Death Rays to Dinner: a lighthearted history of microwave engineering in aerospace *

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25/06/2018

1 Introduction

Over the last century or so, microwave technology has gone from an area of nascent scientific interest to a massive industry with applications across modern life. In earlier years, much of this development was associated with RADAR [1], and, thus, with aeronautical applications. This paper aims to present a vivid and light-hearted broad-brush account of this early development, while including a brief summary of subsequent advances in the fields of microwave technology and radar.

2 Beyond the "beep": what is a microwave, anyway?

Put simply, microwaves are electromagnetic waves with a frequency in a range from around 1-100GHz; different authorities give different definitions, but the general idea is the same. As with so many things in engineering, there are many systems of acronyms which all boil down to the same thing, so in this paper we will prefer statements by plain frequency or wavelength.

The uses of microwave radiation range from cooking to medicine and astronomy, but here the main focus will be on communication, navigation and radar.

3 A Problem of Detection

At risk of drifting from the promised field of aerospace, we begin not in the air, but on the water, with a fatal collision on the River Weser (in Northern Germany). [1] One of the dead was from the village of a German inventor, Christian Hülsmeyer. Hülsmeyer was already an enthusiast of "Herzian Waves", as EM radiation was then known; he was also a prolific inventor, filing around 160 patents over his life. [2].

*Submitted for the Royal Aeronautical Society's N.E. Rowe Lecture Competition, 2018.

[1] The capitalised form RADAR is rarely used today. In the areas discussed here it ran under a variety of names, but the American acronym RAdio Detection And Ranging is the best known today.

Figure 1: Hülsmeyer's Telemobiloscope [3]

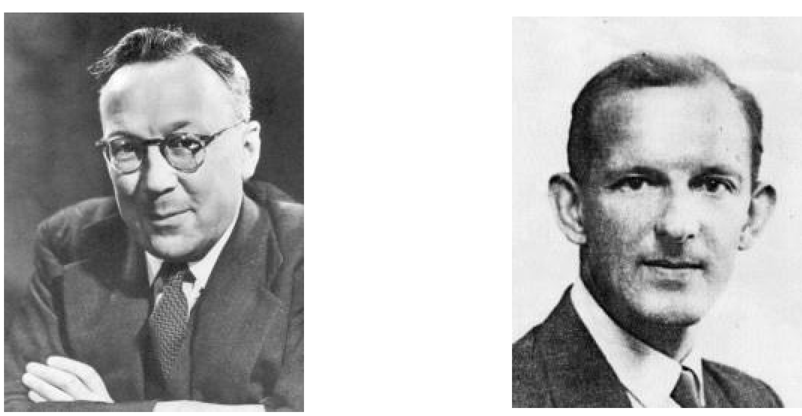
Hülsmeyer's 1904 application was for what he described as his "Telemobiloscope": the British patent application, though, describes very clearly the principle now known as radar, or, as he described it then, "Herzian-wave Projecting and Receiving Apparatus Adapted to Indicate or Give Warning of the Presence of a Metallic Body, such as Ships or Train, in the Line of Projecting of such Waves". [2] Perhaps one can see why later inventors chose acronyms! His earlier patents gave only the bearing of a ship, but he later developed a technique for measuring distance.

For one reason or another, the device never caught on; in a refreshing change from stories of brilliant inventors, Hülsmeyer did not die penniless, but rather made a success of yet more inventions, in the diverse fields of boilers, metallurgy, and light bulbs!

4 Death Rays

In the 1930s, virtually every industrialised nation was working on the problem of radar: Germany, France, Holland, the US, the USSR, and Britain were all at it. (a useful guide to various efforts may be found on Wikipedia, [4]). We will look at the amusing, and, in parts, scarcely believable, story of Britain's radar development.

In 1935, a senior Air Ministry scientific official came across a German media claim of a death ray that could shoot down enemy pilots at significant range. He had his doubts, and asked Robert Watson-Watt, a meteorologist and authority on radio propagation, to investigate the matter.



(a) Sir RA Watson-Watt [5]

(b) AF Wilkins OBE [6]

Figure 2: Two key figures in 1930s British Radar development

Watson-Watt, a noted and busy man, passed the problem to his deputy, AF Wilkins. Consider the back-of-the-envelope calculations Wilkins might have performed: let us say we have an antenna of gain in the target direction G (the effective power density at a point in that direction is G times the power density at that point were the antenna isotropic—in which case the power would be spread equally over a spherical surface with the antenna at the centre).

We assume the pilot is largely water, weighs around 70kg, and has a cross-section of about a square metre; to cause him serious problems we target a 2°C temperature rise; let us also hypothesise that the target aircraft is obliging enough to sit a mere six hundred metres from the "death ray" and waits there, cooking slowly, for a period of ten minutes; the input power the pilot must receive is $P_i = mc\dot{\theta} = 980\text{W}$—no small quantity. The power delivered per unit area is given by $P_i = \frac{P_o G}{4\pi r^2}$ (it decays with the square of the distance from the antenna). This means that the antenna feed power would need to be $P_o = 4.4\text{GW}$ for $G = 1$. For reference, the new £19.2bn nuclear plant at Hinkley Point is to produce a nominal 3.26GW. [7] There is also the problem that, if the antenna were isotropic, everybody else at a similar range would be cooked just as surely as the pilot of our aircraft.

Antenna gain might perhaps save the day, but unfortunately, in 1935, the technology to create any significant amount of power above around a hundred MHz was pretty much non-existent: at lower frequencies, antennas with high gain are very large. To 'win' the scenario above with a believable, if optimistic, continuous power output of $P_o = 50\text{kW}$, an antenna gain of about 49dB would be needed—totally infeasible. This is emphasised when we recall we have assumed all the power is absorbed by the pilot—unlikely—and that he simmers while sitting obligingly still in his aeroplane. Given the difficulty which was encountered in training conventional artillery guns accurately on aircraft in the forthcoming war, the probability of these conditions being true is left to the reader to divine!

5 Reflections

Watson-Watt responded with a memo containing Wilkins' calculations; this showed the death ray idea to be impracticable, but hinted at something more, with a brief note on the use of radio to locate aircraft. [8] In a couple of weeks, a more detailed set of calculations had materialised. It seems probable that Wilkins and Watson-Watt would have used basic optics principles rather than the approach we take here, and thus perhaps obtained a slightly more nuanced answer; for the detail of this, see [9]. It is an accepted truth of the physical sciences that derivations are easier if one knows the expected result, and in the interests of brevity, we will adopt a slightly more straightforward energy-based approach. This should give a close enough idea: Watson-Watt remarked of the reflection calculations he presented: "I am still nervous as to whether we have not got a factor of ten wrong, but even that would not be fatal".

If we let the gain of the transmitting antenna be G_t, the distance to the aircraft r, the target "radar cross-section" (units of area, but also related to geometry, materials etc) be A_t, and the output power P_o, the power impinging on the aircraft is $P_i = \frac{P_o A_t G_t}{4\pi r^2}$. If we imagine the aircraft to be perfectly conducting and metallic, then, for normal impingement of the wave to the surface, all the power will be reflected back (departure from this ideal is often built into the calculation of A_t, and a general loss factor is usually also included). In practice this will be reflected back in an anisotropic way (again usually considered in A_t), but for the sake of simplicity we will assume it is scattered in all directions equally (after all, we are working on the back of a metaphorical envelope). Applying the fact that the power will then again be spread over a sphere, and using an antenna of "effective area" A_r, we obtain a received power $P_r = \frac{P_o G_t A_t A_r}{16\pi^2 r^4}$. An exceptionally convenient relationship between antenna gain, wavelength, and A_e, is derived principally using thermodynamics [10] and states that, for an isotropic antenna, $A_r = \frac{\lambda^2}{4\pi}$; using a receive antenna gain G_r, this gives us "The radar equation":

$$P_r = \frac{P_o G_t G_r A_t \lambda^2}{64\pi^3 r^4}$$

Of great importance in this is the r^4 term: the power is proportional to the fourth power of the range.

In radio communications, the relationship is only as r^2: with radar, the power falls off far more quickly with range. Nevertheless, Watson-Watt and Wilkins' calculations concluded that aircraft detection with radio was very much possible with contemporary technology, and work was soon under way.

6 Biplanes, Bicycles, and ginger Beer

The more detailed memorandum was received by the Tizard Committee, responsible for technological developments of this nature, around 14 February 1935; the first test of the idea was held on the 26th of that month at Daventry, where the signals from the BBC Empire Service short-wave transmitter ($\lambda = 49$m) were successfully used to detect a Handley Page Heyford bomber—the last such biplane in RAF service—at an altitude of 10,000 feet. The humble Heyford, with its fixed landing gear and WW1-style wing struts, was to play another important role in British radar [2] development a few years down the line.

Figure 3: The magnificent (but rather dated) Handley Page Heyford [image is public domain]

"The Daventry Experiment" was met with great enthusiasm by the Air Ministry, Watson-Watt and his merry band of engineers and physicists were posted to Orford Ness, on the East Coast; development proceeded apace. By July 1935, a 40 mile aircraft detection complete with range measurement had been achieved [11], and it became apparent that funding on the order of millions would be needed to progress the system. This required Cabinet-level approval. One civil servant & scientist, A.P. Rowe, noted that, helped by the "persistent urging of Mr Winston Churchill that *something* should be done", approval was gained "readily, after years of starvation,[...] Treasury approval for large expenditures was signified by a nod across the table". While to many the prospect of another war had seemed incredibly remote, the reality—that, to use an anachronistic quotation, "the lamps are going out all over Europe" [3]—was beginning to dawn.

[2] In fact radar was known as RDF, or Radio Direction Finding, during much of the war; this was largely to preserve secrecy, by confusing radar with the navigational technology RDF

[3] Sir Edward Grey, Foreign Secretary, 1914

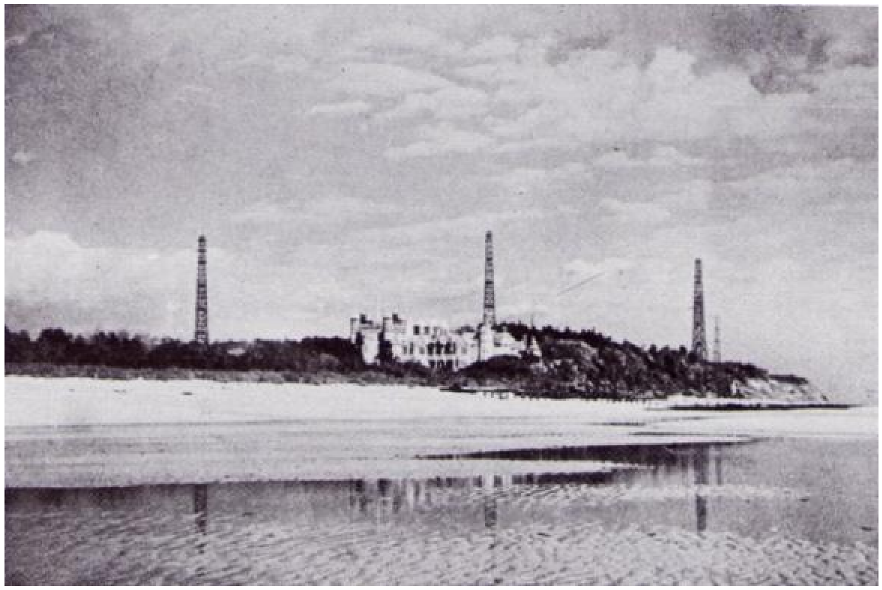
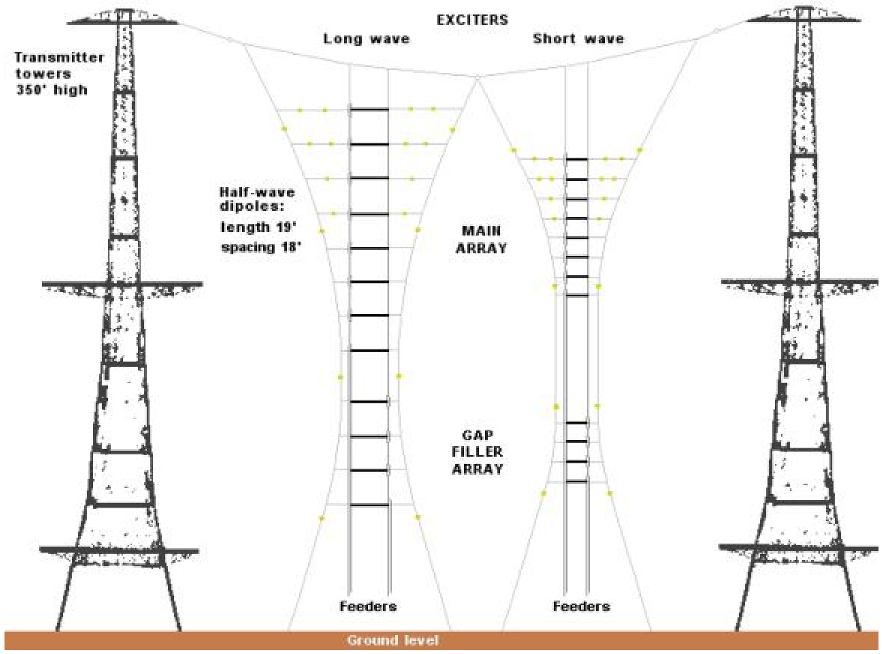


Figure 4: Bawdsey Manor, with some antenna masts in the background [12]

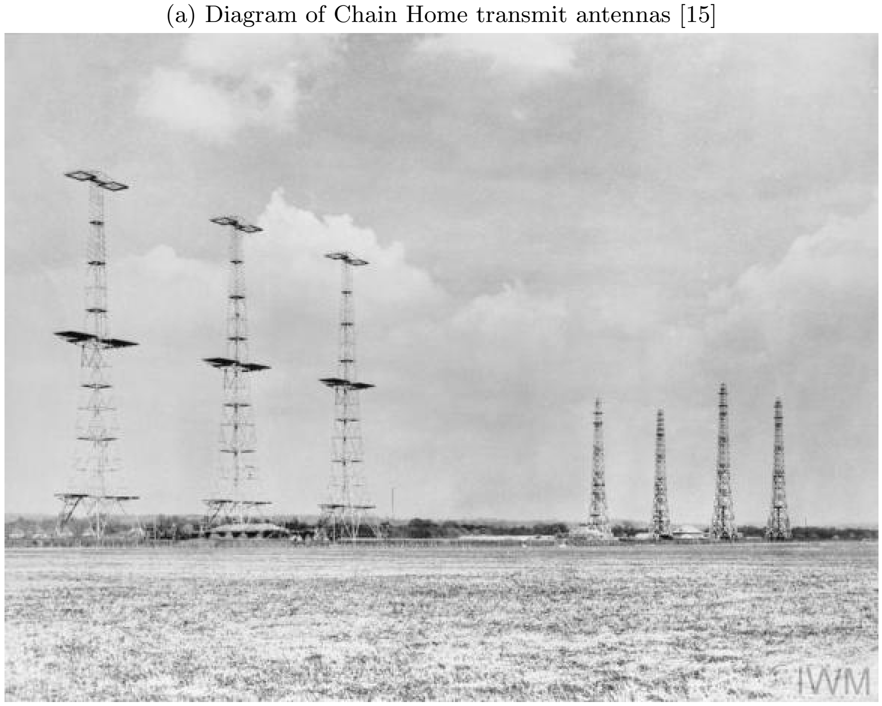
The expansion of the programme continued, and in the late summer of that year, Rowe and a colleague were eyeing up Bawdsey Manor, just by the mouth of the River Deben, as the next location. Requisitioning property was not yet possible, so they retired to a ginger beer stall and heard the gossip that the Manor's owner was looking to sell. The move was made in 1936, and the development of the early warning system known as Chain Home (CH) was under way. On 7 April 1939, Good Friday, this network of stations ranging all the way from the Isle of Wight to the top of Scotland began operation; but alongside this, two other critical developments were the "fruit machine", which automated calculation and reporting of aircraft positions, and the Dowding System, which collated and processed the vast amount of data generated by CH, observer posts and other intelligence, then distributed actionable and clear information to fighter units. [13] It was the Dowding System that featured the plot rooms so often seen in war films.

Figure 5: No. 10 Fighter Group Ops Room, Middle Wallop: the Dowding System in action [14]

CH was not a supremely sophisticated system, and worked at around 30MHz ($\lambda = 10$m). Consequently the antennas were rather large: the transmitting towers were around 350' (107m) high, with two per station supporting a vast array of antennas, and a separate receive array [15]. One of its weaknesses was the lack of coverage at low altitudes, leaving a drastic gap in the battlements of the "castle in the sky". This was plugged with Chain Home Low (CHL), a system potentiated by development of thermionic valves permitting high power output (150kW peak) at shorter wavelengths—here $\lambda = 1.5$m. This featured receive antennas mounted on a small mobile vehicle, which rotated on a fixed mounting; in some early models, the rotation was driven by a WAAF (Women's Auxiliary Air Force) member on a modified bicycle! [16]



(a) Diagram of Chain Home transmit antennas [15]



(b) A photograph of a Chain Home station in Poling, Sussex. Note the three large towers on the left of the image are transmitters and the four smaller (240') towers at the right of the image are the receive antennas, with the receiver station in the middle. [17]

Figure 6: Chain Home antenna systems

7 Battle of Britain—and the Battle for AI

The Dowding system allowed the data produced by CH & CHL to drive fighter intercepts, and this worked excellently during the Battle of Britain: the ability of RAF fighters to remain on the ground until incoming aircraft were detected saved hours of flying time and allowed the (outnumbered) Fighter Command to deploy their aircraft effectively. One official Air Ministry account, from 1941, claims intercept rates from 75-90%—as opposed to 30-50% pre-Dowding. [18]

Soon though, the Luftwaffe switched to area bombing by night: intercept rates for this were initially around 0.5%. Airborne Intercept, AI—radar carried on fighters—was the desired solution. AI is a story in itself, with a primitive version first flying on a Handley-Page Heyford biplane, as used in the Daventry experiment! Radar & AI development changed for the rest of the war, though, with a dramatic breakthrough in 1940 at the University of Birmingham.

8 The Magnetron era

Figure 7: Randall & Boot's original 1940 magnetron core, showing cavities. [19]

The magnetron is a rather mind-bending contraption, in its own way; far from looking like an electronic device inside, it bears more resemblance to some sort of culinary instrument, or perhaps an extrusion die; in fact, it played a great role in ending the war and in Britain's survival. Magnetrons are oscillators which produce microwave radiation at great power, but they are not noted for their frequency stability. They were invented in the US in around 1917, and a greatly advanced and somewhat recognisable patent was awarded to Hans Hollman, one of the key figures in German development of radar, in 1935 [20], but power was limited by thermal constraints. The German programmes believed the magnetron to be far inferior to an amplifier-based signal chain for radar purposes due to the frequency drift between startups and relatively low power output. This last point, though, was blown out of the water in spectacular fashion: in 1940, Randall and Boot, working at the University of Birmingham, produced 400W at $\lambda = 9.8$cm, and in a year had increased the power to 1MW (pulsed). [21] The secret was disclosed to the US, as British manufacturing focussed on immediate war production requirements; the magnetron was described by one US official as "the most valuable cargo ever brought to our shores".

9 RadLab Days

The might of the American industrial complex was thrown behind the project; a special lab at MIT was set up, misleadingly named for a comfortably theoretical research area that could surely have no military application (and thus attract interest from Axis intelligence)—nuclear physics—and so the famous Radiation Laboratory was born. [22] Many of the brilliant minds of American academia were secretly recruited, and research began in earnest into every corner of microwave technology. The ramping up of production of the magnetron and the development of magnetron based radar was a key achievement, but, by the end of the war, the "RadLab" had produced an enormous corpus of knowledge in the field, which was published in a 27 volume series on matters including: waveguides (metallic pipes used to transport microwave energy with very low loss); mixers at microwave frequencies (commonly used devices to change the frequency of a signal for processing); cathode ray tube displays (used for showing results—as in the stereotypical radar display, known as a "plan position indicator"); mechanical computers (for everything from target position estimation to fire control); and servo mechanisms (for antennas that must actively track targets). [23]

10 Bombing: Bad Aim & Bad Eggs

The introduction of "centimetric" (wavelength) radar had an incredible impact on a very important aspect of the war: Wellington bombers equipped with this technology first began hunting the U-boats of the Atlantic in March 1943, after mixed success with lower frequency radar; by June that year, merchant shipping losses had become negligible. [11].

In 1941, the splendidly named David Miles Bensusan-Butt was commissioned to investigate the efficacy of RAF bombing: his results were damning. One in three aircraft involved in night bombing managed to get within five miles of its target, and suggested that many bombs assumed to have been dropped on German cities had in fact landed in open country. [24]

The RAF bristled at this, but a group of "boffins" had been set up in a newly established base in the quiet spa town of Malvern (along with other teams on the South Coast): the Royal Radar Establishment at Malvern survived the war and is still an active defence research site to this day, now run by QinetiQ [25]. This team developed "H2S", the first ground-scanning airborne radar system, and, in February 1943 [11], Bomber Command launched the first H2S enabled raid, on Hamburg. The aircraft fitted with the system, known as "Pathfinders", led larger bombers to their targets and often dropped flares for illumination; the result was significant, though hard to measure—the key advantage was that bombing could be conducted accurately at night and in poor visibility, when fighters found it difficult to catch the bombers—unfortunately this also precluded photographic identification of the bomb site. After the war, R.V. Jones discovered from his former scientific colleague, Carl Bosch, that it had in fact been possible to hear the transmissions from H2S equipped aircraft over Britain from Berlin—and it is was discovered towards the end of the war that some German night fighters had equipment to home on H2S signals—but Jones suggests this did not outweigh the increased bombing accuracy achieved. [8]

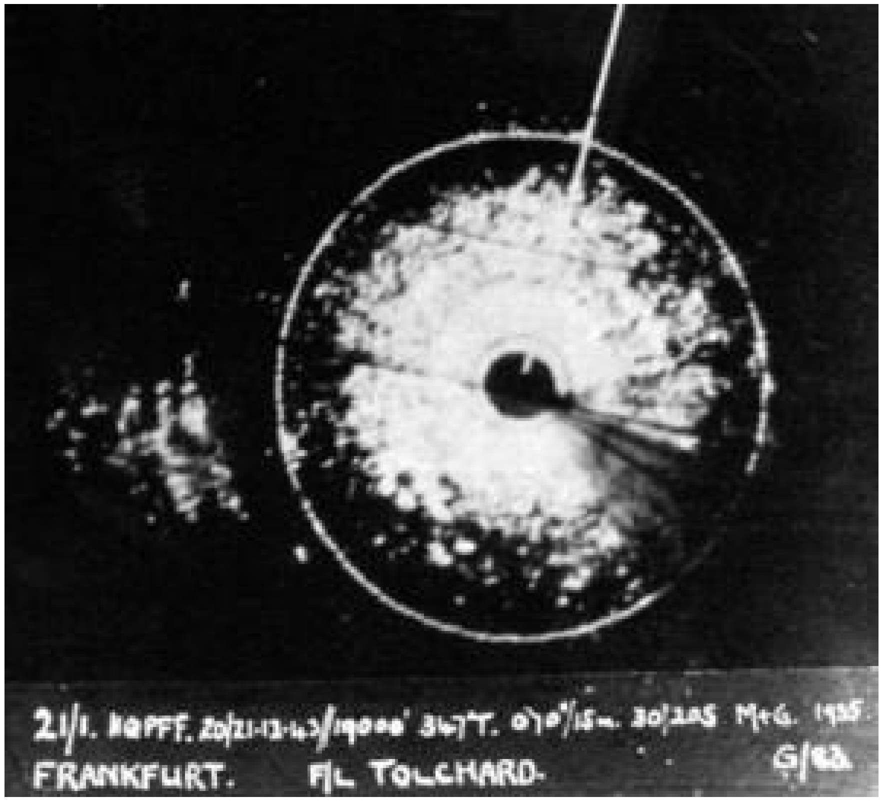


Figure 8: A transparency that could be placed over an H2S display to aid navigation, with annotations. [26]

It would not be unreasonable to ask how the name "H2S" came about: in fact, there are two explanations, the simpler being "Home Sweet Home"—i.e. H^2S. The second, though, fits rather more with the style of humour displayed by so many "boffins". Frederick Lindemann, the top scientific advisor to the Government, had visited the research institute at Swanage and the possiblity of an H2S-like system had been discussed. His reaction was understood to be rather cool, and so when he went back a few weeks later demanding to know what had been done on it, since he thought it such a brilliant idea, he was rather irritated that things had stalled, declaring "it stinks!" H_2S is the chemical formula for hydrogen sulphide, which is known as the gas responsible for the smell of rotting eggs; thus the system was named H2S. Lindemann was later told about "Home Sweet Home" as nobody quite dared give him the true explanation. [8]

11 Dinner

After the war, the field of radar continued to drive microwave technology forwards: one rather more peaceable side effect of high power microwaves soon became apparent. Before the war, demonstrations of "high frequency (HF)" (a mere 3-30MHz—barely alternating current to those concerned with microwaves) transmitters heating food had been made, but the idea went no further, until a Raytheon engineer called Percy Spencer noticed a peanut bar in his pocket heating up as he visited a magnetron testing laboratory. The modern reader may share the author's apprehension regarding what might have happened to Spencer's body if enough energy was being dissipated in his snack to melt it: microwaves in very high doses are known to affect the eyes and the testicles, both of which have very limited cooling blood flow, but although no record could be found of his opthamological health, he is known to have had three children, so it would seem there was no adverse effect in this area! Unfazed by such risks, Spencer continued experimenting, next cooking some popcorn with a magnetron and then proceeding to enclose an egg in a kettle and irradiate it. One of his colleagues, cynical about the whole affair, peered down the spout and ended up, quite literally, with egg on his face: to this day it is known to be a hazardous business to microwave eggs. [27]

Raytheon promptly patented the idea, even going so far as to patent microwave popcorn. [28] The Radarange Microwave Oven was the result: nodding explicitly to its radar heritage in the brand name, it was marketed at restaurants and airliners, but its kin would go on to revolutionise cooking in homes the world over: not entirely without resistance. French restauranteurs were attacked in a 2010 documentary for losing the art of cooking food properly in favour of "nuking" ready prepared food: an award established to reward those using more than 60% fresh ingredients was held by around 3% of restauranteurs.[29] The restaurant critic AA Gill had this to say of one public house in Snettisham: "The menu is, they say, 'a mixture of the traditional with a contemporary twist'. I suspect the twist is the timer on the microwave." [30]

12 Modern Microwave Era

The previous section concludes the premise of travelling through history from "Death Rays to Dinner", but it would be regrettable to omit the enormous and varied improvements which have occurred in microwave applications, particularly in aerospace, since. The 1950s and 60s saw radio used in all walks of life: microwave cooking, of course, but also in such applications as radio astronomy, communications (starting in the 50s, the General Post Office in the UK built an extensive microwave communications network, believing it to be more resistant to nuclear attack than copper cabling [31]), radar for weather, and of course military radar for missile guidance and aircraft use. To give a detailed history of all this is far beyond the scope of this paper, so a very brief run-down of a few key areas, with the occasional anecdote, follows.

Figure 9: The iconic BT Tower [32], built in the heyday of cross-country microwave communications; these antennas were removed in 2011 [33]

In July 1962, Telstar was launched:[34] the world's first communications satellite. It featured travelling-wave tube amplifiers, a sophisticated high-frequency vacuum tube still in use today, and another development to come out of wartime microwave work at the University of Birmingham [35]; the inventor, Rudolf Kompfner, completed a DPhil at Oxford, then moved in 1951 to work at Bell Labs in the US, where he supervised the development of ground stations for Telstar. Unfortunately, the US had also conducted a very high altitude nuclear test, “Starfish Prime”, in July; this produced spectacular artificial auroral light, knocked out telephones on Hawaii, and pumped a great deal of radiation into the Van Allen belts. Telstar and a number of other satellites, including Britain’s first satellite, failed a matter of months after passing through the areas of artificially high radiation. [36] It might be remarked that, while researchers down the ages have often shot themselves[4] in the feet, none before had done so with a thermonuclear weapon.

(a) Telstar. Note the helical antenna at the top of the spacecraft.

(b) The seconds after Starfish Prime

Figure 10: Telstar, and the nuclear test that knocked it out. Telstar image from Wikipedia; Starfish Prime image from Los Alamos Nuclear Laboratory. Both via [37]

The revolution which perhaps had the most impact on our modern microwave world was the transistor: the first transistors appeared in 1947, but it was not until the 1960s that the technology advanced sufficiently for microwave frequency use. [38] The vacuum tube had developed substantially too, but the large glass devices were never bound for portability. In 1971, H.F. Cooke remarked “Microwave transistors are useful as small-signal amplifiers to 6 GHz and power amplifiers to 4 GHz” [39]; microwave power amplifiers are now common far beyond this, and quite possible to at least 100GHz, for example [40]. Microwave transistors are commonly manufactured on substrates like gallium arsenide, due to higher electron mobility (an important metric in transistor substrates) than silicon; unfortunately the cost is also dramatially higher. The enormous demand created by cellular communications, television broadcast, radar, and other microwave applications in recent years has produced impressive results even on silicon: high power silicon amplifiers up to and beyond 2GHz are now commonplace; for an overview of some of this technology, see [41].

13 Radar developments

Before concluding, a brief overview of three important developments beyond the wartime work in the specific field of radar and radio astronomy will be given.

In general radar operation, one of the challenges is to separate out “clutter” (for example waves at sea, ionospheric reflections, buildings etc) from “targets” (for example ships or aircraft). A plenitude of techniques are used for this today, and some feature measurement of “Doppler shift”. The well-known Doppler

[4]The US military was deeply involved with both Starfish Prime and Telstar.

effect, that a frequency shift in signals from a moving target occurs proportional to the radial velocity of this target (i.e. the rate at which the target moves towards or away from the observer), may be used to identify targets with a particular velocity. This has long been a common technique to detect even weak returns which might normally be drowned out by clutter. [42] As in all of this section, it has been greatly facilitated by the increase in computing power brought about by the microprocessor; by the 1970s, the bulky and complicated analogue filters and mixers used for detecting the (small) Doppler frequency had been replaced with digital fast-Fourier transforms. For a detailed discussion of one example of digital radar and its performance, see [43], a performance analysis of the F-16's pulse-Doppler radar. Perhaps a better known application, though, is in meteorological radar, where Doppler measurements are used to ascertain cloud structure and wind velocity, even at the heart of tornadoes. [44]

Another problem in radar has been known to astronomers since the 19th century: there is a fundamental limit on resolution of observations caused by diffraction, known as the Rayleigh Criterion. When an electromagnetic wave diffracts through an aperture (such as an antenna or a telescope), a pattern of maxima and minima (a "diffraction pattern") is generated through interference. For a circular aperture, this takes the form of Airy Disks. The minimum resolvable angle is the angle subtended by the first order maximum (such that if the object were smaller, diffraction effects would prevent its resolution). Although the precise form of the equation varies with the shape of the aperture and hence the arrangement of the diffraction pattern, a representative form is that for a circular aperture, for which, in approximate terms, $\sin\theta_r = 1.22\frac{\lambda}{d}$, where θ_r is half the minimum resolvable angle, λ the wavelength and d the aperture diameter. [45] The key relation is to $\frac{\lambda}{d}$; as we reduce the wavelength, the resolution increases (i.e. the resolvable angle decreases). Similarly, increasing the aperture size improves the resolution. Unfortunately, in aviation use, though the wavelength may be varied (and indeed shorter wavelength is seen to lead to higher resolution), it is fairly obviously impossible for the size of the aperture to exceed the size of the aircraft—right? In fact, this is exactly what "Synthetic Aperture Radar" (SAR) does. Although the mathematics and signal processing practicalities of SAR are rather beyond the scope of this paper, the core principle is to make multiple coherent observations as the aircraft moves and then process them together to give a single image. Thus, the "aperture" is in fact related to the distance traced out by the aircraft during the observation process; far greater resolution may thus be obtained at reasonable wavelengths. This is typically used for ground scanning radar. Similar techniques are used on spacecraft and in radio astronomy; for more information on the techniques involved, see [46].

The final key development is in antenna design: since shortly after Chain Home, which was somewhat forward-looking in a sense by employing a fixed array of antennas and using phase to determine target bearing, the stereotypical radar system has featured a large rotating dish, as often seen on top of air traffic control towers. In reality, however, many modern systems are partially or completely free of mechanical rotation, instead employing a large number of small antenna elements fed with phase differences. In much the same way as the diffraction pattern which brought about the Rayleigh Criterion, the signals from each antenna superpose destructively in some directions and constructively in others, thus creating a directional antenna. Since the phase differences may be altered, the beam can be scanned electronically—this allows very quick movement of the beam. In modern systems, each antenna typically has an integrated power amplifier, phase shifter, and receive amplifier, with the corresponding signals being passed on for processing [47]. This system is known as an AESA, or "Active Electronically Scanned Array". One currently developed European AESA is CAPTOR-E, expected to enter service as an upgrade to the Eurofighter in the next few years [48]. Although of course the full details of this system are classified, a broad outline which is likely to be similar is given in [49]: the radar unit will consist of around 1500 transmit/receive modules in a circular pattern. As one might expect, it will feature synthetic aperture image processing for air-to-ground working, while the system is described as "the most advanced multi-mode pulse-Doppler radar of its generation".

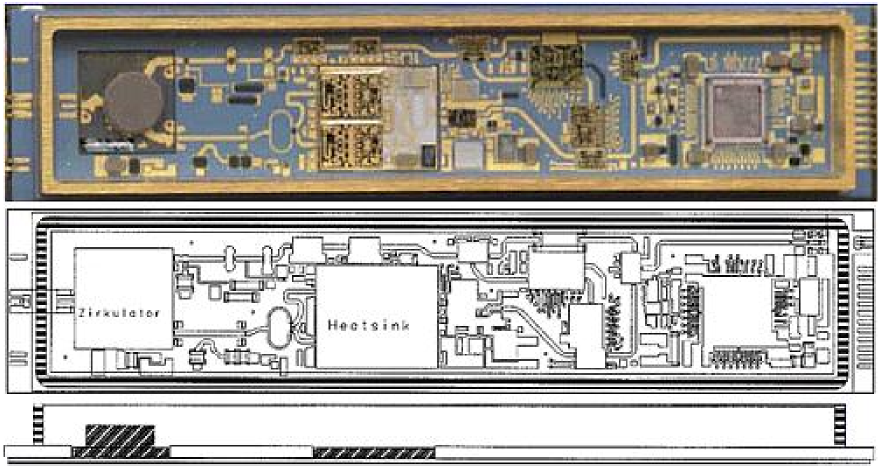


Figure 11: A single T/R (transmit/receive) module from the CAPTOR-E programme with diagram annotated in German. The antenna connection is on the left; the circulator (Zirkulator) isolates the transmitter from the receiver. The two darker coloured chips in the centre of the photograph are the transmit power amplifier transistors. The whole unit is only 64.5mm long. [50]

14 Death Rays—revisited

In the last couple of decades, the death ray discounted in the 1930s has to some extent been revisited: the US Military's Active Denial System (ADS) uses an extremely high frequency oscillator called a gyrotron, rather resembling Randall & Boot's magnetron in function—but not operating principle. The gyrotrons used in the ADS have an output around 100kW [51] [52] and require an electrical input power of about 200kW. There has been some speculation [53] that even this application could be transistorised in the near future.

Though impressive by 1930s standards, these figures are still far below the power we calculated for our 1930s death ray, assuming an isotropic antenna—but there is an important difference. The ADS operates at around 95GHz, $\lambda = 3.2$mm: its large dish antenna can have very high gain. The high frequency also has the desirable consequence that the RF energy penetrates only a few tenths of a millimetre into the skin, causing little or no lasting damage, but enough pain to "deny" the enemy the area. ADS is claimed to have a range of a around a kilometre, so in this respect it is similar to the death ray considered back in the 1930s—simply less fictional. It has one other similarity: it has yet to see the "heat" of battle. [53]

The US Military has also developed a rather different concept of death ray, more akin to those visualised by science fiction authors down the generations: a massive laser. This is rather bulkier than the ADS, the latest versions of which can be mounted on a small armoured vehicle, but has been deployed for some time on a warship in the Persian Gulf. [54]

(a) The Active Denial System on a small lorry [US DoD]

(b) Laser Weapon System, LaWS, aboard USS Ponce [US Navy]

Figure 12: The US Military's Directed Energy Weapons

15 Conclusion

Over the course of this paper, the development of microwave technology has been followed from Christian Hülsmeyer's Herzian-wave based ship-detecting device, through the British strand of Chain Home and Airborne Intercept, into the magnetron era of centimetric radar, and then into the post-war age: microwaves allowing civilians to watch television across the Atlantic via satellite—perhaps a weather report generated with the aid of Doppler radar and discussed over a microwave cellular phone connection—while the popcorn crackles in the microwave oven. Outside, grizzled fishermen may look for flocks of birds feeding on a school of fish with their radar, while air traffic controllers or harbourmasters monitor their respective charges electronically. Fighter aircraft strive to detect one another with ever more sophisticated signal processing techniques, while radio astronomers use aperture synthesis to peer ever harder into the mysteries of the universe. In the near future, expect to see microwave radar appearing in relatively affordable cars, as it already has in the high-end market: whether it is detecting the car in front on the motorway performing an emergency stop and automatically applying the brakes, or allowing the car's computer to execute a perfect parallel park, microwaves will continue to proliferate. In military aerospace, ever more sophisticated radar and communications systems will continue to be developed, as the struggle for and against stealth rumbles on apace. Throughout the hype, though, it will do no harm to have a solid understanding of the history and development behind the system: nor to remember the days when microwaves really did go "from death rays to dinner."

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