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# Radio Science in the UK 1919-2019

UK Contribution to URSI Centenary Book


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**Abstract**

The development of radio science in the UK in the hundred years since the founding of URSI is outlined here. Early research into the ionosphere by Appleton and colleagues experimentally confirmed the existence of a layer of conductive plasma in the earth's atmosphere, and observations of reflections from this layer prompted the invention of radar by Watson Watt and others. The availability of surplus radio equipment after the Second World War was a factor in the development of radio astronomy by Ryle's group in Cambridge and researchers lead by Lovell at Jodrell Bank. Other post-war developments included medical applications, waveguides, computational electromagnetics, novel antennas for electromagnetic compatibility and continued interest in wireless communications, ionospheric propagation and radio astronomy projects like the Square Kilometre Array. The UK's contribution has been enriched by the collaborative, international ethos of URSI.

## 1. Pre-URSI period

Radio science began long before the founding of URSI in 1919, a key step being James Clerk Maxwell's theoretical prediction of electromagnetic (EM) waves in the 1860s, which was validated by Heinrich Hertz, Jagadish Chandra Bose, David Edward Hughes and Oliver Lodge towards the end of the century, and most famously by Guglielmo Marconi, whose experiments in the UK included the first radio communications with a ship from a transmitter on the Isle of Wight.

It is tempting to view the history of radio as "19$^{th}$ century physics leading to 20$^{th}$ century engineering," but that would be an oversimplification. The reality is that the line between engineering and applied physics is a blurred one, and the traffic between fundamental science and practical applications has been two-way. For example we have the theoretical contribution of Oliver Heaviside (who also rewrote Maxwell's EM equations in their currently used form), and also Arthur Kennelly, independently predicting the Kennelly-Heaviside Layer. Practical experiments in the UK and elsewhere showed that this layer reflected radio waves, which lead to the realisation that EM pulses could be bounced off aircraft to determine their range and direction. Radar was a real-world application that had a great influence on the course of the Second World War and later found many peacetime uses. In the post-war period the availability of surplus radar equipment was a factor that enabled rapid developments in radio astronomy, where observations of distant emitters of radio waves gave us new scientific insights into the nature of the Universe.

Organisations like URSI have played an important role not just in fostering interactions between engineers and scientists, but also in promoting partnerships amongst researchers in many countries across the world. A glance at the lists of prizes awarded by URSI [1] shows many who were based in the UK, but an Olympic-Games style medal table would hide the cooperative and international nature of science. Many of the 'big names' in UK radio science were highly active in URSI and valued its promotion of scientific openness and global collaboration. It is notable that URSI was founded the year after the end of the First World War, and that internationalism and peaceful unity are embodied in its very name.

## 2. The Ionosphere

In the UK, a key figure for early research into Ionosphere is Sir Edward Victor Appleton, who was born in Bradford 1892 into a working-class family and became a professor at the age of 32 and Fellow of the Royal Society (FRS) at 35 [2]. Throughout his career he was a great supporter of URSI, serving as URSI President from 1934-52 and Honorary President from 1952-65. URSI's Appleton Prize is named after him, as is the Rutherford Appleton Laboratory in Harwell, Oxfordshire. Incidentally, Appleton was a life-long friend and colleague of the Dutch physicist and radio pioneer

Balthasar van der Pol, another dedicated URSI supporter, after whom the URSI Van der Pol Gold Medal is named. As well as many other distinctions, Appleton was awarded the Nobel Prize for Physics in 1947.

Appleton studied at Cambridge University where he attended lectures by J. J. Thomson, Joseph Larmor and Oliver Lodge. After Cambridge he initially worked with Lawrence Bragg on X-ray crystallography but this work was interrupted by the First World War. He began to take an interest in radio while serving in the army as a Royal Engineer at Aldershot, where the early wireless equipment operated with spark gap sources and crystal detectors. During his service he helped to identify how enemy engineers were listening in on communications, a problem solved with a more secure system called the Fullerphone.

After the war Appleton went back to Cambridge with a position of assistant demonstrator under Ernest Rutherford, famous for splitting the atom, but found he preferred radio science to nuclear physics. Appleton's first paper was published in Wireless World in 1918 [3] where he describes a 'slopemeter,' an instrument for measuring the characteristics of three-electrode valves (Figure 1). These were triodes, the forerunner of the transistor, and used in the first RF amplifiers.

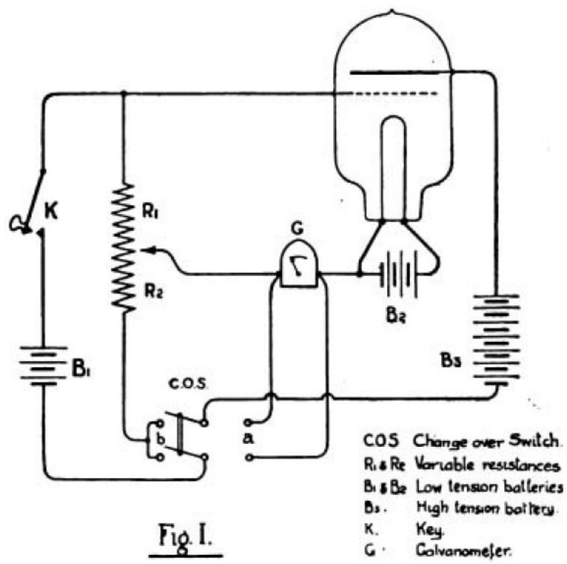
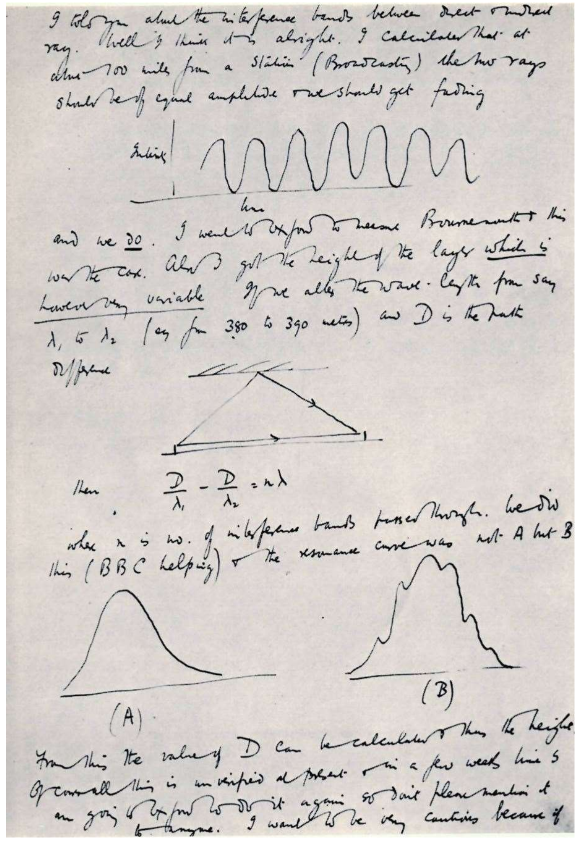



*Figure 1. Appleton's slopemeter, used to obtain the current-voltage characteristics of triode valves (from [3]).*

In the 1920s, Appleton and the New Zealand scientist M. A. F. Barnett in the UK, and also Gregory Breit and Merle Tuve in the USA, showed that radio waves can be reflected from ionised layers in atmosphere. Appleton was more aware than the others of the potential applications of this discovery. Key experiments performed in 1924 confirmed the hypothesis of Appleton and Barnett that fades in signal strength were due to variations in reflections from a conductive layer in the atmosphere, which had been postulated 20 or so years earlier by Heaviside and Kennelly [4]. They collaborated with the Electrical Laboratory at the University of Oxford on this research, and persuaded the British Broadcasting Company (later Corporation) to sweep the frequency of the BBC transmitter at Bournemouth, at a time after public broadcasting had finished for the night. A location was chosen where the sky wave and ground wave were of similar magnitude and therefore interfered either constructively or destructively depending on their phase shifts. As expected, sweeping the frequency caused an oscillatory variation in the combined signal strength (Figure 2).


I told you about the interference bands between direct & indirect ray. Well I think it's alright. I calculated that at about 100 miles from a station (Broadcasting) the two rays should be of equal amplitude & we should get fading

and we DO. I went to Oxford to receive Bournemouth & this was the case. Also I got the height of the layer which is however very variable. If we alter the wave-length from say $\lambda_1$ to $\lambda_2$ (say from 380 to 390 metres) and D is the path difference

then $\frac{D}{\lambda_1} - \frac{D}{\lambda_2} = n$

where n is no. of interference bands passed through. We did this (BBC helping) & the resonance curve was not A but B

(A) (B)

From this the value of D can be calculated & thus the height. Of course all this is unverified at present & in a few weeks time I am going to Oxford to do it again so don't please mention it to anyone. I want to be very cautious because of

*Figure 2. Experimental results in Appleton's notebook, showing interference between sky wave and ground wave as the transmitter frequency was swept, confirming the existence of the ionosphere (from [1]).*

Appleton and Barnett showed that their interference method was more successful than earlier attempts to observe the downward travelling ray with a directional antenna [5]. They also correctly hypothesised that interference was being observed from 'single-hop' and 'multi-hop' paths of rays reflected between ionosphere and ground as illustrated in Figure 3.

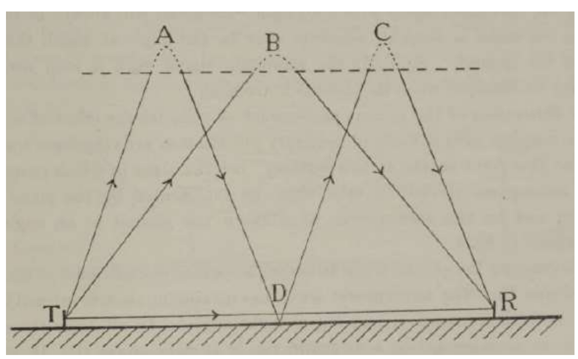



*Figure 3. Appleton and Barnett postulated interference between rays reflected once and twice from the ionosphere (from [5])*

Appleton moved to Kings College London as professor to take up the Wheatstone Chair in 1924, and the ionosphere became his major and life-long interest. Appleton was an early advocate of academic collaboration with industry and with institutions like the BBC; he encouraged John Logie

Baird to develop ultra-SW (i.e. UHF) transmissions of TV signals. He also saw the value of international relationships with researchers in the USA, Germany and elsewhere.

Collaboration between universities and government was important in early ionospheric research in the UK. The National Physical Laboratory (NPL) provided transmitters at Dogsthorpe near Peterborough. With an improved detector, the Eindhoven galvanometer, they showed that the height of the ionised layers changes at dawn, and also during a solar eclipse, so must be influenced by the sun [6].

The Radio Research Station (1924-79) at Ditton Park, near Slough, Berkshire, England was the UK government research laboratory that pioneered regular observation of the ionosphere by ionosondes. It later became the Radio and Space Research Station (1965) and eventually merged with the Rutherford Laboratory. Appleton and radar pioneer Robert Watson-Watt (see next section) both worked there. The British physicist Mary Taylor (later Mary Taylor Slow) was perhaps the first woman to become a professional radio scientist; after studying at Girton College, Cambridge and the University of Göttingen, Germany she became a Scientific Officer at the Radio Research Station in 1929, where she published research on the Appleton-Hartree equation for EM propagation in a magnetised plasma [7].

Appleton's research has thus been useful in plasma physics generally as well as in the field of Antennas and Propagation. He named the layers of the ionisation in the atmosphere – initially the E-layer (E for Electric) and subsequently the D and F layers above and below it. However the word 'ionosphere' to describe the Heaviside-Kennelly layer seems to have been coined by Watson-Watt: in a letter to the Secretary of the Radio Research Board in November 1926 he wrote "We have in quite recent years seen the universal adoption of the term 'stratosphere' in lieu of a previously well established misnomer 'isothermal layer' and the adoption of the companion term 'troposphere' for the 'convection layer'… the term 'ionosphere' for the region in which the main characteristic is large-scale ionisation with considerable mean free paths, appears appropriate as an addition to this series" [2].

Appleton contributed to the International Polar Year 1932-3, a venture proposed by a sub-commission of URSI and lead by Danish physicist Dan Barfod la Cour, with involvement of van der Pol and Watson-Watt. Activities included an expedition to Norway to investigate ionospheric propagation at high latitudes (Figure 4). Using SW and pulse transmitters near Tromsø, the researchers made the first observations of radio 'black-outs' during magnetic storms [8].

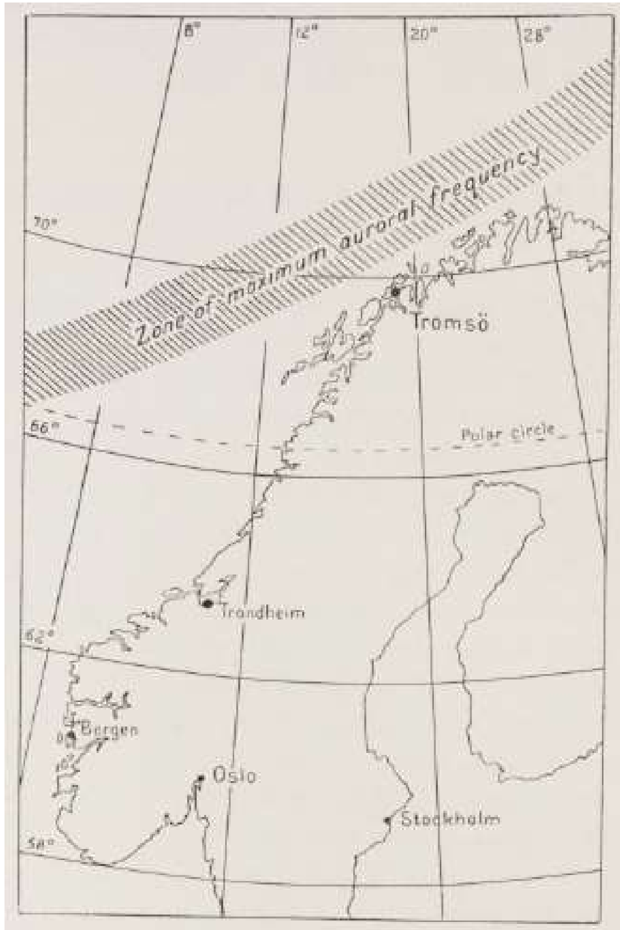



*Figure 4. Map showing that Tromsø (spelled Tromsö here) was well located for research into high-latitude propagation (from [8]).*

Appleton's influence on the development of radar is described in the next section. Pulses, from improved pulse generators, were being bounced off the ionosphere, and this led on to a similar idea where the target is a moving aeroplane. Observers at the Halley Stewart laboratory at KCL in the early 1930's had noted 'blips' on the response when the ionosonde beam directed upwards at the ionosphere was interrupted by passing planes.

Other researchers in the UK joined the field. John Ashworth (or "Jack") Ratcliffe, an influential British radio physicist, was Appleton's student at Cambridge in 1923-4 and did much pioneering work on the ionosphere, immediately prior to the Second World War. He served as URSI Honorary president from 1966-87, and continued his ionospheric research in the post-war period. He published observations on the spreading of radio frequencies by the Doppler effect, noting that this was analogous to broadening of spectral lines in the optical case [9].

William Henry Eccles was a British physicist and pioneer in the development of radio communication. He had assisted Marconi in his experiments, was an early advocate of the Kennelly-Heaviside Layer, and was involved in the early days of the BBC. He was URSI vice-president 1921-34 and honorary president 1934-66. Eccles-Larmor theory is named after him and the Northern-Irish Physicist Sir Joseph Larmor; it explains the mathematics of ionospheric propagation, including the plasma frequency [10].

Sir William John Granville Beynon was URSI president 1972-75 and honorary president 1981-86; he published an account of URSI's involvement in the early research on the ionosphere [11]. After studying physics at the University of Swansea, he joined NPL in 1938 where he worked with Appleton on ionospheric propagation. After the war he returned to Swansea, and then in 1958 moved to what was then the University of Wales at Aberystwyth (now Aberystwyth University) where he carried out rocket-borne experiments in the 1970s. Like Appleton, Granville Beynon saw the value of international scientific cooperation. He played a key role on behalf of URSI in organising the International Quiet Sun Year 1964-65. Figures 5 and 6 are taken from a postgraduate brochure and show research into the ionosphere and satellite communications being undertaken at the Aberystwyth in the 1960s, under the guidance of Granville Beynon.


*Figure 5. Researchers at Aberystwyth in the 1960s using an automatic ionosphere sounder for measuring the height of reflection of radio waves.*

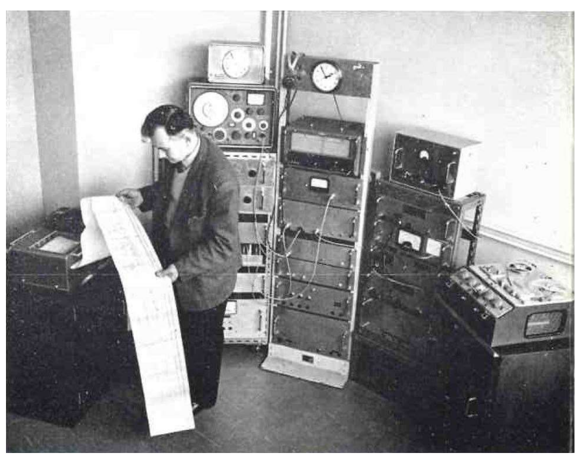


*Figure 6. Equipment at Aberystwyth in the 1960s for recording radio signals from satellites.*

In more recent years, other UK scientists who contributed to ionospheric research include Henry Rishbeth [12], who received the Appleton Prize in 1981 for 'Contributions to studies of the dynamics and structure of the ionosphere F region'. At the University of Leicester, Tudor Jones carried research on the ionosphere, especially at the polar regions. He received the Appleton Prize in 1993 for 'major contributions, individually and in scientific leadership, to the study of ionospheric physics, using radio and radar techniques.' Michael Lockwood received URSI's Issac Koga Gold Medal in 1990 for 'Study of non-thermal ionospheric plasma and ionospheric convection.' Lockwood's work at the

University of Reading in the 2000s contributed to the debate on solar versus anthropogenic influences on global warming.

**3. Radar and Direction-Finding**

Many countries were working on radar research in the 1930s. New devices were important in making progress, as well as advances in theoretical propagation calculations. The resonant cavity magnetron as shown in Figure 7 was radically improved by physicists John Randall and Harry Boot in 1940 at the University of Birmingham [13], making smaller, higher frequency equipment possible. It was an improvement on the older klystron and is still used today in domestic microwave ovens.

*Figure 7. The anode block of the original cavity magnetron built in 1940 by Randal and Boot (from [14]).*

Scottish engineer Robert Watson Watt was a regular participant at URSI meetings. He began his career at the Met Office (the UK's national weather service), where in the 1920s he used radio waves from lightning to track thunderstorms (Figure 8) [15]. In 1927 he was appointed superintendent of the Radio Research Station.

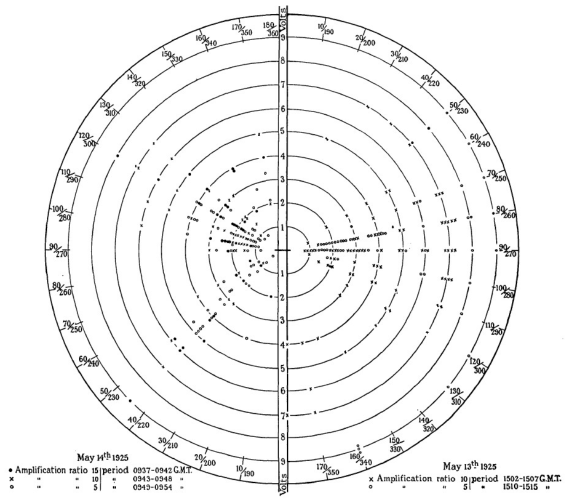



*Figure 8. Watson-Watt and Herd's observation of azimuthal distribution of atmospherics in May 1925 (from [15]).*

High frequency direction finding (HF/DF or "Huff Duff") was developed in the 1930s using Watson Watt's principle. Based on two orthogonal loop antennas (Adcock antennas), connected to an early cathode-ray oscilloscope (CRO), with a slow phosphor and in x-y mode, it gave the angle of direction of incoming signals.

Research on ionosondes at the Radio Research Station, starting in 1932, eventually lead to the British 'Chain Home' radar system that was used in the Second World War (Figure 9). In 1935 researchers at the RRS successfully detected reflections of a 6MHz wave from a BBC short-wave transmitter in Daventry. They subsequently built a SW pulse system at Orfordness that generated pulse widths of only 25μs.

*Figure 9. The last standing transmitter of the Chain Home network, at the site of the former RAF radar station at Stenigot, near Donington on Bain, Lincolnshire (from [14]).*

The rivalry between Appleton and Watson Watt is well known, but both contributed greatly to its success, and Appleton did acknowledge Watson Watt's vision in developing a scientific principle into a practical radar.

Radar was deployed in the war, being crucial to the outcome of the Battle of Britain. The UK offered details of the newly-invented magnetron to the US in exchange for financial and industrial assistance. This gave the Allies better performance than Axis equipment. Airborne radars were being used by 1941, including ground mapping radars (H2S) that were developed by Alan Blumlein, who was killed in a plane crash during the H2S trial, and Bernard Lovell, more famous for his radio astronomy work. These were able to spot submarines from the radar reflection of their periscopes.

Another contributor to this field, from 1922 onwards, was Reginald Leslie Smith-Rose, an English physicist who worked at the National Physical Laboratory and was a world leader in radio direction-finding. He was the first director of the post-war Radio Research Organisation that was formed in 1948, and served as president of URSI from 1960-63.

URSI business during WW2 was minimal and the GA did not restart until 1946 after a gap of 8 years. The Telecommunications Research Establishment (TRE) and the Radar Research and Development Establishment (RRDE) continued their research work at Malvern, Worcestershire, and in 1953 they were combined to form the UK's Radar Research Establishment.

Radar continued to be developed after the war, not just for military purposes, but for making all forms of transport safer (road vehicles as well as aircraft), and technological advances in radar have led to diverse applications including weather radar, ground penetrating radar (GPR) and radio astronomy.

**4. Radio Astronomy**

There had been unsuccessful attempts to detect RF emissions from the Sun in the 1890s. A proposal was made at the URSI GA of 1934 (by a commission headed by Appleton), for a global study of RF noise from stars, but this was not implemented [16].

Radio astronomy proper is generally considered to begin with the work of Karl Jansky in the US in the 1930s, which was taken up by Grote Reber in the early 1940s. However initial developments in radio astronomy in the UK, in research groups at Cambridge and Manchester, were more influenced by RDF and radar. Bernard Lovell's group at Manchester initially worked on meteors and the ionosphere, moving in the 1950s to develop interferometry techniques to study emissions from galaxies and discrete sources. Martin Ryle's group in Cambridge looked at solar emissions and observed what were then termed 'radio stars', and subsequently commenced a programme of cataloguing and mapping.

J. S. Hey had observed radio noise from the direction of the sun, at radio stations on British coast in 1942. After the war, in 1946, Hey and Appleton showed that the power at peak times was much greater than could be explained by black body radiation in that band of the spectrum, and showed it was connected with solar flares and sun spot activity (Figure 10) [17]. Hey went on to work at the Royal Radar Establishment at Malvern, eventually becoming Head of Research there.

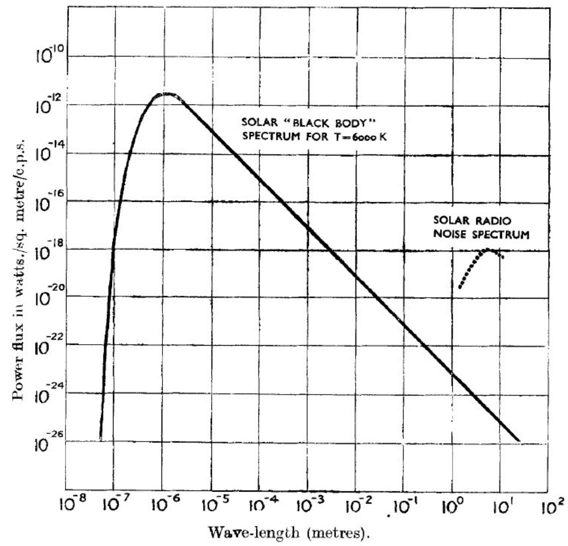



*Figure 10. Appleton and Hey observed RF noise from the sun, and showed that it exceeded the solar black body spectrum (from [17]).*

Ryle also worked initially on radio emissions from the sun [18]. After the war he lead the Cambridge radio astronomy group, and eventually founded the Mullard Radio Astronomy Observatory (MRAO) near Cambridge in 1957. An advocate for the socially responsible use of science and technology, Ryle can be credited with key improvements in astronomical interferometry and aperture synthesis. Using slotted lines, stub tuners and hand-calculation of Fourier transforms, he and his group built the first multi-element interferometer in 1946, which operated at 175MHz, and consisted of a broadside array of dipoles over a ground plane.

The Cambridge group published catalogues of astronomical radio sources. There have been ten of these to date, with the 3C and 4C catalogues in the 1950s being notable for their contribution of radio astronomy to debates in cosmology [19]. In particular the 'log N – log S' relation seen in P. A. G. Scheuer's measurements of the radio source counts [20] provided strong evidence against the steady state theory against its rival big bang theory (which was further strengthened by observations of the cosmic microwave background). Scientific advances and technical developments were thus intertwined.

Radio astronomy at Cambridge continued its contribution to new discoveries in the 1960s. Optical follow-up of the radio source 3C273 (Figure 11) led to the discovery of quasars by Maarten Schmidt in 1963 [21]. A few years later, in 1967, Jocelyn Bell Burnell, a graduate student working with Antony Hewish, used the IPS array that was investigating interplanetary scintillation (Figure 12) to discover the first pulsar.

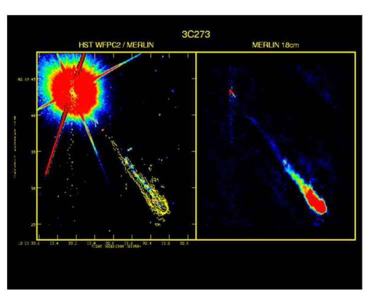



*Figure 11. The 3C273 radio source - Credit Jodrell Bank Centre for Astrophysics*

*Figure 12. The IPS Array for investigating interplanetary scintillation, used to discover pulsars - Credit Graham Woan, University of Glasgow*

Ryle received the Balthasar van der Pol Gold Medal in 1963 for 'Application of the phase switching and aperture synthesis techniques to antennas for radio astronomy', while Hewish was awarded the John Howard Dellinger Medal by URSI in 1972 for 'Advances in radio astronomy.' Ryle and Hewish, but controversially not Bell Burnell, received the Nobel prize for physics in 1974.

Radio-astronomy at Manchester began with ex-army radar equipment, including Yagi antennas using the 4.2m band (71MHz), and a 'large aerial' system [22]. Lovell's group then constructed a home-made paraboloid out of wire mesh, to provide a powerful instrument for its time. This had a narrow beam width that was slightly steerable, and was dubbed the 'searchlight aerial'. The famous 76-metre Lovell Telescope at Jodrell Bank (the location was originally the University of Manchester's botanical grounds) was conceived by Sir Bernard Lovell, and designed by him and engineer Sir Charles Husband. It was largest radio telescope in world when completed in 1957, and tracked the USSR's Sputnik satellite later that year.

Robert Hanbury Brown joined Lovell's group in Manchester in 1949, where his work on airborne radar influenced Reber's research in the US on 'cosmic static'. In 1950, Hanbury Brown and his PhD student Cyril Hazard in Manchester used a 218 foot (66m) paraboloid antenna, with a beam width of 2 degrees, the narrowest in the world at the time, to investigate the emissions at 159MHz from the M31 nebula in the constellation Andromeda (Figure 13). This showed that M31 was an RF source [23].

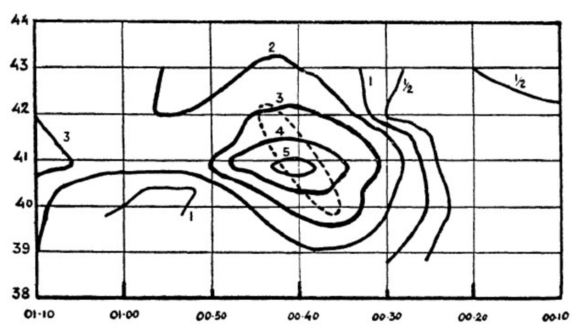



*Figure 13. Hanbury Brown and Hazard's 1951 plot of contours of radio-frequency flux near the M31 source in Andromeda (dotted lines show a corresponding photo), obtained with a 2° beam at 159MHz (from [23]).*

Hanbury Brown's idea of an 'intensity interferometer' was conceived in 1949 and confirmed (with British astronomer Richard Twiss) in 1954. Their concept was also applied to optical radiation and used to measure the angular diameter of Sirius – the first such measurement on a star [24]. Hanbury Brown also worked on plans to use the moon as a radio relay, although these were eventually rendered unnecessary by the development of artificial satellite communications. He moved to Australia in 1962 and continued his research there.

The Multi-Element Radio Linked Interferometer Network (MERLIN), an interferometer array of radio telescopes spread across England, is run from Jodrell Bank Observatory by the University of Manchester. The new radio telescope was finished in 1976, and the rest of the system built in the late 1970s.

The Laing-Garrington effect, an asymmetry in the polarisation of radio emissions from jets that emerge from a double radio source, was important in the development of unified schemes of active galactic nuclei (AGNs). It was discovered in 1988 by Robert Laing and Simon Garrington of the Jodrell Bank Observatory [25].

**5. Post-World-War-Two Period**

Wartime technologies evolved into other peaceful applications. The British science-fiction author Arthur C Clarke proposed satellite communications in 1945: in a letter to editor of *Wireless World* he noted that a satellite in a 24-hour orbit "would remain stationary in the same spot and would be within optical range of nearly half the earth's surface. Three repeater stations, 120 degrees apart in the correct orbit, could give television and microwave coverage to the entire planet" [26].

This idea was subsequently taken up by many countries, and much sooner than the half century predicted by Clarke. A British satellite programme was started, with 'Black Knight' rockets being tested on the Isle of Wight at a site near the Needles, not far from the location of Marconi's ship to shore transmissions at the turn of the century. Their successor, Black Arrow, launched the Prospero satellite from Woomera, Australia in 1971. Funding was then withdrawn, as satellite communications were thought to have no commercial future, and interest moved on to other projects such as Concorde.

Advances in EM theory were made in British universities. Professor Douglas Jones, a mathematician known for his work in electromagnetism, was appointed Chair of Mathematics at the University of Keele in 1957. He was the author of the key EM textbook *The Theory of Electromagnetism*, published in 1964 [27]. Jones was awarded the Balthasar van der Pol Gold Medal by URSI in 1981 for 'Work on electromagnetic theory and, in particular, on the development of a number of analytical approaches'.

Government laboratories such as NPL continued to play a role in radio science. E. H. Rayner at NPL served as honorary president of URSI 1946-63. He had worked on international comparison of radio frequency standards since the 1930s – an article in Nature from 1935 reports that a standard at NPL with "a frequency of 1000 cycles per second, the stability of which is better than one part in ten million" was used to modulate transmissions from three BBC stations, enabling frequency comparisons and also studies of fading [28].

There was renewed interest in the microwave region of the EM spectrum. Harold Barlow worked at University College London in the post-war period on problems involving guided-wave propagation, especially the development of circular waveguides (Figure 14) [29]. In 1969, Barlow was awarded the John Howard Dellinger Medal by URSI for 'Development of waveguides; the characteristics of surface waves.' A. L. Cullen, who was president of URSI 1987-90, started at UCL as Barlow's assistant and continued research at UCL into microwave and mm wave antennas.

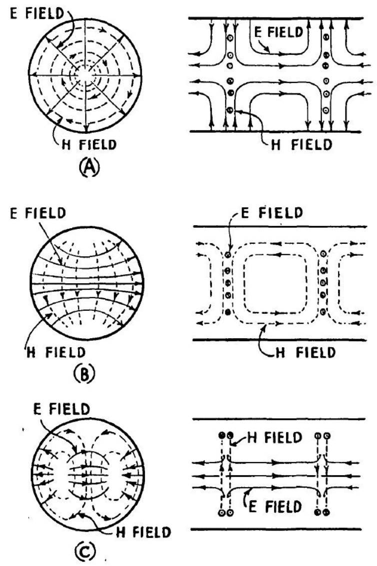



*Figure 14. Barlow's 1947 illustration of the field patterns in cylindrical waveguide, showing E01, H11 and E11 propagation modes (from [29]).*

Radio technologies found valuable uses in medicine. Magnetic resonance imaging (MRI) employs antennas in their near-field, typically at 64MHz, to excite and sense resonances of the hydrogen nuclei in the human body in the presence of a strong magnetic field. Although nuclear magnetic resonance (NMR) spectroscopy had been known earlier, imaging systems were first developed in the 1970s by many researchers including Paul Lauterbur and Raymond Damadian. Peter Mansfield at the University of Nottingham introduced echo-planar imaging which speeded up the measurements, and John Mallard built a full-body MRI scanner at Aberdeen [30]. Lauterbur and Mansfield were awarded the 2003 Nobel Prize in Physiology or Medicine for their work on MRI.

Mallard suggested that differences in permittivity of body tissues could enable a radio frequency or microwave alternative to X-ray imaging, a promising area of application being the detection of breast cancer, where the high water content of tumours should provide high contrast to the surrounding healthy tissue [31]. This idea was taken up by researchers in several countries, including Alan Preece's group in Bristol [32]. Microwaves have also been used to treat cancers, with novel near-field antennas for hyperthermia therapy (known as applicators) being designed at Bristol [33] and also by Jeff Hand's group at Hammersmith Hospital and Imperial College London [34]. Parametric models of tissue dielectric properties were developed by Camellia Gabriel and colleagues which enabled detailed computational electromagnetic models to be created for simulating EMF exposure [35], while at the University of York (and elsewhere), an experimental technique allowed the absorption cross-section of the body to be measured directly in a reverberation chamber at microwave frequencies [36].

The proliferation of electronic devices led to increased problems with radio frequency interference (RFI) and hence greater regulation, including the European Community Directive on Electromagnetic Compatibility 89/336/EEC. The need for industry to limit both emissions and susceptibility of products prompted research in 1990s in the UK and in other European Union countries into improved EMC test methods. A novel antenna design, the Bilog, enabled broadband frequency sweeps without the need to switch antennas; it combined features of bi-conical and log-periodic antennas, and was developed at the University of York by Andy Marvin and Stuart Porter [37].

There were also developments in computational electromagnetics, such as the Transmission Line Matrix method introduced by P. B. Johns and R. L. Beurle of the University of Nottingham in 1971 [38]. 'Intermediate level modelling tools' that bridge the gap between analytical solutions and full-wave solvers, were introduced for EMC problems such as the design of EM shields. An example of these tools is the equivalent circuit of Figure 15 for an enclosure with an aperture, which is represented by a coplanar transmission line coupled to a shorted section of waveguide [39].

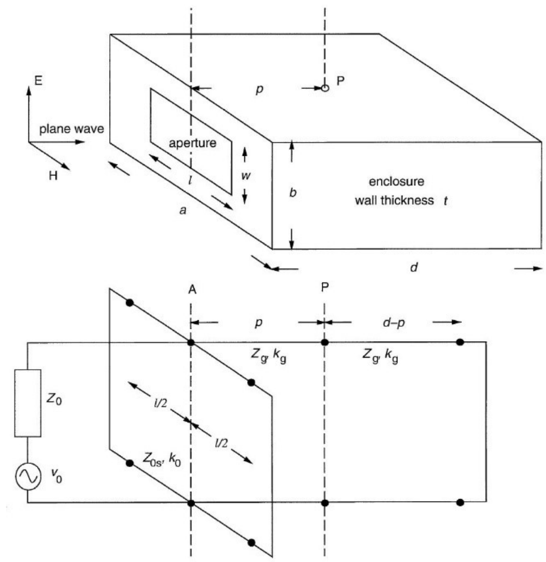



*Figure 15. Intermediate level model of a rectangular enclosure with an aperture, introduced in 1998. The current and voltage at a given distance along the waveguide give respectively the electric and magnetic shielding effectiveness (from [39]).*

The UK Member Committee of URSI in its current form was set up in 1990, as a successor to the British National Committee, after the Royal Society in the UK reorganised the committees responsible for scientific unions. Its activities include the Festival of Radio Science (FRSci, previously National URSI Symposium), an annual one-day event aimed at PhD students and early-career researchers, with prizes for best oral presentations and posters.

An internal review of UK URSI in 1998 noted that UK radio scientists had a good level of participation at URSI conferences and at the GASS, with many elected to official positions such as commission chairs or editor of URSI journals. It also noted that the UK radio science community had particularly strong representation on Commissions B, F, G and H.

**6. Twenty-first Century and Beyond**

In this century, UK scientists and engineers have continued to contribute to URSI, presenting papers at the GASS and serving as commission chairs and in other posts. Paul Cannon of the University of Birmingham was president of URSI 2014-2017.

A glance at the programmes for the last few FRSci's shows that the UK still has an active interest in radio astronomy, including the Square Kilometre Array (SKA), and research continues on many aspects of ionospheric propagation. Another current topic of interest is mm-wave channels for 5G communications. There have been many papers on microwave and mm-wave devices such as dielectric resonators, amplifiers, switches and filters, and on antenna performance and the design of patch antennas and arrays. Propagation scenarios being studied include indoor, urban and vehicle-to-vehicle channels, while bio-medical applications include body-warn antennas, patient movement tracking and detection of breast cancer. Other topics have been wireless sensor networks, metamaterials and reverberation-chamber measurements for electromagnetic compatibility (EMC). Presenters have been mainly from universities, but also from companies like QinetiQ and research agencies such as NPL.

New research topics continue to arise, an example being Sir John Pendry's research at the Blackett Laboratory, Imperial College London on refractive indices and 'perfect lenses,' and associated work on metamaterials that have negative permittivity or permeability [40]. Pendry was awarded the John Howard Dellinger Medal by URSI for 'outstanding advances in electromagnetic and optical metamaterials, the design of the perfect lens and transformation optics' in 2017.

The ionospheric plasma still has a strong influence on radio signals. Electron density enhancements and depletions in the ionosphere cover a wide range of spatial scale-sizes, and these structures and associated density gradients affect radio propagation and signal strength. Ionospheric imaging and modelling have played an important role in understanding and mapping the radio signal paths. Tomographic imaging [41, 42] has been used to identify large-scale ionospheric structure, including patches of enhanced density in the polar cap and blobs and troughs in the auroral and sub-auroral regions. Data assimilation allowed measured data to be combined with a background ionospheric model [43, 44], and modified Taylor diagrams have been used to assess such assimilative models [45]. An ionospheric data assimilation technique capable of resolving travelling ionospheric disturbances was presented by [46], which improved the accuracy of HF angles of arrival predictions. Statistical studies of large-scale ionospheric features have also been carried out. These include investigations of polar patches in the high-latitude plasma flow observed by the EISCAT Svalbard Radar [47] and the main ionospheric trough modelled by the Qinetiq Electron Density Assimilative Model [48]. Influences of geomagnetic storms and auroral precipitation on radio systems have also been studied, with [49] investigating correlation between GPS phase radio scintillation and optical auroral emissions, and [50] examining the characteristics of sudden commencement absorption that accompanies geomagnetic storm sudden commencement.

With the increasing dependency of society on modern technology, precision and safety are increasingly important for future operational systems. For example, improved nowcasting and forecasting of HF propagation is required for trans-polar airline routes [51]. The need for quantification of space weather effects and their influence on the ionospheric plasma is therefore increasingly important, where severe perturbation of the ionospheric plasma can lead to signal degradation or loss. The plasmasphere is also affected by disturbed geomagnetic conditions and its coupling with the ionosphere and magnetosphere is also of interest for operational systems.

Recent advances in radio astronomy include the discovery of rotating radio transients (RRATs) in 2006 using the Lovell Telescope; these are thought to be intermittent pulsars. Jodrell Bank was selected as the permanent headquarters for the Square Kilometre Array (SKA) in 2015. On 7th July 2019, Jodrell Bank Observatory was awarded World Heritage Site status by UNESCO and added to that body's World Heritage List.

The SKA telescope, pictured in Figure 16, will provide a huge leap in radio astronomy capabilities when it comes on line in 2027. UK researchers are heavily involved with the design of the telescope and the definition of the science programme. Key areas where transformational discoveries are expected include: high precision timing of pulsars to test theories of General Relativity and detect very low frequency gravitational waves; exploration of the first stars in the Universe by studying highly redshifted neutral hydrogen emission; investigation of the recently discovered phenomenon of Fast Radio Bursts due to as yet unknown events at cosmological distances.

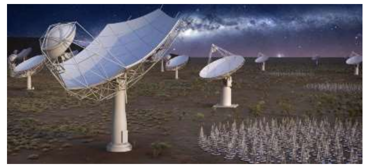


*Figure 16. An artist's impression of the SKA - credit: SKA Organisation*

**7. Conclusion**

Science often progresses in unexpected directions, and those researchers who started investigating the ionosphere nearly a century ago might not have expected that the reflections they observed would lead to the concept of radar, or that the surplus of radar equipment after the war would assist in the development of radio astronomy. Although the main use of radio technology remains in wireless communications systems that connect people across the globe, it has also evolved into new applications which enable us to sense the smallest features of the body and to explore the furthest objects in the cosmos. This has been achieved by scientists, engineers and technologists in universities, companies and national laboratories, and the contribution of the UK researchers has been enhanced by their willingness to collaborate with those in other countries and to adopt the cooperative and internationalist ethos of URSI.

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