50 MHz Propagation by Raytrace from a Structured Sporadic E Layer   N6MW 1/13/19

Es propagation is often described by geometric constructions since the region of enhanced ionization providing the propagation is thought to occur in a fairly limited range of altitudes near 100 km and the vertical thickness of the enhancement, or layer, is thought to be small, perhaps a few kilometers or even less. Furthermore the layers are thought to be locally nearly horizontally uniform with extents of perhaps 10's to 100's of kilometers. These conditions allow the general features of Es propagation to be described fairly well in purely geometric terms as a mirror producing straight line propagation segments. This includes cases where the layer has some modest degree of tilt consistent with some scientific observations. Of course the requirement for Es plasma density to support propagation dependent on the reflection (really refraction) angle must also be taken into account. Relevant detailed discussions of these simplified matters have been provided by N6MW[1] and VK2ZRH[2] and Hawk[3].

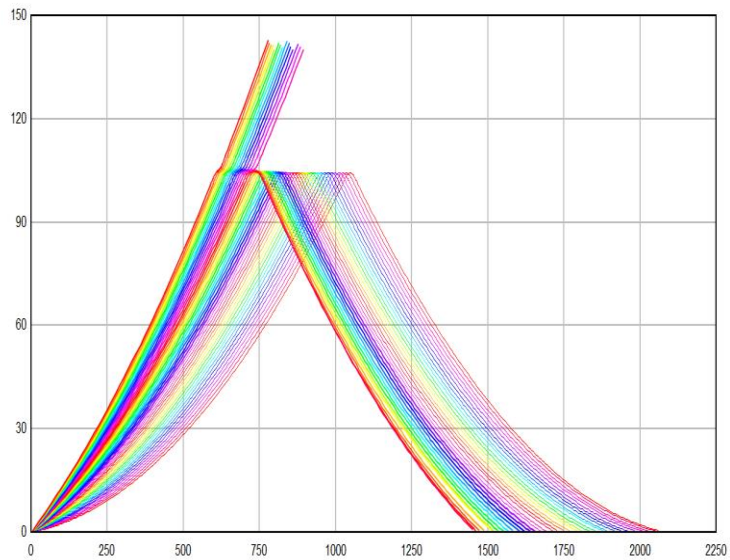
VK2ZRH[2] and Kennedy and Zimmerman[4] have speculated as to how <u>enhanced ranges</u> of propagation could result from more spatially complex structures of the Es ionization allowing chordal or petit chordal modes or ducted modes and/or extreme range modes. However, for Es ionization that is other than locally flat, though perhaps not exactly horizontal (here flat and horizontal refer to being at a constant altitude above the earth), the use of straight line geometrical models becomes quite questionable due to local variation of paths across a narrow range of propagation elevation angle and also to Fresnel Zone effects limits due to small size of a coherent "mirror" region for which diffraction can become a consideration.

It is the purpose of this little report, primarily, is to determine if a reasonably structured Es layer can lead to enhanced ranges for 50 MHz propagation. Here "reasonably" it taken to mean cases that are relatively simple mathematically and not explicitly manufactured to produce a desired result by introduction of odd elements that are not continuous or smooth or conveniently located. (Yes, this is a bit vague.) Given a physically reasonable Es layer that is structured but continuous, one can explore the behavior of propagation using numerical raytrace methods. The coded algorithms used in the current calculations are modified versions of a somewhat simplified 2D raytrace technique developed as part of the Australian Jindalee over the horizon radar program. One limitation occurs when the structures vary significantly over a wavelength (not a problem here) or when the lateral variation of the structures are comparable with, or smaller than, the Fresnel zone dimension. The Fresnel zone can be loosely thought of as the size of a mirror needed for coherent reflection and it is roughly (D/λ)^.5 where D is the range and λ is the RF wavelength. For a range of 1000 km and a wavelength of 6 meters, the radius of the Fresnel Zone is ~ 3 km which then subtends about 0.2 degrees to the transmitter.

First we just illustrate the use of raytracing through the Es region using a layer that is horizontally uniform and has a gaussian profile vertically at "height" with an adjustable peak plasma density (or peak plasma frequency fp) with the form fp*exp(-((height-htpeak)/σ)^2)

where σ is a measure of the vertical thickness of the layer that is taken as 2 km in all the examples used and taking htpeak=105 km.

Figure 1a shows the set of rays for fp peak of 10 MHz with rays at launch angles of 1 to 7 degrees in increments of 1/8 degree. The maximum of 7 degrees is used since larger values with go to shorter ranges which are of less interest. Figure 1b shows the distribution of the ranges at which those rays return to earth. For those higher elevation rays that penetrate the Es layer, the range in 1b is arbitrarily set to a small value for visual purposes. *Note that the plots of rays are ground range versus height although the raytracing is done for a spherical shell ionosphere. As a result, the plotted rays appear as curved outside the Es layer but in physical earth centered coordinates they would be straight lines.*



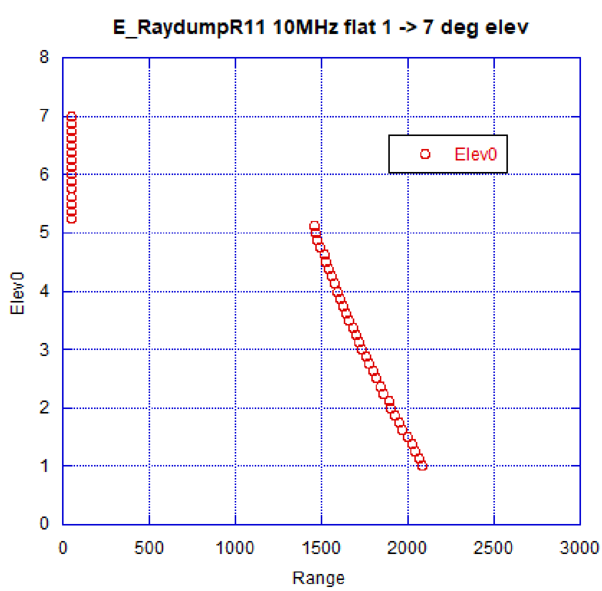


Figure 1. fp=10 MHz flat Es layer (a) raypaths and (b) ranges of return to earth

Figure 2 provides the corresponding results when fp is increased to 12 MHz. Note that all these rays now are returned to earth due to the higher plasma density. However, if higher launch angles were included this would no longer be the case. These results using raytracing strongly resemble those for purely geometric reflections but the physical rays now smoothly turn over near the peak (at 105 km here).

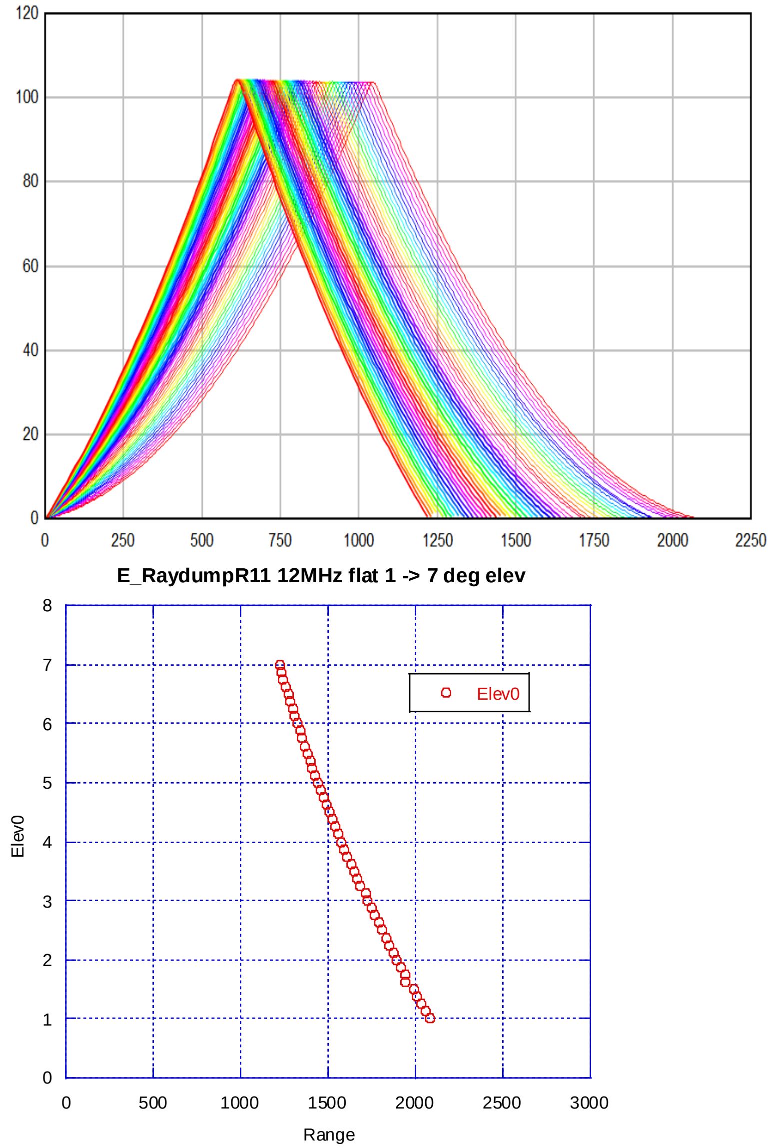


Figure 2. fp=12MHz flat Es layer (a) raypaths and (b) ranges of return to earth

For both Figure 1b and 2b, the rays land on earth in a continuous way and with nearly uniform density and all this is consistent with expectations. The density is a measure of the signal power available at the earth.

Structured Es Layer

In order to get some idea of the potential effects of a horizontally structured Es layer, the uniform layer used before was replaced by one with sinusoidal fluctuations in range by replacing the htpeak parameter with a version that oscillates in Range as follows:

htpeak'(Range) = htpeak + deltaht*sin($2\pi*$(Range/λ+frac))

where **deltaht** is the amplitude of height fluctuation and **λ** is the "wavelength" of these fluctuation in the range dimension (not RF wavelength) and **frac** provides the capability of moving the locations of the fluctuations in range a fraction of the "wavelength" to avoid incidental results that are dependent on the placement of the ionization fluctuations relative to the transmitter location. The character and extent of imposed fluctuations allowed are then controlled and limited by these three parameters. There is nothing physically special about this choice but it does have the feature that it allows the possibility of rays skipping from one peak to the next to, possibly, extend the range of propagation by chordal modes since there will now be local tilts in the Es layer. So overall there are six parameters that could be varied to discover interesting modes of propagation: fp, htpeak, σ, deltaht, frac and λ. However, we will not vary htpeak and σ since it appears they do not provide any significant additional changes. The fluctuation wavelengths used are always such that there are an integer number of the 3 km resolution range grid points for each quarter wavelength to avoid artificial structures due to resolution. (The 3 km grid could be made smaller but it appears adequate to demonstrate the points.)

The range of example parameters looked at were fluctuation **λ** of 48, 96 and 192 km, fluctuation heights of **deltaht** .1 and .2 km, fp of 10 and 12 MHz and **frac** of .25, .5 and .75 with a default value of zero. The primary plan is to see if any selection of these parameters can produce enhanced one hop ranges of propagation and the secondary matter is to see if there are unexpected features of resulting propagation.

First we show in Figures 3 the example of **λ** 96, and fp 10 MHz with **deltaht** of 0.1 and then 0.2 km shown in Figure 4. These can be compared with Figure 1 which is the same except for using the flat case of no fluctuations.

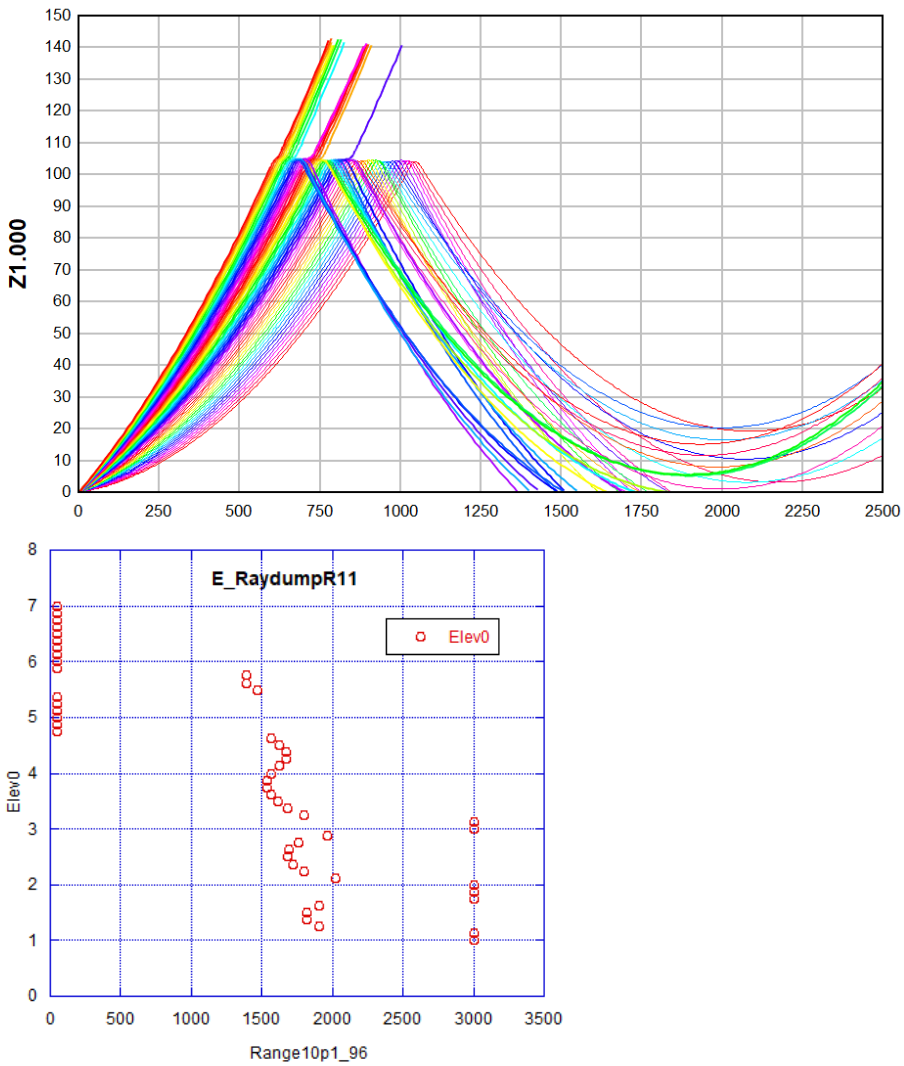


Figure 3. fp=10 MHz λ 96 with **deltaht** of 0.1 km Es layer (a) raypaths and (b) ranges of return to earth

The immediate effects are now the ray elevations that penetrate are more complex, some lower elevation rays now no longer return to earth but could allow chordal modes, and the distribution of ranges for rays returning to earth is no longer monotonically increasing. This fluctuation in range will lead to enhanced signal power in some locations and reduced power on others.

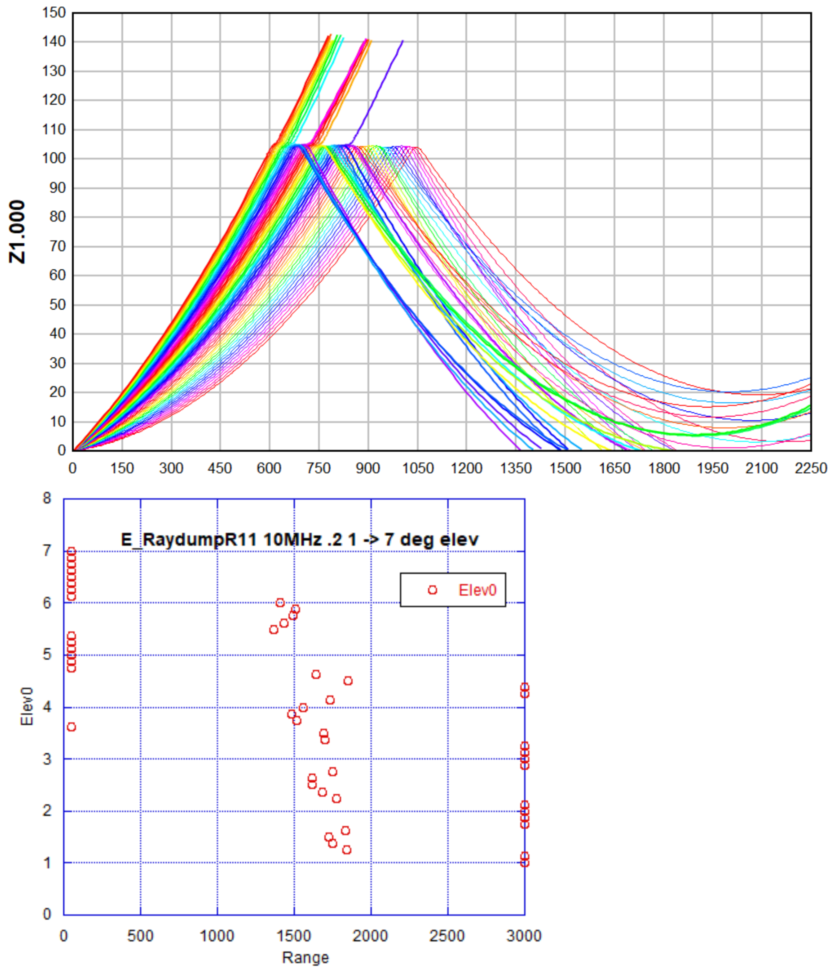


Figure 4. fp=10 MHz λ 96 with **deltaht** of 0.2 km Es layer (a) raypaths and (b) ranges of return to earth

The results here are similar to those for the **deltaht** 0.1 case but the scatter of ranges to earth return is greater with the variation from adjacent launch elevation examples large enough to suggest that the limits of the applicability of raytracing have been reached due to Fresnel effects from large gradients in the plasma density along the paths.

Next we show in Figures 5 the example of λ 96, **deltaht** .2 km, and fp 12 MHz. These conditions are the same as for Fig 2 only now a non-zero fluctuation is added. Figure 6 shows the rays in the region around the refraction altitude overlayed on the contours of the Es layer fluctuations.

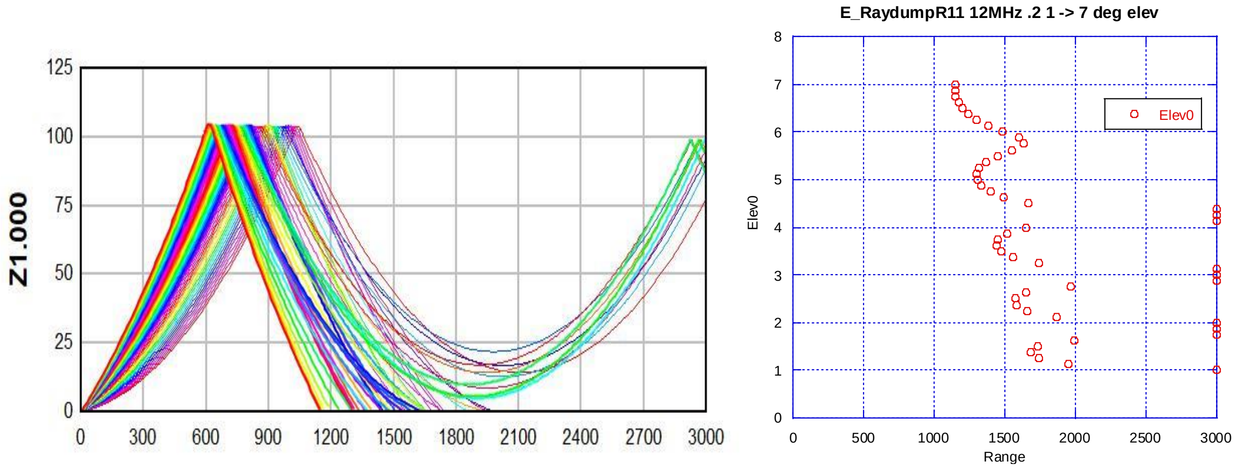


Figure 5. fp=12 MHz λ 96 with **deltaht** of 0.2 km Es layer (a) raypaths and (b) ranges of return to earth

Here we see that the addition of fluctuations causes variation in the ray trajectories so that some launch elevations no longer produce rays that return to earth. As in other cases, these rays that skim the earth but could lead to long chordal modes nearly indistinguishable from 2 hops. In Fig 5b we see that maximum ground range of rays does not extend beyond that for the flat Es layer in Fig 2b. However the distribution of locations the rays return to earth is substantially different. In particular there some ranges 1200, 1300, 1400 and 1600 km where there are concentrations of rays. This will lead to an effect much like the edge of the skip zone for HF F-region propagation and which will show enhanced amplitudes at particular ranges where the slope of the Elevation vs Range curve is large. There are also some ranges between 1500 and 2000 km that will be receiving little if any signal.

Figure 6 illustrates the fluctuating behavior of the rays near the peak for the fluctuating layer with the contours of the layer from Fig 5. There is some expected variation of the turning of the rays with range near the peak but no indication of rays glancing from one peak to the next.

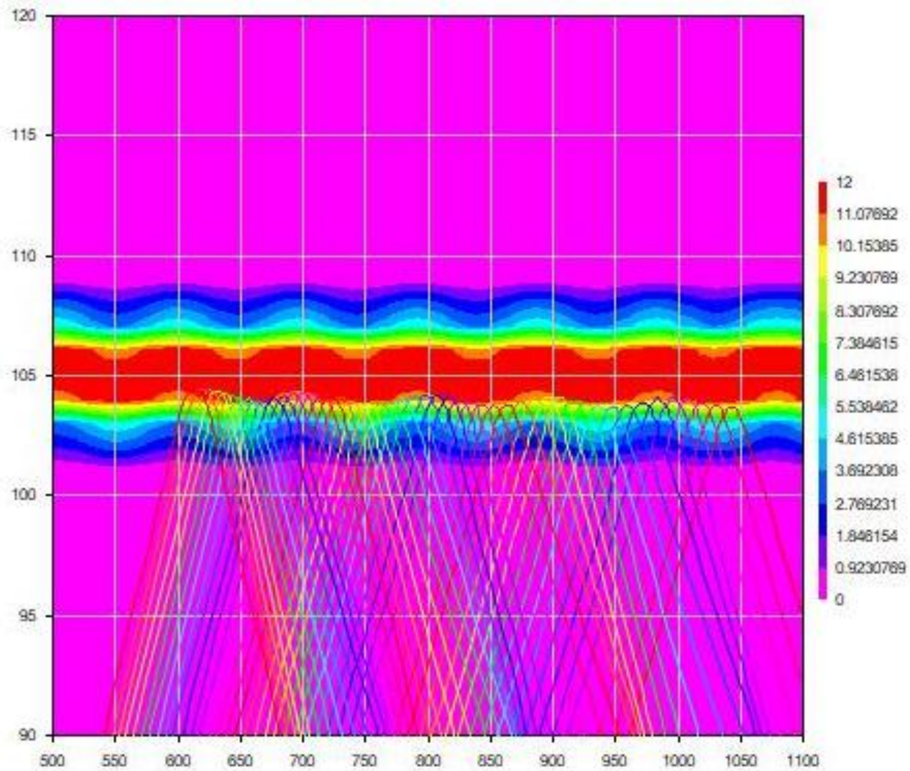


Figure 6. Rays in the region around the refraction altitude for Fig 5 case.

For the next examples we take the case of 10 MHz fp, 0.1 km **deltaht** and extend **λ** to 192 km to see effects of use of a larger spacing between repeating horizontal structures. In addition, the potential effects of different offsets in the structure locations in range using **frac** of 0, ¼, ½ and ¾ are then shown.

Figure 7 shows the ray paths for the launch angles from 1 to 7 degrees as before for the frac = 0 case.

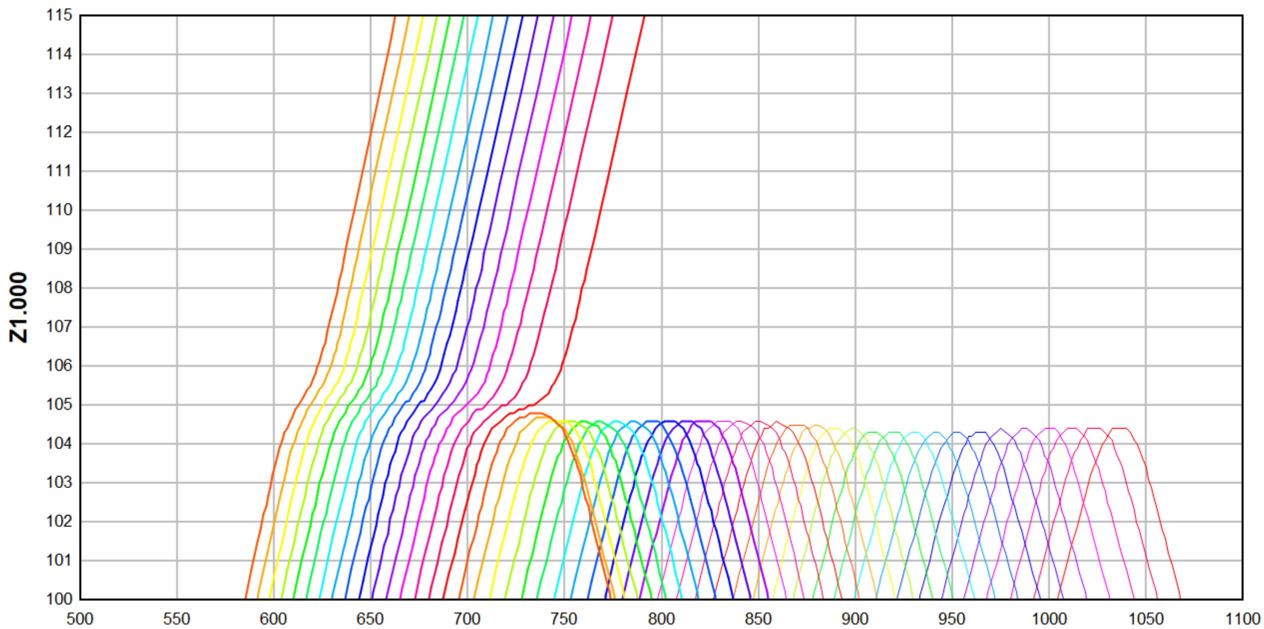
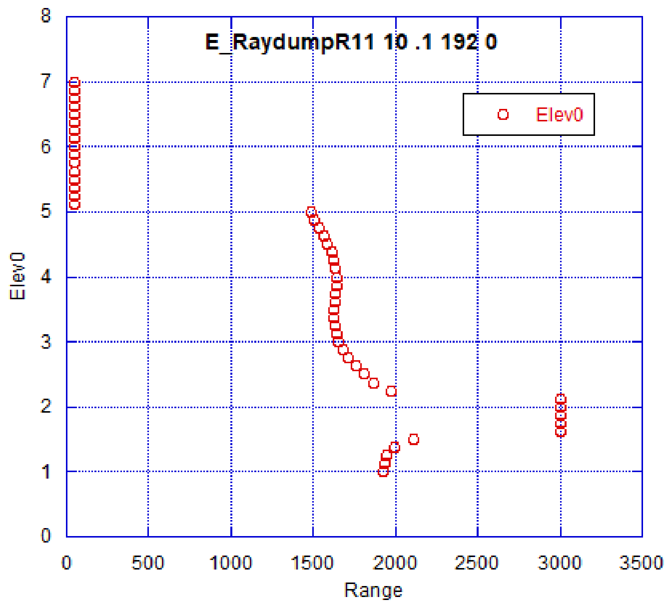


Figure 7. fp 10 MHz, 0.1 km **deltaht** and **λ** 192 ray paths near Es layer for frac = 0.

These rays strongly resemble the no fluctuation case but you can see some variation in peak height of different rays due to the **λ** 192 fluctuations although there is also some variation due to different elevation launch angles. There does not appear to be any special peak to peak modes introduced.

The variation in ranges of the rays with launch elevation angle is then given in Figure 8 for the four values of frac giving different offsets.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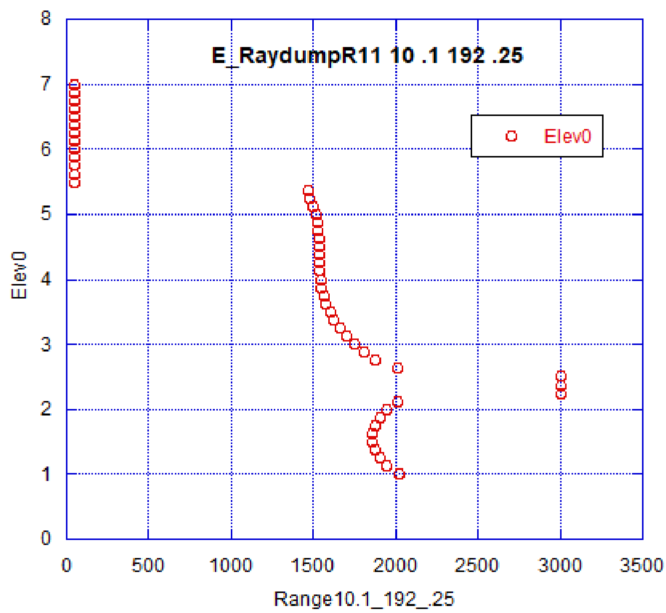
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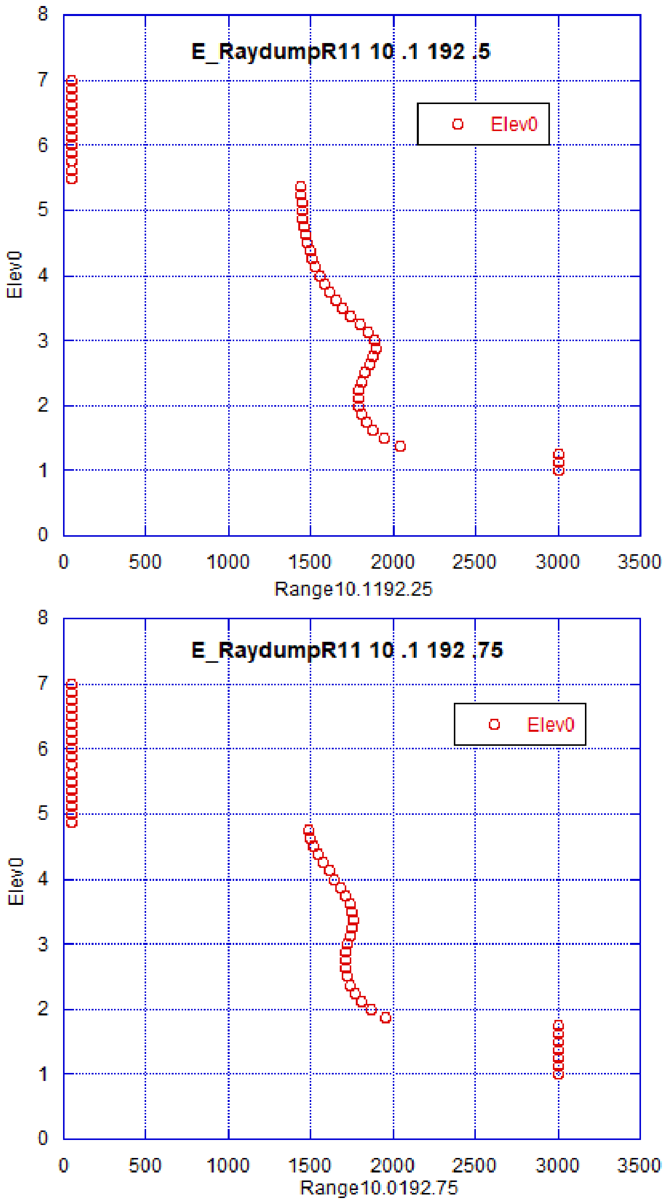

Figure 8. fp 10 MHz, 0.1 km **deltaht** and **λ** 192 variation of ray ranges for the four frac values from 0 to .75.

There are obvious changes with frac including both somewhat different penetration launch angles and different cases providing rays that miss the earth. Again there is a distribution of return to earth ranges but with a slower variation with launch angle due to the larger range scale of the fluctuations. However, once again there are no rays that extend the 1 hop range but there can be regions of signal enhancement.

Simulations of Effects of Sinusoidal Structured Es Layers by Raytrace

Only a limited set of structures have been looked at, all with sinusoidal variation in range. It was hoped that this might reveal some simple conditions that could automatically lead to enhanced range for 1 hop propagation. That did not happen – no surprising modes fell out with any rays that extended the 1 hop range very much at all.

It is certainly possible to imagine Es structures that enhance 1 hop range but this requires, for example, particular structures such as a pair of flat-ish but oppositely tilted regions separated by hundreds of kilometers or more with only lower ionization levels between those regions. Still, the tilts that are required are not very large.

But there are some interesting effects that appear with the sinusoidal variation in range that may account for some things observed by amateur operators at 50 MHz.

It was frequently found that there are regions of 1 hop propagation from 1000 to nearly 2000 km where there are enhanced signal strengths and interspersed reductions. The details of these ground locations depend on the location of the Es fluctuations relative to the transmitter. The effect can cause a modest range of elevation launch angles to propagate to nearly the same range, and then there are other ranges where few of the other elevation launch angle rays land indicating low signal levels.

In order to evaluate these signal fully versus range effects one would need to fold in both transmit and receive antennas elevation patterns [1], especially for higher antennas since than there will be peaks and nulls over a narrow range of elevation angles. The combination of Es fluctuations and antenna patterns could well lead to rather complicated localized ground regions that show strong spatial variation in signal strength. Note that transmit and receive elevation angles will generally be different for these cases, further complicating any analysis.

Another feature commonly seen is the potential for rays deviated by the Es fluctuations that do not return to the earth in standard 1 hop fashion but can skim the earth and then have a second encounter with a more distant Es region. Such propagation has the potential to provide a chordal mode that may return to earth very much like a 2 hop mode. Such long chordal modes may be identifiable from well populated user-supplied spot data if there are nominal 1 hop ranges that show no communications when apparent 2 hop modes across the region are observed. All things being equal, these long chordal modes will have ground ranges that are less than true (longer range) 2 hop modes.

There are Raytrace limitations that occur when the spatial variation of the Es plasma density become comparable with, or smaller than, the Fresnel zone dimensions. While the raytrace algorithm used here does do an interpolation across the surrounding plasma density and so remains fairly stable even with substantial gradients, the true solution to the propagation through such an Es region requires full wave solutions that raytrace may only poorly approximate. There are also potential limitations due to the range resolution, 3 km, and height resolution, 0.5 km, used in the simulations.

Elliptical Es Patches Speculation

It appears (to the author), based on the above numerical experiments, that sharp gradients on the underside of the Es layer might be required to generate peak to peak glancing effects that might extend the range of a ray with chordal or petit-chordal modes[2] but raytrace is not a great tool for that case. However it is a method easily employed, and handles the geometry, so we will now use it for examples just to give a sense of the likely effects. With sufficient geometrical and trigonometric effort this could be done analytically assuming the elliptical surfaces are reflective mirrors but initially it is easier just to do raytracing.

For this we will construct pairs of elliptical Es clouds with the major axis horizontal and the minor axis much smaller roughly consistent with the conventional wisdom. This construction then provides a large, nominally flat, region but with some curvature at the portions away from the center that can act somewhat like tilted mirrors. The test is to see if ground to cloud to cloud to ground (g-c-c-g) propagation can be easily generated with the two smooth spatially offset elliptical patches using profiles that have high plasma densities (10 MHz or more) in the center with a shell with somewhat reduced of the densities at the edges of the ellipses (done to smooth out the gradients to keep raytrace happier).

Of course one could simply add a pair of tilted flat mirror-like Es regions but the constructions need to be very carefully placed and tilted to get a g-c-c-g mode. However in that case there is no difficulty having the Es region subtend a significant portion of the elevation launch angles that is needed to generate useful signal strength on the distant earth. For the ellipses there is a slow but continuously changing curvature of the surface, so the issue of launch angle subtended may be a question – more later on this.

Figure 9 shows an example using two horizontal ellipses at 700 and 900 km with semi-minor axis of 5 km and semi-major axis of 100 km both centered at 105 km height and offset by 200 km on centers with peak fp of 10 MHz. The range of elevation launch angles, now 1 to 8 degrees and still with 1/8 degree resolution, covers the whole of the two Es patches. The relation between the ray locations and the Es patches (solid red) is clarified somewhat by the local region shown in Figure 10 showing the overlay of the contours of the patches and the rays.

While none of the rays reach 2000 km ground range, but that is just because the most distant Es ionization happens to end at 1000 km in this example.

Note that in Figure 9 there are again some launch elevations that penetrate and others that impact the outer edges of the both Es patches (tilted up toward down-range of course) that do not return to earth but retain the possibility of a second encounter with the some more distant E region to provide a chordal mode. However there are no attempted rays that hit the first patch and then are propagated to the second path (petit chordal). It is quite possible that there is some extremely narrow range of launch angles that would achieve such a path. But again, if the range of such ray elevations is very narrow, the resulting signal strength will be greatly reduced.

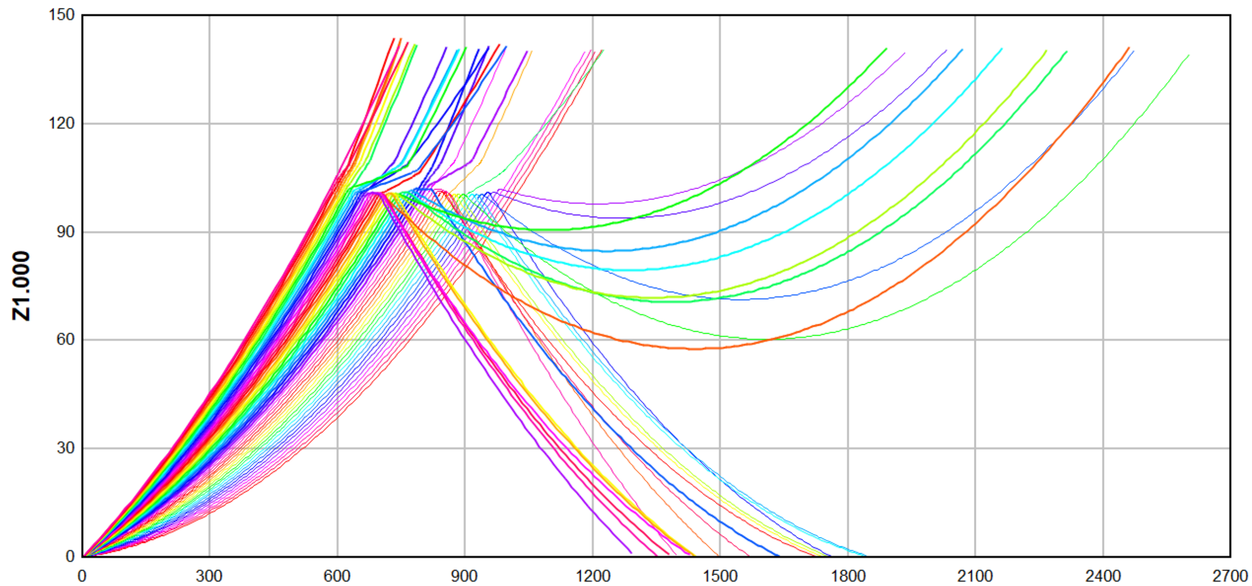

Figure 9. fp=10 two Es ellipses at 700 and 900 km.

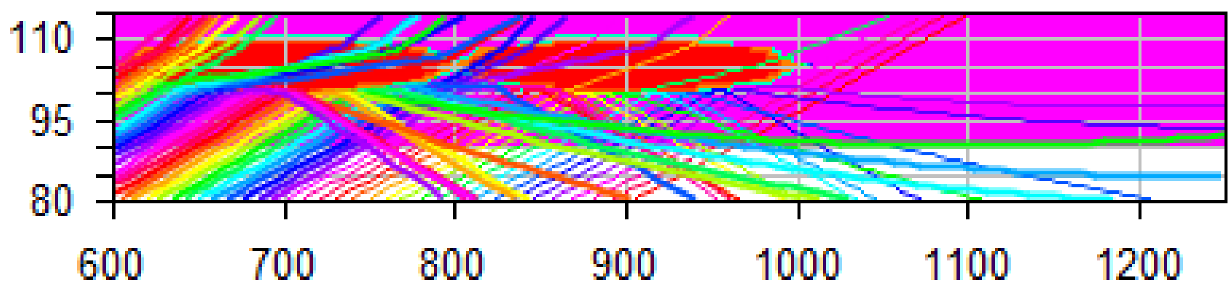

Figure 10. fp=10 two Es ellipses at 700 and 900 km overlay with ellipse contours.

Next we keep the same geometry as in Figure 9 but increase the fp to 12 MHz. Some rays still penetrate on the sides and between the Es patches. There are also some rays that skim the earth and could become chordal modes depending on possible Es down range near 3000 km. However, again there are no patch to patch rays.

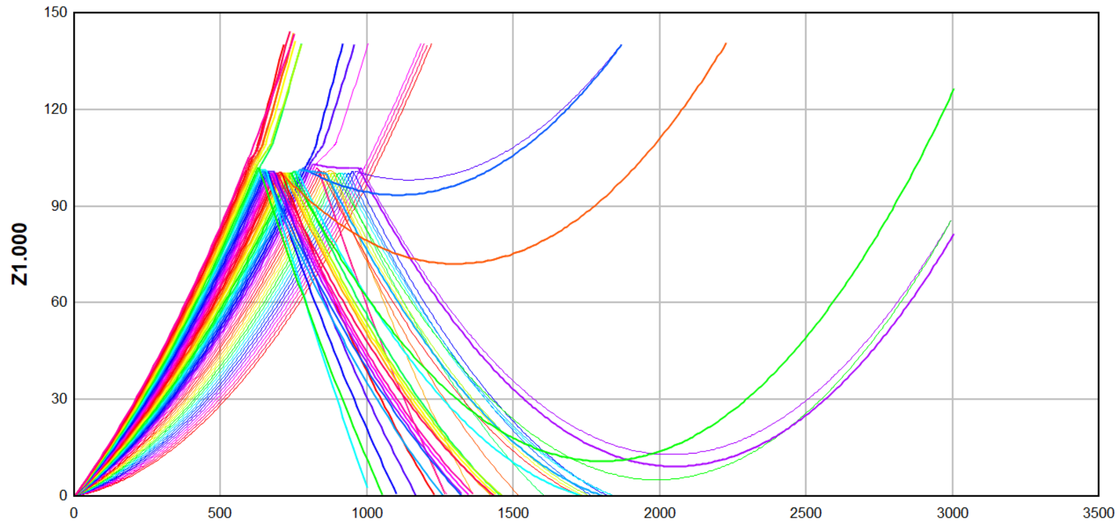

Figure 12. fp=12 two Es ellipses at 700 and 900 km.

Finally we move the ellipse at 900 km to 1900 km with the contrived intention of catching that single ray (red) that has the potential of hitting a second patch if it is at about 1900 km. Note that this ray comes via the first Es patch at 700 km. The result, with nominal ellipse locations pasted in by hand for visual purposes, is shown in Figure 13. Indeed now one ray does return to the earth as a chordal mode to a range of 2500 km which is beyond the 1 hop range. Such modes could, in principle, fill in the range between 1 and 2 hop modes but once again the angular spread between the single ray that returns to earth and the adjacent pair of rays (both do not return) is very large indicating that the signal level will be quite small. Compare the ray spacing here to that at the vastly different return to earth locations from Figure 1.

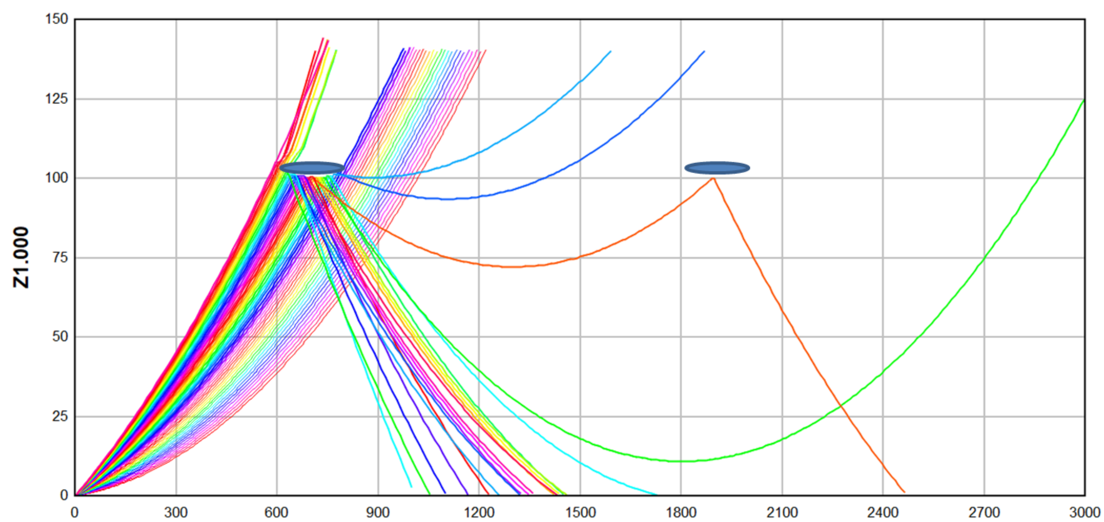

Figure 13. fp=12 two Es ellipses at 700 and 1900 km.

We conclude that the construction of Es structures that can result in significant level signals at distances somewhat beyond the usual one hop range are not so easily arranged, although we cannot rule out other Es structures not investigated might allow that to happen, perhaps even some that may develop in nature.

References

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