SKEWED PATHS TO EUROPE ON THE LOW BANDS

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(this article appeared in the August 1999 issue of CQ)

I started going after 160m DXCC in the fall of 1995. Soon thereafter I subscribed to the topband reflector on the Internet, as it is a valuable aid in finding out when certain 160m operations would take place and the real-time status of those operations.

In addition to "who's going to be on when" threads, another popular thread is propagation - especially those paths that do not appear to follow great circle paths. A recent posting to the topband reflector in reference to the North America-to-Europe skewed path was the observation of Bill Tippett, W4ZV, when he worked SM4CAN on March 10, 1999:

> "*Last night I noticed some very interesting propagation. I first heard SM4CAN around 0230 with a good signal but coming in best via my 80 degree Beverage. My true bearing to SM from here is 34 degrees, so apparently the signal was skewed south by the disturbed geomagnetic field caused by auroral conditions (WWV k=5 at 03 UTC and k=6 at 06 UTC). Kent's signal was also readable on my 40 and 110 degree Beverages but 80 was definitely best. I heard Kent comment to another station that he was hearing us over South America so the skew must have been reciprocal on his side.*"

W4ZV and others have observed this skewed path to Europe many times. Bill saw this skewed path occur more when he was in Colorado (W0ZV), and he even wrote an article back in 1991 for the SWL publication *1991 Proceedings of Fine Tuning* about his observations of long path and skewed path on the lower short-wave frequencies. This article was reprinted in the Top Band Anthology, Volume I (edited by Ward Silver, N0AX) that was offered at the 1998 Pacific Northwest DX Convention in Seattle.

The obvious question for this W4ZV-to-SM4CAN skewed path is: What causes the skewing? Specifically, what in the ionosphere is the cause of this anomaly?

There indeed is an explanation for these skewed paths to Europe. The pieces of the puzzle started falling together when Bob Brown, NM7M, said "go find the gradient and you'll find the answer".

What Bob is referring to is a sufficient horizontal gradient in electron density (an increasing electron density perpendicular to the path) that could significantly skew the signal off one great circle path and onto another great circle path. Just as RF going upward can encounter an increasing electron density (a vertical gradient) and be refracted back to Earth, RF can also be refracted off of one great circle path and onto another by a horizontal gradient. Let's take a look at a map of the ionosphere for the time of the W4ZV-to-SM4CAN QSO to see if there are any horizontal gradients in the area where skewing must have occurred for the skewed path to happen.

Before doing this, a couple comments are in order. First, maps of the ionosphere are usually shown with critical frequencies, or maximum useable frequencies (MUFs) for a given hop length. This is ok, as the electron density is proportional to the square of the critical frequency, and MUFs are proportional to critical frequency. Thus any gradient in electron density will also show up as a gradient in critical frequency or MUF. Second, the propagation of RF down on 1.8MHz is usually confined to the E-region (about 110 km) and lower F-region (200 km or so) because of electron densities and the resulting amount of refraction. Any F-region gradient will have to be looked at in terms of the altitude at which it occurs, as 1.8MHz RF may not get up high enough to be affected by it.

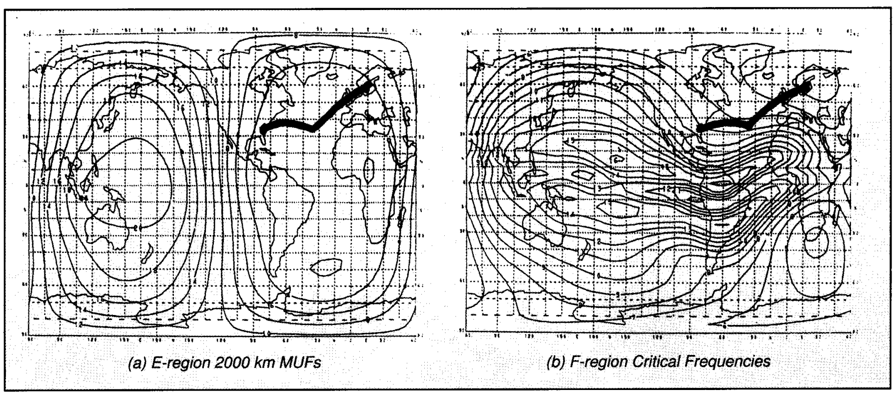

Fig. 1– Ionospheric maps for March at 0200 UTC for SSN = 110.

Figure 1a is a world map of the E-region 2000km MUF and Figure 1b is a world map of the F-region critical frequency. The maps are for March of 1999 at 0200 UTC. Both maps include the skewed path based on W4ZV's and SM4CAN's observations of which Beverages were best for receiving. With their Beverages having 3dB beamwidths on the order of several tens of degrees, though, it's difficult to pin down the exact point where the skewing occurred. The skewed path is in reality two great circle paths - they are straight lines in the real world, but look curved on these maps because the maps are a rectangular projection of the Earth.

There indeed are some horizontal gradients, as shown by those areas where the contour lines are closely spaced (this is similar to a weather map indicating high winds where the contour lines of atmospheric pressure are closely spaced). They're along the sunrise terminator on the left side of both maps, along the sunset terminator in the middle of the E-region map, and in the equatorial region on the F-region map. The sunrise and sunset gradients are far removed from the area we're interested in, so we won't bother with them. But the northernmost edge of the equatorial gradient in the F-region in Figure 1b requires a closer look.

The Proplab Pro propagation software (Solar Terrestrial Dispatch) was used to ray trace a signal coming out of W4ZV on the 80 degree heading. Its ray trace engine includes the effects of the Earth's magnetic field and electron collisions with neutral particles, which are important for accurate results on 160m due to magneto-ionic theory. As expected, since this is an F-region gradient, there wasn't much skewing in the suspect area as the 160m RF just didn't get high enough up into it. It amounted to only a couple degrees off of the 80 degree heading, and this agrees with the results of other ray tracings on 1.8MHz (Oler and Cohen, 1998). It confirms that 1.8MHz energy just doesn't get too high into the F-region before being refracted back to Earth.

But wait a minute - these ionospheric maps come from the database used for propagation predictions, and as such they are monthly median values. In other words, it's a statistical 'average' of what to expect in a one-month period. Any very short-term variations in the data are not shown on these maps, as the variations are just too dynamic.

Do we have any data at these higher latitudes showing the real-time variations and not just the monthly 'average'? We sure do. We have data from incoherent-scatter radar sites operating in Alaska. This allows us to see, on a real-time basis, what's actually going on at these higher latitudes. Let me point out that the data I'll present is several decades old, but it is still relevant and accurate. In the early 1960s, technology advanced to where incoherent-scatter radar could be used to derive electron density profiles. So during the 1960s, the 1970s, and the 1980s, intensive investigations of the high latitude ionosphere were undertaken. Much of the data that we have on the high latitude ionosphere is from this time period.

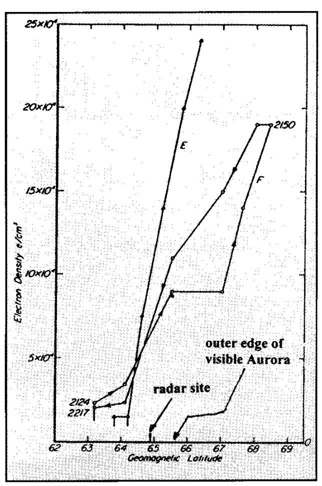

Fig. 2– Latitudinal variation of electron densities for aurorally active night (October 13, 1971).

Figure 2 shows an electron density profile derived from the auroral-zone incoherent-scatter radar near Chatanika, Alaska (Bates, Belon, and Hunsucker, 1973). The y-axis is electron density in electrons per cubic centimeter. The x-axis is geomagnetic latitude.

The scans were along a constant magnetic longitude. The profile is for a night when the authors reported that the geomagnetic field was moderately active as evidenced by observations of the visible aurora.

What's important to note is how steep the gradients are, both in the E-region and in the F-region. In the span of several degrees of latitude, both the E-region electron density and the F-region electron density increase by a factor of at least 10. These gradients are much steeper (by at least an order of magnitude) than any gradient seen in the high latitude area of Figure 1a or 1b. These steep gradients are not shown on the monthly median maps because they are just too dynamic for a monthly median presentation.

The gradient we're seeing in the F-region (two traces are shown - one for the upward sweep of the radar and the other for the downward sweep) is the poleward wall of what's known as the mid-latitude trough. This trough is about 5 degrees of latitude wide, putting the equatorward wall off the left side of the plot at about 60 degrees. As can be seen, the gradient is a sharp reduction in electron density, which translates to a sharp reduction in critical frequency. As noted in the figure, the bottom of the trough is just equatorward of where visible aurora occurs. At first glance, one might assume that this gradient could be important for 160m. But like the F-region equatorial area of Figure 1b, it's just too high to affect our 160m energy (it's been found to be above 300 km).

The gradient we're seeing in the E-region is auroral-E ionization - a sharp increase in electron density peaking at about 110 km. This altitude makes it extremely important for 160m propagation. What's shown in the figure is the equatorward wall (increasing electron density going north) of this steep gradient. The radar profile doesn't show the peak or the poleward wall (increasing electron density going south). This instance of auroral-E ionization occurs just equatorward of the visible aurora. Also note that the radar's minimum sensitivity translates to around 2 times ten to the fourth electrons per cubic centimeter. The normal night-time E-region density is quite a bit below this level at around .3 times ten to the fourth electrons per cubic centimeter, so the gradient is even more extensive than this radar profile shows.

Much effort has been expended in the scientific community studying auroral-E. From these efforts, some very general statements about the steep E-region gradient can be made:

1) The gradient is very dynamic - although it predominantly occurs and is steepest during magnetically active times, it also has shown up during magnetically quiet times

2) The gradient is not confined to the region of visible aurora (the familiar annular ring portrayed in books and on maps), nor is it always right at the equatorward edge of the visible aurora as is seen in Figure 2 - frequently it extends up to several degrees of latitude equatorward of the visible aurora

3) It occurs mostly within several hours of the local midnight portion of the auroral oval, but is not necessarily continuous - gaps can exist

4) Because the outer edge of the auroral oval expands equatorward as geomagnetic field activity increases, this gradient follows along and also moves equatorward

Ok, all this technical information about the ionosphere is interesting, but how does it relate to our skewed path? You've probably figured it out already - this steep E-region gradient occurs in the area where it could provide the skewing for the W4ZV-to-SM4CAN path. How do we know that? As luck would have it, the NOAA-12 satellite made a pass over the northern polar cap around the time of this QSO, and from the data taken by its electron detector the location of the auroral oval can be extrapolated.

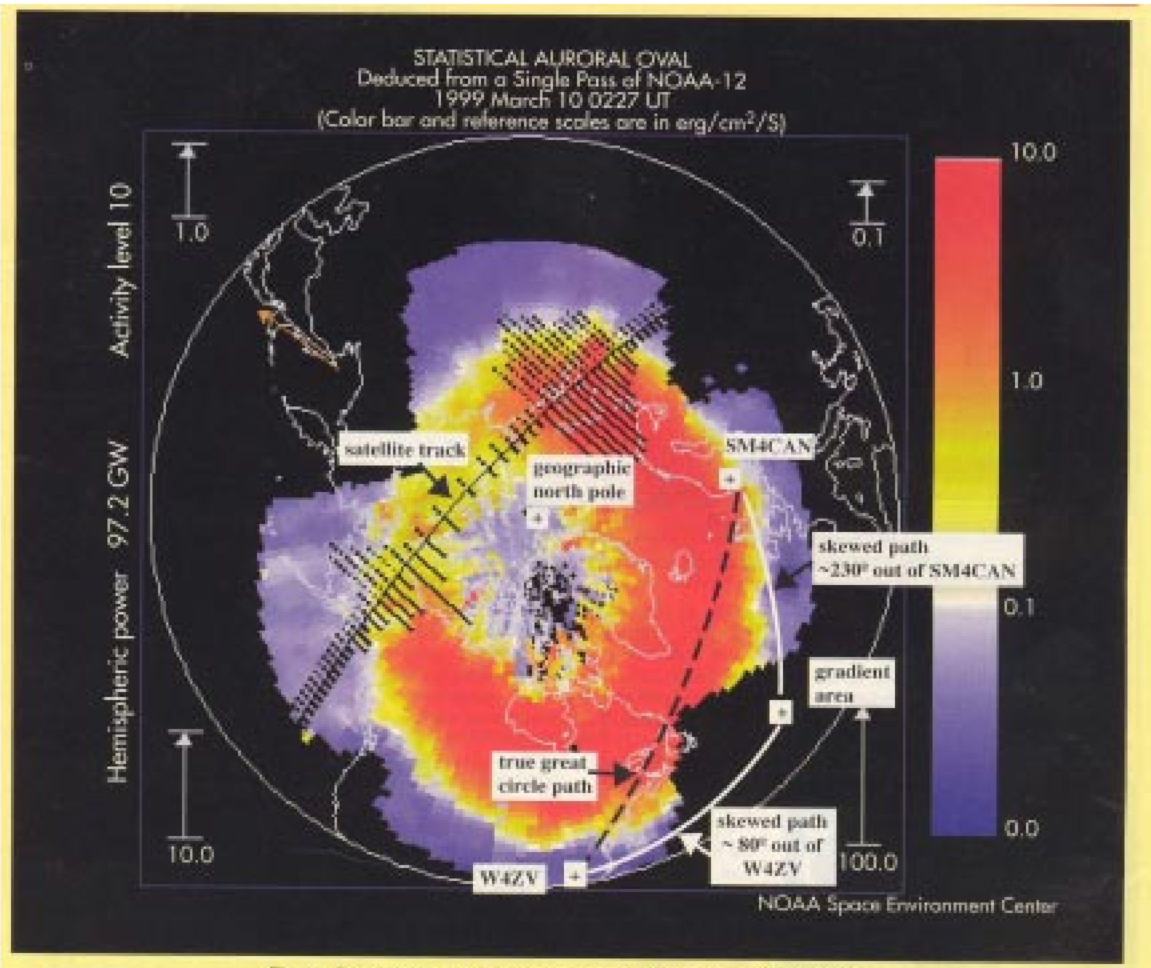

Fig. 3– Satellite photo with auroral oval and W4ZV-to-SM4CAN paths.

Figure 3 shows the satellite data. This is an azimuthal equidistant map with its center at the geographic north pole. The satellite track is the slightly curved line going from the southwest to the northeast just above the center of the photo. The length of the solid lines coming off the track to the southeast are proportional to the logarithm of the average energy flux observed at that location. The dots coming off the track to the northwest are the energy of the electrons - 2 dots are 350 eV and 22 dots are 17.5 keV, with the number of dots in between following a semi-logarithmic relation. All this data allows the auroral oval (the colors ranging from orange through yellow to blue) to be extrapolated and superimposed on the photo.

The orange area is where there is the most electron precipitation - that is, the most electrons spiraling down around magnetic field lines into the E-region and D-region. The yellow area roughly corresponds to the outer edge of the visible aurora. Auroral-E ionization gradients occur anywhere in the orange area, the yellow area, or several degrees equatorward in the blue area. The lack of data just south and east of Nova Scotia and Newfoundland (where the orange area abruptly stops) is not a break in the auroral zone - it's just that the satellite didn't get any data for that area. The auroral zone is certainly there, and it's easy to eyeball in the colors to fill in this missing-data area.

The true great circle path from W4ZV to SM4CAN is also shown in the figure (it's slightly curved because it does not originate from the center of the map), and it's easy to see why the true great circle path would have a problem - it encounters much increased auroral absorption. I have also added the skewed path per Figure 1 (with the same earlier caveat in reference to the exact point of skewing due to the 3dB beamwidths of Beverages). One comment is appropriate - the exact location of the equatorward edge of the visible aurora (the yellow area) could be several degrees either way. That's another way of saying that the extrapolation of the electron energy data from the satellite into an auroral oval is not an exact science. The location shown does agree very well with other sources that have studied the location of the visible aurora versus magnetic field activity.

This data is supported by other data - specifically a magnetogram and all-sky photos from the Swedish Institute of Space Physics in Kiruna, Sweden.

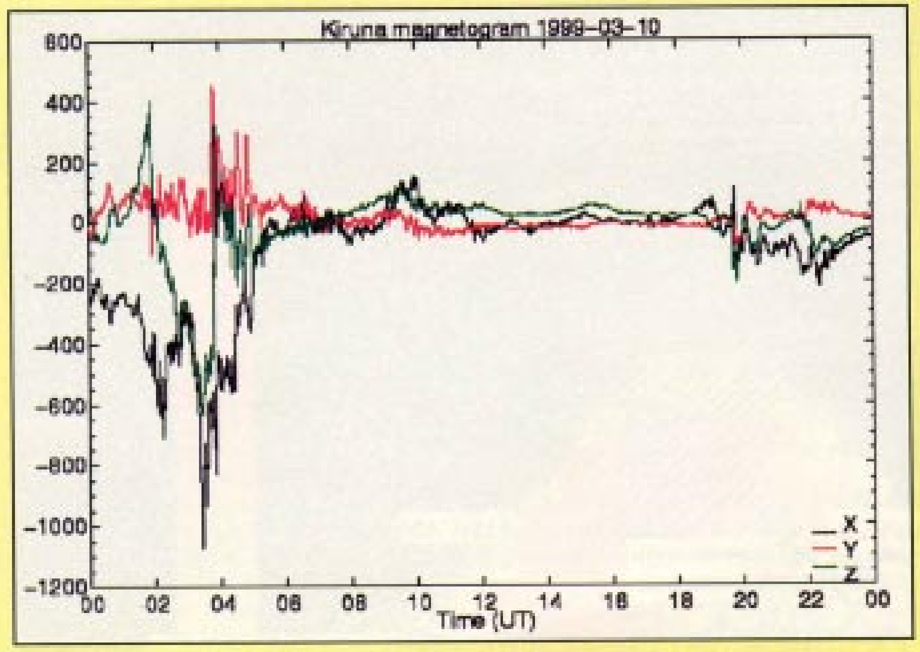

Fig. 4– Kiruna, Sweden magnetogram.

Figure 4 is the magnetogram, showing disturbances in the magnetic field starting a little before 0200 UTC and ending around 0500 UTC. Kiruna reported k indices of 5 for 00-03 UTC and 6 for 03-06 UTC. During this time, the all-sky camera (which is at the focal point of a convex mirror that allows pictures to be taken all around the compass from close in and out to about 1000km at E region heights) recorded much visible auroral activity that extended out to at least the 1000km limit of the camera in the southeast to southwest sector. Photos were taken every minute, and they showed the visible aurora (and hence the electron density gradient) to be very dynamic in location and intensity.

All of this adds up to the following: the signal from W4ZV headed to the east on a great circle path, was skewed off of this path due to the E region gradient at the outer edge of the auroral oval, and then continued on the great circle path that comes into SM from the southwest. The gradient required to do this would be an increasing electron density going south - as stated earlier, this exists on the poleward side of the E-region gradient. A good question to ask is: if the signal is skewed to the north due to the poleward side of the gradient, how does it even get to the poleward side? Wouldn't it first be skewed to the south due to the equatorward side of the gradient? General statement number 3 listed previously about auroral-E ionization explains it - the gradient is not continuous around the outer edge of the auroral oval - there are gaps that the signal can sneak through.

Another good question to ask is: what magnitude of gradient is required to do this amount of skewing? Does it make sense with respect to the data of Figure 2? The amount of skewing, if it is by refraction, is directly proportional to the change in electron density over distance (the gradient) and is inversely proportional to the square of the frequency. Thus the steeper the gradient, the more the skewing for a given frequency. Likewise, the lower the frequency, the more the skewing for a given gradient.

Looking at Figure 1 shows the signal must make almost a 90 degree left turn to come off the easterly great circle path out of W4ZV and onto the great circle path into SM. After much effort with ray tracing under various gradient conditions, it appears that refraction is not the mechanism. The ray just can't turn enough in the relatively short distance (span of latitude) associated with the auroral-E ionization.

Thus it is likely that this gradient is more like a metallic-type reflector, given that it is so steep and it is on the order of a wavelength or so in extent. Using the E region data from Figure 2, the conductivity of this gradient can be calculated - it's in the neighborhood of 1 milliSiemen/meter, which corresponds to the conductivity of poor earth. This certainly says reflection is possible from this gradient. This is an interesting and important result, as it shows that auroral zone gradients can skew signals to the magnitude needed to fit the observations.

When you think about it, this is kind of a nice thing for the auroral oval to do: provide us with another path when it shuts down the normal path due to increased absorption. It's also easy to show that skewing to Europe from W4ZV's old W0 QTH in Colorado is more likely than from his new W4 QTH (as he has observed) due to the relationship of the auroral oval to the W0-to-Europe path. Likwise, it's easy to show that skewing to Japan from his old Colorado QTH is less likely (as he observed) again due to the relationship of the auroral oval to that path.

All of this sounds great because all the pieces of the puzzle seem to fall into place, but still this is just a hypothesis. Doing some ray tracing with the aforementioned Proplab Pro propagation software on this skewed path would go a long way in confirming the hypothesis. But the model of the ionosphere in Proplab Pro (which is selectable between either the CCIR model or the URSI model) does not include the steep and dynamic auroral-E ionization gradients that we're interested in.

So the next best confidence-builder would be someone else's independent study of skewed paths. Indeed, others (Rogers, Warrington, and Jones, 1997) have specifically looked at these paths. Back in March of 1994, they measured the arrival angles in England of signals coming from Halifax, Nova Scotia, on three frequencies: 5.097MHz, 10.945MHz, and 15.920MHz. They used 24-element circular goniometer arrays to measure the arrival angle.

They reported that the bearing deviations from the true great circle short path were far larger and more systematic than had been expected. Their results on 5.097MHz (I'll only summarize these results, as it's closest to our low bands) showed deviations from the true great circle short path of up to 70 degrees. Most of the deviations came from a more southerly direction compared to the true great circle short path of 286 degrees. And the deviations tended to be greater with an elevated k-index. Because of the higher frequencies used in their study (which go higher into the ionosphere), the authors tied the skewed paths to the gradients in the aforementioned F-region trough. Going through the mechanics of this path, including the location of the auroral oval, shows it to be very similar to our East Coast observations of skewed paths to Europe, except for our lower frequencies.

One final comment - John Devoldere, ON4UN, recently released a new edition of his low band DXing book (Devoldere, 1999). The first chapter is devoted to propagation, and one topic of discussion is skewed paths. Devoldere correctly states that this skewing is due to horizontal gradients, but many of his figures (for example, Figures 1-22 through 1-27) hypothesize that the RF follows a smooth curved path around the outer edge of the auroral oval. Due to the intricate horizontal and vertical electron density profile required to do this and the fact that it would have to be continuous all the way around, in my humble opinion it is highly unlikely for this to happen. It is more likely that the mechanism is that which is explained in this article - a signal being skewed off one great circle path and onto another great circle path due to simple reflection from a very steep horizontal gradient.

In summary, the observations of non-great circle paths from the US East Coast (and Midwest) to Europe can be explained by significant skewing of the signal from a steep horizontal gradient in electron density on the poleward side of the auroral- E ionization that is at the equatorward edge of the auroral oval. It is also likely that this mechanism is responsible for skewed path reports from the Pacific Northwest of European stations coming out of the northwest.

Acknowledgments: I would like to thank Stu Cohen N4XX, Cary Oler, Bill Tippett W4ZV, and Dean Straw N6BV for their review and helpful suggestions for this article. I would like to thank Dave Evans and Sue Greer of NOAA/SEC for Figure 3. I would like to thank Urban Brandstrom SM2PQQ for Figure 4. Finally, I would like to thank Bob Brown NM7M not only for his review of this article, but also for his gentle urging that the explanation of skewed paths must deal with the physics of the ionosphere.

References

Proplab Pro propagation software, Solar Terrestrial Dispatch, PO Box 357, Stirling, Alberta, T0K 2E0, Canada (web site http://solar.uleth.ca/solar/www/proplab.html)

Oler, C. and T. J. Cohen; The 160 Meter Band - An Enigma Shrouded in a Mystery - Parts I and II, *CQ Amateur Radio*, Vol 54, No 3, March 1998, pp 9-14 and Vol 54, No 4 April 1998, pp 11-16

Bates, H. F., A. E. Belon, and R. D. Hunsucker; Aurora and the Poleward Edge of the Main Ionospheric Trough, *Journal of Geophysical Research*, Vol 78, No 4, February 1, 1973, pp 648-658.

Rogers, N. C., E. M. Warrington, and T. B. Jones; Large HF bearing errors for propagation paths tangential to auroral oval, *IEE Proceedings - Microwaves, Antennas, and Propagation*, Vol 144, No 2, April 1997, pp 91-96.

Devoldere, J.; *ON4UN's Low-Band DXing*, 3rd Edition, 1999, ARRL, Newington, CT