27
3/29/82
24 cy. to NTS

I-2199

(i)

UCID-19231

MASTER

# Preliminary Theoretical Acoustic and RF Sounding Calculations for MILL RACE


Stephen I. Warshaw
Paul F. Dubois


November 2, 1981

Lawrence Livermore Laboratory




Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore Laboratory under Contract W-7405-Eng-48.


Test Ban Treaty Verification Program

UCID--19231

DE82 009300

# Preliminary Theoretical Acoustic and RF Sounding Calculations for MILL RACE

Stephen I. Warshaw, Theoretical Physics Division
Paul F. Dubois, Mathematics and Statistics Division
University of California, Lawrence Livermore National Laboratory
Livermore, California 94550

November 2, 1981

As participant in DOE/ISA's Ionospheric Monitoring Program, LLNL has the responsibility of providing theoretical understanding and calculational support for experimental activities carried out by Los Alamos National Laboratory in using ionospheric sounders to remotely detect violent atmospheric phenomena. We have developed a system of interconnected computer codes which simulate the entire range of atmospheric and ionospheric processes involved in this remote detection procedure. We are able to model the acoustic pulse shape from an atmospheric explosion, the subsequent nonlinear transport of this energy to all parts of the immediate atmosphere including the ionosphere, and the propagation of high-frequency radio waves through the acoustically perturbed ionosphere. Our calculational methods are derived from acoustic and radio ray tracing procedures which are based on geometric optics, and from finite amplitude acoustic wave propagation theories which take convection and dissipation into account.[1]

Los Alamos' coverage of DNA's MILL RACE event[2,3,4] provided us with an excellent opportunity to assess the credibility of our calculational system to correctly predict how ionospheric sounders would respond to a surface-based chemical explosion. In this experiment, 600 tons of high explosive were detonated at White Sands Missile Range at 12:35:40 local time on 16 September 1981. Vertical incidence RF phase sounders and bistatic oblique incidence RF sounders fielded by Los Alamos and SRI International throughout New Mexico and southern Colorado detected the ionospheric perturbation that ensued. In Figure 1 we show the locations of the explosion site and the various receivers, transmitters, and vertical sounders that were deployed by Los Alamos. The SRII sounders are not shown. It will be observed that most of these monitors lie in or close to the geomagnetic meridian plane passing through the explosion site. Sandia National Laboratories (Albuquerque) also deployed parachute-borne acoustic sensors at stratospheric altitudes to record the ascending blast wave.

LLNL's interest in MILL RACE is due primarily to the fact that atmospheric explosions produce relatively "clean" and widely spreading disturbances of the ionosphere, and that this represented the first such opportunity since 1966[5] to carry out ionospheric probing of the effects of an atmospheric explosion using current technology. Moreover, this is also the first time such an event had been monitored with as large an array of electromagnetic and acoustic sensors as were fielded. MILL RACE thus represented an ideal situation against which to conduct a severe test of our calculational methods, since acoustic and ionospheric data would be available from the probing at a wide range of distances from the explosion site. We would then, with this single experiment, be able to validate our modeling over the wide range of atmospheric conditions it was intended to cover.

In this report, we present a brief account of our preliminary calculations of the acoustic disturbance and the predicted ionospheric sounder signatures for MILL RACE. These calculations are necessarily provisional, because at the time we did them, we did not have the data from the acoustic sensors fielded by SNLA, and so had to make estimates of the acoustic pulse and the angular distribution of the released acoustic energy in the neighborhood of the blast point. We have since received this data from SNLA, and we plan to report on a more improved calculation in the near future.

In the present calculations, we assumed that the explosion can be represented by a point blast, which produces a hemispherically expanding blast wave radiating uniformly outward from this center. We further assumed that the blast wave can be represented by a standard pulse profile which can be scaled to the nominal explosive yield, with additional corrections for siting at the air-ground surface. This profile has been described by Reed.[6] We predicted the course of the blast wave at subsequent times by tracing acoustic rays from the blast center through a vertically stratified windless atmosphere, using the equations of Reference 1. Figure 2 shows our calculation of the acoustic ray paths originating from the explosion and surfaces of "equal time" spaced 30 seconds apart. These isochronal surfaces show nominally where the acoustic wavefront would be at the times indicated. The rays were started from a point on the ground at incident polar angles from -80° to +80° in increments of 5°. The curved character of the ray paths is due to the variation of the atmospheric speed of sound with altitude;[7] this variation is shown plotted in Figure 3.

We initiated our calculations of the nonlinear propagation of the acoustic energy along ray tubes following these ray paths, by use of Reed's pulse shape over a hemisphere of radius 2.7 km centered at the blast point; this pulse is shown in Figure 4. The pulse parameters used correspond to a free air burst of 1200 tons, to account for acoustic radiation into a half space. The evolution of this pulse profile along a vertical and a laterally traveling ray tube is shown in Figure 5, where snapshots of the spatial profile at various times in transit are presented. The equations describing this history are also given in Reference 1. This evolution displays the growth, elongation and decay of the acoustic signal, which appears to be characteristic of long-range vertical transmissions. It will be noted that the laterally-propagating pulse does not display these features to as marked an extent as the vertically-going one, primarily because the lateral propagation does not reach the rarefied and dissipative regions of the atmosphere above 100 km.[7]

By carrying out such calculations along ray tubes for each of the ray paths of Figure 2, we obtained an ensemble of pulses which characterize a three-dimensional acoustic wavefront at various times. This is shown in Figure 6 in which we have plotted the disturbance at various times in the form of contours of acoustic signal strength. By 800 seconds after blast time, the acoustic wave is primarily cylindrical, having been dissipated in the upper reaches of the ionosphere. We ended our acoustic calculation at this time, because the lower-altitude parts of the wave were beginning to enter the caustic regions predicted by the ray tracing at about 200 km radially away from the vertical through the blast point (see Figure 2), and our codes were not set up to handle this contingency. The higher altitude parts could have been continued.

Above about 130 km, where the mean free path is large, the electrons are believed to move preferentially along the geomagnetic field lines when swept along by the acoustic perturbation.[8,9] One way of modeling this effect is to assume that the electron density perturbation has a strength which is proportional to the acoustic pulse strength, but modified by the square of the cosine of the angle between the intrinsic fluid motions and the geomagnetic field direction. Such a modified perturbation, which we used for the radio calculations, is shown in Figure 7 which displays the section of the overall electronic perturbation in the geomagnetic meridian plane at various times. This effect gives the ionospheric perturbation a predominantly southward character. Since the Los Alamos sounders are set up to probe the ionosphere north of the blast site (Figure 1), we have a potential for verifying this model in some detail.

The ambient ionospheric electron density was obtained from an ionogram taken about 8-1/2 minutes before detonation, and is shown in Figure 8. It appears that this ionosphere is unusually even and extensive, which is a fortuitously favorable circumstance for radio sensing of the atmosphere well above 200 km. This makes MILL RACE particularly interesting from a theoretical point of view, because at these altitudes the mean molecular free path and the molecular collision periods begin to approach a substantial fraction of the extent and period of the acoustic perturbation. Under these conditions, the continuum mechanical basis on which our modeling is based is not expected to hold up well.[6] As we will show shortly, this turns out to be gratifyingly not the case.

To obtain predictions of the ionospheric sounder responses, we carried out radio ray tracing using this ionospheric electronic density, on which the electronic perturbation of Figure 7 is impressed. We used a fast, two-dimensional version of the Jones-Stephenson code[10] which we obtained from SRII and further modified to meet our needs; this code is entirely appropriate for ray paths confined to the geomagnetic meridian plane,[11] as appears to be approximately the case for the Los Alamos sounders. In Figure 9 we show calculated radio ray paths for the vertical phase sounder near ground zero, and for the two bistatic links between the transmitter at Stallion Range and the receivers at Mountainair and Los Alamos. In the sounding process, the received phase and arrival time of the radio waves are continuously monitored as the acoustic perturbation ascends past the apogees of these ray paths. Our calculations are accomplished in exactly the same way: as the analytic perturbation is stepped past these heights, the phase and group path lengths along the homed rays are calculated and stored in the form of a time history. One can, indeed, estimate the received signal by comparing Figures 7 and 9.

In Figure 10 we show the ordinary wave signals recorded by the vertical phase sounder at each of the three frequencies at which it was operated. This display is in the form of the time rate of change of the received phase (usually referred to as the Doppler shift), recorded as a function of time since detonation. Extraordinary wave signals were also recorded, but these have not yet been reduced to Doppler signatures. In Figure 11 we show our theoretical calculations for these signatures, which make use of the acoustic calculations described previously. We also calculated the acoustic perturbation corresponding to a 600 ton explosion for comparison purposes, and did a similar radio response calculation; these results are also shown in Figure 11.

In Figure 12 we show similar results for the Stallion-Mountainair bistatic link. In this case Los Alamos obtained the measured ordinary and extraordinary Doppler frequency shift signatures directly by on-line frequency analysis; these are given at the top of the figure. Our predictions for this configuration are shown at the bottom of the figure, for the 1200 ton case only.

On the whole, our calculated estimates of the sounder responses appear to agree remarkably well with the measured data, particularly since this represents a preliminary treatment. We have not yet attempted to predict the signals for the other bistatic links shown in Figure 1, and we plan to do so after we incorporate the more appropriate SNLA acoustic data into our calculations. In this subsequent work, we intend to address some of the discrepancies indicated by our current analysis. In particular, our predicted signals arrive slightly later than the measured ones, and are somewhat stronger. We anticipate that these might be resolved by more careful consideration of the fact that at lower altitudes the acoustic wave from the blast could be ascending at slightly supersonic speeds,[12] which would affect the acoustic ray calculations, and by taking into account the fact that MILL RACE involved essentially a shaped charge, designed to produce an initially cylindrical blast wave propagating mostly laterally. One could then hypothesize that less energy would have been directly upward than would have been the case for an isotropic explosion, and therefore account in part for our overestimates.[13]

## Acknowledgment

We would like to thank David Simons, Dwight Rickel and John Wolcott of Los Alamos for quickly passing on their RF sounding data to us for our analysis; John Banister of SNLA for his acoustic data; and Paul Albee of SEA Inc. for providing us with his two-dimensional version of the Jones-Stephenson code when he was at SRII, which we adapted for these studies.

## References

1. S. I. Warshaw, "On a Finite Amplitude Extension of Geometric Acoustics in a Moving, Inhomogeneous Atmosphere," Lawrence Livermore National Laboratory Report UCRL-53055, September, 1980.

2. MILL RACE Program Document, Defense Nuclear Agency Test Directorate, Kirtland AFB, NM, Report POR 7071, November, 1980.

3. D. G. Rickel and D. J. Simons, "MILL RACE Pre-operations Plan" Draft, Los Alamos National Laboratory Report, April 1981.

4. David J. Simons, Dwight G. Rickel, John Wolcott, Paul A. Bernhardt, Lewis Duncan, Paul Albee and William Broste, Paper SA4-1-A-10 presented at the December 1981 AGU Meeting in San Francisco, EOS 62, 979 (1981) (Abstract only).

5. G. H. Barry, L. J. Griffiths and J. C. Taenzer, Journal of Geophysical Research 71, 4173 (1966).

6. J. W. Reed, Journal of the Acoustical Society of America 61, 39 (1977).

7. U. S. Standard Atmosphere, 1976, NOAA, NASA and USAF, Washington, D.C., Report NOAA-S/T 76-1562, October, 1976.

8. P. R. Albee, SEA, private communication.

9. P. A. Bernhardt, Los Alamos National Laboratory, private communication.

10. R. M. Jones and J. J. Stephenson, "A Versatile Three-Dimensional Ray Tracing Program for Radio Waves in the Ionosphere," U. S. Department of Commerce Office of Telecommunications Report OT 75-76, October, 1975.

11. See, e.g., K. G. Budden, "Radio Waves in the Ionosphere," Cambridge University Press, 1961.

12. C. Berthet et Y. Rocard, Comptes Rendus Acad. Sci. B (France) 267, 202 (1967). (In French).

13. P. R. Albee, SEA, private discussions.

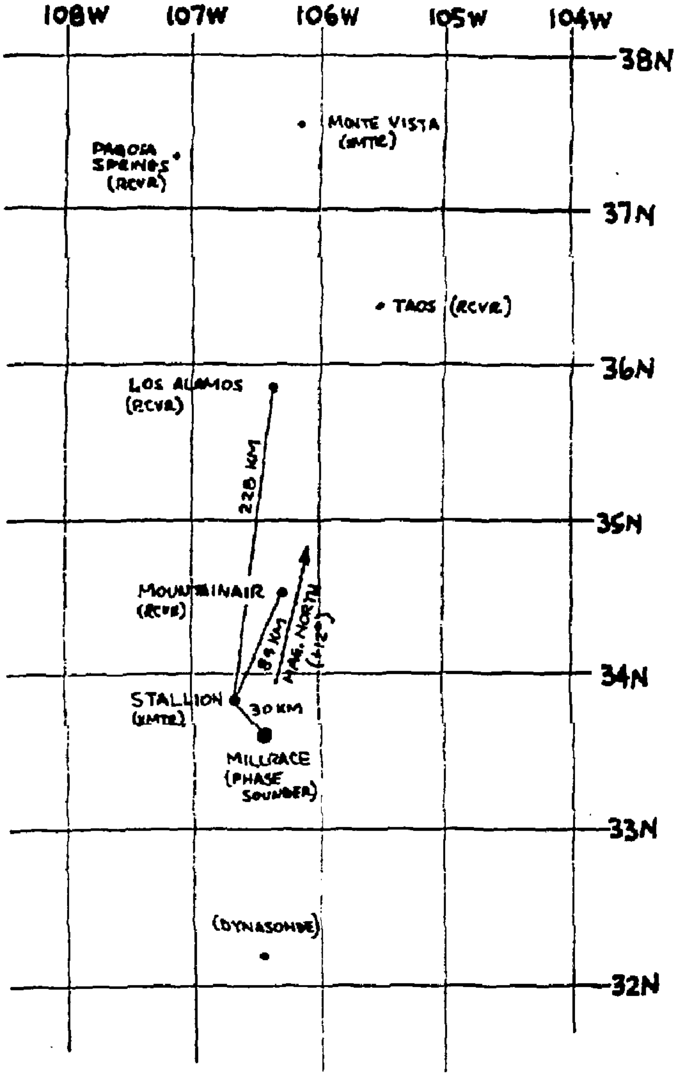



Figure 1 Location of MILL RACE explosion site at WSMR and radar sounding stations fielded by Los Alamos National Laboratory. The bistatic links treated in this report are indicated by connecting lines. The coordinates are in degrees.

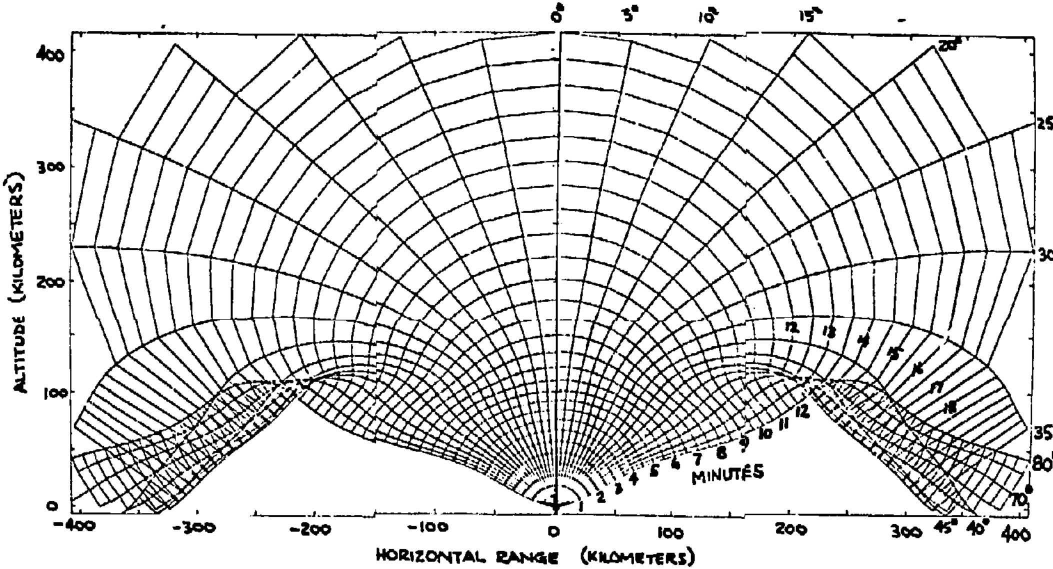



Figure 2 Calculated acoustic ray paths and surfaces of constant arrival time for a surface point source and a standard atmospheric profile, without ambient winds. The initial takeoff angles for the rays are also given on each ray.

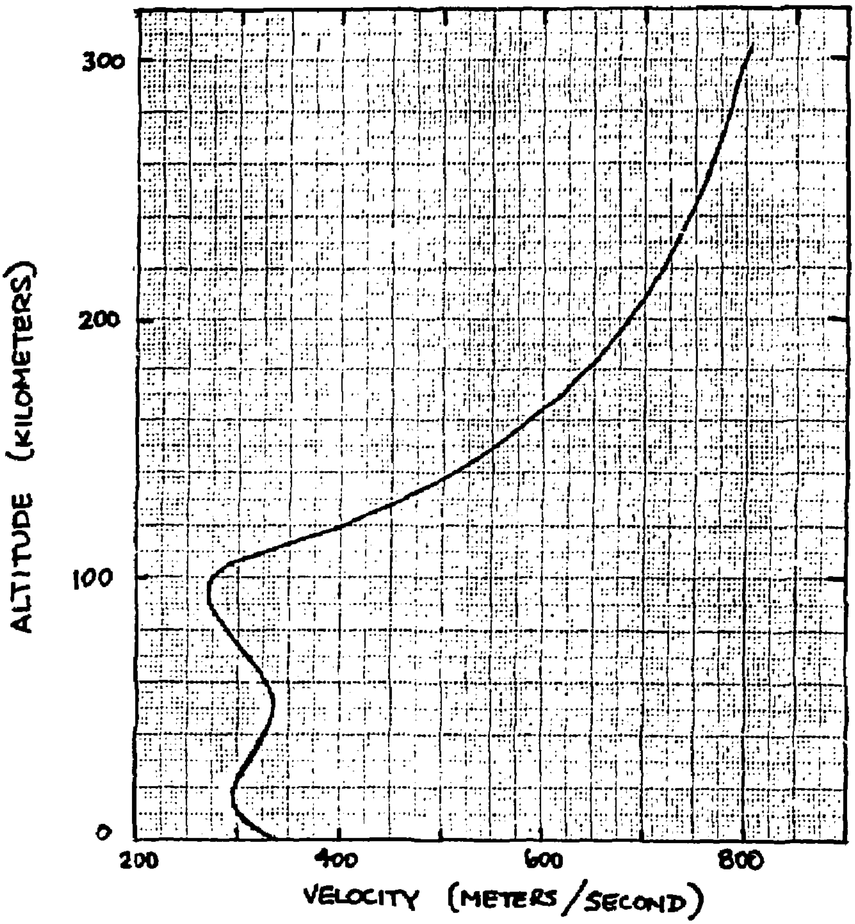
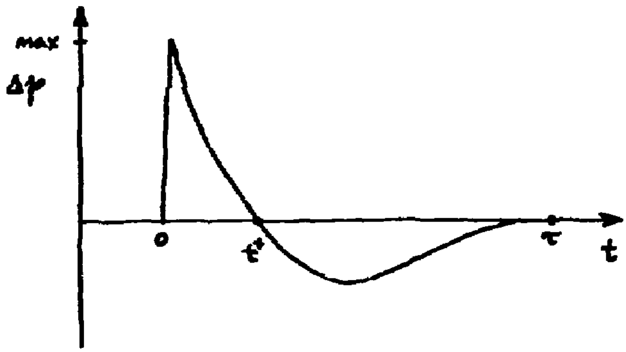



Figure 3 Variation of the atmospheric speed of sound with altitude used for the acoustic ray tracing calculation. This profile is an analytic approximation to the molecular scale speed of sound for the 1976 U.S. Standard Atmosphere.




$$\Delta p = (\Delta p)_{max}\left(1 - \frac{t}{t^{+}}\right)\left(1 - \frac{t}{\tau}\right)\left(1 - \left(\frac{t}{\tau}\right)^{2}\right)$$

$$v = \frac{a_0}{\gamma p_0}\,\Delta p$$

$$0 \leq t \leq \tau$$

Figure 4 Analytic blast wave pulse shape and formula used to initiate atmospheric pulse propagation calculations, as taken from J. W. Reed, J.A.S.A.. 61, 39 (1977).

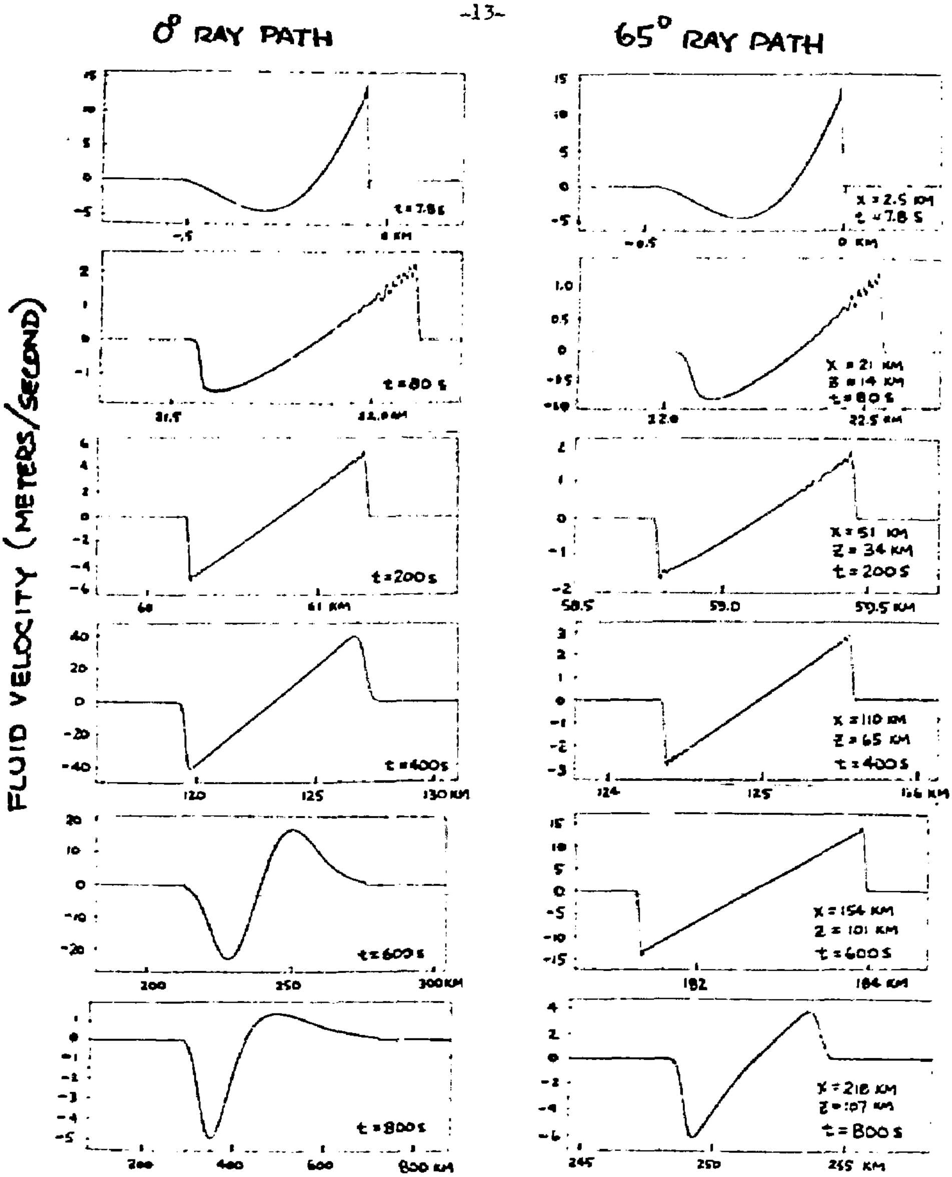



Figure 5  Calculated evolution of the blast wave pulse profile during its propagation from the initial wavefront to the ionosphere, along two different acoustic ray paths of Figure 2. These are snapshots of the pulse at various times. The abscissae are the linear coordinates along the ray path, as measured from the surface of a hemisphere of radius 2.7 km from the blast center. The ordinate is the fluid particle velocity in the pulse.

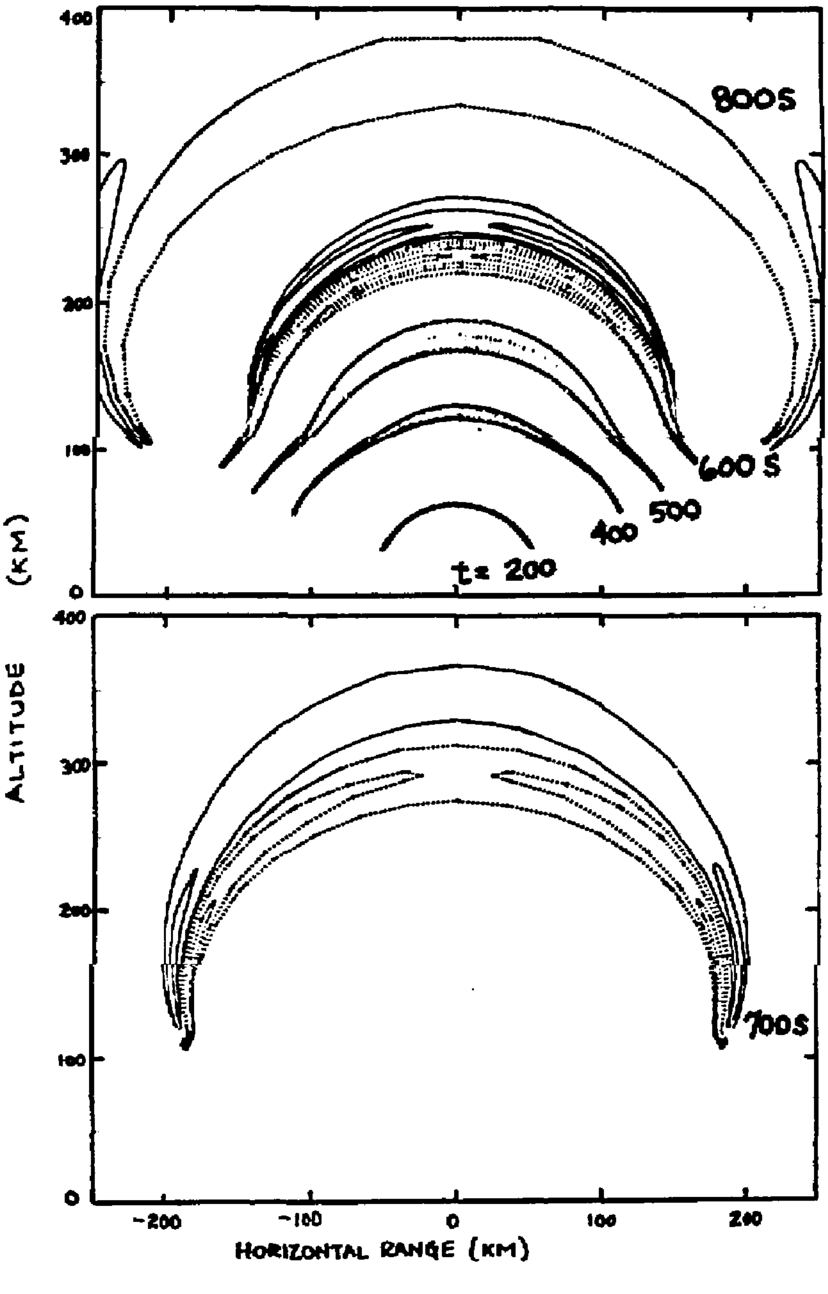



Figure 6 Calculated contours of acoustic signal strength in a vertical plane through the blast center at various times since detonation. The contour levels are in increments of $\Delta\rho/\rho_0$ or $v/a_0$ equal to ±.005, ±.015, ±.025, etc. where the positive levels are solid, and the negative levels are dotted. The 700-second curves have been plotted separately for clarity.

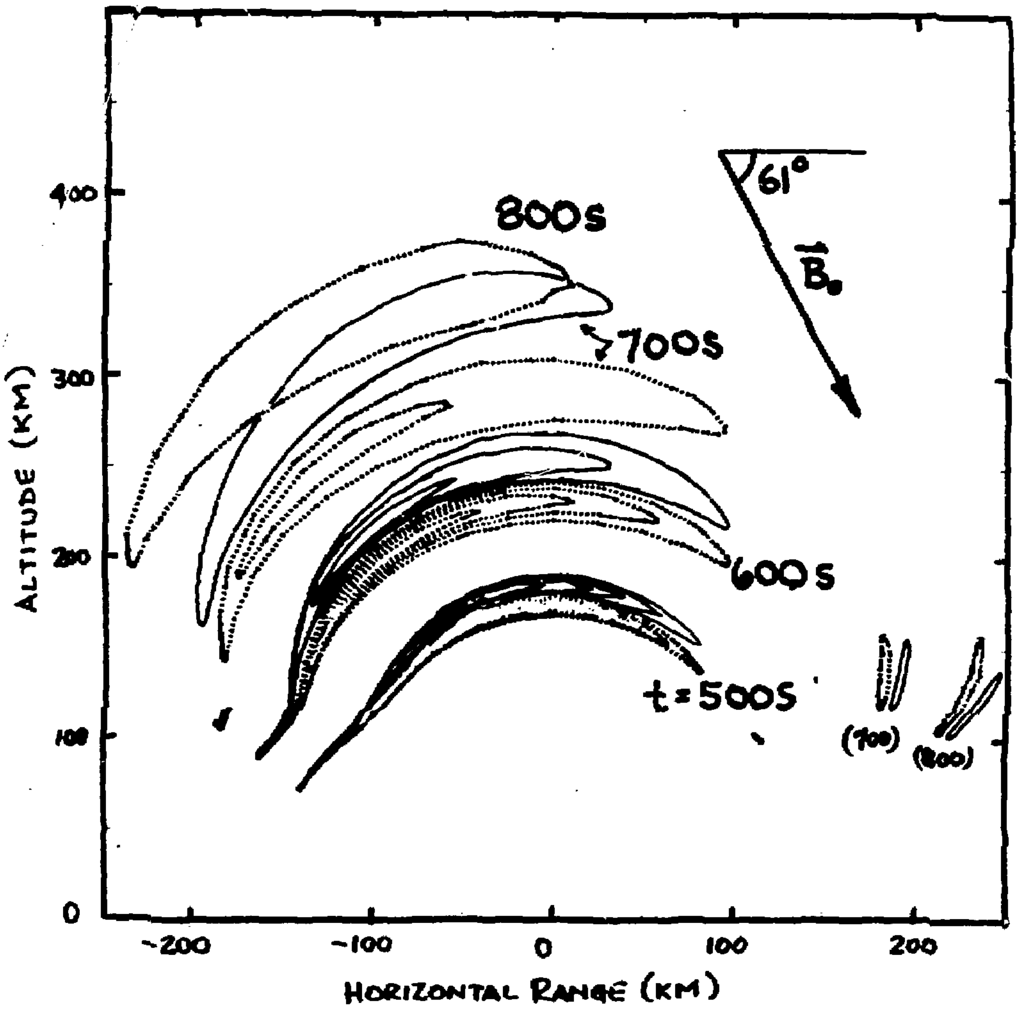



Figure 7 Calculated contours of free electron density perturbation strength in the geomagnetic meridian plane through the blast center at various times since detonation, using same levels as Figure 6.

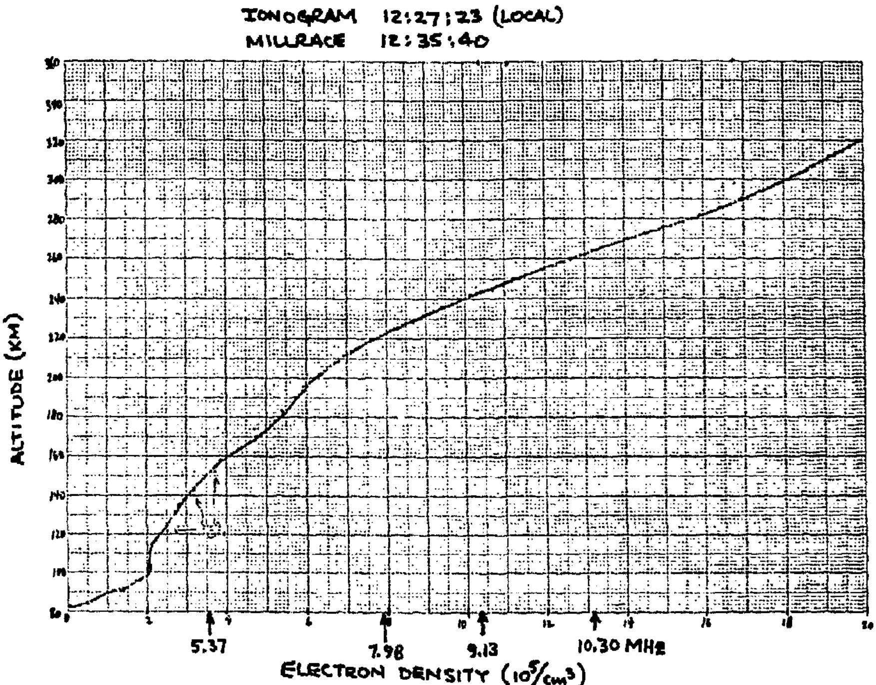



Figure 8 Free ionospheric electron density profile calculated by Los Alamos from an ionogram taken just before detonation. The frequencies indicated correspond to those used for the vertical phase sounder at the blast site. This data was used for the ambient ionosphere in the RF ray calculations.

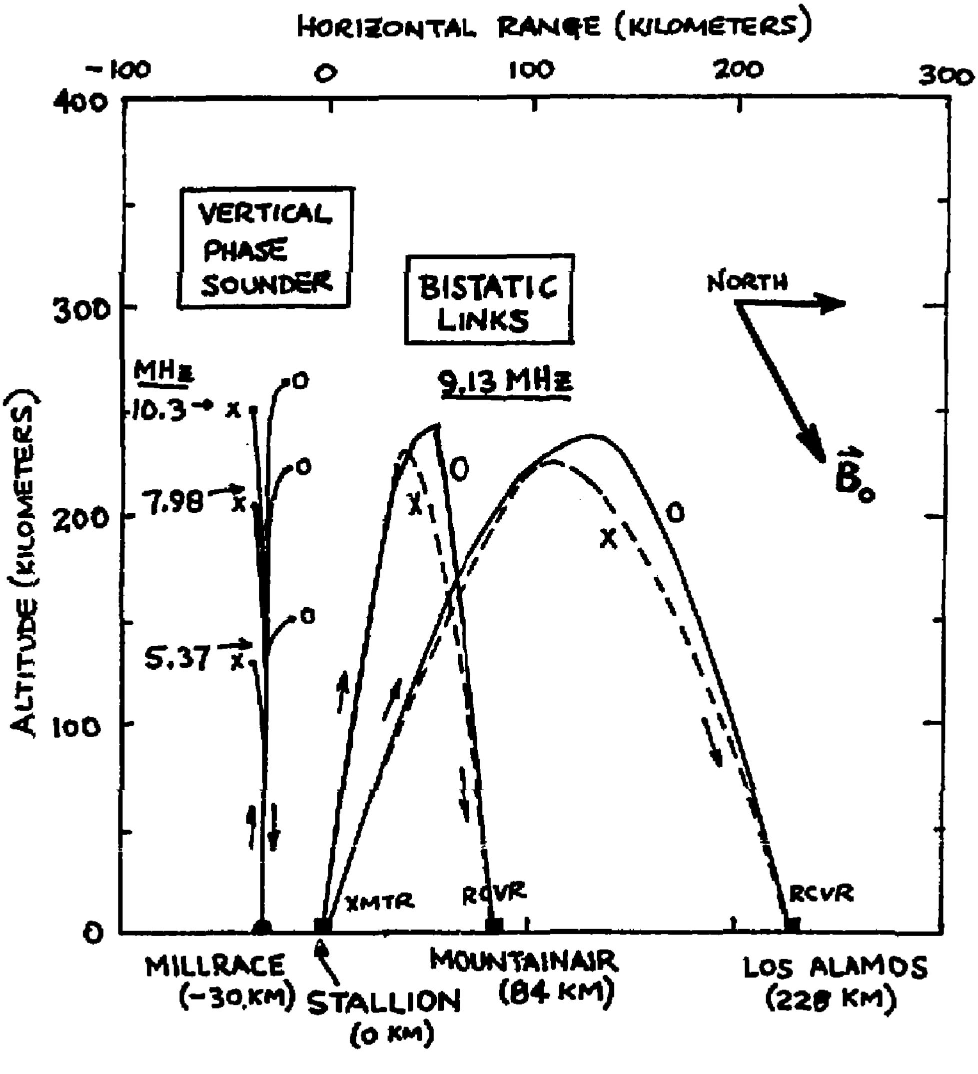



Figure 9 Calculated ordinary (O) and extraordinary (X) RF ray paths for the close-in Los Alamos vertical and bistatic phase sounders, in the geomagnetic meridian plane. The coordinates are centered at the Stallion Range transmitter site. The spitze is clearly evident.

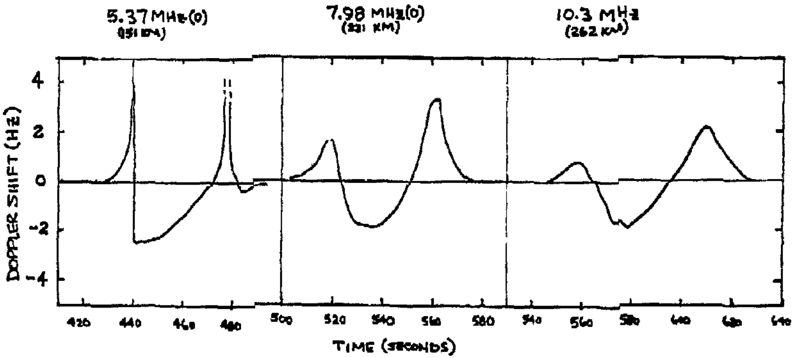



Figure 10 Rate of change of received phase measured by the Los Alamos vertical phase sounder at the three frequencies covered, as the blast wave traveled outward past the reflection heights. Only the ordinary wave data is given.

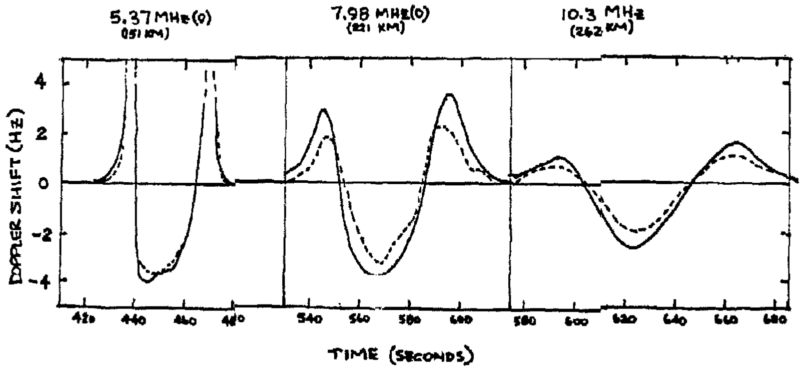



Figure 11 Rate of change of received phase as calculated by the LLNL phase sounding simulation code, using the acoustic information calculated for Figures 5, 6 and 7. The calculation consists of stepping the acoustic perturbation past the RF reflection heights, doing a homed-ray tracing calculation, and recording the calculated phase path length as a function of time. These plots are the resulting time derivatives. Two sets of calculations are presented, corresponding to a point blast source of 600 tons (dashed curve) and 1200 tons (solid curve). Only the ordinary wave calculation is given.

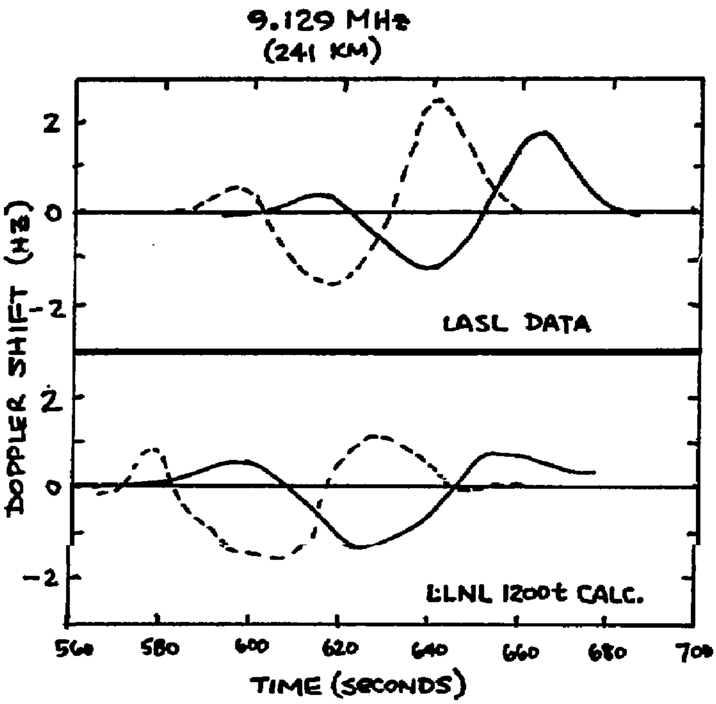



Figure 12 Los Alamos data and LLNL calculation for the rate of change of received phase on the Stallion-Mountainair bistatic link, for the ordinary (solid curve) and extraordinary (dashed curve) wave modes. This corresponds to a 1200 ton point blast source.