Background for Sporadic E, Es, Propagation Evaluation - N6MW Oct 2018

Brief Broad Basics of Radio Ionospheric Propagation

HF propagation, often including Es, is typically characterized by an instantaneous or statistical Maximum Usable Frequency (MUF), which is the highest frequency that can propagate between two points, usually points on the earth and usually for a single refraction, often loosely called a "reflection," off the ionosphere.

For a "flat" or stratified ionosphere (no electron density variation in the horizontal plane), it is well known that for a peak in electron density of Ne, the highest frequency that can penetrate the ionosphere for a vertical ray, known as the Critical Frequency or Plasma Frequency, is given approximately by

$CF = fp = 9(Ne/1.e6)^{1/2}$

where Ne units are electrons/cm^3 and frequency in MHz.

Frequencies lower than fp will always be "reflected" downward for any elevation angle.

For a ray that is launched off vertical and which would, geometrically, encounter the relevant ionospheric layer at an incidence angle of *i* (relative to local vertical), the highest frequency that would be "reflected" downward is the MUF where MUF= fp/cos(*i*). If the layer is flat, the angle at which the ray will be reflected angle *r* is equal to the incidence angle but reversed in sign as in a mirror reflection. This is pictured in Fig 1 where h is the height of the layer and Re is the radius of a spherical earth. The launch elevation angle of the ray, *e* , is then related to *i* by

$\sin(i) = \cos(e)*Re/(Re+h)$

where h is the height of a "thin" layer meaning it has only a small vertical extent.

The ground range to the reflection location along the earth's surface is then

$R = Re*\theta = Re*(\pi/2-i-e)$

where θ is the angle from emitter to apex measured at the center of the earth.

Again this "reflection" will occur only if the radio frequency, f, satisfies the condition

$f < MUF(i) = fp/\cos(i)$.

For a horizontal reflection layer, the reflected ray angle off vertical is $r = i$ independent of frequency as long as the fp supports the propagation frequency.

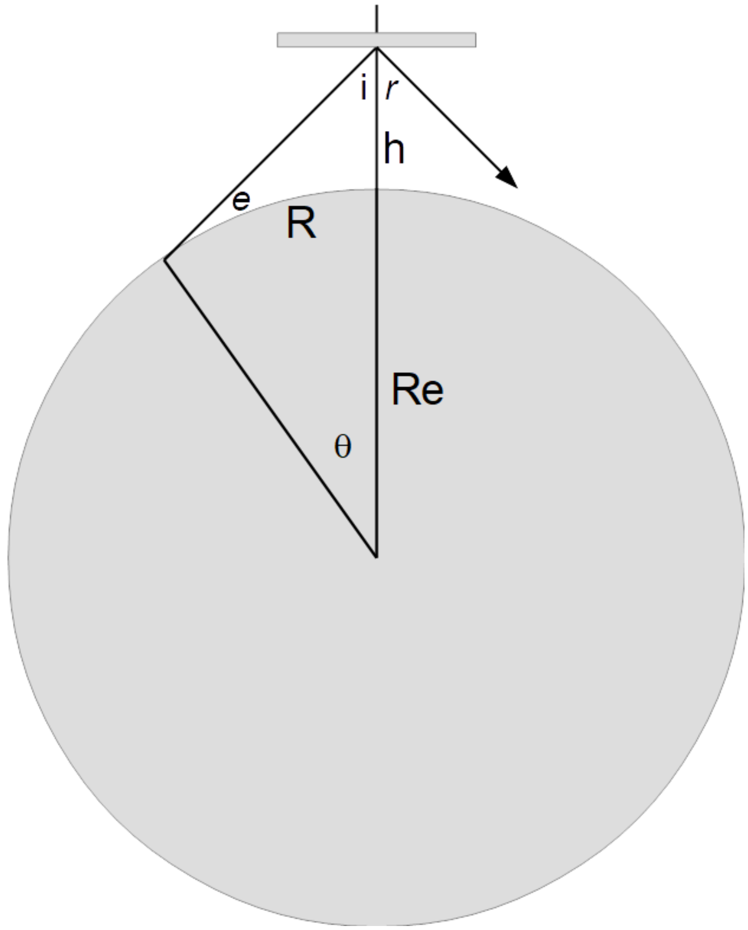

Fig 1. Geometry for a thin ionosphere layer reflection. Not to scale.

This conventional information above ignores complications that occur when the ionospheric layer is not thin. In that case the path a ray takes in the ionosphere is no longer close to straight lines and refraction providing path curvature becomes a significant matter. Therefore in the case of conventional HF propagation off the F layer (~200-500 km), for example, one cannot easily predict the range for 1 hop propagation based on the elevation launch angle alone and the angle *i* is not so meaningful and not readily found without raytrace calculations.

To illustrate this point, here is an example from Sales [1] of, first, a set of rays, all at the same frequency, launched at various elevation angles for no significant Es ionization and, then, for a case that includes substantial Es ionization. The ionospheric layers here are flat with no horizontal deviation. The first case shows that higher elevation rays are bent but still penetrate. Some "high rays" (marked HR) turn over near the peak in electron density profile (using a parabolic profile here) while spending a significant portion the path with low curvature paths. The lower elevation rays are turned over at a lower altitude and extend to longer ranges. These lower rays resemble the simplified description provided earlier. One feature that is evident is there is a region near the emitter where no rays return to earth - this is well known skip zone.

In the second frame with an Es layer added near 100 km, we now see Es paths at lower elevations that are approximately two straight line segments with apex at the Es region. This is because the ionization region in the Es layer has a much thinner altitude range than the higher F region. The details of paths in the figure depend on the values of the frequency relative to the ionospheric electron densities but these cases illustrate general features. For <u>much</u> more comprehensive information on ionospheric propagation, see Basu et al.[2]

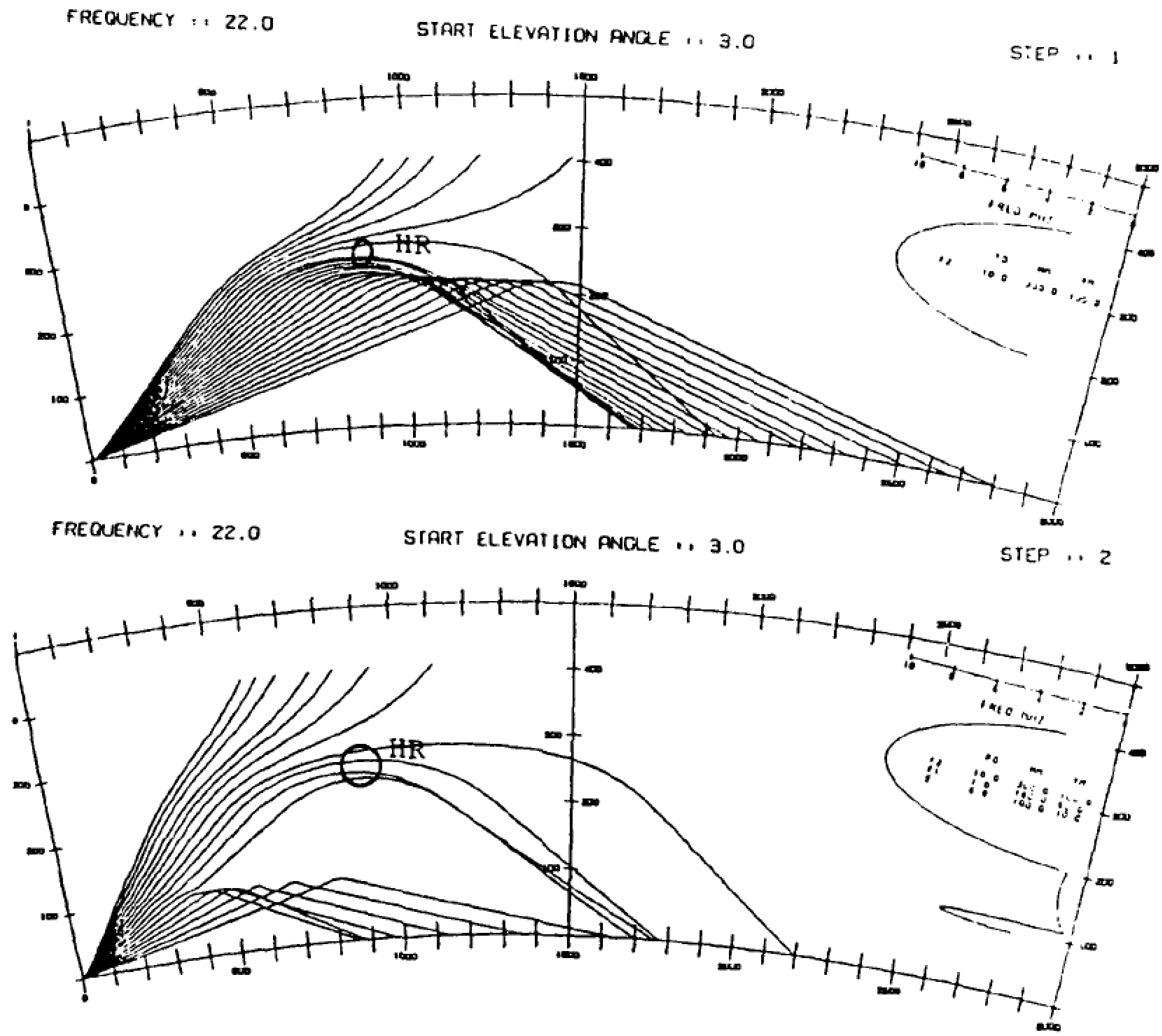

Fig 2. Raytrace examples without (above) and with (below) a significant Es layer.

In the following discussions of Es only, we will assume simple straight line geometrical Es propagation and use a frequency of 50 MHz.

Conventional but Simplified Es Geometric Propagation

The initial parts of the following materials are fully consistent with the Es article laid out by Harrison [3]. However some of the plots and tables are presented here in a different manner so as to help with an expanded discussion.

From Yi Liu et al. [4] the heights of Es layers are considered to be between 90 and 115 km with a mean value of 103 km in one summer season mid-latitude study. Whitehead [5] reports that observations indicate Es clouds are perhaps ~ a km thick and have horizontal extents that can range from 100 m to a thousand km but with common widths of ~100 km. However, it should be noted that the relevant Fresnel zone is the order of a km at 6 meters for a range of 100 km so resolution of width to less than a km is problematic at this wavelength. Larger cloud widths, which are needed for some observations, suggest the typical tilt of these larger Es clouds is ~ 0.6 degrees. Smaller clouds may allow propagation off the edges where the horizontal gradients may be significant, perhaps swamping the effect of tilts.

In a summary article Hawk [6] provides a review of several aspects of Es beyond the material in the current material as well as a useful set of references.

Initially we consider Es clouds that are flat (horizontally uniform), thin, no tilts and of significant horizontal extent to act like a mirror for 50 MHz signals. Further assume for the moment that this frequency is supported by sufficient electron density in the Es layer for reflection of the elevation launch angles used.

It is then straightforward to determine the ranges available to one and two hop paths, where two hops means including a mirror-like reflection off the earth. The second part of the two hop path is then the same as the one hop by the assumption of having equal height Es clouds for the two reflection regions. Again note that the launch elevation angle will equal the elevation angle of the ray returning to earth for both hops under these assumptions.

The ground range to the point of the ray returning to earth is shown in Fig 3 for 4 different Es cloud heights of 90 to 120 km over the range of launch elevation angles (shown in log format). On the right side the critical frequency, labeled foEs required to support this propagation for an h=90 km layer is provided for those elevation angles. The foEs required is only mildly dependent on the height. Conventional wisdom is that the critical frequencies above 20 MHz are not common so reaching ranges a lot less than 1000 km will be increasingly difficult. As expected, higher clouds tend to allow propagation to modestly larger ranges for a given elevation angle.

Here we used a common designation of "fo" which means only the frequency required for the "ordinary ray" is considered. Generally there is also an extraordinary ("x") ray that behaves somewhat differently due to the effects of the earth's magnetic field. It is common to use only this ordinary mode, which is equivalent to ignoring the magnetic field, when the propagation is transverse to the magnetic field. This provides a relatively simple expression for the index of refraction that controls a raytracing approximation.

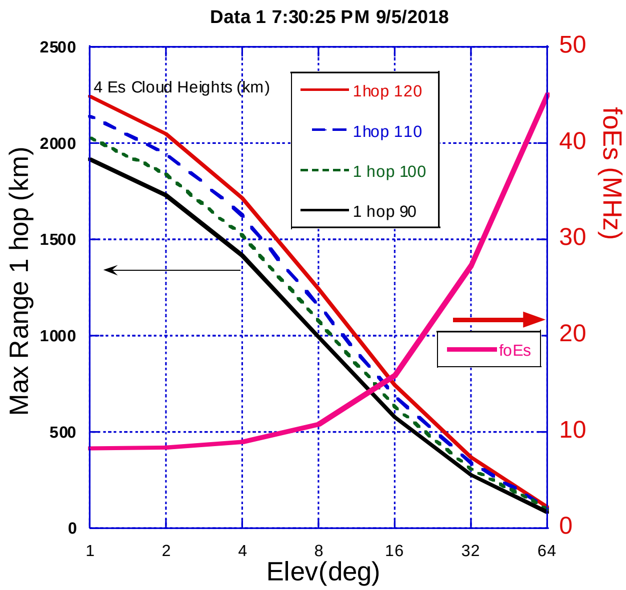

Fig 3. Ground range for ray reflection off a flat layer at 4 different heights versus elevation launch angle. The right scale (red) provides the required plasma frequency for reflection at a given elevation.

Carrying this to both one and two hops, but for a single cloud height of 110 km, the ranges available for a set of elevation angles are provided in Fig 4. Here the 2 hop range is exactly twice the one hop range due to our current assumptions about the Es clouds. Just as needing a higher fp to get propagation to much less than 1000 km for one hop, the same will hold true for two hop ranges much less than 3000 km. This has the effect to limiting available propagation from over 2000 km to less than 3000 km. This region is sometimes called the doughnut hole.

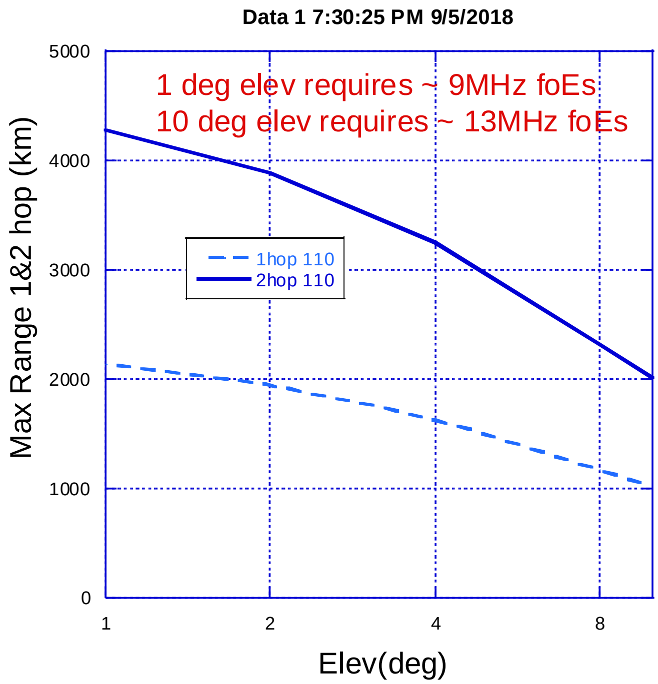

Fig 4. Ground range for one and two hop propagation for a flat Es cloud at 110 km versus launch elevation angle.

Elevation Effects

From the last 2 figures, it is evident that longer distance propagation requires use of lower elevation angles and furthermore lower elevation propagation is allowed by a lower Es critical frequency. Operator control of elevation angle is quite limited and any conventional antenna radiates over all angles. However, the height of antennas has a significant impact on the signal strength at a given elevation angle. For example consider first two antennas at 30 ft above the ground, a horizontal dipole and a 4 element yagi as taken from an EZNEC example using medium soil characteristics. For these antennas, the elevation patterns are quite similar at angles up to 50 degrees with the main lobes both peaking at 11 degrees. Below 11 degrees, the -5dB point is at 4 degrees and -10 dB is at 2 degrees elevation.

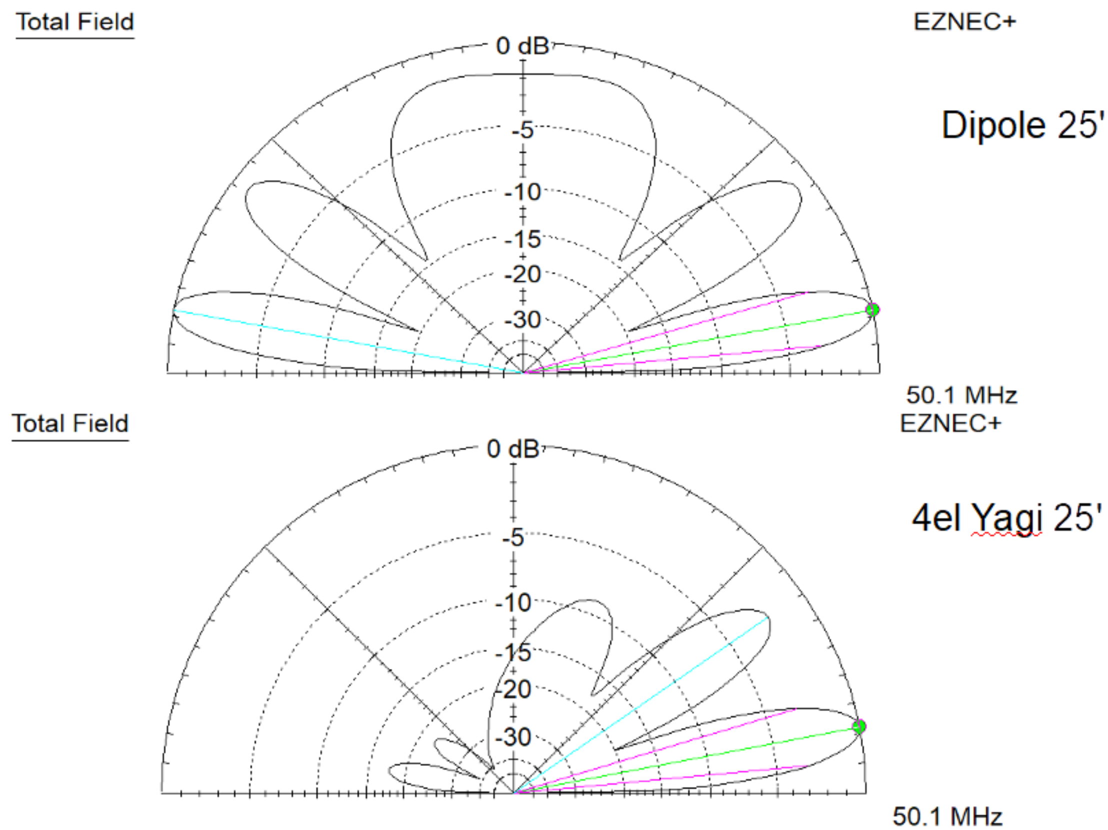

Fig 5. Dipole and 4 element Yagi elevation patterns at 25’ height.

If the antennas are raised to 50' and 75' the elevation patterns progressively move to lower angles with lowest lobe peaks going to 6 and 3 degrees respectively as seen in Fig 6. However, there become relatively low elevations that are in the significant minima of the patterns which can impact communications to some ranges. Therefore in evaluating performance, the height of the antenna is a very important factor and this accounts for the use of high antennas for 50 MHz DX-focused efforts. Of course real world patterns are never so clean and the characteristics at low elevation angles can be altered by local structures and ground features.

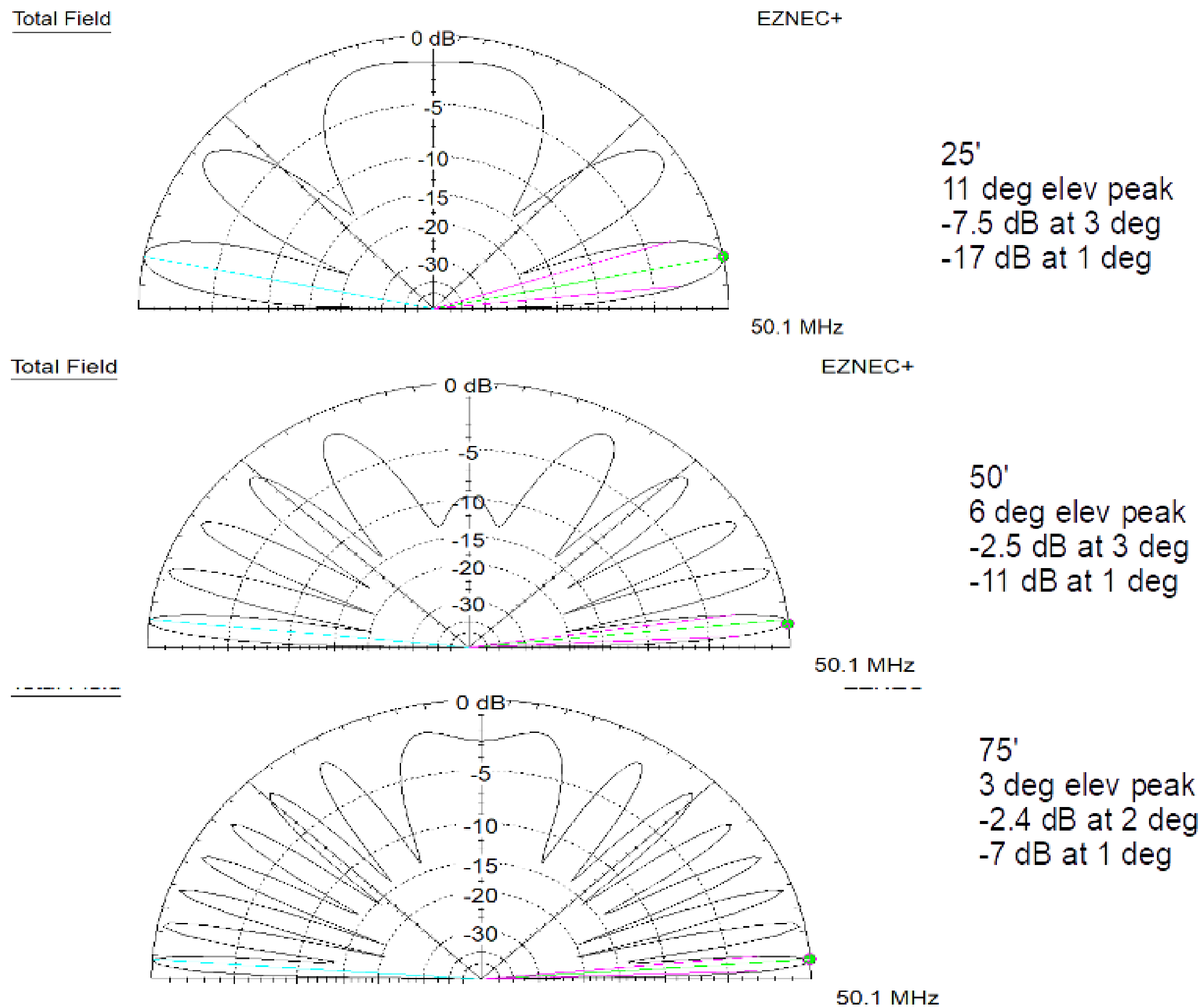

Fig 6. Dipole elevation patterns for heights of 25, 50 and 75 feet.

Effect of Es Layer Tilts on Propagation

The geometry for a tilted reflecting surface as shown in Fig 7 is readily incorporated into the straight line propagation since the reflection is like a mirror but now at the tilted angle labeled ϕ. The result is that the incident angle relative to vertical, i , is unchanged but the incident angle relative to a perpendicular to the cloud is $i' = i + \phi$. The exiting reflected ray then is at an angle relative to vertical of $r' = r + 2\phi$. This angle determines where (or if) the reflected ray returns to earth. If the ray does return to earth it will be at an elevation angle of e' where $\cos(e') = \sin(r')*(Re+h)/Re$. If the right hand side of this expression is less than 1, the ray does return to earth. So as the tilt increases (positive here means right side of the layer away from the emitter is raised in altitude) the point of return to the earth becomes more distant and the return elevation angle e' decreases. At some critical tilt value, the ray just skims the earth (e'=0) and for further tilt increases, the ray misses and goes above the earth's surface and again goes toward the ionosphere. Depending in the tilt of the Es layer where that ray again passes through that altitude again, the ray might be reflected back to the earth - that would usually be referred to as a Chordal path mode as pictured in Fig 8.

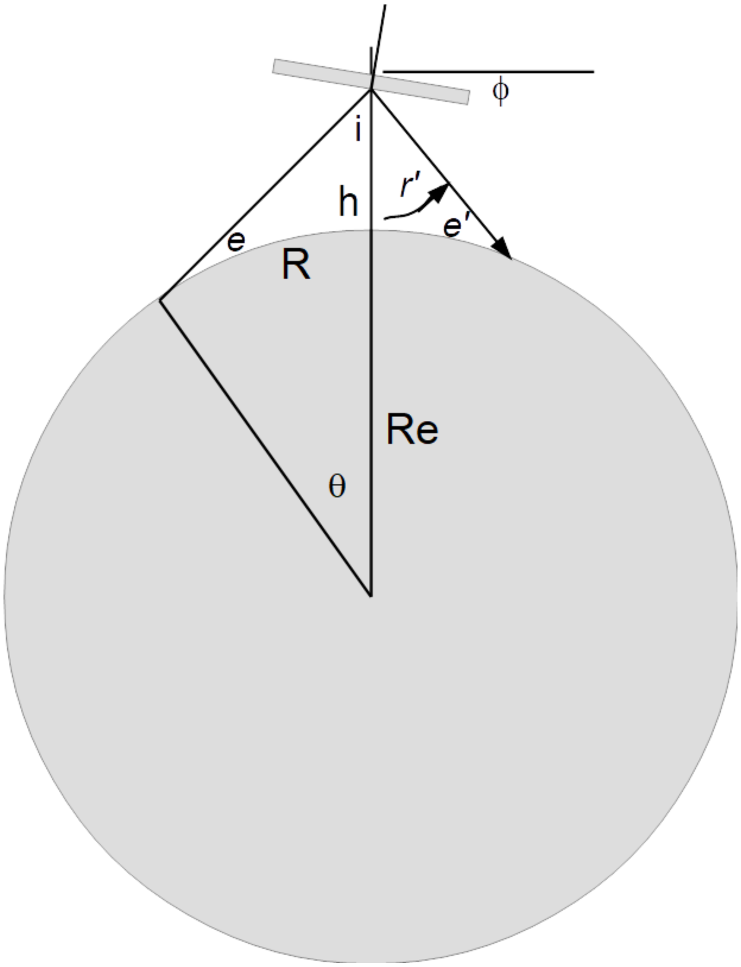

Fig 7. Tilt geometry where tilt angle ϕ would be negative for the pictured case. Not to scale.

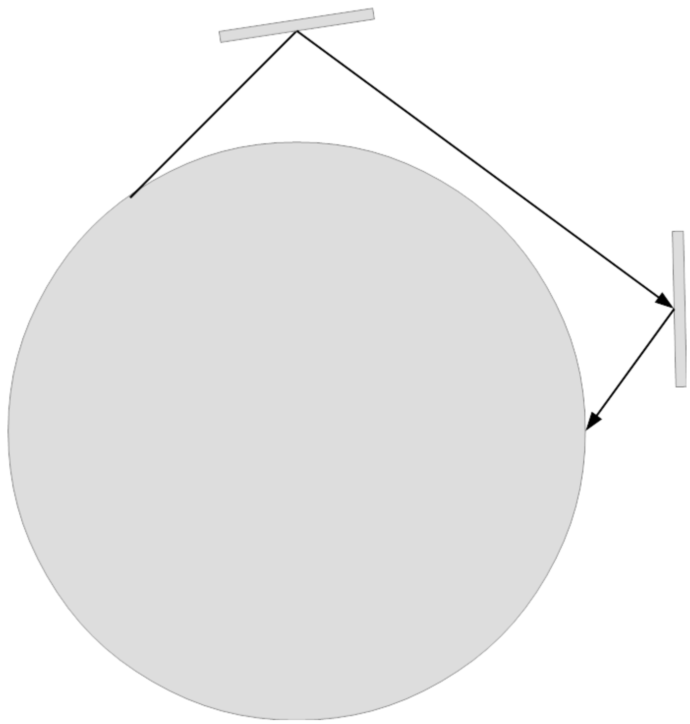

Fig 8. Chordal path mode example. Not to scale.

For flat but tilted layers, it is possible to get a chordal mode only when the initial Es layer has a positive tilt and the second Es layer encountered has a negative tilt. Generally the communication range for this chordal mode will be similar to that for a 2 hop modes.

Next we consider the magnitudes of tilts that can be significant.

Specific Effects for 1 Hop

The variation of a 1 hop propagation starting at an elevation launch angle e due to tilt, ϕ, leads to a down range 1 hop elevation angle of e' upon return to earth. This is shown in Fig 9 for the example of h = 105 km. The effects change only slowly with variation in h. Of course at zero tilt e=e'.

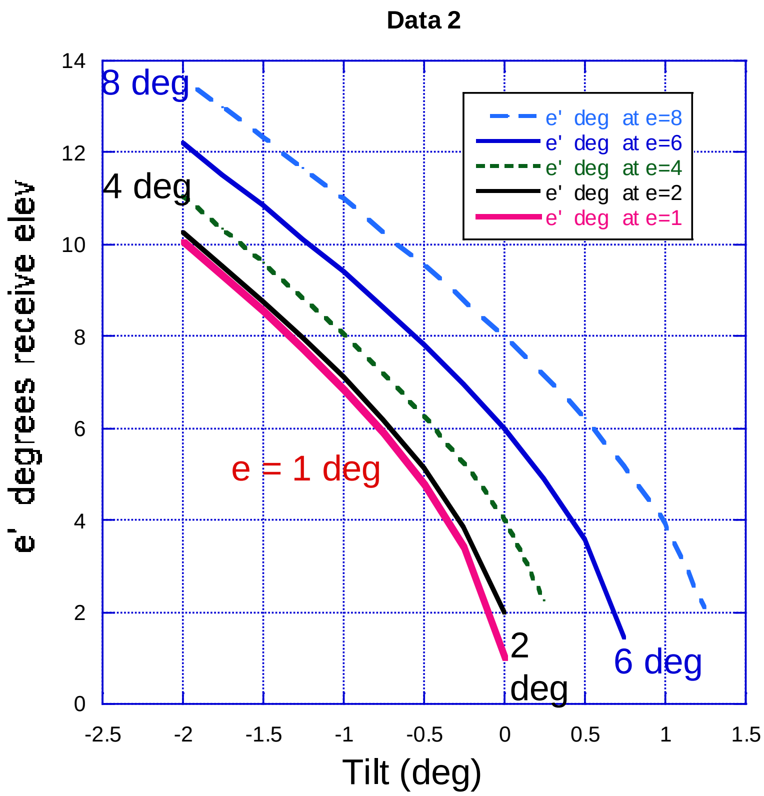

Fig 9. Change of receive elevation e' with tilt.

So for one hop propagation, a positive tilt can extend the range but the receive elevation angle may be so low that the receive antenna will need to be at a substantial height to capture the signal with useful strength. Also note that a positive tilt very quickly can extend the lower elevation outgoing rays so that they cease to return to the earth. This is because for small elevations the ray is already very close to missing the earth due to the earth's curvature. As a result, tilts as small as +0.5 degrees can cause loss of the long range 1 hop connection.

Specific Effects for 2 Hop or Chordal modes

For 2 hop modes where there are no tilts, the result in ranges was shown in Fig 4. However, 2 hop paths with positive tilt for the first reflection may have somewhat longer ranges, for a given antenna elevation pattern, because the reflection off the earth to start the 2nd hop is not limited by antenna patterns and the reflection coefficient off the earth is close to one for very small receive elevation angles (that is very large incidence angles) even for soil properties that are considered poor.

However, if the first Es reflection region has a positive tilt, the second one must have a negative tilt for the signal to return to earth at a receive elevation angle comparable with the launch elevation. The same is true for a potential chordal mode which suffers no ground losses when skimming the earth but the advantage is not very great. It may be nearly impossible to tell the difference between a 2 hop mode with a very low elevation angle at the end of the first hop and a true chordal mode.

But higher elevation chordal modes can have the potential to fill in the range gap between 1 and 2 hops but it will require a significant initial positive tilt followed by a corresponding negative tilt for the two encounters with the Es region. For realistic Es layers, there may be electron density variations or structures that allow propagation that is similar to the effects of simplistic but larger tilts.

[1] G. S. Sales, High Frequency (HF) Radiowave Propagation, PL-TR-92-2123, for Phillips Laboratory, Hanscom AFB, April 1992.

[2] S. Basu et al., https://www.ngdc.noaa.gov/stp/space-weather/online-publications/miscellaneous/afrl_publications/handbook_1985/Chptr10.pdf, IONOSPHERIC RADIO WAVE PROPAGATION

[3] R. Harrison, VK2ZRH, On Sporadic E VHF Propagation and Solving a Mystery about Maximum Useable Frequencies, Part1, in Amateur Radio April 2012. (available online)

[4] Yi Liu et al., The seasonal distribution of sporadic E layers observed from radio occultation measurements and its relation with wind shear measured by TIMED/TIDI, Advances in Space Research, vol 62#2, July 2018.

[5] D. Whitehead, Sporadic E - A Mystery Solved?, QST, November 1997. (Whitehead has other more technical publications that provide a basis for this more magazine article.)

[6] M. Hawk, Mid-Latitude Sporadic E, www.atfda.org, November 2012.