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F-Region Propagation and the Equatorial Ionospheric Anomaly

Unique ionization patterns form in the ionosphere above the Earth's geomagnetic dip equator, which provide several variations of F-region propagation recently displayed on 6 m.

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The 6-m band has always been a fascinating place to study radio propagation. This is partly because ionospheric propagation is relatively rare, at least compared to lower frequency bands. As a result, when something does happen, usually it's easier to determine *what* happened. Despite the poor solar activity numbers, the long-awaited peak of the Sun's southern hemisphere has created a — perhaps brief — bump in 6-m F-layer propagation. This was especially obvious in the upsurge of DX paths during the northern fall of 2013 and spring of 2014. Much of this flurry of activity involved the geomagnetic equator and the *Equatorial Ionospheric Anomaly* (EIA).

The EIA is a unique set of ionization patterns that forms in the E layer above the Earth's geomagnetic equator, specifically the *dip* equator. The dip equator is a line around the Earth showing where the Earth's magnetic field is exactly parallel to the Earth's surface.

The ionization patterns that form along this line provide for a number of variations of F-region propagation, including Transequatorial Propagation (TEP). These propagation types have been around for years. But for some, they are not broadly recognized as distinct forms, and though commonly referred to as TEP, not all of them are TEP. Nevertheless, like balls on a billiards table, the EIA and its effects can really bounce things around. Recently, 6 m has displayed a number of these modes, and a few examples are shown in Figure 1.

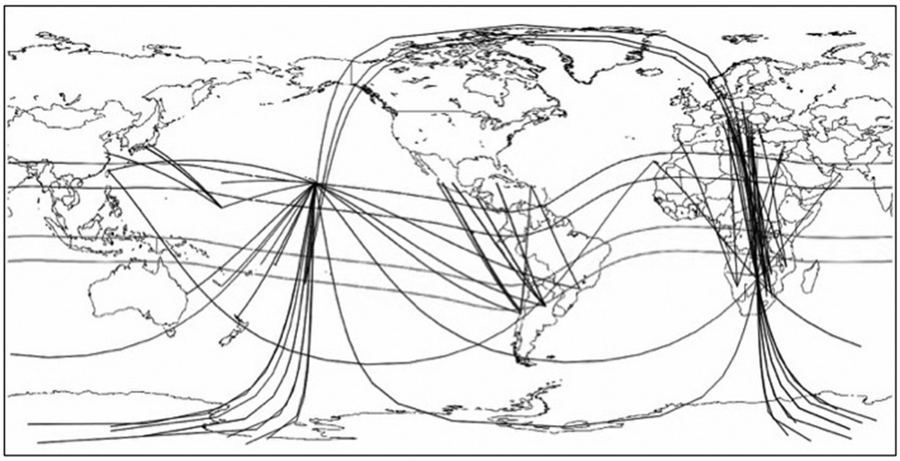


Figure 1 — Several distinct F-layer paths are rooted in the Equatorial Ionospheric Anomaly. Five are shown: aTEP, eTEP, 1- and 2-hop F2, and transpolar long path (TPL). [*G.Projector* map and overlays.]

If the gloomy outlook for the next coming solar Cycle 25 comes to pass, as predicted by a number of prominent solar physicists, then some of the lessons learned at 6 m may well become relevant, not only to 6 and 10 m, but also 12, 15, and 17 m, and maybe even 20 m. The good news is that there are quite a variety of related, but different, F-region skip modes that vitally hinge on the rather special ionospheric conditions that occur in the general vicinity of the dip equator.

Basic Ionospheric Skip

The following review points out a few of the key components that make ionospheric propagation work, and which are important to understanding some of the propagation puzzles.

Ionization

The F2 region lies above about 250 km and goes upward beyond 1500 km. The ionization of the F layer is due primarily to extreme ultraviolet (EUV) radiation from the Sun. When a solar EUV photon collides with a neutral gas atom in the F layer — mostly single oxygen atoms — the photon knocks one of the outer electrons off the atom, leaving a rather heavy oxygen atom with a positive charge of one, and a very light free electron with a negative charge of one. From a radio propagation perspective, the key part is the light, very mobile, free electron. Of course, with more solar activity there are more free electrons.

If a radio wave is sent up into the ionosphere, when it encounters the free electrons, the oscillating electric field of the passing wave causes the electrons to move back and forth at the same frequency as the radio wave. Electronically, these oscillating electrons behave like an antenna, except the electrons are wiggling back and forth in nearly empty space, rather than on a metal wire. This means that a certain fraction of the up-going wave energy will be reradiated back downward towards the Earth by this "free-electron antenna". If the electron density is greater than a certain number, the *entire* radio wave will be reradiated back down, and skip occurs. The amount of ionization required to do this depends on the *frequency* of the upcoming wave, and the *angle* between the wave and the ionosphere itself.

Taking the simpler case first, suppose that a signal is sent straight up, vertically, to the ionosphere directly overhead. If N_e is the free-electron number density, the *maximum* frequency (in MHz) that can be bounced *straight back* down is given by:

$$f_c[\text{MHz}] = \left(9 \times 10^{-6}\right)\sqrt{N_e}$$

$$N_e = \text{electrons/m}^3$$

The *highest frequency* that a straight up signal can bounce straight back down — the *critical frequency* — depends on the square root of the electron density N_e and a known constant.

M Factor and the Angle of Attack

Aiming signals straight up won't produce much DX. One aims at the horizon and that changes the angle with which the signal hits the ionosphere. With a shallower angle there is a higher maximum usable frequency (MUF) and the longer the skip distance. The angle between the wave and the ionosphere is the angle of attack α shown in Figure 2. The increase in the MUF is related to the cosecant of α , called the *M Factor*, and it directly multiplies the effect of the critical frequency f_c. The MUF is,

$$f_{MUF}[\text{MHz}] = f_c \operatorname{cosec}(\alpha)$$

With *M* replacing cosec(α),

$$f_{MUF}[\text{MHz}] = M\left(9 \times 10^{-6}\right)\sqrt{N_e}$$

Under normal circumstances *M* depends on the height of the ionospheric layer. With an antenna aimed at the horizon, the typical F2 hop has *M* near 3.4. However, *M* and therefore the MUF can be much higher under the right conditions.

Specular Reflection

In an elementary picture of ionospheric skip, one imagines that the ionosphere presents a hard-surfaced radio mirror (Figure 2). A radio wave simply bounces off the layer and returns to Earth. This is fairly accurate with sporadic E (Es) skip. In Es a very thin layer of very dense ionization produces a nearly mirror-like, or "specular" reflection. However, this is not the usual case for F-layer propagation.

Refraction

F-region ionization spreads over a large vertical expanse, extending upwards hundreds of kilometers. As a result, the signals are not skipped by a mirror-like bounce, but rather they are gradually bent until they point back downward again, if the MUF is high enough (Figure 3).

Since the F layer is three or more times

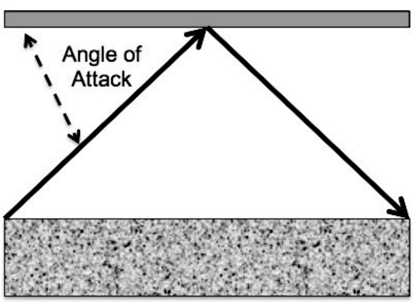


Figure 2 — Es produces mirror-like reflections. Note also that the smaller the angle of attack the higher the MUF for a given electron density N_e.

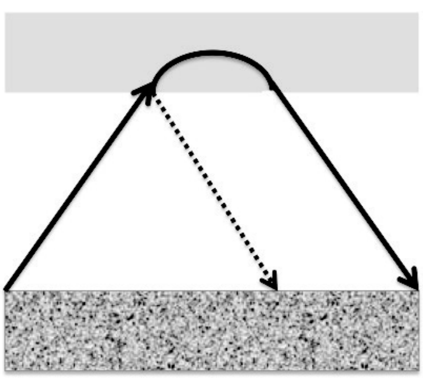


Figure 3 — The large vertical extent of the F2 layer skips a signal by more gradual bending, or refraction. Refraction can provide longer skip distances than the specular reflection (dotted arrow shows reflection).

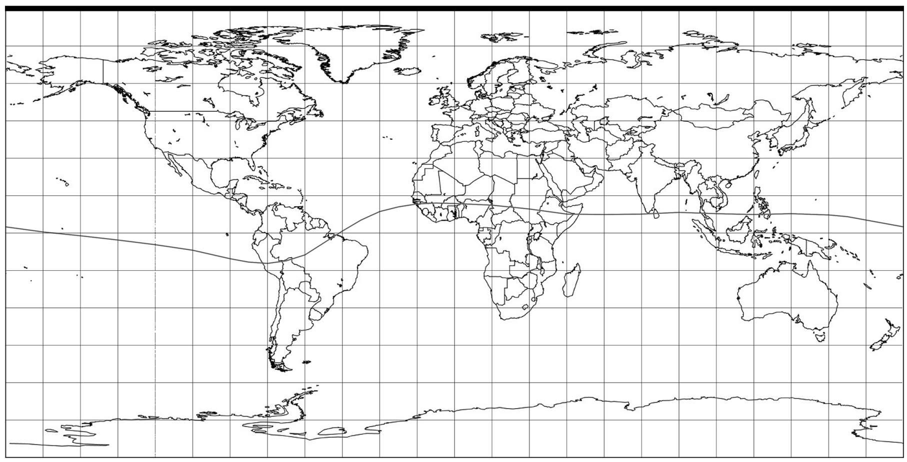


Figure 4 — The wavy line near the geographic equator is the geomagnetic dip equator. The geomagnetic field center is displaced from the geographic center toward the Pacific side, leaving the odd "bump" over the Atlantic. [*G.Projector* map and overlays.]

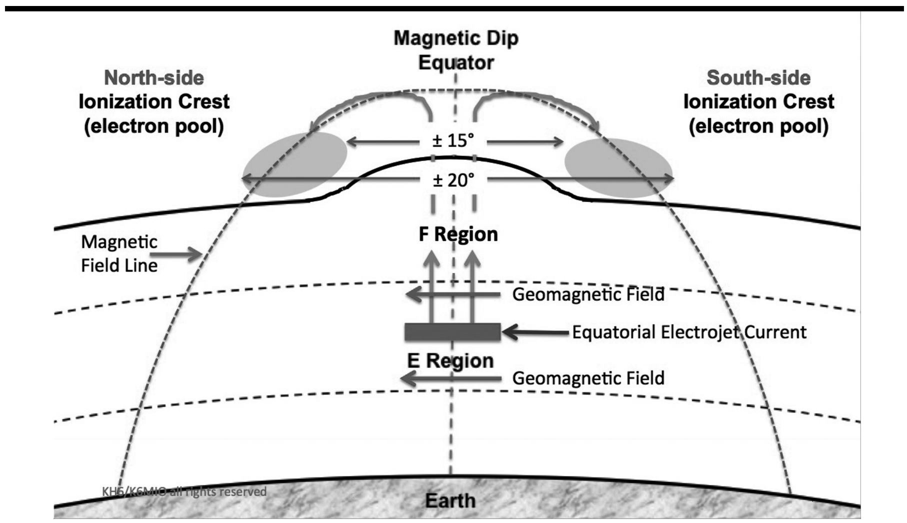


Figure 5 — The daytime fountain produces two regions of enhanced ionization near the dip equator, one centered at about 15° – 20°N and the other about 15° – 20°S.

higher than the E layer, it naturally provides a much longer single-hop skip distance than Es. In addition, once in the F layer, the signal can travel horizontally quite some distance while the refractive bending is taking place. Refraction can provide a longer skip distance than a specular reflection for the same layer height. Frequency is a factor as well. A single F2 hop at HF is about 4000 km. At 6 m it can be as much as 20% longer.

Ionospheric Environment

Simplified views often show the ionosphere as a smooth flat layer. But, the ionosphere is *neither* flat nor smooth. It is not even spherical. These realities have significant impact on the fine details of radio propagation — providing communications opportunities that would not otherwise exist. Making sense of them requires a little deeper look at our planet and how it behaves.

Geomagnetic Field

The Earth's geomagnetic field interacts with the ionized electrons within the various layers, and this produces a range of interesting effects. The simplest pictures of the magnetic field can hide some of its most important characteristics. An important feature is that the Earth's magnetic field is misaligned with the Earth's rotational axis by about 10°. As a result, there are two different longitude-latitude systems. One — the *geographic* system — is based on the Earth's rotation axis. The other — the geo*magnetic* system — is based on the orientation of the geomagnetic field axis. Of course, the rotation axis determines the time of day and the seasons of the year.

Adding complication, the magnetic field is also off center. The center of the magnet is not at the center of the Earth but rather, several hundred kilometers from the center — toward the Pacific side. This weakens the field over the South Atlantic Ocean off Brazil, and causes an abrupt glitch in the geomagnetic dip equator.

The interaction between the offset field center with the Earth's interior structure also leads to distortions in the overall field, so that the magnetic field is not a true dipole. Some maps do show a magnetic-dipole longitude-latitude scheme, but this approximation is not at all realistic for propagation purposes. Figure 4 shows the location of the geomagnetic dip equator — the line of shows where the magnetic field lines are parallel to the Earth's surface. The abrupt distortion on the dip equator is clearly seen over the South Atlantic near Brazil.

Equatorial Electrojet

During the local daytime, in the E-layer around 100 to 110 km, directly over the dip equator, there is a very intense electric current called the Equatorial Electrojet (EEJ). This ribbon of flowing electrons is quite thin and confined to a very narrow north-south range across the dip equator at approximately +3° to -3°. The EEJ is primarily driven by the Sun, which ionizes the daytime E layer and also drives a wind of neutral gases in an east-to-west direction, dragging the free electrons along with them. The interaction with the equatorial geomagnetic field, which is parallel to the Earth's surface, produces the ribbon of current. The current follows the dip equator throughout the year, even though the place-to-place, day-to-day, even hour-to-hour, strength of the current can vary strongly with the season, F10.7 solar flux, diurnal atmospheric tides, lunar tides, and perhaps even vertical drafts caused by tropospheric weather.

Daytime Electron Fountain

When a current flows at right angles to a magnetic field, as it is here, the electrons — and positive particles — are subjected to electromagnetic forces. Within the EEJ, these forces push electrons from the E and F1 layers upwards, at times more than 1500 km, to F2-region heights where the electrons have much longer lifetimes.

As in the E layer, when the daytime Sun heats the F region, it drives the daytime neutral wind patterns. The F2 winds flow outward from the warmed area over the dip equator, and to the cooler regions toward the nearest pole. These neutral winds carry the upcoming electrons with them. As a result, the electrons that are on the northern side of the dip equator are carried further northward, while those on the south side are carried further southward.

Going north and south of the dip equator, the Earth's magnetic field lines gradually tilt downwards toward the Earth, and the fountain electrons follow these field lines. So, as they go north and south, they also descend to lower F2 levels. Finally, the electrons collect in two ionization pools, often referred to as "crests" — one centered around 17° north, and the other centered around 17° south — of the dip equator at altitudes from 300 to over 450 km (Figure 5). Figure 6 shows how these same features show up on a USU-GAIM rendering. USU-GAIM is an ionospheric model developed at Utah State University that uses a wide range of measured data to recreate the state of the ionosphere in 3–D at a given time.[1]

Nighttime Bubble Fountain

When the Sun sets on the E and F2 layers, the electrojet current drops dramatically to the much lower nighttime levels. However, just before the daytime fountain fails there is a brief, but very significant upward surge in the fountain, called the *Pre-reversal Enhancement* (PRE). At this time, the vertical pipeline of daytime ionization is still full from the E layer to the high F region.

The shock of the PRE impulse is believed to trigger a set of atmospheric gravity waves, rather like ocean waves, within the standing vertical electron column. These gravity

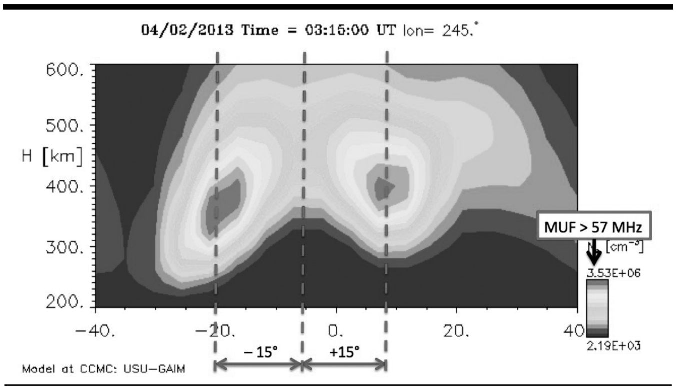


Figure 6 — This electron density map, for 0315 UTC on April 2, 2013 at 85°W (Geomagnetic Equator 5°S), shows both EIA pools have MUFs of about 57.5 MHz at about 390 km. Compare this with Figure 5. [USU-GAIM ionosphere.]

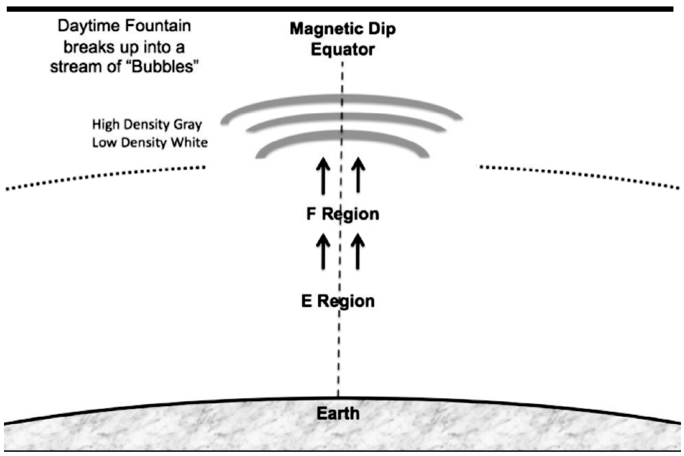


Figure 7 — The dying daytime electron fountain is shocked into a series of standing waves of alternating high and low ionization. The stacked layers are buoyant and float upward.

waves then produce a series of low-density ionization "bubbles" in the otherwise dense vertical column.[2]

These bubbles are 50 to 350 km thick sheets of low-density ionization, called depletions. They are sandwiched in between layers of the original high-density plasma.[3] These *Equatorial Plasma Bubbles* (EPB) can be more than 2000 km wide in latitude.

Like bubbles in a glass of water, these depletions are buoyant and begin to rise, pushing up the denser ionization layers lying above them. Figure 7 shows a portion of this multilayer stack of alternating low- and high-density ionization layers as they float upward — as a nighttime fountain effect — typically between about 1900 and 0000 local solar time (LST). During periods of high solar activity, the bubbles have lifetimes of about three hours, increasing to as much as seven hours during lower solar activity.[4] In latitude, the bubbles span a region from about 20° north to 20° south on the dip equator, with the bulk occurring between about 16° north and south.[5]

Seasons, Times, and Ionization

Since ionospheric free electrons are initially produced by the Sun's EUV radiation, the more directly the Sun is shining down on a given place, the more the ions are produced. If the local time were noon at that place, then having the Sun directly overhead would produce the most ionization. Of course, the Sun's high-noon angle depends on the latitude of that place and the local season.

As the Earth goes through its seasons, the noontime ionospheric Sun angle at a specific point slowly changes, as each of the Earth's two geographic poles alternately tips toward and then away from the Sun. This leads to the cycle of the seasons being reversed between the geographical northern and southern hemispheres.

Summer and Winter

Since the Sun's noontime angles in a given hemisphere are greatest during the hemisphere's local summer, more free electrons are produced in the summertime. If the story stopped right there, then one would expect that the local summer season would be the best for F2 propagation. However, while more ions are produced in the summer ionosphere, another summertime effect in the F-layer chemistry causes these ions to have shorter lifetimes. The electrons are recombined with the positive ions at a much higher rate than in the wintertime. There are fewer net free electrons in the local summer than in the winter, so at mid latitudes, F2 propagation is best in the local wintertime.

The real discussion starts with propagation in the geomagnetic equatorial latitudes, and in particular, paths traveling across the geomagnetic dip equator.

Spring and Fall

In contrast to the extremes of summer and winter, the Sun shines more or less equally on both the northern and southern electron pools during the spring and fall. Even though the Sun angle is not optimum for either the northern or southern side, but the balanced makes skip across the dip equator much more likely. Since spring in one hemisphere is fall in the other hemisphere, there are two times a year when this kind of propagation peaks.

Dates of Seasons

The dip equator sits at an angle to the geographic equator. Going around the world, the peak-to-peak latitude variation between the two equators is about 24° (Figure 4). Furthermore, the warped magnetic field leads to the geomagnetic equator being north of the geographic equator for two-thirds of its way around the Earth. This asymmetry has a subtle effect on the calendar dates of the "propagation season", depending one's geographic longitude.

Strictly speaking, the geomagnetic equinox at a given geographic longitude occurs when the Sun is positioned directly over the geomagnetic dip equator, not the geographic equator. This happens on different dates at different geographic longitudes. So, the magnetic seasons are not exactly the same as the geographic seasons. Given the angle between the dip equator and the geographic equator, this also means that on any given day, the magnetic season changes during the day, as the Sun passes over the various longitudes.

Referring back to Figure 4, stations in the northern hemisphere located at geographic longitudes between the middle Atlantic eastward to the east coast of Australia have their dip equator between 8° and 12° north. As a result, their spring magnetic equinoxes occur 20 to 30 days later than the geographic equinoxes, and their fall equinoxes are 20 to 30 days earlier. Of course, stations at these same longitudes in the southern hemisphere have these same equinoxes at the same dates, but the names of the seasons are reversed.

The northern hemisphere stations located between geographic longitudes corresponding to the central United States eastward to the tip of Nova Scotia have their dip equator between 8° and 12° south. Their fall equinoxes occur 20 to 30 days earlier than the geographic dates, and their spring equinoxes are 20 to 30 days later. In the Southern hemispheres, the dates are the same, but again the seasons are reversed.

In principle, these equinox date shifts affect which weeks of the year are the best for propagation, based on one's longitude. However, there are also many other factors that influence when exactly propagation occurs, including short-term solar activity.

Times of Day

The Sun is the source of the ionization that drives the EEJ, which in turn provides the resulting propagation. The relevant time is at the points in the ionosphere where the skip actually takes place, and not either of the endpoints. That is, the time is the actual Local Solar Time (LST) at the skip points.

On mostly north-south paths, the skip points will be at near the same longitude. These times are essentially the same, and one can talk simply about the path midpoint time. However, there are important cases where the paths have strong east-west differences and the different skip-point times have to be dealt with separately.

Many Flavors of Equatorial Ionospheric Anomaly F2

Let's take a look at some of the many different ways that the EIA can result in interesting F2-based propagation. Notice first that many things routinely called TEP are really several different phenomena. In one way or another, they involve the Anomaly, and some aren't TEP at all. The following breaks these down to basic forms, but there is no doubt that this still is not the complete picture.

Classical Transequatorial Propagation (TEP)

This is perhaps the most commonly known form of Equatorial Ionospheric Anomaly F2 propagation. TEP involves skip paths that cross over the geomagnetic dip equator. It was discovered in late August 1947, as hams returned to the airwaves following World War II, and in the US, on 6 m for the first time. The first contact may have been between W7ACS/KH6 at Pearl Harbor Hawaii and VK5KL.[6]

There are two main types of classical TEP, the afternoon and evening types. They have similarities, but actually work somewhat differently. In both, signals are first propagated up into the F2 layer on the nearside of the dip equator. Then, the signals propagate more or less horizontally across the dip equator, completely within the F region, without coming back to Earth in between. Finally, some distance from the far side of the dip equator, the signals leave the F2 layer and returned to Earth.

The total distance travelled, including through the F2-layer, corresponds to about an F2 "hop and a half", so the total distance between the north and south ground endpoints can be a good deal greater than 5,000 km. It is also a low-loss path. Since the signal doesn't come down at the midpoint, it avoids two passes of D-layer absorption (negligible at 6 m, but a factor at HF) and any mid-path ground effects that a normal double hop would have encountered.

Afternoon TEP (aTEP)

As the world turns, the Sun progressively illuminates the daylight side of the Earth under it. This starts the Daytime Fountain Effect. The Fountain pumps electrons upward from the E and F1 layers into the upper F2 region. This produces two regions where the ionosphere is systematically tilted and the free-electron density is enhanced by the pooling of electrons descending from the top of the fountain.

Generally, the morning hours are spent building up the amount of ionization transported into the F region. When the TEP crests or pools are sufficiently charged up, an upcoming radio wave hitting the tilted corner of the enhanced nearside ionization pool arrives at a shallower angle of attack than if it were a strictly spherical layer. So, not only are the electron densities higher than normal, the M Factor is also higher than the usual 3.4. Both factors conspire to produce much higher MUFs than the surrounding F2 layer. This happens again as the signal skips off the curved surface on the other side of the dip equator and heads back to Earth (Figure 8).

Around the spring and fall *equinoxes*, the solar ionization is more or less equal in both the northern and southern TEP pools. This balanced amount of ionization is favorable to aTEP propagation. Although there are some subtler details, aTEP is much more common around the equinoxes.

Ionization Lanes

For aTEP to work by the afternoon, both the north and south F2 skip points that straddle the dip equator must be ionized at or above the effective MUF required for the frequency involved. These two ionization pools move around the Earth following the Sun. This leads to two lanes or pathways that the ionization pools follow, day after day, on the daylight side of the planet. These lanes lie mostly between 10° and 20° north of the dip equator, and between 10° and 20° south of the dip equator (Figure 9).

Common Paths

The aTEP paths are largely magnetic north-south paths. They usually cross the dip equator within ±15° of the perpendicular, and can reach out to distances of about 7500 km. Figure 10 shows the general appearance of these paths and some of the common geographical regions where they are found. Although, there are some paths that have significant east-west components, these are special cases that will be discussed in later sections.

Times of Day

As aTEP ionization builds up in the morning daylight hours, it often reaches high enough levels for propagation in the early afternoon. This propagation mode then collapses shortly after the path midpoint E-layer sunset, because the daytime electron Fountain shuts down. So, the aTEP time period is about 1300–1900 path midpoint LST.

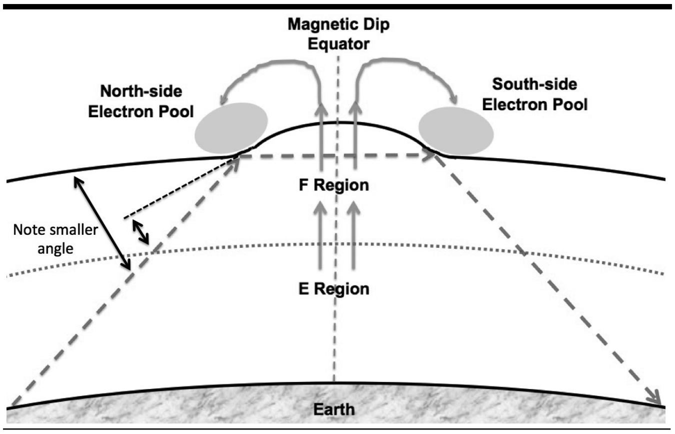


Figure 8 — This shows a transequatorial chordal hop off the tilted north and south skip points. The points are centered between about 15° and 20° north, and south, of the Earth's magnetic equator and cause nighttime TEP in the magnetic tropics.

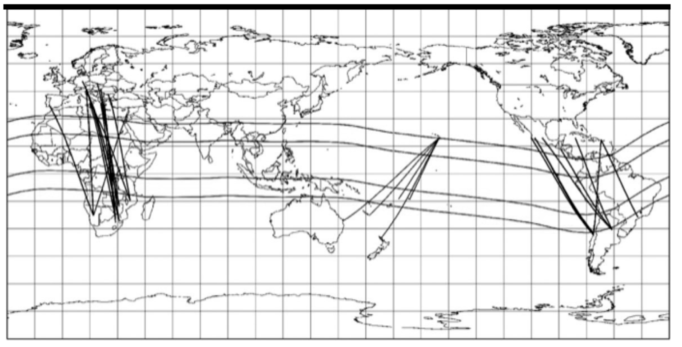


Figure 10 — Both afternoon TEP (aTEP) and evening TEP (eTEP) can produce paths that are approximately perpendicular to the dip equator. These are common examples of these mostly north-south paths. [*G.Projector* map and overlays.]

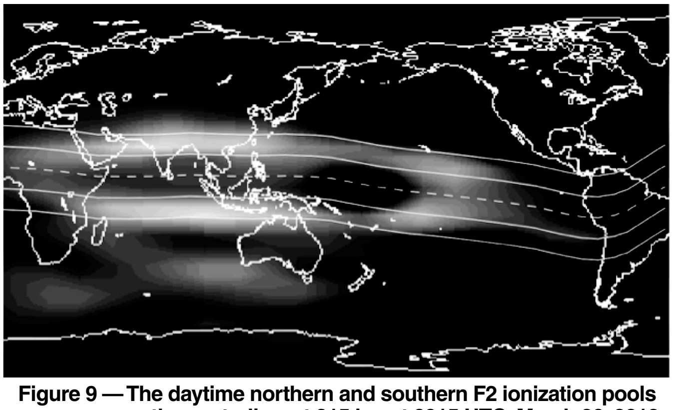


Figure 9 — The daytime northern and southern F2 ionization pools are seen near the centerline, at 315 km at 0915 UTC, March 20, 2013 (March Equinox). Solid lines show the daily paths/lanes they follow from east to west. The central peaks, left of center, show strong north and south electron levels. These are afternoon TEP peaks (aTEP). Two weaker peaks, right of center, are the evening TEP peaks (eTEP). The maximum MUFs were 53 MHz, over India and the Indian Ocean. [USU-GAIM ionosphere; *G.Projector* overlays.]

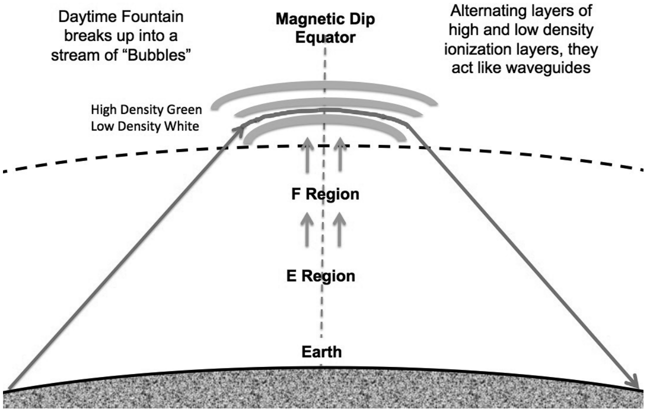


Figure 11 — Stacked layers of weakly conducting regions sandwiched in between highly conductive regions form ducts guiding upcoming radio waves through the dip-equator F region, and back down to the ground. If more than one duct is illuminated, even strong signals can show noticeable multipath effects.

Seasons

Since aTEP works best with equal ionization on both sides of the dip equator, it normally occurs during the two annual spring-fall equinox seasons. This usually peaks during March and April, and then again during October and November. The exact dates may be earlier or later, or longer or shorter, depending on the location of the dip equator, the timing and amount of solar activity, and other effects.

Evening TEP (eTEP)

Evening TEP is the second classical form of TEP. After the Sun sets on the path midpoint E layer, the daytime fountain shuts down, and the nighttime fountain begins producing bubble layers. The bubbles consist of sheets of high density ionization separated by very weakly ionized sheets called depletions. These sandwiched combinations of high — then very low — then high conductivity plasma layers are the key to making eTEP work.

The north and south ends of the depletion layers have openings on each side of the dip equator (Figure 11). A radio signal approaching the bubble stack will find it difficult to penetrate the highly conducting layers, but find it quite easy to enter the low ionization depletion layers. As a result, the depletion layers can act like signal ducts or tunnels through the bubble stack.

Instead of skipping the signal from a dense cloud on one side of the dip equator, to another cloud on the far side of the dip equator (like aTEP), a depletion duct carries the signal in a continuous curved path though the F layer bubbles, following the Earth's magnetic field lines.[7] Once a radio wave enters the duct, it slides along making very high M-Factor grazing incidence skips off the top wall of the duct that guide the signal around its curvature until the signal exits the duct on the other side of the dip equator.

Since the bubble stacks can extend from about 20° north to about 20° south of the dip equator, the general locations of the entrance and exit regions are similar to skip points seen in aTEP.

Since the vertical span of the individual ducts are in the 50 to 350 km range, the ducts are fully capable of transporting signals from at least as high as 432 MHz, and then well on down into the HF range.

With the family of bubbles being stacked up vertically, an upcoming signal can enter more than one guided path at the same time. So, there can be many paths over the dip equator. As a result, even with strong eTEP signals, there are often obvious, profound multipath effects, including deep fading, and echoes.

Common Paths

Usual eTEP paths include the mostly north-south paths, as also seen in aTEP (Figure 10). The observed maximum range is a bit longer than aTEP, going out to about 8800 km. There are at least two other modes that have some characteristics of eTEP, but are or may not be eTEP, as will be discussed shortly in the section on Oblique TEP and Single-Lane F2.

Times of Day

The evening bubble fountain gets underway shortly after the path midpoint sunset and the collapse of the daytime fountain. Various studies of the equatorial plasma bubbles themselves suggest that their active periods are about 2000-2300 LST at the path midpoint. However, propagation observations indicate that they can be effective from about 1900-0100 LST, and in some cases, even later. It is not uncommon to encounter north-south paths that are open in the mid-path afternoon with aTEP, and then later after mid-path sundown, pick up again in the evening hours by eTEP.

Seasons

The eTEP and aTEP seasons are about the same, spring and fall in both hemispheres. Both are facilitated by roughly equal ionization of the E and F layers on both sides of the dip equator.

Oblique TEP

The classical picture of aTEP and eTEP outlined above applies to paths that are largely oriented magnetically north-south. In these cases, there is only modest east-west difference in magnetic longitude, and this presents no mystery. However, paths that cross the dip equator at very large oblique angles must be much longer than nearly north-south paths. Even though the latitude differences between the stations about the dip equator are about the same, the longitude differences can be very large. These include recurring paths between Hawaii and South America. Figure 12 shows common examples of several of these paths. The longest is over 13,000 km, the shortest over 10,000 km, and most are over 11,000 km.

Figure 12 also shows an overlay of a typical USU-GAIM ionization map for that time of day and season. The dashed ovals show the path northern aTEP (left) and southern eTEP (right) skip-point ionization pools at 400 km. Their corrponding southern aTEP and northern eTEP pools are also visbile.

These longer paths pose at least two interesting challenges. The first is that the distance in between the near side lane skip point and the far side lane skip point is simply too long for a chordal or ducted hop. This middle segment would have to be about 5400 km for the shortest path, and about 8500 km for the longest. The basic problem is that the curvature of the Earth would cause the signal path to run into the ground about 2300 km downstream, destroying the path. Even under the most ideal conditions, the paths are 900 km to 4000 km short of the mark.

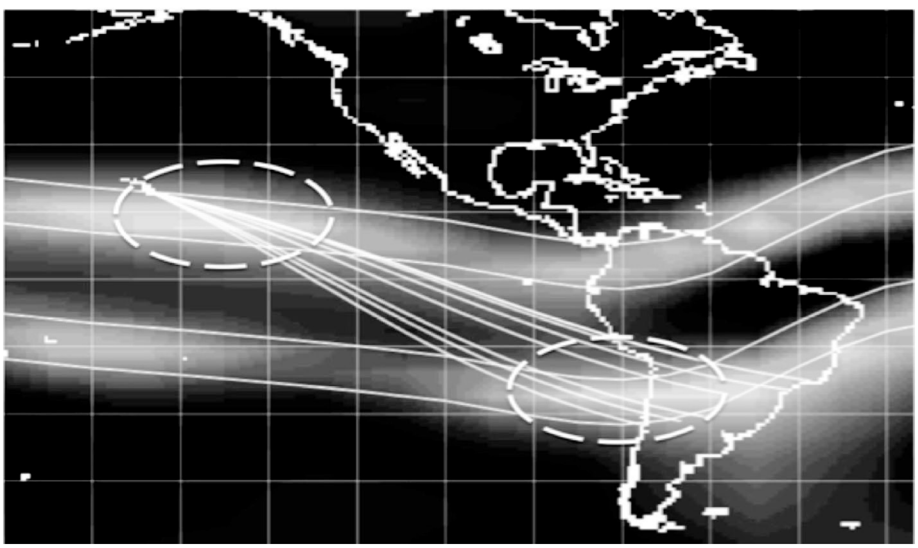


Figure 12 — Dashed ovals show the north aTEP (left) and south eTEP (right) ionization peaks. The lane boundaries are also shown. The southern aTEP (left) and northern eTEP (right) peaks are visible, but not involved in shown the path. [USU-GAIM ionosphere; *G.Projector* overlays.]

Getting the Distance Right

The challenge of going long distances around the curvature of the Earth, without hitting the ground has come up in other contexts. At least some types of 50 MHz long-path propagation show evidence that the very long central portion of the path has one or more segments — some perhaps longer than 11,000 km — that never come back to Earth.[8]

One possibility is a variation of the guided wave scenario. In this hypothesis, the signal skips off, say, the west-end ionization peak as an aTEP hop, and then goes into the region between the two lanes. There it starts nearly parallel to the Earth's surface, and going forward, the horizon moves up to meet it. However, long before it hits the ground, it encounters the topside of the E layer at grazing incidence. MUFs resulting from such skips are typically twice that of normal skips.[9]

This skip sends the signal further on down the path, edging upwards toward the F layer again. From there, F-layer refraction along the path eventually returns the signal path back downward again, to either another topside E skip, or carrying the signal all the way to the east end TEP peak, and from there back to the ground at the end of the path.

A simpler varation of this scheme might be to propose that F-layer refraction simply bends the signals around the curvature of the Earth, from one end to the other, all the way to the east-end TEP peak. Whatever the case, the paths do occur, and do so frequently when TEP is around. The above effects have been observed on other contexts, and they offer plausible explanations here as well. There may be other explanations as well.

Oblique aTEP and eTEP

In addition to path length, the time of day patterns raise another question. The extended paths separate the two end-point stations by five or six time-zone hours — so their Local Solar Times are very different. The observed propagation usually occurs during the west-end mid afternoon, while it is evening at the east end. Adjusting for first and last skip points, the west is still in the afternoon TEP regime and the east is well into the evening TEP regime. The simplest conclusion is that the west end is getting an aTEP hop and the east end is getting an eTEP hop. That may well be what's happening. If so, it is interesting that the two different mechanisms, which work in rather different ways, seem to make such a good connection.

The issue here is that aTEP requires a separate hop on each side of the dip equator, while the usual view of eTEP is that signals are piped all the way across the whole space from the north lane to the south lane, while buried inside the depletion ducts. So, the question would be, how did the aTEP signal from the north side — traveling in between the two lanes — get into the middle of a closed eTEP depletion duct, in order to get over to the south side lane and down to Earth?

The most likely answer is that as the bubbles rise, they also have open edges pointed into the region between the north and south lanes. Recalling that in eTEP all the guiding of the wave comes from high-M skips off the ceiling of the duct. In other contexts, eTEP has been observed to "leak" signals out the bottom of the ducts. So, if a signal coming from the north side can find a hole in the bottom of a duct, or a duct without a bottom altogether, then it could complete the journey on the south end as an eTEP hop.

Common Paths

Highly oblique paths are very common in the Pacific region during the TEP seasons. They may occur in other regions as well, though the combination of the hook-shaped dip equator region over South America, followed by a rather straight, gently northward flowing line out toward Asia may play a role in the frequency of its appearance there.

Times of Day

On the west end they occur during the local afternoon. On the east end they occur in the local evening.

Seasons

Like other true TEP forms, the path seems to favor the equinoxes. The span, from the beginning to ending date, seems somewhat shorter than some other paths.

Single-Lane F2

While much attention has been given to TEP propagation across the dip equator, there is another EIA propagation mode that is simply east-west F2 occurring off only one of the two ionized lanes. The dip equator is not crossed and the far side lane is not involved at all in a given path.

What many don't realize is how high the MUF can be for this mode. The USU-GAIM model shows that the east-west MUF can be well over 66 MHz, without any special angles and M-Factor values. It also need not be near an equinox. The models also show high local wintertime values. In this last regard, the Wake Island (KH9) beacon was into Hawaii almost daily from October 2013 until late April 2014.

Of course, taking advantage of this form of propagation generally requires that the two end-point stations must be on within about 2000 km of the same ionization lane peak. If the path is north-south, then they have to be on opposite sides of the lane. If they are more or less aligned along the lane, then double hop also occurs. That places a lot of constraints on where one has to be and whom one will be able to talk. Nevertheless, this mode happens quite frequently in certain parts of the world, where there are landmasses in the right positions for the required end-point station alignments. Figure 13 shows some actual examples from the western Pacific and the central Atlantic during March and most of April 2014.

Common Paths

From Hawaii these paths go westward toward the northern hemisphere islands including Wake, Guam, Taiwan, the Philippines, Japan, and mainland China. As can be seen in Figure 13, these kinds of paths show up in between the northern part of South America and its maritimes, and northwestern Africa,and martimes, and southern Europe.

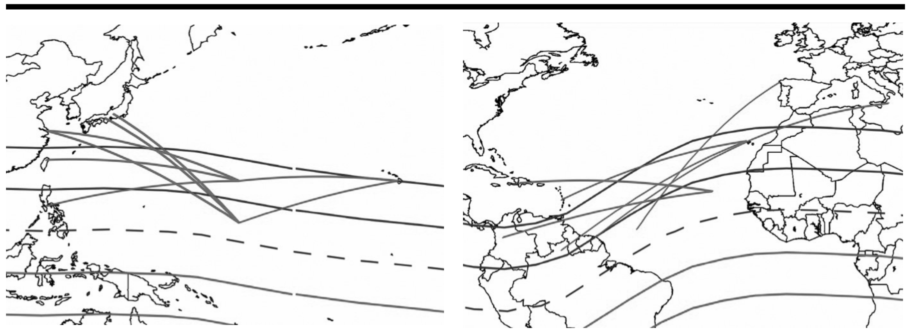
Times of Day

The midpoint time in that example was about 1800. While midpoint times seem to run from 1330-0000 for single hop and 1330-2000 for double hop, earlier times have been seen.

Seasons

Equinoxes generally are best, if not for the positive impact of Fountain ionization, then at least because more people are on the air. Those associated with the northern spring seems to perform better, but the amount of data is small.

There is some evidence suggesting that this sort of propagation should be available in seasons no one is expecting it, such as local winter.



(A) (B)

Figure 13 — These are examples of single- and double-hop Pacific, and Atlantic, F2 paths along, and across, just the north lane alone, during evening TEP hours. Note that the skip points all fall within the north lane. [*G.Projector* map and overlays.]

Non-Great Circle Paths

Nature is an equal-opportunity propagation provider. She is not restricted to using any one propagation mode to move a signal between point *A* and point *B*. It is perfectly possible to have one kind of propagation mechanism hand over a signal to some other kind of propagation mechanism.

In some cases, this results in paths that do not appear to follow a single Great Circle path from end to end. Rather, each of the different modes follows a Great Circle, but not necessarily the same one as the other, due to the different character of the two or more modes involved in the end-to-end path.

Skewed Paths

Of course, there is nothing new about skewed paths, but it is interesting to look at how they might come about. Understanding the possibilities is often hampered if one takes the simplified 2–D skip pictures too seriously, because the ionosphere is a 3–D world. So, not every reflection, refraction, skip, or hop occurs in the vertical plane. Things can be bent or bounced sideways as well.

The EIA is, by its very nature, a 3–D structure. All sorts of interesting things can occur. Whether the lanes are viewed from the side (north-south) or down along their long dimension (east-west), they provide a family of high electron density surfaces that skip signals at many different angles — not just straight ahead — but to the side as well.

Even a small deflection of the signal direction can make a profound difference in the signal path that then follows. When this happens, hybrid paths can be generated that, in the whole, are not Great Circle paths, even though the segments that make them up may well be. Figure 14 shows two examples of this effect.

The first is a variation of a path that, although completely a surprise when it first showed up decades ago (SA-JA), has continued to create excitement under good conditions. This recent example occurred on February 22, 2014 at 0052 UTC with an opening between several LU/CE and BA/BV stations. They are represented here as a single CE-BA path for clarity. The dashed line that runs down toward the South Pole shows the equivalent Great Circle path. However, these were not the directions that the antennas were aimed.

The first path segment from SA westward took almost exactly the same frequent eTEP path from SA to KH6 seen in Figure 12. As in that path, it occurred during the local SA evening. The path from the near side lane to BA very closely follows a known single-lane double-hop F2 path from KH6 to BA/BV. The circle on the plot shows the approximate point that the new path appeared to deviate from the other. The deflection angle is to the left about 14°. The deflection was away from the centerline between the two lanes, suggesting that refraction might have played a role.

The other example is the contact between FK8 and EA8 on November 10, 2013 at 0055 UTC. Again, the plot shows a reasonable estimate of the path actually followed, and also the normal great circle route, this time up toward the North Polar regions. As before, the key information was the station beam headings. FK8 was beaming east and did actually swing the beam looking for the best signal direction.

One interesting thing here is that the local time in FK8 was about 1300, which is consistent with the first segment starting as an aTEP link, looking toward later times to the east. Plotting a Great Circle for this segment suggested that the path appeared to first make a TEP hop to the northern side of both lanes.

Due to the abrupt northward swing of the dip equator over the SA, a little farther downstream it then encountered the north side lane a second time, this time in from the north. From there, it seems likely to have deflected to the left — as was the case in the CE-BA path above. The deviation point in that path's circle is about 13°, and as in the previous example, to the left, away from the lane centerline. After the deflection, the path is consistent with a single-lane one-half-hop F2 path down to EA8.

Common Paths

These are the only two paths for which data are currently available.

Times of Day

Both involved very oblique eTEP hops in the night near longitude 75° W.

Seasons

One occurred in late northern fall and the other in the early northern spring seasons.

TransPolar Long-path (TPL)

Late evening on 9 October 1988, on the rapidly rising leading edge of Cycle 22, a 6-m station in Greece (SV1DH using the special 6-m call, SZ2DH) worked JG2BRI in Japan. What was especially amazing was that it was nearly midnight in Greece and SV1DH was beaming southwest, away from Japan, toward the southeastern reaches of South America! The Japanese station was beaming southeast, at the other side of the south end of South America.

The two stations completed a nearly 31,000 km long-path contact from north of the magnetic equator southwestward encroaching on the Antarctic near the South Pole, and then back north across the magnetic equator again and landing in Japan. The actual signal traveled about three-quarters of the way around the world![10]

There were many TPL openings from KH6 to the Mediterranean and southern Europe near the Cycle 23 solar cycle

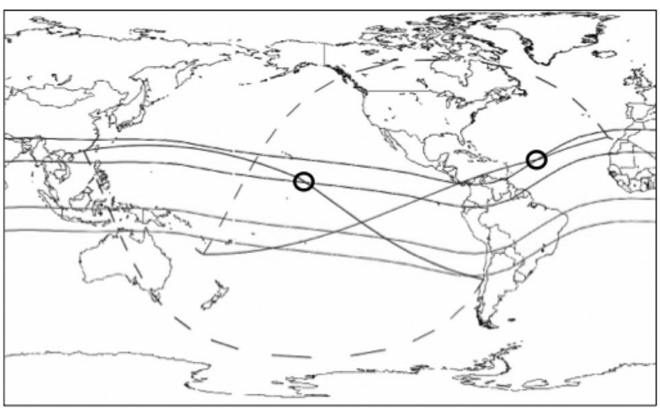


Figure 14 — Both skew paths start as south-lane TEP and then are redirected upon entering a later lane (circles). The path from CE then does a 2F2 hop in the north lane to BA. The FK8 path crosses the north lane and runs into it again, and is redirected to EA8. [*G.Projector* map and overlays.]

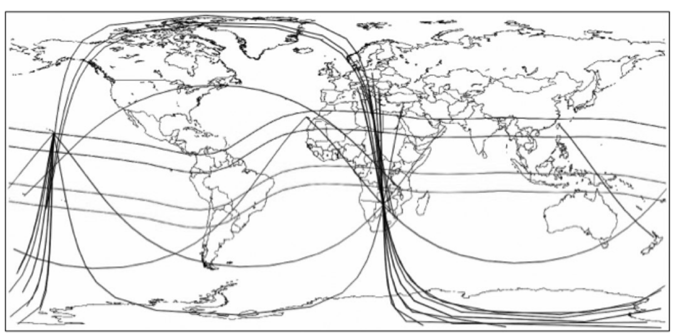


Figure 15 — Various transpolar long paths are shown between KH6 and the Med and A45; KH8 and 5H3; E51 and ZS; and BV and EA8. [*G.Projector* map and overlays.]

maximum, and a few more occurred in Cycle 24 in early 2014. KH6 was on the east end of the link at night, and Europe was on the west end,in their morning.

In KH6, the openings occurred in the late evening usually after 2200 station LST, when TEP was already in evidence over the usual paths (such as VK4), though the TEP was generally sporadic and not particularly intense or widespread. Quite strong backscatter was often heard from headings of about 195°, suggesting lots of ionization and tilted layers. Often the signals were very weak, though a great many SSB contacts were made. On a few occasions, the signals were very loud, allowing contacts with modest power and small antennas.

KH6 also saw the other side of the TPL path, as well, in Cycle 23 and again in early 2014. In these openings, the KH6 stations were on the west end of the path between 0830 and 1100 station LST, beaming around 140° and the path went into A45 and thereabouts in their late evening. Other recent examples include openings between EA8 and BV, and between E51 and ZS (Figure 15). There are many other example paths for this mode, but there are also some geographical limitations. A great many mathematically possible paths end up with one end in an ocean.

Whether going around westward or eastward, there was no evidence of the signals coming back to Earth in between the two ends of the path. These paths cover a lot of water and sparsely inhabited land. Nevertheless, it gives the impression that the signals start off as "ordinary" TEP. But, when the signal skipped off the far side lane, instead of coming back to Earth (say, in VK), some of the signal energy continued at a much shallower angle off the curved surface. This "launched" the signal into a series of high-M skips off the F2, over and over — like a whispering gallery — until the signals hit the anomaly lanes on the far end of the path over northern Africa. At that point, the far side lanes reversed the "launching" process and brought the signal back to Earth (Figure 16).

Midmorning TEP Curiosity

One interesting observation is that the east ends of the circuits, in both the eastern and western hemispheres, seem to systematically be in their evening TEP period. This necessarily means that the western ends of the paths are in midmorning. Normally, this would be too early for aTEP and too late for eTEP. Nevertheless, hundreds of contacts were made in Cycles 23 and 24. The mechanism for this effect might be associated with various observations that indicate that the ionization bubbles, such as associated with eTEP, sometimes have very long lifetimes.[11] Referred to as fossilized bubbles, they may play a role in facilitating this unusual TEP connection.

Common Paths

The paths from Hawaii to the Mediterranean, southern Europe, and the Near East is well known. There have been credible reports between South America and Australia, Polynesia and India, China and the Canaries, and a number of others.

The paths here are generally constrained by the placement of the landmasses within the Earth's oceans. Besides the fact that the stations have to be within access of the TEP ionospheric system, the paths are very long. So, from a given point at one end of the circuit, there are only a limited number of viable places at the other end of the proposed circuit. Nevertheless, some DXpeditions to carefully-chosen islands can produce designed-in opportunities.

Times of Day

Looking west, 2130-0130 station LST. Looking east, 0830-1100 station LST.

Seasons

This propagation seems to be confined to high solar activity and the equinox periods. There are indications that the April time frame is better than the October time frame.

Linking to TEP from Afar

It's reasonable to ask just how far from the TEP lanes can one be and still connect to the various TEP-like modes. The obvious requirement is that the station must be close enough to be able to illuminate the nearside TEP ionization lanes with its signal. This, in turn, is a function of the height of the lanes themselves. For peak regions at 300 and 450 km, these distances are about 2000 and 2500 km respectively. Figure 17 shows the TEP lanes and outer boundary limit lines.

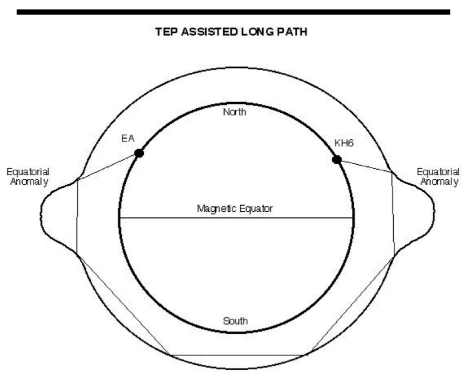


Figure 16 — TEP appears to provide launching points for high M-Factor, shallow attack-angle grazing hops that cover long distances, with higher than normal MUF and low absorption.

In principle, stations within these outer boundary lines should be able to connect directly to the TEP nearside lane.

However, it would also be possible to make a less direct connection from beyond the outer boundary using some different propagation mode to cross over the boundary from the outside. The most likely opportunity is having a sporadic E cloud in just the right place.

If the Es link brings the incoming signal down inside the outer boundary line, then it can begin a second hop. If things are properly lined up, then that second hop can become an F hop going up to the nearside TEP lane, and then complete a full TEP hop. Since single-hop Es can have a range of 1000-2000 km, this has the capacity to stretch the "TEP" range well beyond the direct connection limit. What's more, these paths really happen, as shown in Figure 17. Note that a number of those paths actually link across the boundary line, some from quite a distance. In all likelihood, many of the paths starting inside the boundary line were also Es links.

Common Paths

In the Western Hemisphere, the most common paths are between the US and both the Pacific and South America.

Times of Day

While there are exceptions, this is dominantly an evening affair, suggesting that the TEP component is eTEP.

Seasons

In the Northern Hemisphere the Es links to the TEP system are usually seen in mid to late April, at the time when the ending of the TEP season and the beginning of the Es season overlap. In the Southern hemisphere this would be in early to middle October.

Summary

The Equatorial Ionospheric Anomaly defines the behavior of radio propagation that originates, terminates, or passes through the vicinity of the Earth's geomagnetic dip equator. The daytime core of the EIA is the Equatorial Electrojet, a powerful electron current flowing in the E layer between 100 and 110 km, straddling the dip equator centerline between ±3° of latitude.

During the day, the electrojet and the Earth's magnetic field produce an "electron pump" which drives E and F1 layer electrons upward in a fountain carrying them high into the F2 layer. The fountain overflow settles into two crests or pools, one centered on about 17° north and the other about 17° south of the dip equator, still in the F layer at 300 to 450 km. The ionization peaks in those two pools follow the Sun daily, but lagging behind the Sun by a few hours.

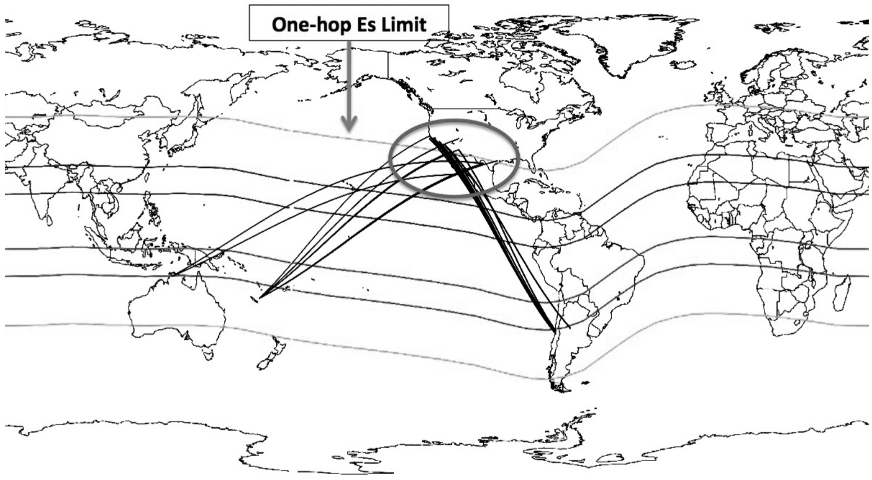


Figure 17 — The outermost lines show the nominal limits for direct TEP access to the more central ionization-lane pairs. Access from beyond the "direct" boundaries requires some additional mechanism, such as Es, to reach inside an outer boundary and link to the TEP. [*G.Projector* map and overlays.]

From local afternoon until sunset, these ionization pools facilitate radio propagation called afternoon TEP, or aTEP. Afternoon TEP skips signals from the ionization pool on one side of the dip equator, to the pool on the other side, allowing signals to cross over the dip equator with paths out to 7500 km.

When the Sun sets, the electrojet loses its energy source and the current ribbon abruptly stops, but a sudden last gasp sends an upward shock wave through the standing column of fountain electrons. This shock creates a series of large, flat "bubbles" of alternating layers of very-highly, and then very-weakly, ionized plasma. These bubbles are buoyant and they rise upward to great heights in the F2 layer, sometimes over 1500 km.

The bubble regions extend outward as much as 20° north and south of the dip equator. They are open at their edges. The weakly ionized layers act as ducts that can guide radio waves from one side of the dip equator to the other, providing evening TEP, or eTEP, propagation out to a total path length of about 8800 km.

The majority of this propagation is along largely north-south paths, which limits the maximum path length. However, there are variations that provide propagation across the dip equator, but with a very large east-west component as well. This Oblique TEP can produce paths to beyond 13,000 km. It generally involves a west-end station in its afternoon TEP regime and an east-end station in its evening regime.

The afternoon electron pools and nighttime plasma bubbles also support single-lane F2 skip from just one pool (either north or south), such as single-hop north-south paths across the lane. If the two stations and the lane are all aligned with each other east and west, then an east-west single or even a double-hop F2 can occur.

In addition, there are forms of propagation that involve a mixture of two or more of these modes in different segments of the same path. One example is very long, skewed paths, which do not follow a single Great Circle path. Another variation is Transpolar Longpath or TPL, which generally are not skewed, but involve TEP twice in the path, with something else different in between. Still another variation occurs when a station, far from the dip equator, uses an Es hop to link into range for a following TEP hop.

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Jim Kennedy, K6MIO, has been licensed since 1955. He has been an avid 6-m operator for much of that time. He holds a PhD in physics from the University of Florida, and has taught astronomy and electronics at the university and college levels. For more than twenty years, he was a senior manager with the National Solar Observatory in Tucson, and later, Associate Director of the Gemini Observatory in Hilo, Hawaii.

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