Radio Science, Volume 30, Number 6, Pages 1855–1867, November–December 1995

VLF signatures of ionospheric heating by HIPAS

T. F. Bell, U. S. Inan, M. T. Danielson, and S. A. Cummer

Space, Telecommunications and Radioscience Laboratory, Stanford University, Stanford, California

Abstract. The amplitude and phase of subionospherically propagating VLF signals are known to be sensitive indicators of the electron density and temperature at *D* region altitudes. In this paper we present new observations at a station in Alaska positioned to provide measurements of VLF signals that have propagated beneath the ionospheric region heated by the high-power auroral stimulation (HIPAS) HF heating facility near Fairbanks, Alaska. Analysis of data from HIPAS campaigns conducted in fall 1992 and spring 1993 has shown that in roughly 60% of the cases analyzed, the amplitude of the 23.4-kHz signal from the NPM transmitter in Hawaii as observed in Fort Yukon, Alaska, exhibited a measurable change in amplitude with the same on/off modulation pattern as that of the HIPAS HF transmissions at 2.85 MHz. In almost 70% of the cases analyzed, the same signal exhibited similar measurable changes in phase. The amplitude changes ranged from -0.2 dB to +0.5 dB, and the sensitivity of the measurement was approximately ± 0.02 dB. The phase changes ranged from -4.5° to -0.3°, and the sensitivity of the measurement was typically ± 0.4°. It is demonstrated that the phase and amplitude changes can be used as diagnostic tools to determine characteristics of the ambient electron density profile above the HIPAS facility.

Introduction

It is well documented that localized disturbances (either in electron density or temperature) in the *D* region cause scattering of VLF waves which are propagating in the Earth-ionosphere waveguide which leads to measurable changes in the amplitude and phase of these signals [*Wait*, 1961, 1962, 1964 a, b; *Bell et al.*, 1990; *Dowden and Adams*, 1990; *Inan*, 1990; *Inan et al.*, 1990; *Poulsen et al.*, 1990 a, b;1993]. The feasibility of measuring the amplitude and phase of VLF waveguide signals scattered by artificially heated portions of the ionosphere has been demonstrated by the experiments of *Barr et al.* [1984, 1985] and *Dowden et al.* [1991]. In these experiments, waveguide signals from the Omega transmitter at Aldra, Norway (12.1 kHz), and the Helgeland transmitter (16.4 kHz) were monitored at Skibotn, in northern Norway, during periods when a patch of the *D* region was heated by the HF heating facility at Ramfjordmoen, Norway, which has an effective radiated power of 360 MW [*Wong and Brandt,* 1990]. When the HF beam was deflected so that the heated ionospheric patch was located near or on the great circle path between transmitter and receiver, a scattered waveguide signal was observed whose amplitude ranged from 1% to 50% with respect to the direct signal from transmitter to receiver and whose phase varied from 5° to 50° with respect to that of the direct signal. Amplitude and phase differences of this magnitude are readily observable with sensitive VLF receivers [*Wolf and Inan,* 1990].

In the Barr et al. and Dowden et al. experiments, both the measurement site and the heated ionospheric patch were located within the

Paper number 95RS02191.
0048-6604/95/95RS-02191$08.00

auroral oval. The outstanding success of these experiments demonstrated that the well-known variability of the auroral ionosphere does not have a significant impact on the ability to measure the phase and amplitude of VLF waveguide signals scattered by the modified ionosphere. Furthermore, the Barr et al. and Dowden et al. experiments demonstrated that the scattered waveguide signals could be observed both under day and night conditions.

In anticipation of the completion of the HAARP (HF Active Auroral Research Program, Joint Services Program Plans and Activities, February 1990) high-power (over 1 GW effective radiated power (ERP)) HF ionospheric modification facility in Alaska, an ionospheric modification campaign was carried out in fall 1992 and spring 1993 using the HIPAS (high-power auroral stimulation) Observatory (normally 55 MW ERP), located in the auroral zone near Fairbanks, Alaska [*Wong et al.,* 1990]. One of the major goals of this campaign was to test a variety of techniques for determining the characteristics of the ionosphere during operations of the HIPAS HF heater.

This paper presents the results from the first application of a VLF remote diagnostic technique for determining the electron density and temperature of the ambient and HF heated *D* region at altitudes of 70-90 km. This technique relies on the simultaneous measurement of multiple VLF signals propagating in the Earth-ionosphere waveguide either directly under or near the heated patch of the ionosphere. The comparison of VLF amplitude and phase measurements with theoretical model predictions al-

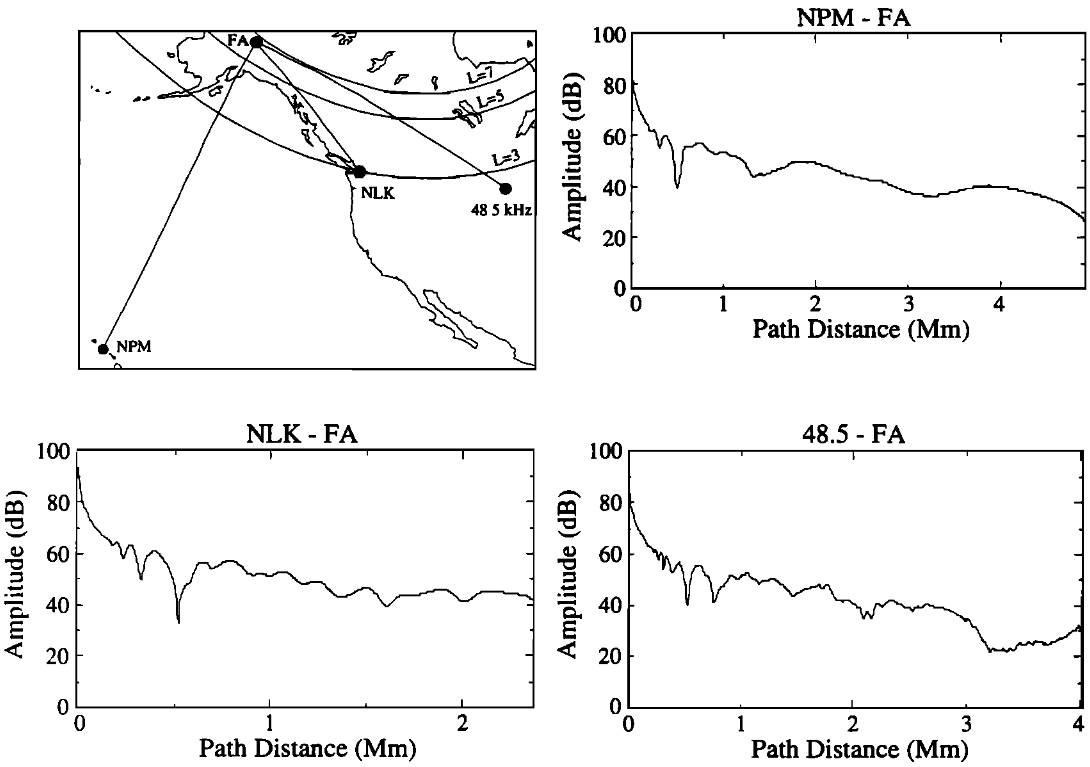

Figure 1. The map shows the three great circle paths between the three transmitters used in this experiment (NPM, NLK, and 48.5 kHz) and a receiving site at Fairbanks, Alaska (FA), together with the loci at 100 km altitude of the feet of the L=3, 5, and 7 field lines. For each source, the ambient waveguide modal structure determines the amplitude of the signal as a function of distance along the path. The signal amplitudes were computed for nighttime conditions using the NOSC LWPC code with its own global ground conductivity map and a typical ambient nighttime ionospheric density profile [*Poulsen, et. al.*, 1993.]

lows an assessment of the electron density and temperature in the heated region.

Description of the Experiments

The VLF data described here were acquired at Fort Yukon (FY), Alaska (145.2°W, 66.6°N, approximately 200 km north of Fairbanks), as part of the Stanford University experiments during HIPAS campaign 1992. The heated *D* region above the HIPAS Observatory (146.8°W, 64.9°N, 40 km east of Fairbanks) was monitored using subionospheric signals from three continuously operating VLF transmitters: NPM (23.4 kHz) in Hawaii (158.2°W, 21.4°N), NLK (24.8 kHz) in Washington (121.9°W, 48.2°N), and Silver Creek (48.5 kHz) in Nebraska (97.6°W, 41.5° N). These three transmitters were selected because of the high signal-to-noise ratio of their signals detected at Fairbanks and because of their relatively simple mode structures. The typical nighttime ambient modal structures of the three waveguide signals are shown in Figure 1. The geometry of the observation site, subionospheric signal paths, and HIPAS is shown in Figure 2. Narrowband (300 Hz) VLF receivers at FY measured and digitally recorded (100 Hz sampling) the amplitude and phase of the three VLF signals for approximately 12-hour periods (typically 0400-1600 UT) each night during the experiments in fall 1992 and spring 1993.

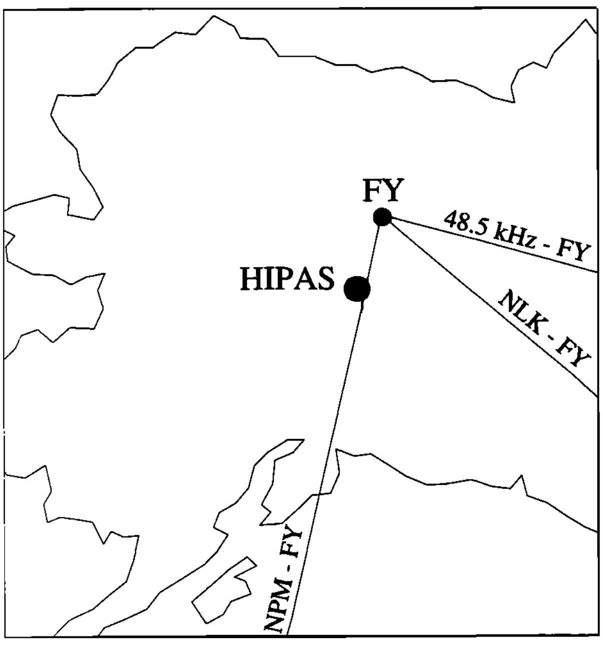

Figure 2. Configuration of the great circle paths between the three VLF transmitters and the observation site at Fort Yukon, Alaska.

The array of eight crossed half-wave dipole antennas at HIPAS (see Figure 3) operated with 55 MW ERP (0.8 MW power with 18.4 dB gain) at 2.85 MHz. Transmission start time was accurate to within ± 25 ms of universal time, maintained using a GPS synchronized clock. The start time of each modulation cycle was accurate to within ± 10 μs.

During the VLF diagnostics experiments, HIPAS operated in three different modes: pulse, dephasing, and painting. In the pulse mode of operation, the HIPAS vertical beam (20° full beam width at half maximum power) was switched on and off at a selected frequency and with a constant duty cycle.

In the dephasing mode the phase of antennas 1, 3, 5, and 6 was switched between 0° and 180° with respect to the phase of antennas 0, 2, 4, and 7 at a selected frequency and with a 50% duty cycle (Figure 3). When the phases were at 0°, the vertical beam was formed in the normal way. When the phases were at 180°, the same radiated power was spread over a larger area in an irregular way with zero power at the zenith.

In the painting mode [*Papadopoulos et al.*, 1990] the HF beam was swept rapidly over an area of the ionosphere above the HIPAS facility which was typically five times the area subtended by the vertical beam used in the pulse mode. If the cooling time constant of the heated electrons is much larger than the heating time constant, the beam can be swept across the entire area before significant cooling occurs. In this way a significant enlargement of the heated area may occur while maintaining approximately the same temperature increase throughout the region. If the painting mode actually increases the horizontal scale of the heated region, then the VLF signal scattered

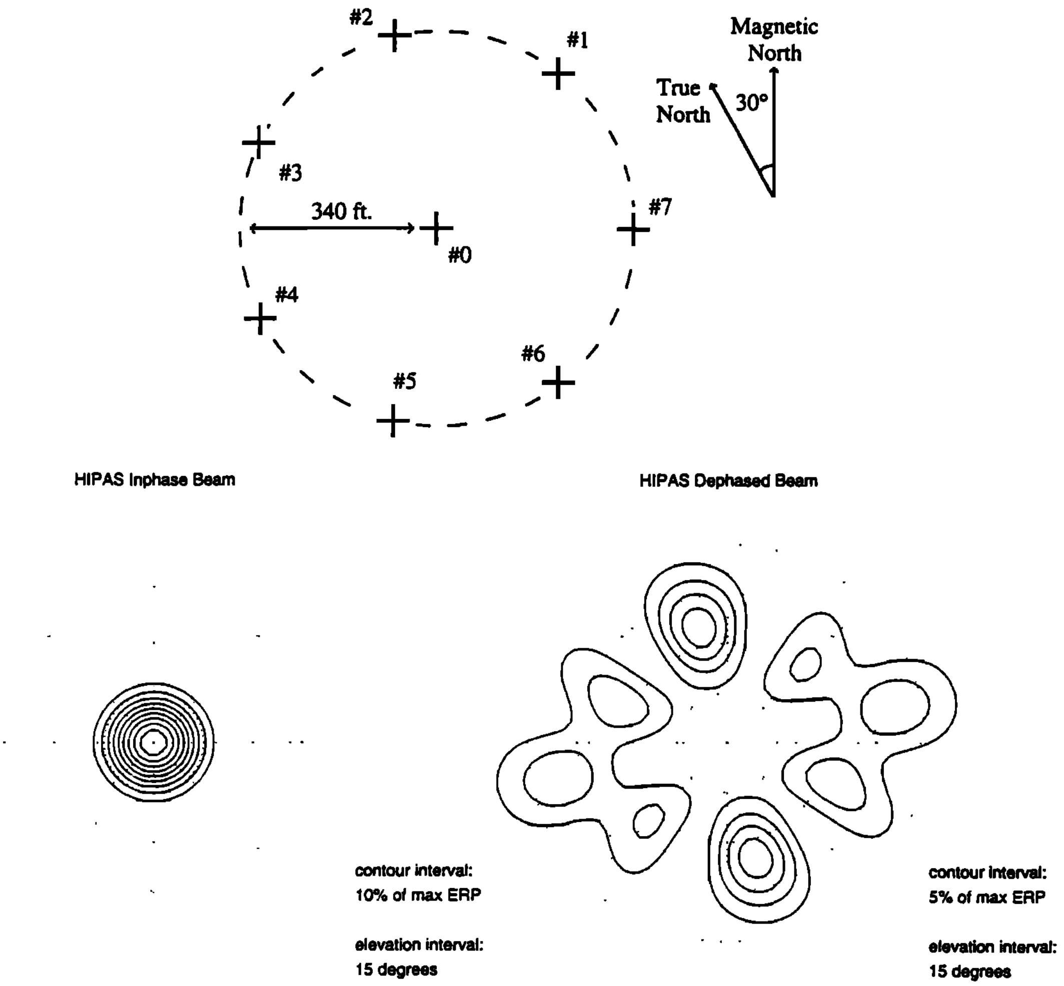

Figure 3. (Top) The HIPAS antenna array of eight crossed dipole antennas as seen from above. (lower left) Azimuth-elevation plot of the normal circular power pattern produced by HIPAS when antennas are in phase. The radial dimension corresponds to the angle from zenith. (lower right) The larger irregular power pattern produced by HIPAS when antennas 1, 3, 5, and 6 are 180 out of phase with antennas 0, 2, 4, and 7. In the dephasing mode, HIPAS switches between the two power patterns at a selected frequency and with a 50% duty cycle.

from the heated region will increase because the scattered signal amplitude is proportional to the diameter of the heated spot [*Poulsen et al.*, 1990b]. This mode is pulsed on and off as in the pulse mode.

For the observations reported in the present paper the particular painting technique employed involved sweeping the beam sequentially at a 10-KHz rate between five angular positions, one directly overhead, and the other four tilted 20° from the vertical and located at the four points of the compass. Thus near 85 km altitude, five nearly identical heated "spots" were produced, with a total heated area approximately five times that produced by a stationary veritical beam. The beam was directed toward each position for a time period of ~100 μs before moving to the subsequent position. Since the beam revisited each position every 500 μs, this particular painting scheme would be successful only if the cooling time was greater than 500 μs. On the other hand, theoretical models [e.g., *Papadopou-*

los et al., 1990] suggest that the cooling time at ~80 km is roughly 10 μs.

Detailed HIPAS operation logs were maintained and provided by the HIPAS Observatory during HIPAS campaign 1992.

Observations

The great circle path of the NPM signal received at Fort Yukon passed within 20 km of HIPAS and provided detectable signatures of HIPAS modulation. The minimum distances from the NLK-FY and 48.5-FY great circle paths to HIPAS were greater than 180 km and 200 km, respectively. Data acquired on these two control paths showed no signs of ionospheric heating.

Figure 4 shows an example of the NPM amplitude observations at FY when the HF heater was operating in the pulse mode at 2 Hz with a 20% duty cycle for 28 min. The upper panel is a plot of raw NPM amplitude data as received at FY versus time. The middle panel is a result of a superposed epoch analysis in which the raw data set from the upper panel is divided into 500-ms serial sections which are subsequently summed and averaged to yield a single 500-ms result. The 500-ms segments are chosen so that the 100-ms on period begins each segment. When the heater is off, the total signal received is simply the unperturbed NPM signal which propagates directly to FY. When the heater is on, the total signal consists of the superposition of the direct signal from NPM and the signal which is scattered from the heated ionosphere over the HIPAS HF heater. Over the first 100-ms, when the heater is on, there is a clear amplitude increase of ~ 0.18 dB. During the subsequent 400-ms, when the heater is off, no such increases in signal amplitude are seen. The lower panel shows the uncalibrated power spectral density calculated using a Hanning-windowed, 50%-overlap, 2048-point FFT. Peaks at 2 Hz and its harmonics show evidence of the 2-Hz rectangular wave modulation of the HF heater signal.

Figure 5 shows that for the heating session of Figure 4, superposed epoch analysis reveals a detectable amplitude change when using only 30 s of raw data. The amplitude change becomes clearer and better defined with longer integration times of 1 min and 5 min.

Figure 6 shows data for a 28-min control period, during which the HIPAS heater was off,

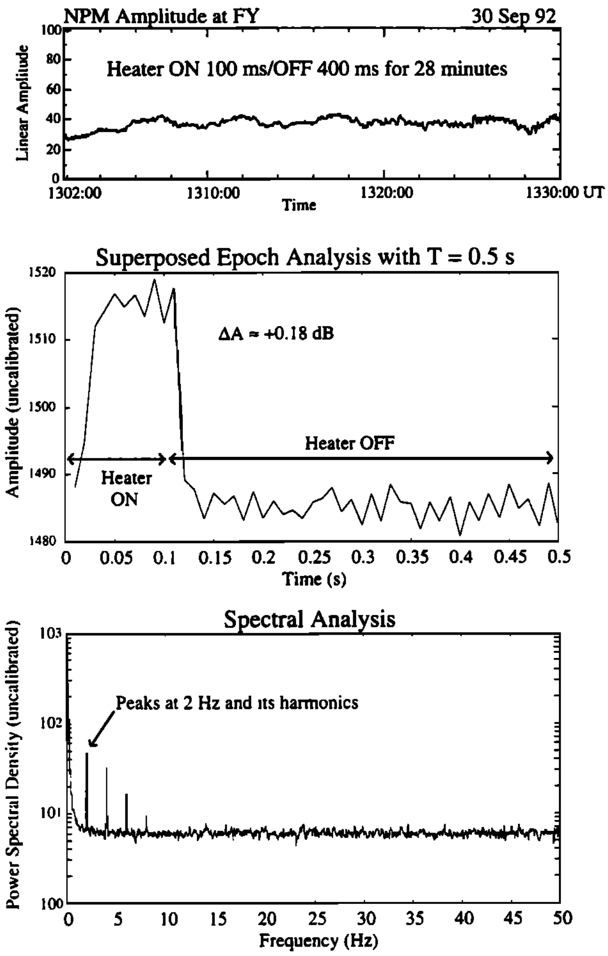

Figure 4. (Top) Raw NPM amplitude data recorded at FY while the HIPAS heater was on for 100 ms and off for 400 ms (2-Hz periodicity), repeated for 28 min. (middle) Superposed epoch analysis (with T=500 ms) of the raw data set from the upper panel. The vertical axis shows uncalibrated superposed linear amplitude with zero suppressed. (bottom) Spectral analysis of the raw data set from the upper panel. The vertical axis shows the uncalibrated power spectral density (logarithmic scale) calculated using a Hanning-windowed, 50%-overlap, 2048-point FFT. The horizontal axis shows frequency up to 50 Hz (Nyquist limit).

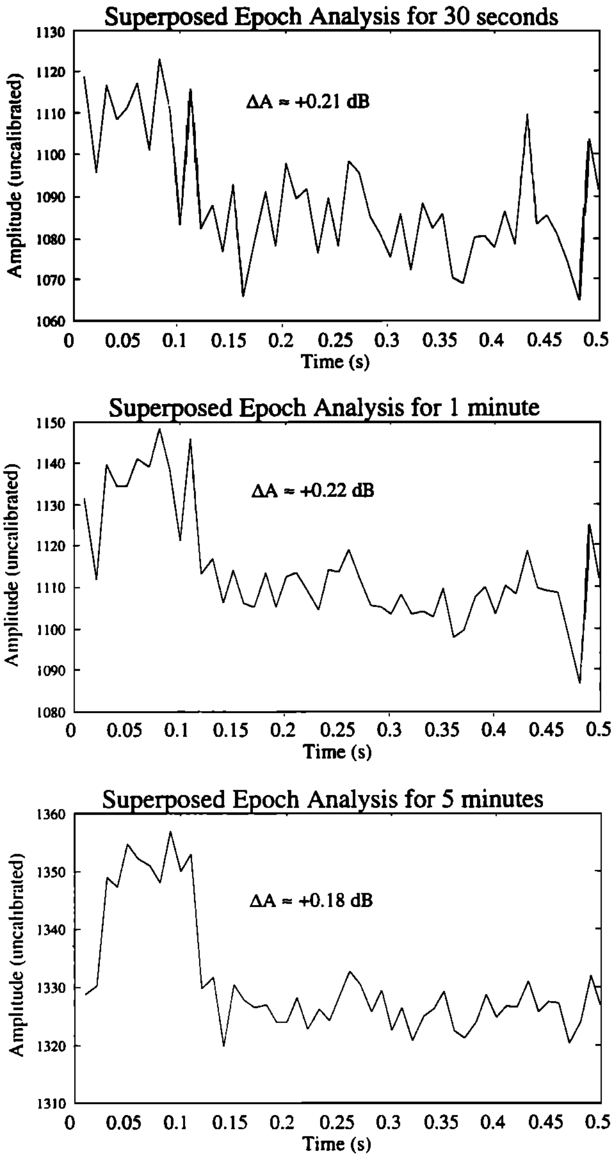

Figure 5. (Top) Superposed epoch analysis with T=500 ms of only the first 30 s of the raw data set from the upper panel of Figure 4. An amplitude increase of 0.21 dB can be detected. (middle) Superposed epoch analysis with T=500 ms of only the first 5 min of the raw data set from the upper panel of Figure 4.

immediately after the heating session of Figure 4. Both the superposed epoch and spectral plots show no apparent change in amplitude or power spectra during this control session.

NPM signal amplitude decreases and phase advances were also observed during heating sessions, as shown in Figure 7. In this example the heater operated in the pulse mode at 1 Hz with a 10% duty cycle for 10 min. The upper panel is a result of a superposed epoch analysis in which the NPM signal amplitude data set of the 10-min heating session is divided into serial sections of 1 s in length which are subsequently summed and averaged to yield a single 1-s-long result. The 1-s segments are chosen so that the 100-ms on period begins each segment. There is

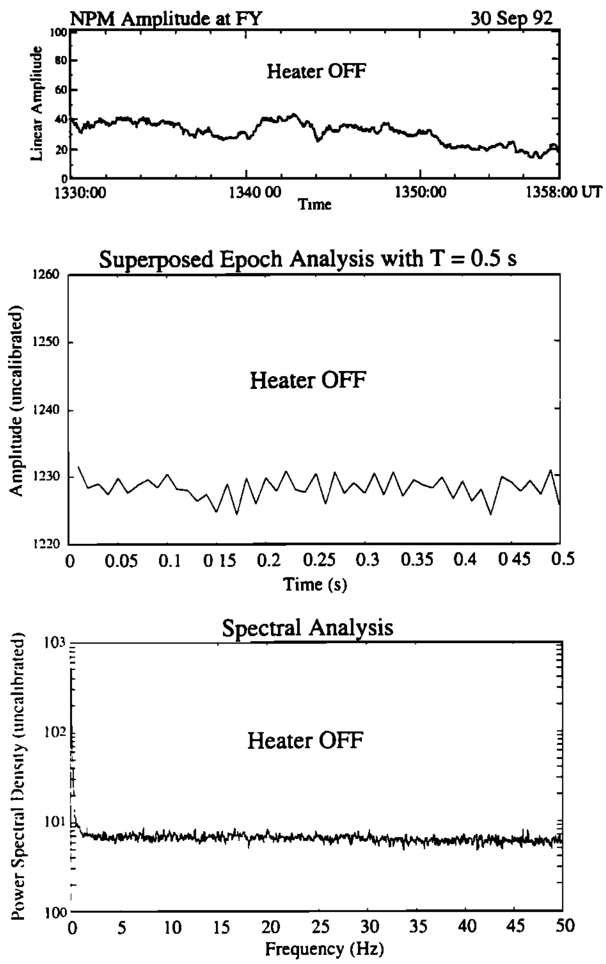

Figure 6. (Top) Raw NPM amplitude data recorded at FY during the 28 min immediately following the heating session presented in Figure 4. During this period the HIPAS HF heater was off. (middle) Superposed epoch analysis with T=500 ms of the raw data set from the upper panel. (bottom) Spectral analysis of the raw data set from the upper panel.

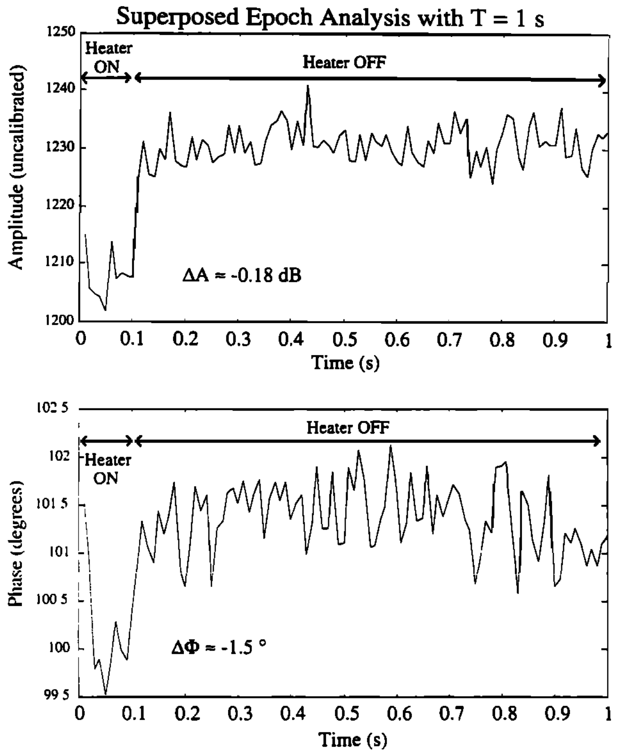

Figure 7. (Top) Superposed epoch analysis with T=1 s of raw NPM amplitude data recorded March 23, 1993, 0920-0930 UT, at FY during which period the HIPAS HF heater was on for 100 ms and off for 900 ms (1-Hz periodicity). (bottom) Superposed epoch analysis with T=1 s of raw NPM phase data recorded at FY during the same heating session shown in the upper panel. The vertical axis shows calibrated superposed phase with zero suppressed.

a clear decrease of ~ -0.18 dB in the NPM signal amplitude during the 100-ms heating portion of the 1-s segment, and no significant amplitude changes during the remainder of the segment.

The lower panel of Figure 7 shows a similar superposed epoch analysis of the NPM signal phase during the same 10-min heating session presented in the upper panel. For this heating session, in addition to the amplitude decrease presented, the heater causes a phase change of $\sim$ -1.5°.

The dephasing mode experiments also produced detectable changes in measured NPM signal amplitude and phase. Figure 8 shows NPM amplitude observations at FY when the HF heater was operating in the dephasing mode at 26 Hz for 10 min. The upper panel is a superposed epoch analysis of the NPM amplitude data set acquired during the 10-min heating session. Thirteen cycles of 26 Hz fit exactly into a time period of 500 ms. Thirteen cycles clearly appear in the upper panel, indicating that for this 10-min heating session, the 26-Hz dephasing mode causes a change of $\sim$ 0.45 dB in detected amplitude. The 26-Hz peak in the spectral analysis of the lower panel shows further evidence of the 26-Hz dephasing of the HF heater signal. In the Figure 8 data, the lack of a sharp on/off signature, such as that shown in Figure 4, results

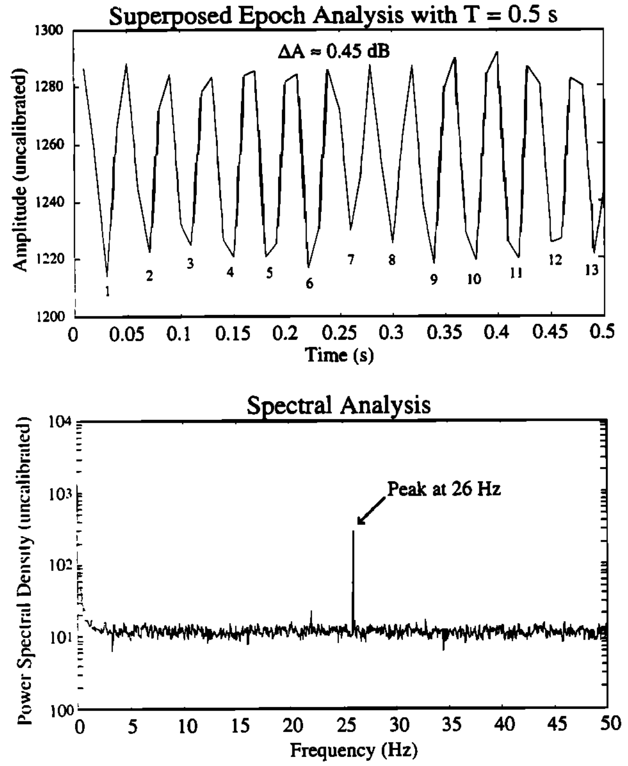

Figure 8. (Top) Superposed epoch analysis with T=500 ms of raw NPM amplitude data recorded March 25, 1993, 0700-0710 UT at FY during which period the HIPAS HF heater was in the dephasing mode at 26 Hz. Thirteen cycles appear clearly in this plot, revealing a 26-Hz change of 0.45 dB in detected amplitude. (bottom) Spectral analysis of the same 10-min NPM amplitude data set analyzed in the upper panel.

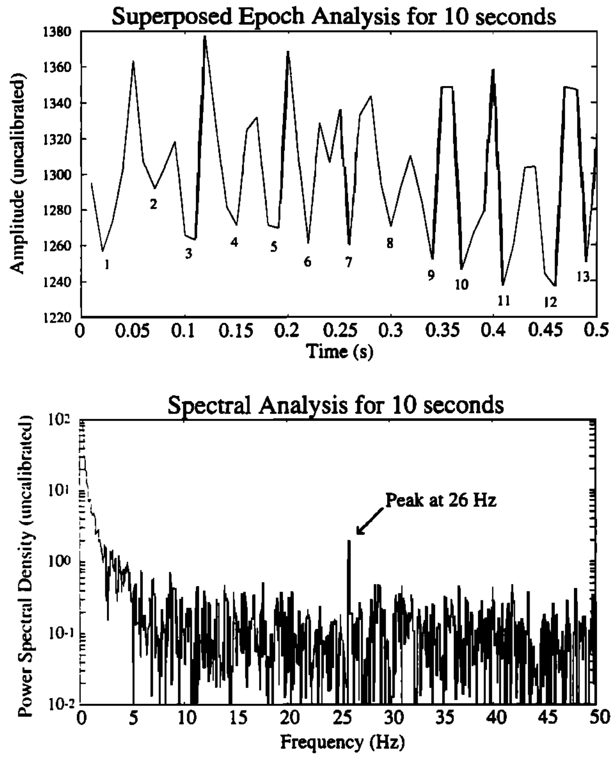

Figure 9. (Top) Superposed epoch analysis with T=500 ms of only 10 s of raw NPM amplitude data recorded March 25, 1993, 0700-0710 UT at FY during the same heating session of Figure 8. After 10 s the superposed epoch analysis clearly shows the presence of 13 peaks. However, the amplitude of the peaks is irregular. (bottom) Spectral analysis of the same 10-s data set analyzed in the upper panel.

from the fact that there are only approximately four samples per cycle.

Figure 9 shows that for the heating session of Figure 8, spectral analysis reveals a detectable peak at 26 Hz when using only 10 s of raw data. However, in the superposed epoch analysis, the amplitude change of the 13 peaks is irregular and some of the peaks are only ~ 0.1 dB above the noise level.

In order to provide a control data set, the NPM amplitude was observed for a 10-min period, during which time the HIPAS heater was off, immediately preceding the heating session presented in Figure 8. This data set is shown in Figure 10. Both the superposed epoch and spectral plots show no apparent periodic change in detected NPM signal amplitude during this control session.

The painting mode experiments produced detectable changes in both NPM signal amplitude and phase. Figure 11 shows NPM amplitude observations at FY when the HF heater was operating in pulse mode at 2 Hz with a 20% duty cycle for 7 min. Figure 12 shows similar NPM amplitude observations when the HF heater was operating in painting mode at 2 Hz with a 20% duty cycle for 7 min immediately after the pulse mode heating session of Figure 11. Both figures show clear evidence of heating, but the painting mode causes a smaller amplitude change of ~ -0.20 dB, while the pulse mode causes a larger amplitude change of ~ -0.28 dB.

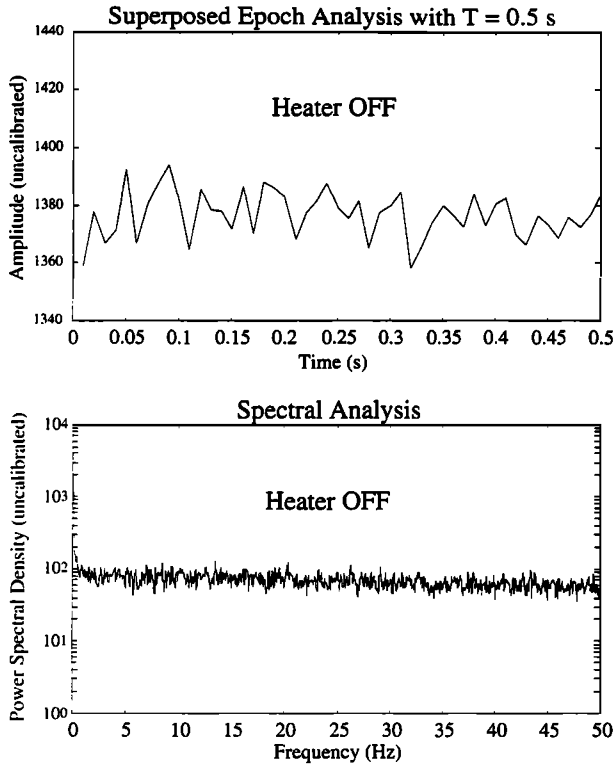

Figure 10. (Top) Superposed epoch analysis with T=500 ms of raw NPM amplitude data recorded March 25, 1993, 0650-0700 UT (a 10-min session immediately before the heating session shown in Figure 8) at FY during which period the HIPAS HF heater was off. (bottom) Spectral analysis of the same 10-min data set analyzed in the upper panel.

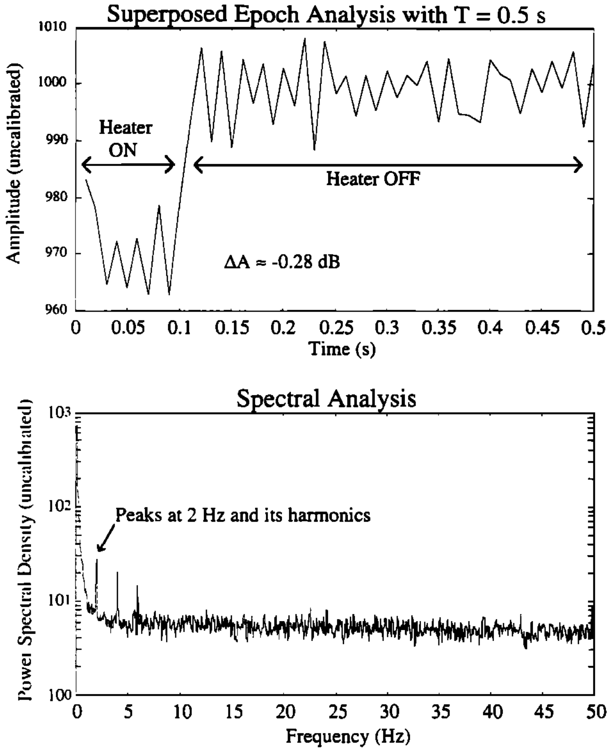

Figure 11. (Top) Superposed epoch analysis with T=500 ms of raw NPM amplitude data recorded October 10, 1992, 0700-0707 UT, at FY during which period the HIPAS HF heater was on for 100 ms and off for 400 ms (2-Hz periodicity). (bottom) Spectral analysis of the same 7-min data set analyzed in the upper panel.

Figure 13 shows NPM phase observations at FY during the same pulse mode heating session of Figure 11. Figure 14 shows similar NPM phase observations for the same painting mode heating session of Figure 12. Both figures show clear evidence of heating, but the painting mode causes a smaller phase change of ~ -2.0°, while the pulse mode causes a larger phase change of ~ -4.5°.

Similar to the amplitude observations presented in Figure 5, superposed epoch analysis (not presented) for the heating session of Figure 13, reveals a detectable phase change when using only 30 s of raw data. As in Figure 5, the phase change becomes clearer and better defined with longer integration times.

NPM amplitude data was obtained for a total of 40 heating sessions, and detectable amplitude changes occurred during 23 sessions, or ~ 58% of the time. Usable NPM phase data was obtained for 19 heating sessions, and phase changes were detected during 13 of these sessions, or ~ 68% of the time. The amplitude changes ranged from roughly -0.2 dB to +0.5 dB, while the phase changes ranged from about -4.5° to -0.3°, with the smallest measurable change set by the prevailing noise level. Typical noise levels were roughly ± 0.02 dB for measured amplitude and about ± 0.4° for measured phase.

Discussion

The main thrust of the Stanford VLF measurements during HIPAS campaign 1992 was

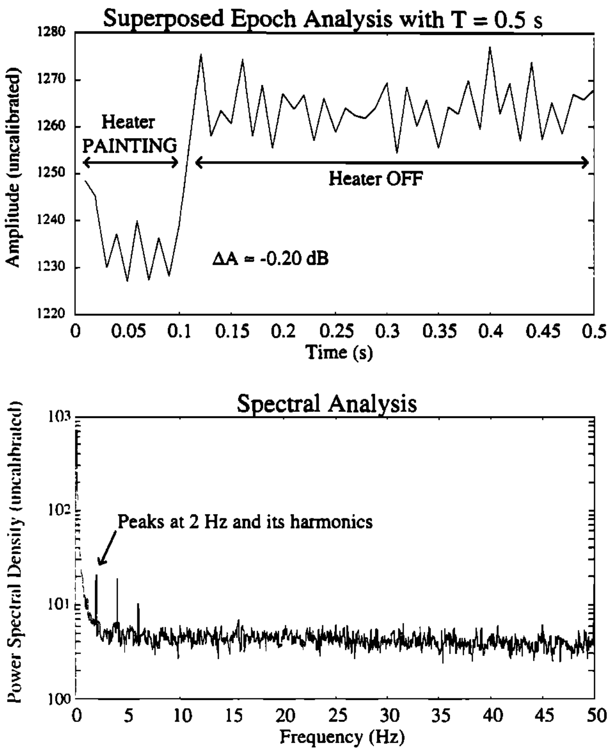

Figure 12. (Top) Superposed epoch analysis with T=500 ms of raw NPM amplitude data recorded October 10, 1992, 0707-0714 UT (a 7-min session immediately after the heating session shown in Figure 11) at FY during which period the HIPAS HF heater was in the painting mode for 100 ms and off for 400 ms (2-Hz periodicity). (bottom) Spectral analysis of the same 7-min data set analyzed in the upper panel.

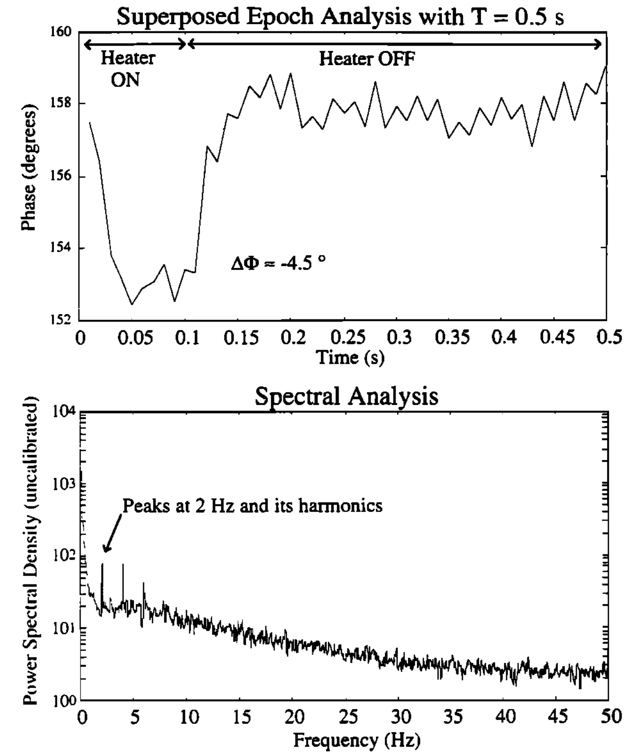

Figure 13. (Top) Superposed epoch analysis with T=500 ms of raw NPM amplitude data recorded October 10, 1992, 0700-0707 UT, at FY during which period the HIPAS HF heater was on for 100 ms and off for 400 ms (2-Hz periodicity). (bottom) Spectral analysis of the same 7-min data set analyzed in the upper panel.

to verify the feasibility of using subionospherically propagating VLF signals as remote diagnostic tools to measure D region modification over the HIPAS heater. Although the earlier experiments of *Barr et al.* [1984, 1985] and *Dowden et al.* [1991] demonstrated the feasibility of similar measurements using the Tromso heating facility, the HIPAS ERP is only one sixth of the Tromso ERP, and the degree of success for the HIPAS observations was difficult to predict. The experimental results presented above show clearly that the ionospheric modifications over HIPAS generally produce measurable changes in subionospherically propagating VLF waves. The next step is to use these measured changes to characterize the disturbed D region over HIPAS during the heating sessions.

The Stanford University VLF diagnostic technique, which will be fully implemented upon completion of the HAARP facility, requires measurements of subionospherically propagating signals at three remote ground stations. Instruments for only two stations, however, had been completed and deployed at the time of HIPAS campaign 1992. The second remote ground station used in HIPAS campaign 1992 was located near Shishmaref, Alaska. This station monitored the ionosphere over HIPAS using the 48.5-kHz signal from Silver Creek, Nebraska. Unexpected high VLF noise levels at Shishmaref generally masked the signal changes due to ionospheric heating. Thus, with data from only one station, we can make only general conclusions at this time.

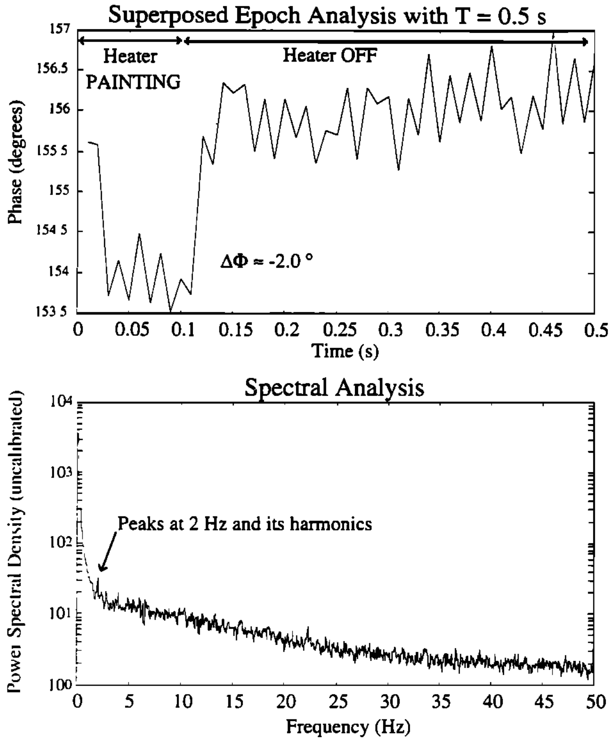

Figure 14. (Top) Superposed epoch analysis with T=500 ms of raw NPM phase data recorded October 10, 1992, 0707-0714 UT (a 7-min session immediately after the heating session shown in Figures 11 and 13) at FY during which period the HIPAS HF heater was in the painting mode for 100 ms and off for 400 ms (2-Hz periodicity). (bottom) Spectral analysis of the same 7-min data set analyzed in the upper panel.

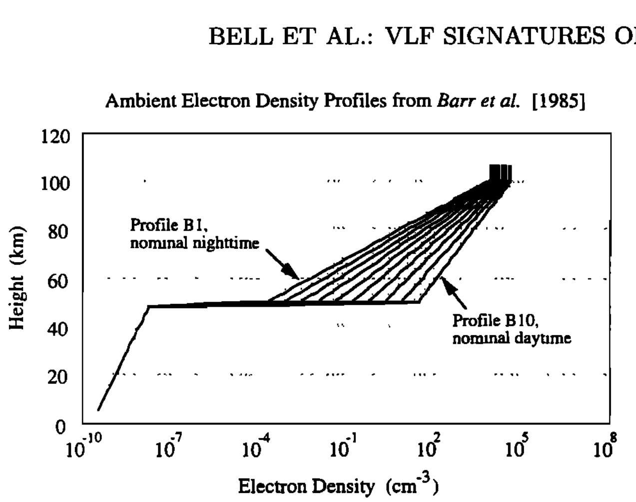

Figure 15. Ten ambient electron density altitude profiles from *Barr, et. al.*, 1985, used over Alaska in the Stanford model to predict amplitude and phase changes in the NPM signal received at FY during HIPAS HF heating. The profiles are numbered B1 to B10 from left to right.

To bring out a few features of the developing VLF diagnostic technique, we present here some of the predictions of our theoretical model for cases in which the ambient electron density and collision frequency are assumed to be known in advance. For the portion of the NPM-FY path over Alaska, the modified electron collision frequency profile was calculated for each of 10 different ambient electron density profiles from *Barr et al.* [1985] (shown in Figure 15), which vary from a nominal nighttime to a nominal daytime ionosphere, using a Stanford University computer code for HF heating [*Taranenko et al.*, 1992] with heating power appropriate for the HIPAS facility. Then the predicted amplitude and phase of the scattered NPM signal at Fort Yukon was calculated for each of the 10 modified profiles using a Stanford 3-D VLF waveguide propagation model, which includes a three-dimensional (3-D) VLF scattering code, with a typical ambient nighttime electron density profile for the portion of the NPM-FY path over the Pacific Ocean [*Poulsen et al.*, 1993]. Figure 16 shows these calculations as compared to similar calculations performed using the same ambient profiles with the HIPAS heater off.

Since the electron density models shown in Figure 15 are essentially two-parameter models, we can distinguish between these profiles using the two measured quantities, ΔA and $\Delta\Phi$. In the upper panel of Figure 16, the model predicts a positive amplitude change for profiles B1-B3 and a negative amplitude change for profiles B4-B10. In view of these results, a preliminary

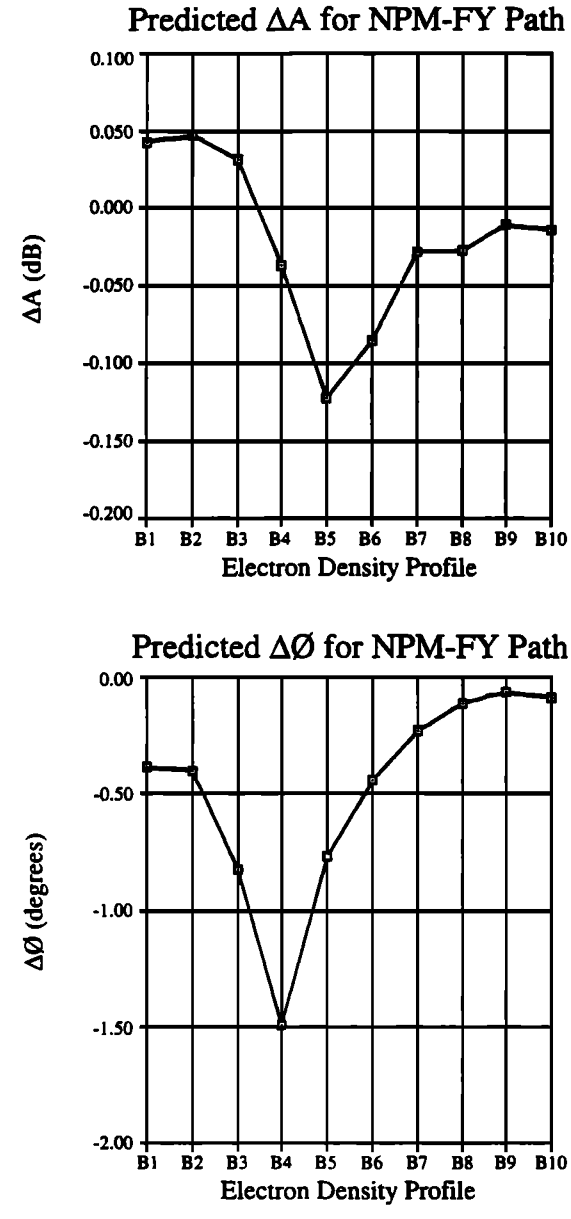

Figure 16. Predicted change in amplitude and phase of the NPM signal received at FY during HIPAS heating for 10 ambient electron density profiles. The numbers on the horizontal axes correspond to the numbered density profiles in Figure 15.

conclusion is that a large positive change in measured amplitude is consistent with either profile B1, B2, or B3, and that a large negative change in measured amplitude is consistent with either profile B5 or B6. Note that very little amplitude or phase change is associated with profiles B7-B10. This situation occurs because of the heavy absorbtion of the HF signal at altitudes below the VLF reflection height.

In the lower panel of Figure 16, the model predicts a negative phase change for all profiles. This prediction is consistent with our experimental results which revealed only negative phase changes. A preliminary conclusion might be that a large negative change in measured phase is consistent with either profile B3, B4, or B5.

Experimental results reveal some amplitude changes up to four times larger than the model predicts and some phase changes over three times larger than the model predicts. We believe that this discrepancy is due to the occasional presence at Fort Yukon of a relative minimum in the NPM ambient signal amplitude. This minimum is caused by destructive interference between the dominant waveguide modes. Similar effects have been noted by *Barr et al.* [1985].

The model results suggest that from amplitude and phase measurements of one VLF signal at one ground station, we can make a limited general assessment of the ambient D region electron density profile as well as the modified electron collision frequency profile. With amplitude and phase measurements of three VLF signals with different frequencies and different paths near HIPAS or HAARP, the VLF diagnostic technique can be used to better characterize both the ambient and modified ionosphere over the HIPAS and HAARP and HAARP facilities.

The experimental results for the painting mode of heating indicates that this technique actually produces slightly smaller VLF amplitude and phase changes than the pulse mode. Since the scattered VLF signal amplitude is proportional to the horizontal diameter of the heated spot in the ionosphere, we conclude that the painting mode was not successful in significantly increasing the horizontal scale of the heated spot. This suggests that the cooling time constant of the heated electrons is smaller than 500 μs, as predicted by theory [*Papadopoulos et al.*, 1990].

The results of the dephasing mode experiments (Figures 8 and 9) suggest that ionospheric diagnostic data can be acquired in time intervals as small as 10-s if the phase-dephase sequence is carried out at a high enough frequency. The critical point is to obtain sufficient data samples during the diagnostic period to significantly increase the S/N ratio of the observed signal through superposed epoch analysis.

From Figure 9 it is evident that 260 samples collected in 10 s is marginally adequate to define the wave amplitude change due to the scattered signal. However, with the planned HAARP facility, which has a maximum ERP of $\sim$1 GW, roughly 20 times that of HIPAS, we would expect to produce a much more intense scattered signal than that produced by HIPAS. Consequently, less averaging will be required to define the amplitude and phase changes due to the scattered signal. Thus we would expect in most cases with the HAARP facility to carry out the planned VLF ionospheric diagnostics on a time scale of $\sim$ 10-30 s. This is an important consideration since it suggests that the VLF diagnostics can be carried out as needed without significant impact on the HAARP experiment program.

Summary

The HIPAS 1992 fall campaign and more recent experiments have established the feasibility of measuring the amplitude and phase of VLF waveguide signals scattered by heated portions of the ionosphere over HIPAS. Observations suggest that these measurements can be carried out in time intervals as short as 10 s when the HF output is modulated at a frequency of 26 Hz (phase-dephase mode). The next step is to use both amplitude and phase measurements of three different VLF signals at three separate receiving sites in order to determine the temperature profile in the heated region over the HIPAS and HAARP facilities.

Acknowledgments. We are indebted to S. Reising and J. Rodriguez for their efforts both in the field and in the laboratory to implement the Stanford VLF measurements. We also acknowledge the valuable assistance of Al Wong and his dedicated HIPAS team. This research was sponsored by the United States Air Force under contract F19628-91-K-0038.

References

Barr, R., M. T. Rietveld, P. Stubbe, and H. Kopka, Effect of a heated patch of auroral ionosphere on VLF-radio wave propagation, *Nature, 309*, 534, 1984.

Barr, R., M. T. Rietveld, P. Stubbe, and H. Kopka, The diffraction of VLF radio waves by a patch of ionosphere illuminated by a powerful HF transmitter, *J. Geophys. Res., 90*, 2861, 1985.

Bell, T. F., W. L. Poulsen, and U. S. Inan, Subionospheric VLF signal variations due to large D region perturbations caused by precipitating energetic electrons, paper presented at XXIII General Assembly of URSI, Prague, Sept. 1990.

Dowden, R. L., and C. D. D. Adams, Location of lightning-induced electron precipitation from measurement of VLF phase and amplitude perturbations on spaced antennas and on two frequencies, *J. Geophys. Res., 95*, 4135, 1990.

Dowden, R. L., C. D. D. Adams, M. T. Rietveld, P. Stubbe, and H. Kopka, Phase and amplitude perturbations on subionospheric signals produced by a moving patch of artificially heated ionosphere, *J. Geophys. Res., 96*, 239, 1991.

Inan, U. S., VLF heating of the lower ionosphere, *Geophys. Res. Lett., 17*, 259, 1990.

Inan, U. S., F. A. Knifsend, and J. Oh, Subionospheric VLF "imaging" of lightning-induced electron precipitation from the magnetosphere, *J. Geophys. Res., 95*, 17,217, 1990.

Papadopoulos, K., C. L. Chang, P. Vitello, and A. Drobot, On the efficiency of ionospheric ELF generation, *Radio Sci., 25*, 1311, 1990.

Poulsen, W. L., T. F. Bell, and U. S. Inan, Three-dimensional modeling of subionospheric VLF propagation in the presence of localized *D* region perturbations associated with lightning, *J. Geophys. Res., 95*, 2355, 1990a.

Poulsen, W. L., T. F. Bell, and U. S. Inan, Subionospheric VLF signal variations due to strong *D* region perturbations caused by precipitating energetic electrons, *EOS, II*, 1535, 1990b.

Poulsen, W. L., U. S. Inan, and T. F. Bell, A multiple-mode three-dimensional model of VLF propagation in the Earth-ionosphere waveguide in the presence of localized *D* region disturbances, *J. Geophys. Res., 98*, 1705-1717, 1993.

Taranenko, Y. N., U. S. Inan, and T. F. Bell, VLF-HF heating of the ionosphere and ELF wave generation, *Geophys. Res. Lett., 19*, 61-64, 1992.

Wait, J. R., Expected influence of a localized change of ionosphere height on VLF propagation, *J. Geophys. Res., 66*, 3119, 1961.

Wait, J. R., An analysis of VLF mode propagation for a variable ionosphere height, *J. Res. Natl. Bur. Stand. U. S. Sect. D, 66*, 453, 1962.

Wait, J. R., On phase changes in very-low-frequency propagation induced by an ionospheric depression of finite extent, *J. Geophys. Res., 69*, 441, 1964a.

Wait, J. R., Influence of a circular ionospheric depression on VLF propagation, *J. Res. Natl. Bur. Stand. U. S. Sect. D, 68*, 907, 1964b.

Wolf, T. G., and U. S. Inan, Path dependent properties of subionospheric VLF amplitude and phase perturbations associated with lightning, *J. Geophys. Res., 95*, 20,997, 1990.

Wong, A. Y., and R. G. Brandt, Ionospheric modification–An outdoor laboratory for plasma and atmospheric science, *Radio Sci., 25*, 1251, 1990.

Wong, A. Y., J. Carroll, R. Dickman, W. Harrison, W. Huhn, B. Lum, M. McCarrick, J. Santoru, C. Schock, G. Wong, and R. F. Wuerker, High-power radiating facility at the HIPAS observatory, *Radio Sci., 25*, 1269, 1990.

T. F. Bell, S. A. Cummer, M. T. Danielson, and U. S. Inan, Space, Telecommunications and Radioscience Laboratory, Stanford University, Stanford, CA 94305-4055. (email: bell@nova.stanford.edu; inan@nova.stanford.edu; markd@nova.stanford.edu; cummer@nova.stanford.edu)

(Received December 28, 1994; revised July 13, 1995; accepted July 20, 1995.)