Low-Angle Radio And High-Frequency Radar: The Ionosphere At Work

by Brian Austin, G0GSF

Bouncing signals off the ionosphere in order to achieve radio communications well beyond the horizon is almost as old as radio itself. In December 1901, when Marconi is reported to have heard the three Morse code 'clicks' of the letter S, the only conceivable way the signal could have crossed the Atlantic – from Poldhu in Cornwall to Newfoundland on the east coast of Canada – was via the ionosphere. The fact that the ionosphere was only discovered almost exactly 23 years later is neither here nor there: it has always existed and it performed just as might be expected on that day in 1901, though there are a few technical subtleties which, even today, remain as no more than conjecture [1].

Whether the sounds Marconi and his assistant George Kemp claimed to have heard were the actual transmissions sent from Poldhu, or just the 'static' bursts caused by the storm that was raging at the time, is a subject guaranteed to generate debate. There are, apparently, as many people prepared to believe Marconi as there are those who take the decidedly opposite view and the discussion between them is usually forthright! [2].

When Marconi repeated the experiment on the *SS Philadelphia*, sailing between Southampton and New York in February of the following year, he certainly received the signals but this time they were also recorded on Morse inker tape, and signed by the captain, so the evidence was irrefutable. The letter 'S' was received up to 2,099 miles from Poldhu while plain language Morse messages were successfully decoded up to 700 miles during the day and 1,551 miles at night [3]. Long-range radio, via the ionosphere, had arrived and it's still very much with us.

Communicating Round The World

My interest in all this was first prompted by an article by the late Les Moxon, G6XN, published in *Wireless World* in 1970 [4]. In it he showed how sloping ground can be used to great advantage to cause the radiation angle of an HF antenna to be lowered considerably compared with that from the antenna when mounted at the same height above flat ground. This was a simple case of what's called ray optics and it follows using the same arguments that apply to light rays from a source placed above a mirror. The inspiration for Moxon's analysis was a remarkable paper, a classic in fact, written soon after the end of WWII about the maximum range to be expected from a radar transmitter [5]. The scene was now set for an interesting exploration into the ways radio signals propagate above the real (rather complicated) earth and how their range might be extended.

Once Edward Appleton had shown, in 1924, that the ionosphere did indeed exist in a number of fairly well-defined layers or regions, from some 80km to around 350km above the earth, he then went on to show how radio communicators might use it to very good effect. And that was the way all long-distance radio communications took place until the advent of artificial satellites in the late 1950s.

From the geometry of the problem, illustrated simply in **Figure 1**, it's evident that radio waves leaving the earth at some very low angle will propagate furthest. But because the ionospheric layers doing the reflecting are actually fairly close to the earth compared with the distances over which propagation is required, it is necessary for the signal to go through a number of 'hops' between the earth and the ionosphere to cover worldwide distances. Each of those hops causes some energy in the radio wave to be dissipated as heat in the earth and in the sea, with the former being considerably more lossy. The ionosphere, by comparison, is a good reflector, but it is clear that using the lowest possible angle of radiation causes the lowest possible loss due to intermediate reflections over the transmission path. Achieving such low-angle radiation requires either very high antennas or the appropriate use of the natural slope of the ground below the antenna, as Moxon described in his *Wireless World* article. In order to make

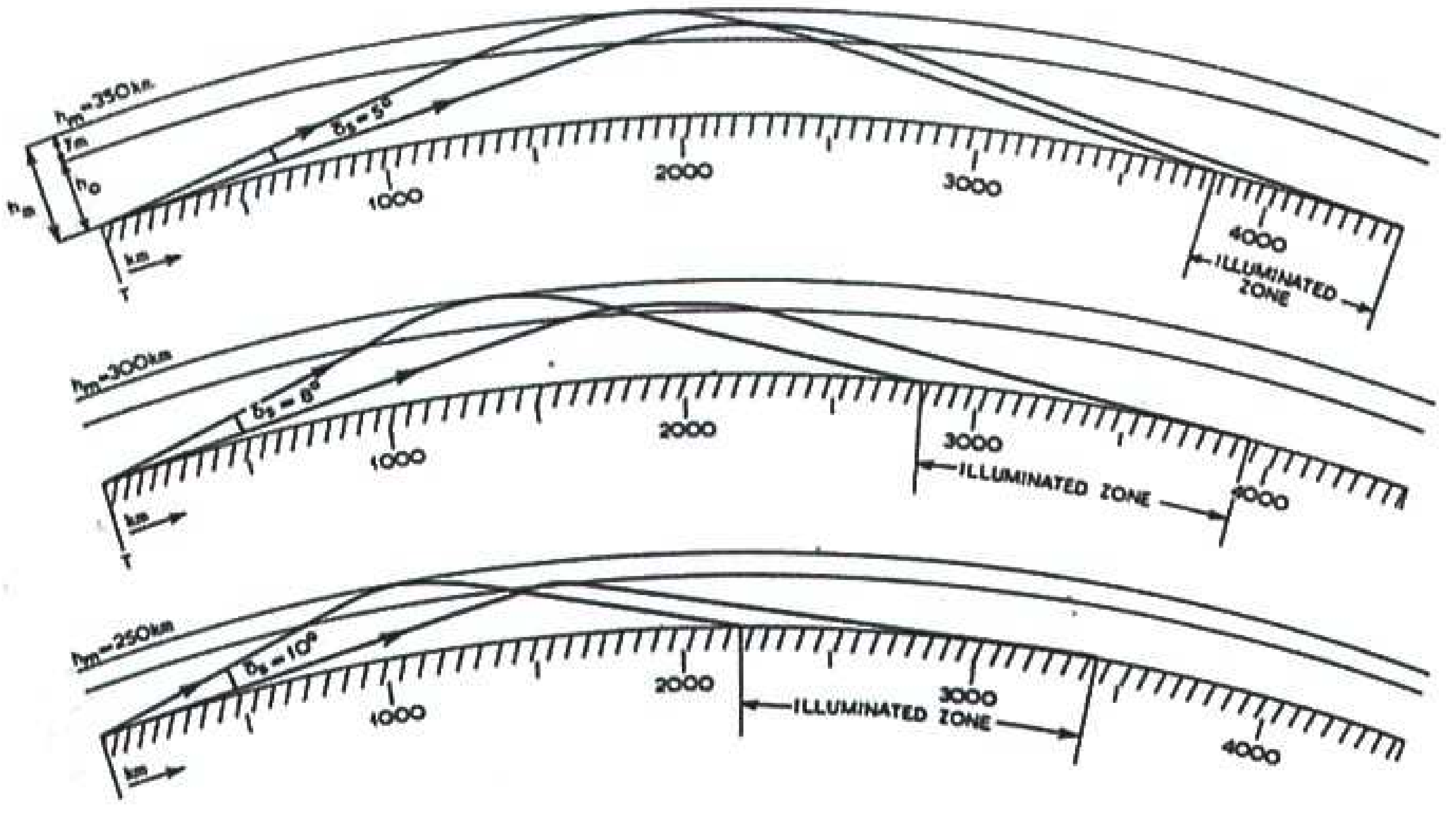

Fig.1. Ray diagram showing one-hop and two-hop propagation

sense of all this one has to first get to grips with the terminology and some of it can be pretty abstruse as the title of the next section suggests.

Chordal Hops, Tilted Layers And The Whispering Gallery

Ionospheric practitioners talk about the MUF, the OWF (sometimes also called the FOT) and the LUF. These terms stand for the maximum usable frequency, the optimum working frequency (of which FOT is the French equivalent) and the lowest usable frequency. All are extremely variable and change with the sunspot count (and hence the 11-year sunspot cycle), the seasons of the year, the geographical locations of the terminals and the time of day. As a result, using the ionosphere to communicate reliability over any given path is a challenge. But the problem is made even more complicated by the fact that the conventional single- and multi-hop paths, to which these terms apply, are not the only ones that will support propagation. And it's those unconventional mechanisms that this article concentrates on.

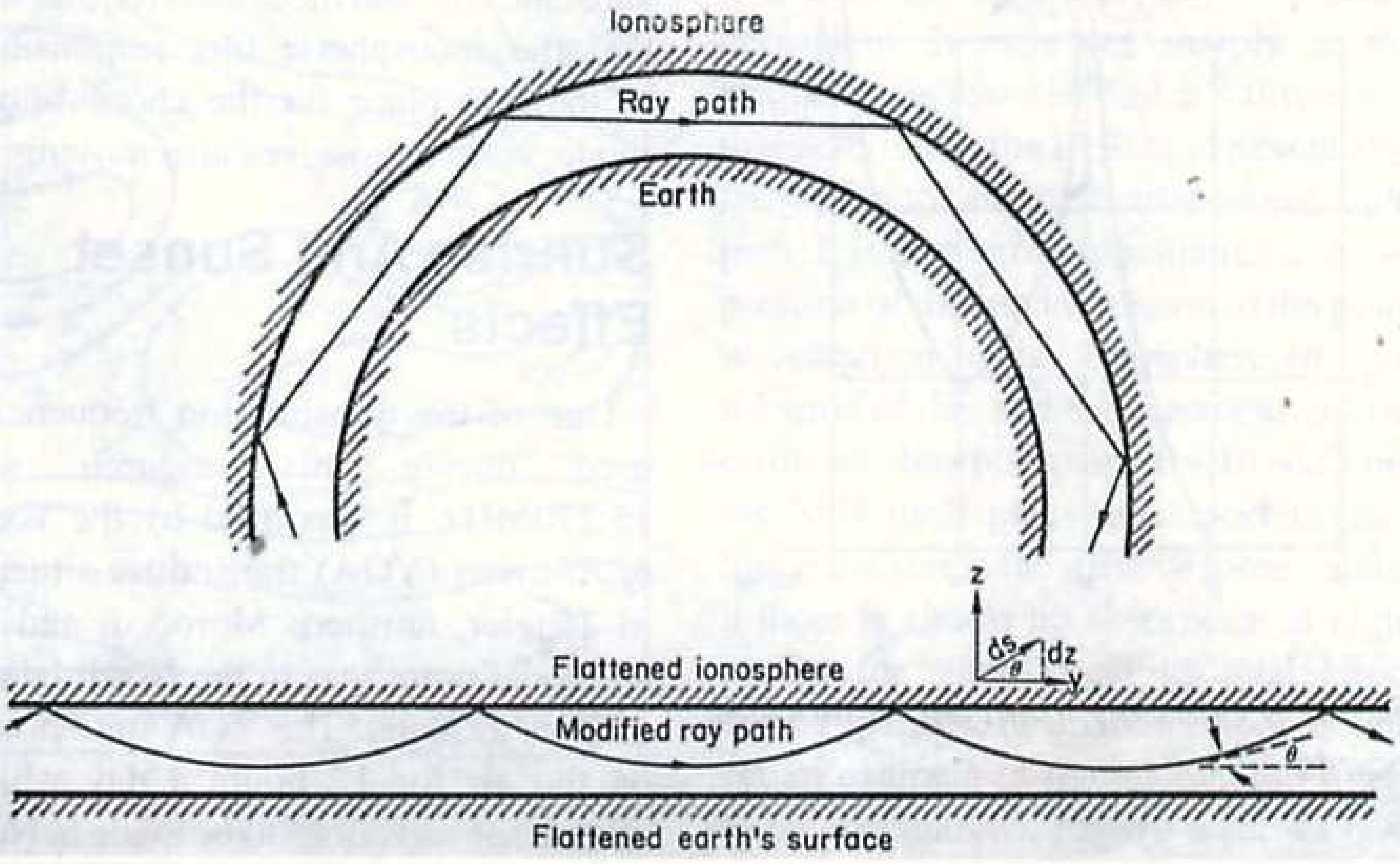

Fig.3. Whispering gallery mode

It was first reported in 1957 that over some very long paths the radio waves do not return to earth for an intermediate hop but they remain within the ionosphere and, as a result, they do not lose energy either to the sea or the ground. Remembering our school geometry, where a straight line drawn anywhere across a circle is called a chord (the one through the centre being its diameter), we can understand why this strange mode is called a chordal hop. It is shown in **Figure 2** and it's evident that this mode will certainly produce long-distance propagation and lower loss. But how does it start and end? That's the role of the tilted layer.

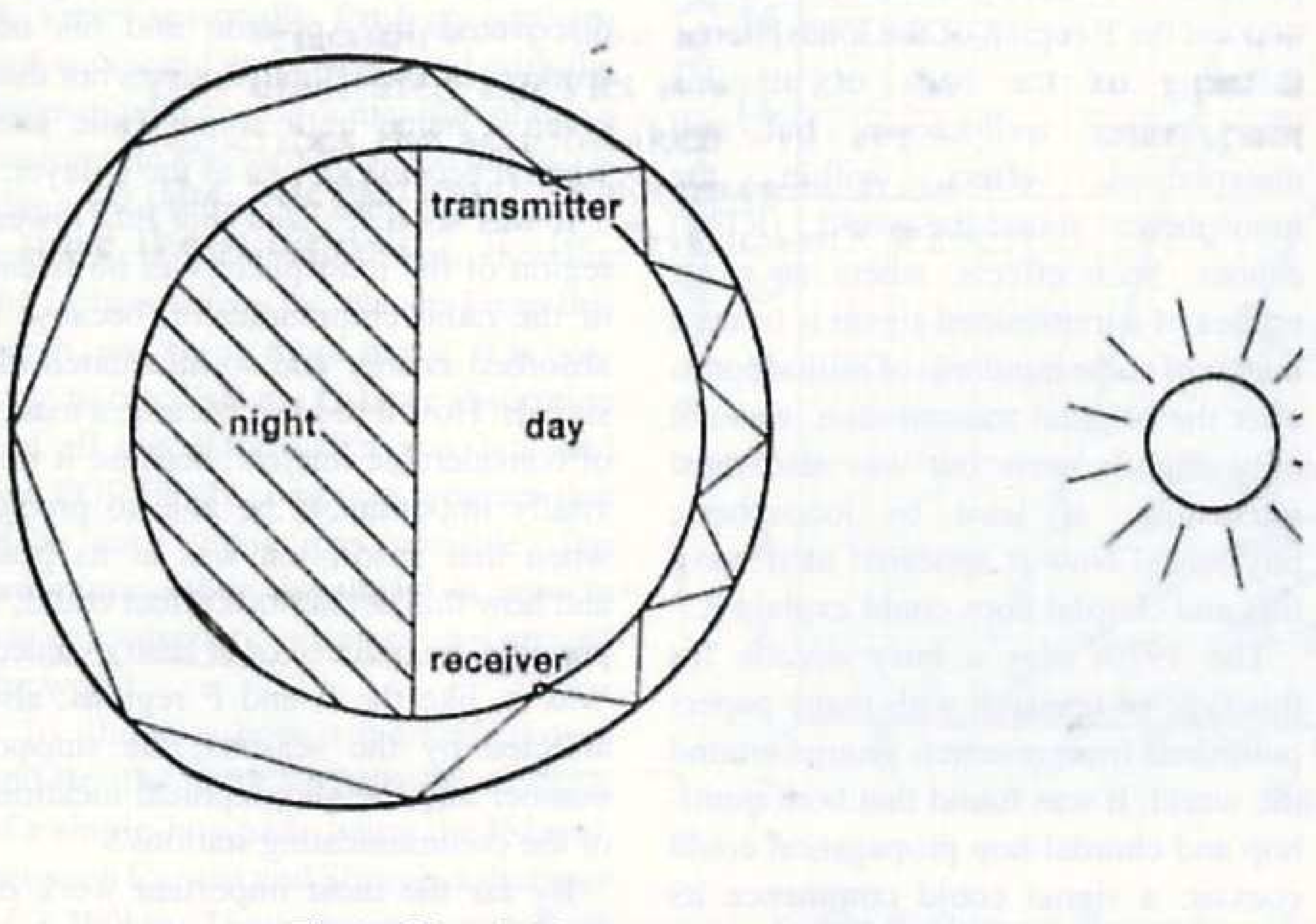

Fig.2. Chordal hop and multi-hop modes

To launch a ray at the appropriate angle so that it stays trapped within a specific layer requires there to be some tilting of the ionized region at such an angle that the incoming energy is directed along the propagation path virtually parallel to the earth below. The energy therefore remains trapped within the ionosphere until it encounters another tilted region that causes it to leave this apparent 'waveguide' and return to the earth. Quite how this happens became the subject of much research once it had been established that such trapped modes of propagation did indeed exist.

When one thinks about it, the chordal hop seems similar to an effect that's well-known to visitors to St Paul's Cathedral in London. If you place your mouth close to the wall of its hemispherical dome, and whisper, someone with their ear pressed against the wall a considerable distance away would be able to hear every word you say. This is the Whispering Gallery at work and it works both for sound waves and for radio waves; **Figure 3**. So tilted layers and trapped modes can do interesting things for radio waves, as long as we can exploit them.

Enter Albrecht And Others

A man by the name of Hans Albrecht, working from his home near Melbourne, Australia, between 1952 and 1957, made a systematic study of long-range communications within the HF (3 to 30MHz) band. This period included both the sunspot minimum of 1953/4 as well as the highest ever recorded sunspot numbers, abbreviated SSN, which occurred during 1957/8. Albrecht concentrated on the communications path between Europe and Australia so, being 'down under', and hence close to the opposite side of the world, he also encountered another strange ionospheric phenomenon that caused a great increase in signal strength. This is known as antipodal focusing; **Figure 4**. Albrecht published his results between 1957 and 1961. Strangely, he chose a rather obscure journal in which to do

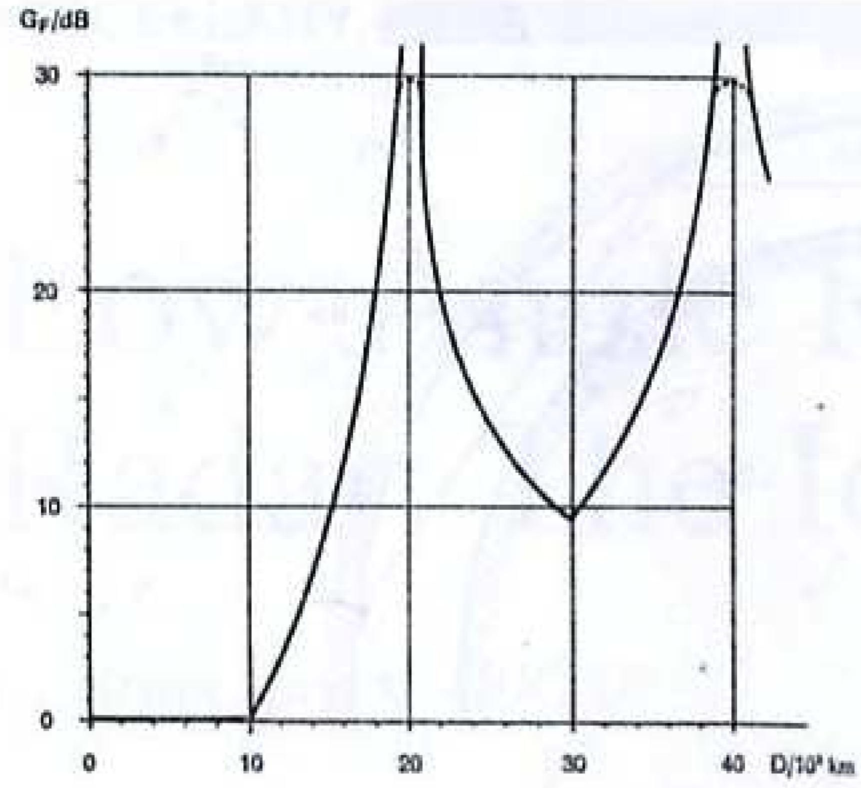

Fig.4. Focusing gain at antipodal points

so and this was to have repercussions later on, as we will see. Albrecht showed, consistently, that the predicted attenuation he had calculated, using the conventional multi-hop theory, was significantly greater than his measured results indicated. This, he concluded, was definite evidence for the existence of both the low-loss chordal-hop path and perhaps, too, of the phenomenon of 'antipodal focusing'.

A decade later a New Zealand physicist by the name of Gary Bold, who was working on a similar problem, published his research findings but without any mention of Albrecht's work. Bold was part of a team at the University of Auckland that had already carried out important work on long-distance radio propagation and, again, due to their geographical location the New Zealanders were well-placed to examine the antipodal effects from radio transmissions starting in and around Europe [6].

This prompted Albrecht to reappear in print himself. He pointed out to his colleagues across the Tasman Sea that he'd been there before them and he cited four papers he'd published in support of his claim. There was no doubting the evidence but the obscurity of their source did not help Albrecht's case. Not too many had noticed them! However, all this is just part of the cut and thrust of scientific research and the antipodean neighbours did not draw their cutlasses (or perhaps their boomerangs). Instead, polite yet firm presentation of the evidence sufficed as Albrecht asserted his priority in the field and credit was therefore given where it was due.

One of many important observations Bold made was that the focal point of those down-coming waves actually moved around, sometimes quite substantially, and the reason for that was that the ionospheric tilts responsible, in the first place for the chordal-hope mode, were themselves also moving.

Sunrise And Sunset Effects

One of the transmission frequencies used during this research was 15.270MHz. It was used by the *Voice of America* (VOA) transmitter situated in Tangier, northern Morocco, and its antipodal point was in the North Island of New Zealand. The VOA station was on the air for 12 hours a day which allowed observations to be made in New Zealand in the early morning through to late afternoon. This was useful because it meant the effects of sunrise and sunset could be observed and that turned out to be crucial. Theoretical work done by others had shown that the chordal hop mode, and also its closely-related relative, the whispering gallery effect, were initiated by tilts that came into being around twilight in the ionosphere.

We should remember that at the altitude of the ionosphere twilight occurs at a different time compared with what happens down here on earth. The results showed that the chordal-hop mode was dominant in the dark hemisphere of the Earth, as evident in Figure 2. Of special interest, too, was the observation that these chordal-hop effects occurred at frequencies up to twice what is called the MUF(4,000) frequency. This is the MUF for transmission, via a single-hop path, over a 4,000km distance. The reason for the '4,000' figure is that it is about the maximum distance it's possible to reach by means of a single hop via the F region of the ionosphere.

Riding on the back of all this was another well-known, but still unexplained, effect within the ionosphere: round-the-world (RTW) echoes. Such effects, where an exact replica of a transmitted signal is heard a matter of some hundreds of milliseconds after the original transmission, was not only slightly eerie but was also most interesting, at least to ionospheric physicists! Now it appeared as if wave tilts and chordal hops could explain it.

The 1970s was a busy decade for this type of research with many papers published from research groups around the world. It was found that both multi-hop and chordal-hop propagation could coexist: a signal could commence its journey through the ionosphere by the conventional multi-hop mode but, subsequently, it was then converted to the chordal mode at some point. The key factor in all this was the position of that critical part of the ionosphere relative to the sun. So, old Sol and the layer tilts he caused, yet again lay behind it all.

The D Layer And Absorption

Whereas the E and F regions do very useful things, the third layer up there is rather destructive. This rather ephemeral region lies between about 50 and 90km above the Earth and it's the most chemically complex of them all. At HF the D region has insufficient electron density to cause any refraction, so radio waves pass through it without being deflected or bent. By contrast in the E and F regions, with their much higher electron densities, refraction occurs – just as happens to light – and this is the key process by which radio waves are returned to earth.

At relatively low altitudes the atmosphere is still pretty dense so ionized particles (electrons and positive ions), caused for whatever reason, rapidly recombine. However, with an increase in height, the ionization processes caused by the Sun and by high-energy particles from well beyond the solar system produce far greater quantities of negatively-charged free electrons and an equal number of positive ions but not all of them recombine. There's a balancing effect at work and the outcome of that is the formation of a weakly ionized region that only exists during daylight hours. This layer is the third of the regions discovered by Appleton and his co-workers in 1927, though it was not then given a name until some while later when it became known as the D-layer.

It was soon realized that this lowest region of the ionosphere was no friend of the radio communicator, because it absorbed energy and so attenuated the signals. How it did this became a matter of considerable interest, because it was vitally important to be able to predict when that absorption was at its peak and how this deleterious effect could, if possible, be reduced or at least avoided. Was it, like the E and F regions, also affected by the seasons, the sunspot number and the geographical locations of the communicating stations?

By far the most important work on predicting D-layer absorption was done

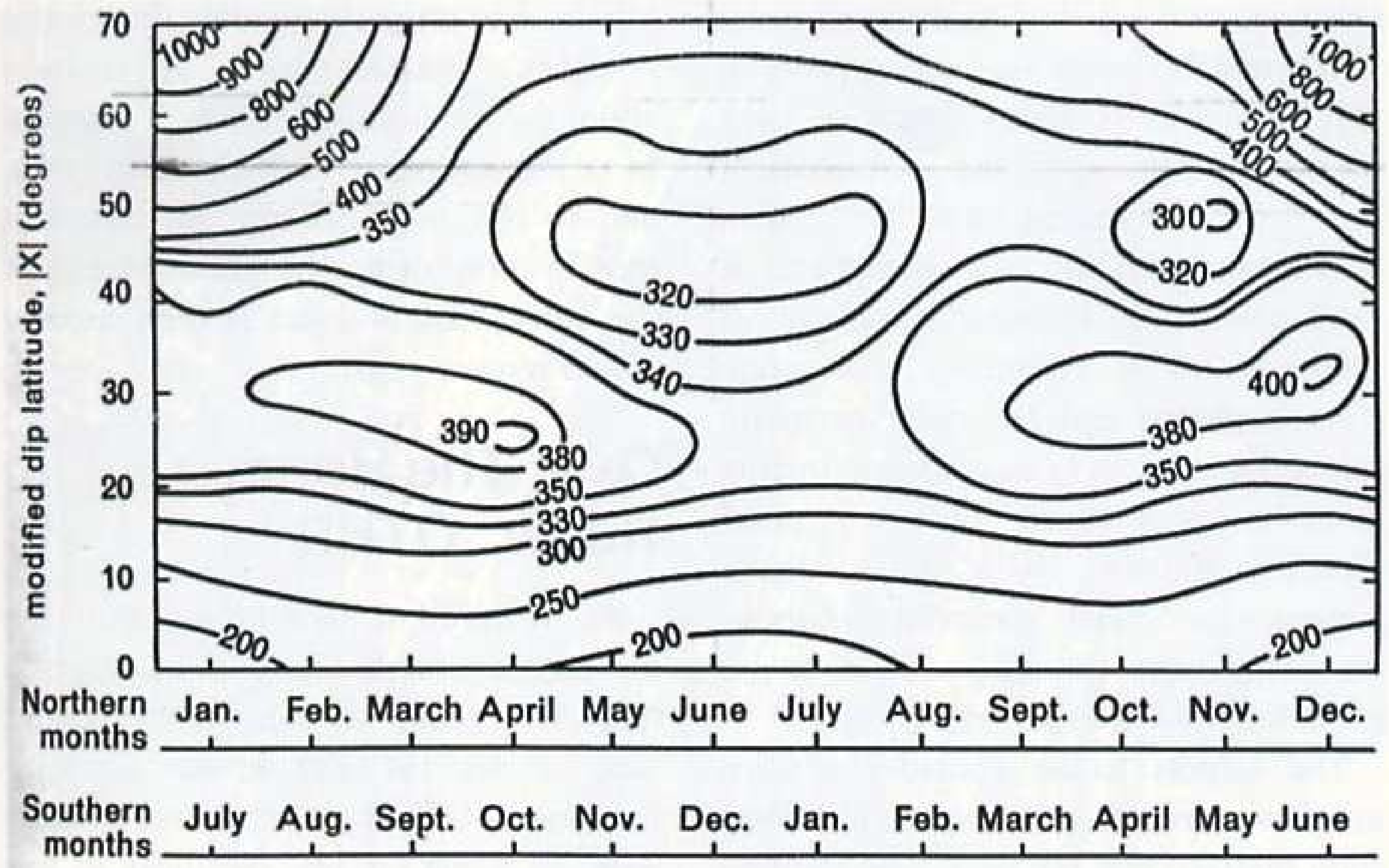

Fig.5. Attenuation factor used in calculating absorption

by a joint Australian and British pairing as recently as 1974. The research was carried out at the Appleton Research Laboratory (the former Radio Research Station made famous by Appleton and Watson Watt) in Slough and the men responsible for the work were Peter George from Salisbury, South Australia and Peter Bradley from the Appleton Lab [7]. As one might expect, a problem like this involving communication paths anywhere on the surface of the earth must involve maps but of mathematically-derived parameters rather than of continents. One parameter of particular importance amongst a multitude of such things was called $A_T(0,0)$. It is the so-called attenuation function. The double-zeroes imply the value of A_T for that time when the sunspot count is zero and the sun itself is directly overhead. How A_T varies seasonally, for both northern and southern hemispheres and with the magnetic dip angle – a measure of one's position on the surface of the earth – is given by **Figure 5** which looks rather reminiscent of weather maps showing the isobars across the planet. From this graph, and many more like it, it is possible to calculate the D-layer absorption and all this information was included in a FORTRAN computer program that made such predictions possible. The programme they developed is now in use at ionospheric observatories around the world.

To illustrate how it worked George and Bradley took a particular example of a single-hop path, using the F-layer, between Cyprus and Slough, a distance of 3,260km. They chose an operating frequency of 23MHz at noon UTC in June 1969 which meant the sunspot number (SSN) was 106 and the take-off angle of their selected antenna was four degrees. The George-Bradley method then showed that over that particular path, and at that time of the day and sunspot cycle, the absorption loss was 6.8dB.

D-layer absorption is very frequency-dependent. It increases sharply as the frequency is lowered and it's this effect that determines the LUF or lowest usable frequency for any particular propagation path. It is also strongly influenced by the position of the sun in relation to the point of reflection in the ionosphere so both the time of day and the season affect the resulting absorption directly. In addition, the SSN itself plays an important part. Since the sun is the driving force behind it there is almost no absorption at night except for some small residual effect during periods of high sunspot count. As an example of the attenuation likely to be encountered, **Figure 6** shows how the D-layer absorption increases sharply as the frequency is decreased. Peak attenuation greater than 22dB occurred at 3.5MHz around midday, whereas it was less than 4dB at the same time on 7MHz over a high-angle NVIS path above central England in June 2006. The seasonal dependence is evident too.

Extending The Range

Communicators mastered the art of long-range radio a long time ago but when radar first appeared during

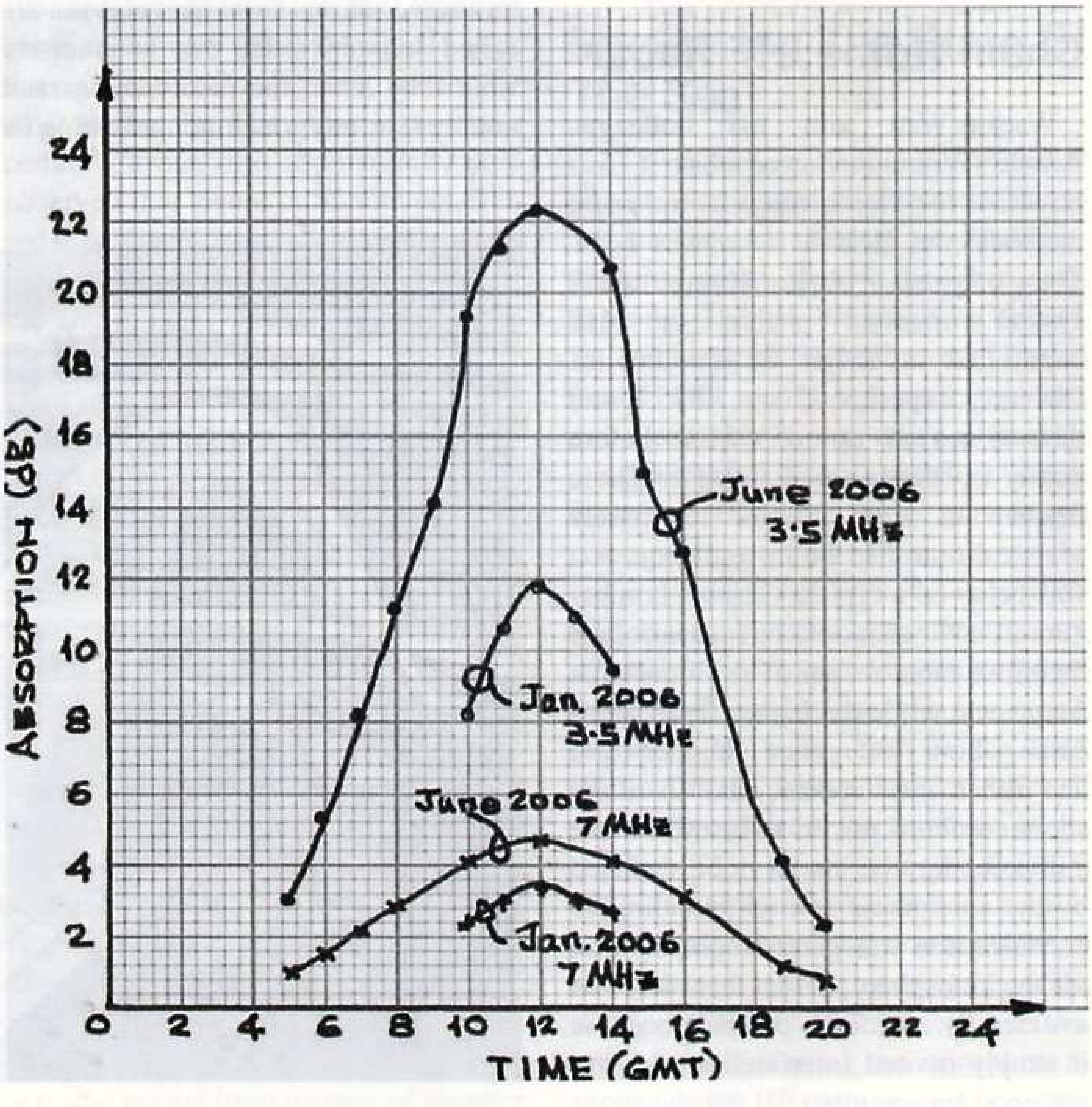

Fig.6. D-layer absorption directly overhead central England

the Second World War its range was generally restricted by line-of-sight considerations with the horizon being about the limit. Of course, from an aircraft the horizon is much further away than when seen from the ground but the essentially optical behaviour of electromagnetic waves still sets the limit. However, there were many applications (such as defence and remote-sensing) which required much longer ranges and so attention was given to using the ionosphere to increase radar range.

The first radars were actually used as early as 1925 to measure the height of the ionosphere. The Americans Breit and Tuve used pulses of RF energy while Appleton and Barnett, in England, adopted the frequency-change method. Their equipment operated at much lower frequencies than the radar sets we use today, while the first signals they transmitted from the ground were returned not by man-made targets such as aircraft and ships but by what came to be called the ionosphere just a year later. It was so named by Robert Watson-Watt the man credited – a decade later – with pioneering the British radar system that was initially called RDF, another term coined by Watson-Watt.

Chain Home: HF Radar

Watson-Watt and his colleague Arnold Wilkins showed that it was possible to detect aircraft by radio methods and British radar was born. The original 'Chain Home' RDF system operated within the HF band, first at 6MHz for the famous Daventry experiment (see *RB153*) and then it moved up to 13MHz before finally settling around 22MHz. These frequencies were selected for purely practical reasons: the lowest because it was believed a typical German bomber aircraft's wings would be resonant (and therefore most responsive) around that frequency, while the higher frequencies came about to reduce thunderstorm and other interference, and to allow shorter antenna towers to be used while still keeping the major lobe radiated by the antenna as low as possible. No consideration was given to propagation via the ionosphere; in fact that was to be avoided by all means possible because it simply invited interference and was not good for security.

However, when the Cold War between the West and the Soviet Union soon emerged in the 1950s as the next great encounter between the super powers, and weapons systems became ever more sophisticated, the requirement for greatly increased radar range also became crucial for the detection of inter-continental ballistic missiles. All likely means of extending radar range were explored and HF radar certainly seemed a viable way to go. Experiments actually commenced in the United States in the late 1940s. All evidence suggests the Soviets started theirs about the same time though, as was to be expected, they told no one!

The targets to be considered were missiles, aircraft and ships but it was soon realized that HF radar also yielded useful information about the state of the oceans, its currents and especially the waves, by what is known as back-scatter. Since HF radio signals are easily refracted back to earth once they encounter the ionosphere, they actually strike their targets (and the sea) from relatively high angles. Therefore it's not just the missiles, aircraft and ships that are 'illuminated' by the HF energy but so is the sea and the land around it. All this is well illustrated in **Figure 7**.

In the more usual world of aircraft and ship tracking by radar such unwanted returns from land and sea are called 'clutter' since that is precisely what they do to the radar screens and much effort has gone into mitigating its effects. But properly handled that clutter contains considerable information about the state of the sea which is useful to oceanographers and meteorologists, and so HF radar became an important tool in monitoring the great oceans of the world. The subject is then usually called remote sensing.

Over The Horizon Radar: OTHR

As with all things to do with the military a suitable acronym to describe this new radar technique that could 'see' beyond the horizon was not long in coming. OTHR soon became a buzz-word in some circles. Needless to say this subject is now vast, and much of it still remains classified, but both the professional and popular technical literature contain some interesting and useful material which provides the background. Perhaps the most extensive, as well as being one of the earliest in-depth articles to appear, was written by two scientists at the US Naval Research Laboratory in Washington in 1974. The title says it all: *Over-the-Horizon Radar in the HF Band* [8]. From it we discover that the US Navy's first experimental HF radar, called MADRE, began operating in 1961.

As one might expect, given that HF radar operates at much lower frequencies – and hence longer wavelengths – than

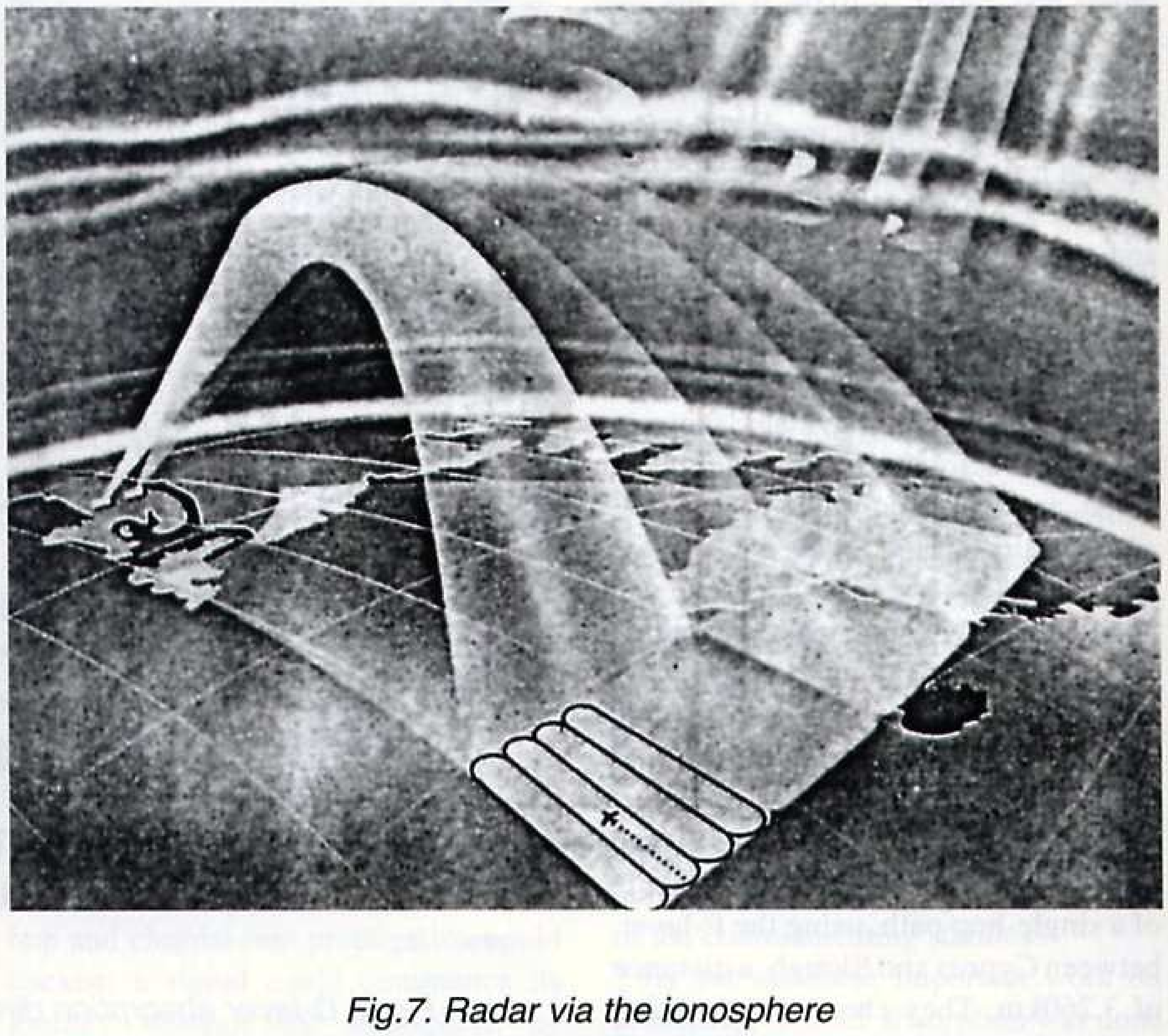

Fig.7. Radar via the ionosphere

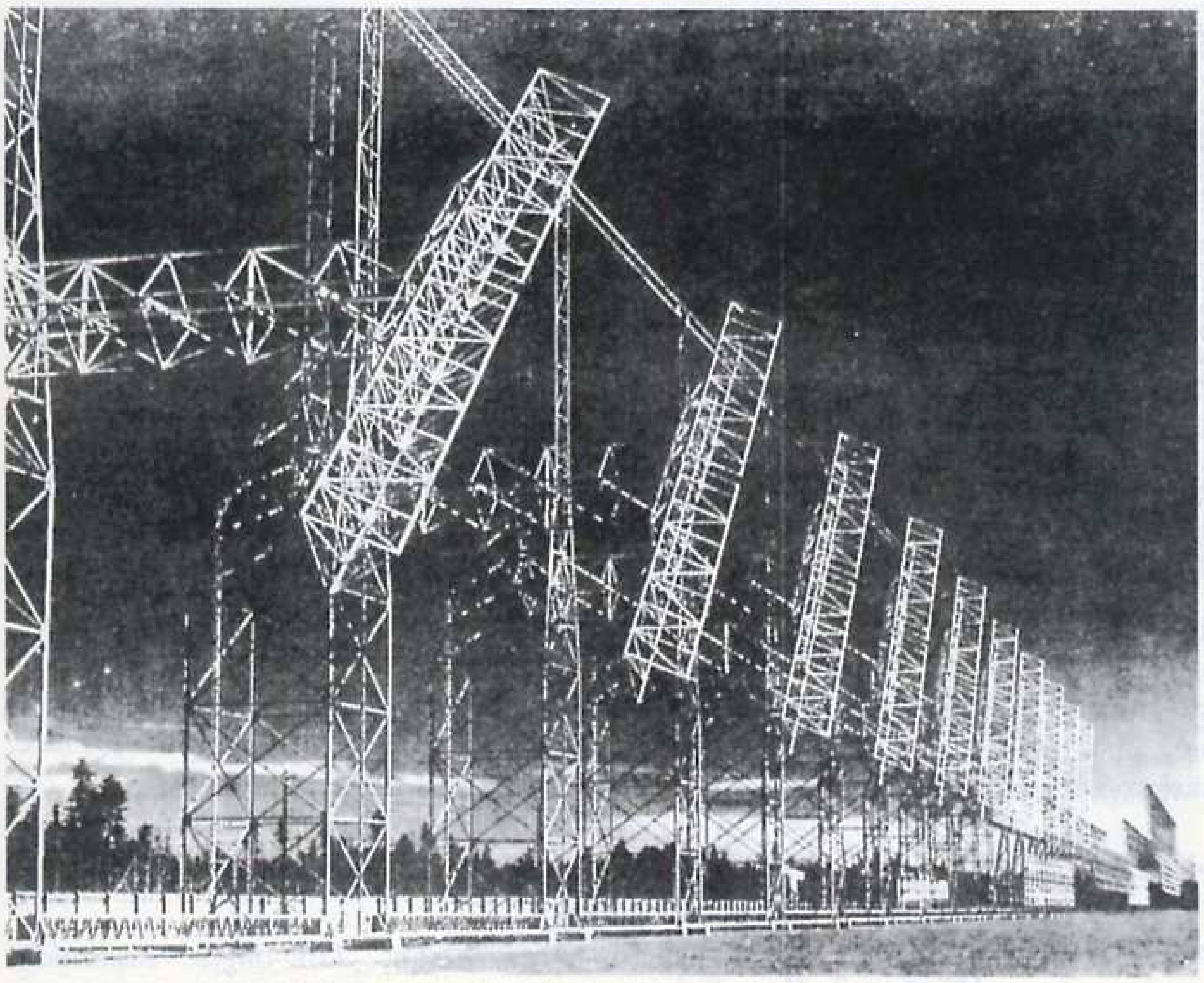

Fig.8. OTHR transmitter antenna array in Maine, USA

conventional microwave radars, the antennas used tended to be massive structures. The MADRE antenna was 98m wide and 43m high and consisted of twenty corner reflector elements. The beam was electronically steered over about 30 degrees either side of the antenna's bore sight. The average power delivered by the transmitter to the antenna was in the range of 5 to 50kW. This is by no means typical of the HF radars than went into service sometime later. By then, once design and operational problems had been ironed out, power levels jumped an order of magnitude at least and average transmitter power in the region of 1MW soon became typical.

The operating frequency range of an OTHR is determined by exactly the same factors that determine which frequencies one should use for long-distance HF communications. The dynamic nature of the ionosphere, as discussed above, requires considerable frequency agility in an OTHR. Ideally the radar should be able to exploit those changing ionospheric conditions by being able to operate right across the HF spectrum from say 3 to 30MHz. However, economic constraints, mainly due to the size of the antenna, limit operation to frequencies somewhat and so 6.7 to 22MHz was the band used by the early US military radars. Many radio amateurs, especially those who were active in the 1970s, will remember the interference caused by the Russian OTHR, soon christened the Woodpecker because of the sound it made as the very powerful signal swept through, and often lingered, within the amateur bands. The Americans were certainly aware of it and naturally they observed that signal in minute detail in order to glean as much information as they could about the characteristics of the transmitters and, indirectly, about the receivers in use. For this, and many other reasons, they carefully tailored their OTHR signals to cause minimal interference to other users of the radio spectrum.

As the US HF radars evolved so did their names. CONUS OTH-B came into service where CONUS implies Continental USA while the attached B indicates that backscattered signals, from whatever target, were of specific interest. The first of the operational US radars was set up in the state of Maine in the early 1970s and it scanned the region to the north-east of the USA. Approaching aircraft and missiles were of specific interest to the radar operators and the radar's ability to look well beyond the horizon increased the early-warning period from matters of minutes with microwave radar to many hours with the HF variety. The capabilities of this radar were impressive. Its frequency coverage was from 5 to 28MHz; the average transmitter power, provided by 12 combined transmitters, was 1MW. When combined with the antenna gain the effective radiated power (ERP) was typically 100MW. The transmit antenna in the state of Maine (see **Figure 8**) consisted of an array of canted dipoles backed by a reflective screen to make the radiation pattern essentially unidirectional. The array was 1,100m long and 41m high. At the radar receiver, located over 100km away to minimize interference between transmitter and receiver, the receive antenna array consisted of 246 vertical elements, each 5.5m high, and also backed by a reflective screen over 1,500m long with a considerable ground screen in front intended to yield the lowest angle of radiation (and hence reception) possible.

Another OTH-B station was set up in California to provide similar coverage of the Pacific region (see **Figure 9**) and together these two stations provided the US with a very wide protective screen having a maximum range in excess of 3,000km extending, sometimes, to over 4,000km, at the whim of the ionosphere, of course.

Monitoring The State Of The Sea

As mentioned before, HF radar provides much useful information about the sea-state as a result of the back-scattered signals from waves and ocean currents. The phenomenon is known as Bragg scattering after the British father and son Nobel laureates who discovered that X-rays were scattered by a crystal lattice. The same effect occurs when radar signals of a wavelength corresponding to that of the waves in the sea are strongly reflected and so provide useful oceanographic data about a very dynamic marine environment. Much work has been done on this fascinating aspect of HF radar, both in the USA and in Britain, where the University of Birmingham was at the forefront of the research. There a team under the direction of Professor Ramsay Shearman, himself a member of the pioneering ionospheric research team at Slough during the 1950s, developed considerable expertise in this area. As well as using the ionosphere to propagate the HF radar signals, sea-state radar also uses the ground wave which hugs the surface of the earth and the

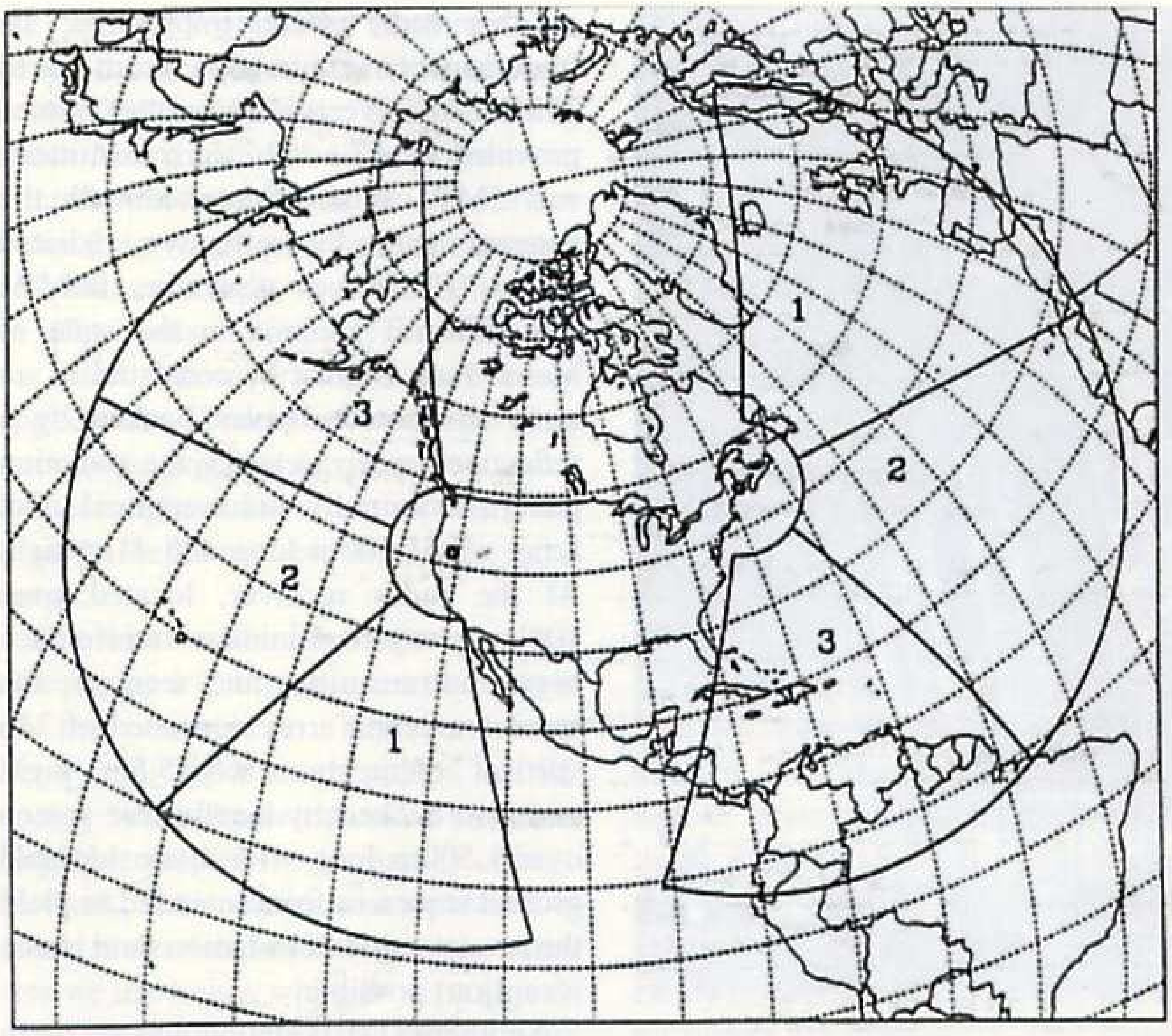

Fig.9. OTHR coverage from Maine and California

sea to provide information about wave and other activity from the shore-based radar station out to distances of some hundreds of kilometres. **Figure 10** shows the coverage from a sea-state OTHR radar located in the south of England.

The Future

Though the Cold War is thankfully now behind us and the need for OTHR has receded, newly emerging political situations around the world always present problems and with them come challenges to both engineers and scientists. The US OTHR system was therefore only placed in 'warm storage' for the time being; it could be restored to full operational effectiveness (with considerably enhanced signal-processing capabilities given the dramatic advances in that subject in recent times) in a couple of years should the need arise. As well as the USA, the UK and the USSR, other countries that developed their own HF radar systems include France, Canada, China and most interestingly, Australia. What is now known as JORN began life in Australia in 1970 as Jindalee, an experimental over-the-horizon radar system. Now, some 45 years later, it is fully operational from a number of distributed transmitter and receiver sites across northern and western Australia. The radar covers some 37,000 square kilometres of sea, island and other territory to the north and north-west of Australia and has a range capability of, so they say, around 3,000 km. Verified detection of targets well in excess of that has been reported.

What started in England in 1901 when Marconi spanned the Atlantic and then, just before WWII, became the remarkable means of detecting an invading bomber fleet has developed into a highly sophisticated technology with important applications in both the civil and military worlds. Without the ionosphere none of it would have got very far.

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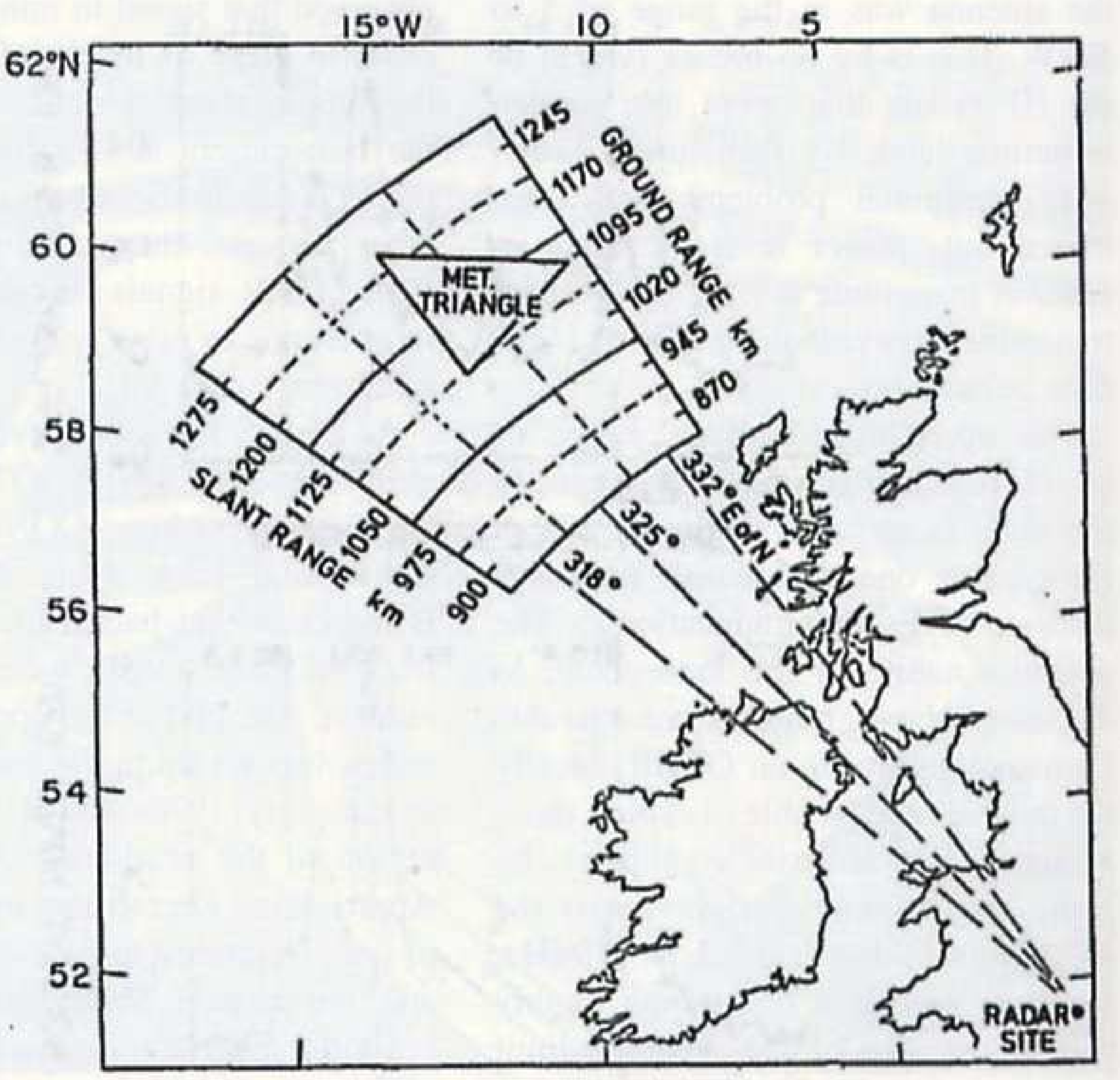

Fig.10. Sea-state radar coverage to the north-west of the UK from a radar site in southern England