Revisited in Year 2000.

Long-Path Propagation

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A Study of New Developments

since the Peak of Cycle 22.

by

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Preface

It seems to me there are two ways to write a preface, one formally:

Long-path propagation is a broad, inclusive subject, dealing with a wide range of geographic locations, the HF and MF ranges of the amateur spectrum and can occur throughout an entire solar cycle. That being the case, the reader should not be surprised to find a wide range of topics discussed in what follows, from the effects of atmospheric gravity waves on the ionosphere to the presence of drifting patches of ionization in the dark, polar F-region.

or another, informally:

Ten years have gone by since I began "Long-Path Propagation" and it is now time for another look at it. But I have not been pounding brass on 20 CW all that time; instead, I have spent a lot of time learning what others had to say about the topic and added a few words of my own. But the big development is that I moved my RF and interests down to the 160 meter band. I simply came to the conclusion that DXing on 160 is the ultimate challenge of amateur radio and and the last great question was long-path propagation on 160; I had to see what the two involved.

But my health failed me and the last contact in my log was a QSO with VK6HD. That covered 14,913 km, about 5,100 km short of qualifying as a long-path contact. But that was done with just 200 Watts and a vertical standing only 10 meters high. So I left 160 with a smile on my face and turned again to writing about long-path. Looking back on it, I suppose I could have done more but with this book, I will leave it to others.

Beyond those words, I wrote this update assuming that the reader is a DXer or a contestor who is interested in propagation and has some experience in making long-path contacts. Thus, the book is devoted more to the new ideas and topics which emerged in the last ten years than a further discussion of the elementary aspects of the matter. I am sure the presentation and discussion in summary form are not perfect but I have done my best; for more detail, the reader should look to the references. In any event, all the faults are mine and I have nobody else to blame. But I hope you can read beyond them to benefit from other's efforts and my understanding of this intriguing subject.

Acknowledgements

I am indebted to many friends for discussions about long-path propagation. Special thanks go to Sheldon Shallon, W6EL, for ten years of stimulating conversations about propagation, DXing and computing. Also thanks to Robert Eldridge, VE7BS, for getting me interested in the 160 meter band and Carl Luetzelschwab, K9LA, for sharing his interest in propagation.

Long-path Revisited

Chapter I-

Introduction-

In a couple months, it will be ten years since I undertook a year-long study of long-path propagation. That was sparked by a long-path contact with a SM5 just after the peak of Cycle 22. We found both long-path and short-path were open at the same time but propagation was actually better on long-path. Being a retired physicist, that seemed like an interesting topic to study and I went right to it, ending up a year later with almost 1,700 LP contacts in my log. But with the passing of ten years, it is of interest to review new developments in regard to LP propagation.

As you know, long-path is in the direction opposite to the usual great-circle path between two points and long-path propagation is realized when signals travel more than halfway around the earth to the second terminus, going more than 20,000 km, the distance from a QTH to its antipodal point on the opposite side of the earth. For my location at 48.5N and 122.6W in Washington, the antipodal point is out in the Indian Ocean at 48.5S and 57.4E, near Crozet Island. So long-path propagation from my QTH involved signals going past Crozet Island, to Africa and Europe. By way of illustration of paths to an antipode, a useful figure for later purposes shows Heard Island and its antipodal point in North America, found in **Figure 1** from Brown (1990), and with great-circles spaced every 10 degrees.

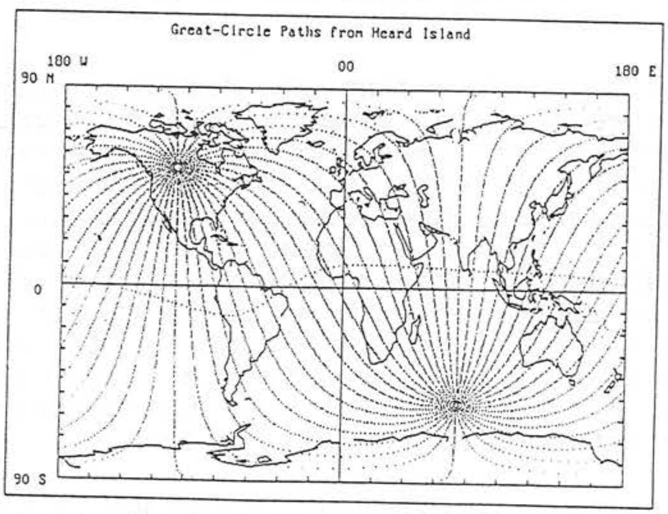


Figure 1 - Great-circle paths from Heard islnd, in 10 degree intervals of heading.

Before proceding, it should be noted that great-circles in such a figure are just geometrical constructs that are independent of frequency and transmitter power. In reality, while signals from a transmitter may start initially along those directions on being launched, they will deviate from those paths, depending on the ionospheric structure encountered at the time, and their effectiveness will change with distance, according to loss in intensity from ground reflections and D-region ionization present along the radio path.

In that figure, it is seen that the great-circles converge on the antipodal point. In the early days of long-path propagation in the upper HF region, it was useful to think of great-circles as approximations to ray paths and their convergence in that figure as a form of ray focusing at the antipode, thus enhancing signal strengths at great distances. But nowadays, because of the large geographic variations in the ionosphere, shown in global maps of the F-layer critical frequency foF2 and heights of the F-layer peak, antipodal focusing is not considered to be of any importance (Davies, 1990). However, it is still of some interest to think of the ray path concept but with modifications which depend on the frequency in use and transmitter power.

For example, ionospheric absorption varies roughly as the square of the wavelength so lower frequencies suffer greater absorption in regions of daylight. Going to a great-circle ray diagram for a given time of day, the placement of the terminator on that map would divide the diagram into regions in sunlight and darkness and the effectiveness of the rays as far as signal intensity would decrease as they went into sunlit regions. In fact, at some distances signals would no longer be heard, so the rays in a diagram for a given transmitter power and frequency could be thought of as ending right there, to show the limits of signal propagation.

Figure 1 shows ray paths using the Mercator projection; that projection progressively distorts map features in going poleward from the equator and in the limit, points for the two geographic poles are distorted into lines at the top and bottom of the figure. Another projection which can be used is the azimuthal equidistant projection; there, the center of the map is at the location of interest and the point at the antipode on the opposite side of the earth is distorted into a circle at the boundary of the map. The advantage of that projection is all the great-circles from the prime location are straight lines that radiate out from the center of the map. But then the appearance of ray convergence at the antipode is completely lost.

In spite of that, there are some advantages to using that projection when it comes to discussing propagation at the two ends of the amateur spectrum. So an azimuthal equi- distant projection with Heard Island at its center is shown in **Figure 2** and the great-circles to the antipode seen in **Figure 1** are now given by straight lines which radiate out from the center every 10 degrees. ending at the outer edge of the figure, 20,000 km from the center.

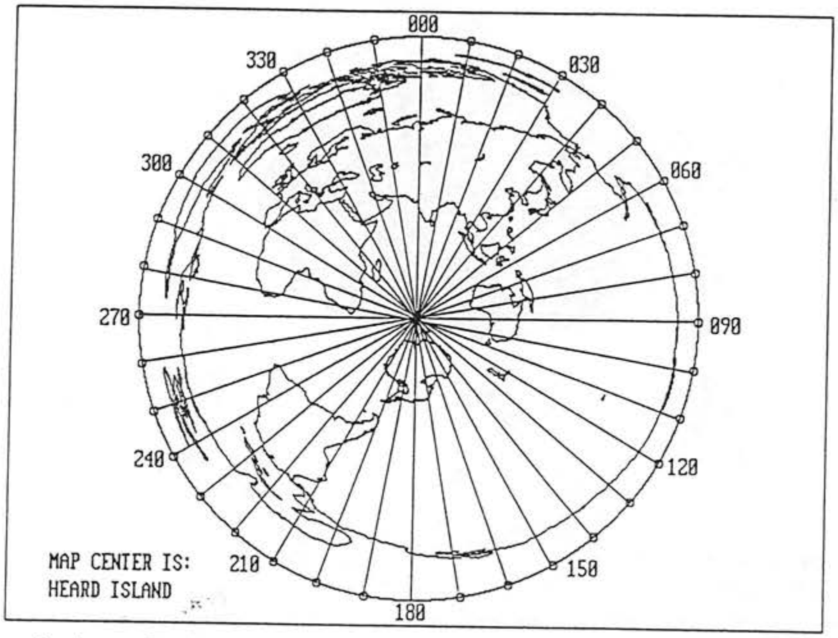


Figure 2 - Azimuthal equidistant map centered on Heard Island

The ray diagram that is appropriate for the high end of the amateur spectrum, at the summer solstice where propagation is MUF-limited, is shown in **Figure 3**. There, ray paths are continuous in the SUNLIT part of the map but are shortened in the dark portions where MUFs may fail after sunset. A similar appearing figure, but now at the winter solstice, is **Figure 4** which is appropriate for the bottom of the amateur spectrum where absorption limits signal propagation. There, ray paths are continuous in the DARK part of the map but shortened in the sunlit part where heavy ionospheric absorption takes place. In addition, that figure shows some ray deviation or curvature due to refraction away from the terminator

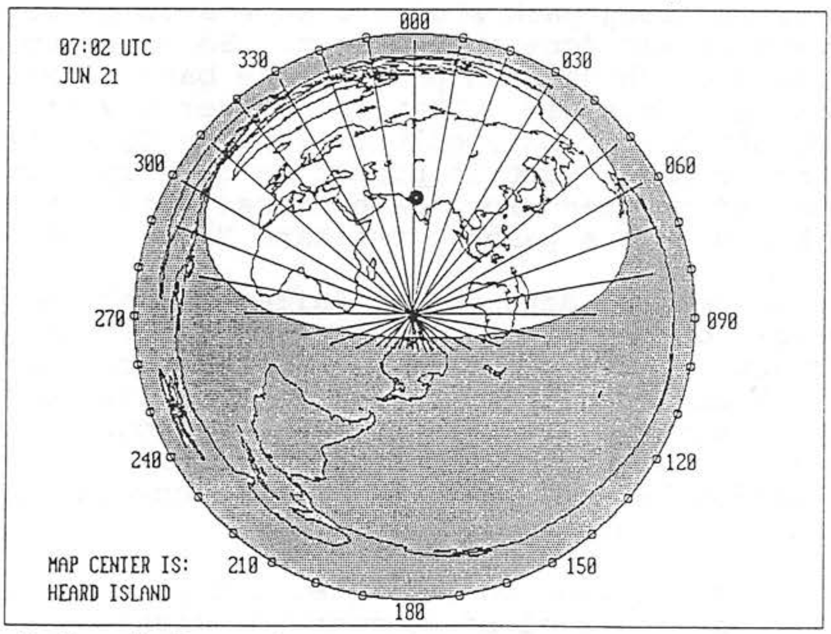


Figure 3 - Azimuthal equidistant map for HF, with sunlight.

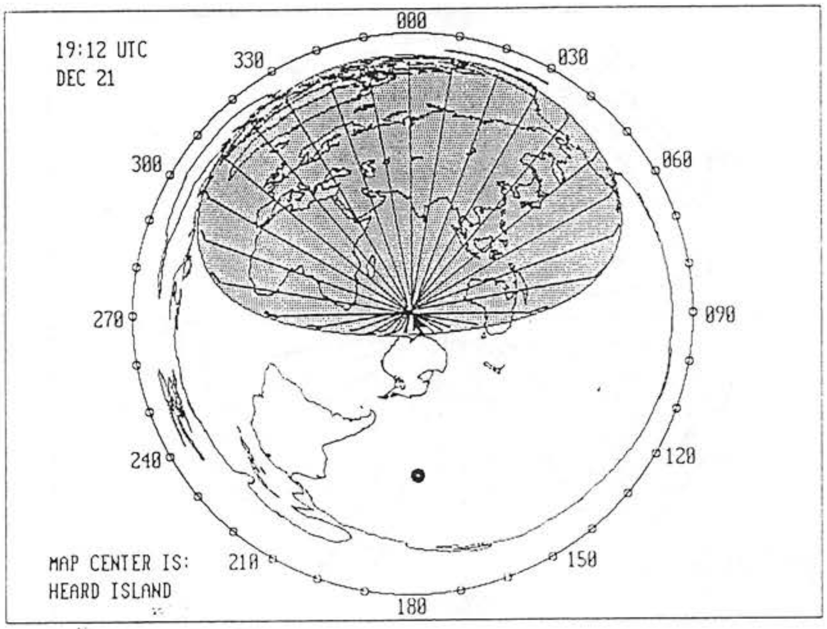


Figure 4 - Azimuthal equidistant map for MF, in darkness

It should be noted that unlike **Figure 2** which is independent of frequency and transmitter power, the lengths of rays in **Figures 3** depend on those parameters, case by case, and thus is limited to specific circumstances and not generally useful. On the other hand, since ionospheric absorption is so heavy down at the bottom of the amateur spectrum, the 160 meter band, **Figure 4** is useful in all circumstances and shows that signal propagation is limited to locations in the dark hemisphere.

Details of the LP Study-

Returning to the long-path study, that was on 20 meter CW, my favorite band, and it was done around dawn. So I was up early every morning, rain or shine, and prowled the band, listening for the sound of long-path signals. That is another way of saying I never called "CQ LP" or "CQ DX", only relying on CQ's that I heard or tail-ending other QSOs. But it proved to be very rewarding, with between one and thirteen long-path contacts in a morning, using only 250 Watts into a generic tri-band Yagi at 38 ft.

Of course, there were days when I failed to make a single LP contact; those were during times of magnetic disturbance and were responsible for how I analyzed the data that was accumulated. For example, I first broke down the data according to season and then looked at magnetic activity. In that regard, I found there was no great difference in the number of contacts I could make, with long-path propagation being a mode for all seasons and almost every day at that stage of the solar cycle.

Having done that, I went on to magnetic circumstances and it became clear that as the level of geomagnetic disturbance grew larger, as shown by the daily Ap index, the probability of long-path contacts became smaller. That, of course, was due to the fact that most of my long-path contacts were ones that went across the high magnetic latitudes, regions where magnetic disturbances can affect ionization in the F-region and disrupt paths by auroral ionization. Actually, with my QTH here in the State of Washington (48.5N/122.6W), there were only a few regions below the southern auroral zone that were accessible by long-path. The rest of the LP went into the southern auroral zone or polar cap so magnetic disruptions were to be expected from time to time.

Since long-path contacts are made by sending RF in directions opposite to the usual great-circle paths, it has to be understood that means the critical frequencies of the ionosphere in that direction support propagation all along the long-path. Put another way, for any individual hop along a long-path, the MUF must be greater then the operating frequency. This is not always the case during a day, with a MUF in some region on the path lower than the operating frequency, keeping the path closed.

But it may be possible for the terminator, a great-circle dividing regions of sunlight and darkness, to move close to the path or briefly coincide with it at sunrise and raise the level of ionization in that part of the F-region to open up the path. Two examples of such circumstances are given in **Figures 5 and 6** from Brown (1992), showing how critical frequencies on a small fraction of the total path may raise the MUF with sunrise, thus fulfulling the condition needed to support LP propagation. Sunrise at lower altitudes, on the D-region where absorption takes place , occurs somewhat later in time and when that happens, long-path openings come to an end because of the increase in absorption.

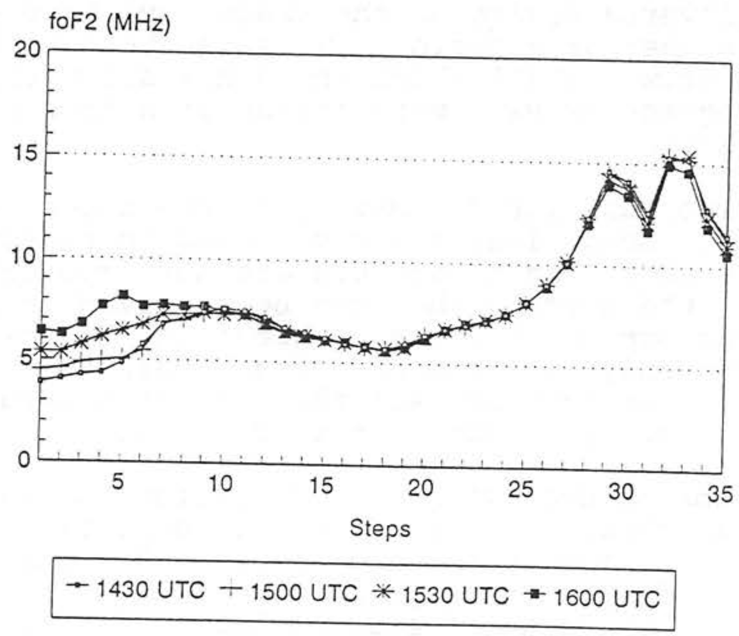


Figure 5 - foF2 variation at sunrise on a long-path to Switzerland

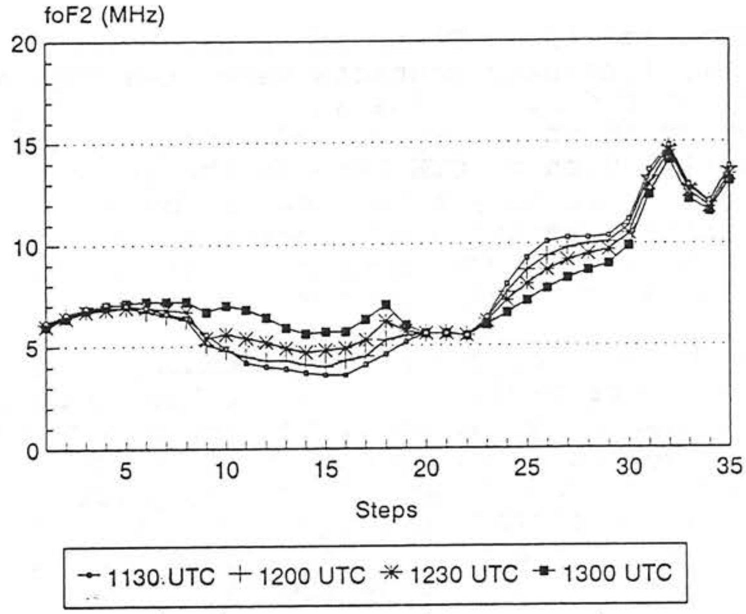


Figure 6 - foF2 variation at sunrise on a long-path to India.

Non-transition Bands-

The LP study on 20 meter CW really gave results which were typical of what is called a "transition band", one of those for which DX openings develop when the MUF on the path is raised by sunrise on the F-region and then closed by absorption, when the sun rises on the D-region. In short, propagation on the 10-18 MHz bands is limited by both MUFs and absorption, whether on short- or long-paths. On the higher bands, 21-28 MHz, propagation is more controlled by MUF considerations than absorption as the latter varies with the inverse square of the frequency, thus playing a smaller part at higher frequencies. This can be seen by looking at **Figure 7** from Brown (1997) which shows how absorption on 28 MHz and the other frequencies vary with height on a "per electron" basis in the D-region.

On the lower bands, 1.8-7.0 MHz, just the opposite is true, there always being enough ionization overhead to support signals on those bands, even at night, so MUFs are not important. But now absorption limits the success that can be achieved in DXing. As a matter of fact, absorption becomes so great on the lower bands that DXing is done only in the hours of darkness on a path and short exposures to sunlight are all that can be tolerated on the ends of a path if long-path DXing is to continue.

The above remarks deal with the ionization in the F- and D-regions. But that should be considered in connection with the details of a path and how it is illuminated. For example, on the highest amateur band, 28 MHz, signals penetrate to the greatest heights in the ionosphere and frequency limits for propagation are set by the ionization level from the illumination at the 300-400 km altitude, the peak of the F-region. That in turn depends on the level of solar activity, the season and the time of day.

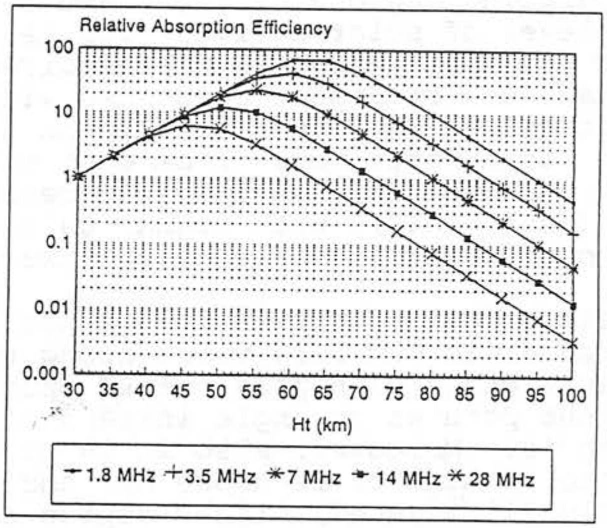


Figure 7 - Absorption efficiency by bands in the D-region.

By that token, the 10 meter band has the longest hops and is used mostly during hours of daylight, when solar UV creates the ionization that supports propagation. But because of infrequent collisions at high altitudes, the recombination of electrons with positive ions is slow after sunset and ionization may persist for a while, extending operations briefly into hours of darkness.

On the lowest band, 1.8-2.0 MHz, the ionization that controls propagation is down low in the D-region where electron collisions with neutral molecules occur at a very high rate. There, signals drive more collisions and signal strength is reduced in those energy transfers, weakly heating the atmosphere. Operations are usually during hours of darkness and end at dawn as absorption increases rapidly with sunrise on a path. But, again, it should be noted there is a variation of absorption with frequency so some sunlight, at low elevation angles, can be tolerated on 40 meter paths, less on 80 meters but practically none on 160 meters.

Path Geometry-

The remarks above bear on the sort of conditions which will yield propagation to distances beyond 20,000 km, half the distance around the earth. For that kind of path, the ionosphere must have critical frequencies foF2 all along it which are above a minimum, roughly the operating frequency divided by a factor of 3.5. So for the 14 MHz band, that critical frequency would be 4 MHz and the extent to which the minimum is exceeded depends on the actual level of solar activity.

The solar zenith angle is constant all along the length of the terminator, separating regions of light and darkness. By that token, the MINIMUM level of solar activity for LP on a given operating frequency would have foF2 at the required value along the path, if and when the terminator coincided with it. This is the gray-line condition and may occur briefly in the morning or evening hours as the terminator moves from east to west. If it is fulfilled around the entire gray line, it can result in round-the-world (RTW) echoes (Hess, 1948), with signal pulses heard from a transmitter a time or two at intervals of 0.13 sec.

At higher levels of solar activity, long-path propagation still involves the same minimum foF2 value along the path but the geometry is less restricted, with possible LP openings when the terminator crosses the path at an angle instead of being required to cross parallel to it. Moreover, also it is possible that the path is open when the terminator is close by, and even if parts of the path are slightly illuminated, with D-region absorption not sufficient to close the path. In that regard, good examples of those two cases are given by contacts during the long-path study, about 80 minutes apart, to India and Angola and with ray paths shown in **Figures 8 and 9**.

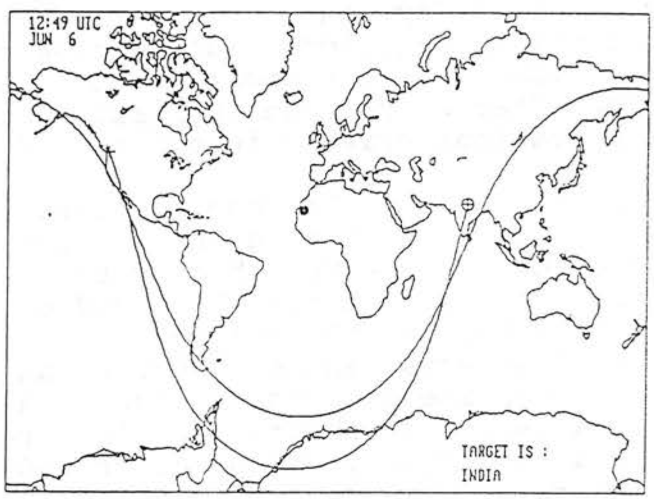


Figure 9 - Mercator map of long-path contact with India.

The contact with India was close to gray line at 1249 UTC on June 6, with the great-circle path in darkness, just inside the terminator for a large part of the path. The second contact with Angola was 80 minutes later at 1407 UTC. But now that path was almost perpendicular to the terminator and going across the dark southern hemisphere, and with sunlight on both ends of the path. For those contacts, foF2 values near the terminator as well as in the dark hemisphere must have been above 4.0 MHz, the latter from ionization remaining in dark hemisphere from the high level of solar activity. But for the Angola contact, absorption along the illuminated path segments close to the terminii was not sufficient to close the path.

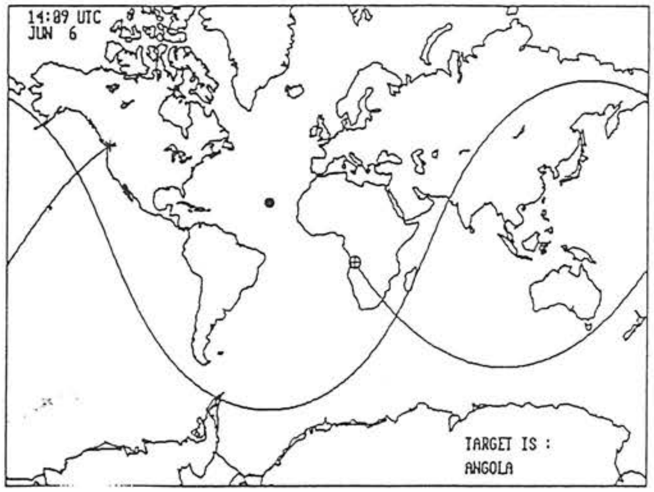


Figure 9 - Mercator map of long-path contact with Angola.

Those two contacts demonstrate that the level of ionization is the most important factor for a long-path contact, with the residual ionization in a dark hemisphere in **Figure 9** just as effective as the fresh ionization close to the terminator in **Figure 8**. Of course, that is the situation on the lower bands where enough ionization lingers all night and the terminator is not directly involved in establishing propagation, instead being hindrance to propagation on 160 meters.

Chapter II

Paths and MUFs-

At the end of the first chapter, it was pointed out that long-path propagation can occur under gray-line conditions, when the minimum value of critical frequency foF2 is fulfilled all along the path by the presence of the terminator nearby. As an example of that path geometry, consider **Figure 10** showing the case for a contact with Norway during the long-path study on 20 meters. The shaded region is the dark hemisphere and its central boundary, the terminator, is inclined at an angle of about 10 degrees east of north.

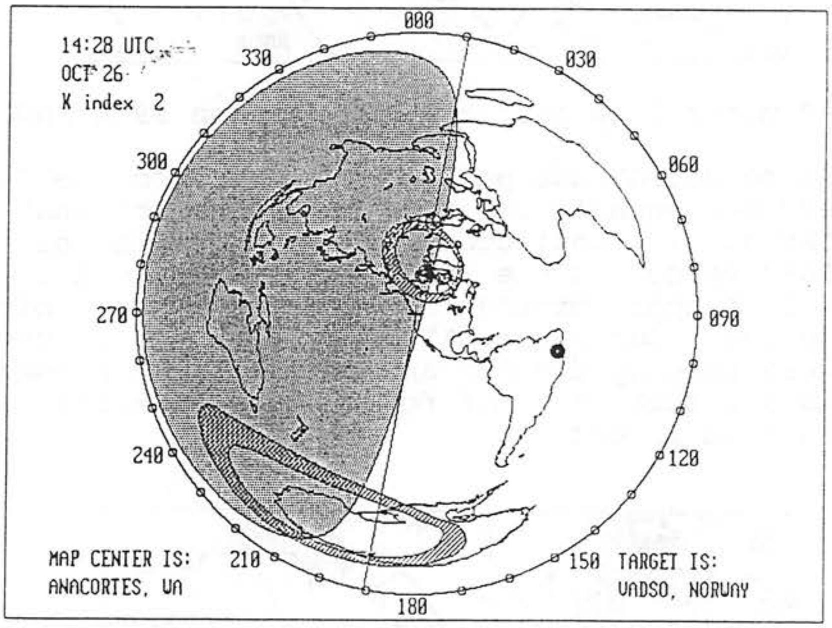


Figure 10 - Long-path geometry for a contact with northern Norway.

The radio path goes south across Antarctica, then up north to Saudi Arabia and ends at Vadso, Norway, at a distance of 33,600 km from Guemes Island, WA. Of that path, 19,200 km was in daylight, the remaining 14,400 km just inside the terminator. The contact was in 1991, near the peak of Cycle 22, and thus the path was in an ionosphere that met the foF2 requirement for propagation on 14 MHz.

An interesting contact at the top of the amateur spectrum, 28 MHz, was made by K9LA in Ft. Wayne, IN, first working JH3DPB in Japan at 1100 UTC on April 11, 1992. A Mercator plot showing the great-circle approximation to the path and the terminator is given in **Figure 11** Most of the path was in daylight, accounting for propagation on 28 MHz. The contact continued for more than two hours but the path finally closed at 1315 UTC, shown in **Figure 12**.

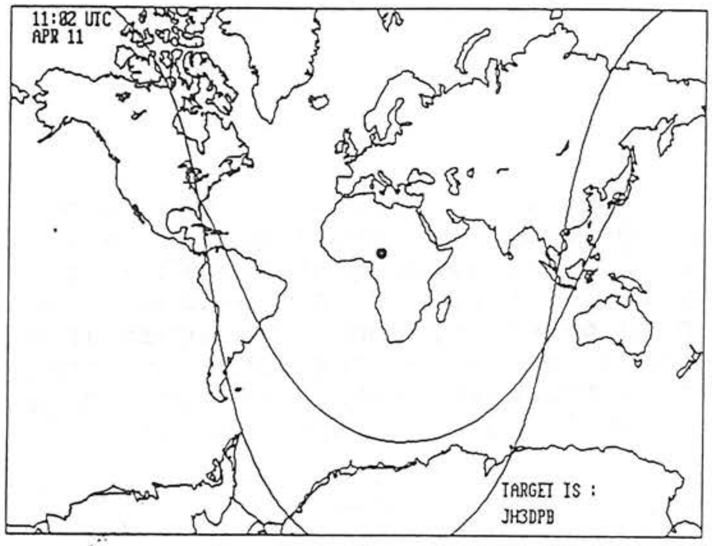


Figure 11 - 10 meter long-path contact between K9LA and JH3DPB.

It should be noted that part of the path, on the Japan end, was in darkness but equally important was the fact that part of the path was across low latitudes. Those latitudes have some of the highest foF2 values in the ionosphere, even in the dark, and thus are able to support propagation without appreciable aid from solar illumination. But **Figure 12** shows that the amount of the path in darkness roughly doubled and reached into higher, southen latitudes. As a result, the MUF for the path finally fell and propagation came to an end.

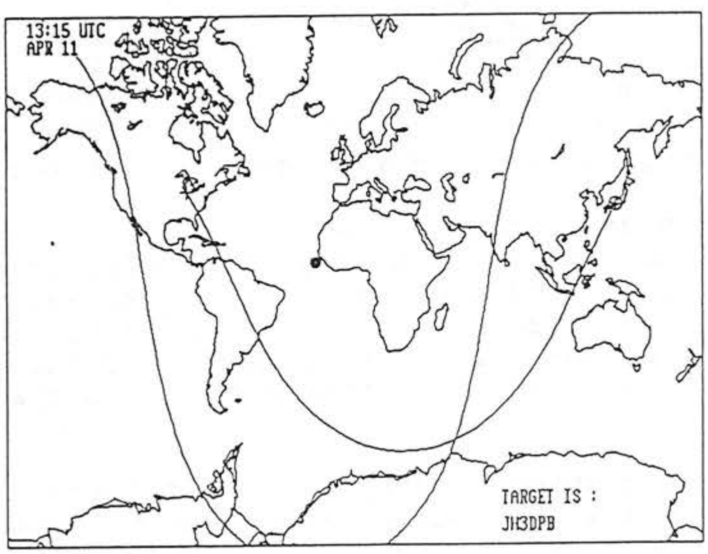


Figure 12 - Long-path geometry at the end of the 10 meter contact

Noise -

The previous discussion dealt with two of the three factors which influence long-path propagation - MUFs and signal strengths. But another one, noise, has to be included now to complete the discussion. In that regard, note should be made of the various types of noise and their frequency dependence which results from ionospheric propagation.

Noise can be of local origin or man-made, of atmospheric origin as well as from the sun or the radio galaxy overhead. Noise, of course, is propagated like any other type of radio signal so it is influenced by ionospheric conditions due to the level of solar activity. Man-made noise is localized around centers of human population and varies largely with the time of the working-day. Atmospheric noise is generated by electrical storms and moves with that activity as the seasons change. A glimpse of one geographical distribution of atmospheric noise is shown in **Figure 13** from Davies (1990).

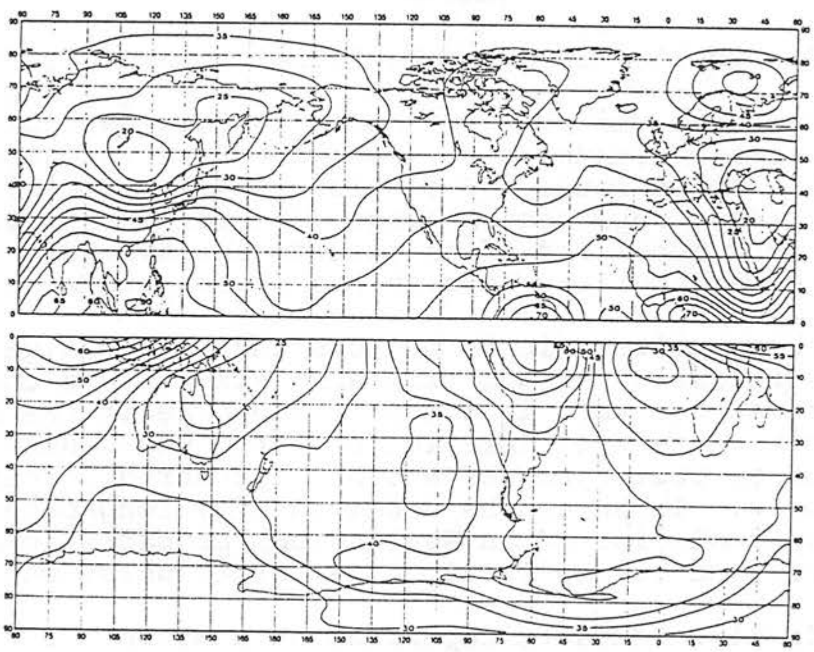


Figure 13 - World map of atmospheric noise (winter, 1200-1600 LT)

Whatever the source, noise is propagated and thus the low end of its spectrum is contained within the lower ionosphere while the high end of the spectrum may penetrate the F-region and be lost into space. That implies a high-frequency cut-off in the noise spectrum, shown in **Figure 14** from Davies (1990). So the 10 meter band is relatively free of propagated noise while the 160 meter band is at the mercy of it, only showing some improvement toward dawn when ionospheric absorption cuts off noise coming from the easterly direction.

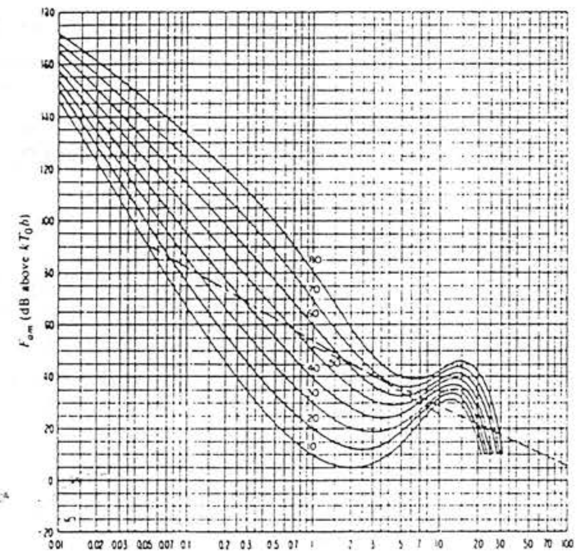


Figure 14 - Probability of atmospheric noise in decile intervals.

Given those remarks, when it comes to long-path DXing, it is clear that success depends on signals which are readable, with an adequate signal/noise ratio. The noise surveys summarized in the figures cited above represent average conditions but man-made noise can be very local and often exceeds the averages that were shown; that is particularly true on the lowest bands.

Beyond those points, it is obvious that antenna gain is very important for readable signals from a DX station and the receiver site is important too when it comes to the type of the background noise. In that connection, predictions from the IONCAP program use noise data on four types of sites - industrial, residential, rural and remote. It should be noted that my long-path study was carried out on small island in Washington, probably something between a rural and remote location as far as noise was concerned.

With effective contacts depending on a minimum S/N ratio and the separate factors which affect both signal and noise, it should be fairly clear that the "reach" of signals from a transmitter depend on more than just transmitter power and antenna. But no mention has been made of the type of ionospheric propagation; that is yet another factor which should be considered, especially with regard to the band in use. In that connection, propagation depends on three different frequencies beside the operating frequency F - the plasma frequency Fn, the electron-neutral collision frequency Fc already mentioned with regard to signal absorption and the electron gyro-frequency Fb in the local geomagnetic field.

The plasma frequency is related to the local electron density and gives the ionospheric penetration frequency for signals to reach the given altitude at vertical incidence while the gyro-frequency is the frequency of gyration of ionospheric electrons around the magnetic field lines and depends on the local field.

At the top of the HF spectrum, the operating frequency is large compared to all three frequencies and oblique propagation is then determined by MUFs or the plasma frequency at the peak of the F-layer. For the transition bands, the operating frequency is comparable to the highest plasma frequencies of the ionosphere, the same is true for the collision frequency but the operating frequency is still large compared to the electron gyro-frequency. So MUFs and ionospheric absorption are both important on the transition bands but magneto-ionic effects have not shown up yet.

But at the low end of the amateur spectrum, the plasma frequency is large compared to the operating frequency, while the electron collision and gyro-frequencies are comparable to it. That removes MUFs from consideration, making absorption much more important. Further, with operating frequencies in the same range as the electron gyro-fequency, propagation changes over from linearly polarized waves to the magneto-ionic modes with two elliptically polarized waves, the ordinary or O-wave and the extra-ordinary or X-wave. In addition, those two waves are refracted and absorbed at very different rates, affecting long-distance propagation of signals.

Low-Frequency Propagation -

Long-path propagation has been known for decades but those contacts were made mainly in the upper part of the amateur radio spectrum. Thus, in that range, MUFs were important and at any given time, they depended on the phase of the solar cycle. Ionospheric absorption was not a large factor and considerable interest was shown in signal refraction which yielded gray line propagation in darkness near the terminator. As noted earlier, both those physical processes vary roughly as the square of the wavelength so not only was wave absorption weak at the highest frequencies but so was the lateral deviation or skewing of signals in the vicinity of the terminator. Thus, great-circle paths were treated as though they represented actual ray paths and the definition of "long-path propagation" involved going beyond the 20,000 km mark on the oppositely-directed great-circle path.

Going down to the low-frequency end of the amateur spectrum, the 160 meter band, the wavelength change makes absorption and refraction about 250 times greater than on the 10 meter band. So absorption and lateral deviation of signal paths can no longer be ignored there. The greater absorption alone forces operations into times when the path of interest is in darkness, with very great implications for long-path propagation. But that also forces a change in the definition of long-path propagation, moving it away from ray paths based on the great-circles used before. Let me explain using the Heard Island DXpedition in 1997.

From that operation, a detailed examination (Brown, 1997) of the logs showed that large number of classical LP contacts, all beyond 20,000 km distance, were made on 40 meters, a few on 80 meters and none on 160 meters. The level of solar activity was such that sufficient ionization was present in the F-region to support ionospheric refraction on the low bands. Because of greater absorption on those frequencies, the distances varied for the lengths of ends of paths extending beyond the terminator, out into sunlight. On the first two bands the lengths of the sections in sunlight became smaller, at most something like a F-hop, 1,500 km on 40 meters, and an E-hop, 750 km on 80 meters. The situation on 160 meters was unique and deserves a discussion of its own.

The 160 meter operations were conducted in darkness and ended at dawn on Heard Island. Contacts with North America began when the sunset terminator crossed the Atlantic Ocean and reached the coast of the USA, swept westward and continued until sunrise at Heard Island. So at that time, the great-circle for the sunset terminator reached the antipodal point in western Canada. That was for signals launched to the west from Heard Island.

Turning to signals launched to the east from Heard Island, those ray paths went toward the West Coast of North America. So contacts in the western part of the USA began at sunset on Heard Island, with the sunrise terminator moving westward from the antipodal point in western Canada for a short period of time and contacts ended when it finally reached the Pacific Ocean.

As a result, there was a "dead zone" between the sunset and sunrise terminators in North America, shown in **Figure 15** from Brown (1997). Ray paths from Heard Island could not get into that large area without being exposed to some sunlight between sunrise and sunset at Heard Island. Because of the heavy ionospheric absorption on 160 meters, no contacts were made with stations in that region. The distances from Heard Island to the region were quite long but did not come up to the 20,000 km necessary for a consideration as a classical long-path contact; that would require reaching some location NE-NW of the antipode in Canada. In any event, the dead zone covering a third of the area of the USA speaks to the power of ionospheric absorption and its role in limiting signal propagation on the 160 meter band.

It should be noted that no tally or census was taken of 160 meter operators within the "dead zone". Certainly it was not as high as on the East Coast of North America which accounted for most of the 160 meter contacts with Heard Island. But there were enough operators listening each day for signals from VK0IR to say that propagation did not reach into the region.

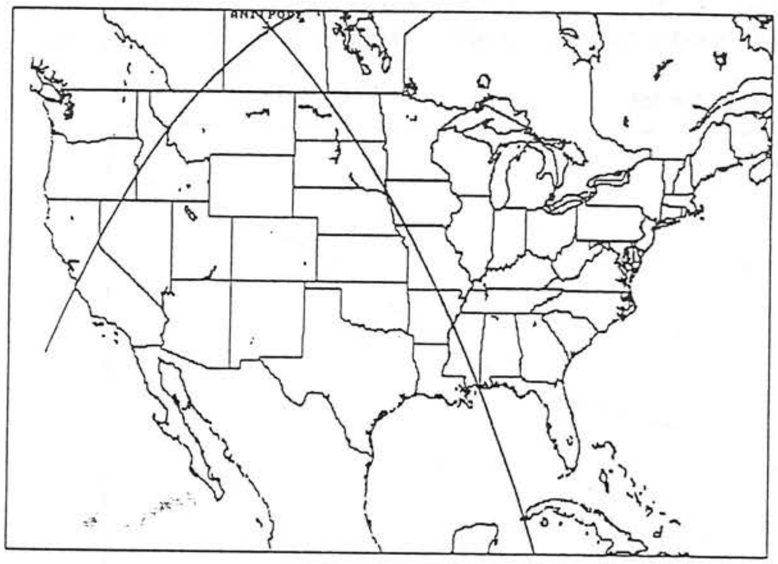


Figure 15 - Map showing 160 meter "dead zone" for VK0IR signals.

Signals entering the region would have to pass through some sunlight at Heard Island, like found on the 80 and 40 meter long-path contacts. So the data can be used to look at the "reach" of signals on 160 meters, their containment in the dark hemisphere that is surrounded by the terminator, as in **Figure 4**, and to discuss the question of whether classical long-path propagation, signals going beyond halfway around the earth, is even possible on that band. In doing so, attention focuses on signal absorption and the fact that radio waves are attenuated exponentially instead of having a fixed range in the ionosphere, like the case for nuclear particles of a given kinetic energy. But the "dead zone" found with the VK0IR DXpedition shows that exponential absorption can give the appearance of a finite range to signal propagation.

Thus, it is of interest to look at attenuation in a quantitative manner as the ionization in the illuminated region beyond the terminator will be sensitive to solar activity. The illuminated region was near Heard Island but since the terminator is a general feature of the ionosphere, it can be examined for its effects on signal attenuation at any convenient location.

In that regard, trial calculations were made using the IONCAP program, with 1.8 MHz signals incident perpendicularly on the terminator. The change in signal strength in going some 250 km across the terminator from darkness into sunlight or vice-versa varied according to sunspot number, shown in **Figure 16**. The Heard Island DXpedition was carried out at solar minimum so calculation of the attenuation shows a loss of 4 S-units in signal strength in crossing 250 km of illuminated region at an angle of 90 degrees with the terminator. For other angles, the number of absorbing electrons encountered increase by the obliquity factor, the secant of the angle between the ray and the normal to the terminator, increasing signal absorption and lowering S/N ratio accordingly.

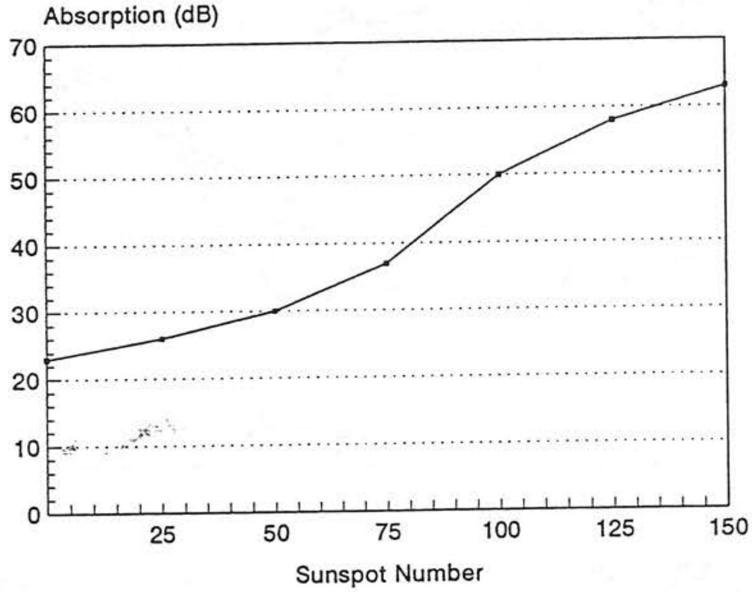


Figure 16 - Absorption of 1.8 MHz signals across the terminator.

Those remarks deal with additional absorption at an end of the path but do not touch on the absolute value of the signal strength that would be involved in reaching the edge of the dark hemisphere. That hemisphere is surrounded by the terminator and whatever the path, ionospheric refraction of any signal by the terminator will be away from the region of greater ionization and have an inward component back into the dark hemisphere. That circumstance was shown in **Figure 4** in the first chapter.

So it is impossible for a ray path to originate in the dark hemisphere and reach a location 20,000 km distant by ionospheric refraction without leaving the region of darkness or passing through some sunlight. As a result, for a classical long-path contact to be made, there must be enough signal strength left over on leaving the far edge of the dark region so as to overcome attenuation on crossing the terminator and still meet the S/N threshhold for readable signals at the terminus. The role of propagation modes on this point will be discussed next.

Chapter III-

Propagation Modes -

The previous chapters started with those classical long-path contacts where ionospheric refraction was the process in control of the ray advance and distances were to locations beyond 20,000 km from the point of origin. Such paths can be represented by great-circles to some approximation and displayed by means of map projections. A high-band LP contact with Japan on 10 meters was shown by the Mercator projection in **Figure 11** while a transition band LP contact with Norway on 20 meters shown by the azimuthal equidistant projection in **Figure 10**. Note that in **Figure 10** the ray path first goes from the point of origin to the antipode, given by the circle at the outer edge of the diagram, and then from the opposite side of the circle to the far LP terminus.

The question whether there is meaning to classical LP contacts on low bands remains to be discussed and no diagram will be given here. But there are other ways beside refraction which could propagate signals to beyond a distance of 20,000 km; those include reflection and scattering, as discussed by Davies (1990).

Reflections usually take place from electron bombardment at high latitudes during auroral displays and geomagnetic storms, adding the reflected path length to the refracted length reaching auroral latitudes. That would more likely apply to signals in the higher frequencies where absorption is less of a problem. Next, scattering would apply more to signals in the low frequency range and be associated with structured regions of the lower ionosphere, perhaps due to the influence of weather systems in the winter months (Brown, 2000). That can be the case as neutral particles far outnumber positive ions and electrons in the ionosphere and the high collision rate between neutrals and ions at the lower altitudes. Thus, neutrals will carry ions with them in their motions, giving structure to the ionosphere and scattering radiation in directions other than the forward direction, which would be the case for a smooth ionosphere.

Reflections are often in one dominant direction so the addition of those path lengths give a fairly clear result. That is in contrast with scattering where a wide range of directions can be involved with re-radiation, making path lengths difficult to determine and compare against the 20,000 km benchmark for long-path propagation around the earth. In both cases the signal may be returned back into the dark hemisphere, making the position of the final terminus quite different from that at direct distances.

Magneto-ionic effects -

The previous discussion involved features of propagation during disturbed conditions, of magnetic or atmospheric origin. Another feature of low-band propagation is added from magneto-ionic propagation effects which appear even in quiet conditions because the operating frequency is comparable to electron gyro-frequencies in the earth's field. Of the two propagation modes that develop, the X-mode is heavily absorbed, dissipating quickly whatever RF power is involved, and propagation depends on the power remaining in the O-mode.

One can explore such propagation on the 160 meter band by using the PropLab Pro program; it gives ray-tracings for magneto-ionic propagation in the O-mode and shows several interesting features of that mode. One important feature is signal ducting, a very efficient mode in which RF is propagated forward between the E-layer and the lower F-layer, without the waves having ground reflections and corresponding signal losses.

Signal ducting (Brown, 1998a) takes place by the vertical excursions of signals in the electron density valley which develops above the E-region at night, as shown in **Figure 17**. As such, it represents another propagation mode, in addition to E-, F- and long E-F hops that are present on 160 meters. The E-F hops are the building blocks for ducted signals, ducting essentially being propagation where several E-F hops, like in **Figure 18**, occur in succession.

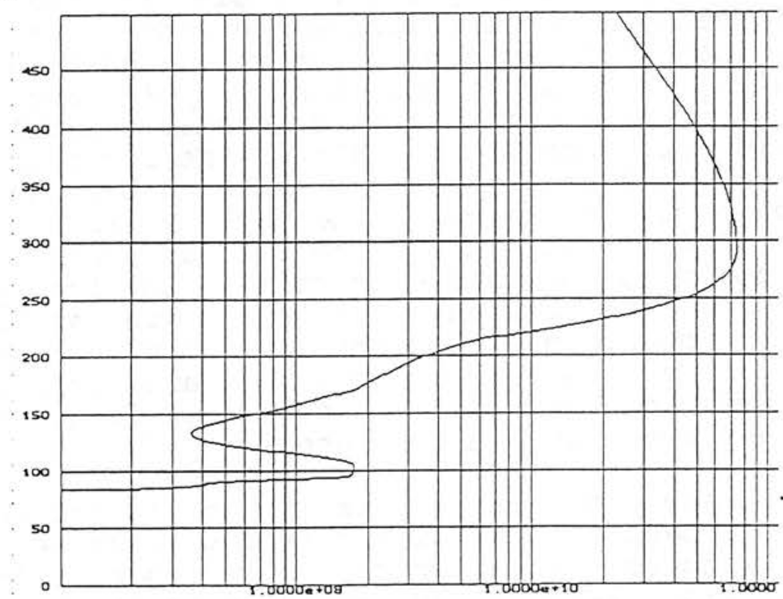


Figure 17 - Night-time valley in the electron density profile.

The distinguishing feature of those hops is they occur at low radiation angles and start when a signal reaches E-layer heights and the wave is advancing almost horizontally. But they do rise above the night-time E-layer, reach a peak altitude within the lower F-region and then go downward again. Their subsequent path depends on their angle on return to the peak of the E-layer, either rising again to another peak or returning to ground.

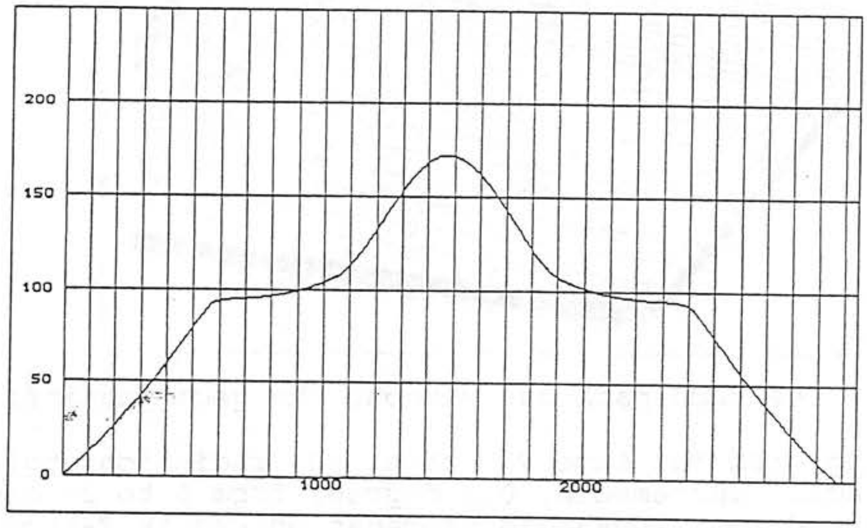


Figure 18 - A long E-F hop, 3,000 km in length.

An example of ducting is shown in **Figure 19**, for a path going north from the mid-Pacific to British Columbia (VE7). That figure was obtained by using PropLab Pro program which has the earth's field factored into the refraction calculations. But the magnetic field can be removed from the calculations and the result is shown in **Figure 20**, with ducting no longer evident. Thus, the effect of the earth's field is to reduce the degree of downward refraction and instead of hops which peak near the limit of Pedersen Rays at the E-layer, downward refraction is less and signals go on into the F-region to start ducting.

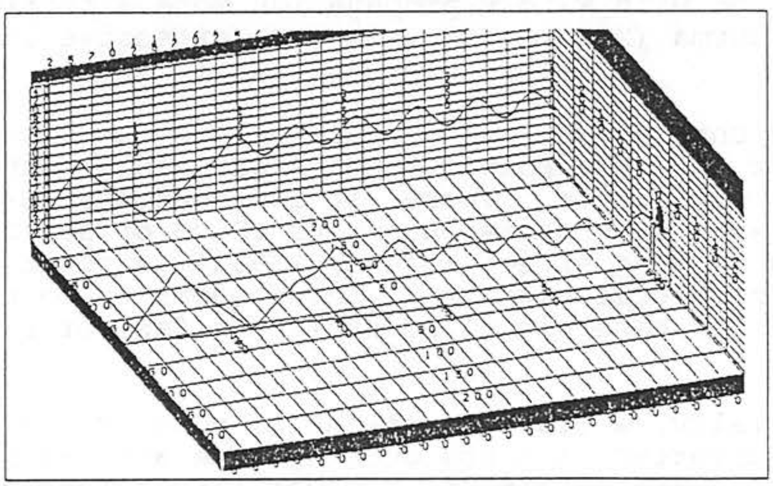


Figure 19 - A ducted path from the mid-Pacific to VE7.

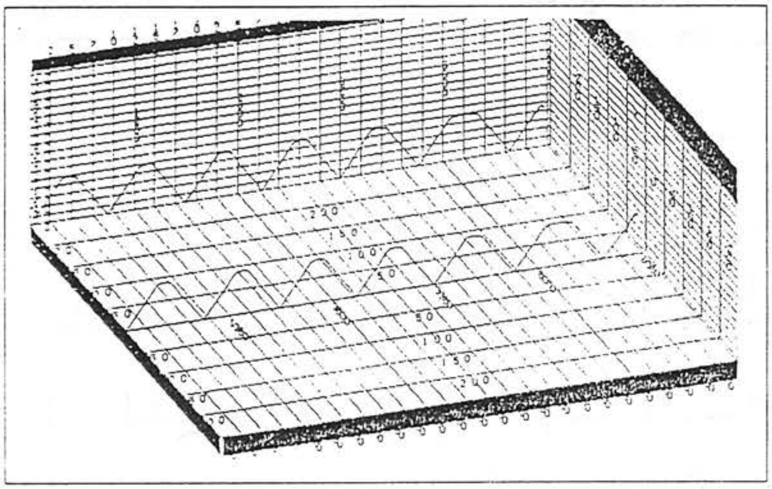


Figure 20 - The same path but without the geomagnetic field.

Working with the same VE7 path, the radiation angle was raised in small increments, 0.1 degree, from 5 to 25 degrees. The results showed that low-angle propagation was by E-hops but at a certain point, E-F hops appeared, then fully ducted signals began about 30% of the time and ended only at the high-angle limit when the signals went over into F-hops.

Those circumstances held for a path going from low- to high-magnetic latitudes, low-latitudes where the earth's field is nearly horizontal to high-latitudes where the field is closer to being perpendicular to the earth's surface, the polar condition. But for paths going the opposite direction, from high-latitudes to low-latitudes, the development of ducting was less frequent, about 10% of the radiation angles between 7 and 25 degrees. In that regard, this result from ray-tracing calculations is much like actual experience on the 160 meter band, there being an asymmetry in propagation with W-to-E propagation more effective that E-to-W, e.g., from Burma (XZ) to USA (W6) more effective than USA (W6) to Burma (XZ).

Beyond that point, the results on ducting from magneto-ionic effects bear on other points, one of particular interest, the dawn enhancement of signals. There, it is found that W-to-E signals show enhancements on occasion, up to 12 dB or so, before dawn. The explanation of that effect (Brown, 1998a) is found in the properties of ducted signals as there seems to be no other effect which could increase signal power in the face of rising absorption at dawn.

Essentially, a fraction of the RF power radiated by an antenna is diverted into the ducting mode and overflies ground stations while the remaining RF power is propagated by normal modes, E-F and F-hops. In the course of time, as the terminator moves from east to west, the ducted signals are finally brought down by that feature or some sort of irregularity in the ionosphere, giving a signal enhancement by adding the power of ducted signals to that propagated by normal E-F and F-hops. A two-year study of dawn enhancements (Hall-Patch, 1999) using signals from broadcast stations near the 160 meter band showed enhancements generally occur when signals encounter tilts in the F-region associated with the advance of the sunrise terminator. That also supports the ducting hypothesis but there is evidence that not all signals are ducted nor survive until reaching the dawn tilts of the F-region.

Beyond that, by not suffering ground reflections, ducting provides a means of bringing a larger fraction of the radiated power from an antenna to distant regions than would be possible by conventional F-hops. The latter do suffer losses due to ground reflections and absorption in the remnants of the D-region present at night. But with ducting found at a multiplicity of radiation angles, it is difficult to determine the actual division of power between the two types of modes.

Thus, while the propagation of signal power by conventional modes with ground losses can be calculated by using refractom in the IONCAP program, the actual case which includes the possibility of ducting leads to an ambiguity in the power reaching any point that is distant from the transmitter. That leads to uncertainty as to which signal mode is dominant, as a function of distance from the transmitter. Thus, with ground and D-region losses on F-hops, the "reach" of propagation by F-hops may be limited by noise, antennas and the sensitivity of receivers, with ducting then required for signals to reach beyond that distance. In that regard, the signal calculations in Appendix I suggest limits of propagation by F-hops, depending on details of the altitude profile and rates of electron-neutral collisions.

Power Coupling -

Earlier, it was noted that wave propagation changes in going between the high and low ends of the amateur spectrum. That is due to the fact the operating frequency changes, from being large compared to the gyro-frequency of electrons in the earth's field to being comparable to it. That change in propagation means that RF waves go from having simple linear polarization to two types of elliptical polarization, O- and X-modes, with opposite senses of rotation of the electric field vector.

Theoretically, that idea emerged by adding the geomagnetic force on ionospheric electrons when the index of refraction of the ionosphere is derived. The theory was due to Appleton (1925) and on the direction of wave propagation relative to the earth's field. As a result, there are two extremes of actual wave propagation, parallel to the field, as possible at the magnetic equator where the field is horizontal, and perpendicular to the field, as at the two magnetic poles where the field is vertical. Those two extremes are termed the longitudinal and transverse modes and clearly, with long-distance propagation, it is possible that the mode of signal propagation will range between those extremes as signals advance through the field.

But waves enter and leave the ionosphere so there will be both entrance and exit conditions, the ionospheric modes at where the electron density goes to zero at the bottom of the ionosphere. Those polarizations will depend on the local magnetic field so propagation may be broken down into three parts, the limiting polarizations (Davies, 1990) at entrance and exit from the ionosphere as well as the change in magneto-ionic modes as waves go across the ionosphere between the sites with those limits.

The limiting polarizations have meaning particularly when the wave polarization of transmitting or receiving antennas are considered. Most often, on the low bands, transmitting antennas have vertical polarization, because horizontal antennas would have to be very high to be effective and vertical antennas have the smaller "footprint". So the question becomes one of comparing the polarization of waves leaving or reaching an antenna system and the limiting polarization at the bottom of the ionosphere; that determines the degree of polarization mismatch and the power transfer to and from the ionosphere with the antennas.

The actual problem for real paths is rather complicated as a map of the earth's magnetic field is required to find limiting polarizations at transmitter and receiver sites. Then wave directions must be related to the local magnetic field to separate O-modes from X-modes, the latter suffering so much absorption as to be taken out of the propagation picture. So O-modes must then be resolved into their linear components to obtain the fraction of power which is received by the polarized antenna or sent up into the ionosphere.

This problem was worked out by BBC engineers over 30 years ago (Phillips and Knight, 1965) but their results, as applied to the 160 meter band, have been summarized (Brown, 1999) and then considered for the equatorial case, relevant to DXpeditions and contesting (Brown, 1998b), as well as mid-latitude situations in the USA. For the low latitudes, the magnetic field is in the horizontal, N-S direction so a horizontal antenna would produce radiation where the E-field is horizontal too. That being the case, if the antenna were laid out in the N-S direction, the radiation would have its E-field in that direction and, thus, parallel to the geomagnetic field. That means the ionospheric electrons could be excited in N-S motions, parallel to the field and without any opposition from magnetic interactions, and the RF power would then be completely coupled from the horizontal antenna into the ionosphere and propagated in E-W directions as an O-wave.

On the other hand, the X-mode is excited when the electric field is perpendicular to the magnetic field, as for low-angle E-W propagation from a vertical antenna at the equator. As a result, an opposing force by the local magnetic field would hinder the motions of ionospheric electrons and power coupling radiation of the X-mode would be reduced to zero. This is shown for radiation in the E-W and other directions in **Figure 21**, using the radiation pattern of a vertical antenna, for a location at Togo, Africa (7S, 1E). By the same token, the power coupling for the E-W and other directions is shown in **Figure 22**, using the low-angle radiation pattern for a horizontal antenna running N-S at Togo, Africa.

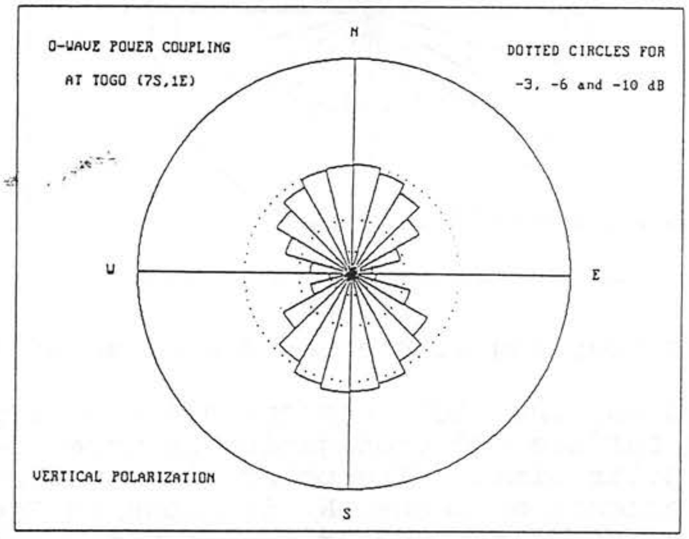


Figure 21 - Power coupling with a vertical antenna.

For propagation in the N-S direction, along the horizontal field lines at the equator, the magneto-ionic theory gives two circularly-polarized waves for the O- and X-modes. Looking north, in the direction the field vector points, the X-mode is the one with right-handed rotation while the O-mode has left-handed rotation. The O-wave can be resolved further into two linear-polarizations that are 90 degrees out of phase and the coupling of those waves are the same with vertical antennas and horizontal antennas running in the E-W direction.

Obviously, this is a complicated matter and best studied by going to reference material. For low latitudes, it can be put in summary by saying that vertical antennas perform best in the N-S direction, parallel to the field, and worst in the E-W direction. If propagation in that direction is of interest, a horizontal antenna running N-S is the best choice.

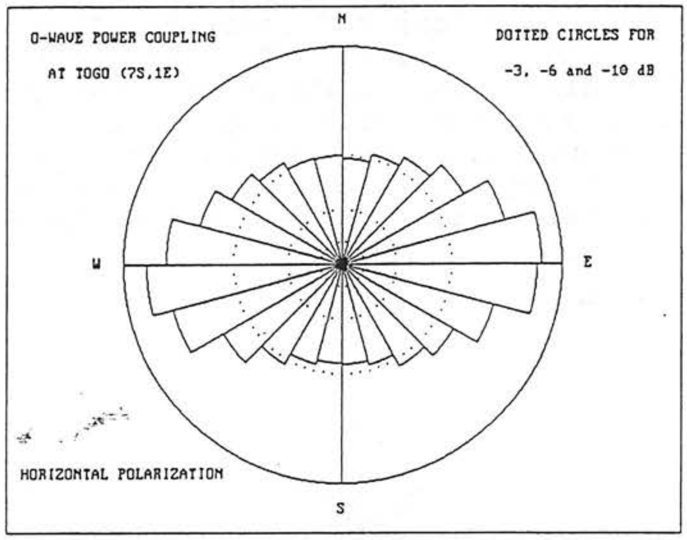


Figure 22 - Power coupling with a horizontal antenna

For higher latitudes, the field direction has a large dip angle with the earth's surface and propagation is more like that expected at the polar limit. The polar diagram for power coupling with a vertical antenna at Omaha, NE is shown in **Figure 23**. As a result, the figure shows that power coupling for radiation which leaves an antenna on a poleward path is greater by about 2 dB than on an equatorward path. Similar results are obtained at locations on the East and West Coasts of the USA. Power coupling at other locations can be evaluated by using the methods of Phillips and Knight (1965).

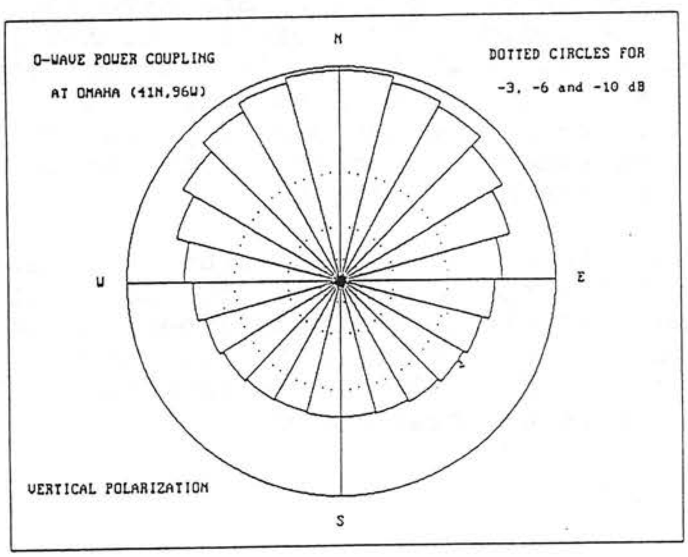


Figure 23 - Power coupling with a vertical antenna at Omaha, NE

Chapter IV -

Long-Distances and Long-Path Propagation-

The previous discussion of magneto-ionic theory is but a brief summary of some features which are well-known and have been accepted for over 70 years in scientific and radio engineering circles. But there has been little study or understanding of them by amateur radio operators, mainly due to the fact that the field is in advanced science and engineering courses at the university level. Moreover, there has been little experimentation in the area of propagation, with the result magneto-ionic effects are not recognized as part of the amateur radio experience when it comes to propagation. (The beautiful, patient work of VE7DXR on dawn enhancements is a notable exception.)

But there are a number of recurrent themes about propagation on the 160 meter band which are heard too often to be ignored - DXing requires common darkness, DXing is the best around dawn, occasionally DX signals are very strong, W-to-E paths are more effective, there is often a dawn enhancement of signal strength, signals change from low-angle to high-angle as dawn approaches, to give a few. Those all have a magneto-ionic foundation, with absorption and signal ducting playing the important roles. But if any one is to be singled out as showing the presence of a magneto-ionic effect, ducting, it is the dawn enhancemant of signals. An example of a dawn enhancement from the study by Hall-Patch (1999) is found in **Figure 24**.

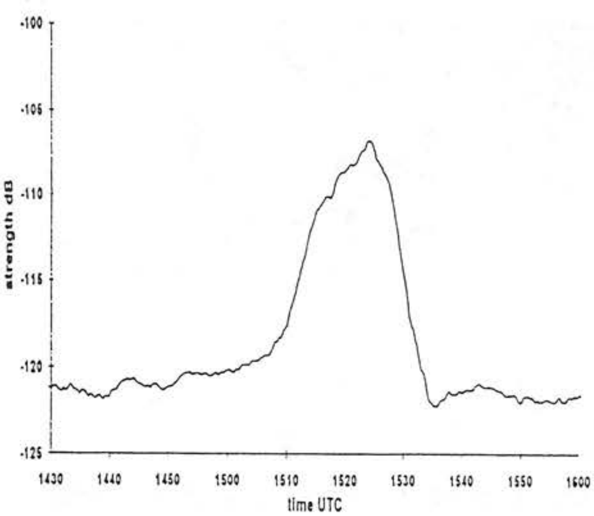


Figure 24 - A dawn enhancement of HLAZ signals on 1566 kHz.

That shows the signal trace for a Korean broadcast station on 1566 kHz and a strong enhancement peaking at 1524 UTC on November 30, 1998. As remarked earlier, the interpretation is that dawn enhancements represent the release of signal energy ducted between the E- and lower F-regions; it is refracted downward to ground level on encountering the tilt of the F-region around dawn, adding ducted energy to that propagated as F-hops. That interpretation seems inescapable. Putting it simply, how else can DX signals increase in strength in the face of a rising sun and increasing ionospheric absorption than by the release of ducted signal power?

As for long-path propagation, it is well-known in amateur radio circles and has been pursued on the high bands when solar activity peaks in the eleven year cycles and on the lower bands in the winter when there is more darkness on frequently used paths. So there are those who approach long-path DXing as a sport on the usual HF bands and others who search for it on the lowest band, 160 meters. But there are aspects of signal ducting in there; we just have to look hard to find them.

But there is one, outstanding difference in results at the two ends of the amateur spectrum - long-path distances can be attained on HF between stations which are both located in the sunlit hemisphere, as between my QTH and Angola on 14 MHz in **Figure 9**. Other examples were found on 7 MHz and 3.5 MHz in contacts made during the Heard Island DXpedition and one example on 3.5 MHZ is shown in **Figure 25**. That contact was made shortly after sunrise on Heard Island and before sunset in California, with the two ends of the path in sunlight. That is not the case for claims of long-path distances down on the 160 meter band; both stations are always within the dark hemisphere and with "common darkness" regarded as an essential for DXing on 160 meters.

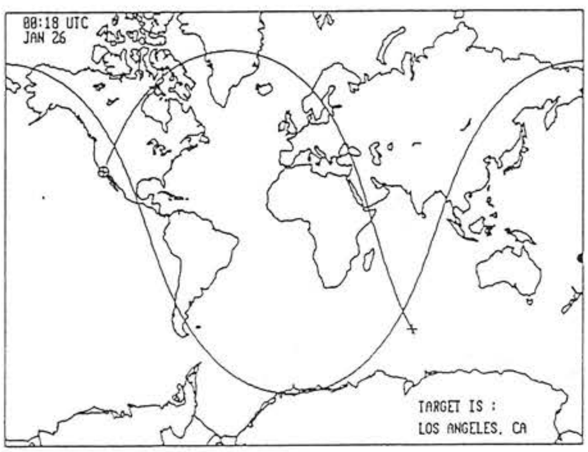


Figure 25 - **Long-path on 3.5 MHz from Heard Island to California.**

Statistical Long-Path Studies-

One way to learn about long-path propagation is to just sit down and do it, as best one can by getting on the air and building up statistics. My own study started that way, stimulated by a contact with a SM5. But others have done it, in their own way and on their own band. A good example is the work of Carl, K9LA, on 10 meters. He was spurred on by a long-path contact with VS6DO during a DX phone contest in '86. One thing led to another and in '89 he began working JAs on a regular basis via long-path from his QTH in the Midwest. That involved keeping schedules too, looking at the duration of long-path contacts.

But somewhere along the line, he got lucky - meeting K2ARO who had a log full of JA and VK long-path contacts on 10 meters, from early 1979 to 1993. The long-path from K2ARO to JAs as well as VK6s was simple and direct with essentially the same antenna orientation, making the study quite interesting. With the amount of K2ARO's log data, it was possible to find the seasonal aspects of long-path openings on 10 meters as well as their dependence on solar activity. Both are indicated in **Figure 26** but more detail is found in the article (Luetzelschwab, 1995) that summarizes the extensive observational material.

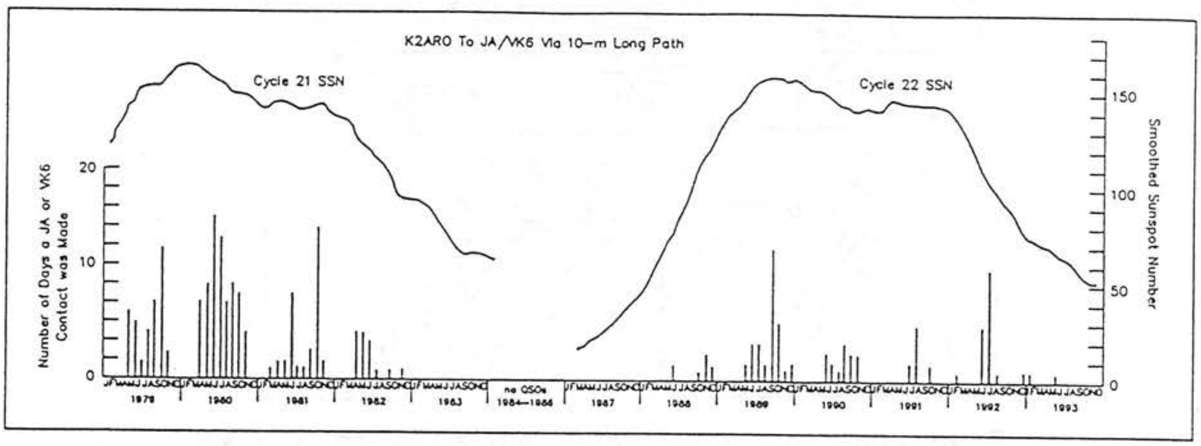


Figure 26 - K2ARO's data; note correlation with sunspot number.

Another way of looking at long-distance propagation and cases of long-path is to review the logs from DXpeditions. It has been something of personal interest of mine for several years and the following logs have been reviewed:

VK9XY, Christmas Island; VK9CR, Cocos Island; XZ1N, Burma; S21XX, Bangladesh; VK0IR, Heard Island; P29XX, New Guinea; 8Q7AA, Maldives; ZL7DX, Chatham Island as well as the recent DXpedition, XZ0A, to Burma.

Those DXpeditions were unique in that they provided data from point sources of radiation, covering a wide range of directions and bands but in a short period of time. Of particular interest were the contacts made on the 160 meter band but those differed considerably, with VK9XY and VK9CR only contacting a few stations. The rest of the DXpeditions had a good number of contacts on 160 meters but the "reach" of the DXpedition signals seemed limited, with contacts falling short of classical long-path and meager, at best, to one coast of the USA or the other because of local noise and effects on polar paths.

But the Heard Island situation was unique in that it ran into a seasonal "dead zone" covering about one-third of the USA and no 160 meter contacts were made within that region, only contacts to the east and west of it. That zone developed because of heavy absorption of 160 meter signals during hours of daylight at the transmitter site. For 80 meters, the situation was different, as shown in **Figure 27**, with a number of 80 meter long-path contacts within the dead zone because absorption is lower on 80 meters by about a factor of four, as shown earlier in **Figure 7**.

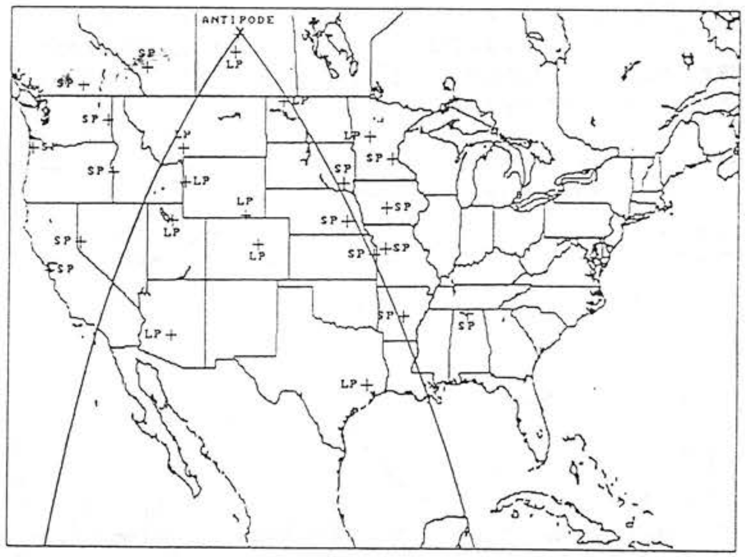


Figure 27 - Dead zone and long-path contacts on 3.5 MHz.

P29XX DXpedition to New Guinea was interesting in that it involved a large number of contacts but there was no possibility of making contacts close to the antipode as it is out in the Atlantic Ocean, as shown in **Figure 28**. In spite of that, the geographic distribution of contacts showed an interesting property of 160 meter propagation - a finite "reach" for 160 meter signals. Thus, signals leaving P29XX toward the west coast of the USA carried all the way to the East Coast, with contacts made all up and down the eastern seaboard. The far distance of contacts was about 14,500 km, all well and good for 80 meter and 160 meters.

On the other hand, signals leaving P29XX toward Europe were carried to the west coast of France on 80 meters but did not go beyond the western border of Germany on 160 meters, a distance of 14,400 km. So there was a finite "reach" on 160 meters, in spite of the fact there was no lack of 160 meter stations in western Europe ready to make contacts.

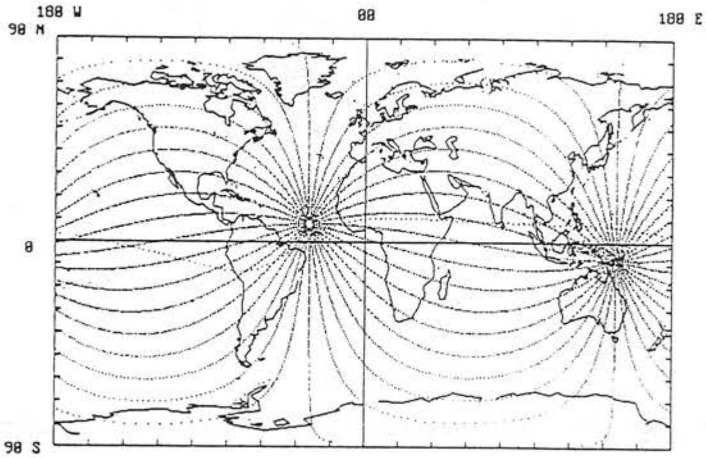


Figure 28 - Great-circle paths from P29XX in Papua, New Guinea.

The ZL7DK DXpedition to Chatham Island, New Zealand is even more interesting with regard to 160 meter propagation as its antipodal point was in southern France, some 100 km west of Marseille, as shown in **Figure 29**. While there was a "dead zone" at that time of year (Brown, 1998c), it was only about an area of 1,000 sq.km., shown in **Figure 30**, and much smaller than was the case during the VK0IR DXpedition.

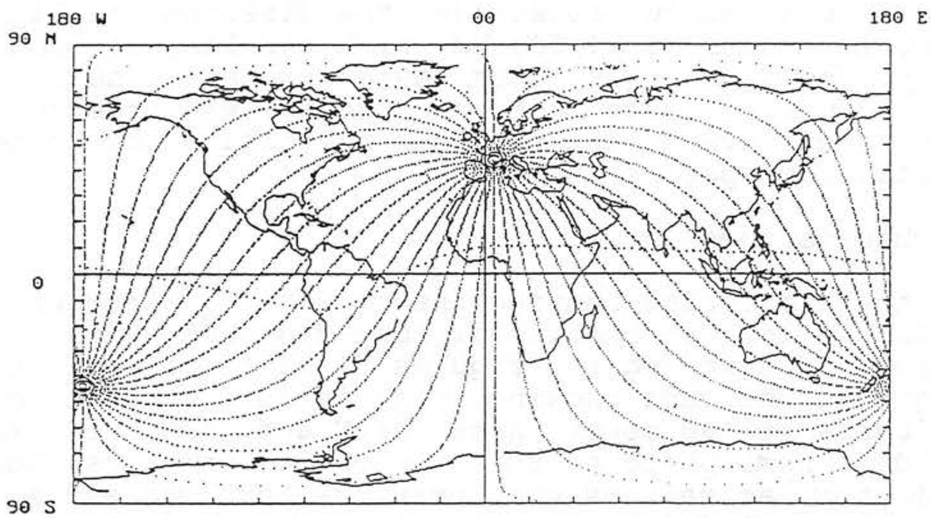


Figure 29 - Great-circles paths from Chatham Island, New Zealand.

It is of interest to note that contacts with Chatham Island were made during a period of magnetic quiet and with stations to the west and east of the dividing meridian through the antipodal point. Thus, signals sent to the east from Chatham Island reached as far as England and Ireland while signals sent west of Chatham Island reached western Europe. The distribution of 160 meter contacts shown in **Figure 30** shows a division along the meridian through the antipodal point, stations in Ireland and England contacted ZL7DK in the morning hours near dawn while a few hundred km to the east, contacts were made with ZL7DK in early evening.

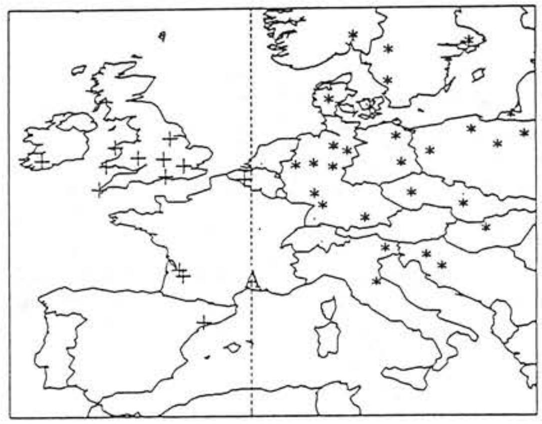


Figure 30 - Morning (+) and evening (*) contacts with ZL7DK.

In point of fact, the times of contacts differed by 13 hours for stations separated by as little as 200 km in E-W directions. But there weren't "cross over" or classical long-path contacts on 160 meters, with no stations in western Europe contacted in the morning hours nor stations in the U.K. region contacted during the evening hours. In fact, frustrations were often expressed when one group of stations heard the other group contacting Chatham Island but Chatham Island was not to be heard by the first group.

Looking at the various locations, the distances in **Figure 29** were somewhat in excess of 19,000 km, with the longest from Chatham Island to ON4UN's QTH. But there were still no long-path contacts on 160 meters. But just the opposite was true on 80 meters, with "cross overs" and contacts fulfilling the criterion for a classical long-path contact.

Individual Observations-

Beyond the statistics showing the results of DXpeditions, it is of interest to look at individual long-distance contacts made on 160 meters. In that regard, **Figures 31-33** are a collection of azimuthal equidistant maps showing long-distance contacts on 160 by two distinguished 160 meter DXers, W4ZV and K1ZM. The maps outline the dark hemisphere at the time of the contacts, bounded by the terminator, as well as the locations involved and a line showing the classical definition of a long-path contact for those locations.

The contacts are arranged chronologically by months in the winter seasons and the distances between the transmitter and receiver sites in that group ranged from 9,300 km (W0ZV-UA9UCO) to 14,600 km (K1ZM-9V1XQ). While the distances are not unusual, the contacts were out of the ordinary as apparent directions of the signals were from the SSW or SSE, depending on the time of day. In any event, the classical long-path shown in the figures goes many thousands of kilometers in sunlight and 160 meter signals never could have survived in those conditions.

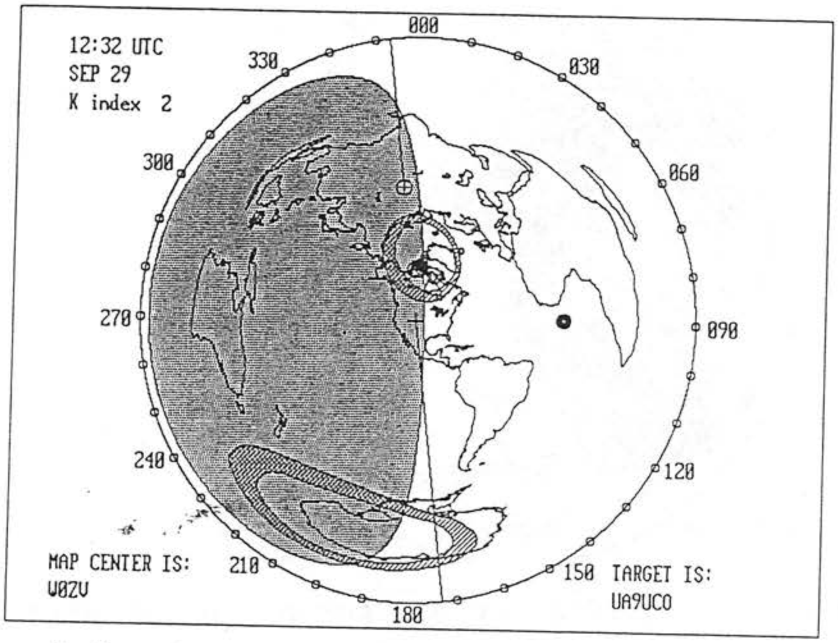


Figure 31 - Azimuthal equidistant map for contact with UA9UCO.

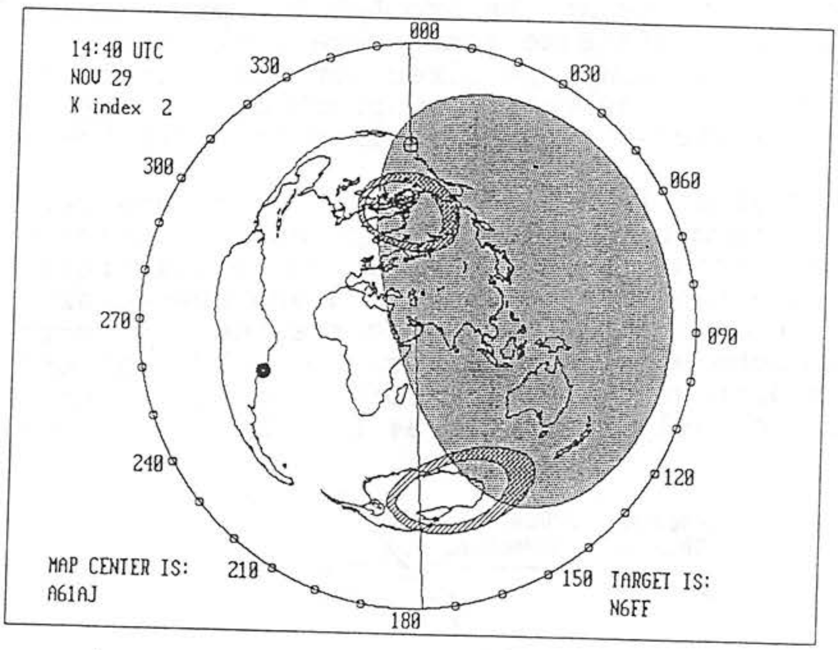


Figure 32 - Azimuthal equidistant map for contact with N6FF.

Thus, the question is how signals reached the station in the center of the maps, with apparent incoming directions from the SSW or SSE. The explanation offered by the DXers was that the paths were a form of long-path propagation, longer than short-path and skewed in direction, with the signals guided by the terminator. That explanation was offered almost a decade ago (Tippett, 1991) but has been challenged recently (Brown, 2000).

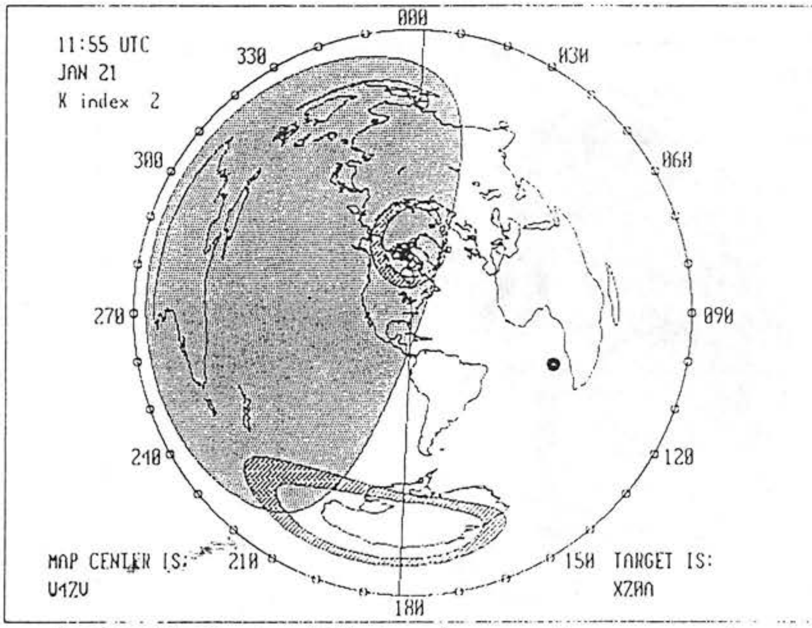


Figure 33 - Azimuthal equidistant map for a contact with XZ0A.

The counter argument is that the guidance path has not been verified by ray tracing using the PropLab Pro program and the current International Reference Ionosphere (IRI, 1990). At best the path is unstable in time and direction and instead of guidance, the path is either heavily absorbed as it approaches the terminator or is refracted away, back into the dark hemisphere.

Thus, the original interpretation neglected any refraction of signals along the terminator and the apparent direction of arrival gave the wrong direction for the path to the transmitter. In a sense, that is like the case in satellite and spacecraft tracking where the apparent directions must be corrected for refraction in the residual ionosphere overhead if tracking observations are to be used to yield data suitable for orbital calculations. This geometry is shown clearly in Figure 34 from Davies (1990).

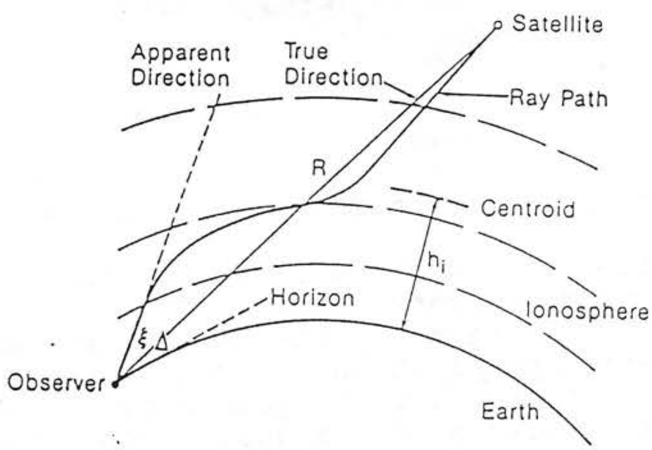


Figure 34 -Ray path between a satellite and ground station.

The 160 meter observations still stand, no doubt about it, so the real question is how the signals came to the receiver from apparent directions off to the SSW or SSE. The explanation (Brown, 2000) is that the incoming signals are really short-path signals that have been scattered by the ionosphere, the result of the neutral atmosphere coupling turbulence from winter weather fronts into the ionosphere. By way of justification, ozone data was presented showing the rise and fall of the ozone layer during winter; that is expected to affect the lower ionosphere by its turbulence as the collision frequency between neutral species and positive ions is very high.

Thus, positive ions and electrons are carried along with the neutral motions in the winter storms. That serves to reduce wave refraction and then substitutes scattering as the means of wave propagation. Since scattering gives radiation in a wide variety of directions, it seems likely that short-path signals to lower latitiudes were scattered back in direction to give the apparent incoming directions from the south.

That type of skewing is not all that common, with only a few events observed per year, but path directions can be changed far more often by reflections of waves off of ionized forms from auroral events (Luetzelschwab, 1999) or electron bombardment of the atmosphere during geomagnetic storms (Brown, 1998d). That is particularly the case during times of high solar and magnetic activity. Then, actual skewing depends how the waves pass by the ionized forms, from the lower latitudes as with European signals approaching the northern auroral zone, or from higher latitudes as with Scandinavian signals approaching the poleward limit of the expanded auroral zone during magnetic storms. In any event, signals are refracted horizontally away from regions of higher ionization, whether of auroral origin or due to the ionization gradient across the terminator.

Chapter V -

The Magnetosphere -

In the past decade, amateur radio circles have become more aware of how the view of the earth's magnetic field has changed with the exploration of space which started back in the '60s. Thus, the earth's field is no longer regarded as symmetrical like that from a bar magnet sitting deep in the earth. Instead, another topology has become known, with the geomagnetic field compressed on the side toward the sun and field lines trailing back, behind the earth on the opposite direction, as in **Figure** 35.

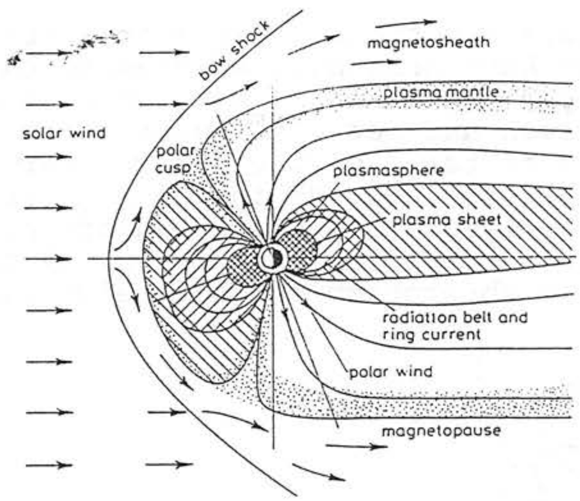


Figure 35 - Geomagnetic field lines in the magnetosphere.

Beyond that, it became apparent this distiortion of the field lines resulted from the impact of the solar wind on the outer field and was something that would vary with changes in the density and speed of protons that are blowing by the earth. But earlier, there were strong clues pointing in that direction from the dynamics of the aurora, geomagnetic field variations and effects on radio propagation. Indeed, as early as the late '20s, studies of radio propagation on commercial voice circuits across the Atlantic showed adverse effects as those forms of activity increased. In addition, in that era, the occurrence of "polar radio blackouts" was known but their origin was not apparent nor understood in scientific circles.

The transfer of that knowledge was slow but it finally did expand beyond the scientific community and reach amateur radio circles in the last decade, largely due to information from government research activities becoming available on the Internet. Thus, nowadays, one sees daily reports on solar and geophysical activity, complete with sunspot counts as well as various magnetic indices and ionospheric effects at the polar latitudes.

Perhaps the most concise way of looking at the matter and how it would affect long-distance propagation is by using azimuthal equidistant maps which carry projections of the auroral zone and polar cap on the earth's surface. That can be used to place radio paths in their positions relative to high latitude disturbances. The actual location, height and form of aurora were found in the early studies of auroral morphology and were first based on the long series of all-sky camera photographs made of the aurora. But the use of satellites now provides a very different approach, with observations of the energy brought to the earth's atmosphere by the influx of auroral electrons. Those records are valuable in making daily forecasts of auroral or magnetic activity,

But there are always fluctuations in statistical forecasts and it is worthwhile to know something of them so that exceptions to those forecasts can be understood. With that in mind, it should be noted the growth and decay of auroral activity on a given day are described in terms of the auroral forms and their variation with longitude and latitude in the night-time sector. Typically, around the early evening hours, aurora are narrow, quiet arcs at high altitudes and accompanied by little magnetic activity nor appreciable absorption of radio signals.

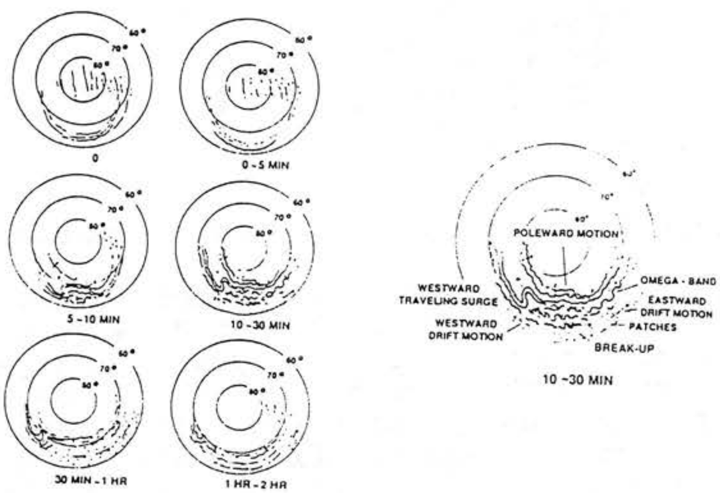


Figure 36 - A drawing showing the development of auroral forms.

The visible aurora is distributed along an oval-like curve and with an increase in auroral activity (Akasofu, 1964), the auroral oval expands poleward, extending the visible aurora to higher latitudes. The number of auroral arcs increases and there is also an expansion of the aurora to lower latitudes and to the east and west as well. In the midnight sector, the aurora becomes very active, breaking up into striated, rayed structures coming down to the 100 km level, illustrated in **Figure 36**.

The statistical side of propagation may be given by auroral maps showing the path in question, as in **Figures 37-40**. Those cover the range of geomagnetic activity from Kp=0 to Kp=9, in Kp steps of 3, and show a long-path from my QTH to South Africa. The path goes into the southern hemisphere and barely reaches the edge of the southern auroral zone for Kp=0. But for higher Kp-values, the auroral zone expands and the path would reach into the polar cap when Kp=6 and Kp=9.

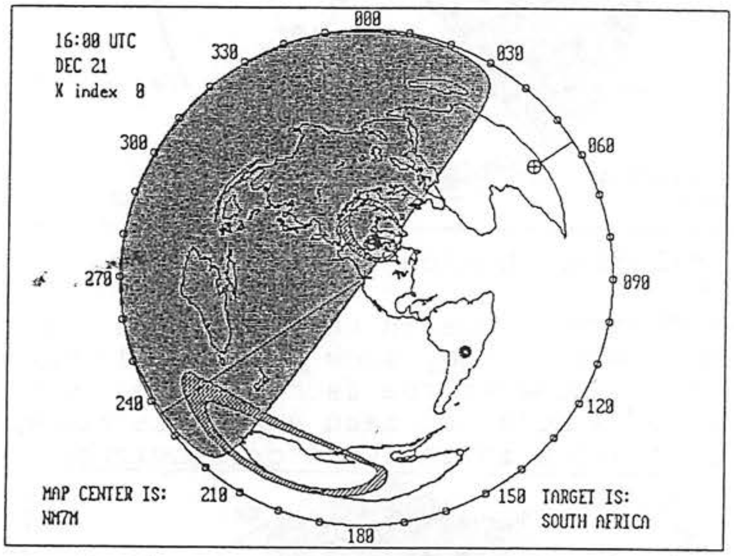


Figure 37 - Auroral distribution for Kp=0.

For signals going across the auroral zone, the amount of absorption depends on the number of free electrons encountered along the path and the height or geometry of the path. Skewing, on the other hand, depends on the electron density gradient and orientation of the signal path relative to the gradient.

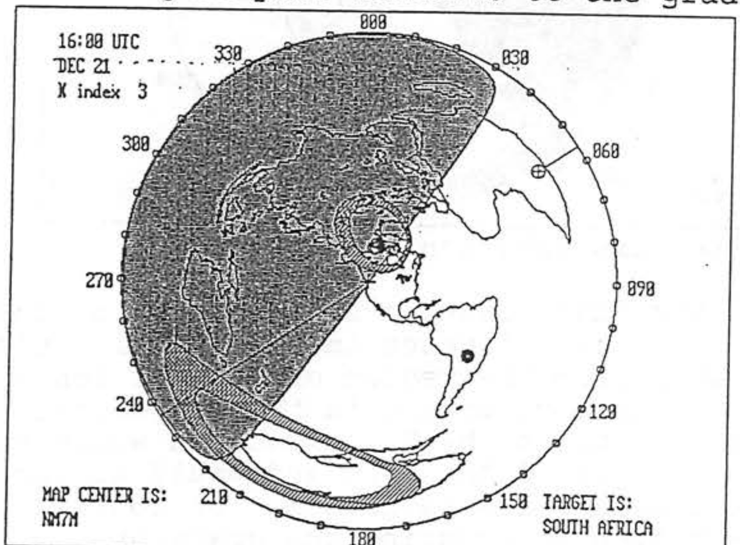


Figure 38 - Auroral distribution for Kp=3.

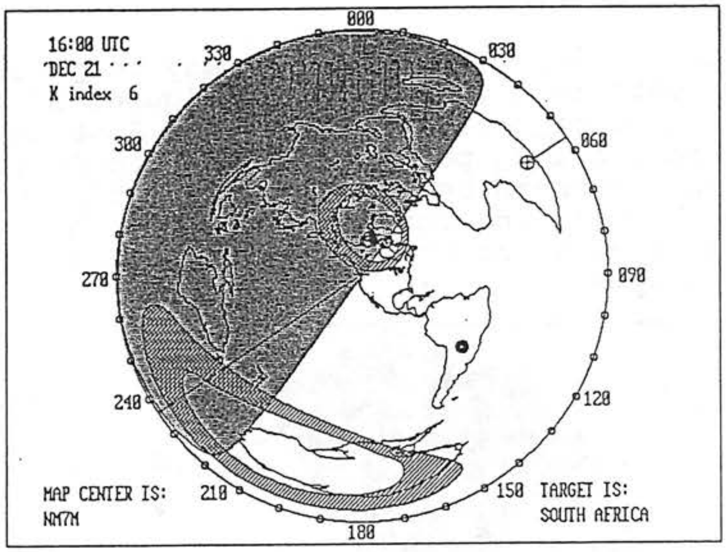


Figure 39 - Auroral distribution for Kp=6.

The auroral distributions in these figures are statistical summaries. In that sense, they show probable locations of auroral particle bombardment; however the fact that the distribution is shown to be continuous does not mean any instantaneous auroral influx is that continuous in latitude or longitude.

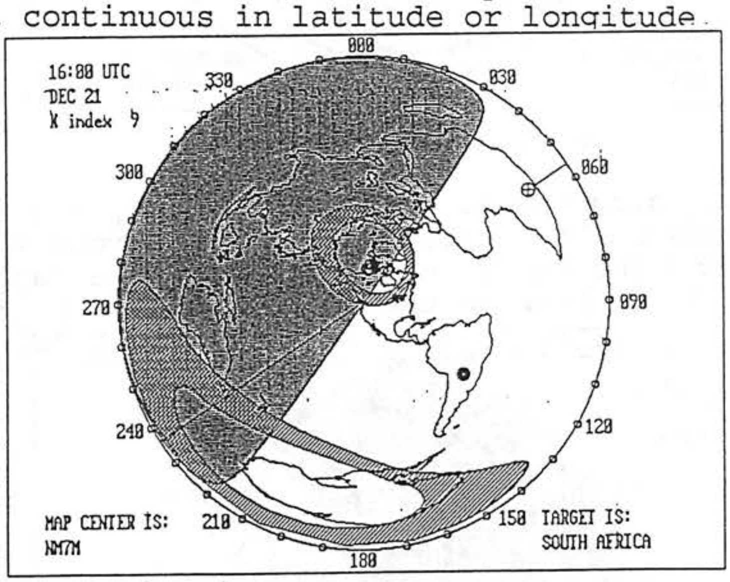


Figure 40 - Auroral distribution for Kp=9.

However, if the instantaneous distribution of ionization does vary rapidly over a short distance in the N-S direction, a signal would be skewed away from the region of greater ionization if its ray path had a component of motion in the E-W direction. On the other hand, a path going in the N-S direction would not encounter a gradient perpendicular to the path and would go through the region with little transverse deviation. Of course, it would still suffer absorption in crossing the gradient.

The direction of skewing would depend on whether the E-W part of the path was equatorward or poleward of the auroral ionization in the gradient. Both are possible, depending whether the path approaches the auroral ionization from lower latitudes, below the auroral zone, or higher latitudes, within the auroral zone. The latter, of course, would require that the signals penetrate the auroral oval at some longitude east or west of the midnight activity. In the first case, the skewing would be toward lower latitudes while the second case would be just the opposite.

With very high levels of geomagnetic activity, it is seen in **Figures 36-40** that the auroral zone shifts further equatorward and at high disturbance levels that are characterized by K-indices greater than 7, it is quite possible for the auroral zone to expand by a large factor and be located over mid-latitude regions. In such cases, sites which are normally taken to be located near auroral latitudes may then be well INSIDE the storm position of the auroral region and within the polar cap. In that case skewing of signals could take place at the poleward edge of the auroral ionization.

An excellent example of that is found in the case of a QSO between SM6CPY and W0ZV in Colorado (Tippett, 1998). On April 4, 1988, they had a 160 meter QSO at 0413 UTC during a magnetic storm when the A-index was 103, well above the typical A=5-10 for quiet conditions. So instead of being at a sub-auroral latitude, the Swedish station was INSIDE the active auroral zone and expanded polar cap, receiving W0ZV's signals from the direction of South America (255 deg E of N) instead of Colorado (315 deg E of N).

That large a deviation in direction brings up yet another possibility, wave reflection by intensely ionized auroral regions which are less than a wavelength across. The question then, in the case of the contact with Sweden by W0ZV, was whether the large change in direction was due to a reflection off poleward segments of the auroral ionization rather than a gradual refraction over a smooth, extended region; lacking ionospheric data, the actual situation cannot be resolved at this late date.

During storm conditions, the rayed auroral structures may be ionized and structured to the extent that they also scatter radiation as well as reflect it and that can give rise to multi-path effects with echoes coming from unusual directions. That does not fit the definition of skewing but it is one more unusual aspect of the direction of signal propagation.

Under disturbed conditions, but not as extreme as the above, stations in the USA could still note some skewing of signals from Europe due to auroral effects. In that case, European signals would be approaching the auroral ionization on its equatorward side and their bearing in the USA would be different because of the skewing that results.

Both absorption and skewing vary roughly with the square of the wavelength of the radiation so signals in the lowest part of the spectrum suffer the greatest effects. But absorption varies with the electron density along a path and at auroral latitudes that is related to the energy spectrum of the incident electrons, with low energy (around 1 keV) electrons creating ionization at high altitudes (around >400 km) and high energy electrons (>50 keV) depositing ionization down around the 60-90 km level. The usual green and violet light associated with the visible aurora is emitted at altitudes around 100-125 km, as shown in **Figure 41**, and are associated with incident electrons around 10 keV.

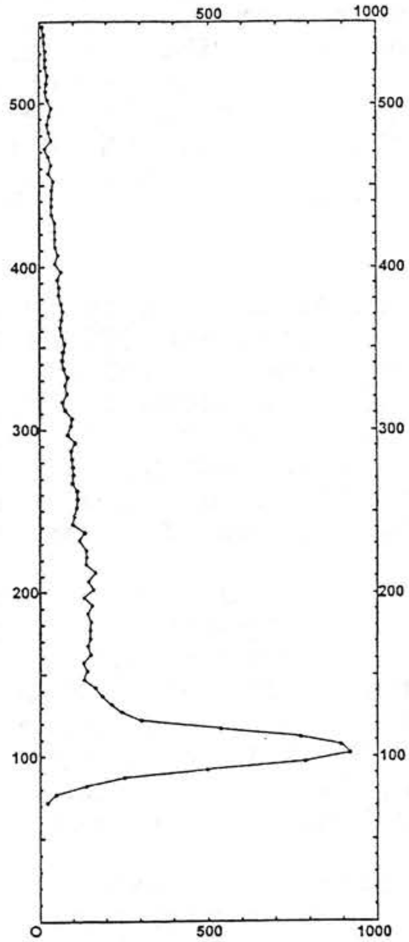


Figure 41 - Vertical distribution of the height of auroral forms.

From the ground, different techniques are used to study the emissions in those energy ranges - meridian scanning photometers, all-sky cameras and the launching of balloon-borne Xray detectors - and they are not necessarily done simultaneously. Thus, it is difficult to specify the equatorward and poleward limits of the various parts of the electron spectrum at a given time. But it can be said that the high aurora from very low energy electrons plays no role in affecting the propagation of 160 meter signals below the F-region peak as they never reach those heights, as may be seen from the vertical excursions of signals in **Figure 19**. Beyond that, without detailed, simultaneous observations in the rest of the energy spectrum, it is impossible to give a definitive answer or interpretation of observations of signal skewing.

That last point brings us back to the matter of the expansion of the auroral zone with increasing magnetic activity. In that regard, **Figure 35** showed that there were still dipole-like field lines in the present model of the magnetosphere; their limit is at auroral latitudes and electron bombardment in the night-time hours is related to processes on field lines that go back into the magneto-tail.

But there is also the polar cap that is within the bounds of the auroral oval. That region is connected to field lines at the highest latitudes and is open to particles coming from the sun, particularly low-energy protons which are released during solar flares. Those can travel down the field lines, bombard the polar cap and some of the protons can even reach the D-region, giving rise to heavy ionospheric absorption that last for days at a time. Those are "polar cap absorption events" and may wreak havoc on propagation across the polar caps, whether on the higher bands of the amateur spectrum or the lower bands.

Chapter VI-

In the Polar Cap-

With regard to **Figures 37-40**, they give greater meaning to propagation questions than using the simple idea that an auroral zone exists, a region where visible aurora are observed most often. The optical phenomena are but a small part of the matter and it was not until the last decade or so that wider discussion was given to the idea of the polar cap and associated phenomena inside the auroral zone; all that thanks to observations by the NOAA polar satellites. Those data, statistical plots of the auroral electron influx in both polar regions, show the inner and outer boundaries of the auroral zone. Beyond that, the variation of electron power input and particle influx with magnetic index Kp was studied and the geometry has even been included in the mapping utility in the DXAID program, meant for amateur radio consumption.

So those figures point to the fact there are variable limits to where electrons reach the atmosphere at high latitudes, one just equatorward of the auroral zone and the other on the poleward side. The poleward edge marks the boundary of closed field lines in the magnetosphere and beyond that limit, the region connects to field lines which drape back into the magnetotail. And when, on occasion, they are connected with the interplanetary field, those field lines may admit the low-energy particles that stream by the earth from the sun.

Of particular interest to propagation are effects when solar protons can penetrate the magnetosphere to ionize the D-region in the polar cap, giving rise to polar cap absorption (PCA) events. Penetration can also occur if particles have magnetic rigidities or momenta greater than the cut-off thresholds imposed by the geomagnetic field at lower latitudes (Davies, 1990).

Those events correspond to the "polar radio blackouts" known back before WW-II and are now understood as due to protons and other heavy particles which are emitted in solar flare processes. In fact, in contrast to earlier days when information was more of a speculative nature, satellite observations now can provide us with flux data on the various energy ranges - protons around 1 Mev for events at satellite altitudes, 10 Mev for ionospheric events at polar latitudes and the 100 MeV range for protons reaching the top of the atmosphere (35 km) at high latitudes. The higher energy events in the 1-2 GeV range arrive at ground level and rare 10 GeV events that can reach equatorial latitudes are reported by cosmic ray neutron monitors.

While satellites give early warning of occurrence of solar proton events, PCA observations come from ionospheric observations at Thule, Greenland and in the form of ionospheric absorption of galactic cosmic radio noise arriving vertically on 30 MHz. But the solar protons have access to both polar caps, within the inner bounds of the two auroral zones, and would affect any propagation paths directed toward those large regions.

There were 14 PCA events during the earlier long-path study, just after the solar maximum of Cycle 22. At this point in Cycle 23, the rates of PCA events as well as major magnetic storms are considerably lower and perhaps 6 PCAs have been seen in year 2000. Most of those events, a few dB in magnitude on 30 MHz, still cause havoc on the bands because D-region absorption varies roughly as the square of the wavelength. So in one of the polar regions, a 2 dB event for a single vertical pass of galactic noise on 30 MHz goes over to 8 dB or so on 14 MHz, and then about 25-30 dB for loss of 14 MHz signals on an oblique pass up and down through the ionosphere in the PCA region.

Solar proton events are reported in proton flux units (p.f.u. or protons/cm^2/sec/steradian) for particles above 10 MeV energy. As noted above, there were 14 solar proton events in the year of the earlier study. Those ranged from two above 1,000 p.f.u., five above 100 p.f.u. and the rest below 100 p.f.u. By contrast, in year 2000 there was one large solar proton event (2,400 p.f.u. >10 MeV on July 14, 2000) but another 5 solar proton events where the proton flux was less than 100 p.f.u.

Ionization from solar protons can cover an entire polar cap so even small events like 2 dB on 30 MHz give rise to heavy path losses. But in Cycle 22 there was one event with 17 dB absorption recorded at Thule. That gave a total "black out" and propagation did not recover for several days, until low energy solar protons had diffused away from the vicinity of the earth where they were held by the interplanetary magnetic field.

From the perspective of long-path propagation, it should be noted that there is a day/night effect in those long-duration PCA events, with night-time recoveries toward normal propagation. So in the early morning hours of winter on the West Coast, when long-path contacts with Africa and Europe are attempted toward the south, there is some sunlight in Antarctica. That means signals going across the southern region would experience the full effects of the absorption due to any solar proton bombardment in effect at the time.

But with darkness expected in the Arctic during those hours, the day/night effect would reduce signal absorption there by a factor of 3-4, depending on season. By that token, a PCA event reported at Thule, Greenland in the winter could well give an underestimate in the forecast when it comes to signal absorption on long-path propagation in the Antarctic. Of course, that assumes solar protons had equal access to both polar caps, not always a good assumption judging from satellite data.

In any event, the day/night effect is of atmospheric origin, with D-region electrons released by proton bombardment being captured by some molecules to form heavy negative ions at night. During the day, solar UV photons detach electrons from negative ions about as fast as they are captured, thus maintaining a high level of absorption by free electrons. The dusk and dawn twilight variations of negative ions are not the same, however, due to a rather complicated chain of reactions in the ion chemistry of the two regions. That topic is of greater importance to long-distance propagation at the low end of the amateur spectrum and will be discussed fully when the topic is considered.

Those events arise from solar flare activity but there is another bombardment of the polar cap, sort of a polar drizzle, that takes its toll on high-latitude paths. One can note that sort of occurrence by going to the NOAA polar satellite data and looking at the bombardment all along the satellite tracks. Of particular interest are solar electrons recorded from time to time by the auroral electron detectors at latitudes well inside the auroral zone. They are seen in the data but no particular note is made of them in the reporting process as their energy input is small compared to that which reaches the auroral zone. While the occurrence of those events represents nothing new in the last ten years, their recording is something new and of note, thanks to the NOAA satellites and the Internet.

Drifting Patches of Ionization-

But in the last ten years, one thing that is new in matters dealing with the polar cap is the realization that propagation may also take place when signals encounter drifting patches of F-region ionization. Such patches are of magnetospheric origin rather than due to sunlight and may be present in the dark, winter polar cap, supporting propagation as high as on 30 MHz. The patches have been known in scientific circles for more than a decade, found by their characteristic optical emissions and also detectable by ionosonde techniques.

Like the regular ionospheric regions, anything that will support vertical signal reflection will also support oblique signal propagation. In that regard, GM4IHJ and I didn't know of the patches and were surprised to find 29 MHz signals coming from the RS-12 satellite over the dark polar cap in the winter of '91-'92. One beautiful example of that sort of observation is shown from GM4IHJ data (Branegan and Brown, 1993) in **Figure 42**, a RS-12 satellite pass where the signals were heard continuously from Africa, across the terminator and into the polar cap, and on to south of the Kamchatka Peninsula. All that distance beyond the usual satellite "footprint" was thanks to drifting patches of F-region ionization.

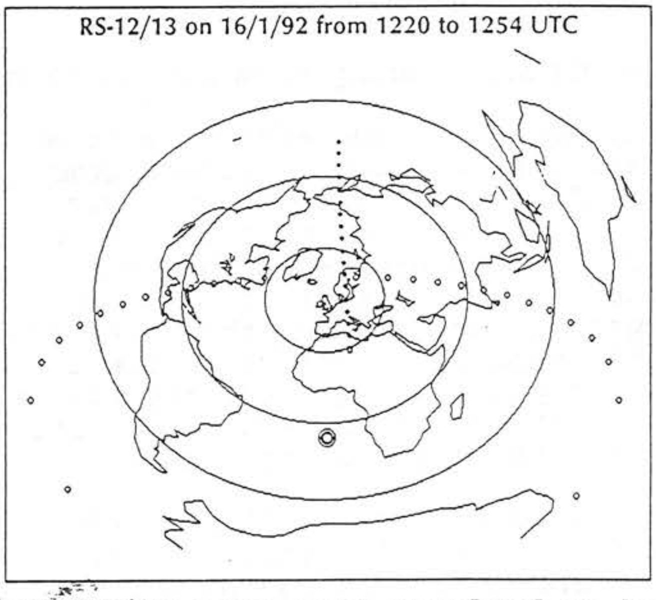


Figure 42. RS-12 satellite pass over Scotland to beyond Kamchatka.

Those patches are found around local noon in the northern polar cap during the months of winter. When it comes to long-path propagation here in the USA, we usually think of winter long-paths going into the southern polar cap during times of sunlight at those latitudes, with the sunlight providing the necessary ionization to support the critical frequencies along the paths. By that token, drifting patches of ionization in the northerm hemisphere would seem to be of little or no interest to long-path propagation. But North America is not the whole world by any means and there are other locations at which long-path propagation involves paths that go across the dark polar cap in the northern hemisphere.

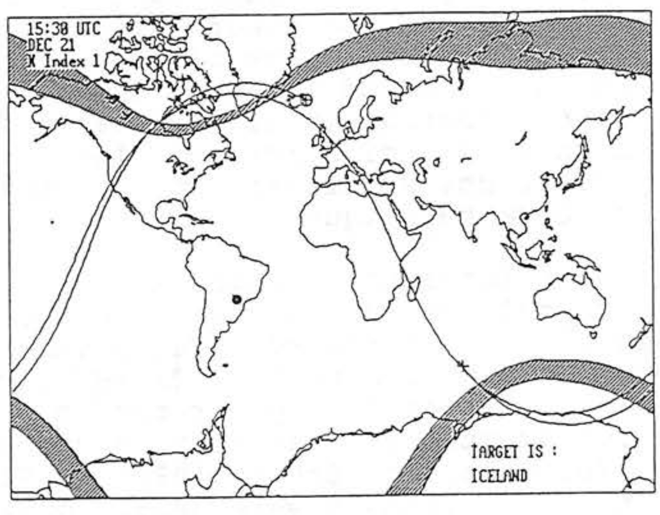


Figure 43 - Winter long-path from Heard Island to Iceland.

Paths from Heard Island are a case in point and **Figure 43** shows a HF path that goes past the edge of Antarctica, across the entire Pacific Ocean before entering the dark polar cap over Canada, Greenland and Iceland. If extended, that path would go into Europe and be a viable long-path connection to Heard Island. So drifting F-layer ionization in the northern polar cap could give the last bit of support needed for a long-path contact on HF from Heard Island into Europe.

While I must confess I know of no such long-path connections recently, there are cases of unusual night-time propagation on 10 meters which seem to be related to the drifting patches. A 15,000 km QSO across the dark polar cap by W4ZV with XZ0A in Burma is a case in point, at 1300 UTC on January 13, 2000.

Into the Auroral Zone -

The current understanding of auroral processes involves the energization of magnetospheric electrons in the magnetotail and their being sent earthward as field lines in the magnetotail collapse inward toward the dipole field lines that make up the closed portion of the magnetosphere. Again the details are left to magnetospheric physicists to worry about. But the range of phenomena which result from bombardment of the auroral zone by those energetic electrons is considerable, even though the energy input is small compared to what reaches the earth from the sun's visible radiation.

For our purposes, we need to know just what happens, when and how it can affect propagation. Magnetic storm and auroral effects work across the entire amateur spectrum, from affecting MUFs for long-path propagation in the the highest part of the HF range to auroral absorption and skewing at the lowest, and can play an important role in long-distance propagation.

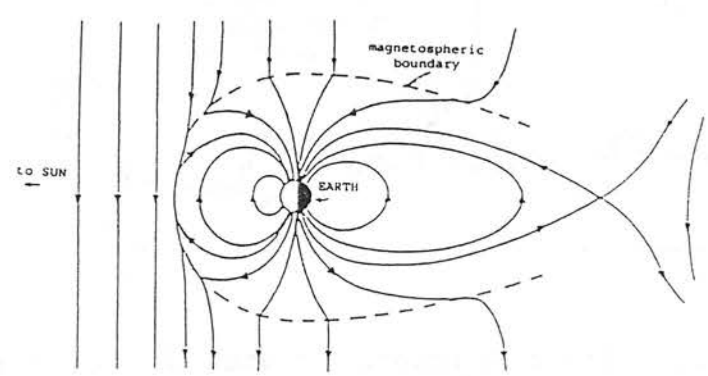


Figure 44 - Field line interconnection when interplanetary field points to the south.

The MUF question goes to F-layer ionization held on high-latitude field lines and how they are affected by increases in solar wind pressure at the front of the magnetosphere. The solar wind carries interplanetary field lines with it and when any south-pointing field lines reach the front of the magnetosphere, (Bz<0), a merging of field lines often takes place, as seen in **Figure 44**, carrying closed field lines from the front of the magnetosphere back toward the tail (Campbell, 1997). F-region ionization on those field lines is lost, going back into the magnetotail, and MUFs on paths across such regions are lowered as a result.

Magnetic energy can be stored in the magnetotail in that way but at some point an instability can develop leading to collapse of some tail field lines, giving rise to electron acceleration and bombardment of the atmosphere. With the return of field lines to the inner region of the magnetosphere, the MUFs recover slowly as the electron population on the field lines returns largely from solar ionization of the atmosphere. For very intense magnetic storms, with Ap close to 200, recovery is a drawn out process, taking days of sunlight to fully replenish the depleted F-region.

The interconnection of terrestrial and interplanetary field lines also results in an increase in the size of the polar cap as field lines which were originally closed now go back into the magnetotail. Thus, if a solar proton event were in progress when the field change took place, the polar cap would be enlarged and PCA conditions would extend over a greater area. That change takes place at the time when the change in interplanetary field, to the south, reaches the front of the magnetosphere.

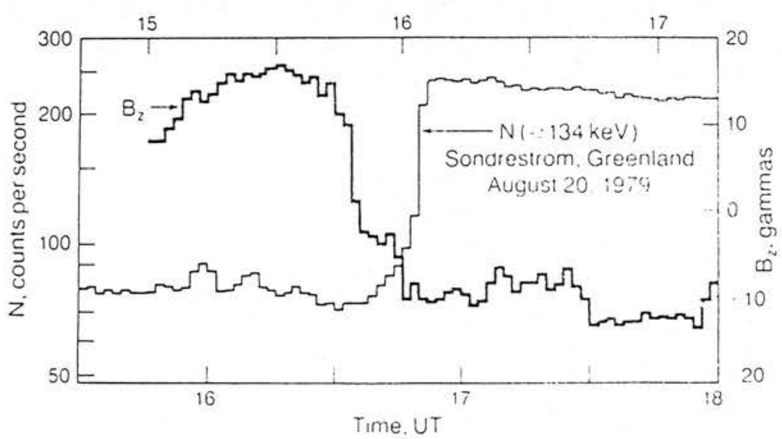


Figure 45 - Change in radiation intensity when Bz turns south. Note two time axes, Bz upper and radiation lower.

But the interplanetary field is carried by the solar wind at a finite velocity so any change in field at the front of the magnetosphere might be forseen by a satellite magnetometer out in front of the earth at a suitable distance. Such changes in field are now reported from the ACE Spacecraft about 1,500,000 km in front of the earth. Earlier, the ISEE Spacecraft was located there and on one occasion it reported a change in interplanetary field direction during a solar proton event in August 1979. That opened up the auroral zone 45 minutes after the field change at the satellite. In effect, it moved a balloon-borne radiation detector from the auroral zone into the solar proton influx in the polar cap, as seen by the intensity increase following the field change shown in **Figure 45**. (Note the two time axes, the upper one at the ISEE satellite and the lower one at the balloon-borne detector.)

The ACE Spacecraft occupies that position again, out in front of the earth, and reports changes in the solar wind on a regular basis. Those reports give warning of possible magnetic activity, which give rise to auroral effects such as absorption of radio signals. But those data are reported also for the benefit of the power industry, to alert them to any major change in the solar wind which, through a major geomagnetic storm, might disrupt the northern power grids in the USA and Canada. The hope is to avoid a repeat of an event of the type which was encountered in March 1989 and interrupted the power distribution grid serving 9,000,000 people in Quebec for a full day.

But more often than not, simple propagation predictions can be made from high-latitude magnetometer data, with times of low magnetic activity reported in the hope that the solar wind stream would be stable and, again, give rise to similar low activity on the next solar rotation. It should be noted there is ample evidence for such stability, particularly after solar maximum when solar streams show a strong recurrence tendency.

Such reporting is now done in the winter for 160 meter DXers by using the data from the Meanook magnetometer in western Canada. But it has a more general meaning than just for the northern hemisphere as a study (Brown, 2000b) of magnetometer data from both hemispheres shows the two track rather closely. So times of magnetic quiet in the southern hemisphere data can be inferred from quiet times in the northern data.

But it should be noted that auroral activity has different degrees of effect across the amateur spectrum. That is because of the magnitude of auroral effects, absorption and skewing, vary with wavelength or frequency. So observations of absorption at auroral latitudes typically use instruments similar to those for PCA studies at Thule, Greenland. That would be the riometer (Relative Ionospheric Opacity METER) developed back during the IGY. Those instruments are sensitive receivers and typically operate on 30 MHz, just above the amateur band to avoid any propagated interference. Their antennas are either directed vertically or toward the pole star.

With an influx of auroral electrons, the instruments will show absorption of cosmic radio noise of 1-2 dB during an average event. In contrast to PCA events, when protons produce a modest increase in ionization in the D-region (where the electron-neutral collision frequency is high), auroral electrons produce heavier ionization in the E-region (where the collision frequency is much lower). In any event, there is no day/night effect with auroral absorption (AA) events as negative ions do not form in the higher, auroral region. Moreover, it has been found that the influx of electrons takes place simultaneously in both hemispheres, with comparable effects in conjugate regions, locations in the two hemispheres which are connected by geomagnetic field lines.

So one can say that long-path propagation on the 10 meter band, with signals going across Antarctic latitudes, would not be affected too seriously by absorption if a typical auroral event were in progress in the two hemispheres. But absorption varies roughly with the square of the wavelength so it would begin to take a significant toll on signals down on 7 MHz. On the lower bands, operating experience as well as DXpeditions shows that additional auroral ionization has quite devastating effects, especially down on the 1.8 MHz band. Those include not only absorption but skewing and multi-path effects.

Chapter VII -

Forecasting Long-Path-

As indicated way back in the first paragraph of Chapter I, I began studying long-path propagation quite by accident - working a SM5, finding that both short- and long-path were open on 20 CW at the time and that long-path gave better propagation. I just kept doing "more of the same" until one day long-path didn't work as before. At that point, I started to look around, at the path lengths and propagation prediction techniques, to see what was going on in the ionosphere.

Path lengths were rather startling. True, long-path means a distance greater than 20,000 km, half-way around the earth. But the distances on the SM5 contact were sort of a surprise, 7,400 km on short path and 32,600 km on long-path, shown in the azimuthal equidistant map in **Figure 46**. In the course of the year, I worked a number of SMs and LAs at those distances and got used to the idea. I forget the call but the one I enjoyed the most was an LA who lived down in a fjord and the only way out in my direction was long-path, down the fjord. That was long-path, no doubt about it!

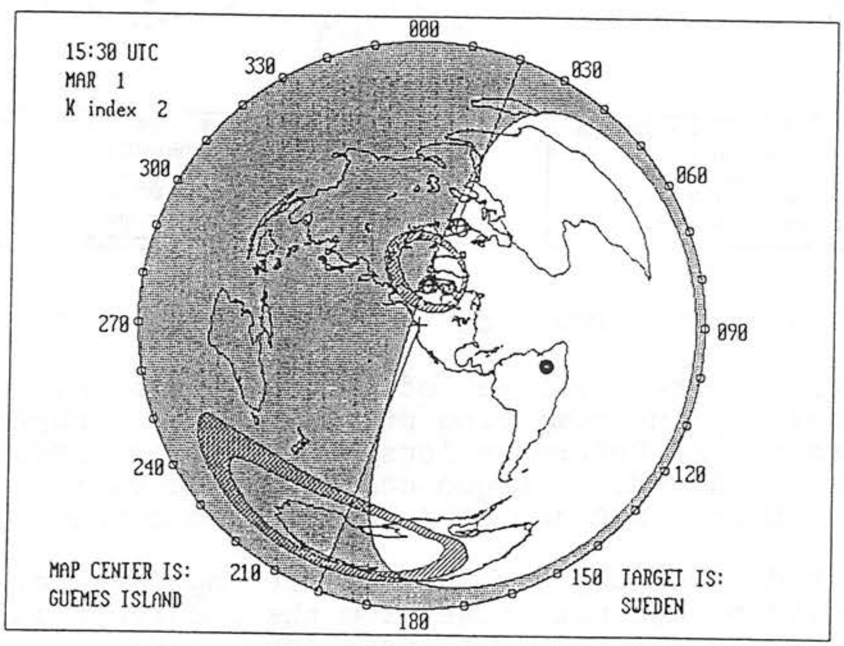
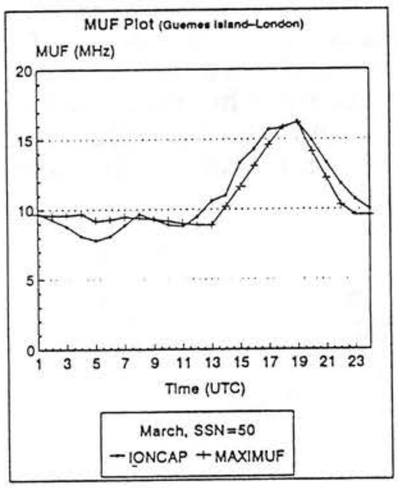


Figure 46 - Azimuthal equidistant path from Washington to Sweden.

Propagation predictions were another matter. Back in December '82, the publication of the MINIMUF program in QST caught the attention of the ham radio community and I devoted a lot of time to propagation prediction programs, learning HOW they worked as well as just how WELL they worked. I should point out those two ideas are quite different. So with my computer, I explored MINIMUF, MINIFTZ4, MAXIMUF and then I bought a copy of IONCAP.

I was able to dig the F-layer algorithms out of the first three programs but IONCAP was in a compiled version so all I could do was work with it. In fact, since it enjoyed universal respect in the radio science community, it became the benchmark program against which all others were tested, at least for a few years.

Those tests were interesting, programs like Micromuf 2+ and Maximuf by Raymond Fricker giving short-path predictions which compared quite favorably to results from IONCAP, in shape and in magnitudes, as shown in **Figure 47**. The MINIFTZ4 program gave good agreement in shape but tended to differ in magnitudes, as shown for another path in **Figure 48**.



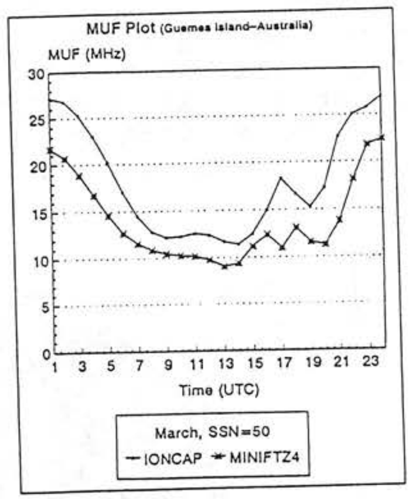


Figure 47 - MAXIMUF MUF Plot   Figure 48 - MINIFTZ4 MUF Plot

However, the true features of IONCAP F-layer algorithm were unknown, hidden by the compiling process. Then I purchased a copy of the International Reference Ionsphere, vintage 1990, and my whole approach changed. I began comparing the various F-layer algorithms with the CCIR and URSI standard ionospheres.

Others had made comparisons too, putting foF2 values from the various algorithms against those from the reference ionospheres. The method used by Damboldt and Suessmann (1988) was to calculate foF2 values from MINIMUF over a grid, points at 19 latitudes and 12 longitudes, as well as twelve months of the year, 24 hours of a day and two sunspot numbers (0 and 100), and then compare values from the algorithm with corresponding values from a CCIR Atlas of Ionospheric Characteristics.

In addition, they did the same sort of calculation using the F-layer algorithm in MINIFTZ4. Their results showed an average difference of 1.0 MHz between MINIMUF and the Atlas while the algorithm from MINIFTZ4 showed only a difference of -0.09 MHz; standard deviations for the two algorithms were 4.4 MHz and 2.3 MHz, respectively.

In a summary manner, that approach showed the algorithm in MINIFTZ4 gave more meaningful foF2 values than the one in MINIMUF. But those were just numerical values, heaped in a pile and without any reference to where agreement was good, bad or indifferent. A better approach was needed for my purposes, hopefully long-path predictions, so comparisons were made (Brown, 1997), point by point, on a global map.

The comparisons were made between the F-layer algorithms and the reference ionospheres in two ways. Qualitatively, foF2 values were calculated from the algorithms to make foF2 maps by curve-plotting and those were compared with foF2 maps from the reference ionospheres, from +80 to-80 in latitude, using 10 degree steps, and from 0 to 360W longitude, in 12 degree steps. I won't belabor the point but the global plots of foF2 from the MAXIMUF algorithm agreed very well, when it came to shapes and magnitudes of the iso-frequency contours, with those from the reference ionospheres.

However, the foF2 map from the MINIMUF algorithm had little visual resemblance to a real ionosphere. The MINIFTZ4 program, on the other hand, had a kinky aspect along all its iso-frequency contours, due to the manner of interpolation used in developing the database for its algorithm. That aspect of MINIFTZ4 was not evident in using the program for propagation predictions.

Going back to the various comparisons of path predictions, it would seem fair to say that successful prediction programs require F-layer algorithms that produce foF2 maps that really look like an ionophere. That should be the first test of any new propagation program, the appearance of a global foF2 map from its algorithm and how it compares quantitatively with values from one of the recent versions of the reference ionospheres.

The other approach to comparing algorithms with the reference ionospheres was to find the differences between the calculated foF2 values and those given by the reference ionosphere and to form a global plot, point by point, in two different formats: using an "O" when the value was within 1 MHz of the reference value or when it was within 15% of the reference value and departures from those limits were shown by "+" or "-".

The 15% limit is the more demanding of the two and such a global map for Fricker's MAXIMUF F-layer algorithm is shown in **Figure 49** for the case of 06 UTC in March and a SSN of 50. The calculations also admitted the method of Damboldt and Suessmann

(1988) and that showed the need for an offset of 0.52 MHz to MAXIMUF to make values from the Fricker algorithm reduce the total difference between calculated values and those from the reference ionosphere to zero.

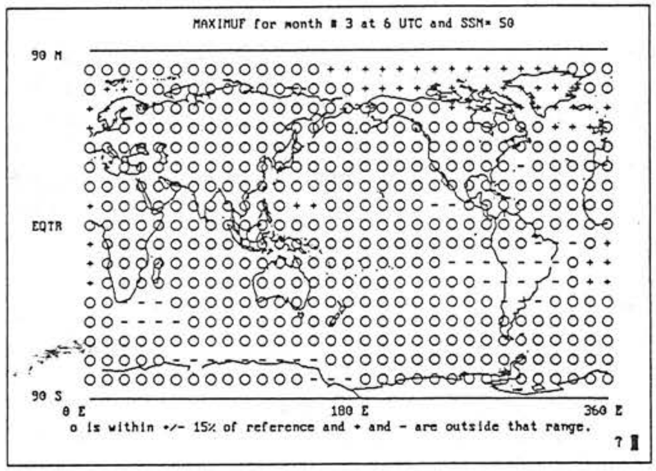


Figure 49 - Global Map of foF2 differences.

Comparisons were made with the other available algorithms but Fricker's MAXIMUF was by far the best. And by choosing various months and SSN, a table of offsets was produced which would give better agreement of the maps with the reference ionospheres. At the time, that result seemed promising since it was easy to do calculations with Fricker's algorithm and computers were becoming faster and faster all the time. In time, however, nothing has been done to incorporate those results in propagation programs that use Fricker's F-layer algorithm. At this point, a more likely development in the future is give up using algorithms and go directly to data in a reference ionosphere, using that data make propagation predictions.

MUF Calculations -

Historically, propagation predictions in the HF range used the control point method where hops were tested at about 2,000 km in from the two ends of a path and the lowest of the MUFs taken as the MUF for the entire path. The idea was that paths were more likely to fail at the ends, not in their middle. That is all well and good if the end points are such that a path does not reach the auroral zone or higher latitudes; there, critical frequencies are quite variable, day by day, possibly violating the premise on which MUFs are calculated.

That is not the case, of course, if a path has intermediate latitudes which are lower, in an absolute sense, than those at the end points; the MUF for an intermediate hop at lower latitudes is always greater than the hops at the two ends and MUFs for such short-paths are quite reliable, at least if the F-layer algorithm is a good one. That is where Fricker's algorithms come in; they are the best of the ones tested against IONCAP and reference ionospheres.

Those remarks apply to MUF calculations for short-paths, say like the 7,400 km path on 20 meter CW to the SM5 at the start of the long-path study. But other bands can be explored, from 10 meters down to 80 meters. As you might expect, the results vary from one propagation program to the other, largely due to the differences in their F-layer algorithms.

There are differences in predictions of the magnitude of MUFs but predictions as to the times when the bands open end close show common features - the lower bands open first and close last. That gives rise to the operating strategy of starting on the highest band of interest and moving down in frequency, band after band, as they close.

In connection with predictions, if and when bands are open, the most common complaint is propagation programs underpredict when it comes to durations of openings and MUFs. Of course, that complaint does not recognize predictions are based on statistical data, the critical frequencies used in MUF calculations being median or 50% values. Put another way, for a given path, date and time, the experimental observations yield two other frequencies - the FOT, a frequency above which propagation is possible 90% of the time or 27 days of the month and HPF, a frequency above which propagation is possible 10% of the time or 3 days of the month. Using those values instead of the median, 50% value, would give somewhat different predictions. But that is the method and we just have to live with it. It helps if the predictions are not taken too literally, knowing of the fluctuations in critical frequencies.

But using the control point method for long-path calculations is a bit extreme, say for the 32,600 km path to the SM5. In the first instance, the short-path involves 3-4 hops while the long-path has more than 10 hops, depending on the radiation angle. There are far more chances for hops or propagation to fail with long-path. That is particularly the case as typical winter long-paths go to high, southerly latitudes, in contrast to the lower, northerly short-paths. It would seem to be a miracle that long path would work at all; but it does, no doubt about it. So, in general, control point methods have their short-comings when it comes to predicting long-path propagation and all the propagation programs show it by not often predicting long-path opportunities.

But those prediction programs also consider signal strength, not just MUFs, and a program can predict failure if the absorption on a long-path is so great as to reduce the signal or signal/noise level to one below what can be heard at the far terminus. The MINIPROP program is a case in point. One can choose a signal or signal/noise level for reporting as well as the availability or MUF for the path. The first part assumes a power level of 100 W while the MUF is independent of power. In any event, for either short- or long-path, the MUF varies, going through a peak for the original NM7M-SM5 contact whether for short- or long-path, But for long-path, it responds with "all received signal levels are suppressed", meaning that the signals fell below the threshold that was deemed to be an acceptable minimum for a contact.

Again, the control point method is the problem as it does not consider the possibility of chordal hops on a path, regions where there are high, ionospheric reflections without any intermediate ground reflections. Thus, the failure to consider those more efficient hops leads to an underestimate of signal strength and a false sort of prediction, failure because of insufficient signal strength.

But, as could be expected, the control point method works well on long-path predictions if the intermediate hops are at lower latitudes than the terminii, as was the case for short-path. This was brought home to me in a forceful way when solar activity had declined significantly after the peak of Cycle 22 and I was no longer able to work long-path from my high latitude. One morning I was surprised to hear K5NU calling "CQ LP" in 20 meter CW. I thought the season was over and asked if he was having any luck. Well I was bowled over by the list of DX he had worked: Angola (D2), Zimbabwe (Z2) and Madagascar (5R), to name a few.

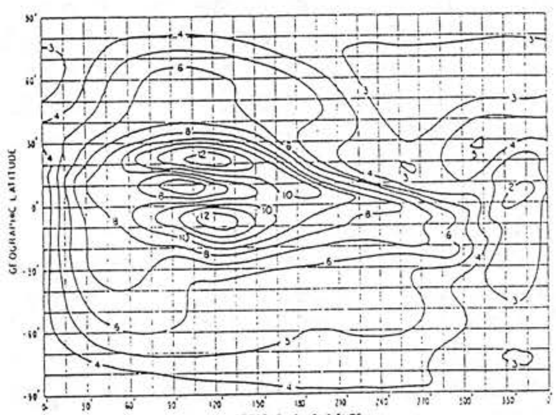


Figure 50 - foF2 map for 0600 UTC in March for SSN=12.

Then it dawned on me; he was at a low latitude, at 28 N in Portland, TX, and he had been working long-path into the region around South Africa where the latitude was about 27 S. That gave nice symmetrical paths that straddled the equatorial anomaly in the ionosphere, shown in Figure 50. The critical frequencies in that region are the highest in the ionosphere, even above 8 MHz at times of sunspot minimum.

For a change, the control method would work quite well in predicting 14 MHz long-path propagation at those latitudes. While it is not something new, say in the last ten years, it is a realization that may have escaped you too so I think it is worth mentioning.

So far, the discussion of propagation prediction has dealt with the top of the amateur spectrum and down into the transition bands, 10-18 MHz, where MUFs and signal strength are both of importance. But the lower bands are different in that MUFs are essentially of no concern. That is the case as critical values of foF2 are high enough to almost always support oblique signal propagation across the ionosphere at the lower frequencies.

In short, RF on paths at those frequencies, 7 MHz and below, is trapped in the ionosphere, not penetrating beyond the F-region overhead nor escaping to infinity at the usual propagation angles. Even at vertical incidence, 1.8 MHz RF does not penetrate the ionosphere, going in or out, and that means that galactic radio noise at that frequency can only be heard above the ionosphere, not from within it.

Storm Conditions -

Those remarks depend on the ionosphere not being disturbed, as during meteorological or magnetic storm conditions, and signals propagated by ionospheric refraction. The physical requirements for refraction at any operating frequency are that the electron density in the ionosphere vary slowly over regions at least a wavelength in extent in all directions.

Since collisions between neutral particles and ionization occur at a high rate, 1 MHz or greater, in the lower ionosphere, that requirement means refraction can take place only so long as the atmosphere is relatively calm on that distance scale. Put another way, it simply requires that atmospheric motions are not transporting the positive ions and electrons by any significant motions, greatly unbalancing the distribution of ionization. Otherwise, propagation will be by wave scattering in regions having a smaller spatial structure, so-called ionospheric irregularities, or reflection by regions in which the electron density is high and varies rapidly over spatial dimensions small compared to a wavelength.

And that demand for refraction becomes increasingly greater at longer wavelengths and can be something of a problem on the 160 meter band. So any atmospheric disturbance with a scale size the order of 160 meters can disturb the ionosphere as far a refraction on that band is concerned but higher bands would be less affected. Atmospheric effects will be discussed more fully at a later point in regard to long-distance propagation on 160 meters.

During magnetic storm conditions there are other effects, due to the presence of electric fields, which can arise in the ionosphere from interaction of the solar wind and the geomagnetic field. Those, like creation of drifting patches in the F-region at polar latitudes, are magnetospheric in origin and and involve transport processes of ionization which are just too involved for discussion here. So we have to leave it there, keeping in mind that whatever the origin, any sort of storm conditions can affect ionospheric propagation, particularly at the longest wavelengths.

Long-Path at Low Frequencies -

But what about long-path predictions at lower frequencies? In that regard, experimental observations show that long-path propagation does take place, in the classical sense with signals going between points that are separated by more than half the distance around the earth. Those sorts of contacts were found in the logs of the VK0IR and ZL7DK DXpeditions, on 7 and 3.5 MHz. While those are recent cases, re-affirming the broad range of experience by amateurs over several decades, the matter of long-path on 160 meters is open to question at the moment. Much more later on that point.

But if there is any question about making predictions at low frequencies, it has to be with the actual paths that are followed in covering those sorts of distance. Those are probably not precisely the paths which go with the great-circles which define long-paths in a geometrical sense. That is the case as horizontal refraction or skewing takes place in the ionospheric structures that are encountered, going as the square of the wavelength and thus giving greater effects or departures from great-circles at the lower frequencies.

Since MUFs are not important on the lower frequencies as long as storminess is not in effect, propagation predictions come down to the matter of paths, short or long, and estimates of signal strength along them using ionospheric absorption. Those have to do with the length of the paths, the number of ground reflections, D-region traversals and the amount of sunlight/darkness along the path. In the simplest terms, darkness is required all along a path for it to be viable and the amount of illumination and how it changes will determine how useful a path would be.

But as a practical matter, propagation programs simply use great-circles connecting the terminii, ignoring the effects of any ionospheric structure along the paths in making the absorption calculations. That is about the best that can be done by simple methods; otherwise, the matter becomes one involving ray-tracing, such as done by the PropLab Pro program (Oler, 1994). While those methods are very instructive, in a scientific sense, they prove to be too cumbersome and time-consuming for routine use.

But there is one aspect of low-band propagation that has not been mentioned so far - signal ducting, for operating frequencies that are comparable to the electron gyro-frequency about the earth's magnetic field. Like chordal hops on the high-frequency bands, those do not involve any intermediate ground reflections and thus are efficient when it comes to propagating signals. So they have to be folded into any signal strength estimates to obtain a better value in considering long-distance propagation.

Chapter VIII -

Other Sources of Motion -

The discussion in the last chapter dealt with the possibility that atmospheric motions, from storm conditions of geomagnetic or meteorological origin, could affect low-frequency propagation by shifts in the distribution of ionization. As indicated, that could change propagation from refraction in a smooth ionosphere to one by scattering from ionospheric irregularities. But even without any storm conditions, there is evidence for some motions in the atmosphere at high altitudes - winds deduced from visible meteor trails as well as from radar data on motions of meteor ionization. In addition, thermal motions of the atmosphere are expected from heating and vertical expansion of the atmosphere at sunrise.

Beyond the transport of ionization due to electric fields, generated by the interaction of the solar wind with the earth's field, there is also the possibility that auroral energy will be transfered to the atmosphere as heat with the incidence of auroral ionization during a magnetic storm. Thus, levels of constant ionization density may move up or down, even become tilted. All of those have an effect on the refraction process by bending rays vertically, to increase or decrease the lengths of paths, or horizontally, to skew them one way or the other but always away from regions of greater ionization.

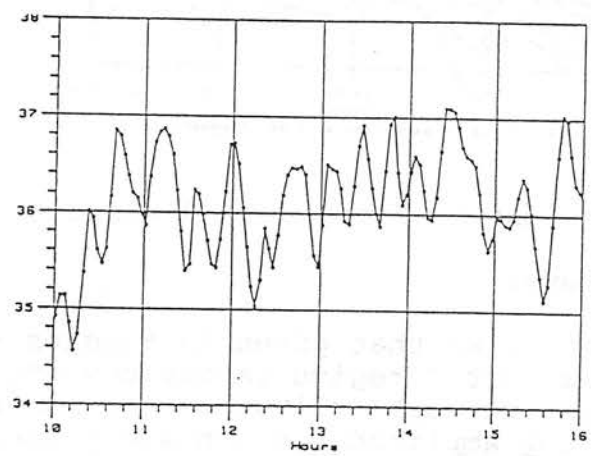


Figure 51 - MUF(3000) values in 3-minute intervals.

Additional information about ionospheric motions is obtained from ionosondes when observations are taken at short intervals. An example is MUF(3000) recordings, the maximum useable frequency for a 3000 km path centered on a given location. Thus, **Figure 51** shows soundings taken at 3-minute intervals (Paul, 1989) that would apply for the MUF on a 3,000 km path centered at Brighton, CO in February, 1981. The MUF(3000) variations in **Figure 51** show oscillations with the MUF values having periods ranging from 20 to 30 minutes.

Those variations may result from waves propagating through the ionosphere, as suggested by the virtual height data shown in **Figure 52**. There, ionosonde data at 5-minute intervals, from fixed frequencies near the critical frequency foF2, show some wave-like variations with the maxima and minima of virtual heights appearing later at lower frequencies (heights). That particular dataset suggests a vertical downward velocity component of about 160 m/s while time variations in **Figure 52** suggest a wavelength in the range 240 to 360 km. Taken together, the data in **Figures 51 and 52** indicate the main effect of those waves propagating through the F-region is a variation of the height of the layer and to a lesser degree, a variation in the electron density.

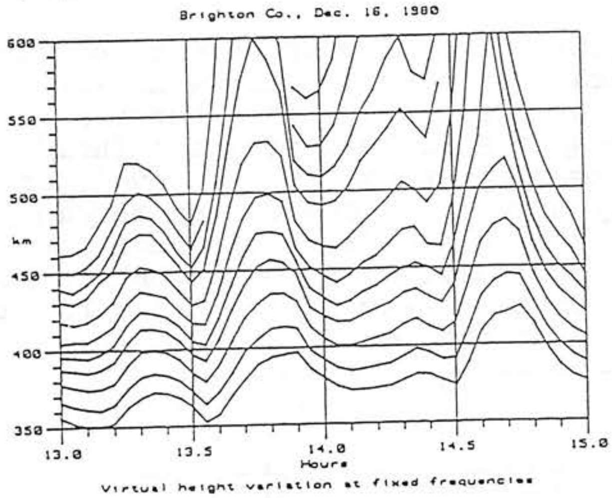


Figure 52 - Virtual height variations in 3-minute intervals.

Atmospheric Gravity Waves -

The ionosonde data like that given in **Figures 51 and 52** support the hypothesis that F-region variations are due to the coupling of ionization, through collisions, to atmospheric gravity waves (AGW) with varying amplitudes which are present all the time. More generally, however, AGW are transverse waves that propagate in the neutral atmosphere and are maintained by gravity and buoyancy but damped by viscosity.

As shown above, they can be seen from traveling ionospheric disturbances (TID) they generate in the ionosphere. Sources of AGW (Hunsucker, 1987) include not only heating from precipitation of energetic electrons at auroral altitudes noted above but other large expenditures of energy at lower altitudes - turbulence in the troposphere, stratospheric winds from weather systems and events of geological origin such as earthquakes and volcanic eruptions.

The large-scale AGW, with periods from 1 to 3 hours and speeds of 500 m/s in the horizontal direction, seem to originate in auroral regions. The medium-scale AGW come up from below the ionosphere, have periods 20-45 min and speeds from 80 to 450 m/s while small-scale AGW, with short periods (2-5 mins) and speeds the order of 300 m/s, are associated with regions of wind shear and atmospheric turbulence. As shown by the virtual height data in **Figure 51 and 52**, large-scale AGW affect the height of higher ionospheric regions, thus having a significant effect on the geometrical aspects of HF wave propagation.

The same is probably true of the lower F-region and the E-region, where 160 meter and MF signals are propagated. Thus, there will be variations in electron density levels at a given geodetic height as well as density variations from AGW which produce tilts of the surfaces of constant electron density. Those will contribute to the variability of ionospheric modes through changes in hop length as well as the initiation and termination of ducted signals.

Beyond Motions -

In addition to density changes at a given geodetic altitude from mass motions, there is the question of the composition of the atmosphere, particularly the role of some minor constituents which have an anthropogenic origin. Among others, those include nitric oxide (NO) which is a by-product in the exhaust of jet engines and carbon dioxide (CO2) which results from the widespread use of fossil fuels. Those minor constituents are created in specific locations but their presence is related to transport through slow atmospheric circulation, making them highly variable in their concentrations.

Water vapor and ozone are two other trace constituents which are highly variable because of transport but they are produced continually by the effects of solar radiation, heating of the oceans in the first instance and photo-dissociation of molecular oxygen, a major constituent of the atmosphere, in the second. Beyond its importance to atmospheric processes, ozone is of particular interest in connection with the lower ionosphere as it is transparent to visible radiation but largely opaque to UV. Thus, it limits the UV photo-ionization of the neutral atmosphere and photo-detachment of electrons, firmly bound to negative ions, at low altitudes around sunrise, an important time for low-band propagation.

While ozone is a trace constituent in the atmosphere, its effects on the ionosphere can be used to demonstrate something of the state of motion of the neutral atmosphere. In that regard, an experiment was conducted in which 55.5 kHz signals were monitored on a one-hop path from near Sacramento, CA to Guemes Island, WA. Those signals were reflected by the ionization gradient at the bottom of the D-layer and interfered destructively with the ground wave. That gradient results from the formation of negative ions at night, reducing the free electron density in the region.

At dawn, the gradient is lowered by the photo-detachment of electrons from the negative ions with the incidence of solar radiation on the D-region. The lowering changes the phase difference between the skywave and ground wave and gives an interference minimum which can be timed, day by day. But the lowering of the gradient does not follow the incidence of visible radiation at sunrise; it is delayed 15-30 minutes, the time required for solar UV to rise above the solid earth AND the ozone layer.

Such observations (Brown, 2000) have been carried out for two years and the time delays for the intensity minimum, shown in **Figure 53**, were used to estimate the height of the ozone layer and its variations. Of particular interest is the rise and fall of the ozone layer in the winter season when weather fronts intrude on the layer, in line with the solar UV path to the VLF signals below the D-region.

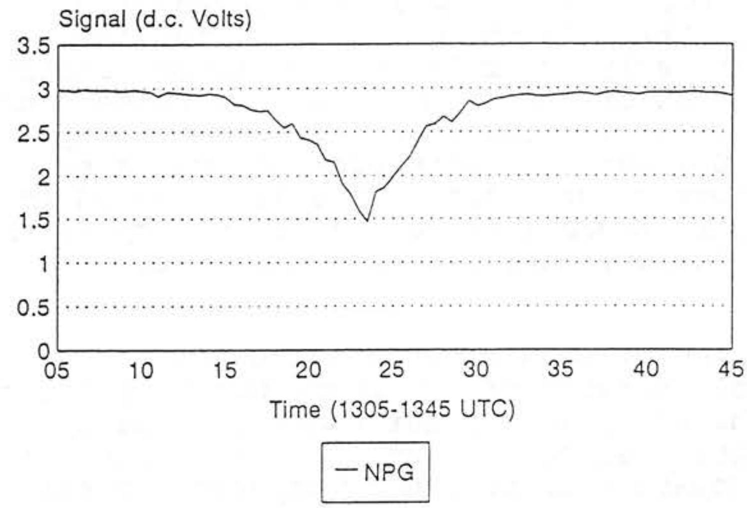


Figure 53 - Variations of 55.5 kHz signals.

Figure 54 shows variations in the height of the ozone layer during the winter of '99-'00. While the observations are day by day, they show the height of the ozone layer can change by large amounts and that implies motions of the atmosphere in the change from one height to another. Those motions are also shared by the ionization and may contribute to signal scattering by ionospheric irregularities which are formed from time to time.

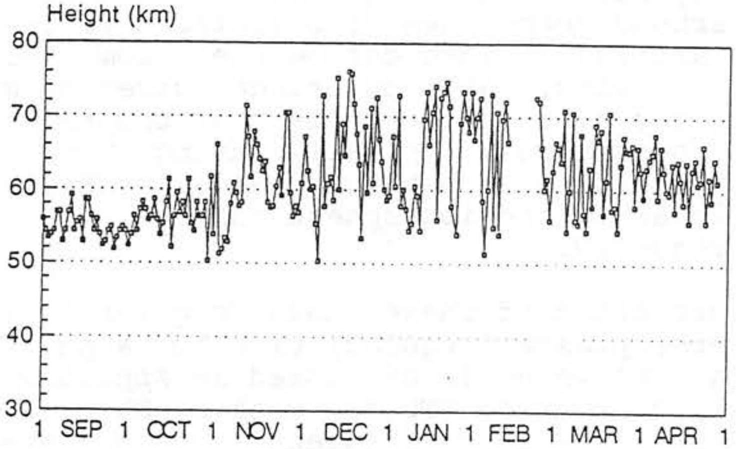


Figure 54 - Height Variations of Ozone Layer, '99-'00.

Long-Distances on Low-Bands -

The above discussion points to the various processes which have an effect on the propagation paths of signals on the low bands. The basic link between motions of the atmosphere and the ionosphere is collisions between neutral particles and positive ions, of comparable mass but far outnumbered by the neutrals. And ionospheric electrons follow the positive ions because of mutual electrostatic attraction; but electrons collide with neutral particles too and that process is responsible for the ionospheric absorption that gives rise to signal loss. In opposition, as it were, to loss by absorption is signal ducting in the electron density valley between the E-layer peak and the lower F-region, shown earlier in **Figure 17**.

Ducting can pass signals along very efficiently but it will come to an end (Hall-Patch, 1999) when ducted signals encounter downward tilts in the F-region near the terminator. Like normal propagation on low bands by E-F hops and F-hops, those are then converted to E-hops as they near the terminator and are finally absorbed in the region of dense ionization.

Those remarks imply the terminator is the "end of the line" for low-band signals. That is the case but only if the signals ever get that far with any strength. In saying that, it should be recognized that ducted signals can be brought down to ground level by an ionospheric irregularity at any point, even before reaching the terminator. Beyond that, signal survival depends on loss of intensity as well as the mode of signal propagation on leaving the transmitting antenna and the degree of power coupling into the ionosphere from polarization differences.

Having spoken of the "end of the line" when signals reach the terminator, it is worth noting that low-band signals are really contained completely within the bounds of the dark hemisphere as the ionization overhead keeps them from rising more than about a few hundred km in altitude. That can be seen from their effective vertical frequency (Davies, 1990) on launch, given by multiplying their frequency by the sine of the angle that the RF approaches the bottom of the ionosphere. Typically, using about 20 degrees for a launch angle, that works out to about 0.63 MHz; so 1.8 MHz signals rise no higher in the ionosphere than vertically-directed signals of that frequency.

A timely illustration of these ideas is given by **Figure 55** which is a transverse plasma frequency plot for a path from Burma (XZ) to California (W6) which is discussed in Appendix A. The plot is for January 26 at 1430 UTC and with a SSN of 100 and an magnetic index Ap of 5. The iso-frequency contours are at 0.2 MHz intervals and 1.8 MHz signals launched at 20 degrees from Burma (on the left) would proceed toward California (on the right) but in their refraction, they would never rise higher than the 0.6 MHz contour. Moreover, F-hops and ducted signals would be returned to ground level by refraction from the downsloping contour around the 11,000 km marker. The sunrise terminator is close to 13,500 km and after ground reflection, signals are absorbed in the intense ionization located there.

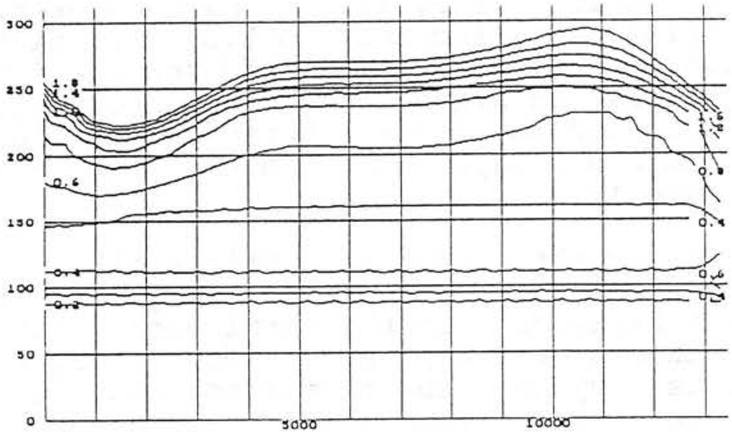


Figure 55 - Transverse Plasma Frequency Plot - XZ (L) to W6 (R)

The question then has to do with the paths that RF follows when contained within the dark hemisphere - whether they go out to the terminator, with signals absorbed exponentially in the ionization which bounds that great-circle, or do other processes come into play from ionospheric structures encountered along the path. Aside from the terminator, there is little else of a rapidly varying nature in the ionosphere, only slow changes of electron density associated with geomagnetic field variations in the vicinity of the magnetic dip equator. The earth's field does organize the high ionosphere but it is more gradual than rapid. So paths may depart from great-circles but not in a radical fashion unless gradients in electron density arise from storm conditions.

Low-Band DX Paths -

It is of interest to look at possible signal paths in the dark hemisphere, such as the three different DX contacts shown in **Figures 31-33** - W0ZV-UA9UCO, A61AJ-N6FF and W4ZV-XZ0A. It was noted in that discussion the oppositely-directed signal paths that define the classical long-path direction at the top of the amateur spectrum could not be considered as applying down on 1.8 MHz; there was just too much ionization from sunlight for signals to survive very far in that direction.

Other interesting contacts are given in **Figures 56-59** - K1ZM-XZ1N, W4ZV-JJ1VKL/4S7, W4ZV-3W5FM and K1ZM-4S7RPG - and the distinguishing feature of those contacts is like the others, the use of directional receiving antennas. Those gave observations which showed the apparent directions of incoming signals were to the SSW or SSE, instead of the short-paths that would be expected from the NE or NW, as suggested by the figures.

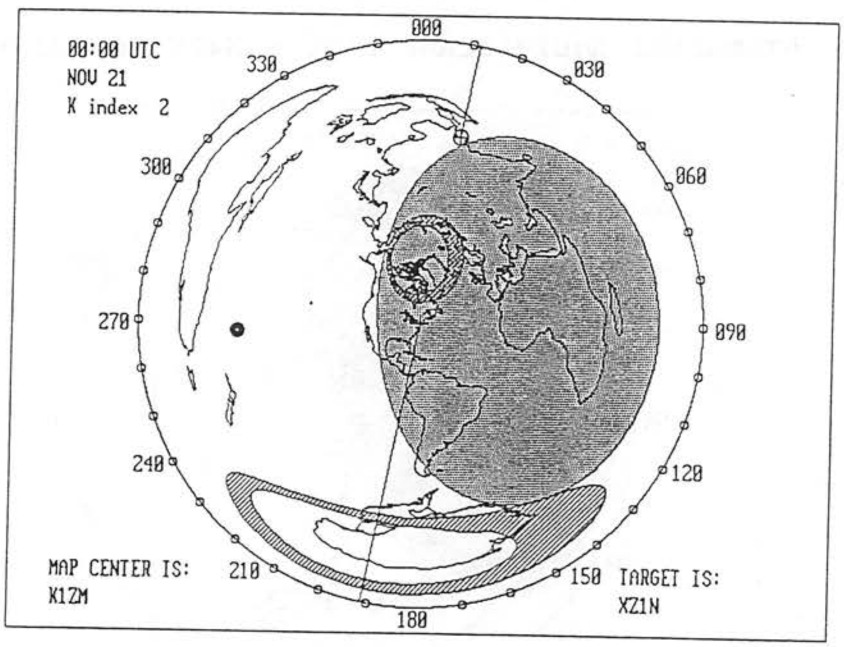


Figure 56 - Azimuthal Equidistant Plot - K1ZM to XZ1N.

By way of interpretation, it was proposed (Tippett, 1991) those signals were guided along by the terminator on reaching that location and at some point, the signals then left the terminator region and went on the the far terminus. No consideration was given to the refraction and absorption that surely took place near the boundary and signals were considered a form of long-path propagation, remaining within the dark hemisphere.

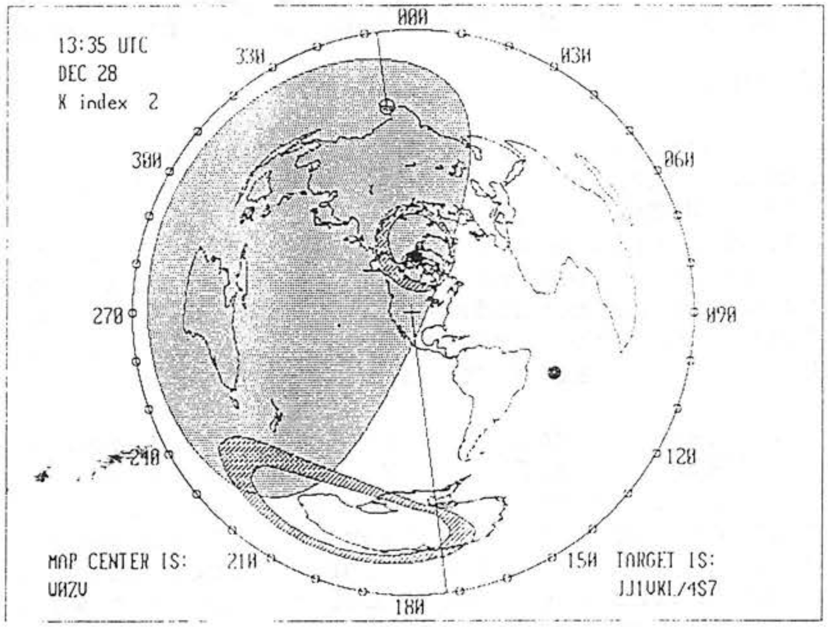


Figure 57 - Azimuthal Equidistant Plot - W4ZV to JJ1VKL/4S7.

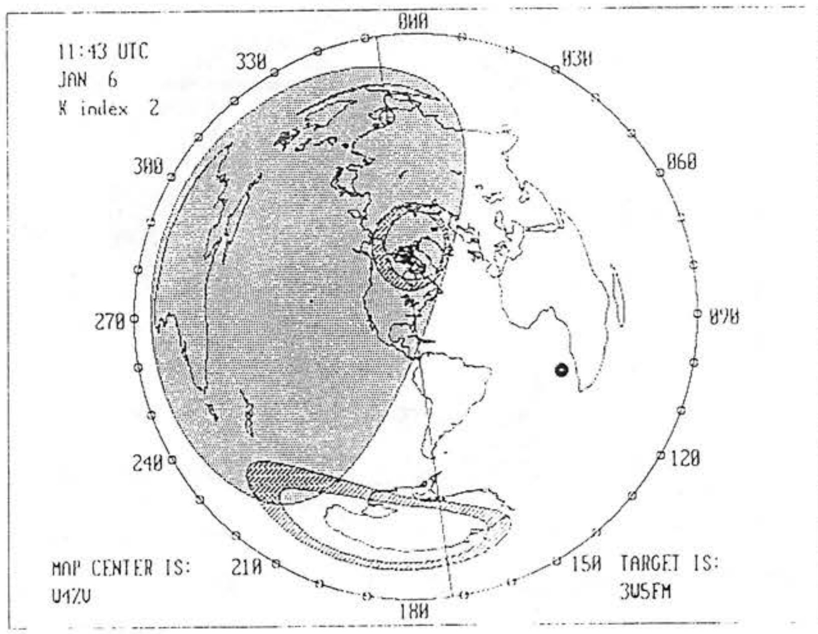


Figure 58 - Azimuthal Equidistant Plot - W4ZV to 3W5FM.

In that regard, two other contacts by K1ZM are interesting, the one with 4S7RPG and the other with XZ1N. Both look like "end of the line" contacts in that their part of the path was close to the terminator. In fact, it was crossing their locations and putting them into daylight, truly an "end of the line" situation but in an entirely different context - closing the path at the point of origin.

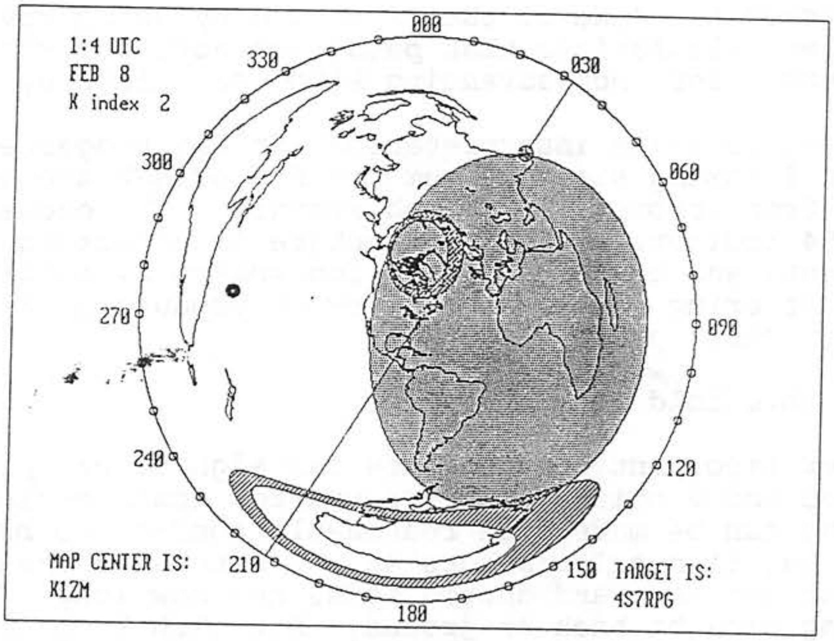


Figure 59 - Azimuthal Equidistant Plot - K1ZM to 4S7RPG.

But in reality, they would be more like "head of the line" situations, when it comes to terminator guidance, as the two locations were being overtaken by the terminator as sunrise approached and coming into gray-line situations. If one accepts the idea of terminator guidance and signals approaching the far terminus in the Northeast of USA from the SSE, the 4S7 path was ideal and would reach close to the southern tip of South America, about 25,000 km along the terminator, before turning north for another 10,000 km or so to reach the terminus in the USA. All that from 100 Watts into an inverted L instead of 13,700 km on short-path from 4S7RPG? The terminator path from XZ1N is about the same. Both of those contacts stretch ones imagination and are just too good to be true if one considers ionospheric absorption.

Beyond being "too good to be true", the idea of signal guidance by the terminator violates considerable experience with the PropLab ray-tracing program, in particular, and the physics of the propagation, in general. With regard to the latter, there is a strong electron density gradient along the terminator and signals should be skewed away from it, into the dark hemisphere. In addition, there should be considerable signal loss in that area. So those shortcomings of the model point out significant inconsistencies or differences with accepted reality.

Another way is by showing, quantitatively, that ray-tracing with the current models of the ionosphere fails to verify the existence of such a reliable path along the terminator. That has been done (Brown, 2000b) in three ways: showing that the path along the terminator is very unstable, suffers heavy absorption when it reaches the "end of the line" and by using ray-tracing to show detailed calculations that paths are actually refracted AWAY from the terminator, not advancing ALONG or guided by it.

As an alternative interpretation, it was suggested (Brown, 2000b) that incoming signals from the SSE or SSW are due to back scattering from strong, short-path signals. The ozone data shown in **Figure 54** indicate how the atmosphere is disturbed by incoming weather fronts and coupling of the ionosphere by collisions would give the scattering centers necessary to produce back scattering of the RF on short-path.

Signals at Threshold -

Another important point is how far signals can propagate and yet be heard above noise. In that regard, ionospheric absorption calculations can be made with reasonable confidence but the weak link in propagation calculations on 160 meters is the division of RF power between hops and ducted modes and how long RF survives before being brought back to ground. But with PropLab Pro, the two types of propagation can be evaluated separately.

The matter of survival of signals from Burma to the West Coast has been looked at by Carl Luetzelschwab, K9LA, and the details of his results are given in Appendix A. In essence, that work considers both ducted and multi-hop signal paths and shows that the limit of multi-hop propagation at a level above receiver noise is about 10,000 km, making the efficiency of ducting an important matter in long-distance contacts.

That calculation is based on a determination of the minimum detectable signal (MDS) of a receiver and how the strength of incoming RF compares with that power level. The calculation is carried out step by step, from the transmitting antenna, through the ionosphere and to the other antenna which feeds the receiver. Since electromagnetic energy is absorbed exponentially, there is no finite or discrete range for signals, only a gradual decline with distance that can be used in a comparison of strength from an incoming signal at the antenna and the MDS.

So for given conditions, an increase or decrease in power from the transmitter to the antenna can affect the signal relative to the MDS threshold. A ten-fold increase in power giving 10 dB additional signal intensity would help surmount the threshold while 10 dB of ionospheric absorption from a PCA event could lower the signal signal strength so that, while still there physically, it might be below the MDS and communication would be impossible.

Actually, the ionospheric details of the propagation show that signal strength depends on mode, direction of propagation along a path and radiation angle. With the PropLab Pro program, it can be shown there is a shift in the complexity of propagation modes with increasing launch angle, the number of F-hops and E- hops changing for a given overall distance of propagation. In addition, ducting may also appear among the modes. But most important of all, it has been shown (Brown, 1998a) by PropLab Pro calculations how low-band propagation can be non-reciprocal in nature because of polarization differences.

This is a magneto-ionic effect and is due to the fact that propagation relative to the direction of the geomagnetic field may be quite different at the two ends of a path. In that regard, the XZ-to-W6 calculations in Appendix A are for a path where the propagation is nearly along the field direction at the XZ end as the geomagnetic field is nearly horizontal at the low-latitude, XZ end. On the other hand, the field lines are at high angles at the high latitude, W6 end. These two extremes are quasi-longitudinal and quasi-transverse in the terms of magneto-ionic theory and Appendix A shows how the modes and ionospheric absorption differs acccording to direction.

Chapter IX -

The discussion thus far has dealt with MUFs, absorption and skewing, but more as topics than in detail. Now we turn to the question of absorption and examine it so as to speak of the distance that signals can travel and still be heard above the noise. This bears on the question of long-path, for one thing, and the divisions between multi-hop modes and the role of ducting.

Signal absorption occurs because of collisions between the ionospheric electrons along a path and the neutral constituents of the atmosphere. The RF waves excite electron oscillations at the wave frequency and those are responsible for more collisions. Earlier, **Figure 7** showed how absorption, on a per electron basis, varied according to band and height. Actual amounts of absorption then depend on the electron density as a function of height. That in turn depends on the illumination in the lower ionosphere and the ion chemistry of the region.

The discussion now centers on the low bands in the amateur spectrum and that means propagation in darkness, away from the major source of ionization, direct sunlight, and focusing on the sources at night - Xrays and UV from starlight, galactic cosmic rays and solar radiation scattered down into the dark hemisphere by the geocorona. Those are weak sources of ionization but their effects are largely in the deeper parts of the D-region, where electron collisions with neutrals occur at the highest rates.

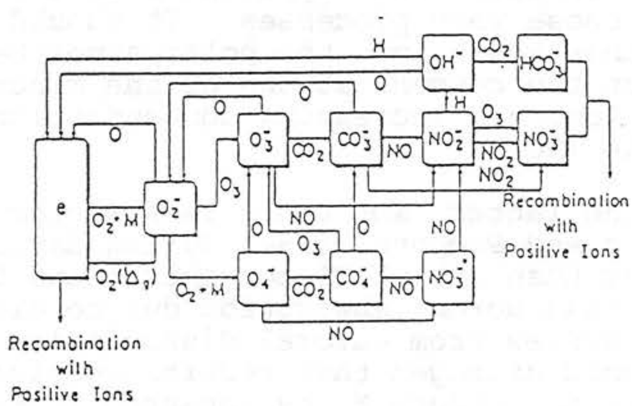


Figure 60 - Negative ion reaction scheme in lower ionosphere

Negative Ions -

As a result, processes involving electron chemistry below the 90 km level are of utmost importance. Those are related to the formation of negative ions by molecules capturing electrons as the sun sets. The process begins with molecules of oxygen and ends with very stable negative ions in the dawn ionosphere. The process is quite involved, as shown by the reaction scheme (Reid, 1975) in **Figure 60**, and depends on various trace constituents in the atmosphere - ozone, carbon dioxide, and oxides of nitrogen.

In that diagram, the left side represents the start of negative ion formation at sunset when electrons are captured by moleular oxygen. How the reaction goes from there on depends on the concentrations of the atoms and molecules of oxygen and the availability of the minor constituents - nitric oxide, carbon dioxide, ozone and nitrous oxide. The trace constituents may or may not be in abundance, depending on transport processes, so progress of negative ion formation toward the stable, terminal ions on the right of the diagram, may follow different routes, at different times. Since absorption depends on the presence of free electrons in the ionosphere, this variability in negative ion formation can lead to variations in signal strengths, and from a meteorological origin.

Toward dawn, the formation of terminal ions reduces the free electron density below the normal levels that might be expected from the sources of ionization. As a result, absorption may be at low levels when the terminal ions are in abundance, at higher levels where the opposite is true. And there could be geographic differences in these matters, like differences in the weather.

In any event, these processes can be expected in the dark ionosphere and also to be in effect with stronger sources of ionization, such as solar proton bombardment during polar cap absorption events. In fact, the day/night effect found with PCA events result from those very processes. It should be added that transport process that reach into the polar atmosphere from lower latitudes can affect the concentrations of the minor constituents there, stabilizing some and increasing concentrations of others, notably nitric oxide (NO).

In regard to the latter, NO, there is a winter anomaly in absorption (Appleton and Piggott, 1954) during daytime hours which is related to higher than normal NO concentrations in winter. The anomaly is greater than normal absorption due to electrons from additional NO that arises from auroral dissociation of nitrogen molecules. The atomic nitrogen that results combines with the molecular oxygen ion to produce NO by ion-atom interchange. The NO undergoes meridian circulation into the polar cap where it is quite stable in the absence of illumination. Then, on circulation back to lower latitudes, the NO represents additional targets for solar UV and results in more free electrons, but only during the daytime.

There has been a confusion in amateur radio circles about the winter anomaly, incorrectly suggesting that the higher than normal absorption occurs on days with polar warmings, called STRATWARMS. While it is not expected to occur during hours of darkness, when 160 meter DXing is conducted, the idea is still abroad; however, a careful study of 160 meter DX contacts (Luetzelschwab, 1998) finds no evidence for the effect. Hopefully, the matter will come to rest there.

The negative ion cycle shown above starts with molecular oxygen ions which easily undergo photo-detachment by visible radiation. At sunset, that stops and the ions move toward the right in the diagram, the route depending on which trace molecules are available. The terminal ions on the right bind the electrons firmly and require UV for their detachment.

At sunrise, the arrival of UV is delayed until the sun rises above the solid earth AND the ozone layer. As a result, low-band DX openings last longer than expected from ground sunrise. Beyond that, absorption is less in night-time hours than expected for the level of ionization; in disturbed conditions, polar cap absorption noted in dark regions gives an underestimate of radiation influx in the opposite hemisphere.

Signal Testing -

Whatever the circumstances, the absorption per km of path length varies as the product of the electron density and the electron-neutral collision frequency; in addition, there is a "resonance denominator" from magneto-ionic theory which must be considered. The denominator is much like that in a series L-C-R circuit where losses are very high when inductive and capacitive reactances become equal. The form of the denominator is given by the expression

[(XL-XC)^2 + R^2]

where the operating frequency plays the role of the inductive reactance and the electron gyro-frequency replacing the capacitive reactance and the resistance is replaced by the electron-neutral collision frequency. One last detail: the minus sign is replaced by a +/- sign, the plus sign for the O-waves and the minus sign for the X-waves of magneto-ionic theory.

Clearly, X-waves suffer heavy absorption, as shown by the numerical example where the collision frequency at a given altitude is 0.1 MHz, the gyro-frequency is 1 MHz and the operating frequency is 1.8 MHz; that gives X-wave absorption (in dB/km) a factor of 12 greater than O-wave absorption, say 72 dB as compared to 6 dB. So X-waves don`t survive long in that environment and whatever power is radiated as X-waves, possibly up to half the transmitter output, is lost to heating the atmosphere.

With that formalism in hand, the "reach" of propagation by a system, transmitter and antenna, is a matter of finding electron densities along paths and using one more variable, the electron-neutral collision frequency. That was an item of great importance some years ago, being explored in the laboratory as well as by rocket experiments, recording the signal strengths of onboard transmitters as they rose through the absorbing region. At this point, the data are in good agreement, theory and experiment, and will be applied in Appendix A to address questions having to do with the propagation of 160 meter signals.

The discussion begins with a 160 meter path, from Burma (XZ0A) to California (W6), on January 26, 2000 at 1430 UTC, about 45 minutes before dawn. The idea is to find how far signals carry in the short-path direction before falling below the minimum discernable signal level (MDS) of a receiver and then becoming unreadable. The path length is 13,500 km but rather than get involved in the final aspects of the path, which may differ for multi-hops and ducting modes, the study is done in the ionosphere, at a point before that starts and at 10,000 km distance from the transmitter.

So the PropLab Pro program was used to look at the mode structure on the path, then putting in all the gains and losses - antennas, electron-neutral collisions in the ionosphere, ground reflection and signal spreading - to see what intensity is left after 10,000 km and how it compares with the MDS. This will show how far multi-hops can carry signals, when efficient ducting takes over on long-haul DXing and even show the degree to which grayline propagation contributes to DXing on 1.8 MHz. This result will serve to put a bound on speculation about possible paths and have amateur operators look more closely at the mechanisms and limits of propagation.

Chapter 10 - **Ten Years in a Nutshell -**

Computing -

The earlier long-path study was conducted on 20 meter CW from April 1991 on to March 1992. Before that, most computers were limping along with 2-8 MHz clock speeds and propagation programs were few in number, say MINIMUF, MINIFTZ4, MAXIMUF. Those were available in source code and much in the way of experimentation was going on, even the writing of prediction programs that would handle long-path problems. But when IONCAP program was adapted from main frame status to fit on desktop PCs, then the program development by amateurs began to decline as a result, particularly when IONCAP derivatives came online, say CAPMAN and PROPMAN.

The commercial propagation programs were more complex, now including estimates of signal strength for paths and the man-made noise that had to be overcome for useful communications. The earlier idea that MUFs were most important, enshrined in monthly plots in QST, was losing ground and interest growing whether signals could go through the ionosphere and still be heard above the noise. But long-path directions were included in the options.

One of the early programs in amateur circles was MINIPROP by Sheldon Shallon, W6EL. It came on the scene in 1985, using the F-layer algorithm from MINIMUF. It included a long-path option and went through a series of upgrades, starting with substitution of the MAXIMUF algorithm, and had further refinements, such as a mapping utility, until December 1996 when MINIPROP PLUS was finally withdrawn from the market. Its Version 2.5 remains my favorite propagation program because of its speed and versatility.

The programs based on IONCAP, such as CAPMAN, have drivers which are a vast improvement over the original program. Capman does have all the range of options or methods in IONCAP but for amateur purposes, more practical methods are available first. I still use IONCAP in very technical matters as others I deal with use the same program, enabling rapid comparison of results.

The program, PROPMAN, was based on IONCAP but is limited in its applications as it only uses the signal/noise methods in IONCAP. That being the case, it serves best as a program for the lower bands where MUFs are not needed. On review, it was found (Luetzelschwab and Brown, 1995) to lack a long-path option. That is explained by the fact that the program was originally prepared for use by the Department of Defense, not for an amateur audience.

A number of auxiliary programs appeared too - one of the most important was DXAID, for its marvelous mapping utility. It has both Mercator and azimuthal equidistant map capability and those maps are used throughout this book as they show both short-and long-paths as well as the terminator for any date and time. Those features are particularly helpful in dealing with paths close to the terminator. In addition, it includes auroral zone mapping for various levels of the magnetic activity, given by the K-index and based on data from the NOAA satellites.

Other important auxiliary programs that appeared in the last decade include IRI 1990, the International Reference Ionospheres, and IGRF, the International Geomagnetic Reference Field. Those programs provide background material to go with predictions, especially as the awareness of the importance of magneto-ionic theory grows.

That was particularly aided by the introduction of the Skycom and PropLab Pro programs, starting back in 1994. Those programs were based on work done in the mid-60s by scientists at the Central Radio Propagation Laboratory in Boulder, CO. Like IONCAP, the ray-tracing program was re-written so it would fit within a desktop computer. That enabled those seriously interested in propagation to have visual representations of what was only given in tables by MUF programs - graphics displays of the type and height of hops, for one thing. A long-path option was included in the programs.

Even more powerful displays, particularly at low frequencies, were the cases of ducting that came out of ray-tracing as magneto-ionic methods are used in PropLab Pro. There were sound reasons in theory to expect ducting in that part of the spectrum but it is quite another matter to see the ray-traces develop, oscillating up and down between the E- and lower F-regions, and moving forward without any intermediate ground reflections. Absolutely beautiful to behold!

Of course, it was the growth in speed as well as capacity and expansion of computer use with the Internet that set the tone of the last decade of the 20th Century. Web sites blossomed like dandelions and every bit of geophysical and solar data that is related to the magnetosphere and ionosphere is now available for online inspection or downloading. In that regard, by going to http://www.sec.noaa.gov/today.html you can see the current solar Xray flux, such as shown in **Figure 61**, as well as aspects of the current satellite environment, in **Figure 62**, that are found out at geosynchronous orbit (6.6 Re), where GOES 8 and 10 are located.

The data in those figures is taken close to earth, within the magnetosphere, and their availability represents quite an advancement. But the latest improvement in the website for the Space Environment Center (SEC) at NOAA (http://sec.noaa.gov) now includes data on the solar wind from the ACE satellite out in front of the earth. The data take the form of solar wind dials, as in **Figure 63**, allowing amateurs to get 15-minute averages of real-time solar wind data - the vertical component of the magnetic field, the solar wind speed and the dynamic pressure.

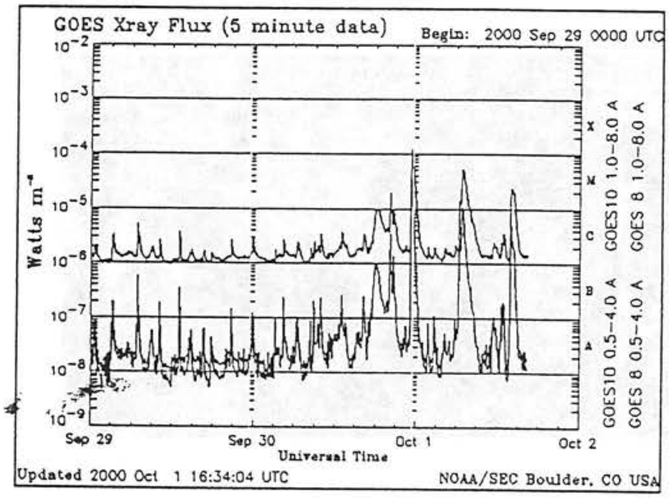


Figure 61 - Xray Fluxes at Satellite Altitude

If that were not enough, the user can even "animate" the display to see a movie of the solar wind data during the previous 12 hours. Those are the BIG VARIABLES that set the stage for what follows later at the magnetosphere and, more particularly, in the ionosphere as the solar wind blows by the earth.

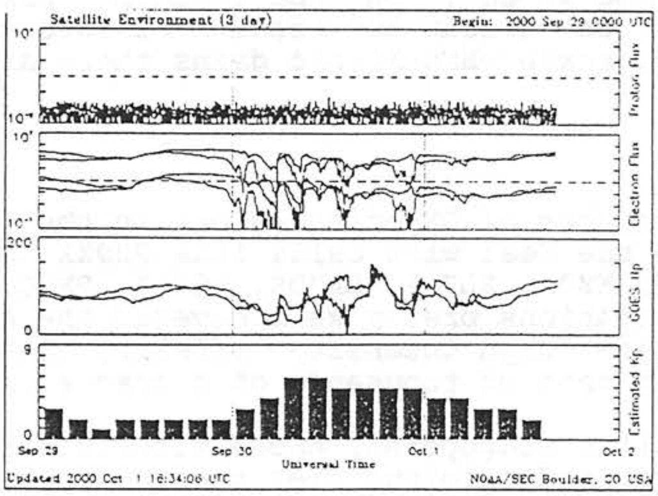


Figure 62 - Particle and Magnetic Data from Satellite Altitude.

That movie, showing variations of the principal features of the solar wind, is truly part of "the information age" when it comes to radio propagation. But that is a problem - too much information and too little understanding. This is the case as there has not been a corresponding increase in education nor training in the amateur ranks, at least that I have seen.

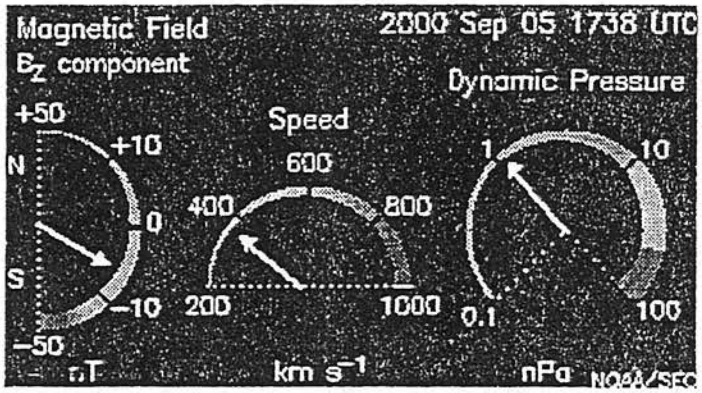


Figure 63 - Solar Wind Dials from ACE Spacecraft.

So people are exposed to more and more data that they don't understand nor do they know where it comes from or how it is taken. The magnetic K-indices are but one small example. In that connection, sad pleas for their explanation are often seen on the DX reflectors; the data are there but nothing in the way of explanation or interpretation. This observation of mine is not new; others have made it too. But the troubling part is that it is getting worse as the amount and breadth of information grows and continues to outstrip what little gains there are in real understanding.

DXpeditions -

There were a number of DXpeditions out in the field during the decade, off to the West with calls like P29XX, S21XX, VK9CR, VK9XY, VK0IR, XZ1N, XZ0A, ZL7CI, ZL7DK, 8Q7AA, 9M0C, to mention several. Those operations pretty well covered the bands, from 10 to 160, and some were "high intensity" affairs, with large groups of operators making tens of thousands of contacts in a few weeks.

From a scientific standpoint, those efforts offered great promise as they provided opportunities to study propagation from point sources of radiation over short periods of time. From my perspective, some proved to be invaluable in the knowledge they provided. By going through a number of the logs, I worked up plots of many long-path contacts from 10 to 80 meters, no doubt about it. However, 160 meters was another matter; hard as I looked, not a single case of long-path propagation was to be found in the logs. Usually the long-haul contacts on 160 came up short as they ran into trouble in the auroral zone or the polar cap.

Some of the locations were unique, some of the timings were unfortunate. Taking the bad part first, the limitation of the ZL7CI to daylight hours on Campbell Island was most unfortunate. The antipodal point for Campbell Island is on the west coast of Ireland and it could have been instrumented in a major way if night-time operations had been approved by the New Zealand government. With proper assurances, maybe the New Zealand DSIR could be persuaded to allow another DXpedition and night-time operation; the benefits would far outweigh the risks to the island's environment.

While discussing unfortunate choices, some DXpeditions were undertaken at low-latitude locations without any regard for noise or local thunderstorm activity. Those efforts usually were not "planned" and happened because there was no other possibility in the timing. But having served as propagation advisor for several DXpeditions, I can say plans made for the winter solstice prove to be far more satisfactory to all concerned than those for equinoxes and toward the summer months. Further, the chances of magnetic disturbances are far less as can be seen in **Figure 64** showing the distribution of magnetic storminess.

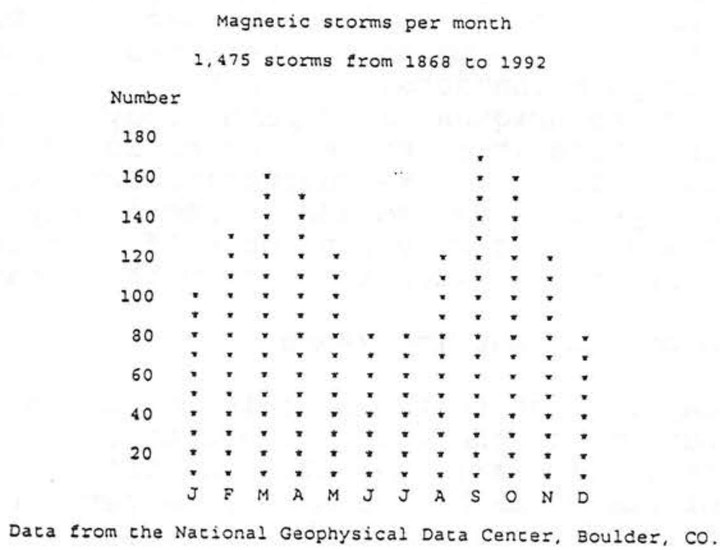


Figure 64 - Distribution of Magnetic Storms by Month.

The most interesting operation of all was at Chatham Island, by the ZL7DK operators. The antipodal point for Chatham Island is located on the southern coast of France and ZL7DK on 160 meters yielded fantastic results, as shown earlier in **Figure 30**. But again, in spite of the incredible opportunity, there were no long-path contacts made on the 160 meter band. Given the importance of that result, another DXpedition from Chatham Island should stand with the highest priority for the next solar minimum. The next DXpedition should be exclusively for propagation studies on 160 meters and as many stations recruited as possible for the U.K. and European areas.

DX Contesting -

When DX contesting is taken afield, like a DXpedition, the high rate of contacts offers the possibility that the logs will be of value for propagation studies. However, I must confess that my experience in this regard is rather limited (Brown, 1998b), only following two major efforts, that of the British group that went to Togo and signed 5V7A in '96 and '97. The logs from Togo showed little in the way of long-path contacts on any of the bands but the main effort by the group was contesting, not DXing, and I learned more about demographics and its relation to contesting than long-path propagation.

On the other hand, the VK0IR DXpedition to Heard Island did include some time in a DX contest but with the great interest in Heard Island, per se, it made the contest time quite unimportant. As mentioned earlier, long-path contacts were made by VK0IR in considerable numbers on 40 meters, fewer on 80 meters and none on 160 meters.

One amusing point about long-path propagation and contests came up during my original study. I made a point of not trying any long-path DXing on weekends with international DX contests as contest operators seemed to be more interested in short-path contacts than long-path contacts. In that regard, on more than one occasion after the original long-path study, I stumbled onto stations in South Africa while contesting on 20 CW; I could hear them on long-path while they were chattering away with each other during their exchanges. I called and raised a couple of them via long- path, then was told firmly that only African contacts were counted in the contest. So much for long-path propagation.

The Main Results of the Last Ten Years -

Looking back, I point to two DXpeditions as making the greatest contributions to the study of propagation, in general, and long-path, in particular: the ZL7DK and VK0IR efforts. The huge dead zone of the VK0IR has to make a believer of anyone who doubts the strength of ionospheric absorption, particularly on the 160 meter band.

But the ZL7DK DXpedition reached farther and was more significant in its contribution to the study of propagation with the small pattern of contacts in the antipodal area, separated by a narrow region. Those were due to absorption of signals starting at the transmitter as sunlight swept across the field of view of the antenna. The figure is repeated here for emphasis, all the contacts in the U.K. (shown by a "+") coming after sunset at Chatham Island and contacts in Western Europe (shown by a "*") coming many hours later, just before before sunrise.

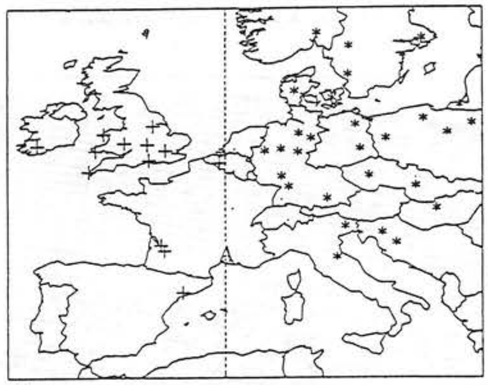


Figure 65 - ZL7DK Contacts near its Antipodal Point.

Those important results were due to the efforts of more than one person but the next one, the study of dawn enhancements of low-frequency signals, was due to just one person and continued over a period of two years. Here, I am talking about the fine work of Nick Hall-Patch, VE7DXR. His recordings of low-frequency broadcast stations indicate dawn enhancements are due to ducted signals being released and adding their signal strength back to a receiver at ground level. Such recordings surely point to the role of magneto-ionic effects in propagation.

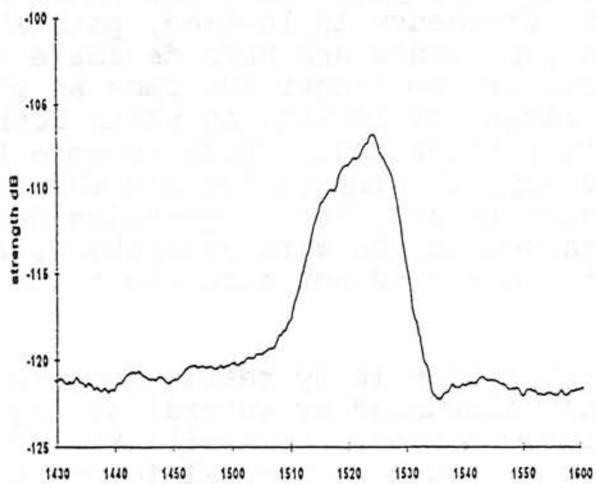


Figure 66 - Dawn Enhancement on 1566 kHz.

Finally, on the more theoretical side, a major addition to the tools for use in understanding propagation resulted with the release of the SKYCOM and PROPLAB PRO software, starting in 1994. Those programs are versatile, giving ray-tracings along paths, ionospheric maps of the E- and F-regions, maps of the geomagnetic field and electron density profiles. The magneto-ionic ray-traces of the PROPLAB PRO program are particularly informative when seen in conjnction with maps of the geomagnetic field. One of the ray-traces is included here, again for emphasis.

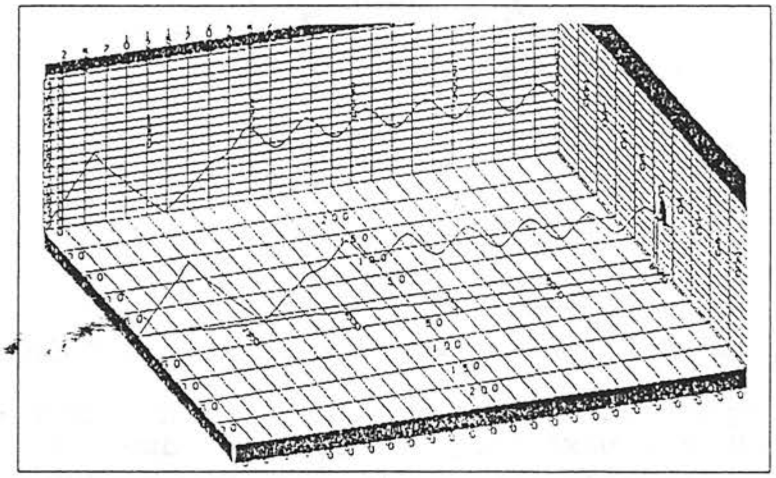


Figure 67 - Ray-Trace showing a F-hop and Ducting.

Conclusion -

Long-path propagation begins simply at the highest end of the HF spectrum, where signal absorption is quite small and MUFs are most important. As the frequency is lowered, path skewing and absorption increase in importance and MUFs decrease in that regard while great-circle paths are no longer the same as radio paths. There is a transition range, 10-18 MHz, in which both MUFs and absorption are important; below that, there is more than enough ionization overhead to support propagation and then absorption and skewing play the dominant roles. For frequencies down at 1.8 MHz, signals are fully contained in the dark hemisphere, not able to penetrate the ionization overhead nor past the terminator which bounds the region.

Propagation in that region is by refraction when the ionosphere is quiet, not disturbed by auroral or magnetic storms. But under disturbed circumstances, there will be locations with locally intense ionization, such as auroral forms, and propagation may result from reflection by highly ionized regions. Finally, in the presence of severe weather conditions, atmospheric motions coupled to the ionosphere by ion-neutral collisions may break down the smooth ionosphere into irregular regions and signals will be propagated by scattering, instead of refraction or reflection.

While there are sound experimental demonstrations of long-path propagation on all the other amateur bands, there is no such evidence on the 1.8 MHz band. What were thought to be examples of long-path propagation now seem to be cases where back scattered signals from short-path propagation come in from near an apparent long-path direction. This limitation on propagation is the result of the major role played by ionospheric absorption on the low band of the amateur radio spectrum.

Appendix A -

An Investigation into Propagation Modes and Absorption on 160 m.

Carl Luetzelschwab, K9LA

With absorption varying inversely proportional to the square of frequency, our 160m amateur band suffers the most attenuation due to electron-neutral collisions. Qualitatively, this is well understood, but there's little, if any, quantitative data in the amateur literature that truly shows the impact of absorption on 160m.

In Ionospheric Radio Propagation (Davies, 1965), Figures 7.5 and 7.6 present graphical data that allows one to estimate absorption on a per-hop basis. But this data is for twilight and daylight conditions (solar zenith angles less than 102 degrees) and only goes down to operating frequencies of 3.5 MHz or so. There's a good reason for this lower frequency limit - the calculation of absorption was simplified by ignoring the effect of the Earth's magnetic field at operating frequencies near the electron gyro- frequency. With electron gyro-frequencies in the 0.7 - 1.7 MHz range, depending on magnetic field intensity, any rigorous calculation of absorption must take the Earth's magnetic field into account.

With no quantitative data for guidance, amateur radio propagation enthusiasts can easily get into trouble with signal path speculation without any physical boundaries to restrict the propagation of 160m energy. But in 1995 help for amateur radio operators arrived. It's in the form of ray-tracing software called Proplab Pro.

Proplab Pro is a sophisticated 3-dimensional ray-tracing program that is sold by Solar Terrestrial Dispatch (Oler, 1994). It is based on the ray-tracing model developed by Jones and Stephenson in the late 1960s. Those developers were with the same Boulder group that gave us the well-respected IONCAP propagation prediction software.

Proplab Pro uses the IRI (International Reference Ionosphere) model of the ionosphere. Its ray-tracing engine uses the Appleton-Hartree equations of motion for electromagnetic waves in an ionized medium in a magnetic field, allowing both ordinary and extraordinary waves to be traced. The Appleton-Hartree equations also include the effects of electron collisions with neutral particles - the cause of absorption. Thus, when the calculations for the ray path are made, accurate calculations of absorption are also made. This software allows one to study propagation on 160m in two key areas: hop structure, including ducting and non-great circle paths, and received signal power using appropriate models of antenna patterns.

Such a study was undertaken on 160m using data from the XZ0A DXpedition in January/February 2000. The XZ0A operators made just over 250 QSOs with North America on 160m at North America sunrise. The bulk of the QSOs were with stations west of XZ0A's antipodal longitude - that means the short path for these stations was from their northwest. But most of these stations reported hearing the XZ0A signal best from the southwest. This is an interesting observation, and is consistent with other observations on 160m and 80m that indicate that signals commonly come out of the southwest at North America sunrise. Theories on how the signals arrived out of the southwest are usually based on the signal following the terminator out of North America to the southwest, then to extreme southern latitudes and finally into XZ0A from their southeast.

This path is approximately 22,000km in length, whereas the short path is around 13,000km - quite a difference. On the surface this southwest path sounds plausible, as no quantitative data exits to confirm or refute the hypothesis. Thus the specific task of this study was to estimate how far 160m energy can go before being unreadable at a receiver. To do this, Proplab Pro was used to evaluate a 10,000km short path out of XZ0A toward W6 on 160m on January 26, 2000, which was one of the days that XZ0A made numerous contacts.

Specifically, Proplab Pro was set up for:

1) XZ0A at 10N/98E and 10,000 km to target at 53.8N/158.2W
2) January 26, 2000 at 1430 UTC (entire path was in darkness)
3) SSN = 100, Ap = 5 (from 1/26/2000 data)
4) 1500w transmitter power into an isotropic radiator
5) ordinary ray with electron-neutral collisions enabled
6) Appleton-Hartree ray-tracing model (with magnetic field)

With respect to item 6, Proplab Pro users can also select the Sen-Wyller ray-tracing model. When this option is used, the value for the electron-neutral collision frequency is different than the Appleton-Hartree method because of how the energy of the electron thermal distribution is defined. The two methods give comparable absorption results, though, so either can be used for absorption calculations. But the Sen-Wyller option does not include the effects of the magnetic field. Because of the importance of the magnetic field in the hop structure on 160m (Brown, 1998), the Appleton-Hartree method was used, with 83,000 electron-neutral collisions per second at 100km (Detrick and Rosenberg, private communication).

The ray-tracing effort was done from 0 degrees to 25 degrees in 0.1 degree steps. The results showed a very structured order to the possible modes propagating over the 10,000km path. Table I summarizes the Proplab Pro results in terms of the mode and the minimum, maximum, and average total absorption. In addition, the elevation angle at which average absorption occurs is identified. This is used in conjunction with antenna patterns to calculate signal power at the receiver.

Summary of Modes and Absorption Over 10,000km Path in Darkness

mode	minimum absorption	maximum absorption	average absorption	elevation angle
1F + 6E hops*	---	---	83dB	7.0 degs
2F + E hops	85dB	107dB	98dB	10.5 degs
3F + E hops	114dB	128dB	120dB	14.4 degs
4F + E hops	124dB	157dB	130dB	17.6 degs
5F + E hops	146dB	184dB	149dB	21.4 degs
1F + duct	32dB	48dB	38dB	8.1 degs
2F + duct	42dB	81dB	53dB	12.4 degs
3F + duct	48dB	95dB	74dB	15.9 degs
4F + duct	81dB	112dB	89dB	19.6 degs
5F + duct	95dB	138dB	106dB	23.4 degs

* only occurred at one elevation angle

Several general trends can be seen in this data:

1) As the elevation angle is increased, invariably absorption increases due to more transitions through the absorbing region (more hops). This indicates that low elevation angle radiation (at least for transmitting) is extremely important on 160.

2) Ducting is a very common occurrence - ducting occurs because of the electron density valley above the E region peak in the dark ionosphere.

3) The best multi-hop mode has, on average, 45dB more absorption than the best ducting mode. Ducting is very efficient without its multiple transitions through the absorbing region.

With accurate absorption data now available, it is not too difficult to assess the impact of absorption on 160m. This is done by using the Friis Transmission Equation (Kraus, 1988) and adding in loss terms for absorption and ground reflections:

$$Pr = Pt + Gt + Gr - La - Lg - [32.5 + 20\log(F) + 20\log(D)] \quad (1)$$

where

Pr is the received power in dBm
Pt is the transmitted power in dBm
Gt is the transmitting antenna gain in dBi
Gr is the receiving antenna gain in dBi
La is the total loss due to absorption in dB
Lg is the total loss due to ground reflections in dB
F is frequency in MHz
D is distance in km

The term in brackets is the free space loss due to spherical spreading of the energy - one over distance squared.

Assuming 1500w (61.8dBm), 1.83MHz, and 10,000km, equation (1) simplifies to:

$$Pr = -55.9\text{dBm} + Gt + Gr - La - Lg \qquad (2)$$

Next, assuming vertical monopoles over average ground at both ends and a conservative 2dB loss per ground reflection (the path is mostly over water), the data from Table I can be used to calculate received signal power.

For the "1F + 6E hops" mode, equation (2) results in:

$$Pr = -55.9\text{dBm} + (-4\text{dB}) + (-4\text{dB}) - 83\text{dB} - (2\text{x } 6)\text{dB}$$

$$= -158.9\text{dBm with vertical monopoles at both ends}$$

A summary of Product Reviews in QST from 1996 through October 2000 indicates that the average minimum discernible signal (MDS) of a "DX/Contest" amateur radio transceiver on 1.8 and/or 3.5 MHz is -138dBm, with the best at -143dBm.

The best multi-hop mode is 16dB below the internal noise floor of the best receiver. The internal noise floor of the receiver will be considered to be the limit for reception. Admittedly, this does not address the fact that good CW ops can copy a signal several dB below the noise. On the other hand, this also does not address any atmospheric or man-made noise. For example, -115 dBm of noise in a 500 Hz bandwidth was measured on a vertical in Georgia in the morning on one day in August 2000 (Rauch, 2000). This is only one piece of data on a summer day (winter days should be quieter), but it indicates that reception of a signal right at the receiver MDS or several dB below it may not be achievable. Thus, the limit of reception being the receiver MDS is a valid compromise. It also indicates why low noise Beverage receiving antennas are beneficial for serious DXing on 160m.

Going one step farther and assuming 4-Square antenna arrays at both ends (approximately +2dBi at 7 degs), equation (2) results in:

$$Pr = -55.9dBm + (+2dB) + (+2dB) - 83dB - (2x\ 6)dB$$

$$= -146.9dBm \text{ with 4-Squares at both ends}$$

This is still 4dB below the MDS of the best receiver. All the other multi-hop modes, "2F + E hops" to "5F + E hops", are well below the receiver MDS. The conclusion from this effort is that multi-hop propagation on 160m is limited to just under 10,000km. On the other hand, going with the average absorption loss of the best duct mode of Table I ("1F + duct" mode) and using vertical monopoles at both ends results in:

$$Pr = -55.9dBm + (-3.5dB) + (-3.5dB) - 38dB - (2x1)\ dB$$

$$= -102.9dBm \text{ with vertical monopoles at both ends}$$

This is a respectable signal, some 40dB above the best receiver's MDS. Working through the other duct modes indicates that the "2F + duct" mode is about 25dB above the best MDS, and the "3F + duct" mode is right at the best MDS. Thus the "1F + duct" mode, the "2F + duct" mode, and possibly the "3F + duct" mode are the only modes capable of being received at distances greater than 10,000km.

The important question to ask now is can the "1F + duct" mode and the "2F + duct" mode be received at the 22,000km distance, as was hypothesized earlier for the southwest at sunrise observation by following the terminator?

With a good understanding of the modes and absorption of 160m RF in the dark ionosphere, ray-tracing was used to study how propagation worked along and near the terminator. Three important effects were seen:

1) Low elevation angles gave multi-hops, and resulted in significantly more absorption than for the dark ionosphere case. This result was expected, as absorption should be higher than in the dark ionosphere.

2) Higher elevation angles also gave multi-hops, but they also penetrated higher into the ionosphere, and skewed into darkness, due to the electron density gradient across the terminator, and away from the target.

3) Most significantly, though, was the fact that ducting was not seen along or near the terminator due to the electron density valley above the E region peak not being well formed along the terminator.

In summary, 160m DXing over paths longer than about 10,000km must be done via ducted modes in the dark ionosphere. Grayline DXing on 160m does not appear to be a viable mode for anything but short distances (significantly less than 10,000km) via multi-hop (no ducting). Both of these conclusions come from an analysis based on ionospheric physics. This still leaves the question of the observations of southwest at sunrise. Any explanation probably involves scattering or skewing in a dark ionosphere coupled with ducting.

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