Extreme Multi-Hop 50 MHz E_s

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Introduction

Even in the absence of high solar activity, six meters still seems to provide plenty of excitement and excellent opportunities for studying ionospheric propagation. The band is on the border between HF and VHF and thus, six meters sits at the edge of what's possible for ionospheric propagation. Unlike HF, when six-meter propagation does occur, it often shows only one or two modes at a time, making it easier to sort out what's going on.

It is well known that temperate-zone sporadic E-layer propagation (E_s) has a pronounced seasonality, with a major peak in the local summer and a minor peak in local winter. It also has systematic diurnal variations favoring roughly 0700 to 1230 Local Solar Time (LST) and a smaller peak around 1600 to 2200 LST (Whitehead, 1989).

Single-hop E_s paths out to 2,200 km and double-hop out to 4,400 km are fairly common, especially during the local summer: mainly May, June, and July in the Northern Hemisphere, and December, January, and February in the Southern Hemisphere.

Though more rare, during the summer E_s season there are many well-documented episodes in which short-path 50-MHz propagation has occurred over distances from 6,600 km to more than 13,000 km. If these are viewed as cases of "ordinary" multi-hop sporadic E propagation (nE_s), then they represent three to six hops ($3E_s$ to $6E_s$). Table 1 shows the approximate near and far edges of the ground footprints for successive E_s hops (Kraft and Zimmerman, 2009).

Table 1 Ground Footprints for Successive E_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

The path between Japan and the North American west coast has been open many times since at least June 1977. More recently, the path between Japan and the central and eastern regions of the US and Canada, and the Caribbean has attracted a lot of attention. Similarly, the path between the North American east coast and Europe has been active, as has the path between Japan across Asia to Europe and the Mediterranean. Very recently, the Southern Hemisphere path between the west coast of South America, and New Zealand and Australia has emerged.

Especially for the distances exceeding three hops (>6,600 km), there has been considerable speculation about whether these longer paths result from ordinary nE_s skip or some other mechanism(s). Higasa (2006 and 2008) called special attention to this phenomenon, referring to it as "Short-path Summer Solstice Propagation" or SSSP. The intention of the current paper is to shed additional light on some possible explanations for these events.

Reaching the Ground?

The notion of SSSP resulted from trying to explain the received signal strength over so many *hops*[1]. Besides free-space losses, each progressive hop of ordinary multi-hop E_s diminishes the signal level

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[1] "Hop" is taken to mean a single ground-ionosphere-ground skip.

both by scattering when the ray path hits the ground (or just grazes past it) and by additional passages from the absorbing D layer (although at 50 MHz, D layer absorption is negligible).

Believing that nE_s ground-encounter losses would leave too little signal after the equivalent of five or more hops, Higasa, and subsequently Kusano and Obara (2007), suggested that the signal was *not* coming back to the ground on the *intermediate* hops, but going directly to the next skip point[2]. They suggested various possibilities including chordal hops[3] and bottomside-to-topside skip ducting. Both these phenomena are known to exist in other circumstances (Davies, 1990; Kennedy, 2000 and 2003).

So, in testing these ideas, how would one tell whether the signal had, or had not, come back to earth on a given intermediate hop? This would be easy for a double-hop path over well-populated land. One would simply look for evidence of signals propagating to or from the intermediate point. However, this is not always easy, or even possible, on very long paths, due to geography and other issues.

There are four factors that influence whether or not one could tell if an intervening hop came to earth:
- Path line itself (usually a Great Circle, but not always),
- Geographical location of the ground footprints (water, smooth or rough terrain, etc.),
- Population density within those footprints (is anybody there to listen or be heard?), and
- Distance, in terms of longitude (what time is it at each *skip point*?).

For example, indications are that the path taken by SSSP from Japan to North America is indeed a Great Circle route. However, hops one and two would come down over the Pacific Ocean and the Bering Sea. Hops three and four would come down in sparsely populated regions of western Alaska and western Canada. So, the likelihood of the signal actually being heard by anyone at hops one and two is essentially zero, and it is not much better at hops three and four. However, hop five lands squarely in the well-populated eastern half of the US, which is generally where the existence of the propagation first comes to light.

The question of whether or not intermediate hops come back down to the ground is approached here first by looking at two different well-documented examples of openings at four-hop ($4E_s$) distances between Hilo Hawai`i and the North American Mainland. This path is particularly useful because, although the first eastward hop lands in the Pacific, the subsequent hops two, three, and four all land in North America, making it possible to determine with some confidence whether those last three hops came to earth in the normal way.

Hawai`i – 2 July 2000

In the case of 2 July 2000, QSOs were logged with 206 stations in North America. It was possible to identify credible grid squares for 193 of these stations. The latitude and longitude of the grid-square centers for each of the 193 stations were determined and the Great Circle distance calculated between Hilo and each station's *grid square*. Two plots (Figs. 1 and 2) were then obtained, one showing the geographical location of each grid worked (there may be many stations in a given grid), and the other showing a frequency-of-occurrence histogram of all the *stations* worked, as a function of path length.

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[2] "Skip point" refers to the point where the ionosphere refracts or reflects the wave onward.
[3] A "chordal hop" skips from one E_s skip point directly to the next skip point, without coming to earth in between.

There are several things that stand out in Figures 1 and 2. Perhaps most obvious is that they both show that the Hawai`i signals did indeed come to earth at hops two, three, and four. Another is that, as shown in both Table 1 and Figure 2, the empty spaces *between* footprints (the "gaps") get smaller as the hop count goes up. In fact from hops four and five on, all of the footprints overlap each other.

Other important items are:

- 1E$_s$ was in the ocean, so there is no information about whether it came to earth on not,
- 2E$_s$ dominates, *as one might expect*; it was the closest and the signals were the strongest,
- 2-3E$_s$ long gap out to 5,750 km probably reflects the low population density at that range,
- 3E$_s$ picks up toward the east end, probably due to larger population density,
- 4E$_s$ produced a number of contacts, also probably influenced by population density.
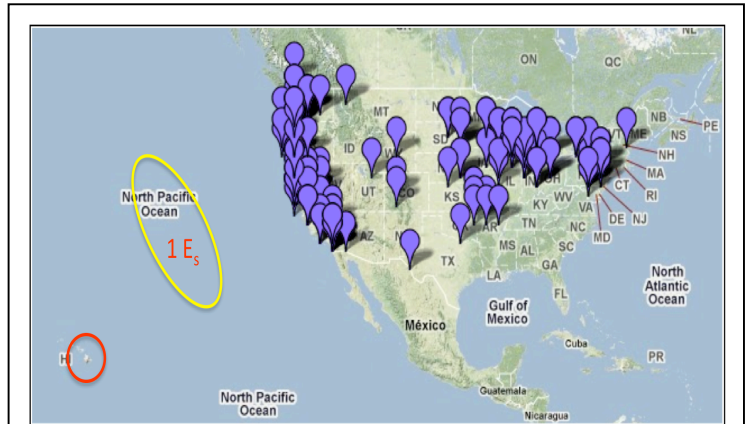

Figure 1: 2 July 2000, this shows the grid-square distribution worked from Hawai`i. The regional population densities and skip gaps are reflected in the distribution of the squares worked. *Map credit Google Maps.*

There were always some signals in the gaps *between* footprints. No doubt this results from the footprint-size calculation assuming that the ionosphere is both *smooth* and *perfectly spherical*. The appearance of signals in the gaps is clear evidence that this is not really the case – smooth and spherical are (over) simplified assumptions.

Sporadic E layers generally are *not* smooth and *not* flat. This leads to scattering by irregularities in the layer(s). (There will be more discussion of this point later.)

One can then conclude that the 2 July 2000 opening looks like what one would expect for nE$_s$ – many strong signals close, fewer and weaker signals at each hop farther away.

Hawai`i – 6 July 2009

The 2009 opening was another outstanding opening from Hawai`i; 183 stations were worked and 167 had identifiable grid squares. However, the plots reveal that it was quite a different opening than the one from 2000. In many important respects, Figures 3 and 4 paint essentially the *opposite picture* from that of Figures 1 and 2:
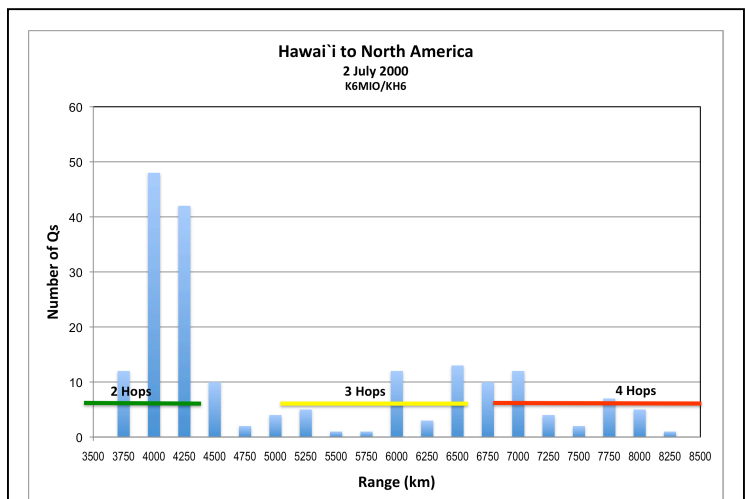

Figure 2: The number of stations worked is reflected in the distances, regional population densities, and the approximate radial locations of the various skip footprints.

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- $1E_s$ still has no population, so it isn't clear what happened there,

- $2E_s$ has a *huge* population, and yet it shows only a few (and quite weak) stations compared to later hops,

- $2\text{-}3E_s$ still have a population-density gap that goes well into hop three,

- $3E_s$ is about the same as the 2000 event,

- $4E_s$ *dominates* the whole scene, and the signal levels were fairly good.

Figure 3: The 6 July 2009 grid-square distribution worked from Hawai`i. Only a handful of stations and grids were worked for hops two and three. *Map credit Google Maps.*

E-layer scattering still probably accounts for the signals in the gaps (and perhaps those seen at the second hop). There is no $5E_s$ information, as both $5E_s$ and $6E_s$ land in the Atlantic Ocean.
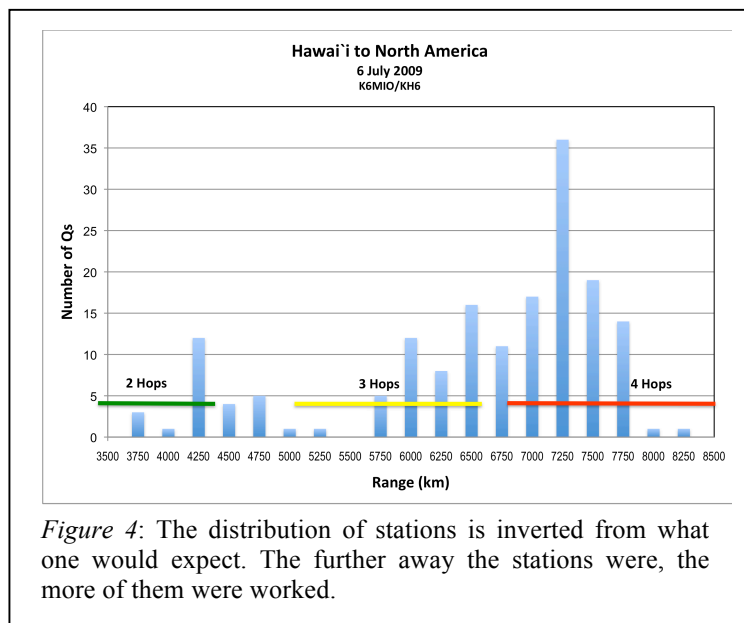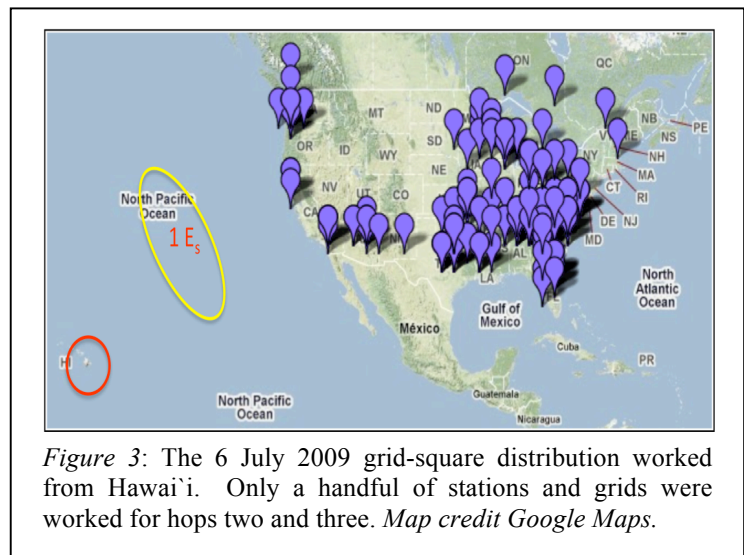
Interpretations of the Hawai`i – North America Data

The 2000 Hawai`i opening clearly shows:

> Ordinary $2E_s$, $3E_s$, and $4E_s$ *is* occurring with the two- and three-hop signals coming to earth.

The inverted 2009 skip-range distribution shows that little of the signal came to earth at hop two, and that hop three was not much better. However, hop four was strong and in good shape. This supports the notion that, in the case of *this* opening:

> Conditions existed that propagated most of the signal over the top of the hop two and three landing footprints.

> Quite usable signal strengths were delivered to the hop-four footprint.

Figure 4: The distribution of stations is inverted from what one would expect. The further away the stations were, the more of them were worked.

These two latter findings are quite consistent with the notion advanced by Higasa, and Kusano and Obara, that SSSP may be due to the intermediate-hop ray paths not reaching the ground.

Japan – 3-4 June 2006

Kusano and Obara showed 2006 data from Yoshi Miyamoto, JM1DTF. Two contiguous days of those North American openings were processed the same way as the Hawai`i data. In addition to the fact that these two contiguous openings demonstrated at least a five-hop range, the key things to note in Figures 5 and 6 are:

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- $1E_s$ and $2E_s$ have no populations at all (over water),
- 3 and 4 E_s has *almost* no population (generally very rural areas),
- 5 E_s *dominates* – the population is quite *large*, but with *weak* signals (almost all made on CW),
- 6 E_s is out of land, except for some of the Caribbean islands.

It should also be noted that during these two days it is not known if the ray path came to earth at hops one, two, or four. While there is no available information about signals in the gaps, Jimmy Treybig, W6JKV, operating in Alaska during a similar opening, reported that he heard only the Japanese stations and that they were "at ESP levels" for hours, which is consistent with weak E-layer scattering out of the main overhead path.

Interpretations of the Japan – North America Data

In accord with Higasa, and Kusano and Obara, it is reasonable to conclude that:

> At times there were one or more mechanisms at work leading to E-layer propagation characterized by intermediate hops that largely do not return to the earth, until they reach the path end point.

A Global Phenomenon

SSSP-like propagation is definitely a global occurrence. The northern paths from Japan westward to Europe and also eastward to North America are well known. (There also is a North America to Europe path, but ordinary $3E_s$ or $4E_s$ may account for this.)

The southern equivalent of the Japan to North America path showed up in the southern summer of 2009-2010, (December 2009 and January 2010), as seen in Figure 7.

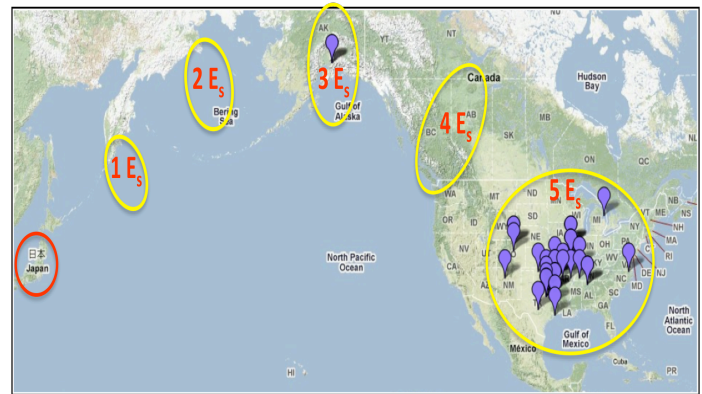Perhaps even more unexpected, during this same 2009-2010 period there were at least

Figure 5: The Great Circle path from Japan goes northeast over water, turns southeast over Alaska, and east of Vancouver to the eastern US. It requires five hops; the first two would land in the ocean (see also Fig. 7). *Map credit Google Maps.*
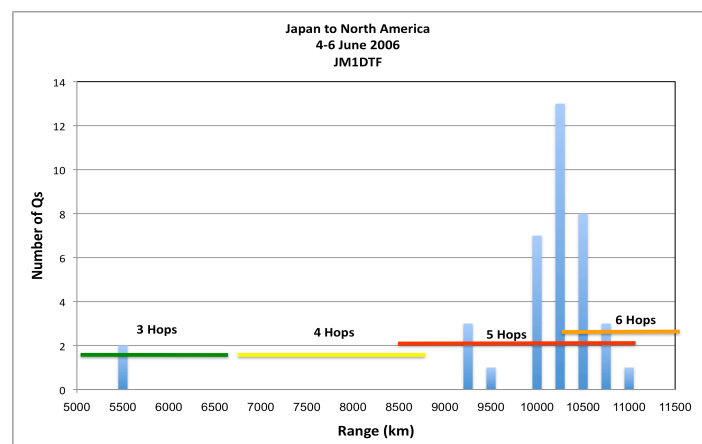

Figure 6: With the exception of two contacts at three hops (Alaska), all of the contacts were made at five-hop distances, demonstrating a typical case of what has been labeled SSSP.
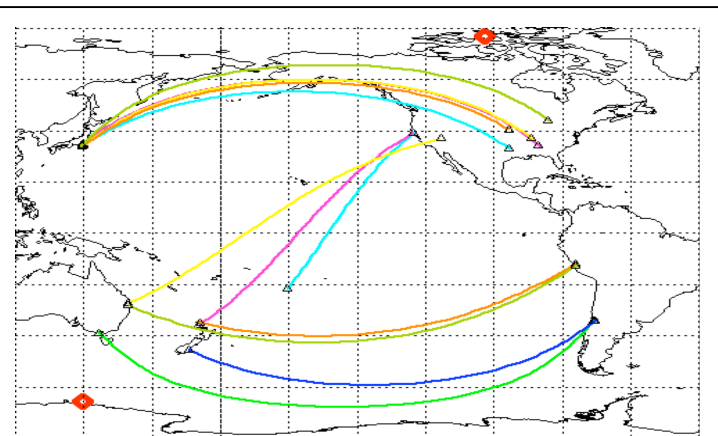

Figure 7: Recent SSSP paths from 2006 through early 2010. The path from Japan westward to Europe is not shown.

three, unprecedented, cases of 50-MHz propagation *across the equator* between the western US and the Cook Islands, New Zealand, and Australia. While there is too little data to establish whether these are also forms of E_s propagation, the fact that they occurred co-temporally with the southern major E_s peak and the northern minor E_s peak, and the South America to New Zealand and Australia openings is certainly suspicious (more on this later).

The M Factor

At this point, it is worth reviewing some of the basic physics of ionospheric propagation, and in particular, the relationship between the ionospheric free-electron density, the angle between layer and the upcoming signal ray path, and the maximum usable frequency (MUF). If a wave is launched straight up vertically – at a 90° angle to the layer – under normal circumstances the layer will reflect it straight back down *if* the signal frequency is at or below the *critical frequency*, f_0. Put another way, f_0 is the MUF for a signal going straight up and skipping straight down again. The only *variable* that the critical frequency depends on is N_e – the free-electron number density. The critical frequency is given by the relation:

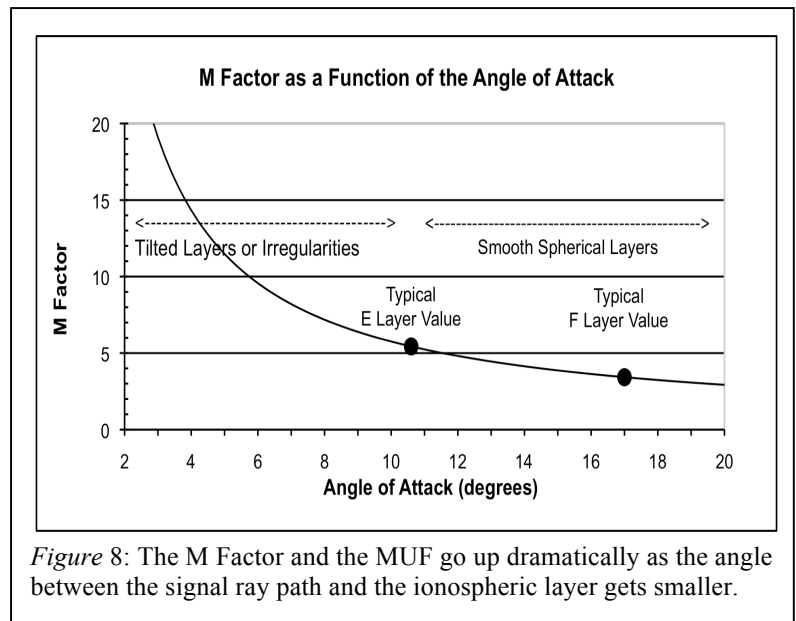$$f_0 = \sqrt{\frac{N_e e^2}{4\pi^2 \varepsilon_0 m}} = \sqrt{N_e} \times (9 \times 10^{-6}) \; ; \;\; \text{in MHz}$$

In this case, N_e is the number of electrons per cubic meter, and the constants are the electric charge of the electron (e), the permitivity of free space (ε_0), and the mass of the electron (m).

The value of f_0 can be determined fairly easily with a vertical incidence ionosonde. However, one needs to be able to relate f_0 to the MUF at more useful angles, such as those actually used for communications. Fortunately, there is a simple relationship between f_0 and the angle between the signal path and the layer, and the MUF, here called f_{max}.

$$f_{max} = \text{cosec}(\alpha) f_0 = M f_0$$

M (the so called *M Factor*) is cosec (α), where α is the angle between the signal path and the plane of the bottom of the E-layer cloud (the angle of attack). The lower the transmitted angle of radiation, the smaller the α, the bigger the M, and the higher the MUF – all *without changing* the free electron density.

Of course, the ionosphere is curving around the Earth, too. So under normal circumstances, there is a limit to how high the M Factor can go. As Figure 8 points out, the M Factor is higher for the E layer than the F layer, because being a lower layer, the angle α gets closer to zero (Kennedy 2000 and 2003).

Figure 8: The M Factor and the MUF go up dramatically as the angle between the signal ray path and the ionospheric layer gets smaller.

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Moreover, the following sections will show that there are other special circumstances that can change the ray path *after* the signal has left the antenna and that can result in very shallow angles of attack and very high, but *localized*, MUFs.

Possible Mechanisms

All these SSSP scenarios postulate that there is a way to propagate signals for long distances without any significant ground interaction. In general terms, this is a three-step process, each of which requires that Nature provide special ionospheric conditions at *every* skip point. If the required conditions are absent at any skip point, the path communications circuit will fail. This is another way of saying that, on a day-to-day basis, the propagation is likely to be rare.

Insertion (*First skip point*) – The *first* skip point must *redirect* the *steep-angle* of the upcoming transmitted signal ray path so that it is *inserted* into the beginning of the series of shallow-angle intermediate hops.

Long Haul (*Intermediate skip points*) – The *intermediate* skip points must support *shallow-angle* forward propagation without coming to earth.

Recovery (*Last skip point*) – The *last* skip point must *redirect* the intermediate-hop *shallow-angle* signal into a *steep-angle* ray path, so the signal is *recovered* from the intermediate skip-point hops and sent back down to earth.

As one might expect, the *Insertion* and *Recovery* steps are really the same kinds of processes. Absent significant magnetic field interactions, they are generally reciprocal. Although there are these three steps, it is useful to break the communications *path* into two parts: the required *endpoint* conditions and the required *intermediate-hop conditions*. The Long Haul intermediate hops are discussed first.

Intermediate Hops – The Long Haul

There are at least three plausible mechanisms for extended paths with no, or very weak, intermediate hops: chordal hops, E-layer ducting, and progressive refraction. These are all known phenomena that have been observed in other contexts (Davies, 1990). In what follows, it is significant that chordal hops and ionospheric ducting both depend on the fact that the shallower the angle between a signal ray path and the ionospheric layer, the higher the M Factor and the higher the resulting MUF. Though technically a little different, progressive refraction also achieves the same result.

Figure 9: To illustrate all four processes on one graphic: Point **A** depicts a curved/tilted E_s surface redirecting and inserting a shallow-angle ray path; **B** shows the resulting chordal hops; **C** depicts bottomside-topside ducting; and **D** shows stratified refraction redirecting the ray path to the ground.

Chordal Hops

Ignoring for the moment how it got there, *if* the upcoming ray path from the ground-based antenna was somehow bent away from its original path so that it hit the sporadic E cloud at a much shallower angle (often called "grazing incidence"), then the signal could skip off the cloud, also at a shallow angle, but with a *much lower* free-electron density than otherwise required.
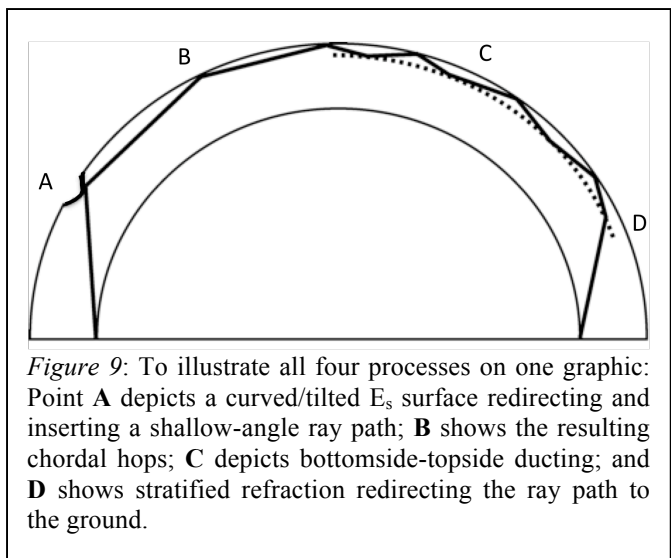
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The skip angle would not be enough to return the ray path to the ground, but it could send the path forward nearly parallel to the Earth's surface. With the Earth's curvature, the path would eventually run into the E-layer again farther downstream, *without* ever hitting the ground (Fig. 9), as a chordal hop. The *second* encounter with the E layer would still be at a very shallow angle, and this could produce yet another chordal hop, and so on. If suitable clouds were available farther downstream, this could go on until something else bent the path *sharply* enough to bring it back down to earth.

E-layer Ducting

The comprehensive E_s review by Whitehead (1989) points out that it is not uncommon for temperate-zone E_s to be *vertically stratified* into a series of thin, stacked layers, usually spaced about 6 to 10 km apart. More recent work by Wu, et al. (2005) supports this finding.

If, as in a chordal hop, the ray path were going nearly horizontally in the E region, it could get caught *skipping in between* two stratified E_s layers – one above the other. Like chordal hops, all the skips between the layers would be at grazing incidence, so the MUF would be much higher than it would be if the ray were arriving at usual angles. As a result, the signal could safely propagate in this *bottomside-topside duct*, even if the ionization were too weak to support skipping an upcoming signal at the usual upcoming angles. The duct would not have to be continuous, either. It would only require that, at several strategic points along the way, there were other ducts or layers to capture the signal and bend it on around the path.

Progressive Refraction

Though perhaps less probable, the signal could be *refracted* by a continuous partially ionized E-layer (or even the F-layer) such that it was gradually bent around, roughly following the curvature of the Earth. This differs from ducting in the sense that there really is no topside-bottomside skipping. Rather than acting like a system of mirrors, the ionosphere would be behaving like a lens.

While technically possible, this mechanism would normally require a fairly thick vertical ionized region, which is quite the opposite of what is seen in sporadic E. As a result, it seems unlikely to be a useful E_s mechanism. It is more likely to show up in the F layer.

Poor Intermediate Conditions

One of the factors that may be key to SSSP is that each of the three intermediate mechanisms above can work quite well under *poorer* ionization conditions *in between* the first and last skip points than that required for conventional nE_s paths. SSSP would rely either on grazing incidence skips or (less likely) gradual bending, which *do not* require the higher free-electron density necessary to skip at usual angles at *any* intermediate skip point. By contrast, normal nE_s paths require the *full* amount of ionization at *every* skip point.

Earth-to-Sky and Sky-to-Earth

The question then becomes, how did the upcoming wave get bent around at the beginning and pointed into the chordal hop, duct, or progressive refraction in the first place, and how does it get turned around again at the end and come down? Here again, there are multiple possibilities.

Tilted and Curved Layers

While the ionosphere is often thought of as having single layers that are smooth and parallel to the Earth's surface, Whitehead (1989) also points out that it is common for E_s clouds to be vertically *tilted* up to *15° or more*. At times, their lower faces form small-scale curved surfaces.

One way that the upcoming wave could be bent around to a grazing-incidence angle that would support any of chordal hops, E-layer ducting, or progressive refraction would be if the *upcoming* signal ray encountered a *well ionized* tilted or curved layer.

Since the layer tilt or curve would make the angle of attack lower, the MUF would be higher than normal[4] and it could bend the ray path around and point it into a chordal hop, a duct, or progressive refraction situation. At the far end of the path, the same process in reverse could bring the wave back down to earth.

Stratified Refraction

There is another plausible insertion/recovery possibility. Suppose there were at least *two* stratified E_s layers, and the lower of the two layers was *less* ionized than the upper layer. The *upcoming* signal might pass *through* the lower layer, but be *refracted* just enough by it that the ray path was bent over and hit the upper, *more* ionized, layer, which then skipped the signal forward nearly horizontally.

Like tilted or curved layers, this could lead to a series of chordal hops, *or* if the lower layer were long enough, it could set up the ducting scenario described earlier, since the new skip angle could be shallow enough to skip off the weaker lower layer. At the far end of the circuit, stratified refraction or a tilted layer could point the signal back to earth.

The diagram in Figure 9 shows examples of curve/tilted layers and stratified refraction insertion and recovery, as well as intermediate chordal hops and ionospheric ducting. These four factors are the key candidate components of an SSSP link. Any combination of these that provided the insertion and recover processes, and the intermediate skip points could provide propagation on a given day.

Local Solar Time

Figure 10 is a plot based on work by E. K. Smith (in Davies, 1990) and shows the commonly observed diurnal E_s MUF peaks in the morning, and late afternoon and evening. Since temperate-zone E_s propagation has these known local-solar-time preferences, another question is whether long east-west paths, with their two end skip points widely separated in both space and time, exhibit any LST preferences for the *path* as a whole?

With the large longitude differences between $5E_s$ and $6E_s$ stations at similar latitudes, the LST time differences between the first and last skip points would always be of the order of nine or ten hours. What may be more significant though, is *which* nine or ten hours of the day are important?
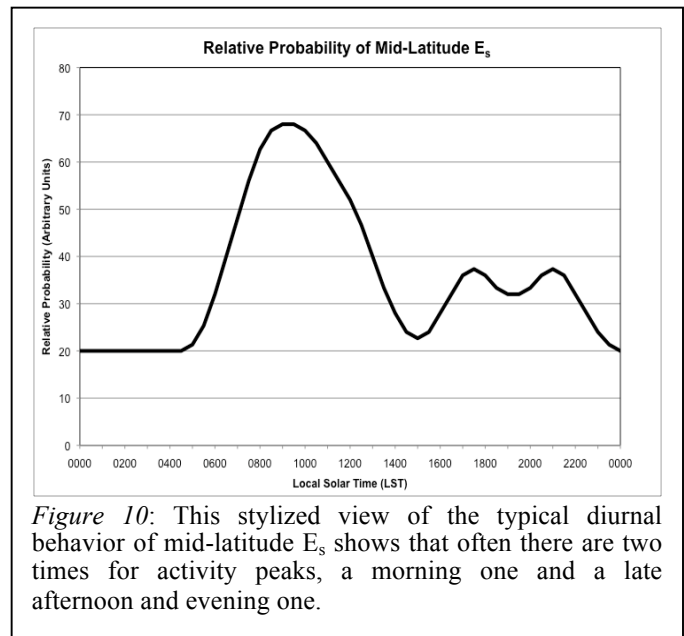
Figure 10: This stylized view of the typical diurnal behavior of mid-latitude E_s shows that often there are two times for activity peaks, a morning one and a late afternoon and evening one.

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[4] Professional researchers still assert that they have never measured an E-layer critical frequency (f_0E_s) high enough to support 2-m E_s and yet 2-m E_s happens. One likely explanation is chordal skipping directly between two tilted or curved layers, producing very high grazing-incidence MUFs not detectable by vertical incidence sounders.

Some LST Data

Figure 11 shows scatter plots of each contact *greater than 8,500 km* against the west-end LST on the vertical axis and the east-end LST on the horizontal axis. The top plot shows the northern summer 2006 (Figs. 5 and 6) JM1DTF openings. The bottom plot shows the known southern summer 2009-2010 events, which occurred between Bolivia and Chile, and New Zealand and Australia. The longest range for these contacts was between OA4TT and VK4CZ, an amazing 13,044 km (±), which is the equivalent of six full hops.

Interpretations of LST Data

These $5E_s$ and $6E_s$ equivalent-distance contacts occurred between about 0800 and 1200 LST for the west-end stations and between about 1600 and 2000 LST for the east-end stations.

> Could the west stations be making use of their morning MUF maximum, while the east stations are making use of their afternoon-evening MUF maximum?

Early on Late

Multi-hop E_s diurnal relationships have been looked at before. For example, Kennedy, Mobile, and Magnani (2001), Magnani, Mobile, and Kennedy (2001), and Kennedy (2001) presented a trio of papers on the diurnal E_s impacts for $2E_s$, $3E_s$, and $4E_s$ paths, where they plotted the data against the LST at the path *midpoints*.

However, for the longer paths considered here, Figure 11 suggests that LST near the path *endpoints* may be much more important than the *midpoints*. These paths may work best when the west-end stations are enjoying their Figure 10 morning "sweet spot", while the east-end stations are enjoying their Figure 10 afternoon-evening sweet spot. If so, one should be looking at how the two LST sweet spots are positioned with respect to the first and last skip points.

Figure 11: Top – The JM1DTF 2006 northern summer openings are tightly grouped in a time "box" of west 0800-1200 by east 1600-2000. Bottom – With one exception, the 2009-2010 southern summer openings also fit quite well into the same box.

Noting that, generally, the *end points* of the various paths in question are in the temperate E_s zone, Figure 12 shows the relative joint probability of the two endpoints overlapping and feeding into each other as a function of the LST *time difference*.[5]
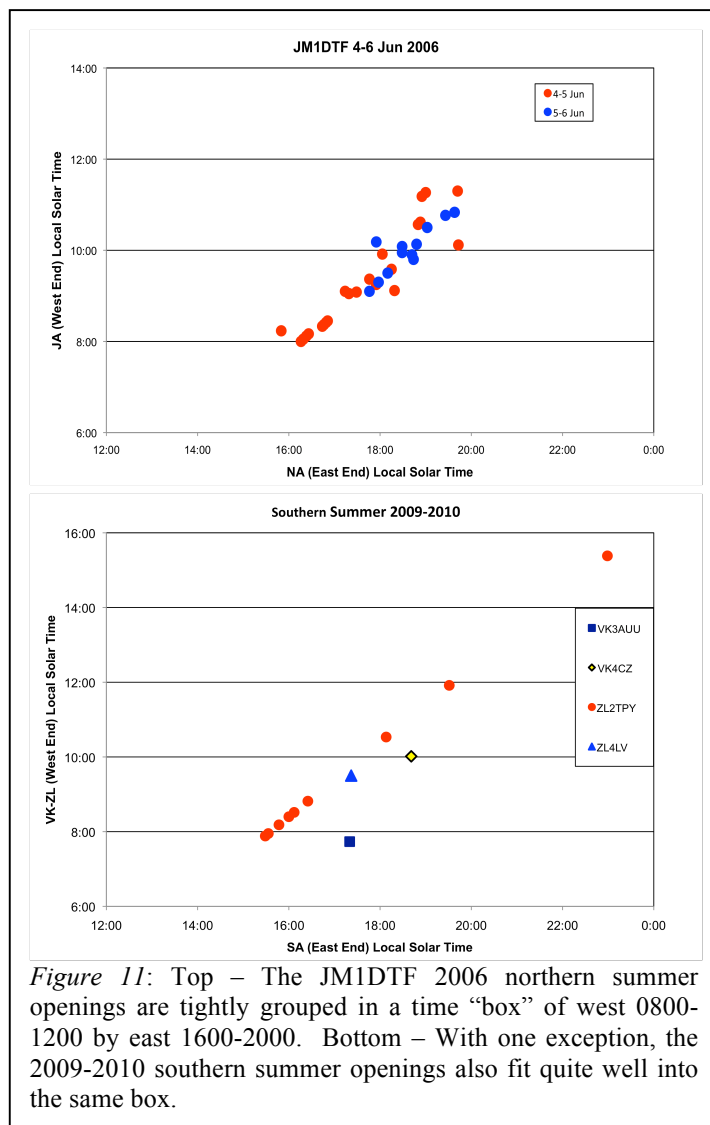
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[5] See the Addendum on page 16 for a fuller description of the "early window on late window" phenomenon.

The plot shows that when the *first and last skip points* are separated in longitude such that the LST *time difference* is in the general vicinity of 9.5 hours, then the *early* peak at the *west* station feeds signals more or less directly into the *late* peak at the *east* station.

Using the half width of the curve as a standard, the width of the joint sweet spot runs from an LST difference of about 5.5 to 13 hours, with the *maximum* probability found at 9.5 hours. However, anything over 12 hours would be long-path propagation (perhaps possible, but not yet reported); so for the present purposes, only LST differences of up to 12 hours are considered.

Table 2 shows the range of distances for two stations located in the same hemisphere at 35° latitude, which is consistent with the JM1DTF data in Figure 6. His shortest and longest paths were 9,343 and 10,896 km. These distances correspond to a *first-to-last skip-point* separation of 7.7 and 8.9 hours, respectively. Note too that Table 2 shows that the 13,000-km Bolivia to Australia path is very near the 9.5-hour optimum separa-
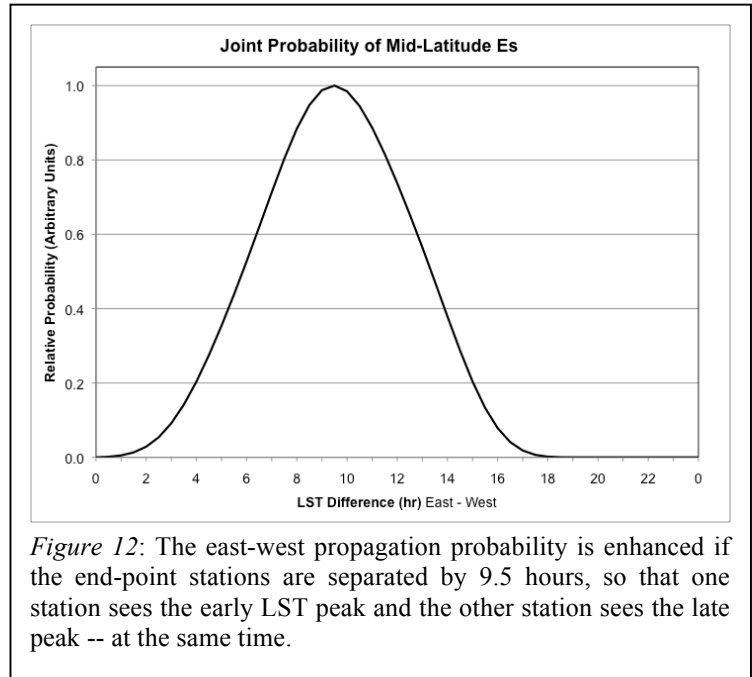

Figure 12: The east-west propagation probability is enhanced if the end-point stations are separated by 9.5 hours, so that one station sees the early LST peak and the other station sees the late peak -- at the same time.

tion. It is clear that the ranges between all those stations were well within the 5.5- to 12-hour envelope around the nominal 9.5-hour maximum.

Interpretations of the LST Time Differences

There is good evidence to suggest that most of the reported extremely long E_s paths include the favorable overlap of the early and late LST E_s probability peaks. One would expect that this would be the case whether the propagation were ordinary nE_s or chordal/ducting SSSP paths.

Table 2 Optimal Ranges Available at ±35° Latitude				
ΔLST (hr)	ΔLon (deg)	First to Last Skip Point (km)	Station to Station (km)	Equivalent nE_s Hops
5.5	83	7,328	9,030	5
9.5	143	11,325	13,025	6
12.0	180	12,245	13,945	6

9,000- to 14,000-km paths benefit from the favorable overlap of the early and late LST E_s MUF probability peaks.

This further suggests that these observed very long paths are *indeed* variants of E_s propagation.

Summary and Discussion

Sporadic E has a number of characteristics that make it rather distinct from F_2. It occurs at a height of about 100 km, while F_2 is at 300 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 F_2.

The ionization formation process for E_s clouds is both very different and less well understood, compared to F_2. A consequence of this different ionization mechanism is that the morphology of E_s clouds is also quite different from F_2. 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 F_2 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 is fairly common,

Tilted layers are common, at times by 15° or more with respect to the vertical, and

The underside of an individual cloud can be curved or rippled, rather than flat.

Ordinary nE$_s$

Some long summer propagation can certainly be explained by the traditional view of multi-hop skip. The July 2000 event discussed above shows that under good conditions $4E_s$ is quite workable. Kraft and Zimmerman (2009) have argued that at least some of the observed very long propagation out to more than $5E_s$ might be explained that way.

Philosophically, this is probably a very prudent *starting point*. It springs from Occam's Razor:

Whenever there is more than one possible explanation for some unknown phenomenon,
the *simplest* explanation is often the right one.

The core of the Higasa, and the Kusano and Obara, arguments is that ordinary multi-hop E_s would be weaker than chordal or ducting processes due to the ground scattering losses on each intervening hop. While this may be true (at least in some cases), their thesis was based on assumptions about the ground losses, but apparently without considering possibility of comparable *ionospheric-scattering* losses for chordal or ducting hops.

Impact of E$_s$ Scatter

Since E_s is composed of many distinct, relatively small, clouds that are always in motion, each skip point region is likely to be full of many dynamic inhomogeneities. This means that there necessarily will be scattering losses from chordal and ducting hops as well. No doubt these account for seeing some signals in the gaps and at the $2E_s$ and $3E_s$ ranges in the 2009 Hawai`i data, and the appearance of signals in the gaps in the 2000 Hawai`i data.

A second issue is that the longest-range conventional skip hops occur when the signal ray path only grazes the Earth's surface, rather than fully colliding with it. In these maximum-hop-length cases, the ground scattering losses would likely be much lower than for shorter individual hops.

The 2009 Hawai`i chordal/ducting event *may* have provided a little stronger signals than the 2000 $4E_s$ event, but even if so, these two cases represent just *one sample* of each kind of event. (Experiences with F-layer transequatorial long path, which is dominated by chordal F_2 hops, show a wide variation in signal strength from one opening to the next. Some openings are very weak and others are unexpectedly strong.) So, one must be careful about assuming too much about scatter from just two events.

The 2000 Hawai`i to North America openings demonstrate that traditional $4E_s$ *does* occur, and that does *not* exclude the possibility of $5E_s$. (In the Hawai`i case, $5E_s$ and $6E_s$ are both in the Atlantic Ocean, so there was nothing to see at that range.)

> Both normal nE_s and SSSP can account for 4Es-range propagation (6,800 – 8,800 km). Regular nE_s *may* go farther, SSSP definitely *does* go farther.

Temperate Zone[6] SSSP

This phrase refers to east-west paths between endpoint stations residing in the *same* temperate zone, either both north or both south of the equator. As can be seen from Figure 7, the effect is found in both the Northern and the Southern Hemispheres, and can produce paths exceeding 13,000 km. The propagation occurs during the local summer E_s seasons in both hemispheres.

The 2009 Hawai`i to North America data demonstrate that paths equivalent to four hops occur that substantially bypass some or all of the intervening ground-skip points. Furthermore, the 2006 Japan to North America openings are completely consistent with five hops in which some of the intermediate ground-skip points are missing.

While $5E_s$ cannot be completely eliminated as the cause, the evidence strongly suggests that the 2006 Japan openings involved missing intermediate hops. There are also many different anecdotal reports for different openings that indicate the absence of intermediate hops that "should" have been there.

> It seems likely that at least some the reported events with the range of $5E_s$ or longer, labeled as SSSP, are the result of chordal hops, ducting, or progressive refraction. Like nE_s, the Earth's geography makes it difficult to find unequivocal evidence.

Trans-Equatorial SSSP?

The recent paths across the equator occurred when the Southern Hemisphere was in the middle of its major summer E_s season, and the North was in its minor winter E_s season. It is tempting to speculate that the propagation was also a variation of E_s – at least in part. The issue becomes one of understanding what the mechanism was for getting across the equator. Three options present themselves:

TEP,

F-layer progressive refraction, or

Blanketing Equatorial E_s.

At first glance, TEP seems unlikely in December and January, especially with very low solar activity. Given the low solar activity, progressive refraction also seems unlikely. Nevertheless, F_2 electron-density maps were obtained from the NOAA Space Weather Prediction Center for the days and times of the key events (Codrescu, 2010). These showed that, at best, the events occurred an hour or two before the peak of the northern branch of the equatorial anomaly reached the line of the path.

The maximum value of the modeled N_e was less than 10^{12} e/m^3, producing f_o values in the 5 to 8 MHz range for the northern fork of the anomaly. Due to the season, the southern fork was asymmetric, weaker, and not well aligned with the northern fork on the path lines in question.

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[6] In some respects, calling it "temperate zone" is a term of convenience, referring to the location of the first and last skip points. It is acknowledged that the paths may well encroach on the auroral regions at some point.

It would require at least $2E_s$ or the equivalent SSSP to get from North America to the vicinity of the northern branch of enhanced ionization. If one supposed a zero angle of departure from the last E skip point, the most favorable angle of attack for a *spherical* F layer would be about 14° at 300 km (an M Factor of 4.1). But, the angle would have to be 8° or less (M Factor at least 6.5) in order to produce a successful F-layer hop.

Of course, TEP works because of pairs of curved F-layer surfaces that provide chordal hops. There is no known information about the shape of the isoelectronic lines on the underside of the F-layer at either of the north and south branches of the anomaly. So, it is hard to estimate the likelihood of that having occurred. Likewise, there is not enough information to explore progressive F-layer refraction. Certainly, the F-layer conditions do not appear to have been conducive, but it is not clear what happened, so neither TEP nor progressive refraction can be ruled out altogether.

Blanketing Equatorial E_s *might* be a better candidate[7]. It is essentially a daytime effect, with many of the same characteristics as temperate-zone E_s. If it were present, which is unknown at the moment, it might well have filled the gap between northern and southern temperate E_s farther north and south.

Polar Mesospheric Summer Echoes

It has been suggested that the Polar Mesospheric Summer Echo (PMSE) phenomenon might play an important role in SSSP. While an interesting and worthwhile suggestion, on closer inspection it seems highly unlikely to be the case. As Luetzelschwab (2009) has pointed out, this is a very weak effect that requires significant power and very large antennas to demonstrate.

Perhaps more importantly, PMSE works at 50 MHz only because of *vertical* stratification of the background electrons just below the E layer, with a size scale of about *3m*. This forms a *tuned* three-dimensional scattering structure. As the upcoming (vertical-incidence) signal is scattered straight back down, the scattered signals from each progressive level end up in phase with each other, due to the fortuitous half-wave spacing of the scattering centers. Since the 3-m stratification is in the *vertical* plane, it would *not* be useful for the largely *horizontally* propagating waves of a skip signal.

There was a suggestion some time ago that, instead of electrons, metal coatings deposited on ice crystals in the region might be responsible for PMSE. But, there was an error in the physics and, even when the error was fixed, it failed to predict important known features of the effect.

In any case, as a high-latitude phenomenon, it certainly did not play a role in the transequatorial events that occurred in December 2009 and January 2010.

Final Conclusions

Ordinary nE_s is clearly usable out to at least four hops (8,250 km), and may be viable beyond that point.

Propagation out to 8,250 km has been shown with the hops two and three (and perhaps one) that were weak and barely present (perhaps audible because of scatter), which is consistent with the notion that SSSP involves intermediate hops that do not reach ground level.

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[7] There are actually two forms of equatorial E_s. The other type is referred to as the Q type. It is a form of FAI that is rather weak and not regarded as useful for communication circuits.

Tilted/curved E_s layers or refraction by multiple layers appear to play a key role in SSSP by inserting and recovering signals at opposite ends of a very long path. The bulk of the path between the first and last skip points is propagated by some combination of chordal hops and bottomside-topside ducting (and perhaps progressive refraction), all of which require lower electron-density values than normal nE_s hops.

Moreover, the coincidence of low-electron-density intermediate-hop mechanisms and the overlap of the morning and afternoon-evening diurnal E_s peaks at the two end skip points in the 9,000 to 14,000-km range, may well make SSSP a more *probable* occurrence than nE_s for paths over about 8,500 km.

Closing Comments

There is a lot more to learn about this subject. The work presented here is done on the basis of the observations cited. It is inevitable that there are many observations, that were not available for this analysis and which, if examined, might lead to different conclusions.

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Addendum
Early Window on Late Window[8]

During an E_s season in a given hemisphere (north or south), it is common to find that the probability of the critical frequency, f_0, and thus the MUF, Mf_0, exceeding a certain value shows two peaks as a function of Local Solar Time (LST)[9] as shown in Figure 13.
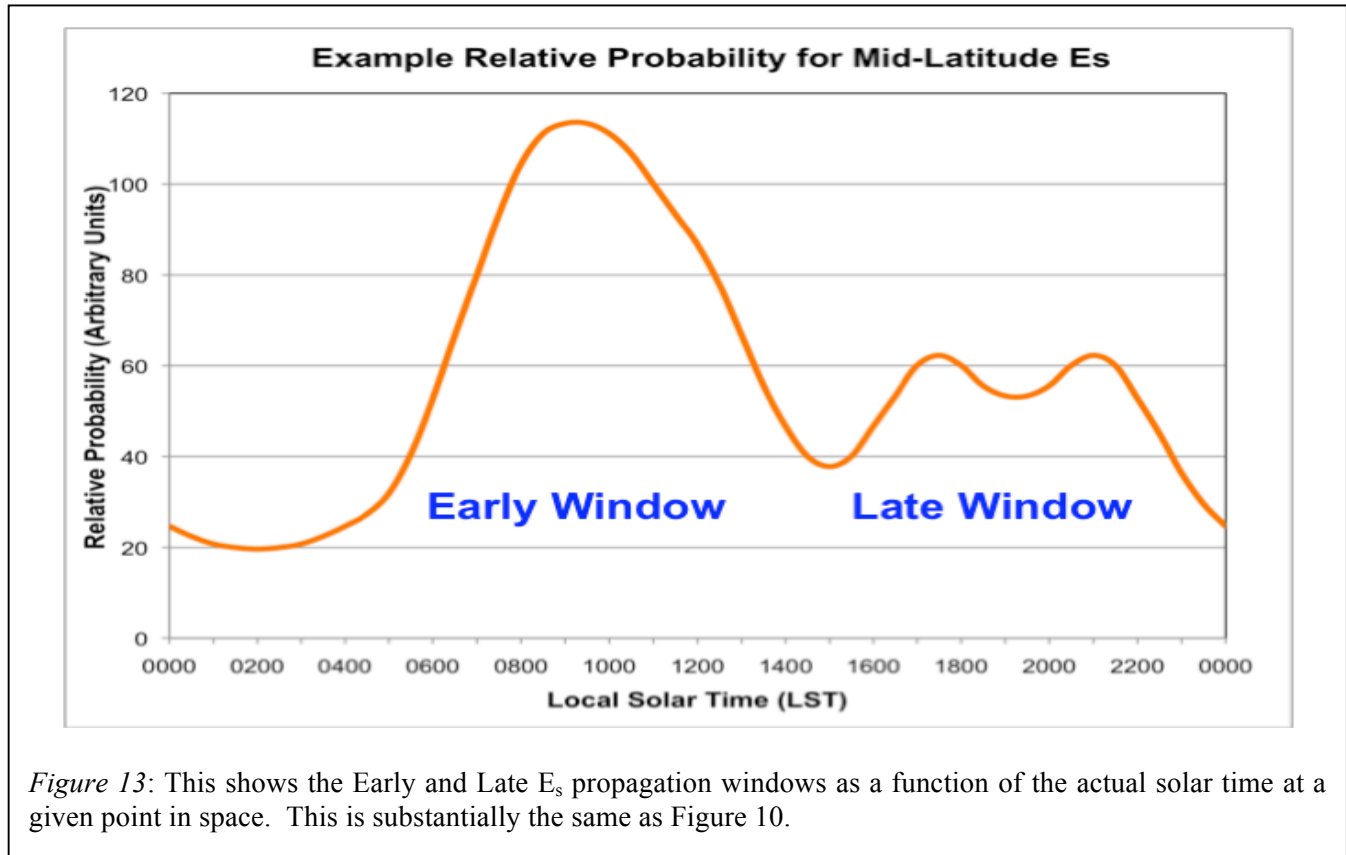

Figure 13: This shows the Early and Late E_s propagation windows as a function of the actual solar time at a given point in space. This is substantially the same as Figure 10.

This same plot can also be looked at in a different context, in which *time* is *fixed* (as a snapshot) at the location of the west-end station for a given family of paths. If this is done, then the horizontal *time* axis in Figure 13 can be reinterpreted as corresponding to a *distance* eastward from the west-end station. For example, Figure 14 shows a snapshot taken at 0700 LST at the west-end station.

Let us further suppose that the "probability of the MUF exceeding some certain value" shown Figure 13 can be scaled as a reasonable *proxy* for the *value* of the MUF itself. In this case, Figure 14 shows the MUF to the east of the west-end station, as a function of the distance from the west-end station.

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[8] Based on the slide presentation delivered on July 24, 2010 at the Central States VHF Society Conference in St. Louis, MO.

[9] LST is the actual time, based on the Sun, as observed from a specific longitude, corresponding to a given station location. It will be within 30 minutes of the Standard Time at that longitude, provided that the Standard Time is determined strictly by 15° time-zone longitude boundaries (in some places the lines are drawn differently for various reasons).
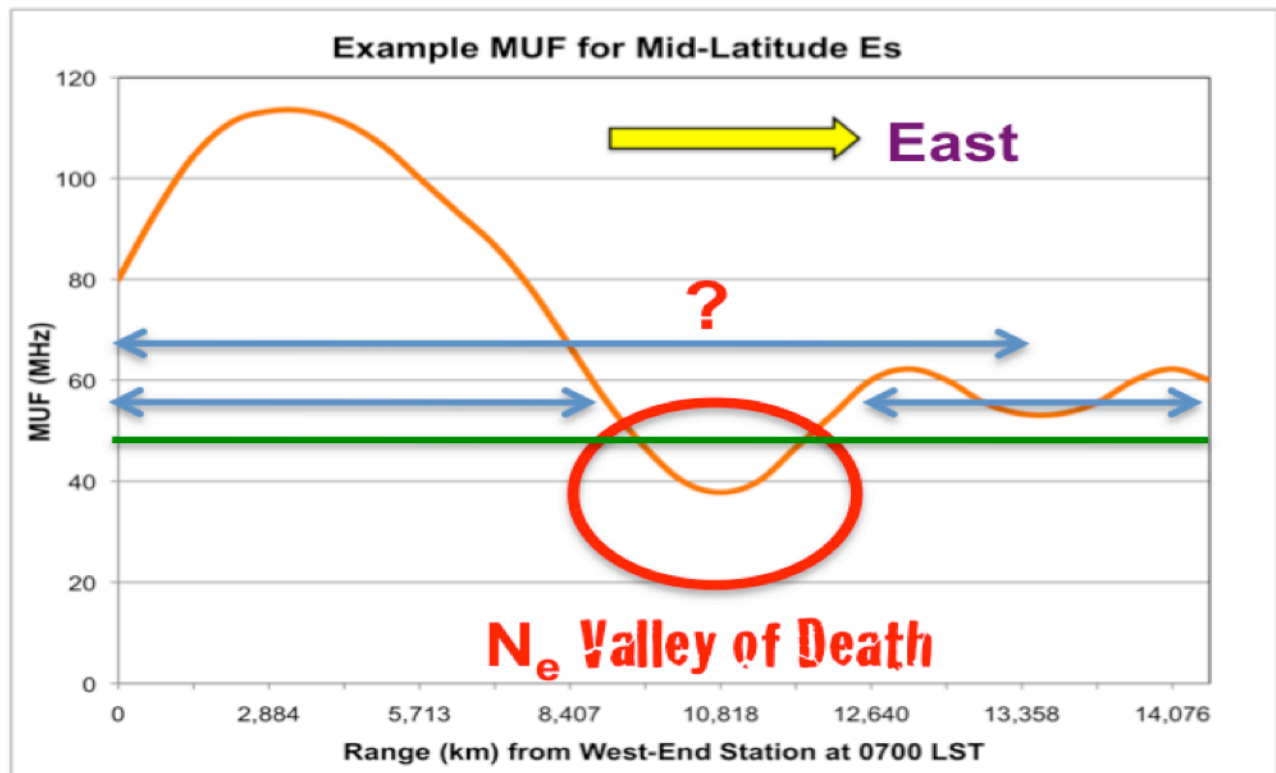
Figure 14: This variation of Figure 13 is scaled to show an example of the MUF as a function of distance from the west-end station (at a latitude of 30°) at 0700 Local Solar Time. The green line shows 50 MHz.

In this particular 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 skip 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. Chordal or Top-Bottom propagation across the N_e gap, which can succeed with a much lower electron density (e.g. SSSP), or

2. Sufficient overall ionization so that the dip between the Early and Late windows never gets *below* 50 MHz (very long nE_s).

Evidence suggests that, for paths greater than about 8,500 km, Chordal hops or Top-Bottom ducting may be more common, though there are some cases where such paths appear to have opened with ordinary nE_s multihop (option 2. above).