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AN EMPIRICAL INVESTIGATION OF HIGH-FREQUENCY GROUND WAVE PROPAGATION

Under the sponsorship of the Defense Nuclear Agency, The Johns Hopkins University Applied Physics Laboratory investigated high-frequency ground wave propagation as a nuclear-survivable means of communication for land-mobile missile systems in Europe. Using a frequency band of 20 to 30 MHz and a portable, broadband, discone antenna, high-frequency ground wave propagation characteristics have been demonstrated that could be exploited in communication systems. Test results show that with such antennas, the upper part of the high-frequency band could be used to achieve non-line-of-sight, nonfading, communication over short-range paths for both military and civilian applications.

INTRODUCTION

In 1984, the Defense Nuclear Agency (DNA) asked APL to determine whether high-frequency ground wave (HFGW) signals could be used as a means of communication to support the Pershing Weapon System in Europe. It was speculated that HFGW propagation might be used for Pershing communications in the event of a post-nuclear loss of the ionosphere, which could disrupt ordinary HF sky-wave links. The Pershing Weapon System was an intermediate-range nuclear land-mobile missile system deployed in western Germany until the advent of the Intermediate Range Nuclear Forces Treaty.

As part of the investigation, the Laboratory was asked to perform empirical measurements of HFGW propagation in environments representative of Pershing operating areas. Although theory was to be the basis for planning tests and analyzing the outcome, we were specifically directed to produce empirical results rather than a paper study that relied on computer modeling. As much as possible, Army equipment was to be used in the tests. In addition, realistic and practical recommendations were desired; that is, suggested enhancements to communications that might result from the study could not involve purchases of major new equipment, and all suggestions had to be compatible with the Pershing system's requirements for portability and ability to operate while hidden in the forest. To be considered useful, intelligible voice communication links of at least 40 km had to be achieved in mountainous terrain. Significantly greater ranges were undesirable since one goal was to reduce the possibility of interception at hostile listening sites lying just outside the area of operations.

Ground wave communication is usually associated with frequencies of a few megahertz or less, large antennas, and a requirement for power that could not realistically be met by a land-mobile missile unit in the field. Broadcast stations in the AM band, for example, typically use ground wave communication to provide nonfading day-and-night coverage to a primary service area. A station operating at a frequency of 1 MHz might use ground wave signals transmitted at 50 kW to cover an area out to about 80 km (depending on ground conductivity). The antenna for a commercial broadcast station might be a structural steel tower at least one-quarter wavelength high (75 m at 1 MHz) that functions as a vertical radiator.

The technical challenge given APL by DNA was to demonstrate that nonfading, non-line-of-sight ground wave communication could be provided within the operational constraints of the Pershing system. Although the signal levels required did not have to meet the standards of commercial broadcasting, radio equipment available to the Pershing system had a maximum transmission power of only 400 W. Furthermore, the antenna used to radiate ground wave signals had to be portable and small enough to be hidden in the woods. Finally, unlike a commercial broadcasting station operating on a single assigned frequency, Pershing units were required to change frequencies daily to maximize communication security and minimize the jamming potential. Accordingly, any candidate antenna had to be broadband enough to transmit efficiently throughout a significant range of frequencies.

This article describes the approach used to achieve HFGW capability within the constraints of Pershing operational requirements. In addition, it shows how HFGW connectivity has been demonstrated in several challenging environments to support the potential transfer of this technique to non-nuclear applications.

CHARACTERISTICS OF GROUND WAVE

Our objective is not to develop the theory of ground wave propagation, nor to provide a bibliography of past work, but rather to define terms and describe the characteristics of ground wave signals pertinent to understanding the results reported in this article.

For our purpose, a ground wave is defined as the RF electromagnetic wave that travels along the interface between the Earth and the air, passes along the interface between the foliage and the air, diffracts over mountaintops, arrives at the receiving antenna after reflection from the Earth's surface or from the sides of mountains, and travels directly from the transmitting antenna to the receiving antenna on a line-of-sight path. The last component is the least interesting; we therefore made every attempt to avoid line-of-sight paths in the tests described in this article.

Figure 1 shows the radiation emanating from a transmitting antenna on the Earth's surface. An isolated HF transmitting antenna radiates energy into the air as well as along the ground. Ray 1 represents a wave gliding along the interface between the air and the ground. Ray 2 represents a wave traveling directly to a distant mountain and diffracting from the mountain peak. Because of this diffraction, some energy breaks away and passes into the valley while other components go skyward. Ray 2, however, follows the energy traveling to the second peak, diffracting from it, and heading to some point on the other side. Ray 3 represents energy traveling into the sky, interacting with the ionosphere, and reflecting back to a distant point on Earth. The energy designated by ray 4 passes through the ionosphere and into space. Whether a skyward-bound ray refracts from the ionosphere (ray 3) or passes into space (ray 4) is determined by the frequency of the RF radiation, the angle at which it hits the ionosphere, and the condition of the ionosphere (depending on time of day, season, latitude, and the effect of solar perturbations).

Beginning with the work of Sommerfield,[1] many theoretical investigations of ground wave propagation have been conducted. Some of the most useful and concise information is provided by the International Radio Consultative Committee.[2] Recently, computer programs have become available that use theory to predict ground wave propagation over given paths. One example is the Communication Interference/Jamming Propagation Analysis System developed by the SHAPE Technical Center, located in The Hague, The Netherlands. That system combines the Terrain Integrated Rough Earth Model ground wave propagation program developed at the DoD Electromagnetic Compatibility Analysis Center with a shell that includes Defense Mapping Agency terrain elevation data. As a result, the program can predict the ground wave signal level that might be received at a particular point, given the coordinates of the transmitting antenna and the specifications of the communication equipment being used. In addition to terrain elevations, however, ground wave propagation depends on ground conductivity, dielectric constant, and foliage characteristics. These factors must be specified in detail to achieve accurate results from modeling. Consequently, even with the availability of sophisticated ground wave programs, it remains prudent to support the computer modeling of ground wave links by empirically measuring the propagation over a number of representative paths.

In addition to such factors as the conductivity and dielectric constant of the ground, ground wave propagation depends on the polarization of the radiation. The range of vertically polarized ground wave far exceeds that of horizontally polarized radiation. Accordingly, an antenna that produces vertically polarized radiation (e.g., a vertical monopole) is superior to an antenna that produces horizontally polarized radiation (e.g., a horizontal dipole) if one wishes to optimize ground wave propagation.

Figure 2 shows the theoretical field strength of electromagnetic waves versus distance for vertically polarized waves at different frequencies over an area having

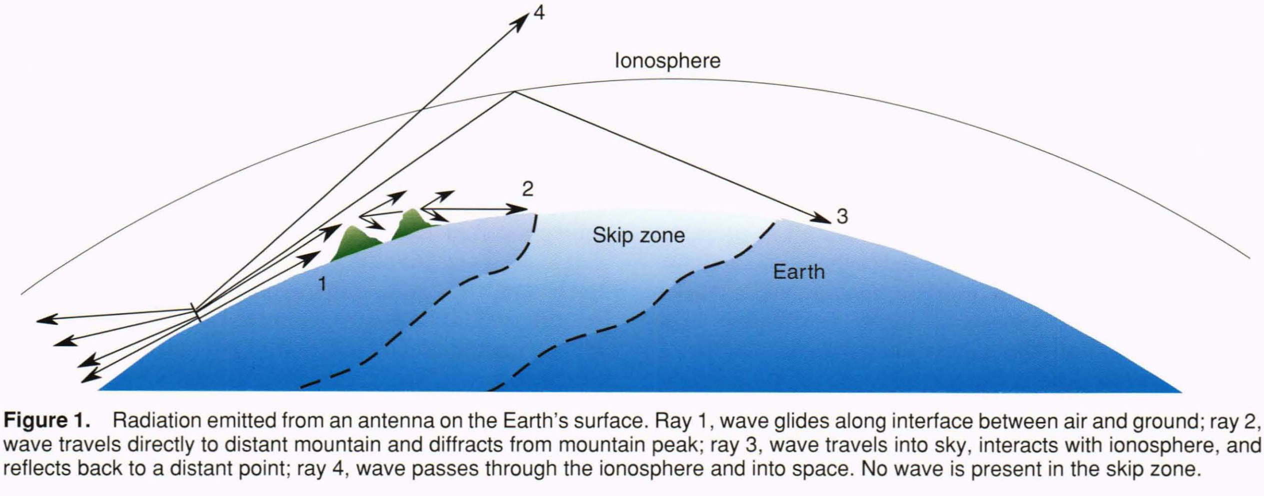

Figure 1. Radiation emitted from an antenna on the Earth's surface. Ray 1, wave glides along interface between air and ground; ray 2, wave travels directly to distant mountain and diffracts from mountain peak; ray 3, wave travels into sky, interacts with ionosphere, and reflects back to a distant point; ray 4, wave passes through the ionosphere and into space. No wave is present in the skip zone.

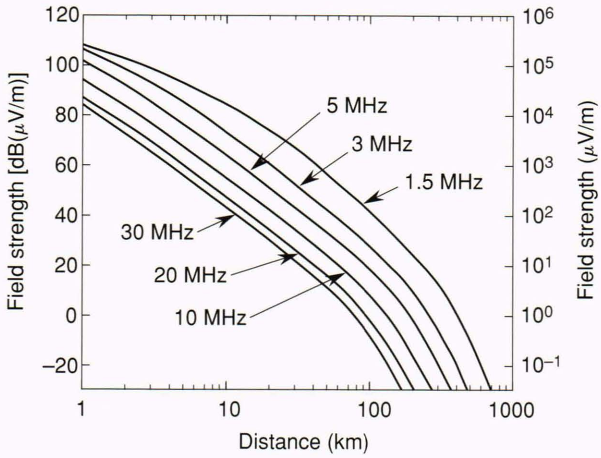

Figure 2. Ground wave propagation curves for wet ground (conductivity = 10^{-2} s/m, dielectric constant = 30). Provided by the International Radio Consultative Committee.

conductivity and dielectric constant representative of wet ground. The radiating element is assumed to be a short vertical monopole at ground level radiating 1 kW. The receiving antenna is also at ground level at various distances across a smooth, homogeneous, spherical Earth. The data, provided by the International Radio Consultative Committee,[2] show that the lower the frequency, the greater the ground wave range, all other things being equal. In addition, theory shows that ground wave propagates over wet ground better than dry ground.

Often, the highest-priority design goal of the communicator is to achieve the maximum range possible. Consequently, one usually associates ground wave communication with frequencies in the lower part of the HF band and below. Lower frequencies, however, require large, stationary antennas for efficient radiation. In the effort described in this article, a particular, relatively short (about 40 km) range was desired. Equally important as achieving the desired range were the requirements for reliability in a nuclear environment, non-line-of-sight connectivity in mountainous terrain, and a portable, unobtrusive antenna.

SELECTION OF THE BAND

To achieve the maximum range with the lowest power, the use of a resonant antenna was desirable for both transmission and reception. Conversely, optimum portability was sought. With these constraints in mind, 20 MHz was chosen as the lower limit of the frequency band to be tested. A resonant antenna could then be constructed with a height of less than 4 m. The upper frequency was taken to be 30 MHz because this is the upper limit of the HF band and the cutoff point of most military HF transceivers. The 20- to 30-MHz band offers additional advantages. As we will show, ranges of interest are achievable in mountainous terrain with reasonable transmission power levels. Beyond the ground wave range, however, a skip zone exists that extends for hundreds of miles, wherein no ground wave or sky wave is present (Fig. 1). Accordingly, for signals transmitted in the 20- to 30-MHz band, there is a large region surrounding the area of communication coverage from which it is unlikely that one could intercept or determine the location of the radiating antenna. Beginning at about 800 km, interception of a skipped signal occurs a few percent of the time. Although the skip probability increases beyond this point, the error associated with locating a transmitting source also increases.

A further advantage of the chosen band is the relatively low noise level, particularly in rural areas, where HFGW might be used. In urban environments, wideband noise signals from electrical equipment can be a source of annoyance; however, these are extremely limited in range. The few other users of this band are likely to be transmitting from a nonresonant antenna or one that is horizontally polarized, and thus the resulting ground wave is weak. Consequently, competing noise sources within ground wave range are few and weak in rural areas. In and around cities, one might find competing signals in certain frequency ranges or at certain locations, particularly during the day; however, if one scans the spectrum from 20 to 30 MHz, one finds the overall noise background to be significantly lower than that in the lower portions of the HF band.

Interfering distant stations are limited by the skip characteristics discussed earlier. At night this band is particularly quiet as local noise sources are extinguished, and the probability of distant signals skipping decreases, particularly after midnight. This contrasts with the environment found in the lower part of the HF band, where short-range communication suffers at night since it is more difficult for the ionosphere to support high angle skips, and the fading of the absorbing part of the ionosphere (D layer) allows distant stations to interfere. A study by Laycock et al.[3] of percent congestion values versus frequency range documents this phenomenon for the environment of western Europe. Data taken at a rural site in central England show no congestion for most frequency intervals in the 20- to 30-MHz band. By contrast, the lower region of the HF band was almost 100% occupied, particularly at night.

PROPERTIES OF THE DISCONE ANTENNA

Military users need HFGW signals that can change frequencies quickly to avoid jamming and reduce the probability of interception. Furthermore, portability and speed of erection and disassembly are important. The discone antenna was found to have the desired characteristics. This antenna, comprising a disc and a cone, is omnidirectional and wideband, with a nominal 50-Ω impedance that produces vertically polarized radiation.[4,5] For HF and very-high-frequency (VHF) applications, the disc and cone are usually not solid, but are made up of spokes. The height of the antenna is set by the length of the cone spokes, which are chosen to be equal to one-quarter the wavelength of the lowest desired frequency (cutoff frequency) and the cone angle, which is typically 30°. (For optimum performance, the cone spokes are chosen so that the cutoff frequency is taken to be about 1 MHz lower than the lowest frequency to be used.) Figure 3 shows the

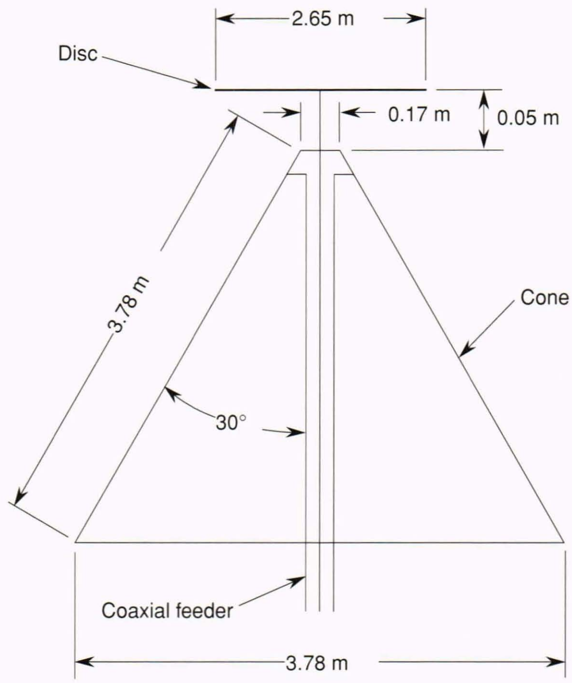

Figure 3. Dimensions for a discone antenna with a cutoff frequency of 19 MHz.

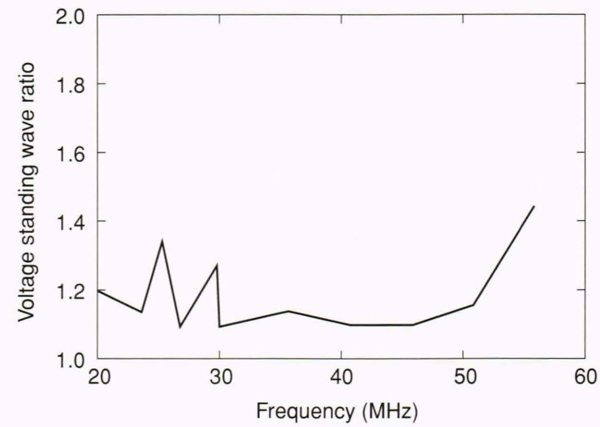

Figure 4. Voltage standing wave ratio versus frequency for a discone antenna with a cutoff frequency of 19 MHz.

dimensions of the discone antenna used in the work described in this article. Eight spokes were used on the disc and cone for the first discone built at APL. Subsequently, a discone was tested that used only six spokes on the disc and six for the cone. No difference in performance was measured between the two configurations.

Beginning just above the cutoff frequency, the discone antenna has had a good voltage standing wave ratio (VSWR) for many decades. Figure 4 shows the VSWR versus frequency measured for a discone antenna having a cutoff frequency of 19 MHz. A 50-Ω HF transceiver will transmit and receive efficiently on this antenna throughout the 20- to 30-MHz band without the need for an antenna matching unit. Also, the discone lends itself to using spread spectrum or frequency hopping techniques throughout this 10-MHz band.

The discone antenna can be made portable. Erected, it stands about 4 m high. Experience has shown that this size is reasonable for use in wooded, tactical positions. A discone antenna has been fabricated at APL that weighs less than 3 kg and can be carried by backpack when disassembled. Assembly and disassembly each take about ten minutes.

MEASUREMENTS OF HFGW PROPAGATION OVER DIFFICULT TERRAIN

Using discone antennas and frequencies in the 20- to 30-MHz band, HFGW ranges have been measured in several environments. Initially, measurements were made in the mountains of western Germany, in a region representative of the Pershing operational environment.[6] Later in the program, range measurements were performed elsewhere to demonstrate the applicability of the technique to other systems.[7]

Propagation in the Mountains of Western Germany

Using a discone as the base station antenna, single-sideband (SSB) voice and continuous wave (CW) test signals were transmitted at 26.725 MHz. The output power was 100 W. Identical results were obtained using both military (AN/GRC-193A transmitter) and civilian (Yaesu model 757GX transceiver) radio equipment. A second discone antenna was moved to positions increasingly distant from the base station. At each test site, voice contact was established and a CW signal was transmitted. At the receiving location, measurements were made of the CW signal-plus-noise level and noise background using another Yaesu transceiver that had been calibrated by injecting known CW power levels and measuring the audio power out. Using this method, suggested and implemented by J. D. Colson of the Space Department, a calibration curve was constructed that one could use to relate the measured audio signal to the CW signal being received.

Figure 5 shows the region in which four of the paths were surveyed. The signal-plus-noise to noise ratios (*S/N*s) and the received power levels measured over the four paths are given in Table 1. Only path 1 into the Schwäbian Alps represents a maximum range. (Maximum range was defined as the greatest distance at which an intelligible voice signal could be received. Quantitatively, this was taken to be the point where the CW was about 10 dB. Although the *S/N* was less than 10 dB over path 1, the voice signal was intelligible. Furthermore, the test team did not have total flexibility in selecting sites because of administrative constraints.)

Even though signal levels indicated that greater range was possible along the other paths, the test team could not proceed further because permission had not been received from the host government.

All paths listed in Table 1 were mountainous and were not line-of-sight. To illustrate, Figures 6 and 7 show paths 1 and 4, respectively. Elevation in meters is plotted against distance in kilometers. The transmitter was located at the 0-km point, and signal measurements were made along the path. An attempt was made to find points in the valleys along the path where dropouts would occur; none were found, however.

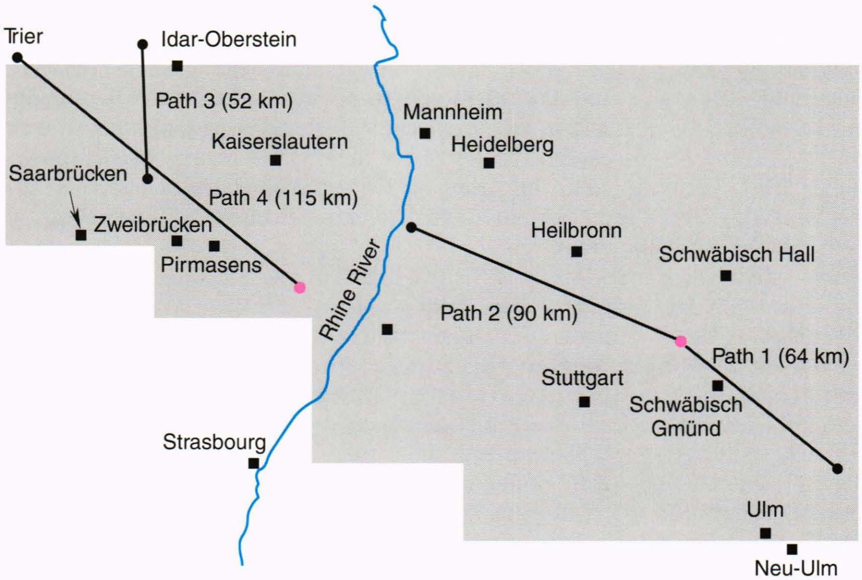

Figure 5. Map showing region of four high-frequency ground wave test paths listed in Table 1. The transmitting antenna was placed at the sites designated in red. The paths surveyed are represented by the black lines.

Table 1. Results of tests of high-frequency ground wave propagation over four paths.[a]

Path	Range[b] (km)	S/N[c] (dB)	Received signal power (dBm)
1	64	<8	<−114
2	90	16	−102
3	52	28	−92
4	115	16	−102

[a]All measurements were made at 26.725 MHz using a transmission power of 100 W.
[b]Only the range for path 1 represents a maximum value. The signals received on other paths indicated greater ranges could be achieved, but administrative reasons prevented further investigation.
[c]S/N = signal-plus-noise to noise ratio.

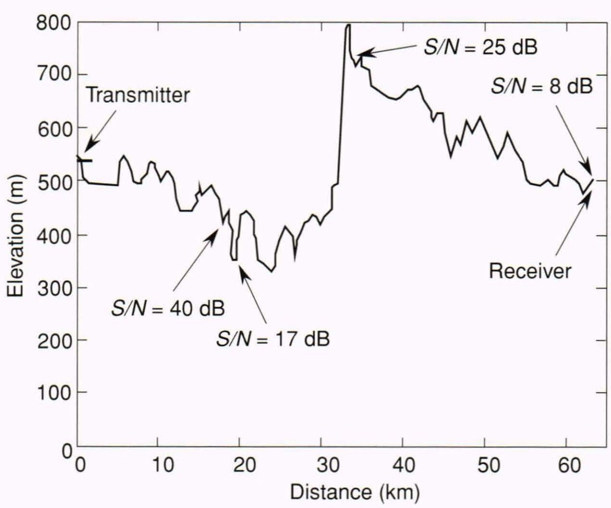

Figure 6. Terrain profile for path 1 into the Schwäbian Alps shown in Figure 5. S/N = signal-plus-noise to noise ratio.

Propagation in the Fjord Environment

The fjord environment near the Arctic Circle presents many challenges to short-range RF communication. It may be difficult to establish sky-wave links in this region, particularly at night and during the winter, because of ionospheric phenomena peculiar to that part of the world. The mountainous terrain makes it impractical to use VHF signals, which require line-of-sight paths. The VHF repeaters can be used, but it is impossible to locate a reasonable number of repeaters to provide a high degree of coverage over an area of high mountains separated by deep valleys and fjords. In addition, in a hostile environment, repeaters could be eliminated. Satellite communication could be used, provided a satellite is available and is high in the sky. Access to satellites at low elevation angles is likely to be blocked by mountaintops. Accordingly, one of our goals was to determine whether HFGW

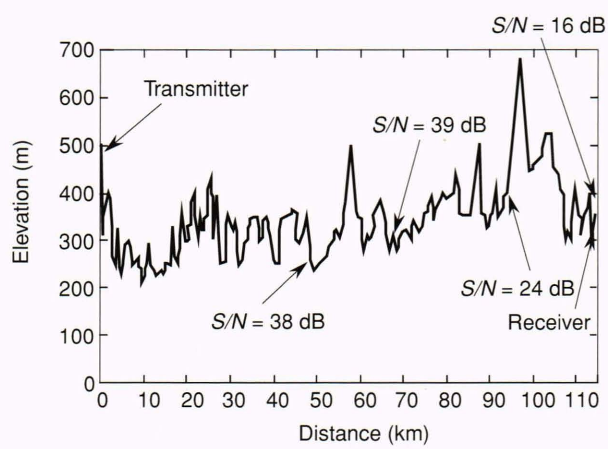

Figure 7. Terrain profile for path 4 across the mountains west of the Rhine shown in Figure 5. S/N = signal-plus-noise to noise ratio.

could provide an additional means to communicate over short distances at high latitudes in the fjord environment. The test was conducted with the cooperation and participation of the Norwegian Defense Electronics Agency (NODECA) and the Radio Branch, Communications Division, of the SHAPE Technical Center.

Over a one-week period in September 1991, HFGW signal measurements and two SSB communications were successfully achieved at the end points of thirteen out of fourteen attempted paths originating at a base station near Bjerkvik in the fjord region of Norway, above 68°N latitude. Backpack discone antennas developed at APL were used to radiate 100-W SSB signals. Discone antennas were also used to receive. Test frequencies, provided by NODECA, were 19.168, 24.024, 25.434, and 27.758 MHz, designated as channels 1 through 4, respectively. (Although the lowest frequency was below 20 MHz, the VSWR was found to be usable and thus provided a test frequency near the bottom of the 20- to 30-MHz band.) Path lengths varied from 19 to 83 km. We will discuss five of the most challenging paths.

Figure 8 shows the terrain profile for the first test path. Along this path a mountain range rose to over 400 m within 4 km of the base station and then peaked at 1000 m at about 28 km. The remote station was located on the shore of Lavangs Fjord. As indicated in the figure, a small island was located at about 38 km. The CW data were collected on only one frequency owing to a procedural misunderstanding. Although the *S*/*N* was only 8 dB, intelligible SSB voice communication was accomplished and was used to direct the operator at the base station. It would have been interesting to move the remote site farther from the 1000-m peak and determine the extent to which a change in the signal diffracted over the peak might be observed, but circumstances did not permit such a test.

Site 2 was selected after studying the results obtained for path 1 to determine whether the high ridge rising from the base station would prevent a useful signal from being obtained along the path intersected by the ridge. Figure 9 shows the terrain profile. The ridge rises immediately from the base station (the high peak at about 12 km), and the range is about three-fourths that of path 1. In addition, the mountain ridge blocking the path from the base station intersected the path in a way that precluded any possibility of signals being scattered toward the remote station from mountains on either side of the direct path. The mountain rose slowly behind the remote station so that backscattering was unlikely to contribute to the signal. Very good SSB voice communication was established, and *S*/*N*s of 14 and 16 dB were measured at the remote station on two frequencies. Administrative constraints caused the test to be terminated before measurements could be made on the remaining test frequencies, although good voice communication was achieved on them.

Much of the test time was consumed by driving to the remote sites. After discussing this issue, a Norwegian test participant suggested that the backpack discone antenna could be placed on the bow of a small fishing boat. The plan was to use the boat to travel into several of the fjords and make measurements more quickly than possible by driving to equivalent sites along the shore. This was the configuration used to obtain the data for seven of the paths investigated.

Soon after getting under way on the boat, the testing team tried to measure the HFGW signal level over a line-of-sight water path 20 km from the base station. The signal was too strong to measure with the equipment being used since it drove the receiver far into the region where the automatic gain control was activated, and no reliable reading could be obtained. The SSB voice signals were, of course, extremely loud and clear.

Remote sites were selected in bays and fjords so that the paths to the base station were not line-of-sight. For example, Figure 10 shows the terrain profile for the propagation path encountered by the signal traveling from the base station to sites 3 and 4, located in the Beisforden Fjord. After making initial measurements at site 3, which was on the most distant shore, the boat proceeded toward the other shore and the base of the mountain, which rose over 1400 m from the fjord. We maintained voice contact as we moved toward the mountain. At site 3, *S*/*N*s were still quite high (24 to 28 dB). The two remote sites were far up a narrow fjord. Accordingly, any significant amount of signal was unlikely to have been contributed by scattering off mountains located on the other side of the bay from which the fjord led. On the far side of Beisforden, however, the mountain rose sharply up from the fjord. Thus, some signal could have arrived at the boat as a result of diffracting from the high peak at 17 km, then backscattering from the peak rising from the distant shore. Nevertheless, the results strikingly illustrate a situation wherein the use of VHF repeater and

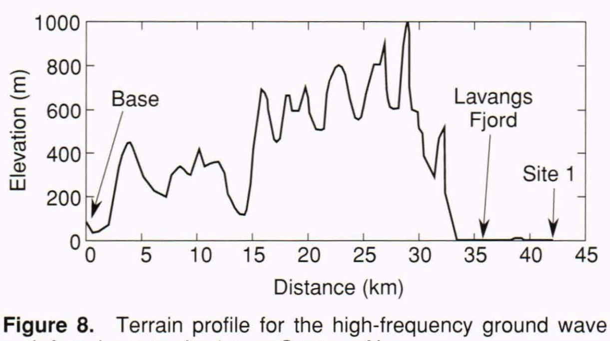

Figure 8. Terrain profile for the high-frequency ground wave path from base to site 1 near Santorg, Norway.

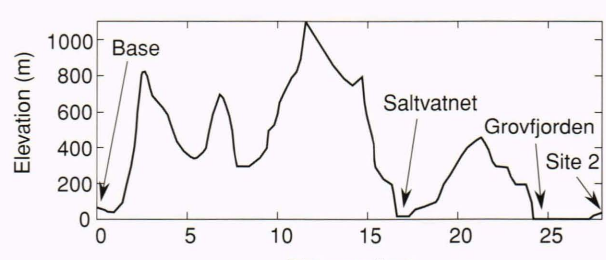

Figure 9. Terrain profile for the high-frequency ground wave path from base to site 2 near Fornes, Norway. The path crosses Saltvatnet Lake and Grovfjorden Fjord.

satellite relay systems would have been difficult, but the use of HFGW would have been trivial.

Site 5 was chosen as a worst-case scenario. The remote antenna was located within 50 m from a cliff rising 100 m. The base station was 35 km away on a line slanting toward a mountain range that included a peak over 1200 m high, as shown in Figure 11. No contact was possible over this path. The background noise level was measured to confirm that the failure resulted from inadequate HFGW signal propagation and not because of high noise background. As the numbers in Table 2 show, the noise background was quite low.

The terrain profile for the path to sites 6 through 8 is shown in Figure 12. Site 6 was slightly to the side of the small hill shown in the figure, with nothing but water intervening between it and the base station. Consequently, the path between site 6 and the base station was line-of-site, 40 km across the Ofotfjord. The signal was very strong, and we could not measure the level on channel 1 because of the activation of the automatic gain control. The results obtained at sites 7 and 8 were satisfactory and are listed in Table 2.

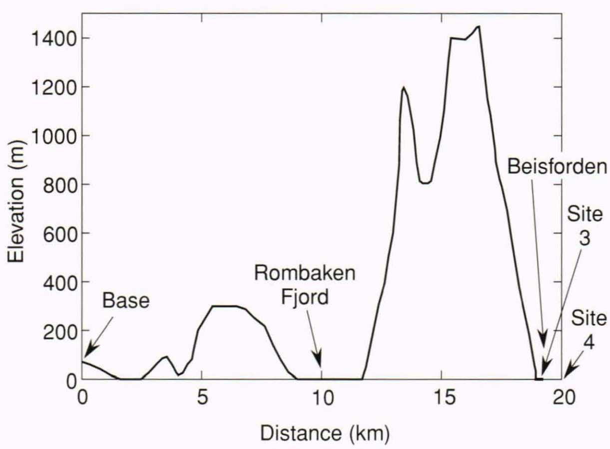

Figure 10. Terrain profile for the high-frequency ground wave path from base to sites 3 and 4 in Norway. Signal measurements were made from a boat on Beisforden Fjord.

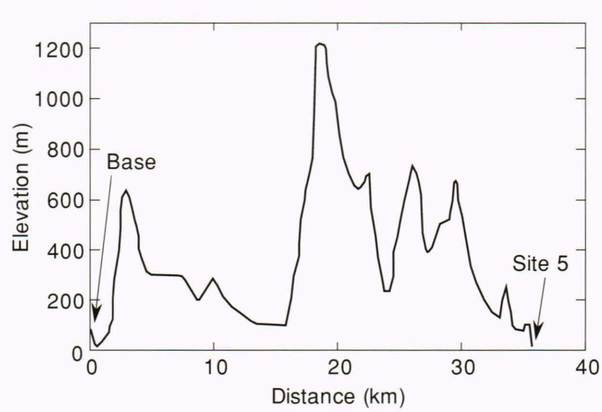

Figure 11. Terrain profile for the attempted high-frequency ground wave (HFGW) path from base to site 5 near Sandstrand, Norway. No HFGW communications could be established over this path.

Table 2. Results of high-frequency ground wave measurements in the fjord environment.

Remote site	Range (km)	Channel	*S*+*N*[a] (dBm)	*S*/*N*[b]
1	43	3	−108	8
2	28	1	−106	14
		3	−108	16
3	20	1	−86	37
		2	−89	35
		4	−88	40
4	19	1	−92	30
		2	−98	25
		4	−107	24
5	35	1	none	—
		2	none	—
		4	none	—
6	40	1	−+[c]	
		2	−68	57
		4	−73	52
7	48	1	−++[d]	−++
		2	−108	9
		4	−114	10
8	54	1	−83	37
		2	−89	35
		4	−94	31

[a]*S*+*N* = signal plus noise.
[b]*S*/*N* = signal-plus-noise to noise ratio.
[c]+ = signal level too strong to measure with available instrumentation.
[d]++ = strong interference.

SIGNAL STABILITY OF HFGW

When we reported the results of the first HFGW tests in Germany, some reviewers observed that the ranges we were achieving could only be obtained in the 20- to 30-MHz band if the paths were line-of-sight. When we showed from the terrain profiles that the paths were not line-of-sight, some reviewers expressed concern that we must be receiving sky-wave signals and mistaking those for ground wave. An examination of theoretical models

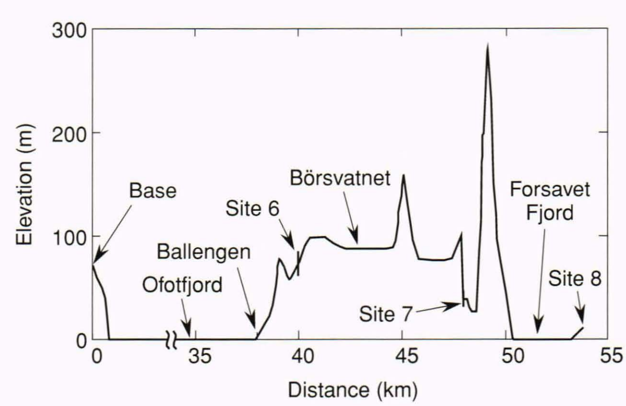

Figure 12. Terrain profile for the high-frequency ground wave path from base to sites 6, 7, and 8 in Norway. The path crosses the Ofotfjord Fjord, Börsvatnet Lake, and Forsavet Fjord.

designed to predict ionospheric propagation showed that virtually no possibility existed that signals in the 20- to 30-MHz band could be made to skip off the ionosphere to points within 100 km of each other. Nevertheless, in keeping with the spirit of the investigation, we were required to demonstrate empirically that what we were measuring was ground wave, with little or no sky-wave component.

One can determine in several ways whether a signal propagates between two points by means of ground wave or sky wave. We chose a straightforward approach that required no additional equipment beyond the transceivers already at hand. The technique was based on the following argument: whereas the sky-wave signal level varies widely with time as the ionosphere changes, the ground wave signal level is expected to be more stable. Accordingly, if the received power level remains steady when the ionosphere changes, this stability supports the claim that the signal is truly ground wave. Three tests were performed over paths that were not line-of-sight in the mountains of Germany; signal levels were measured over a 24-h period. The results, along with path lengths, are listed in Table 3. The CW signals were transmitted at 100 W using a discone antenna. Another discone at the end of the path was used to receive the signals, and measurements were made with a calibrated Yaesu 757GX transceiver. Measurements of received signal levels were taken every 15 min for 24 h. Figure 11 shows the results for 26.725 MHz taken along path 3 in Figure 5 (test 3) in February 1986. The signal levels stayed constant within ±2 dB, which was near the resolution of the method used to make the measurement. These results are representative of the data obtained during all three tests. No evidence of sky-wave fading was seen.

DEMONSTRATION OF DIGITAL CAPABILITY

Several tests have been conducted that demonstrated digital communication over HFGW links. One test used terminal node controllers tied to HF transceivers and personal computers to transmit frequency-shift-keyed (FSK) packets over mountainous terrain in western Germany. The signal comprised two tones, 2.060 and 1.460 kHz (600-Hz shift). The carrier frequency was 26.850 MHz transmitted at 100 W. The test packet message was 1800 characters in length, divided into eighty-character packets. After each packet was transmitted, a digital signal verifying correct receipt of the packet (checksum) was required from the receiving station before the message continued. If an incorrect checksum was received, the packet was automatically retransmitted. Thus only complete, perfect messages could be passed. The data rate was 300 baud. The *S/N*s were also measured over every path using a 100-W CW signal as the test frequency. The SSB voice contact was also attempted for each path.

Tests were performed in the area shown in Figure 5 over seventeen mountainous paths having ranges of 22 to 117 km. Voice communications were established over all paths. The test packet message was exchanged between stations over all paths of 60 km or less. The packet message was successfully passed over only one of the three paths about 100 km long. No message could be exchanged over a 117-km path for which the *S/N* was less than 8. Virtually all paths were non-line-of-sight. Because the test schedule was conducted in conjunction with a military exercise, some paths were investigated during the day and others at night. No correlation was found between successful packet communication and time of day, except that, in general, the background noise was much lower at night.

Testing has also been conducted in western Germany using mobile military radio teletype equipment, which uses a data rate of 50 baud and an output power of 200 W. The teletype equipment produced a coded signal consisting of a 2-kHz audio tone, which is shifted ±425 Hz. The two resulting audio tones are processed and transmitted like SSB signals. Using discone antennas and frequencies throughout the 20- to 30-MHz band, the teletype units provided communications between battalion headquarters and six batteries, both day and night, over a four-day period. The exercise took place in mountainous terrain; propagation distances ranged from 14 to 50 km. Messages were easily passed at will, and no problems attributed to HFGW were experienced.

In July 1991, tests were performed with the U.S. Air Force 7th Weather Squadron, based in Heidelberg, Germany, to assess the use of HFGW to pass weather net data. This effort was conducted in collaboration with the Office of the Army Material Command Field Assistance in Science and Technology Science Advisor to Headquarters, U.S. Army Europe (USAREUR). The Weather Squadron currently uses near-vertical-incidence sky-wave (NVIS) links as a means of communication; however, these are subject to fading at night and degradation in a nuclear environment wherein the ionosphere is disrupted.

The USAREUR Automated Weather System uses a Harris RT-1446HF transceiver and an RF-3466 high-speed HF modem that can transmit FSK data at rates from 75 to 2400 baud in steps. Base station equipment can transmit with an output power of 500 W, whereas the mobile units are limited to 100 W. Backpack discone antennas were used at both the base and remote stations to establish HFGW links. The frequencies used for this test were 23.130, 23.823, and 25.065 MHz, designated channels 1 through 3, respectively. The test message was 100 letter A's arranged in ten rows and columns. The message score was simply the percentage of A's received correctly.

Table 3. Results of high-frequency ground wave signal stability measurements performed during a 24-h period over non-line-of-sight paths.

Test	Range (km)	Frequency (MHz)	Received signal power (dBm, ±2)
1	49	22.733	−105
		26.725	−102
2	49	22.733	−98
		26.725	−96
3	52	27.733	−98
		26.725	−92

The test team decided to perform all HFGW communication tests for the 7th Weather Squadron between 10:00 PM and 4:00 AM to demonstrate HFGW performance when NVIS links are most vulnerable to fading. During the tests, the units were restricted to property controlled by the Army. This resulted in limiting our selection of paths and, since the available sites were located in urban surroundings with high background noise and large buildings, the test environment represented worst-case scenarios rather than what one might expect in the tactical situation. We will discuss one of the more interesting paths in detail.

Figure 13 shows the terrain profile for the path between the base station at Seckenheim (near Heidelberg) and the mobile station at Ober Ramstadt, west of Frankfurt.

The quality of the messages received at Ober Ramstadt was quite good and, as expected, was fairly stable throughout the night. The average percentages of correct characters arriving at Ober Ramstadt from Seckenheim between 1:00 to 2:00 AM, 2:00 to 3:00 AM, and 3:00 to 4:00 AM are given in Table 4 for each channel, along with the number of messages over which the average was taken. An equipment problem reduced the testing time available from 2:00 to 3:00 AM. The messages received at Seckenheim were not so good; none could be received at 2400 baud. The problem was attributed to a high background noise level in the urban environment surrounding the Seckenheim station, abetted by the limitation of the mobile station to an output power of 100 W. By dropping the baud rate to 300, however, an average message score of 96% was achieved at Seckenheim.

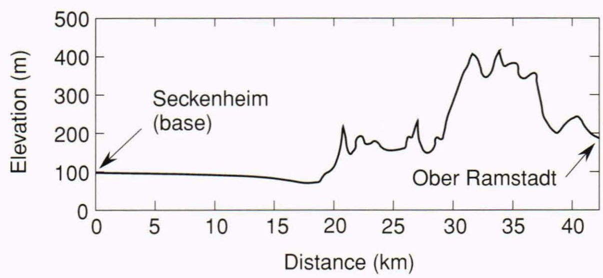

Figure 13. Terrain profile for a high-frequency ground wave path in Germany over which digital weather data were passed at a baud rate of 2400.

Table 4. Message quality received at Ober Ramstadt from Seckenheim.

Hour interval (AM)	Channel	Baud rate	No. of messages	Avg. score (%)
1:00-2:00	1	2400	2	95
	3	2400	3	91
	1	300	3	100
	2	300	3	100
2:00-3:00	2	150	5	100
3:00-4:00	2	2400	3	96
	2	1200	3	92
	2	600	3	99
	2	300	2	100

WIDEBAND FREQUENCY HOPPING

Both the wideband nature of the discone and the propagation characteristics of ground wave in the 20- to 30-MHz band suggest that frequency hopping or other frequency distribution techniques could be exploited to achieve greater communication security and to minimize the possibility of electronic countermeaures.

Figure 4, showing the VSWR of the discone versus frequency, demonstrates the ability of the discone to transmit and receive efficiently throughout the 20- to 30-MHz band. Accordingly, frequency hopping over almost the entire 10-MHz bandwidth should be possible without sacrificing output signal strength and without requiring a matching circuit to protect the transmitter from reflected power. In addition, data obtained during range testing in a variety of environments have shown that the ground wave signal levels are often in the usable range throughout the 20- to 30-MHz band.

We tested HFGW wideband frequency hopping over a 16-km propagation path through Fort Monmouth, New Jersey. The terrain over which the signal passed was flat but heavily developed. Two discones were used, along with two AN/GRC-106B frequency hopping transceivers provided by the U.S. Army Communication Electronics Command. The output power was 20 W. The transceivers were programmed with six sets of frequencies, shown in Table 5. Both the normal hopping rate and the faster enhanced rate were tested for SSB voice quality.

Good voice communication was established on all hopping sets using the discone antennas. The transceivers had two options: to have a matching circuit between the transmitting circuit and an external antenna or, alternatively, to connect the transmitter directly to the antenna. This latter function is to be used with a 50-Ω antenna. Accordingly, no difference was detected in the quality of the wideband frequency-hopped voice signals when the matching circuit was in series with the discone and when it was removed.

By contrast, a whip antenna attached to the backpack radio was unable to provide an intelligible voice signal in the hopping mode for any of the sets listed in Table 5. Voice contact established using the whip antenna on a single frequency would immediately be lost when frequency hopping was begun, even though the matching circuit was used. This demonstrates the need for a wideband antenna when hopping sets that cover a band of several megahertz are used for HFGW communications.

Table 5. Hop sets for discone-to-discone frequency hopping.

Set	Frequency range (MHz)	No. of frequencies
1	20.0-23.9999	>100
2	24.0-29.9999	>100
3	20.0-23.9999	2
4	24.0-29.9999	2
5	20.5-23.5000	4
6	24.0-29.9999	6

POTENTIAL APPLICATIONS

In the 20- to 30-MHz band, HFGW has been found to have unique features that could be exploited in special applications where short-range, nonfading, non-line-of-sight connectivity is desired. The relatively compact, portable backpack discone antenna makes HFGW links achievable between stations that must be mobile and have limited available space for antennas. The broadband nature of the discone antenna makes it ideal for HFGW applications that require both an efficient antenna and the ability to change frequency easily. The discone antenna also allows for broadband frequency hopping to eliminate interference problems and minimize the possibility of interception.

Military Uses

The APL HFGW effort was originally targeted toward providing intrabattalion communications in a nuclear environment in which the ionosphere was disrupted. The importance of meeting such a need now appears diminished, but there remain many military applications for which short-range, nonfading, non-line-of-sight communications are desirable. A few specific applications are suggested here.

Transfer of weather net data at night. The passage of weather net data at night using HFGW has been demonstrated at data rates up to 2400 baud. The HFGW provides an inexpensive supplement to NVIS communication, which can fade at night. An ideal system would use HFGW along with the capability to seek the best frequency between stations (automatic link quality assessment) but also would self-adjust the baud rate, and thereby minimize degradation caused by local interference.

Communication in the fjord environment. Again, HFGW in the 20- to 30-MHz band can provide communication links in a region of the Norwegian fjords where NVIS connectivity is unreliable and (because of the high mountains and deep valleys) VHF repeater systems and satellite links are of limited utility. The use of HFGW can provide an additional tool to expand communication coverage from ship to ship, from ship to shore, and between shore points separated by mountains.

Naval communications. Theoretically, ground wave propagates better over the sea than over land. In addition, HFGW could be used in regions such as the Mediterranean to provide non-line-of-sight communication between ships separated by islands. And, since the discone antenna is easily added to standard HF radio systems, it could be used on allied ships to provide an HFGW capability, which is compatible with U.S. systems.

Tactical video data. Finally, although not yet demonstrated, it is speculated that by using data compression techniques and exploiting the wideband characteristics of the discone antenna, we may be able to transmit maps of troop deployments, battlefield photographs, and even video to guide robotic vehicles over non-line-of-sight paths using HFGW.

Civilian Uses

Fire jumpers. Forest fire crews communicate between base stations using frequencies that can only provide line-of-sight connectivity. Base stations separated by mountains rely on a repeater system carried aboard an aircraft. The use of HFGW could provide an inexpensive supplement to this system, which would operate when weather conditions or cost considerations did not allow aircraft to participate.

Remote telephone in mountainous terrain. In mountainous areas of the United States, as well as other countries, the rugged terrain and sparse population make it impractical to lay telephone lines. In areas of high mountains and deep valleys, cellular telephone systems are often impractical because even the highest peak cannot provide non-line-of-sight coverage to enough of the homes scattered throughout the region to make the system cost-effective. This situation is compounded by the problem of getting permission to install a repeater in the best spot. Using HFGW, it would not be necessary to select the highest peak for the repeater location to achieve coverage into the valleys. The residential customer would be equipped with a solar-powered HF telephone system that uses a discone antenna. The ideal system would use automatic frequency selection to avoid interference problems or frequency hopping, which, in addition, would ensure privacy.

Emergency communication in mountainous terrain. Emergency relief efforts in areas of the world without a reliable telephone system or where a disaster has disrupted local communications could benefit from HFGW.

Differential Global Positioning System (GPS) surveying. Hydrographic surveys achieve enhanced accuracy by using a GPS receiver at a known point ashore in conjunction with GPS receivers aboard a mobile survey platform. The shore station collects GPS information, computes navigation corrections, and broadcasts those corrections to the mobile unit through a communications link. The non-line-of-sight, nonfading capability of HFGW would provide more latitude in selecting the reference site and therefore could help lower costs and the time involved in surveying a region.

CONCLUSION

Empirical evidence shows that HFGW in the 20- to 30-MHz band could be used to provide nuclear-survivable, nonfading, non-line-of-sight communication links having ranges as high as 115 km in mountainous terrain. This range could be accomplished with portable, wideband discone antennas and by using readily available transmission power levels. Signal processing techniques could extend the range. If spatially distributed systems are used to relay messages, communication coverage could be provided over large regions with few, if any, inaccessible points, even in mountainous terrain. Wideband frequency hopping could be exploited to maximize security and provide antijamming capability without reducing the communication coverage. In addition to military applications, HFGW could be applied to provide communications to support a number of civilian activities.

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