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Some Reflections on the History of Radar from its Invention up to the Second World War

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Electromagnetic Waves – Maxwell and Hertz

In his famous 1865 paper '*A Dynamical Theory of the Electromagnetic Field*' Maxwell derived theoretically his famous equations of electromagnetism which showed that these equations implied that electromagnetic disturbances travelled as waves at finite speed. From the fact that the speed of these waves was equal (to within experimental error) to the known velocity of light, Maxwell concluded with the immortal words:

"This velocity is so nearly that of light that it seems we have strong reason to conclude that light itself (including radiant heat and other radiations if any) is an electromagnetic disturbance in the form of waves..."

In 1887/88, Heinrich Hertz undertook a celebrated series of experiments to discover whether electromagnetic radiation existed as waves travelling at the speed of light. When Hertz discovered that they did, he said *"...Maestro Maxwell was right..."*. The electromagnetic waves that Hertz had generated had a frequency of some 75 MHz – well into the region that we now call *'radar waves'*. Hertz showed that such waves are reflected from metal objects.

But Hertz had not appreciated the use that was to be made, in the future, of electromagnetic waves. We now know that there is a very large spectrum of radiations of different frequencies, from gamma rays to radio waves, with a multiplicity of applications. Radar waves are one of the *"other radiations"* as referred to above by Maxwell. Their frequency is in the radio frequency (RF) part of the spectrum with a range typically 40-600 MHz.

Who invented radar?

It is a much discussed subject as to who should receive the credit for the invention of radar. There are several candidates:

In 1895, in Russia, Popov had developed a system to detect lightning. He had used a spark-gap transmitter and noted the effect on ship targets.

In 1922, in the U.S.A., A. Hoyt Taylor and L.C. Young of the Naval Research Laboratory had found that a wooden ship crossing the path of a 60 MHz radio link produced a detectable effect and patented a system based on this finding.

In 1924, in England, Sir Edward Appleton had measured the height of the ionosphere using reflections of a radio signal (from a BBC broadcast transmitter) received at Oxford.

In 1927, in France, Pierre David had observed similar effects and, in 1930, had conducted further trials, leading to a deployed forward-scatter radar system to protect the naval ports of Brest, Cherbourg, Toulon and Bizerte (Algeria).

In 1935, in the UK, Robert Watson-Watt had a claim to be *'the father of radar'* on the basis of the Daventry Experiment (described later in this article) and his development of a radar detection system (Chain Home) for the R.A.F. in World War II.

But, to the author, the priority for the invention of radar should go to a German, Christian Hülsmeyer, a young engineer who in 1904 built and demonstrated a device to detect ships. He had witnessed a collision between ships on the Rhine in foggy conditions, with significant loss of life, and reasoned that it ought to be possible to provide forewarning using reflection of electromagnetic waves. He patented his idea in several countries and tried to interest shipping companies and navies in his invention. But in this he was not successful – perhaps because they considered that wireless telegraphy, recently demonstrated by Marconi, was all that they needed. And so interest lapsed for a decade or two.

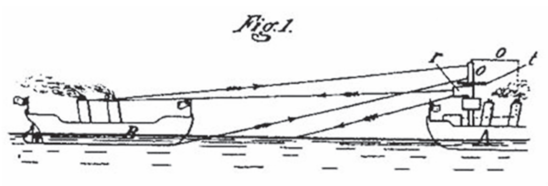

Figure 1: An illustration taken from Hülsmeyer's patent (1904).

Watson Watt and the Chain Home British radar

German bombing of the U.K. during WW1 provided a foretaste of what might be expected in any subsequent conflict. In 1932, Prime Minister Stanley Baldwin stated in an address to Parliament that *"...the bomber will always get through..."* and this prediction seemed to be borne out by R.A.F. air exercises in July 1934 when, for more than half the day, bomber attacks managed to reach their targets without being intercepted by fighters. But a young civil servant, A.P. Rowe, did not believe that such pessimism was necessarily justified and his insistence led to the setting up of the Committee for the Scientific Survey of Air Defence (the *'Tizard Committee'*). This proved to be an extraordinarily effective group of scientists and oversaw much of the early development of radar in the UK.

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In January 1935, Watson Watt had been asked by the British Government to investigate the feasibility of electromagnetic *'death rays'* to disable aircraft. This was largely prompted by the claims of the Hungarian-American, Tesla, that it would be possible to disable entire armies at ranges of 200 miles. In the UK, a prize was offered by the Air Ministry for anyone who could kill a sheep in this way, at a distance of 100 yards. But the sheep were quite safe!

Watson Watt and Arnold Wilkins concluded, in an elegantly-reasoned report, that death rays of this kind were several orders of magnitude short of feasibility; however that detection of aircraft using radio waves should be possible. At almost the same time they demonstrated the detection of aircraft at a range of up to 8 miles, in what has become known as *'the Daventry Experiment'*. By June 1935, they had demonstrated a radar to measure aircraft range.

This led to the development, in the UK, of the *'Chain Home'* radar system. In technical terms, Chain Home itself was primitive: it used a low frequency in the radio wave band (20–30 MHz), with separate transmit and receive antennas and fixed floodlight transmit illumination. The polarisation of the radio waves was horizontal, since it was believed that to first order an aircraft target would behave as a horizontal dipole. The arrival of echoes, both in azimuth (horizontal angular direction) and elevation, was measured at the receiver by means of goniometers (devices to measure angles). The transmitter used a high peak power-pulse (350 kW, later 750 kW) of 20 μs duration and a very low frequency of transmission (between 20 and 30 MHz) and with pulse repetition frequency (50 Hz) synchronised with the frequency of the mains power grid (also 50 Hz) so that all the Chain Home radar stations avoided mutual interference.

A network of such radar stations was established on the east and south coasts of the UK, becoming operational just in time for the outbreak of WW2 and was a major factor in the victory of the Royal Air Force in the Battle of Britain. Figure 2 shows the antennas of one such radar station.

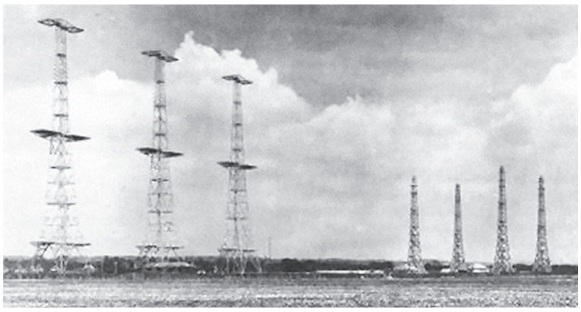

Figure 2: The British Chain Home radar at Poling on the south coast of the UK. The transmit antennas are suspended between the towers on the left; the receive antennas are on the four wooden towers on the right, with each tower initially operating on a separate frequency.

Although the Chain Home radar was basic, its effectiveness was largely due to the way in which it formed part of an air defence system, bringing the information from the individual radar stations to a central control room at Bentley Priory (near London) thus ensuring that the scarce fighter resources were in the right place at the right time. This was recognised afterwards by Churchill himself:

> *"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".*

Curiously, a Graf Zeppelin airship (LZ-130) with signal interception equipment had made an electronic intelligence-gathering mission up the North Sea on 2/3 August 1939, one month before the start of WW2 and had seen the British Chain Home radar stations and detected the signals. But they concluded that the low frequency and the low pulse repetition frequency must be associated with defective insulators on the National Grid or with radio navigation or communications rather than radar - an expensive mistake. It was not until about one year later, in August 1940, that the British radar sites were identified by the Germans as surveillance radars with their quite unique floodlight illumination and were subjected to bombing and jamming, though this was pretty half-hearted and only lasted for a few months and was largely ineffective.

German radars

Freya radar

British knowledge of German radar, at least initially, was equally sketchy. Pulsed signals had been intercepted which might well have been associated with radar. Air reconnaissance photographs showed some unusual objects which were believed to be the antennas of German *'Freya radars'.*

Würzburg radar

This immediately led to air reconnaissance of other potential German sites and, in November 1941, a reconnaissance Spitfire aircraft photographed a site next to a villa on a clifftop on the north coast of France, not far from Le Havre, which had a structure with a dish antenna. The photographs showed the antenna both from the front and the side. This was a *'Würzburg radar'*, which operated at a frequency around 550 MHz.

Moreover, this Würzburg radar seemed only lightly defended and members of the French Resistance determined that the beach below the cliff was not mined. This prompted R.V. Jones, the British Assistant Director of Scientific Intelligence, to propose a daring paratroop raid by dead of night, to dismantle and take what hardware they could and photograph the rest and return to England having rendezvoused with Royal Navy craft at the beach (the *'Bruneval raid'*). The raid was spectacularly successful, bringing back not only several parts of the radar for detailed analysis but also a captured radar operator.

The report on the inspection of the hardware showed that the Würzburg radar was sophisticated, and notably well-engineered. It was built in a modular form (Figure 3) which made fault-finding and maintenance relatively easy. It used an elegant transmit-receive switching arrangement based on precisely-matched lengths of transmission line. Also the selectivity curve (tuning sensitivity) of the receiver was carefully measured, showing its bandwidth and the out-of-band rejection, both these affecting the possibility to jam the Würzburg. The report concluded that jamming the Würzburg would not be especially easy, but equally that it would not be easy for the Würzburg to change frequency in response to jamming, since this required the lengths of the transmission lines to be readjusted. The report presented a calculation that determined that the radiated power from a British self-screening jammer over the whole 531–567 MHz band would need to be at least 12 watts. A British jammer called *'Carpet'* was developed on the basis of this calculation and produced in quantity. It was used with great success through the rest of the war both by Royal Air Force and US Army Air Force aircraft.

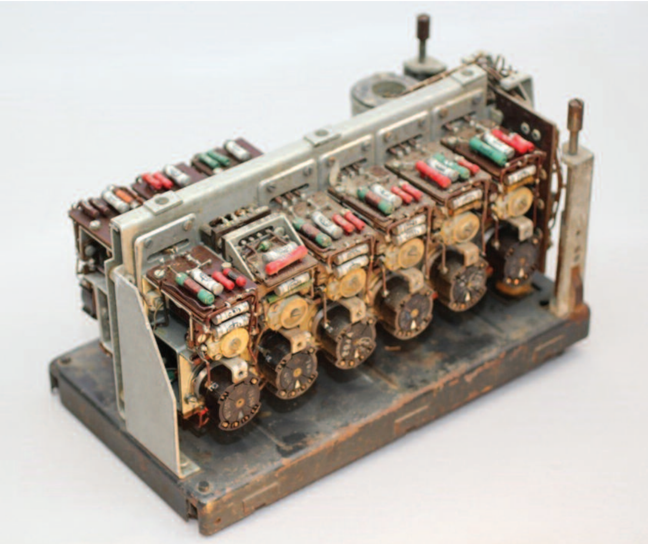

Figure 3: The amplifier module of the Würzburg radar, showing the construction method (photo: Scott Landers).

From the serial numbers on the individual modules, it was possible to estimate the rate of manufacture of the modules to be approximately 100 units per month. It is perhaps remarkable that the preliminary report on the examination of the equipment was dated 24 March, just over three weeks after the raid itself. This is but one example of how such work was treated with the highest priority, with the scientists working all hours possible.

Klein Heidelberg radar

'Klein Heidelberg' was the name of a German WW2 air defence radar which used the transmissions from the British Chain Home radars as its signal source – what would nowadays be called a bistatic radar. It was developed because, from about 1943 onwards, the effectiveness of conventional German air defence radars had been badly disrupted by Allied jamming and other countermeasures. Because it emitted no signal of its own and because the antennas were mounted on existing radar installations, it was virtually undetectable and, in fact, the Allies did not find out about it until late 1944, from interrogation of a captured German radar operator.

The principle of operation of the Klein Heidelberg radar was to measure the difference in arrival time (at the Klein Heidelberg receiver) between the directly transmitted pulse from the Chain Home transmitter (say at Dover) and the Chain Home pulse reflected off the target aircraft. Knowing the distance from the Klein Heidelberg receiver to the particular Chain Home radar station enabled the total distance travelled by the reflected pulse to be calculated. This total distance defined the ellipse on which the target must lie (as, on an ellipse, the sum of the two distances from a point on an ellipse to the two radar stations at the poles of the ellipse is a constant[1]). A measurement at the receiver of the direction of arrival of the echo established the target location (Figure 4).

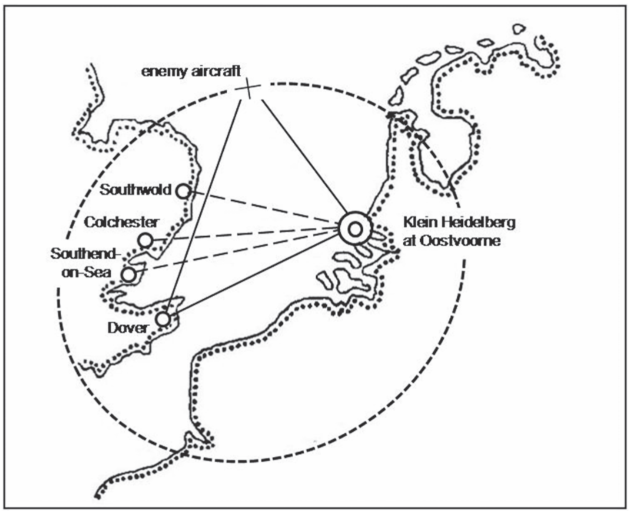

Figure 4: Principle of operation of Klein Heidelberg.

The Germans built six of these Klein Heidelberg radars: four in France, one in Belgium and one in The Netherlands and the reported detection range of aircraft targets was in excess of 400 km. It was ingenious and certainly decades ahead of its time.

The Allies did not know about the Klein Heidelberg radar at the time of the D-Day landings in 1944. They developed a comprehensive plan to attack German radars across the whole of the north coast of France in the weeks leading up to D-Day and, in fact unwittingly, the plan included four of the Klein Heidelberg sites as priority targets. This and the fact that some of these radars never reached full operational status probably explains why Klein Heidelberg was not more effective in the air defence of Germany.

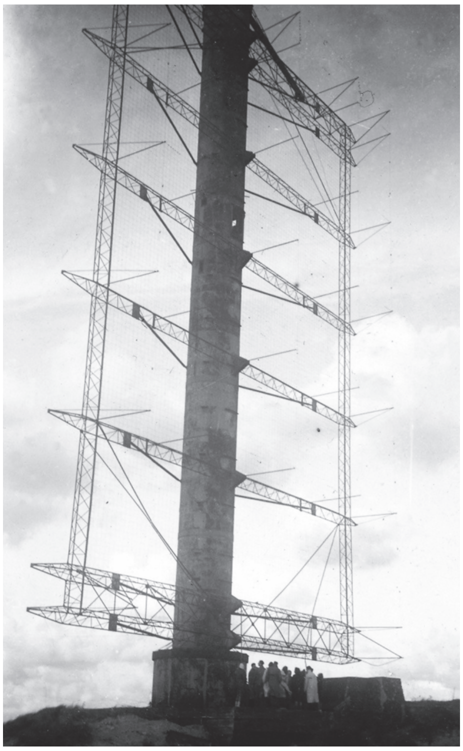

Figure 5: The antenna of the Klein Heidelberg radar at Oostvoorne, photographed in 1947. The size of the antenna can be appreciated by observing the people standing by the pedestal (photo: Jeroen Rijpsma).

1 The use of geometry is reminiscent of Maxwell's first paper to the Royal Society of Edinburgh (when Maxwell was only 14!) where he generalised the drawing of an ellipse by drawing oval shapes where, for example, a piece of string is tied at a pin with the other end of the string being wrapped round a second pin before being tied at the pencil).

Radar detection of the German V1 and V2 rockets

German scientists and engineers devoted substantial resources to the development of the V-1 and V-2 rockets.

The V-1s were the first of the *'cruise missiles'* and were first launched against London in June, 1944 – just one week after the D-Day landings. These *'Buzz-Bombs'* or *'Doodelbugs',* with the characteristic note of their pulse-jet engines, became a familiar threat.

The V-2 ballistic missiles were about 13.6 m in length and 1.65 m in maximum diameter (Figure 6). Their fuel was a 75% ethanol/water mixture with liquid oxygen as oxidant. They carried a warhead of about 750 kg of explosive and had a maximum range of about 320 km. Their development required substantial advances not only in the rocket motor design but also in guidance and in supersonic aerodynamics. A key figure in the project was Wernher von Braun, who after the war emigrated to the United States, where he helped lay the foundations of the U.S. Space Program. The first successful test flight of the V-2 took place on 3 October 1942.

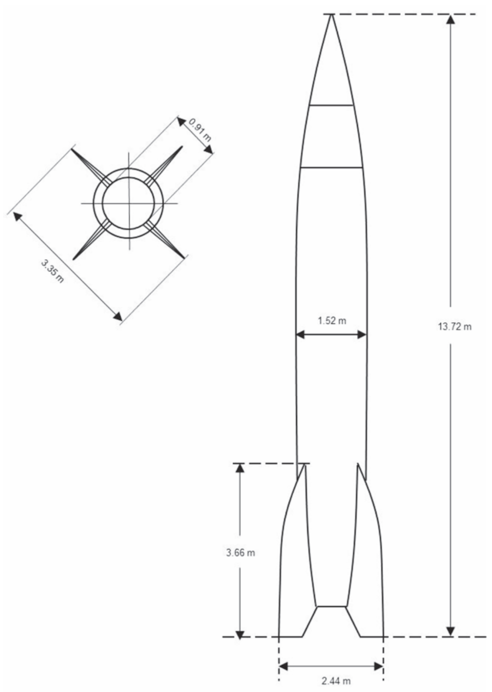

Figure 6: Dimensions of the V-2 rocket.

By April 1943, British Intelligence had found out about the German rocket work. In response, two committees were set up: one to evaluate the size and warhead potential of the projectile and the other to devise countermeasures. The threat was given the codename *'Big Ben'.*

The British were able to estimate the radar cross-section of the V-2 as a function of aspect angle and transmission frequency. This showed that relatively low frequencies were to be preferred since, although the cross-section was less, the echo was broader in angle and hence detectable over most of the trajectory. This must have been one of the first examples of radar signature modelling in this way. Of course, there were no computers, so the calculations would have had to be performed by slide rule or mechanical calculating machines.

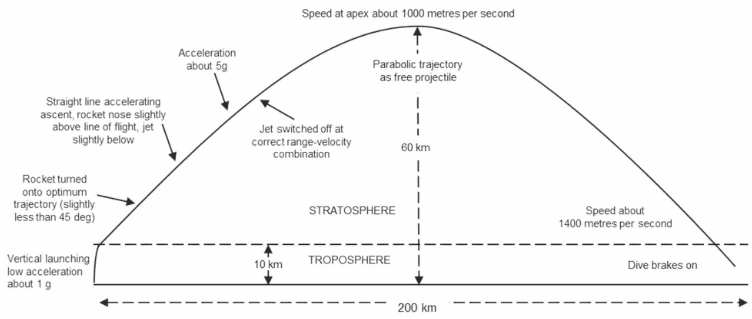

Figure 7: Estimated trajectory of the V-2 rocket, p456 adapted[i].

The preference for a low frequency suggested that the Chain Home radars might be used to detect the V-2s and this was implemented. Special techniques to display and record the echoes were devised, codenamed *'Oswald'* and *'Willie'.* Because the time of flight of the V-2 was only about five minutes (the V-2 coming in at 3,000mph), detection in this way did not provide any useful warning but it did allow the trajectory to be tracked back and the launch point estimated so that these could subsequently be attacked. The same essential principle is used today in weapon-locating radars.

Parts from two crashed V-2s – one from Sweden and one from Poland – found their way to British scientists and allowed them to estimate the parameters and the trajectory (Figure 7). The first V-2s were launched on London on 7 September 1944, by which time the British clearly had a good idea of what to expect. But, unlike the V-1s, due to the supersonic velocity of the V-2s, there was no audible warning of their approach: the first noise was the explosion of the warhead, followed immediately by a sonic boom.

By 7 April 1945, 1,115 V-2s had successfully been launched against the UK. Slightly more than this number were launched from Germany toward targets on the European mainland, notably the Belgian city of Antwerp which was an important port for Allied supply routes.

Conclusions

The study of this period of history provides some unusual and fascinating examples of science and engineering. It is hoped to be able to continue the story in a subsequent piece to cover the post-war and modern eras.

Acknowledgements

I am grateful to many people who have helped by provision of material and through invaluable discussions but particularly to Dr Phil Judkins for his insightful comments and for his friendship and encouragement over many years.

References

Three books about the history of radar from the beginning to its important use in World War II are those by Brown[ii], Swords[iii] and R.V. Jones[iv].

i Griffiths, H.D. (2016), *Early history of bistatic radar,* EuRAD Conference 2016, London, 6/7 October.

ii Brown, L., (1999), *Technical and Military Imperatives: a Radar History of World War II*, Taylor and Francis.

iii Swords, S.S., (1986), *Technical History of the Beginnings of Radar*, Peter Peregrinus.

iv Jones, R.V., (1978), *Most Secret War*, Hamish Hamilton, London.

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