The Century of Radar

- from Christian Hülsmeyer to Shuttle Radar Topography Mission -

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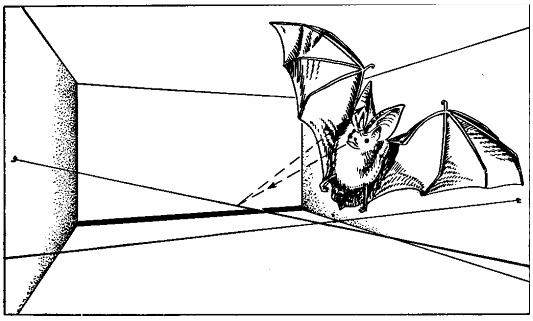
Some famous engineers of the 20th century can count themselves lucky that the bat left the technical invention of RADAR to them. The principle of radar, as a matter of fact, is used by this nightly hunter since early epoches of living creatures on earth. It does, however, not transmit electromagnetic but ultrasonic waves by an appointedly developed voice organ and receives their echoes by antenna-like ears.

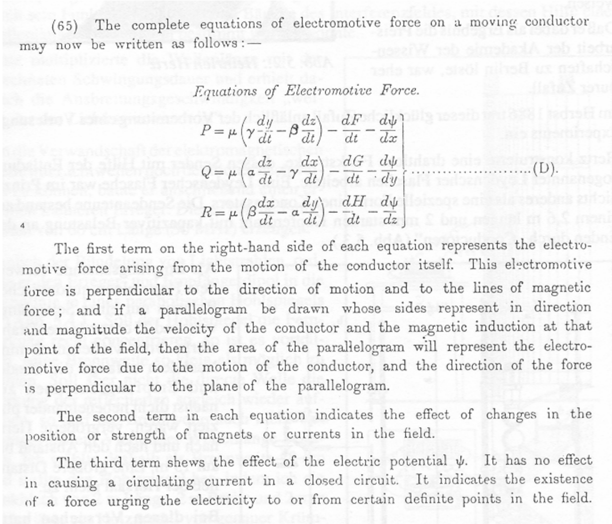


The bat: acoustic detecting and ranging

This technique allows the bat to detect and range obstacles in its flight-path and, surely of the same importance, to track and hunt potential prey.

Electromagnetic Waves

The 19th century prepared the theoretical ground as a precondition for the rise of radar a hundred years later. It was one year after the first German railway between Nuremberg and Fuerth attracted attention, when the great English scientist Michael Faraday in 1836 formulated, in a much less popular way for the time being, the theory of the electrical and magnetical field. In 1865 the Scottish mathematician and physicist James C. Maxwell established the fundamental equations on the theory of electromagnetic waves.



(65) The complete equations of electromotive force on a moving conductor may now be written as follows:—

Equations of Electromotive Force.

$$P = \mu\left(\gamma\frac{dy}{dt} - \beta\frac{dz}{dt}\right) - \frac{dF}{dt} - \frac{d\psi}{dx}$$
$$Q = \mu\left(\alpha\frac{dz}{dt} - \gamma\frac{dx}{dt}\right) - \frac{dG}{dt} - \frac{d\psi}{dy} \quad \text{.......................(D).}$$
$$R = \mu\left(\beta\frac{dx}{dt} - \alpha\frac{dy}{dt}\right) - \frac{dH}{dt} - \frac{d\psi}{dz}$$

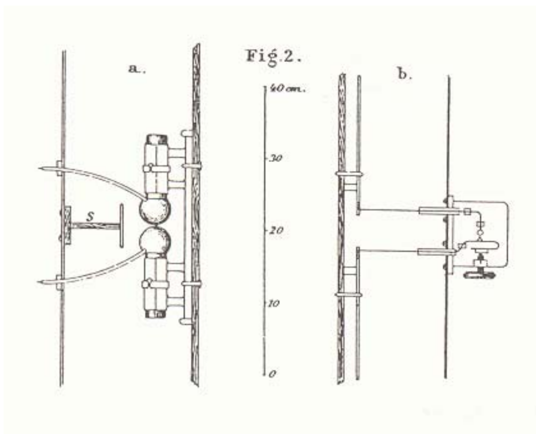
The first term on the right-hand side of each equation represents the electromotive force arising from the motion of the conductor itself. This electromotive force is perpendicular to the direction of motion and to the lines of magnetic force; and if a parallelogram be drawn whose sides represent in direction and magnitude the velocity of the conductor and the magnetic induction at that point of the field, then the area of the parallelogram will represent the electromotive force due to the motion of the conductor, and the direction of the force is perpendicular to the plane of the parallelogram.

The second term in each equation indicates the effect of changes in the position or strength of magnets or currents in the field.

The third term shews the effect of the electric potential ψ. It has no effect in causing a circulating current in a closed circuit. It indicates the existence of a force urging the electricity to or from certain definite points in the field.

J. C. Maxwell and his *Equations of Electromotive Force*

It took then 23 years before the correctness of his theory could be demonstrated experimentally. The first *Mercedes* had just initiated the era of motorized road traffic, when the German physicist Heinrich Hertz in 1888 published his fundamental work „Über Strahlen elektrischer Kraft (About Radiation of Electrical Force)“ for the Berlin Academy of Science. The document describes the basic features of electromagnetic waves, such as their propagation, polarisation, refraction and, of major importance for the later radar application, their capability of being reflected by metallic structures.



H. Hertz and his first transmitter and receiver

In a recent publication the IEEE Aerospace and Electronic Systems Society named Heinrich Hertz the first *Radar Scientist* whereas the German Christian Hülsmeyer was introduced as the world’s first *Radar Engineer.*

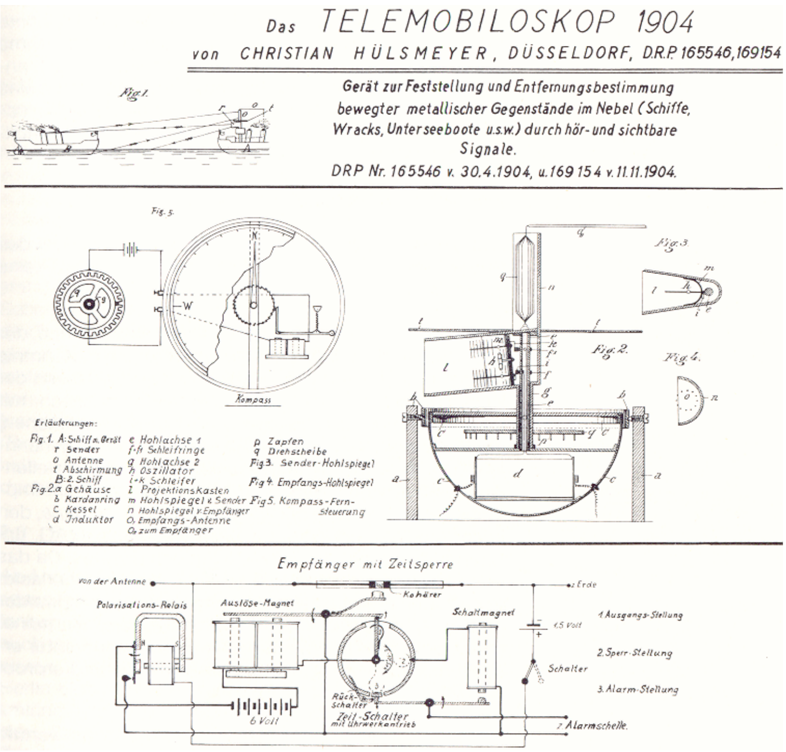
But who was Christian Hülsmeyer?

Christian Hülsmeyer

Christian Hülsmeyer was born on December 25, 1881, in Eydelstedt in northern Germany. On his father's suggestion he started his professional education at the Lehrerseminar (teachers' seminar) in Bremen. He had the opportunity to meet a teacher there, who allowed him to use the school's laboratory for his long cherished experiments with electromagnetic waves. A ship's accident on the river Weser under bad weather and visual conditions with a young man of Hülsmeyer's acquaintance losing his life finally strengthened his idea to use the reflections of electromagnetic waves to warn of obstacles ahead of a ship's course.

In 1899, only one year later, Hülsmeyer moved to the Siemens & Halske company in Bremen. There he consequently developed his idea and found a merchant named Mannheim who was willing to act as a sponsor for commonly founding the company "Telemobiloskop-Gesellschaft Hülsmeyer & Mannheim". Now his invention had obtained a name: *Telemobiloskop.*

It was on May 17, 1904, when Hülsmeyer, 22 years of age at that time, gave a remarkable presentation of his apparatus, which was basically a radio transmitter and receiver, at the yard of the Dom-Hotel in Cologne for representatives of shipping companies and reporters from local newspapers. Next day a second, even more impressive public demonstration took place at the Hohenzollern Bridge across the river Rhine. The *Telemobiloskop* was pointed with its antennas towards the river and reliably rang a bell whenever a ship passed by. It must be clearly emphasized that the set-up was built without any amplifying elements like tubes or transistors; none of these devices was available in those days.



Basic outline of the *Telemobiloskop* and the historical test site in Cologne

A few weeks later Hülsmeyer demonstrated the *Telemobiloskop* very successfully on board of the tender *Columbus* at the "Technical Nautical Meeting" in Rotterdam/ The Netherlands in front of an international attendance. He managed to detect ships in distances up to 3 km. The technical and scientific society now took notice of his invention, as well.
On April 30, 1904, already, Hülsmeyer had filed his invention at the German Patent Office in Munich with the title „Verfahren, um entfernte metallische Gegenstände mittels elektrischer Wellen einem Beobachter zu melden". The following English patent of June 10, 1904, reads „Hertzian-wave Projecting and Receiving Apparatus Adapted to Indicate or Give Warning of the Presence of a Metallic Body, such as a Ship or a Train, in the Line of Projection of such Waves".


KAISERLICHES PATENTAMT.

AUSGEGEBEN DEN 21. NOVEMBER 1905.

PATENTSCHRIFT

— № 165546 —

KLASSE 74a.

CHR. HÜLSMEYER IN DÜSSELDORF.

Verfahren, um entfernte metallische Gegenstände mittels elektrischer Wellen einem Beobachter zu melden.

Patentiert im Deutschen Reiche vom 30. April 1904 ab.

Fig. 1.

C. Hülsmeyer in 1904 and his patent

Hülsmeyer's apparatus consisted of a transmit and receive antenna, a double spark gap acting as the radio frequency generator and a coherer as the receiving element. The operating frequency can only be presumed today, but due to the principle of the generation a spectrum of several hundred Megahertz must have been transmitted. The complete frontend could be rotated by 360° in azimuth synchronously to an electro-mechanical device which Hülsmeyer called *Kompass.* This part of the *Telemobiloskop* indicated the direction of a target reflecting the incident waves.
Quite obviously Hülsmeyer provided the basis for a technique going to be called RADAR (Radio Detection and Ranging) many years later, even if he directly demonstrated only the feature „Detection" and not „Ranging". However, he realized this during his experiments and filed an additional patent in 1904 entitled "Improvement in Hertzian-wave Projecting and Receiving Apparatus for Locating the Position of Distant Metal Objects". He proposed two methods to measure the elevation angles of the *Telemobiloskop's* antennas and to derive a target's distance thereby.

The tragedy of Hülsmeyer's entire work towards wireless direction finding was, at the end, that he did not succeed to persistently convince potential military or civil users and customers to support his invention. Besides lacking interest of his contemporaries he suffered from the given fact that electronic techniques were still in their absolute infancy in the early 20th century. His ideas were, as those of many other inventors in history, far ahead of his times.
Hülsmeyer then disappointedly terminated all his work in this field and turned towards other technical areas. He became a successful business man who filed a long row of patents on various topics. On January 31, 1957, he died in Ahrweiler near Bonn.

The Forgotten Invention

During the first quarter of the 20th century wireless communication stood in the footlights of the application of electromagnetic waves. Hülsmeyer's invention had faded from memory. The Italian Guglielmo Marconi added an antenna to a spark gap and transmitted telegraphic signals over several kilometers in 1886 already. His experiments rose to a first peak, when he crossed the atlantic over 3,600 km from England to Newfoundland by wireless signals in 1901. In the years to follow Marconi's inventions spread to a wide commercial field, in parallel to the development of electronic techniques. In 1922 he again recognized the possibility to detect metallic objects by reflected electromagnetic radiation. And again his initiative, too, did not find any echo from the scientific and technical community.
His thoughts were caught on in the same year by two Americans, A. H. Taylor and L. C. Young from the US Naval Research Laboratory (NRL), who experimented with frequencies of approx. 60 MHz and observed strong interferences in their receiver whenever the antenna beam of their transmitter was directed to moving objects. They stated that the variation of the received fieldstrength must have been caused by the interference of the waves travelling towards and back from a reflecting target.
Three years later, in 1925, the Americans Breit and Tuve were the first to use broadband pulses ranging from 3 to 30 MHz for measuring the height of different layers of the ionosphere. They can be looked upon as the inventors of pulse technique.

Re-Invention of the Radar Principle

Only in the early thirties of the century in several countries in Europe and overseas the value of the radar principle was finally recognized, predominantly based on its military potential. From that time on it is very difficult to draw an unbroken picture of all radar developments, independent from each other in the beginning and later on linked more and more, running into a struggle of action and reaction during World War II.
In order not to go beyond the limits of this essay, the focus shall be on the evolution in Germany, with a look to the UK and USA, as well. However, for historical fairness, it needs to be mentioned that operational radar systems, too, were available at the beginning of World War II in September 1939 in France, the Soviet Union, Japan, Italy and in The Netherlands.

Funkmeßtechnik Gets Mature

In 1931 Dr. Rudolf Kühnhold of the Nachrichten-Versuchsabteilung (Department of Signals Research) of the German Navy in Kiel filed a patent of what today is called SONAR for detection and ranging of objects under water by ultrasonic waves. At the same time Kühnhold thought of electromagnetic centimeter waves to be used outside water for the same purpose. In order to realize those ideas he effected the establishment of a new company, the GEMA (Gesellschaft für Elektroakustische und Mechanische Apparate) in 1934, dedicated to the development of wireless direction finding equipment.
In September 1935 GEMA demonstrated in front of high-ranking Navy officials an instrument that for the first time could be named Radar, although this abbreviation was not yet introduced in Germany at that time. The set consisted of a pulsed transmitter at a frequency of approx. 600 MHz with an output power of 800 W. The travelling time of the pulses to and back from a target was measured to derive the target's distance, thus adding the ranging-feature to what Hülsmeyer had demonstrated 31 years before. The antennas used for transmitter and receiver were pine-tree arrays consisting of 10 pairs of dipoles in front of a reflecting wall. A small artillery training boat could be detected over a distance of 8 km.
In the same year Dr. Wilhelm Runge of TELEFUNKEN worked on radio links in the UHF-range. Driven by curiosity, he put the antenna of such a 600 MHz transmitter next to a second antenna connected to a detector, both positioned on the ground and looking upwards to the sky. He managed to receive clear echoes from a *Ju 52* aircraft flying in a height of 5,000 m across this experimental radar.
As a third company Lorenz successfully tested a radar at 430 MHz with a transmitter power of 400 W on the roof of their laboratories in Berlin in 1936.

It needs to be mentioned that, besides industry, significant research and development work in the radar field was performed at that time by notable German institutions like the DVG (Drahtlos-Luftelektrische Versuchsgesellschaft Gräfelfing) and FFO (Flugfunk-Forschungsinstitut Oberpfaffenhofen), a predecessor of today's DLR (Deutsches Zentrum für Luft- und Raumfahrt, German Aerospace Center).

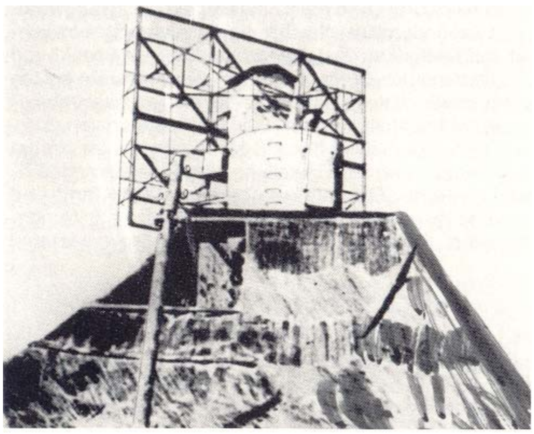
Radar was definitely born now!

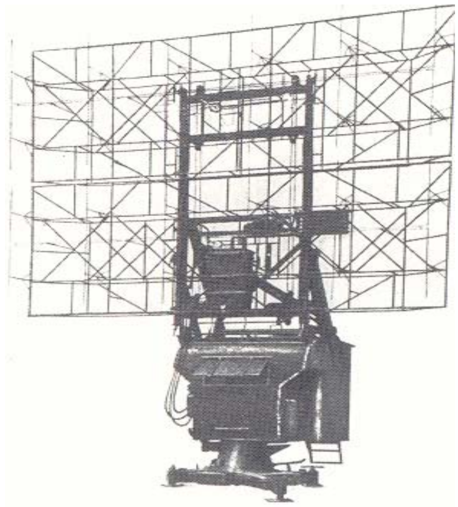
Industry and research establishments had layed the foundation-stones for an intensive development yielding a multiplicity of famous radar equipment to arise. In Germany they were summarized under the synonym *Funkmeßtechnik,* which might be translated as *Radio Measurement Technique.*

German *Funkmeßtechnik* in World War II

The evolution of radar technology in Germany in the years before and, even more, during World War II was in many aspects impaired by external influence. The political rulers of that time carried very limited attention and support towards this promising innovation. Being forced to work in an absolutely unfavourable environment, it becomes clear how fundamental and far-sighted the achievements of the German radar engineers need to be judged. In the following a number of pace-making representatives of past radar equipment shall be introduced.

Freya came forth from the work with pulsed radars at GEMA and was used first in 1938 by the German Navy for coastal aircraft reporting services. It worked at a frequency of 125 MHz with an output power of 8 kW. Tracking of a target was performed by two squinted antenna beams to enable minimum tracking. An angular measurement accuracy of ± 0.8° was yielded.

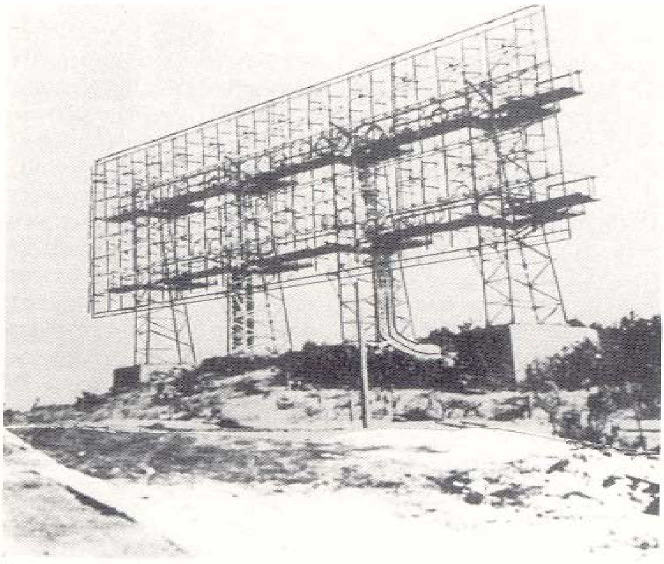
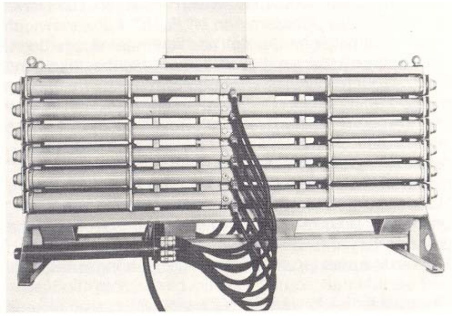




First stationary *Freya* on Wangerooge and a first series set of *Freya*

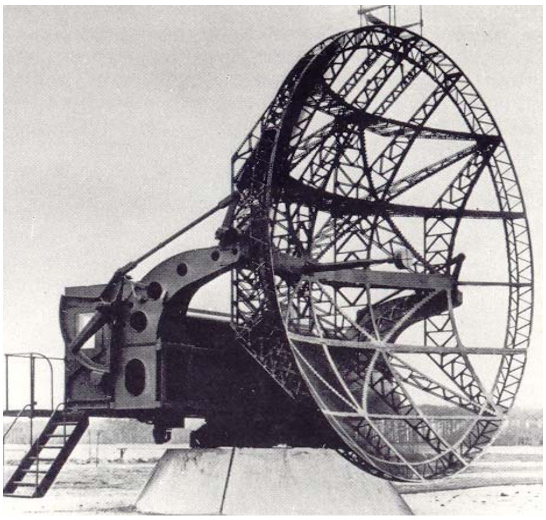
Freya's crucial test took place on December 18, 1939, on the isle of Wangerooge when a formation of British bombers could be detected over a distance of 130 km approaching over the Bay of Heligoland. Consequently, German fighters could be alarmed. This was, hence, the first air force action in Germany supported by radar.

It is, as well, impressive that today's state-of-the-art phased array radars with electronically steered antennas have their roots more than 60 years ago. *Mammut 1* was a huge anti-aircraft radar consisting of eight *Freya* antennas resulting in an antenna field of 10 m x 25 m. The beam direction could be steered in azimuth by ± 50° using helical lines as phaseshifters named *Wellenschieber*. *Mammut 1* was able to scan the air region from the channel coast to the midlands of England. Aircraft taking off there could be detected in real-time.

Long-range radar *Mammut 1* and phaseshifters for electronic beam-steering

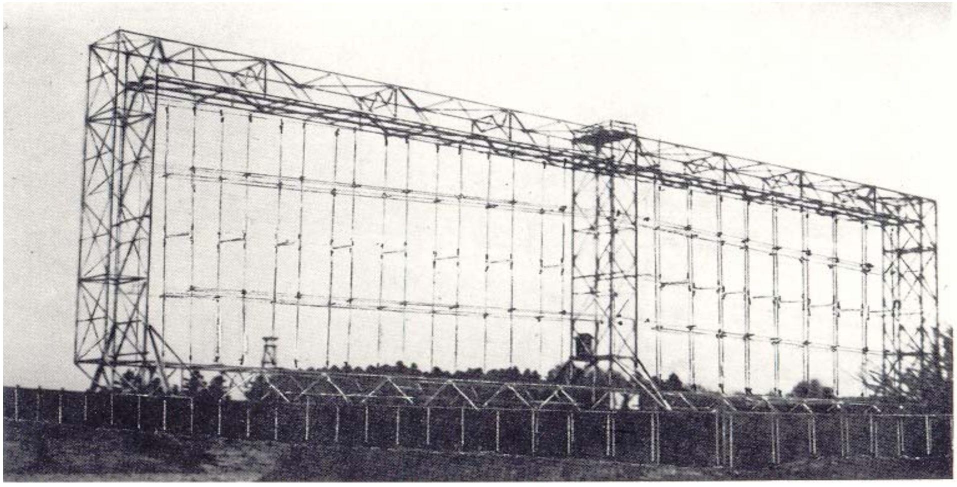
In March 1939 TELEFUNKEN introduced *Würzburg,* an anti-aircraft artillery radar with its characteristic 3 m parabolic reflector antenna. *Würzburg* worked at a frequency of 565 MHz with 8 kW pulse output power yielding an instrumented range of 40 km. In its version *C*, as an improvement over the *A*-version, the feeding dipole of the antenna rotated excentrically, thus yielding an antenna beam revolving on the envelope of a cone. Conical scan was born. The measuring accuracy was now ±25 m to ± 40 m in range and ± 0.5° in azimuth and elevation. In total, a series of 4,000 *Würzburg* sets were built until the end of World War II.

Würzburg A and *Würzburg-Riese*

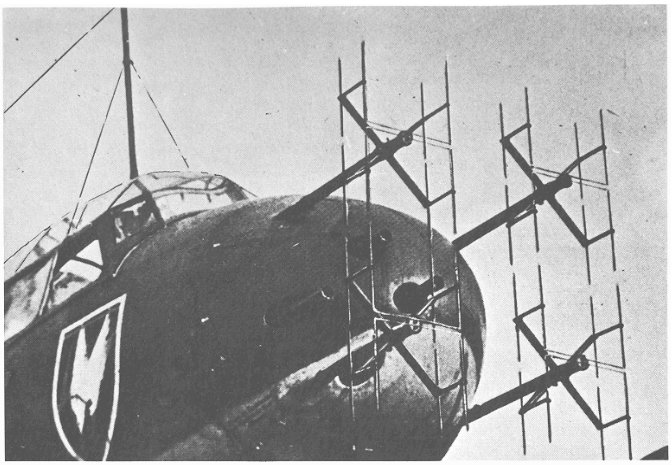
In order to support *Freya* in guiding fighter aircraft, *Würzburg-Riese* was established as a tracking radar with a reflector of 7.4 m diameter and an increased range of up to 70 km.

Another highlight of German radar development anticipating a technique used much later was *Knickebein J*, one of the first experimental over-the-horizon radars. It was first operated by TELEFUNKEN in 1941 at a frequency of 30 MHz at the upper end of the HF-range. Making use of the physical fact that in this frequency range transmitted and received signals can be reflected by the ionosphere and the earth's surface, targets up to distances of several thousands of kilometers could be detected.



Radio localizer *Knickebein J*

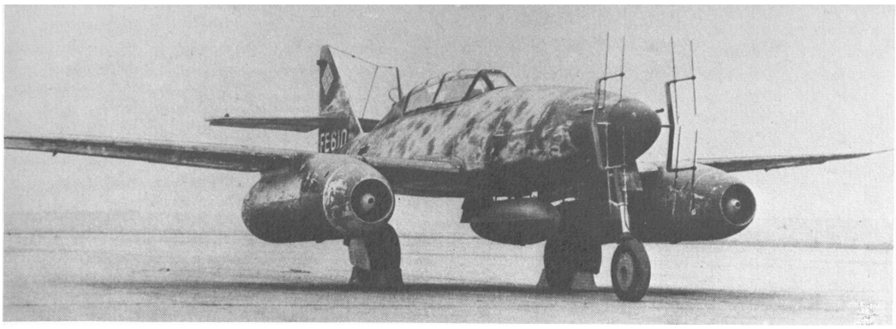
An essential representative of airborne radars was *Lichtenstein BC* developed by TELEFUNKEN for night-fighters and ready for first missions in autumn 1941. It was operating at a frequency of 490 MHz, the output pulse power was 1.5 kW. The antenna array consisted of four quadrants, each provided with four dipoles and reflectors. Target tracking was achieved by feeding the quadrants via a circular phasing line by means of a mechanically rotating capacitive switch, thus yielding a conically rotating antenna beam. Within a range of 4 km a measuring accuracy of ± 100 m and ± 2.5° could be realized.



FuG 202 Lichtenstein BC installed to a *Ju 88*

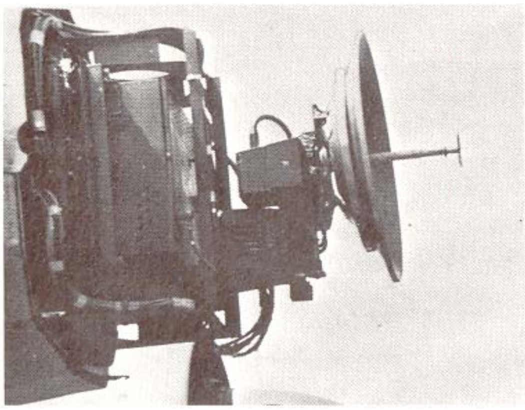
Later versions called *Lichtenstein SN2* came into use at frequencies below 100 MHz, as well, to increase range. More than 2,000 sets of those have been built.

In parallel to the *Lichtenstein*-activities, the SIEMENS company and FFO developed the *Neptun* family, mainly suited for smaller aircraft. As one of a number of variants more than 150 sets of *FuG 218 V* were built, operating in the frequency range of 162 to 187 MHz with a transmit power of 2 kW and, as in the case of *Lichtenstein*, with a group of Yagi-antennas consisting of dipoles and reflectors.



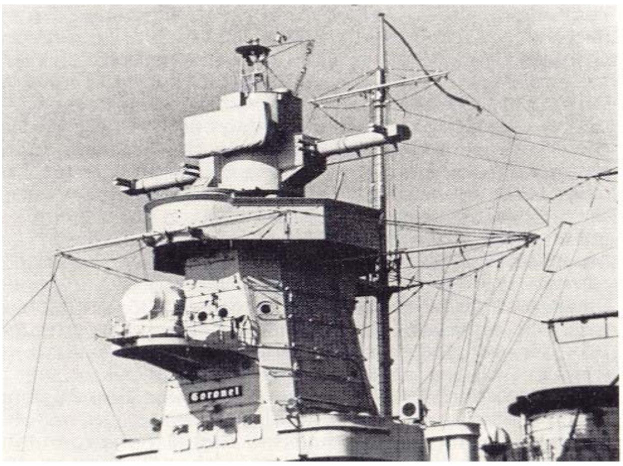
FuG 218 Neptun installed to a jet night-fighter *Me 262*

The first German airborne radar featuring main characteristics of modern fighter radars appeared in 1943, built by TELEFUNKEN and denoted *Berlin N1A*. It worked at a frequency of 3.3 GHz with a parabolic reflector antenna of 70 cm diameter and a rotating feeding dipole. The radar was mounted under a wooden radome at the nose of *Ju 88* aircraft. An output power of 15 kW generated by a magnetron transmitter rendered a range of 9 km against airborne targets. 25 sets in total have been built.



Microwave airborne radar *Berlin N1A*

The application of ship-based radar was much less emphasized in the beginning of the war than anti-aircraft or airborne radar. Only the experience gained with first experimental radar sets on ships made the importance of this revolutionizing achievement obvious to the German Navy. Many tactical rules lost their value; no difference existed any more between day and night with a radar in operation, fog or bad weather were no longer impervious.
The initial sets of *Seetakt (seetaktisch,* engl. *sea tactical)* equipment originated directly from the work of GEMA in 1935. The first ship to be equipped with the system *FuMG 38 G* was the armoured vessel *„Admiral Graf Spee“* in 1938. The radar was operated at approx. 500 MHz with an output power of 1 kW.

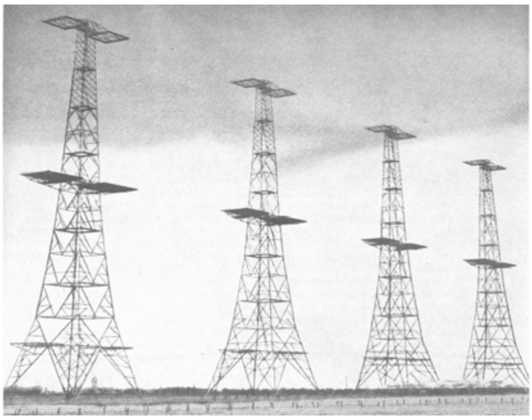


FuMG 38 G (covered by sailcloth) mounted on the mast of the armoured vessel *Admiral Graf Spee*

Due to its location close to the top of the mast, the range against other large ships amounted to 25 km; the maximum angular error of bearings was ± 5°. It is interesting to note that the radar antenna was mounted in the plane of the optical rangefinder and was moving with it. Starting in 1939, *Seetakt*-sets were installed to a considerable number of German ships. *Seetakt* was used as land-based radar, too, along the German coasts and in the occupied countries from 1942 onwards.
During the war also *Würzburg* and *Lichtenstein* sets were adapted to the Navy's needs to work on board of different ships. Even submarines have been equipped with radar, however with severe difficulties due to strict spatial limitations and severe environmental conditions, e.g. shock-waves from water bombs.

British Radar Development in the Course of World War II

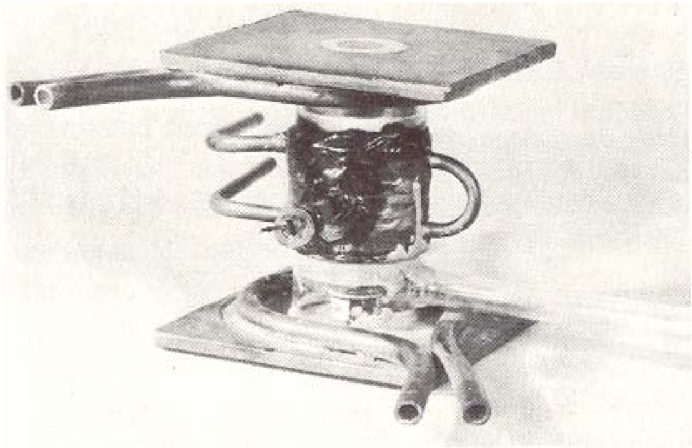
The political recognition that Great Britain could be opposed to a potential threat caused by the German rearmament resulted in the meaningful memorandum „Detection and Location of Aircraft by Radio Methods" drawn up by Robert Watson-Watt, head of the National Physical Laboratory, in February 1935. This was the birth of British radar development, primarily aiming at an early warning system for air defence.
In March 1936 the first land-based station of the later called *Chain Home* became operational at Bawdsey Manor on the Thames Estuary. From spring 1939 onwards a number of 20 stations controlled the air space along the entire south- and east-coast of England. The transmitters at the 80 m high *Chain Home* towers were operated at frequencies between 22 and 30 MHz with powers of 200 kW, thus yielding ranges of up to 200 km against air targets. Shortly after *Chain Home Low* followed, as a completion, in the frequency range of 200 MHz to detect low flying aircraft and to enhance locationing accuracy.

Towers of *Chain Home*

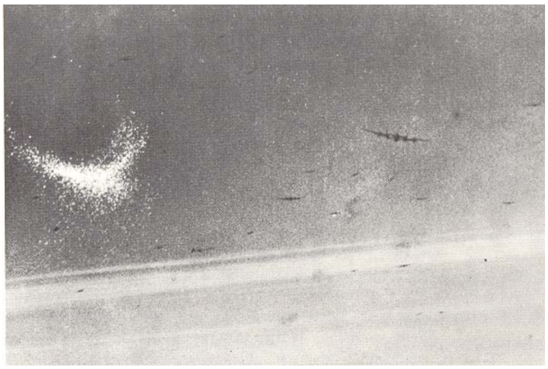
The first effective airborne radar was installed into a British fighter aircraft in autumn 1940. In April 1941 already, a number of 110 aircraft was equipped with radar sets operating in the 200 MHz range.

A milestone towards higher frequencies was the invention of the multi-segment magnetron by F. Randall and A. H. Boot at the University of Birmingham in February 1940. It initiated microwave radar in the frequency range of 3 GHz. Primarily in order to force along the promising magnetron technology, British and American development work was merged at the MIT (Massachusetts Institute of Technology) in the USA.



Magnetron of Randall and Boot in 1940

A very effective method of radar-jamming was first employed by British bombers during their attack on Hamburg in July 1943. Small tin-foil strips called *Window*, with the synonym *Düppel* used in Germany, had been cut to half the wavelength of the German fire-control radars and were then dropped from aircraft in huge numbers, thus forming reflecting clouds for the *Würzburg* radars and screening the entire raid.

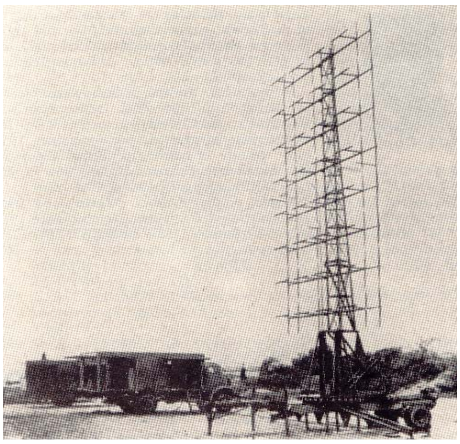
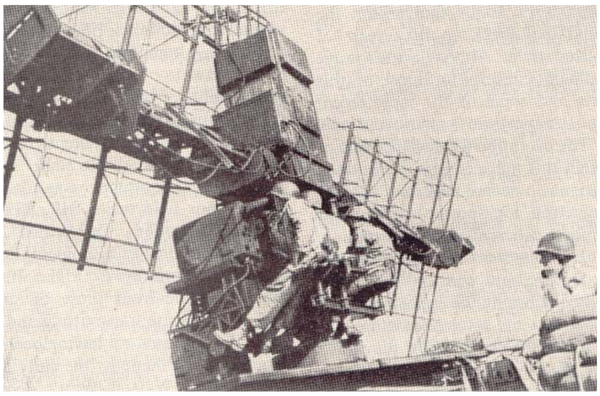
 

Production of *Window* and *Lancaster*-bombers dropping them over Germany in July 1943

As a counter-countermeasure the first ideas of MTI (Moving Target Indication) were born in German radar laboratories which could be used to suppress unwanted echoes from *Window* against those from moving air-targets. Many *Würzburg* sets have been upgraded with this technique thereupon.

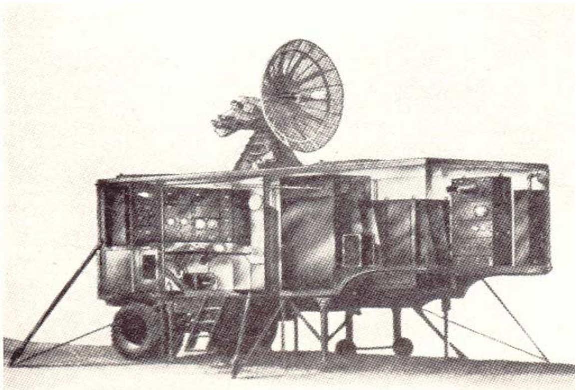
A View Across the Atlantic: US Radar until 1945

In the United States of America time was not quite as pressing as in Germany and Great Britain, as regards the development of radars when World War II broke out. Work on pulsed VHF equipment was carried out mainly at the NRL. When the USA entered the war, the air surveillance radar *SCR-270* working at a frequency of 106 MHz and the anti-aircraft tracking radar *SCR-268* at 205 MHz were available for use.
In June 1937 already, the US Air Corps had set out the specification for a detector and tracking equipment with a required range of 50 miles. This specification resulted in the *SCR-270* (mobile) and *SCR-271* (fixed) radars with a power of 100 kW peak at 106 MHz. Some 800 sets of this design were eventually built. The *SCR-270* successfully detected Japanese aircraft approaching Pearl Harbour in December 1941, however, the associated command and control system did recognize the significance of the radar echoes too late. Most of the battleships of the US Pacific Fleet were destroyed or seriously damaged.

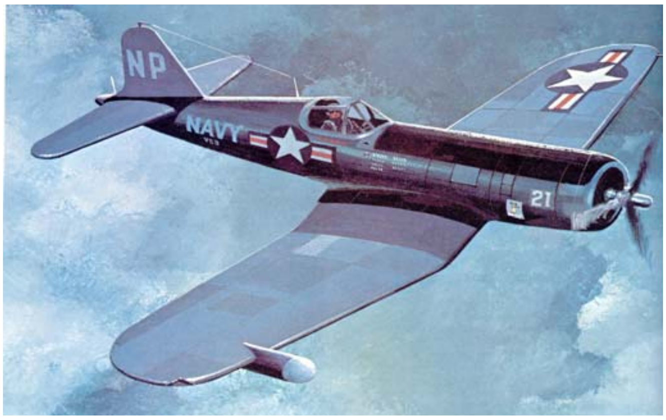
Air surveillance radar *SCR-270* and anti-aircraft tracking-radar *SCR-268*

SCR-268 was initially tested by the US Army at Fort Monroe during December 1938. The antenna consisted of two arrays of dipoles and reflectors for the azimuth and the elevation beams. Processing and tracking were carried out by operators viewing cathode-ray tubes and manually controlling the antenna pedestal. Due to an angular measuring accuracy of only 0.5°, which was unsufficient for anti-air fire control, the *SCR-268* had to rely on accompanying optical trackers to refine its angle data. For night operations an illuminating searchlight was slaved to the radar tracker.
Based on the work on magnetrons jointly with the British at MIT, in 1943 production of the first microwave anti-aircraft gunfire control radar *SCR-584* began. It was operated in the range of 3 GHz with an improved angular accuracy of 0.1°. Optical tracking was no longer needed.



Anti-aircraft gunfire control radar *SCR-584*

US airborne radars profited by the MIT activities on microwave power generation, as well, and were very advanced at the end of World War II. As a first night-fighter the *Vought F4U-4N Corsair* was equipped with a radar from 1944 on which worked in the 10 GHz range already.



Night-fighter *Corsair* with radar *AN/APS-6*

This radar *AN/APS-6* was developed by the Sperry company and had emerged from the former *SCR-537* working at a frequency of 9,375 MHz with 40 kW of output power. At the right wing of the aircraft a gun had been removed and the radar together with the radome were installed. The *Corsair* was primarily in service at the US Navy until the Korean War.

Post-War Radar Developments

At the end of World War II radar development in Germany came to a complete stop. Any research work in this field was prohibited by the Allies until 1950. Nevertheless, basic architectures of radar systems had been evaluated, the principles of pulse- and continuous wave (CW)-radars and their applications for surveillance and target tracking were established and understood. This was a sound basis for a re-start of a newly rising German radar industry. German companies were first allowed to build British and US radar equipment on a licence basis from 1950 on, e.g. for civil air traffic control or maritime surveillance applications.
In the USA radar development proceeded significantly after the war. The area of coherent system operation and Doppler signal processing, for instance, saw many advances. On the other hand, high-power Klystron tubes for the first time enabled coherent locking of a receiver to the transmitted pulse, yielding first MTI-systems to go into operation. Further, the new technique of pulse compression had been combined with coherent Doppler signal processing to achieve fine resolution both in range and Doppler. Another important innovation in tracking radar technology was the monopulse tracking system. In parallel to all theoretical work the increasing availability of new technologies, only to mention semiconductors or microprocessors, were keys for the radar evolution.
As a real milestone the idea of Synthetic Aperture Radar (SAR) needs to be mentioned, introduced by C. Wiley of Goodyear Aircraft Corporation in June 1951. He postulated that extremely high angular resolution of a radar could be achieved by frequency analysis of the received signal of a coherent radar. In July 1953 a group of scientists of the University of Illinois demonstrated first experimental results with a SAR.

In the years to follow, radar development in Europe and worldwide became more and more linked between different countries. Therefore, the further history of radar is no longer traceable on a national basis only. The following sections of the essay will review radar topics of the second half of the 20th century with respect to typical applications and technical milestones.

Air and Sea Traffic Control

A first significant civil post-war radar application was Air Traffic Control (ATC) providing airport and air route surveillance, as well as Ground Controlled Approach (GCA) to enable safe approach and landing of aircraft at night and under adverse weather conditions. A representative ATC radar in use at a number of places in Europe was the *Ground Radar System (GRS)* developed between 1955 and 1957 by TELEFUNKEN. Very impressive was its antenna with a reflector of 7 m x 14.5 m and a weight of nearly 30 tons. *GRS* was operated in L-band (1,250 to 1,350 MHz) with a range of 220 km and a height detection range of up to 16,000 m.
The *SRE-M (Surveillance Radar Equipment-Medium Range)* family is the successor of *GRS* and in operation since 1976 until today. It is equipped with a coherent Klystron-transmitter providing a pulse output power of 2.5 MW. The range against a target with a radar cross-section of 8 m² is in the order of 550 km.

Air traffic control radars *GRS* and *SRE-M*

The largest vessel traffic control system worldwide equipped with radar is installed at the estuaries of Elbe, Weser and Jade in northern Germany. The core of this system called *SEATRACK 7000* is a surveillance radar working in X-band (8.8 to 9.2 GHz) over variable instrumented ranges from 12 to 48 km. A number of up to 200 fixed or moving targets can be detected and localized per second.

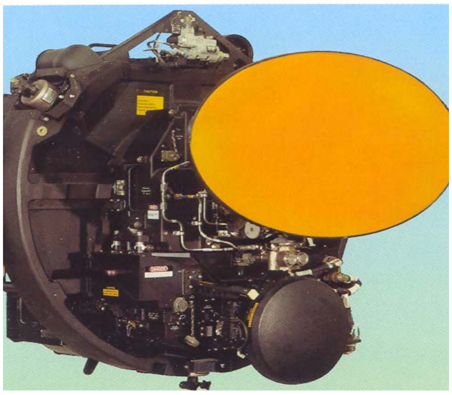
Traffic control center and operating room of *SEATRACK 7000*

Airborne Radar

Military airborne radars for fighter applications belong to the technical drivers in the radar field. The customers demand a number of system issues which are often very hard to harmonize, such as highest performance, low mass and volume, limited power consumption, extreme reliability, redundant functionalities.
The first airborne radars of the post-war time had been members of the "analogue" radar generation. *NASARR (North American Search and Ranging Radar)* was one of the last representatives of them being used in the *F-104 Starfighter.* The navigation- and fire control radar was produced from 1961 to 1966 by an European consortium under licence of the US company Autonetics.

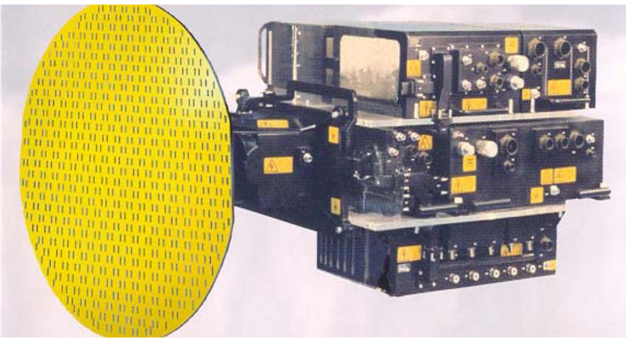
Airborne radar *NASARR* for fighter aircraft *F-104 Starfighter*

The important step from analogue to digital radar was initiated in the mid sixties. The result were radars with almost all system parameters being controlled by software. *APG-65* for the *F-4 „Phantom“* was one of the first digital radars. The later *„Tornado Nose Radar“* can moreover be named a digital multifunctional radar. Different operation modes are available controlled by the radar processor, like air-to-surface mapping, air-to-surface attack or terrain following during low level flight.



Tornado Nose Radar and multi-role aircraft *Tornado*

A high-end multifuntional fighter radar is *Captor* for the *Eurofighter* aircraft. Four nations developed and now build this radar: Germany, Great Britain, Italy and Spain. This also illustrates what has been already said above, the international character of development and production of today’s highly sophisticated radars.
Captor operates in X-band with a flat plate slotted array antenna, mechanically gimballed in azimuth and elevation, and a transmitter equipped with a Travelling Wave Tube (TWT). Signal- and dataprocessor are realized completely digitally. The radar disposes of more than 30 operational modes, like velocity search, track-while-scan, range-while-scan, or terrain profile measurement, only to mention a few of them. *Captor* provides *Eurofighter* with simultaneous multiple target engagement, raid assessment and target identification features.

Multifunctional radar *Captor* and its platform *Eurofighter*

As far as antenna performance is concerned, *Captor* has reached the highest level that can be realized in this technology. However, one system inherent drawback remains: the limited spatial agility of the the antenna beam due to the mechanically moved flat plate array. For this reason, the future of airborne radars clearly belongs to those using electronically steered antennas.

Shipborne Radar

One of the first modern shipborne radars finally becoming a standard equipment of the German Navy was *TRS-N.* After being developed by TELEFUNKEN in the fifties and sixties, a number of 69 sets have been delivered. *TRS-N* was a dual-band system with switchable frequencies of 5.5 and 9.5 GHz. For both frequencies one common antenna system with a parabolic reflector was used. The radar was mostly used for smaller units of the Navy, such as boats for mine-hunting.

Shipborne radar *TRS-N*

Earlier than on board of aircraft the already mentioned technique of radar with electronically steered antenna beams gained a footing in the area of shipborne and land based systems.

Phased Array Radars

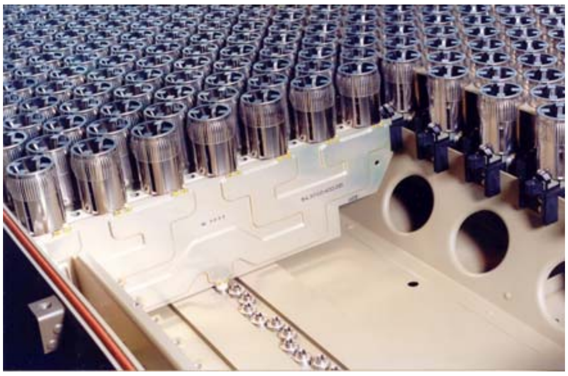
The new generation of radar experiences a quantum leap stepping from mechanically moved to electronically steered antennas. Phased array fighter radars are in a hot development phase presently and on their way to go into service in the near future. In the area of shipborne or ground based radars which are typically less ruled by restrictions with regard to weight, volume, power consumption and cooling issues, phased array radars are standard since a couple of years.

Phased array radars use antenna apertures equipped with hundreds or thousands of individual radiating elements instead of a reflector antenna with one feeding element or a phase fixed slotted waveguide array. Each one of those elements can be manipulated in its amplitude and phase characteristic thus enabling the array to create wavefronts of many shapes. Being of a reciprocal nature, the antenna reveals this ability both for transmit and receive. In practice the antenna beam direction can be moved by about ± 60° while staying within the limits of an acceptable efficiency. Compared to a radar with a classical, mechanically moved antenna a phased array radar offers the immense benefit of being able to switch from one position of the antenna beam to another without preceptible delay.
Two basic types of phased array radars exist. One with a central power generation, a distribution of the transmit power by an appropriate passive network - waveguides for instance - and radiating elements steerable in attenuation and phase. The second and more advanced active phased array radar uses a multiplicity of so-called Transmit/Receive Modules (TRMs), each one of them operating as a complete and highly miniaturized transmitter/receiver frontend with gain and phase being adjustable by an Antenna Control Unit (ACU). This technique yields the state-of-the-art AESA (Active Electronically Steered Array) radar. Over the passive phased array it offers the advantage of a remarkably higher reliability, as its performance is no longer depending on a single power generating element, e.g. a TWT. Thus it incorporates the feature of „graceful degradation“. This implies that from a total of typically 1,000 to 1,500 TRMs in case of an airborne fighter radar, for instance, 5 to 10 % may fail before a degradation of the radar system performance is observed.

One of the first and, besides, an absolutely impressive representative of a land-based long-range/high-resolution phased array radar is *AN/FPS-108 Cobra Dane.* It went into operation in 1977 on Shemya Island near the tip of the Aleutians intended to observe potential Soviet missiles reentering near the Kamchatka peninsula. *Cobra Dane* was developed by the Raytheon Company and operates in L-band (1,215 to 1,400 MHz). A total of 15,360 TRMs covers an antenna aperture with a diameter of 29 m. The radar transmits 15.4 MW of peak power (920 kW average) enabling the surveillance of targets with a range resolution of 1 m in a 120° wide sector and up to a range of 1,000 nautical miles.


Cobra Dane and part of its array

A typical example of a mobile air surveillance radar is *TRMS-3D (Telefunken Radar Mobil Such-3D)* developed during the years from 1971 to 1979. It is a passive phased array radar operating in C-band (4 to 8 GHz) with 4,000 radiating elements forming the antenna which is electronically steered in elevation and mechanically rotated in azimuth. *TRMS-3D* displays up to 4,000 targets simultaneously within a range of 200 km and up to a height of 10,000 m.

Mobile air surveillance radar *TRMS-3D* and a section of its antenna array

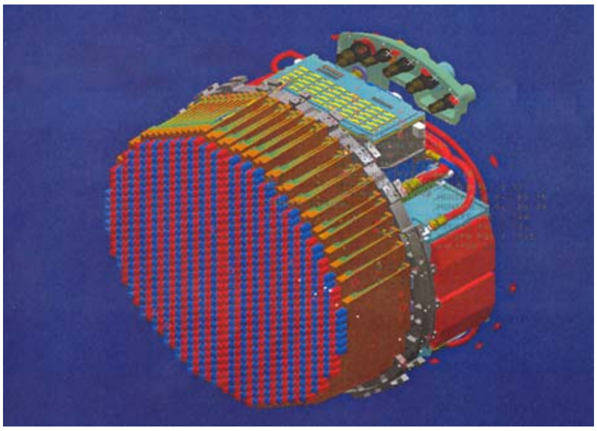
A new generation of 3D-shipborne radar for sea- and air-surveillance came up in the eighties designed on the basis of the existing *TRMS.* These naval radars opened a drastically increased performance for this application compared to existing systems with reflector antennas. In 1992 TELEFUNKEN SYSTEMTECHNIK delivered the first system called *TRS-3D/16* to the Danish Navy for supporting their new ships of the *SF-300* series.

TRS-3D/16 on board of a Danish Navy *SF-300*

An airborne long range surveillance radar is *AN/APY-2* for *AWACS (Airborne Warning & Control System)* developed by Westinghouse. The antenna, a passive phased array in elevation, is rotating together with a so-called *Rotodome* at 6 rpm on a pedestal mounted on top of the fuselage of a Boeing *E-3A Sentry*, the military version of the legendary *B 707*. The stacked waveguide array consists of 28 lines with the same number of phase shifters and has a dimension of 8.0 m x 1.6 m. *AN/APY-2* operates in S-band (2 to 4 GHz) and can track low flying targets up to a range of 370 km based on an own flight level of 10,000 m. *AWACS* went into operation in March 1977.

Boeing *E-3A Sentry / AWACS* and antenna of *AN/APY-2* Radar

The most challenging application for an AESA radar doubtlessly exists on board of a fighter aircraft. Aiming on this application the trinational demonstrator *AMSAR (Airborne Multi-Role Solid State Active Array Radar)* is currently in the integration phase. *AMSAR* is a joint development of EADS (Germany), BAES (UK) and Thales (France). The 60 cm diameter array operates in X-band and consists of 1,000 TRMs in GaAs-MMIC (Monolithic Microwave Integrated Circuit) technology. It features all advantages of an AESA radar, e.g. beam steering at zero delay, adaptive power management, interleaved operating modes. The array configuration provides signal access to several sub-arrays, thus providing the basis for Adaptive Beam Forming (ABF) in receive operation to suppress jammer signals.



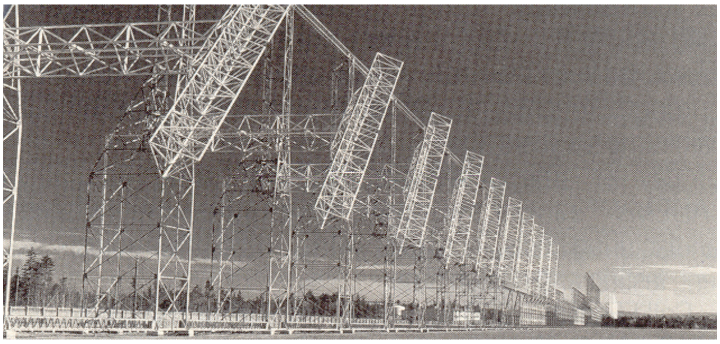
AMSAR demonstrator and X-band TRM

AESA radars installed on ships have meanwhile reached the maturity of being series produced. The German Navy presently equip their frigates *F 124* with the multi-functional radar *APAR (Active Phased Array Radar)* which is a core element of a complex defence system against sea- and air targets. *APAR* is a trinational development programme of EADS (Germany), Thales-NL (The Netherlands) and Nortel (Canada). It consists of four active arrays with 3,200 TRMs each, operating in X-band and covering the complete 360° azimuth plane. Being a multifunctional radar, *APAR* executes a whole range of tasks, such as target search and detection, calculation of target trajectories, estimation of the threat situation, target illumination and guidance of missiles. The first system was installed on the frigate *F 124 "Saxonia"* in the year 2000.

Frigate *F 124 "Saxonia"* and *APAR*

Radar at Extreme Frequencies

Typically radar plays its role at microwave frequencies in the range of 2 to 20 GHz. However, specific radar applications exist in a frequency spectrum ranging from some Megahertz to beyond 100 GHz. Over-the-horizon radar, for instance, operates at frequencies below 30 MHz and makes use of propagation phenomena initially known from HF-communications. Signals at frequencies from approx. 1 to 30 MHz, i.e. wavelengths from 300 to 10 m, can propagate far beyond the „radio horizon“ by help of reflections at conductive ionospheric layers and the earth’s surface.
The *AN/FPS-118 Over-the-Horizon Backscatter (OTH-B)* radar went into service in 1990 at Moscow/Maine, USA, and is a recent representative of this technique. It operates at frequencies from 5 to 28 MHz. The transmitting antenna is more than 1,200 m long, its height varies from 10 to 45 m. A number of 12 transmitters provides 1 MW of output power. The receiver site is located around 150 km away at Columbia Falls/Maine. Within a detection range from 500 to 1,800 nautical miles *AN/FPS-118* is able to detect targets like small aircraft and even cruise missiles.

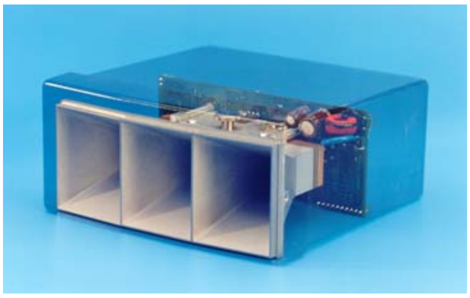


Antenna group of *AN/FPS-118 OTH-B*

On the high frequency end of the radar spectrum, in W-band (75 to 110 GHz), since about 1970 military interests initiated the development of radar seeker heads for autonomously guided missiles and ammunition. Due to the very short wavelengths of only 3 mm quite compact modules can be realized as well as small antennas with relatively high gain. For the standard artillery calibre of 155 mm a prototype of a radar seeker head has been designed and built at a frequency of 94 GHz with a diameter of less than 100 mm.

Flight profile of a terminally guided artillery shell and 94 GHz seeker head

As a spin-off of military millimeterwave radar, commercial applications came up in the seventies with the aim of automobile collision avoidance. As soon as the paralysing „oil crisis“ of those days had left its fright to the automobile industry, the vital interest arose to further fit out cars with high-tech equipment, preferably in safety related areas.
From the beginning, German companies as former AEG-TELEFUNKEN, SEL and VDO were active in this field. Millimeterwave technology increasingly becoming mature at that time offered clear advantages to realize highly miniaturized radars for observing the space ahead of a car and operating independently of day and night or adverse weather conditions. The intention was and is still today to give the driver a well-timed warning of obstacles or other vehicles in a distance that could become dangerous with respect to the present velocity of the own car.



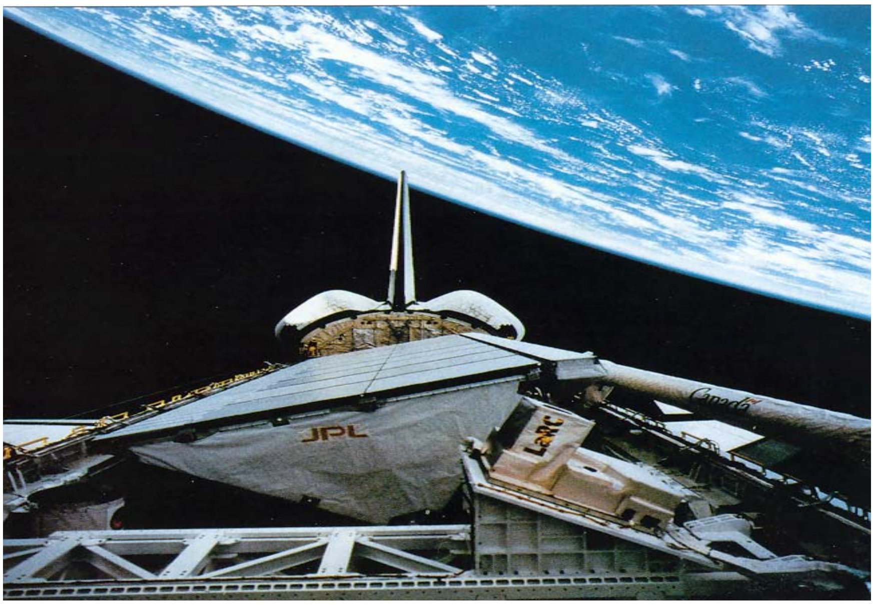
Test with an early 35 GHz automotive radar and later prototype of a 77 GHz frontend

Today these ACC (Adaptive Cruise Control) systems work at 77 GHz, a frequency internationally allocated to this application in the meantime. Their functional basis is, different from classical pulse radar for long ranges, FM/CW (Frequency Modulated/ Continuous Wave) operation with transmit powers of typically 10 mW for ranges from 2 to 150 m. MMICs make very compact and, of predominant interest in the commercial field, affordable systems possible.
It is worth mentioning that ACC-systems will most probably be the first millimeter-wave radars to be really mass-produced. As one of the first car manufacturers, Mercedes-Benz introduced their ACC system *Distronic* at 77 GHz for S- and E-class cars in 1999.

Driver’s view to the *Distronic* display and *Distronic* control unit and radar sensor

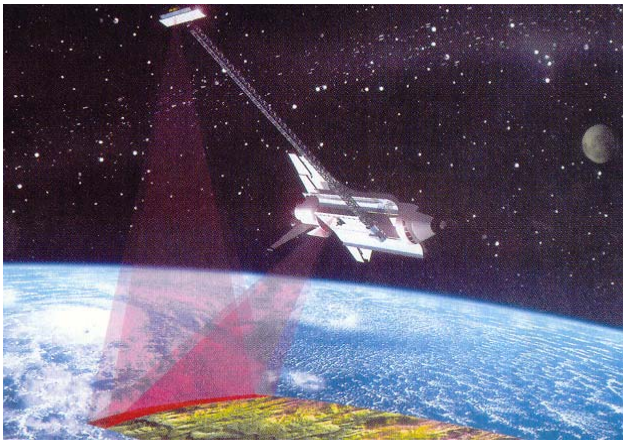
Spaceborne Radar

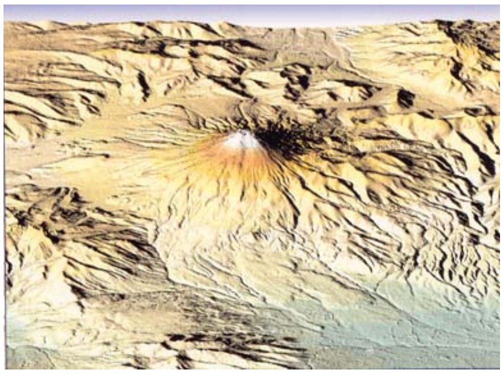
In 1994 NASA initiated the programme „Mission to Planet Earth" with the aim of space-based earth and environmental observation using radar. Space shuttle *Endeavour* was the platform for those experiments. In a co-operation of NASA/JPL (National Aeronautics and Space Administration / Jet Propulsion Laboratory), DLR (Deutsches Zentrum für Luft- und Raumfahrt) and ASI (Agenzia Spaziale Italiana) two Synthetic Aperture Radar systems were developed in C- and X-band: *SIR-C (Shuttle Imaging Radar, Version C)* at 5.3 GHz and *X-SAR* at 9.6 GHz. In addition, an L-band SAR was on board.
For the first time this mission offered the possibility to inquire into radar signatures of earth at different frequencies, polarisations and incident angles over land and sea. All three SARs worked completely synchronously to find identical backscattering geometries, thus yielding the possibility to compare the received signals gathered at different frequencies. The received radar raw data were transmitted to a ground station and processed there in real-time to SAR images.



SIR-C/X-SAR on board of space shuttle *Endeavour*

Six years later, from February 12 to 22, 2000, the STS 99 mission of *Endeavour* was again the platform for a most remarkable radar experiment in space. *Shuttle Radar Topography Mission (SRTM)* was launched with new SAR equipment, however, based on *SIR-C/X-SAR*. From an orbit of 233 km height in average a 3D-cartography of the earth's surface was performed for areas between 60° of northern and 56° of southern latitude; more than 80 percent of the land surface of earth were covered. The total measuring time comprised 222 hours yielding radar data corresponding to the capacity of about 20,000 CDs.

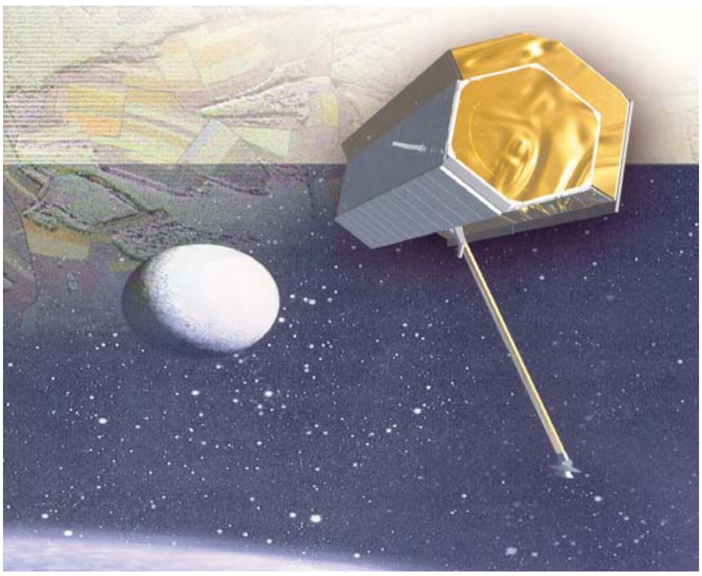




Space shuttle *Endeavour* in *SRTM* and 3D-radar image of Cotopaxi/Equador

SRTM was technically based on an interferometric SAR. Transmitter and receiver antennas of both sensors were located in the shuttle's payload bay, whereas secondary receiving antennas were, in addition, mounted to a 60 m long expounder made of carbon fibre. This was, by the way, the longest structure in space until then. The interferometric system generated excellent 3D-images with a lateral resolution of 30 m and a height resolution of 6 m. Mainly warning systems for aviation will benefit from these information, not available since then, especially of less civilized areas of the world.

The next step of satellite based geo-information will be the mission *TerraSAR*. The project will be realized jointly by Astrium (EADS and BAE Systems) and DLR, responsible for the X-band satellite *TerraSAR-X,* and ESA (European Space Agency) realising the L-band counterpart. The programme *TerraSAR* will be exclusively dedicated to commercial earth observation and is planned to be launched in 2006.



Artist's view of *TerraSAR-X*

Viewing the Future

The ring is closed now from Christian Hülsmeyer's experiments in 1904 to *SRTM* in 2000. Looking back to the radar evolution that took place in the 20th century, the progress is almost unbelievable. However, there are - fortunately - no indications that new ideas of engineers in the radar community will fail to appear in the future.

One of the main visions are Multi-Sensor-Systems, i.e. the merge of radar and infra-red sensors and possibly others in order to join their strengths to a combined system and to avoid their individual drawbacks.
Airborne radars will increasingly have to deal with stealth issues of modern aircraft. The contradiction of an aircraft being stealthy for itself and a radar possibly betraying it by radiation has to be solved; bistatic radar with a receiver on board and a deposited radar-illuminator are under investigation presently.
Radar antennas, may it be on land, sea or airborne platforms, will no longer remain discrete structures covered by radomes but will be realized as Conformal Arrays adapted to functionally given surfaces of the platform. The next generation of AESA radars will consist of more than one array only to cover operationally needed wide scan angles.
Last but not least, digital radar data processing will be enhanced by parallel processing procedures and higher data rates to achieve spatial fine-resolution and sophisticated operating modes.

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