Jim Kennedy and Gene Zimmerman, 2010, "Extreme Range 50 MHz E_s: Part 1 SSSP", *Proc. 45th Conference of the Central States VHF Society*, ARRL. With further revisions July 2011.

Extreme Range 50 MHz E_s: Part 1 – SSSP

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Introduction

We have continued to see many instances of surprisingly long, yet still short-path, propagation on six-meters in both the northern and southern hemispheres. In the main, these have been east-west paths either entirely above, or entirely below the Equator, reaching ranges of up to about 11,000 km. They seem to occur exclusively during that hemisphere's local summer, strongly suggesting that some form of E_s mechanism(s) plays an important role.

In the northern hemisphere, this effect has been seen repeatedly for paths between JA-NA, NA-EU, and EU-JA. In the southern hemisphere, the paths have mostly been seen between ZL/VK and western SA. Han Higasa JE1BMJ called this effect to broad attention, naming it Short-path Summer Solstice Propagation (SSSP) in the Japanese publication *CQ Ham Radio* (Higasa 2006 Japanese, 2008 English).

What follows is a deeper discussion of this kind of propagation, based on a broader range of observations and some comparisons with data-driven models of the ionosphere. A companion paper in these Proceedings (Kennedy and Zimmerman, 2011b) addresses the equally strange recent propagation across the equator between ZL/VK and NA. The following reviews will help set the stage.

SSSP Review

In the case of the east-west "SSSP" effect, Han questioned whether these long circuits were entirely traditional multi-hop skip, nE_s (*n* is the number of hops, see Table 1). He suggested that the *intermediate* hops might be chordal hops[1] (from tilted E_s clouds), which never came back to earth in between skips off the ionosphere, until the last hop. The concern was that the distances were so great that it would require at least five hops ($5E_s$) and that the path losses beyond 9,000 km might be too great for a successful contact.

**Table 1
Ground Footprints for
Successive nE_s Hops**

Hop	Min (km)	Max (km)
1	1,700	2,200
2	3,400	4,400
3	5,100	6,600
4	6,800	8,800
5	8,500	11,000
6	10,200	13,200

Kusano and Obara (2007) also suggested that the signal was *not* coming back to the ground on the intermediate hops. In addition to Han's chordal hops, they suggested that it might also be due to bottomside-to-topside skip ducting, in which the signal travels for a time skipping in between two layers of E_s clouds, where one set of clouds is above the other. Both these phenomena are known to exist in other circumstances (Davies 1990; Whitehead 1997a, Kennedy 2000, 2003, and 2010).

These two proposed processes are both variations of chordal propagation and will be referred to here as "chordal" unless it is important to differentiate them. The problem in telling the difference between nE_s and either of the two chordal modes is that one must determine *by observation* that the signal's ray path did, in fact, come back down to earth in between skips off the ionosphere.

One of the authors (Kennedy 2010) recently discussed these possibilities at some length, based on data from some well-documented band openings. That article used data from some KH6–NA openings, in which the second, third, and fourth nE_s hops would all have landed in populated areas of North America (from KH6, the first hop lands in the middle of the Pacific).

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[1] A "chordal hop" skips from one E_s skip point directly to the next skip point, without coming to earth in between.

In the two cases studied in that paper, one opening showed that hops two, three, and four were all clearly evident by multiple contacts within each skip footprint, with identifiable skip-distance gaps, and with diminishing numbers of contacts with distance.

In the other case, there were virtually no contacts at hop two, some at hop three, and a large number at hop four. Though signals were not very strong, band conditions actually got better as the distance increased. This particular opening occurred on a day when there was an intense E_s opening in the eastern part of NA, and there were very poor conditions from the western half of NA to anywhere.

The study went on to look at two instances of fairly intense SSSP between JA and NA. In both cases, there was little evidence of the signals coming down to earth, though in one opening there were two KL7 contacts. The difficulty here was that the first two skip footprints from JA both land in the Pacific Ocean or the Bering Sea and the next two come to earth in KL7 or VE7. In all four cases, the population of active six-meter operations is very small.

Finally, the work showed that, whatever the detailed propagation mechanism, the very long east-west SSSP had a very specific diurnal (time-of-day) relationship. All of the incidents in the study occurred when the local solar time (LST) at the west-end station was during its traditional morning E_s peak, and the LST at the east-end station was during its afternoon/evening peak. Put another way, the end-to-end distance had to be about 9.5 time zones apart *and* the actual LST had to be about 0930 ±3 hours on the west end and about 1930 ±3 hours at the east end (more on this later).

Four preliminary conclusions were drawn from these results:

1. Chordal E_s modes do occur, and while less common, probably aren't all that rare.
2. There is good evidence that nE_s occurs out to at least four hops (≈8,300 km).
3. It was inconclusive as to whether the SSSP mechanism was nE_s or chordal E_s, or something else.
4. E_s was no doubt a part of the process, especially in view of the diurnal effects (LST).

E_s Review

Since the following discussions will involve E-region ionization, it might be helpful to take a quick look at how radio propagation works in that region.

The Sun and the Rain – of Meteors

The E region of the ionosphere is generally considered to be the altitude range between 90 and 130 km. The ionization found at these levels arises from two main sources, solar radiation (at ultraviolet (UV) and soft X-ray wavelengths), and the vaporization of incoming meteors.

Every day about 1,000 tons of very small meteoric particles hit the Earth's upper atmosphere. Most of these so-called *sporadic* meteors are smaller than a grain of sand. They do not appear to be associated with the larger swarms of meteors normally associated with the recurring meteor showers. Generally, these particles are metal rich, containing nickel, iron, and a number of other elements.

Though the E-region atmosphere is very thin, it is dense enough for atmospheric friction to heat up and vaporize the incoming particles. The intense heat raises the particle temperature high enough to both vaporize the particles and also ionize them into positive metal ions and negative free electrons.

Due to the greater mass and higher temperatures of the positive metal ion cores, the subsequent loss of free electrons due to recombination is a much slower process than that for the lighter background gases. As a result, the metal ions have longer lifetimes than those created by the Sun's UV and X-rays by photoionization.

As noted, meteors are coming in and producing ions all the time, day and night, having only small variations with the time of day. However, the Sun only produces ions during the day (roughly 0600-1800 LST). As a result, at a given point in the E layer, the total ionization from both the Sun and meteors is highest during the day, but does not go to zero during the night – the meteor component remains.

What may be surprising is that, even in the daytime, the large-scale E-region ionization is fairly weak. Daytime Maximum Useable Frequencies (MUFs) are on the order of 16-22 MHz. So, something *else* has to happen that increases the electron density by at least a factor of ten in order to produce an MUF above 50 MHz. Nevertheless, it will turn out the combination of daytime solar and meteor ionization does provide the *reservoir* of electrons needed to produce sporadic E.

Winds Aloft and Vertical Compression

As is the case in the lower atmosphere, there are identifiable wind patterns in the E region. There are recognized flows in both the *zonal* directions (east to west and west to east), and in *meridional* directions (north to south and south to north).

For example, the zonal winds, in combination with the Earth's magnetic field, seem to play a special role in enabling sporadic E propagation below about 120 km. In the Temperate Zone, the Earth's magnetic field has a significant component parallel to the Earth's surface, and the zonal winds flow horizontally at roughly a 90° angle to that field. As these winds blow, they try to carry both the neutral and ionized particles along with them. As the free electrons are dragged through the magnetic field, at roughly a 90° angle to the field, this produces a sideways electromagnetic force that bends the electron paths either upward or downward into orbits circling the field lines, rather than continuing to move along with the wind.

If the wind speed varies with altitude, there will be a wind shear at the boundary between the upper and lower flow. This produces net forces that push the electrons vertically into very thin sheets in the wind-shear region. The net effect is that the electrons, which originated in a rather large and weakly ionized volume of space, are compressed vertically into thin sheets with much higher ion densities. This raises the local electron density (N_e) and with that, the MUF – and E_s happens.

But then, why doesn't this happen every day of the year?

Seasons and Meteors

Radar studies of incoming sporadic meteors have shown that there is a significant *seasonal* variation in the meteor counts at mid latitudes. In both the northern and southern hemispheres, the meteor count rates are three to six times higher in the hemisphere's local summer. This is due to the 23° inclination of the Earth's rotation axis to its orbital plane around the Sun (which causes the seasons in the first place). During the local summer, the hemisphere in question is aligned more directly with the plane of the Earth's orbit and thus it is more nearly aligned with the direction of the Earth's orbital velocity, as it sweeps up the meteors, while moving around the Sun.

More importantly for radio propagation, there is a very *strong positive correlation* between the sporadic meteor counts and the E_s critical frequency (Haldoupis et al. 2007): the higher the meteor count, the higher the MUF. The implication is that the enhancement of the general E-layer ionization, caused by the local-summer peak in sporadic meteors, increases the overall supply of electrons in the large-scale E-layer "reservoir". Then, as a *separate step*, when local conditions are right to trigger the wind-shear vertical-compression effect, E_s occurs with MUFs that are much higher than they might be during the other seasons of the year. This appears to explain the summertime *major* E_s peak.

In the study cited, the radars were at 54.6° N and 38° N. They show clear indications of a minor winter meteor *peak* in early January roughly corresponding to the winter E_s peak, with the deepest *minimum* in mid February.

Another study (Younger, et al. 2009) shows strong summer meteor peaks at both 68°N and 68°S, with *no* winter meteor peak. Near the geographic equator (8°S), the seasonal meteor counts and seasonal variations are much less pronounced. Unlike the temperate region, there is a small meteor peak in *both* the summer *and* the winter.

With both studies taken together, the implication is that as one moves further toward the equator from 68°, the summer meteor peak eventually begins to decline and the winter peak begins to emerge.

Atmospheric Tides and the Valley of Death

The Earth's atmosphere is an ocean of air. Like the ocean of water, it sloshes around, and it is subject to tidal forces from outside influences. While there are a number of different tides in the atmosphere, one of the most prominent outside influences is the heating of the atmosphere caused by the Sun every daytime. During the day, the Sun heats the surface of the Earth, which in turn heats the air in the lower atmosphere immediately above it. The heated air in that region expands, causing the dayside atmosphere to balloon upwards at all levels. The heating is more pronounced over land than it is over the ocean.

As the Earth turns under the Sun, this bulge follows the Sun, moving around the Earth once a day. In addition to this 24-hour tidal period, there also is a 12-hour tide and even an 8-hour tide (Haldoupis et al. 2004). Of these, the 24-hour tide is the strongest, while the 12-hour one is next and the 8-hour somewhat weaker still. These tides produce systematic updrafts and downdrafts as they wax and wane. These vertical winds interact with the horizontal zonal and meridional winds to alternately enhance and diminish the vertical compression of the E-layer ionization.

The joint effect of these three tides seems to explain the well-known diurnal variations in the probability of E_s propagation. The overlapping of these three signals produces a three-humped probability curve, shown schematically in Figure 1. The morning peak is consistent with the overlap of all three of the 24-, 12-, and 8-hour peaks, while the double humped afternoon-evening peak appears to be a result of the overlap of the 12- and 8-hour peaks. After the end of the late window, the disappearance of the solar component of E-layer ionization leaves only the meteoric component. Consequently, E_s above 50 MHz rarely occurs after midnight LST.

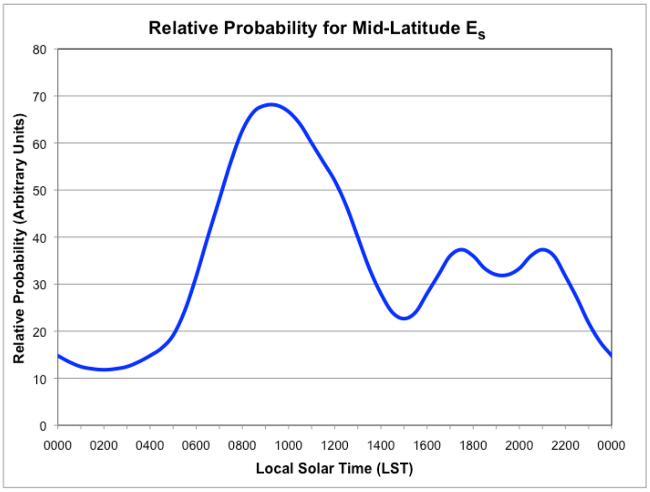

Figure 1: This stylized view of the typical diurnal behavior of mid-latitude E_s shows that the propagation probability often peaks during two time periods, a morning period and a double late afternoon and evening peak period.

It was noted in the earlier discussion that a telling characteristic of SSSP is that the west-end station is almost always in the morning LST peak, at the same time that the east-end station is in its afternoon-evening peak. The information in Figure 1 can also be looked at in a different context, in which *time* is *fixed* at the location of the west-end station for a given family of propagation paths. If this is done, then the horizontal *time* axis in Figure 1 can be reinterpreted as a corresponding *distance* axis, eastward from the west-end station.

Figure 2 shows a snapshot taken at 0700 LST for the west-end station. The probability of the MUF exceeding some certain value, as shown in Figure 1, can be scaled as a rough *proxy* for the *value* of the MUF itself. In this case, Figure 2 shows a schematic of the MUF to the east of the west-end station, as a function of the distance from the west-end station. In this example, the key feature is that the MUF minimum between the Early Window and the Late Window dips below 50 MHz. Evidence suggests that this is often the case. As a result, the only eastward stations accessible to the west-end station are those that are still in the *same* Early Window as the west-end station.

Much further out, the stations within their Late Window can communicate with each other. But the N_e electron-density gap in the middle (the N_e "Valley of Death") stops ordinary nE_s multihop propagation from going between the Early and the Late Windows. There are two obvious situations that would allow the Early and Late Window stations to communicate with each other:

1. A chordal hop that bridges *across* the N_e gap (chordal hops require a much lower electron density than nE_s, see the M-Factor discussion below), or
2. Enough overall E_s ionization so that the dip between the Early and Late Windows never gets *below* 50 MHz in the first place (an especially good day, with very long nE_s).

It is possible that, past 8,500 km, chordal E_s *might* be more common. But, longer paths have been seen with at least some ordinary nE_s hops (see Figure 3).

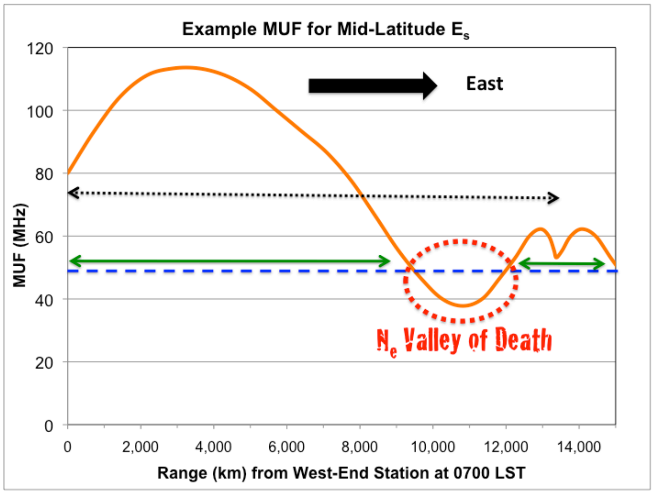

Figure 2: Remapping Figure 1 shows the MUF as a function of distance from the west-end station at 0700 LST (30° lat). The dashed line shows the 50 MHz MUF cutoff points. The solid arrows show the reachable paths. The dotted arrow shows what's possible if the valley is bridged.

The range out to the Valley of Death *varies* with the two stations' latitude. It's *not* always 8,500 km, that for the two stations at 30° latitude. The range gets smaller as the latitude gets larger, that is, closer to the poles.

Chordal Hops, MUF, and the M Factor

The suggestion that SSSP may include chordal skip mechanisms was partly motivated by the fact that a chordal hop can skip successfully with a much lower level of ionization, N_e. This is because the value of the MUF depends on both N_e *and* the *angle* between the signal ray path and the bottomside of the reflecting layer at the skip point. Expressed in MHz, the MUF is given by:

$$MUF = M\sqrt{N_e}\ \mathrm{x}\ (9\mathrm{x}10^{-6}),\quad \text{for } N_e \text{ in electrons/m}^3$$

M is the so-called M Factor, which is the cosecant of angle between the signal path and the plane of the skipping layer. As the angle gets smaller, *M* gets bigger. One gets a higher MUF *without* a change in N_e. (If N_e is expressed as electrons/cm^3, the value of the constant is $9\mathrm{x}10^{-3}$).

The M factor comes seriously into play when one considers any of the chordal-hop variations. All of these involve signal ray paths that have been modified from normal nE_s angles into very shallow ("grazing incidence") angles, which can greatly increase the M factor leading to a higher MUF for that hop than would be possible for nE_s. Put in different terms, in principle, chordal signals can skip successfully with a lot lower N_e than can nE_s.

It is fairly common for E_s clouds to be tilted with respect to the ground, sometimes as much as 60° (Whitehead 1997b). Typically, what happens in a chordal situation is that the upcoming signal ray from the antenna on the ground first hits a tilted or curved cloud at what is now a shallow angle and is bounced off, more or less parallel to the ground. From there it might skip off of one or more flat E_s clouds, and still not come to the ground, until it finds another tilted cloud that points it back down again. All of these hops would require much less N_e than a traditional nE_s path.

Some Other E_s Important Characteristics

Sporadic E has a number of features that make it rather distinct from F2. It occurs at a height of about 90 to about 150 km (most commonly below 130 km), while F2 is around 250 km and above. The lower E-layer height leads to shallower angles of attack for an upcoming wave, leading to higher values of the M Factor and thus higher MUFs than F2 with the same levels of ionization.

The ionization formation process for E_s clouds is both very different and less well understood, compared to F2. A consequence of this different ionization mechanism is that the morphology of E_s clouds is also quite different from F2. These complex processes lead to a variety of strange circumstances:

- Cloud layers are very thin, tens of meters to a few kilometers
- Clouds are smaller in horizontal extent than in F2 region, averaging around 100 km
- Large areas of ionization are composed of swarms of individual clouds
- Clouds in the swarm are in motion horizontally and vertically (usually descending)
- Vertical stacks of two, three, or more layers are fairly common
- Tilted layers are common, at times by as much as 60° with respect to the vertical
- The underside of an individual cloud can be curved or rippled, rather than flat.

SSSP 2010

The previous paper (Kennedy 2010) explored just the JA-NA paths. Since that time, a fairly large amount of 2010 northern summer data were compiled on both the JA-NA and NA-EU paths[2] in order to characterize and compare these two different paths in more detail. Propagation reports were gathered from a variety of sources, including web-reflector postings and direct reports from the operators themselves.

In the end, the strategy was to select two different NA stations that had a lot of activity, one to JA (KØHA) and the other to EU (W7MEM), in an effort to get a coherent picture of paths radiating from one single starting point. In both cases, the data used for this report were from the openings of 19-20 June 2010. The intention was to establish a balanced view of what was taking place over essentially the same paths to those two remote destinations. As with the 2010 study, the idea was to see what evidence there might be for chordal versus nE_s hops, and see if the diurnal “early peak on late peak” timing was indeed a persistent feature.

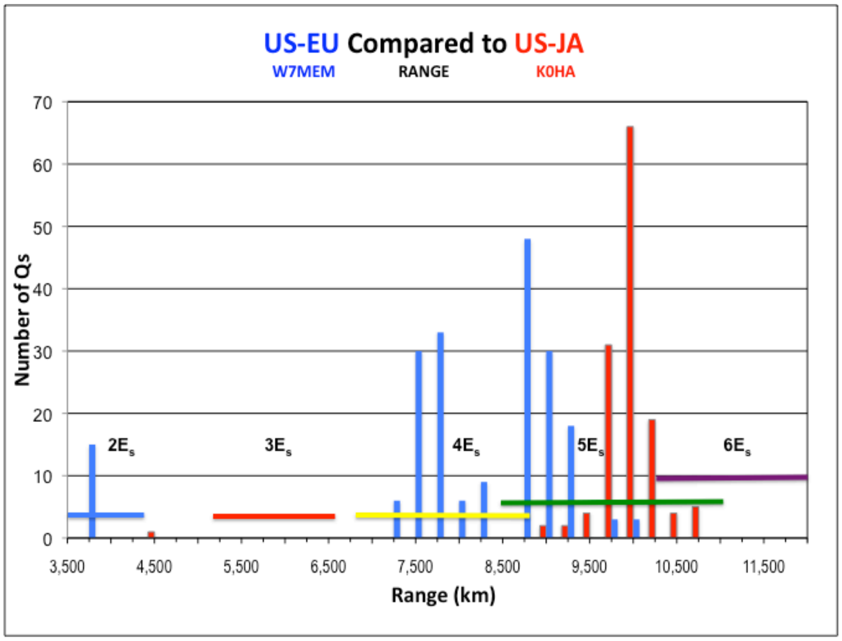

Figure 3: The range between W7MEM and EU contacts (open bars) are compared to those between KØHA and JA (filled bars). The EU path shows typical evidence of both hops four and five. The JA path shows only hops two and five (see text).

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[2] The authors apologize to our JA constituents. We don’t have sufficient data to study the EU-JA circuits. Data originating from a single station in either JA or EU contacting multiple stations at the other end would be most welcome.

It must be pointed out that unequivocally demonstrating that a given 10,000 km path is the result of every hop coming to earth is a “hard” problem. With the distances involved, the realities of geography, climate zones, human infrastructure, and human population demographics, it would be a challenge to design an experiment where E_s of one form or another could happen *and* there would be a suitable population of radio operators in place and on the air at every hop footprint – oceans and polar regions are bound to get in the way.

JA–NA Path Ranges

Figure 3 shows a comparison of the JA and EU path data sets. The JA path result is much like the previous study. Except for a single KL7 at about 4,500 km, there is no other evidence of intermediate hops reaching the ground between NA and JA.

As noted, on that great circle path, the population of radio operators at all of the intermediate skip footprints (western Canada, Alaska, the Bering Sea and the Pacific ocean) is either very low or none at all. Consequently, it is still unclear whether these paths are nE_s or chordal E_s.

NA–EU Path Ranges

This is the first time the NA-EU path has been explored using the current techniques. Fortunately, this path’s deeper end-point provides a bit more information.

There is clear evidence of hops two[3], four, and five reaching the ground. Single hop was ignored in the study, direct hops two and three land in the vicinity of Hudson’s Bay and central Greenland and Iceland before making landfall in Europe. Looking more closely at Figure 3 one can see at least two distinct populations of contacts at the four- and five-hop ranges, separated by what appears to be a skip-distance gap at about 8,500 km – where one would expect it – between hops four and five.

Figure 4 shows a great circle map centered on the average path midpoint. It shows the range of path tracks over the wilderness to finally reach the hops four and five footprints. Another interesting feature is the presence of multiple contacts from about 9,000 km to about 10,000 km, as hop five opened inland to central Europe and the Mediterranean. These are clearly at distances comparable to those required for the JA-NA path, and here those last two hops (at least) look very much like nE_s. Of course, there is nothing to say some hops might be chordal and others nE_s.

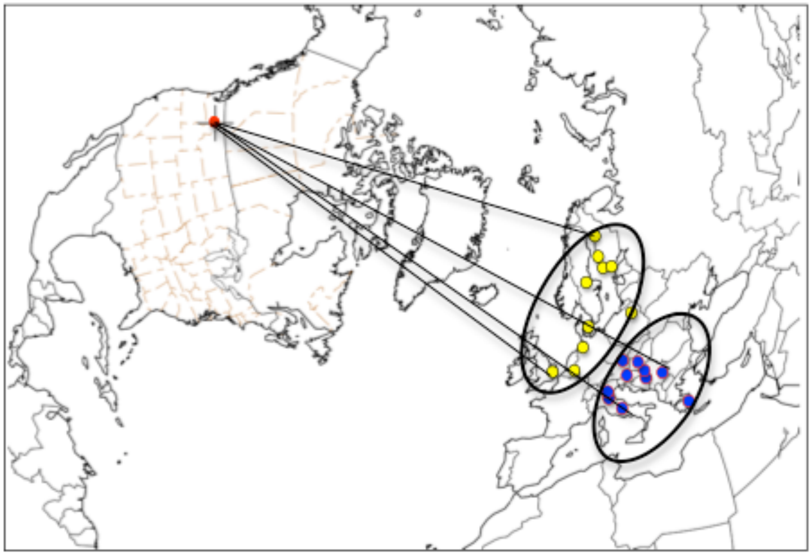

Figure 4: This great circle map* is centered on the average path midpoint. It shows the hops four and five footprints in the two ovals on the right, with circles and dots at some actual contact locations. The straight lines show the azimuthal range of the signal ray paths, and the sparsely populated regions they traversed prior to hop four.

Early-on-Late Diurnals

The remaining measureable here is the details of the time-of-day relationships between the west-end and east-end station in each individual contact, for both the JA and EU paths. The E_s morning probability peak is from about

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[3] The $2E_s$ was from W1 and W2 and 40°-50° east of the great-circle path to EU, and probably not good indicators here.

* Background map credit: Joe Mack NA3T and Mike Katzmann NV3Z, see www.wm7d.net/azproj.shtml

0630 to 1230 LST, and the afternoon/evening peak is from about 1530 to 2030 LST (see Figure 1). Figure 5 dramatically shows that *both* the JA-NA and the NA-EU contacts were made exclusively *within* this west-end east-end window overlap (Kennedy 2011).

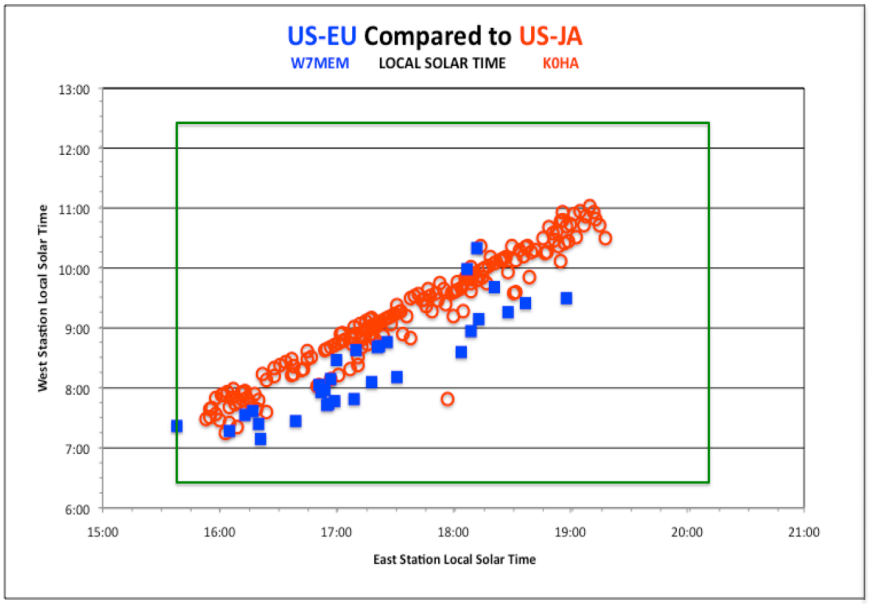


Figure 5: The circles represent each JA-NA contact LST at the west and east ends of the path. The squares represent the same for the NA-EU paths. Both clearly show the Early-Window-on-Late-Window effect.

It is the difference in longitude between the east-end and west-end stations that sets the LST time *difference* (9 to 10 hours on average). However, the *absolute* time of day is a free parameter. The fact that the actual LST at each end fits within the E_s peak probability times also strongly suggests that some kind of E_s mechanism is at work.

If a contact is in the LST early-on-late box, and *if* there *is* a Valley of Death, the Valley lies *somewhere* in between the two stations.

ZL/VK–SA SSSP

The 2009-2010 southern summer provided a number of what appear to have been east-west SSSP contacts between ZL/VK and the SA west coast. Their characteristics seem to mirror those of the northern hemisphere effect. Only two or three such contacts have come to light in the 2010-2011 southern summer.

What Was Going On In the Ionosphere?

Clearly there are ionospheric processes going on that led to these uncommon forms of propagation. In order to explore this in more depth, an effort has been made to recreate the state of the ionosphere as it may have been while these events were occurring.

Ionospheric Models

Unfortunately, *directly* doing this in any detail, in three dimensions, by making measurements of the free-electron density, N_e, everywhere, is not currently possible. However, there are a large number of measurements of other relevant quantities that *are* made on an ongoing basis. So, while it is by no means trivial, it is possible to input those data into the known equations of the physics of the ionosphere to do a three-dimensional recreation, with generally good fidelity. There are a number of ionospheric modeling programs that do precisely that.

The model used here is called the Global Assimilation of Ionospheric Measurements model (USU-GAIM). It was developed at Utah State University (Schunk, et al. 2004). The ionospheric model was run for the entire day on the dates of the events studied. It produced a snapshot of the global ionosphere in three dimensions from 92 km to over 1,000 km for each fifteen-minute period through the day. The models were run at the Community Co-ordinated Modeling Center hosted at NASA's Goddard Space Flight Center.

Although the USU-GAIM model is quite good, it is a large scale, global model. In order to cover the territory, it works on a somewhat coarse grid pattern. It calculates values for every 4.66° of latitude and 15° of longitude. As a consequence USU-GAIM cannot recreate small-scale or rapidly occurring events. This includes the many manifestations of E_s. The spatial features of typical E_s are made up of many relatively small clouds, which are often in rapid motion. As a result, the USU-GAIM model is used *only* to show the location and size of the E-layer electron "reservoir", and the approximate value of its electron supply. It *cannot* show when and where the E_s is, but only where it *could* be, *if* the vertical compression mechanism goes to work.

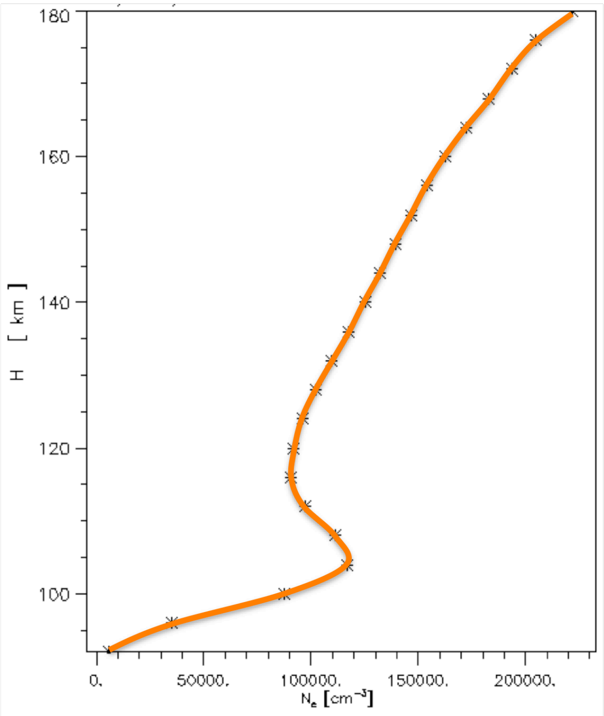


Figure 6: USU-GAIM N_e rendition for 0300 UTC 02/20/2010 at Lat -30, Lon 180. The E-layer peaks at 105 km, then drops by about 25% by 118 km, and then resumes increasing going upward toward the F layer.

E-Layer Valley

As a general rule, if one plots the value of N_e starting at the surface going upwards, N_e increases with altitude until after the F-layer peak. However, there is an exception in the E-layer, which may turn out to be important to the discussion. E-layer N_e does increase with height, but only to a point (about 105 km in Figure 6) and then it actually goes down for a bit, before it begins to climb again. This feature is referred to as the E-layer Valley (Davies, 1990).

It demonstrates that there can be, in effect, at least *two* E-layer reservoirs to feed the formation of E_s. One corresponds to the region of the E-layer "peak" (here about 105 km), and another region of equal or higher N_e 10 to 40 km above the "peak" (here about 32 km).

It is an observational fact that E_s most often tends to be seen around 105 km, however, one or two additional layers *above* the lowest one are seen at times.

20 June 2010

This is a first look at a study in progress. A lot of the available detailed data have not yet been fully explored. However, samples from various dates indicate that they may have many characteristics in common.

The 20 June 2010 date was selected as the first for a more extensive review because, from NA, the band opened to EU in the morning around 0700 LST. As the Earth turned that same day, in the afternoon it opened from NA to JA at about 1600 LST (about 0800 JA). This suggested an opportunity to look at the evolution of the ionosphere over a roughly 13-hour period, where, perhaps, the same or similar conditions may have persisted.

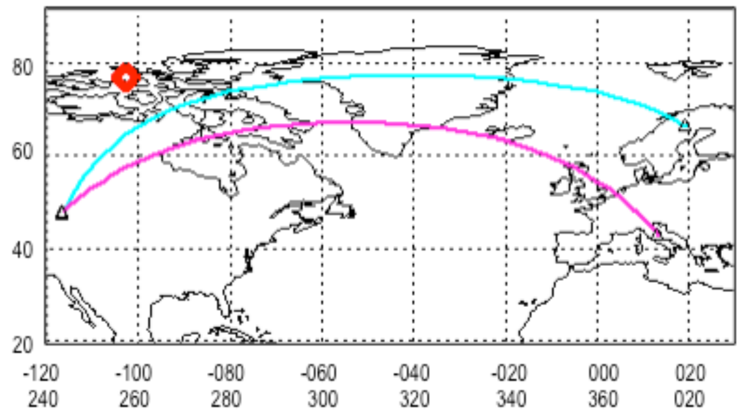


Figure 7: 20 June 2010 NA-EU path extremes. The second longitude scale is in the "all east longitudes" notation used by USU-GAIM. The diamond near (80, -100) is the magnetic north pole.

NA-EU Path

Figure 7 shows the range of course lines for the W7MEM to EU paths, and the latitudes and longitudes covered. In latitude, the paths extend from about 40N to about 76N, and in longitude, from about 120W to 20E. There are also two longitude scales. The upper one is in the more common Longitude East and West format, here running from 120W (-120) to 020E. The lower scale is an "East only" scale used in many of the USU-GAIM displays. It simply measures everything going eastward, from 000 through 360. This scheme will be used in most of the remaining maps.

E-Layer Reservoir

Figure 8 (Lower) is a contour map of the modeled daytime E-layer reservoir, showing its broad expanse. Though N_e levels are decreasing to the north, they are adequate for E_s formation of over the path in question.

Arctic F-Layer Finger

The contour map of the F2 region in Figure 8 (Upper) shows that there was a *separate* F2 *finger* centered over Greenland at 69N and 275 km (top half of frame). It is quite separate from the *main* daytime equatorial-anomaly F2 ionization lobe (out of frame at bottom). This structure was centered very close to the Figure-7 path midpoint, and it was elongated in the east-west direction.

While this is *not* about F2 *propagation*, hold onto the thought that this enhanced F2 ionization generally *overlays* the main portion of the E_s paths between W7MEM and EU.

USU-GAIM is a 3D model. Figure 9 shows a vertical north-south slice down through the F2 structure along longitude 310E. It shows how this structure dominates the region from about 55N to past 80N.

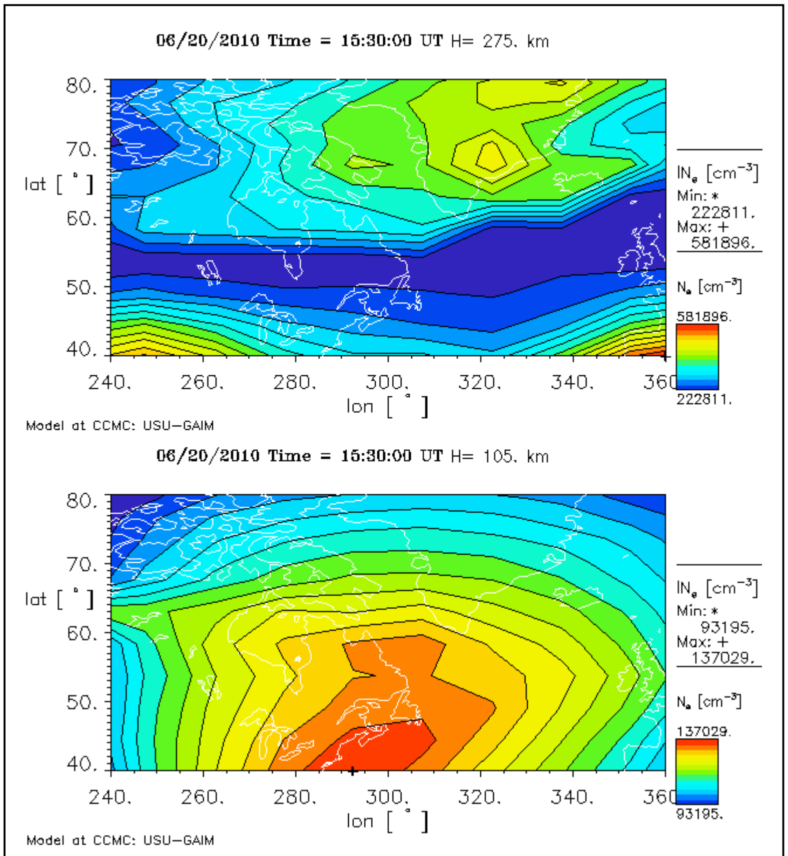


Figure 8: **Upper**: At the opening midpoint time, note that there is a "finger" of F2 ionization overlaying the central portion of the path region, with lower fringes reaching from south-central Canada to east of Iceland. The main F2 region is seen building south of 40N.

E-Layer Valley Again

Figure 9 also shows the F2 high-density peaks around 250 km are pushing higher levels of ionization all the way down into the E layer. This shows that the upper ridge of the E-layer Valley, in Figure 6, is just the long, low-side tail of the *F-layer* ionization.

Much of the east-west path was near latitude 70N. Figure 10 shows an east-west cut through only the *E-layer Valley* portion of the ionosphere (92-135 km). The west end of the path is on the far right and the east end is on, or just past, the far left. Figure 11 shows a north-south cut along the mid-path longitude.

These show an E-layer reservoir peak near 103 km, then a valley, and starting about 115 km, there is a steadily increasing reservoir that, near 128 km, reaches the same N_e levels as the lower 103 km peak. The N_e values were on the order of 100,000/cm^{-3}. These are normal summertime values corresponding to MUFs greater than 15 MHz.

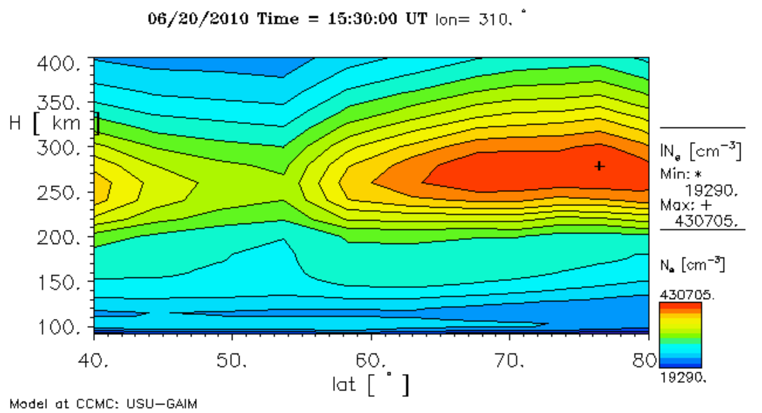


Figure 9: This is a vertical slice downwards through the Figure 8 data, cut at 310E longitude near the path midpoint and its northernmost excursion. The feature leftward from 55N is leading to the main F2 lobe much further south.

The point is that these conditions existed in two places in the Valley that were only 25 km apart in the vertical direction. The elevated F2 conditions above the E layer brought the upper side of the Valley closer to the lower side, so that if wind shear was around, the opportunity for both the upper and lower level to participate was enhanced. More importantly, this condition existed over much of the entire NA-EU path.

JA-NA Path

Consider the conditions later that afternoon, looking now from NA toward JA. Figure 12 shows the path tracks. JA is a rather small target compared to all of EU. The paths are all very similar. The real difference is in how far south the paths go on the west end.

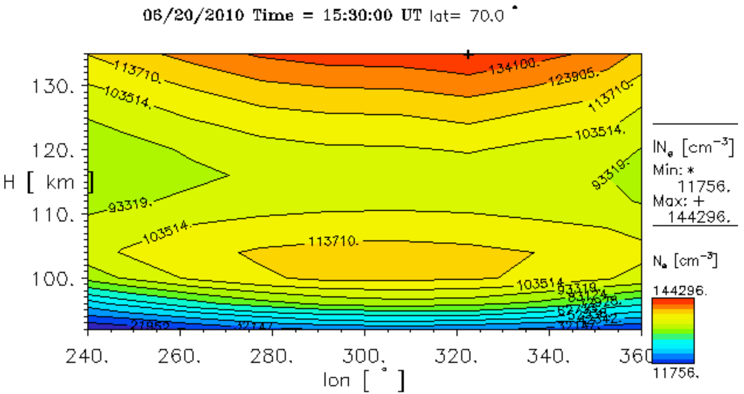
These paths don't go as far north as the EU paths. Some of those went nearly to 80N; here they are all peak at about 60N. The other difference is the ionosphere, and the F-layer in particular. The persistent ridge-like F2 peaks tend to track 10°-20° north and south of the magnetic equator. Due to the magnetic equator's inclination to the geographic equator, the angles of these ridges are somewhat different over the Pacific than over the Atlantic.

Arctic F-Layer Finger

Figure 13 (Upper) shows that there is also a northern finger or ridge-like feature of locally enhanced ionization that seems disassociated with the persistent diurnal F2 ionization maximum produced by the equatorial anomaly. Unlike the NA-EU case, where the ridge overlaid almost the entire path, the Pacific ridge was south and west of the optimum location and was only associated with about the eastern half of the path.

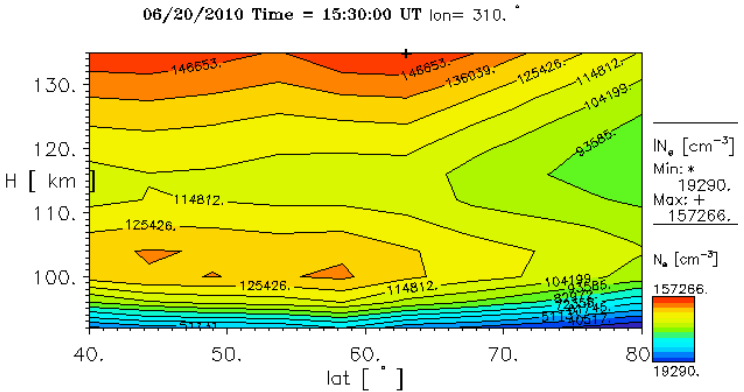
E-Layer Reservoir

Figure 13 (Lower) shows that the shape of the normal E-layer ionization patch, which provides electrons for E_s, was shaped and centered in the northern Pacific in such a way that it produced a nearly constant of reservoir ionization on the path from western Canada until Japan.



Model at CCMC: USU–GAIM

Figure 10: This is an east-west vertical slice through the Figure 8 image at 70N latitude running most of the path, showing the E Valley between 92 and 135 km.



Model at CCMC: USU–GAIM

Figure 11: This is a north-south slice through the E Valley at the northernmost path point at about 310E. It shows that the north-south channel between the Valley walls extends over 4,000 km.

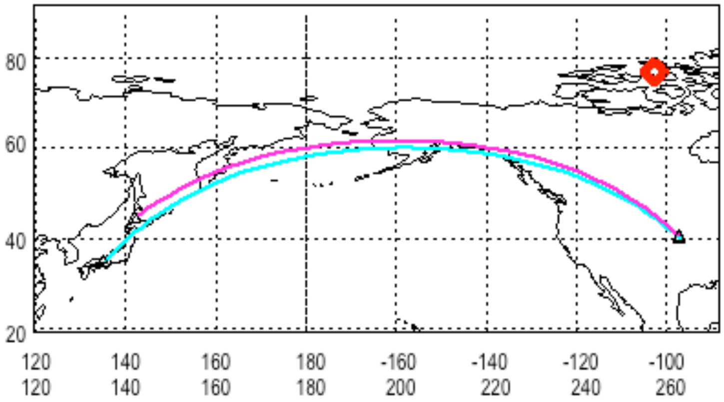


Figure 12: 20 June 2010 JA-NA path extremes. The second longitude scale is in the "all east longitudes" notation used by USU-GAIM. The diamond near (80, -100) is the magnetic north pole.

Figure 14 indicates that despite the less than optimal alignment of the F2 ridge, the F-layer ionization is apparently enhancing the upper edge of the E ionization Valley.

Figure 15 is a close up look at the east-west ionization along the path as seen at 55N. It will be noted from Figure 12 that the path remains in that general latitude vicinity for quite some distance. It shows that, like the NA-EU case, there is a second region of enhanced E-layer ionization of the upper side of the valley that is only 10-15 km away. In the east-west direction this seems to provide a *channel* for the development of E_s both around 105 km and 125 km.

Finally, Figure 16 shows a north-south cut near the path midpoint, along latitude 190E. Here again, there is a resemblance to the NA-EU case in that it also shows that the north-south dimension of the channel region is quite extensive.

What Might Be Happening?

In order to address this question, the first step is to focus on defining the problem.

Why Shouldn't These Paths Work?

The initial concern was that the paths were so long that ordinary nE_s would be so attenuated by absorption and scattering after so many sky and ground encounters that there would not be enough signal left at the far end. This led to suggestions that tilted-layer chordal hops, chordal skip ducting between layers, or even progressive refraction during long passages through ionized regions, might preserve the signal strength sufficiently.

Though arguments have been advanced, it has never been conclusively shown that it could *not* be nE_s. Nevertheless, some amazing propagation involving chordal modes (Kennedy 2003) have shown up in the F layer, so it is reasonable to explore them in the E layer.

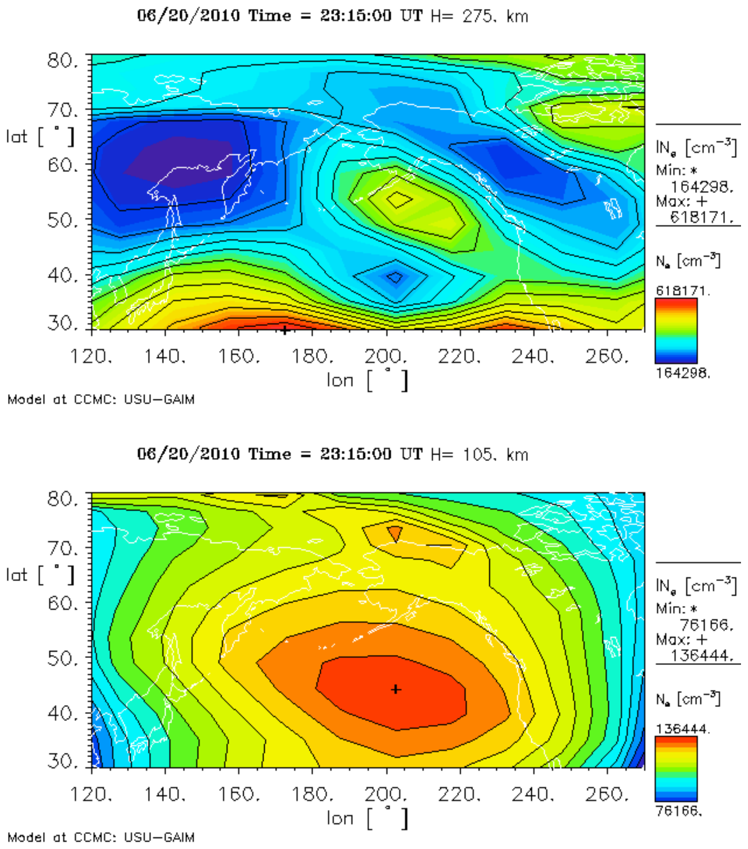


Figure 13: **Upper**: At the opening midpoint time there is a small finger of F2 ionization in the vicinity of the first half of the path, south of KL7, though it is not optimally aligned. The main F2 region is seen building south of 30N. **Lower**: The underlying E-layer provides roughly equal amounts of N_e all along the path route.

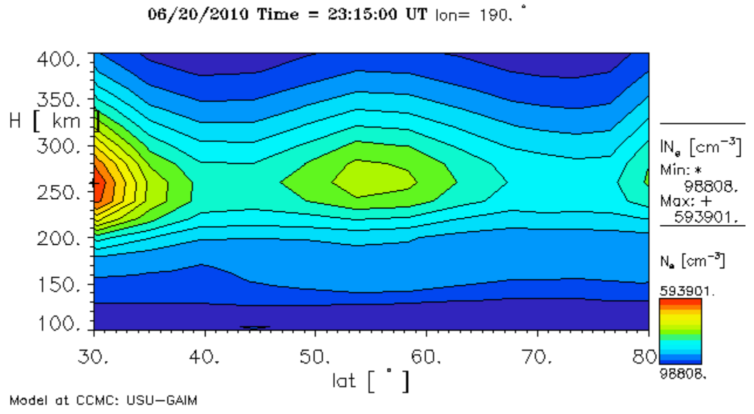
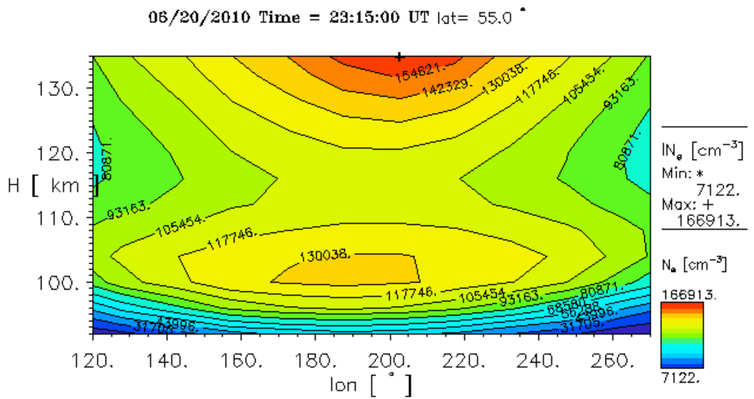


Figure 14: This is a downward slice through the Figure 13 data at the path midpoint (190E) showing the F-layer enhancement due to the finger. Though the alignment with the path overall is a bit off, it seems to be projecting an enhancement toward the E layer.

There is another issue that has emerged in looking at this problem and that is the matter of the long-known diurnal pattern of E_s, as discussed and diagramed in Figures 1 and 2. What is seen is that paths like JA-NA and NA-EU seem to only work consistently when the west-end early and east-end late probability peaks overlap. It suggests that something must be happening in the *middle* of the path to get over the hump.



Model at CCMC: USU–GAIM

Figure 15: This is an east-west vertical slice through the Figure 8 image at 55N latitude running most of the path, showing the E Valley between 92 and 135 km.

Why Do They Work?

The answer to that is still unknown, but the limited work on this so far suggests a couple of hypotheses.

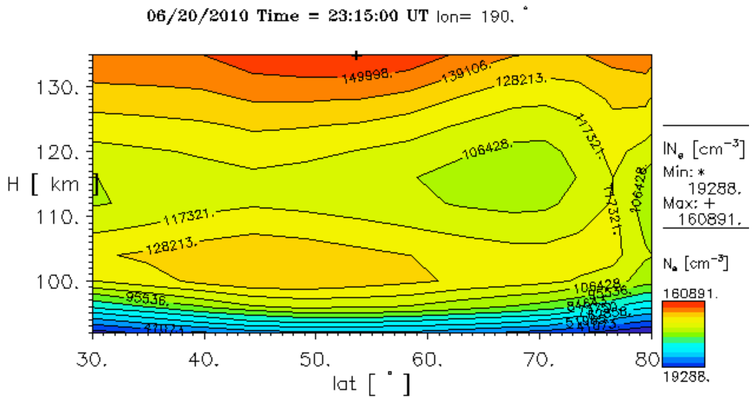
F-Layer Ionization Above and Channels in the E-Layer Valley Below

Proceeding from the following observations:

- There is a known E-layer Valley
- E_s has been observed at least as high as 150 km, although it is rare
- Multiple E_s clouds between 100 km and about 135 km are more common
- Wind shears and vertical motions are all associated with the actual occurrence of E_s
- Though the diurnal E_s probability is lower at the path midpoint LST, the N_e reservoir is *maximum* there;

consider the following scenario:

It is plausible that E_s occurrences in a given region would be *enhanced* if the upper branch of the Valley (fed by the F layer) were squeezed down, physically closer, to the normal E-layer peak. If the two comparable levels of ionization were closer together, they could more easily participate in the available wind-shear engines at about the same time. This would lead to E_s clouds at, say, both 110 and 125 km, more or less simultaneously. If this were the case, then an important factor in these unusually long E_s links might be the positive influence of *having a well-ionized F region above the E-layer path*.



Model at CCMC: USU–GAIM

Figure 16: This is a north-south slice through the E Valley at the northernmost path point at about 190E. It shows that the north-south extent of the channel between the Valley walls is over 3,000 km.

Only two openings have been examined in this detail yet, so the statistics are very shaky. Nevertheless there are a couple of apparent possibilities. In both the NA-EU and JA-NA openings, it appears that there was a *channeled* E layer (not a single layer) at 105 km, about 25 km high, and 3,000-4,000 km wide that extended over much, or all, of the path. This could have led to a couple of things, beyond just good conditions, all the “old” ideas are still on the table, perhaps even enhanced by the following conjectures:

Doubling the Odds – Much of the time E_s is *not* composed of a single sheet of intense ionization thousands of kilometers wide and long. Most E_s is made up a conglomeration of many, relatively small (up to 100 km horizontally), very thin clouds (tens of meters to a few kilometers vertically). Usually they are in motion, with the E-layer winds. As a result, E_s is usually porous; the signal not only hits the clouds and maybe skips, but also passes through the spaces in between them and keeps going up. If there were two (or three) sets of cloud producers, one above the other, the odds of getting an nE_s hop, or an ordinary chordal hop, goes up.

Bottomside–Topside Ducting – This physical configuration may also set up the between-layers ducting situation mentioned earlier. There is no way to tell for sure, but if Bottom–Top ducting were to happen, it would appear that this "channel" structure would be the ideal setting for it.

Discussion and Conclusions

The intention of this study was to look further into the east-west SSSP phenomenon to see how it behaved at different longitudes. In the northern hemisphere, it reviewed the well-known JA–NA path with more and new data, and added a comparable study of the NA–EU path. It would be useful to look at the EU–JA path, but at the time there were insufficient data available to do it justice. Perhaps, this will be possible in the future.

One concern that has been raised in the past has been whether there could be an E_s path behaving according to mid-latitude "rules", if it involved latitudes as far north as 60N to 76N. It is common to talk about the transition from mid-latitude E_s to auroral E_s being at about 60N. However, this boundary actually has a wide range, depending on whether it is day or night and whether the geomagnetic field is quiet or active.

On the daytime side of the Earth the auroral oval is pushed rather far to the north, as far 80N. In the present case, the path midpoints were all on the daylight side. Moreover, during quiet geomagnetic times, such as have prevailed these last few years, the ionosphere south of the (northern) auroral circle has the same seasonal and diurnal rules at ordinary "mid-latitude" E_s (Hunsucker and Hargreaves, 2003). Thus, it may well be that the unusually long quiet Sun may have something to do with the amount of this propagation seen in recent years.

East-west SSSP propagation still has all the earmarks of an E_s propagation mode, or modes. The biggest clues are the fact that it is a local summer-season event, and it exhibits a quite rigid adherence to the diurnal E_s early-on-late effect. Almost without exception, the west-end stations are in their morning peak E_s probability window, while the east-end stations are in their afternoon-evening E_s probability window.

The maximum range of any path by SSSP will probably be constrained by the geographic limitations of the early-on-late overlap. In detail, this distance varies with station latitude. Lower latitudes have longer geographically possible early-on-late distances going out beyond 14,000 km. Typical maximum values at mid latitudes are in the neighborhood of 11,000 km.

Conclusions – The findings regarding SSSP from this more extended study are:

1. The evidence remains strong that these events are some form of E_s;
2. It is not clear whether some of these hops were chordal E_s modes;
3. Like the 2010 study, there is good evidence for nEs playing a role for at least some of the hops;
4. The character of the JA-NA and NA-EU phenomena seem to be essentially the same;
5. F-layer enhancement of the E-layer Valley may play a role;

A Final Caveat – Although the studied openings and paths appeared representative of other known similar events, the detailed comparison to the ionospheric model was restricted to this one 24-hour period. While the characteristics, such as the diurnal patterns, were essentially the same as many other observed events, one must be cautious about assuming that the conclusions here are generally valid, until more samples are studied.

Acknowledgements – The USU-GAIM Model was developed by the GAIM team (R.W. Schunk, L. Scherliess, J.J. Sojka, D.C. Thompson, L. Zhu) at Utah State University. The authors wish thank the USU-GAIM team and the Community Coordinated Modeling Center group at the NASA Goddard Space Flight Center for sharing and running the ionospheric models presented here. They also thank Bob Culbertson, WA3YGQ for assistance in identifying useful research papers regarding the link between meteors and E_s.

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