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OBSERVATIONS OF TEC FLUCTUATIONS FROM AN EXPLOSION ON THE EARTH'S SURFACE

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Abstract

We report observations of perturbations in the ionospheric total electron content (TEC) caused by acoustic waves propagating from a large chemical explosion in southern New Mexico at the earth's surface. Fluctuations in TEC were measured by two arrays of receivers that monitor the phase of the 136 MHz beacons on two geostationary satellites. One array, located in northern New Mexico, observed fluctuations in the region where acoustic waves from the blast impinged directly on the ionosphere, while the second array, in Texas, was located to observe fluctuations caused by ducted acoustic waves. The TEC disturbance at the New Mexico array had an amplitude of about 2×10^{14} m^{-2} (more than 10 times the array noise level), while the amplitude at the Texas array, at a range of 900 km, was only a few times the instrumental noise level. Noise background analysis shows that the probability that a comparable or larger response at the New Mexico array might have been caused by a background noise event was less than 1%. The corresponding probability for the Texas array was 3%.

Introduction.

Ionospheric responses to ground-level explosions have been observed for many years (for a review, see [Blanc, 1985], using HF sounding or other techniques that detect the motion of the lower ionosphere in response to acoustic gravity and perhaps other waves produced by the explosion. We have observed the ionospheric response using an array of phase-detecting receivers, an approach apparently first suggested by Mass [1963, pp. 276-277]. The potential advantages of the technique are (1) the extremely high sensitivity of phase to small TEC perturbations, and (2) an apparently low background noise level at infrasonic frequencies.

The TEC along a line of sight to a satellite is sensitive to the presence of an acoustic wave if several conditions are met. First, the line of sight must be roughly parallel to the wavefronts, so that the integral does not contain many cycles of the acoustic wave. Second, the earth's magnetic field vector must have an appreciable component along the acoustic wave vector **k** (the sensitivity is proportional to $\alpha = (\hat{k} \bullet \hat{B})^2$, where **B** is the earth's magnetic field. Ideally, α=1, but for the actual geometries used, it was much lower.

Description of the experiment.

The TEC array described in [Carlos and Massey, 1994] and a similar array in Texas were used to observe the ionospheric response to a large (8.5×10^{12} J, 2 kT HE equivalent) chemical explosion that took place on 10 July, 1993 at the White Sands Missile Range in southern New Mexico. Two geosynchronous satellite beacons at about 136 MHz were observed: GOES-2 and ATS-3. Figure 1 shows the geometry for the two stations. For the New Mexico array, the line of sight to the GOES satellite was reasonably tangent to the wavefronts, with α ranging from 0.15 to 0.38. In Texas, α was about 0.12 at the San Antonio stations. The acoustic waves from the explosion propagate directly to the penetration points from the New Mexico array, and calculations are presently underway to determine the actual ray trajectories using measured temperature profile data.

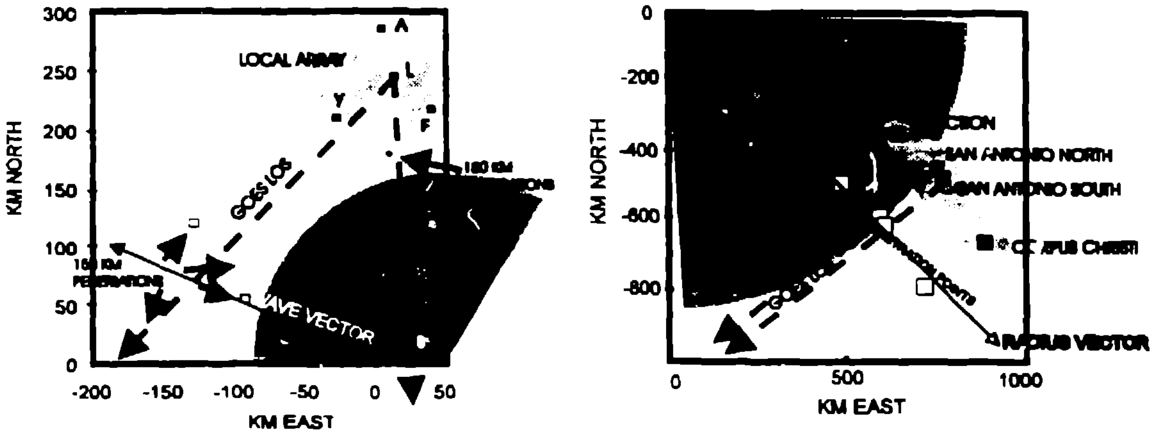

Figure 1. Geometry for the two observing arrays. The origin is at the explosion site. Left: the New Mexico array, right: the Texas array.

New Mexico array results.

Fluctuating TEC data for the GOES line of sight from the New Mexico array, processed as described in [Carlos and Massey, 1994], are shown in figure 2. Clear signals are seen at all stations, with varying lags. To estimate **k**, we performed 2D slowness filtering (slowness is just the inverse of velocity) at the time of peak response. The result is shown in figure 3. The peak radian power is found with a velocity filter set for 520 m/s (trace velocity) at an azimuth of -66° from north, as would be expected for an acoustic wave propagating directly from White Sands to the ionospheric penetration points (see figure 1). TEC fluctuations of comparable strengths were seen on the ATS-3 lines of sight, but because the wavefronts were not tangent to the lines of sight, the waveforms detected became de-correlated soon after the arrival of the first front.

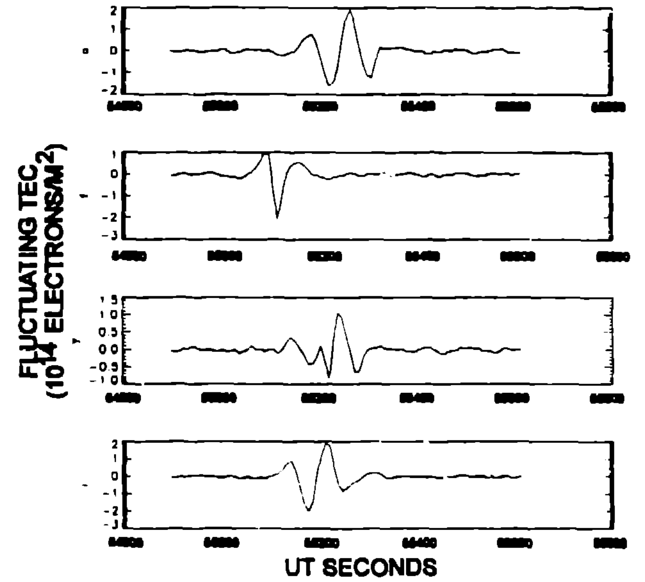

Figure 2. Fluctuating TEC along the GOES line of sight from the New Mexico array. The explosion took place at 54600 seconds UT. From top to bottom, the locations are Abiquiu, Santa Fe, San Ysidro, and Los Alamos

For the GOES-2 line of sight, the array estimate of the peak TEC fluctuation was 1.25×10^{14} m^{-2}. The unperturbed TEC, which we estimated by using GPS TEC data and a spherical shell model for the ionosphere was 2.2×10^{17} m^{-2}. The perturbation peaked at about 550 seconds after the blast. An acoustic ray-tracing code is being used to compare these results with theoretical predictions.

Data from the array taken over a period of 14 days were analyzed to determine the frequency of background events that appear similar to the response from the explosion. The presence of an "event" was defined by looking at the cross-covariance, integrated for 400 seconds, between two stations (Santa Fe and Los Alamos) that were well aligned along the wave direction from the explosion.

We required that:

1. The normalized cross-covariance (NCV) must peak at a lag corresponding to trace speeds from 250 to 750 m/s, corresponding to acoustic wave trace velocities, and exceed 0.8 (an arbitrary choice: the explosion produced a cross-correlation of 0.94).
2. The cross-covariance (radian power) must exceed the instrument noise level by 15 dB.

With these requirements, 6 "events" were found in 14 days (3024 400-second windows), implying a probability of a false event of 0.2% in any 400 second window. There was no obvious grouping of the background events in time or lag. We presume that they are caused by natural sources.

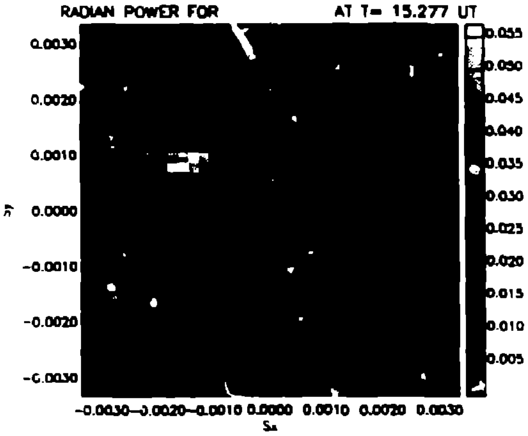

Figure 3. Plot of radian power in the slowness plane for the GOES line of sight to the New Mexico array. Slowness is in m/s, with north being positive on the vertical axis, and east being right on the horizontal axis. The greatest power occurs at a velocity of 520 m/s and azimuth of -66° from north, as expected from the geometry (figure 1 left).

Texas array results

The Texas array was located at a distance from the explosion for which there is no direct acoustic ray path (according to a ray-tracing code with realistic temperature profiles, and accounting for the curvature of the earth). Thus any acoustic wave detected there that is associated with the explosion must have refracted off of the thermocline at the top of the thermosphere, reflected once from the earth's surface, and returned to ionospheric heights. Although the viewing geometry to GOES-2 is quite good, the magnetic coupling is poor (12% of optimum, as explained above). The observed signal-to-noise ratio (SNR) was quite poor, and we resorted to cross-correlation analysis using the San Antonio stations (with the New Mexico array providing a satellite phase reference) to prove that a signal was indeed present. Figure 4 shows the TEC fluctuation data for the two San Antonio stations. A possible signal is seen beginning at about 2500 seconds after the explosion, but the signal-to-noise ratio is very low. To determine whether a wave was actually present, we computed the lagged NCV between the two signals, using overlapped windows of 1000 second duration. Figure 5 shows the result. Near the bottom of the plot (before the explosion) the covariance peaks at zero lag, because of noise introduced by the satellite reference signal from the New Mexico array. Because this reference is subtracted from both San Antonio signals, it appears with zero lag. The feature we attribute to acoustic wave passage appears at 57500 seconds peaks at a lag of -77 seconds, corresponding to southward propagation with a trace speed of 400 m/s. At later times, the dominant correlated power returns to zero lag.

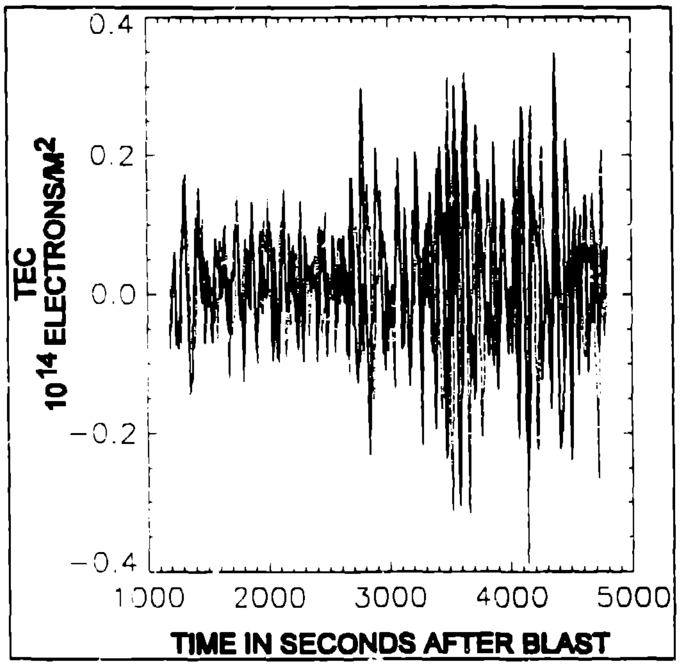

Figure 4. Fluctuating TEC measured from the north (solid line) and south (dashed line) stations at San Antonio, Texas. Cross-correlation analysis shows that a wave was present in the interval 2500-3500 seconds. Lower correlation at later times may be a result of integration through many acoustic phases.

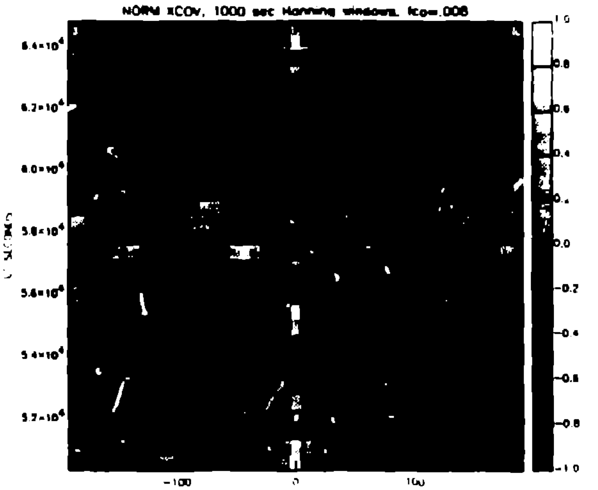

Figure 5. Plot of the normalized cross-covariance in overlapped 1000 second windows, between the two San Antonio stations, as a function of time (vertical axis) and lag (horizontal axis). Positive lags correspond to northward propagation. The feature attributed to the explosion occurs at 57500 seconds UT, or about 3000 seconds after the explosion, at a lag of -77 seconds.

The San Antonio data are obviously less convincing than the New Mexico data. We therefore repeated the noise background analysis described above, using 20 days of data from the San Antonio stations. The event criteria were the same as for the New Mexico data except that we looked at all data with a NCV greater than 0.6. (The explosion produced a NCV of 0.69). One background event had a NCV of 0.77; all others were less than 0.69. In all, 13 background events were found in 20 days (1728 1000-second windows), corresponding to a probability of 3% that a background event would have occurred within one hour of the expected time of arrival of the acoustic wave from the explosion. We therefore conclude that the observed event was quite unlikely to have been a randomly-occurring background event, and was therefore a response to the explosion.

Conclusions.

Arrays of phase-detecting receivers have been used to observe fluctuations in the TEC along lines of sight to VHF beacons on geosynchronous satellites. Phase measurements are extremely sensitive to TEC; our receivers can resolve fluctuations as small as 10^{13} m^{-2}. The TEC along a line of sight responds to an acoustic wave propagating in the duct between the earth's surface and the thermocline at about 100 km provided that the line of sight is reasonably parallel to the wavefronts, and that the acoustic wavevector have a substantial component along the geomagnetic field. We observed the response to a 2 kT chemical explosion at White Sands, New Mexico, with TEC arrays in the vicinity of Los Alamos (150 km range) and near San Antonio, Texas (at 850 km range).

A clear response was seen by the New Mexico array, and statistical analysis shows that there is a minuscule probability that the response was due to a background event. The response to the ducted wave at San Antonio was much weaker (only a few times the instrumental noise), but statistical analysis again showed that it was very unlikely to have been a result of a randomly occurring background event.

We are now using similar TEC arrays to observe acoustic waves produced by the exhaust plume from the Space Shuttle's main engine burn, which occurs during nearly level flight at about 100 km altitude. Cylindrical wavefronts produced by the plume's expansion have been detected from stations located in West Virginia, Kentucky, and Illinois.

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