Performance Limiters of Near Vertical Incidence Skywave Propagation

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***Abstract*— Near Vertical Incidence Skywave propagation (NVIS) is defined as providing continuous coverage from near zero kilometers (just beyond line-of-sight) up to a couple of hundreds of kilometers (km) from the transmitter with no skip or dead zone. NVIS communications are especially effective during disaster relief operations when infrastructure was severely damaged. Being able to accurately determine the performance limiters of NVIS propagation can help in the planning of High Frequency (HF, 3 to 30 MHz) emergency communication links. Widely varying radial distances (from as little as 50 km and up to 160 or even 320 km) for the coverage attainable by NVIS propagation are commonly found in the literature. It is very difficult to plan a NVIS link for homeland security, disaster relief, etc. when the published guidelines vary to such a degree. In this study, a scientific approach is utilized to determine the NVIS performance limiters for varying solar conditions, times of day and geophysical locations.**

***Index Terms*— ground electromagnetic constants; International Reference Ionosphere (IRI); interferometric direction finder (DF); ionogram; Near Vertical Incidence Skywave (NVIS).**

I. Introduction

Although the coverage offered by modern communication systems (cellular telephones, Wi-Fi, satellite, etc.) expand on nearly a daily basis there are still instances where traditional HF skywave communications are viable and cost effective alternatives. Examples include the aftermath of natural disasters such as earthquakes, tsunamis, tornadoes, mudslides, floods, etc. or man-made tragedies such as terrorist attacks. Under these circumstances, networks may become overloaded or the infrastructure severely damaged, reducing the capabilities of the network [1]. This can especially be problematic in lesser developed countries where back-up networks may be less common or capable [2, 3].

A good example of where HF systems can be useful is when a group needs to operate deep in a remote ravine where the geography may negatively influence the commonly used line-of-sight communication channels such as Very High Frequency (VHF) radio or cellular telephones and an alternative communications mode needs to be utilized. Distances involved are typically short in terms of how the crow flies, but the terrain may be very challenging. Under these circumstances, NVIS propagation as depicted in Fig. 1. are very effective [4]. The high take-off angle for NVIS communications is quite the opposite of long distance HF communications where low radiation angles are typically required [5, 6]. In many tactical military deployments, short-range skywave communications are for security reasons also preferable to using the local cellular network. This is especially applicable during peacekeeping missions in foreign countries where unlawful elements may have access to cellular networks, thus potentially compromising any operations.

Central to successful NVIS communications is the selection of an antenna with the required high angle radiation characteristics and an operational frequency that will be refracted back to Earth and not penetrate the ionosphere to be lost in space. The area covered by NVIS propagation is determined by the radiation characteristics of the selected antenna and the propagation of the operational frequency through the ionosphere [5, 6]. (If propagation is possible the transmitted power can be increased or other measures (such as the cancelling of interference) be implemented to achieve the required received signal-to-noise-ratio.)

In this study, the soil moisture technique is used in conjunction with a previously published universal soil model to accurately determine the ground parameters (conductivity and relative dielectric constant) for the frequency of interest. The radiation characteristics of a popular NVIS antenna, the low half-wave dipole, are then analyzed using these ground parameters and the area covered is determined by ray-tracing at the applicable frequency through an electron density profile calculated by the International Reference Ionosphere (IRI). The coverage obtained when working near the Frequence Optimum de Travail (FOT) is analyzed as well as for operational frequencies lower than the FOT. The results obtained indicate that the area covered by NVIS propagation is under certain conditions significantly larger than the accepted norm.

II. Frequency range for NVIS propagation

For NVIS communications the operational frequency needs to be below the (vertical) critical or plasma frequency of the F2 layer, *foF2*, to ensure that no skip zone exists [7], thus ensuring continuous coverage from just beyond line-of-sight up to distances of a few hundred kilometers. Although the Extraordinary wave, *fx*, may provide enhanced coverage [8],

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use is made of the critical frequency of the Ordinary wave, *foF2,* as it is currently the most widely published ionospheric propagation metric.

The critical frequency is defined as the highest frequency at vertical incidence that the ionosphere will reflect back to Earth and that can be monitored with a receiver that is collocated with the transmitter [9, 10]. This ensures continues coverage from near zero km onwards with no skip zone present. Although according to the secant law higher frequencies will propagate at oblique angles over longer distances [11], the maximum useable frequency (MUF) for NVIS remains equal to *foF2* to comply with the requirement of no skip or dead zone in the target area.

It is possible to use the MUF to determine an Optimum Working Frequency (OWF) or FOT [12]. The FOT is the frequency that is equal to the lower decile value of the thirty or thirty-one individual MUFs for the month. The OWF or FOT is the internationally agreed standard for the best or optimum frequency to use at a given hour on a given circuit. Its use will result in successful communications (at least as far as the correct choice of frequency is concerned) 90% of the time (27 days of the month) [13]. It is possible to get an estimated value of the FOT (EFOT) by taking 85% of the median MUF [14, 15]. 85% of the *foF2* is thus a convenient definition to calculate the FOT for a NVIS circuit.

III. Antennas and antenna heights for NVIS propagation

For portable and tactical deployment scenarios, compact, low weight antennas are preferred. It is also required that the antenna radiates the majority of the energy at the (high) elevation angles required by NVIS communications. The basic half-wave dipole antenna deployed low above the ground is a good candidate to satisfy the requirements of NVIS antennas [16].

Witvliet *et al.* determined that the height for maximum NVIS gain is between 0.18λ and 0.22λ above the ground, and for the optimum signal to noise ratio (SNR) the dipole antenna must be 0.16λ above the ground [6].

The vertical radiation angle of a dipole antenna increases as it is brought closer to the surface of the Earth. The electromagnetic constants (ε_r and σ) of the soil at the operating frequency are required to accurately model the behavior of a dipole antenna in close proximity to the Earth. It used to be challenging to determine the required electromagnetic constants with useful accuracy, but the soil moisture technique in conjunction with Longmire's universal RC network soil model can now provide the constants at any frequency of interest [17] with little effort.

IV. Radiation characteristics of a low dipole antenna above a non-ideal Earth

With accurate electromagnetic constants for soil available it becomes possible to accurately model the radiation characteristics of a dipole antenna at heights optimum for NVIS applications. The EZNEC 5+ [18] implementation of the Numerical Electromagnetic Code (NEC) [19] was used to determine the radiation pattern of a dipole antenna at various heights above a real Earth.

EZNEC 5+ uses the NEC2 calculation engine and the user interface allows the operator to supply the required electromagnetic ground constants for the frequency at which the antenna is simulated. The electromagnetic constants for a common soil moisture content of 20% (σ = 0.01 S/m and ε_r = 31.4 at 5 MHz) were used for the calculations. At a height of 0.2λ the beam width is 115.8° and the −3 dB or half power points are at elevation angles of 32.1° and 147.9º as depicted in Fig. 2.

Calculating the radiation patterns for dipole antennas at a height of 0.2λ over the typical 2 to 12 MHz NVIS frequency range resulted in nearly identical results as those obtained in Fig. 2.

V. NVIS area coverage

As a worked example, the 2012 version of the IRI [20] was used to model the noon ionosphere above Grahamstown, South Africa (33.3°S, 26.5°E) during a period of low solar activity. The smoothed sunspot number (SSN) was varied until the electron density as a function of height profile calculated by the IRI compared favorably with that measured by the Grahamstown ionosonde.

In Fig. 3. the E layer is from approximately 290 kHz to 3.3 MHz. Between the E layer and the F1 layer is a region known as a valley where the electron density decreases with height. The F1 layer is from approximately 3.3 MHz to 4.3 MHz. The F2 region is from 4.3 MHz to 6.5 MHz with the top side of the ionosphere extending above a height of 280 km. The critical frequency of the F2 layer, *foF2*, is at approximately 6.5 MHz. The FOT is taken as 85% of the *foF2*, resulting in a frequency of 5.5 MHz.

In Fig. 4. ray-tracing techniques implemented for a curved earth and ionosphere [21] were used to graphically illustrate the signal propagation through an ionosphere with a *foF2* of 6.577 MHz. The oblique distances at an operational frequency of 5.5 MHz were determined for elevation angles between 0 and 90°.

In Fig. 4. an elevation angle of 32° (near the −3 dB point of the radiation angle of a low dipole antenna as determined in Fig. 2.) corresponds to the transition between the E and F layers, with E layer propagation occurring at elevation angles of 35º and less. At an elevation angle of 35 º, the propagation is not well defined as it is at the Maximum Useable Frequency (MUF) of the E layer [22]. At distances between 360 km and approximately 820 km, propagation via both the E- and F layers become possible at elevation angles of between 12 and 58º. This multipath propagation may result in signal fading or inter-symbol distortion due to the different path lengths. Multipath propagation may reduce the effectiveness of the communications link [23] and should in general be avoided. More reliable results will be obtained if the majority of energy is transmitted at elevation angles of 40° and higher, which is above the Highest Possible Frequency (HPF) of the E layer. From Fig. 4. it can be determined that NVIS propagation (no skip zone and no multipath propagation present) is possible from just beyond line-of-sight up to a distance of 360 km. Similar results for the calculated ground distances before the onset of multipath propagation were also obtained for other times of the day, as long as the operational frequency was equal to the FOT.

When the operational frequency is much lower than the FOT, the ground distance obtainable with a dipole antenna at low height is considerably less than when making use of the FOT. In the ray-tracing result of Fig. 5. the operational frequency is 4 MHz, quite a bit lower than the FOT of 5.5 MHz.

Once again multipath propagation involving the E layer limits the achievable ground range. In Fig. 5. multipath propagation may occur at elevation angles of between 25 and 72º, corresponding to distances of between approximately 180 and 460 km, limiting NVIS propagation to a maximum of 180 km. This distance is considerably less than the 360 km achievable when operating at the FOT under similar conditions.

If the operational frequency is above the MUF, a skip zone will exist. The signal will penetrate the ionosphere at elevation angles above that associated with the MUF and be lost in space as illustrated in Fig. 6. These conditions do not comply with the criteria for NVIS propagation.

During high solar activity the *foF2* was measured as 11.384 MHz by the Louisvale, South Africa (28.5°S, 21.2°E) ionosonde. This resulted in a calculated FOT of 9.75 MHz. Ray-tracing ground distance results at 9.7 MHz for elevation angles of zero to 90° are presented in Fig. 7.

In Fig. 7. it can be seen that propagation over ground ranges of between zero and approximately 640 km can be achieved before the onset of multipath propagation. This corresponds to elevation angles of between 90 and 42º. Fig. 7. indicates that the area covered by stable, single layer NVIS propagation during high solar activity can be substantially more than the "up to 160 or 320 km" [24] or 200 km [25] taken as a general rule of thumb, or the "about 250 km" as indicated by the ITU [26].

When the operational frequency is decreased from the optimum value of 9.7 MHz to 5 MHz, multipath propagation once again may become problematic between distances of 250 to approximately 580 km as illustrated in Fig. 8. In Fig. 8. multipath propagation due to the E layer thus potentially occurs between elevation angles of 17 to 68º.

The NVIS performance limiting factors were also investigated for the nighttime ionosphere above Louisvale at 22h00 UTC during high solar activity. The *foF2* was 3.53 MHz.

The FOT for the ionosphere of Fig. 9. is 3.0 MHz. Ray-tracing through the electron density profile of Fig. 9. results in the elevation-distance graph of Fig. 10.

In Fig. 10. it can be seen that there is no E layer that can cause multipath propagation present, resulting in a ground range of 800 km at the low dipole antennas' –3 dB elevation angle of 32º.

VI. Measured Results

Ray-tracing through the IRI indicated that the performance obtainable with NVIS propagation is during the daytime limited by multipath propagation via the F and E layers. It also became clear that the obtainable coverage can far exceed the accepted norm (about 250 km according to the ITU [26]) when the operational frequency is close to the FOT. These unexpected results were validated by the oblique results obtained with the South African ionosonde network operated by the South African National Space Agency (SANSA) [27], as well as by measurements with an interferometric HF direction finder (DF), typically used in Electronic Warfare (EW) and law-enforcement applications [28].

According to the Grahamstown ionogram of 15 April 2015 (Fig. 11.), the *foF2* is at 11.063 MHz. The NVIS FOT is thus at 9.403 MHz.

On the Grahamstown ionogram of Fig. 11. vertical incidence results for propagation of the Ordinary wave is represented by the red graph and that for the vertical incidence Extraordinary wave by the green graph. The black line is the calculated real height electron density profile. Also visible is oblique propagation to two other stations in the South African ionosonde network over the frequency range of approximately 6 to 14.8 MHz. These transmissions are from the Hermanus (34.5°S, 19.2°E) and the Louisvale ionosondes at distances of 762 and 763 km respectively. At the Grahamstown NVIS FOT of 9.403 MHz, oblique propagation is visible to both the other ionosonde stations. (Propagation on frequencies above the Grahamstown *foF2* of 11.063 MHz will result in the presence of a skip zone, thus not complying to the requirements for NVIS propagation.) The oblique ionogram results of Fig. 11. confirm the presence of NVIS propagation over distances of at least 763 km at the FOT of 9.403 MHz, nearly double that of the highest previously published value.

A wideband interferometric DF manufactured by GEW Technologies (Pretoria, South Africa) was deployed at Pretoria, South Africa (25.7°S and 28.3°E) to measure the wave angles of the Durban, South Africa (29.7°S and 31.0°E) maritime transmissions over the 520 km path. Measurements were performed at various frequencies and times that corresponded to both the FOT for the circuit as well as frequencies considerably lower than the FOT.

The propagation of the Durban maritime transmission at 8.631 MHz as measured by the interferometric DF was found to be stable, refracted from a single layer of the ionosphere and via a single hop.

At the time of the measurement the *foF2* or NVIS MUF was at 11.06 MHz. The operational frequency of 8.631 MHz is below the *foF2*, resulting in continuous coverage from just beyond line-of-sight onwards. From the presence of single layer, stable propagation as determined by the interferometric DF it can be concluded that NVIS propagation is applicable. The NVIS propagation distance of 520 km achieved on the Durban to Pretoria circuit exceeds the previously published maximum NVIS distance of 320 km by more than 60%, indicating that the previously published distances may not be applicable under all conditions.

At approximately the same time, there was also a transmission from the Durban maritime transmitter site on 6.409 MHz. This frequency is considerably below the calculated NVIS FOT of 9.403 MHz.

The DF results for the 6.409 MHz transmission from Durban indicated the presence of three propagation paths over the 520 km distance. This is clearly a situation that needs to be avoided as the multipath propagation can lead to fading of the received signal as well as inter-symbol interference on data transmissions [16]. In this instance, 6.409 MHz is considerably lower than the FOT for NVIS propagation and should only be utilized on shorter paths. It can be concluded that it is definitely not the optimum frequency for NVIS communications over the 520 km circuit.

VII. Conclusion

NVIS propagation is defined as (short-range) HF skywave communications from just beyond line-of-sight up to a distance of a couple of hundred km's, as long as there is no skip or dead zone present. A systems approach was utilized to provide a technique to determine the factors limiting the performance of NVIS communications. The influence of the ground that is in close proximity to the antenna, the radiation characteristics of a low dipole antenna as well as the propagation medium were analyzed to determine the NVIS performance limiters.

Accurate ground electromagnetic constants were used to model the radiation characteristics of a low dipole antenna at a height that is optimum for NVIS communications (approximately 0.2λ). Using a NEC based calculation the –3 dB point of the radiation pattern was determined to be at an elevation angle of approximately 32°. The elevation angles applicable to NVIS propagation is therefore limited to a lower limit of 32º above the horizon up to vertical incidence (elevation angle of 90º). (With elevation angles as low as 32° applicable, NVIS is probably a bit of a misnomer.)

Ray-tracing through the daytime electron density profile calculated by the IRI revealed that during both low and high solar activity the performance of NVIS propagation is limited by multipath propagation due to the presence of the E layer. During nighttime better performance can be achieved due to the absence of the E layer. In all the instances studied distances greater than 320 km can be achieved as long as the operational frequency is close to the vertical incidence FOT. The achievable distances are thus considerably more than the previously accepted norm.

An operational frequency considerably lower than the FOT results in a reduced ground range due to the possibility of multipath propagation. Multipath propagation may have a considerable negative impact on the reliability of the communications and operation on a too low frequency should be avoided. The previously generally accepted norm for achievable NVIS communications distances corresponds fairly well to distances achievable when utilizing a frequency much lower than the FOT. For optimum NVIS coverage it is recommended to select frequencies close to 85% of the *foF2*. This value can be referred to as the FOT for NVIS propagation.

With the performance limiters of NVIS propagation properly established it is now possible for disaster relief agencies and homeland protectors to use the approach described above to optimally plan their emergency HF communication links. Optimum performance at all hours of the day as well as all ionospheric conditions are now attainable.

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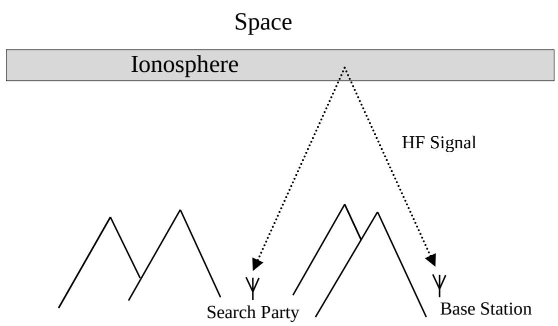

Fig. 1. An example of short-range NVIS communications in mountainous areas.

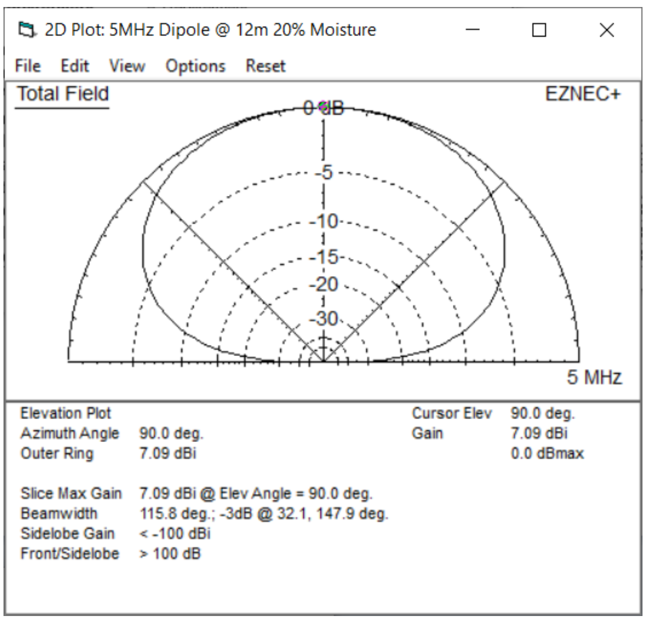

Fig. 2. Elevation plot of a 5 MHz half-wave dipole antenna 0.2λ above an accurate Earth as calculated by EZNEC 5+.

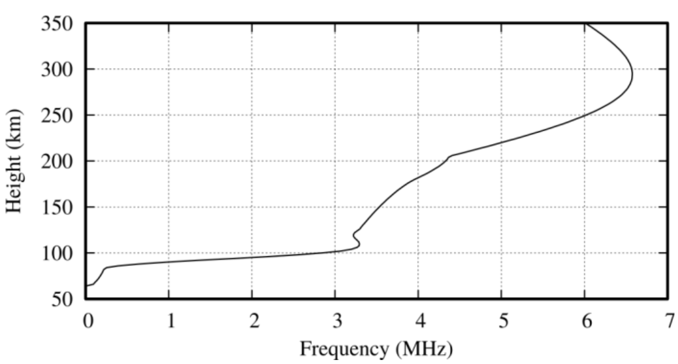

Fig. 3. Low solar activity, noon electron density profile for Grahamstown, South Africa as calculated by the 2012 IRI.

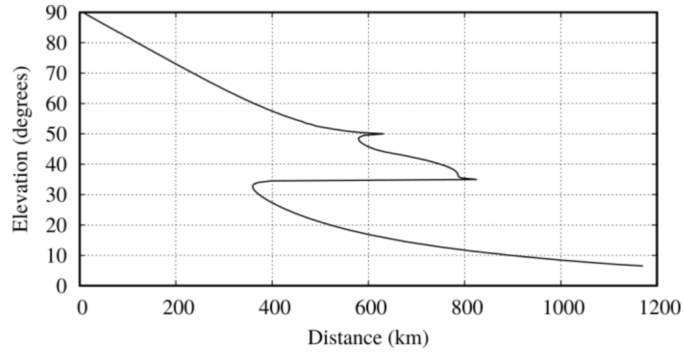

Fig. 4. FOT (5.5 MHz) ground distance results (horizontal axis) when ray-tracing through the Grahamstown, South Africa ionosphere of Fig. 3. for elevation angles from zero to 90° (vertical axis) during low solar activity. The ionosphere is not penetrated at this frequency as 5.5 MHz is below the *foF2* of 6.5 MHz.

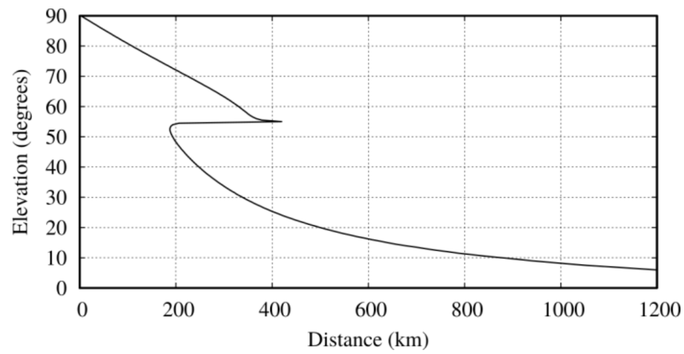

Fig. 5. Ground distance results when ray-tracing through the Grahamstown, South Africa ionosphere for elevation angles from zero to 90° during low solar activity. The frequency is 4 MHz, considerably lower than the FOT.

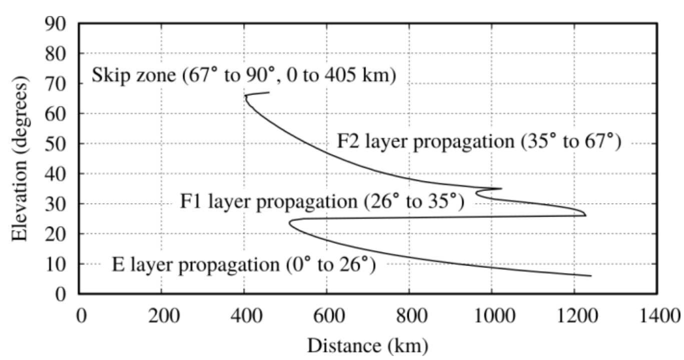

Fig. 6. Ground distance results when ray-tracing through the ionosphere for elevation angles from zero to 90° at an operational frequency considerably higher than the *foF2*. A skip or dead zone exists up to 405 km, thus not complying with the criteria for NVIS propagation.

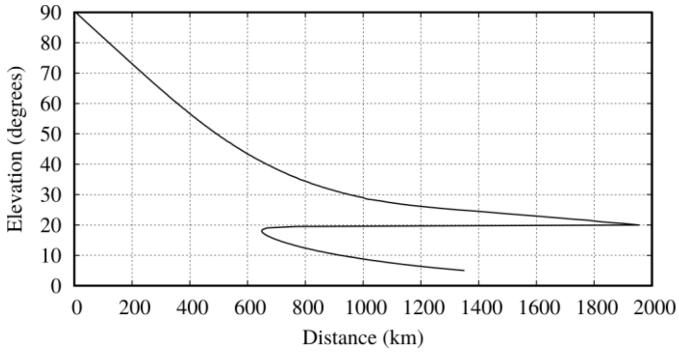

Fig. 7. FOT ground distance results when ray-tracing through the noon Louisvale, South Africa ionosphere for elevation angles from zero to 90° during high solar activity.

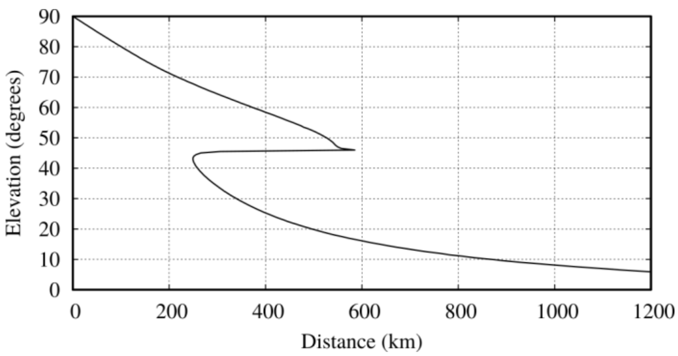

Fig. 8. Ground distance results when ray-tracing through the noon Louisvale, South Africa ionosphere for elevation angles from zero to 90°. The frequency is 5 MHz, considerably lower than the FOT.

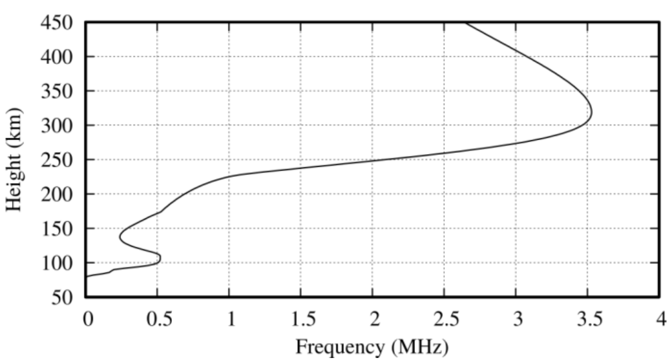

Fig. 9. High solar activity, night (22h00 UTC) electron density as a function of height profile for Louisvale, South Africa as calculated by the 2012 IRI.

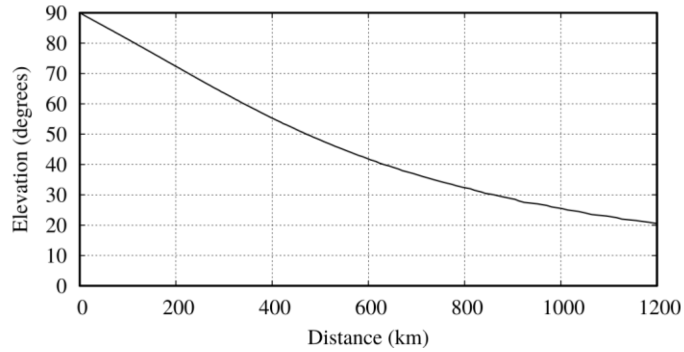

Fig. 10. FOT (3.0 MHz) ground distance results when ray-tracing through the night time Louisvale, South Africa ionosphere of Fig. 9. for elevation angles from zero to 90°.

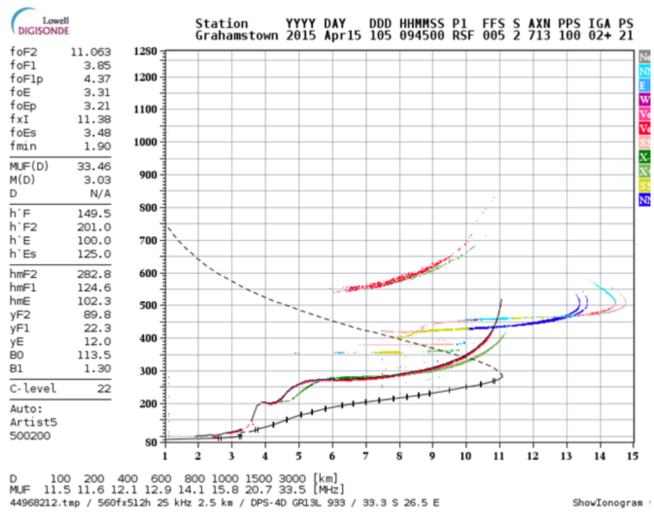

Fig. 11. Grahamstown, South Africa ionogram for 15 April 2015 with *foF2* at 11.063 MHz. Double bounce vertical results can be seen between heights of 550 to approximately 850 km.