NEAR VERTICAL INCIDENCE SKYWAVE
The propagation mechanism, the impact of antenna, backscatter and solar flares

dr. ing. B. A. Witvliet

Ministry of Economic Affairs & Climate
Radiocommunications Agency, Spectrum Management
9726AH Groningen
The Netherlands
ben.witvliet@agentschaptelecom.nl

&

University of Twente
Faculty of EEMCS, Radio Systems
7522NB Enschede
The Netherlands
b.a.witvliet@utwente.nl

SUMMARY

Radiocommunication using the ionosphere as a natural passive high-altitude reflector provides an excellent resort when all other technical telecommunication infrastructure (cellular networks, internet, landline networks) are destroyed by natural disaster or human conflict. It is also an attractive solution when satellite coverage is either difficult to access, e.g. in the polar regions, mountainous areas and in tropical forests, or too expensive, e.g. for NGO's working in poor and remote regions, or humanitarian organizations providing basic healthcare is such regions.

A contiguous area with a radius of at least 200 and up to 400 km of radius may be covered with excellent signal strength using Near Vertical Incidence Skywave (NVIS) propagation. However, this requires proper knowledge of the underlying physics and occurring phenomena supplemented by practical skills to operate such radio links ('operating practice').

This invited paper will provide insight into NVIS radio wave propagation and the influence of the antenna on the propagation channel and the radio link budget, obtained by empirical scientific research. It will show the impact of a solar flare on radio propagation and background noise, as well as night-time above-the-MUF propagation. This research, which started as a part-time PhD research, won the 2016 Anton Veder Scientific Research award.

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1 INTRODUCTION

It has not been that long ago, that all our international telephone conversations were conducted via radio transmissions using the ionosphere as a high-altitude reflector. Large radio stations at both sides of the Atlantic Ocean transported two-way voice channels through the changeable ionosphere. Two-way conversations were possible by separating the transmit and receive location geographically. In The Netherlands high-power transmitters were used in Radio Kootwijk near Apeldoorn, while sensitive receivers with highly directional antennas were located at first in Sambeek, later in Nederhorst den Berg near Hilversum, a separation of more than 60 km. Advanced techniques were used to compensate for the variation of the electron density in the ionosphere, and to counter multipath effects (selective fading) on the radio channel. Several inventions that we now know from modern radio applications such as antenna diversity [1], polarization diversity [2], adaptive beamforming [3] [4] and frequency diversity [5] stem from that era. In the 1950's, a reliable global network of HF telephony was established to extend the national cable telephone systems [6]. This changed slowly but inevitably after the introduction of telecommunication satellites and the first transatlantic cable (TAT-1, 1956) [7] capable of voice transmission (1962) [8]. In the subsequent years, the large international HF radiotelephony stations lost the competition to these newer solutions that provided better voice quality, better reliability and more bandwidth, and one by one they closed down. In a much slower trend, the same is happening to HF broadcasting, which is gradually replaced by satellite broadcasting and rebroadcasting on VHF FM networks.

While HF radiocommunication has left these mainstream public applications, it persists in niche domains for which the independence of terrestrial or satellite networks is essential. Examples are humanitarian work, disaster relief, sensor networks on Antarctica [9], military applications, and long-distance aviation [10].

2 NEAR VERTICAL INCIDENCE SKYWAVE PROPAGATION

Imagine an antenna that radiates electromagnetic waves upwards into the sky, after which the waves are reflected in the ionosphere at a height of 250 to 300 km, to 'rain back' on earth like a fountain, as depicted in Figure 1. With this mechanism, which is known as 'Near Vertical Incidence Skywave' (NVIS) propagation [11], a contiguous area of 200 km radius can be covered using a single radio station, without the need for any other preinstalled infrastructure and without other parties having access control. NVIS has been used extensively by Médecins sans Frontières, who provide basic healthcare in remote and poor regions of the globe that often lack any telecommunication infrastructure, or where that infrastructure has been destroyed by a natural disaster or human conflict. It has also been used to re-establish communications after Hurricane Katrina and the subsequent flooding in New Orleans destroyed the telecommunication infrastructure [12], to coordinate relief work.

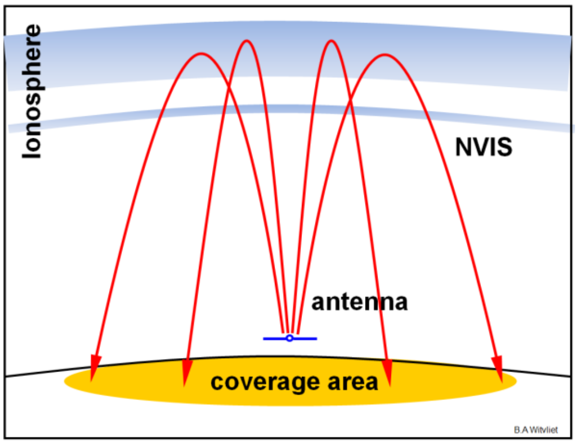

Figure 1. Near Vertical Incidence Skywave (NVIS) propagation: vertically emitted radio waves are reflected when their frequency is lower than the critical frequency of the ionosphere. Picture from [13].

Vertically emitted radio waves are reflected in the ionosphere at a height where the wave frequency equals the plasma frequency, of which the latter is directly related to the local electron density [14]. This can be at a height between 80 and 100 km at or slightly below the local maximum of the electron density of the E-region. Or at heights between 200 and 350 km, at or below the maximum electron density in the F-region of the ionosphere. When the wave frequency is higher than the peak plasma frequency or ‘critical frequency’, vertically emitted waves will pierce the ionosphere, while lower angle waves will still be reflected, causing a zone around the radio station that is not covered, the ’skip zone’ [15]. This is not desired in humanitarian communications, where a contiguous area directly around the station must be served. As the ionization of the atmosphere is driven by the solar radiation, the electron density and the electron density distribution of the ionosphere follow a diurnal cycle, modulated by the solar activity and space weather events.

3 FACTORS INFLUENCING THE NVIS LINK PERFORMANCE

To optimize NVIS link performance, we will consider the radio wave propagation, adapting the antenna to the propagation, as well as modulation and coding. This is also the sequence in which optimization must take place.

3.1. RADIO WAVE PROPAGATION

The propagation mechanism is often considered a given that cannot be changed. However, the way that radio waves propagate through the ionosphere and the resulting radio channel can be changed drastically by changing parameters of the radio system and especially the antenna. We therefore have to understand the propagation mechanisms to use them optimally.

3.1.1. Frequency selection

As discussed above, selection of the right frequency is essential to achieve optimal radio wave propagation. Ionospheric models that assimilate real-time measurements in the background ionosphere model IRI, such as IRTAM and NECTAR [16], can help finding a set of frequencies for the current state of the ionosphere, including space weather effects. When the wave frequency exceeds the instantaneous critical frequency, the ionosphere becomes translucent and the NVIS propagation path disappears.

3.1.2. Night-time propagation above-the-MUF

The incoming signal does not fully disappear however; the transmitter can still be received, albeit much weaker, typically 45-50 dB lower than the daytime NVIS signal. This can be seen in Figure 2, showing both the night-time above-the-Maximum Usable Frequency (MUF) propagation and the daytime NVIS propagation. In this example, at night, the signal-to-noise ratio (SNR) is still 20 dB, as was demonstrated by briefly switching off the transmitter at 02:30 UTC. Measurements using a professional direction finder have shown that this signal arrives at low elevation angles from all azimuths. Apparently, as lower angle waves are still reflected by the ionosphere, the scattering of waves on large surfaces of land at distances between 500 and 2000 km returns energy from many directions, adding up to a somewhat diffuse and noisy signal, well above the ambient noise.

3.1.3. The ionosphere, a doubly refractive medium

As follows from the formula describing the refractive index of a plasma in the presence of a magnetic field, and empirically proven by Appleton and Builder in 1933, the ionosphere is birefractive [17]. This phenomenon causes the NVIS radio waves to split in an ordinary and extraordinary component, each with elliptical (nearly circular) polarization of opposite rotation sense. As each of them experiences a different refractive index, their path through the ionosphere is different, resulting in different delays and attenuations. On reception, their recombination creates ‘polarization fading’: rapidly varying amplitude and polarization, in a seemingly random pattern. Also, the critical frequency of both waves differs, and the NVIS propagation of the extraordinary wave lasts significantly longer than that of the ordinary wave, which can be seen in Figure 2. This gives rise to the ‘Happy Hour’ phenomenon: at sunrise and after sunset there is a time interval in which only the extraordinary wave propagates. In that interval there is less fading and the polarization is circular. The rotation sense is right-handed in the Northern hemisphere.

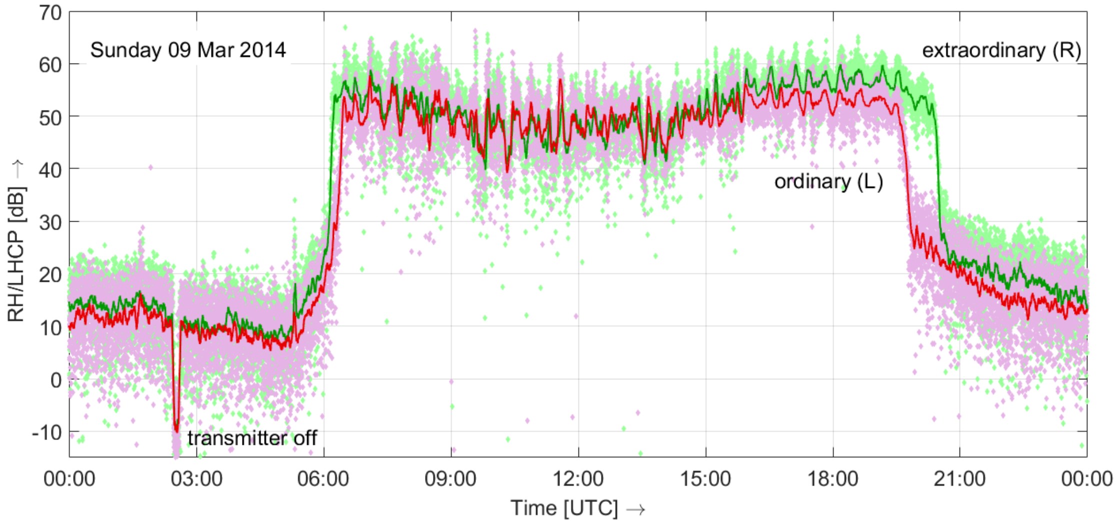

Figure 2. Daytime NVIS and night-time above-the-MUF propagation. Reprocessed measurement data from [18].

3.1.4. D-region absorption and space weather

During daytime, the optimum frequency will be close to the critical frequency, as the absorption of the D-region, at heights between 60 and 80 km, increases with decreasing frequency. Space weather in the form of solar X-ray flares can cause a dramatic increase of D-region ionization and absorption. This is phenomenon is known as the 'Mögel-Dellinger effect', a 'Sudden Ionospheric Disturbance' (SID) or a 'Short-Wave Fade-out' (SWF).

An example of such an SWF is given in Figure 3, where an X1.6 solar flare occurred at 14:05 UTC during a 7 MHz NVIS propagation measurement. All radio signals were suddenly attenuated by more than 40 dB. The background noise also dropped 12 dB, which demonstrates that most of the radio noise in a remote rural location arrives via the ionosphere. The onset of an SWF is always sudden, the recovery is gradual. An SWF may also last considerably longer than this example, depending on the characteristics of the solar flare.

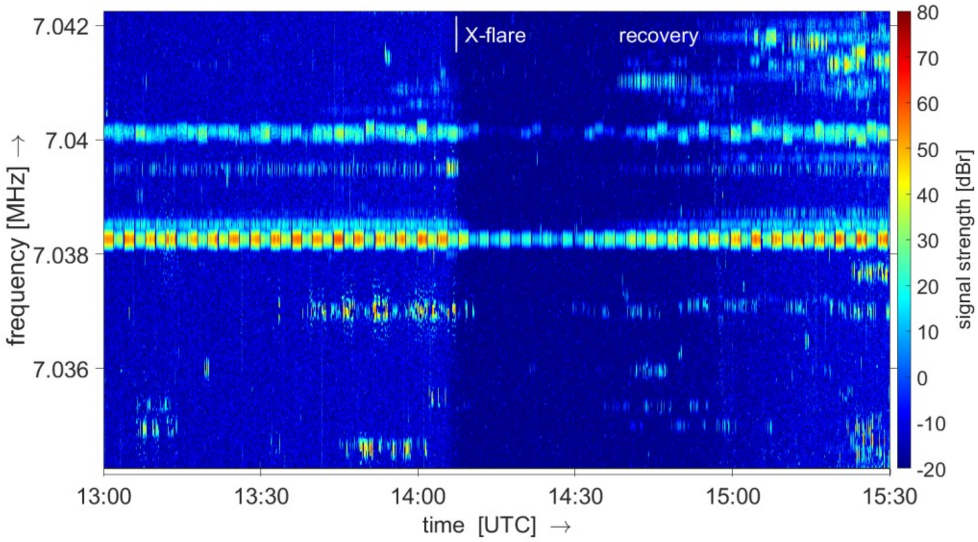

Figure 3. Impact of a solar X-ray flare, suddenly increasing D-region absorption. Reprocessed measurement data from [19].

3.2. INFLUENCE OF ANTENNA CHARACTERISTICS

The antenna radiation diagram, radiation efficiency and directivity have a direct impact on the path loss and SNR. Antenna polarization also influences the temporal characteristics of the radio channel such as time dispersion, Doppler dispersion and selective fading.

3.2.1. Antenna diagram

The elevation angle resulting from NVIS propagation can be simulated using ionospheric raytracing software. The results vary with the sunspot number, which influence the vertical electron density profile of the ionosphere, and the frequency, which influence the height at which the radio wave is refracted. Figure 4 and 5 show these simulations for a sunspot number of 10, representing a solar cycle minimum, and 120, representing a solar cycle maximum [20]. For distances less than 200 km and F-region reflection, the elevation angle varies between approximately 60° and 90°. Considering this, vertical antennas must be considered very poor NVIS performers, as they radiate most of their energy at much lower angles, typically with a maximum at an elevation angle of 20° to 30°. Their antenna diagram has a pronounced null at the zenith and at NVIS angles their antenna gain is 12 – 30 dB less then at the angle of maximum radiation. Therefore, even if their efficiency would have been good - which is not the case - vertical whip antennas on cars perform very poorly for short-range HF communication [15]. For NVIS, an antenna must be selected that radiates towards the zenith. A horizontal resistor terminated folded dipole antenna (T2FD) will outperform the whip antenna by 15-30 dB, mainly because of the favourable vertical radiation diagram. In emergency situations, when communication cannot be establish using the whip antenna, to string-out a simple horizontal wire may help to re-establish vital communications.

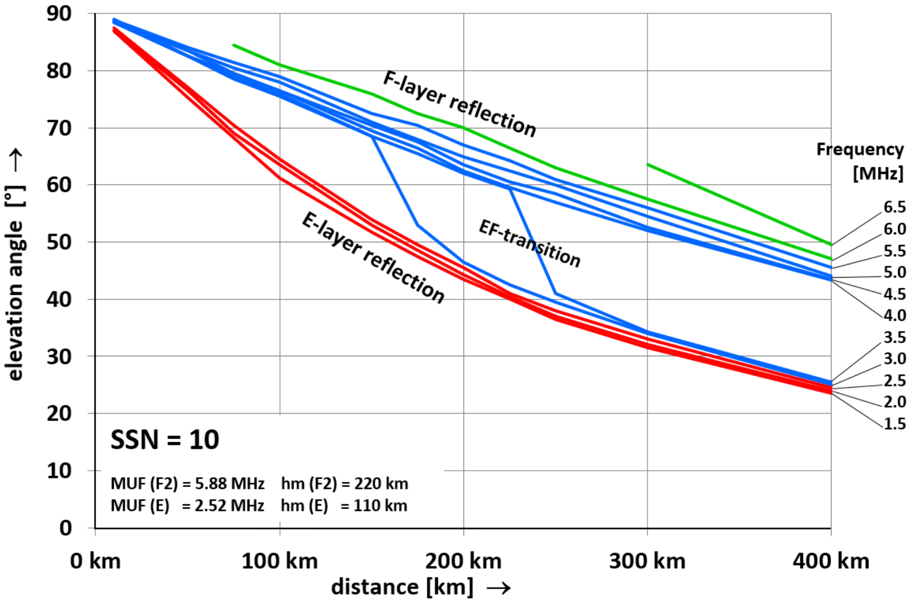

Figure 4. Simulated elevation angle versus distance. Sun spot number is 10. Figure reproduced from [13].

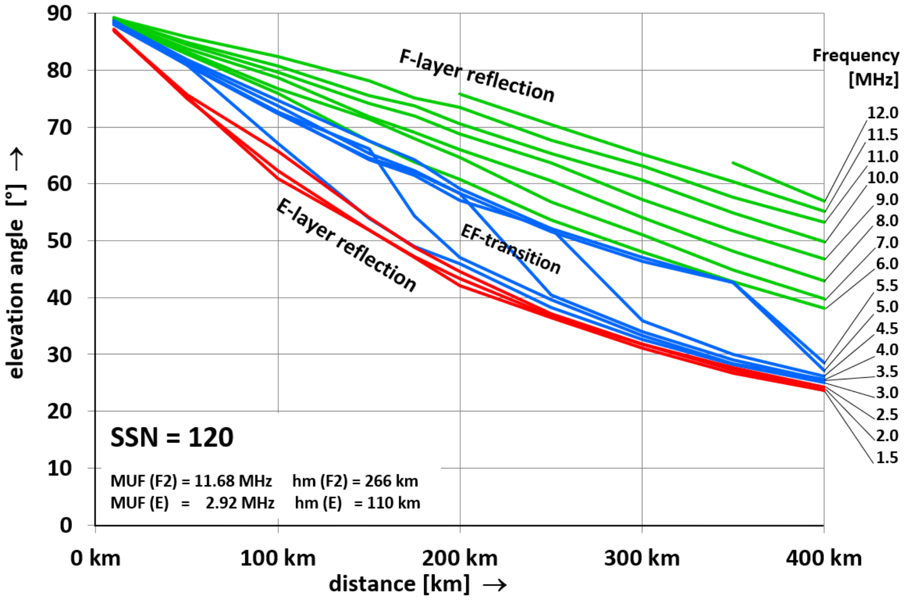

Figure 5. Simulated elevation angle versus distance. Sun spot number is 120. Figure reproduced from [13].

3.2.2. Radiation efficiency of the transmit antenna

Concerning the horizontal T2FD antenna it is important to note that the optimum height is not 'as low as possible' as some non-scientific sources claim. At low heights, the ground absorption increases rapidly, exceeding 10 dB at 0.03 λ, resulting in a low antenna gain at low heights. The optimum height is also not 0.25 lambda for radiation towards the zenith, as some scientific source will. Both the ground losses and the directivity created the interference of the antenna and its ground reflection image change with height and must be considered.

Simulations and measurements have confirmed that the optimum height depends somewhat on the ground type, but ranges from 0.22 λ (dry sandy soil) to 0.19 λ lambda (farmland and marshes) [15]. At this height, the antenna gain of a simple half-wave dipole for NVIS elevation angles is 10-15 dB higher than at 0.03 λ. Optimum antenna heights can be found in Table 1:

TABLE 1
Optimum NVIS Antenna Height

Soil type	σ	ε_r	Transmit	Receive
urban / sandy soil	1 mS/m	5	0.22 λ	0.11 λ
lake / sweet water	5 mS/m	80	0.20 λ	0.08 λ
farmland	20 mS/m	17	0.19 λ	0.08 λ
marsh	30 mS/m	20	0.18 λ	0.08 λ
sea / salt water	5000 mS/m	80	0.13 λ	0.04 λ

The height can also not be increased at will. While the antenna gain may increase at heights above 0.25 λ, the maximum radiation will shift to lower angles while the gain at NVIS elevation angles decreases. At heights that are a multiple of 0.5 λ a null appears at the zenith, making the antenna a very poor performer for NVIS.

The antenna gain of a T2FD antenna, which is popular amongst humanitarian and military users, depends on antenna length and frequency and is generally 5-7 dB lower than a resonant half-wave dipole at the same height. A vertically oriented Log-Periodic Dipole Antenna (LPDA) may provide 6 dB gain over a dipole antenna, but is a bulky structure to install and maintain. Alternatively, colinear arrays may be constructed of horizontal dipole elements, all installed at equal heights.

3.2.3. Directivity of the receive antenna

At frequencies at which NVIS propagation is possible, typically between 3 and 10 MHz, the ambient electromagnetic noise is substantial. Therefore, the SNR on reception is not determined by signal strength and the receiver noise, but by the ratio of the incoming signal and the ambient noise. Ground losses and antenna efficiency equally influence the strength of wanted signal and ambient noise, and leaving the SNR unaltered. Therefore, on reception, antenna gain is not important, only directivity is.

If we investigate the impact of receive antenna height, we find that directivity changes slowly with height, with only 1 dB variation between at 0.01 λ and 0.25 λ. [15]. For reception therefore the antenna height is not very critical. The optimum heights can be found in Table 1.

If we assume that radio noise arrives from every direction, while the wanted signal arrives from NVIS elevation angles, the ideal antenna would only receive within a cone of 30°

around the zenith, suppressing noise coming from all other directions. Contrary to the transmit antennas, where large structures are needed to achieve high efficiency, receive antennas can be small and may be integrated with an active element to form an active antenna. Arrays of such small antennas may be used to create a single beam towards the zenith 60° beamwidth, suppressing noise from all other directions to greatly improve SNR. This is especially important in asymmetric communication systems, where a fixed station with high power and a large antenna communicates with fields crew using low power and small antennas.

3.2.4. Polarization

As we have seen in Section 3.1.3, the ionosphere is birefractive, and that the received incoming wave is actually a summation of the ordinary and extraordinary waves, which have unequal and varying delay and hence phase difference. Their interference results in multipath fading even for a single-hop propagation path. As both waves have circular polarization with opposite sense, the resulting polarization will vary rapidly. This ‘polarization fading’ can be eliminated by matching the polarization of the transmit or the receive antenna to one of the characteristic waves, eliminating reception of the other. This only needs to be done at one end of the radio link.

Very large circularly polarized NVIS antennas, such as spiral reflector antennas and crossed LPDA’s pointed vertically are sometimes used in fixed installations for marine NVIS communications. However, even two perpendicular Inverted Vee dipoles suspended from a single mast, followed by a phasing network, will make an excellent circularly polarized NVIS antenna.

With a receive antenna that simultaneously receives both polarizations, an effective diversity system can be made, which may improve performance when unfavourable space weather causes instable conditions in the ionosphere such as Travelling Ionospheric Disturbances [21]. Such a receive system can be realized with a dual channel direct sampling digital receiver, each input connected to one of the above-mentioned perpendicular dipoles (or the elements of another dual polarization antenna). Two polarized receiver data streams can then be realized by adding the phasing in the digital domain.

Dual circular polarization antennas can also be integrated in existing MIMO systems, effectively doubling the number of MIMO channels and minimizing antenna correlation [22]. It was proven in [18] that the isolation between the ordinary and extraordinary waves exceeds 25 dB, therefore entirely different signals could be sent via both waves, if matched circular polarization is used on both sides of the radio link. This can be used to double the channel capacity, even without resorting to MIMO coding.

3.3. MODULATION AND CODING

The optimization of the propagation channel by selecting the optimum frequency, the realization of optimum receive and transmit antennas and the effective use of antenna polarization must be completed first, thereby optimizing the resulting radio channel in terms of path loss, fading, SNR and distortions. The measures in the sections above will result in a modified, more stable and less distorted radio channel, over which adapted modulation and coding schemes are likely to gain higher data throughput and reliability.

3.3.1. Modulation systems for night-time above-the-MUF propagation

As we have seen, night-time above-the-MUF propagation produces weak signals, but signals that remain well above the ambient noise. This signal could still be used to transfer a few 'golden bits' in case of an emergency. For example, if an ambulance of a humanitarian organization breaks down in the inlands of Congo, at a time when NVIS propagation is no longer available, an alert signal with position information can be coded in a handful of bytes and sent. However, the observed night-time above-the-MUF signal sounded noisy, as if modulated by fast amplitude variations similar to signals in troposcatter radio systems. Hence new modulation and coding solutions are necessary for this propagation mechanism. It is important to remember that for night-time above-the-MUF propagation the antenna should be adapted too: this is not NVIS propagation and the signals typically arrive from all around, and at elevation angles between 10° and 45°.

4 TOPICS FOR FURTHER RESEARCH

More research to realize wideband antenna with a more constant radiation pattern and higher efficiency than the widely used T2FD antenna would improve HF communications, not only for humanitarian applications, but also for general utility communications in Lower- and Middle-Income Countries and island states.

Receive antenna arrays to improve the SNR of NVIS radio links are also sought after, for which active antennas with low internal noise level and large intermodulation free dynamic range (IFRB) are needed, preferably with dual polarizations.

More research into the scattering night-time above-the-MUF propagation is desired, investigating channel distortions that may consist of short-term amplitude variations, time dispersion and Doppler spread. Recording the radio channel for playback would be helpful to design and test modulation and coding systems that will work in this channel.

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