Beyond-line-of-sight propagation

by David M. Fiedler and George H. Hagn

The US Army has utilized high frequency (HF) radio (2-30 MHz) for both strategic and tactical communications purposes for approximately the last 60 years in order to achieve ranges beyond line-of-sight (BLOS). In particular, HF was used in WWII, the Korean War, and the war in Southeast Asia to provide tactical communications over BLOS ranges in difficult terrains (mountains and jungles, for example). Initially, the mid-1970s Integrated Tactical Communications Systems (INTACS) study showed existing tactical HF links being replaced by satellite links. A more recent recognition of the cost, vulnerabilities, and availability of satellites, and HF technology advances have led to a renewed recognition of the military utility of modern HF systems for satisfying these requirements. Additionally, in today's tactical units, HF radio is a major means of communication which must be used in any "come-as-you-are war." Therefore, it is timely to reconsider the propagation modes and antennas recommended for tactical use. Over the years, the theory of HF communications and its military applications have been described in various US Army technical and field manuals which today have culminated in publications such as FM 24-18 (Field Radio Techniques), FM 11-65 (High Frequency Radio Communications) and TM 11-666 (Antennas and Radio Propagation). All of these publications place primary emphasis on what in the past have been the most useful modes of HF radio propagation for military purposes. These modes are useful for short range (0-50 miles) tactical communication (see figure 1) and for long range communication (see figure 2) and include modes such as:

Direct Wave Mode: Defined as the component of a wave front that travels directly via line-of-sight (LOS) from the transmitting antenna to the receiving antenna (see figure 1). This mode is very useful for air-to-ground communications since terrain features which absorb RF energy normally are not in the propagation path. Over the ground, however, the range for this mode is limited by terrain absorption and by path blockage caused by terrain features.

Ground-Reflected Wave Mode: Defined as the component of the radiated wave that reaches the receiver after being reflected from the ground (see figure 1). Since the ground-reflected wave travels a longer distance, it arrives at the receive antenna later than the direct wave, and it can cancel or enhance the direct-energy waves of depending upon the geometry, frequency, and the reflection coefficient of the ground. The ground-reflected wave can be used for communications under some circumstances if the reflected wave is somehow less attenuated than the direct wave at the receiver — although most of the time, it is undesirable since it tends to weaken the direct wave for most tactical geometries at HF.

Space Wave Mode: Defined as the combination (the vector sum) of the direct and ground-reflected waves. Militarily, the phenomena associated with the space wave led to much maneuvering on the battlefield to assure that the communications equipment was sited on the highest ground in order to reduce the effect of terrain on range and effectiveness. The space wave provides the best propagation mode for short-range LOS tactical HF communications once the location problems are overcome.

Surface Wave Mode: Defined as that component of the groundwave (see e below) that travels along the earth's surface (see figure 1) and is primarily affected by the conductivity and/or dielectric constant of the earth. When the transmitting and receiving antennas are located close to the earth (as they are in most tactical communications applications), the direct and ground-reflected waves tend to cancel each other. In this case, the resulting composite signal is principally that of the surface wave. The surface wave diminishes in strength with height above the ground, and usually it is not very useful above about one wavelength over the ground. The energy of the surface wave is absorbed by the earth at twice the rate of the direct wave mode (in dB) as it travels over the ground. A distance is reached where it can no longer be used for communication. This usable distance over the earth's surface can be increased by polarizing the wave in a vertical orientation since the earth produces much less of an attenuation effect on vertical than on horizontal polarization for antennas located near the earth.

Groundwave Mode: Defined as the vector sum of the space wave and the surface wave. This formulation of the theory of groundwave propagation by

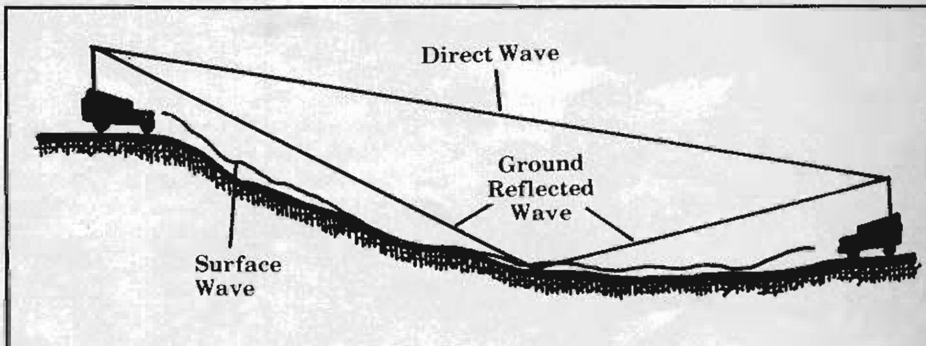


Figure 1. Possible routes for ground waves.

modes and antennas

A. Sommerfeld in the early 1900s was made practical for engineering use by K. A. Norton in the late 1930s and early 1940s. As stated in FM 24-18, under ideal conditions, useful groundwave energy can extend to ranges up to 50 miles. This is well BLOS; however, there are much more common conditions which limit useful groundwave propagation to as few as 2 miles, for example, manpack radio operations in a wet, heavy jungle. This wide variation in range is due to the varying condition of the earth (ground conductivity, vegetation, terrain irregularity, and so on), the atmosphere, and radio-noise; and thus it cannot be controlled by the communicator. This can be a disaster when trying to establish effective communications for command and control (C^3) in units deployed over a wide area when the communications planner does not properly consider the impact of these effects on the performance of his communications systems.

Classical Skywave Mode: Skywave is defined as those types of radio transmission that make use of ionospheric reflection. Skywave modes can provide communication over longer distances than can be achieved via groundwave. The reflection of HF energy from the ionosphere back to earth is dependent upon such things as the number of free electrons per unit volume in the ionosphere, the height of the ionized layer, operating frequency, incidence angle, etc. These variables, however, are not the main subject of this article. A good detailed description of this mode is given in TM 11-666 and in reference six at the end of this essay.

Figure 2 (see also references 1-3 at the end of this paper) depicts the skip-zone problem that faces tactical communicators. Under ideal conditions, the groundwave becomes unusable at about 50 miles. Under actual field conditions, this range can be much less, again sometimes as few as 2 miles. Successful skywave communication for any length of path and system depends upon the selection of a frequency which is low enough to be reflected by the ionosphere. The selection of the proper antennas is also important. Whips are commonly used, and they have low gain for skywaves on such short paths. Therefore, frequency selection and/or antenna choice can leave a skip zone of at least 50 (and more probably 70) miles where HF communication will not function. Translating this into terms of military deployments, this means that units such as long-range patrols, armored cavalry deployed as advanced or covering forces, air-defense early-warning teams, and many division-CORPS, division-BDE, division-DISCOM, division-DIVARTY stations using whips are in the skip zone. Thus they are unreachable by HF radio under skip zone conditions even though HF is a primary means of communication planned for use by these units.

A closer examination of figure 2 shows a wave striking the ionosphere at a high angle and being reflected into an area covered by a strong groundwave signal. This wave is labeled "skywave not effective" in all references because the groundwave signal strength is much stronger than the skywave signal. Unfortunately, the figure is misleading in several ways. Energy radiated in a near-vertical-incidence direction is not reflected down to a pinpoint on the earth's surface. If it is radiated on too high a frequency, the energy penetrates the ionosphere and continues on out into space. Energy radiated on a low enough frequency is reflected back to earth at all angles (including the zenith) resulting in the energy striking the earth in an omnidirectional pattern without dead spots (without a skip zone) if an efficient short-path antenna such as a doublet is used. Such a mode is called a near-vertical-incidence skywave (NVIS) mode. This mode is shown in figure 2, but the concept is illustrated in figure 3. This effect is similar to taking a hose with a fog nozzle and pointing it straight up. The water falling back to earth covers a circular pattern continuously out to a given distance. A typical NVIS received-signal pattern is shown in figure 4, and the path is shown in figure 5. The main difference between this short-range NVIS mode and the standard long-range skywave HF mode is the lower frequency required to avoid penetrating the ionosphere at the near-vertical angle of incidence of the signal upon the ionosphere. In order to attain an NVIS effect, the energy must be

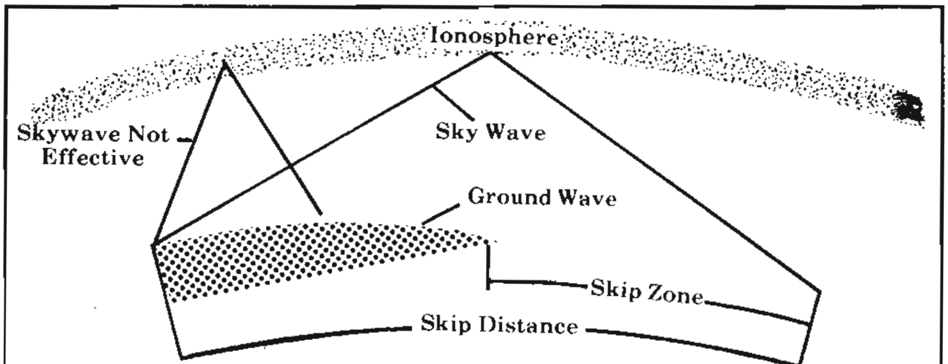


Figure 2. Skip Zones.

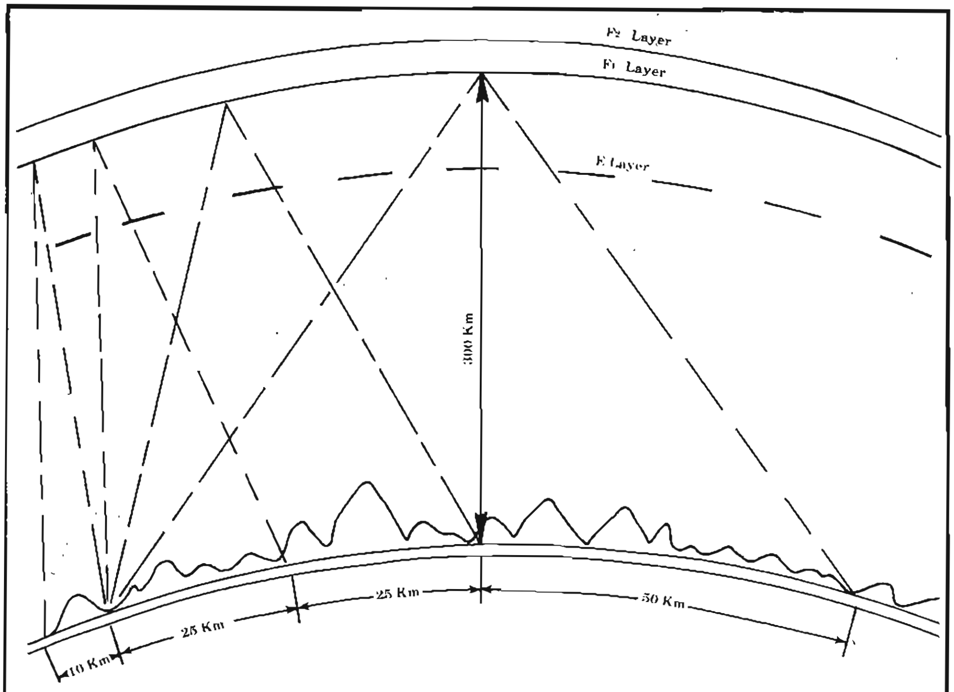
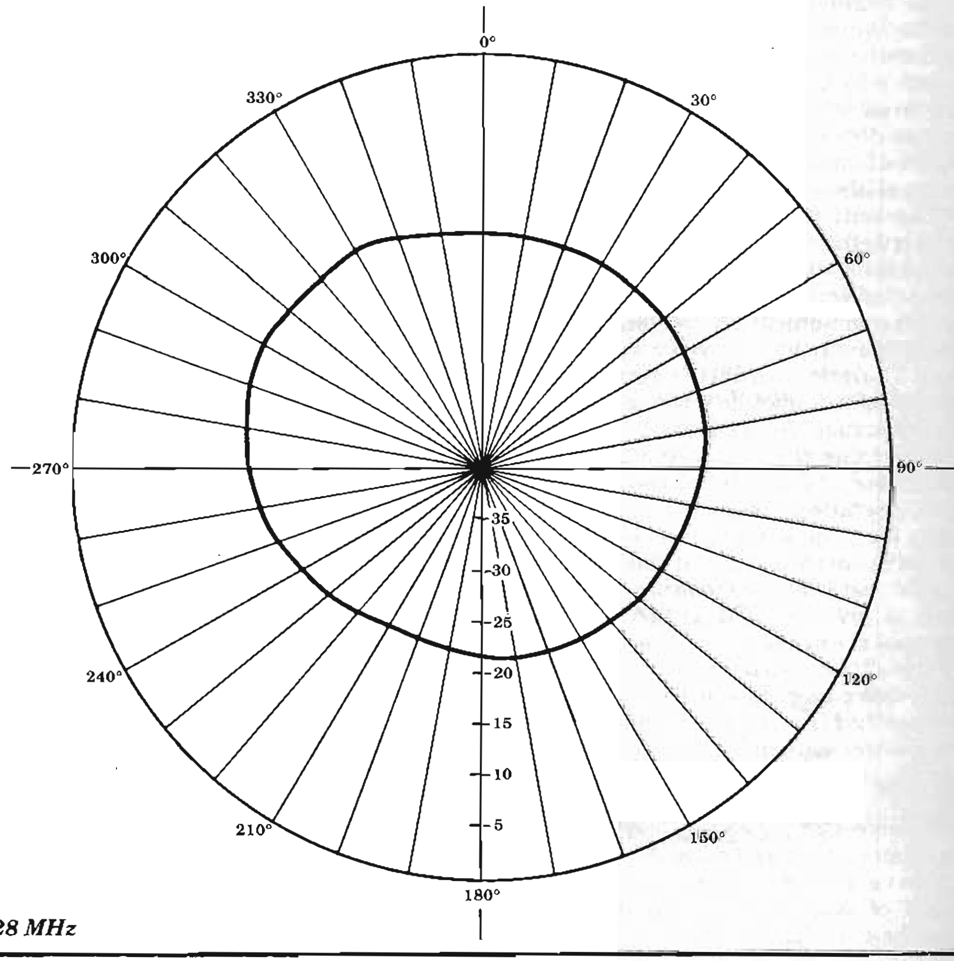


Figure 3. NVIS Propagation Concept.

radiated strongly enough at angles greater than about 75 or 80 degrees from the horizontal on a frequency that the ionosphere will reflect at that location and time. The ionospheric layers will reflect this energy in an umbrella-type pattern with no skip zone. Any groundwave present with the NVIS skywave signal will result in undesirable wave interference effects (fading) if the amplitudes are comparable. However, proper antenna selection will reduce groundwave radiated energy to a minimum, and this will reduce the fading problems. Ranges for the NVIS mode are shown in figure 5 for a typical ionosphere height (300 km) and takeoff angles. Since NVIS paths are purely

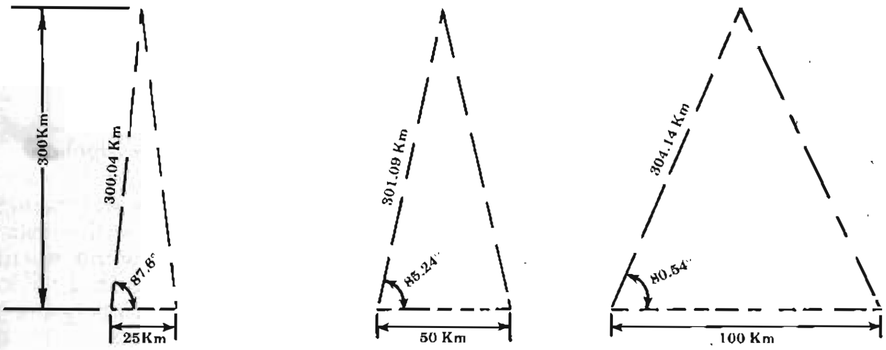


10 May 74
11:30 Hours
-18.5 dB relative to half-wave horizontal dipole

(Ricciardi and Brune, 1979)

Figure 4. NVIS Antenna Pattern 4.328 MHz

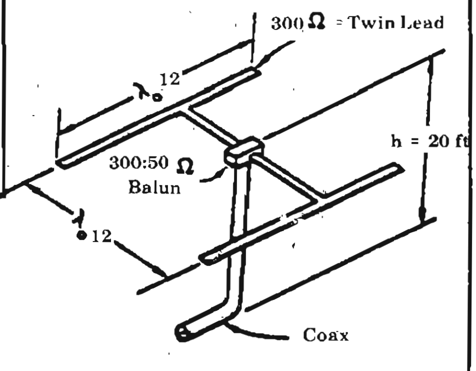
skywave, the path losses are nearly constant at about 110dB +10dB. This is significant for the tactical communicator since all the energy arriving at his receive antenna is coming from above at about the same strength over all of the communications ranges of interest. This means the effects of terrain and vegetation (when operating from defiladed positions such as valleys) are greatly reduced, and the receive signal strength will not vary greatly with relatively small changes in location.



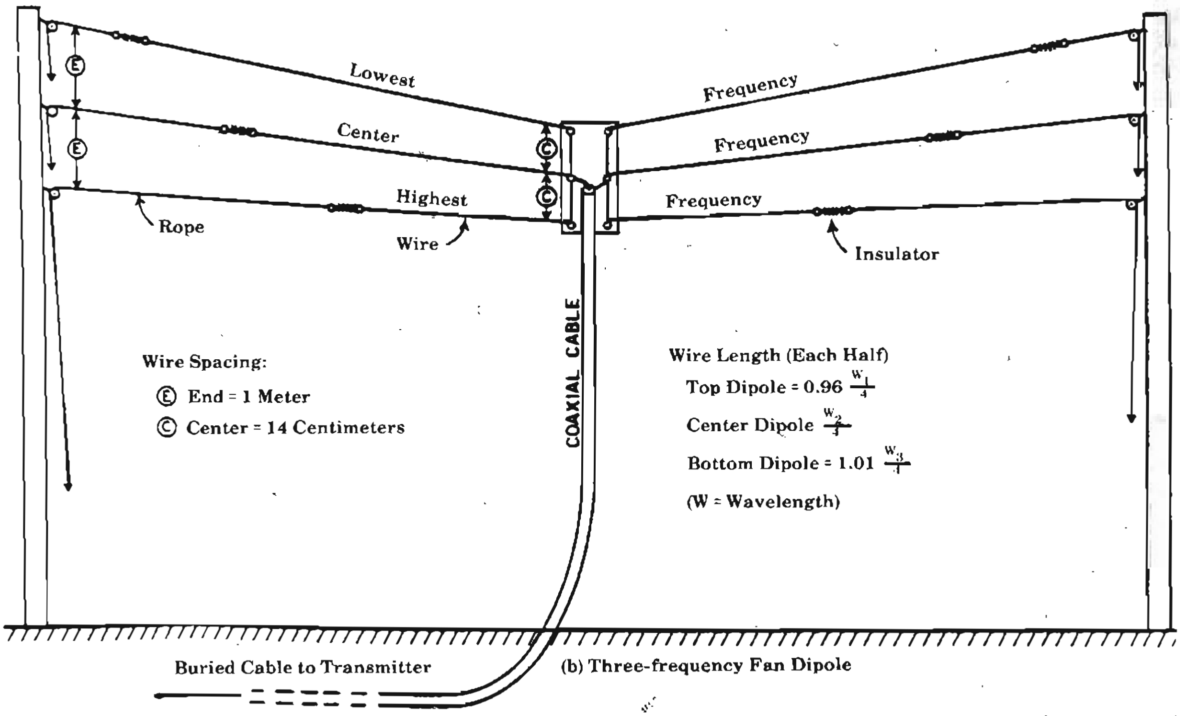
Ground Range Km	Radio Path Length Km	Range Variable 20 log d	V Loss dB
25	600.5	55.57	0
50	602.08	55.59	.02
100	608.28	55.68	0.11

Night or Day absorption, turn-around, normal atmospherics.
Average Path Loss (3 to 5 MHz) + 110 dB + 10 dB.

Figure 5. Path Length and Incident Angle (NVIS Mode.



(A) Shirley Dipole Array



(b) Three-frequency Fan Dipole

Figure 6. Shirley and Fan Dipole NVIS Base Station Antennas.

Antennas	Clearing	75-ft Forest	Clearing	50-ft Forest	Clearing
h/2 Unbalanced single-wire dipole	=1.0	-2.8	0.0	-1.2, -1.7	0.0
h/2 Balanced single-wire dipole	=0.5	-3.7	No data	No data	No data
h/2 folded Dipole (300:50 U balum)	=0.2	-1.0	No data	No data	No data
h/4 Short (loaded to h/2) dipole	-3.0	-5.2	No data	No data	No data
h/2 Sleeve dipole (on ground)	-32.1	-28.3	No data	No data	No data
3-Freq. fan dipole @ 15 ft	-0.4	-5.1	No data	No data	No data
3-Freq. fan dipole @ 12	-2.4	-5.6	No data	No data	No data
3-Freq. fan dipole @ 9	-4.0	-8.1	No data	No data	No data
Shirley folded dipole	=3.0	-0.3	No data	No data	No data
3 h/4 Inverted L (l:h = 2:1)	-0.0	-2.8	No data	No data	No data
3 h/4 Inverted L (l:h = 3:1)	-0.8	-3.3	No data	No data	No data
3 h/4 Inverted L (l:h = 4:1)	-1.0	-5.8	No data	No data	No data
3 h/4 Inverted L (l:h = 5:1)	-2.0	-6.3	-10.2	-10.7, -12.5	-9.0
30° Slant wire (h/r elevated)	-10.1	-14.8	-11.8	-13.5, -14.2	-14.0
60° Slant wire (h/r elevated)	-11.8	-14.8	No data	No data	No data
10-ft Square (vertical plane) loop @ 6 ft	-24.1	-25.3	No data	No data	No data
16.5-ft Whip	-41.5	-44.0	-31.7	-25.0, -25.2	No data

Summary of relative gain toward the Zenith for Field-expedient HF Antennas (in dB)

Table 1.

This is especially important for helicopters flying nap-of-the-earth beyond VHF radio range.

The need for short-range HF communications without skip zones is obvious. Therefore, our next problem is how to generate the required radiation characteristics. Fortunately, this is not difficult since 1/2-wave dipole antennas located from 1/4 to 1/10 wavelength above the ground will cause the radiated energy to be directed vertically. Table 1 shows the relative gain toward the zenith of the most common types of HF field-expedient antennas. This table shows that the 1/2-wave Shirley Folded Dipole (see figure 6) has the most gain toward the zenith (with the other dipoles being almost as good). The Shirley dipole is a good NVIS base station antenna, but it is limited to a band of frequencies within about 10 percent of the design frequency. The fan dipole (see figure 6 and table 1) performs almost as well, and it provides more frequency flexibility (day, night and transition period frequencies). For tactical communications, these dipoles can be easily deployed in a field-expedient manner because they can be located close to the ground. For mobile (or shoot and scoot) operations, vehicle-mounted antennas are required. The answer to this problem is the standard 16 1/2-foot whip bent down into a horizontal position. In this configuration, the whip is essentially an asymmetrical dipole (with the vehicle body forming one side) located close to the earth, with a significant amount of energy being directed upward to be reflected back by the ionosphere in an umbrella pattern. For use while operating on the move, of course, the whip antenna must be tied across or parallel to the vehicle or shelter. This configuration is more like an asymmetrical open-wire transmission line, and it also will direct some energy upward — although with less efficiency. There are still no skip zones with proper frequency selection, but received signal levels are weaker than with the whip tied back. Special NVIS antennas designed primarily for helicopters are also useful for this application, and they can be modified for shelter and ground vehicular operation.

Traditionally, wire dipole antennas have always been sited so that the broadside of the antenna was pointed toward the receive station. This is the correct approach for long-haul paths. When using the NVIS mode, this antenna orientation is unnecessary. For NVIS operation, the antenna orientation does not matter since all the energy is directed upward and returns to earth in what is essentially an omnidirectional pattern. In operational terms this means that the dipole should be erected at any orientation that is convenient at the particular radio site without regard to the bearing of other stations. This holds true except when operating in the region of the "magnetic dip equator." When operating within 500 km of the dip equator, the dipole antennas should be oriented in a magnetically north-south direction for greater received signal levels for all NVIS path bearings. US Army Special Forces made use of this dipole north-south orientation in their HF single sideband (SSB) net in the Mekong delta during the Vietnam War with excellent results. Traditional antenna orientation (broadside to the path direction) must be retained when operating on longer skywave paths near the dip equator and elsewhere.

While use of the NVIS technique does provide BLOS "skip-zone-free" communication, there are some drawbacks to its use that must be understood in order to minimize them. These include:

Interference between groundwave and skywave: Both an NVIS and groundwave signal are present the groundwave can cause destructive interference. Proper antenna selection will suppress groundwave radiation and minimize this effect while maximizing the amount of energy going into the NVIS mode.

High-takeoff angles: In order to produce radiation which is nearly vertical (i.e., NVIS), antennas must be selected and located carefully in order to minimize the groundwave radiation and maximize the energy radiated towards the zenith. This can be accomplished by using specially designed antennas or by locating standard dipole (doublet) antennas 1/4 to 1/10 wavelength from the ground in order to direct the energy toward the zenith.

Frequency selection: In skywave propagation, there is a critical frequency (f_o) above which radiated energy generally will not be reflected by the ionosphere but will pass through it. This frequency is related approximately (by a constant k slightly greater than unity which depends primarily on path length) to the angle of incidence (o) and the classical maximum usable frequency (MUF) by the equation: MUF = k f_o sec (o).

This means that the useful frequency range varies in accordance with the path length: the shorter the path the lower the MUF and smaller the frequency range. The lowest useful frequency (LUF) is determined primarily by the effective radiated power and the noise and interference at the receiver. Practically speaking, this limits the NVIS mode of operation to the 2-4 MHz range at night and between 4-8 MHz during the day. These nominal limits

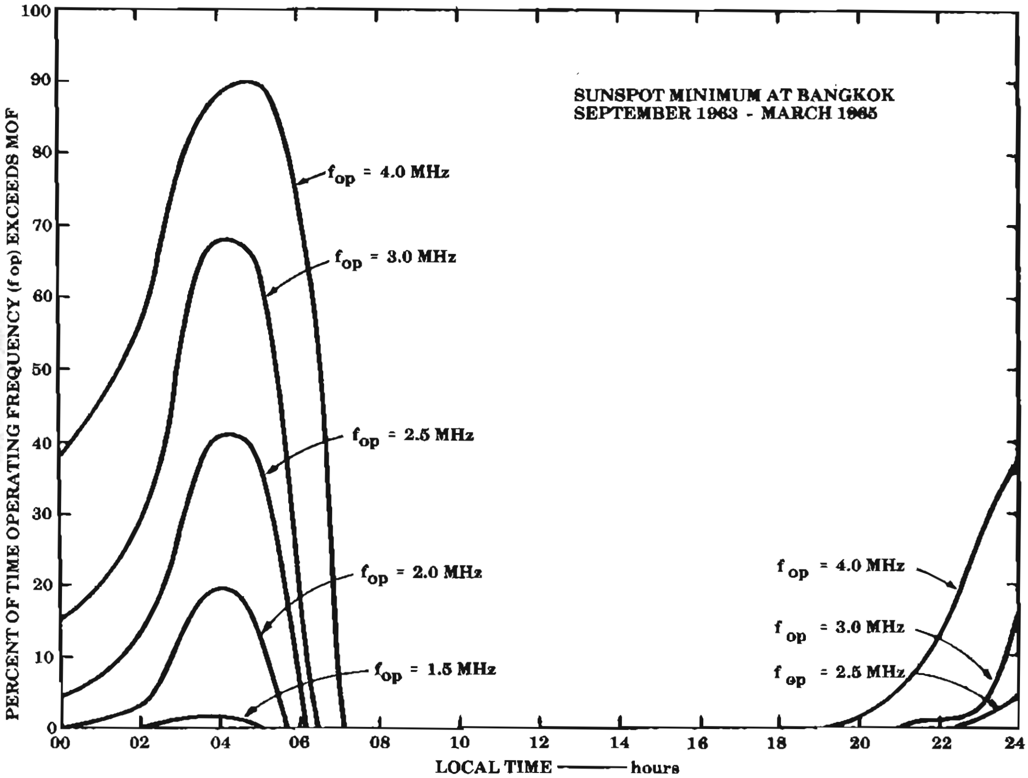


Figure 7. Percent of time the Operating Frequency Exceeds MOF of an NVIS path of length less than 50 KM

will vary with the 11-year sunspot cycle and they will be smaller during sunspot minimums (1985-86 for example). Figure 7 is an example of the percent of time an operating frequency would have exceeded the maximum usable frequency (MUF) during a solar minimum. This restricting of the frequency range is due to the physics of the situation, and it cannot be overcome by engineering. Therefore, problems can be expected when using on the NVIS mode in the low end of the HF spectrum. These problems include:

The range of frequencies between the MUF and the LUF is limited, and frequency assignment may be a problem — especially during the minimum part of the 11-year solar cycle when many users are crammed into the smaller available HF spectrum.

The lower portion of the band which supports NVIS is somewhat congested with aviation, marine, broadcast, and amateur users which limits frequencies available — even during the solar maximum.

Atmospheric noise is higher in this portion of the HF spectrum in the afternoon and at night.

Man-made noise tends to be higher in this portion of the HF spectrum.

All of these drawbacks of NVIS transmission, except the limited frequency range, can be overcome with relative ease. Once this is done, the many advantages to the tactical communicator are clear. They include:

Skip-zone-free omnidirectional communications.

Terrain-independent path loss resulting in a more constant received signal level over the entire tactical operational range instead of widely varying path loss with distance, and the corresponding uncertainty in operational range.

Capability of operating from defiladed positions eliminating the restriction on the tactical commander to control the high ground for HF communications purposes.

Non-critical antenna orientation of doublets and other linear antennas such as inverted L's.

Several electronic warfare advantages. First, lower probability of geolocation: NVIS is received from above at very steep angles. This makes direction finding (DF) from nearby (but beyond groundwave range) locations more difficult. Next, harder to jam with groundwave jammers (the most common tactical HF jamming mode) are subject to path loss. Since all NVIS radiated energy arrives from above (skywave), terrain features can be used to attenuate a groundwave jammer without degrading the desired communication path. When operating against a station using NVIS propagation, the jamming signal will be attenuated by terrain while the skywave NVIS path loss will be constant. This forces the groundwave jammer to move very close to the target or put out more power, and either tactic makes jamming more difficult. Finally, it requires only low-power operation: the NVIS mode can be used successfully (due to the constant path loss of tolerable size) with very low-power sets provided that proper frequency and antenna selections are made. This will result in much lower probabilities of

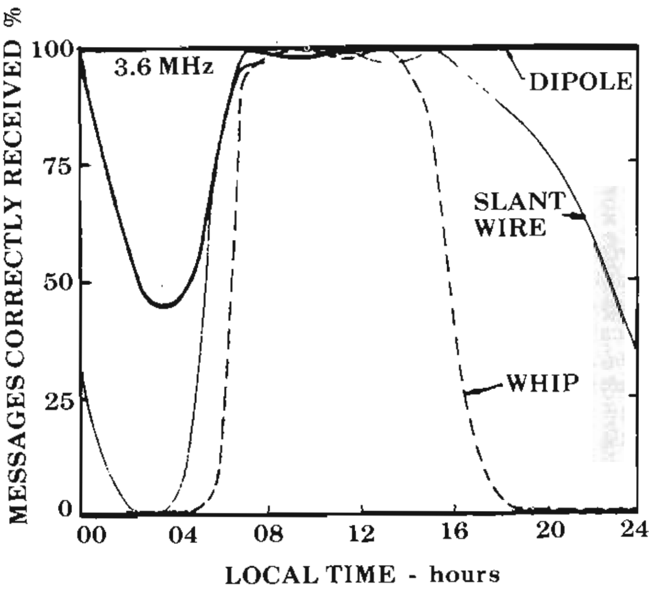


Figure 8. Communication success with AN/PRC-74 as a function of time of day and antenna type over 12-mi path in low mountains, spring and summer 1963.

intercept and detection. Figure 8 shows results obtained in Thailand jungles and mountains with the 15-W AN/PRC-74 operating with selected antennas on one SSB voice frequency (3.6 MHz) over a 24-hour period during the 1963 sunspot minimum. Clearly the 1/2 wave dipole provided the best results, and it was operating NVIS for ranges beyond about 5 miles. The whip was operating groundwave out to about 20 miles and NVIS beyond, and the slant wire was intermediate between the dipole and whip. The performance with the dipole would have been even better if a frequency change (QSY) had been permitted near dawn (see figures 8 and 9), but QSY was not permitted in the test.

With this date in mind, tactical communicators should add another dimension to their thinking and planning. NVIS techniques must be considered under the following conditions:

- When the area of operations is not conducive to groundwave HF communications (e.g., mountains).
- When tactical deployments that place stations in anticipated skip zones when using traditional antennas (whips), frequency selection methods and operating procedures.
- When operating in heavy, wet jungles (or other areas of high signal attenuation).
- When prominent terrain features are not under friendly control.
- When operating from defiladed positions.
- When operating against enemy groundwave jammers and direction finders.
- When flying close to the ground in helicopters or in light aircraft.

Along with the addition of the NVIS technique to our tactical HF communication thinking, it is also necessary to amend our training and doctrine to reflect more completely all HF modes available to the communicator. The Air Force has incorporated some of this information into their literature, but we have been unable to find any Army TM, FM, or POI which properly describes the advantage of the short-path skywave techniques discussed in this paper. In all cases, these techniques are either ignored or down played. In the past, this situation was unfortunate, but it was tolerable since the groundwave HF techniques being used supported, for the most part, tactical operations. At present, and more importantly after implementation of Division 86-style operation, HF radio and the NVIS mode take on new importance. HF radio and the NVIS mode take on new importance. HF radio is quickly deployable, securable, and capable of data transmission. Therefore, it will be the first (and frequently the only) means of communicating with fast-moving or far-flung units. Also, it may provide the first long-range system to recover from a nuclear attack. The planned Objective HF Radio (OHFR) will meet these requirements.

With this new reliance on HF radio, the communications planners and operators must be familiar with NVIS techniques and their applications and shortcomings in order to provide more reliable and responsive communications for the field commanders. In order to do this, NVIS must be learned, it must be taught and it must be used. Field tests with both the New Hampshire and New Jersey Army National Guard (50th Armored Division) have shown that even using obsolete radio equipment (for example, the AN/GRC-26D) and standard wire dipoles (AN/GRA-50) cut to the right frequency and located 1/4 to 1/10 wavelength from the ground, excellent results can be obtained on both air-to-ground and ground-to-ground paths. During these tests, NVIS radio was used to replace HF groundwave nets and VHF nets that required several ground and airborne retransmission stations to communicate to stations previously unreachable (without relays) due to skip zones and unsuitable terrain.

We urge that those whose problems we have described try NVIS and observe the positive results. We also urge the Army to incorporate NVIS into communication training and amend the reference TMs and FMs to include the use of the NVIS technique.

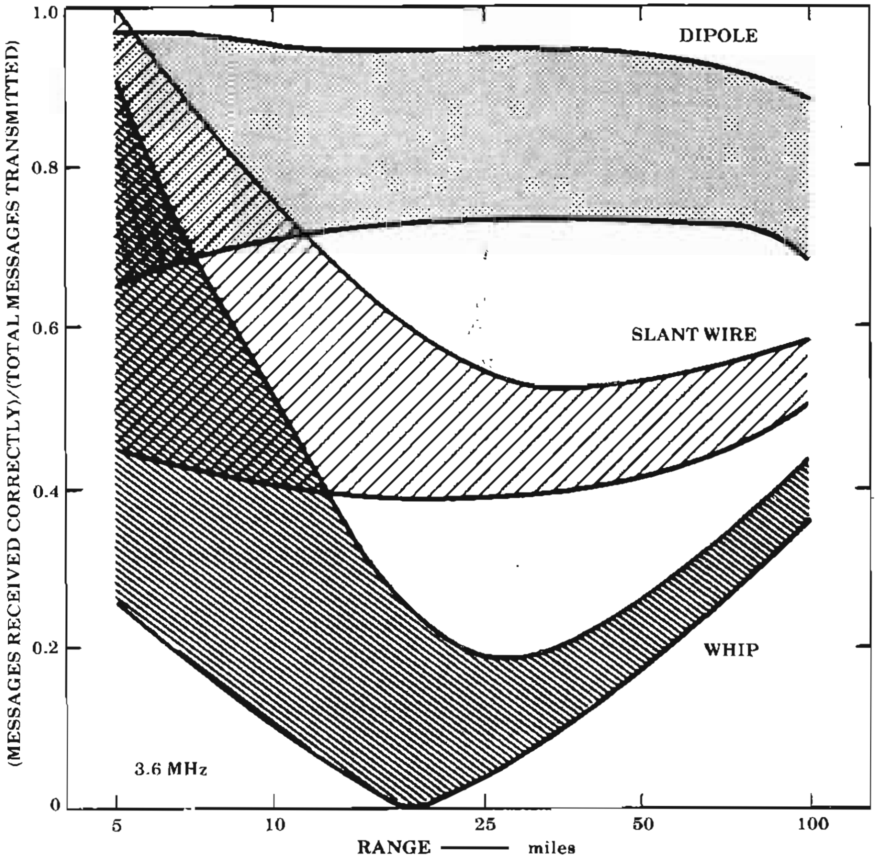


Figure 9. Communication success as a func of range for AN/PRC-74 in mountainous and varied terrain - incl jungle - in Thailand

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