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An Overview of Extreme Es Propagation

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Remembering Gene – During 2010 and 2011, the author and Gene Zimmerman (W3ZZ–SK) – despite his evolving illness – collaborated to explore likely mechanisms for the extremely long Es or Es-assisted propagation, which had showed up along the paths shown in Figure 1. This effort resulted in two papers that were presented at the 2011 Central States VHF Society Conference (Kennedy and Zimmerman, 2011a and 2011b). They were subsequently published serially in both CQ VHF and DUBUS (see references). The following discussion is a review of their key points and findings in a single unified format.

How Far Can E Skip Go? – During the recent prolonged period of very low solar activity at the end of Cycle 23 (from 2006 and even into 2012), some surprisingly long-haul propagation paths were noticed. These paths ranged from 9,000 km to over 15,000 km. Though *not* long enough to be technically “long-path” (they were *less than* halfway around the world), still they were remarkable. It’s not clear if this elevated awareness resulted from some real quirk of physics during low solar activity, or from dedicated VHF DXers, in the absence of F2, digging ever deeper. Certainly, there is some evidence that these paths had been seen at various earlier times. Whatever the case, they did show up, and they created quite of a stir within the six-meter DX community.

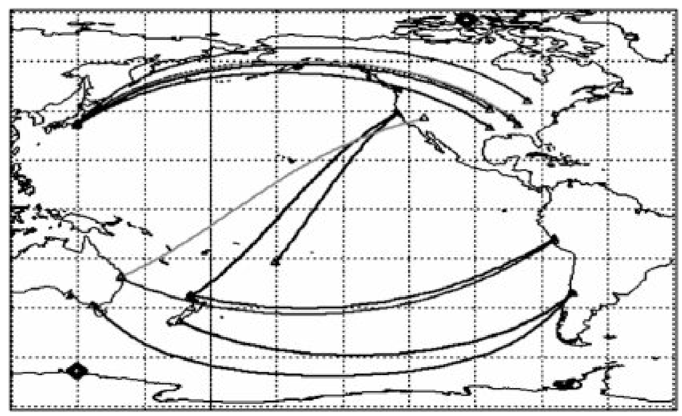

Figure 1: These are actual examples of paths observed across the Pacific between 2006 through early 2012. The East-West paths in each hemisphere occur during the local summer E_s season. The North-South path between southern Oceania and North America occurs during the southern summer E_s season.

Since one or both ends of these paths *always* occurred during the local summer Es season, it seemed likely that Es might be connected with the propagation. However, initially there was quite a debate about the true nature of the cause and its connection to Es.

Causes and Characteristics of Es – A quick review of how Es happens and behaves will help clarify a discussion of these events, and how they relate to Es.

How and Where Es Happens – The E layer lies in the ionosphere roughly between 95 and 135 km. This is the same region where most incoming meteors vaporize as they hit the Earth’s atmosphere. Most of these space travelers are “random meteors” and not directly associated with meteor showers. They are dominated by tiny particles the size of a grain of sand or smaller. They are constantly raining down on the top of the earth’s atmosphere. As a result, the E region is composed of the usual *light* atmospheric gases (nitrogen, oxygen, etc.) *and* a variety of *heavier* elements, metals mostly, that make up the meteoric material coming in from outer space.

During the daytime, some of the light gas atoms and much heavier metal atoms are ionized by the solar radiation, leading to free elections and positive ion cores. At night, as the Sun’s rays go away, the light gases lose their ionization almost immediately. However, the metallic ions last much longer, and remain for quite awhile. As a result, the total ionization tends to peak in the mid-to-late morning, and then gradually decrease through the afternoon. After dark, *only* the metallic contribution lingers on into the evening hours.

The normal E-layer ions are distributed over a wide *vertical* region of space (~40 km). The usual electron density is *rarely* high enough to produce MUFs *even* as high as 22 MHz! The *normal* E-layer electron density is simply *inadequate* to produce six-meter propagation. Six-meter skip requires something *special*.

Es is called "sporadic" because it is *very localized* and *comes and goes*. At a given place, it's *not there* most of the time. It's the result of interactions between E-layer winds and the Earth's magnetic field. Under the right conditions (a horizontal wind shear), electromagnetic forces cause free electrons *above* a given level to be swept *downward*. At the same time, those forces also cause electrons *below* that level to be swept *upward* – and they all *meet* in the middle. The result is a *very thin cloud* of ionization, whose density is many times the "background" E-layer ion density. So, by itself, the E layer just provides a low-density electron *reservoir*. When magnetic-field and wind conditions are right, they squeeze lots of low-density electrons down into a thin, high-density sheet.

When Does Es Happen? – This is really a two-part question. It has to be looked at from the perspectives of both the time of year (the *season*), and the time of day (the *diurnal* pattern).

Es Seasonal Variations – Es is best in the local summer. This seems to have to do with the meteoric material that contributes the *long-lived* ionization in the first place. There is a measurable enhancement of the number of random meteors swept up during each hemisphere's (north or south) local summer. This is due to the angle of each hemisphere with respect to the Earth's orbit around the Sun during its own local summer. There is a *very* good correlation between observed Es MUFs and the radar meteor counts throughout the year (Haldoupis et al., 2007).

Es Diurnal Variations – The creation of ionization varies with the Sun during the day. If that were the only factor, one would expect that late morning through mid afternoon would be best, but that's only part of the story. Remember, to have Es, one has to have both the background "reservoir" of E-layer electrons *and* also the wind-shear effect.

The wind-shear effect is influenced by *tides* in the Earth's atmosphere. When the Sun comes up in the morning, it not only begins ionizing the E layer, it also begins heating the entire atmosphere from top to bottom. As the heat builds up, it causes the entire atmosphere to expand upward. This causes *updrafts* at all levels of height, including the E-layer. During the latter part of the afternoon, and on through the night, the atmosphere cools and progressively contracts again, producing *downdrafts* at all levels.

The overall result is an atmospheric tide that rolls around the Earth with a 24-hour period. For various reasons, this tide also excites at least its second and third harmonics, producing a weaker 12-hour tide and a still weaker 8-hour tide (Haldoupis et al., 2004). The up and down drafts, produced by this trio of tides, effect on the likelihood of Es-cloud formation throughout the day.

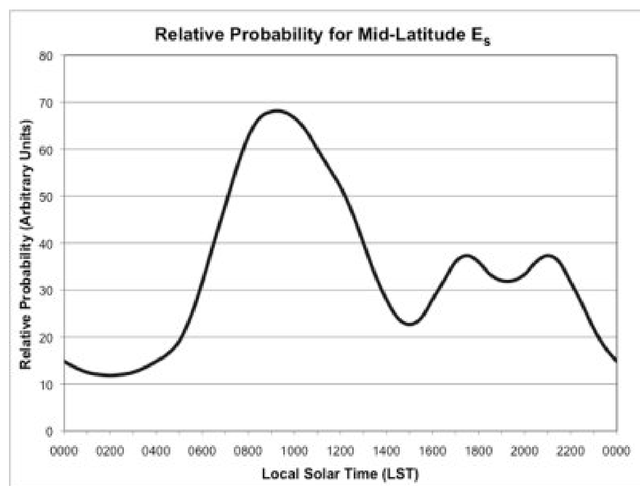

Figure 2: This stylized view of the typical diurnal behavior of mid-latitude E_s shows that the propagation probability often peaks during two time periods, a morning period and a double late afternoon and evening peak period.

The interaction between the vertical tidal winds, the horizontal wind shears, and the Sun's production of the background E-layer electrons leads to the well-known diurnal variation of the probability of summertime Es (Figure 2). There is a midmorning peak, an early afternoon dip, and then a weaker later afternoon-into-evening peak. So, during a given day, there are *two* windows of opportunity, the *early window* and the *late window*.

How Does Es Make Propagation? – There are at least two generic ways that Es ionization can propagate skipped radio signals (Figure 3). One of these has at least three variations. Any, or all four of them, are viable candidates for producing very long-range propagation, either separately or in combinations (Kennedy, 2010).

"Ordinary" Es (nEs) – The usual picture of E skip is that the signal leaves the transmitting antenna, goes off into the sky until it reaches an Es cloud, where it is then reflected by the cloud, almost like a mirror (a *specular reflection*). Then it comes back down to Earth again at a distant point. After this one hop (1Es), it may head off into the sky again, and then skip off yet another cloud, and come down a second time even farther away (2Es). In principle, if the clouds are there, it can continue doing this (giving 3Es, 4Es, etc.). Of course, the signal gets weaker with every progressive hop.

Chordal Hops – The extreme thinness of the Es ionization sheets leads to situations where skips can occur that are *longer* than a normal single hop, *without coming to Earth in the middle*. All chordal processes have this characteristic. These skips occur at very small angles to the Es clouds, so they also produce much higher MUFs than would occur from an ordinary nEs skip.

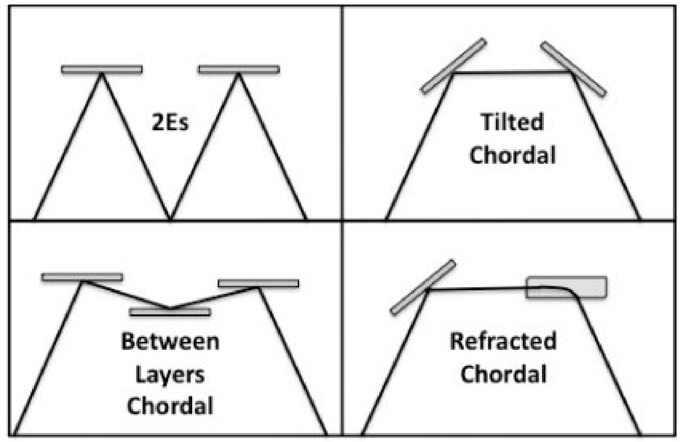

Figure 3: "Ordinary" nEs propagation is only one variety of Es. There are different variations of chordal Es types as well.

Tilted Layers – Es clouds are often tilted with respect to the surface of the Earth, sometimes at large angles. This can give rise to a situation where an upcoming signal may, instead of coming back to Earth, be skipped off at a shallower angle, more or less parallel to the Earth's surface, and travel for a long time in the upper atmosphere. If it finds another suitably tilted Es cloud further down stream, it may then be bounced back to Earth after a fairly long distance. This is typically what one calls a *chordal hop*, but there are other similar and related variations (again, Figure 3).

Between-Layer Ducting – Since Es clouds are so thin, it is also possible for *more* than one cloud layer to form, at *different* E-layer altitudes, sometimes even over the same location. This can lead to chordal hops *between* the upper and lower layers of Es clouds, producing a chordal, duct-like effect.

Transient Refraction – Usually, Es skips are nearly mirror-like reflections. However, there is another effect that does happen from time to time. Although it doesn't last very long, it can be spectacular while its there. It is actually a form of *refraction*, rather than reflection. When the Es ionization is *marginal* (the MUF is not quite high enough for a normal nEs skip), it may still *refract* or bend the signal down more or less parallel to the Earth's surface. If the signal encounters yet another cloud, further down stream, it may reflect, or refract, it even more, so that it eventually comes back to Earth. Technically, this is also a chordal hop.

One example is a western station looking east at 08:00 local solar time, and hearing a station *two* hops further east, but *not* hearing any *single-hop* stations in-between. Then, a few minutes latter, the double-hop signal disappears, and single-hop stations begin to show up. Here, the east-end cloud skipped the "double hop" signal down stream to a *weak* west-end cloud, which bent it downwards and brought it back to Earth. As the Sun got *higher*, the west cloud's ionization increased, and everything went to normal shorter hop nEs. Another example is northern- or middle-tier US stations working transequatorial propagation to South America, *without* hearing the southern tier US stations at the same time. This is a case of Es refraction linking to ordinary F-layer TEP.

Extreme Range Es and Es-Assisted Propagation – Returning to the main subjects, the basic issues addressed were how signals might have effectively been propagated over such long distances and how that related to the state of the ionosphere. The first question on this list was, whether the propagation was associated with Es, or was it something entirely new? The problem was broken down into two components, the:

East-West propagation phenomenon, and the

North-South propagation phenomenon.

East West Extreme Es (EWEE) – For quite some time there was an active and healthy debate about whether the *east-west* openings could *even be* Es, due to the very long range of the paths seen. These paths showed up in four clearly identifiable geographic regimes, three in the Northern Hemisphere and one in the Southern Hemisphere:

Eastern Asia with North America (primarily JA with NA),

North America with Europe (NA with EU),

Europe with Eastern Asia (primarily EU with JA), and

Western South America with Southwest Pacific (primarily SA with ZL/VK).

Generally speaking the JA-NA and NA-EU paths extend out to over 10,000 km, putting them mostly in the 5Es category (Table 1). The EU-JA path is similar. There are very few documented contacts between SA and ZL/VK, but there are credible ones that exceed 14,000 km. To date, the best-studied paths are JA-NA and NA-EU.

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
7	11,900	15,400

Path Mapping – One of the key questions was whether or not the propagation was ordinary nEs, or one of the chordal modes discussed above. Kennedy (2010) showed that out to four-hop distances, *both* 4Es and chordal hops were seen at different times on the KH6-NA path. But, the paths now being considered start at five-hop distances and some go beyond.

To address this, actual data from some recent openings on both the JA-NA and NA-EU paths were plotted with respect to their actual great-circle routes across the ground.

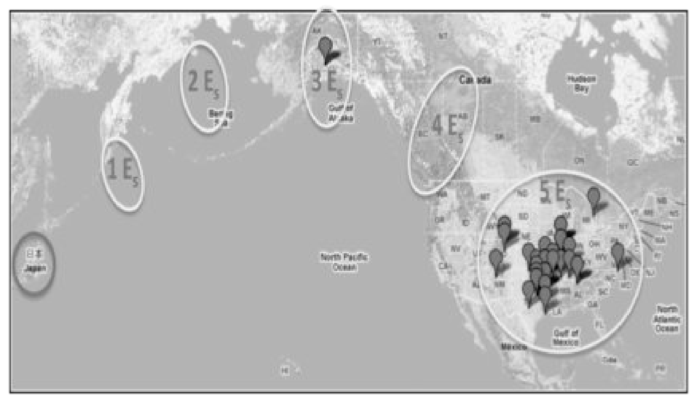

Figure 4: The Great Circle path from Japan goes northeast over water, turns southeast over Alaska, and east of Vancouver to the eastern US. It requires five hops, and from JA, the first two would land in the ocean. *Map credit: Google Maps.*

Figure 4 shows the JA-NA path. It illustrates a very practical problem in determining nEs vs. chordal. For paths as long as these, almost any path, to anywhere, must cross over long stretches of essentially uninhabited territory, be it land or sea. Where there are very few people, there are even fewer ham operators. So, how would anyone know if the signal came down to Earth in between the starting and ending points?

The question is still open For the JA-NA path. There were a couple of instances of contacts with KL7 that suggests that signals, at least at times, came down at that one ground point. But, that says nothing about the other three intermediate ground points.

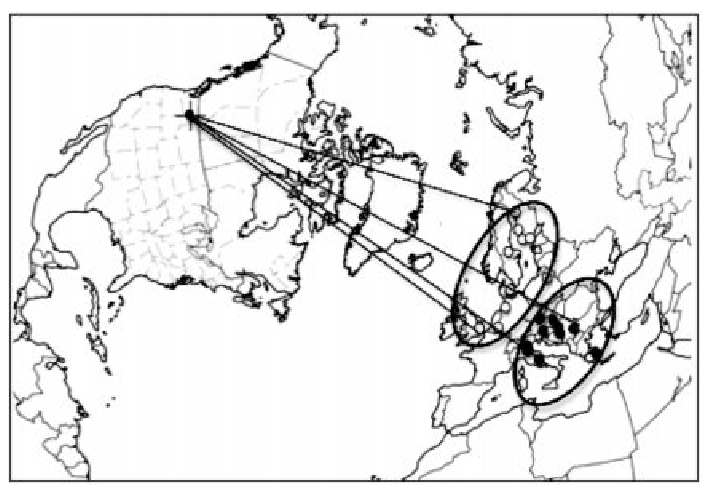

Figure 5: The hop four and five footprints are in the two ovals. Note the sparsely populated regions prior to hop four. *Map credit: Joe Mack NA3T and Mike Katzmann NV3Z, see www.wm7d.net/azproj.shtml*

Figure 5 shows a somewhat different presentation for the NA-EU data. This study was designed to focus on a single NA station for each of the two paths (KØHA for JA and W7MEM for EU) to show each individual data set as coming from a single starting point. Unlike the JA case, there was a broader depth of stations along the great-circle path. Although there is a lot of sparsely inhabited space for hops one, two, and three, it clearly shows that *both* of hops four and five were present. Yet, hops one, two[1], and three are still anyone's guess.

Figure 6 compares the *ranges* of both the JA-NA and NA-EU paths, using data from the northern summer of 2010. The results are the same as the two previous figures, but the presentation is different. It shows that the JA-NA contacts lay neatly in the 5Es range, as indicated by the fourth horizontal arrow. As before, the NA-EU data clearly show the presence of two distinct ground footprints, indicating hops four and five. Despite the presence of population centers *between* hops four and five, there is a clear propagation *gap* right where one would expect – at the four-hop and five-hop boundary.

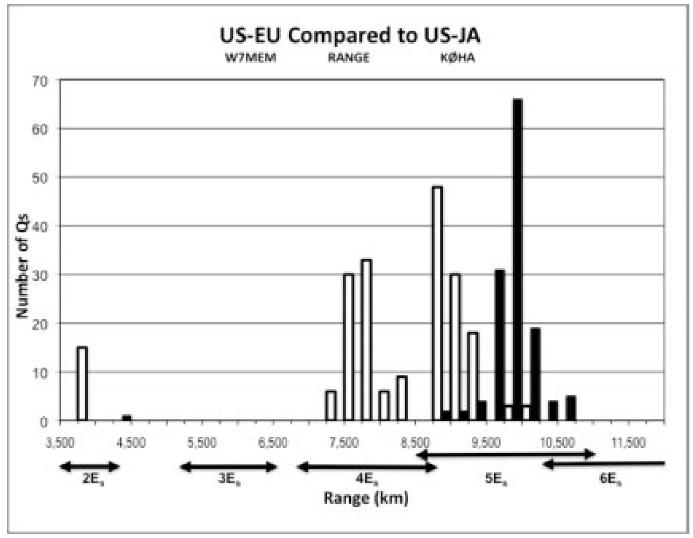

Figure 6: The range between W7MEM and EU contacts (open bars) are compared to those between KØHA and JA (filled bars). The EU path shows typical evidence of both hops four and five. The JA path shows only hops two and five (see text).

Diurnal Windows – There is another place to look for clues of Es-relatedness, and that is the time of day at *each end* of the path involved. Figure 2 showed the two typical blocks of time that are favored by Es. Roughly, these are about 06:30-12:30 and 15:30-20:30 *local solar time* at the location of the end station in question.

While it might not appear obvious at first glance, this timing is an issue for very long paths. *If* two stations are working each other via Es, the *maximum* distance between stations *in the same* morning or evening time block is about 8,000 km (four hops). However, the paths in question here go out to more than 10,000 km. *If* it really were Es of some kind, one way it *could* work, would be if the *west* station was in its *morning Es peak* and the *east* station was in its *afternoon Es peak*.

Figure 7 plots each JA-NA and NA-EU contact by its west-end and east-end local solar times. It clearly shows that each of these contacts, *without exception*, occurs when the west-end station is within its early time window, and the east-end station is within its late time window.

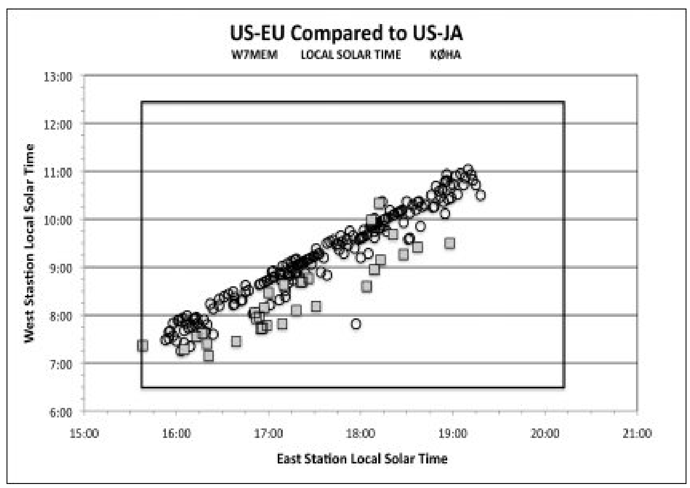

Figure 7: The circles represent each JA-NA contact LST at the west and east ends of the path. The squares represent the same information for the NA-EU paths. Both clearly show the Es Early-Window-on-Late-Window effect.

Mid-Path "Valley of Death" – The tricky part of the path is what happens in the *middle*. This was the key issue that originally generated so much controversy about these openings. To illustrate this, one can transform Figure 2's *time* axis, by converting it into the *distance* from a west-end station, looking east at 07:00 LST (Figure 8). This shows that, under *good* conditions, the *weak point* in the MUF (the possible *Valley of Death*) would occur between about 9,000 and 12,000 km to the east. However, this depends heavily on how well ionized the Es is in the first place, *and* how well it is distributed along the overall length of the path.

[1] The NA-EU contacts shown at 2Es were actually W1 and W2 stations 40-50° off the NA-EU path, and are not reliable indicators of whether there was 2Es on the main path.

If the Es is broadly distributed *and* the overall ionization is *high* enough, then the MUF may *never* dip *below* 50 MHz *anywhere* on the path. In this case, *nEs* will work just fine for the whole path. On the other hand, even *if* the Es is broadly distributed, *very often* the ionization and, thus, the *nEs* MUF, are rather lower, so that the Valley of Death does occur. However, even so, at times, the *chordal-hop* mechanisms can still work in the mid-path regions, since chordal hops require *lower* values of ionization for the *same* value of MUF.

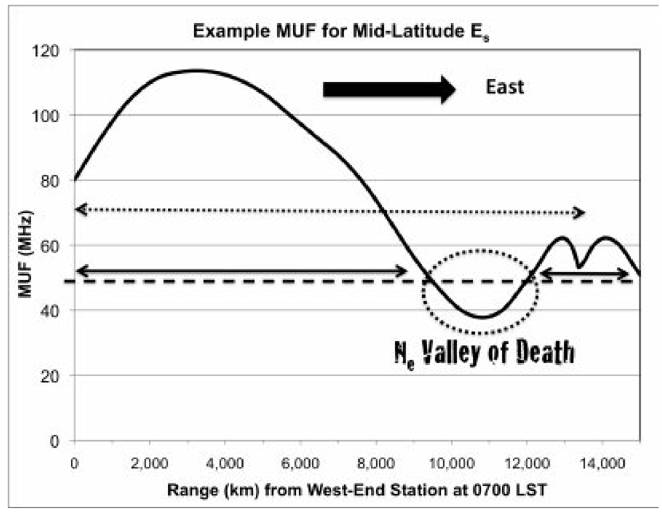

Figure 8: Remapping Figure 2 shows the MUF as a function of distance from the west-end station at 0700 LST (30° lat). The dashed line shows the 50 MHz MUF cutoff points. The solid arrows show the reachable paths. The dotted arrow shows what's possible if the valley is bridged.

Kennedy and Zimmerman (2011a) showed that, for both the JA-NA and NA-EU paths, the ionospheric conditions were *favorable* for Es formation along the paths *and* they were possibly even *enhanced* near the midpoint. Such conditions could have played a role for either nEs or chordal Es near the path midpoints.

East-West Conclusions – Since these events only seem to occur during the principal summertime Es season, and furthermore, *only* when both stations are in their respective opposite Es time windows (the early-on-late window effect), this strongly indicates that EWEE is indeed a form of Es propagation. The data also show that ordinary nEs skip plays a role in the paths, at least at times. However, it does not *exclude* the possibility that some of the chordal-Es modes may also be involved.

Low Solar Activity a Factor? – It was also pointed out that a possible key to making the mid-path portion of the circuits work might well be the presence of low solar activity. EWEE seems to be a *largely daytime* effect, which is normal for the mid-latitude Es at the *end* points. However, at some NA-EU *endpoint* latitudes, the resulting path *midpoint* can be as far north as 75°.

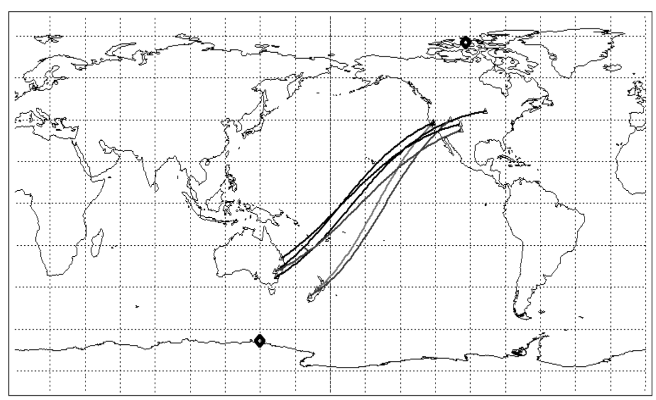

Figure 9: These great-circle paths show NA and ZL/VK path end points, as were observed on January 11, 2011.

On the *dayside* of the Earth and during persistent periods of *low* solar activity, these high latitudes can still be in the daytime *mid-latitude Es* regime, and exhibit the observed behavior. However, during periods of *high* solar activity, this northern latitude can be in the *auroral Es* regime. This is dominantly a *nighttime* effect, and the path would fail. So, low solar activity *may* be a real factor on the NA-EU path. *However*, the JA-NA path only reaches about 60°N and would be *much less* influenced by solar effects.

Transequatorial Es-F2-Es (TEFE) – Rumors had been around for some time about occasional *very weak* signals being heard *coming from* the southwest Pacific during the northern hemisphere wintertime. Some folks *in* the southwest Pacific have talked about "Christmas Surprise" propagation from the north Pacific, although not necessarily from North America.

Then, in the northern wintertimes of 2009, 2010, 2011, and 2012, there was a spate of contacts between North America and both ZL and VK, and some neighboring islands – which did indeed come as a "surprise" to a lot of people. Some of these paths are shown in Figure 9. They range from 10,500 km to nearly 16,000 km!

Figure 10 shows the distances and call areas involved between NA and ZL/VK on the right-hand side. The left-hand side shows some shorter openings, which lie along the same great-circle routes. The second Kennedy and Zimmerman paper (2011b) looked at how this might have happened and *why* they happened *when* they did.

The first thing that jumped out was that the openings happened in the midst of the Southern Hemisphere's principal summertime Es season. While this would be an obvious explanation for propagation *within* the Southern Hemisphere, it didn't seem to explain the link across the equator and, all by itself, it doesn't explain the propagation in the Northern Hemispheric either.

Of course, one could imagine the possibility of having wintertime Es in the north, but that still left the issue of getting across the equator.

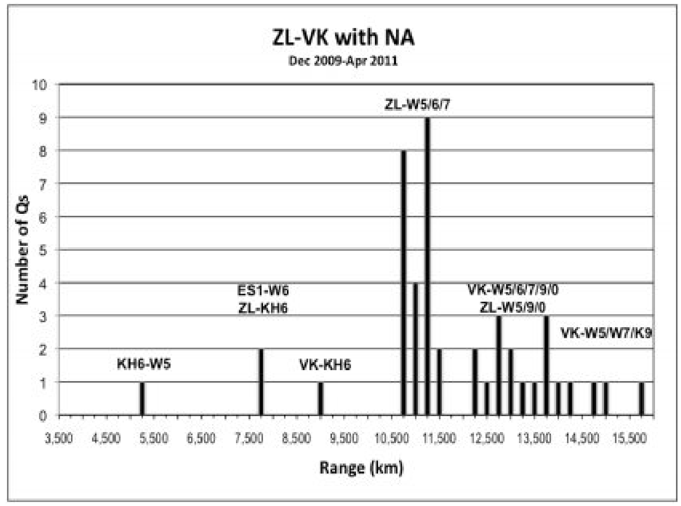

Figure 10: Almost all of the right-hand side across-the-equator contact ranges were equal to, and many exceeded, those seen in the more common EWEE. The challenge is sorting out what was happening that enabled these events.

Es Diurnal Windows Again – The success with the "early-on-late-windows" approach to EWEE encouraged looking at the same relationships for the north-south propagation. Figure 11 shows the various contacts plotted against the local solar times at each end of the path. The first thing to notice is that the *east-end* (NA) stations where almost always in their afternoon-evening Es window. It is also true that about two-thirds of the west-end stations were in their morning peak (below the dashed line). However, a fair number of contacts occurred in the south's usually low-probability early afternoon (above the dashed line).

So, the time-window correlation is similar to the EWEE plot, but it's not quite as convincing and, thus, it still leaves some questions. In addition, there still is the matter of how the signals get across the equator.

To address the open issues, the authors then examined the state of the ionosphere, as they had done for EWEE. They made use of an ionospheric modeling program developed by researchers at Utah State University, called the Global Assimilation of Ionospheric Measurements model (USU-GAIM). The program takes a large number of real-world measurements of solar and terrestrial parameters and produces a three-dimensional reconstruction of the likely state of the global ionosphere every 15 minutes, over a given interval of time. In this case, the specified dates and times were the *actual* dates and times when these very long-range band openings occurred.

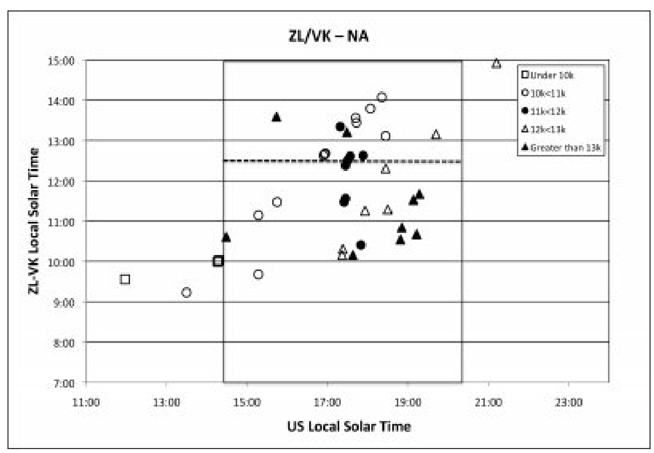

Figure 11: For ZL/VK–NA, the east-end stations are almost always in their E_s afternoon/evening peak period (vertical solid bars). Most often the west-end stations are in their morning peak (from the dotted line on down), yet a number of contacts occur in the usually low-probability afternoon area above the dotted line.

Equatorial F Layer – At this point, it will be helpful to have a brief discussion of how the *F layer* behaves near the *geomagnetic equator* (not the *geographic* equator). The Earth's magnetic field is only roughly aligned with its rotation axis. The north magnetic pole is located in the extreme northern part of Canada, and the south magnetic pole is south of Australia at the edge of Antarctica. Since the magnetic poles are tilted, the *magnetic* equator is also tilted with respect to the *geographic* equator.

During the local daytime, there is a persistent east-to-west *electric field* in the E-layer that runs right along the geomagnetic equator. It's called the *equatorial electrojet*. The electrojet drives a dayside, west-to-east electron current in a narrow E-layer region along the magnetic equator. These electrons interact with the Earth's magnetic field to produce an "*afternoon fountain*" of free electrons scavenged from the E and F1 regions and flowing up into the F2 region (Davies, 1990). This causes the development of *two* large, F2 ionization clouds, which *follow* the Sun around the Earth every day, but lagging behind it just a bit. One cloud is at about 20° north of the geomagnetic equator and the other one is across from it at about the 20° south of the geomagnetic equator.

Near the *equinoxes*, the Sun's radiation ionizes these northern and southern "*equatorial-anomaly*" clouds about equally. This then can lead to a well-known F2-layer chordal-hop phenomenon, called TransEquatorial Propagation (TEP). It often occurs in the afternoon and evening for stations within a one-F2-hop distance of the geomagnetic equator. *However*, near the summer and winter *solstices*, the F2 "*winter anomaly*" strongly favors *only* the *winter-side* cloud. While the winter MUF can be quite *high*, the summer-side cloud's MUF is quite *low*. Thus, TEP *fails* because it requires both the north and the south clouds to work.

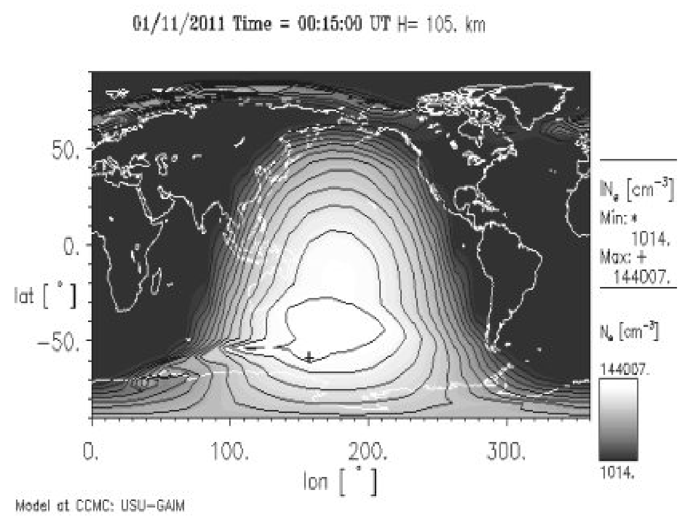

Figure 12: The USU-GAIM model describes the E-layer N_e at 105 km for 0015 UTC 01/11/11. It shows the expected east-west elongation permitting ZL/VK Es formation. It also shows a north-south branch that projects northward past the equator

Look at the Whole Ionosphere – By looking at the ionosphere *at all altitudes*, not *just* the E layer, some interesting insights developed, which appear to have shed light on the problem.

T-Shaped E Layer – The first interesting observation was that, during the local summer, the E-layer ionization pattern takes on an unexpected shape. Figure 12 shows that the *horizontal* axis of the background ionization is along an *east-west* line spanning across both ZL and VK, at the same time the band was open to NA. Of course, this E-layer background ionization is the reservoir of electrons that, with the wind-shear effect, results in the east-west summertime Es in that region.

What was not expected was that there also is a long *north-south* branch of E-layer ionization. As a whole, the background E layer ionization is shaped more like an inverted "T".

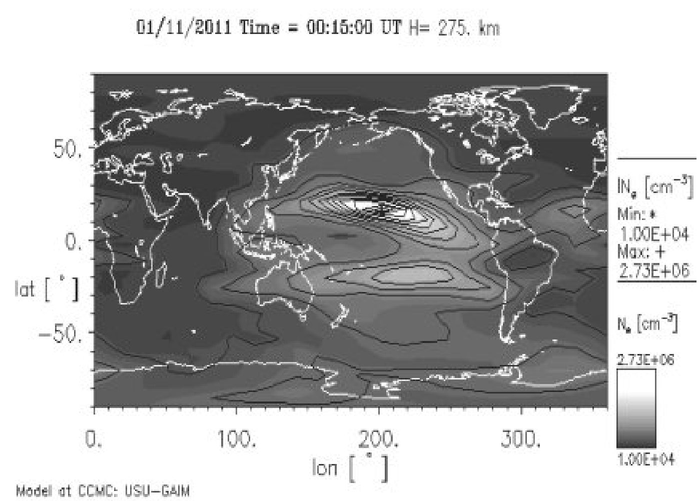

Figure 13: The USU-GAIM F-layer model N_e at 275 km for 0015 UTC 01/11/11 shows a strong northern F2 branch, with an MUF at 50 MHz, well positioned to feed into or out of the north end of the southern E-layer reservoir.

This north-south feature even reaches north above the equator at weaker levels. South of the equator, the strongest levels lay roughly along the great-circle path that NA signals would have to follow in the Southern Hemisphere to reach ZL/VK. By itself, the north-south branch isn't enough to explain propagation all the way to NA, but it may help.

A Lonely Northern F2 Cloud – At the same day and time, the F2 region (Figure 13) shows what one might expect – the (summertime) southern branch cloud of the F2 equatorial anomaly is *very weak*. However, the northern F2 branch is much more robust, with a sharp peak just south and a bit east of KH6. However, what *was* a surprise was that, in spite of *very low* solar activity, the *northern* branch MUF was *sitting right at 50 MHz*!

(Just as an aside – This means that single-hop F2 would have been possible on that day and time, for stations that were on opposite sides of the cloud, with each lying about 1,500 to 2000 km from the cloud. However, there are few, if any, pairs of islands that would meet this requirement. So, who would have known that there was a path open out there, going from nowhere to nowhere?)

Summer Es to an F2 Cloud to Winter Es – The most likely mechanism for these incredibly long paths (Figure 14) is: Starting from ZL/VK, first the signal goes north about three hops along the elongated leg of the inverted E-layer "T" – either by nEs or chordal Es. As the Es MUF fades south of the magnetic equator, the signal escapes the E region, going off toward the strong F2 cloud just north of the equator. It skips off the F2 cloud for one hop, coming down in an empty spot in the north-side Pacific. It then heads off again to find a winter Es cloud several hundred kilometers west of the West Coast. After one Es hop, it finally lands in the western US. On at least one occasion, a *second* winter Es hop took it all the way into the Middle West.

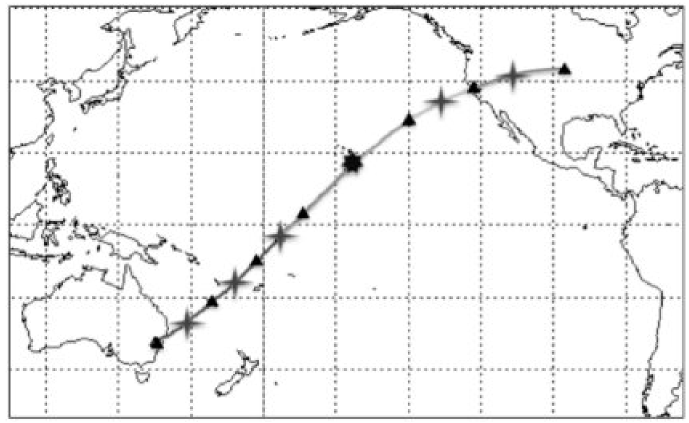

Figure 14: The path from ZL/VK starts in the south, with three summertime Es hops, then one single-hop F2 skip, and finally one or two wintertime Es hop(s) into NA. The triangles mark ground the points in the hops, the four-point stars are Es cloud points, and the seven-point star is the F2 cloud point.

Why is Only the ZL/VK-NA Path Seen? –The ionospheric maps show that, if the seasons are reversed (that is to northern summer and southern winter), the northern Pacific E hops are probably there. Certainly, 2Es and 3Es between KH6 and NA happen every summer season. However, for whatever reason, the ionospheric models show that the *southern winter* equatorial anomaly is *significantly weaker* than the northern winter anomaly. Thus, the southern winter F2 MUF is noticeably *below 50 MHz*, and the path doesn't work.

Over the Atlantic, there are *alignment* problems with the equatorial anomaly and the great-circle path between, say, NA and ZS. Like the Pacific, the Atlantic *southern* winter anomaly is also quite *weak*. Moreover, *Es itself* is quite rare over ZS, making even the Es hops very unlikely in the south. In short, the terrestrial and ionospheric geographies favor the ZL/VK-NA path in the southern summer, and they do *not* favor the northern summer in either the Pacific or the Atlantic. In addition, southern summer Es is unlikely in the ZS region in the first place.

North-South Conclusions – The link with the southern hemisphere Es season is not coincidental. Es plays a key role in this long-range propagation, either as nEs or one of the chordal forms. Likewise, the NA stations, which had to rely on *winter* Es to link to the F2 and then to the southern Es, needed their afternoon-evening late Es window to make the circuit work. The fact that there was a F2 cloud with MUFs around 50 MHz, right at the place where the Es ran out, both north and south, strongly points to F-layer involvement. The southern summer was in full swing, and at times the ionization was *high enough* that contacts were made even during the usually low-probability early afternoon – that is, there was no Valley of Death. Finally, the fact that this one path over the Pacific is the *only one* observed, matches very well with the observed geographic misalignments and poor F-layer conditions for the other three obvious path choices, which all provide strong evidence for the F2 component.

(As another aside: if it should turn out that Cycle 24 is a disappointment for worldwide F2 DX in the next few years, EWEE and TEFE may both help fill the gap.)

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The Community Co-ordinated Modeling Center group at the NASA Goddard Space Flight Center ran the computer models for the selected dates and times.

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