of the Radio Division of the Naval Research Laboratory was, even in his student days, before World War I at the University of North Dakota, involved in radio work. In September 1922 with Leo Clifford Young, while experimenting at 60MHz, he discovered and realised the importance of the radio-detection of obstacles. When Leo Young and Lawrence Pat Hyland in June 1930 were checking the transmissions of a 32.8MHz ground beacon, they noticed regular disturbances in their readings, which were caused by aircraft flying overhead. The incident was brought to the notice of Hoyt Taylor and this led directly to the initiation of the Navy's radar programme and to the work of Robert Page.[6]

The Army Signal Corps formulated in 1931 a rather general project for the detection of aircraft, which had materialised by 1933 into a radar project. Major W. Blair, Director of the Signal Corps Laboratories, and the man responsible for this, had carried out for his degree of Ph.D. (granted in 1906) research on the characteristics of radio waves in the frequency band 860MHz to 3GHz. It is interesting to note William H. Wenstrom's 'Historical Review of Ultra-Short Wave Progress' of 1932.[7] Wenstrom was attached to the Signal Corps Radio Laboratories at Fort Monmouth. His paper is a review, from Hertz's experiments to the year 1931, of work carried out at frequencies above 40MHz. With fifty four references and a description of Spark, Regenerative, Barkhausen-Kurz and Magnetron oscillators, together with a brief mention of some propagation experiments which had been undertaken in France, Germany, Japan, the United States and Great Britain, this review was a useful feasibility study for work undertaken later by the Signal Corps.

Bell Telephone Laboratories carried out comprehensive programmes, examining how radio waves are affected both by time and distance, from 1920 onwards.[8] The extensive set of transmission experiments at frequencies between 64MHz and 81MHz of Englund, Crawford and Mumford which began in 1930 and was reported on in 1933 was particularly significant in that the investigators measured the magnitude of the signals re-radiated from passing aircraft.[9]

Work, which parallels that commonly carried out today in mobile radio studies in urban environments, was presented in 1935 by Burrows, Decino and Hunt: the large variations in field-strength recorded while driving through the business district of Boston 1.5 miles from a 34.6MHz transmitter are given.[10]

In Russia, A. S. Popov was carrying out experiments at metric-wavelengths before the beginning of the century.[11] In examining the early history of radar in Russia one finds reference to the All-Union Electro-Technical Institute [Vsesoyuznyi

Elektrotechnicheskii Institut: VEI]. In 1926, the radio department of this institute was involved in a programme of research on metric wavelengths, including the attenuation caused by objects and the effect on received signals incurred by varying distance and the heights of the transmitting and receiving antennae.[12] In 1928 the radio department measured the received field not only near the ground but at more elevated heights using balloons and aircraft.

In Germany in the early 1930s, one sees research of quality and significance being undertaken. Apart altogether from ionospheric high-frequency work, research in the UHF and microwave bands was in progress. Telefunken and particularly W. T. Runge were interested in decimetric waves and indeed a logical development can be seen from their 600MHz work to the famous Würzburg series of gun-laying radars.[13]

A particularly interesting example of theoretical work was that set out in two papers of F. Ollendorf. One, published in 1932, is concerned with propagation over towns.[14] The other, published a year earlier, deals with the disturbance effected on the fields of radio-waves which pass by common objects such as houses, towers or hills and describes how these objects can be modelled.[15] It concludes that diffracted waves are a hindrance in telecommunications but may be used constructively if the topography of an area is taken into account. This paper and its conclusions have the flavour of very recent work in mobile radio studies.[16]

In Holland, in 1934, experimentation under the auspices of the Physics Laboratory of the Netherlands Armed Forces on a 240MHz point-to-point telecommunications link by Van Weiler, Staal and Gratama led to the production of a very limited number of 428MHz simple gun-laying sets.[17]

In Britain, the successful Daventry Experiments of the 25 February 1935 was a feasibility study for the Chain Home System. It had been requested by Air Marshal Sir Hugh Dowding for the benefit of the Committee for the Scientific Study of Air Defence. The frequency of the signal being monitored was 6MHz and the technique used was a well tried procedure for the man in charge of the demonstration, A. F. Wilkins.[18]

In 1935, all the necessary framework of techniques and equipment was at hand principally because of the work programme of the Radio Research Board, that had been established under the Department of Scientific and Industrial Research in 1920.[19]

Pierre David is perhaps the best known of the French pioneers of radar, his name being associated with the 'barrage électromagnétique' bistatic continuous wave system. In the first World War he was associated with General Ferrié and did considerable work on VHF propagation during the post-war years and into the 1930s.[20] Engineers of the SFR (Société Française Radioélectrique), among them M. Ponte, H. Gutton and S. Berline, were involved in propagation work at 16cm wavelength in the mid 1930s. In 1934 the French Navy had requested propagation measurements on 16cm as a possible alternative to an infra-red short-distant signaling system which was under development. SFR experimented first with transmitters using Barkhausen-Kurz valves and later with split-anode magnetrons. The SFR obstacle detector apparatus aboard the Normandie in 1935 and, later in 1938, the much improved system at Saint-Adresse paralleled their telecommunications work at that time. (The use by SFR of oxide-coated cathodes in their magnetrons in 1939 and the transfer of this knowledge by M. Ponte to G.E.C. at Wembley in 1940 was a critical factor in the success of Britain's first cavity magnetrons).

The names of H. Yagi, S. Uda and K. Okabe are invariably associated with extensive propagation work at ultra-high frequencies in Japan from the 1920s to the War years.[21] Japanese radar emerged directly from research activities in propagation and in magnetron development.[22]

3. World War II

A necessarily brief look at some of the propagation activities in the United States, Britain and Germany will be attempted. A review of ionospheric research, which was considerable in these countries and in Japan, will however not be given.

On Thursday 16 November 1944, a "Third Conference on Wave

Propagation", which lasted for three days, was opened at the National Academy of Sciences, Washington, D.C., by Charles R. Burrows, Committee for Propagation, NDRC (National Defence Research Committee).[23] In attendance from Britain were E.C.S. Megaw, F. Hoyle and Lieut. Cdr. F. L. Westwater, Naval Meteorological Service. The Conference programme, which was well-balanced, would be considered quite relevant today. This particular event has significance in that it reflects the close cooperation that existed between the Propagation Group (Group 42) of the Radiation Laboratory and the British Ultra-Short-Wave Propagation Panel. It also indicates that the importance of propagation studies was realised, even in the midst of war.

Donald E. Kerr's 'Propagation of Short Radio Waves', published in 1951, while being an excellent textbook on tropospheric propagation, summarises within some seven hundred pages the work of Group 42 of the Radiation Laboratory and of other researchers in the United States and Britain.[24] The book devotes a chapter to experimental studies which include both one-way transmissions and radar transmissions carried out over land, sea and lake paths. The test areas included the United States, Great Britain, the Mediterranean, the Persian Gulf and India and, as might be expected, many instances of superrefraction are alluded to.

The British one-way and radar-transmissions carried out in the Irish Sea (on 3cm, 9cm and other wavelengths), and described by Kerr, are treated in more detail by E.C.S. Megaw; his paper is an excellent overview of the experimental work undertaken in Britain during the war on very short and, especially, centimetric waves.[25] Megaw refers to the striking increase in range of 50cm and 10cm stations on the south coast observed during the summers of 1940 and 1941 respectively. In July 1941, the RDF Applications Committee of the Ministry of Supply appointed the Ultra-Short-Wave Propagation Panel to study these "anomalous" propagation phenomena.

Much work was carried out in providing a theoretical understanding of anomalous propagation, whereby echoes could be obtained from objects close to the ground and well beyond the line-of-sight range and, conversely, no echoes could be obtained from targets well above the line-of-sight. T. C. Eckersley and H. G. Booker in Britain[26] and W. H. Furry in the United States[27] are associated with the provision of a suitable theoretical framework for this 'duct' propagation phenomenon. The phase-integral theory which had been applied to the problem of diffraction around an imperfectly conducting earth was developed so as to include a stratified atmosphere near the earth. The solving of the ensuing scalar wave equation for the electromagnetic field adopted the approximate solution of the W.K.E. method, which had been used in wave-mechanical problems independently by Wentzel (1926), Kramers (1926) and Brillouin (1926).[28]

It is hardly necessary to stress that the object of these research studies, during the war years, was not knowledge per se, but the solving of very practical difficulties of radar coverage for existing systems, or the prediction of performance for new systems. One could, for instance, cite work on the H2K project which used the 1cm K-band. The H2K equipment aimed at providing a very high-resolution bombing radar and its development required the acquisition of a considerable knowledge of atmospheric absorption mechanisms.

In highlighting German propagation studies of particular relevance to radar one could mention W. Pfister of the Ferdinand Braun Institute but chiefly one should underline the activities of W. Lehfeldt of Siemens.[29] Lehfeldt was located at the Irschenberg outstation of the Ferdinand Braun Institute and carried out a research programme on metric and centimetric waves (l = 10m - 1cm) from 1940-1945. The programme was very comprehensive, covering different types of terrain and paths varying from 30 to 200 miles. The measurements paralleled those of the Americans and British and may well have exceeded them in the variety of paths and frequencies tested. Horizontal and vertical polarizations were employed and transhorizon reception was investigated.

There are records of RCS (radar cross section) measurements being carried out by Gh. Bachem and O. Stutzer during the first year of the war on an outdoor range using scaled down models of aircraft such as the ME 109 fighter (1:10 model) and Ju-52 (1:10 and 1:37.5 models) transport aircraft.[30] An appropriate scaled down wavelength for frequencies appropriate to the Würzburg and Freya radars was used: the models, suitably supported, were positioned 30m from the transmitter-receiver combination. A single thin resonant dipole served as a back scatter standard. The transmitter used a 2-segment magnetron, that generated a 10W continuous-wave which was amplitude-modulated at 1000Hz.

4. The Post-War Era

Mention has just been made of RCS measurements carried out in Germany in the early days of the war. During the war and into the post-war era the scattering cross-section of targets and its estimation and measurement became a central topic in radar science, linked as it was to radar range estimation.

In certain military situations radar cross-section minimisation techniques became important. Again, in some cases, it became necessary to consider not only the back scattering properties of a target, as in the monostatic radar case, but also the more complex situations occurring in bistatic radars. When the target is the earth's surface in a mapping or remote sensing exercise, scattering from a multitude of complex scattering elements must be considered: the differential scattering cross-section (i.e. scattering cross-section per unit area) of terrain echo and of sea clutter is then used.

From the "Terrain Identification" project of E.G. Bowen in 1939 using 1.5 metre airborne radar to the present day, the study of radar targets, discrete and distributed, has, world-wide, been vast.[31]

The radar cross section handbook of G. T. Ruck et al, published in 1970, and the more recent publications of M. Skolnik and of F. T. Ulaby and M. C. Dobson help to bring into focus the enormous amount of theoretical and experimental work undertaken in this whole area.[32]

HF (3 to 30MHz) Over-the-Horizon (OTH) radars will not be discussed, except merely to note that information on the transmission path is vital to their use.

It may well be asked if the material alluded to above correctly comes within the category of "propagation"? While radar systems are no respecters of man-made semantic boundaries, nevertheless it may be helpful to recall that propagation studies related to microcellular systems deal in many cases with penetration into buildings and with multiple indoor and outdoor scattering from a variety of targets.[33] The properties of the various scatterers become all important when one is trying to assess the behaviour of the radio field.

Today one finds that the propagation effects that determine the detection performance of ground-based radars against low-flying targets apply equally well to ground-based tele-communications systems.[34] The same radio channel prediction models can be used in either case.

Multipath factors which are a cause of problems in tracking radars are equally unwanted in radio digital communications systems.

In solving certain ground-based radio problems or in designing a new radio network, one can obtain invaluable information on the propagation medium or 'channel' which exists between a transmitter and receiver by measuring the "impulse response" of the channel using a "channel sounder": this instrument is a type of bistatic radar.

O. E. de Lange of Bell Laboratories was possibly the first to report on the technique, where he transmitted microwave pulses with a duration of 0.003 microseconds over a 22 mile path, partly over water and partly over rough land terrain, between Murray Hill and Crawfords Hill, New Jersey, in 1950.[35] In the introduction to his paper, he wrote:

> This experiment was set up with two main purposes in view: First, as a means of studying microwave propagation, especially with regard to multi-path transmission effects and second, to determine the effect of a transmission path upon the shapes of very short pulses, particularly to learn what restrictions

might be imposed upon minimum pulse length or spacing between pulses by distortions produced in the transmission medium.

An alternative to this direct method of obtaining the impulse response is to transmit a noise-like signal and to then use its correlation properties at the receiver to obtain an approximation to the impulse response of the channel: in other words, use a phase-coded pulse compression radar.[36]

In designing a ground based telecommunication system or going through a diagnostic procedure on an existing system, it is customary to complement the measuring programme by using prediction models. Much research has been done and continues to be done, internationally, in developing suitable models for various topographical scenarios. In UHF mobile channel characterisation and modeling, radar information may be used. This is particularly so when the propagation medium and propagation mechanisms between transmitter and receiver are viewed three-dimensionally. When scattering surfaces are rough, bistatic cross-sections may be taken into account; also, land use and surface texture factors can be obtained from satellite-based SARs (Synthetic Aperature Radars) such as the ERS-1.[37]

5. Conclusions

An attempt has been made to show that propagation studies hold a special place in the history of radar. They were vital to its conception and birth.

It is interesting to note that, today, radar methodologies are used in probing the fine structure of the radio propagation channel, itself.

Radar transmitter and receiver design is important as is antenna system design. The latter interfaces with the channel, which is the medium where matter and waves interact; sometimes simply, sometimes unpredictably. Mastery of this medium, like mastery of the high-ground in matters military, will bring, maybe not "victory", but certainly success to the radar designer.

The historian who is attempting comparative studies of radar's technical progress may discover, in radio wave propagation research in any particular country, a useful indicator of potential for radar development.

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THE CONTEXTS FOR THE DEVELOPMENT OF RADAR: A COMPARISON OF EFFORTS IN THE UNITED STATES AND THE UNITED KINGDOM IN THE 1930s

If we consider radar only in its narrow definition of a detection system, many parts of the history of early radar can be avoided in the telling, but if we concentrate on a narrow story, we miss a complex, cultural web of its development in the United States and the United Kingdom. For example, work at the Massachusetts Institute of Technology, Bell Laboratories, various Naval laboratories, the Bureau of Air Commerce, Sperry Corporation, and Stanford University in the 1930s and 1940s is left out of the story. This paper follows those earlier technical developments in their cultural contexts--MIT pre-Radiation Lab, the klystron invention, and the Oliphant group at Birmingham--offering a perspective on technical developments primarily in the United States. These developments grew out of the needs and desires of a more socially related kind rather than defense needs, but they were to have very significant impacts on later defense-related systems involving klystron technology. While illustrating the point about the influence of the social context, this story is meant to be complementary to the dramas about early radar for defense purposes reported by other authors.[1]

High-Voltage Research in California

First, why the klystron out of California? Our California story begins at the turn of the century. One of the primary technological problems encountered in the electrification of Pacific coast cities, especially Los Angeles and San Francisco, around

1900 was the transmission of electric power generated by hydroelectric plants high in the Sierra to users on the Pacific coast, hundreds of miles distant. Aided by the Pacific Gas and Electric Company, one of the leading corporate architects of Northern California's hydroelectric system, Harris J. Ryan of Stanford University's electrical engineering laboratory took up the problems associated with long-distance transmission in an innovative high-voltage laboratory designed by him. As Thomas Hughes has shown in Networks of Power, Ryan was able to bring his scientific training forcefully to bear upon the problems and to identify such things as the corona effect, which accounted for power losses from high-voltage, long distance transmission.[2]

The problem of long-distance transmission of very high voltages also interested the Southern California Edison Company, which constructed a million-volt testing laboratory at the California Institute of Technology in 1922. The company planned to use the laboratory to solve problems attending the projected transmission of power from Boulder Dam. Although Southern California Edison planned its laboratory primarily for technical problems in electrical engineering of the sort Ryan's had tackled, it also attracted to Caltech in that year America's most prominent physicist, Robert Andrews Millikan.[3] Millikan was assured that he could use the laboratory to solve a number of "high potential problems" in pure physics. Among these problems he wanted to study the energy distribution across the wave-length spectrum of X-rays "produced at very high voltages," and this effort played an important part in the subsequent California story, but not for work at Caltech.

The laboratory's voltage source was a four-stage cascade transformer. Four 250,000 volt transformers were connected in series to produce 1,000,000 volts from terminal to ground. Caltech's electrical engineer in charge of the laboratory, Royal W. Sorenson, designed the device, and found it somewhat difficult to build because there was an "apparent inclination on the part of the manufacturing companies to discourage a college laboratory from having such equipment." His principal supplier, Westinghouse, had to be educated to the special character of academic laboratories "because of a lack of previous similar connections."[4]

R. D. Bennett came to Caltech in 1918 to pursue postdoctoral study of high-voltage X-ray scattering. In attempting to build a suitable tube, he encountered problems caused by field-current emission. Charles C. Lauritsen was asked to help Bennett to apply one million volts to his X-ray tube using the high-voltage laboratory as a voltage source, thus avoiding "the expense and difficulty connected with the construction and maintenance of a satisfactory source of high potential."[5]

To fund the development of the tube, Millikan looked to the medical applications that might be made of high-voltage X-rays. This would justify philanthropic investment in the tube. Funding for cancer research and therapy was increasing rapidly in the late 1920s because of the perceived growing incidence of the disease. Millikan had shown himself to be a master of entrepreneurship in building up Caltech through appeals to similar social needs. A patron for medical research with the new X-ray tube was soon found: Seeley G. Mudd, a local cardiologist, who set up a Seeley W. Mudd X-Ray Research Fund in memory of his father.[6]

Cancer specialists disagreed about the utility of such a powerful X-ray tube in treating the disease. Francis Carter Wood of the Crocker Institute of Cancer Research at Columbus University felt the tube was "the exact step forward that we need for the treatment of cancer," while Fred Stewart, a cancer specialist at New York's Memorial Hospital, felt that in radiotherapy "the tendency [was] in the opposite direction, small quantities of energy over a long period of time."[7] A Los Angeles radiologist, Albert Soiland, agreed to supervise therapy with the Lauritsen tube and began treatments with 600,000-volt X-rays in October 1930.[8] These early trials suggested that radiotherapy-resistant patients were helped, but Wood called a halt to them as premature. A new medical tube was built and a medical advisory board was constituted to oversee the work.[9] What had begun as a scientific instrument based on one technology became another kind of tool to be used by the practitioners of a second technology, medicine.

To house the new medical tube, Millikan had to raise more funds and turned to W. K. Kellogg, the Corn Flakes King. Kellogg gave $150,000 in return for "credit of some sort."[10] The resulting Kellogg Radiation Laboratory was completed in 1932. It housed a 1.2 Mev X-ray tube, with an electron filament. It was, Lauritsen claimed, the answer to "all high-voltage X-ray requirements where compactness and simplicity of construction are desired." This included industrial as well as medical uses; for example, very high-voltage X-rays were needed to inspect welded joints in metals.[11] The new departure was rewarding to pure physics research at Caltech especially, and at other institutions as well. A number of Caltech postdoctoral fellows and graduate students used the tube in their studies, and the nuclear physics program at Caltech during the 1930s was funded by a "bonus from the medical research" with high-voltage X-rays.[12]

Other California research centers in physics sought such equipment for technological as well as scientific purposes. Success in acquiring it depended upon the entrepreneurial skills of the physicists. Failure set in motion a search for low-cost alternatives, one of which was a device fundamental to the klystron.

Ernest Lawrence of the University of California succeeded in developing an alternative to the Lauritsen X-ray tube in the early 1930s. Lawrence and David Sloan, a research engineer he recruited from General Electric's Schnectady laboratory, worked on a series of machines designed to accelerate protons and electrons to use in nuclear physics experiments: the cyclotron, heavy-ion linear accelerator, and an electron accelerator. This last device had not yet been successful when, in June 1931, Lawrence spoke at an American Association for the Advancement of Science symposium on "The Production of High-Speed Electrical Particles" at Pasadena. W. D. Coolidge of General Electric, Merle Tuve of the Carnegie Institution of Washington, and Lauritsen also described their work in this field at the symposium, while Alexander Goetz reported attempts to "harness lightning" for high-voltage research by A. Brasch and F. Lange in Italy. Lawrence observed Lauritsen's success in funding and building the million-volt X-ray tube, and urged Sloan to redouble his efforts to build a successful electron accelerator that might be of use in a high-voltage X-ray tube. Sloan later recalled that "it was easier to get money for medical things than for pure physics things in those days," but he over-rated Lawrence's insight when he remarked, "I'm sure nobody else thought of getting these things into hospitals at that time."[13]

Sloan used a modified version of Tuve's Tesla-coil electron accelerator for the heart of the X-ray tube he built in 1931. By enclosing the entire accelerator in a vacuum tube, he created a compact accelerator that Lawrence believed would "supplant all other techniques in the production of high-voltage X-rays."[14] Lawrence succeeded in winning the backing of the Research Corporation and the Chemical Foundation for further research on the tube. These "non-profit" patent pooling agencies were interested in breaking the hold of General Electric and other large companies on the X-ray market, and Lawrence persuaded them that the Sloan tube would prove viable as an alternative to existing commercial tubes. These hopes were not fulfilled, although prototypes of the Sloan tube were installed in the University of California Medical School and the Crocker Institute at Columbia University.[15] Funds given to finance these prototypes also subsidized physics research at the Radiation Laboratory, as had funds for Lauritsen's tube at Pasadena.

Research on X-Rays at Stanford

Meanwhile, at Stanford, the feedback from the application of high-voltage technology to medicine by scientists almost brought together the practitioners of science and technology in the 1930s. Stanford University radiologist Robert R. Newell attended the Pasadena AAAS meetings where Lawrence and Lauritsen described their experiments. Although he felt that "higher voltages on X-rays tubes would not prove the solution of the cancer problem," he was willing to try out the approach, and asked the chairman of the Physics Department David Locke Webster to build him a high-voltage X-ray tube.[16] Webster did not share his predecessor's disdain for engineering and technology. He was particularly interested in X-rays, and had transplanted his research program in X-ray spectroscopy to Stanford from MIT. With P. A. Ross, he had helped demonstrate the Compton Effect experimentally in the mid-1920s and had constructed a 200,000-volt X-ray tube for physics research purposes in 1927. His purpose was to measure the X-ray spectral line intensities of atoms using ionization by cathode-ray impact. These measurements would help determine the probability of ionization of the inner electronic shells.[17]

Webster drew upon the medical profession for his research facilities, soliciting old medical X-ray apparatus and testing X-ray equipment used by physicians in return. His research program was part of a larger cooperative effort in medicine, the life sciences, physics, chemistry and mathematics, which encouraged the application of physical techniques to medical problems.[18] He readily acceded to Newell's request for a high-voltage tube, and recruited F. B. Duveneck to assist him. Duveneck "contributed valuable ideas on the development and construction of new apparatus, as well as important work in superintending and testing it," just as did Sloan and Lauritsen.[19] With graduate student A. W. Hackney, Duvenek built a 400,000-volt X-ray tube for deep therapy, "along lines suggested on the basis of clinical advantages" by Newell. It permitted physicians to "avoid undesirable changes of posture by the patient, and yet treat internal cancers from several points of entry, by having rays available of any desired inclination."[20]

Although the Newell tube was strictly for medical purposes, i.e. a straightforward technological endeavor, Webster's involvement in the project set him to thinking of the advantages of such a tube for his own research. Recognizing that Lauritsen's tube had been based upon the high-voltage source at Caltech, he sought to make use of Ryan's three-million-volt source at Stanford. In 1933, he suggested to the president of Stanford, Ray Lyman Wilbur, that a:

> desirable line of expansion in super-high-voltage physics, which means practically at the present time the bombardment of atoms with charged particles

> driven by voltages above 200,000. The presence of equipment for engineering work at these voltages in the Ryan Laboratory and their experience in this line suggests that Stanford is an ideal place for development in this field. Our own expansion from 200,000 volts to 400,000 in the construction of a tube for therapeutic work for Dr. Newell has been made possible by the use of the Ryan Laboratory equipment and without knowledge of X-ray and high-vacuum technique we could easily use voltages as high as those now in use at [Caltech], up to 1,200,000 volts; and in all probability we could go up to the limit of the Ryan laboratory equipment . . . 2,100,000 volts effective [which] involves voltages at the peak of the wave nearly up to 3,000,000 volts, or about two and one half times as high as those now in use at the California Institute of Technology. Their experience and that of workers in radioactivity have shown that there is a vast variety of new phenomena to be investigated in this field.[21]

Webster and his colleagues solicited the help of a number of people in the field in planning their tube: Lauritsen, General Electric's W. D. Coolidge, and MIT's Robert J. Van de Graff, a power engineer turned physicist. Electrical engineers like Ryan and J. S. Carroll also helped.[22] An outdoor laboratory, connected to the Ryan Laboratory by transmission lines, was planned to house the tube. However, the entrepreneurial skill which had raised money for scientific instruments by citing their medical utility was not part of Wilbur's repertoire, perhaps because he was a trained physician. The $30,000 required to build the tube was never raised.

At Stanford, in contrast to Caltech and the University of California, a genuine "user-generated" need for high-voltage X-ray technology produced the Newell tube. Scientific interest in a very-high-voltage tube followed, almost but not quite bringing to full circle the series of interactions begun in Ryan's laboratory. Failure to complete the circuit through entrepreneurship, however, created a need for another approach to the problem of high-voltage research at Stanford.

The Klystron

While Webster sought funds for a high-voltage tube, he was training a young student, William W. Hansen, whom he believed would be a substantial addition to his faculty. Hansen assisted Webster with a number of projects while still an undergraduate, and the senior physicists encouraged him to pursue graduate study in

X-ray crystallography at MIT. Hansen followed Webster's advice and returned to Stanford as a faculty member in 1934. Conscious of Webster's frustrated hopes for a high energy X-ray tube, Hansen sought possible ways of circumventing the financial problem by using unconventional designs. Eventually, he focused on resonating cavities as a means of transmitting energy to and from electrons.[23] The publication in early 1939 of this work on resonating cavities, a device he called a rhumbatron, had important implications for the radar work at Birmingham.

Russell Varian, another of Webster's students in these years, and a close friend of Hansen's, participated in discussions with Hansen in 1934 about X-ray equipment. One early scheme considered was a coaxial resonator. Varian noted that "greater efficiency would result if the center conductor were enlarged near the current loop and made smaller near the voltage loop," and the two began to worry about losses due to radiation of the electron beam, which in this configuration would move the currents further from the axis. Hansen recalled performing, while in graduate school, an analysis of electromagnetic radiation in which he had demonstrated "that one could have non-radiating oscillations inside a sphere." He concluded this would be an ideal resonator because "the high-voltage parts [were] as far apart as possible, and the high-current region had the maximum amount of conductor."[24]

The device Hansen contemplated constructing at this time consisted of an evacuated resonator, somewhat shorter axially than a sphere, driven by triodes. As Hansen noted:

> Electrons would be injected along the axis with considerable initial velocity and some would be accelerated by their passage through the resonator. Absolutely the only visible practical trouble with the device was that tubes known then would not work at very short wavelengths . . . so that it would be necessary to make the device of considerable size -- say 10 or 20 feet in diameter.[25]

Other members of the department, more sanguine about obtaining funds to enable construction of conventional systems, disapproved of proceeding with this idea. So

Hansen concentrated on mathematical analysis of the system: it led him to a breakthrough in the design of his resonator.

Out of this analysis came new solutions of the wave equation in cylindrical coordinates and an expansion of Green's function.[26] These were used "to produce quantitative results for circular cylinders with flat ends" to show that "this was a perfectly satisfactory shape." Within a year, Hansen had convinced his colleagues that construction of such a device was the only direction available to them. A working model in February 1936 confirmed the theory. But while simple enough in theory and prototype, in practice it was another matter entirely. Over the next year-and-a-half, Hansen built his "Big Rhumbatron," as he called it, but major problems with the triodes, cooling system, and blocking condensers limited efficiency. A technological approach was required.

Varian was not present during all this period of 1934-37. He worked for the Farnsworth Television Laboratory in San Francisco, spent time in his own research laboratory, and studied at Stanford. Russell and his brother, Sigurd, often talked about inventions, and Sigurd especially hoped to strike it rich by this route. Sigurd, a pilot for Pan American Airlines, corresponded with Russell about various technical ideas, among them was the necessity for a system to detect unseen flying aircraft. Russell mulled over the problem and concluded that a means of detection by radio waves could be developed, but equipment of reasonable size would require radio waves of centimeter wavelengths. "By mid-1936, it occurred to Russ that Hansen's new resonator might be adapted in some way to generate these waves."[27] For the next six months, Russell and Sigurd investigated the principles and worked on several designs. Russell was responsible for reestablishing the connection with Hansen:

> [He] knew that at shorter wavelengths the efficiency of resonant circuits would be very low, but he did not realize initially that the flight time of electrons in a conventional tube would become even a greater fundamental limitation.[28]

In the spring of 1937, the Varians proposed to Hansen that they come to Stanford where all three could work on the development of an efficient microwave power source. The Varians' desire for a useful microwave power source and Hansen's concern about the triodes in his high-voltage resonator complemented each other. Russell Varian and Hansen invented a number of possible oscillators. One such design was a circular swinging beam tube that would energize the rhumbatron through a series of holes in the rhumbatron along a circular path. Sigurd Varian actually tried to build such a model. On June 7, 1937, as recorded in his research notebook, Russell invented the bunching principle. This discovery resulted from Russell's attempt to classify the various designs the group had discussed, to ensure no obvious possibilities had been omitted. Russell described his new idea, the keystone of klystron operation, in his notebook as follows:

> The new method is a sort of grid control, but none of the electrons are prevented from passing the grid. They were merely slowed down or accelerated . . . Under these conditions, the electrons after passing the control grids will have variable velocities depending upon the phase of the oscillating circuit when the electrons went through. If the electrons continue in a straight line the accelerated ones will tend to catch up on the retarded ones, and the stream of electrons will transform from a uniform beam to one consisting of a series of concentrations or waves of electrons having the same frequency as the exciting frequency. One of the beauties of the system is that a mutual conductance is independent of frequency.[29]

There follows a mathematical analysis of this principle, showing how the mutual conductance and the amplification factor would depend upon the various operating parameters. What was needed now was a source of an electron beam, a design for the resonators, and systems for tuning and coupling them.

A consideration of earlier resonator designs set them on incorrect paths. Fortunately, their procedure of repeated mathematical analysis of all ideas pointed up their incorrect assumptions. As Hansen later wrote:

> I soon rediscovered reentrant ends however and was even able to do more. For I found an exact solution for a resonator consisting of a sphere with two reentrant cones. Calculations showed that this shape had a very high shunt impedance and

> a surprisingly short wavelength for its size. But the mathematics was unfamiliar and so looked odd and nobody but myself had much faith in it. In particular, it seemed unreasonable that one could get a short wavelength with the two reentrant cones infinitely close together. These doubts were resolved by the construction and test of a large scale model of the resonator. This was constructed by S. Varian of cardboard coated with copper foil.[30]

By August 1937, their model and measuring equipment had been completed and they successfully tested the device. Sigurd removed the tube and replaced the tungsten grid wires and on August 30, 1937, the tests were repeated:

> We dug up [according to Sigurd] an old dime store cat's whisker crystal detector and a galvanometer and picked up rf energy all over the room. We made a quick check on the frequency by moving the crystal detector through the standing waves in the room. In our excitement we figured the wavelength to be 6.5 centimeters and were very embarrassed later to have to admit we measured half wavelengths or 13 centimeters being the correct wavelength.

Everyone celebrated their success, knowing full well the implications of having achieved this wavelength and energy. Sigurd's wife wrote to their cousins on the following day:

> I had not written sooner, as Sig was about due to make a test on that 'rumbatron' (sic) and wanted to wait and let you know the outcome. Well, yesterday he called me up in wild excitement to say the thing had oscillated. This, of course, means the victory is practically won and it is just a case of time before they get the other little items straightened out. Dr. Webster was so thrilled that he invited the physics department and myself over to his house for beers.[31]

This assessment proved overly optimistic as it required four years of further development before the klystron became a production-line item. The next four years proved to be a trying period for the Stanford team, while Stanford patented the klystron immediately, they entered into a development contract with the Sperry Gyroscope Company without realizing all the implications of development. The tension between industrial proprietary rights and academics' propensity to open publication strained relations between the two groups. But many compromises and successes, and then the war-time situation, kept tempers under control. While Hansen and Varian continued their usual procedure of analysis, with increasing regularity they turned over designs for others to develop. We will return to the klystron story in a moment, but first we need to consider events at MIT in the 1930s.

Massachusetts Institute of Technology

During the 1920s, universities, colleges, and institutes began to develop radio communications options for their electrical engineering programs. MIT was no exception. Edward L. Bowles, a talented MIT graduate, took on the responsibility for broadening the MIT program to include radio communications.[32] Bowles called on friends at Bell Laboratories to help. At the end of the 1920s, Bell staff offered courses at MIT on electric wave filters and on network analysis and synthesis.[33] Through a serendipitous connection, Bowles became involved in research on radio for navigation and offered courses in this specialty. The connection was a wealthy financier with a hobby in radio: Colonel Edward H. R. Green, who devoted a portion of his estate at South Dartmouth, Massachusetts, near New Bedford, south of Boston. After a year of studies on antennae, fading on various wavelengths, and changes in signal strength, Green made it known he would like to start investigations into other aviation issues. A number of researchers from electrical engineering and physics took up the challenge.[34] "The Institute," according to a recent history, "recognizing that fog was a primary menace to aerial navigation, proposed to Green that an extensive fog research program be set up...."[35] In the fall of 1928, several studies commenced. Bowles and his group believed that three approaches were possible: radio, infrared, and sound. Julius Stratton focused on radio, using 40 cm waves. As an aside, an early desire for two-centimeter radiation as part of an electromagnetic radiation transmission investigation led Vannevar Bush to attempt to produce a generator using magnetrons as a source, without success. Work was slow; fog was not as cooperative as the researchers. So, they turned to theoretical investigations of radio transmission in fog. These studies led "in 1932 to methods and devices for the determination of particle size and distribution in actual fogs," and "a practical means of estimating light transmission of different colors under fog conditions in an airport."[36]

Among Bowles associates in this research program was Wilmer L. Barrow, who joined the group in the fall of 1931, after completing his doctoral studies at the Technische Hochschule of Munich. He set about to study "the properties and peculiarities of wave propagation, attenuation, reflection, and polarization," of waves below a meter in wavelength. The rest of the story of the Barrow horns, in which transmission takes place without a central conductor, is relatively well-known and need not be repeated here. However, the horns became an integral part of subsequent instrument landing system research organized by Bowles.

Bowles's "comprehensive program of research involving navigation in fog and the theory and application of microwaves furnished the foundation for a special study of instrument landing for airplanes." This work was done with the cooperation of C. Stark Draper for the Civil Aeronautics Authority (CAA):

> In it the applicability of the Barrow horn radiators for producing radio beams and the first application of centimeter waves to the problem have been demonstrated....The first application of the Stanford new ultra-high frequency generation, the Klystron, was made here in this research...[37]

These research efforts during the 1920s and 1930s, while not connected to military or wartime needs, laid the groundwork for MIT's capability to successfully operate the MIT Radar School and the MIT Radiation Laboratory. And this ties the first two parts of my story together.

Further Development of the Klystron

We mentioned earlier the development contract entered into by Stanford University and the Sperry Company. Sigurd Varian arranged a meeting with members of the Bureau of Air Commerce (the antecedent of the CAA) and the Bureau representatives asked if a Sperry employee who was interested in the tube could be present. Hugh Willis of Sperry was favorably impressed with the demonstration of the klystron at Stanford and encouraged the company to enter negotiations with Stanford. Before any contract was agreed to, Sperry asked Edward Bowles to evaluate the klystron and the project group at Stanford. He did this favorably and, as we mentioned, a contract was tendered to Stanford by Sperry. He also arranged for the test of the klystron as a source of energy for the one of MIT's blind landing system designs.[38]

Over the next two years at Stanford and later at the Sperry facility on Long Island, many improvements were made in the design of the klystron and Sperry developed manufacturing techniques to make the tube. The Varians and William Hansen did not like their stay at Sperry, but decided to remain because of the war effort. The three worked on different aspects of the klystron program, and in different locations at the facility. They were anxious to return to California and get on with their plans to organize an engineering laboratory.[39] This laboratory idea evolved into the Varian company, organized in 1948, which was instrumental in many electronic areas after the war. At the beginning of 1940, Sperry reported that a klystron system could train a straight beam upward at a shallow angle so that incoming planes could start a long, regular glide from a distance. At the time, Sperry was involved in development of control instruments to operate with the klystron for use in automatic take-offs and landings. The klystron was already in use in planes as a sonic altimeter, and the beam could be trained at an angle ahead of the plane to detect obstructions a mile away by reflection.[40] However, the honor of incorporation of the klystron into effective radar systems went to the British.

Hansen and the Varians published several papers related to the klystron in 1938 and 1939, and these came quickly into the hands of Marcus Oliphant and his group working on a war-related task--to make a shortwave radar system.[41] The group visited the Chain Home radar stations to learn more about radar and returned to Birmingham in September 1939, a fateful month. Most of the group focused on various aspects of klystron development, because of its promise as a generator of high-frequency microwaves. In an attempt to modify the klystron to achieve higher pulse power levels, the Oliphant group tried to focus a reasonable beam current through the klystron cavities and drift tube. The tube was only a continuous wave tube and its pulsed power was not much larger than its CW power. Magnetic focusing in klystrons, so common after the war to solve this problem, was not feasible in 1939. The lack of success must have deflected the attention of historians to their work. It is interesting to note that most treatments prior to 1980 of technical radar development in the United Kingdom do not focus on the group's work with klystrons, but instead center attention on the work of Sir John Randall and Dr. Henry Boot with the magnetron. We do not say this with any desire to denigrate the work of Randall and Boot; their work proved to be most important both during and after the war.

In spite of the dearth of power in the klystron for transmission purposes, this was no impediment to its use as a receiver. The klystron's size made it feasible for inclusion in airborne systems, whereas the size of the magnetron system was too large. Consequently, the klystron was used as a receiver in airborne radar systems, and as an oscillator powering magnetrons in ground systems.[42]

We need not repeat what is described in other articles in this volume or elsewhere about the development of the magnetron in Birmingham and its subsequent use in radar stations.[43] We would like to emphasize, however, in contrast to the Stanford invention case, that the radar developments in the United Kingdom were almost exclusively defense related. This may explain why radar system development was so advanced in the United Kingdom relative to the United States, if a few years can be said to be an advance. On the other hand, the emphasis in certain sectors of the United States on blind or instrument landing systems enhanced other commercial developments before and during the war.

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Walter Kaiser

THE DEVELOPMENT OF ELECTRON TUBES AND OF RADAR TECHNOLOGY: THE RELATIONSHIP OF SCIENCE AND TECHNOLOGY

1. Science and Technology

There are obviously many important aspects of radar history, for example, the impact of new weapons like bomber planes and U-boats, the political context immediately after World War I, the needs of the military in the pre-war phase of Word War II, and the national styles in radar development. In this paper on radar I want to concentrate, however, on the interaction of physics and technology.

At least since the end of World War II and until 1960, a sort of a one-dimensional and highly politically loaded science policy dominated science and technology in the United States and consequently also in Europe, and most likely in the eastern countries too. The underlying model was very simple "assembly line" model. Assembly line refers to an almost perfect line consisting of pure science, applied science, invention, development, engineering and marketing, which eventually transforms basic knowledge into a new technical product. According to this mode of thinking, spending money (e.g. federal funds in the United States, or federal and state funds in Germany) on science will lead within a certain time to innovative products, or to a new process, or to advanced systems in technology, with the consequence of new industries and more jobs. Today the assembly line model is still "state of the art" in politics, at least in that part of politics which is visible in public.

I do not want to fill the framework of this assembly line model with some more or less new historical material. Actually the history of science and technology neither tells the story of a mutual nourishing science and technology since the scientific and industrial revolutions in the 17th and 18th century, nor does it tell the smooth story of a perfect interplay of modern science and technology. One has to consider the highly polemic debates on the role of science as opposed to practical engineering at the young technical universities in Germany around 1890. To move to the 20th century: At the end of the 1950s both industry and the military in the United States became aware of the unexpectedly small number of innovations in technology produced immediately by scientific research. General Electric, evaluating its own expenditures on Research and Development, during the first fifty years found that its fundamental research looked more like a gamble, made possible by the "strong financial status" of General Electric. Project "Hindsight" sponsored by the Department of Defense furnished a number of only 0.3 per cent of innovations resulting from undirected scientific research.[1]

So it is not at all surprising that a number of historians of science and technology now reject the oversimplified assembly line model. American historians of technology in particular proposed a more complex model of interaction of science and technology.[2] They stressed, for example, the engineer's ability to foresee the future limitations of a technical apparatus or of a technical system (an example for this "presumptive anomaly" is the development of the transistor, when the vacuum tube was "state of the art" in electronics). Science is then no longer a source proper but merely a resource for the development of technology. Historians of technology also pointed out that, unlike science, technology may create large and complex systems. Those systems need to be developed in a well balanced manner, i.e. they do not allow for what Thomas P. Hughes called "reverse salient points". On the other hand growing systems may internally gain enormous momentum, but they are also shaped by the political, economic, and geographic conditions of their surroundings. Finally, historians described more precisely the role of the typical research entrepreneur, an individual who is able to bridge the gap between the needs of both science and industry. The essence of all this historical analysis is to view science and technology as autonomous regions of human knowledge.

2. Electromagnetic Waves

The beginning of radar development was almost pure science. When Heinrich Hertz was able to produce and to detect electromagnetic waves in the years 1886 to 1888, he was primarily concerned with the theoretical predictions of Maxwell's electromagnetic theory of light. Most impressive were the quasi optical experiments of Hertz, e.g. the reflection of electromagnetic waves.[3] When Ludwig Boltzmann, Ignaz Klemencic and Ernst Lecher, among others, analyzed experimentally the reflection of electromagnetic waves by dielectric surfaces, metallic surfaces and wire structures, they were aware of the corroborative capacity of those experiments. Similarly Hertz's striving to close the gap between the phenomena of optics and the phenomena of light, and Righis and Rubens experiments with very short waves were part of the process of experimentally testing Maxwell's theory.

However, the application of this basic knowledge in electrodynamics to the field of electrical engineering still seemed to be far away. Heinrich Hertz felt that his findings in electrodynamics were more of a problem of applicability in technology than a promising new road.[4] Moreover, when after a delay of ten years, Guglielmo Marconi and others developed the technology of wireless telegraphy, the rich contents of the preliminary experiments in microwave physics to some extent were overshadowed by the success of radio communication based on very long electromagnetic waves. Due to this focus in electrical communication technologies physicists and engineers dealing with short wave technologies were almost outsiders in their communities.

Actually there were a number of forerunners in the field of ranging and detecting with help of electromagnetic waves.[5] As early as 1904 Christian Hülsmeyer applied for a patent for the detection of ships. Another application was the use of electromagnetic waves as a measuring method in geophysics and in mining. O. Trüstedt of Freiberg and Heinrich Löwy of Göttingen proposed new methods to search for deposits of iron-ore or occurrences of subterraneous water. There were the proposals of Marconi, and the accidental observations of reflection of waves made by engineers working with short electromagnetic waves. The problem was, however, that the accompanying technology of transmitting and receiving high frequency pulses was only gradually able to meet the requirements of the measurement of distances by the reflection of electromagnetic waves.

3. Electrons Tubes - Transit Time Devices

Since the middle of the thirties, as a consequence of the aggressive tone of voice of Hitler and of the growing political tensions, the development of radar technologies accelerated in a number of countries: the United States, Great Britain, France, Japan, the USSR, and Germany. Whereas Great Britain had aimed at an operational system of radar to protect the big coast line since 1935 - if we speak of national styles - the United States and Germany concentrated more on the development of rather sophisticated single components. The development of metal-ceramic triodes in Germany was still in the field of grid controlled tubes. The success of these grid controlled tubes which were able to produce rather powerful pulses (of 50 to 100kW) in the decimeter range (25 to 50 decimeters) considerably delayed coordinated research and development beyond this type of tube until 1943.[6] With the exception of Abraham Esau few people in Germany realized the potential of centimeter waves for radar development.

With respect to the production of very high frequency pulses, communication engineers in radar development outside Germany experimented very early with electron tubes, which were based on the effects of transit time of the electrons. In principle the development of transit time tubes was one of the possible solutions to the problems caused by the "traditional" grid controlled tube in expanding the frequency range towards higher frequencies, namely deliberately using the disturbing effects. So the engineers no longer tried to reduce the disturbing effects of the transit time of the electrons. They now designed valves the other way round with a planned interaction between electron beams in the tube and localized or traveling electric fields.[7] As early as 1920 Heinrich Barkhausen had invented the first transit time type valve, a tube which was later called retarding field tube. The three effects characteristic of transit time devices were already present in the retarding-field tube: velocity modulation, bunching, i.e. conversion of velocity modulation into density modulation, and power transfer from the beam to the oscillating circuit. Most important, wavelengths could be achieved with retarded field tubes in the range of 30 to 50 centimeters, and the power output was of an order of magnitude of 5 Watts.[8]

4. The Klystron

The klystron, however, was to become most important. Precursors in the field of klystrons were Joh. Müller, B. Brüche and A. Recknagel, and A. Arsenjewa-Heil and O. Heil in Germany.[9] As Arthur Norberg in his paper in this volume points out, the theory of oscillations in cylindrical resonant cavities comes from William W. Hansen of Stanford University. The invention of the klystron eventually came out of that now classic 1939 paper by the brothers Russell H. Varian and Sigurd E. Varian at Stanford University.[10] Basically the klystron is a tube where the electron velocity is modulated by a High Frequency field in a cavity, which leads to the formation of groups of electrons.[11] These bunches of electrons excite oscillations in a second cavity at the end of their transit way.[12] After the publication of the Varian brothers the development of klystrons spread out to several countries. Important at first was the British development program undertaken by M. L. Oliphant and J. Sayers in the Physics Department at the University of Birmingham under contract with the Department of Scientific Research and Experiment of the Admiralty Office. Although Oliphant had acquired valuable information about the klystron research of the Varian brothers from a Stanford visit[13] he had severe problems in achieving oscillations and in putting enough power into the tube, and in focusing the electron beam with its necessarily limited cross-section.[14] In Germany research and development remained rather haphazard. There were some klystrons developed, e.g. by the AEG company, mostly in the decimeter range. Klystrons in the upper centimeter range developed at the

Flugfunk-Forschungsinstitut suffered from very poor output of 60mW.[15] Typical of the lack of coordination and of a straightforward engineering and development of klystrons in Germany were the numerous attempts which were made to calculate the klystron efficiency for large-signal operation from the first principles, namely from the mean exit velocity of electrons. Restricting calculations to small-signal operation and using approximate solutions, researchers in the United States were immediately able to improve the design of the klystron.[16]

Moreover, in the United States soon after the invention of the klystron by the Varian brothers, J. R. Pierce and W. G. Shepherd, working at the Bell Laboratories, developed the reflex klystron oscillator. Different from the "original" klystron, in the reflex klystron the density modulated electron beam emitted by a hot cathode and traveling through grids is electrostatically reflected by a repeller. However, the space in between the grids, which functions as a single resonant cavity is decisive. The dimensions of the cavity could be chosen so that the tube allowed for oscillations in the range of ultra high frequencies, and it was possible to tune the tube. Although klystrons working in the range of microwaves in practice had only small outputs they played a peculiar role in radar development. Obviously at first they did not match the requirements for long range radar transmitters. On the other hand they offered enormous advantages for the part of the detectors in radar systems. This was especially true for the reflex klystron.

The need for this application of a local ultra high frequency oscillator came from the lack of low-noise detectors for a direct rectification of UHF signals reflected from a target. With the help of reflex klystrons as oscillators one could heterodyne down (or "beat" down) the reflected radar pulse and amplify it at a much lower frequency. Thus the local oscillator was to be operated at a frequency that was separated only by a small Intermediate Frequency (IF) from the frequency of the transmitter. In order to mix the frequency of the incoming signal with the frequency of the local oscillator and eventually beat down the reflected signal, the local oscillator needed to be very stable, and ideally, to follow any variations in the transmitter frequency.[17] Although local oscillators based on the klystron were widely used in early radar equipment, their use in transmitters was still clearly limited due to the restricted power in the case of microwaves.

5. The Cavity Magnetron

As in the United States, an intensive interplay of science, government, and military authorities was the basic feature of British radar development. In the autumn of 1939 the British Coordination of Valve Development Committee, which acted on behalf of the Army, the Navy, and the Air Force, assigned contracts to the universities of Birmingham, Oxford, and Bristol for the development of valves functioning at a wavelength of 10 cm. An important part of this interaction between science and the military was the effort of the group of physicists working with Mark Oliphant at the University of Birmingham, mostly under contract with the admiralty.[18] Although Oliphant's laboratory was dedicated to nuclear physics and to the design of a cyclotron, the outbreak of World war II and the secret deployment of a chain of radar stations at the coast made research in the field of transit time electron tubes an urgent need starting in 1939. Here too - as mentioned before - the klystron was a candidate as an advanced electron tube. However, it was not the klystron group that experienced the breakthrough in British radar development. They struggled with focusing a "reasonable" beam current through the klystron cavities and drift tube. Disappointed by unsuccessful attempts to develop Barkhausen-Kurz tubes as receivers and to excite cavities by gas discharge tubes, Henry A. H. Boot and John T. Randall concentrated on what they thought to be the more favorable geometry, namely the geometry of the magnetron. But Randall's and Boot's development of the cavity magnetron obviously was far away from straightforward scientific research.[19]

Problems in the interaction of physics and technology were all too common in the technology of valves. For one thing there were the problems of the technology of vacuum, the problem of inserting or melting metal leads into the glass bulbs, the difficulties with the seals, the degassing of electrode materials, and the choice of cathode materials. There was a whole bundle of problems in the engineering and production of electron tubes. These problems had an enormous impact on the stability of the discharge process, on the efficiency, and on the durability of the tubes. On the other hand the early publications of Owen W. Richardson on the emission of electrons by hot metals more frightened than convinced engineers of the wisdom of a technology based on vacuum techniques and on electron emission. Later theoretical physicists disturbed engineers with their continuous reformulation of Richardson's equation for the saturation current, dependent on the voltage applied to the anode. So it is not at all surprising when the physicist Hans Rukop, who was the head of the development of valves in the Telefunken company, felt a real "anti-physical" spirit among his engineers.[20] Even when the transistor became available the critical assessment of Richardson's law for the emission of electrons had not come to an end.

Hartmut Petzold put it the other way around.[21] He pointed out that despite the fact that the theoretical explanation of electron emission continuously changed, engineers were able to come to the right conclusions and, moreover, the industry was able to establish a full grown mass production of electron tubes. Sociologists Wolfgang von den Daele and Peter Weingart[22] stressed the fact that sciences even if they have not yet developed any mature theory have enormous technological potential. Obviously one can achieve much more in engineering than in explaining a field theoretically, especially if one is concerned with the improvement of an existing technological system and not with the creation of a completely new system. The reason is the close relationship between experiment and engineering. Experimental science is able to produce technology without theory. Moreover, even in a full grown science with a perfect interplay of experiment and theory the further development of technology still may depend on the experimental methods of trial and error.

This method of trial and error was clearly used by Randall and Boot in inventing the multicavity magnetron. On one hand they wanted to confine the radio frequency fields in resonators, as was the case in the klystron. On the other hand they "felt" that a compact magnetron like metal structure with their high conductivity for electric currents and for heat might be appropriate to "dissipate" the heat resulting from the desirable high power. In general the magnetron consisted of a massive copper cylinder as an anode, and of a concentrically inserted hot cathode. Decisive for the functioning of the tube was, however, a homogeneous static magnetic field parallel to the axis of the cylinder. Trying to refine this basic structure by introducing six cavity resonators, Randall and Boot started from very simple physical models.[23] Obviously in an extension of Hertz's circular wire resonators, using a gap as a detector, Randall and Boot shaped the cavity resonators as cylinders connected with slots to the central bore of the anode block. From H. M. Macdonald's 1902 book on electromagnetic waves they took the ratio of the resonant wavelength and of the diameter of Hertz's wire loop resonator, namely 7.94.[24] As Randall and Boot wanted to produce microwaves in the region of 10 centimeters they gave the cavities a diameter of 1.2 centimeter. Even using mere tungsten wires as cathodes, and not, as was known from the French development, large oxide cathodes, the evacuated tube worked. Moreover, the oscillations were extremely powerful from the beginning. Rough estimates were in the range of several hundred, or more precisely of 400 Watts. The only explanation at first seemed that the oscillation was not really producing microwaves but metric waves. However, measurements of the wavelength with help of Lecher wires revealed a wavelength of 9.8 centimeters.[25]

In two ways Randall and Boot were lucky with their intuitive development of the cavity magnetron. For one thing they circumvented a detailed study of the work which had already been done in the field of the magnetron.[26] Also they were not aware of the problems of sudden changes of modes of oscillation of the tube. So it seems appropriate to discuss in more detail the mechanism of operation of the magnetron.

6. Modes of Operation of Magnetrons[27]

As early as 1921 A. W. Hull in the United States analyzed the trajectories of electrons in a cylindrical diode in the presence of a magnetic field parallel to the tube's axis.[28] Hull, who undertook experiments at the General Electric Company's laboratories around 1925, utilized the tube not only as a magnetically controlled switch but also as an amplifier and an alternating current generator. But only August Zacek of Prague and independently Hidetsugu Yagi in Sendai, Japan, were able to introduce the magnetron into high-impedance and low-loss resonant circuits and thus produce microwave energy. The mode of operation of these tubes was what has come to be known as cyclotron oscillation.

A much more stable and efficient mode of operation of a magnetron with a segmented anode is the so-called negative resistance type, which refers to oscillations due to negative resistance type parts in the characteristic curves of gas discharges like in the glow discharge. In the case of a split anode magnetron, a potential difference is set up between the two segments of the anode. Consequently the current going to the anode segment of the lower potential increases, and vice versa, the current going to the anode segment with the higher potential decreases. If an oscillating circuit of suitable damping is connected to the anodes this characteristic curve gives rise to the desired oscillations. This negative resistance mode of operation depends on a marked increase in the strength of the magnetic field and of a division of the cylindrical anode into a split anode. Erich Habann of Jena in his 1924 doctoral thesis, a theoretical study, analyzed this new mode of operation proposing the cylindrical anode be cut into two segments.[29] In 1927 K. Okabe, a co-worker of Yagi, utilized the split anode magnetron as a generator producing 40 centimeter waves.

What eventually has proved to be the most effective mode of operation is a third type of oscillations, namely the rotating field or the traveling wave oscillations. In 1934 K. Posthumus, working at the Natuurkundig Laboratorium ("Nat Lab") of the N. V. Philips Gloeilampenfabrieken at Eindhoven developed a four segment split anode magnetron. In his theoretical explanation of his magnetron, Posthumus pictured the electronic nature of the oscillations as an interaction mechanism between the electrons and the tangential component of a traveling wave of the radio-frequency.[30] The rotating field's velocity is basically equal to the average velocity of the electrons. There occur, however, electron motions such that the sign of the rotating field and consequently the sign of the tangential force acting on the electrons is retarding. This is precisely the mechanism of the electron's transfer of energy taken from the d.c. potential source to the oscillation and inevitably also to the thermal energy of the anode. In 1937 F. Herriger and F. Hülster, working in the Telefunken-Laboratorium, pointed out that the radial component of the rotating traveling field keeps the electrons in proper phase for the interaction with the radio frequency field.[31]

A great number of engineers in the English speaking countries, e.g. E. G. Lindner, C. W. Hansell, C. W. Rice, and A. L. Samuel contributed to research and development in the field of magnetrons, as was the case in Japan, Russia, Czechoslovakia, and in France.[32] Although there were also remarkable activities in Germany, particularly at the Telefunken laboratories,[33] the cessation in the development of centimeter wave devices in 1940 caused a delay which could not be overcome before the end of the war.[34]

Despite the existence of highly coordinated research and development in the English speaking countries these activities led only to the generation of a general understanding of the mechanism of oscillation of the magnetron at first. Not really influenced by the somewhat confusing discussion on operating mechanisms of magnetrons, Randall and Boot at the University of Birmingham, as we know, achieved a direct breakthrough with their invention of the cavity resonator magnetron. They knew of some bad experiences in the development of the Barkhausen-Kurz tubes as detectors for microwave radar systems, and of some of the shortcomings of klystrons. With regard to magnetron operation they found Posthumus's theory of rotating electric fields and traveling waves "most acceptable", and they utilized the basic features of Hertz's experiments with wire loop resonators in a very intuitive way.[35] Obviously they did not consider the multitude of resonance frequencies in a cavity resonator.[36] And, as mentioned already, they were very lucky that the instability brought about by oscillations on different modes did not affect the further development in the laboratories of the British General Electric Company at Wembley until some time after the Birmingham experiments had indicated good stability.[37]

By mid 1941, during the production and early use of the eight cavity magnetron NT 98 and of other early cavity magnetrons, instabilities were observed. Certain tubes in one production lot did not oscillate at the expected frequency and suffered from a loss in efficiency.[38] Moreover this mode jumping seemed to set an upper limit both to power and to efficiency. Experiments showed that contrary to the early expectations the cavity magnetrons were able to oscillate at several discrete output frequencies. In July or in August, 1941, J. Sayers at the University of Birmingham, who was earlier charged with the development of the klystron, found a solution to the problems of mode jumping.[39] Sayers found that connecting alternate segments of the anode block at one end of the tube and connecting the intervening set of alternate segments at the other end, selected among the competing modes of oscillation the desired pi-mode, in which adjacent anode segments are 180 degrees out of phase. The pi-mode is the only singlet mode and thus has the highest efficiency.[40] This empirically found connection of alternate segments by short copper wires ("straps") was called "strapping". Although strapping seemed to be an abandonment of the concept of multicavity resonators, this measure was an immediate success in the adjustment of the tubes. As was the case with the mechanism of magnetron oscillations, the effect of strapping turned out to be much more complex than just selecting the pi-mode. Actually strapping shifted the frequency of the unwanted modes away from that of the pi-mode.[41]

High frequency technology was certainly not the only reason for the victory of the Allied Forces. But no doubt radar became one of the most important fields of technology during the Second World War. The fact that the German Telefunken laboratories simply copied the British cavity magnetron found in a downed bomber near the city of Rotterdam is evidence enough of the threat of British radar and of the disaster of German radar development. The immediate development of Germany's own devices in the cm-range suffered, however, from the exhaustion of its industry and economy since 1943.[42] Only the introduction of detectors based on semiconductor devices indicated some success in catching up with British technology.[43] Although the progress of research and development in Germany's radar technology was hampered by direct interventions of the administration and by a failed science policy, the success story of radar in the UK and in the US on the other hand is no historical evidence for the model of the perfect interplay of modern science and technology. Not only was the organisation of the interplay in the context of the Second World War in the UK and in the US decisive, but so also were the enormous expenditures on research and development in the area of radar technology, especially in the US. The Massachusetts Institute of Technology's Radiation Laboratory accounted for about 25% of the total contract outlay of the Office of Scientific Research and Development (OSRD). The Army and Navy together spent $1.5 billion on Radiation Laboratory radar sets, a figure approaching the expenditures of $2 billion within the Manhattan Project.[44]

Finally, it was only after the extensive use of empirical design procedures that the theoretical investigation of the operating mechanism of magnetrons became important in suggesting ideas for new devices or for improvements in existing devices. As analytical methods of calculating electron trajectories in magnetrons were unsuccessful, the promising approach was their approximate calculation by numerical methods.[45] Most important was Hartree's method of self-consistent fields. This method starts with an - ideally good - initial estimate of the electric field in the interaction space of the tube and with the consequent calculation of electron trajectories and of a space-charge distribution. In an iterative procedure electric field, electron trajectories and space-charge distributions are recalculated until the electric field derived from the electron trajectories is the same as the field in which the trajectories were calculated.[46] But the theoretical analysis remained difficult. As a consequence of the absence of a wholly satisfactory theory of the magnetron in designing new devices, electrical engineers around 1960 still made considerable use of scaling laws, as established jointly during the Second World War by J. C. Slater and by Bell Laboratories.[47]

7. Mass Production

An important aspect of the invention of the magnetron was the production of the new device, and this was related to the problem of the interaction of science and technology. The Physics Department of the University of Birmingham was not able to match any needs of engineering and of production of the tubes on an industrial level. So, as mentioned above, it was crucial for the outcome of the war that E. C. S. Megaw of the British General Electric Company immediately adopted the results of Randall, Boot, and of Sayers.[48] The manufacture of the production version eventually was undertaken in England by the British Thomson-Houston Company, the Marconi-Osram Valve Company, and the General Electric Company.[49] But even more important was the Henry Tizard mission's transfer of the knowledge of the cavity magnetron to the United States, especially to Bell Laboratories. In cooperation with J. C. Slater of the Massachusetts Institute of Technology (MIT) Bell Laboratories established experimentally the above mentioned scaling principle. By appropriately scaling the physical dimensions and operating voltages, currents, and magnetic fields it was possible to design a multicavity magnetron operating at a shorter wavelength starting from an already successfully operating magnetron designed for longer wavelengths.[50]

One of the engineering problems solved in the United States was the proper choice of material for the cathodes. Only with the use of complicated matrix cathodes which were built with a machined nickel base, a sintered mixture of nickel powder and barium and strontium carbonates, was it possible to produce cathodes which could resist the enormous currents and frequent arcing.[51] Eventually the productive power of the production branch of AT&T, namely Western Electric, and of the Raytheon Company, made the cavity magnetron the mass produced device which was needed in the radar equipment of the Allied Forces. Important to production was the newly developed technique for hydraulically pressing the profile of the cavities and the anode bore into a cylinder of oxygen free high conductivity copper.[52] In addition the magnetron makers in the United States had advanced materials available, especially in the case of permanent magnets.[53] The combined efforts of research, development and engineering, and large scale production resulted in the manufacture of more than 100,000 magnetrons in Western Electric factories.[54] Without specifying their source, Randall and Boot even spoke of some 250,000 magnetrons supplied to the British government.[55]

8. Conclusion

In summary, the development of radar technology widely depended on the availability of fast electronic devices. Crucial for the application of radar during World War II were electron tubes oscillating at a wavelength in the range of centimeters. The success of metal-ceramic triodes, used in the decimeter range, and the failure to realize the advantages of centimeter waves delayed research and development of transit time tubes and magnetrons in Germany. On the other hand, the success of British radar technology came with the cavity magnetron as a powerful oscillator in the centimeter range. Although the cavity magnetron was created by physicists, their methods were far from directly applying science. Obviously the theoretical knowledge about the modes of operation of the segmented multicavity magnetron was very poor.

Moreover, it was not clear at first, in which wavelength range the tube might work. Decisive for the supply of the Allied Forces was the ability of Western Electric and Raytheon in the US to overcome the difficulties of the mass production of magnetrons. Thus the development of radar technology is - among other things - an outstanding example of the complex problems in the interaction of science and technology.

Acknowledgment

I am indebted to my retired colleague Herbert Döring for valuable help and for suggestions in writing this article.

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Charles Süsskind

RADAR AS A CASE STUDY IN SIMULTANEOUS INVENTION

Probably the earliest event in the development of radar was an observation of Heinrich Hertz, more than a century ago, in 1887, when he was setting up his experiment that was to confirm Maxwell's theory on the propagation of electromagnetic waves. Hertz noted that bringing any object near his set-up, even his own hand, affected his measurements; and of course he noted that a metal plane produced a reflected wave that combined with the transmitted wave into a standing wave, whose length could be measured.[1] The development of radiotelegraphy followed a few years later; so did the discovery of the electron by J. J. Thomson in 1897 and the beginning of electronics, with the invention of the cathode-ray tube by Ferdinand Braun in the same year. By the turn of the century, the directional antenna had been devised: the first patent was granted in 1899, and such antennas were used to track thunderstorms, to concentrate a weak transmitter's power in a desired direction, and to obtain a ship's bearing relative to a shore station.[2]

The developments of two prerequisites of radar thus had their start before the twentieth century had begun: radio direction finding and cathode-ray oscillography. But there were three more branches of radio technology that contributed heavily toward making radar possible: echo ranging and pulse techniques, radio altimeters, and ultra-high-frequency electron tubes.

Echo ranging got its start in experiments to confirm Kennelly's and Heaviside's postulates that there must be an ionized layer above the earth.[3] They came to this conclusion independently in 1902, to account for Marconi's success in bridging the Atlantic by wireless telegraphy in 1901; but a definitive proof did not come until 1925, when Appleton and Barnett were able to measure the height of the layer accurately.[4] Incidentally, each of these advances resulted in Nobel Prizes in physics: J. J. Thomson in 1906, Braun and Marconi in 1909, and Appleton in 1947; only Hertz was not so honored, because he tragically died very young, in 1894, two years before the Nobel Prizes were instituted. Nor were the remaining "prerequisites" so honored, doubtless because they were considered engineering (rather than physics) advances, and there is no Nobel Prize for engineering. Yet the most important was the invention of the multivibrator circuit by two physicists - Henri Abraham and Eugène Bloch - in 1919.[5] This circuit makes it possible to produce sharp single pulses of energy separated by many pulsewidths, a method that was applied by Breit and Tuve in measuring the height of the ionosphere more accurately than Appleton and Barnett had done, and independent of them.[6] And there we have one example of independent, simultaneous invention, although the methods by which the results were achieved were actually quite different in this instance.

If the height of the ionosphere could be measured by electromagnetic waves, why not the distance between two points on the earth? And how about the distance between an aircraft and the ground? That led to the development of altimeters, most prominently by Lloyd Espenschied, which played an important part in the development of radar, in particular centimetric pulsed radar.[7] But the most important single factor that retarded this development was the lack of a high-power oscillator. Vacuum-tube oscillators had come a long way since Lee de Forest had invented the triode in 1906[8] and Fritz Lowenstein had first used it as an oscillator in 1912.[9] Yet the triode oscillator tube had an important limitation: the higher the frequency (i.e., the shorter the wavelength), the smaller the tube had to be, and hence the lower its power. A high-power ultra-short-wave oscillator - the configuration needed for radar - was a contradiction in terms.

There was one candidate, an electronic oscillator that did not depend on the triode principle - the magnetron. It had been devised in America by A. W. Hull in 1921.[10] Improved versions appeared in 1924 in Czechoslovakia and in Germany,[11] in 1927, in Japan,[12] during the early 1930s in Britain[13] and again in America,[14] and in 1940 in Russia.[15] One modification, the idea of replacing the two smooth concentric cylinders of the original magnetron configuration by an outer cylinder that had cavities drilled into the outer cylinder, occurred to engineers in America, Britain, Germany, and Russia almost simultaneously. In fact, that development represents a separate instance of simultaneous invention. Some of the modified magnetrons operated at decimetric wavelengths - but alas still at minuscule powers. A really high-power microwave magnetron, at centimetric frequencies, did not appear until World War II, at a university laboratory in Britain; it was entrusted to a still neutral America to be adapted for mass production, since British electronics manufacturing facilities were stretched to their limits by 1940.[16]

Apart from the high-power magnetron, the development of the various components of a functioning radar system enumerated above is described in the open literature of the 1920s and 1930s. To be sure, the military laboratories of the several participants carried on their work in secrecy, with each laboratory convinced that it was well ahead of the others - if they gave any thought at all to their competitors. It is noteworthy that the British disclosed their success with the high-power magnetron to the Americans only with the greatest reluctance: not a few people at the top of the British chain of command thought that neutral America could not be trusted with such an important secret. The Americans in turn were so careful with their own advances that some observers say that the U.S. Army did not know very much or care very much about what the U.S. Navy was doing - and vice versa - let alone about what was going on in other countries.

But pre-war radar development was not restricted to government laboratories. Private inventors and university engineers and scientists were making individual contributions, and their counterparts in the electronics industry were also active, especially equipment manufacturers and service organizations (such as telephone companies) that saw commercial possibilities in radar. These possibilities revolved in the first place around contracts from government laboratories to devise production models of the equipment that resulted from the work of these laboratories; but in some instances the larger firms took it upon themselves to do research on their own accounts, unhampered by government restrictions. Of course the government might ultimately become a buyer - a client from which rich contracts would flow - but meanwhile the important thing was to gain an advantage over one's competitors.

So it came about that part of the early work on radar, especially maritime radar, took place in the open, with industrial firms competing for development contracts and undertaking in-house projects. A good example is the attempt to equip the French liner Normandie with a radar that would enable it to avoid the fate of the Titanic. (This example has been chosen in part because French radar developments are not otherwise treated in the present volume.)

We know that no centimetric pulsed radar to detect aircraft was possible in the mid-1930s. No oscillator was available that would produce enough power even in the continuous-wave (CW) regime, let alone pulsed. But the French were trying. Two systems were under development, both CW. One was a transmitter at metric wavelengths, developed by Pierre David for the French army; the other was a decimetric transmitter operating at 16 cm, developed by Henri Gutton for the company called Société Française Radio-Electrique, or SFR.[17] (It later became part of Compagnie Générale de Télégraphie Sans Fil, or CSF.) A test to detect flying aircraft was arranged by the French navy at Toulon in February 1935. (The French navy was more worried about an attack from Italy than from Germany.) The SFR system lost the competition -- not much power was available at 16 cm -- and the government work would henceforth be concentrated on the David system.

Since SFR had lost the government trials, it had to find another client. An obvious one was the French Line, which was readying its liner Normandie for transatlantic traffic. The French Line was a good prospect. Two months after the Toulon trials, it asked SFR to install its experimental equipment on another one of its ships, the Oregon, and make tests at 16 cm and also at 80 cm to determine whether reflections from the coastline could be detected. There was too much interference between transmitter and receiver at 80 cm; but at 16 cm, parabolic-mirror antennas with no crosstalk could be used that reached up to 8 km to get echoes. In July 1935, 16-cm equipment was installed on the Normandie.[18]

Of course, it was one thing to detect a coastline, and quite another thing to detect a ship or iceberg, let alone an aircraft. Here even the 16-cm equipment failed, because the transmitter and the receiver antennas could not be sufficiently separated on the deck of a ship; nor could the distance be measured with sufficient accuracy. SFR continued to modify its equipment for the next two years and a half, but the results were not too encouraging - until early in 1938, when a 16-cm magnetron was introduced and it became possible to locate not only ships but also nearby aircraft by a pulsed source. And that was the first centimetric pulsed radar.[19]

Now what is particularly relevant here is that this entire episode was conducted without any security precautions. Not only the trade journals in France and Britain published fairly detailed accounts of it, but because the driving force was a firm looking for customers, SFR, there was publicity from the manufacturer itself, right to the outbreak of World War II. One can find reports on the Normandie trials in Wireless World for 1935 and 1936.[20] There is fairly detailed description in SFR's own Bulletin, a French-English house organ, on "SFR obstacle detector Type D.16" in the autumn 1935 issue.[21] And once they got a pulsed 16-cm oscillator - the magnetron made available in 1938 - the SFR engineers published a fairly detailed description in an engineering journal, the Bulletin de la Société Française des Electriciens.[22] This paper appeared in April 1939, only a few months before the outbreak of World War II, after the German occupation of Austria and of Czechoslovakia. The paper was titled "Detection of obstacles in navigation in zero visibility", and the authors noted enthusiastically that "the apparatus can serve equally well for the detection of aircraft, for which it has the advantage of providing the coordinates with sufficiently high precision".[23]

We thus see that work toward the evolution of radar carried on in industrial laboratories was reported in the open literature right up to the beginning of World War II, although there is no evidence that, for example, the French work was followed with much interest in America or Germany, or that secret work being done in government laboratories was the objective of the efforts of the espionage agencies of potential adversaries. Not even allies such as France and Britain exchanged much information. Not until the spring of 1939 did these two countries exchange information and a promise to cooperate, but the cooperation did not get very far in the short time - less than a year - that France remained a combatant. There is even some evidence that the reservations that many organizations have about accepting another organization's developments played a part - what Americans call "N.I.H.", which does not stand for the National Institutes of Health, but for "not invented here".

One of the clearest examples is the behavior of the Germans after they occupied the northern and western parts of France, including Paris. They scarcely bothered to find out what progress the French government laboratories and private firms had made in radar, although they could have learned a lot. Not until after the 1940 air war we know as the Battle of Britain, which was so costly to the Germans, did they send a group of officers to interrogate the puppet government in Vichy, but they were not told much, and they never learned of the clandestine radar work that continued until they occupied the Vichy part of France as well, when all such work in France came to a stop.[24]

So much then for the common sources available to all. First, there was the published literature on what might be called the main components of radar: direction finding, the cathode-ray tube, echo ranging and pulse techniques, altimeters, UHF oscillators, all in the open literature. Second, there were the pre-war attempts at maritime and anti-aircraft radar, partly in the open literature and partly secret, but (except for British anti-aircraft radar just below the UHF range) quite primitive and certainly not in quantity production. Third, again excepting Britain, little thought had been given to operational or tactical use of radar, such as having a command network that could direct a defense against an air attack based on information from a chain of radar interceptor stations. For example, the Japanese air attack on Pearl Harbor in 1941 and the attack on the Philippines the next day were both picked up in advance by American radar, but no defense could be organized on the basis of this information.[25]

That was the situation at the outbreak of World War II. At that point, all sources of common information dried up; and of course the military laboratories never had revealed their work in the open literature, not even to their counterparts in allied countries.

Yet within a time span of a few years, before the war ended, each of the major industrialized countries - America, Britain, France, Germany, Italy, Japan, Russia - had developed radar along much the same lines separately (though not at the same rate); timely advances made on the basis of captured equipment or espionage were quite rare. To be sure, America and Britain exchanged information after 1940, and there was some technology transfer from Germany to Japan, but most of the major advances were <u>not</u> made on the basis of information obtained from abroad.

Simultaneous invention occurs when technology has reached a certain level at which the prerequisites have been achieved and the next step occurs to several minds at once. This process has not been systematically studied, yet may be important from a theoretical as well as a practical standpoint. For example, it has implication for a country's science and technology policy: how should such policy be formulated to support and encourage invention? What are the implications for education and training, for patenting procedures, for business, for international relations? These are some of the problems that support the view that simultaneous invention is a subject worthy of study; and that the history of radar presents us with an excellent exemplar.

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Hartmut Petzold

SOME PROBLEMS OF RADAR SYSTEMS HISTORIOGRAPHY

1. The Place of Radar Systems in The Historiography of Electrical Information Technology

What is the place of radar, radar systems and radar history within the descriptive and analytical history of electronic information technology? How can historians determine this place? How can they differentiate it from the telecommunication systems such as telegraphy, telephony and television on the one side, and computation and automation on the other? These problems are not trivial, and they cannot be solved by technical or axiomatic definitions. Historians, rather, have to investigate the role that radar played in society: did radar change only technological artifacts and procedures during the last fifty years or did it change the world and human society?

Articles and books on the history of radio and television, and on the corresponding inventions and developments, considered problems in an isolated fashion and in a single national context. In most cases scientists and authors ignored parallel developments in other countries, as well as the numerous relations between these different national technical projects. The historiography of computing has been devoted mostly to inventors, individual machines, families of machines, the machines of a company, or those of a nation.

The stories of telecommunication and also those of computing can be divided into the stories of the famous heroes -- no historian can ignore them -- and those of the rest. The history of this "rest" is not only a wide but an endless field. Up to the present (and probably also into the future) this history has been studied only in pieces. Its fragments must be compiled from isolated papers, essays and memoirs and some detailed sources.

Undoubtedly, most historical research on radar has focused on the Second World War, a context in which it is clear that the efforts of radar engineers and scientists could change world history. For the period through 1945, at least, some of the important radar scientists and engineers are well known. After the end of the war they were treated as war heroes. The military context and the scientific and engineering efforts of anglo-american radar have been studied only within national boundaries. However, during the war years, this pattern of research limited by national boundaries was superseded in large part by the transnational needs of the war effort.

In contrast to this, in the post-war decades the focus of the continuing development of military radar was no longer the "hot" war, but the new cold war. Historians know nearly nothing of radar developments in socialist countries. That it cannot have been marginal, they can conclude mainly from the scale of the West's response.

A particular historiographical problem of military radar systems during the cold war concerns the question of their role as an important technological part of a potential political and military threat, in contrast to their actual utilization during the war. Another problem of radar historiography since 1945 probably arises from the fact that the political historiography of cold war is still controversial. Moreover, the history of radar since 1945 is not only the history of radar systems for missile raids or defense of air raids, but also the history of radar systems for securing naval and aircraft traffic, measuring of speed of automobiles, and observing planets and stars.

Already by 1946 radar was used to observe the moon, and since 1958, when the efficiency of radar sets improved, astronomers observed other planets with radar. In 1962 they obtained echoes from Mercury, and in 1963, echoes from Mars. Much of the initial work involved only a detection of the planet and an accurate measurement of its distance from earth. Improved facilities later permitted the reception of much stronger echoes, whose range and spectral broadening revealed information on planetary surface properties and rotation rates otherwise unobservable by astronomers. The modern radar astronomers pioneered the sophisticated signal detection and spectral analysis techniques. Thus radar systems opened a new chapter in the history of modern astronomy with consequences for the history of science and the world.[1]

Obviously there is one common technological base for all branches of the electronic information technology like telephone, radio, television and computing. Part of it is radar. The common electronic technology consists of technical artifacts, material ones like components, apparatuses, networks, but also immaterial ones like procedures, methods, computer software etc. From the beginning the historical development of this common technology was determined by the individual developments of all partial systems and these technical artifacts as a result of the permanent work of an always growing number of engineers, scientists, and technocrats. For example, the definition of the radio tube arose out of some particular problems of the telephone and of wireless systems since the beginning of the century. Later the tube also became fundamental for the television, the computer, and radar. The tube allowed the emergence of new systems, and all these new systems in turn led to modifications of the old tubes. Analog mechanisms played a role with the transistors and the sophisticated digital chips and other components on one side and the new digitalized and computerized networks on the other.

I believe that one should note well the difference between the material technical artifacts and the immaterial ones. In this manner, historians can find places for "the" magnetron, "the" klystron, and all their particular modifications and types on the material side. This would include, for example, the one concrete specimen of the collection in the Deutsches Museum. I am not so sure how to divide and arrange the immaterial artifacts. Surely, computer programs, in particular radar computer programs - under the label "software" -- constitute one weighty part. Another part comprises written procedures that a number of highly qualified engineers achieved with a great deal of work, e.g. the sophisticated modulation procedure of a particular airborne radar system.

An important aspect of the historiography of radar systems, like that of some other telecommunication systems, concerns the specific connections between structures and their functioning procedures, as well as national or international, civilian or military bureaucracies of every description. Historians can study written sources on numberless networks of contracts, obligations, laws, and conditions that stamped the formation and the character of the historical artifacts. For example, the chronicler of German radar, Fritz Trenkle, reported how, since the First World War, the general problem of radio bearing, including the first sets and procedures, emerged from the general observation of radio operation of the military enemy. The technological contrast resulted also from the political and military antagonism between the states, their governments, their military commands, and their bureaucracies. It was they who assessed the possibilities and decided what was to be done.[2]

In Western Germany the Bundestag decided the technical task for the civilian aircraft traffic control in March 1953 with the "Gesetz über die Bundesanstalt für Flugsicherung" (Law on the Federal Institution on Air Traffic Control). Article One stated that this institution should be the "allein zuständige Behörde", the authority with exclusive responsibility. During these years the occupation authorities controlled the supreme power.[3] These are only two aspects of German political history that touch on the German part of the radar history. The problem of Germany's limited political sovereignty, which has been a controversial issue up to the present, played an important role in this story. The validity of the Potsdam convention and the recognition of the two German states are part of this discussion. Historians of radar in Germany, and also in Europe, must include these difficult problems of political history, which are also problems of political bureaucracies.

Conventionally, the technical history of radar presents different radar sets with a lot of data, antennas, technical connections between different radar stations, and automation of processes with computers. Between these technical aspects and the political-bureaucratic ones lies a peculiar but typical complex of instructions, plans, schedules, competences, etc., where numerous exact data are affixed. I want to designate this as one of several "abstract buildings of immaterial artifacts." These buildings were the products of the work of a large number of qualified engineers, organizers, and political bureaucrats who were usually representatives of some institutions.

Because it is so abstract, our senses cannot immediately perceive this building in its parts and as a whole. Experts needed to invent many more or less abstract methods, symbols and diagrams, to enable them to talk among themselves about these "immaterial artifacts", and also to communicate and make decisions about them with politicians and the public.

Analyzing the historical immaterial artifacts of radar, historians still work in the archives with paper records. They traditionally began their work with studies of the biographies of the individuals, companies, or political situations and continued with some unprinted but also written sources. They also have learned how to work with verbal materials. But they have not, in general, looked closely enough at material artifacts to understand all the meanings of these immaterial artifacts.

Historians can draw conclusions about historical individuals or social groups from the technical differences only in the material artifacts in technical museums. The radio receiver from a home in a typical American small town of the thirties, the telephone switchboard from a German Post office before the First World War, and the fire control radar devices from a warship in the Gulf of Tongkin - as well as their components (vacuum tubes, transistors), and the complete networks, show the mark of their inventors, military generals, political leaders, the corresponding companies, and the political bureaucracies, that were designing, manufacturing, operating, and using them. They also show the mark of the people who had to come to terms with their scrap when they were no longer useful.

The approach that starts from the analysis of some historical technical artifacts is still the less common one, even for historians of technology. This approach is beset by a number of methodological problems, and perhaps also by a certain contempt from traditional historians and social scientists. Nevertheless, I cannot see any reason in principle that historians who take this approach could not address all general questions and fields of historiography. In doing so, they could not only uncover new historical facts and arguments, but they could also show the merits of analyzing artifacts in technological collections and museums for scientific historiography which have only been used timidly by historians thus far.

2. Radar And Public Opinion: Why Has The Historiography of Radar After 1945 Been A Stepchild?

Although all electronic systems have important military connections, historians are not criticized severely if they discuss only the civilian aspects of these systems, e.g. in their representation of "the" history of radio. Obviously, radar history is an exception to this rule.

One difference between radar and the other systems is that none of the numerous variants of radar included sets that were mass produced and sold on a market to an untrained broad public, as radios or televisions were. Even today, cheaper systems for private yachts or aircraft are much more exclusive possessions than a stereo color television. Radar manufacturers aimed no sales propaganda at the general public, as television and radio manufacturers did. Additionally, because the individual consumer did not purchase radar sets, the user feed-back was filtered by some bureaucratic institutions.

The general public was told of radar's historical importance indirectly through stories and reports: for example, that wars were decided by radar, that disasters could be prevented by radar, or that they could not be prevented in the face of radar. The overriding message in these stories was that the new radar system for the new generation of military jets would cost a great deal of money. The wealthy individual of the post-war decades, who was accustomed to pay his new television at the store counter, where he got "his" receipt and "his" guarantee certificate, was compelled, through taxes, to pay for the radar set for the new "Starfighters" or "Tornadoes" of "his" air force, without being asked individually.

Connections between all telecommunication systems and some bureaucracies are obviously inherent. Radar always seemed to be much more exclusively tied to national, international, military and civilian institutions and bureaucracies, than other systems. Bureaucracies do not like public discussions with controversial results. They usually prefer mechanical deterministic rules and do not take the different opinions of the general public into consideration when they make their decisions.

3. Some Geographical Aspects of The History Of Radar

One of the questions in the history of radar, as well as in the history of telegraphy or radio, concerns its geographic dimensions and dynamics. The following example, which comes from Henry Guerlac's book[4], shows the geographical dimensions of the early U.S. radar: From 1940 until 1945 the National Defense Research Committee developed about 150 radar systems for installation on land, on shipboard, and in aircraft, for purposes ranging from early warning against enemy planes, to blind bombing, to anti-aircraft fire control. Results of the work of the members of the Radiation Laboratory came to all principal theaters of the war: to the European and Mediterranean fighting fronts, the China-Burma-India theater, and the Pacific. There was a British branch of the Radiation Laboratory, a small group in Australia, one at the Mediterranean Allied Air Forces Headquarters at Caserta, Italy, and an Advanced Service Base in Paris.

Already by 1939 there were secret radar development programs in England, France, Germany, Canada, and the USA. However there were no programs at that time in the USSR, China, Japan, or Italy. The geographical spread of American stationary radar installations was already impressive by 1942: the Army's Aircraft Warning Service had 46 installations in the U.S.A., 10 in Panama, 5 in Puerto Rico, 12 in Hawaii, 14 in Alaska, and several in the Philippines. There was a complete chain along the east coast from Maine to Key West, Florida, and another along the west coast. Other installations were in Trinidad, British Guyana, and Jamaica. There were British bases in the Bahamas. After the American occupation of Iceland in July 1941, 3 installations were erected there. Since then the radar network became more complete and grew denser permanently.

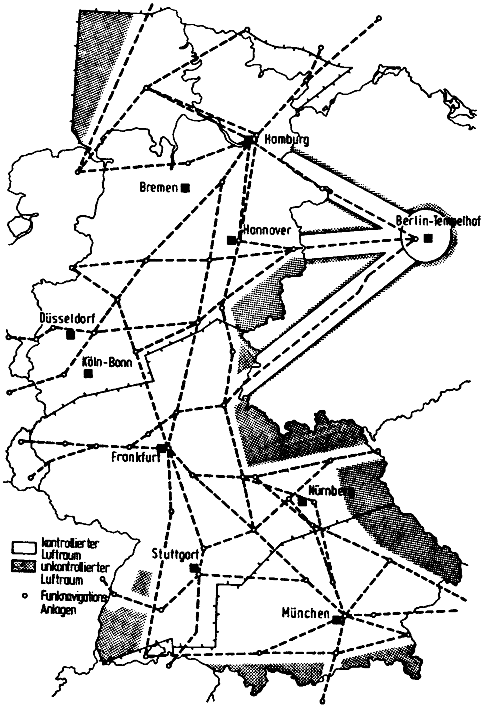
In this sense, development of radar is one part of a more general historical process by which electrical information networks came into being and grew denser geographically. It seems to be an important task for historians and particularly technical historians to describe this phenomenon, to analyze and interpret it. With a map of the world, but also with one of a smaller region, one can show how the networks grew from one historical moment to the next. Social historians can ask: what were the changes for the people living in a region before and after the radar network was established?

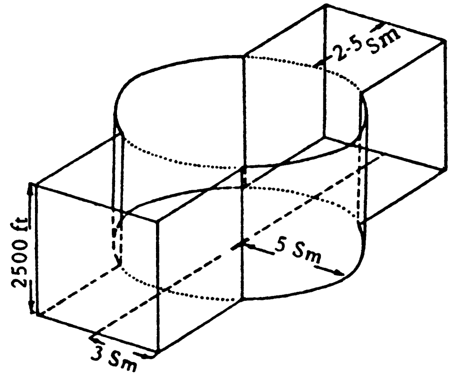
4. Some Illustrations

The following pictures from the early 1970s shall illustrate what is meant by the "abstract building." The first ten refer to the early West German aircraft traffic control.

Fig. 1: A plan of the old FRG with three corridors to West Berlin. The light regions were controlled, the dark ones uncontrolled airspace. On this geographical map one can immediately recognize a part of the border-line between the technical as well as the political systems.[5]

Figs. 2a, 2b: One can see the three-dimensional divisions of the airspace over an airport. The lines and planes are furnished with data and measurements but also with technical terms.[6]





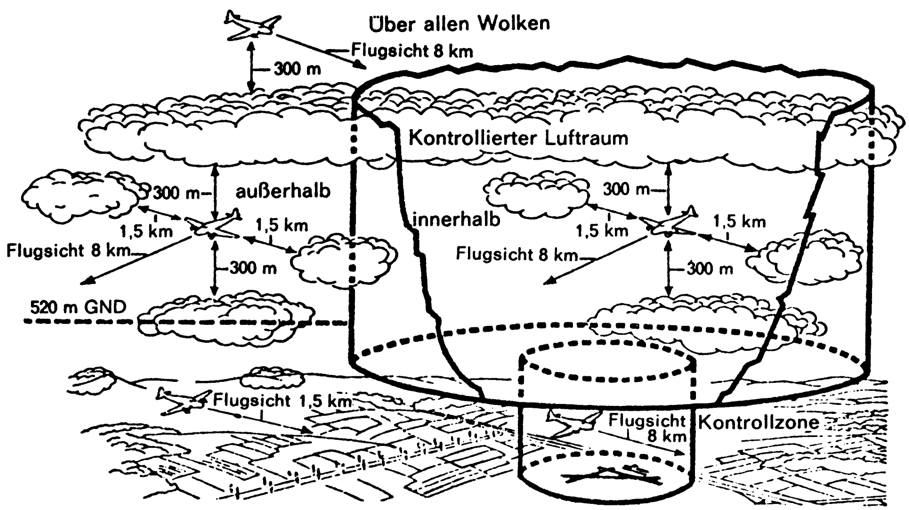


Figure 1--top left
Figure 2a--top right
Figure 2b--bottom

Fig. 3: This diagram shows the "organization" of the airspace. Such diagrams with measurements and technical terms have been critical to the management of all communication processes for some bureaucracies.[7]

Fig. 4: Aeronautical maps with their parameters. Such maps represent the organized airspace for the pilot when he is analyzing his environment by radar.[8]

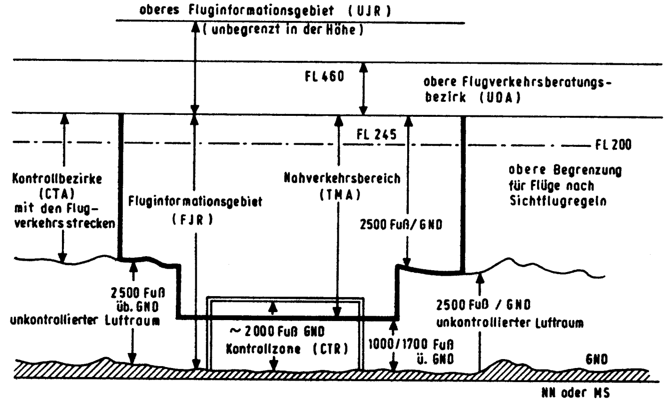
Figs. 5a, 5b, 5c: The "abstract building" includes instructions concerning what the pilots must do in situations where two aircraft must maneuver without conflicts. This picture shows the peaceful version. The military fire control by radar presents the contrary task.[9]

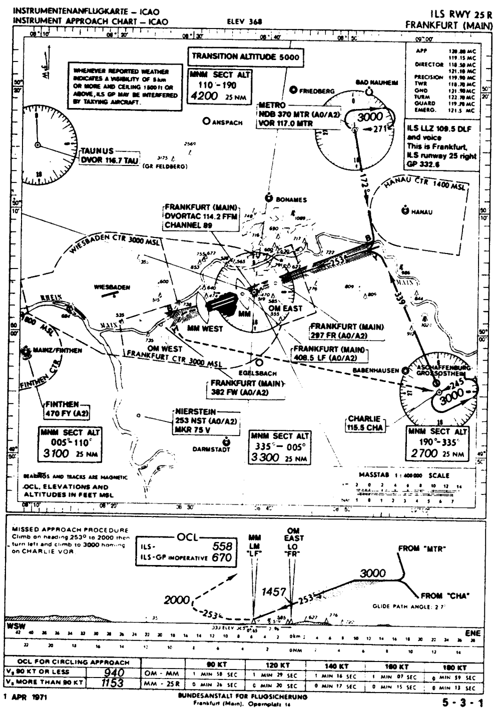
Fig. 6: In West Germany three medium radars for civilian control of air-routes (GRS-system) with ranges of ca. 220 km were installed. They were supplemented by six SRE-LL facilities. The old FRG including West Berlin - more exactly said, Berlin and parts of the GDR - were covered by this multi-radar system. The map shows the geographic plan of this.[10]

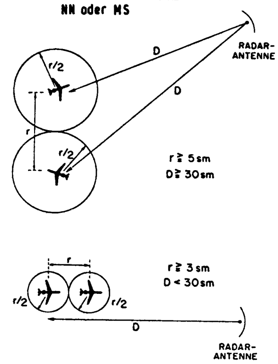
Fig. 7: Another schematic diagram of the technical system for air traffic control. There is a primary and a secondary radar, radiotelephony, diverse computers, and some cable connections with other equipment.[11]

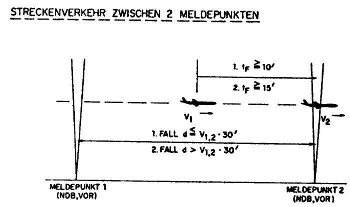
Fig. 8: Antennas represent the most impressive part of the technical system one can see, and usually its picture symbolizes the whole radar system. Here is an antenna of an Airport Surveillance Radar system used for ranges up to 100 km.[12]

Fig. 9: ... a Precision Approach Radar used for distances to 20 km ...[13]









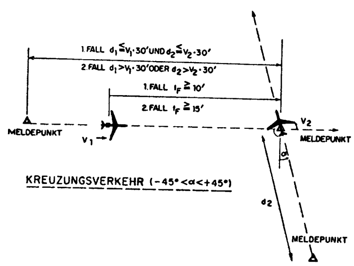
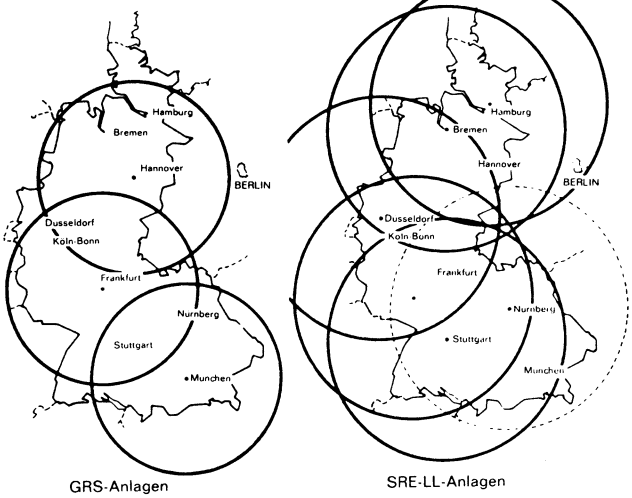
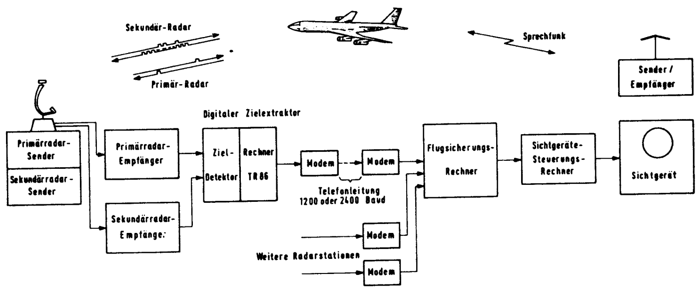
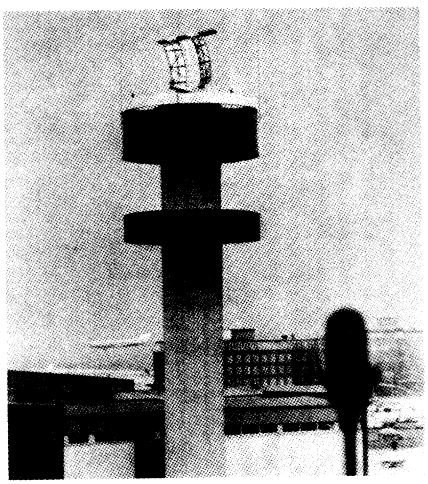


Figure 3--top
Figure 4--left
Figure 5a--right top
Figure 5b--right middle
Figure 5c--right bottom







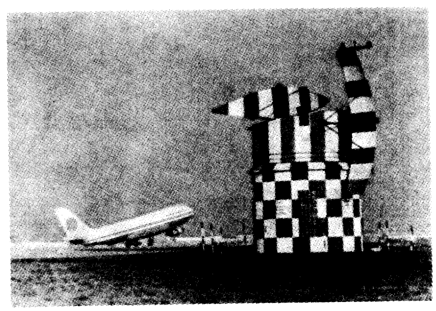


Figure 6--top
Figure 7--middle
Figure 8--bottom left
Figure 9--bottom right

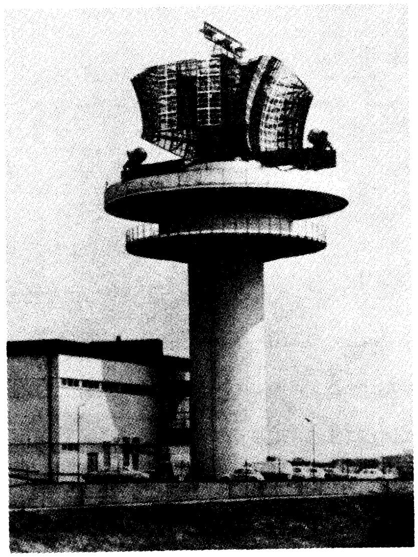
Fig. 10: ... the antenna of the medium SRE-LL equipment. Here each reflector produces one beam for low targets and one for high ones. On the top one can see the antennas for secondary radar monopulses.[14]

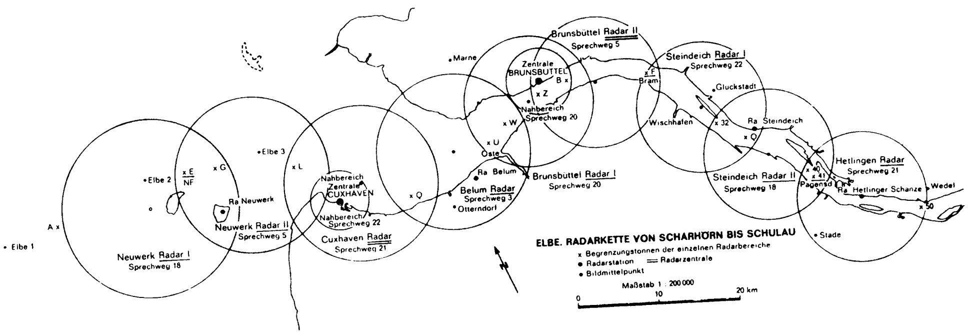
Fig. 11a, 11b: Stationary radar chains for ship control during the early seventies. The two maps show the radar coverage of the river Elbe from Hamburg to the North Sea. The radar images are transmitted to the radar central offices on cables or by directional radio. One of the main technical problems consists in the large difference in size between the smallest target, for example a seamarker or a small boat, and a giant tanker. The correct and definitive interpretation of the different echoes at the radar screen is a difficult task![15]

Fig. 12: One of the stationary antennas at St.Pauli in Hamburg harbor during the early 1970s.[16]

Fig. 13: The caption of this textbook picture from 1961 is "Carrier task force weapons systems characteristics."[17] It describes a military field. Radar historians must ask: what are the differences between civilian and military applications of radar? What is the aim of the complex weapon system? Following Clausewitz the aim is to impose one's will upon a military enemy. Another important question is: what is the moment when a political antagonist becomes a military foe? Books give various answers. There are many cases where this transformation was initiated by the surprising action of a weapon system. This is one of the dangerous aspects of all weapon systems, and it seems as it is more dangerous when dealing with more sophisticated systems.

The military situation is dissected into a defined quantity of parameters and transformed into a technical problem. Most of these parameters can be quantified - for example by radar - and become a continuous stream of input data for the diverse computers in the system.





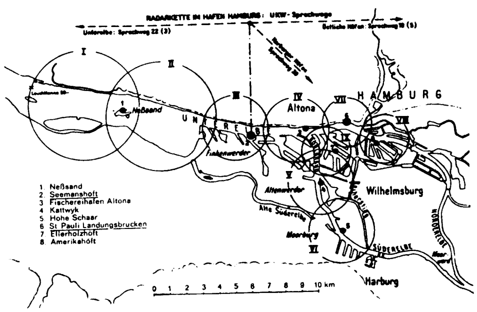
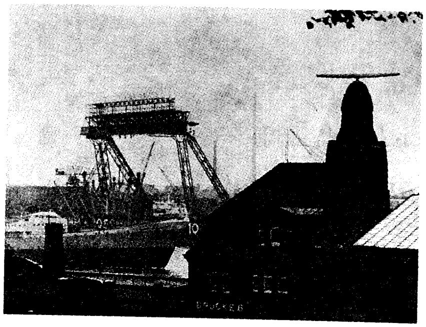
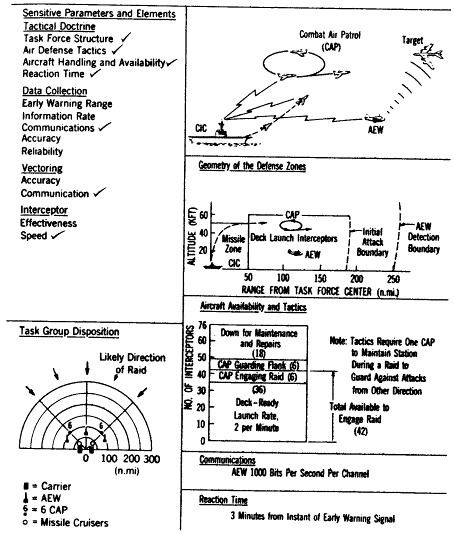


Figure 10--top
Figure 11a--middle
Figure 11b--bottom





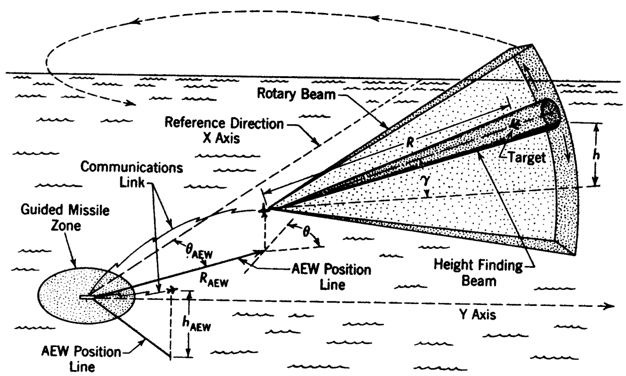


Figure 12--top left
Figure 13--top right
Figure 14--bottom

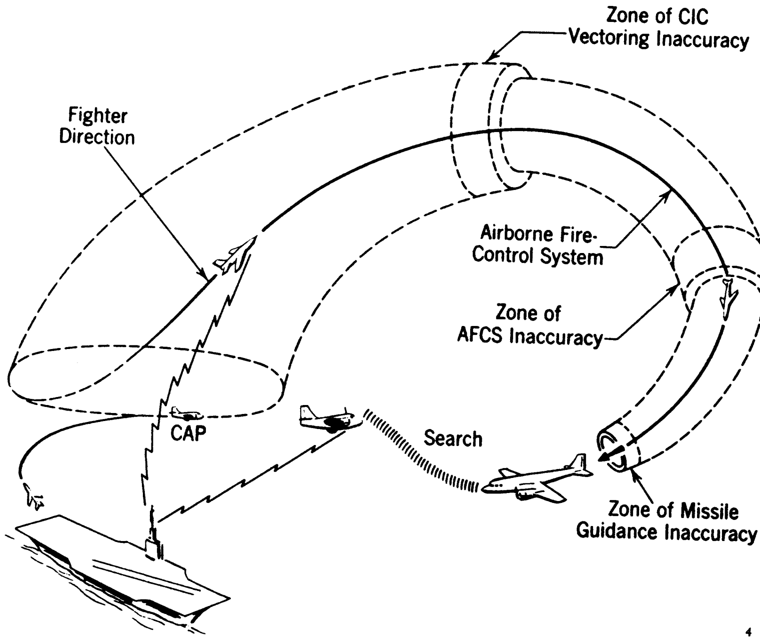
The theater includes two aircraft carriers and three missile-firing cruisers. One of the carriers is the place of the Combat Information Center. There are aircraft with airborne early warning radar. They detect the target and communicate information about it by radio to the ships and the jet fighters patrolling in the air and taking off from the carriers.

Fig. 14: A fan beam is rotated through 360 degrees while a pencil beam is nodded up and down past the target to measure height. This picture illustrates that the system technology of an airborne early warning system belongs also to the context of dynamical systems described by analytical geometry. One can detect direct connections to the tradition of this part of mathematics.[18]

Fig.15: From a textbook of military airborne radar two radar, showing systems as part of the combat tactical system: The search radar of the Airborne Early Warning aircraft and the airborne fire control system of the fighter.[19] The technical parameters from the tactical scenario determine the direction of the "improvement" of planned radar sets as well as technical innovations at the radar can change the tactics.

Fig. 16: This schematic picture shows the Tornado jet fighter, which is not only an aircraft but also a complete weapon system. The different radar sets and antennas are a constituent part of it. One can see the antennas of the forward-looking ground-following radar (1), the forward-looking ground-mapping radar (2), the IFF (Identification Friend of Foe, a secondary radar system)(3), and the radar warning receivers (4, 5).[20]

The Multi-Role Combat Aircraft Tornado is, historically, the largest armament project in Europe. This aircraft occupied politics of several western nations from the 1960s until the 1980s. It is an essential part of the history of the Cold War.



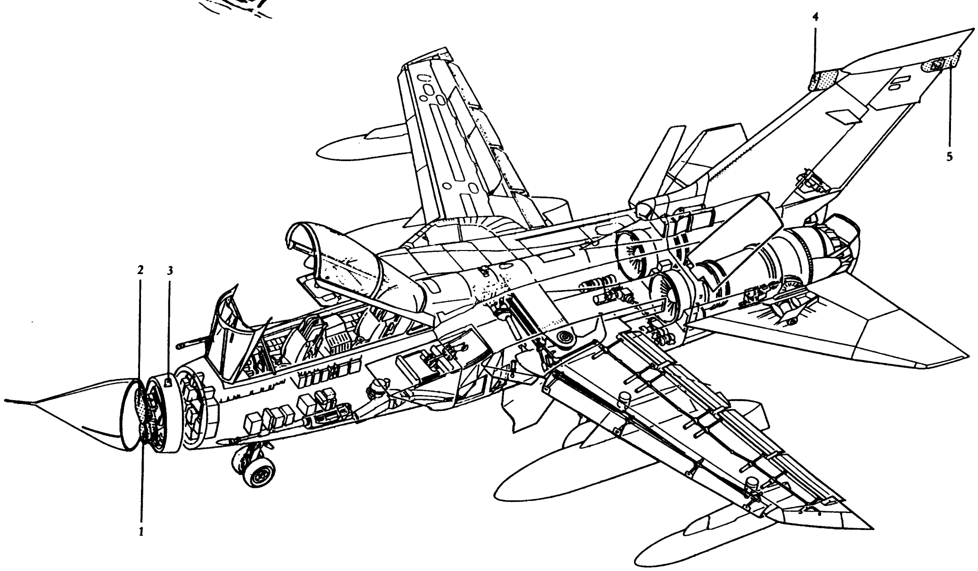
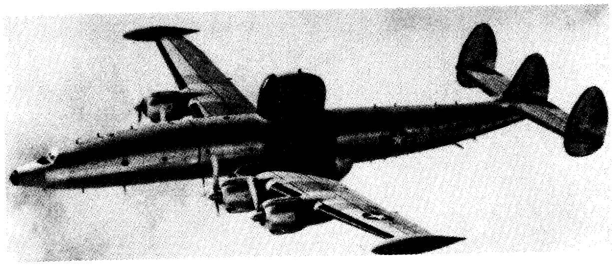
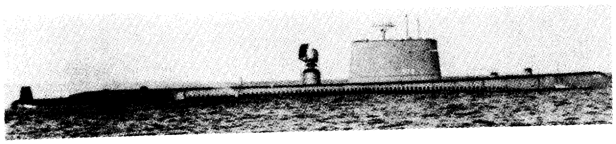


Figure 15--top
Figure 16--bottom





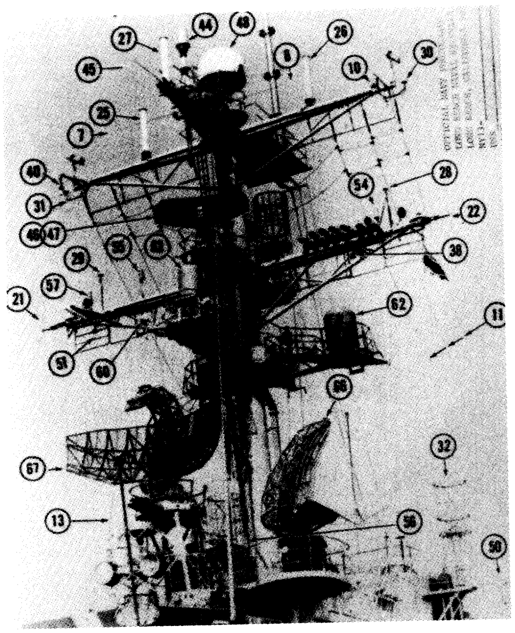


Figure 17--top
Figure 18--middle
Figure 19--bottom left
Figure 20--bottom right

Fig. 17: This and the following pictures are examples in which visible artifacts belong to large radar systems. These are the pictures the public saw and which impressed them. The deformed aircraft is one of the visible parts of an airborne radar system.[21]

Fig. 18: ... the same for a submarine radar system.[22]

Fig. 19: The antenna wood of a warship gives an impression of the large number of radio and radar systems used.[23] They include a large number of visible apparatuses inside of the ship and in other places and a gigantic cloud of diverse fields of electromagnetic waves around the antennas. The invisible part includes a large package of bureaucratic instructions and computer software.

Fig. 20: This picture of a Soviet ship in an American book can demonstrate that a photograph of an enemy warship with radar antennas can be used as the key for the knowledge of the whole radar system - and also of the unsolved technological problems.[24]

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Alan Beyerchen

ON STRATEGIC GOALS AS PERCEPTUAL FILTERS: INTERWAR RESPONSES TO THE POTENTIAL OF RADAR IN GERMANY, THE UK AND THE US

1. Terminology

It is important to open with an explanation of the terminology used here. Radar is the use of radio waves for detection and ranging, employing a variety of devices and procedures as well as serving a variety of purposes. Although civilian purposes are certainly important, my focus here is on the military purposes, especially in the period before very many procedures and devices had been brought into being.

Historians of technology sometimes choose to analyze patterns of change in phases: invention, research, development, and innovation follow one another in a complicated sequence with various feedback loops.[1] Innovation typically involves market considerations, which within military purposes are usually replaced by mission considerations. Furthermore, a distinction should be made between innovation as the spread of the new "best practice" and diffusion as a closely connected, later phase designating the spread of the new "average practice." The introduction of new military doctrine is in general closely associated with the diffusion phase.

Here it is also useful to distinguish technical, operational and technological change during each of these phases as used in this essay. "Technical change" can be understood as a matter of <u>equipment</u> or physical devices. When a new radar set or specifically designated system is mentioned, technical change is involved. "Operational change" designates the new function of sets or systems and the <u>procedures</u> for their collective employment. To envision radar as the technique of detecting targets by means of radio echoes, generating a range of devices and practices, is to focus on operational change. "Technological change" connotes the new set of parameters, that is, the new <u>context</u>, emerging from the interaction of technical and operational change with each other and with the environment. To understand radar as transforming the context of combat is to consider the logic in technological. Technological innovations are thus understood as changes in the best practices involving mission considerations in war. These distinctions are as arbitrary and overlapping--yet as useful--as the analogous distinctions among tactics, operations and strategy in military theory.

2. The Germans

The Germans emerged from World War I with the desire to alter the international status quo. Their policy was essentially a grand strategic offensive, in which aircraft, submarines and tanks--the most potent offensive weaponry to emerge from the Great War--would be key elements. Radio communication greatly enhanced the effectiveness of these weapons systems by providing a means of command and coordination of fast-moving or far-flung formations. As Tony Devereux has so aptly noted, although the Germans maintained their First World War preference for radio telegraphy aboard bombers and ships, including submarines, they placed great emphasis on equipping their single-seater aircraft and armored units with voice radio sets and radio networks to link units and echelons. They also continued to place their faith in effective encryption techniques.[2] Germany was committed to the strategic offensive, but radar was perceived as fundamentally defensive. With its potential filtered through the lens of the strategic offensive, radar received some technical, less operational, and hardly any technological attention until well into the Second World War. The Germans planned to know by radio where their forces were located. They also expected to use signals intelligence to determine the locations of enemy forces.

In terms of <u>technical</u> change, the claim to key innovation belongs more properly to the Germans than to the British. The Germans produced the broadest range of radar sets, with finer resolution, better capabilities, more rugged construction and greater versatility than anyone else before the outbreak of the war. They were also the first systematically to explore centimeter wavelengths, which turned out to be the most crucial portion of the frequency spectrum for radar developments later in the war.[3] Some of their equipment, such as the Giant Würzburg used for Ground Control Intercept, were superior to their Allied counterparts throughout the war.[4]

Yet clearly the Germans did something wrong. In fact, they did many things wrong, the most important of which was to overemphasize technical innovation and take operational and technological innovation for granted. By mid-1936 they had committed 230,000 Reichsmarks (nearly $60,000) in various Navy and Air Force projects, but these allocations pale in relation to other aspects of the their military build-up.[5] The Germans also produced a gaggle of competing agencies and research programs that did not communicate well with each other. Furthermore, for technical reasons they abandoned centimetric radar research in favor of longer waves. And they became complacent, inferring their own superiority from the technical intelligence available to them.

In some ways they were the victims of their own early successes and positive reinforcement of their preconceptions. Examples of the latter include the favorable outcome of the line of "Freya" stations in coping with the first British bombing raids, and the inferiority of a British 4 m set captured at Dunkirk.[6] Thus the Germans were encouraged to fall in the direction in which they were already leaning, toward the belief in the primacy of technical innovation. Once they woke up due to the capture of a British H_2S centimetric bombing radar set in 1943, they again forged ahead technically and began to catch up operationally and technologically, but it was too late to retrieve the situation in the closing stages of the war.

From the military point of view, the crucial development was the failure of the Germans to use technical advance to spur operational innovation and diffusion, and institute consequent changes in doctrine. Older practices were simply retained with innovative equipment long after the procedures should have been transformed. For example, when defensive, long-range "Freya" radar sets emerged as an invention from the German laboratories and then as an innovation from the manufacturers, they were viewed according to prevailing doctrine as an enhancement or replacement for the ground observer corps. R. V. Jones was in charge of assessment of German technical innovations for the British during the war. He has astutely observed:

> German philosophy ran roughly along the lines that here was an equipment which was marvelous in the sense that it would enable a single station to cover a circle of radius 150 kilometers and detect every aircraft within that range. Thus it could replace a large number of Observer Corps posts on the ground, and so was a magnificent way of economizing in Observer Corps. Moreover, where we had realized that in order to make maximum use of the radar information the stations had to be backed by a communications network which could handle the information with the necessary speed, the Germans seemed simply to have grafted their radar stations on to their existing Observer Corps network which had neither the speed nor the handling capacity that the radar information merited.[7]

The Germans thus constructed their mental image of radar within a passive operational system, in glaring contrast with the dynamic operations they conceived for other machinery of direct use to their strategic offensive. Thanks to some very perceptive individuals in key positions and an overriding sense of urgency about the need for warning about numbers and direction of impending attacks from the air, the British could conceptualize much more effective operational ways to employ their new devices.

3. The British

In contrast to the Germans, the British were on the grand strategic defensive after World War I. They placed great emphasis on signals intelligence, which had already proven its worth in that war. For this reason, they also expected their own and enemy policy to be radio silence. Radar offered a form of intelligence of great defensive value and it was perceived by the British as a technical, operational and technological response to the German threats. British radar systems became part of the technical countermeasures to aircraft and submarines. Radar employment patterns became part of the operational countermeasures to German bomber, surface warship, or wolfpack deployment procedures. And from the military viewpoint, radar's ultimate purpose was a technological countermeasure--a form of grand strategic response--to the technological changes in the mobility and velocity of combat missions made possible by the radio-coordination of enemy air and sea offensive formations.

Despite skepticism in some quarters, the British generated strong financial support for radar research nearly from its inception. By the end of 1935, their commitment was already over £100,000 (over $300,000), and by 1939 it had climbed to over £10 million. Until the invention of the resonant cavity magnetron in 1940, however, these outlays did not advance the British technically ahead of the Germans. Their primary concern was to get something in place before it was too late, and they often had to opt for what could be done at the moment rather than engineer the most versatile or well-crafted equipment.[8]

The British more than made up for the deficiencies of their systems, however, by the manner in which they employed them. Therefore, they can properly lay claim to the key innovations in terms of <u>operational</u> change. The distinction was understood and articulated by Churchill in his memoir of the Second World War. In describing the German efforts before the outbreak of war in 1939 to discover the existence of British radar, he explained:

> The Germans would not have been surprised to hear our radar pulses, for they had developed a technically efficient radar system which was in some respects ahead of our own. What would have surprised them, however, was the extent to which we had turned our discoveries to practical effect, and woven all into our general air defence system. In this we led the world, and it was operational efficiency rather than novelty of equipment that was the British achievement.[9]

This is an accurate assessment of the general situation, and displays a keen perception of the contrast between technical and operational lead in technologies, namely novelty of equipment versus effective adaptation of military thinking to perhaps less advanced devices.

By the end of the First World War, British military planners had two interlocked strategic nightmares to confront: the threat of submarines past, and the threat of bombers future. The first specter threatened to reinforce the consequences of Britain's position as an island by isolating it from the resources of the remaining world. The second threatened to destroy Britain's isolation by invasion of the skies overhead, as well as to destroy the viability of naval power on which rested defense against the submarine threat. Ultimately both would be dispelled by the employment of radar.

The initial technical response to the submarine threat was to continue the line of development laid down in the victory over the German U-boats, namely Asdics. These were systems, in Churchill's evocative words, "of groping for submarines below the surface by means of sound waves through the water echoed back from any steel structure they met" and they were "the sacred treasure of the Admiralty."[10] They would prove indispensable for meeting the submarine danger in the Second World War, but they would also prove insufficient. Ultimately airborne radar would prove crucial for anti-submarine warfare, because the aircraft could make better use of advances in electronics than the submarine, and even such radar as was available before the advent of centimetric wavelength devices made a difference.[11]

As to the other nightmare, serving officers and civilians alike believed the conservative leader Stanley Baldwin, when in November 1932 he proclaimed in the House of Commons that "the bomber will always get through."[12] Baldwin was arguing for disarmament as the only feasible response, while the Royal Air Force was committed to deterrence by means of its own bomber force. The idea was not necessarily that enemy cities would be obliterated, but that the enemy air fleet could be destroyed on the ground in the home country, along with its bases.

A critical boundary emerged between those who believed that the bomber must always get through and those who believed that it must not get through. The former included the vast majority of the RAF, for, as one writer has noted, "Since its very earliest days the belief in the offensive role of the Service had possessed religious force, with Bomber Command as the priesthood."[13] Those who sought to resist the bomber included Air Vice-Marshall Hugh C. T. Dowding, who both headed Fighter Command and served as Air Member for Research and Development. The counter-current around Dowding created the conditions for rapid phase change once a new idea emerged.

As a consequence of the tension between adherents of the bomber and of the fighter, seeing through the perceptual filters of the offensive and of the defensive respectively, the situation in England was fundamentally different than that in Germany at the time. German fighters were designed to escort bombers in total commitment to the offensive, and Hermann Göring's Luftwaffe and Four-Year Plan offices controlled much of the pace of rearmament. Compared to radio, radar remained a peripheral innovation until Germany was forced onto the strategic defensive. The situation was thus insulated from change and remained structurally stable. In contrast, Britain's fundamentally defensive grand strategy created a hearing for the defensive, no matter how overshadowed by conventional wisdom and airpower doctrine of the time.

The cascade of events in the crucial 1934-35 period, involving isolated civil servants, a small advisory committee of scientists around Henry Tizard, and the radio research scientists Robert Watson Watt and A. F. "Skip" Wilkins, has been told many times. Watson Watt was the impresario of radar, formulating the crucial proposals for it in early 1935 and energetically fostering its development thereafter. Wilkins led a small, ingenious and dedicated team, which often escaped bottlenecks by acquiring off-the-shelf components, many from the US.[14] By September 1935 the plans for completion of a line of sound mirrors along the coast were definitively scrapped.[15] The mirrors, meant to detect incoming bombers in time for evacuation of probable targets, had been a technical innovation within the context of belief that the bomber would always get through. Their obsolescence was a sign that a new context was emerging.

This is a story marked by memorable characters, but two are particularly noteworthy. Dowding was indisputably the pivotal military figure, providing the pull toward new operational developments and innovation. He took a strong personal interest in radar research and development, going up in the research aircraft to see the project's progress for himself. He also insisted that military personnel be posted right with the "Boffins," as the civilian researchers became known. This was meant to insure that the RAF personnel actually understood what was happening and that the civilians could be kept aware of military constraints and needs.[16] Furthermore, the basic tactics and requirements for night airborne interception were his own ideas.[17]

Dowding was no orthodox thinker, and perhaps understood the technological implications of radio better than any other figure in the RAF. When a few years earlier he had been in charge of fighter defenses in a summer air exercise, he quietly posted radio vans under the likely paths of incoming bombers. As the bombers passed overhead, his observers would radio the news, so he always managed to have his fighters in position to receive them (as he was to do using radar in 1940). When the umpires changed the rules on him, he decided to place a wireless on board one of his fighters (unusual for the time) and ordered it to follow the bombers back to base and radio their position--which he then attacked as the bombers were on the ground refueling, destroying the entire "enemy" force.[18] The central location that was set up for radar information and fighter control at Bentley Priory produced the kind of qualitative change that was typical of his innovative mind.

The other key figure was Tizard. In terms of the military mission, one of his most important contributions was the experiment in August and September 1936, in which the station at Bawdsey Manor was incorporated into RAF exercises focused on the Biggin Hill airfield. The exercises were meant to determine the number of interceptions that could be expected by day by using radar location and how close to a bomber it was possible to direct a fighter by ground instructions. Coordination of air warning, a filtering process for cross-referencing and assessing available information, and an efficient communications network for alerting the fighters and guiding them to their targets were developed. Although the experiment was started with only tepid support, during 1936 and 1937 Tizard gained the respect of operational commanders and the experiment generated the basic procedures with which the Battle of Britain would be fought.[19]

Tizard also realized that with Chain Home radars in place enemy bombers were likely to be driven from the day sky into the night, with consequent urgent need for airborne interception. Ground control could not "vector" fighters (a phrase that came out of the Biggin Hill Experiment) close enough to see enemy bombers at night (about 300 m). What was needed was a radar small enough to place on board a fighter, and the job of turning a room full of equipment weighing tons into a mobile rig weighing less than a man was turned over to E. G. "Taffy" Bowen, a young physicist who had been on Wilkins's initial four-man team. By September 1937, Bowen's research group had managed to invent a self-contained airborne set at 1.5 m that found the Fleet during exercises when the Coastal Command was grounded due to weather, was able to detect other aircraft, and could be used for rudimentary navigation along the coast.[20]

As war approached, radar became an ever more effective component of British defenses. By the time of the Munich crisis in the autumn of 1938, five radar stations were on line with supplementary mobile sets, and in October the filter room was opened at Bentley Priory, the nerve center of the Fighter Command defense system. The technical innovation of radar devices had given way to diffusion. Growing numbers of civilian and military personnel became familiar with the new equipment and the procedures for employing it, and even more were affected while shielded from direct knowledge of this fact by the need for secrecy. Furthermore, as more and more aircraft needed to be fitted with radar sets in the winter of 1939-40, bottlenecks formed and had to be broken with unlikely measures. One was a change in air fitness rules regarding eyesight that allowed more school teachers to become airborne radar operators. Another was a selective draft of ham radio operators to provide enough technicians to service and repair radar sets.[21] In effect, the British urgency led not only to the use of off-the-shelf components for equipment, but off-the-shelf personnel, too. Another sign of diffusion was that Bowen moved on from work concerning air-to-surface-vessel radars (ASV) for sighting surface ships, to the more sophisticated problem of detecting submarines.[22]

Operational development of radar had been completed by the outbreak of war and operational innovation was in full stride. British technological innovation was the outcome of the interaction of new equipment and procedures, and the changed context meant new parameters for both in turn. Dowding and Tizard, a military man and a scientist with the same strategic goals, were the two figures who understood earliest and perhaps best how the context of combat was being transformed by radar. Each pressed for operational development and innovation that would spur technical advance. As new devices became available, they availed themselves of the possibilities, but they did not rely on technical innovation to alter procedures and thinking. In pointed contrast to the Germans, who economized on ground observers, they perceived the full potential of radar for contesting control of the air. As R. V. Jones has reflected:

> The essential point of our radar philosophy was that it enabled us to overcome the fundamental problem of intercepting the enemy not by flying continuous patrols, which would have been prohibitively expensive, but by sending up our fighters so as to be at the right place and the right time for interception. In other words, we regarded the main contribution of radar as a means of economizing in fighters, one of our most precious commodities.[23]

It is clear that the British constructed a definition of radar in terms of controlling fighter aircraft defenses that was vastly superior to the German definition in terms of ground observer warning. But it is important here not to pass too lightly over the word "philosophy." Thinking through (or rather among) the implications of fundamental change requires an interaction of practical and philosophic bents of mind that few persons possess.

The logic of the technological innovation Dowding and Tizard perceived was a function of the velocity of contemporary combat and the German use of radio to manage faster-moving formations than could be coordinated without radio communication. They sensed the need for a synergistic response to the increased tempo of attack and defense produced by newer aircraft, and were together the innovators of the interconnected early warning system, filter room and command system. As Devereux has commented, the individual Chain Home station left much to be desired in comparison with a "Freya" station. Yet centralized control made all the difference:

> Experience has since shown that any chain of defensive radar stations gathers extra strength from being centrally linked. It is able to react more quickly and effectively. The Freya coastal chain reacted rather slowly until increasing defensive urgency compelled central linking.[24]

Dowding and Tizard understood that sound-ranging though acoustical mirrors and the single-minded deterrent strategy of Bomber Command were parts of the same logic -- a logic imposed by the perceptual filter of belief in the invincibility of the strategic offensive. Fighter Command's warning at the speed of light, timely assessment of incoming data from warning systems, and economical deployment of defenses could counteract a radio-coordinated threat with a different logic perceived through the lens of the strategic defensive. This logic would underlie British success in the air battles of 1940-41.

4. The Americans

At least until 1939, and in some ways until 1940, the Americans, like the British, had a stake in maintaining the international status quo. But they acted as if they did not realize it. In effect, American policy was one of grand strategic indifference. Lacking the offensive determination of the Germans and the defensive urgency of the British, the Americans lagged behind both technically and operationally. In the words of one historian, in contrast to the development of radar in Britain as "a definite solution to a pressing problem," radar in the U.S. began only as "a vague answer to uncertain threats."[25]

Yet the Americans were not <u>far</u> behind, due to the competitive thrust of American industry and the general technical proficiency of American researchers. Once it appeared in 1940-41 that Germany would be successful in altering the international configuration of power, the Americans lurched toward a more definitive strategy and began to accelerate technological innovation. They were finally galvanized onto the grand strategic offensive by Pearl Harbor, with marked consequences for the direction and pace of radar development that take us beyond the scope of this essay.

With successful equipment and demonstrations fostered mainly by personnel at the Naval Research Laboratory (NRL), it is clear that in the 1936-39 period the Navy perceived the value of radar. Successful demonstrations led by the summer of 1936 to increasingly higher priority for radar, and to funding perhaps on the order somewhat less than $50,000. But major pockets of doubters persisted. One of those was in the Bureau of Ordnance, whose responsibilities included fire-control systems. Effective gun-laying radars would have to use higher frequencies, preferably in the centimetric range. Aside from a liaison officer to NRL, no enthusiasm for this work could be kindled among Bureau personnel. Added to general skepticism was the concern for immediate practicality over long-term research and development, and for questions of bureaucratic turf.[26] The Army Signal Corps project had to overcome its own obstacles, but in August 1936 the Army shifted $80,000 to its radar project.[27]

In general the American effort was similar to the German, in that technical advances filtered upward from long-standing small bands of researchers. It contrasted with the specific administrative decision in the British case, and with the way the British "old boy" system of acquaintanceships cut through the kind of institutional boundaries that compartmentalized American research and allowed a Dowding or a Tizard to emerge as a centralizing figure. The American effort was also funded in competing projects on a scale closer to the German than the British in the crucial 1935-36 period. Lastly, like the Germans, the Americans had neither an airborne interception nor ASV program, and, although interested, they were not pressed by defensive necessity to explore more persistently the possibility of centimetric radar. Only with the events of 1940 did a greater sense of urgency appear.

The invention of the resonant cavity magnetron came too late to play a role in the Battle of Britain that summer, but it was just in time to play a key role in America's preparations for war. The stories of the Tizard mission in September 1940 and the erection of the Rad Lab at MIT are well known and dramatic. How well did the American military personnel and institutions adapt to these changed circumstances, in which civilian scientists would take over direction of technical and in many cases even operational innovation in military technologies? Overall, the interaction of military personnel and civilians both at the Rad Lab and out in the field was by all accounts very constructive and mutually beneficial--as it generally was in England and was not in Germany.[28]

American innovation was not just a matter of following the British lead. There were many other technical innovations traceable to American initiative, yet the greatest American contribution was perhaps technological rather than technical or operational. Although the British were also shifting from the strategic defensive and acquiring a better understanding of the offensive capabilities offered by radar (as evidenced by their development of the H_2S navigation rig for bombers), the Americans intensified the pursuit of devices and procedures that supported the strategic offensive. The new navigation techniques needed for longer-range bombing and the aggressive combination of ASV with operations research fit within an altered context for combat. So did the extensive radar countermeasures effort.[29] Yet the fact that before the Americans were officially at war there were some holdover attitudes is indisputable--the ignoring of radar warning in Hawaii on December 7, 1941, was proof enough of the persistence of older perceptual filters.

5. Reflections

The incorporation of radar into Second World War military planning and operations is a vast subject, and space precludes even a brief discussion here. Instead, I offer a few thoughts on some facets of military adaptation to the potential of radar.

The need for cross-checking with other forms of intelligence makes it very difficult to distinguish the real military effectiveness of radar from signals intelligence and other sources of information as the war began in earnest. For example, during the

Battle of Britain, intercepts of German radio transmissions were often more valuable than radar contact.[30] Also, radar was later credited with influence in the war as a cover for the more highly secret signals intelligence sources. As good as the techniques of operations research were, its reputation likewise benefited from these security priorities. Since part of the adaptation to a new technology involves learning how to gauge its effectiveness, this is a nontrivial open issue in understanding military adaptation to radar.

Another key element in such an understanding was the frequently small number of individuals at the sharp end of significant change. This fact enhanced the prospect of the disproportionate influence of chance, personality, and motivation, leading to situations where incalculably small factors were amplified to produce those macroeffects characteristic of the radar effort of a given country.

This was perhaps why the intermingling of scientists and military personnel worked as well as it did for the British and Americans. Unplanned insights and solutions emerged from their interaction. This implies the importance of both a cadre of technical talent inside military organizations and an accessible reservoir of talent outside. Furthermore, it highlights the need for permeable boundaries between types of personnel as well as conceptions, a situation difficult to maintain since bureaucracies are generally designed to seal off rather than facilitate contact across boundaries. Yet this situation did and does occur.

It may be that key actors perform their roles because they are capable of sensing the changing context and adapting to it. Some persons, such as Dowding or Tizard, were capable of looking at technical change without a focus so sharp that it cast the implications of that change into darkness. Sometimes a less intense focus offered them greater acuity for what was at the borders of their vision. This may be the best way to sense the strategic direction of complex, unstable processes characterized by positive feedbacks and phase shifts.[31]

Finally, it seems to me that strategic goals form the purpose within which technical, operational, and technological changes occur in military affairs. These goals shape and are shaped by institutions as well as the thinking of individuals, and they constitute important perceptual filters for both. Without sufficient attention to such filters, the story of radar is at best incomplete.

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Michael Aaron Dennis

ECHOES OF THE PAST: HENRY GUERLAC AND RADAR'S HISTORIOGRAPHIC PROBLEM

Henry's War

"Must have patience with these guys as they try to remember. It is rewarding." Written in a fairly legible hand, in a small, pocket notebook entitled Personal and Secret Diary, these are the word of Henry Guerlac, the MIT Radiation Laboratory's historian. Dated 14 July 1943, a Wednesday, the entry recorded Guerlac's impressions of an account of West Point's Bastille Day celebrations; his attempt to discover more about radar's role in anti-submarine warfare through a conversation with Sam Seeley; and the discussions at a Division coordinator meeting, one "with poor attendance, but interesting."[1] What was so "rewarding"? Most immediately, it was Guerlac's conversation with Seeley, who was "very slow warming up, but good after he got going." However, the phrase "these guys" refers to more than Seeley, it is a generalization from his experiences over the previous months imbibing the Radiation Laboratory's distinctive culture. Living and working in the laboratory, Guerlac was more a Malinowski among the physicists than a Ranke in the records room.

By 1944, Guerlac wrote to his employer, the University of Wisconsin, that:

> [I] enjoyed my work here immensely and feel among the undeserving favored few whose work in the war uses their peacetime abilities and conversely gives them a chance to learn more and gain more experience.[2]

Some of what Henry Guerlac learned found its way into his massive and posthumously published manuscript, Radar in World War II. Described by Daniel Kevles as "the best official history," Guerlac's manuscript has long been a resource for both historians and participants seeking to understand radar's history and wartime development in the United States.[3] Guerlac's tour in the Rad Lab even figures in the received wisdom of the history of the history of science in America. As John Heilbron explained in his 1986 History of Science Society Lecture:

> Henry Guerlac remained in front of all his colleagues, temporally speaking, without leaving the eighteenth century; it was characteristic of the discipline at the time, as well as Guerlac's own methods of work, that he did not publish, or recruit students to work on, the lengthy history of radar research at MIT that he had written as an applied historian during the war.[4]

For historians of science and technology, Guerlac's time in the Rad Lab has been, at best, a curiosity or a piece of professional trivia. The absence of a book appeared to indicate that the author, who helped establish the history of science as an American academic discipline, agreed with Heilbron's assessment on the status of "applied work." Guerlac did little to counter such beliefs. Thanking Karl Wildes for a copy of the manuscript in 1974, Guerlac observed that "I have never had a copy of my own." In his collected essays, Cornell's first professor of the history of science merely listed his two radar-related publications, but he reprinted neither.[5] An annotation to the documents describing the manuscript at the National Archives states that "the original manuscript of Radar was destroyed as soon as the typing was completed and hence it no longer exists." Although several people, including Charles C. Gillispie encouraged Guerlac to publish the manuscript, he hesitated. Even in 1985, as Tomash and the American Institute of Physics planned to publish the work, the retired professor remained "very reluctant."[6] He was unsure of who owned the copyright, uncertain as to who had written what parts of the work, and convinced:

> that it was not really history of science or technology, nor intended for the general reader. I was hired to write a government report, not to write what I consider history...too much of it is dull, dull, dull.[7]

Few would argue with that stylistic assessment, but we can take issue with Guerlac's own understanding of his past. Too much of our understanding of Radar in World War II is based upon our knowledge of Guerlac's post-war career as a student of Lavoisier and Newton. We do not know him as the author of a 1941 Harvard dissertation entitled, Science and War under the Old Regime: A Study of the

Development of Science in an Armed Society, a work far more sophisticated and exciting than much current history of science and technology. Guerlac's historiographic sensibility developed in the thirties, long before the great schism between internal and external approaches to the history of science became an invidious distinction. Nor do we appreciate the problems involved in attributing authorship to the radar manuscript. As the excerpt from his notebook reveals, the task of assembling the history was far from the world of note-taking and textual analysis. Understanding radar's history demanded more than access to documents, it was a test of the historian's ability to simultaneously live with, and apart from, his subjects. Furthermore, we fail to ask why was a historian in the Radiation Laboratory? What was the connection between Guerlac and others, like James Phinney Baxter, author of the Pulitzer Prize winning popular history of wartime research and development, Scientists Against Time? I question not the veracity of Guerlac's manuscript, but the circumstances surrounding its production. We might tell a story quite different from the received wisdom of the field and learn more about radar, the Radiation Laboratory and the history of science. More assay than essay, this paper locates Guerlac at four different sites: Harvard, the Rad Lab, the Bowman Committee, and Cornell. Radar will appear clearly in the final three, but the very framework which made understanding the new technology possible appeared in his dissertation. In turn, we can see how the importance of the history of science waxes and wanes with the fortunes of the state.

Science and War (I)

The son of a Cornell professor of French literature, Henry Guerlac was a native Ithacan, a graduate of Ithaca High School and Cornell University.[8] Graduating with a degree in chemistry, Guerlac traveled to Cambridge to work in L. J. Henderson's Fatigue Laboratory. There Guerlac's duties consisted of running on a treadmill for studies of lactic acid production; he was the control, the unathletic graduate student. Through Henderson's machinations, Guerlac found himself elected to the Harvard Society of

Junior Fellows in 1933. A new institution, the Society provided individuals with three years of funding to pursue a course of study. For Guerlac, membership in the Society occasioned a significant change of interest from the sciences to history and the history of science. Indeed, giving individuals the freedom to develop new interests and fields was one of the Society's aims; nor was Guerlac the only person to shift from the sciences to the humanities. Twenty years later Thomas Kuhn would make a similar journey. Seminars with Crane Brinton and other luminaries of Harvard's history department, as well as George Sarton, were the means through which Guerlac managed the transition from the laboratory to the library.

How Guerlac chose his dissertation topic remains unclear; even in his autobiographical essay there is no mention of the thesis, only a brief aside on his research trip to France during the summer of 1939. Nonetheless, the dissertation is a remark- able document which demonstrates Guerlac's engagement with con- temporary discussions of the relationship between science and its social context, including the work of Hessen, Bernal, Clark, Crowther, Hogben, Merton and Stimson.[9] According to Guerlac, economic depression, "the rise of Hitler, and the brigandage of Mussolini in Ethiopia and of Hitler in Spain" had produced a "sociology of science" which demonstrated "concretely how the development of science has been conditioned by economic forces, by religious preoccupations, and by the imperatives of naval expansionism."[10] Unfortunately, all of these writers had examined only one country and one time period, seventeenth century England. An anglocentric focus produced a skewed historiography. Had more attention been paid to France, especially during the eighteenth century, the "intimate connection between science and war would have attracted notice." Guerlac's thesis would:

> trace some of the influences to which science was subjected by having developed in our armed society; and to show how in certain instances the course of scientific progress was determined by the impact of military needs and by the organization of the armed state.[11]

Unfortunately, Guerlac only finished two thirds of his projected study. After 360 pages, in which he moved from Malinowski, Werner Sombert, and Francis Bacon to a discussion of the Ecole de Mézières, the pre-revolutionary French school for military engineers, the impoverished graduate student called it a dissertation. The argument was really quite simple:

> modern science developed in part at least by borrowing from practical and humble craft traditions; that these craft traditions became increasingly significant with the development of the modern state; and that among these mechanical arts the art of war played a significant role, especially through military engineering.[12]

We can translate Guerlac's framework into one closer to us in time. Charles Tilly, the sociologist and historian, observed that "war makes states," and conversely, states make war.[13] Guerlac attempted to argue a similar point in his thesis: war makes science and, in turn, science makes war. Since war and the state were inseparable, the state made both war and science. Though Guerlac tempered his claim with an acknowledgment of individual motivation and curiosity he presented a radically social vision of knowledge production, where the historian investigated the military's engineer's practice, the institutions for training engineers, the pedagogical materials used in those institutions, and the distribution of resources, including analyses of books and their publishers. To many of us, such a study might appear like something we would enjoy reading today -- I did -- but it is important to realize that Guerlac was not alone in making such arguments. Others like Lewis Mumford made similar claims and Guerlac corresponded with Edgar Zilsel, the now infamous sociologist of science, who argued for the craft origins of modern science. A 1942 essay by Waldemar Kaempffert, the New York Times science writer and a friend of Zilsel's, entitled "Science, Technology, and War," argued that the biological sciences lagged far behind the physical sciences because the later were sources of profits and weapons.[14] There was however an important difference between Guerlac and others; in the fall of 1941 he had taken up a position as an assistant professor in the history of science at the University of Wisconsin, Madison.

Before Guerlac left Cambridge, George Sarton explained that the history of science is still very much undeveloped, especially from the teaching angle, and that every teacher of it--every good teacher--is a pioneer and an adventurer.[15]

With the U.S. entry into the war on 8 December 1941, Guerlac's adventure was about to begin anew. Eager to serve, Guerlac wanted to do his part for the war effort. Before the U.S. involvement, Guerlac helped organize the Madison Free France chapter, arranging to show Casablanca to raise money. Even Sarton wanted to help win the war, suggesting that he address a "vast" enemy audience and, "lecture them slowly to death. This would beat the best devices of the Inquisition, and they undoubtedly deserve it."[16] Such a lecture series may have ended the war sooner, but it was not developed as a practical weapon, save on Harvard undergraduates. At Madison, Guerlac lectured on science and war for university faculty members involved in defense related research.[17] Perhaps this is how he obtained his position at the Rad Lab, but it is also possible that the leaders of the wartime National Defense Research Committee (NDRC) and Office of Scientific Research and Development (OSRD) were looking for a historian of science to document the new relations between researchers and their military patrons.

In January 1943, Vannevar Bush and James Conant, leaders of the wartime research and development effort, decided to hire James Phinney Baxter III, president of Williams College, as the official NDRC-OSRD historian. There were several reasons for hiring a historian. First in 1942, President Roosevelt issued an executive order to the heads of all war agencies to produce an administrative history. Second, Bush and Conant believed that the history of the OSRD and the NDRC would have "real importance in the study of the relationships which should be established upon the termination of the war." Third, as one History Office staff member explained:

> [i]t is often said that OSRD is the war agency most admired by other Washington war agencies. Perhaps it would be more accurate to say that it is the agency which

other agencies would praise first, or second only to themselves. It deserves a history worthy of its extraordinary performance.[18]

Baxter was especially well qualified for his position; in 1933 he published, Introduction of the Ironclad Warship, a work linking technological change and naval politics which was met with acclaim and is still considered a "basic modern source on the topic."[19] Baxter also had an advantage over Guerlac. As president of Williams he possessed a social standing to which Guerlac could only aspire; Baxter could grease the wheels of access for the younger historian. It was not unusual for Baxter to take potential sources to dinner at one of his various clubs in Washington, DC or Boston and lubricate tongues with wine and whiskey.[20] What was unusual was that Guerlac was the only other professional historian hired by the NDRC/OSRD. It was a sign of the importance Bush and Conant attached to the new technology, the paucity of historians of science interested in the relations between science and war, and a challenge for the Rad Lab's new employee.

What exactly did Guerlac do in the Historian's Office? For one thing, he spent only part of his day there. Although I have only read through two surviving wartime notebooks, it appears that Guerlac was quite busy. In the mornings he might work his way through records which he subsequently organized according to his own needs or he edited and wrote up the interviews he con- ducted on a regular basis with laboratory members. At lunch he often joined Rabi, Ridenour or Ed Bowles and picked up the latest laboratory gossip. Afternoons were spent on regular walks through the various Rad Lab buildings on the MIT campus, conducting interviews, gathering photographs, and insinuating himself into the everyday life of the lab. More importantly, members of the staff appear to have sought him out to outline their views on the work underway in the various divisions as well as laboratory events in general. Guerlac had access to everything that went on at the Rad Lab; indeed, he sat in on the Steering Committee meetings. What is striking about Guerlac's field notes is their richness and the absence of such riches in any version of the Radar manuscript. For example, in his entry for 16 November 1943, Guerlac describes a lunch with Loomis, who carries on about two things -- the postwar plans for the Radiation Laboratory and Project Y. According to Loomis, the military would take over the lab, turning it into a permanent service microwave laboratory. MIT administrators were pleased with this possible scenario. Loomis then informed Guerlac that:

> Y will probably need an historian. Project Y is drawing many of the best nuclear physicists, partly Loomis feels, because they don't dare stay away. So many advances in nuclear physics will result from Y that anyone not in it will feel the difference. After the war, Rad Lab physicists--for example--will be far behind.[21]

Here we have two important claims. As we know, the Radiation Laboratory disbanded after World War II, replaced to some extent by MIT's new Research Laboratory for Electronics. What happened to the plan mentioned by Loomis? Was there a debate among the laboratory's members on the postwar future of the institution? Such debates and struggles took place at other wartime laboratories, but Loomis' comments make a more fundamental point; a permanent service laboratory for microwave research would have been impossible to conceive before the war. By late 1943, such a plan was more than conceivable; some Rad Lab members championed the proposal. With respect to Project Y, which was Los Alamos, we get a real sense of how individuals calculated the possible postwar returns of their wartime research. Even Rabi discussed the atomic project in the Southwest with Guerlac; long before Trinity, the bomb cast its shadow on the Rad Lab.

Going Native

For anthropologists, the greatest problem of field work is the problem of going native. That is, it is altogether too easy to identify too closely with the group one is studying. Guerlac maintained his identity as a historian, but others clearly saw him as another researcher, one intrigued by the problem of supporting postwar research and development. Unlike others, who planned for the Rad Lab's future, Guerlac had an opportunity to craft an important part of Vannevar Bush's famous report, Science--The

Endless Frontier. In particular, Guerlac was a member of the Secretariat of the Bowman Committee charged with determining what the government could do to "aid research activities by public and private organizations." This was the committee which developed the instrumentality, or organization, called the National Research Foundation. What is fascinating about Guerlac's role here is two-fold. First, Rabi, a Bowman committee member, had Guerlac assigned to the Committee's secretariat. Second, Guerlac proceeded to produce a variety of reports for both Rabi and the other committee members on current debates over the postwar organization of research, especially the Wilson Committee, and an extensive report on government support of science before World War II. This is an episode which Guerlac and his admirers have never discussed, but it is a remarkable demonstration of the respect in which the young historian was held by his superiors, as well as an instance when history appeared to matter to more people than historians. Guerlac claimed in 1952 that "Paul Samuelson and I did a good part of the writing of the draft the Committee finally accepted...a report which laid down the main lines of what is now the National Science Foundation."[22] For an assistant professor, with only one publication, this was an accomplishment, but writing up Radar remained.

History and policy were related. The official histories would lend support for the support of research after the war. As Harold Hazen, head of the wartime fire control effort observed, the motivation for writing histories of OSRD activities was to produce a document which might, "convince Congress that broad support of civilian scientific research and development of national defense is a sound and profitable undertaking deserving its support."[23] The strategy was two pronged. Baxter, the official historian would produce a short and popular account which would go to press as quickly as possible. Little, Brown and Company believed that Baxter's volume would be a best seller. To acquire Baxter's volume, the publisher had to accept what the OSRD called the Long History--eleven volumes of "history" written by the participants themselves. Guerlac's history would be part of this series and published with the other volumes.

There was every expectation that Guerlac's history would appear with the others.[24] Unfortunately, the long history had problems: there was no single editor, no specified editorial policy, and as one reader remarked, "it is mediocre as history...containing vast deserts of technical detail."[25] For Little, Brown and Company, the Long History was a "grisly commercial experience."[26] Furthermore, Guerlac's history did not appear in the long series. Why?

Along with his assistant, Marie Boas, and a number of secretaries, Guerlac began drafting his account in the summer of 1945. Two problems immediately confronted Guerlac. First, there was the question of postwar employment. By the fall of 1945, Guerlac had three different offers -- from MIT, Wisconsin, and Cornell. At MIT, Guerlac proposed the creation of a program in the history of modern science--the 19th and 20th centuries. Wisconsin and Cornell both offered the author of a single publication full professorships in the history of science. It was Sarton who provided Guerlac with powerful advice:

> In Cornell (an perhaps in Wisconsin) you would be at once a respected member of the faculty, with a good chance of becoming an important one. At the MIT you would always be an outsider among technicians, somewhat like a professor of English in a conservatory of music. A kind of nuisance, tolerable or intolerable, according to the individual concerned.[27]

Second, the approach which Guerlac decided to follow, what he called the biography of a secret weapon made the task nearly impossible. A biography had to engage the problem of radar's genealogy; its wartime development in Britain and the United States; the practices and cultures of the Rad Lab, the TRE, and the British extension of the Rad Lab; and the story of radar's use in combat. Ironically, Guerlac's proposed approach resembles nothing so much as a Latourian account of science in action which follows radar from birth through its adolescence in combat. With such an expanded scope, Guerlac's text would require thousands of man-hours to complete, even though Guerlac had staff members write up various chapters which he then edited. Finally, such an expanded project would require that every military agency involved clear the manuscript. These were problems with no easy solutions; Guerlac missed the deadline for the Long History and Little Brown and Company refused to publish the volume. By 1947, already at Cornell, Guerlac investigated the possibility that the MIT Press might publish the radar book. Even MIT declined to publish the volume; Lee Dubridge, the wartime leader of the Rad Lab, observed that "it would be a great shame that in the published history of the OSRD the history of its largest single activity failed to appear."[28]

There were other attempts to publish Radar, but none succeeded. Part of the problem was that there was, and remains, no stable text. I have found at least three versions of the manuscript, all with interesting variations in emphasis. Although Guerlac claimed not to have a copy of the manuscript, he appears to have possessed at least several drafts of various chapters, especially those concerned with the origins of radar. That interest was driven by more than personal concern; during the post war period Guerlac was asked on more than one occasion to determine who had priority in inventing different aspects of radar.[29] During one of those priority disputes Vannevar Bush wrote Guerlac, noting that:

> there is so much to this whole radar matter that some time I should think it would warrant an entire book. Such a book, in fact, could be a rather attractive thing, for the ramifications of the development of radar illustrate the interaction of the development of science and its applications in a rather fascinating manner. I hope it will be done, for I think quite alot of people would welcome it.[30]

I found no reply from Guerlac.

What comes around goes around

In her magnificent éloge of Guerlac, Marie Boas Hall concluded by remembering that Guerlac had been born under Halley's comet and that in the year of his death it returned, although much diminished. Although brief, I have suggested here that a similar transit takes place in our understanding of Guerlac and his texts. Crafted as part of the interwar understanding of science and technology, Guerlac wanted us to believe that the state made radar and radar made the state. As the state which radar makes enters a new era, it is only fitting that we begin to address Guerlac's problem and solution. For as James Conant wrote to Guerlac, "the history of science is more analogous to military than political history...the trouble with the discipline of the past has been that it has influenced only an infinitesimal faction of those who might benefit from its study."[31]

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I am indebted to several archivists whose collections made this paper possible. The staff of the Cornell University Library Department of Special Collections assisted me in the use of the Guerlac Papers; Helen Samuels, Kathy Marquis, and others welcomed me at the MIT Archives; and Marjorie Ciarlante has been an indispensable guide in the OSRD records. Thanks to Mrs. Rita Guerlac for permission to quote from the Guerlac Papers.

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John Becklake

THE STATE OF HISTORICAL RESEARCH IN GREAT BRITAIN

Introduction

As the title implies, I have attempted in this paper to provide an overview of the activities in Great Britain devoted to the history of radar. I take this to cover not only academic research, but also the preservation of artifacts, archives and sites by national and private organizations. I also include in this survey some information on research and preservation work on related technologies such as thermionic devices, etc.; a knowledge of which is essential to the proper understanding of the development of radar systems as a whole.

The overall discipline of radar history in Great Britain is relatively uncoordinated, but I suspect this might also be the case in the USA and Germany. Many quite major initiatives have been undertaken here. These include the work of the Naval Radar Trust and Derek Howse to produce a publication on the history of naval radar in the Second World War, the establishment of the Historical Radar Archive in 1990 and the Communication and Electronic Trust in the 1980s, the initiatives of the Institution of Electrical Engineers in organizing various historical symposia and the work of my own establishment, the Science Museum, in building up the National Radar Collection. But these and many other ventures are often linked only by the "bush telegraph", although I suppose nearly all of them have links, however tenuous, with the Institution of Electrical Engineers.

This paper is divided into 3 main sections. In the first I survey the material evidence, the objects, that are preserved in public and private hands in Great Britain. In the second I discuss the archives and finally I consider the activities currently in progress in radar historical research.

The Collections

The value of the object for historical research has been debated almost ad-infinitum. I do not intend to continue this debate here with a list of the types of evidence that can be found in an original artefact, but I do want to make my position clear. I regard the object, not just as a piece of display material for use in an exhibition, but as a vital element of any programme of historical research with any technical pretensions. It also goes without saying that we must be extremely vigilant regarding the "restoration" of artifacts as much of the evidence originally available can easily be erased.

I make no apologies, therefore, for starting my presentation on the radar history work in Great Britain with a consideration of radar artifacts preserved in our museums, trusts and display centres. A list of the major collections is given in the Appendix. Most of these are military orientated and deal mainly with Second World War material, and there is an abundance of material in Great Britain relating to the important wartime radar developments in Great Britain and, to a lesser extent, Germany and the USA. Much of this material is, unfortunately, inadequately documented and in certain cases, for example at the RAF Museum, an airborne radar is considered as an integral part of the aircraft and does not appear in its records as a separate item.

One of the most comprehensive radar collections in Great Britain is held by the Science Museum in London. At present we are in the process of extracting the radar material from the various collections in which it has resided (Communication, Navigation, Air Transport, etc.) and cataloguing it, for convenience, as a subsection of our Electronic Component collection. It contains artifacts ranging from the equipment used in Watson Watts' Daventry experiment of 26 February 1935, through examples of Second World War radars and reputedly the first port radar installation anywhere in the world from Liverpool to civil airport surveillance and blind landing radar systems of the 1970s. We also hold a large and important collection of the individual electronic components that are the building blocks of radar. Among these are the original Boot and Randall cavity magnetron, examples of British, USA, German and Japanese magnetrons and, a recent acquisition, the Royal Signals and Radar Establishment's collection from Malvern.

The other major radar collection in Great Britain is held by the Communications and Electronics Museum. This is a Trust established in July 1984 to preserve a representative collection of civilian and military communication equipment from a merger of two major collections of a Mr. Douglas Byrne (civilian) and Dr. Graham Winbolt (military). This collection is at present stored at several sites around the country and comprises the most comprehensive collection of British, German and American radars in Great Britain. Access to all this material is not easy and is by appointment only, but I am told, and this can be confirmed by Graham Winbolt that a catalogue exists of the several hundred tonnes of equipment in the collection.

There are also many individuals, often members of the Communication and Electronics Museum Trust, who have small private collections containing radar equipment but these are too numerous to note here. Of the other collections listed in the appendix, it would be worth emphasising those at the Imperial War Museum, London and the Museum of Artillery, Woolwich. But the overall point I feel which comes out of this survey is the imbalance between military and civil radars and the low level of coherent collecting of modern artifacts.

In the context of objects and historic sites, it appears that there are several Chain Home Towers still standing at:

- Swingate, Dover - 3 masts (2 full, 1 part) but no gantries
- Great Baddow, Essex - re-erected mast will all 3 gantries
- Dunkirk, Canterbury - 1 mast, no gantries
- Stenigot, Louth - 1 mast, 2 gantries

- Bawdsey - 1 mast with lower gantry
- and there is a rumour of a mast at Great Bromley in Kent.

An original Operations Hut (empty) for Chain Home Low exists at Humberstone, near Cleethorpes.

The Archives

As indicated in the Appendix, most of the establishments that hold radar collections also contain a certain amount of written material relating to their objects. These are usually manuals and technical documents, however the most important archives are not associated with collections.

By far the largest and most important collection of archival material relating to radar resides in the Public Record Office at Kew, a suburb on the south west outskirts of London. This is the official national repository for files, reports, etc., generated by government establishments, the armed forces and parliament. Similar to the National Archives in Washington, access to the PRO is free and the records are arranged in subsets with, for example, material relating to Naval Radar in ADM 220, to airborne radar and work at Malvern in the AVIA subsets.

Another excellent source of material and pictures relating to British military radar work during and after the Second World War can also be found at the Defence Research Agency, Malvern, where much of the work was carried out. This contains the records of the establishments that have been subsumed into the Defence Research Agency - the Air Defence Experimental Establishment, Services Electronics Research Laboratory, Telecommunications Research Establishment, Signals Research and Development Establishment, Royal Radar Establishment and the Royal Signals and Radar Establishment. All the pictures and most of the reports are catalogued and convenient to access.

The third major source of written material on radar is the Communication and Electronics Museum Trust. Again, as with the objects held by the Trust, the archives are not so readily available as those at the Public Record Office or Defence Research Agency, Malvern. They are, however, extremely comprehensive and rich in material, particularly of a technical nature.

Note should be made here of the work of the two groups mentioned earlier:

- The Naval Radar Trust
- The Historical Radar Archive

These have been, and are, collecting more personal archives - notebooks, snapshots, reminiscences etc., of the men and women who developed, operated and relied on the early wartime radars.

We must mention here the vexed question of company archives. It appears that very little exists of the company records of the major British radar firms. For example, although Marconi hold a fine collection and archive relating to the original Marconi Company at Chelmsford, they have very few records relating to their radar activities. Similarly little officially exists of the Decca Company's work, except that kept in the filing cabinets of employees. GEC-Ferranti have nothing at Edinburgh, although some of their records survive at the National Museum of Scotland.

Publications and Research

As a generalisation the publications that have appeared in Great Britain from researchers or interpreters on the history of radar fall into three categories.
These are:

1. Personal memoirs from engineers who were active in the field
2. Histories of specific aspects of the story, e.g.. Naval Radar, etc.
3. The compilation of lists of historic radar sites, oral histories, etc.

Although not meant to diminish in any way the value of these outputs, I think it is true to say that there is very little academic work by trained historians being carried out in Great Britain on the history of radar.

Among the recent memoir publications, all released by Adam Hilger, are:

- Radar Days by E G Bowen (1989)
- Boffin by R Hanbury-Brown (1991)
- Echoes of War: the Story of H_2S Radar by Sir Bernard Lovell (1992)

All three authors were active in radar development before and during the war. Bowen worked at the Air Ministry Research Station at Bawdsey from 1936-40, mainly on airborne radars, before joining the Tizard Mission to the USA in 1940. Hanbury-Brown joined Bowen's team at Bawdsey in 1936 and continued radar development work during the war on ASV (Air to Surface Vehicle), IFF (Identification Friend or Foe) and night fighting systems. Both Bowen and Hanbury-Brown ended up in Australia. Lovell began work on radars at St. Athans and then Christchurch before moving to Malvern as part of the Telecommunications Research Establishment.

By the same token many of the papers to be found in the important volume, Radar Development to 1945, edited by Russell Burns and published in 1988 by Peter Peregrinus were written by those who actually participated in the radar activities they describe.

Among the general survey publications that have appeared in Great Britain over the past few years that are worthy of note are:

- Metres to Microwaves : British Development of Active Radar Components for Radar Systems 1937 to 1944 by E. B. (Brian) Callick, published by Peter Peregrinus in 1990, and
- Messenger Gods of Battle : Radio, Radar, Sonar, the Story of Electronics in War by Tony Devereux, published by Brassey's in 1990.

Two further books are due to appear in 1993. These are:

* Radar at Sea : the Royal Navy in World War Two by Derek Howse; and,
* The History of RAF Ground Radar - 1935 to 1975 by Jack Gough

The former publication, due to be published by MacMillan early in 1993, was written by Derek Howse, former Curator of Navigation at the National Maritime Museum at Greenwich, London, on behalf of the Naval Radar Trust. The Naval Radar Trust was formed in December 1986, following the need perceived by Professor J F Coates, Emeritus Professor of Engineering at Cambridge University, himself a pioneer of radio technology, to document the history of Naval Radar 1935-1945. Radar at Sea is aimed at the general reader but it is envisaged that its publication will be followed by a series of monographs on more technical aspects of the problem. The archival material containing personal notebooks, recollections, photographs, etc., acquired during the production of this book will be deposited as Class 'NRT' at the Churchill College Archives, Churchill College, Cambridge.

The second book by Jack Gough, ex-Superintendant of ground radars at the Defence Research Agency, Malvern is sponsored by the Royal Air Force and is scheduled to be published by Her Majesty's Stationery Office in April 1993.

The names of those active in academic publication on Radar History can be counted on the fingers of one hand, they include:

* Dr. Russell Burns, ex-Dean of Engineering at Nottingham University, now working on:
  a) a biography of E. Blumlein, and
  b) early history of radio proximity fuzes.

* Mr. Stephen Travis, a student at Bath University, who is working on a Ph.D. on the history of H_2S

* Dr. Richard Trim is preparing material for a book on IFF to be published by Artec House.

We also ought to include in this category the work of Dr. Sean Swords from Trinity College, Dublin, although strictly speaking he does not come from the area covered by this survey.

Conclusion

There is a wealth of material relating to the development of radar preserved in Great Britain. This material comprising objects, archives, taped interviews, etc., is kept by a variety of establishments and Trusts ranging from national institutions such as the Public Record Office and the Science Museum, which are specifically mandated to preserve such historical material, through smaller but still public funded bodies like the military museums, whose future is less secure than the national institutions, to the Trusts set up by interested individuals and which rely on volunteers and donations to keep afloat. There also appears to be in Great Britain, based no doubt on the wave of nostalgia for the period of the Second World War now that time and memory have hidden the bad parts, a large number of individuals pursuing research into the history of radar in their spare time.

In conclusion, there appear to be several messages arising from this initial survey. These include:

1. The fragmented and "lumpy" nature of historical radar research in Great Britain. The major bodies do not always know what each other holds and the work of, for example, the radar trusts appears to proceed in splendid isolation. What I feel is needed is a body, preferably an existing one, that can clearly be recognised as holding the central coordinating and information collating role for all radar history activities in Great Britain. I use the word coordinating advisedly, because I believe the last thing we need is a body with any executive powers. During the course of this survey, I kept my eyes open for such a body - one that will stand the test of time - and my instinct kept returning to the possibility of a joint alliance of the Institution of Electrical Engineers,

its S7 History Committee and its Archive Committee in collaboration with the Science Museum.

2. A certain lack of any detailed knowledge about the objects and archives even by the institutions that hold them. This is obviously not universally true and, in many cases, such as the Public Record Office, the system works very well. It was obvious, however, that many institutions, particularly where objects are concerned, treat radar as the poor relation. There are, for example, no acceptable displays of radar history in the whole of Great Britain. What is needed, at the very least, is a simple listing of all preserved radar objects in the country plus an indication of the associated archives. The Science Museum will have such a list available for its collection in about 6 months.

3. The sparsity of high quality academic research on radar history being carried out in Great Britain. This really means a massive under use of the available resources. Much work is and has been carried out on parts of the story such as IFF by Richard Trim and Naval History by Derek Howse, but very little attention is given to radar as a whole.

All however is not gloom. The objects are preserved and the archives exist. All that I feel is needed is a stimulus to document these and to use them. This stimulus could easily derive from the initiative we see here this week - to start an international collaborative radar history project.

Appendix

RADAR COLLECTIONS AND ARCHIVES IN THE UK

- The Science Museum
  Exhibition Road
  London SW7 2DD
  Contacts: J Becklake - 071 938 8095
  E Davies - 071 938 8101
  Large Collection of objects which includes electronic components as well as

complete radar systems. Mainly British and of WW2 vintage but also covers radars from other countries. Civil radars also collected including the Liverpool Port radar - reputedly the first port radar in the world. Also holds the RSRE Collection. The archives mainly comprises technical manuals.

- Communications & Electronics Museum Trust
  The Cottage
  Castle Road
  Pucklechurch
  Bristol, Avon
  Contact: G Winbolt, Chairman of Trustees - 027 582 2843
  A broad, comprehensive collection of communication equipment including radar. Contains objects mainly from the UK, USA and Germany and is especially strong in 1935-1955 technology. The archives are an extensive collection of manuals and reports not all on radar.

- REME Arborfield Museum
  Isaac Newton Road
  Arborfield Garrison
  Arborfield, Reading RG2 9LD
  Contact: B Baxter - 0734 763 567
  Small collection, mainly components but includes portable radar sets of 1970s vintage. Archives include Army usage.

- Museum of Artillery
  Repository Road
  Woolwich
  London SE18
  Contact: S Walter - 081 316 5402
  Medium sized collection of British Army radars, primarily of WW2 vintage Extensive but uncatalogued archives.

- National Maritime Museum
  Romney Road
  Greenwich
  London SE10 9NF
  Contact: G Clifton - 081 858 1167
  Representative collection of mainly civil marine radars from the period 1945 to 1973. A small amount of military material. Archives comprise of Radar instruction manuals. Uncatalogued [4 box files off].

- RAF Museum
  Grahame Park Way
  Hendon, London NW9 5LL

Contact: R Funnell - 081 205 2266 ex 210
Extensive but uncatalogued collection, mainly contained in the host aircraft. Dates from World War II through to the Valiant and Vulcan radars of the 1960s and the Bloodhound and Rapier missile radar. Extensive archives, especially as related to RAF radar stations of WW2.

- Imperial War Museum
  Lambeth Road
  London SE1 6HZ
  Contact: J Bullen - 071 416 5000 ext 5271
  Extensive collection of British military radars but also contains German Würzburg. Holds 4 radars on HMS Belfast. Large archive, includes the wartime CIOS, BIOS and FIAT reports.

- Sussex Combined Services Museum
  The Redoubt Fortress
  Royal Parade
  Eastbourne BN21 4BP
  Contact: M Moss - 0323 410 300
  One object only, the Decca Marine Radar Type 12, circa 1952-54. Used by the Army as GS No.1 Radar. There is a Technical Manual for this radar.

- National Museum of Scotland
  Chambers Street
  Edinburgh EH1 1JF
  Contact: B Major - 062 088 308
  Collection stored at East Fortune, several kilometres from Edinburgh. Small collection - main emphasis Ferranti radars - includes Lightning and Buccaneer radar. Unidentified collection of British and German wartime radar components. The archives are principally the complete set of technical drawings from Ferranti A1 23.

- Museum of Science & Industry
  Liverpool Road
  Manchester M3 4JP
  Contact: L Fitzgerald - 061 832 2244
  2 objects only - approach radar for Manchester Airport (Plessey) of 1970s vintage, and the APS 20 Marconi Radar contained in a Shackleton aircraft. Manuals for Shackleton radar.

- National Museums & Galleries on Merseyside
  Liverpool Museum
  William Brown Street
  Liverpool L3 8EM

Contact: D Williams - 051 207 0001 ex 454
Small collection relating mainly to marine radar.

- HMS Collingwood
  511 Building, HMS Collingwood
  Fareham, Hants PO14 1MS
  Contact: Lt. Cdr Legg - 0705 822 351 ex 535
  Basically an electronics and communications museum concentrating on artifacts which illustrate the development of electrical engineering in the Royal Navy. Includes a number of important radar artifacts including components from the Graf Spee, Naval 10 cm Type 271 and Type 79B of 1939. Extensive archives - mainly photographs, manuals and servicing charts.

- RAF Neatishead
  Nr. Horning
  Norwich
  Contact: Ft. Lt. Fitzmaurice or WO. Kilroy - 0692 630 930 ex 7230
  A proposed new radar museum based around the existing operations room of the station.

- DRA Malvern (formerly RSRE)
  St. Andrews Road
  Malvern, Worcs WR1 3PS
  Contact: P Trevett - 0684 895 5964
  Collection transferred to Science Museum in 1991. Extensive collection of official reports and photographs, all indexed, relating to the work of DRA Malvern and its antecedents:- RSRE, RRE, SRDE, TRE, SERL and the Air Defence.

- Public Record Office
  Rushin Avenue
  Kew, London
  General enquiries: 081 876 3444
  No objects. Official repository of British Government archives - similar to National Archives, Washington. The major source of radar archives in Great Britain.

- Institution of Electrical Engineers
  Savoy Place
  London WC2R 0BL
  Contact: L Symon - Tel: 071 240 1871
  One of the original 12 production 10cm magnetrons, as taken to the USA on the Tizard mission in 1940. The archives contain the Harry Boot papers.

- Historical Radar Archive
  Little Garth, High Street
  Scampton, Lincoln LN1 2SD
  Contact: Sqdn Ldr M Dean - 0522 730 338
  Directory of names and addresses of RAF personnel who worked on radar.
  Details of the WW2 RAF radar sites.

- Churchill Archives Centre
  Churchill College
  Cambridge
  Contact: A Kucia - 0223 336087
  Holds the papers of E G Bowen, Sir Robert Cockburn, Professor R Keynes and A K Wilkins. The archives of the Naval Radar Trust will soon be transferred.

Andrew Goldstein

SOME UNPUBLISHED U.S. SOURCES FOR RADAR HISTORY

Introduction

Radar has an extensive history that now goes back almost 100 years. In an authoritative article on developments in radar since the 1930s, radar historian David Barton identifies four stages of the technology's growth: pre-war, World War II, post-war, and modern.[1] Barton devotes most of his article to the modern period, but without a doubt, the periods that has been of greatest interest to historians are his first two, the years immediately before and during the second world war.

The availability of a rich selection of unpublished primary sources-- archives, manuscripts, and oral histories--offers good prospects for the historian interested in radar during this period. This article describes some of these sources, most of them listed in two reference guides published by the IEEE Center for the History of Electrical Engineering.[2] These resources provide a particularly inviting opportunity to the historian because there is material to support any of a number of thematic approaches to the subject. The scholar interested in technical issues can find information suitable for reconstructing the history behind specific breakthrough inventions. Those interested in the influence of institutions on technical change will be gratified to find that there are records available from each of the major public, commercial, and military organizations involved with the technology. Others who take a biographical approach will find abundant material in oral history interviews and collections of personal papers.

Pre-War

Despite the fact that engineers had achieved facility with radio wave transmission and detection by the turn of the century, it was not until the 1930s that researchers began making steady progress with radar. A flavor for the pre-history of radar can be obtained through H. L. Chadbourne's typescript "William J. Clarke and the first American radio company," held at the University of California at Berkeley. In this 1982 document, the author describes Clarke's pioneering work near the turn of the century using spark gap transmitting equipment to do radar experiments. More useful information about pre-war radar is found in two oral histories recorded with Robert Watson-Watt, the leader of the early British radar development effort. Watson-Watt's involvement in radar stemmed from his atmospheric studies, but in the environment of impending war, his work was applied to military defense. In these interviews, conducted in 1961 and 1964, Watson-Watt discusses his 1935 memorandum on radiation detection which led to the British Chain Home, a system of radar stations (they were called R.D.F. stations in England at that time) erected in 1938 to give advance warning of approaching aircraft. Watson-Watt also speaks about airborne radar, the H_2S bombing radar, and the United States' interest in radar. The Watson-Watt interviews are on deposit at Columbia University.

Klystron and Magnetron

The Chain Home stations were large installations with massive reflectors needed to accommodate the 10-meter wavelengths that the system used. Two electronic components were instrumental in shrinking radar equipment down from this unwieldy size: the klystron and the magnetron. The first of these was invented in 1937 by two brothers, Russell and Sigurd Varian. Russell, the older, more scientific, brother, recorded his thoughts in lab notebooks as he conceived of the electron-bunching principle that underlies the klystron's capability to produce microwave frequencies. Among Russell's papers on deposit at the Smithsonian are his two notebooks from the crucial days, 12 April-14 July 1937. Subsequent stages of the invention process, the development of the prototype and the securing of outside support, are explored in a pair of oral history interviews conducted by historian of technology Arthur Norberg in 1974 and 1977. Norberg interviewed Edward L. Bowles and John R. Woodyard, two electrical engineers who worked closely with the klystron in its earliest stages. Woodyard was a graduate student at Stanford where the Varian brothers worked. Bowles was a professor at MIT who reviewed the early klystron in 1937 for Sperry Gyroscope, the electronics manufacturer that the Varians turned to after the military declined to support their research. In the interviews, which are stored at the Bancroft Library of the University of California at Berkeley, the two men speak of the design of the klystron, Sperry's involvement with its development, and the refinement and use of the tube during World War II.

A different perspective on the same events can be found in the papers of William Webster Hansen. Hansen, the Stanford physicist whose work on resonance circuits is what drew Russell Varian to Stanford, developed a component called a rhumbatron that was the immediate predecessor to the klystron. Among Hansen's papers, which are on deposit at the Stanford University archives, are notes on various experiments, especially concerning radar technology, klystron development, and microwave mechanics. Other papers at Stanford, from both the physics and the engineering department, contain documents pertaining to Hansen's lab, where research on klystrons and microwave continued during the war. and letters which tell of the arrangement the university had with the Varian brothers. Also of interest is the *Klystron Survey* prepared for Sperry Gyroscope by Colemann Dodd in late 1945. This unpublished volume, kept at the Bancroft Library, includes descriptions of tubes and the comments of Sperry's customers.

In early 1940 University of Birmingham researchers Henry Boot and John T. Randall invented the cavity magnetron, capable of generating the high power (10,000 watts), and short wavelength (10cm) radio waves necessary for a compact, high-resolution radar system. It was this device, brought to the United States by a scientific information exchange mission led by H. T. Tizard, which greatly accelerated radar research in this country. The recollections of the two physicists about the research leading up to the cavity magnetron, and their impressions of contemporary work taking place in America, are available to scholars in two oral history interviews kept at the Bancroft Library.

Rad Lab and Radio Research Lab

In mid-October 1940, just one week after the Tizard mission shared its cavity magnetron secret with United States scientists, the newly-organized National Defense Research Council (NDRC) decided to establish a laboratory to experiment with radar systems that used the component's microwave output. Taking advantage of a convention of nuclear physicists scheduled for the last days of October at MIT, the NDRC pulled together top researchers from across the country to quickly assemble the core staff of its new facility--the MIT Radiation Laboratory. The Rad Lab, as it was known, became the most productive radar research organization in the world. A civilian operation run by physicist Lee DuBridge and staffed with physicists and engineers, the Rad Lab designed over 100 different radar systems during the course of the war.

Historians from the IEEE Center for the History of Electrical Engineering visited the 50th anniversary reunion of the Rad Lab, held in 1991, to record oral histories with the legendary institution's alumni. Interviews with 40 former administrators, researchers, technicians, and clerical staff were recorded to gain a technical and social picture of the lab. The interviews focused on the themes of the Rad Lab's microwave research, its interactions with the military and with industry, and the role of women at the Rad Lab. Notable figures interviewed include Nobel laureates Robert Pound, Edward Purcell, and Norman Ramsey as well as other familiar Rad Lab personalities such as Kenneth Bainbridge, Britton Chance, Ivan Getting, E. C. Pollard, and Jerome

Wiesner. The range of subjects interviewed, and the detail of the discussions with each subject, make the Rad Lab collection a suitable source for either a top-down administrative history or a bottom-up social history of this important institution. The IEEE History Center has edited and indexed these transcripts and they are available, collected together as a bound volume entitled "Rad Lab: Oral Histories Documenting World War II Activities at the MIT Radiation Laboratory."

One of the participants of this interview project, Kenneth Bainbridge, had already conducted an oral history interview in which he discussed many of the same issues. That interview, conducted in 1960, is stored at Columbia University. Apart from his work at the lab, Bainbridge calls special attention in this interview to a radar development trip he made to England in 1941.

Additional materials pertaining to the Rad Lab can be found in the collected papers Karl Compton, the President of MIT during the Rad Lab years. The collection, stored at the MIT archives, contains reports, memoranda, and committee materials documenting the activity of the MIT President and his staff. Of all Compton's activities, his involvement with the Rad Lab is particularly well covered through correspondence with figures such as DuBridge and Alfred Loomis, the chief of Division 14 of the NDRC, the body that commissioned the Rad Lab. Similarly, the papers of F. Wheeler Loomis, the lab's Assistant Director, contains official correspondence, a speech on managing the lab, and an oral history conducted in 1965. These materials are at Loomis's *alma mater*, the University of Illinois at Urbana-Champaign. In the interview, Loomis discusses his role in staffing the Rad Lab, relations with the federal government and industry, and the job of preparing the Rad Lab's history. For this latter task, Loomis engaged Cornell historian of science Henry Guerlac. Guerlac completed a large two-volume work in 1947, but for reasons outlined in Michael Dennis's "Echoes of the Past: Henry Guerlac and Radar's Historiographic Problem," the volumes escaped publication.[3] For many years, they could be found only at a few sites, in microform at the Library of Congress, for example. In 1987, however, Tomash Publishers interceded and brought Guerlac's book to public view.[4]

While the Rad Lab staff was experimenting with radar system, down the Charles River scientists at the Harvard Radio Research Laboratory were working just as hard on radar countermeasures. The Radio Research Lab was run by Frederick Terman, the well-known engineering professor from Stanford University. His personal papers, held by the library at Stanford, contain correspondence and reports relating to the operation of the lab. A different perspective on the Radio Research Lab experience is captured in on oral history conducted with one of the electrical engineers who worked there, Oswald Villard. The lab was organized under the NDRC Division 15, which was Chauncy Guy Suits. Interviews with both Suits and Villard are held by the IEEE Center for the History of Electrical Engineering. The administrative records of the lab have been deposited into Harvard's Pusey Library by the university's physics department.

In 1941 the NDRC, which oversaw both the Rad Lab and the Radio Research Lab, came under the purview of the newly created Office of Scientific Research and Development. The papers of this civilian organization contain contracts, test reports, research reports and other material relating to radar. They are stored at the National Archives and Records Administration, in Washington DC.

The Military

The military's critical role in the development of radar during the war is well documented. The U.S. Army Signal Corps, which also has records at the National Archives and Records Administration, preserved documents describing this unit's interest in radar. A former Signal Corps radar specialist, Erwin Tomash, reports first-hand the Army's experience with radar in an oral history interview now held by the Charles Babbage Institute at the University of Minnesota at Minneapolis. At Stanford University, in the Hoover Institute on War, Revolution, and Peace Archives, the papers of Oliver W. Miller, a Colonel in the U.S. Air Force, contain news releases, radio messages, printed matter, photographs, clippings, and maps relating to the development of radar and its applications in the U.S. and Canadian air defense forces, up to the early 1950s.

The Naval Research Lab (NRL), which began experimental work with radar in the early 1930s, deposited the papers of Vice-Admiral Harold G. Bowen, who directed the NRL from 1939 to 1942, at Princeton University. Among these are his papers on naval radar research. Additional material can be found in the papers of Harold R. Roess, an electrical engineer who worked on radar and antennas at the NRL. Roess's papers include correspondence, blueprints, schematic drawings, technical reprints, manuals, photos, and notes. Other sources concerning the Navy's use of radar include the papers of Edward J. Fahy, a ship's officer who issued official correspondence about radar, and those of John Monsarrat, a radar specialist aboard the USS Langley during WWII. Both of these collections reside at the Naval War College, Naval Historical Collection, in Newport, Rhode Island. Technical details of how radar was developed for, and tested on, submarines are included in the papers of Navy Officer Charles Andrews Lockwood. This collection is kept at the Naval Historical Foundation collection at the Library of Congress, Manuscript Division. The U.S. Naval Institute Collection at the U.S. Naval Institute holds a large number of oral histories conducted between 1971 and 1981. At least two of these, with Edward Ruckner and with Joseph M. Worthington, concern radar history. In addition, Harvard University holds some printed material from its Naval Training School, which might shed light on the important process of training military personnel on this new equipment.

Industry

Certain firms that played important roles in the development or manufacture of radar systems or components have also made available records pertinent to radar history. Varian Associates, the electronics company built by Russell and Sigurd Varian, has deposited the minutes of meetings, reports on subsidiary companies, catalogs and other promotional literature at the University of California at Berkeley. Sperry Gyroscope, the first company to pursue the Varian's klystron tube, has engineering department reports, patent reports, financial records, and the correspondence of General Manager J. C. Rutherford on deposit at the Hagley Museum in Wilmington, Delaware. The Babbage Institute holds oral history interviews with Frank C. Mullaney and William Butler, attesting the participation of, respectively, General Electric and RCA in radar research during the second world war.

AT&T, through its research division, Bell Laboratories, was extremely active in the area of radar. The laboratory notebooks of the numerous scientists and engineers who worked on the technology are available at the AT&T archives at Warren, NJ. Even work done before the war, such as that of waveguide pioneer George Southworth, who is represented with a collection of papers that includes a 75-page research history of waveguides, is covered in AT&T holdings. The papers of another Bell employee, Ernest Galen Andrews, consists of papers, drawings, plans, and patents relating to Andrews' work on radar at Bell. The collection is held at the Dartmouth College Library. Also, oral histories with Bernard Oliver, Charles Townes, John Pierce, C. Chapin Cutler, and Gordon Teal all touch on radar work at Bell, if only briefly. The Oliver interview is at the Charles Babbage Institute. The other four are held by the IEEE Center for the History of Electrical Engineering.

Individuals

A few other personal experiences with radar development set a valuable backdrop to the source already discussed. Ella Mae and Lawrence R. Quarles discuss the impact of wartime radar work on electrical engineering in an oral history they conducted jointly in 1977. The interview is deposited at the University of Virginia in Charlottesville. Berkeley holds an oral history, conducted in 1972, with 1951 Nobel Laureate in physics Edwin McMillan in which he discusses his work on radar at Berkeley during the war years.

Post-War

Despite the overwhelming preponderance of sources dealing with radar history during the second world war, there are still a few materials that could inform a history of the post-war period. In an oral history interview that is on deposit at the IEEE Center for the History of Electrical Engineering, physicist Marvin Chodorow concentrates on radar work at Stanford after 1947. He discusses later klystrons, and the work and personalities of his colleagues, Russell and Sigurd Varian, William Hansen, Edward Ginzon, and Frederick Terman. Chodorow has also donated to the Bancroft Library a 1960 report, co-authored with Charles Süsskind, on various kinds of microwave tubes. Vannevar Bush, who played a large role in mobilizing American science during the war, did a small amount of consulting for Raytheon after he retired in 1956. His work on the Nomad radar during this period is the subject of some of the documents in a collection of his papers held by the MIT Library. Leo Silvio Lavatelli, a University of Illinois physicist, worked on projects Quick Fix and Mink Rafax after his tenure at Los Alamos during the war. These projects were Department of Defense attempts to create tactical air control systems to provide ground control of weapons systems (primarily aircraft) in combat by utilizing advanced radar and communication equipment. The records of Lavatelli's involvement are at the University of Illinois at Urbana-Champaign. Also, the University of California at Santa Barbara, in its Romaine trade catalog collection, holds several trade catalogs of radar apparatus.

Because artifacts are a valuable scholarly resource, mention should be made of museums that collect and display items of interest to the radar historian. Beside the well-known Smithsonian National Air and Space Museum, other important facilities within the United States include the MIT Museum in Cambridge, Massachusetts, the Historical Electronics Museum in Baltimore, Maryland, the Foothills Electronics Museum in Los Altos, California. The latter of these, due to funding difficulties, has retired its permanent exhibit space.

Other Resources

In addition to all of the above-mentioned primary sources in radar history, a vast selection of analytic and synthetic writing on the subject exists in unpublished or semi-published form. Articles in newsletters published by special interest groups often contain valuable information that is difficult to find elsewhere. Some work, memoirs written by engineers or talks given at ceremonial functions, for example, do not get even this circulation. The historians at the IEEE Center for the History of Electrical Engineering keep track of this informal work and are available to guide researchers through it.

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2. The reference works are Joyce E. Bedi, Ronald R. Kline, and Craig Semsel, Sources in Electrical History: Archives and Manuscript Collections in U.S. Repositories (New York: IEEE) 1989, and Center for the History of Electrical Engineering, Sources in Electrical History 2: Oral History Collections in U.S. Repositories (New York: IEEE) 1992.

3. See Dennis's paper in the present volume.

4. Henry Guerlac, Radar in World War II (Los Angeles, CA, Tomash Publishers) 1987.

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AN ANNOTATED BIBLIOGRAPHY OF RADAR HISTORY

The published material bearing directly on the history of World War II radar development is remarkably large when one considers that there have been few attempts to evaluate and synthesize it, none that consider the whole international field. Equally remarkable is the poverty of published material for the time after 1945. The bibliography presented here makes no pretense of completeness but will serve as an introduction to the subject. It is intended primarily as a reader's guide and is limited to material that I have read or examined. There is no reference to archival collections, oral histories or other bibliographies. All has been obtained from the collections of twenty-seven libraries through inter-library loans or visits. The material is organized into twelve sections according to subject.

1. History: Antecedent, Books

Giulio Douhet, The Command of the Air. New York: Coward-McCann, Inc., 1942. A translation by Dino Ferrari of items originally published in 1921, 1926 and 1927. pp. 394, no illustrations, no index, no references. Air power enthusiasm that distorted pre-1940 military thinking with extravagant claims. It is easy to ridicule these writings, but most of his conclusions arose because he did not have to contend with radar in his thinking.

William Mitchell, Winged Defense: The Development and Possibilities of Modern Air Power -- Economic and Military. New York: G. P. Putnam's Sons, 1925. pp. 261, photographs, appendices, no bibliography. Same comments as for Douhet.

J. M. Spaight, Air Power and the Cities. New York: Longmans, Green and Co., 1930. pp. 244, no tables, no graphical material, many references as footnotes. Justifies future aerial bombardment of cities on the basis of precedence from naval bombardment. Predicts that aerial bombardment will make warfare quick and less bloody.

2. History: Antecedent, Journal Articles

J. Bion, "Le Radar," La Revue Maritime, pp. 330-346, July 1946; pp. 456-471, August 1946. A popular article of doubtful reliability. Emphasizes French work.

James E. Brittain, "The Magnetron and the Beginnings of the Microwave Age," Physics Today, pp. 60-67, July 1985. Concentrates on the work done before Randall and Boot.

Carl R. Englund, Arthur B. Crawford and William W. Mumford, "Some Results of a Study of Ultra-short-wave Transmission Phenomena," Proceedings of the Institute of Radio Engineers, vol. 21, pp. 464-492, 1933. A Bell Labs report of 3.7- to 4.7-m experiments in which the effects of airplanes were observed.

Abraham Esau and Walter M. Hahnemann, "Report on Experiments with Electric Waves of about 3 Meters: Their Propagation and Use," Proc. IRE, vol. 18, pp. 471-489, 1930. The German short wave master.

E. Gibon, "L'Evolution de la Detection Electromagnetique dans la Marine Nationale," L'Onde Electrique, vol. 31, pp. 53-64, 1951. French work before and during the War. Vichy French ships were equipped with radar but destroyed when the Germans tried to seize the fleet.

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W. D. Hershberger, "Seventy-five Centimeter Radio Communication Test," Proc. IRE, vol. 22, pp. 870-877, 1933. Reports propagation significantly beyond line of sight. The inventor of "Knickebein" may have read this. Hershberger was a key designer of Signal Corps radar.

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L. F. Jones, "A Study of the Propagation of Wavelengths between Three and Eight Meters," Proc. IRE, vol. 21, pp. 349-386, 1933. Studies in preparation for television broadcasting discloses strong interference and reflection effects.

Guglielmo Marconi, "Radio Telegraphy," Proc. IRE, vol. 10, pp. 215-238, 1922. This oft-cited review has Marconi's radar suggestion. It offers nothing that Hülsmeyer, of whom he was probably not aware, had not put into practice twenty years earlier.

C.D. Tuska, "Pictorial Radio," J. Frank. Inst., vol. 253, pp. 1-20, 95-124, 1952. Tuska was Director of patents for RCA and points out the suggestions that were in the air before the war. Describes RCA's own work.

Merle A. Tuve. See Memoirs and Biographies: Journal Articles.

I. Wolff, E. G. Linder and R. A. Braden, "Transmission and Reception of Centimeter Waves," Proc. IRE, vol. 23, pp. 11-23, 1935. Describes the microwave equipment that RCA demonstrated to the Signal Corps.

Hidetsugu Yagi, "Beam Transmission of Ultra Short Waves," Proc. IRE, vol. 16, pp. 715-741, 1928. The Japanese short wave master.

V. K. Zworykin, "Description of an Experimental Television System and the Kinescope," Proc. IRE, vol. 21, pp. 1655-1673, 1933. Hard tube cathode ray oscilloscope with electro-static focusing. One of six papers in this volume describing the first RCA television.

3. History: Specific to Radar, Books

David Kite Allison, New Eye for the Navy: The Origin of Radar at the Naval Research Laboratory, NRL Report 8466. Washington: U.S. Government Printing Office, 1981. pp. 228, photographs, numerous references. Traces radar from its inception to the outbreak of war. Details of techniques and personnel. Well told.

Ralph B. Baldwin, The Deadly Fuze: Secret Weapon of World War II. San Rafael, California: Presidio Press, 1980. pp. 332, a few photos, no references, tables. Good study of the proximity fuze. Heavily based on Applied Physics Lab archives, which misses some material.

Arthur O. Bauer, Deckname "Würzburg": Ein Beitrag zur Erhellung der Geschichte des geheimnisumwitterten deutschen Radargeräts, 1937-1945, translated from Dutch by H. Lisssok. Nesselrode Strasse 7, 4352 Herten, Germany: Verlag Historischer Technikerliteratur, no date, purchased 1992. pp. 136, drawings, photos, references, no index. Details of circuits, construction, employment and techniques used against counter-measures for all of the Würzburg models. The author has restored one to operating condition.

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Scientific Research and Development. A brief treatment of everything with obvious limitations of a 1946 perspective.

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Robert Morris Page. See Technical: Books.

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David Pritchard, The Radar War: Germany's Pioneering Achievement 1904-45. Wellingborough, Northamptonshire: Patrick Stephens Limited, 1989. pp. 240, photographs, diagrams, glossary, detailed index of radar sets and auxiliary systems. Most of this book is taken from Fritz Trenkle with ample quotations from R. V. Jones. It is useful for a long interview with Wilhelm Runge and biographical material about other German radar men.

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Albert Hoyt Taylor, *The First Twenty-five Years of the Naval Research Laboratory*. Washington: Navy Department, 1948. pp. 75, photographs, no tables, no references, no index. The extensive radar material is a condensations of Taylor's *Radio Reminiscences* (See Memoirs and Biographies: Books). There are a number of personal recollections of people and events at NRL.

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George Raynor Thompson, Dixie R. Harris, Pauline M. Oakes and Dulany Terrett, *United States Army in World War II. The Signal Corps: The Test (December*

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29 "A personal reminiscence: the beginnings of radar 1930-1934," L. A. Hyland.
35 "Early history of radar in the US Navy," R. M. Page.
45 "Dr. Henri Gutton, French radar pioneer," R. B. Molyneux-Berry.
53 "The development of UK naval radar," J. F. Coales and J. D. S. Rawlinson.
97 "The history of the Italian radio detector telemetro," M. Calamia and R. Palandri.
106 "Air defence, some problems," R.W. Burns.
132 "CH -- the first operational radar," B. T. Neale.
151 "A personal reminiscence: RDF and IFF," R. H. A. Carter.
162 "Ground control interception," F. Putlev.
177 "The development of airborne radar in Great Britain 1935-1945," E.G. Bowen.
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Wesley Frank Craven and James Lea Cate, editors, The Army Air Forces in World War II. Chicago: University of Chicago Press, 1948 to 1958. 7 volumes, photographs, tables, numerous references, glossaries. A valuable source but the poorest of the three service histories in its treatment of radar.

Richard B. Frank, Guadalcanal: The Definitive Account of the Landmark Battle. New York: Random House, Inc., 1990. pp. 800, extensive notes, references, index and tables; photographs and maps. Careful report and understanding of radar employment.

Noble Franklin, The Bombing Offensive Against Germany: Outlines and Perspectives. London: Faber and Faber, 1965. pp. 128, no references, no tables, no illustrations. A succinct and clear account of Charles Webster's and Noble Franklin's four volume The Strategic Air Offensive Against Germany.

Mitsuo Fuchida, and Masatake Okumiya, Midway: The Battle That Doomed Japan: The Japanese Story. Annapolis, Maryland: U.S. Naval Institute, 1955. pp. 266, photographs, appendices with organization and losses. The Pacific War through Midway from the Japanese and Fuchida's personal point of view.

Max Hastings, Bomber Command. New York: Dial Press, 1979. pp. 399, photographs, drawings, tables, references. The history of the strategic bombing offensive is told with chapters of straight history alternating with chapters describing the events as they affected the air crews and the German civilians.

David Irving. See Memoirs and Biographies: Books.

John Keegan, The Price of Admiralty: The Evolution of Naval Warfare. New York: Penguin Books, 1989. pp. 353, photographs, glossary of nautical terms, references. Descriptions of four crucial naval battles with a keen understanding of the technical matters. The accounts of the Battles of Midway and the Atlantic allow the evaluation of the radar contribution.

Horst-Adalbert Koch, Flak: Die Geschichte der deutschen Flakartillerie, 1935-1945. Bad Nauheim: Verlag Hans-Henning Podzun, 1954. pp. 243, many good illustrations, many tables, list of abbreviations. Air defense as seen from the point of view of the defending gunners. Useful material on origins of antiaircraft artillery.

Kriegstagebuch der Seekriegleitung, 1939-1945. Herford-Bonn: Im Auftrag des milirärgeschichtlichen Forschungsamtes, Verlag E.S. Mittler und Sohn, 1988. Photostat copies of navy monthly war diary, one volume per month, 36 volumes so far, through August 1942.

Alan J. Levine, The Strategic Bombing of Germany, 1940-1945. Westport, Connecticut: Praeger Publisher, 1992. pp. 235, bibliography. An excellent synopsis that draws almost entirely on the official histories. Does not introduce anything new of substantial importance.

Donald Macintyre, The Battle for the Mediterranean. New York: W.W. Norton and Company, 1964. pp. 216, many photographs, few references. There is no listing under "radar" in the index, but the author understood its significance, and its critical employment is described.

Martin Middlebrook and Chris Everitt, The Bomber Command War Diaries: An Operational Reference Book. New York: Viking Press, 1985. pp. 804, statistical details of raids, squadrons, bibliography. Useful reference.

Samuel Eliot Morison, History of United States Naval Operations in World War Two. Boston: Little, Brown and Company, 1947-1962. 15 volumes. The official history told by the master historian, who was often present and who appreciated radar.

S.W.C. Pack, Night Action off Cape Matapan. Annapolis, Maryland: U.S. Naval Institute Press, 1972. pp. 146, photographs, maps, nine appendices giving details of equipment, personnel, action and more. How three radar sets put an end to any threats by the Italian surface fleet.

Dudley Pope, 73 North. Annapolis: Naval Institute Press, 1989. pp. 320, photographs, no references, appendix on arctic convoys. The Battle of the Barents Sea. Graphic descriptions of radar use illustrating the strengths and weaknesses of meter-wave sets.

Alfred Price, Aircraft versus Submarine: The Evolution of the Antisubmarine Aircraft, 1912-1972. London: William Kimber, 1973. pp. 268, many photos, maps, diagrams, some references. Excellent historical treatment, mostly about World War II but with only 8 pp. on the Pacific War and 19 on post 1945 matters.

Alfred Price, Battle over the Reich. New York: Charles Scribner's Sons, 1973. pp. 208, many photographs, no references. The air attacks on Germany and the defeat of the Luftwaffe.

R.A.F. Air Historical Branch, The Rise and Fall of the German Air Force, 1933-1945. New York: St. Martin's Press, 1983 (a reprint of the classified, 1948, Her Majesty's Stationery Office edition). pp. 425, photographs, maps, tables, no index. An admiring evaluation of the enemy but with very little about radar.

J.M. Spaight, Bombing Vindicated. London: Geoffrey Bles, 1944. pp. 159, no tables, no graphical material, very few references. Obviously written to counter criticism of area bombing. His predictions of fourteen years earlier seem forgotten.

Captain Stephen Wentworth Roskill, The War at Sea, 1939-1945. Vol. 1, The Defensive (1954), Vol. 2, The Period of Balance (1956), Vol. 3, part 1, The Offensive (1960), Vol. 3, part 2, The Offensive (1961) (a part of History of the Second World War. United Kingdom Military Services, Sir James R.M. Butler, editor). London: Her Majesty's Stationery Office. photographs, maps, drawings, tables, appendices, staffing lists.

Friedrich Ruge (Translated by M.G. Saunders, R.N.), Der Seekrieg: The German Navy's Story, 1939-1945. Annapolis: United States Naval Institute, 1957. pp. 440, photos, illustrations, no references. History of the war at sea. Examines the German lack of understanding of the importance of the sea, even to a continental power, and the consequences of this lack. Well aware of the importance of radar. Extensive index.

Air Marshal Sir Robert Saundby, Air Bombardment: The Story of Its Development. New York: Harper and Brothers, 1961. pp. 260, photographs, no tables, no maps, no references. The author was Deputy Commander-in-Chief of Bomber Command during 1943-1946 and a strong believer in strategic bombing.

Dudley Saward. See Memoirs and Biographies: Books.

Ronald Schaffer, Wings of Judgment: American Bombing in World War II. New York: Oxford University Press, 1985. pp. 272, no photographs, one map, essay on extensive sources. How the Army Air Force slipped into area bombing in Germany because of the weather and inaccurate radar, and how it planned area bombing of Japan because of the nature of the targets.

John Terraine, A Time for Courage: The Royal Air Force in the European War, 1939-1945. New York: Macmillan Publishing Co., 1985. pp. 828, extensive references and notes, appendices, abbreviations, tables. Excellent summation with many quotations. Derived almost exclusively from secondary sources.

United States Army in World War II. Washington: Office of the Chief of Military History, 1948 to 1985. 71 volumes. An enormous, detailed undertaking. Sufficiently rich in radar that the three Signal Corps volumes, previously cited, are prime sources. Obviously of value for the operational aspects of the war.

Derek Wood and Derek Dempster, The Narrow Margin: The Battle of Britain and the Rise of Air Power, 1930-1940. Washington: Smithsonian Institution Press, 1990. pp. 384, many photographs, extensive technical appendices, including listing of the RAF air crews, bibliography. The most recent of three revised editions, the other two having been published in 1961 and 1969. The standard work. Has an excellent understanding of the application of radar.

6. History: Military, Journal Articles

Vice Admiral Charles A.Lockwood, "Electronics in Submarine Warfare," Proc. IRE, vol. 35, pp. 712-715, 1947. Several detailed and exciting examples of the use of radar by American submarines. The author commanded U.S. submarines in the Pacific from 26 May 1942 until the end of hostilities.

Robert C. Rasmussen, "It Helped Sink Six Jap Warships," *Bell Laboratories Record*, vol. 24, pp. 201-202, 1946. Describes the use of radar in the Second Battle of Savo Bay or Battle of Cape Esperance (Guadalcanal).

7. Administration, Intelligence and Policy

Francis Harry Hinsley, *British Intelligence in the Second World War: Its Influence on Strategy and Operations, Vol. 1*. New York: Cambridge University Press, 1979. pp. 601, no photographs, a few diagrams and tables, extensive index. Details of the importance of Enigma reports through 1941. Has as appendices a translation of the Oslo Report and descriptions of the German beam navigation systems.

Francis Harry Hinsley, *British Intelligence in the Second World War: Its Influence on Strategy and Operations, Vol. 2*. New York: Cambridge University Press, 1981. pp. 850, no photographs, several maps, 83 pp. of index. Material on the realization by Britain of Germany's radar capabilities and early counter measures.

Francis Harry Hinsley, *British Intelligence in the Second World War: Its Influence on Strategy and Operations, Vol. 3, Part 1*. New York: Cambridge University Press, 1984. pp. 693, no photographs, several maps, 96 pp. of index. Material on German flak, night fighters, U-boats and their radars.

Francis Harry Hinsley, *British Intelligence in the Second World War: Its Influence on Strategy and Operations, Vol. 3, Part 2*. New York: Cambridge University Press, 1988. pp. 1038, no photographs, several maps, 60 pp. of index, 13 pp. bibliography, list of prefixes. Details about the neutralization of German coastal radar in preparation for the Normandie Invasion.

Arnold Kranish, *The Griffin*. Boston: Houghton Mifflin Company, 1986. pp. 294, photographs. Biography of Paul Rosbaud, purported to be the author of the Oslo Report.

C.P. Snow, Science and Government. Cambridge, Massachusetts: Harvard University Press, 1961, Appendix 1962. pp. 88 and 37, no indices, no tables or photographs. An examination of the conflict between Tizard and Lindemann. That it was not thought balanced by all is shown in the Appendix that answers remarks in Birkenhead's biography of Lindemann.

Irvin Stewart, Organizing Scientific Research for War: The Administrative History of the Office of Scientific Research and Development. Boston: Little, Brown and Company, 1948. pp. 358, no illustrations, few references. Almost unreadable but useful in understanding the interconnections.

8. Memoirs and Biographies: Books

Luis W. Alvarez, Alvarez: Adventures of a Physicist. New York: Basic Books, Inc., 1987. pp. 292, no useful illustrations, no references. Describes his work at the Radiation Laboratory, especially his contribution to MEW, antisubmarine warfare, the Eagle system and to blind landing of aircraft.

The Earl of Birkenhead, The Professor and the Prime Minister: The Official Life of Professor F.A. Lindemann, Viscount Cherwell. Boston: Houghton Mifflin and Co., 1962. pp. 400, a few photographs, no references. A remarkably candid telling of Lindemann's side of the great conflict.

E.G. Bowen, Radar Days. Bristol: Adam Hilger, 1987. pp. 231, photographs, appendices of critical documents and production, list of abbreviations, bibliography, a large index considering the short text. Important recollections by the first staff scientist hired by Watson Watt. More important, Bowen was the inventor of air-borne radar and the British member of the Rad Lab. Lots of detail for so short a book with frank evaluations of policy and personnel.

Harold G. Bowen, *Ships, Machinery and Mossbacks: The Autobiography of a Naval Engineer*. Princeton, New Jersey: Princeton University Press, 1954. pp. 397, no photographs, appendices on ship machinery, no bibliography. Bowen was Director of NRL during the war. His history of radar is flawed.

R. Hanbury Brown, *Boffin: A Personal Story of the Early Days of Radar, Radio Astronomy and Quantum Optics*. Bristol: Adam Hilger, 1991. pp. 184, photos and drawings. One of the first radar men. Writes of many coworkers.

Ronald William Clark, *Tizard*. Cambridge, Massachusetts: The M.I.T. Press, 1965. pp. 458, photographs, references, bibliography. The facts about the eternal advisor. Important coverage of the mission to the U.S. Not lively reading.

Alexander Dahl, *Bumerang: Ein Beitrag zum Hochfrequenz-krieg*. Munich: J.F. Lehmanns Verlag, 1973. pp. 93, photos, drawings, index that also defines the terms. Dahl and other radio amateurs countered Oboe, which had the German code name Bumerang. Filled with technical details and human experiences.

Adolf Galland, *Die Ersten und die Letzten: Die Jagdflieger im zweiten Weltkrieg*. Darmstadt: Franz Schneekluth, 1953. pp. 392, photos, a few maps and graphs, no index but a detailed table of contents. In addition to his oft cited quotation about British radar in 1940 Galland describes his experiences as a very experienced flier who became the commander of Luftwaffe fighters but ended the war as a pilot.

Ivan Alexander Getting, *All in a Lifetime: Science in the Defense of Democracy*. New York: Vantage Press, 1989. pp. 622, photographs, no tables, few references, three detailed indices. A readable and comprehensive autobiography by a great engineer that is packed with history. The chapters on SCR-584 and Raytheon are especially useful.

Jeremy Howard-Williams, *Night Intruder: A Personal Account of the Radar War between the RAF and Luftwaffe Nightfighter Forces*. London: David & Charles, 1976.

pp. 184, photos, diagrams, a short bibliography, glossary. Much detail about operation and tactics of those using AI radar, engagingly told. Several insightful incidents.

David Irving, The Rise and Fall of the Luftwaffe: The Life of Erhard Milch. London: Weidenfeld and Nicolson, 1973. pp. 451, photographs, references. Milch organized the Luftwaffe. His replacement by Udet for technical decisions was the beginning of a series of bad decisions that was not, probably could not have been made good later.

Reginald Victor Jones, The Wizard War: British Scientific Intelligence, 1939-1945 (American edition of Most Secret War). New York: Coward, McCann and Geoghegan, Inc., 1978. pp. 556, illustrations, glossary, few references. Very important book written by the chief of British Scientific Intelligence. Has details of German and British beam navigation.

Generalfeldmarschall Albert Kesselring, Soldat bis zum letzten Tag. Bonn: Athen um Verlag, 1953. pp. 475, photographs, maps, no references, appendix. The author, who did not learn to fly until 1933, commanded Luftflotte 2 in 1939-41 during the Battle of Britain and the invasion of Russia; after that he commanded ground and air forces. The appendix "Die deutsche Luftwaffe. Ihr Aufstieg und Niedergang" gives an insider's view.

Bernard Lovell. See History: Specific to Radar, Books.

Jack Nissen and A.W. Cockerill, Winning the Radar War: A Memoir. New York: St. Martin's Press, 1987. pp. 224, twelve photos, no references. Nissen started in 1937 as technician, later set up and operated stations, took part in the Dieppe Raid to examine a Freya for radar intelligence. The radar history is wrong more often than right.

General Sir Frederick Pile, Ack-Ack: Britain's Defence Against Air Attack During the Second World War. London: George G. Harrap and Co., 1949. pp. 410, photographs, detailed index. The story told without illusion but with great pride in the men and women of his command. Discloses a picture of the air war completely different from that seen by fliers. Radar as seen by the gunners. Has important things to say about countering the V-1s with anti-aircraft fire. A fine read.

Ernest C. Pollard, Radiation: One Story of the MIT Radiation Laboratory. Durham, North Carolina: The Woodburn Press, 1982. pp. 197, no illustrations, no index, no references. Very chatty. Bland descriptions of co-workers. Vivid description of the tests of the SG prototype aboard ship.

Radiation Laboratory Staff Members. Cambridge, 1946. pp. 175, extensive glossary called "index," no illustrations, originally classified RESTRICTED. Lists staff by division with biographical information.

John S. Rigden, Rabi: Scientist and Citizen. New York: Basic Books, Inc., 1987. pp. 302, excellent index and notes. Two chapters describe Rabi's leadership at the Radiation Laboratory.

Albert Percival Rowe, One Story of Radar. Cambridge: The University Press, 1948. pp. 208, seven photos, three of TRE lab sites. A short treatment of the British work, but one that is full of information and understanding.

John Rowland, The Radar Man: The Story of Sir Robert Watson-Watt. New York: Roy Publishers, no date but not before 1962. pp. 144, no index, no tables, no illustrations of consequence. Of no value whatsoever. A book for young people obviously copied out of Watson-Watt's autobiography with no evidence of anything new.

Dudley Saward, Bomber Harris: The Story of Marshal of the Royal Air Force Sir Arthur Harris. Garden City, New York: Doubleday and Company, 1985. pp. 347, photographs, a few graphs and maps, bibliography. This authorized biography is a spirited defense of a comrade and of the use of area bombing. There are remarkably few references to radar (called RDF except once), especially strange given that Saward was Harris's radar officer.

Ed Simmonds and Norm Smith, Radar Yarns: Being Memories and Stories Collected from RAAF Personnel Who Served in Ground Based Radar During World War II. Forster, N.S.W., Australia: E.W. & E. Simmonds, 2 Hind Avenue, 1991. pp. 227, maps, no index. A pot pourri of people, places and pleasantries.

George C. Southworth, Forty Years of Radio Research: A Reportorial. New York: Gordon and Breach Science Publishers, 1962. pp. 274, illustrations, no index, no references. An autobiography that provides much material on the thinking of radio engineers in the 1920s and 1930s. Describes how Southworth invented microwave waveguides.

Albert Speer (translation by Richard and Clara Winston), Inside the Third Reich. New York: The Macmillan Company, 1970. pp. 596, photographs, sources cited in notes. Speer was Minister of Armaments and Production, yet he mentions radar only three times (in passing). He does not mention any of the radar men, not even Martini; neither Telefunken nor GEMA appear in the text. Electronics production comes up briefly only once.

Albert Hoyt Taylor, Radio Reminiscences: A Half Century. Washington: U.S. Naval Research Laboratory, 1948. pp. 248, no illustrations, no photographs, no tables, no index, no references. Autobiography of the man behind American radar. Good insight into the electronics of the 1920s and 1930s with much detail about equipment, designs and hundreds of participants about whom not a word of disparagement.

Sir Robert Watson-Watt, The Pulse of Radar: The Autobiography of Robert Watson-Watt (American edition of Three Steps to Victory). New York: Dial Press, 1959. pp. 438, no illustrations, no index, no references, glossary. Very important for all of its faults. Shows a unique, strong minded man.

Robert Wright, The Man Who Won the Battle of Britain. New York: Charles Scribner's Sons, 1969. pp. 291, no references, no tables, no illustrations. The life of Hugh Dowding, who commanded Fighter Command from July 1936 to November 1940. He saw the value of radar from the first and built an integrated air defense system around it. Much of the book deals with contentious disputes about tactics in 1940.

Harold A. Zahl, Radar Spelled Backwards. New York: Vantage Press, 1972. pp. 171, illustrations, a few references, no index. A little about early Signal Corps work. Describes 1933 measurements of over the horizon propagation at 400 MHz. Chatty and disorganized.

9. Memoirs and Biographies: Journal Articles

Luis W. Alvarez, "Alfred Lee Loomis -- Last Great Amateur of Science," Physics Today, vol. 36, No. 1, pp. 25-34, 1983. Adapted from Biographical Memoirs: National Academy of Sciences, vol. 51, pp. 309-341, 1980. Deals extensively with Loomis's radar work. Alvarez's comments on radar history brought letters to the editor in the issues of June 1983, pp. 101-104; October 1983, pp. 119-120; May 1984, p 13.

P.M.S. Blackett, "Tizard and the Science of War," Nature, vol. 185, pp. 647-653, 1960. An obituary to match the one about Lord Cherwell listed below by R.V. Jones. The pair should be read one after the other.

R.W. Burns, "A.D. Blumlein -- Engineer Extraordinary," Engineering and Science Education Journal, February 1992, pp. 19-33. Biography of the key designer of H_2S.

IEE Proceedings, vol. 132A, No. 6, pp. 325-444, October 1985. Special issue on the history of radar. Articles written immediately after the war. Individual papers follow:

325 Editorial: "Historical radar."
327 "Memoirs of radar research", J.D. Cockcroft.
340 "The work of TRE in the invasion of Europe," J.W.S. Pringle.
359 "ASV: The detection of surface vessels by airborne radar," R.A. Smith, R. Hanbury Brown, A.J. Mould, B.A. Walker and A.G. Ward.
385 "The development of centimetre AI," W.E. Burcham.
394 "Oboe: History and development," A.H.Reeves and J.E.N. Hooper.
399 "H_2S and the navigator," E.L. Killip.
401 "Historical note on H_2S," A.G.B. Lovell.
404 "The new H_2S," J.B. Smith.
411 "History of fighter direction," N. Orgel.
423 "The radio war," Sir Robert Cockburn.
435 "The story of IFF," Lord Bowden of Chesterfield.
438 "D-13: some personal memories of 24-28 May 1944," Sir Martin Ryle.
441 "Development of radar for the Royal Navy," J.D.S. Rawlinson.

R.V. Jones, "Obituary: The Right Hon. Viscount Cherwell, P.C., C.H., F.R.S.," Nature, vol. 180, pp. 579-581, 1957. Rich in detail, candid in tribute.

Bernard Lovell, "A discussion comment," Proceedings of the Royal Society, vol. 342, pp. 479-480, 1975. Contradicts the interpretation of A.P. Rowe, p 119, on employment of H_2S.

J.T. Randall, "The Cavity Magnetron," Proceedings of the Physical Society, vol. 58, pp. 247-252, 1946. How it came to be.

M.A. Tuve, "Early days of pulse radio at the Carnegie Institution," _J. Atmospheric and Terrestrial Physics_, vol. 36, pp. 2079-2083, 1974. Describes the 1925 ionosphere work.

10. Technical: Books

Bell Telephone Laboratories Technical Staff, _Radar Systems and Components_. New York: D. Van Nostrand Co., 1949. pp. 1042, drawings, photographs, tables. Essentially a textbook with a little historical material in the Introduction, first two chapters and the chapter on silicon diodes. Duplicates historical material found in the Bell System house journals.

Norman Friedman, _Naval Radar_. Annapolis: (American edition) Naval Institute Press, 1981. pp. 240, many photographs, tables, glossaries, references. An excellent textbook of historical value because of an historical approach and the complete listing of all naval radars since Seetakt and CXAM with details of each for eights nations. It is the only way to untangle the U.S. Navy's use of radar in World War II.

John J. Kovaly, _Synthetic Aperture Radar_. Dedham, Massachusetts: Artech House, Inc., 1976. pp. 333, drawings photographs. A collection of reprints of 33 original papers with introductory and explanatory comments. Follows the history of the development of the field.

MIT Radar School Staff, _Principles of Radar_. Cambridge, Massachusetts: Technology Press, 1944. pp. 922, many excellent drawings, no index, almost no references. Must have been put together from class room instruction sheets. Originally classified as CONFIDENTIAL.

Robert Morris Page, _The Origin of Radar_. New York: Doubleday and Company, 1962. pp. 196, no references, chronology, good illustrations. A good account of the work

at Naval Research Lab with technical explanations aimed at beginning physics level. Part of Doubleday's Science Study Series. A parochial report but one that gives clear explanations of design problems.

Louis N. Ridenour, Editor in Chief, Radiation Laboratory Series. New York: McGraw-Hill Book Company, 1947. 28 volumes. An encyclopedia of microwave radar published immediately after the war. These books were widely used by engineers in all branches of electronics and had a significant effect on design style. Reprintings of various volumes appeared throughout the succeeding decades.

Robert J. Schlesinger with the collaboration of Kirk Abbey, Richard W. Ehrhorn, Kenneth J. Friedenthal and Stanley H. Logue, Principles of Electronic Warfare. Englewood Cliffs, New Jersey: Prentice-Hall, Inc., 1961. pp. 213, diagrams, no photos, bibliography. A respected textbook.

Karl R. Spangenburg, Vacuum Tubes. New York: McGraw-Hill Book Co., 1948. pp. 860, many excellent drawings. Excellent text on klystrons, Barkhausen tubes and magnetrons.

Frederick Emmons Terman, Radio Engineers' Handbook. New York: McGraw-Hill Book Co., 1943. pp. 1019, many excellent drawings, good index. The standard reference for engineers during the war.

R.A. Watson Watt, J.F. Herd, and L.H. Bainbridge-Bell, Applications of the Cathode Ray Oscillograph in Radio Research. London: His Majesty's Stationery Office, 1933. pp. 290, illustrations, no index, references. An historic book that shows Watson-Watt's style..

11. Technical: Journal Articles

Sir Edward Appleton, "The Thirty-sixth Kelvin Lecture: 'The Scientific Principles of Radiolocation,'" J. IEE, vol. 92 (Part I), pp. 340-353, 1945. An introduction with a unique flavor.

R.E. Burgess, "Noise in Receiving Aerial Systems," Proc. Phys. Soc., vol. 53, pp. 293-304, 1941. Places the concept of antenna temperature on a solid theoretical basis. See also Dicke et al. in Science Issuing from Wartime Work.

E.U. Condon, "Principles of Micro-Wave Radio," Reviews of Modern Physics, vol. 14, pp. 341-389, 1942. Thorough theoretical review. Remarkable for its appearance in the open literature.

Jackson H. Cook, "Airborne Search Radar," Bell Laboratories Record, vol. 24, pp. 321-325, 1946. Description of AN/APS-4 by its project engineer.

John H. DeWitt, "Technical and Tactical Features of Radar," J. Frank. Inst., vol. 241, pp. 97-123, 1946. A tutorial. Photos of SCR-271, AN/TPS-3, AN/TPL-1, SCR-584, SCR-784 and AN/MPG-1.

Electronics (magazine). A series of articles published after the war that give technical details. Except as noted the articles do not have authors named. Individual papers follow:

Sep 45, pp. 100-109, "The SCR-268 Radar."
Oct 45, pp. 92-97, "Radar Warfare."
Nov 45, pp. 94-99, "The Loran System - Part I."
Nov 45, pp. 110-111, "Proximity Fuze."
Nov 45, pp. 112-115, "Ground-Controlled Approach for Aircraft."
Nov 45, pp. 116-119, "Radar Specifications."
Dec 45, pp. 92-97, "Fire-Control Radar MPG-1" by H.A. Straus et al.
Dec 45, pp. 98-103, "Generator-Powered Proximity Fuze" by R.A. Huntoon and B.J. Miller.

Dec 45, pp. 104-109, "The SCR-584 Radar."

Dec 45, pp. 110-115, "Loran Receiver-Indicator."

Jan 46, pp. 92-97, "Radar Countermeasures."

Jan 46, pp. 98-104, "Radar on 50 Centimeters" by H. Zahl and J.W. Marchetti.

Jan 46, pp. 110-117, "The MPG-1 Radar" by H.A. Straus et al.

Jan 46, pp. 126-131, "Cavity Magnetron."

Feb 46, pp. 92-97, "The Resnatron" by W.W. Salisbury.

Feb 46, pp. 98-103, "Radar on 50 Centimeters" by H. Zahl and J.W. Marchetti.

Feb 46, pp. 104-109, "Proximity Fuze for Artillery" by H. Selvidge.

Feb 46, pp. 110-117, "The SCR-584 Radar."

Feb 46, pp. 118-123, "Germanium Crystal Diode" by E.C. Cornelius.

Feb 46, pp. 135-137, "Cavity Oscillator Circuits" by A.M. Gurewitsch.

Mar 46, pp. 140-147, "The MPG-1 Radar" by H.A. Straus et al.

Apr 46, pp. 92-98, "Radar Echoes from the Moon" by J. Mofenson.

May 46, pp. 114-115, "Japanese Magnetrons."

May 46, pp. 138-143, "Radar for Blind Bombing - Part I" by V. Holdam, S. McGrath and A.D. Cole.

Jun 46, pp. 142-149, "Radar for Blind Bombing - Part" II by V. Holdam, S. McGrath and A.D. Cole.

C.E. Fay, "High-Vacuum Oxide-Cathode Pulse Modulator Tubes," Bell System Technical Journal, vol. 26, pp. 818-836, 1947. Problems of the wartime tube designer. No history.

J.B. Fisk, H.D. Hagstrum and P.L. Hartmann, "The Magnetron as a Generator of Centimeter Waves," Bell Sys. Tech. J., vol. 25, pp. 167-348, 1946. A detailed analysis of cavity magnetron operation.

G.T. Ford, "Characteristics of Vacuum Tubes for Radar Intermediate Frequencies," Bell Sys. Tech. J., vol. 25, pp. 385-407, 1946. The 6AK5 story.

H.T. Friis and W.D. Lewis, "Radar Antennas," Bell Sys. Tech. J., vol. 26, pp. 219-317, 1947. Technical details with photographs of 17 different antennas.

F.S. Goucher, J.R. Haynes, W.A. Depp and E.J. Ryder, "Spark Gap Switches for Radar," Bell Sys. Tech. J., vol. 25, pp. 563-602, 1946. Details of a method of modulation. Many photos and drawings.

Nathan I. Hall, "The SL Radar," Bell Laboratories Record, vol. 24, pp. 353-357, 1946. Description of SL, a 10-cm set for surface ships, by its project engineer.

J.S. Hey, S.J. Parsons and F. Jackson, "Reflexion of Centimetric Electromagnetic Waves over Ground, and Diffraction Effects with Wire-Netting Screens," Proceedings of the Physical Society, vol. 59, pp. 847-857, 1947. Excellent description of the difficulties in determining elevation at low angles.

L.W. Morrison, "The Radar Receiver," Bell Sys. Tech. J., vol. 26, pp. 693-817, 1946. Survey of the subject with drawings and photographs.

E. Peterson, "Coil Pulsers for Radar," Bell Sys. Tech. J., vol. 25, pp. 603-615, 1946. Details of a method of modulation. Photos and graphs.

J.R. Pierce and W.G. Shepherd, "Reflex Oscillators," Bell Sys. Tech. J., vol. 26, pp. 460-681, 1947. Theory, practice and some history.

A.L. Samuel, J.W. Clark and W.W. Mumford, "The Gas-Discharge Transmit-Receive Switch," Bell Sys. Tech. J., vol. 25, pp. 48-101, 1946. Details of construction and operation.

J.H. Scaff, and R.S. Ohl, "Development of Silicon Crystal Rectifiers for Microwave Radar Receivers," Bell Sys. Tech. J., vol. 26, pp. 1-30, 1947. Technical details but history as well.

Edwin G. Schneider, "Radar," Proc. IRE, vol. 34, pp. 528-578, 1946. An introduction to the subject. Of little interest, except that it gives an immediate postwar view.

W. Tinus and W.H.C. Higgins, "Early Fire Control Radars for Naval Vessels," Bell Sys. Tech. J., vol. 25, pp. 1-47, 1946. Details of CXAS and Marks 2, 3 and 4. Numerous diagrams and photographs.

C.L. Van Inwagen, "SJ Radar for Submarines," Bell Lab. Rec., vol. 24, pp. 402-06, 1946. Description of SJ.

12. Science Issuing From Wartime Work

Wilmer C. Anderson, "A Measurement of the Velocity of Light," Review of Scientific Instruments, vol. 8, pp. 239-247, 1937. A confirmation of the erroneous measurement of Michelson et al.

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I am indebted to David Allison, John Bryant, Robert Buderi, Paul Forman and David van Keuren for suggestions and to Mr. Shaun Hardy for library assistance in preparing this bibliography.

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