Between Dusk and Dawn

Exceptional propagation on 60 metres

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PROLOGUE

Observations, on which this article is based, took place well before the disappointing decisions regarding 60 metres in ZL and VK. In my opinion, the reasoning behind decisions not to allocate 15 kHz and 15 W EIRP, is very difficult to follow. Such an allocation would have negligible consequences for primary users, whilst interference from pirates, over the horizon radar and from ever increasing man made noise, surpasses any negative effects from an allocation by far. If clean spectrum is so important, why is addressing interference not on top of priority lists of governments?
I doubted many times whether I would publish the results of my research. Because why should we give away knowledge to governments that act incomprehensibly?
Still, I think it's good to show that opportunities to gain knowledge about propagation are missed by not assigning the 60 meter band. Publishing also demonstrates that amateur research is beneficial to the general interest. We, as a community, should emphasise this aspect. I would strongly encourage amateurs to consider methods to systematically gather propagation data. WSPR is an excellent example. What is still missing, is a global network of receivers and it might be a suggestion to develop such a network. Supporting this kind of initiatives should be a top priority for radio societies.

INTRODUCTION

The author became intrigued by ionospheric propagation during the late 70’s of the previous century. Having read about good propagation on the six metre band during the peak of solar cycle 19, he became curious and he decided to build a 50 MHz converter. No amateur signals were heard, until March 1979, when hearing the ZS6PW beacon from South Africa was a tremendous surprise. During the peak of solar cycle 21, various openings were witnessed. A logbook of observations was kept and audio recordings were made.

Permissions to transmit on six metres were granted to radio amateurs in The Netherlands in 1988, provided that we would report their findings. That was the start of a very interesting journey, discovering much about the ‘behaviour’ of the 50 MHz band. Collected data was analysed and two reports were written on the subject and presented to the government on behalf of the amateur societies.

In December 2015, Dutch radio amateurs got access to the 5 MHz band. Around that time, the 2015 World Radio Conference decided to allocate a small segment of the 5 MHz band to the amateur service. Over time, many countries implemented the allocation.

Interesting propagation properties were discovered, like signals strengths peaking, apparently around sunrise and sunset. With series of transmissions during longer periods, measurement samples were gathered, demonstrating that signal strength enhancements show consistent overall patterns.

More research followed, looking for explanations for the signal strength peaks. It was also found that during these peaks, the transmission loss (path loss) between transmitter and receiver is substantially lower than propagation models predict. These grey line "enhancements" were already known to radio amateurs and discussed in various publications. However, the suggested explanations were unsatisfactory. The author decided to dig deeper. This article summarises the findings.

The author wishes to thank all those who contributed to the research, in particular 3D2AG, VK7BO, ZL2BH, ZL2CC, ZL4OL and PG0DX, for all transmissions, reports, enthusiasm and very valuable input for this study.

Supplementary information can be found under the tag "E-F valley" on the website of the author: http://www.dx.nl

BRIEF DESCRIPTION OF THE IONOSPHERE

It can be assumed without doubt that ionospheric properties are responsible for the observed signal enhancements. A brief summary will follow next.

General backgrounds

A research paper, written in 1934 by Kirby, Berkner and Stuart, provides an interesting historical summary. The success of Marconi in 1901 with transatlantic radio contacts aroused a lot of attention from scientists. In 1902, Kennely published the first suggestion of an ionised upper region in the atmosphere, responsible for rays to travel beyond the horizon. The theory about propagation of light waves, as presented by Lorenz in 1909, was applied in 1912 by Eccles and in 1924 by Larmor, who reasoned that waves were bent by refraction, rather than reflection.

In 1925, Appleton, Nichols and Schelleng pointed out that refraction and absorption in the ionosphere is considerably modified by the earth's magnetic field. Nichols and Schelleng showed that waves would be split by magnetic double refraction and that the two resulting components behave differently. A few years later, Breit and Appleton described the quantitative effects and Appleton gave an equation for the index of refraction.
These papers provide the foundation for a theoretical discussion of the action of the ionosphere and much of it still stands today.

During the 1920's, various workers reported evidence of the ionosphere, using radio sounding techniques. Over time, more experiments and improved techniques led to better understanding of the behaviour of the ionosphere. A simplified representation states a stratified model with an absorbing D-region and two "reflecting" layers (E and F) above. The D-region is found between circa 60 and 90 km. The E layer height is about 100 km and the F layer is found at roughly 250 km.

Many factors affect the properties of the ionosphere. Solar radiation is the prime ionising force. Diurnal and seasonal variations as well as the 11-year solar activity cycle lead to considerable differences. The magnetic field of the earth further affects the ionosphere. Sudden disturbances resulting from solar eruptions can have remarkable effects and sporadic ionisation can cause specific variations.

The ionosphere is very dynamic and changes continuously. Wave propagation follows these changes and transmission paths are very dynamic.

Ionospheric propagation around 5 MHz

The degree of ionisation of the E and F layer differs considerably. The ionisation of the E layer follows the zenith angle of the sun and the E layer disappears almost immediately after sunset. The recombination of electrons and ions in the F layer is slow, so that the F layer gradually disappears during the night. Practically speaking, the F layer is most important for the 5 MHz band while the E layer generally is of lesser importance.

A distinct disruptive feature is absorption in the D-region. This region generally does not return rays like the E or F layer above, but acts as an insulation blanket and significantly weakens signals. The absorption reaches its maximum around midday, with the highest rates during the summer. Frequencies around 1000 to 1400 kHz are affected most, slowly decreasing on higher frequencies. D-region absorption diminishes at night, which is why low frequency bands are best during dark hours, taking advantage of the F layer that is still present.

Figure 1 shows a scatter plot of signal to noise ratio versus time (UTC) for signals from England to The Netherlands.

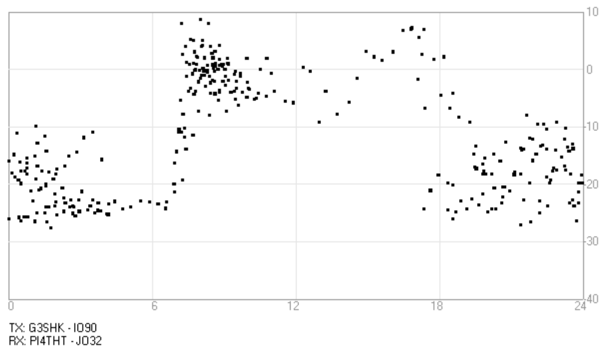

Figure 1 - G3SHK to PI4THT - February 2018
The plot shows the sudden amplitude rise at sunrise and the decay after sunset.

The plot is typical for short range contacts. After sunset, the F2 ionisation decays and as soon as the ionisation becomes insufficient, the signal suddenly drops. After sunrise, the F2 layer builds again and as soon as the MUF rises above 5 MHz, signal strengths suddenly increase. At the other hand, D-region absorption will start to develop, weakening signals until midday. On summer days, this effect is most pronounced. During the evening and night, weak scattered signals can remain. Distant paths crossing daylight experience very high D region absorption and are of little practical use. The 5 MHz band is generally at its best for DX when the path passes the dark part of the globe.

The regular E layer critical frequency is closely related to the solar zenith angle. The daytime critical frequency is usually below 5 MHz. Near vertical rays will pass the E layer and will be returned by the F layer if its electron density is sufficient. For longer distances however, the E layer can refract waves back to the earth. The E layer electron density is much weaker at night, which leaves the F layer to be the primary refracting layer. If the F layer electron density becomes too low, ionospheric propagation will fail.

Anomalies

Sporadic E

Sporadic E (Es) is an interesting anomaly. Its frequency of occurrence depends on season and latitude. At moderate latitudes, Es is most likely in the summer period. The critical frequency of Es can extend up to the VHF range and can blanket the ionosphere above. Sporadic E sometimes is so intense, that ionospheric propagation on the 144 MHz amateur band occurs. Es is also seen in polar regions, especially when charged particles from eruptions of the sun enter these regions.

Disturbances

During strong magnetic disturbances (effects resulting from solar events), typical quick fading is observed. Signals are usually weaker as well.

Although infrequent, strong solar flares can result in sudden blackouts that are caused by exceptional high ionisation in the D-region. Signals can disappear completely and will return slowly after the event.

Sunrise and sunset enhancements

This article focuses on this effect, where signal strengths apparently peak around sunset and sunrise. Various scenarios were considered. Ray tracing experiments revealed results that agree with the observations. This will be discussed later.

RESEARCH METHODS

Various applications and data sources were used to support the research. Books and articles provided more insight into fundamental backgrounds and related research was studied.

Amateurs from New Zealand and Europe actively participated in experiments, during different seasons, leading to many observations and valuable data. Much of this was applied.

In general, it is essential to use consistent and accurate data. During the past, it was difficult to measure accurate field strengths with common amateur equipment, especially with weak, narrowband signals.

This situation changed with the introduction of the WSJT software. It estimates the signal to noise ratio (SNR) remarkably well and consistent, independent of the radio equipment used. This led to an immense improvement of data quality. The received field strength can be derived from the SNR when background noise power and antenna gain are known.

Both WSJT-X and JTDX (a fork of WSJT-X) have become very popular on the HF bands. Received messages, including timestamps, callsigns and SNR values, are saved to a file. Beacon mode (WSPR) reports are uploaded to a database (wsprnet.org). The author developed additional software to extract and process data for analysis.

The application Proplab Pro 3 was used extensively. This propagation prediction application can perform 3D ray tracing to simulate how radio waves travel through the ionosphere. The simulations are based on empirical models, describing the ionosphere throughout the year, taking various environmental properties into account, such as solar activity and the earth magnetic field. Proplab proved to be essential to shed light on mechanisms that might explain the observed signal enhancements.

TRANSMISSION LOSS

Establishing received power

One of the most challenging aspects is to establish the true field strength at the receiver location. Uncertainties about noise environment and antenna gain have to be taken into account. The overall loss between transmitter and receiver depends to a great extent on the propagation properties between the stations and the antenna patterns at both ends.

WSJT software reports the SNR relative to 2.5 kHz. Knowing the background noise level is necessary to derive the signal power from the SNR. The noise level from the dipole antenna of the author varied between about -85 and -80 dBm in 3 kHz bandwidth, measured with a professional spectrum analyser.

Antenna gain

Horizontal dipoles are popular, because they are simple, cheap and easy to put up. These antennas radiate most energy upward, when the antenna height over ground is less than a third wavelength. Towards the horizon, the gain drops to zero (in theory). The actual radiation angle is usually unknown, so the precise gain is educated guesswork. We should not forget the surroundings of a station, like obstacles and terrain which modify the free space antenna pattern.

The author uses a doublet with balanced feeder and tuner, roughly equal to a half wave dipole on 60 metres.

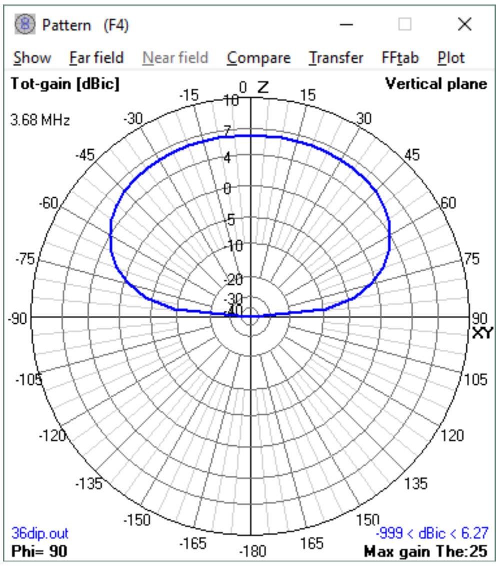

Figure 2 - Theoretical pattern for a low dipole

The above figure shows a typical radiation pattern for a dipole at a quarter wavelength above average ground. As will be shown later, elevation angles between about 7 to 20 degrees above the horizon are most likely, which implies gain ranges between -5 and 0 dBi.

OBSERVATIONS

Over time, various contacts were made with stations in the Pacific area. Reception reports, often surprisingly good, were also analysed.

The Australia case (PA2S to VK7BO)

VK7BO, located on the island of Tasmania, started monitoring the 60 metre band late 2015, just after Dutch radio amateurs got access to the band. At the time, 100 Watts output power was allowed in The Netherlands.

The author was quite surprised to find his signal reported on the automated digital signal reporting systems pskreporter.info and hamspots.net. VK7BO was contacted to verify the validity of the reports. The signal of the author was detected in Australia many times.

VK7BO often operated his receiver unattended, automatically uploading reports. By transmitting periodically with 50 Watts and fetching reports from hamspots.net and putting it into Excel files, data was gathered.

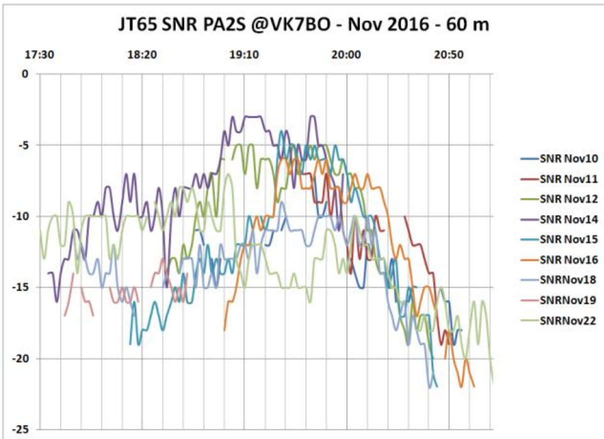

Figure 3 - SNR plotted against time (UTC), PA2S to VK7BO, showing distinct peaks before declining steadily.

The rising sun in Australia causes increase of D region absorption, which is almost certainly responsible for the decline after about 19:30 UTC. The decline rate is consistent, but the upslope is slower and less consistent. These grey line enhancements were reported in the literature, but no conclusive explanation was provided. The research journey started with a lot of reading and looking at propagation prediction models.

VOACAP software was tried first to get transmission loss values based on models. VOACAP estimated the loss between 160 and 170 dB. The path loss derived from the observations was much lower, around 142 dB during the peaks.

Various transmission loss calculations found in the literature assume the sum of free space path loss, D region absorption and ground reflection losses, said to be about 6 to 7 dB per hop over ground and about 1 to 2 dB for hops over the ocean. Applied to the VK7BO case, assuming at least 7 hops, the "hop loss" would be in the range of 4 times 6 dB (land) and 3 times 2 dB (ocean). The overall loss would then be 131.6 dB (free space loss) plus 30 dB (absorption + hop loss), resulting in 161.6 dB loss. Close to VOACAP but far from 142 dB.

An ITU field strength measurement campaign was found, spanning 6 years between 1983 and 1989. The measurements were taken in Germany from a 5 MHz transmitter in Canberra, Australia. Although the two paths are not the same, the ITU campaign results agree with the findings of the author.

The Fiji case (PA2S to 3D2AG)

In September 2017, a contact was made with 3D2AG, located on the island of Fiji. The contact took place in the morning in Europe via the long path (around 24.000 km).

The author measured the noise level to be about -80 dBm in 2.5 kHz bandwidth. The reported SNR of -23 dB corresponds to -103 dBm received power. The transmitted power was +47 dBm (50 W) and isotropic antennas were assumed (0 dBi gain). The estimated path loss is 150 dB, which is 15 dB above the free space loss, again a remarkably low value.

The New Zealand case

After radio amateurs in New Zealand were granted access to the 5 MHz band with 10 Watts EIRP, contacts were made with stations in Europe. The best propagation occurred during the morning in Europe / evening in New Zealand. The long path passes South America and the distance is about 21,500 km.

One of the most notable aspects of the New Zealand case is the exceptionally low transmission loss, estimated to be around 140 dB or perhaps even less.

The author made his first contacts with New Zealand in February 2018. A good opening occurred on 11 February, with FT-8 reports from ZL4OL peaking around -15 dB. At the time, the background noise level was -80 dBm in 2.5 kHz, received power thus near -95 dBm, equalling around 135 dB transmission loss.

Over time, a small group of stations from New Zealand and Europe started checking propagation very regularly and the recurring daily pattern was seen throughout three seasons. The peaks also tracked sunrise and sunset clearly.

In October 2020, FT8 transmissions of ZL4OL were received by the author during a number of days that month, peaking better than -10 dB on October 10th. Based on a measured background noise level of -85 dBm, the received power was estimated to be -95 dBm, resulting in 135 dB loss, similar to the value in February 2018.

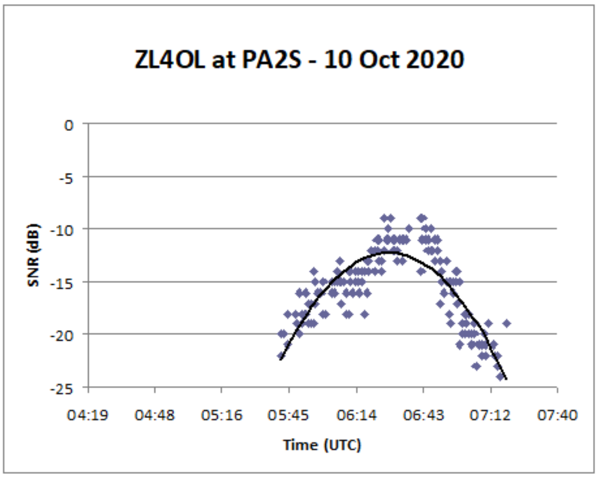

Figure 4 - SNR plotted against time (UTC), ZL4OL to PA2S between 04:30 and 07:30 UTC. The peak around 06:30 is clearly visible.

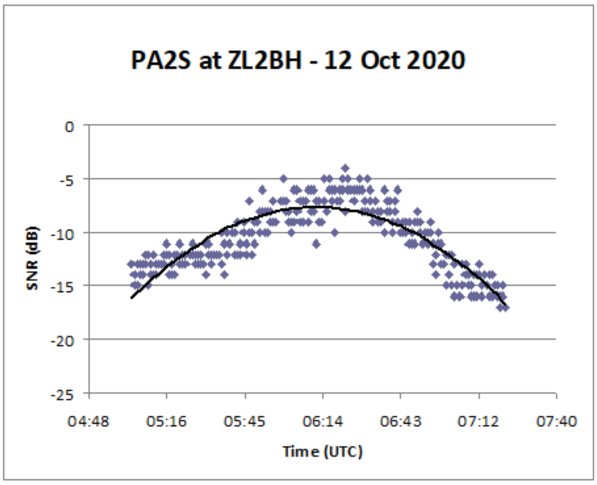

Figure 5 - SNR plotted against time (UTC), PA2S to ZL2BH. The peak is somewhat earlier.

Transmissions in the direction to New Zealand showed that the SNR of PA2S in New Zealand was peaking between -10 dB and -5 dB at ZL2BH and around +0 dB at ZL4OL. All reports were normalised to 10 Watts EIRP.

ZL4OL is located in the south, close to the coast and his terrain descends towards the ocean. He also reported a very low background noise level. If the minimum expected level is assumed, the path loss would be around 139 dB. The free space loss for 21,500 km is 133.6 dB. It follows from these and other observations that the path loss during the enhancements can be as low as 2 to 6 dB above the free space value.

DISCUSSION

The experiments show that ionospheric propagation on 60 metres between Europe and Oceania has characteristic features, like signal strength enhancements during sunrise and sunset. The estimated transmission loss reaches lower values than propagation models suggest. The path between New Zealand and Western Europe is especially noteworthy, because of the exceptional low loss and the fact that openings occur almost the year round.

This paragraph discusses possible causes for the observed signal enhancements. Sources of uncertainty are taken into account as well.

Day to night transition effects

Comparing the peak SNR times with sunrise at the east end of the path between Europe and New Zealand revealed that the peaks occur when the sun is a few degrees above the horizon. Peak times on consecutive days vary very little which indicates that the effects are closely related to solar irradiation changes around twilight.

Sunrise/sunset enhancements are associated with a tilted F2 layer by a number of writers. Some authors claim that the best improvements occur when the transmission path is perpendicular to the terminator or grey line.

Interesting maps are provided by the Lowell GIRO Data Center. These maps are based on the IRTAM model, refining the IRI model with measurements of ionosondes to obtain a near real time "weather map" of the ionosphere. The F2 height maximum maps show the tilts at sunrise and sunset (green to blue transition, down towards the sunlight side). The next map shows the approximate path between VK7BO and PA2S, which is near straight on this map projection.

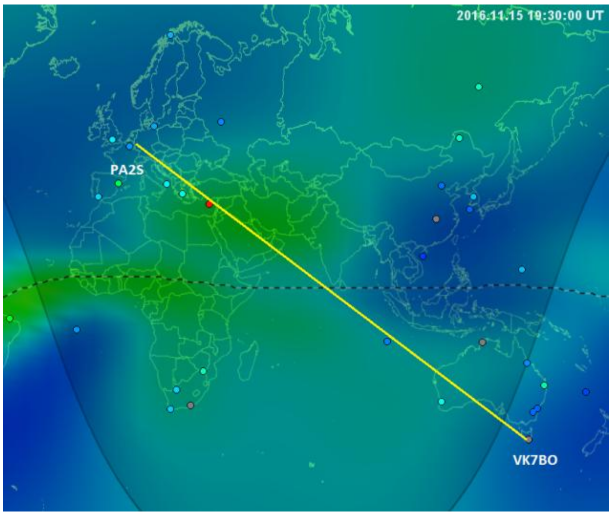

Figure 6 – IRTAM F2 height map, VK7BO to PA2S, 15 October 2016, 19:30 UTC. Blue areas have the lowest heights.

The tilts behave like a tilted mirror, which reduces the elevation of rays. Ray tracing calculations confirm this.

The F2 layer ionisation gradually diminishes during the night, but the E layer ionisation drops immediately after sunset. As will be shown, twilight changes can explain the exceptional observations.

Ionospheric focusing

Some writers suggest that the tilts cause the ionosphere to behave like a parabolic mirror, focusing rays which then reinforce each other.

Although focusing could explain signal enhancements, there are some essential requirements to be met.

The observed enhancements repeat practically every day with time differences of about a quarter of an hour. This implies that the parabolic mirror should essentially be at the same location every day. It is also important that the shape is parabolic for the focusing to occur at all.

The dynamic nature of the ionosphere and the strong influence of solar and magnetic phenomena on the F2 layer, leading to substantial day to day variations, raises the question if the position and shape of the F2 layer fulfils the requirements just mentioned.

Uncorrelated rays, with random amplitude and phase, will only add when the phase difference is less than about 90 degrees. When phases are near opposite, they will effectively cancel. The amplitude at the receiver is the result of a vector sum of the received power induced by all rays. It is also important to note that if the rays travel across different paths, these rays arrive with random phase and amplitude. The net gain will be small in such a case.

It is the opinion of the author that only tightly correlated rays can result into notable signal strength increases. F2 layer focusing is considered to have a low probability.

Ionospheric ducting

A specific type of propagation on 160 m was suggested in 2000 by Bob Brown, NM7M (SK), where rays travel trough a duct between the E and F layer. During the hours of darkness, a zone of low electron density exists between the E and F regions, referred to as the E-F valley. Rays can refract back up to the F2 layer from the E layer when the valley is "deep enough" and when rays come down at a very small angle (grazing angle) with respect to the E layer.

The possibility of E-F valley ducts occurring on 5.3 MHz was demonstrated with ray tracing, using Proplab Pro software.

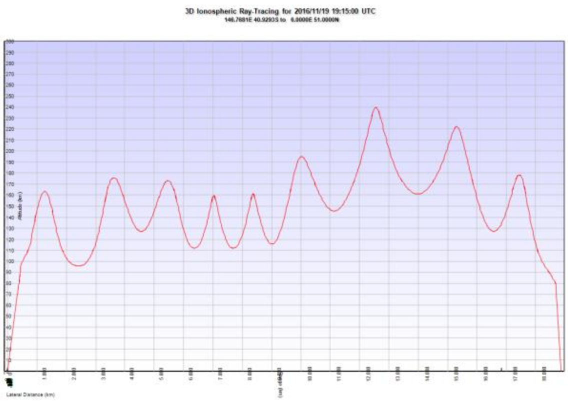

Figure 7 – 3D ray tracing graph, showing a duct between VK7BO to PA2S

The 3D ray trace graph is based on solar and magnetic data for October 2016 and the IRI-2007 model. The transmitter (VK7BO, sunrise) is left, the receiver (PA2S, after sunset) is to the right. The ray goes up and returns from the F2 layer at a low angle and bends up again from the E layer. It continues to bounce between the E, F1 and F2 layers. It exits the duct and returns to the ground at the receiver end of the path.

It was found that propagation between Europe and New Zealand is very remarkable with exceptional low losses. The composition of the ionosphere is very specific at the optimum times.

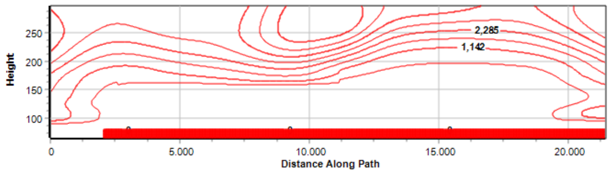

Figure 8 - Electron density profile, PA2S (L) to ZL4OL (R)

Figure 8 shows the electron density profile in October 2020 around 06:30 UTC between PA2S and ZL4OL. This profile can be described as a slice of the ionosphere along the path. The patterns at the left and right are typical for the condition for rays to enter or exit the E-F valley duct.

Ray tracing with a range of elevation angles revealed that entry into the duct occurs within a specific range of angles. Outside this range, most rays follow a usual hopping pattern. This effect is mirrored at the opposite end of the path.

Opportunity windows

A very interesting effect was discovered by the ray tracing experiments with elevation angle ranges, increasing in steps of 1 degree. Two distinct "opportunity windows" were discovered where rays enter or exit the duct.

Two mechanisms are suggested to explain these windows. The F2 layer tilts at the night to day transition, return incoming rays shallower then they came in, causing rays to reflect up from the E layer.

This process is shown in figure 9.

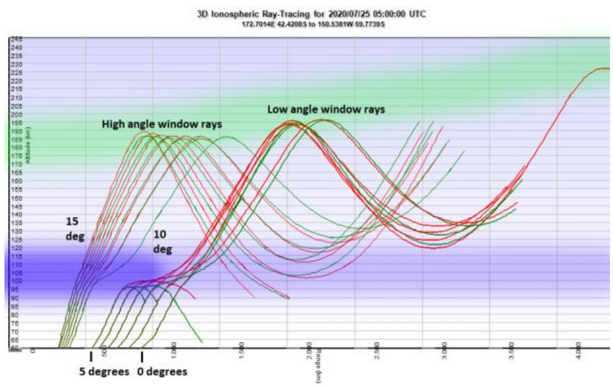

Figure 9 – Ray tracing illustrating the two windows to enter or exit the E-F valley duct.

During sunrise and sunset, the E layer electron density increases or decreases sharply. We could consider the E layer as a canopy, moving to the west. It became apparent that the lowest rays pass underneath the canopy, but higher angle rays touch the denser part of the canopy, to be refracted down to the ground. With increasing elevation, rays will penetrate the E layer. The E layer bends the rays somewhat down, to arrive at the F layer with shallow angles, followed by refraction up from the E layer, entering the duct. At some point rays descend too steep and pass the E layer down to the ground, starting a hopping pattern.

Tracing at 5 minute intervals showed that at sunrise, the low window opens up and gets wider. This is followed by a transition period where both mechanisms are present (figure 9 was made during transition). Next, the low window closes and a narrow high window is present until that mechanism fails. Figure 10 illustrates this.

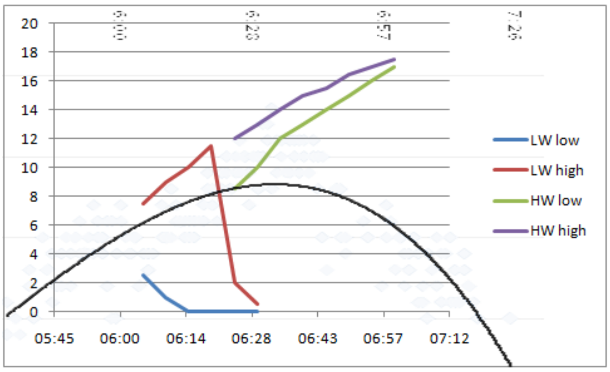

Figure 10 - E-F duct windows as a function of elevation angle and time, with SNR of ZL4OL at PA2S superimposed.

The SNR curve (black) was superimposed to show the relationships during this time frame. It seems that the best propagation occurs around the transition period. It has to be emphasised that the transition period is associated with E layer gradients during sunset and sunrise, which are mostly controlled by the sun.

Focusing at the edge of the canopy

Rays in the low window are refracted more with increasing elevation angle. Figure 9 illustrates this. At the edge, the E layer has horizontal gradients, with the greatest density at the day side. This behaves like a convex lens which is able to focus rays. Because these rays are close together, it is likely that the refracted rays have small enough phase differences in order to reinforce each other. A ideal lens with a diameter of one wavelength has a theoretical gain of nearly 10 dBi, so a relatively small focusing area with a size of a few wavelengths can provide noticeable gain.

Because the peak SNR times closely correlate with sunrise/sunset times, it is believed that this type of focusing contributes to the enhancements.

Absorption

The electron density of the D region is closely related to the solar zenith angle. Because the rays travel into or from the dark, the D region ionisation is weak, causing minimal absorption. The decrease in SNR after the peak is almost certainly due to the increasing ionisation in the D region after sunrise at the eastern end of the path.

Ray tracing showed that the absorption around the optimum time can be in the magnitude of 5 dB for a single passage through the D and E regions. The greater the elevation, the lower the attenuation. This is because the high waves travel through a smaller amount of ionised plasma. When the rays travel entirely through the duct, only two passages occur. In that case, the absorption would be around 10 dB and the total transmission loss between isotropic antennas would be approximately the free field attenuation plus (2 * 5 =) 10 dB. If focusing is responsible for some additional enhancement, then we are getting close to the best observations.

It is noteworthy that both rise and fall rates of the Europe to New Zealand SNR values are steeper than the VK7BO case, which indicates that similar (and mirrored) effects occur simultaneously at both ends. The path from PA2S to VK7BO had only one endpoint during sunrise (VK7BO). The location of PA2S was already past sunset and did not fit the E layer "canopy theory", Most of the enhancement is believed to be caused at the sunrise end. It has to be remembered that the height of the F2 layer changes most around sunrise.

Polarisation

The magnetic field causes double refraction, splitting linear polarised waves into (approximately) circular polarised waves. The direction of the circular polarisation is opposite in the northern and southern hemispheres. It is therefore possible that the circularly polarised waves are "reversed" in the other hemisphere, back to (almost) linear polarisation. If this effect actually occurs, it could cause some improvement. Nothing about this was found in the literature, but this effect is certainly worth further investigation.

Usual hopping

Despite the fact that the E-F duct theory, including any focusing, provides a plausible explanation, usual hopping paths cannot be ruled out completely.

Ray tracing showed that absorption values can be close to the E-F duct mode. However, additional losses due to intermediate ground reflections have to be taken into account. Since the long path from Europe to New Zealand travels mostly over the ocean, the losses from ground reflections are relatively low. Proplab calculates the expected field strength at each location where the rays hit the earth, taking into account previous ground or water reflections. The results show that the field strengths with hopping are about 5 to 10 dB less than via the E-F duct. It has to be remembered that hopping lacks the "E canopy" focusing mechanism.

Other possibilities

A paper by Carrara (1970) suggests a mode where rays are guided by the F2 layer. Instead of bouncing between F and E layers, the ray follows the bottom side of the F2 layer. Carrara analysed experiments with satellites carrying HF beacons. Entry of the satellite rays into the duct is easy, because they originate from higher up.

Calculations suggest that a guide could exist, where F2 tilts during dawn and dusk provide entry/exit mechanisms, comparable to the high window described in this article. The paper indicated very low path losses, similar to the observations on 60 metres.

Although the suggested guided propagation with its very low path loss could provide an explanation, it is the opinion of the author that the conditions for such a guide require a more or less circular and constant F layer with minor variations in electron density and height, because rays would otherwise deviate from the guide. Looking at the properties of the F2 layer, many dynamics are seen in both density and height. The probability that the conditions for the suggested guide are fulfilled consistently and repeat daily, looks to be insufficient to support the observations.

CONCLUSIONS

Translating observed signal to noise ratios to field strength has to be taken cautiously. Both background noise level and antenna radiation patterns have to be known. The noise level can be measured with appropriate equipment. Antenna patterns can be estimated with modelling software. Angles of arrival of signals are uncertain but ray tracing results can provide guidance.

The transmission loss from The Netherlands was estimated for the observed cases to be about 142 dB to Australia, 150 dB to Fiji and around 135 dB to New Zealand, the latter being closest to the free space loss. A long time ITU measurement campaign provided reference values which agree with the estimations.

Ray tracing confirms that E-F valley ducts can exist on 5.3 MHz. The calculated transmission losses match the observations within a reasonable margin.

F2 layer tilts at sunrise and sunset enable rays to return to the E region at grazing angles, in order to enter or exit the duct.

An interesting effect was found, showing that two different modes exist where rays can reach the E-F duct. At the sunrise end, the duct opens for low rays first, to be followed by a transition period, after which only higher rays can enter the duct. This effect is also found at the sunset end, but to a lesser extent. The observed times relate closely to solar zenith angle, emphasising the importance of the E layer in the overall process.

The signal peaks coincide with the transition period, at which time possible focusing effects can occur, caused by horizontal gradients in the E region which converge rays. If this assumption is correct we find that the overall transmission loss can be close to the free space value.

Usual hopping modes cannot be dismissed entirely, but signals are weaker because of ground reflection losses. E layer focusing effects were not identified with ray tracing.

Guided propagation where rays travel just below the F2 layer is considered less likely, because F2 layer density and height vary considerably along the path, which is likely to steer rays away from the guided path. The fact that the SNR curves follow a consistent diurnal pattern does not match with the more dynamic nature of the F region.

It can be concluded that propagation via the E-F duct, amplified by focusing, is considered to be the most likely mechanism to explain the observed signal enhancements.