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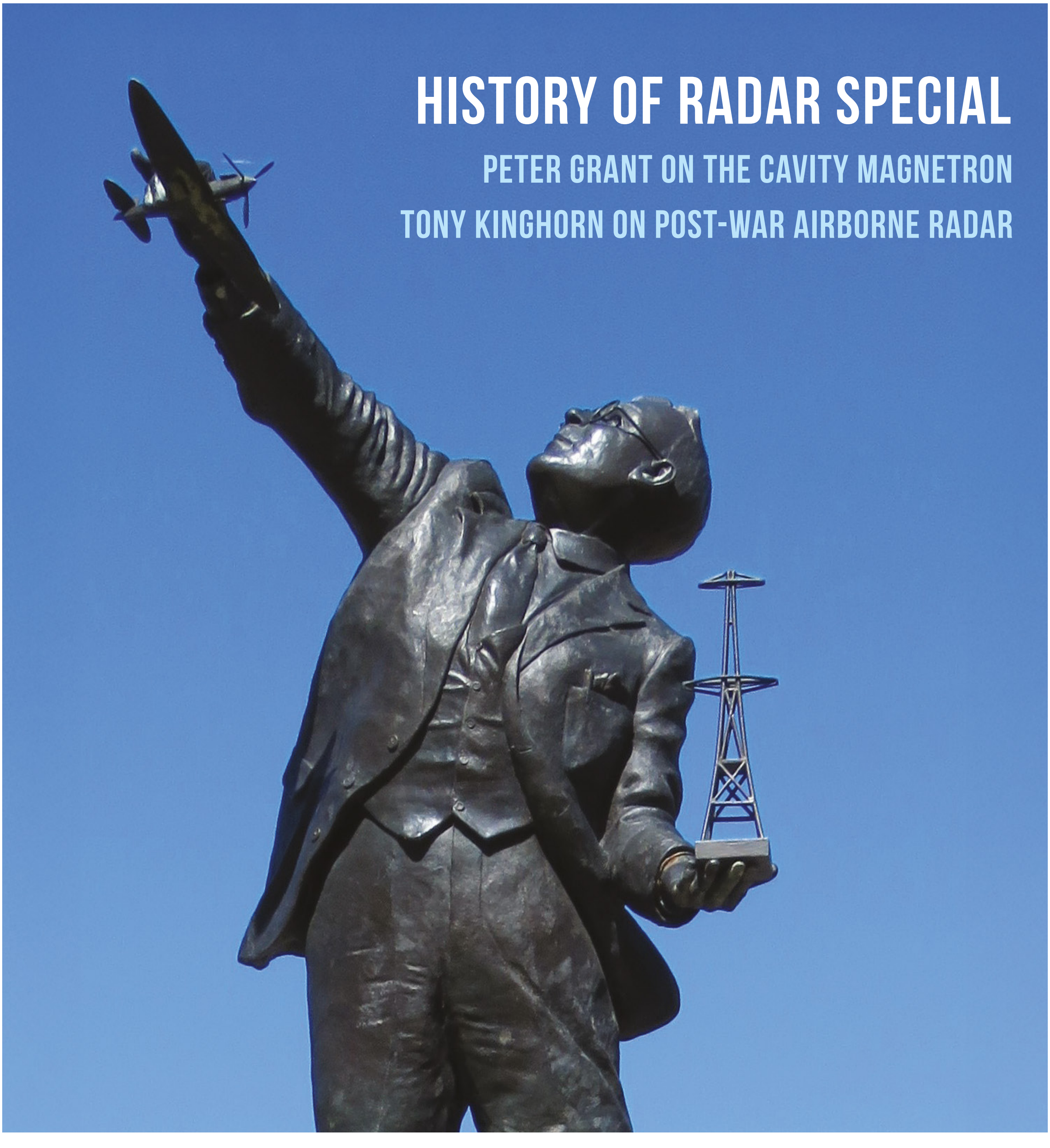
The Maxwellian

THE JOURNAL OF THE JAMES CLERK MAXWELL FOUNDATION



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EDITORIAL TEAM

FROM THE CHAIR OF THE JAMES CLERK MAXWELL FOUNDATION

Dr David Kerridge

It's a great pleasure to introduce the first issue of *The Maxwellian*, the successor to the *James Clerk Maxwell Foundation Newsletter*.

A prime objective of the Foundation is to raise awareness of James Clerk Maxwell's life, his remarkable personal scientific accomplishments, and his influence on others who have advanced scientific knowledge and understanding. *The Maxwellian* will play an important role in realising this aim. Maxwell's equations of electromagnetism underpin a myriad of technologies central to modern society and this issue of *The Maxwellian* includes articles describing the development of radar.

Another asset to the Foundation for its ambitions to 'spread the word' about Maxwell is its ownership of Maxwell's birthplace at 14 India Street, Edinburgh. We run weekly guided tours for small groups, often including visitors from all around the globe, and around 300 members of the public visit over the Edinburgh Doors Open weekend in September each year. In 2024 we have also hosted 12 larger group tours including visits from schools. The books and documents held in the Foundation's library constitute a valuable resource for research.

For those who don't have the opportunity to visit India Street the Foundation's website provides a portal to a wealth of information on Maxwell and his life and science. A recent addition is a link to an online version of John Arthur's book, *Brilliant Lives: The Clerk Maxwells and the Scottish Enlightenment*, detailing the lives and many achievements of Maxwell's forebears. Website visitors can take an interactive virtual tour of 14 India Street, and this capability will soon be extended to other locations significant in Maxwell's life, both in Edinburgh and close to the family estate at Glenlair in Dumfries and Galloway.

I hope you will enjoy reading this inaugural issue of *The Maxwellian* and look forward to receiving future issues.

FROM THE LEAD EDITOR

Dr Chris Pritchard

As we launch this new journal, we should not forget the admirable service of the Editor of its forerunner, David Forfar, who oversaw nineteen issues of the Foundation's *Newsletter* over a twelve-year period from early 2012. It is not our intention to simply continue in the same vein but to expand our horizons to feature a broader spectrum of material, though we will rarely deviate far from James Clerk Maxwell's life, contributions to science and influence.

Although I have the privilege of leading this enterprise, working with me is a team with considerable expertise and experience in physics, physics education and physics exposition. They are Dr Catherine Dunn of SSERC (Scottish Schools Education Research Centre), Dr Howie Firth (writer, broadcaster and Director of the Orkney Science Festival), Professor Peter Grant (formerly of Edinburgh University) and Professor Martin Hendry (of Glasgow University). I came to the Foundation as a historian of mathematics with a particular interest in Maxwell's friend, Peter Guthrie Tait, and to editing through similar ventures with mathematics education bodies.

As to our agenda, we hope to include material at a variety of levels, some of which will be accessible to senior school students, certainly to undergraduates, teachers, those involved in the public engagement with science and interested amateurs. In due course – it won't happen all at once – we will include book reviews, items in the news (such as breakthroughs in science and the announcements of awards). We will ask experts in their fields to write on specific topics but would also encourage readers to approach us if they have ideas for an article they wish to submit. At the moment we expect to publish two issues of *The Maxwellian* per year.

This inaugural issue features articles on the history of radar and, in particular, the cavity magnetron. The development of these technologies was made possible by Maxwell's work on electromagnetism. Peter Grant takes the story up to the Second World War and Tony Kinghorn extends it to the present day, specifically with regard to airborne systems. We hope you will also find worthwhile a review of Bruce Ritchie's new biography of Maxwell which looks at his faith, his physics and the interplay between them.

THE CAVITY MAGNETRON

The Revolution in Microwave Energy Generation

By *Peter Grant*

Introduction

James Clerk Maxwell produced the first theory for electromagnetic waves in 1865, and later, after Maxwell's death in 1879, Heinrich Hertz provided, in 1888, the first practical demonstration of the generation and detection of these electromagnetic waves using a spark generator [1]. Guglielmo Marconi then further applied electro-magnetic wave propagation to radio communications, culminating in his first transatlantic transmission of the Morse coded letter "s" in 1901 using a spark generator in Cornwall and flying the Canadian receiver antenna on a kite.

Subsequent communication systems became more efficient when the transmissions used a specific frequency, rather than the wide range of frequencies generated by the spark transmitters. Early communication systems typically operated at frequencies in the range 1-20 MHz. Today broadcast radio ranges from 1-100 MHz (for FM radio) while mobile cellphone systems generally operate at 1,000-5,000 MHz and beyond.

In February 1935, the Daventry radar experiment, conducted by Robert Watson-Watt, detected the presence of an aircraft by using reflected radio waves. Watson-Watt was born in Brechin (Figure 1) and studied at the then University College in Dundee. During WW2 he became Scientific Advisor on Telecommunications to the Ministry for Aircraft Production, travelling to the US to advise on the severe inadequacies of its air defence. He was knighted in 1942 and is buried in the yard of the Episcopal Church of the Holy Trinity in Pitlochry.

Fig. 1. Watson-Watt statue in Brechin
(Image: K. Dickin, CC BY-SA 4.0. Wikimedia Commons)

In December 1935 the Chain Home (CH) radar system was designed to cover the approaches to the Thames Estuary, identify the presence of incoming hostile aircraft and direct their interception by fighter aircraft [2]. This system used 100 kW to 1 MW high energy pulses generated at 20-50 MHz and the system was later extended to cover nearly all the UK coastline. Compared to today's radar systems this was a rather basic design with tall wooden and steel towers supporting the physically large antennas (Figure 2). By 1940 the coverage had been extended to the British east coast, Figure 3.

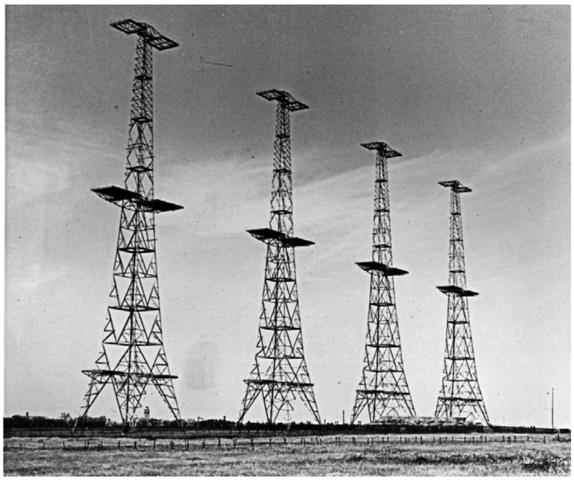

Fig. 2. Chain Home radar towers at Swingate in Kent
(Wikipedia Commons)

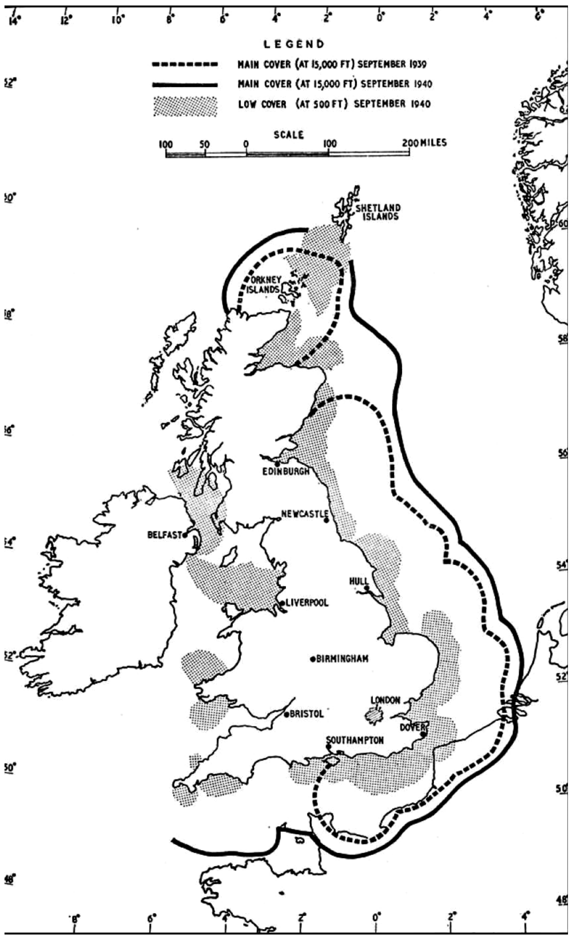

Fig. 3. CH radar system coverage 1939-40,
(Wikipedia Commons)

However, at this time, there was a pressing need to achieve high-power microwave energy efficiently, typically at 10 cm wavelength (3,000 MHz operating frequency), in a lightweight generator to enable the transition from land-based into much higher resolution airborne radar systems.

Airborne radar systems entering service in 1939, which were initially deployed for ship detection, used VHF frequencies around 200 MHz (a wavelength of 1.5 m) which were somewhat higher than that used in the Chain Home system. They typically employed half-wavelength dipole antennas fixed to the airframe (Figure 4) and the large flat vertical sides of the ships made for excellent radar targets. It was realised that operating at even higher frequencies would allow the use of even smaller antennas and be highly desirable for airborne operation. However, at that time, it was not possible to generate sufficient transmitter power, especially at centimetre wavelengths. Achieving this goal was a topic of extensive research.

Fig. 4. Typical early airborne radar antennae

John Randall and Harry Boot of the University of Birmingham spent the summer of 1939 visiting one of these Chain Home installations and this encouraged them to attempt to develop these high-power microwave generators [3]. Implementation of an airborne radar necessitates the use of higher microwave frequencies to achieve the smaller-sized transmitter and receiver antenna designs required for inclusion within the restricted dimensions of an airframe and the shorter wavelength of microwave frequencies provides the improved resolution of target objects. Early efforts at generating these microwave frequencies in the 1930s often used klystron and magnetron tubes but their power output was far too small to achieve the required range to construct an airborne long-range night-fighter or anti-submarine radar system. In 1938 the shortest wavelength on which any significant power could be generated was ~ 1.5 m (200 MHz).

Magnetron designs

The magnetron name originally arose out of work by Albert Hull in 1921 at General Electric (GE) Schenectady, New York, on the use of magnetic fields to control the current in a vacuum tube [4]. The magnetron comprises a heated cathode located at the centre of an electrically charged ring-shaped anode. In a cavity magnetron the anode is designed with slots or resonant cavities and is combined with a large magnet. The electrons generated by the heated cathode then travel towards the anode in a curved or circular path, under the control of the electric and magnetic fields. As the electrons move past the cavities, the cavities resonate and emit microwave radiation, whose frequency is controlled by the precise dimensions of the cavity resonators. A loop or waveguide is then deployed within the magnetron structure to access and recover the microwave energy.

The development of magnetrons was initially undertaken at Bell Telephone Laboratories in America from 1934, by Philips, the UK General Electric Company (GEC), Telefunken and others, but these devices were limited to rather modest ~10 W output power levels and not the kW levels required for airborne radar. Early cavity magnetron designs had been investigated and patented by several independent groups in the late 1930s, such as Hansen at Stanford, Samuel at Bell Labs, Hollmann and Engberg at Telefunken in Germany, Posthumus at Philips, Ponte and Gutton in France, Alekseev and Malairov in Russia, Okabe and Nakajima in Japan [4]. However, in spite of the published papers and patents, not all the designs were actually constructed as prototypes and, generally, the resonator concept was often rejected as somewhat inflexible.

Nowhere in the world in 1939 was there a working, pulsed, *cavity magnetron* capable of generating 10 kW or more peak power at wavelengths of 10 cm or less, which had a compact portable size, used a small permanent magnet and which was readily capable of being manufactured at scale [5].

Design breakthrough

The radical improvement in power and manufacturability was achieved by the 1939 *resonator cavity design* of John Randall and Harry Boot, working on an Admiralty-funded contract, at the University of Birmingham and they secretly patented their device in August 1940. Cavity magnetron designs were in fact 'simultaneous inventions' in many different countries but dissemination of the various design details was rather patchy [4, 5].

Randall has claimed that he arrived at the inspirational idea of using concentric cavities when he researched the design of the original Hertz oscillator, which was an open single ring. Randall had earlier visited, while on holiday, the University College bookshop in Aberystwyth where he found and acquired a copy of Jones's translation of Hertz's *Electric Waves* [3]. What is difficult to establish is precisely how much Randall and Boot were inspired by the cavity klystron of Hansen and other cavity-anode ideas that had existed since 1934! The Birmingham group were not fully aware of these other developments; for example, the Alekseev and Malairov four-segment Russian cavity magnetron which produced 300 W at a wavelength of 9 cm was unknown in England in 1939. The Russian results were only published first in Russian in 1940 and later in English in 1944 [6]. We also know subsequently that in 1939 Shigeru Nakajima had designed in Japan an eight-cavity magnetron at 10 cm. Nakajima's magnetrons were identical in every respect to the British prototype but this was only discovered in 1953 when Nakajima visited the London Science Museum where he saw the Birmingham resonator design. Thus, Randall and Boot are today widely credited with implementing the first high-power version of this microwave device which was easily reproducible and readily adapted for mass production.

Randall and Boot developed their cavity magnetron design in November 1939 and they showed their first copper block to Lawrence Bragg and Edward Appleton when they visited the Birmingham laboratory. In late 1939 Randall and Boot had converged on a six cylindrical resonator geometry, with its slots parallel to the cathode axis, which they opened into the anode-cathode space as a cylindrical extension of the original Hertzian dipole, Figure 5. The resonating chambers were built with quarter-wave deep radial slots designed with a physical size which was matched to the wavelength of the operating microwave frequency to boost the signal. Randall's structure is claimed to differ from the prior cavity designs as he was thought to be the first person to introduce cylindrical symmetry [4].

Fig. 5. Anode block of an early cavity magnetron as built by Randall and Boot, by Science Museum London, via Wikipedia (CC BY-SA 2.0).

A significant difference between the Randall & Boot cavity magnetron design and those previously patented was that nearly all the others had their anode system inside a glass envelope containing a vacuum whereas the Birmingham valve had its vacuum system inside the anode structure. This novel design feature ensured much more efficient cooling of the anode system to permit the higher power dissipation and enable the generation of the larger output power.

On 21 February 1940 when initially switched on the device produced about 400 W continuous wave power at 10 cm wavelength and it lit a neon lamp located some distance from the device. Figure 6 shows the device which is sandwiched between two square water-cooled plates. Randall and Boot's technical innovation is now considered as an *unprecedented achievement* compared to all the pre-existing magnetron designs [7]. It represents a major technological revolution as they made the novel, innovative steps which paved the way for manufacture of generations of magnetron devices at exactly the right time for the war effort even though their device was only a laboratory prototype, not suited to field operation.

Fig. 6. Randall and Boot's original 1940 cavity magnetron: London Science Museum, Science & Society Picture Library, image c034430

Following this advance, in April 1940, the Admiralty sponsors signed a contract with GEC, Wembley, to extend the Birmingham design into an operational device. The GEC device had to operate with neither vacuum pumps nor an external generator of the magnetic field. The GEC engineers were led by Eric Megaw, the British expert on magnetron design and marine radar. He had already published several reviews of the mechanisms for magnetron generation, including split-anode designs, and he performed the required industrial development on the Birmingham prototype device [8].

In May 1940, just before the fall of France, Maurice Ponte brought to GEC two samples of the French magnetron device he had developed with Henri Gutton [5]. They had developed a device that incorporated an oxide-coated cylindrical cathode to replace the spiral filament and this provided the increase in power, operation with very high voltages and much longer device lifetime. Ponte was not shown the cavity design secret, but his visit provided Megaw with valuable design information that was incorporated into the next GEC device.

GEC further improved the design of the vacuum seals with copper and glass braised joints and this removed the pump requirement and they combined the multi-resonator system of Randall and Boot with a large oxide-coated cathode to turn it into a readily manufacturable device, with a small permanent magnet, to achieve its more rapid introduction for service use. This air-cooled GEC E-1189 magnetron, as designed for an airborne radar trial, combined a compact sealed-off all-metal and air-cooled housing, a reduced axial dimension minimising the air gap for the magnet, with an enlarged thoriated-tungsten spiral cathode. In the summer of 1940 the GEC design gave an output of 3 kW when employing a 1000 Oersted permanent magnet and the power was improved within months to 25 kW, and on to over 100 kW by 1941 [5]. This magnetron design which was detailed in Randall and Boot's patent was subsequently standardised for use initially in the British naval radar type 271 [9]. Although the Birmingham innovations developed the initial cavity magnetron design, re-engineering it into a device that could be readily manufactured was the work of Megaw and colleagues at GEC.

Another Birmingham individual who contributed to the development was Jim Sayers who brought his prior knowledge of klystron vacuum tube design when he noted the excessive frequency noise. He thus suggested strapping the alternate cavities to constrain them to generate oscillations in one or more particular modes, to the exclusion of others over a wide range of operating conditions [10]. The number of possible modes or frequencies in the generated oscillations are limited by electrical connections or 'straps' between selected points on the resonator system and this 'strapping' technique, which provided the major improvement in frequency stability, continues in use and in patent awards today. With the introduction of strapping the GEC-1189 magnetron was adapted into the British CV-64 production magnetron shown in Figure 7.

Fig. 7 CV-64 Magnetron: London Science Museum, Science & Society Picture Library, image 1971-249

Technology transfer

With France having just fallen in WW2 and Britain lacking the funding and manufacturing capability for the cavity magnetron on the required massive scale, Churchill agreed that Sir Henry Tizard should offer the magnetron to the Americans in exchange for their financial and industrial help. The GEC E-1189 10 kW magnetron was taken on the Tizard Mission in September 1940 [5, 11].

As the discussion at the mission meeting turned to radar, the US Navy representatives detailed the problems with their short-wavelength systems, complaining that their klystrons could produce no more than 10 W. One of the British mission members, Edward (Taffy) Bowen, a Welsh physicist and Chain Home radar pioneer, pulled out from his briefcase the GEC cavity magnetron and explained that it could already produce 1000 times that power [12]. Subsequent testing at Bell Labs showed that the new design produced 10 times the output power at 5 times the frequency of the best performing American devices! Bell Labs quickly began making copies and the design details were shared with Western Electric and Raytheon as well as REL in Canada.

Further, in 1940, the Radiation Laboratory was set up on the campus of the Massachusetts Institute of Technology (MIT) to develop various radar systems using this cavity magnetron design. The 1940 cavity magnetron thus became the heart of more than 150 new radars of all categories designed between 1941 and 1944. Figure 8 shows Alfred Loomis, an American financier of radar research, Henry Tizard and Lee Alvin DuBridge, who led the wartime magnetron development at MIT, examining a wartime magnetron.

Fig. 8. Loomis, Tizard and DuBridge with a cavity magnetron (1949) © MIT Museum

Airborne radar

High power magnetron pulses generated from a device the size of a small book and broadcast from an antenna only a few centimetres long, reduced the size of practical radar systems by orders of magnitude. The cavity magnetron thus enabled new compact radars to be designed for deployment on aircraft such as submarine hunters and night-fighters and also on the smallest of escort ships. A 10 cm wavelength radar achieves superior angular resolution and different objects such as water, open land, built-up areas of cities and towns produce quite distinct returns which have very different radar signatures enabling mapping of the ground below the aircraft to assist navigation as well as targeting munitions delivery, even through cloud. Figure 9 shows a typical early airborne radar image.

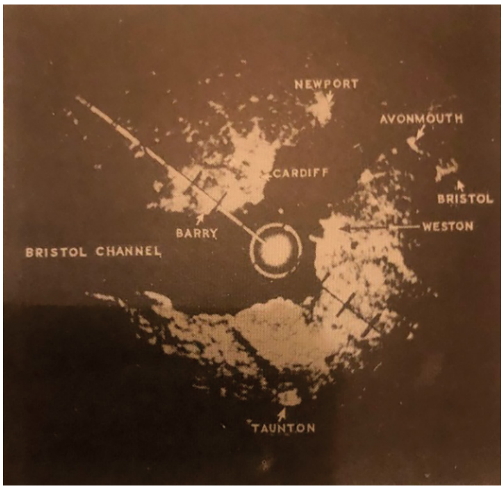

Fig. 9. Wartime Radar Image of Bristol Channel, from Inter-services Radar Manual, 2nd edition January 1950, War Office code No. 1543

In May 1940, an experimental radar set containing a GEC pulsed 10 cm cavity magnetron (Figure 7) had been built at the Telecommunications Research Laboratory, Swanage, and by September 1940, a surfaced submarine could be detected at a range of 7 miles [3].

The most widely-used British airborne radar which used the cavity magnetron was called H2S. Figure 10 shows the H2S scanning antenna. This operated at S-band (around 3 GHz), produced images and was last used in anger during the Falklands War in 1982. Alan Blumlein of EMI, who was central to the development of the H2S airborne radar system, died in Wales after a Halifax trials flight crash on 7 June 1942. A memorial window at Goodrich Castle in Herefordshire, Figure 11, commemorates Blumlein and the other engineers, scientists and servicemen who were involved in WW2 radar development. Some H2S units remained in service for more than 50 years, until 1993. The US equivalent radar operated at X-band (around 10 GHz), was denoted H2X, and saw service from October 1943.

Fig. 10. H2S radar scanner fitted below an aircraft with the dipole antenna replaced by a waveguide and reflector (Wikipedia Commons)

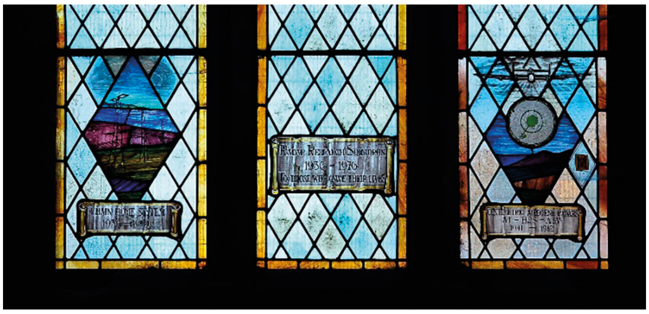

Fig. 11. Lower panes of a memorial window in Goodrich Castle, commemorating the development of radar (Wikipedia Commons)

From 1940 onwards the Allies of WW2 held a technical lead in radar systems that their counterparts in Germany and Japan were never able to close, even though they had previously researched and patented earlier versions of these magnetron devices. The development of the cavity magnetron was so sensitive that aircraft were not permitted to fly over Germany until 1943 and they were fitted with explosives to destroy the magnetron if the plane was shot down, to ensure that the enemy were unable to learn about the device.

In February 1943 a Stirling bomber carrying a cavity-magnetron powered 10 cm H2S radar crashed near Rotterdam. As a result, the Germans finally acquired a complete H2S system and quickly copied it but it was too late to have a significant effect on the outcome of the war. By the end of WW2, practically every Allied radar was based on a cavity magnetron. By 1945, some 250,000 magnetrons in total had been delivered for UK deployment. In 1947 British cavity magnetron production was taken up at English Electric Valve (EEV) in Chelmsford.

Subsequent recognition

Randall and Boot's innovative development of the magnetron into a high-power readily manufacturable device was "massive technological breakthrough" and "deemed by many, even now, to be the most important invention that came out of the Second World War"!

Jim Sayers joined John Randall and Harry Boot in securing a 1949 'Royal Commission on Award to Inventors'. This assessed how much Civil Servants should receive when the "British Crown" profited from their inventions and the three inventors were awarded the very significant £36,000 prize, which would be worth well over half a million pounds today!

The official historian of the American Office of Scientific Research and Development, James Phinney Baxter III, wrote: "When the members of the Tizard Mission brought the cavity magnetron to America in 1940, they carried the most valuable cargo ever brought to our shores."[13]

Professor of military history at the University of Victoria in British Columbia, David Zimmerman, stated: "The magnetron remains the essential radio tube for shortwave radio signals of all types. It not only changed the course of the war by allowing us to develop airborne radar systems, it remains the key piece of technology that lies at the heart of your microwave oven today. The cavity magnetron's invention changed the world."[14]

Eric Megaw's major design contributions were recognised by his appointment, by the King, in 1943 as a Member of the Order of the British Empire (MBE). He was awarded the Duddell Premium award from the Institution of Electrical Engineers in recognition of his work on generating ultra-short waves. In a letter to Megaw's secretary after his death in 1956, Sir Edward Appleton, who in 1940 had been a member of the Committee for the Scientific Survey of Air Defence, wrote, "Those who were in the business know how much the practical development of the cavity magnetron - the development that made it something that could go into operational use - was due to Megaw." [15]

These historical developments, to engineer the high-power device which further expanded the application of Maxwell's electromagnetic waves to lightweight radar systems are commemorated at the University of Birmingham outside the Poynting building where Randall and Boot made their highly significant 1940 technical innovations (Figure 12).

Fig. 12. University of Birmingham historical plaque

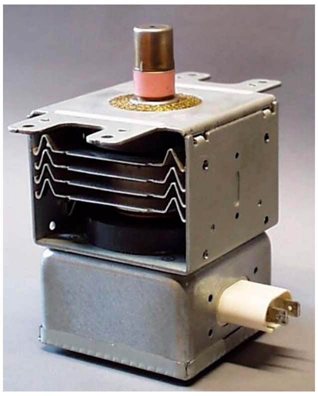

Fig. 13. Cavity magnetron from today's microwave oven (Wikipedia Commons)

Today's £60 cavity magnetrons (Figure 13) are found in microwave ovens in 93% of UK households, with US sales exceeding 10 million ovens each year. Thus, almost everyone uses electromagnetic waves, as first proposed by Maxwell, and we rely heavily on these Birmingham innovations for efficient low-power cooking.

References

[1] Forfar, D. O., 'Homage to Heinrich Hertz', *JCMF Newsletter* No. 16, Summer 2021. www.clerkmaxwellfoundation.org/Newsletter_2021_Summer.pdf

[2] Griffiths, H. D., 'Some reflections on the history of radar from its invention up to the Second World War', *JCMF Newsletter* No. 8, Spring 2017. www.clerkmaxwellfoundation.org/Newsletter_2017_Spring.pdf

[3] Boot, H. A. H. and Randall, J. T., 'Historical notes on the cavity magnetron', *IEEE Transactions on Electron Devices*, vol. 23, no. 7, pp 724-729, Jul 1976. doi: 10.1109/T-ED.1976.18476

[4] International Conference 'Origins and evolution of the cavity magnetron', *Proceedings IEEE* Cat. No. CFP10771-CDR, ISBN: 978-1-4244-5610-9, Library of Congress: 2009938875, 19-20 April 2010.

[5] Blanchard, Y., Galati, G. and Van Genderen, P., 'The cavity magnetron: Not just a British invention', *IEEE Antennas and Propagation Magazine*, Vol. 55, No. 5, pp. 244-254, October 2013. doi:10.1109/MAP.2013.6735528

[6] Alekseev, N. F., Malairov, D. E. and Bensen, I., 'Generation of high-power oscillations with a magnetron in the centimeter band', *Proceedings Institution Radio Engineers*, vol. 32, pp 136-139, 1944. doi: 10.1109/JRPROC.1944.230035

[7] H.A.H. Boot and J. T. Randall, "The cavity magnetron", *Journal Institution of Electric Engineers*, vol. 93, Issue 5, pp. 928-938, 1946. doi: 10.1049/ji-3a-1.1946.0183

[8] Megaw, E. C. S., 'The high-power pulsed magnetron, a review of early developments', *Journal of the Institution of Electrical Engineers*, pp. 977 – 984, vol. 93, Issue 5, 1946. doi: 10.1049/ji-3a-1.1946.0187

[9] Randall, J. T., Boot, H. A. H. and Wright, C. S., 'Magnetron: Improvements in high frequency electrical oscillators', UK Patent GB 588185A, filed Aug. 22, 1940. https://patents.google.com/patent/GB588185A/en?oq=GB+588185

[10] Sayers, J., High frequency electrical oscillator', US Patent 2546870 awarded 27/03/1951 on priority 03/10/1941. https://patents.google.com/patent/US2546870A/en?oq=US2546870

[11] Marsh, A., 'From World War II radar to microwave popcorn, the cavity magnetron was there", *IEEE Spectrum*, November 2018. https://spectrum.ieee.org/tech-history/dawn-of-electronics/from-world-war-ii-radar-to-microwave-popcorn-the-cavity-magnetron-was-there

[12] Bowen, E. G., *Radar Days*, Adam Hilger, Bristol, 1987.

[13] Schroter, B. 'How important was Tizard's box of tricks?", *Imperial Engineer*, vol. 8: p. 10, Spring 2008. www3.imperial.ac.uk/pls/portallive/docs/1/44009701.

[14] Hind, A., 'Briefcase 'that changed the world', BBC News, February 5, 2007.

[15] Callick, E. B., *Metres to Microwaves: British Developments of Active Components for Radar Systems 1937 to 1944*, London, UK, Peter Peregrinus Ltd. on behalf of the Institution of Electrical Engineers, 1990, pp. 62-75.

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EIGHTY-FIVE YEARS OF AIRBORNE RADAR
PUTTING MAXWELL'S THEORY INTO ACTION

By *Tony Kinghorn*

Introduction

James Clerk Maxwell published his theory of electromagnetic waves in 1865, and in 1888 Heinrich Hertz carried out a practical demonstration of the generation of these waves using a spark-gap transmitter. By 1901, Guglielmo Marconi had harnessed this work to demonstrate long-range radio communications.

The origins of radar stem from the work of Christian Hülsmeyer in Germany, who in 1903 filed a patent for a device he called the 'Telemobiloscope'. Hülsmeyer, inspired by Hertz's discovery that electromagnetic waves could be reflected from metallic objects, realised that this phenomenon could be used to detect unseen objects, such as other ships in fog.

Hülsmeyer's work did not immediately flourish but in the inter-war years several workers in different countries independently developed early forms of radar, inspired by the same basic ideas. Analysis of radio propagation using Maxwell's theories led to the realisation a radio detection system must have the ability to transmit large amounts of power, so that the tiny echoes from distant objects would be strong enough to be detectable; and that to localise an object in angle it was desirable to have a large receiving antenna which could be used to deduce the angle of arrival of the echo. To estimate range it was necessary to measure the very small time delay between transmission and reception of electro-magnetic waves propagating at the speed of light, again as described by Maxwell's theories.

Wartime developments [1]

The Second World War gave a vast impetus to the development of radar. Prior to 1939 the UK had developed an effective ground-based early warning radar system, using very low frequency (20 MHz~30 MHz) transmissions. The long wavelength (~15 m) of these transmissions dictated that they required very large antennas to detect the angle of arrival of echoes with sufficient accuracy to allow defending aircraft to intercept the enemy. These systems – the so-called Chain Home – were thus, of necessity, very large and ground-based. It was clear that a compact radar small enough to be mounted on an aircraft, if possible, would be immensely useful to enable interceptions in darkness and adverse weather. Early crude low-frequency systems were developed and worked, after a fashion; but they had very limited capabilities (Fig. 1).

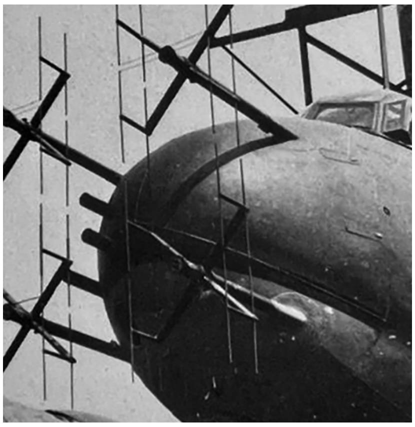

Fig 1. Early Low Frequency (UHF) Airborne Radar for terminal intercept (FuG202, Telefunken). Image: Imperial War Museum.

The breakthrough came in 1940 with the invention of the cavity magnetron, a very small device which could generate high powers (100kW+) at wavelengths of a few centimetres. (Fig. 2). Pioneering work was done by John Randall and Harry Boot at the University of Birmingham and further developed into a practical device by engineers at the British General Electric Company, led by Eric Megaw.

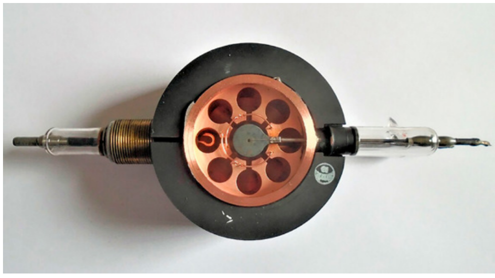

Fig 2. Interior of an early Cavity Magnetron showing the circumferential cavities, the size of which governs the oscillation of the device at a precise frequency. Image: Philip Judkins.

Early airborne radars were quickly developed with the following key features:

- a transmitter capable of generating very short pulses with high peak power (cavity magnetron),
- a mechanically steerable antenna ~ 10-20 wavelengths across, capable of forming a narrow beam,
- a sensitive receiver with a cathode ray oscillograph that allowed the operator to measure the time delay, and hence the range, of a target echo.

One of the first such operational magnetron systems, developed in 1941, is shown in Fig. 3.

Although the cavity magnetron was invented in the UK, Churchill quickly realised that he needed the help of the US to industrialise production on the scale needed to meet the German threat. A secret mission, (known as the Tizard Mission after Sir Henry Tizard, the chief scientist who had orchestrated the developments) was sent to the US with an early example of the cavity magnetron, as well as other key material on British wartime developments. The mission achieved its aim and magnetron production rapidly took off.

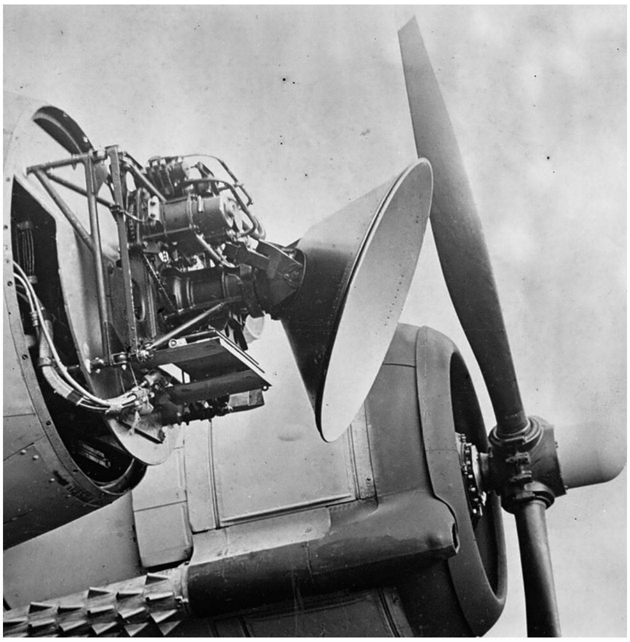

Fig 3. **AI Mk VIIIA** Air to Air radar (UK, 1941); installed in the nose of the fuselage of the Beaufighter, this S-band system had a peak power of 25 kW and a 12° beamwidth steerable parabolic antenna. It transmitted pulses at the low rate of 3 kHz. Image: Imperial War Museum (IMW Non-commercial licence)

Another major consequence of the Tizard Mission was the establishment of the so-called Radiation Laboratory at MIT in Cambridge, Massachusetts. This huge research organisation, which grew to over 5000 staff, investigated a wide range of radar-related topics. After the war its results (amounting to a 28-volume set of papers) were published. Many of the ideas were impractical at the time but they provided a massive resource for post-war researchers, and they underpinned many of the later developments described here.

Incidentally, in the UK early radars were known as RDF (radio direction finding) but the US coined the neat palindromic acronym RADAR – RAdio Direction And Ranging – and the name has stuck to this day.

Post-War developments

The work done during the Second World War formed the basis of airborne radar for the next 15 to 20 years; indeed, some systems very closely related to their wartime predecessors were in service as late as the 1980s. During this period airborne radars had characteristics which were largely dictated by their physical realisation. The magnetron transmitters operated at a fixed frequency, governed by the dimensions of the device; they transmitted pulses at a fixed repetition rate, governed by the design of the circuits; the antennas had a fixed beam pattern, dictated by their physical shape, and scanned simple regular patterns, controlled by fixed electronic designs. Although such systems worked well enough, they were inflexible, and their characteristic signatures made it relatively easy for adversaries to detect them and develop effective jamming systems.

This was thus a period of consolidation and incremental improvement. The radar shown in Fig. 4 pioneered the introduction of 'monopulse'- using interferometry to greatly improve the accuracy of angle measurement, even on a single radar pulse. This required precision engineering at an unprecedented level, and manufacture involved the development of machine tools which were the forerunners of today's precision CNC machining systems.

Fig 4. **AI23** (AIRPASS I) Radar (Ferranti, 1950s); wholly analogue air intercept radar for the RAF Lightning aircraft, employing monopulse for high angular accuracy. Image: Leonardo.

The radar shown in Fig. 5, developed for the Royal Navy, was similar in its essentials to AI23 but with one important difference – it saw the introduction of transistors to replace the thermionic valves hitherto used in the low power electronics in the system. This was the point at which airborne radar began to move significantly beyond the designs developed during the war.

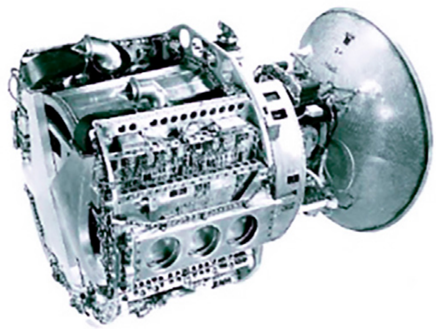

Fig.5 **Blue Parrot** (AIRPASS II) (Ferranti, 1960s). Anti-shipping radar for the RN Buccaneer aircraft. Image: Leonardo.

1970s: Significant new developments

The first major change saw the adoption of the 'spin tuned magnetron' as the transmitter, eclipsing the original cavity magnetron. This device worked by changing the physical shape of the resonant cavity and hence the frequency at which the magnetron generated pulses: this was done by rotating a small metal rotor within the vacuum tube by means of an external motor and a magnetic coupling. The period of rotation was asynchronous with the radar's pulse repetition frequency, the net result being that each successive pulse generated by the magnetron was at a completely different frequency (although typically within ±5% of the carrier frequency). For the radar to work, the receiver had to be rapidly re-tuned pulse-to-pulse using a sample of the transmitted signal as a reference. This innovation gave two main benefits – much improved immunity to jamming (as the jammer could not predict what frequency on which to transmit) and the elimination of 'second time around' echoes, as these would arrive on the incorrect frequency and hence be ignored.

The second major change was in the radar display, which hitherto had been a dimly-glowing screen which was very hard to use in an aircraft, except by a dedicated operator. An early approach used back-to-back cathode ray tubes in a closed unit, one producing the classical radar screen and the other scanning it to drive a bright TV display. A better approach exploited the power of early digital integrated circuits to make a device known as a 'scan converter' – essentially a digital memory mimicking a classical radar display, which could then be used to drive a bright TV display. Although this seems incredibly crude by modern standards, the improvements in usability were immense and allowed radar to be used effectively by a single pilot.

The third major change brought the designers right back to the fundamentals of Maxwell's equations. Hitherto, antennas had been designed as quasi-optical reflectors, which were bulky, heavy and inefficient. The new approach employed a flat panel comprising parallel waveguides, with precision slots machined into the structure to let a precisely-calculated amount of the radar's energy escape at predetermined locations. Provided the slots were accurately made, such a 'planar waveguide array' could produce a very precise and efficient antenna beam; moreover, the antenna could be extremely light (often being made of aluminium) and could thus be rapidly scanned to bring the radar beam to bear.

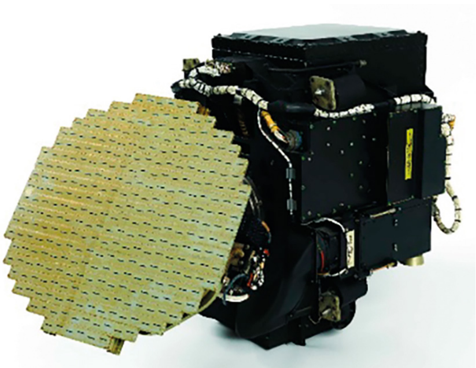

Fig. 6 **Blue Fox Radar** (Ferranti, 1970s). Fire control radar for the Sea Harrier, showing the planar waveguide antenna. Image: Leonardo.

The fourth major change was the adoption of early steps to provide multi-functionality. Up to this point, radars had just done one thing – for example air-to-air intercept, or sea surface surveillance. These newer radars could do both, with equal facility. An example of such a radar incorporating these advances is Blue Fox, developed for the Royal Navy Sea Harrier (Fig. 6). This radar proved very effective in the Falklands War [2].

Coherent radar and digital processing – the first major revolution

Thus far, radars had been entirely analogue. Receivers used tuned circuits and filters to detect the radar echoes, which were amplified and displayed at the appropriate range and angle to the operator on an analogue display. This process simply detected the amplitude of the radar echoes, it destroyed any information about the frequency or phase of the signal. This was a major disadvantage, as the radar echo in an airborne system is usually frequency-shifted with respect to the transmitted signal due to the relative velocity between the radar and the target. This effect (the Doppler shift) is of course another consequence of Maxwell's equations. If the Doppler shift can be measured, it allows the speed of a target to be estimated, but more importantly it allows the airborne radar to discriminate between a small fast-moving target and the static background echo from the earth's surface (which is normally much larger, and obscures the target).

A radar which attempts to exploit the Doppler effect must ensure that its transmitted pulses are all at precisely the same frequency and are phase-locked to each other – this is the fundamental requirement for a so-called coherent radar. To achieve this the first step was to abandon the venerable magnetron, since each pulse generated by a magnetron, whilst similar in frequency, has no phase relationship with its predecessor. Transmitting the required coherent pulse train was achieved by using a stable low-frequency quartz crystal oscillator to create a reference signal, which was then transformed to the required radar frequency and amplified to high power in a vacuum tube device called a Travelling Wave Tube Amplifier. This produced the required high-power signal, and the radar thus transmitted a train of 'coherent' pulses, essentially short sections of a stable underlying fixed frequency signal. (Fig 7.)

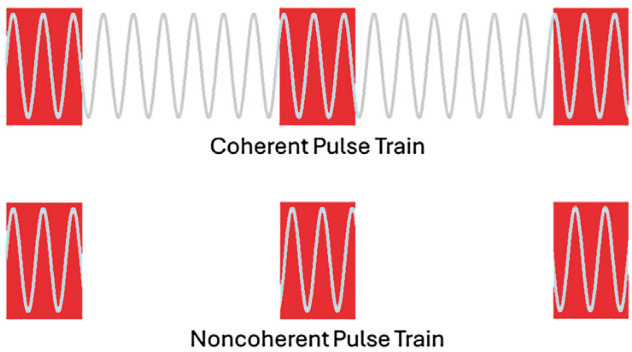

Fig. 7 Comparison of coherent and noncoherent pulse trains. The self-oscillating magnetron (bottom) produces a series of pulses on essentially the same frequency, but with random phase from pulse to pulse, which prevents Doppler measurement.

The second step was to develop a receiver which could amplify the radar echoes and compare them with the same reference oscillator as the transmitter in order to preserve the phase of the received signal.

Early attempts to exploit Doppler phenomena using analogue processing achieved limited success as the obstacles were formidable – for example, such radars employed banks of hundreds of tiny precision-tuned filters, which were highly vulnerable to vibration and required frequent re-tuning. These radars were notoriously unreliable, it being said that if one was working when the aircraft took off, it would definitely have failed by the time the aircraft landed! The breakthrough was to convert the received signal to digital form, so that all subsequent processing could be implemented digitally. This was enabled through developments in digital processing and microprocessors in the late 1970s and early 1980s.

This digital signal processing offered a practical, robust and far more functional solution than its analogue predecessors. Doppler-shifted echoes could be extracted by creating the digital Fourier Transform of the received pulse train, a process which could be efficiently carried out using the Fast Fourier Transform (FFT) algorithm. This typically produces a 2D digital 'map' with radar range on one axis, and relative velocity on the other. Targets of interest appear as isolated peaks in this 2D array, which can then be thresholded to isolate a target and extract information about it.

All this was easier said than done with early digital processing technology, and much ingenuity was used to implement early systems. However the rapid development of integrated circuit technologies, microprocessors and analogue-to-digital convertors allowed huge improvements within a remarkably short time. Furthermore, the use of reprogrammable digital processing allowed the same radar processing hardware to be quickly reconfigured to carry out a wide variety of different tasks. In a short space of time radars appeared offering twenty or more different modes of operation – effectively the equivalent of twenty different radars in one.

Perhaps the first airborne radar to incorporate most of these advances was the AN/APG-65 radar developed by the Hughes Aircraft Corporation for the US Navy's F-18 aircraft in around 1980. As in the early days of radar, parallel independent developments were under way in other countries, and the Blue Vixen radar developed by Ferranti in Edinburgh for the Royal Navy Sea Harrier (Fig. 8) incorporated similar advances.

These radars transformed the capabilities of the aircraft for which they were developed. They provided multi-function radar capabilities (air-to-air, air-to-sea, air-to-land) and, crucially, they enabled the detection of low-flying targets whilst looking down – there was now nowhere for the enemy to hide. Digital processing also allowed these radars to track multiple targets simultaneously, greatly increasing their effectiveness.

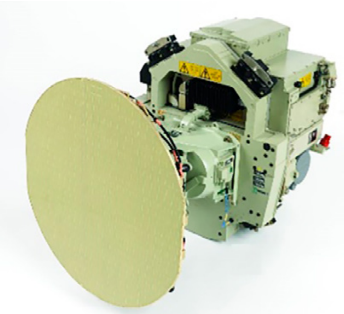

Fig. 8 **Blue Vixen** (Ferranti, 1980s); fire control radar Royal Navy Sea Harrier FA2. Image: Leonardo.

Antenna technologies

Early radars were able to provide an accurate estimate of target range by measuring the time between the pulse transmission and the reception of an echo. All electromagnetic waves, as predicted by Maxwell, travel at the speed of light, so measuring target range simply required the ability to make an accurate time measurement.

Measuring target position is not so simple. In principle it is easy – an antenna of length d, to first order, creates a beam of width λ/d where λ is the wavelength of the radar's transmission. This is a well-known consequence of diffraction theory for any system involving wave propagation, and the electromagnetic waves employed in radar are no different. If we consider an antenna mounted in the nose of an aircraft, the maximum size available may be typically around 1 metre across. At the long wavelengths (~3 m) used in the earliest airborne radars, such an antenna would provide little or no directional information. This is why the cavity magnetron was such a breakthrough – it provided useful power at around 3 cm wavelength, so our notional 1-metre antenna could now provide a much narrower beamwidth of around 0.03 radians or 0.7°, a practically useful figure. (It is worth noting that in absolute terms it is still not that accurate – this example is equivalent to localising a target to a region of around 3 km at a range of 100 km.)

Improvements in angular *accuracy* (not resolution) were achieved using interferometry, essentially by comparing the phase of a received signal from two halves of a physical antenna. This typically provided a ten times improvement in accuracy.

Clearly there would be value in employing a much, much larger antenna, for example to provide high resolution radar imaging. Although physical antennas of such a scale are impractical in most aircraft, a clever technique called Synthetic Aperture Radar (SAR) can achieve this. In simple terms, a coherent airborne radar can collect data as it flies along, and this recorded data can be used to construct a 'synthetic antenna' twice as long as the flightpath (twice because the radar transmits *and* receives). This can deliver truly remarkable photographic quality radar imagery with sub-metre resolution at very long ranges (Fig. 9). However, SAR is only useful when observation of static targets over many seconds is possible. Airborne radars are usually used in highly dynamic situations, so physical antennas remain essential for most purposes.

Fig. 9 Synthetic Aperture Radar Image. Light areas show high radar reflectivity. The dark areas in this image of an airfield are tarmac, with parked aircraft clearly visible. Image: Leonardo.

As we have seen, early radars employed quasi-optical reflector antennas, which were then superseded by planar waveguide antennas. These types essentially provide a single fixed antenna beam, and moreover they need to be mechanically scanned to cover a useful area of search. Such scanning systems are heavy, bulky and slow. A far better solution is to create an antenna where the signal across the antenna face can be controlled electronically to a high degree of precision. As long as independent control can be provided at numerous locations less than half a wavelength apart, such an antenna can synthesise a beam of any shape (subject to the l/*d* diffraction limit) anywhere in the hemisphere in front of the antenna. Such an antenna is known as a *phased array*, because the principal method of control is phase shifting the radar signal at a multitude of points across an antenna array. Early phased arrays retained a single powerful transmitter (as in mechanically-scanned radar) and used an array of passive phase shifters to steer the radar beam. This approach worked, but had practical disadvantages in terms of weight, efficiency and reliability.

The next major breakthrough was the advent of powerful solid-state amplifiers which were small enough to be placed at every element of a phased array. The single high-power vacuum tube transmitter could now be dispensed with. Instead, an array of hundreds or even thousands of tiny transmit/receive modules could be used to make up an antenna. (Fig. 10). A device of the type illustrated uses Gallium Arsenide (GaAs) or Gallium Nitride (GaN) semiconductor devices to provide high power transmission, low noise reception and amplitude/phase control to adjust and steer the radar beam.

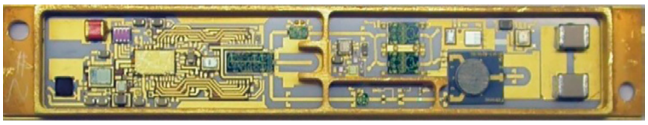

Fig. 10 Radar Transmit/Receive Module (measuring about 15mm × 100mm). About 1000 such devices are typically used to construct an airborne antenna. Image: Leonardo.

This type of antenna is known as an Active Phased Array Antenna (AESA) and it is now the *de facto* standard for modern airborne radar. It offers numerous advantages: it is highly reliable and fault-tolerant; it allows the radar designer to optimise the antenna for each individual radar task; and it allows very rapid beam steering to optimise search and tracking functions. One of the most powerful features of AESA radars is their ability to make a tentative detection then rapidly re-examine the area of sky to establish a track or, if necessary, to dismiss the detection as a false alarm. This technique can extend the practically-useful range of the radar by a considerable amount, as the radar can concentrate its transmitted energy in space where it is most effective.

A typical modern fighter radar employing AESA technology is shown in Fig. 11. This type of radar provides a wide range of functions: air-to air search and track; air-to-sea search and track; ground moving target detection and tracking; conventional and synthetic aperture ground mapping; target identification; and so on. The AESA offers much more performance than its mechanically-scanned predecessors, as well as much higher reliability.

In spite of these notable advances, in one respect these state-of-the-art radars still resemble their predecessors, in that the radar essentially has a single antenna beam, so at any one time the radar's energies are concentrated on a single direction.

Fig. 11 **Raven ES-05** (Leonardo, 2010s). Active array fire control radar for the Saab Gripen E/F. Image: Leonardo.

Multi-function Radio Frequency (RF) Systems [3, 4]

From the outset, the capabilities of radar systems have largely been constrained by technology. This is particularly true for airborne systems, which have had to comply with stringent constraints on size, weight, power and (especially) cooling. Compact, efficient technologies are essential.

Today's radars are still limited in one important respect – they all essentially operate over a limited radio frequency band. The most popular for airborne radar is X-band covering typically 8GHz-10GHz (although most radars only operate over part of the band). This is largely a technological limitation, although there are also regulatory constraints (to avoid interference with other systems).

As Maxwell's work showed many years ago, electromagnetic radiation behaves in the same way over an extremely wide range of wavelengths. What is different is how different wavelengths propagate in the atmosphere, and of course how antennas of a particular size behave at different wavelengths. In practical systems there are notable benefits in being able to operate at very different frequencies. This has long been recognised in ground and ship-based radars. An example of a modern warship (Fig. 12) carries two principal radars: a low frequency (L-band, ~1 GHz) radar for very long-range search; and a high frequency (S-band, ~3 GHz) for surveillance, precision tracking and missile guidance. Together these radars provide a wide range of functionality, but as can be seen they take up considerable space and employ very different technologies and designs. In addition, such a warship carries a sophisticated range of electronic warfare equipment operating over even wider frequency bands.

Fig. 12 **Royal Navy Type 45 Destroyer** showing L-band search radar (aft) and S-band Multi-function radar (masthead dome). Image: BAE Systems.

The space constraints of an aircraft make it impossible to carry numerous separate systems, as in the warship. As a result, aircraft have had to make do with a much more limited range of functionality; typical modern fighter aircraft may carry only a multi-function X-band radar and a separate very wideband electronic warfare system, which has considerable limitations on its angular accuracy and discrimination due of the small size of its antennas.

The next breakthrough is to encapsulate very wide band operation in the large single antenna hitherto limited to narrow band radar use. To make such an idea practical requires, perhaps unsurprisingly, a fundamental reappraisal of antenna design, which once again brings us back to the fundamentals of electromagnetism. Maxwell's equations are not amenable to analytic solutions, but modern numerical techniques can be used to find and optimise solutions for very complex wide bandwidth antenna designs. Without delving into the detail, the key to wideband antennas is to ensure that the propagation of electromagnetic waves from the internal circuitry to free space is well-matched over all frequencies of interest over all scan angles of interest. This is a phenomenally complex optimisation problem, but solutions *have* been found, enabling phased-array antennas to be designed which can operate over multiple radar bands. This is, however, only half the story; in addition to the electromagnetic design of the array face, the electronics controlling the array must be equally wideband. This is a far from trivial problem, and involves (amongst many other factors) detailed numerical electromagnetic modelling and optimisation of individual semiconductor devices.

The goal of this work is to create a multi-function RF system which can deliver the functionality of multiple different conventional systems within a single physical entity, reconfigurable solely through software. These functions include:

- Air-to-air radar, search and track
- Air-to-ground and air-to-sea radar
- High resolution mapping radar
- Target identification
- Wideband precision emitter location
- Electronic attack (high power jamming)
- Long range secure communications

A new system incorporating these advances, and more, has been developed for the Royal Air Force Typhoon aircraft (Fig. 13). This probably represents the state-of-the art in modern airborne radar.

Fig. 13 **ECRS Mk 2** (Leonardo, 2020s). Multi-function RF System for Eurofighter Typhoon. Image: Leonardo.

The future

There is no doubt that digital processing and phased-array antenna technologies have massively increased the capabilities of airborne radar, taking it from the single-function capabilities of early radars to today's multi-function RF systems. One area, however, that has so far remained analogue is the technology of radio frequency antenna beamforming. This is primarily a technology issue. Even the best of today's digital technologies struggle to operate at the high radio frequencies of interest, and the processing requirements needed to emulate analogue beamforming are immense – a real issue for an airborne system with limited power and cooling.

Overcoming these obstacles, if possible, offers enormous potential. Whilst an analogue system can only synthesise a few beams at best, a digital system can synthesise hundreds or even thousands of beams simultaneously. This offers the enticing concept of a 'staring array' which can receive signals from all directions simultaneously, enabling ultra-rapid responses and an unparalleled ability to detect fleeting objects or signals.

Ground-based systems, operating at lower frequencies, are already implementing such digital antennas; the lower data rates and the freedom from constraints on space, weight, power and cooling makes this a much easier proposition [5].

Adopting this approach in airborne systems is a much bigger challenge. A key enabler is the development of complex microwave integrated circuits, so that complete receivers can be constructed on a single chip; these technologies are rapidly proliferating, driven by the mobile communications industry. A full digital airborne multi-function system will have the ability to generate around 10,000 times more data than current state-of-the-art systems. Dealing with this volume of data – comparable to the internet traffic of a large city – is itself a major challenge, but again suitable solutions are becoming practical. Current developments are now focussed on these technologies, and they are likely to be a key element of the future Global Combat Air programme (Fig. 14).

Fig. 14 **Global Combat Air Platform** (2035+). Multi-function, multi-platform combat system. Image: BAE Systems.

Conclusion

Maxwell's insights into the nature of electromagnetism were incredibly prescient. It took some forty years before the earliest primitive radar employing his principles was conceived, and for well over a hundred years since then technology has limited our ability to exploit the phenomena described by his theories. Only now, when digital technologies have advanced to the point where they can accurately measure the characteristics of electromagnetic waves in real time, can we begin to approach exploiting the full potential of the phenomena described by Maxwell's theories.

Reaching this level of technological capability has itself necessitated an unprecedented understanding of electromagnetics, made possible only by numerical analysis of Maxwell's equations, a job which still taxes even the most advanced computers.

Airborne radar is just one field that has benefitted from these advances in understanding. It is a remarkably challenging area of engineering endeavour, but the advances over the last 85 years have been immense. Fully digital wide bandwidth systems are undoubtedly the future. The remaining technological challenges will tax the ingenuity of engineers for some time to come, but the capabilities of these future software-based systems are likely to be limited only by the imagination of their designers.

References

[1] Johnson, B, 1978. 'The Secret War', *BBC 1978* pp. 63-121.

[2] Ward, S, 1992. *Sea Harrier over the Falklands: A Maverick at War*, Leo Cooper.

[3] Kinghorn, T. 2008. 'Where next for Airborne AESA Technology?', IEEE International Radar Conference, Rome (reprinted in *IEEE A&E Systems Magazine*, Nov 2009, pp. 16-21).

[4] Farina, A., Holbourn, P., Kinghorn, T., Timmoneri, L., 2013. 'AESA Radar – Pan-Domain Multi-Function Capabilities for Future Systems', 2013 IEEE International Symposium on Phased Array Systems & Technology, Boston, USA.

[5] Haimerl, J. A., Hudson, B., Fonder, G. P. and Lee, D. K., 2016 'Overview of the large digital arrays of the Space Fence Radar', 2016 IEEE International Symposium on Phased Array Systems and Technology (PAST).

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IN THE NEWS

MICHAEL FARADAY'S NOTES AND THE ROYAL INSTITUTION CHRISTMAS LECTURES AT 200

Scientists do not work in a vacuum, neither do they work wholly independently, even if their collaborators are not contemporaries. Perhaps Newton summed it up best when he wrote, 'If I have seen further it is by standing on the shoulders of Giants'. Maxwell's 'Giant' was undoubtedly Michael Faraday, and he was effusive in his acknowledgement of that fact, writing in the introduction of *A Treatise on Electricity and Magnetism*:

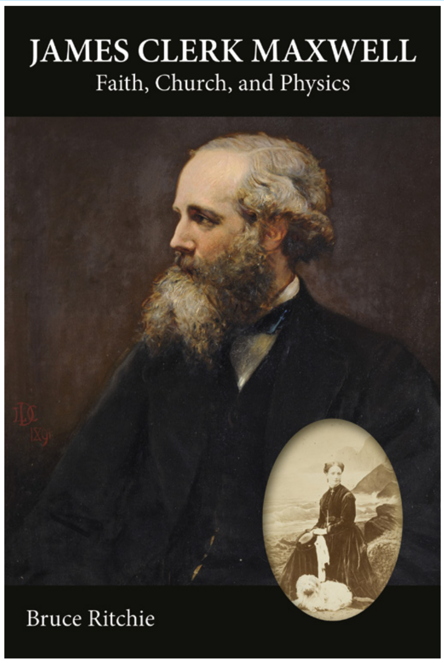
> If by anything I have here written I may assist any student in understanding Faraday's modes of thought and expression, I shall regard it as the accomplishment of one of my principal aims — to communicate to others the same delight which I have found myself in reading Faraday's Researches.

Thanks to Donna Ferguson, writing in *The Guardian* (15 March 2025), the editors of *The Maxwellian* are pleased to learn that Faraday's handwritten notes on a series of lectures given by Humphry Davy at the Royal Institution in 1812 have been unearthed from the RI's vaults. Currently little-known and as a result little-studied, they are being digitised and made available online. In fact, the first batch were uploaded for public viewing on 24 March to mark the bicentenary of Faraday's Royal Institution Christmas Lectures.

Portrait of Michael Faraday
by Thomas Phillips, 1842 (Public domain)

BOOK REVIEW
JAMES CLERK MAXWELL: FAITH, CHURCH AND PHYSICS
by *Bruce Ritchie*

Handsel Press, 2024. Paperback, 474 pp., £15



In March 2024, I had the pleasure of attending a talk at Maxwell's home in India Street in Edinburgh's New Town given by Bruce Ritchie to launch his new book *James Clerk Maxwell: Faith, Church and Physics*. Ritchie's book is a biography with a special theme – Maxwell's faith, Maxwell's physics and the interplay between the two. Like no previous biography of him and written as it is with such clarity, it promises to contribute considerably to Maxwellian scholarship. In Britain in the middle of the nineteenth century some 60% of the population attended church regularly. Maxwell's parents were profoundly religious. The Clerks on his father's side were Presbyterians, members of the Church of Scotland, while Frances Cay, Maxwell's mother, was from an Episcopalian family who worshipped in St John's Church on Edinburgh's Princes Street.

Not only was Maxwell immersed in the teachings of the Bible from an early age, he was able to quote long passages from it. At the Edinburgh Academy he excelled in Scripture, Greek and Latin. Here, his best friends were Lewis Campbell and Peter Guthrie Tait, both of whom went on to hold prestigious chairs in Scottish Universities. Both were devout. Maxwell would go to the Presbyterian church on Sunday morning, the Episcopalian in the afternoon, becoming steeped in the catechisms of both traditions in the process. Sundays were for matters spiritual, and later in life Maxwell would spend hours after church reading the great theologians. His faith, as well as expressing itself in acts of kindness, included 'intellectual assent to credal doctrines'. In Tait's view, he was a 'sincere and unostentatious Christian'.

When he entered Edinburgh University in 1847, Maxwell attended the mathematical lectures of Philip Kelland and the Natural Philosophy lectures of James Forbes, both Episcopalians. Another of his lecturers, William Hamilton, introduced him to the writings of the celebrated philosophers which he read avidly and often in the context of his religious beliefs and scientific pursuits.

At Cambridge University, to which Maxwell transferred in 1850, he showed unusual talent, especially in mathematics, graduating as Second Wrangler. Elected to the Apostles, an exclusive club for the finest thinkers at Cambridge, he engaged in debates on faith, morals and social reform. It was here that he discussed Christian Socialism with its leading proponent, F D Maurice. Maurice went on to establish Working Men's Colleges where, in keeping with his practical Christianity, Maxwell would later offer talks.

Maxwell was appointed to the chair of natural philosophy at Marischal College in Aberdeen in 1856 and it was here that Maxwell found a partner for his relatively short life. The pious Katherine was the daughter of the college's principal, the evangelical theologian, Daniel Dewar. In married life, the couple's daily Bible study was planned and carried through whether together or apart. This shared faith, pursued fervently in conversation and letters, is covered in detail in Bruce Ritchie's book.

As to Maxwell's involvement in the Church, we need to understand a little about the duties of the landed gentry to which his family belonged. When Maxwell was a boy, his father shared responsibility for the minister's stipend with other moneyed landowners. Where necessary, he found or arranged the finance to build new places of worship, including Corsock Kirk to which the family migrated from Parton Kirk. Upon his father's death, Maxwell became the laird of Glenlair, taking on these responsibilities in earnest. When the new parish of Corsock was established, Maxwell became a trustee (later, chair of the trustees), raising significant funds for the church. He also became an elder, responsible with others for pastoral oversight, moral discipline, trusteeship and parish education. Here we see another aspect of Maxwell's practical Christianity.

When Maxwell turned to physical research in the years following his graduation, his initial focus was on the ideas which Michael Faraday had shared earlier in a Royal Institution lecture, including that light may be propagated through lines of force, and that there may be several types of force including gravitation, electrostatic and magnetic. In the mid-1850s, Maxwell would model these forces using structurally-similar equations by invoking Faraday's notion of lines of force rather than Newton's action-at-a-distance. And taking results from William Thomson he also observed that electric and magnetic phenomena were analogous to fluids affected by heat.

Maxwell established his reputation by providing a firm theoretical support for Laplace's conjecture on the nature of Saturn's rings. And prompted by these researches he moved seamlessly to the kinetic theory of gases in 1860 and provided the first statistical distribution of science.

Maxwell's most original research was carried out during his five years at King's College London from 1860. Here, he demonstrated his theory of colours by creating the first projected colour image of a tartan ribbon, coauthored a report on measuring electrical resistance, and made strides in his researches on electromagnetism. He was elected a Fellow of the Royal Society and awarded its Rumford Medal: in short, he was now dining at science's top table. He presented mechanical models of magnetism, electric currents and static electricity, based on molecular vortices, in a paper on 'physical lines of force' and from experiments, he discovered that the velocity of transverse vibrations and the speed of light were in accord. Action at a distance was replaced by the electromagnetic field. Maxwell's next key paper, 'A dynamical theory of the electromagnetic field' saw his first attempts to formulate the interconnections mathematically in what are now termed 'Maxwell's Equations', twenty in number in this paper, later reduced to twelve by Maxwell and finally to just four by Heaviside. All light and electromagnetic phenomena could be modelled using partial differential equations in which the electric and magnetic fields varied in space and time. The field was irreducible and hence elemental. The world is made of fields, not of particles; it is dynamic, not static. Faraday's conceptions were correct and demonstrable.

'Retiring' from King's in 1865, rather surprisingly, the Maxwells returned to Glenlair so that he could focus exclusively on his researches. It was at this time that Maxwell's demon was invoked in connection with Tait's *Sketch of Thermodynamics*. Contrary to the Second Law, could even a tiny number of molecules pass from a colder body to a warmer body? Though initially posed as a thought experiment, the possibility, however minuscule, would render the law stochastic. Order would emerge out of chaos as entropy decreased. It was an idea that troubled many physicists. Maxwell saw the consequent irreversibility of the dissipation of energy as establishing that the universe had a beginning and hence the need for the hand of God.

Perhaps the most important facet of Maxwell's scientific thinking was his use of analogy, and Ritchie rightly discusses it at some length. We get a real feel for it from a quotation from Maxwell's *Elementary Treatise on Electricity*:

> The similarity which constitutes the analogy is not between the phenomena themselves, but between the relations of these phenomena.

'Illustrative analogies' arose from accidental similarities, 'objective similarities' were born of a common physical factor. But there was also an analogy, Maxwell argued, between the way nature is constructed and the way we think about it. 'The only laws of mind are fabricated for it by matter', as he put it. Bruce Ritchie argues that for Maxwell,

> science was the task of thinking in faithful conformity to the inherent structure and dynamical configuration of the universe as it came from the wisdom and power of the Creator.

According to the author, Maxwell's principal conviction was that 'any entity or event in nature had a natural cause discoverable by science, hence there would never be a gap into which God could be introduced as the only possible solution'. As a result, he did not rail against the theory of evolution as it emerged from Darwin's pen, though he believed that the notion of 'survival of the fittest' should have incorporated positive, altruistic qualities from the affective domain, not simply those such as strength and fecundity which he deemed negative.

At a lecture in 1873, Maxwell argued that since there must be entities in nature which are indivisible (and unseen), and since these entities are not compounded of other entities, they had not been 'manufactured' over time. It is only those entities compounded of others and the process that caused their composition that bear examination. The following year, the materialist followers of Darwin, John Tyndall and Thomas Huxley led the criticism of Maxwell's lecture and of theism in science more generally at the British Association meeting in Belfast. Maxwell and Tyndall actually got on well, but Maxwell's friend, Tait, and Tyndall did not, and with Tyndall and Huxley denying a role for God, it was Tait and Balfour Stewart who responded in their books, *Paradoxical Philosophy* and *The Unseen Universe*.

Fifty years ago, Bruce Ritchie's mentor at Edinburgh University, the theologian Thomas Torrance, helped shift thinking on science and religion away from the classic question of whether science confirms or refutes the existence of God to reflect on how we picture an idea in science and in religion. His influence on Ritchie was profound and this is clear in the book's closing chapter in which the author sums up his understanding of the interplay between Maxwell's science and his faith. He argues that Maxwell first perceived the whole and then ventured to understand its parts, notably in his electromagnetic researches. And his focus was not on entities but on the relations between them. This is how he could conceive of the field continuum. Entities existed only because of the field, the field held the entities, they were as one or not at all. Torrance argued that it was Maxwell's faith which enabled Maxwell to transform his whole conceptual framework, with the doctrine of the Trinity – in which the Holy Trinity only exists in a three-fold continuum, as one or not at all – providing an analogical model which allowed him to think about physical reality in a new way. To Maxwell the relations were analogous and because of the latter he could conceive the former, and this was 'regulatory', unconscious or semi-conscious.

The symptoms of the abdominal cancer from which Maxwell would not recover became pronounced in the spring of 1879 and by the autumn he was told that he had only weeks to live. Despite being in considerable pain he travelled from Glenlair to Cambridge. As he approached death, he claimed that he had studied most philosophical systems and found none that would work without a God.

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… 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 propagated through the electromagnetic field according to electromagnetic laws.

James Clerk Maxwell (1865)

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