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The effects of 450 kg surface explosions at the E layer of the ionosphere.

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Abstract

A network of hf ionospheric sounders consisting of two transmitter and two receiver stations was deployed to detect the effects of acoustic waves generated by surface ground motion following an underground nuclear test (UGT) at the Nevada Test Site. The frequency of the transmissions were chosen so that the hf radio waves were totally reflected in the E layer of the ionosphere at an altitude of approximately 100 km. The transmissions were highly stable cw tones at two frequencies separated by 100 kHz so that two altitudes separated by approximately .5 km could be sensed. The network sampled four geographic locations in the ionosphere ranging from almost directly overhead of the UGT out to a horizontal range of 60 km. The ionospheric sounders detected disturbances on all the paths beginning at approximately 325 s after the UGT which persisted for up to 100 s. These disturbances will be described in detail in a later paper. Shortly after the UGT an extended series of ionospheric disturbances were detected which we ascribe to the arrival of acoustic shock waves at the E layer caused by the surface detonation of ordinance with effective yields of 450 kg of high explosive during an unrelated exercise conducted by the U. S. Air Force at a nearby bombing range. The conjunction of these disturbances produced a direct comparison of the effects of UGT's and surface explosions in the ionosphere. In this paper we describe the effects produced by the surface explosions and interpret the disturbance in terms of diffraction induced by electron density changes accompanying the passage of the acoustic waves from the explosions through the reflection altitudes.

1 Introduction

Since 1977 the Los Alamos National Laboratory has conducted ionospheric sounding experiments in conjunction with a number of underground nuclear tests (UGT's) at the Nevada Test Site (NTS). The program originated from a suggestion by *Wouters* [1971] that acoustic waves produced by the heave of the ground surface above the explosion would propagate into the upper atmosphere where their interaction with the natural ionospheric plasma would alter the ambient electron density and thus affect radio waves propagating through the ionosphere. Ionospheric measurements have been reported in connection with UGT's conducted by France in the Pacific [*Blanc*, 1982, 1984] which showed that the duration of the acoustic wave at the E layer of the ionosphere (100 km altitude) was a few seconds. Similar results have been obtained by Los Alamos for NTS events; however, following directly the disturbance ascribable to the passage of the acoustic wave through the reflection height of the probe radio transmission, NTS events usually produce a prolonged disturbance for up to 100 seconds. We ascribe this after-effect to acoustic waves generated by surface seismic waves radiating out to ranges of 100 km from surface ground zero, that is, the point at the surface directly over the UGT. To test this hypothesis, we deployed a network of sounders to probe the ionospheric E layer at horizontal ranges from almost directly overhead out to 60 km in conjunction with the Bexar UGT of April 4, 1991. This UGT took place at 1900 UT (1100 PST) below Pahute Mesa at the NTS; the location of ground zero (GZ) was 37.296°N , 116.313°W , 2.14 km elevation. The reported body wave seismic magnitude, m_b , was 5.6.

In an exercise unrelated to the UGT, the US Air Force conducted a training mission on the same day during which ordinance was detonated at a bombing range just north of the NTS. The exercise resulted in multiple detonations of pairs of 500 pound bombs producing surface explosions with yields of 450 kg. Distinctive signatures of these surface explosions were observed by our ionospheric sounders during a period of 20 minutes following the UGT. Similar signatures were detected at the time of another Air Force training mission during the afternoon of the same day. The conjunction of these disturbances produced a direct comparison of the effects of UGT's and surface explosions in the ionosphere. We will report on the effects produced by the UGT in a later paper; in this paper we concentrate on the effects that we attribute to the conventional surface explosions because they represent a well-defined point source which will aid in the interpretation of the more complicated effects produced by a UGT.

Ionospheric disturbances induced by large surface explosions have been described by a number of authors [*Barry et al*, 1966, *Jones and Spracklen*, 1974, *Jacobson et al*, 1986]. The blast wave from the explosion expands in a approximately hemispherical front; its profile at altitudes up to the E layer has an N wave form, that is, leading and closing shocks with a linear ramp between [*Warshaw and Dubois*, 1981]. The acoustic wave produces a change in electron density which at the hf reflection altitude produces diffraction of the radio waves [*Jacobson et al*, 1986]. The expanding acoustic wave front causes the diffraction source to move at a high horizontal speed inducing a

Doppler shift of the scattered hf. We use our hf receive arrays to verify the angle of arrival of the scattered hf and also the propagation speed of the disturbance across the array is consistent with the diffraction hypothesis. We then calculate the diffraction produced by the effect of a weak N wave to determine the amplitude and length of the acoustic wave. These parameters are shown to be consistent with a simplified theory of the non-linear propagation of the N wave from a surface explosion of the presumed yield.

2 Experiment

We deployed a network of hf cw radio transmitters and receivers operated in bistatic mode to probe the ionosphere from directly overhead of the UGT out to a horizontal range of 60 km. The relation of the network paths to the NTS is shown in Figure 1. Two transmitters were located at the Tonopah Test Range (TTR) (37.78°N, 116.76°W) and another two were located at the EPA (Environmental Protection Agency) Farm on the NTS (37.21°N, 116.04°W). The transmitters consisted of 150 W linear amplifiers fed by frequency synthesizers; the synthesizers were locked to a rubidium clock (EPA) or to an oven-controlled crystal (TTR) to maintain stability. The outputs of the linear amplifiers were fed to separate vertical delta antennas erected on the same mast at each transmitter station. The frequencies of the two transmitters at each station were separated by 100 kHz in order to probe slightly different heights in the ionosphere. Between stations, the frequencies of the transmitters were separated by 30 Hz so that both stations would be within the passband of a receiver (100 Hz).

Receive stations were located at Well5e (36.82°N, 115.97°W) on the NTS and at Indian Springs (ISP) Air Force Base (36.58°N, 115.67°W). A triangular array of antennas was deployed at Well5e and a linear array at Indian Springs. Magnetic loops of 1 m diameter were used as the receive antennas for the cw transmissions. The bottom of the loops were supported approximately 6 cm above the ground surface. The output of each antenna after 30 dB amplification was fed into two Racal 6790GM receivers operated in cw mode with a bandwidth of 100 Hz. The beat frequency of each of the receivers was set so that the audio outputs of the detected multiplexed transmission frequencies were 20 Hz (EPA) and 50 Hz (TTR). The beat frequency of the receivers were locked to a rubidium clock. The audio output of each receiver was digitized at 200 Hz and stored on magnetic disk for later processing.

An ionosonde was operated at Well5e prior to the detonation of the UGT. Sporadic E with a maximum frequency of 5 MHz was observed two hours before the event (1700 UT) but had disappeared by 1800 UT at which time the critical frequency of the E layer (f_oE) was 4.1 MHz. Unfortunately, increased absorption prevented the detection of returns by the ionosonde below 5 MHz at 1840 UT. At that time, the critical frequency of the F layer (f_oF_2) was 12 MHz. After the event (1930 UT), low frequencies were again observable and $f_oE \approx 4.2$ MHz while $f_oF_2 \approx 12.5$ MHz. The cw transmission frequencies were set to 3.82 and 3.92 MHz to ensure uniquely E layer

Figure 1: Location of transmit and receive stations in relation to NTS.

Path	Apogee (km)	Latitude (N)	Longitude (E)
TTR-Well5e 3.82	97.74	37.33	-116.37
TTR-Well5e 3.92	98.25	37.34	-116.37
TTR-ISP 3.82	96.21	37.20	-116.22
TTR-ISP 3.92	96.65	37.21	-116.22
EPA-Well5e 3.82	100.49	37.05	-115.99
EPA-Well5e 3.92	101.30	37.05	-115.99
EPA-ISP 3.82	99.50	36.91	-115.83
EPA-ISP 3.92	100.38	36.92	-115.84

Table 1: Ray Tracing Results

propagation for all the paths at the time of the UGT. The TTR-Well5e path operated through the afternoon hours until about 2400 UT; the transmission frequencies were reduced to 3.02 and 3.12 MHz at 2200 UT to track the decrease in f_oE .

The reflection height at each frequency will vary slightly depending on the range between transmitter and receiver which varies for each of the four paths. Our cw transmissions do not allow us to directly determine the reflection height so we must rely on numerical ray tracing in a model ionosphere to examine the effect of frequency and path length upon reflection height. The ionospheric density is based on the Ionospheric Conductivity and Electron Density (ICED) empirical model which should be very reliable at mid-latitudes [Tascione *et al*, 1988]. We chose a sunspot number of 200 and a Q index of 1 as input into the model; the model $f_oE \approx 4.2$ MHz. Figure 2 shows the calculated (*o*-mode) raytrace between TTR and Well5e while Table 1 lists the height and geographic coordinates of the apogee for all the calculated rays. One notes that the apogees vary over an altitude range of about 4 km and that because of magneto-ionic effects the apogees are north of the exact mid-paths especially on the shorter paths. For the TTR-Well5e path which had an apogee almost directly over GZ we may compare the expected delay time for acoustic propagation between the ground (altitude 2 km) and apogee (altitude 98 km) in a model atmosphere (327 s) with the measured arrival time of the disturbance (328 s) which indicates that the hf ray trace in the model ionosphere is consistent to better than 1 km in reflection altitude.

3 Results for Surface Explosions

In this report we will concentrate on the analysis and interpretation of the effects produced by the ordinance explosions.

Figure 2: Raytrace between transmitter at Tonopah Test Range and receiver at Well5e at 3.82 and 3.92 MHz. The dashed lines indicate contours of constant plasma frequency in 1 MHz steps. The upper plot is a detail of the reflection region showing the difference in the paths of the two frequencies. Straight line segments connect the calculated path points.

3.1 *Power spectra versus time*

Because the cw transmissions consisted of pure hf tones the Fourier power spectrum of the received signal would consist of a single peak if the ray were reflected from a stable ionospheric layer. A weak ground wave (-40 dB) was detectable in EPA transmissions which may be ascribed to their relatively short paths. Also the extraordinary mode may be expected to make an insignificant contribution to the received signal because it is highly absorbed at the frequencies employed in the experiment. In general, the ionosphere is not stable so that there are usually time variations in the phase of the received signal which may be interpreted as Doppler frequency shifts. Negative Doppler shifts correspond to increasing phase paths. Multiple ionospheric reflections (multipath) will appear as several peaks in the power spectra if the separate paths have different Doppler shifts. Thus weak modes may be apparent because they are Doppler shifted away from the more dominant modes; such is the case for the modes resulting from the interaction of the acoustic waves from the surface explosions with the ionosphere. Our method of calculating the evolution of the Doppler power spectra is based on the short-term Fourier transform. One divides the total time series of data into smaller sub-intervals (12.8 s) and calculates the spectrum during that sub-interval. The length of the sub-interval is chosen to give adequate frequency resolution without smearing produced by changes during the sub-interval. The sub-window is then advanced some fraction of its length and a new power spectrum calculated. The results may be visualized in a three dimensional plot which shows power at a given frequency and time as a grey level.

The power spectra versus time after the detonation of the UGT in seconds and Doppler frequency in Hz for the 3.82 MHz transmission for the TTR-Well5e path are shown in Figure 3. The primary reflection appears as a peak at a frequency of 0.6 Hz; the offset is the result of the small frequency difference in the output of the crystal controlled synthesizer at the transmitter compared to the rubidium oscillator at the receiver. A disturbance occurs between 325 s and 500 s associated with the UGT. We are here concerned with the multiple weak chirps which appeared between 550 s and 1250 s. The chirps start at positive Doppler indicating an initially decreasing phase path, go through zero Doppler and then continue to negative Doppler. Chirps appear on all the paths but are not identical. The preponderance of power at negative Doppler that is shown in Figure 3 is typical but does vary among the paths.

Figure 3: Power spectrum of cw transmission between Tonopah Test Range and Well 5e versus time in seconds after 1900 UT. The plot shows spectral power coded according to the scale at the top at a given Doppler shift versus time after the detonation of the UGT. A disturbance associated with the UGT occurred at between 325 and 500 s followed by chirps moving from positive to negative Doppler associated with the ordnance explosions.

Path	Chirp Rate (Hz/s)	Model Chirp Rate	Range (km)	Delay Time (s)
TTR-Well5e	-0.38 ± 0.08	-.40	22.1	0
TTR-ISP	-0.15 ± 0.06	-.16	29.1	1
EPA-Well5e	-0.10 ± 0.01	-.11	48.6	38
EPA-ISP	-0.053 ± 0.006	-.057	68.6	69

Table 2: Comparison of measured and model chirp rates.

Figure 4 shows the power spectra in more detail for the time period from 500 to 1000 s for the four different paths. The start time for the EPA-Well5e spectra are delayed 45 s relative to that of the TTR-Well5e spectra to align the features of interest; the start time of the EPA-Indian Springs spectra are delayed 70 s. There is a close correspondence of the appearance of chirps on all the paths indicating the multiple occurrence of some source which produced a disturbance on each path. The time delay on the EPA-Well5e and EPA-ISP paths indicates that the sources were closer to the TTR-Well5e path.

3.2 Time delay between frequencies

We may compare the time of occurrence of the chirp on the same path between the two frequency transmissions that were separated by 100 kHz. This comparison is made in Figure 5 for the TTR-Well5e path at two times. We note that the chirp appears similar at both frequencies but that it occurs approximately 3 s later on the higher frequency transmission. All the chirps on this path showed approximately the same time delay between frequencies. The other paths also showed time delays between frequencies. This time delay indicates that the chirp originated in the ionosphere and was not a sub-ionospheric reflection from an airplane in which case it should have occurred simultaneously at both frequencies. It also indicates that the source of the chirp propagated upward at approximately the speed of sound given that the reflection heights of the two frequencies were separated by 500 m.

3.3 Doppler versus time

Inspection of Figure 4 indicates that the chirp shows an approximately linear dependence of the frequency on time. The slope of the chirps shown in Figure 4 varies on the different paths and their mean values are given in Table 2. On the other hand, for a given path the different chirps appear very similar indicating that the sources were localized in space.

Figure 4: Time history of power spectrum of cw transmissions at 3.82 MHz showing occurrence of chirps on different paths: (a) TTR-Well5e, (b) TTR-ISP, (c) EPA-Well5e (delayed 45 s), (d) EPA-ISP (delayed 70 s).

Figure 5: Comparison of power spectra for the TTR-Well5e between the 3.82 and 3.92 MHz transmissions at two different times: (a) 3.82 MHz 915-965 s. (b) 3.92 MHz 915-965 s. (c) 3.82 MHz 775-825 s. (d) 3.92 MHz 775-825 s. Note the later occurrence time on the higher frequency transmission.

3.4 Angle of arrival of hf

Since the hf transmitters and receivers were phase stable it is possible to use the receive arrays as interferometers to determine changes in angle of arrival of the hf. We do not know the absolute phase shifts at the different receivers so it is necessary to estimate these shifts by assuming that the mode with a Doppler shift near zero arrives from the direction calculated by the ray-trace described above. We may then employ Doppler filtering to examine the angle of arrival of the chirp modes. Our method of calculating the angle of arrival is based on the delay-and-sum beam former algorithm. Suppose that the vector $\mathbf{r}$ with components (x, y, z) represents the location of an antenna; we assume a rectangular coordinate system in which x is East, y is North, and z is vertical. Relative to an antenna at the origin, the phase of a plane wave with wave vector $\mathbf{k}$ at a point $\mathbf{r}$ is $\exp(-i\mathbf{k} \cdot \mathbf{r})$. Define η as the zenith angle of the ray and ξ as the azimuth angle. Then the wave vector $\mathbf{k}$ has the components $k(-\sin \eta \sin \xi, -\sin \eta \cos \xi, -\cos \eta)$ where k is the free space wave number. If F_i is the complex amplitude at antenna i , then the output of the beam-former, $f(\sin \xi, \sin \eta)$, is

$$f(\sin \xi, \sin \eta) = \sum_i F_i \exp(i\mathbf{k} \cdot \mathbf{r}_i) \quad (1)$$

for an incident plane wave. If $\langle F_i F_j^* \rangle$ represents the coherence of antennas i and j , then the direction of arrival may be estimated by searching for a maximum in the correlation

$$|f(\sin \xi, \sin \eta)|^2 = \sum_i \sum_j \langle F_i F_j^* \rangle \exp\{-ik \sin \eta [(x_i - x_j) \sin \xi + (y_i - y_j) \cos \xi]\} \quad (2)$$

since all the antennas were in the horizontal plane ($z = 0$). We calculate the coherence in the Doppler frequency domain using the Fourier transform of the time series in the interval of interest. The angle of arrival estimates are subject to aliasing in the sense that many different directions can give the same correlation but Figure 6 shows the correlations obtained on the EPA-Well5e path for the two transmission frequencies for directions near the nominal ray. We did not examine each chirp in detail but chose an occurrence with a relatively good signal to noise ratio for analysis. The solid contours are those obtained with a Doppler filter between -0.4 and 0.4 Hz for a 25.6 s time period beginning at 600 s. The peaks at $\sin \eta \approx .21, \sin \xi \approx -.12$ represent the nominal arrival direction and show a correlation above 90%. The dashed contours represent the correlation for the negative Doppler portion of a single chirp; they were obtained with a Doppler filter between -1.5 and -0.5 Hz for a 25.6 s time period beginning at 588 s. The correlations are also above 90%. There is a distinct displacement of the contours at both frequencies which is consistent with an angle of arrival of the chirp from the east of the nominal direction and also more vertical.

Figure 6: Contours of the correlation of the 3.82 and 3.92 MHz transmissions for the EPA-Well5e path versus angle of arrival across the array. The solid contours are the correlation of the nominal ray path while the dashed are those of the **negative Doppler** portion of the chirp between 588 and 614 s. The chirp is offset to the **south-east** of the nominal arrival.

3.5 Propagation speed and direction

We can also use the receive arrays to determine the speed and direction of the chirp over the array based on a delay-and-sum beam former algorithm. We first calculate the cross correlation, $G_{i,j}(\Delta t)$, between antennas i and j for time delay Δt as the inverse Fourier transform of the cross-spectrum of the time series for each antenna during the period of interest. Before calculating the inverse transform we apply a Doppler bandpass filter to isolate the chirp from the nominal reflection. The time delay between antennas i and j , $\tau_{i,j}(\mathbf{s})$, of a disturbance with slowness, $\mathbf{s} = (v_x/v^2, v_y/v^2, 0)$, a vector proportional to the inverse velocity, is

$$\tau_{i,j}(\mathbf{s}) = \frac{\mathbf{v} \cdot (\mathbf{r}_j - \mathbf{r}_i)}{v^2} = \mathbf{s} \cdot (\mathbf{r}_j - \mathbf{r}_i) \quad (3)$$

where $\mathbf{v} = (v_x, v_y, 0)$ is the velocity in the coordinate system described above. We define the total correlation for the array, $g(\mathbf{s})$, as the incoherent sum of the correlations of the separate antennas for slowness $\mathbf{s}$ [Jacobson and Carlos, 1988]; that is,

$$g(\mathbf{s}) = \sum_i \sum_j |G_{i,j}(\tau_{i,j}(\mathbf{s}))|. \quad (4)$$

We then search the slowness plane for the vector which maximizes the total correlation.

The results of the slowness calculation for one of the chirps is shown in Figure 7 on two paths Well5e-TTR and Well5e-EPA. The solid contours were obtained from the 3.82 MHz data while the dashed contours were from the 3.92 MHz data. The Well5e-TTR data were Doppler filtered between -1.5 and 0 Hz; the slowness was calculated during a 6.4 s time period beginning at 547 s for 3.82 MHz and 550 s for 3.92 MHz. The peak correlations were approximately 90%. The 3.82 MHz contours peak at a slowness magnitude of 0.75 s/km and an azimuth of 212° while the 3.92 MHz peak occurs at 0.59 s/km and 180°. The Well5e-EPA data were Doppler filtered between -1.5 and -.5 Hz; the slowness was calculated during a 25.6 s time period beginning at 588 s for both 3.82 and 3.92 MHz. The peak correlations were approximately 97%. The 3.82 MHz contours peak at a slowness magnitude of 1.11 s/km and an azimuth of 137° while the 3.92 MHz peak occurs at 0.98 s/km and 143°.

4 Model

4.1 Location of source

The chirp Doppler signal appears to come from scattering of the hf radio waves from the electron density perturbation near the reflecting region as the hemispherically expanding acoustic wave intersects the plane of the reflection. This is a full wave effect involving the diffraction of the radio wave from a structure with lateral dimensions of the order of a kilometer. A similar effect was observed in connection with the passage of the acoustic wave from a much larger surface explosion through a sporadic-E

Figure 7: Contours of the time delay correlation of the chirp in terms of the slowness across the Well5e array for the two transmitters. The solid contours are the correlation for the 3.82 MHz frequency while the dashed are for 3.92 MHz. The positive x axis is east; the positive y axis is north.

Figure 8: Schematic diagram of the intersection of the acoustic wave from an explosion with the hf reflection altitude in the ionosphere.

layer [Jacobson, *et al.*, 1986]. At any given instant of time after the explosion the acoustic disturbance will be confined to a thin shell at the approximately hemispherical phase front of the acoustic rays [Warshaw and Dubois, 1981]. After a period of approximately six minutes the portion of the shell directly over the explosion will have reached the E layer of the ionosphere. Because of the relatively high ion-neutral collision frequency in the E-layer, the acoustic wave will induce an electron density perturbation directly proportional to the neutral density perturbation. In general, a portion of the shell will be above the reflection height of the hf and another portion will be below the ionosphere as illustrated in Figure 8. The sensitive region for the hf will be the portion of the shell in the ionosphere near the reflection height. We can estimate the Doppler shift of the scattered hf by calculating the time rate of change of the geometric path from the transmitter up to the scattering point and down to the receiver. Suppose that the ground range between transmitter and receiver is $2d$ while the explosion originates at a range r from the mid-point of the path and at an azimuth θ relative to the direction from receiver to transmitter. Assume a rectangular coordinate system with origin at the mid-path and y axis parallel to the line from the receiver to the transmitter. If the hemispherical shell expands at a speed c_s and the scattering point is on the radius connecting the mid-path and the source then the coordinates, $(x_r(t), y_r(t), z_r)$, of the scattering point will be given by

$$x_r(t) = \sin \theta \left[r - \sqrt{(c_s t + \sqrt{r^2 + z_r^2})^2 - z_r^2} \right], \quad (5)$$

and

$$y_r(t) = \cos \theta \left[r - \sqrt{(c_s t + \sqrt{r^2 + z_r^2})^2 - z_r^2} \right]. \quad (6)$$

We assume that the height of the scattering point, z_r , is equal to the reflection height of the hf and is constant in time. We have chosen the origin of time to be the instant that the hemispherical surface reaches the mid-path. Then the geometric path length, $p(t)$, is given by

$$p(t) = \sqrt{x_r^2(t) + (y_r^2(t) - d)^2 + z_r^2} + \sqrt{x_r^2(t) + (y_r^2(t) + d)^2 + z_r^2}. \quad (7)$$

The Doppler shift, $\Delta f(t)$, of the scattered hf with wavelength λ is defined as

$$\Delta f(t) = -\frac{p'(t)}{\lambda} \quad (8)$$

and one can show that to second order in time

$$p'(t) \approx \frac{2c_s^2(z_r^2 + r^2)(z_r^2 + d^2 \sin^2 \theta)}{r^2(z_r^2 + d^2)^{3/2}} \left[t - \frac{3c_s z_r^2}{2r^2(z_r^2 + r^2)^{1/2}} t^2 \right]. \quad (9)$$

The exact location of the ordinance detonations was not disclosed to us. However, a location at 37.46°N, 116.18°W gives the chirp rates listed in Table 2 using (8) and (9) with a sound speed, c_s , 0.3 km/s. Such a location, 22 km northeast of GZ, is within the broad area designated for the exercise and is also within 5 km of an area listed on aviation charts as a bombing and gunnery range. The consistency of the measured and model chirp rates using such a location indicates that a single source could produce the chirps on each of the four paths. Because of the almost linear alignment of the hf reflection points a source located roughly symmetrically on the opposite side of the line would not be inconsistent with the observed chirp rates. However the results of the slowness calculation shown in Figure 7 indicate that the source was to the north of the hf reflection points. Table 2 also lists the horizontal range from the presumed source to the hf reflection point; using those ranges and the hf reflection heights in Table 1 we can calculate the delay time for the arrival of the chirp relative to arrival time on the TTR-Well5e path. These delay times, calculated with an average sound speed of 0.3 km/s, are also listed in Table 2 and are consistent with the estimated delay times given in connection with Figure 4. For comparison with the slowness results, the azimuth of the Well5e-EPA reflection points relative to the presumed source is 149°; the azimuth of the Well5e-TTR reflection points is 221°. The speed of the disturbance over the array, v_d , will be twice the speed of the disturbance in the ionosphere:

$$v_d = 2c_s \sqrt{1 + \frac{z_r^2}{r^2}}. \quad (10)$$

When the values for z_r and r listed in Tables 1 and 2 are inserted into (10), then the expected magnitude of the slowness on the Well5e-TTR path is 0.37 s/km and on the Well5e-EPA path is .72 s/km. These predictions are not inconsistent with the relatively low resolution slowness measurements shown in Figure 7.

4.2 Calculation of the diffraction effect

To estimate the power that may be expected in the scattered field we develop a simplified model of the effect of a perturbation on a vertically incident hf wave. *Kiang and Liu* [1985] have treated hf reflection at vertical incidence from an ionosphere with random electron density irregularities using a multiple phase screen technique assuming that most of the hf energy is scattered through small angles. We have adapted their technique to a deterministic irregularity; however, because the electron density gradient of the bottom side of the E layer is so steep we numerically integrate the parabolic wave equation directly rather than employ their phase screen calculation.

We assume a Cartesian coordinate system in which the ionosphere occupies the half-space $z > 0$ with a monochromatic plane wave with radian frequency ω incident from free space ($z < 0$). The ionosphere is characterized by a relative permittivity, $\varepsilon(\mathbf{r})$, comprising a linearly stratified component, $\varepsilon_0(z) = 1 - z/z_r$, and a perturbation, $\varepsilon_1(\mathbf{r})$. We ignore magneto-ionic effects due to the geomagnetic field. The incident plane wave is scattered by the perturbation as it propagates upward to the turning level, z_r , and is again scattered by the perturbation after reflection. The accumulated phase and amplitude distortion will give a diffraction pattern at the receiver height, $z = -z_L$.

Assuming that we can neglect polarization changes, the electric field, $E(\mathbf{r})$, will satisfy the scalar Helmholtz equation

$$\nabla^2 E(\mathbf{r}) + k^2 \varepsilon(\mathbf{r}) E(\mathbf{r}) = 0 \quad (11)$$

where k is the free space wavenumber. Following the development of *Kiang and Liu* [1985], we seek a solution for $E(\mathbf{r})$ which is a product of the field in the absence of perturbations, $E_0(z)$, and the modified complex amplitude, $u(\mathbf{r})$,

$$E(\mathbf{r}) = u(\mathbf{r}) E_0(z). \quad (12)$$

The unperturbed field, $E_0(z)$, can be expressed as

$$E_0(z) = E_0^{inc}(z) + E_0^{ref}(z) \quad (13)$$

where

$$E_0^{inc}(z) = C_s \{ \text{Ai}[s(z)] - i \text{Bi}[s(z)] \}, \quad (14)$$

$$E_0^{ref}(z) = C_s \{ \text{Ai}[s(z)] + i \text{Bi}[s(z)] \}, \quad (15)$$

and

$$s(z) = -k^{2/3} z_r^{2/3} (1 - \frac{z}{z_r}) \quad (16)$$

[*Kravtsov*, 1965]. Ai and Bi are the Airy functions and C_s is a complex constant depending on the phase of the field below the ionosphere. The notation in (13) indicates that $E_0^{inc}(z)$ behaves asymptotically as an upward propagating component, while $E_0^{ref}(z)$ behaves like a downward propagating component. Our data indicates

that the perturbation scatters energy only within approximately 10° of the nominal ray path. This indicates that most of the energy is scattered into the forward direction so that there is no significant mixing of the upward and downward propagating components. We therefore treat each component separately but properly connect them at the turning point, z_r .

With the assumptions just described, the upward propagating component of the wave field may be written as

$$E(\mathbf{r}) = u(\mathbf{r})E_0^{inc}(z) \quad (17)$$

which when substituted into the Helmholtz equation (11) gives

$$2g(z)\frac{\partial u(\mathbf{r})}{\partial z} + \nabla^2 u(\mathbf{r}) + k^2 \varepsilon_1(\mathbf{r})u(\mathbf{r}) = 0 \quad (18)$$

where

$$g(z) = \frac{k^{2/3}\{\text{Ai}'[s(z)] - i\text{Bi}'[s(z)]\}}{z_r^{1/3}\{\text{Ai}[s(z)] - i\text{Bi}[s(z)]\}}. \quad (19)$$

With the assumption that the scale size, l_e , of the variations in u defined as

$$\frac{\partial^2 u(\mathbf{r})}{\partial z^2} \approx \frac{1}{l_e} \frac{\partial u(\mathbf{r})}{\partial z} \quad (20)$$

is much greater than $1/2g(z)$ then (18) reduces to parabolic form

$$2g(z)\frac{\partial u(\mathbf{r})}{\partial z} + \nabla_\perp^2 u(\mathbf{r}) + k^2 \varepsilon_1(\mathbf{r})u(\mathbf{r}) = 0 \quad (21)$$

where $\nabla_\perp^2 = \partial^2/\partial x^2 + \partial^2/\partial y^2$. The advantage of using the parabolic form (21) is that the determination of u reduces to an initial value problem; *Kiang and Liu* [1985] employ a multiple phase screen approach to solve (21) over a large vertical distance in the F region. We are interested in reflection over a shorter distance in the E layer so that a more direct numerical approach such as Crank-Nicholson with an initial value of $u(z=0) = 1$ is convenient; we then step $u(\mathbf{r})$ in altitude to some $z > z_r$.

In analogy to (17), the downgoing component may be written as

$$E(\mathbf{r}) = u(\mathbf{r})E_0^{ref}(z). \quad (22)$$

In the same manner as for (21) one obtains a parabolic equation for the modified complex amplitude of the downgoing component given by

$$2g^*(z)\frac{\partial u(\mathbf{r})}{\partial z} + \nabla_\perp^2 u(\mathbf{r}) + k^2 \varepsilon_1(\mathbf{r})u(\mathbf{r}) = 0 \quad (23)$$

where g^* is the complex conjugate of (19). The total field, $E(\mathbf{r})$, comprised of (17) and (22) must vanish at some level above the reflection height, z_r ; since the unperturbed field, $E_0(z)$, also goes to zero above z_r , the modified complex amplitude, $u(\mathbf{r})$, for the

upgoing and downgoing components must approach the same value above z_r . Thus (23) may be calculated for $u(z = 0)$ using the initial conditions for $u(z > z_r)$ given by the solution of (21). For $z > z_r$, $\text{Im } g(z) \rightarrow 0$ so that (23) approaches (21); therefore the height at which the solutions are matched can be chosen arbitrarily in the limiting region since the change in u calculated from (17) will be reversed by the change calculated from (22).

The solution for the downgoing amplitude at the receiver height, $u(x, y, -z_L)$, may be derived using the Fresnel approximation [Papoulis, 1968]. That is,

$$u(x, y, -z_L) = \frac{ik}{2\pi z_L} e^{ikr_0} U\left(\frac{-kx}{z_L}, \frac{-ky}{z_L}\right) \quad (24)$$

where U is the two-dimensional Fourier transform of $u(x, y, 0)e^{-ik(x^2+y^2)/2z_L}$ and

$$r_0 \approx -z_r - \frac{1}{2z_L}(x^2 + y^2). \quad (25)$$

We assume that the neutral density perturbation, $\Delta\rho(x, z)$, has an N wave behavior which is the asymptotic form of a transient pulse [Pierce, 1981]. That is,

$$\frac{\Delta\rho(x, z)}{\rho(z)} = \frac{az'}{l} \left(\tanh \frac{z' + l/2}{e} - \tanh \frac{z' - l/2}{e} \right) \quad (26)$$

where a is the amplitude of the perturbation, l is the length of the N wave, e defines the dimensions of the leading and trailing edges, and $z' = z - z_r + xs$. The slope s defines the tilt of the N wave and is assumed to be independent of x and z ; that is, we are simplifying the geometry of the hemisphere to a tangent plane at the reflection height. For the E region altitudes of interest here the response of the ionospheric plasma mirrors exactly the changes in the neutral density because of the very high electron-neutral and ion-neutral collision frequencies. At 100 km altitude, the ratio of the ion gyrofrequency to the ion-neutral collision frequency is approximately 0.05. For such a collision dominated regime, in the frame of reference moving with the neutral particle velocity, $\mathbf{U}$, the plasma velocity, $\mathbf{V}'_j$, is given by

$$\mathbf{V}'_j = b_j \mathbf{E}' - D_j \frac{\nabla n}{n} + \left(\frac{D_j}{H_j} \right) \hat{\mathbf{g}} \quad (27)$$

where j indicates the ion species, n is the plasma density, and $\mathbf{E}' = \mathbf{U} \times \mathbf{B}$ [Kelly, 1989]. The third term on the rhs of (27) represents the effect of gravity: $\hat{\mathbf{g}}$ is the unit vector in the direction of the gravitational force, $H_j = k_B T_j / M_j g$ is the scale height, and $D_j = k_B T_j / M_j \nu_{jn}$ is the diffusion constant. The ratio, D_j / H_j , is approximately .003 m/s for ions at 100 km altitude and thus may be neglected in comparison to the peak neutral particle velocity, U , which is of the order of 1% of the sound speed or approximately 3 m/s. The second term on the rhs of (27) represents diffusion along the plasma density gradient and is approximately equal to $2D_j a / l$ or about

Figure 9: The instantaneous complex amplitude at the ground of a reflected hf signal for an N wave perturbation with an maximum relative overdensity, a , of 0.01 and length, l , of 300 m.

.002 m/s for ions at 100 km altitude. The first term, representing the response to the electric field in the transformed coordinate system, is proportional to the mobility, $b_j = q_j/M_j \nu_{jn}$ and is approximately .1 m/s for ions at 100 km and a dip angle of 60° . We neglect this term both because it is relatively small and because it generates a horizontal drift which to first order will not alter the density. Thus (27) reduces to $\mathbf{V}'_j \approx 0$ or $\mathbf{V}_j \approx \mathbf{U}$; since for a sound wave $U/c = \Delta\rho/\rho$ the change in plasma density will be $\Delta n/n = \Delta\rho/\rho$ based upon conservation of mass and with the assumption that plasma production and loss are negligible. The more mobile electrons will move to maintain charge neutrality.

We have calculated the diffraction effect as described above under the following conditions which were chosen to match the EPA-Well5e path: for the perturbation, we take $a = .01$, $l = .3$ km, $e = .01$ km, $s = .5$, and $z_r = 13$ km. The calculation is performed over a 160 km aperture which was divided into 4096 elements; we use a numerical step in the z direction of $\lambda/2$. We use a wavelength, $\lambda = .075$ km and an altitude, $z_L = 88$ km. The results of the calculation for the complex amplitude, $u(x, -z_L)$, at the ground are shown in Figure 9. The effect of the perturbation is apparent near the origin; there is also a diffraction effect at the edges of the aperture unrelated to the perturbation. We may convert these results for the amplitude versus

distance to amplitude versus time at a single location if we assume that the perturbation moves with a constant speed, v_x , in the x direction: $u(t, -z_L) = u(-v_x t, -z_L)$. We can then obtain the power spectrum versus time in the same format as for Figure 3. Using a value of v_x of 0.7 km/s we obtain the result shown in Figure 10. The results displayed in Figure 10 show good agreement with the experimental results in Figure 4 for the signal level and duration; the predominance of power at negative Doppler is not well matched and may indicate the need for a calculation in terms of oblique propagation or a need to account for the hemispherical curvature of the acoustic disturbance.

$$A = 0.010 \quad L = 0.30 \quad S = 0.50 \quad V = 0.$$

Figure 10: Power spectrum versus time at a single location obtained from the results shown in Figure 9 by assuming that the perturbation moves with a constant speed of 0.7 km/s.

5 Discussion

The disturbances described above were likely induced by the detonation of about one half ton of conventional explosive. A surface explosion effectively doubles the energy emitted into the atmosphere; thus the detected explosions correspond to the detonation of a 1 ton of high explosive (4.2 GJ) in free air. Most of that energy will be dissipated in the lower atmosphere and will not reach the ionosphere; moreover, because of finite-amplitude effects, the profile of the acoustic pulse will change during propagation. The acoustic energy density, w , of a spherically expanding wave is given approximately by [Pierce, 1981]

$$w = \frac{(\Delta\rho)^2 c_s^2}{\rho}. \quad (28)$$

For the N wave described in (26) the energy density per unit area, σ , is approximately

$$\sigma = \frac{1}{3} \rho c_s^2 a^2 l. \quad (29)$$

If we consider an N wave propagating in the vertical direction, z , then the energy loss at the leading and trailing shocks is given by

$$\frac{1}{\sigma} \frac{d\sigma}{dz} = -\frac{\gamma+1}{2} \frac{a}{l} (1-6a) \quad (30)$$

to second order in a [Kahalas and Murphy, 1971]; γ is the ratio of specific heats which equals 1.4 for a diatomic gas. The length of the N wave, l , increases as the pulse propagates due to non-linear stretching; Kahalas and Murphy [1971] give the rate of stretching as

$$\frac{dl}{dz} = \frac{\gamma+1}{2} a - \left(\frac{\gamma+1}{4} \right)^2 a^2 \quad (31)$$

Banister [1982] also included energy losses associated with viscosity and heat conduction over the internal gradient of the N wave; their contribution to the energy loss is

$$\frac{1}{\sigma} \frac{d\sigma}{dz} = - \left(\frac{4}{3} \mu + \frac{\gamma-1}{\gamma} \frac{\kappa}{C_v} \right) \frac{12}{\rho c_s l^2} \quad (32)$$

where μ is the viscosity, κ is the thermal conductivity, and C_v is the specific heat and constant volume. Combining the two losses, (30) and (32), and invoking energy conservation over a unit solid angle, one obtains

$$\frac{2}{z} + \frac{1}{\sigma} \frac{d\sigma}{dz} = -\frac{\gamma+1}{2} \frac{a}{l} (1-6a) - \left(\frac{4}{3} \mu + \frac{\gamma-1}{\gamma} \frac{\kappa}{C_v} \right) \frac{12}{\rho c_s l^2}. \quad (33)$$

Using (30), one obtains an equation for the rate of change of the amplitude

$$\frac{2}{a} \frac{da}{dz} = -\frac{2}{z} - \frac{1}{\rho} \frac{d\rho}{dz} - \frac{1}{l} \frac{dl}{dz} - \frac{\gamma+1}{2} \frac{a}{l} (1-6a) - \left(\frac{4}{3} \mu + \frac{\gamma-1}{\gamma} \frac{\kappa}{C_v} \right) \frac{12}{\rho c_s l^2} \quad (34)$$

which with (31) may be solved numerically [Banister, 1982]. The initial conditions for a and l may be determined from scaling laws [Kahalas and Murphy, 1971]; for an explosion with a hydrodynamic yield of 1 ton (4.2 GJ) $a = 0.0536$ at a range of 134 m at which point the length of the positive portion of the pulse is 16 m. We have included a correction for the elevation, 1.6 km, at the presumed location of the explosion. We will assume that the waveform has evolved into an N wave so that the initial $l = 32$ m; then the total initial acoustic energy is .40 GJ or 19% of the yield of the detonation. The parameters in (34) are $\mu = 1.709 \times 10^{-5}$ Pa-s, $\kappa = 0.0233$ W/m K, and $C_v = 736.7$ J/kg K; we assume that the propagation takes place in an isothermal atmosphere with a scale height of 7 km and $c_s = 300$ m/s. To compare with the results of the diffraction calculation which models the acoustic disturbance at a zenith angle of 26° we change z to a radial variable and modify the scale height to 7.8 km. The results of the calculation for the amplitude, a , and the length, l , is shown in Figure 11; the values at the range (110.6 km) corresponding to the hf reflection altitude are $a = .0069$ and $l = 340$ m. The agreement with the results derived from the diffraction calculation is good and indicates that the surface explosions are the most likely source of the observed disturbances.

6 Conclusion

We have observed ionospheric disturbances in the E layer from explosion sources in close proximity in time and location to a UGT source. The weak explosion sources produce ionospheric effects by a diffraction mechanism detected by our hf sounders; the effect is detected by our cw systems because the diffraction point moves at a rapid speed resulting in a Doppler shift of the scattered hf. These explosions give us ideal point sources with which to interpret our results for the UGT. We believe that at least some of the prolonged disturbance associated with the UGT may also be interpreted as a diffraction effect associated with acoustic waves generated by surface seismic waves radiating outward from the source. The explosion sources will also give us a calibration point for the strength of the acoustic wave generated by the UGT.

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Figure 11: Calculated amplitude, a , and length, l , of an N-wave pulse versus distance from a half-ton surface explosion.

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