Appleton's ionosphere

Article

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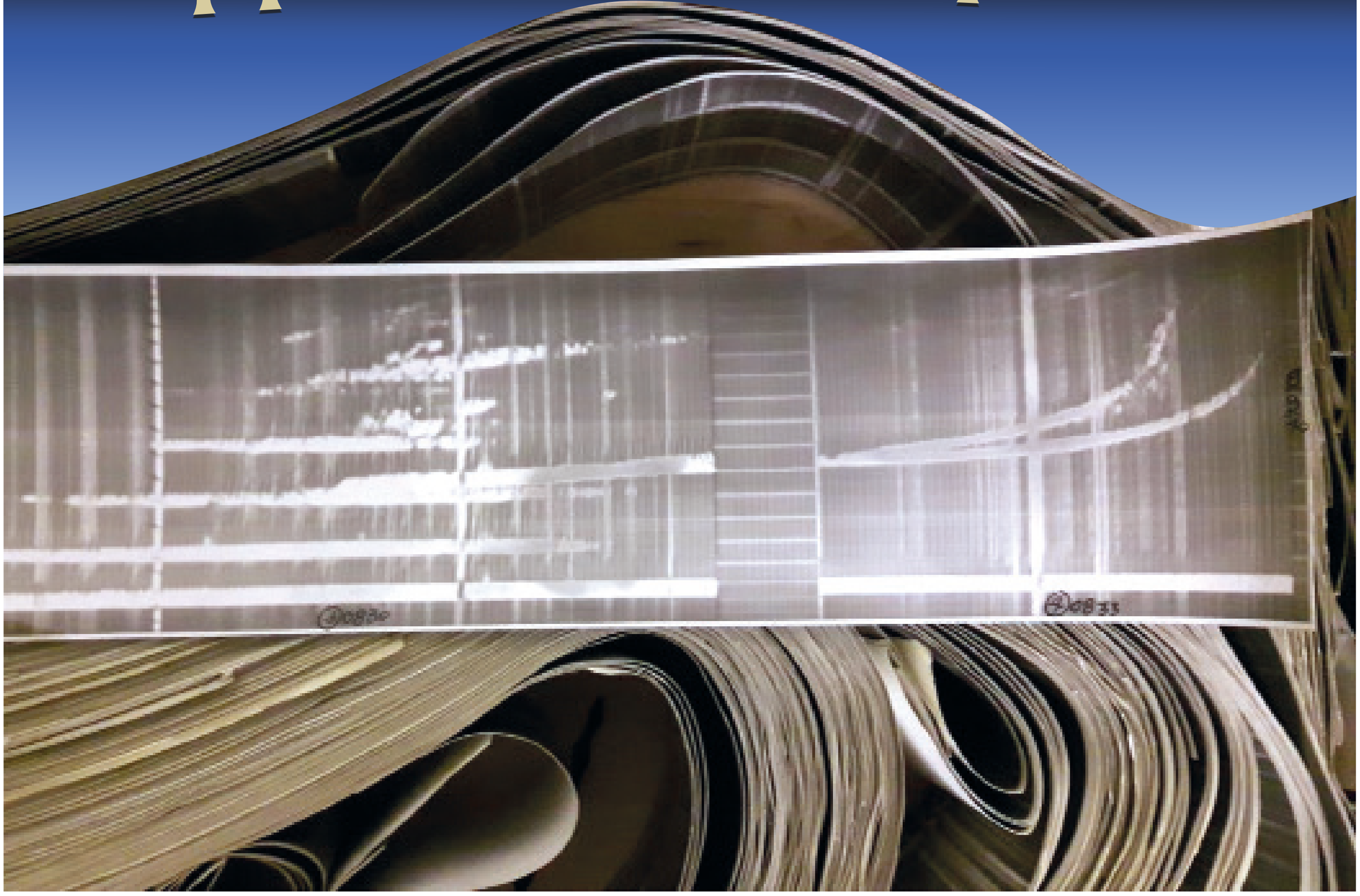


A sample of the Slough ionospheric archive. Approximately 250 000 such ionograms require digitisation with subsequent ionograms stored on 35mm film and latterly digitally. (Ditton Park Archive at the UK Solar System Data Centre)

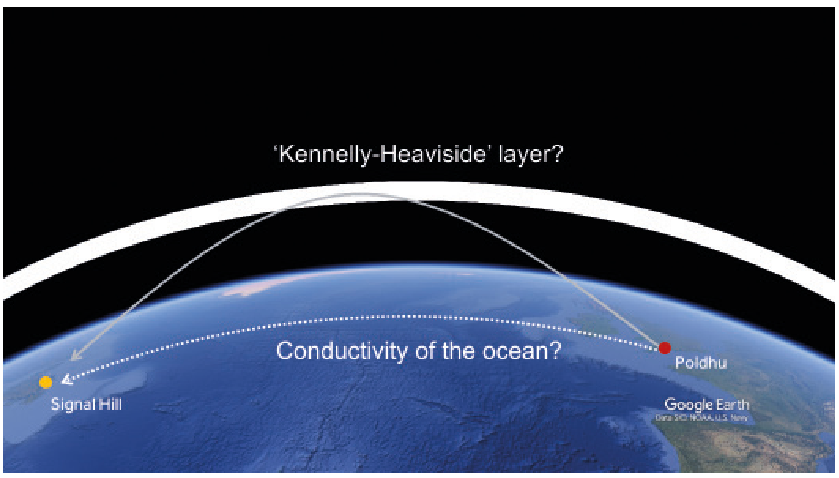
A century after Appleton's pioneering experiment, his measurement techniques still underpin our monitoring of the Earth's ionosphere. Christopher Scott and Matthew Wild assess their influence.

In two pioneering experiments conducted on 11 December 1924 and 17 February 1925, Edward Appleton and his research student Miles Barnett demonstrated the existence of a radio-reflecting layer in the Earth's upper atmosphere, later to become known as the ionosphere (Appleton and Barnett 1925a,b). The centenary of these remarkable experiments seems a fitting time to look back at how they revolutionised our understanding of wave propagation in the atmosphere and formed the foundation for the subsequent 100 years of ionospheric science.

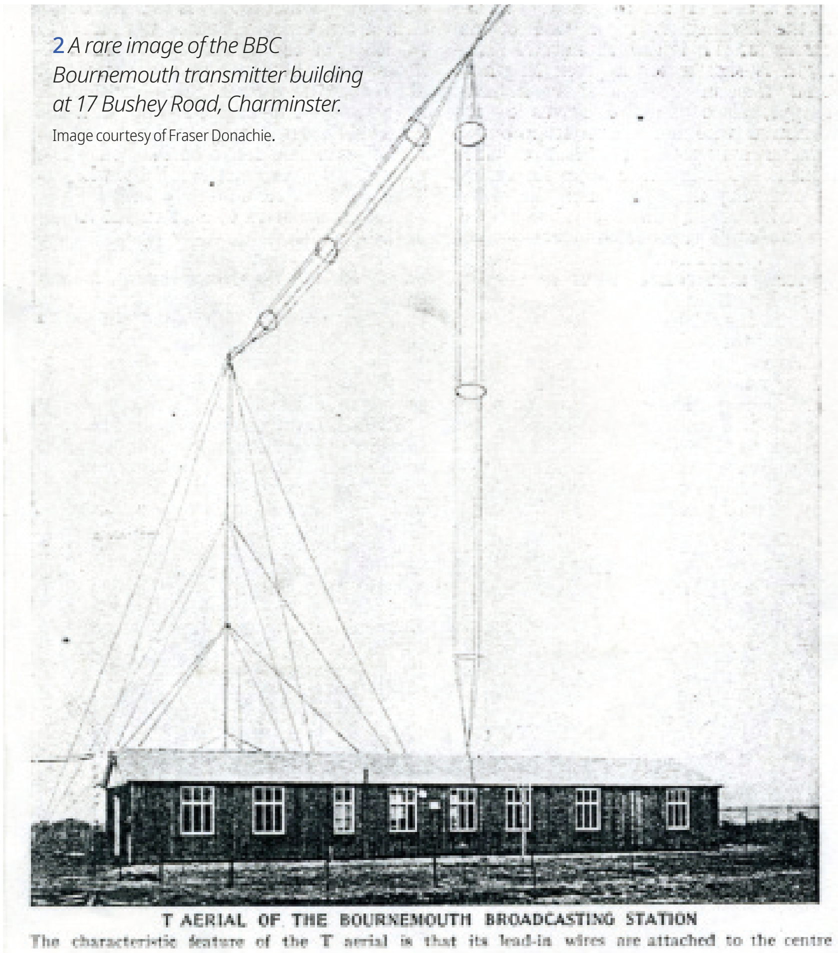
In the late 19th and early 20th centuries, 'wireless' radio communication was being developed, championed by Guglielmo Marconi; information exchange by Morse code became a staple for communications over ever-increasing distances (e.g. Griffiths 2018). On 12 December 1901 Marconi conducted a famous experiment in which he claimed to have received a radio signal at Signal Hill in Newfoundland that had been transmitted from Poldhu, Cornwall, in the UK, more than 3600km away. This is widely considered the first successful reception of a transatlantic radio signal.

The efficacy of this experiment has subsequently been questioned because it involves a known message – the Morse code letter 's' – transmitted at a pre-arranged time during daylight hours, when radio absorption is at its greatest. Ratcliffe (1974) subsequently conducted a forensic analysis of Marconi's experiment and concluded that the spark-gap transmitter used created a broad spectrum of radio frequencies. While centred on a frequency of 800kHz, Ratcliffe reasoned that there was likely to have been a significant transmission at 3.5MHz, which was far more likely to have been received, especially given that the receive antenna was itself not tuned to a particular frequency.

Marconi conducted further experiments that consolidated his initial result but why was this achievement so remarkable? Radio is a form of light and light was known to travel in straight lines, so it



1 *The geometry of Marconi's trans-Atlantic transmission. A radio wave transmitted from Poldhu on Cornwall, UK was received at Signal Hill in Newfoundland – but how? Two theories were put forward.* (Google Earth, using data from Data SIO, NOAA and the U.S. Navy)



2 *A rare image of the BBC Bournemouth transmitter building at 17 Bushey Road, Charminster.* Image courtesy of Fraser Donachie.

remained unexplained as to how Marconi's signal could have been received in Newfoundland when it would have had to travel around a significant fraction of the globe to do so (figure 1).

Various suggestions were put forward to explain the experiment. Some suggested that the conductivity of the ocean may have affected the path of the radio waves. Others, notably two scientists named Arthur Kennelly and Oliver Heaviside, proposed the existence of a radio reflecting layer in the upper atmosphere. Heaviside is credited with suggesting the existence of such a layer in an article on telegraphy published in the *Encyclopaedia Britannica* (Heaviside 1902), while a more considered explanation was given in the same year by Kennelly (Kennelly, 1902) who reasoned that the existence of such a layer was the natural consequence of the rarified nature of the upper atmosphere above 80km altitude. A more detailed discussion of this early work can be found in the article by Griffiths (2018).

As the early 20th century progressed, the use of radio for communications was becoming ever more popular, leading to the formation of the British Broadcasting Company (BBC) on 18 October 1922, with the first programme being broadcast within weeks. By 1927 the BBC had become a public corporation financed by a licence fee.

Recognising the emergence of this new technology, in 1920 the Department of Scientific and Industrial Research formed the Radio Research Board with the remit to "direct any research of a fundamental nature that may be required, and any investigation having a civilian as well as a military interest" (Gardiner *et al.* 1982). The first board was chaired by the Admiral of the Fleet Sir Henry Jackson and had some influential members, such as Lord Rutherford. The board oversaw several subcommittees whose membership included scientists, notably Edward Appleton and Robert Watson-Watt. One topic of special interest to Appleton was the fading of radio signals at night. He reasoned that this phenomenon could be explained by the interference of two radio signals that had travelled through different paths in the atmosphere, consequently arriving at the receiver with a phase difference which caused destructive interference of the superposed waves.

Enter Appleton

In March 1925, Edward Appleton submitted a letter to *Nature* (Appleton and Barnett 1925a) in which he described the results of an experiment providing evidence for the existence of a radio reflecting layer.

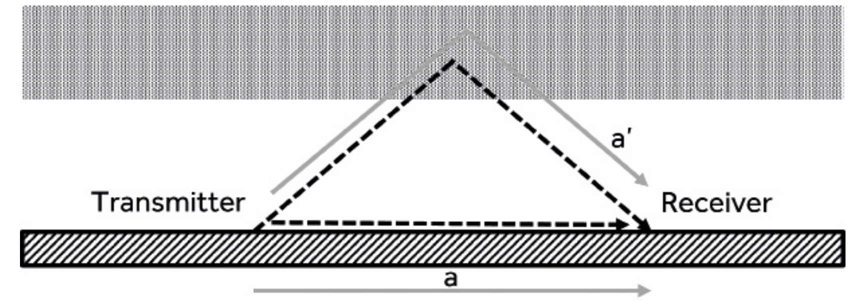
3 *While the BBC Bournemouth buildings no longer exist, the plans do, and so it is possible to overlay its position on a modern photograph* (Google Earth; plans courtesy of Fraser Donachie.)

This work was described in more detail in a later publication (Appleton and Barnett 1925b). Appleton's hypothesis was that one of the wave paths leading to the radio interference at the receiver travelled along the ground while the other arrived via a radio-reflecting layer in the Earth's upper atmosphere. He referred to these waves the 'direct-wave' and the 'indirect-wave'. His previous experiments had shown that the fading was most pronounced when the receiver was around 100km from the transmitter and so he set up an ingenious experiment to test this.

On 11 December 1924, and again on 17 January 1925, Appleton arranged with Captain A G D West, the assistant engineer at the BBC, to use the recently commissioned transmitter at Bournemouth for such experiments, after the day's programmes had finished (Appleton and Barnett 1925a). Very few images of the BBC transmitter building at Bournemouth exist but those that do reveal it to have been a modest single-storey structure with transmit antennas above (figure 2). The size of the antenna was necessary to generate radio signals at the required frequencies. While the transmitter buildings no longer exist, the plans do and we can once again use Google Earth to locate the area today – on Bushey Road in Bournemouth, next to the cemetery (figure 3). There are more details in an excellent history of the BBC Bournemouth (Donachie 2022), written to celebrate the centenary of the station.

Knowing that he needed a separation between transmitter and receiver of around 100km, Appleton set up equipment to receive the signal in the Electrical Laboratory at the University of Oxford. It can be seen (figure 4) that the path of this signal is sufficiently short that the reception of both sky and ground waves was possible, unlike Marconi's intercontinental experiment.

The experiment that Appleton devised was simple and elegant. He likened his experiment to the well-known optical experiment 'Lloyd's mirror' that results in light waves that travel on different paths generating light and dark interference fringes. Similarly in Appleton's experiment, the two radio waves would be travelling along different paths, resulting in fading as a result of destructive interference between the two signals.



5 *The geometry of Appleton's experiment. The direct wave along the ground would travel a distance, a, to the receiver, while the indirect wave would travel a greater distance, a'. By changing the wavelength of the carrier signal slowly throughout the experiment, Appleton was able to estimate the path difference (a'-a) from the number of signal maxima he observed. From this he was able to estimate the height of the reflecting layer to be 80–90km.*

"Appleton arranged with the assistant engineer at the BBC to use the transmitter at Bournemouth for such experiments, after the day's programmes had finished"

For a direct path along the ground, *a*, and an indirect path via the atmosphere *a'*, the indirect wave would arrive *N* wavelengths, *λ*, behind the ground wave, where;

$$N = \frac{a' - a}{\lambda} \qquad [1]$$

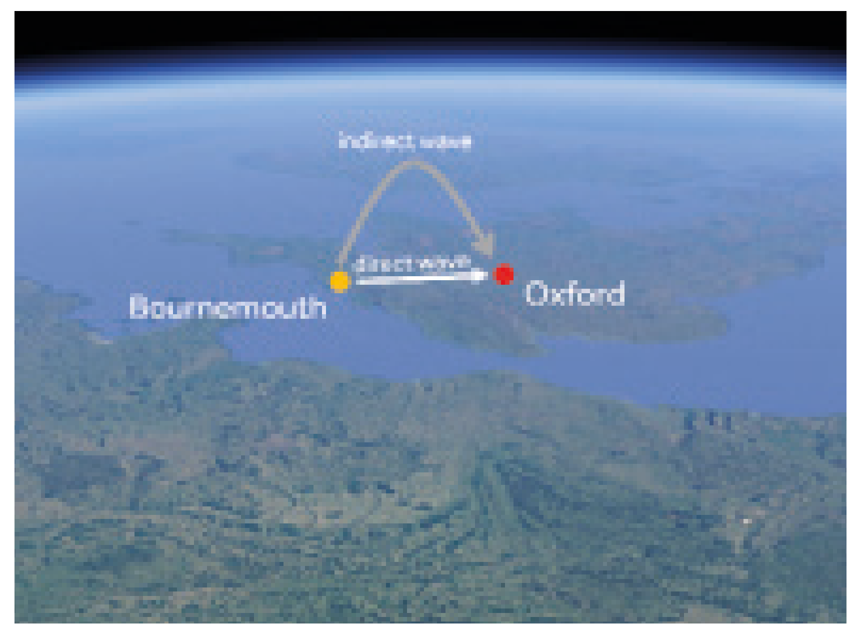
By arranging for the wavelength of the radio signal to be changed continuously but very slightly over a range, *δλ*, throughout the experiment, Appleton was able to estimate the number of signal maxima, n, throughout the interval;

$$n = \frac{\delta\lambda}{\lambda^2}(a' - a) \qquad [2]$$

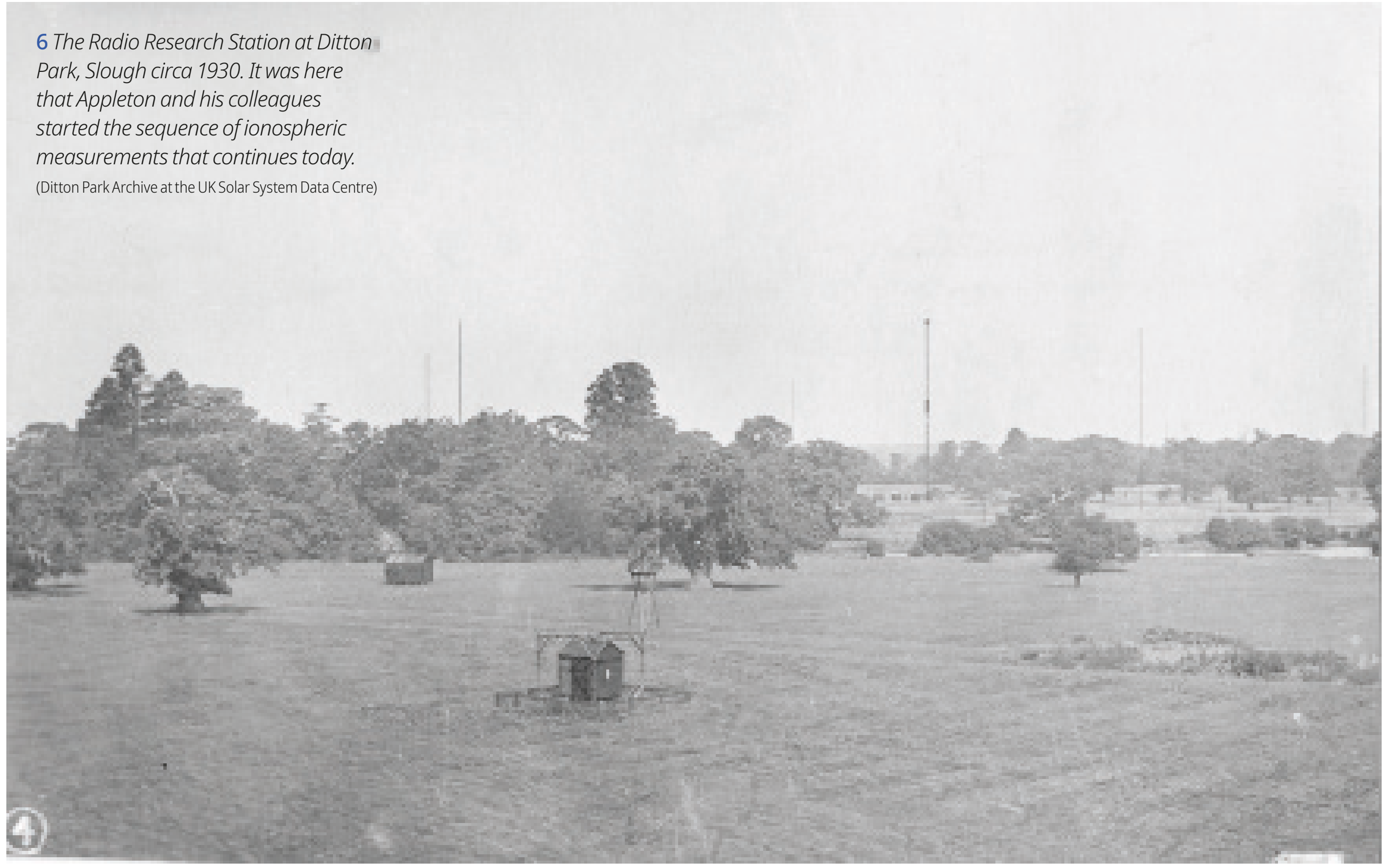
As the wavelength, *λ* and the change in wavelength, *δλ* were known, the number of fading events he detected would reveal the difference in path length between the two signals. Since the direct path distance, a, was known, the indirect path length, *a'*, could be calculated, from which the height of the reflecting layer could be derived.

The wavelength of the BBC transmitter was increased from 385 to 392m over a time interval of around one minute. Appleton detected variations in the strength of the signal via the deflection of a galvanometer and, while he was unable to visualise his results, the average number of maxima he observed during the experiments (4.5) indicated an indirect path length, *a'*, of 100km from which he estimated the presence of a radio reflecting layer at an altitude of around 80–90km (Appleton and Barnett 1925a).

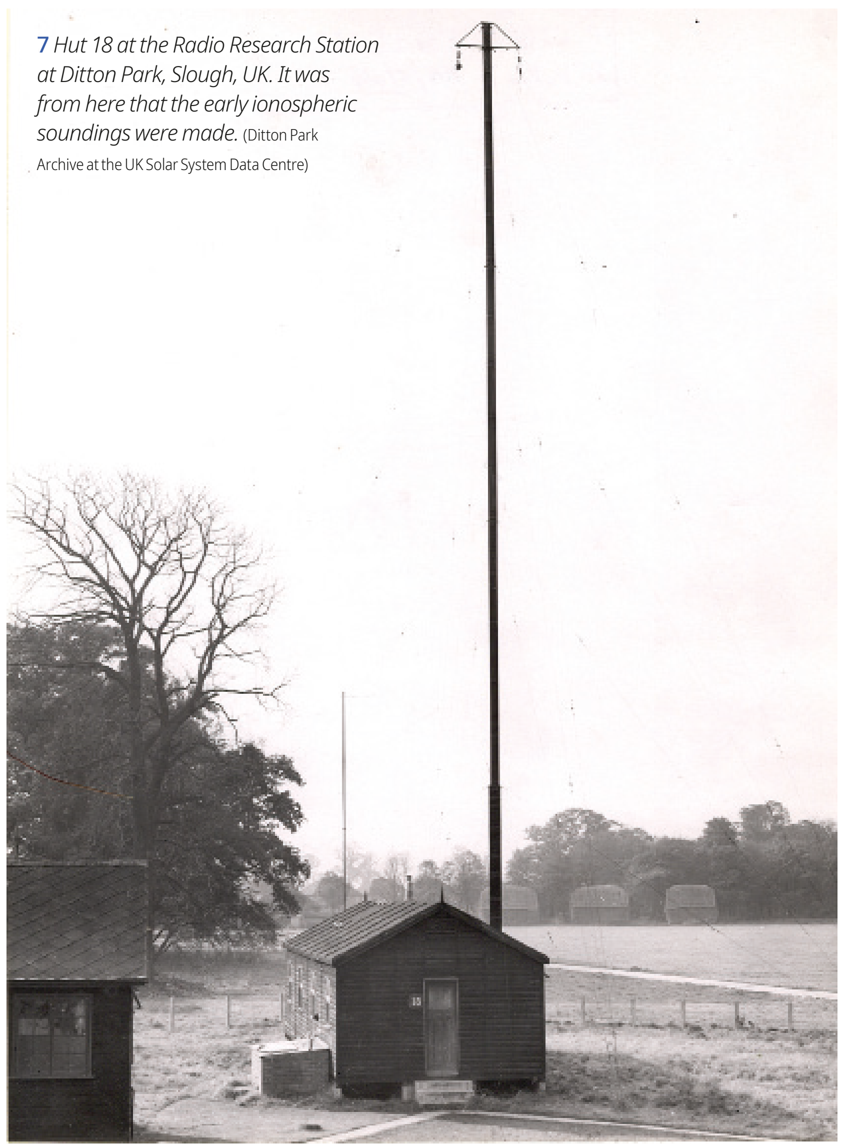
The minutes of the Radio Research Board are maintained within the Ditton Park Archive (tinyurl.com/5yh3677f) held by the UK Solar System Data Centre (www.ukssdc.ac.uk) at the Rutherford Appleton Laboratory, UK. The minutes indicate that both Appleton and Captain West of the BBC were invited to attend some of these meetings, with Appleton reporting on the progress of his work following the success of his initial experiment. Appleton discussed the challenges he had faced in conducting these experiments, not least those arising from the natural variability of the atmosphere, interference from overseas radio stations and the intermittent transmission of Morse signals. Subsequent work, again using the Bournemouth transmitter whose signals were received at the Radio Research Station at Peterborough, honed the 'frequency change method'. The time interval over which the frequency was changed was reduced to a few seconds (in order that the results would not be dominated by natural fading events) and an oscilloscope was used to visualise the variations in signal strength,



4 *The scale of Appleton's experiment. A radio wave from BBC Bournemouth was received at Oxford, 140km away. This path was sufficiently short that both a 'direct' wave along the ground and an 'indirect' wave via the upper atmosphere would both arrive at the receiver. Appleton interpreted the fading of such radio signals as destructive interference caused by the phase difference resulting from the different paths the two waves.* (Google Earth, using data from Landsat/Copernicus, Data SIO and NOAA)



6 *The Radio Research Station at Ditton Park, Slough circa 1930. It was here that Appleton and his colleagues started the sequence of ionospheric measurements that continues today.* (Ditton Park Archive at the UK Solar System Data Centre)



7 *Hut 18 at the Radio Research Station at Ditton Park, Slough, UK. It was from here that the early ionospheric soundings were made.* (Ditton Park Archive at the UK Solar System Data Centre)

which could then be photographed. These simple, yet elegant, images were subsequently published in Appleton and Barnett (1926). It is interesting to note that, since this work was conducted under the direction of the Radio Research Board, the manuscript was submitted to the journal by the chair of the committee, First Admiral of the Fleet, Sir Henry Jackson FRS.

While initially referred to as the 'Kennelly-Heaviside layer, the name 'ionosphere' was subsequently coined by Appleton's colleague, Watson-Watt (Rishbeth, 1994). Appleton was later awarded the Nobel Prize for his work on the ionosphere, and the 'frequency change' experiment was explicitly mentioned in the citation.

Height of the reflecting layer

In the summer of 1925, shortly after Appleton had conducted his initial experiments, two engineers, Gregory Briet and Merle A Tuve, working in America, demonstrated a technique to measure the height of the reflecting layer by modulating the amplitude of the radio signal, effectively sending up a short radio pulse and inferring the height of reflecting layer from the time delay of the returned echo (Briet and Tuve 1926).

In a report submitted to the Radio Research Board, the programme of work for the radio research station at Peterborough reports on the continuation of the 'frequency change' experiments but also proposes developing the 'amplitude modulation' method of Briet and Tuve and using an oscilloscope to visualise the results. It is further proposed that comparison be made between the two methods in order to determine the degree of penetration into the ionised layer by different wavelengths.

In the minutes of their meeting held on 2 October 1930, the committee agreed to recommend: "that every available means should be used to carry to a numerical solution the general problem of the propagation of electrc [sic] magnetic waves in an ionised medium surrounding an imperfectly conducting earth, account being taken of the effects of the terrestrial magnetic field and of absorption effects, and that Prof Hartree should be asked to suggest means of close collaboration between himself and workers for the Committee towards the solution of the general problem stated above."

Douglas Hartree, at the time, held the Beyer Chair of Applied Mathematics at the University of Manchester. Both Appleton and Hartree had been working independently on such theoretical considerations. While never co-authoring a joint paper on the subject, their work ultimately led to the development of the Appleton-Hartree equation, which can be used to describe the propagation of radio waves through an ionised gas. One result of this theory is that a radio wave will be returned from an altitude where the resonant 'plasma' frequency of the free electrons matches the radio frequency;

$$f = 8.98\sqrt{N} \qquad [3]$$

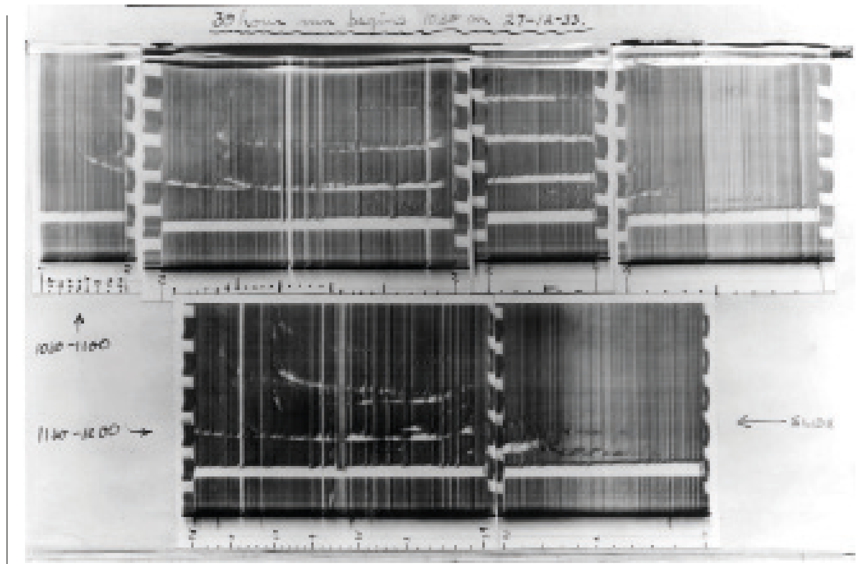
where f is the radio frequency in Hz and N is the electron concentration (m^{-3}). With the ionisation in the atmosphere varying with altitude, different radio frequencies are therefore returned from different heights and, by changing the radio frequency, it is possible to build up a height profile of ionisation in the atmosphere.

The minutes of the Propagation of Waves committee of the Radio Research Board held on 26 November 1929 note that "Professor Appleton reported that he thought it should be possible to develop a method for the measurement of the ionisation constant of the upper layer, by measuring the wave-length of the waves turned back at the layer at practically vertical incidence". Appleton had realised the scientific potential of Breit and Tuve's radio pulse technique. By transmitting a sequence of pulses of different frequencies and timing their return, it proved possible to build up a height profile of these radio-reflecting layers.

By July 1930, Appleton (now the chair of the Radio Research Board's Committee on the Propagation of Waves and Directional Wireless) was reporting that work was underway at the Radio Research Station, under his supervision, to "determine the wavelength that just penetrated the ionised layer" while also looking into "...the effect of magnetic storms upon the deviation caused by the layer".

Over the next decade, Appleton and his colleagues at the Radio Research Station in Slough (figures 6 and 7) developed equipment to record the vertical structure of the ionosphere, and in 1933 started a sequence of routine soundings in order to understand how the ionosphere is formed and what causes it to change. Indeed, the late Henry Rishbeth (an RAS fellow and former student of Jack Ratcliffe, who had studied under Appleton) once remarked that, for some time during the early days of ionospheric research, when people referred to the ionosphere, they really meant "the ionosphere above Slough".

For each radio pulse, the separation between ground and ionospheric echoes were displayed on an oscilloscope. By arranging for a roll of photographic paper to move past a slit on the oscilloscope screen as pulses were transmitted over a range of radio frequencies, an analogue plot of echo time-delay (proportional to altitude) versus radio frequency (proportional to the square root of the ionospheric electron concentration) could be produced (figure 8). These original soundings still exist and are held in the physical archives of the UK Solar System Data Centre at the Rutherford Appleton Laboratory in Oxfordshire.



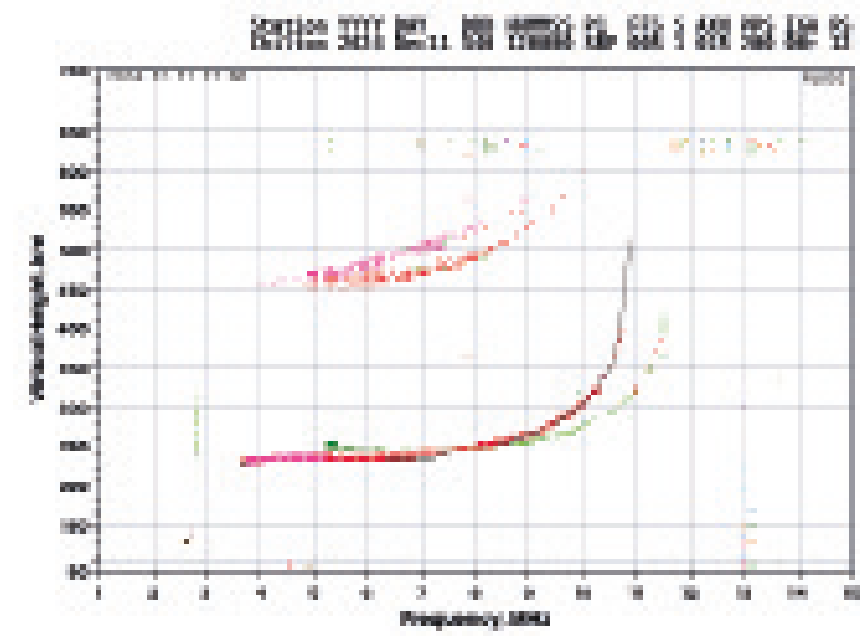
8 *An example of an early ionospheric sounding from 1933. Photographic paper was fed past a slit in front of an oscilloscope on which the ground and ionospheric echoes were displayed for a given frequency. By moving the paper and changing the frequency of the radio pulse, a plot of time-of-flight (proportional to height) against frequency (proportional to the square-root of the electron concentration) was generated. In these early plots, frequency increases from right to left.* (Ditton Park Archive at the UK Solar System Data Centre)

"With the ionisation in the atmosphere varying with altitude, different radio frequencies are therefore returned from different heights"

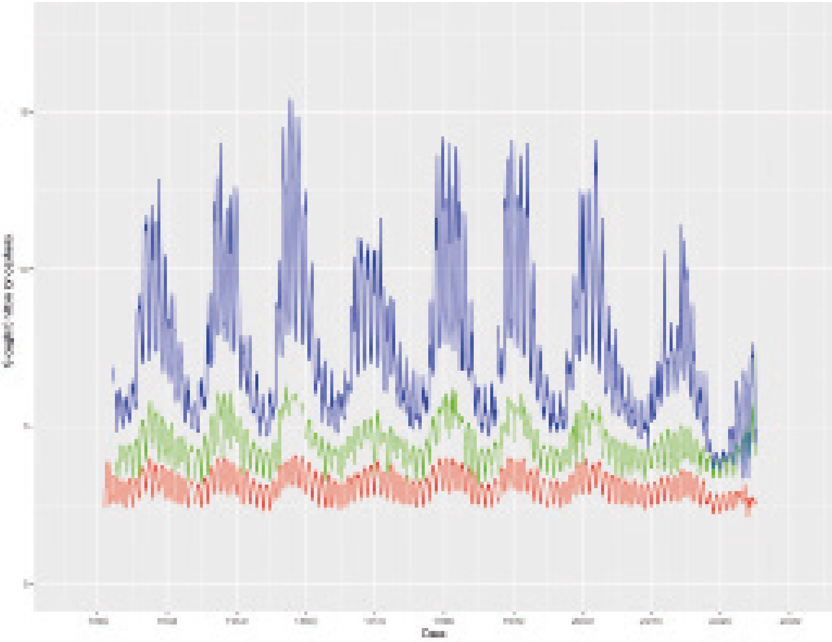
This sequence of measurements continues today at the Rutherford Appleton Laboratory in Oxfordshire (figure 9). It is the longest continuous sequence of ionospheric measurements in the world (figure 10). These data are still in demand from the ionospheric and radio science communities, and are either used directly or are fed into commercial data products for operational users such as commercial airlines, satellite operators and the military.

While key parameters were recorded from each of these 'ionograms' at the time, the original soundings still exist, with the archive containing an incredible amount of useful scientific information. They record, for example:

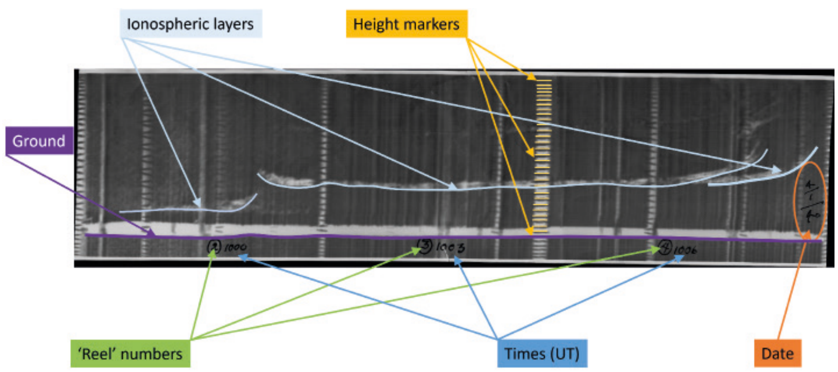
- variations in the Sun's Extreme Ultraviolet and X-ray emissions and solar activity long before the space age, especially during 'space weather' events when solar eruptions reach Earth (e.g. Davis *et al.* 2013);
- the response of the ionosphere to astronomical



9 *A modern ionogram taken by the digital ionosonde at Chilton, Oxfordshire. This sounding was taken on 11 December 2024 – 100 years after Appleton's original experiment.* (UK Solar System Data Centre)



10 *Monthly median values of the three main ionospheric layers for the entire Slough/Chilton sequence. Appleton's radio reflecting layer, now called the E-layer is shown in red, with two higher altitude layers, the F1 shown in green, and F2 shown in blue. The values, in MHZ, represent the highest radio frequency that can be returned from each layer (equivalent to the peak electron concentration). While initially manually scaled from the ionograms, since around 2005, these parameters have been automatically scaled.* (UK Solar System Data Centre)



11 *An annotated ionogram showing what information needs to be identified on each sounding. It is proposed to serve scanned images online via a citizen science project.* (Ditton Park Archive at the UK Solar System Data Centre)

phenomena such as meteor showers and solar eclipses (e.g. Scott *et al.* 2016);
- shockwaves launched by explosions on the ground (e.g. Scott and Major 2018);
- enhancements due to terrestrial lightning (Davis and Johnson 2005);
- long-term changes to the composition of the neutral thermosphere, in which the ionosphere is embedded (e.g. Scott *et al.* 2014);
- the ionospheric response to climate change (Rishbeth 1990).

This final point was proposed by Rishbeth (1990). As the lower atmosphere traps heat, the upper atmosphere is expected to cool, with the ionospheric F2 peak (at around 250–350km) predicted to have contracted by around 20km over the time span of the Slough/Chilton data sequence. This prediction has been the subject of considerable work by many scientists worldwide (e.g. Bremer 2004). Most recently, however, it has been shown that the methods used, which rely on the tabulated ionospheric parameters, contain an inherent bias (Scott *et al.* 2024). Estimating this long-term change in ionospheric height is possible but it would require going back to the original soundings and considering the effect of the whole ionospheric profile.

Preserving historic environmental data is vitally important particularly when there is information about long-term changes that go beyond the scope of modern measurements. In justifying this statement, it is helpful to draw an analogy with other high-profile science projects such as the Large Hadron Collider: Suppose all the scientific goals of such a project were met and the facility was closed and decommissioned; later, fresh research raised the possibility of further exciting science with such a facility. Given the scientific and political will, the infrastructure could be rebuilt, the new experiments run and the new data examined. But in contrast, it will never again be possible to repeat observations taken at, say, noon on 19 February 1937. Without the historical ionospheric data, answers to the scientific questions listed above would have been lost, while other, as yet unimagined, hypotheses would go untested.

Digitisation

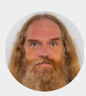
As described in this article, only one copy of each of the early Slough soundings exist, each recorded on photographic paper. Many of these are more than one metre in length. With some of these ionograms now approaching 100 years old, this unique archive is in danger of being lost. Despite the technical, logistical and financial challenges, we are working to preserve this archive by scanning the original ionograms with the aspiration to make them available online. In addition, we are developing a citizen science project to enable volunteers to record the information they contain (figure 11). In this way, the information will once again be available for use by modern generations of scientists and engineers. There has recently been much excitement in applying Artificial Intelligence to accelerate such tasks. While this may indeed be true, a human-identified test set is still required in order to calibrate the efficacy of such methods.

A century after Appleton's pioneering experiment, the measurement techniques that he and his colleagues developed are still underpinning our monitoring of the Earth's ionosphere. Initiatives such as the International Polar Year in 1932 and the International Geophysical Year in 1957/58 led to a proliferation of instrumentation around the world, with international agreements to share the data leading to the formation of 'World Data Centres'. While these halcyon days of ionospheric measurement and data sharing appear to have passed, a global network of ionospheric monitoring stations still operates, with data being used to inform users on current radio communication and space weather conditions. A century after Appleton's original experiment, the techniques he and his colleagues developed are as relevant as ever. ●

AUTHORS

Christopher Scott, Professor of Space & Atmospheric Physics at the University of Reading. He is increasingly turning to historic data to address modern scientific questions.

Matthew Wild, Manager of the UK Solar System Data Centre, curating data from the earliest solar and geophysical measurements to the latest spacecraft missions.



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