1. Sixth Appleton Memorial Lecture

The Ionsphere and Radio Engineering

by G Millington

My Lord President, Ladies and Gentlemen

When I received the invitation to give the Sixth Appleton Memorial Lecture, I was sent a list of my predecessors, and I could not help noticing that I am only the second who is not a Fellow of the Royal Society. I therefore count it a great honour to have been chosen, and I trust that I may not prove unworthy of the confidence that has been reposed in me. Were it a condition that the lecturer should have known Sir Edward personally, then I would at least qualify, for it was in 1923 when I was a freshman at Clare College, Cambridge, that my tutor sent me for supervision in mineralogy to Dr Appleton, a young don at St. John's College.

I quickly came under the spell of his teaching ability and soon learned that he was engaged on some important radio experiments, more especially as Barnett from New Zealand, who was working with him, was a research student at Clare College. It was also my privilege as an undergraduate to know J A Ratcliffe who later joined in ionospheric research and who shared with Appleton a reputation for brilliant and lucid lecturing, as I found during my own time as a research student at the Cavendish Laboratory. It was Professor Rutherford's custom to call the less able of his students into his office after a couple of years and tactfully suggest to them that they should go into industry, so that I lost touch with Appleton and his work when I left the Cavendish at the end of two years and went into acoustical research for the Columbia Graphophone Company.

However, when I had to leave this work at the end of two years, I had the inestimable privilege of joining T L Eckersley at what is now known as the Marconi Company, which brought me right into the field of radio-propagation research, of which one fact was ionospheric propagation. In time I renewed acquaintance not only with Appleton's work but also with Sir Edward himself, more especially in the post-war years at the various URSI Assemblies I was privileged to attend.

Now, with my invitation I was informed that the lecturer was not necessarily bound to talk about Appleton's field of work, but in view of my case history, it was suggested that I should take as my subject 'The Ionosphere'. I suppose that I could have prepared a survey of other people's work, but there are many in this country, including some who knew and worked with Appleton, who are actively engaged in modern ionospheric research and who could more fittingly undertake this task. I shall return at the end of my lecture to the impact of this work on radio engineering, but it is my main intention to give a historical review of ionospheric research done under the auspices of an industrial firm with its engineering applications in view.

In these days when research has to be related more closely to development and production, it must be remembered that practically nothing was known about propagation, so that under the guidance of T L Eckersley's genius many contributions were made to fundamental ionospheric research, which in the early days was vital to the successful operation of radio communications depending on the ionosphere. I should like to make it plain that I realise that much of what

I am to describe was paralleled with work done at the Radio Research Station at Slough, more especially on the practical side; indeed we had a close and happy collaboration, following up one another's ideas, so that at this point in time it is difficult to say where they originated. After all, they were at that time under the wing of D S I R and so were engaged on industrial research.

Although the actual discovery of the ionosphere is often associated with Appleton and Barnett's frequency-change experiment, involving interference effects between a direct and a reflected wave, the postulation of a conducting layer in the upper atmosphere that could reflect radio-waves back to the earth dates from the earliest days of long-distance radio transmission, and is associated with the names of Kennelly and Heaviside. It is difficult to say whether Marconi knew that he would have the help of the ionosphere to get his signals from Poldhu to Newfoundland in face of the mathematicians who based their calculations on pure diffraction round the curve of the earth. Suffice it to say that it was soon realised that some such mechanism must be operating, and in 1914 Eccles had derived a simple formula for the refractive index of an ionised medium, from which it followed that an ionised layer of increasing electronic density with height would return an incident wave back to earth by a process of refraction rather than of reflection. Watson who first put the theory of diffraction round the earth on an unimpeachable basis, then proceeded to include the effect of an upper conducting layer in his analysis.

During the first world war, Eckersley explained the night time effect of the deviation of the bearings on medium-wave direction-finders in terms of a wave reflected from the Heaviside layer with its plane of polarisation tilted. I have always felt that he came almost as near as Appleton to proving the existence o the ionosphere, for it is a subtle philosophical point when inference becomes proof. Some people would say that the first real proof was when Breit and Tuve first isolated an echo by using a pulse signal, but even so echoes may not be coming from where we think they are.

But I want to begin my story proper with my first slide, and here I would like to make the point that in view of the histroical nature of my talk, I have prepared no new slides but only old ones reduced where necessary to the standard 2" by 2" format with the kind help of my erstwhile colleagues in the photographic department of the Marconi Research Laboratories. This slide shows a map of the world and is a reminder of the famous journey round the world in the steamships "Dorset" and "Boonah" undertaken by Tremellen and Allnutt measuring signal-strengths at great distances from the long-wave stations then in operation in 1922. It may be noted in passing that the Austin and Cohen formula dates from measurements made in 1909-1913, but the work of Tremellan and Allnutt, planned by Capt. Round, T.L. Eckersley and F C Lunnon, stands out as a classic for all time when one remembers that the equipment had to be thought out, designed, built and tested from scratch.

Tremellen was a superb experimenter, unrivalled for his patient and painstaking observations. As far as I know, like many of the pioneers in the early days of the Marconi Company, he possessed no high academic qualifications, but he had a shrewd judgment and was responsible for many valuable ideas in the development of our knowledge of radio-propagation. On this voyage he discovered the so-called East-West effect and made most valuable observations on the thunderstorm sources of atmospheric noise. Eckersley, on the other hand, was the consummate mathematician wh had a flair for applying his mathematics to a practical problem, even though it was not every radio-engineer who could follow his reasoning. The results were published in a mammoth paper in the Journal of this Institution, running into nearly eighty pages including ten pages of discussion. It would do many engineers good to turn back to papers such as this to see how the giants of that generation did their work.

Here I only want to make the point, in our present context, that Eckersley invoked the Heaviside layer in his analysis of the experimental results and deduced the height of its lower edge as between 40 and 100 km. Two years later he wrote another classic paper on "Short Wave Wireless Telegraphy" and in a later paper on "An Investigation of Short Waves" published by the Institution in 1929, he explains that the work of Appleton and of Breit and Tuve has led him to revise his estimates of the height of the layer, and that he has found an error of a factor of 2 by which his results should have been increased. But what was this to a genius like Eckersley who had the reputation of being able to draw a curve through one point because he knew its shape?

These two papers on short waves are a reminder that in the early 1920's the high-frequency band, as we should now call it, was given over to the amateurs, because it was thought to be useless for long-distance communication on account of its very limited ground-wave range. As we now know, the amateurs were able at times to communicate over very great distances, and Marconi in his yacht Elletra scored another of his remarkable successes by systematically studying the properties of short-wave propagation, showing how the signal-strength varied with time of day and season, and the necessity to adapt the frequency of the wave to these propagation conditions.

As we now know, for these results the higher layer, discovered by Appleton and named after him, is mainly responsible. It is now known as the F layer, which resolves under some conditions into the F_1 and F_2 layers, which the lower Heaviside layer was called the E layer to leave room, so Appleton said, for the discovery of further layers below it. But it was on the basis of Marconi's experiments that the Company took the bold move of proposing the abandonment of the Government's project for an Empire Chain of Long-Wave Stations of which the Rugby station was the prototype, by a system of short-wave beam stations that would be much cheaper and with much greater band-width capacity. This is not the place to describe the brilliant work of Franklin and his team in achieving the practical realisation of the plan. It is, however, worth noting that the beam stations went o the air at about the time the ionosphere was proved to exist, and also that the ceremonial opening of the Canadian Beam Circuit coincided with an exceptional ionospheric disturbance.

Eckersley's papers on short waves were based on a mass of observations on the beam circuits made by Tremellen and a small team of assistants. At the same time G M Wright and S B Smith were developing the facsimile system for sending pictures over these high-frequency circuits. Briefly the picture was put on a rotating drum and scanned by a spot of light which eventually provided the keying signal for the transmitter, while the received signal was used to reconstitute, the picture on another rotating drum by a photographic process. It was in a sense of form of television whereby a still picture was transmitted over a period of many minutes.

The operation of the beam circuits for morse traffic and facsimile revealed many of the problems that arise in high-frequency propagation, and Eckersley in his series of papers discusses the phenomena of scattering, fading and distortion, much of which is caused by multipath reflections between the earth and the ionosphere. He explained magnetic storms in terms the accepted theory of the influx of electrified particles and related this to the phenomenon of "whistlers" or "musical atmospherics"

observed on long waves. This slide, which shows the falling frequencies in a whistler train as a function of time, reminds us that Eckersley established from the magneto-ionic theory the law that the time delay is inversely proportional to the square-root of the audio frequency.

. was at about this time that I joined Eckersley, and I hope I may be pardoned for describing some of the work which he gave me to do. But as a brief interlude, I want to show the

next three slides as a refresher in the basis of our subject. The first shows the basic phenomenon of ionic refraction, and the

next the ray paths for a frequency above the vertical incidence critical frequency, with the skip distance, the high and low-angle rays and an escape ray. The curvature of the earth would need to be added to illustrate the phenomenon of a maximum usable

frequency. The last shows the use of a pulse signal giving rise to an echo signal resolved from the direct signal between the transmitter and receiver as used by Breit and Tuve, since it was at this time that the pulse technique was developed as a powerful tool in ionospheric research.

The facsimile tests had some of the characteristics

of pulse transmissions as this slide shows, where echo signals blurring the print are clearly visible. These echoes often severely limited the speed at which the pictures could be received, although as the

next slide shows the situation improved late at night as the density of the ionosphere decreased and the higher order multi-path echoes dropped out, though there are some signs of mutilation by fading. Eckersley hit upon the idea of transmitting a narrow

bar to act as a pulse, and in this slide the multiple echoes are clearly seen with less multi-path on the higher frequency. There are also signs of synchronisation difficulties, while the

next slide shows the decreasing multipath with the onset of night.

One of my first tasks was to measure up many of these pictures and to refine the description Eckersley had already given, by which he deduced the equivalent height of the reflecting layer. In principle, from the spacing of the successive echoes it was possible also to deduce the distance away of the transmitter, assuming it was not already known, and in the second world war this was made the basis of range estimation. But it was subject to ambiguity if it was not certain which echoes one was dealing with, while it was based on much too ideal a model of the ionosphere. It would need the resources of modern electronics to explore its possibilities more adequately.

Meanwhile Tremellen spent many days and nights in the hut shown here which many of you will recognise as a direction finding installation of the type devised by Adcock and in use at the Radio Research Station. It was designed to be free from the night-effect of the type described by Eckersley when using a simple rotatable loop aerial or the Bellini-Tosi fixed loops working into a goniometer as in the Adcock system. However, although the horizontal members connecting the vertical aerials to the goniometer were screened or buried in the ground, it was difficult to prevent some signal being picked up on these members and coupled by capacity into the vertical aerials.

To overcome this trouble the spaced loop system was devised,

Shown in principle in this slide, where it is simplest to think of the pick-up of the frames in terms of the magnetic field. This system was also developed at the Radio Research Station but here we see the original frames set up at Chelmsford to test out the idea which was subsequently embodied in

this rotating system, with which it was possible to measure both the azimuth and the elevation angle of an incoming signal. Eckersley used this instrument as a wireless interferometer to study scattering back from the E layer.

But to return to Tremellen sitting in his little hut, it is incredible what he was able to learn about scattering merely by listening in a pair of phones, for at that time oscillographs with built-in time-bases and all modern accessories did not exist. I was given the task of building such an equipment and began by sending a colleague to a grocer's shop to get a couple of biscuit tins. Not that the Marconi Company couldn't afford anything better, but that I was brought up in the string and sealing-wax tradition, and it was one of Eckersley's dictums not to spend time making the apparatus better or to last longer than was needed for the job in hand. Moreover in those days a resistance was something that could be held in the first and pressed home into a respectably sized clip, while one did not need a high-power microscope to make a soldered joint.

When my work of art was fixed on to the end of the Adcock direction-finder and Tremellen turned into the Ongar transmitter beamed on Salisbury in Rhodesia, we saw this which was exactly what Tremellen had predicted. As Ongar was due west from Chelmsford and Salisbury nearly due south, it was possible to turn the goniometer to suppress the

scattering as here, and then to supress the direct ground wave

leaving the scattering at its maximum as shown here

This experiment showed that the scattering was coming back from the direction in which the beam was pointing, and it also gave a measure of the distance from which the scattered energy was returned.

It was obviously desirable as a next step to use pulse transmissions, but at this time no simple method of keying a high-power commercial transmitter with narrow pulses was known. There was at Ongar a 40 kW transmitter with four spot frequencies covering a frequency range of about 10 to 20 MHz in modern parlance. It took ten or more minutes to change the transmitter from one spot frequency to another. To key it, the grid of a certain valve, called, I believe, the sub-absorber valve, had to brought up from about - 60 volts to zero volts. To do this rapidly, and for a very short time, I had the idea of putting a large choke in the anode circuit of a valve with a very small grid base, and of then cutting the valve off by applying a large negative voltage swing to its grid obtained from a mains transformer. This caused a very large positive voltage pulse to appear across the choke as the current through it was rapidly cut off. The valve used had an indirectly heated cathode and the anode current was effectively cut off when its grid was held at - 6 volts.

I did not do any sums, I simply went into the disposal stores where there were many relics of the early days of radio and found a large coil of wire wound round a bundle of iron wires, and the voltage peak developed across it when the value was cut off was enormous. I often wonder how the value stood it, but it did. However, when we tried it in the grid circuit of the sub-absorber valves at Onger, nothing happened. In my innocence, I had overlooked the fact that when the grid of the valve was brought up to zero volts it was passing 60 milliamperes of grid current. I had therefore to supply not only volts but power, as the valve was in effect throwing a resistance of about 2000 ohms across the choke. This difficulty was overcome by using four valves in parallel so that the choke could store up enough magnetic energy to drive the sub-absorber valve.

The resulting pulse from the transmitter was locked to the mains and its width was about 100 microseconds, while it had the full 40 kW peak power. This Ongar pulse circuit was used for many years after our experiments as a piece of test equipment at the transmitting station. This slide illustrates the

types of pulse pattern obtained with the 40kW transmitter. The first one is merely a reminder that as we advanced towards the sunspot maximum of 1938, for some part of the time the lower of the spot frequencies could be below the critical frequency of the F layer, so that nearly vertical incidence F echoes were seen, remembering that Ongar is only a few miles from the receiving site at Chelmsford. The second trace merely indicates that for most of the experiments there were no such reflections.

However, under these conditions, due to the high power used, the actual type of trace obtained is the third one, where you will see that there is a spread echo marked L which we called "long scatter" and which can obviously be identified with the scatter dot seen on the previous slides. There are also individual echoes of short delay marked S, and these Eckersley envisaged as being scattered back from blobs of ionisation in the lower ionosphere, mainly in the E Layer, but some as low as 60 kM above the earth. It is now known that most of these short distance scattered echoes are reflections from meteor trails, though we were unable to find any certain correlation because of the elementary technique we were using.

The long scatter Eckersley thought was due to waves from the transmitter being reflected from the F layer and scattered back from blobs in the upper part of the E layer and returned by reflection from the F layer. The time delay of the scatter group increases with the amount by which the working frequency exceeds the vertical incidence critical frequency of the F layer, and under the conditions shown in the first trace in the slide, the scatter should start ahead of the 2F echo. This was indeed observed, but it is now known that the bulk of the scattering is from the ground which is illuminated by a wave reflected from the F layer and returned along the same path.

The next slide shows two of our many photographs, and serves, if nothing else, to disclose how crude our technique was in those pioneering days, though it was remarkable how much was nevertheless found out about the fundamental properties of scatter transmission. The work was done using mainly an omnidirectional aerial, and it was followed up by the beautiful work of Shearman and his colleagues at the Radio Research Station using a rotating beam and P P I presentations of the multiple scattering. In this slide the short scatter is shown on a P't or time presentation and illustrates the transitory nature of the reflections from individual meteor trails.

An important development of this short scatter, suggested by Booker and others, was forward-scatter mode of transmission with which the name of Dana Bailey is especially associated. This is not the place to go into details, but it is a good example of the application of fundamental ionospheric research to radio-engineering. It was claimed in the immediate post-war years that within a few years it would render high-frequency circuits obsolete. At an URSI meeting at the Hague in 1954, I strongly contested this view and time has proved me right. Commercially the system was not really economic and it suffered from severe band-width limitations due to time spread of the signals and back-scattering troubles at times of high sunspot activity. It has only proved viable for military purposes with the aid of very sophisticated circuitry to combat the deficiencies of the propagation medium

Returning now to the problem of pulse transmitters, for ionospheric sounding, our first venture in this field was a mechanical device using a rotating drum or disc which made a momentary contact at each revolution. With the advent of neon tubes and then of thyratrons, simple time-bases and electronic pulse circuits were devised. It was not until the locking together of the different parts of electricity grid that we were able to synchronise the pulse transmissions from a arately sited station with the time-base at the receiver, though originally this was crude, and it is essentially poor by modern standards of synchronisation with highly stable crystal oscillators.

With the advancing knowledge obtained by ionospheric sounding, higher echo resolution becomes necessary, with the need for narrow pulses with short tails, that is with rapid cut-off.

It was customary to obtain the sharp start to a pulse by the flashing of a thyratron and it seemed to me that it should be possible to sharpen the tail of the pulse by the flashing of another thyratron. I thought out the basic principle of doing this and with the help of Falloon I devised a circuit which worked first time and had a controllable pulse width. However, on examining the circuit diagram, we decided that it shouldn't have worked, because we had overlooked that at a certain point in the cycle of operations a bias voltage was needed for which we had not planned. We then realised that this voltage was being supplied at the required moment from another part of the circuit which we had not anticipated, which only goes to show that two wrongs can make a right.

I recall all this because the knowledge that we had been working in the field of narrow and high-power pulses led to a deputation coming to see us, which in retrospect must have been concerned with the development of radar. I believe that the double thyratron circuit was initially used in the original CH radar transmitters before the development of delay-line techniques, though I was never allowed to see the inside of one of the stations.

I have already recalled that from the early experiments with high-frequency communications it was realised that the propagation conditions varied with the time of day and the season of the year, and in due time with the epoch of the solarcycle, and that the ionisation must therefore be due to radiation from the sun. The need was therefore felt for some kind of chart that could be used in conjunction with a map of the world, from which the state of the ionosphere at a given time and place could be assessed, and the frequency to be used for a given circuit could be decided. The first such charts were the Eckersley-Tremellen shadow charts which divided the ionosphere over the earth at any given time into a series of zones shaded in increasing depth to represent the decreasing ionisation with the onset of night, lightening off again with the onset of daylight. A prominent feature of the charts was the sunset-sunrise line which broadly speaking was the boundary between the lighter and the darker portions of the charts. Charts were thus needed for the different seasons of the year.

At the same time theoretical work was being done on the electron density in the ionosphere on the assumption that it was caused by a beam of monochromatic radiation from the sun. The rate of change of ionisation in the atmosphere depends not only upon the strength of the ionising radiation but also on the rate of recombination of the electrons with the ionised molecules. The actual mechanism of ionisation and recombination and its relationship to the chemical constitution of the atmosphere is a most difficult physical problem and has been the subject of a vast amount of research. It is still one of the topics of modern ionospheric studies.

Sidney Chapman, the great geo-physicist who died earlier this year, was one of the first to show how an incoming solar radiation can give rise to a layer with a well-defined level of maximum ionisation within it. This work was very recent when I began my radio career, and Eckersley put me on the job of using Chapman's theory to construct some ionisation charts. An essential parameter is the recombination coefficient, and on the assumption that the rate of recombination is proportional to the square of the electronic density, as assumed by Chapman, this coefficient can found experimentally by finding the density of ionisation during the night by measurements of the vertical incidence critical frequency. This slide shows how th theoretical curve fits the measured points with an appropriate choice of coefficient edless to say I have chosen a quiet night when the ionosphere is well-behaved, which it seldom is!

I make no apology for the fact that in this slide and the succeeding ones I have made no attempt to bring the legends and figures up to the modern standard of legibility, since it is the shape of the curves that matters in the present context. The first task was to solve the basic ionisation equation, which is a first-order no linear one, at a given latitude to show the variation of density with the time of day at a given season. The problem is complicated by the fact that the height at which the maximum ionisation occurs varies with the time of day, but simple approximate methods were found that were accurate enough for the purpose in hand without the use of a computer. The curves in this slide show the variation of maximum electron density throughout the day, the top curve being for the equator and the bottom one for latitude 60° in the winter. They show the relatively rapid build-up after sunrise and the slower decay as night comes on, and for the recombination coefficient chosen, the maximum is well after mid-day. They are intended to refer to the F layer. For the E layer where the rate of recombination is much greater the curves are nearly symmetrical about mid-day.

From such curves, maps can be drawn that give contours of constant maximum electron density at a given time over the earth, and here such a map is shown for the equinox, as is evident from the symmetry about the equator. The rapid build-up at sunrise, the region of maximum density, and to slower night-time decay are clearl seen. The contours can be labelled in terms of vertical-incidence critical frequency, which will depend upon the epoch of the solar cycle, and this is one reason why I hope that you can't read the labels on them, so that I don't have to tell you what they mean. This slide shows the corresponding curves for winter in the northern hemisphere, and of course summer in the southern hemisphere, and it will be noted how the curves are related to the sunrise-sunset line shown as a chain-line. These contour maps show a general agreement in their general features with the original Eckersley-Tremellen shadow charts and supported the use that was made of such charts in planning high-frequency communications.

These maps were drawn on a Mercator projection. If they are drawn on a polar projection it becomes very evident that on the basis of the theory used there is virtually no ionosphere in the polar regions in the winter-time. As we shall see in a moment, in reality things are far different, but first we have in this next slide some contours for the E layer which is very much better behaved then the F layer. These are typical of the ones which are actually used in prediction work, and I think you will see that they are similar to the kind of theoretical chart I have shown you; they also show the near symmetry about mid-day to which I have already referred.

At this point it is interesting to show for comparison a more modern prediction chart based on measurements made at ionospheric sounding stations in various parts of the world. The maximum usable frequency or MUF at zero distance is the vertical incidence critical frequency, and I am not worrying you here with the time of the yea or the epoch of the solar cycle, because all I want you to notice is the distortion of the contour lines compared with the idealised ones I have shown you. This slide shows the corresponding contours for transmission to 4000 kM, which is about the limi for a single hop path. They are very similar to the zero distance ones the MUF bei increased by a factor of about 3.

It is convenient to anticipate here another feature of prediction work, namely the effect of atmospheric noise, for which analogous charts have been constructed from world-wide measurements. This slide shows a typical noise map, and here again I can only refer you to the areas of high noise level in the tropical regions, as I cannot enter here into the technicalities of the system of labelling the noise levels shown here.

other phenomenon controlling the use of the ionosphere for communications is the actual absorption of the wave energy by collisional processes mainly in the lower part of the ionosphere in what is called the D layer and which has been the subject of Piggott's monumental researches at Slough. It increases with decreasing wave-frequency, so that for a given high-frequency circuit there is not only a maximum usable frequency MUF, but also a lowest usable high frequency LUHF at a given time. This is shown on the next slide, where the OWF is the optimum working frequency, about 15% below the MUF to allow for day-to-day variation in the ionospheric conditions. If the station has the choice of only two frequencies allotted to it, then the slide suggests the best choice for the conditions shown, and where the frequency should be changed to avoid the limitations of theLUHF and to take advantage of the high day-time value of the MUF, while catering for the minimum value of MUF before the dawn. An actual example is shown in this slide, where the circuit has a choice of three frequencies.

Returning now to the distortion of the prediction charts, it is now known that there are two major causes. In the first place the ionising sources, partly electromagnetic radiation in the ultra-violet and X-ray part of the solar spectrum, and partly corpuscular radiation from the sun, is much more complex than assumed by Chapman in his idealised model. Secondly, a major and related factor is the magnetic field of the earth. Although Appleton was foremost an experimenter, he was one of the founders of the magneto -ionic theory of the ionosphere, showing that the effect of the magnetic field is to make the ionosphere anisotropic and therefore doubly refracting, so that, as in crystal optics a single incident pulse is reflected as an ordinary and extraordinary pair of echoes. Some of Appleton's early work with pulses was concerned with beautiful demonstrations of this double refraction. The ordinary ray is only truly ordinary in special cases, though at vertical incidence its critical frequency is independent of the magnetic field. With decreasing frequency the extraordinary wave is heavily absorbed, and in general it has often been assumed that for the more important ordinary ray the effect of the earth's magnetic field can be neglected.

However, it is now known that the earth's magnetic field has a profound effect on the ionosphere itself, both on the incoming streams of charged particles that help to form the ionosphere, and on the movements of the electrons constituting the ionosphere. Incoming particles are deflected into the polar regions, giving a very different picture from the one shown in the theoretical charts we have seen, while at the equator, or rather the magnetic equator, there is a piling up of electrons at about 10^{0} on either side with a minimum in between as shown in this slide.

This magnetic latitude effect was discovered by Appleton, though I shall say more about this in a minute. It will be seen that to some extent this effect at the equator is associated with a re-distribution of electron-density with height, the available total electron content vertically being spread out with a reduced maximum at a greater height.

In the ionosphere the ordinary and extraordinary waves have characteristic polarisations, and at vertical incidence in these latitudes, where the earth's magnetic field is within about 20^{o} of the vertical, the polarisation is circular, the rotation of the field vectors being left-handed or counterclockwise for the ordinary wave and right-handed or clockwise for the extraordinary wave, looking in the direction of propagation. For a given frequency the extraordinary wave is reflected from a lower height and arrives back at the earth ahead of the ordinary wave.

It is therefore a crucial test of the magneto-ionic theory to measure the polarisations on a frequency sufficiently high for the echoes to be resolved. Ratcliffe and White built a polarimeter at Cambridge using a pair of crossed vertical loops and found agreement with Appleton's theory. However, on going into the experimental set-up more carefully, Ratcliffe discovered that he had got a pair of wires the wrong way round, which reversed his result (shades of Telstar and Goonhilly to those who know to what I am referring!). He wrote to Appleton, who had gone off for a holiday in Switzerland, to tell him the sad news. But his letter crossed with one from Appleton saying that he had gone through his mathematics again in which the result depends upon the two solutions of a quadratic equation, and had found that he had got the + - sign the wrong way round. So this is another example of two wrongs making a right.

At this period Eckersley was doing a vast amount of theoretical work on oblique incidence propagation in a magneto-ionic medium, most of which was never published. In it he derived what is now known as the Booker quartic equation and from which I acquired my own knowledge of magneto-ionic theory. However, I believe that originally he got his signs wrong and he gave me the job of building a crossed-frame polarimeter. In doing so I made a very careful study of which way round the wires should go. In the sequel my experimental results agreed with Appleton's and Ratcliffe's conclusions in their corrected form.

Eckersley hit on the simple idea of deturning one frame forward by 45° of phase, and the other backward by 45°, thereby degrading the performance of both frames by only 3 decibels and making them in phase quadrature. In effect they converted the incoming circularly polarised waves into linearly polarised signals, and by a goniometer technique as in an Adock direction-finder, the goniometer could be placed in one position to suppress one signal and accept the other at maximum. By a movement of the goniometer the roles of the echoes could be changed, so that by moving the goniometer to-and-fro between the two positions, a beautiful see-saw effec of the echoes was obtained. If an echo was elliptically polarised, the position and ratio of the axes of the polarisation ellipse could be found by rotating the frames about a vertical axis into the required position and finding the position of suppression on the goniometer scale.

This slide shows the polarimeter I built with the tuning condensers in the middle of the frames at the top. I worked out a simple lining-up technique by injection from a built-in oscillator. We made many experiments with this apparatus, although later on it was superseded by more sophisticated comparator techniques using twin-channel amplifiers and phase-changers. In this slide, the sequence of echo patterns are shown corresponding to successive frequencies on a vertical incidence ionogram. A similar sequence is obtained working on a single frequency and allowing the density of the ionosphere to decrease with time, passing in turn through the times when the ordinary and then the extraordinary wave penetrated the ionosphere. During the war, the Germans had many pulse transmissions on the air, presumably for ionospheric sounding, which we observed, and at the oblique incidence the still more striking sequence of events occurred, shown in my next and last slide. The high-angle echoes were present, giving four in all, and then the ordinary low and high-angle echoes coalesced to give a strong focussed echo as it went into the skip, followed by the same procedure for the extraordinary echoes. With the polarimeter the echoes were shown to be ordinary or extraordinary according to the scheme shown.

The mention of the war brings me to an important phase in the application of ionosph knowledge to radio communications. It must be remembered that at the beginning of the war the use of the frequency spectrum above the high-frequency band was in its infancy, so that high-frequency propagation by way of the ionosphere was vital in the war-time communication system. As we have seen, it was already known that the propagation conditions were very variable from day-to-day not only with regard to the limit set by the MUF, but also by the LUHF, particularly at times of magnetic storms and sudden ionospheric disturbances.

It was therefore decided to set up a Bureau that would obtain information of the state of the ionosphere and pass it on to the armed Services requiring it for operational planning. In view of the research that had been carried out at ıelmsford, and latterly at Great Baddow, the Baddow Research Laboratories were chosen as the home for the Bureau with Eckersley as the chief scientist. It was known as the I S I B, the Inter Services Ionosphere Bureau. I have been asked more than once, by those interested in the biography fo Sir Edward Appleton, whether he had any part in the setting-up and the running of the Bureau, but to the best of my knowledge he played no active part in it, and I can recall no occasion of his coming to Baddow in connection with it, which was not suprising in view of all his other commitments at that time.

Eckersley's research team had come under the wing of the Air Ministry, and a group of aircraftsmen under an officer was stationed at Baddow to make hourly measurements of ionospheric characteristics. By modern standards the experimental technique was primitive, as the transmitter receiver equipment was only semi-automatic, and the equivalent height was tabulated step-by-step as the frequency was increased until the critical frequency was reached. The figures were then phoned through to the operations room where a group of WRNS plotted them, for the Admiralty also had a finger in the pie; and subsequently there were two American Army Officers who, to change the metaphor, came into the picture somewhere, one of whom at one period was Dana Bailey, whom I have already mentioned, and who is now international chairman of the C C I R study group on Ionospheric Propagation. We like to feel that we taught him about the ionosphere. My colleague and friend of many years, Gerald Isted, was in charge of all the experimental equipment and the training of the airmen and a wonderful job he made of it.

My job was to teach them about the ionosphere in a series of simple lectures to give them an interest in their work and some idea of what it was all about. These lectures were subsequently written up as an Admiralty handbook and later became a D S I R Special Report, the only one, as far as I know, not written by someone at the D S I R. I also amused myself with the polarimeter work that I have already described, and the occasional airman who was seconded to work with me, must have wondered what it had got to do with winning the war.

Returning to the Operations Room, I don't know what happened to the ionograms after the W R N S had drawn them. Presumably the information was passed on to a higher authority in London, and I have often wondered what momentous decisions were taken on information on the ionosphere that we would now regard as meagre in the extreme. I may have spoken rather playfully, but seriously it was a remarkable organisation that was a forerunner of the world-wide system of prediction centres now in operation. Naturally it was found after the war that other nations similarly appreciated the need for such information. I have already mentioned the German pulses which we intercepted, while the Japanese were also very active in this field. In the U S A the Central Radio Propagation Laboratory was born, to give it the later name by which it came to be known. It has changed its name more than once and is now a world data centre at Boulder, Colorado.

One of the great figures behind the scenes at Baddow was Tremellen who did an immense amount of patient work on the application of the ionospheric information to operational problems. He was the inventor of the two control point method of decidi whether a circuit would be workable at a given time. The control points are points 2000 km along the propagation path from either end, and represent the reflection points in the F layer for the limiting distance of a single hop in the reflection process by multiple-hops. It was based on the experimental evidence that the path would be operational if the electron density were high enough to sustain a reflectio at the control points, even though it was too low to reflect the waves in the middle of the path. In other words, if the wave got a good send off and the conditions were good at the reception end, it would somehow get through. The reason for this is not yet fully understood, but it has stood the test of time, and I believe that it is not entirely unknown at the Post Office Corporation and at the Ministry of Posts a Telecommunicationsin this day and age.

he I S I B at Baddow also saw some of the first work on the issuing of storm warnings, and for this purpose magnetometer measurements were made of disturbances to the earth's field, while constant touch was kept with the receiving stations of the beam circuits, expecially the North Atlantic routes where the propagation paths passed near or through the auroral regions.

It was at Baddow that some of the first noise-charts were devised and indications were also found of the influence of the earth's magnetic field on the electron density in the ionosphere. After the war, Dana Bailey had the task of finding out what the Japanese had been doing in ionospheric work during the war and came across a description of the magnetic latitude effect to which I have already referred. This is a case of the independent discovery of the same phenomenon in different parts of the world, as Appleton had not come across this work until I drew his attention to it after the publication of his own work.

I cannot leave the I S I B without a passing reference to one of its most successful functions. Remembering the R A F - W R N S set-up, it proved to be ideal as a matrimonial agency.

It was inevitable that after the war the emphasis in industrial propagation research should pass from the ionosphere to the troposphere with the remarkable developments in V H F and U H F techniques in war-time radar. Moreover, the feeling was growing that as far as fundamental ionospheric research was concerned, enough was known for the purposes of high-frequency communications. It was felt that work of the type done at Baddow during the war should now be done, for instance, by Government research organisations for the benefit of users in general.

Ionospheric sounding had been carried out at Slough since before the war, and there was no need to continue routine measurements at Baddow so geographically near to Slough. All workers in the field are familiar with their prediction service of ionospheric characteristics, while the application of their results to the special requirements of the Services has been carried out by the Joint Radio Propagation Board.

At the I T U Conference at Atlantic City in 1947, the Consultative Committees were reconstituted, and the Committee for International Radio C C I R started up its work again under its first Director, Prof. Dr. van der Pol. Of its study groups, we are concerned here only with study group 6 on the Ionosphere, first under the chairmanship of Dr Howard Dellinger and now under Dr Dana Bailey. For many years the work has been divided between a number of working groups.

One of these deals with atmospheric noise, the methods of measurement, the acquisition of data, and the provision of noise charts showing the distribution of noise as a function of position, time of day and the season. These have been collected in a special Report known as Report 322, and the main work of the group is the revision of this Report which is a continuing study as more data become available. Other Groups are concerned with the acquisition of data of ionospheric characteristics and the making of short and long term predictions. This work has been greatly enlarged in the last few years by the use of computer techniques and the production of an atlas of ionospheric characteristics in another Report known as Report 340.

A parallel problem is the prediction of high-frequency field-strengths for given ionospheric conditions along the propagation path. This is an extremely difficult problem, and many variations have been proposed for making the calculations. After more than twenty years there is only provisional agreement on a computer method that is to be the subject of trial for comparison with field-strength measurements made over practical circuits.

This work has indeed been revolutionised by the use of computer techniques, but while this is a logical and inevitable step in the process of making predictions and producing charts, there is the danger to my mind of giving the results and appearance of accuracy that they may not really possess. It is possible by sophisticated interpolation and extrapolation to produce from inadequate data, charts which have an apparent wealth of detail which may be illusory. Earlier on I showed you a prediction chart of M U F produced, I believe, before the construction of such charts was computerised, in which much of the detail was based on very scanty data and where some simpler contours would have been all that the data justified, at least in certain parts of the world.

It is a moot point just how accurate such charts need to be to meet the needs of those who plan and use high-frequency circuits. From talking with some of them, I have the feeling that the provision of more accurate and detailed prediction maps will have diminishing returns, since by and large the users have a pretty good idea of how to plan their circuits in the light of experience and the knowledge of general ionospheric conditions over a sunspot cycle. We must not, forget, however, that on the way mistakes have been made. Although the allocation of frequencies in the region of 40 MHz to television was consistent with existing techniques, it is interesting to speculate whether it would have been used, had as much been known then as now about the F layer at sunspot maximum. Likewise interference on the FM sound channels due to the existence of sporadic E proves at times to be very troublesome. But this is a problem common to most uses of radio, where the variations in the medium impose limitations on its use, with the acceptance of some interference on the basis that some cake is better than no cake at all.

Another one of the Working Groups of Study Group 6 deals with the general problems of such interference, and special attention is being given to sporadic E, particularly in equatorial regions. One important aspect of the ionospheric charts is the light they throw on the mechanism of long-distance propagation, whereby, for instance, unexpected modes of propagation may operate, due to such features as tilted layers and the magnetic field effects of the type already mentioned. Such modes help to show why the two control-point method has been so successful, and why frequencies well above the predicted MUF can be consistently used at certain times on some circuits.

There is a school of thought which says that with better short-term prediction methods, a complete and more economical re-allocation of the high-frequency spectrum could be made, by steering the frequency to remain close to the MUF where multi-path troubles are removed and the focussing properties near the skip-distance can be utili Sophisticated oblique incidence sounding techniques have been directed to this end. It is difficult to see how this proposal could work commercial circuits though it may have military applications.

One further aspect of the C C I R work of special interest concerns field-strength predictions on medium and low frequencies. In this country we think of these frequency bands in terms of ground-wave day-time broadcasting which is spoilt by night-time ionospheric propagation when absorption in the D layer is low, except at short-distances. However, they are being used increasingly for long-distance night-time broadcasting especially in tropical countries. Provisional propagation curves now exist, and it is a pressing requirement to extend their use to areas outside the European Broadcasting Area to which the data upon which they are based refers. In the tropical countries where the earth's magnetic field may be nearly horizontal, the characteristic polarisations in the ionosphere may be nearly linear, and it is possible that a conventional antenna may happen to excite mainly the extraordinary mode which is highly absorbed. The whole problem of the polarisation of the waves has therefore come back into prominence and is being actively studied in this connection. The proposal also to use very high-power medium and low-frequency transmitters has likewise raised again the problem cross-modulation in the ionosphere known as Luxembourg effect in which the magnetic field plays an important part near the gyro-frequency.

Some years ago, I gave a lecture in this theatre entitled "The Challenge of the Medium". My theme was that the propagation medium, be it the ionosphere, the troposphere, or the earth with its irregular surface, holds out the prospect of communicating by the medium, but what it offers with one hand it seeks to take away with the other by its imperfections. In the case of the ionosphere, there are all the problems we have been discussing, but perhaps most of all there are the limitations imposed by multi-path time delays, fading, both long term by changing ionospheric conditions, and short-term by interference effects, including polarisation changes, and distortion of one sort and another. Eventually nature sets the ultimate limit , but the radio engineer accepts the challenge and overcomes these restrictions to a greater or lesser degree by ingenious technical devices.

Here I can only list some of the principal features involved. First there is the general principle of diversity reception and possibly transmission, to overcome fast fading, using space, frequency and even polarisation diversity. With the aid of modern electronics there may be automatic selection of the channel which is best at any given moment. Allied to these are steerable antennas to choose the strongest echo under multi-path propagation conditions, such as the MUSA and MEDUSA systems. I have already mentioned the possibility of working near to the M U F, and the sophisticated techniques used for forward-scatter circuits.

Then there is the whole subject of error-correcting codes and of systems which by cooperation between the transmitting and receiving ends of a circuit, sound out the ionosphere and then send the message while the going is good, often at high-speed, as in the case of propagation by reflection from individual meteor trails. Recent years have seen great improvements in voice transmission over high-frequency circuits, notably the Lincompex system in which the Post Office has made a major contribution. As far as I understand it, it uses a compressor expandor technique to provide a signal of constant amplitude for transmission, together with a signal which conveys the information of the amplitude variations in the original voice signals, which is then used at the receiving end to restore these variations to the received voice signal.

In referring to the Ongar transmitter we used in the 1930's, I mentioned the time taken to change it from one frequency to another. Economically, high-frequency communications have been given a new lease of life by the great advances that have been made in transmitter and receiver design, notably the use of wide-band amplifiers and crystal controlled devices of extreme accuracy for rapid frequency changing Along with this has gone the design of wide-band antennas, such as log-periodic antennas, and antenna farms from which an antenna with the required directional characteristics can be rapidly selected.

The design engineers will probably consider this brief review of their art as very incomplete and amateurish, and even, I fear, inaccurate, but it has been my main purpose to show that what they have to do has been imposed on them by the nature of the medium upon which high-frequency communications depend. I think it is a good thing to remind them of all the fundamental pioneering research which has helped to build up the industry of radio-engineering in which they are engaged.

In conclusion, I take up briefly, as anticipated at the beginning, the impact of modern ionospheric research on radio engineering. As is well-known, most of this work is done using satellites and rockets. Many of the experiments concern the physical properties of the ionosphere, making direct measurements of the electronensity and of the incoming radiations, but many involve the use of radio transmitters and receivers. Outstanding in this work is the top-side sounding of the ionosphere, with which the name of the Canadian Alouette Satellites will for ever be associated. It has been revealed that the structure of the ionosphere is much more complicated than was suspected, and that in its formation the earth's magnetic field plays a dominant part. In particular, the nature of the magnetic latitude effect is now much better understood and its relation to the electron density as a function of the height.

Ducts have been found to exist along which high-frequency signals can be propagated, and it has been a matter of discussion at C C I R whether they can be exploited for communications. However, they are transitory and difficult to predict, and the question is more likely to be whether they are an asset or a liability as a propagation mode, as in the case of meteorological ducts and anomalous tropospheric propagation.

This modern research may also help in the problem of predicting sudden ionospheric disturbances and magnetic stórms. In the days of the I S I B, the hit-miss predictions, if I remember rightly, were not more than about 50% reliable, and it is a moot point whether those running the high-frequency circuits like making provision for changing their frequencies on the basis of a warning that does not materialise or prefer to cope with adverse conditions when they do arise.

I have said nothing about space communications, because they are mainly carried out on the very high and extremely high frequencies. There is, however, the problem of scintillation, caused by the irregularities in the ionosphere, to the waves that have to pass through the ionosphere to and from the earth stations, and also of the rotation of the plane of polarisation caused by the Faraday effect due to the anisotropic nature of the ionosphere. This depends upon the total electron content along the propagation path, and a measurement of the effect is a method of determining this quantity in the ionosphere.

Perhaps one of the most remarkable features of modern ionospheric research is the use of the low and very low frequencies. Eckersley's original theory of whistlers, incomplete and imperfect as it was, formed the basis of the modern theory given by Storey and Helliwell, and the observation of whistlers within the ionosphere has led to some of the most advanced thinking on the formation and constitution of the ionosphere.

We began with Tremellen and Allnutt measuring the field-strengths of very low-frequency waves propagated round the earth. The theory of the mechanism of this propagation is one of the most difficult in the whole subject of radio, as it involves mode propagation in a duct between the earth and the ionosphere where a full wave treatment is necessary and the earth's magnetic field plays a vital part. Following on the work of Ratcliffe at Cambridge, Budden and his collaborators have made fundamental advances in this field, as has also Wait in the U S A .

It is a two-way traffic, as the theory with the aid of models of the ionosphere has thrown great light on the structure of the D layer, by comparing theoretical values of field-strengths with experimental results, while there have been great repercussions on the use of the very low frequencies for navigational aids and time measurements from a study of the phase stability of this type of propagation.

May this cooperation between the physicist and radio-engineer ever endure to their mutual benefit.