History of Radar

The Instruments of darkness tell us truths, Win us with honest trifles, to betray's In deepest consequence.
Macbeth

Roger Allan examines the growth of radar from a weather system to one of the most important technologies of WWII, including some surprising facts about German research.

Bell Laboratories engineers testing waveguide antennas in New York, 1939. These were discovered by British scientists and were a pioneering contribution to WWII radar technology.

THE FIRST KNOWN usage of radar and radar jamming properties for the purposes of survival occured in Central America a long time ago when the *Melese Laodamia* Moth evolved a system whereby, upon hearing acoustic signals from a bat hunting for its prey, it could reply with signals of its own which effectively jammed the radar. These moths have been in the radar jamming game for some millions of years, and probably started it all.

However radar, as we know it, is the science of locating distant objects by radio and had its beginnings in the very early days of radio. The scattering of radio waves by material objects — the fundamental process of radar — was first observed by Hertz in his classic experiments conducted in 1886 when he demonstrated the existence of radio waves. But it was not until 1904 that the Royal German Patent Office granted a patent to cover the basic radar idea, subsequently patented in a number of countries, to the young German inventor Christian Hulsmeyer. His device comprised a wireless transmitter and receiver mounted side by side, so that:

> "waves projected from the transmitter can only actuate the receiver by being reflected from some metallic body, which at sea would presumably be another ship."

Hulsmeyer called his invention the 'Telemobiloscope' (or the German equivalent), and it was designed to ring a bell whenever the receiver picked up echo signals. As there was then no way in which radio waves could be amplified, his device could not have had a range of more than a few hundred yards at best, and further could not have determined the direction in which the echoes were being received. No one bought a Hulsmeyer Telemobiloscope, and it faded into obscurity.

The Early Days

The first usage of the Hertzian scattering property was by Appleton and Barnett working at Cambridge University in Britain who in 1924 used it to determine the height of the reflecting regions of the upper atmosphere using a process known as the *frequency modulation method.* In this process the transmitted frequency is increased linearly at a definite rate. The wave returned from the ionosphere (the subject of the experiment) at a range R is delayed by a time interval $2R/c$, where c is the velocity of the radio wave. The latter wave therefore differs in frequency from the wave then being transmitted upwards and the two waves incident on the receiver interfere, producing a beat. The measurement of the beat frequency determines the range.

The following year the Americans Breit and Tuve introduced the *amplitude modulation method,* in which they radiated pulses of 1/1000th second duration in a vertical direction. The time of transit of the radio waves being constant and known, they were able to determine directly the height of the ionosphere. This pulse beat method is currently the most practical and widely used, though for some specialist applications the frequency modulation method may still be most appropriate.

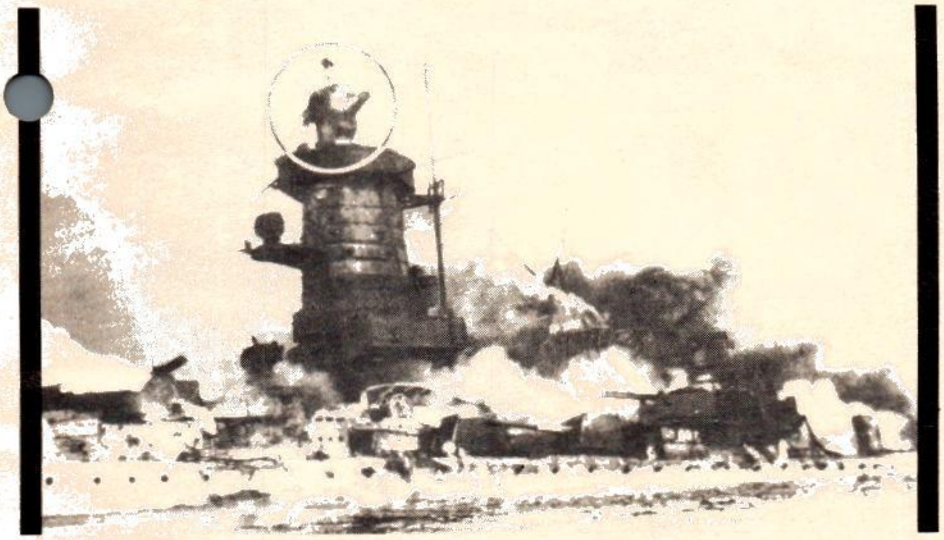
The first reported observation of the reception of radio waves scattered by actual aircraft in flight was made in 1932 by British Post Office engineers, but they regarded this as interference and failed to realize its possibilities.

American and French developments in radar technology prior to and for most of the war years was at best spotty, involving a complicated history of experiment, early total failure and qualified success. As the French developments ended with the fall of France, and the American efforts were largely copies of or improvements on British systems, they will not be mentioned here, other than to say the American efforts were concentrated in the hands of Bell Laboratories and the Microwave Committee of the U.S. National Defense Research Committee.

The British efforts were rather more extensive than their allies, and their story is fairly well known even to the general layman.

Essentially, the development of British radar dates from the establishment by the Air Ministry during the winter of 1934-35 of a committee for the scientific survey of air defence. This committee received, among other suggestions, a carefully worked out plan for the radio pulse-echo detection of aircraft submitted by the Scottish physicist then heading the radio department of the National Physical Laboratory, Robert Watson-Watt, later knighted for his contributions to radar.

The first experimental system of the type proposed by Watson-Watt was set up in the late spring of 1935 on a small island off the east coast of England. By the fall of 1935 the main features of a chain of warning stations to protect England had been worked out, and construction of the first five stations was begun in 1936. By March 1938 these stations, which protected the Thames estuary, and were known as the CH stations (for Chain Home) were complete and under Royal Air Force personnel.



The *Graf Spee* after being scuttled by the German Navy in 1939. The circle shows the radar aerials mounted on the front of the main director tower.

Development then shifted to air-borne radar equipment. Two types were designed: a set for the detection of surface vessels or surfaced submarines by patrol aircraft (called ASV for air-to-surface vessel) and equipment to enable nightfighter aircraft to home on enemy aircraft (called AI for aircraft interception).

An experimental ASV system was successfully demonstrated during British fleet manoeuvers in September 1938. Experimental AI equipment was demonstrated to the Chief of RAF Fighter Command in August 1939, just a month before the outbreak of WWII.

The focussing of radar energy into shaped beams is especially important in the case of air-borne radar, for energy reflected when the radar beam strikes the ground or sea beneath the plane can mask entirely the much weaker echoes of the targets sought. Shaped beams can be obtained by the use of very large antennas or very short radio wave lengths of a few centimetres.

By early 1940 the multicavity magnetron had been developed to the point where it gave about ten kilowatts of pulse power. The invention of this tube made microwave radar practical for the first time.

Wartime radar developments by the British were numerous and far reaching with many different types developed.

Aircraft Warning Systems

The earliest sets used were those of the CH system. These large installations used radio waves about ten metres in length and gave their display on a scope. Target bearing was found by comparing the intensity of the target signal received on one fixed receiving array with the intensity of the echo from the same target received on another fixed array aimed in a different direction: the elevation of a target plus its altitude was measured in a similar way. These CH radar stations remained the principal reliance of the British radar defence during the war, and were used in 1944 and 1945 for the detection of German V-2 rocket launching positions.

The German *Freya* radar site, photographed by the British in 1941. German radar technology was far more advanced than is usually believed, but was not used for the same strategic purposes as the Allied units.

Later aircraft warning sets used shorter radio wave lengths, usually about 1.5 to 3 metres. At this wavelength, a relatively narrow beam can be produced by an antenna array small enough for installation on shipboard, or for use in a transportable ground equipment array. At the same time, the use of a radar beam requires continuous scanning in azimuth in order to cover all directions from the station.

In early 1944 there was introduced a microwave early warning radar, operating on a wave length of 10 cm, which was highly successful. The radar beam produced by this set was only 1° wide in azimuth; in consequence the ability of the set to resolve closely spaced targets on its PPI (Plan Position Indicator) display was very much better than that of earlier equipment having broader beams. The large RAF raids, comprising more than 500 aircraft, could be separated with each aircraft seen separately.

Identification Equipment

When a radar indicator shows echoes from dozens or even hundreds of aircraft, it becomes important to know which of these aircraft are friendly and which hostile. This led to the early development of IFF equipment (Identification Friend or Foe) in which all friendly aircraft were equipped with a transponder which gave a coded response when the aircraft carrying it was in the beam of a radar set. Arrangements were made to display this response on a scope which was either that used by the challenging radar set, or on a special scope associated with the radar. Aircraft showing an IFF response were taken to be friendly, aircraft not showing such a response were doubtful. Either they were hostile, or they were friendly planes whose transponders were out of order or not turned on.

Control of Aircraft Interception

The observation was made by the British that since a hostile plane and a friendly fighter can be seen on the indicator of a single radar, it might be possible for a ground controller, viewing the radar scope, to coach the fighter into position to make an interception. The development of the Plan Position Indicator greatly facilitated such ground control of interception. Special radar equipment, called GCI for Ground Control Interception was introduced early in the war with great effect.

When the Germans abandoned daytime attacks on England at the end of 1940, the technique of ground control became more exacting. It was no longer sufficient to bring the defensive fighters into the general vicinity of the enemy aircraft and then to rely on the pilot's vision to complete the interception. A skillful ground controller could, under favourable circumstances, bring a fighter close enough to his target to enable a visual contact to be made even at night, though with extreme difficulty.

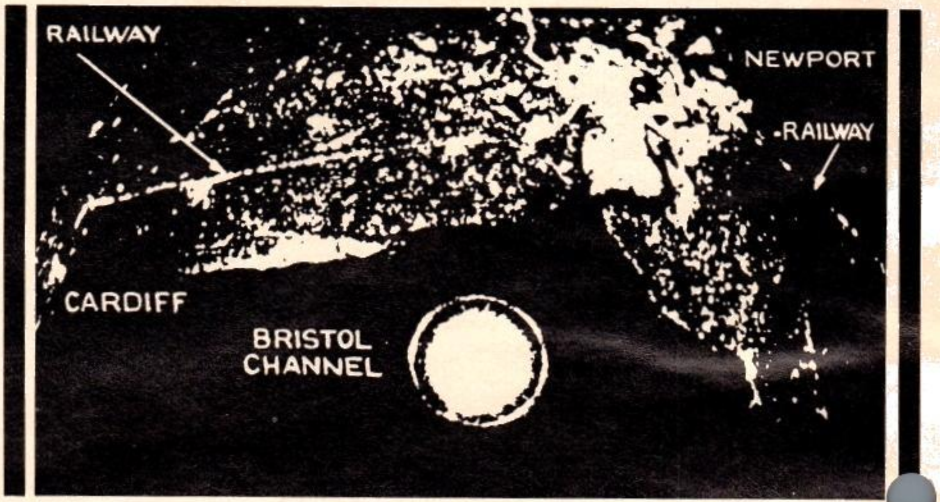
AI Radar

To help overcome the difficulties mentioned above, nightfighters were provided with air-borne radar sets with a range of a few miles. The ground controller coached the nightfighter into a position a mile or two behind the hostile plane, a little below and on the same course. He then instructed the radar observer in the nightfighter to turn on his AI equipment. If the early phases of the interception had been successfully carried out, the hostile aircraft gave a signal on the AI radar and combat was joined.

By the time reliable microwave AI equipment had been developed by the Allies they enjoyed such thorough air superiority that it did not play a major tactical role. The early British 1.5 metre AI equipment used in 1940 and 1941 had many drawbacks, but it was sufficiently effective to enable the RAF to master the night bombing capability of the Luftwaffe.

Air-Borne Radar for Bombing Purposes

During trials of AI and ASV radar it was found that microwave equipment with its narrow beam could give a sufficiently good picture of the terrain beneath the aircraft to enable navigation. Cities and built up areas returned a much stronger signal than open ground, and hills, rivers, railway lines and coast lines were especially well defined. Called H_2S (for Home Sweet Home — the pilots also using it to return to base) the RAF used it to guide its pathfinder aircraft. These pathfinders dropped flares on the target at which the main force aimed by ordinary optical means or by Oboe (mentioned below).



The H_2S radar navigational system. The terrain below the aircraft was shown in sufficient detail to guide the pilot to a target and home again.

Beacon Bombing Systems

Radio beacons give an immediate response to a radar challenge and as such can provide an excellent means for measuring the range to a point whose nature is known. Two such measurements based on a single point enable the exact position of such a point to be found by triangulation. Since range can be measured conveniently and accurately by pulse-timing methods, very precise positions can be determined.

Two different bombing systems were based on this principle during WW II. In one of them, called Oboe, the aircraft carried a radio beacon. The beacon was challenged by two ground stations, and the range of the aircraft from each station measured. Signals were sent to the plane by radio to keep it on a circular course of constant range from one station, called the 'cat'. The other station, called the 'mouse' sent to the aircraft signals indicating the exact moment of bomb release necessary to hit the previously chosen target.

Oboe was highly accurate; with good ground and air crews the operational errors were less than 250 yards from an altitude of 30,000 feet. Its limitations were that, since it depended on the ability of ground stations to see the signals from a beacon in the bombing aircraft, it would not work over the optical horizon (about 250 miles at 30,000 feet), that it demanded a high degree of co-ordination between two widely separated ground stations, and could only handle one aircraft at a time.

In the second type of beacon bombing system, H, beacons were placed on the ground at accurately located spots and the integration and display equipment was carried in the bombing aircraft. Each aircraft could challenge the ground stations independently of all the other planes that might be doing so at the same time.

German Developments

Customary histories of radar, primarily for reasons of national pride, tend to concentrate on British and American efforts, while leaving the German devices pretty much as unknown quantities. In fact, until the latter stages of the war, the Germans had the best of the lot — they just didn't use them as well as they might and didn't have enough of them.

German efforts date back to 1933 when Dr. Rudolph Kuhnold, the head of the German signals research department, while working on sonar, decided that the same sort of process might work for aircraft detection. Initially, Kuhnold's work involved a device which operated on a frequency of 2,000 metres and didn't work — due to difficulties in tube design, his machine only put out 0.1 watt of power. Later the same year, however, the Dutch Philips company designed a tube capable of generating 70 watts — much more powerful than any built before. Rebuilding his device to fit the new tube, Kuhnold in March of 1934 set it up overlooking Kiel harbour and was able to pick up the battleship *Hessen* lying at anchor 600 yards distant.

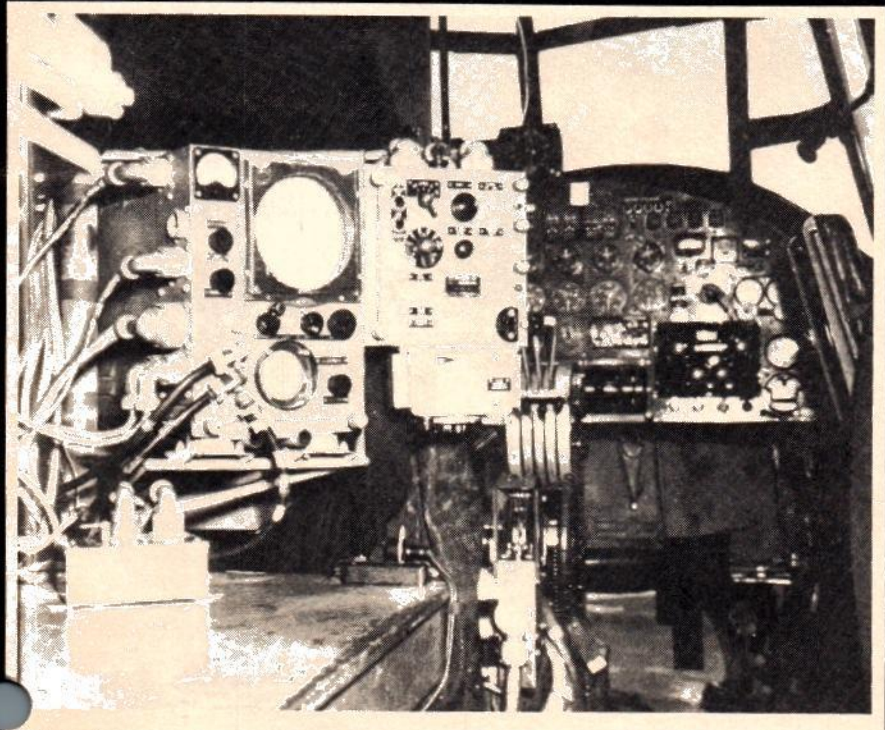
The prototype was improved and set up near Lubeck where Kuhnold ran a demostration for German naval officials, picking up echoes from a ship seven miles away and from a passing sea plane which happened to cross through his beam about 700 yards distant. Impressed, the officials awarded a development grant to the Gema company for further development. In the next ten months, Kuhnold independently invented pulse transmissions and was able, in September 1935, to demonstrate a system to Admiral Raeder which picked up coastlines at 12 miles and ships at seven.

The code name for this device was the DT-Gerat, which ostensibly stood for *Dezimeter Telegraphie* which would link the system with the network of point-to-point wireless communication stations publicised by the German Post Office. In the next year, the Gema company altered the frequency of DT to 150 MHz, extending its range to thirty miles. With further modification, this system became the *Freya* radar operating at 125 MHz — the most important German early warning system up to the middle of the war. The first deliveries of *Freya* to the German navy took place in 1938 and, while providing good early aircraft warning, was useless as a gunlaying device. The Gema company then produced the *Seetakt* version of *Freya* which was mounted on a number of warships, notably the *Graf Spee* and the *Bismarck*.

Not to be left behind, the Telefunken organisation entered the field of radar development, producing the *Wurzburg* radar in 1938. It was a small, highly mobile set with the ability to plot aircraft to within very fine limits at ranges up to twenty-five miles, operating on 560 MHz. It was designed as a gunlaying apparatus.

Comparisons

A comparison of abilities at the commencement of hostilities might be useful. The *Freya* had a maximum range of 75 miles, gave full 360 degree cover and was fully mobile, but it could not measure the actual altitude of approaching aircraft. The British CH had a maximum range of 120 miles and could determine an aircraft's altitude, but it could only gaze over a 120 degree arc and required four 300 foot high permanent transmitter aerials. The *Wurzburg* was small, highly mobile, with a range of 25 miles and the best resolving power of any of the systems.



The H_2S indicator as seen by the navigator of a British Lancaster bomber. Its ability to aid the aircrew in returning to base accounted for its nickname of "Home Sweet Home".

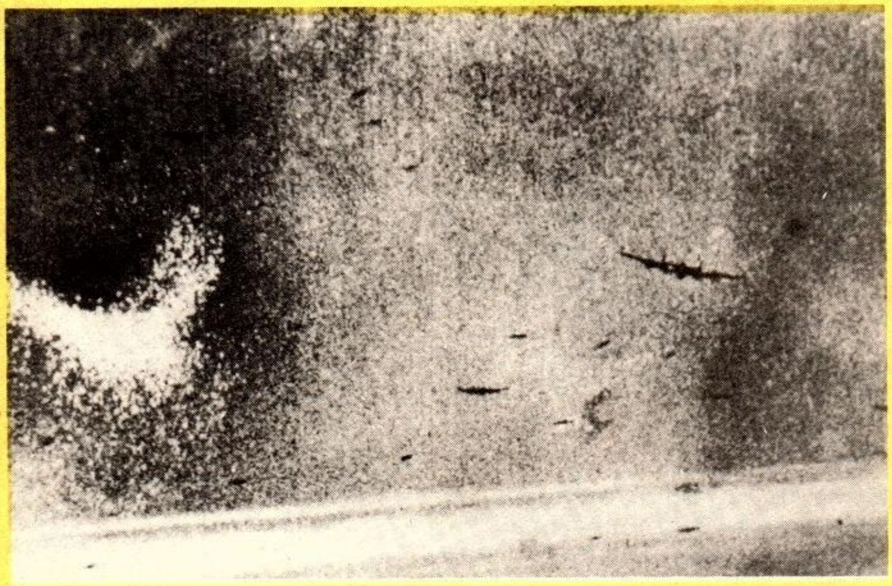
The introduction of the *Wurzburg* gunlaying radar took longer than anticipated, and without radar the gunners still had to seek out their target using searchlights and an optical range predictor. This created problems in usage until the end of 1940 when *Wurzburg* production got in stride and was paired with a *Master* searchlight. In this coupling, the radar would spot the aircraft and automatically guide the *Master* searchlight (which emitted a faint blue colour) which would lock onto the aircraft regardless of what evasive manoeuvers the plane underwent. Four other searchlights, of the customary white colour, would then be switched on and likewise lock on the plane, permitting the flak gunner ample opportunity to fire.

Further, the *Wurzburg* sets fell short of what was required. The trouble was that its range was so short that it was often impossible to find the attacking bombers' altitude in time for night fighters (when not coupled with a *Master)* to reach it, and unless the interception was quickly completed, the bomber passed out of the *Wurzburg's* range unscratched.

Ground reflection also made it difficult to follow aircraft flying below 6000 feet. The Telefunken company set about dealing with these problems, and during the spring of 1941 introduced a new device, called the *Giant Wurzburg*. Essentially, all they had done was to increase the *Wurzburg's* reflector disk from ten feet to twenty-five feet — this had the effect of narrowing the beam width while more than doubling its range, enabling it to detect aircraft over forty miles away. It had a static mounting.

Fighter Control

To convert the range and bearing information derived from the radar into a form in which it could be used by the fighter controller, the German airforce developed the *Seeburg* table. It looked rather like a dias with two



Strips of aluminum foil were dropped from aircraft to jam enemy radar. The strips were cut to a small size, but returned as much radar signal as an entire aircraft.

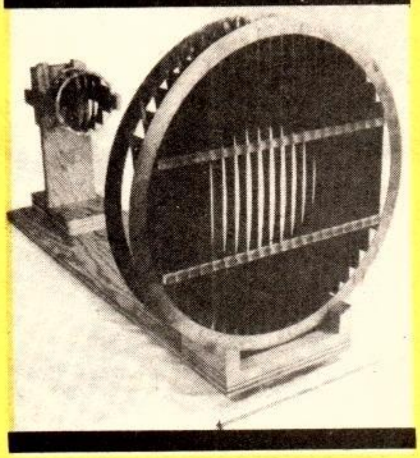
flights of steps leading up to a table at the centre. The table top consisted of a frosted glass screen with a map of the area and a grid painted on it. Beneath this screen was a second table, round which sat two men operating light projectors, one to project a spot of red light indicating the bomber's position and the other to project a blue spot, indicating the fighter's position, onto the screen above. Each man was connected to one *Wurzburg* set by telephone. As the two coloured spots of light jerked across the frosted glass screen, a man at the top of the dias followed them with a coloured wax crayron. The fighter controller could see the progress of the interception and broadcast instructions to the fighter aircraft by radio telephone.

In 1942 it was decided that what worked with *Wurzburg* should also work with *Freya*, and so *Mammut* was built by the I.G. Farben company. Essentially, it was an enlarged Freya with a reflector ninety feet wide and thirty-five feet high — about the size of a tennis court. The structure did not rotate, but found the direction of the target by swinging the beam electronically through a limited arc of 100 degrees. The huge reflector squashed the beam into a narrow pencil, which could reach aircraft 200 miles away.

Like *Freya*, *Mammut* could not measure altitude, and so a second new radar was introduced in the same year, *Wasserman*, built by the Gema company, which gave accurate height, range and bearing of an aircraft up to 150 miles away. It employed an aerial mounted on a rotating tower with a reflector 130 feet high and twenty feet wide. *Wasserman* was the finest early warning radar to be produced by either side during WW II.

In the same year a third new form of German radar was introduced manufactured by Telefunken and named *Lichenstein*. It was an airborne radar, designed to be fitted to night fighters to enable their crews to engage Allied bombers even in the darkest night. It worked on 490 MHz and had a maximum range of two miles and a minimum range of 200 yards or so. The minimum range was important, since fighters had to get quite close to their target before firing. That there is a minimum at all becomes evident from technical considerations: the radar transmits a pulse, and while it does so, the extremely sensitive receiver has to be switched off; otherwise it would suffer damage. The receiver cannot pick up echoes from targets nearby, because the transmitter is still radiating its brief pulse and the receiver is still switched off. This dead distance between the radar set and its nearest visible target is proportional to the length of the transmitted pulse. 200 yards is very good.

The remainder of the war primarily consisted of minor improvements to the basic designs, improvements in aerial configuration, particularly for on-board radar systems, and a decrease in the wavelengths used.



An 18 inch waveguide lens, developed during WWII. These considerably reduced the size of radar aerials for airborne use. The smaller lens behind it is a directional feed.

Typical of the rather peculiar methods which were sometimes employed by wartime British Intelligence in trying to untangle German radar efforts is the story of how Dr. R. V. Jones derived some circumstantial evidence that the Germans had portable radar in 1940. British Intelligence knew that the Germans had a device called *Freya* but what it was no one knew. Jones researched the mythological background of the goddess Freya, and initially came up blank. She was the Nordic goddess of Beauty, Love and Fertility. Jones delved deeper into her background and found that Freya's most prized possession was an exquisite necklace called *Brisingamen*, but to acquire it she had had to sacrifice her honour and be unfaithful to the husband she loved. Heimdal, the watchman of the gods, guarded Brisingamen for her, and Heimdal could see one hundred miles in every direction, by day and by night. Jones reported to the Chiefs of Staff:

"It is unwise to lay too much stress on this evidence, but these are the only facts that seem to have any relation to our previous knowledge. Actually, Heimdal himself would have seemed the best code name for R.D.F. (radio direction finding, eg. radar) but perhaps it would have been too obvious. It is difficult to escape the conclusion therefore that the Freya-Gerat is a form of portable R.D.F.

Freya may possibly be associated with Wotan — she was at one time his mistress — although it would have been expected that Hitler would have in this case chosen Frigga, Wotan's lawful wife."

Strange are the ways of the wartime intelligence community!

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