# 50 MHz Long-Path Propagation

Jim Kennedy, KH6/K6MIO

## Introduction

Operation over long distances on six metres can be very challenging. The fact that F-layer ionospheric propagation is relatively rare provides some interesting opportunities to observe some propagation modes in isolation that, while they may occur more often at lower frequencies, are often masked by other propagation modes occurring at the same time.

Among the most interesting cases are Transequatorial Propagation (TEP) and two TEP-related beasts: Transpolar Long-Path Propagation (TPL) and Trans-equatorial Long-Path Propagation (TEL). Under suitable conditions, these latter modes can produce spectacular six-metre openings spanning well over half-way around the world, *if* one is lucky enough to be in the right place at the right time.

## Transequatorial Propagation – A Review

TEP is a propagation mode that can allow VHF stations located in the *magnetic* tropics on *one side* of the earth's geomagnetic equator to communicate more or less on a north-south line with similarly placed stations on the *other side* of the magnetic equator, over distances of several thousand kilometres, generally in the afternoon or evening. The ionospheric skip points are located in the $F_2$ layer near the equator [1]. This effect is very well documented at 50 and 144 MHz, and has occurred more rarely at 222 and even 432 MHz.

The first recognition of this effect on six metres appears to have occurred in late August 1947, near the peak of Solar Cycle 18*. On the 25 August, KH6/W7ACS at Pearl Harbor worked VK5KL in Darwin, to set a new six-metre DX record. Two days later XE1KE in Mexico City worked a stunned LU6DO in Argentina [2]. At about the same time, stations in England and the Netherlands worked stations in Southern Rhodesia and South Africa [3].

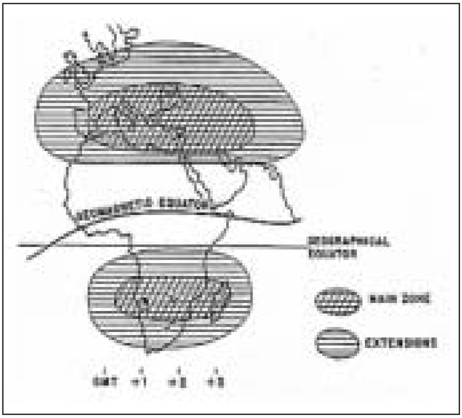


**Figure 1: Path footprints for the southern Africa to Mediterranean TEP path, as seen by ZE2JV and 5B4WR in 1958 [3]. (Copyright ARRL, reprinted by permission.)**

These patterns have been observed repeatedly since then, especially during solar maximum. While a total mystery at first, the basic mechanism began to come into focus as the result of amateur

* This was the first solar maximum for the six-metre band. Prior to World War II, the band was five metres.

and professional studies beginning with the International Geophysical Year (1957-58), and it continues to be the subject of study today.

During that time, it has become obvious that stations with the good fortune to be located within about ±40° of the magnetic equator can enjoy rather good propagation, often in the dead of night, with their neighbours on the opposite side of the equator. Notably, this effect occurs for a month or two in the spring and fall around the equinoxes, centred on March and October.

Moreover, the paths need not be strictly north-south. South America and Hawaii work each other frequently, and South American stations also work into Southern Europe often. While these stations are indeed on opposite sides of the magnetic equator, there is a very significant east-west component to these paths, in addition to north-south.

## Ions and angles

To best understand the causes of TEP (and TPL and TEL), one should note that the Maximum Usable Frequency (MUF) on a given path depends vitally on two factors, the *ion* density (free electrons) in the reflecting layer, and the *angle* with which the radio wave encounters that layer.

***Ionisation*** – When an upward-moving radio wave reaches, say, the F layer, the electric field in the wave forces the electrons in that layer into a sympathetic oscillation at the same frequency as the passing wave. The oscillating electrons in the layer can *reradiate* the upcoming wave downward, like a static reflector. Thus, the wave appears to skip off the ionosphere and then come back to earth at some distant point.

Since the ionospheric electron density gradually increases with height (up to a point), the skip actually occurs as a more or less gradual bending or *refraction* of the wave back around toward the ground, rather than a discontinuous reflection as from a mirror. But for many purposes, this subtlety is not too important. However, we will come back to the refraction concept a little later.

Let's consider the effect of the electron density on a wave taken in isolation from other effects, such as the earth's magnetic field. To do this, we look at a radio signal being sent *straight up*. One can calculate the so-called *critical frequency*, $f_c$, as the highest frequency that the ionosphere can reflect the signal *straight back down* again. This critical frequency† is given by:

$$f_c = \mathrm{sqrt}\,(Ne^2/4\pi^2\varepsilon_0 m)$$

or

$$f_c = \mathrm{sqrt}\,(N) * (9\mathrm{x}10^{-6})$$

$N$ is the electron number density, $e$ is the electron charge, $\varepsilon_0$ is the permittivity of free space, and $m$ is the mass of the electron. Except for $N$, everything else has a known constant value.

The point is that the highest frequency that will skip vertically back down is the square root of the electron density times a fixed number. So, for example, in order to skip a signal at *twice* the current maximum frequency, the number of electrons must be increased by a factor of *four*.

† Strictly speaking, the earth's magnetic field leads to two critical frequencies, $f_o$ and $f_x$, corresponding to the 'ordinary' and 'extraordinary' wave propagation modes. These differences are not important in the current discussion.

But, what if the signal is sent at some angle other than straight up?

***Angle of attack*** – To answer this question we must add the concept of the angle of attack‡. This is the angle that the direction of the moving wave makes with respect to the ionospheric layer. In the above example, the wave strikes the ionosphere with an angle of attack of 90° (i.e. going straight up vertically into the horizontal layer). In the more general case, the MUF is determined by *both* the maximum *electron density* that the wave encounters in the ionosphere *and* the *angle* at which the wave hits the reflecting/refracting layer.

If a signal that is sent off very near the horizon (e.g. with a zero angle of radiation), due to the curvature of the ionosphere around the earth, the signal will normally hit the ionosphere at an angle of attack between 10° to 20°, depending on the layer in question. The MUF in MHz (represented by $f_{max}$) can be calculated from:

$$f_{max} = \text{cosec}\,(\alpha) * f_c$$

or

$$f_{max} = M * \text{sqrt}\,(N) * (9\text{x}10^{-6})$$

where $\alpha$ is the angle of attack. Note the MUF depends on *both* the density of the electrons *and* the angle $\alpha$.

The cosecant of $\alpha$ is called the 'M factor'. As the angle gets smaller, the cosecant gets larger. As a result, the *smaller* the angle of attack, the *greater* the MUF.

This is the radio equivalent of skipping stones off the surface of a lake. If you toss a rock into a lake so that it hits the water at a high angle of attack, it will break the surface and sink. However, if it hits the surface at a very shallow angle of attack (*grazing incidence*), the rock will skip off the surface instead.

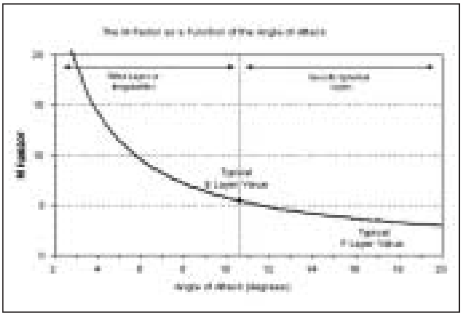


**Figure 2: *M* (cosec $\alpha$) varies with angle of attack. A smooth spherical ionosphere gives angles between 10 and 20 degrees. Tilted layers can produce lower angles, and very exciting results.**

So, in principle, the MUF approaches infinity as the angle of attack approaches zero! However, such small attack angles are geometrically impossible to achieve from a ground-based station 'illuminating' a *smooth*, *spherical* ionosphere. Under these circumstances, simple geometry would show that M H•3.4 at the F layer§. However, the operative key words here are 'smooth' and 'spherical', there is a lot more to say about that.

## How does TEP work?

It is not uncommon for north-south multi-hop F-layer openings on six metres to have no evidence of stations at the end of the *first* hop. This is often due

‡ This is a borrowed aeronautical term. I prefer looking at the angle between the layer and the wave direction, but physics texts normally use its cousin, the 'angle of incidence' – the angle between the vertical to the layer and the wave direction (90° minus the angle of attack). The equations change a little, but the answers are the same.

§ It is important to note that the angle of attack is *also* effected by the radiation angle of the antenna. Hence, a low angle of radiation actually *increases* the MUF for a given system.

to an F-layer ionospheric bulge along the magnetic equator known as the *equatorial anomaly*.

Within ±20° of the earth's magnetic equator there is a pronounced outward bulge in the ionosphere. Though generally regarded as an afternoon or early evening phenomenon, it occurs at other times as well. It is thought to be produced by a combination of a persistent thickening of the F layer near the equator, caused by the favourable angle of the Sun's incoming radiation, and another effect called the *afternoon fountain* [4].

The afternoon fountain pumps electrons upward from the E and lower F layers into the upper $F_2$ region, significantly enhancing its electron density. This effect appears to be the result of an interaction between the earth's magnetic field and west-to-east afternoon E-layer electric fields.

The equatorial bulge produces two regions, one north of the equator and the other south, where the ionosphere is systematically tilted and the electron density enhanced. This occurs at the points where the normally spherical ionosphere is bent upwards to form the

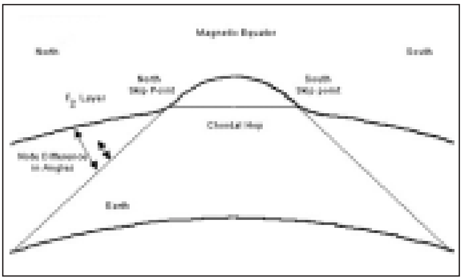


**Figure 3: A diagram of a transequatorial chordal hop off the tilted north and south skip points. These points each lie between about 0° and 20° north and south of the earth's magnetic equator and clearly cause night time TEP in the tropics.**

bulge. An upcoming wave will hit the tilted near corner at a shallower angle of attack than it would have with the usual spherical layer. This means that it will have a higher MUF for the same value of electron density. The M factor is larger than the nominal 3.4 – perhaps by quite a bit.

The wave need not be bent all the way back toward the ground. If it is bent enough to cross the equator and hit the tilted layer on the far side, *without coming back to earth*, the second tilted surface may bring it down to earth again. This skip from one corner of the bulge to another is referred to as a 'chordal hop'. It will produce a much higher MUF than a traditional skip point [5].

Since it really represents an $F_2$-layer 'hop and a half', the distance between endpoints can be a good deal greater than 5,000 km. It is also a low-loss path. Since the wave doesn't come down at the midpoint, it avoids two passes of D-layer absorption that normal double hop would have encountered.

In order for this form of propagation to function, *both* the north-side and south-side tilted regions need to be ionised enough to make the path work. If either one is insufficient to skip, then the whole path fails. Since there is little ionisation margin at six metres, the best chance for this to occur is when both sides of the magnetic equator are equally illuminated by solar radiation. This situation only occurs around the two equinoxes when the Sun is most nearly directly over the equator. As observed, the best months seem to be March and October.

So, the afternoon fountain causes enhanced electron densities and tilted layers to form within 20° of the magnetic equator late in the day or early in the evening. These conditions can persist long into the night with some contacts taking place long after local midnight (common for South America to Hawaii). They readily provide near grazing-incidence chordal hops at six metres.

On any given day, the bulge may not be exactly centreed on the magnetic equator. Typically, the two corners will be anywhere from 15° to 40° apart, and each will be somewhere within 0° to 20° from the equator on its respective side. In order to access these skip points, the stations must be within one-half F hop of the nearest corner – this is the 'TEP zone'.

As noted, for operators who have the good fortune to be in the TEP zone, the paths themselves do not have to be strictly north-south. In the simplest case, the two stations are on opposite sides of the magnetic equator, although they can be at a considerable angle to the north-south line, as noted earlier. All that is necessary is that the two corners be at usable chordal skip points.

In reality, many contacts made using TEP are a form of enhanced forward scatter, or even side scatter. If the stations are substantially east or west of each other (in geomagnetic coordinates) their signals will enter the region between the two chordal skip points at a considerable angle to a north-south line. When this happens, the signals may bounce back and forth *within* the north and south walls of the equatorial bulge, using the bulge as a *duct*.

East-west signals can be thought of as zigzagging north and south in the short term, but generally moving along in an east-west direction under the bulge until they find a weak point and break out. From there, they may go either north or south, depending on which side they find the 'door' out.

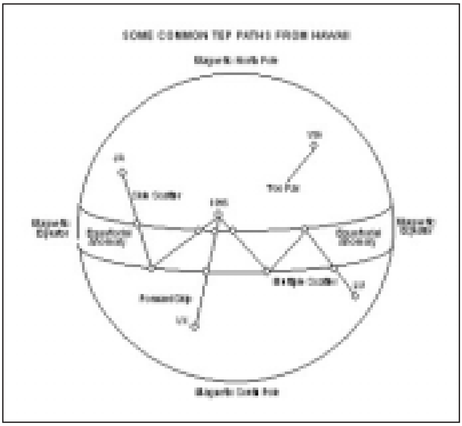


**Figure 4: In geomagnetic coordinates, Hawaii is nearly due north of Australia and these TEP paths transverse north-south paths often behave like conventional skip. Signals are usually clean and stable. East-west signals from Japan and South America can have heavy scatter modulation, at times resembling aurora, and display Doppler effects as well.**

A typical example of across-the-equator TEP is the night time pipeline that often exists between Hawaii and Australia (for example, Hilo and Townsville). Geomagnetically, this is nearly a north-south path. Usually signals are pretty clean, and quite strong (50 watts and a long wire will do).

On the other hand, it is not that uncommon for Hawaiians to hear Japan at the same time – and on the same beam headings as Australia – on what sounds like backscatter. Japan and Hawaii are on the same side of the equator and mostly east-west of one another.

Finally, propagation across the equator, but largely *along* the equatorial anomaly, can produce very strong signals, such as the link between Hawaii and South America. However, these signals can be strongly distorted indicating significant scattering within the duct.

### Cycle 23 Long-Path Observations

The peak years of Solar Cycle 23 offered a number of opportunities to observe long-path propagation at 50 MHz. The material that follows is the result of the analysis of more than 314 contacts and their accompanying temporal, geographic, geomagnetic, ionospheric, and solar circumstances. Table I shows the contributors to the data and the general areas they worked into.

**Table I: Sources of Data Used in the Study, 1999-2002**

| *Reporting* | *Working To:* | *Contacts* |
|---|---|---|
| S79MXU | South Pacific | 1 |
| KH8/NØJK | Africa, Middle East | 2 |
| 8R1/W7XU | Indonesia, Indian Ocean | 3 |
| FY/W7XU | Australia, Australian Maritimes | 8 |
| FO5RA | Africa, India, Middle East | 10 |
| CEØY/W7XU | India, Indonesia | 11 |
| 9G/W7XU | Japan, Philippines | >30 |
| KH6/K6MIO | Europe, Africa, Middle East | 249 |

These reported contacts were all initially thought to be long-path contacts by the reporting stations. However, each report was carefully reviewed as to beam headings and endpoint separations in an effort to discern whether they were, in fact, long-path circuits.

It became apparent that the contacts fell into one of three categories: long path via one of the Poles (TPL), long path via the magnetic equator (TEL), and short path via the magnetic equator (though over quite long distances). TPL was by far the most common of the three effects.

### Sampling in Time

Before proceeding, some caveats are in order. The data about to be presented do not represent a controlled scientific experiment. For example, the stations at both ends of the various circuits were not all operational 24-hours a day, seven-days a week. So some events, or *the lack of events*, were not observed. Another factor is that the events all occurred during the peak years of the cycle, so one cannot logically infer conditions during other phases of the solar cycle.

### Landmasses and Populations

The earth is mostly covered with water. Given the long-path distances, and what appear to be constraints on the propagation directions relative to a station, there may not be any stations available for some - otherwise technically possible - paths. Likewise, even on the world's actual landmasses, there is not a uniform distribution of amateur stations. Both of these facts will affect the sampling statistics; the conclusions must be viewed in light of these limitations.

### Transpolar Long-Path Propagation (TPL) – Really Stepping Out

Late in the evening on 9th October 1988, on the rapidly rising leading edge of Cycle 22, a six-metre station in Greece (SV1DH using the special six metre call, SZ2DH) worked a station in Japan (JG2BRI). What was especially amazing was that it was nearly midnight in Greece and SV1DH was beaming southwest, *away from Japan*, toward the southern 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 southward encroaching on the Antarctic near the South Pole, and then back north across the magnetic equator again and landing in Japan. The actual signal travelled about three-quarters of the way around the world! [6, 7]

## Now Where Did That Come From?

Yes – where indeed? While perhaps not the first transpolar six-metre long-path contact, this example demonstrates the profound propagation effects that can occur. One plausible answer points back to the power of grazing-incidence reflections.

## Looking at 2000-2002

The peak years of Cycle 23 provided a number of TPL openings to the delight of operators in southern Europe, Africa, the Middle East, India, Hawaii, equatorial South Pacific and elsewhere.

Perhaps the most widely known, if only because of the number of contacts made, were the series of spring and fall openings in 2000, 2001, and 2002 between Hawaii and the Mediterranean and Southern Europe – over the South Pole. However, during this same period of time, there were many other contacts taking place in other parts of the world. These included contacts between Ghana and Japan/Philippines (South Pole), Easter Island and India/Indonesia (North Pole), Tahiti and the Seychelles/Ethiopia (North Pole).

Figure 5 shows the relationship of the path endpoints for a sample of these contacts. The map is in *geomagnetic* coordinates, rather than geographic coordinates. The map consists of three 'earths'. The central one represents the location of the reporting station, while the upper one represents the corresponding station for contacts over the North Pole and the lower one represents the corresponding stations for contacts over the South Pole**.

*Notice that all of the stations, at both ends of each circuit, are in the TEP Zone[††].*

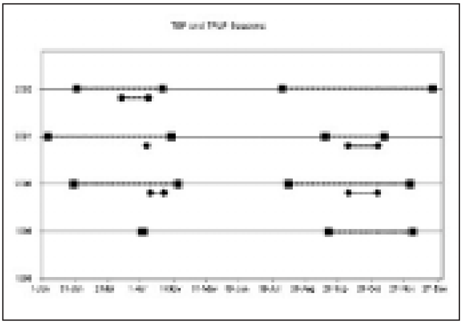


**Figure 6: A diagram showing the seasonal occurrence of both TEP and TPL as found in the KH6/K6MIO log. Bars with square ends indicate the range of dates over which TEP was in evidence from time to time. Bars with round ends indicate the range of dates during which TPL was sometimes observed.**

## Time of Year

Figure 6 shows a comparison of the seasonal occurrences of both TEP and TPL. There may well be other instances that occurred, but were not observed at that station. The seasonal effects appear to be essentially the same for TEP and TPL, near the equinoxes, centred on March and October.

** Due to the map projection, the actual great circle ground tracks are not accurately shown, especially at the poles.

[††] The TEP-zone boundaries are rough estimates. A few of the stations in the lower left of Figure 5 fall around the northern boundary, but these are actually in the observed TEP zone, as can be seen from Figure 1.

## Time of Day and the Presence of TEP

A typical Hawaiian TPL opening occurs near solar cycle maximum on an evening when TEP is already in evidence over the usual paths (e.g. VK4), but the TEP is generally sporadic and not particularly intense or widespread. Quite

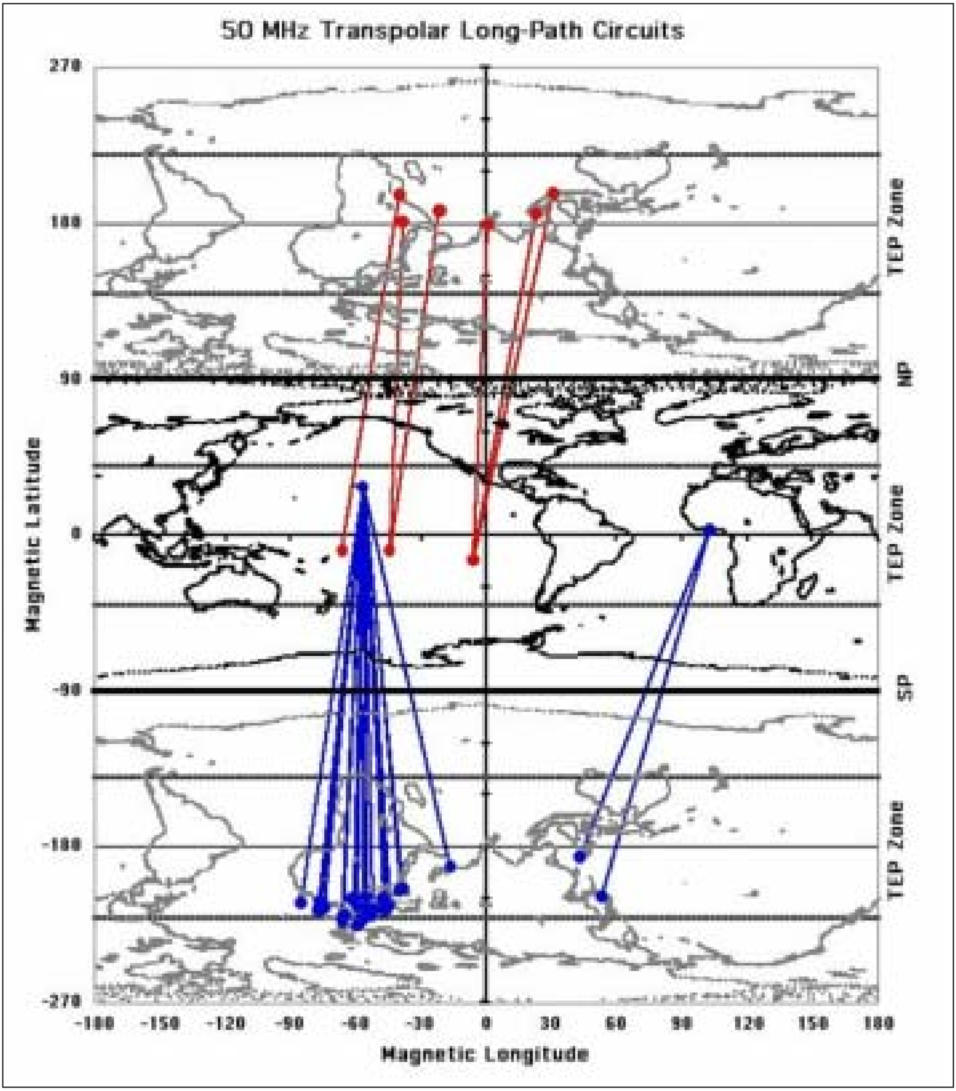



**Figure 5: A world map in *magnetic coordinates*. It shows 36 typical TPL contacts made in 2000-2002. The *middle* third shows the reporting stations; the *upper* third, the stations worked over the North Pole; and the *bottom* third, the stations worked over the South Pole. The curly lines in each third represent the approximate limits of the TEP zone. The map projection distorts the actual signal path between the respective stations, especially near the poles. But, it accurately shows the endpoint relationships.**

strong backscatter coming from headings of about 195° is very common, suggesting lots of ionisation and tilted layers. Television carriers on 48 MHz are heard at about the same headings, usually with many offsets, often quite strong. Sometime within an hour or two of midnight, some very weak signals may show up on 50.110 MHz. After a few attempted calls, signals improve, callsigns are finally worked out, and the contacts begin into southern Europe.

Usually, signals are very weak, and power is quite helpful. However, on a few occasions signals are enormous (e.g. 50 watts to an indoor wire dipole in Portugal working Hawaii), and even QRP is possible.

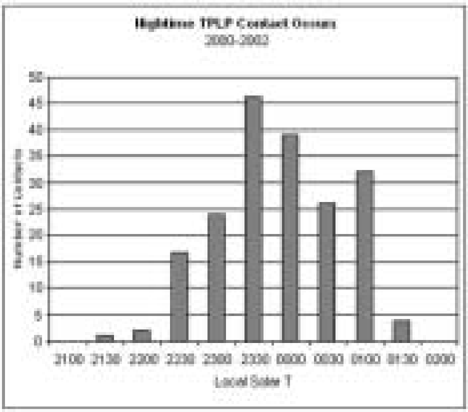
Examination of the Hawaii and other data show that there is a clear correlation between the occurrence of the contacts and the station's Local Solar Time (LST). This is particularly in evidence when one calculates the actual solar time at the latitude and longitude of the stations involved, and not just the time held by clocks in the entire time zone.

On the night time side, they occur within an hour or two of local midnight. Since the paths extend more than halfway around the world, one would expect that if it were midnight at one location it would be near midday at the other. In fact, on the daytime side, they occur within an hour or two of 11:00 LST. Figure 7 shows the distribution for the Hawaii-Mediterranean path.

This pattern appears to be independent of the station's location, and independent of whether the path has gone over the North Pole or the South Pole.

However, the events seem to be anchored in the Night time TEP. It is important to note that, for the Hawaiian circuits, I have *no* reported cases of TPL when TEP was *not* actively present around the time of the night time side opening.

While it was not uncommon to hear a few Australian stations coming into Hawaii before, after, and occasionally during the TPL, the Australians were not



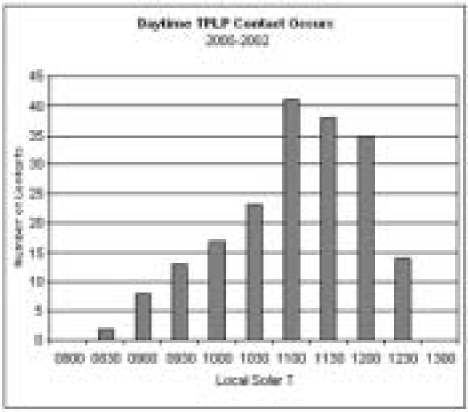




**Figure 7: This frequency of occurrence histogram estimates the likelihood of TPL as a function of time of day. The average time on the night time side is 23:51 LST, and on the daytime side it is 11:01 LST. Local solar time is that actual solar time at the station, not the Time-Zone clock time.**

hearing the Europeans at all, to their frustration. Interestingly, the same was true for stations in New Zealand and the South Pacific.

Except for normal TEP stations on the other side of the equator (who were not hearing the TPL), during the Hawaiian openings, *I did not observe a single instance of signals from any intermediate point*, despite the fact that the signals travelled the equivalent of many F-layer hops.

The TPL did not appear to have come down to earth anywhere in between the two endpoints.

It would be proper to ask whether the Hawaiian contacts were only made at night. Well, not quite. All except three contacts, were at night. During the daylight hours, there were two contacts with Oman, and one with Italy, all made about 08:30 LST on various dates. These three were all on east-of-south headings, rather than on the night time west-of-south headings, but more on this in the next section.

On the night time side, the propagation always occurred in the latter part of the typical period for evening TEP, and some TEP was in evidence.

## Antenna Headings

While the expression 'over the poles' has been used frequently here, that is really shorthand for 'near the Poles'. The real poles of interest here are probably the *geomagnetic* poles, rather than the geographic ones. The geographic and magnetic poles are offset by about 11° of latitude.

In the Hawaiian openings, the night time openings were almost always close to the long-path great circle headings to Europe. These headings are about 15-20° west of south. Signals travelling on these great circles will reach about 70° S geographically before heading north. This takes the path very close to the South Magnetic Pole (65°S, 139°E geographic, in 1988).

The observed Hawaiian morning openings had headings of about 160°, again quite close to the expected great circle route for Oman‡‡, about 20° east of south. It was tempting to conclude that night time openings systematically went somewhat west of south, and daytime openings went somewhat east of south. Comparing these observations with the data from stations in other parts of the world, the indications are that the characteristics seen in Hawaii were typical.

*All of the TPL contacts reported occurred such that the daytime station was always beaming somewhat east of the pole, and the night time station somewhat west of the pole*

Notwithstanding, the Hawaii log reveals that during a number of the night time openings, strong 48 MHz TV carriers were heard from the 160° heading, but no stations appeared to be present (there are very few in that part of the world, and it was well into the work day). It is possible that this east versus west phenomena was just a result of the landmass and population effect.

Although the observed headings seem to vary little, nevertheless, a few

‡‡ The Italian contact was certainly an anomaly. It was heavily modulated by multipath and very weak. It occurred less than a minute before an Oman contact, which showed none of this. I am quite sure that Italy in the morning was a case of sidescatter as described earlier for TEP. Except, scattering was happening on the other side of the world!

stations were worked whose g*reat circle* bearings deviated from the above headings by as much as 30°. It is not clear whether, in the heat of rapid-fire DX exchanges, the antenna heading could have improved the signal if adjusted, or if 'steering' of the signal was occurring in the ionosphere, with modest great circle deviations.

I suspect the answer is that a combination of both was happening. Certainly, when signals were 'good enough', the tendency was to work what was there. On the other hand, there was at least one unusually intense opening, where I found the 'best' heading started at 200° but swung as far east as 170° and then back again. During this excursion there was no clear difference in the geographical location of the stations being heard, that is, it was not obvious that the footprint was changing significantly at the same time.

Generally, the paths involve offsets from north or south, but not more than about 20°.

## The Path Footprint

The characteristics of the path footprint are shown by the latitude and longitude changes that occur between the location of one station and the other. Table II shows the average change in latitude and longitude with respect to the reporting station, along with some measures of variability. There are 14 North-Polar contacts, based on several reporting stations and paths, on the right, and 234 contacts (all the Hawaii-Europe path) on the left, where at least the grid squares of both stations, and hence, the approximate endpoint latitudes and longitudes could be known.

Both longitude tables are in good agreement with the average change being in the 193°-197° range. They also agree very well regarding the longitude range about the average. Both show a standard deviation of 10° and quite similar values for the minima and maxima.

The centre of the 'other-end' footprint would be about 194° of longitude away, with a core footprint width of ± 10° with some endpoints as far as ± 30° from the centre.

**Table II: TPL Footprints Relative to the Reporting Station, 2000-2002**

| | North-Polar Paths Contacts = 14 | | South-Polar Paths Contacts = 234 | |
|---|---|---|---|---|
| | **Lat** (deg) | **Lon** (deg) | **Lat** (deg) | **Lon** (deg) |
| Average Change | 196 | 194 | 242 | 193 |
| Standard Deviation | 6 | 11 | 4 | 10 |
| Minimum | 188 | 187 | 233 | 166 |
| Maximum | 214 | 216 | 250 | 222 |

The latitude changes between the two tables are a different story. Here we see a difference of almost 50° between the averages, although the standard deviations are very similar. One notes that, compared to the South Pole, there were very few North-Polar contacts. Figure 5 suggests a possible explanation for both the number of contacts and the latitude differences: the landmass/population question. If the North-Polar paths do have the same range of latitude changes as the South-Polar paths, the footprints of the *observed* North-Polar paths would fall mostly in the Indian Ocean, with few stations to work, and badly skewed statistics.

## Footprint Changes in Time

There was some question as to whether there was any systematic trend in the centre of the footprint as a function of time, either during a given opening, or during the season. The results were inconclusive. Although there are some weak indications of trends in the footprint centre during a single night's operation, there was no consistent pattern from night to night, nor with the progression of the season.

## Solar-Terrestrial Conditions

It is clear that solar and geomagnetic activity have an important effect on the occurrence of TPL. A careful examination of these conditions during all of the reported TPL episodes confirmed the anecdotal information that a quiet geomagnetic field, in the presence of elevated solar activity, appear essential.

Comparisons were made to several geomagnetic parameters and the conclusion was that TPL seems to be sensitive to all of them, as shown by the Figure 8 analysis of the KH6/K6MIO data, using the number of contacts in a given opening as a measure of propagation 'quality'.

TPL appears to be *most* sensitive to the high-latitude (polar) K index, where $K_{hi}=0$ was the dominant value for the South-Polar path. The planetary K index, $K_p$, was also low, but the propagation was tolerant of somewhat higher values (averaging about 1).

94% of the Hawaii contacts were made while $K_{hi}=0$. In every case, $K_{hi}$ and $K_p$ were 3 or less.

The *daily* 10-cm flux ranged from 141 to 229, with an average of 181. However, the *smoothed* flux was confined to the rather narrower range of 168 to 196.

*37% of the contacts occurred with daily fluxes between 141 and 188. As with other $F_2$ propagation forms, elevated smoothed values (168-196) seem more significant than the daily values.*

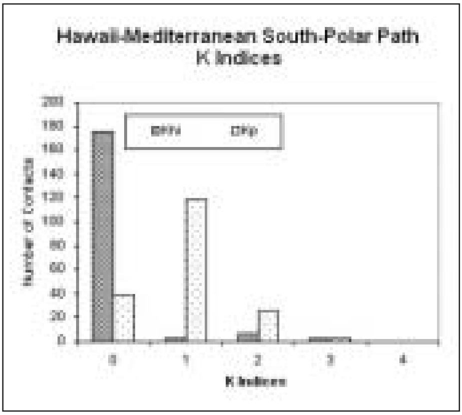



**Figure 8a: South-polar TPL appears to require very quiet polar magnetic conditions and fairly quiet global conditions.**

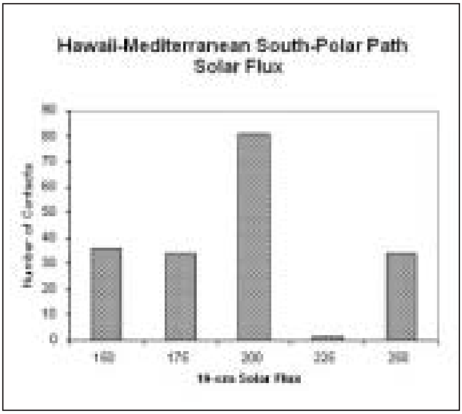



**Figure 8b: Although favouring solar flux around 195, TPL appears to be fairly insensitive to the exact flux, occurring throughout the 150-250 range.**

Though not shown here, the same analysis of the South-Polar contacts from Ghana to Japan and the Philippines look almost identical to the Hawaii data.

As with the statistics for the path footprints, the 14 North-Polar contacts in the data are anomalous. As with the South-Polar paths, the $K_{hi}$ indices were about one point less than the $K_p$ indices, *however* the median $K_{hi}$ was 2, with a number of contacts made at 4. The mean solar flux value was 229. It must be borne in mind that there is really very little data in this case (14 contacts versus over 220 for the South-Polar case), which may have skewed the statistics. In addition, the indications are that the 14 contacts correspond to the 'edges' of the nominal footprint, rather than the centre.

## The TEP Connection

There is strong evidence to support the proposition that there is an essential connection between TEP and TPL:

1. TPL stations at both ends of the circuits are in the TEP zone.

2. The TPL equinox seasonal effect is the same as TEP, principally March and October.

3. TPL normally seems to occur only when some evidence that TEP is present.

An additional piece of evidence is seen in Figure 9. It shows that the TPL Mediterranean footprint from Hawaii is also an excellent match to the TEP Mediterranean footprint from southern Africa. Note that the great circle path coming from Hawaii goes north from South Africa and slightly west.

The Hawaiian TPL signals came down in just the right spot to suggest that the last hop was actually TEP!

## Close, but no cigar

It is interesting to note that there were a few short openings between Hawaii and South Africa in 1999 and 2000. South Africa is almost exactly halfway around the world from Hawaii, and it is on the *same* great circle as the TPL path from Hawaii to Mediterranean Europe.

Like TPL, they occurred during the solar-cycle-peak years, with comparable solar flux levels, during the TEP season, when some TEP is present.

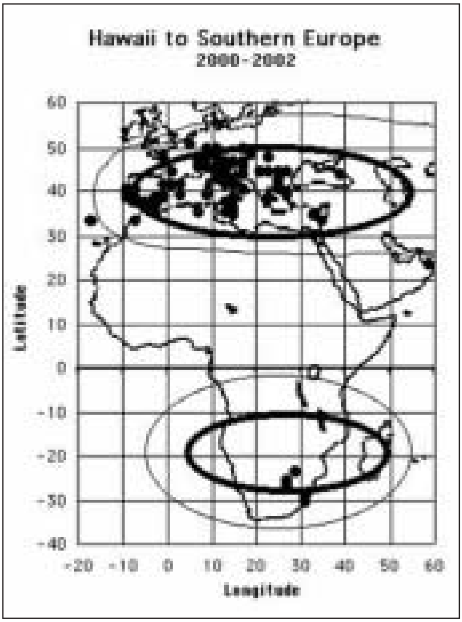



**Figure 9: The footprints of the Hawaii TPL to the Mediterranean, and the non-long-path South Africa contacts. Dots show the Hawaii contacts. The ovals are the Figure 1 TEP footprints for the south African-Mediterranean path. These strongly suggest that both Hawaii propagation forms are related to some kind of TEP insertion or launching effect.**

However, unlike TPL, the K indexes were systematically 4 or higher.

This appears to be some form of propagation *in between* TEP and TPL. It is much *too far* to be normal TEP. On the other hand, although the path crosses through the South Magnetic Polar region, it is *not* TPL. It is *not* long path of any kind, because it is a few hundred kilometres short of the halfway point around the world.

This all suggests that medium to high values of K bring the polar signals back to earth in South Africa, while low values of K may allow them to continue on to the Mediterranean.

Figure 9 shows another curiosity, during these short-path openings to Africa, the Hawaiian signals *land* within the *starting* footprint for southern Africa TEP to the Mediterranean. That is to say, when K is high, the Hawaiian signals *end* at the point that the South African signals *start* from, on their way to Mediterranean TEP. But, when K is low, these signals seem to pass by South Africa and *land* where the South African TEP lands, in the Mediterranean basin.

This latter point, together with the observation that TPL does not appear to come down to earth anywhere in between the two endpoints, suggests that the Hawaii-South Africa path and the Hawaiian TPL signals have crossed the South Magnetic-Polar region at about the same point; but that in the first case, they were directed downward, and in the second case, they were directed to (another) chordal hop.

## How Might TPL Work?

Consider the following scenario. Suppose that it is during the spring or fall equinox period, and that TEP is present. An upcoming wave from a transmitter within the TEP zone illuminates a range of the curved surface on the near-side TEP skip point. That wave is deflected, not at a single angle, but over a range of vertical angles as shown in Figure 10 (based on the, technically more correct, refraction model for skip).

A whole range of rays, at various angles, would proceed across the equator and hit the curved surface at the far-side skip point. Some rays would be bent enough to go back down to earth as normal TEP, *accounting for the fact that some TEP is present around the TPL openings*. Some rays would be bent very little and escape into space.

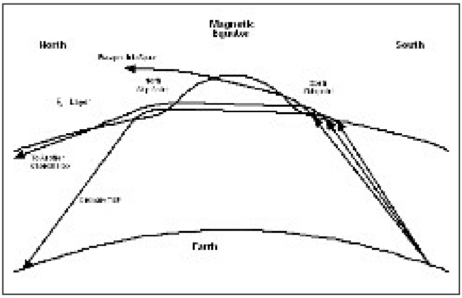


**Figure 10: Refraction in the equatorial anomaly of rays transmitted at slightly different angles can lead to some parts of the signal escaping from the $F_2$ layer, or returning as TEP, *or* being injected at small angle of attack to produce further chordal hops.**

In between these two extremes, some rays would be bent back below the $F_2$ layer but not enough to reach the earth. These rays would go forward until they hit the underside of the $F_2$ layer again, taking what is now a second, high-MUF chordal hop.

The significant point is that, the chordal hop from the equatorial anomaly has *injected* a fraction of the signal energy into the ionosphere at such a shallow angle that, even in the case of a smooth spherical ionosphere, the wave may now continue skipping around the earth in a series of high-MUF chordal hops.

In a smooth, spherical ionosphere, this signal would be trapped forever in a series of grazing incidence hops, and never returning to earth. But, in reality, it will eventually encounter the equatorial anomaly on the *other side* of the earth. There, the 'injection' process could be reversed and a fraction of the arriving signal sent back down to the earth on the far side of the magnetic equator, as if it were TEP – but from very far away.

This would mean that stations on the north side of the equator could communicate over the South-Polar region with stations north of the equator on the other side of the earth. Stations south of the equator could communicate over the North-Polar region with other stations south of the equator on the other side of the earth.

Figure 10 also explains why the station on the right hears both TEP and TPL, and the TEP station on the left does not hear the TPL at all – it goes completely overhead.

Consider the practical example of a path starting in Hawaii and ending in Spain. The long-path link passes southwest from Hawaii, between Australia and New Zealand, the western edge of Antarctica near the South Magnetic Pole, Africa, and finally to Spain. The key factor here is that the first and last hops are off the equatorial bulge, as suggested by Figure 11.

If conditions are right at both ends (and in the middle) the chordal hop can be shallow enough that, when bouncing off the southern edge of the anomaly, it never comes down to earth. Instead it continues to bounce like a rock skipping across a lake as the curving ionosphere keeps coming back to meet it again.

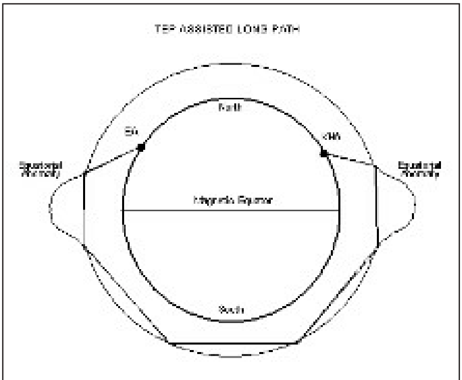



**Figure 11: TEP can provide the launching points for shallow attack angle grazing hops that cover long distances, with higher than normal MUFs and low absorption. At such times, long-path can be a superior mode of propagation.**

If the same conditions seen south of Hawaii also exist at the magnetic equator over northern Africa, the shallow skipping wave will finally be bounced down *out* of the ionosphere by the northern edge of the bulge, landing in Spain. Since there is little D-layer absorption and the MUFs are very high due to the angle, the long path is actually possible, while the short path, with its entirely traditional earth-sky-earth hops, is completely out of the question.

***Other Possibilities -*** This picture is probably over simplified, and does not contain all Nature's of subtleties. There may well be other kinky things thrown in.

For example, there are known $F_2$-layer tilts near the *magnetic* North and South Poles in the vicinity of geographic latitude 70°-80°, that may play a role in getting the signal across the pole [8]. There can be bumps that look a lot like the TEP bulge, but on a smaller scale. These could pass a chordal hop through the polar region.

It is also true that near the equinoxes, the signals cross the day/night terminator (the grey line) near the South Pole at nearly right angles, where there are also tilts created by the day/night transition. Any or all of the above effects may play a role.

Another related possibility is that the trip over the Pole may be the result of ducting effects, such as a radio frequency 'whispering gallery' [9].

## Transequatorial Long Path – another way to go far

In addition to TPL, there is at least one other kind of long path. This phenomenon occurs more or less along the equator – Transequatorial Long Path (TEL).

In April 2000 a station in American Samoa (KH8/NØJK), beaming east, contacted a station in Jordan at 0700 LST. A few months later in October 2000, between 0600-0800 LST, a station in French Guyana (W7XU), also beaming east, worked a number of Australian stations in Queensland and the Northern Territories. The later contacts happened during a time that there was a daytime $F_2$ opening between French Guyana and Europe and the Mediterranean. The beam headings were 045° toward southern Europe.

Samoa, Jordan, French Guyana, and Queensland/Northern Territories are all in the TEP zone, but the great circle routes were not transpolar at all. In both cases, the mostly eastbound signals from the west stayed in the TEP zone, crossed the magnetic equator once into darkness, landing at the other end of the circuit between about 2000-2100 LST. All the contacts were definitely long path, traversing longitudinal distances of 190-206°.

## Time of Day

Since the path was between a daytime station on the west working east to

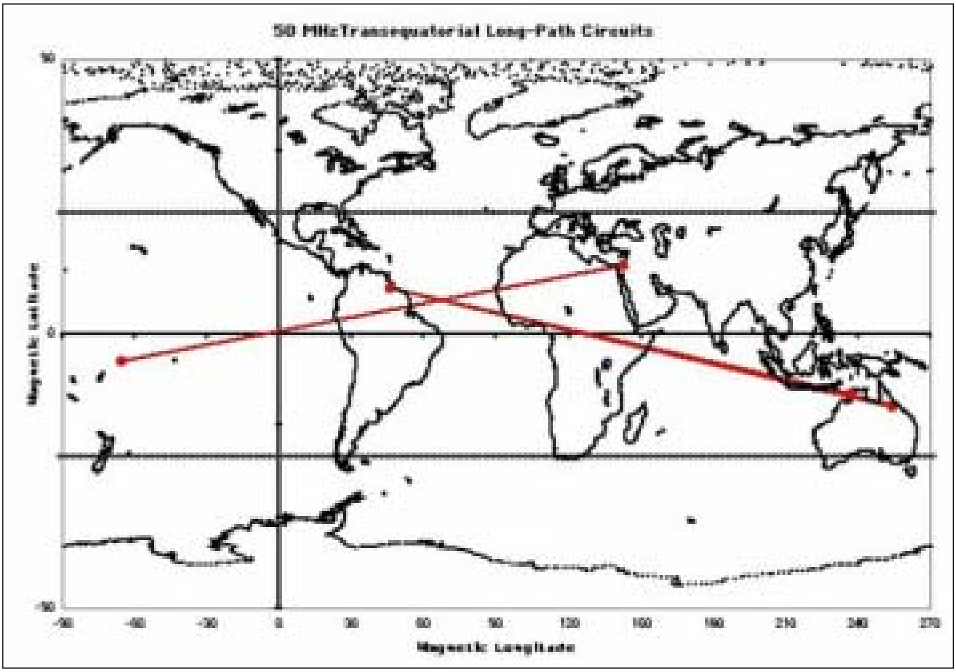



**Figure 12: This map shows three examples of TEL (VK8 and VK4 overlap). The west-most station in each case is in daytime and the east-most station is in night time. Note that only one crossing of the magnetic equator has happened in each case. The map projection distorts the actual great circle routes and headings.**

a night time station, where the night time path was apparently provided by normal TEP, one would expect to see a normal TEP time-of-day pattern for the night time station. Figure 13 shows that this is very much the case for the seven identified TEL contacts.

For the daytime side, the requirement is really that the station be far enough west that the contact actually stretch more than halfway around the world (or else it would not be classified as long path). Thus, one would need at least a 12-hour time change.

If the night time pattern is early evening, then the daytime pattern must be early in the daylight hours. Figure 13 shows that this is indeed the case, with most of the contact times clustering about 0700 LST.

## How does TEL work?

There is evidence that there may actually be *two different mechanisms* at work here.

In the first case, as in the discussion of Figure 4, fairly long east-west TEP is quite common. The paths from South America to Europe and Hawaii to South America are typical examples. These particular circuits are more or less along great circles. They cross the magnetic equator at very shallow angles. The path stays within the north-south boundaries of the equatorial bulge for a significant fraction of the trip. The end-to-end path length is typically 10,000-12,000 km. This is about 60% longer than traditional north-south TEP, although it is far short of long path (the half-way distance is about 20,000 km).

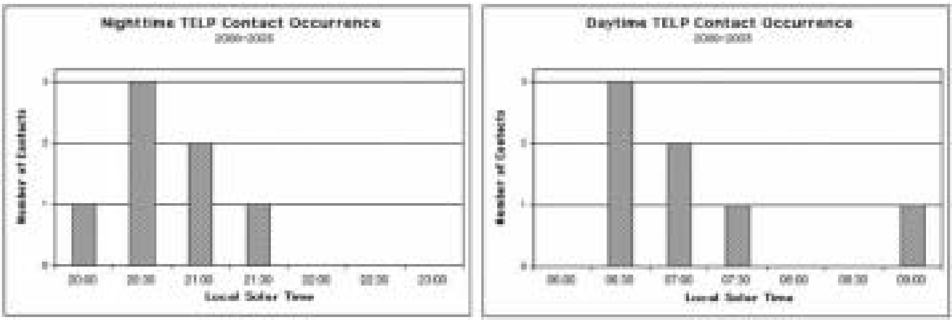



**Figure 13: The frequency of occurrence of TEL as a function of Local Solar Time shows that the night time (east-end) station has the typical early-evening TEP pattern. The daytime (west-end) station must be up early in the morning in order to be far enough from the night time station to produce long-path.**

## Solar-terrestrial conditions

There were only seven instances of true TEL in the data. Generally, the K indices were much higher than for TPL. Six of these contacts occurred when the mid-latitude index $K_{mid}$ = 3 and $K_p$=4. The remaining contact occurred when the values were 1 and 2 respectively.

It typically occurs in the mid-to-late evening hours on the *east end* of the circuit and in the afternoon on the daytime, west end of the circuit. In this regard it resembles TEL, except that, being a shorter path; the daytime end is fewer time zones away.

Thus it is afternoon, rather than first

thing in the morning, on the west end. It is entirely possible that some TEL is an extreme case of this same east-west TEP effect.

On the other hand, some of the contacts are consistent with a *daytime multi-hop $F_2$ link that connects to a final, classical night time TEP hop*.

The multiple $F_2$ hops are probably enhanced by the normally more strongly-ionised north and south equatorial-anomaly ridges, as the signal moves eastward. However, it may well leave the TEP zone altogether for a short while before the great circle brings it back south again.

The characteristics are that the daytime station will be looking east into an active $F_2$ opening slightly to the north, if north of the equator, and slightly south if the daytime station is south of the equator. To get the longest throw, early morning is best (0600-0900 LST).

If conditions are right and the $F_2$ hops go far enough, a link to TEP from the daytime station's side of the equator to TEP across to the other side of the equator can occur. Unlike TPL, normally there is only one magnetic equator crossing (nearer the eastward, night time station).

## Almost, but not quite

Like the first form of TEL, not all $nF_2$-TEP links are long path. It just depends on how far the multi-hop $F_2$ can go before finding the night time TEP zone. Examples of long-throw *short paths* are Hawaii to St. Helena Island and Tahiti to the Arabian Peninsula. Not long path, but probably the same propagation mode.

Altogether there were 18 cases of very long short-path contacts linking to TEP one way or the other – very much like TEL, but not long enough. The contact times on the night side ran from 2000 to 0000 LST. On the day side, they ran from 0900 to 1400 LST. These generally occurred with $K_{mid}$ between 0 and 3, $K_p$ between 1 and 3, and the solar flux between 157 and 217.

## Discussion and Summary

At the outset of this study, the plan was to try to characterise the transpolar form of TEP-enabled long path (TPL) based on the observations and perhaps to offer some plausible explanations for the effect. However, it became evident there was a second form (or forms) of TEP-enabled long path, which I lumped broadly into the transequatorial classification (TEL).

## First, some caveats

While there were hundreds of contacts in the TPL database, there were just *seven* in the TEL category, along with only 18 contacts in the apparently related long-reach short-path mode. As a result of the small number of samples in the TEL data, one should be cautious about drawing very strong conclusions about its characteristics.

There were only 14 contacts for the North-Polar TPL case. Consequently, there may be too few to describe the statistics of the effect. There are also significant landmass effects. North-Polar TPL connects stations in the magnetic Southern Hemisphere with stations on the other side of the earth but *also* in the magnetic Southern Hemisphere. The problem is that, to a much higher degree than the Northern Hemisphere, the Southern Hemisphere is mostly water! So, the spatial distributions of the expected footprints are not well sampled either.

## TPL

The TPL contacts noted in 2000 - 2002 occurred between stations that were both in the TEP zone, essentially on the same side of the magnetic equator. It appeared as if they were working TEP across the equatorial anomaly – except that they were linked to each other on the far side of the equator by a very long-range propagation mechanism that involved a more or less great-circle path near one of the poles.

The observational evidence is generally consistent with a model calling for the TEP mechanism to inject a portion of the upcoming signals into shallow-angle of attack chordal hops on the far side of the equator. However, this is really not certain.

For example, the day-night terminator for these paths was being crossed at nearly right angles in the vicinity of the respective Pole. It is possible that a Grey-line hop may have played a role there. Such a picture calls for enough ionisation at the day side of the anomaly to allow some form of morning TEP.

Another issue is with conditions on the daytime side of the circuit. Morning TEP is not very common, but one should consider Figure 10, with signals travelling in the opposite direction. Here, the incoming day-side wave is arriving *from* a chordal hop, *not* the earth's surface. Thus, it needs a much shallower refraction angle to get back to earth, than a normal TEP signal. Thus, the day-side electron density would not have to be at the higher night-side levels in order to redirect the signal back to earth.

In any case, this requires the coincidence of favourable conditions over a very long path, and it is no surprise that it is relatively rare.

***Where can you get TPL?*** – This is a matter of looking at where paths start and where they end and then asking whether there will be anyone there at the other end of the path.

The experience is that both stations must be in the TEP zone. Generally, the paths involve offsets from true north or true south, but not more than about 20°. The centre of the 'other-end' footprint would be about 194° of longitude away (east or west), with a total width of ±30°. The latitude change can range from about 190° to 240° on centres with a range of ±15° or so.

If one takes a look at the Figure 5 world map and picks a proposed starting location in the TEP zone in the central 'earth', then the possible TPL path options would be those areas in a wedge about ±30° from the same magnetic longitude in the upper or lower earth, between the TEP-zone lines. One should be looking at paths that cross the magnetic equator near the starting station and again near the ending station.

***North-Polar TPL Route*** – Recalling that this is a Southern Hemisphere to Southern Hemisphere path, a look at Figure 5 will show that the only significant landmasses in the southern TEP zone are Australia and the southern halves of South America and Africa. Australia and Africa mostly match up with Atlantic and Pacific Oceans, respectively.

Nevertheless, North-Polar TPL ought to be possible between the vicinity of the northern strip of Australia and south eastern South America (southern Brazil, Paraguay, Uruguay, and north eastern Argentina). If this were to occur, one would expect the South American end would be in local early morning and the Australian end near local midnight.

| Table III: Summary for Conditions for TPL and TEL | | | | |
|---|---|---|---|---|
| **Season** | March ± 1 mo. *and* October ± 1 mo. | | | |
| | **Transpolar Long Path** | | **Transequatorial Long Path** | |
| **K Index** | $K_{w}$, $K_{p}$ d•2 | | $K_{md}$ d•3, $K_{p}$ d•4 | |
| **Solar Flux** (10 cm) | Daily e•150 | Smooth e•165 | Daily e•175 | Smooth e•165 |
| **Station Location** (in the TEP Zone) | North of M. Eq. | South of M. Eq. | North of M. Eq. | South of M. Eq. |
| **Daytime End** | 1100 LST±2 hrs. | | 0730 LST±1.5 hrs. | |
| Antenna Heading | SSE 160°±20° | NNE 020°±20° | ESE 120°±20° | ENE 060°±20° |
| **Night time End** | 0000 LST±2 hrs. | | 2030 LST±1 hr. | |
| Antenna Heading | SSW 200°±20° | NNW 340°±20° | WSW 240°±20° | WNW 300°±20° |

Referring back to Figure 5 will also reveal a number of South Pacific islands that have plausible paths to southern parts of Africa and South America.

***South-Polar TPL Route*** – This approach connects the northern TEP zone to its northern counterpart on the other side of the earth. Figure 5 suggests that circuits from Southeast Asia to Central America and northern South America should work, along with the well-known Hawaii to Mediterranean path.

### TEL

Whether extreme east-west TEP or multi-hop $F_2$ to TEP links, TEL seems to be rarer, since it appears to depend on the long reach of $F_2$ mechanisms for much of the propagation distance. Consequently, it requires not only a geometrically usable connection to TEP on the eastward end of the circuit, but also good daytime $F_2$ conditions as well. Nevertheless, it can provide very long paths in a generally east-west direction.

A consequence of the day-to-night connection is that the daytime station is aiming generally east and the night time station is aiming generally west. In all probability, the $F_2$ hops are aided by the enhanced ionisation along the equatorial-anomaly ridges. If good $F_2$ conditions exist beyond the TEP zone, the path may leave the zone and re-enter it again as it approaches the other station.

### Long-throw transequatorial short path

The east-west TEP and $nF_2$-TEP modes are fairly common within the TEP zone. They appear to result from the same phenomena that cause TEL, except that the links are shorter. Like TEL, the daytime station is aiming generally east and the night time station is beaming generally west.