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DETECTION OF PROPAGATION FROM A HEATED IONOSPHERE

Powerful high-frequency radio waves are being used to modify the ionospheric plasma in order to study its characteristics by observing the response to the perturbation. One result observed during controlled experiments, where the high-frequency carrier is modulated by a frequency in the extremely-low-frequency to very-low-frequency range, is the detection of radio waves beneath the heated region and at distances of several hundred kilometers. The possible applications of this propagation phenomenon and its research implications are discussed.

INTRODUCTION

Civilian and military leaders are constantly assessing current and planned research and technology programs to ensure that their products satisfy critical command, control, communications, and intelligence (C^3I) requirements.[1] The demands of worldwide C^3I missions dictate that the results of research and technology programs be monitored to assess their impact on the future of communications connectivity.

One such program involves experiments to modify the ionosphere by heating the ionospheric plasma with high-power, high-frequency (HF) radio waves. The interaction of the heating wave with the plasma alters not only the wave but the region through which it passes in a nonlinear process. The basic physics of the ionosphere is studied by observing the ionosphere's response to HF perturbation.

Experiments began over 15 years ago using an HF transmitter at Plattville, Colo. Observed results from that facility, as well as from a second HF facility located near Arecibo, P.R., are summarized in the literature.[2] Observations recorded at other HF experimental transmitter facilities near Gorky and Murmansk in the U.S.S.R.[3] and near Tromsö, Norway,[4] have provided a growing number of contributions to the field of ionospheric plasma physics.

The propagation phenomenon that is the focus of this article involves an effect characterized by the plasma demodulation of a modulated HF carrier. It results from irradiation of the ionospheric plasma, with its existing current system, by a strong HF wave that is modulated at some lower frequency, f. Radiation at the modulation frequency has been detected both beneath the heated region and at ranges of hundreds of kilometers from the transmitter.

The experimental techniques discussed below were developed under an Office of Naval Research contract by a group of Pennsylvania State University engineers, scientists, and graduate students from 1980 through 1987. The transmitters used are located at Arecibo, P.R.; Jicamarca, Peru; and the High Power Auroral Stimulation (HIPAS) facility near Fairbanks, Alaska.

An equally vigorous research effort is being conducted using the HF heating facility at Ramfjordmoen near Tromsö, Norway.[4] That facility was developed primarily by the Max Planck Institut für Aeronomie, which emphasizes research on the auroral current system.

The material presented highlights results obtained using the Arecibo HF transmitting facility, operating with over 150 MW of effective radiated power at a frequency of 3.170 MHz and a square-wave modulation frequency of 2.5 kHz. An ionospheric heating theory and a brief discussion of the dynamo and equatorial current systems are followed by a description of transmitter and receiving subsystems and their modulation modes. Typical local and long-path results are presented and compared to a reported propagation experiment using the Tromsö transmitter. Closing comments discuss ongoing research being conducted by the Pennsylvania State University at the HIPAS facility, followed by some thoughts about the application of this propagation phenomenon to satisfy future communications needs.

IONOSPHERIC HEATING THEORY

A theory describing the generation of extremely-low-frequency (ELF) and very-low-frequency (VLF) radiations through heating of the existing current system is described using the approach found in Ferraro et al.[5] The ionospheric plasma is irradiated by a high-power HF electromagnetic wave at a frequency, f_1, that is modulated at a frequency, f_2, in the ELF/VLF range. The periodic plasma heating that results from the wave produces the emission of radio waves at f_2, an effect characterized by the plasma demodulation of the modulated HF carrier.

The basic geometry and concept behind the description of the phenomenon are shown in Fig. 1. The electrons within the volume of plasma irradiated by the modulated HF wave undergo periodic heating at the HF modulation frequency. Since ionospheric conductivity is sensitive to the electron thermal balance, it also varies periodically, modulating the natural ionospheric currents (e.g., dynamo, polar electrojet, and equatorial electrojet)

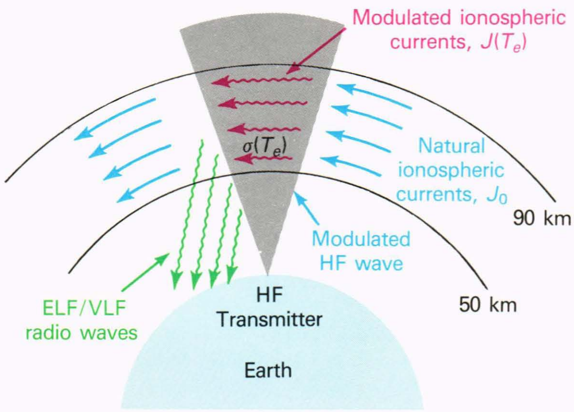

Figure 1—The geometry of the heating experiment. The natural ionospheric currents are modulated and radiate radio waves.[5]

that pass through the heated region. Under ambient conditions, the current density of the ionosphere is given by

$$\bar{J}_0 = \bar{\sigma}_0 \bar{E}_G \ , \tag{1}$$

where $\bar{\sigma}_0 = \bar{\sigma}(T_n)$ is the ambient conductivity tensor with neutral temperature, T_n, and $\bar{E}_G$ is the strength of the geoelectric field that drives the currents. Within the heated region, the current density is

$$\bar{J} = \bar{\sigma}(T_e)\bar{E}_G = \bar{J}_0 + \Delta\bar{\sigma}(T_e)\bar{E}_G \ , \tag{2}$$

where T_e is the temperature of the electrons and

$$\Delta\bar{\sigma}(T_e) = \bar{\sigma}(T_e) - \bar{\sigma}(T_n) \ . \tag{3}$$

Thus, HF modulation of the ionospheric conductivity causes periodic current at the modulation frequency, f_2, of density

$$\bar{J}_{f_2} = \Delta\bar{\sigma}(T_e)\bar{E}_G \ , \tag{4}$$

which is the source of radiation at f_2 from a wireless ionospheric antenna system.

Neglecting the effects of electron thermal conductivity and plasma transport, the electron energy balance equation can be written[5,6]

$$\frac{3}{2} n_e K_B \frac{\partial T_e}{\partial t} = P_e - \sum_j \left(\frac{dU}{dt}\right)_{e,j} \ , \tag{5}$$

where n_e is the electron density, K_B is Boltzmann's constant, T_e is the electron temperature, P_e is the rate of electron thermal energy production caused by HF heating, and $(dU/dt)_{e,j}$ is the rate of electron thermal energy loss resulting from the jth collision process between electrons and neutral particles. It is assumed that the electron and neutral particle energy distributions are Maxwellian and are characterized by temperature T_e and T_n, respectively, with $T_e = T_n$ before the introduction of HF heating.

When a region of the ionosphere is illuminated by an HF source radiating at f_1, the local power density, S, at height h is given by[5,6]

$$S(h) = S_0 \left(\frac{h_0}{h}\right)^2 \exp\left[-2K \int_{h_0}^{h} \chi(h')\, dh'\right] , \tag{6}$$

where $S = P_T\, G/4\pi h_0^2$ is the power density at some reference height, h_0, below the base of the ionosphere, and P_T is the transmitter power (rectangular heating pulse assumed), G is the antenna gain over isotropic radiation, K is the free-space propagation constant, and $\chi(h')$ is the absorption index at height h'. The HF source is assumed to radiate vertically in a narrow beam over which the antenna gain is essentially constant.

Differentiating Eq. 6 with respect to height yields

$$\frac{\partial S}{\partial h} = -\frac{2}{h} S - 2K\chi S \ , \tag{7}$$

where $-2/h\, S$ accounts for the decrease in power density as the HF beam spreads with increasing height and $2K\chi S$ represents the power dissipation per unit volume as a result of electron absorption. Therefore, referring to Eq. 5,

$$P_e = 2K\chi S \ . \tag{8}$$

As a heating pulse propagates through the ionosphere, energy absorbed from it is converted to electron heating (Eq. 8). Electron heating modifies the absorbing properties in the region of propagation (since χ is a function of T_e) through its dependence on the electron neutral collision frequency, $\nu\,(T_e)$. Thus the heating pulse causes additional absorption on itself.

Using Eqs. 5, 6, and 8, electron heating results were obtained by Tomko[6] for a strong field; an HF heating signal with an effective radiated power of 100 MW in the extraordinary mode at 5.0 MHz, modulated at 2 kHz, was one signal considered. With a 0.25-ms pulsed HF signal in the D region at 70 km, the electron temperature reaches a steady-state value such that the T_e/T_n ratio increases from 1.0 to 3.5 in less than 0.25 ms. The plasma cools somewhat faster than it heats up, while the power density remains constant. At 90 km, the electron temperature requires approximately 3.5 ms to reach a steady-state value. The energy density does not remain constant at 90 km as it does at 70 km but drops abruptly from its initial value to a steady-state value in about 0.5 ms. This effect is caused by self absorption and reduces the available heating power in the upper D region.

Periodic temperature variations caused by the pulsed HF heating transmitter at an ELF/VLF rate can alter ionospheric conductivity in two ways. For times less than 10^{-2} s, the collision frequency is modifed, while for times greater than 10^{-2} s, the electron density is modified. The manner in which ionospheric conductivity depends on the electron neutral collision frequency, ν_{en}, and the electron density, n_e, is given by[5,6]

$$\sigma_p(T_e) = n_e(T_e) \frac{e^2}{m_e} \frac{\nu_{en}(T_e)}{\omega_G^2 + \nu_{en}^2(T_e)} , \qquad (9)$$

$$\sigma_H(T_e) = n_e(T_e) \frac{e^2}{m_e} \frac{\omega_G}{\omega_G^2 + \nu_{en}^2(T_e)} , \qquad (10)$$

and

$$\sigma_L(T_e) = n_e(T_e) \frac{e^2}{m_e} \frac{1}{\nu_{en}(T_e)} , \qquad (11)$$

where m_e is the electron mass; ω_G is the gyro frequency; and σ_p, σ_H, and σ_L are the Pedersen, Hall, and longitudinal conductivities, respectively. By keeping heating periods less than 10^{-2} s, electron density modifications can be neglected.

THE DYNAMO CURRENT SYSTEM

Solar thermal energy and lunar gravitational attraction produce tidal forces in the atmosphere with periods related to the 24-h solar day and the 24.8-h lunar day. These forces set up tidal waves that create a primarily horizontal motion of the air across the geomagnetic field. The motion induces an electromotive force, $q = (\bar{U} \times \bar{B})$, where q is the particle charge, $\bar{U}$ is the velocity of the particles, and $\bar{B}$ is the geomagnetic flux density. The force field causes ions and electrons to drift with different velocities, producing what are referred to as dynamo currents.[7]

The induced electric field is perpendicular to both the air velocity and the magnetic field. At points where the current is not solenoidal, deviation from charge neutrality sets up a distributed space charge, and a polarization electric field is established. This polarization effect occurs where the dynamo field drives a current vertically through layers of different conductivity such that the divergence of $\bar{J} = 0$ everywhere. Most theories on these solar quiet currents set the vertical current equal to zero, making it horizontal with respect to an overhead coordinate system. Consequently, the conductivity tensor can be reduced from a 3 × 3 to a 2 × 2 tensor. Using a coordinate system with x and y as the coordinates for magnetic south and east, respectively, the conductivity can be expressed as

$$\sigma' = \begin{bmatrix} \sigma_{xx} & \sigma_{xy} \\ -\sigma_{xy} & \sigma_{yy} \end{bmatrix} , \qquad (12)$$

where

$$\sigma_{xx} = \frac{\sigma_L \sigma_p}{\sigma_L \sin^2 I + \sigma_p \cos^2 I} , \qquad (13)$$

$$\sigma_{xy} = \frac{\sigma_L \sigma_H \sin I}{\sigma_L \sin^2 I + \sigma_p \cos^2 I} , \qquad (14)$$

and

$$\sigma_{yy} = \frac{\sigma_H^2 \cos^2 I}{\sigma_L \sin^2 I + \sigma_p \cos^2 I} + \sigma_p , \qquad (15)$$

with I being the magnetic dip angle.[7] Periodic temperature variations will cause periodic variations in σ_{xx}, σ_{xy}, and σ_{yy}, in turn modulating the horizontal current system.

THE EQUATORIAL ELECTROJET

The large concentration of current flowing at the magnetic dip equator can be developed from Eqs. 13, 14, and 15. Considering the dip angle, $I = 0$, from Eq. 13 at the magnetic dip equator, $\sigma_{xx} = \sigma_L$; from Eq. 14, $\sigma_{xy} = 0$; and from Eq. 15,

$$\sigma_{yy} = (\sigma_p^2 + \sigma_H^2)/\sigma_p = \sigma_c , \qquad (16)$$

where σ_c is the Cowling conductivity. The high southward conductivity, $\sigma_{xx} = \sigma_L$, along the magnetic field lines ensures that these lines are approximately electric equipotentials. The east–west conductivity, σ_c, is extremely large and accounts for the highly conducting strip along the magnetic dip equator.[7]

Figure 2 shows the yearly average flow pattern of the solar quiet (Sq) current systems as they relate to dip latitude.[8] These geomagnetic variations of the ionospheric current systems are caused principally by the dynamo action discussed earlier. The currents are calculated through observation of the earth's magnetic field intensity, H, in amperes per meter. The inclination or dip, I, between the horizontal magnetic field intensity and the total magnetic field intensity at any location is used here. The magnetic dip equator is the focus of points where the magnetic field is parallel to the earth's surface. The current flow is counterclockwise in the northern hemisphere and clockwise in the southern hemisphere, with a large concentration at the dip equator.

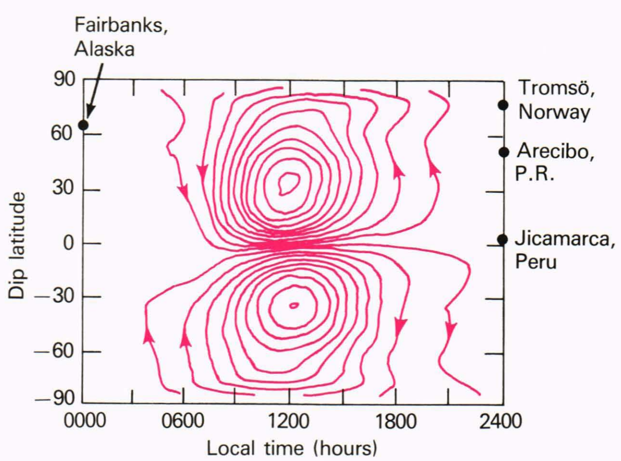

Figure 2—The yearly average flow pattern of solar quiet current systems caused by dynamo action in the ionosphere. Dip latitudes for four transmitter facilities are shown. The value of the current intensity between two consecutive lines is approximately 25 × 10^3 A increasing from zero intensity at the outermost contour and increasing toward the vortices.[8]

THE TRANSMITTER SUBSYSTEM

The approximate magnetic dip latitude is shown in Fig. 2 for Tromsö, Arecibo, Jicamarca, and Fairbanks. The key parameters for the two transmitter and receiving facilities considered for reported results are summarized in Tables 1 and 2. The receiving location for local data was Los Caños, P.R. The approximate ship location for long-path data results is also listed.

The two transmitter-heating modulation modes used during experiments to generate ELF/VLF radiation from the ionosphere are shown in Fig. 3. Figure 3a shows the on/off mode most used for ionospheric heating (e.g., a 3.170-MHz carrier is on for 2 min and off for 2 min).

Table 1—Comparison of transmitter facilities.

	Arecibo	*Tromsö*
Geographic location	18°28′33″ N 66°30′57″ W	60°36″ N 19°12″ E
Magnetic latitude	32°N	67°N
Magnetic dip (deg)	51	78
Frequency (MHz)	3–12	2.5–8
Power (maximum)	800 kW	1.2–1.4 MW
Antenna	4 × 8 array of orthogonal planar log-periodic dipole arrays	6 × 6 array of orthogonal fan dipoles
Antenna zenith gain (dBi)	23–26	24
Antenna beamwidth (deg)	5–10	8.5
Effective radiated power (MW)	160–320	300–350
Duty cycle	Variable	Variable

Table 2—Comparison of experimental receiving locations.

	Los Caños	*Ship*
Geographic location	18°26′25″ N 66°43′75″ W	15°31.85′ N 65°41.98′ W
Physical location	7.5 km SW of transmitter	Caribbean Sea, 300 km SE of Arecibo

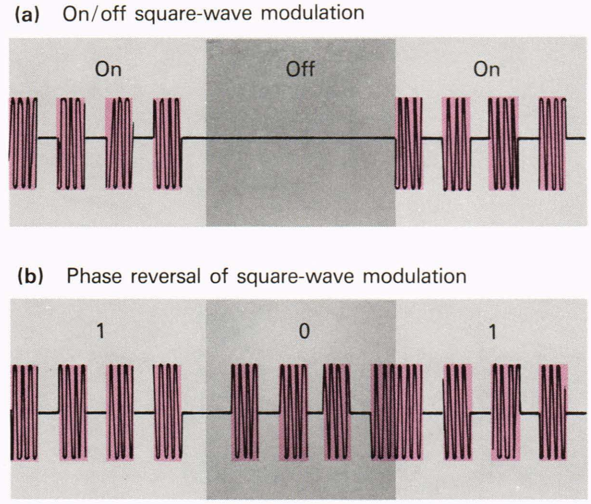

Figure 3—Transmitter heating modulation modes for the generation of ELF/VLF radiation; (a) the on/off modulation with 50% duty cycle, and (b) phase reversal modulation used with synchronous averaging.

During the on period, the carrier is square-wave modulated at a frequency of 500 to 5000 Hz, with an optimum 50% duty cycle determined through experimentation. Figure 3b shows the communication of a stream of logical ones and zeros through the phase reversal of the square-wave modulation at prescribed times determined by the number of points to be sampled for synchronous averaging detection. For these experiments 256 points were used, requiring approximately 1 min to transmit each bit. The carrier must be on at all times.

RECEIVING SUBSYSTEM

A complete description of the receiving subsystem is presented in Ref. 9. A block diagram of the ELF/VLF receiving subsystem is shown in Fig. 4. Three receiving options may be used. The first option uses in-phase and quadrature outputs of a synchronous detector (lock-in analyzer), along with the automatic gain control (AGC) voltage from the heater monitor receiver. These outputs are sampled by the data acquisition system and recorded on magnetic disk. The AGC voltage from the heater monitor receiver can be recorded to define the heater on/off status. The in-phase and quadrature outputs from the synchronous detector are stored on floppy diskettes and are used to calculate the magnitude, phase, and spectrum of the ELF/VLF radiation using VAX 11/780 offline processing. The second option for receiving is the ONO-SOKKI CF-920 signal analyzer, which provides on-line fast Fourier transform (FFT) and correlation analysis of synchronous averaged data, with the storage of raw or processed results on 3.5-in diskettes. The third option uses the same concept of synchronous averaging with Apple II data control computer programs. Digitized data are averaged over 256 samples to detect the deterministic signal component and to cancel the effect of random noise. Results are stored on floppy diskettes and processed off line to examine the data collected.

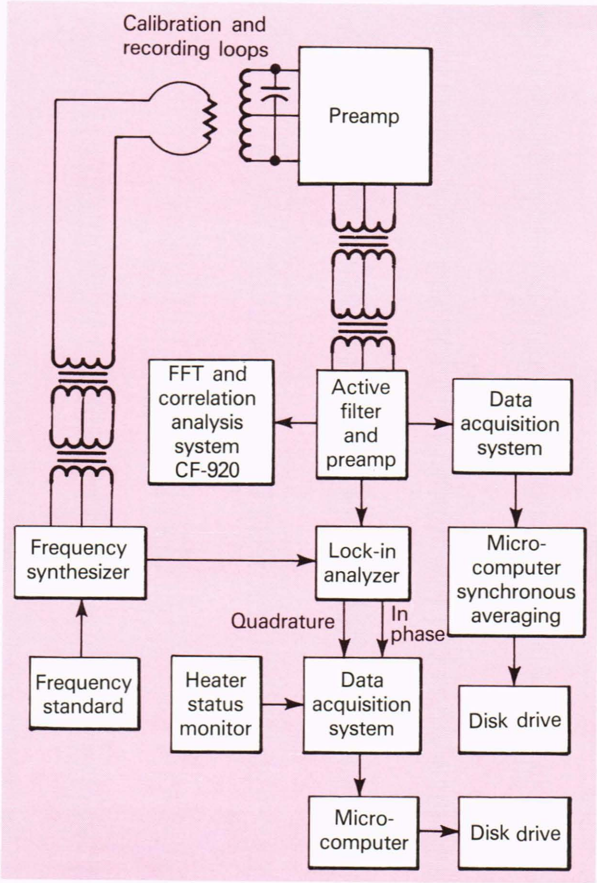

Figure 4—Block diagram of the ELF/VLF receiving subsystem. Three separate receiving options are shown as an output of the active filter and preamplifier.[9]

The receiving loop antenna used during the experiments described was 1 m in diameter, consisted of 200 turns of no. 14 wire, and had a tuned quality factor of approximately 55 at 2.5 kHz. A 0.5-m-diameter one-turn loop was coaxially mounted with the main loop and used during receiving system calibration. A preamplifier and a capacitor turning box were attached to the antenna.

Conventional on/off data were used with the FFT to investigate the presence of the 4.17-mHz frequency component associated with the on/off envelope. This type of signal processing has been enhanced by the recording of noise associated with each frequency. The signal amplitude spectrum is then compared to the noise amplitude spectrum as a diagnostic to establish the presence of a long-path signal. The latter two receiving options discussed above were experimentally exercised in January and July 1984 to receive a transmitted four-bit character string with a 180° phase shift between logical ones and zeros. The phase-shifted data, obtained from the CF-920 analyzer and the Apple II computer, substantiated the results of the conventional on/off technique for local and long-path signals.

LOCAL RESULTS

Experiments were coordinated with the Arecibo Observatory operated by Cornell University under contract with the National Science Foundation. The observatory, located 25 km south of Arecibo, provided logistic support to the heating transmitter at Islote, P.R., and a quiet receiving site at Los Caños, approximately 7.5 km southwest of the transmitter. The heater array was studied in detail by Carroll et al.,[10] who concluded that the main lobe, side lobes, and grating lobes produced multiple sources in the ionosphere, leading to nulls below the heated region (at approximately 3.5 kHz and 500 Hz) at a 5.1-MHz heating frequency. Since the nulls were much less pronounced at 3.170 MHz, this was the primary heating frequency used. It was also discovered through experimentation that a 50% duty cycle for the modulation waveform gave the best heating results with O-mode antenna excitation. Local and long-path results were observed only between sunrise and sunset at the heating facility.

A typical local signal obtained at the Los Caños receiving site is shown in Fig. 5.[9] The dark portions of the x coordinates in Figs. 5a and 5b represent the heating-on time. The 240-s period with a 4.17 mHz primary component allows comparison of the signal-plus-noise amplitude with the signal-plus-noise spectrum. Good phase stability can be observed during the heating period on numerous occasions from the modulation of the dynamo current system. The phase plot in Fig. 5b also shows a phase drift attributed to the frequency offset of the transmitter standard, which was corrected when a cesium beam standard was used.

Results obtained by Ferraro et al.[8] indicate a phase height of the ELF/VLF generation near 70 km. The interesting feature is that higher modulation frequencies have lower phase centers. It is well established that the time constants for heating and cooling the D region are shorter at lower altitudes;[6] therefore, it is expected that the higher modulation frequencies will result in smaller electron temperature changes at higher altitudes, and the lower region would be the region of dominant current.

In May 1983, the receiver equipment was installed near Lima, Peru, and data on the local effects of equatorial electrojet heating from the Jicamarca transmitter were examined on a very limited basis to observe local phase and amplitude data.[11] Results obtained in this experiment were similar to the local Arecibo findings; however, they were less intense because of transmitter parameters.

LONG-PATH PROPAGATION RESULTS

In January 1984, a shipboard experiment was conducted, with data collection at a point approximately 300 km southeast of the Arecibo heating facility.[9] The experiment included 2-min on/off modulation of the 3.170-MHz carrier at 2.5 kHz. The receiving equipment was located on the bridge, and the loop antenna was located either on the port or starboard bridge wing, the plane of the loop being aligned with the bearing to Arecibo. Noise recordings were included at each frequency for comparison to any 4.17-mHz dominant signal-plus-noise spectrum detected.

Figure 6 compares this on/off signal at 2.5 kHz with a noise spectrum recorded at approximately the same time period. Though not as pronounced as the local sig-

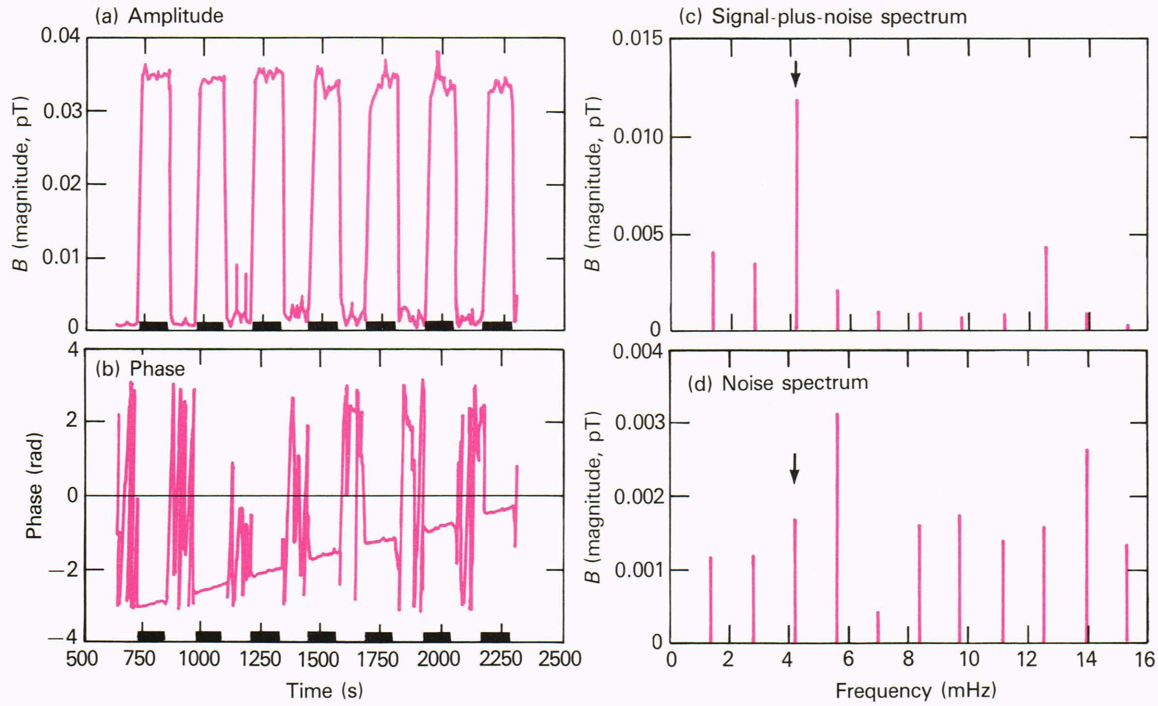

Figure 5—Amplitude, phase, and spectrum of a local (Los Caños) signal plus noise at 2.5 kHz, January 11, 1984, 1730–1800 UT compared to a 2.5-kHz background noise spectrum with an effective radiated power of 160 MW.[9]

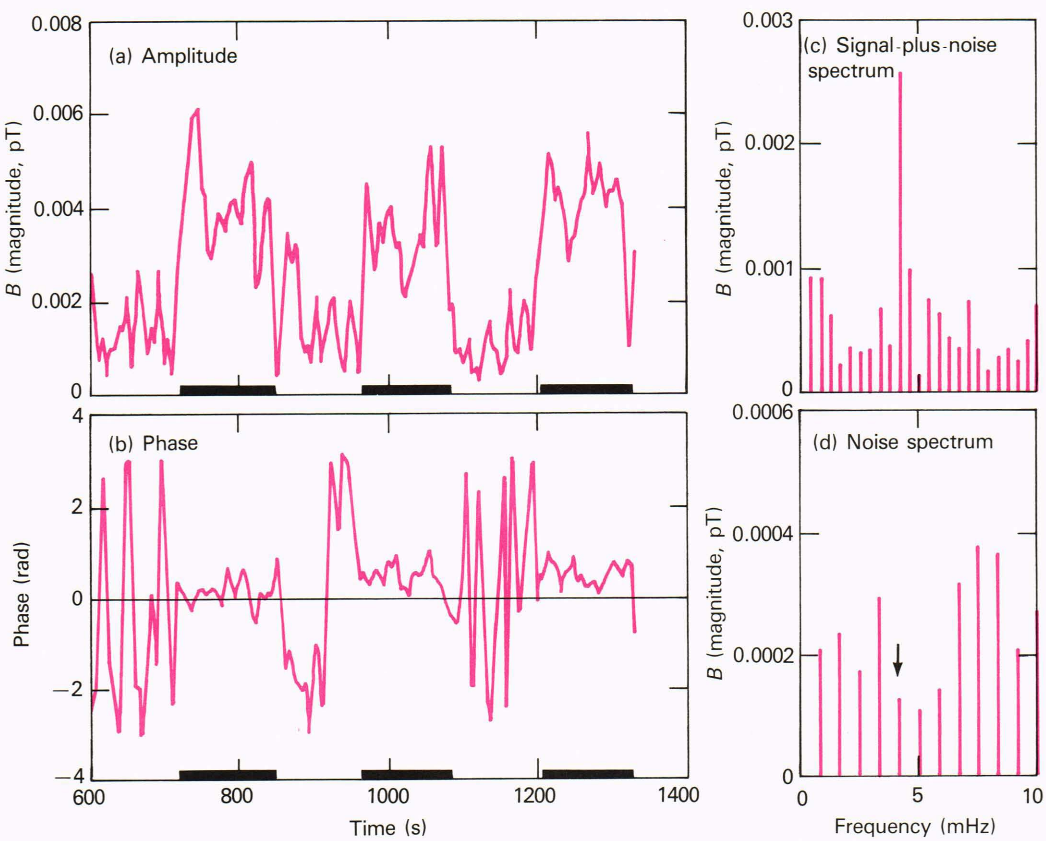

Figure 6—Amplitude, phase, and spectrum of a ship signal of 2500 Hz, January 15, 1984, 1400–1500 UT, 300 km southeast of the Arecibo transmitter, with on/off modulation.[9]

nals recorded under the heated region at Los Caños, the energy propagation is evident through increased amplitude and phase lock during the heating-on period. The dominant 4.17-mHz spectral component during this period compared to noise further confirms the presence of the radiated energy.

Recent long-path experiments have been conducted using the heating facility at Ramfjordmoen near Tromsö.[12] A theoretical model that assumes the source to be a point dipole located in the ionosphere at the height of the maximum ELF/VLF Hall current was used, with propagation in the earth–ionosphere waveguide. The heating transmitter, operating at 2.75 MHz in the extraordinary mode, with an effective radiated power of 270 MW, was modulated at frequencies ranging from 223 Hz to 5.44 kHz. ELF/VLF signals were received by Lyckssle, Sweden (554 km south of the heating transmitter), over the entire frequency range, with maximum amplitudes of magnetic flux density $|B|$ of 0.05 pT.

An investigation of the injection of energy into the earth–ionosphere waveguide by multiple ionospheric sources has been completed by Werner et al.[13] Hertzian dipole sources located at an altitude of 70 km, with a frequency of 1 kHz and radiating 1 kW, are postulated as a linear array separated as a function of wavelength. The magnetic field components are determined at receivers located several hundred kilometers from Fairbanks. The ground HF transmitter characteristics needed to produce the ionospheric sources are not discussed.

Pennsylvania State University is currently operating under an Office of Naval Research contract through a university research initiative award. Experimental emphasis has now shifted from mid-latitude to polar ionospheric modification. The Plattville, Colo., transmitters have been relocated to a site 30 miles east of Fairbanks and are used to feed a circular eight-element crossed-dipole array (i.e., the HIPAS facility). The initial Alaskan campaign was conducted during a three-week period in June 1987 when a series of highly successful experiments was conducted in cooperation with the University of California, Los Angeles and the University of Alaska, Fairbanks. The objective of the experiments was to study the polar ionosphere above Fairbanks by observing the propagation detected from the HF perturbed region using an improved receiving subsystem.[14] The primary results noted were a large increase in the amplitude of the detected signal compared to mid-latitudes and an extremely stable phase during the heating period. The properties of the polar electroject described in Ref. 15, together with recordings from diagnostic equipment, will be used to examine the large quantity of data collected.

CONCLUSIONS

There is experimental evidence to show that when the lower ionosphere is irradiated by a high-power HF transmitter with the carrier modulated in the ELF/VLF range, energy at the modulation frequency is detected both beneath the heated region and at a distance of several hundred kilometers. The possible application of the phenomenon to satisfy future communications needs requires that results of all research in this area be monitored.

The availability of survivable, endurable communications is a continuing requirement for strategic forces. Large land-based transmitter facilities are needed to generate ELF/VLF propagation in the earth–ionosphere waveguide. This limitation might be overcome if future research in ionospheric modification could produce reliable communications from an ionospheric antenna.

The characteristics of the HF transmitter facility needed to produce optimum ionospheric heating and resultant energy injection in the earth–ionospheric waveguide must be developed from theoretical and modeling studies. Structure, excitation, frequency range, gain, and beamwidth are a few of the factors that should be modeled. The mobility of the transmitter must be emphasized for survivability and rapid relocation.

Radiation detected from a heated ionosphere at mid-latitudes is observed only during daylight hours. The results of the above experiments, which use the polar current systems, suggest that the strength and availability of those ionospheric currents might produce the amplitude and phase stability for long-path communications at all hours. Future experimentation needs to focus on the capability of the polar ionospheric antenna to extend the strategic communications capability. Specifically, the ELF range should be emphasized to take advantage of the seawater penetration capabilities of this frequency range.

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