LA-UR-96-2236

CONF-960848--2

Title: DETECTION OF THE LARGE METEOROID/NEO FLUX USING INFRASOUND: RECENT DETECTION OF THE NOVEMBER 21, 1995 COLORADO FIREBALL

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Submitted to: Conference: SPIE Denver '96 Symposium
Denver, CO - August 4-9, 1996

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Detection of the large meteoroid/NEO flux using infrasound: Recent detection of the November 21, 1995 Colorado fireball

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ABSTRACT

During the early morning of November 21, 1995, a fireball as bright as the full moon entered the atmosph... over southeastern Colorado and subsequently produced audible sonic boom reports from Texas to Wyoming. The ... was detected locally by a security video camera which showed the reflection of the fireball event on the hood of ... truck. The camera also recorded tree shadows cast by the light of the fireball. This recording includes the audio of a strong double boom as well. Subsequent investigation of the array near Los Alamos, New Mexico operated by Los Alamos National Laboratory as part of its commitment to the Comprehensive Test Ban Treaty negotiations, showed the presence of an infrasonic signal from the proper direction at about the correct time for this fireball.

The Los Alamos array is a four-element infrasonic array in near continuous operation on the Laboratory property. The nominal spacing between the array elements is 55 m in the North/South direction and 80 m in the East/West direction. The basic sensor is a Globe Universal Sciences Model 100C microphone whose response is from about 0.1 to 300 Hz (which we filter at the high frequency end to be limited to 20 Hz). Each low frequency microphone is connected to a set of twelve porous hose wind noise filters in order to decrease the signal/noise ratio ... signals during strong winds.

The preliminary characteristics of the signal include the signal onset arrival time of 0939:20 UT (0239:20 MST), with a maximum timing uncertainty of ± 2 minutes, the signal onset time delay from the appearance of the fireball of 19 minutes, 20 seconds, the total signal duration of 2 minutes 10 seconds, the source location toward ... degrees from true north, the horizontal trace velocity of 429 m/sec, the signal velocity of 0.30 ± 0.03 km/sec, ass... 400 km horizontal range to the fireball, the dominant signal frequency content of 0.25 to 0.84 Hz (analyzed in a frequency interval from 0.2 to 2.0 Hz), the maximum signal cross-correlation of 0.97 and the maximum signal amplitude of 2.0 ± 0.1 microbars. Also, on the basis of the signal period at maximum amplitude, we estimate a source energy for this event of between 10 to 100 tons of TNT (53.0 tons nominal).

Keywords: Infrasound, bolides, NEOs, long-range sound propagation, blast waves, meteor sounds

1. INTRODUCTION

1. Bolide Physics

1.1. Continuum Flow Regime: Atmospheric Interactions

The fundamental physics of atmospheric entry for non fragmenting bolide entry (at the stagnation point) ... developed in detail in ReVelle (1979; 1993). The key dimensionless similarity parameters are the Knudsen (neutral mean free path/characteristic body dimension), Reynolds (inertial/viscous forces), Mach (speed of a body compared to the adiabatic phase speed of acoustical waves), the Bouguer numbers (a means of estimating the optical thickness of the shock ablation layer and measured by comparing the fluid flow distance to the photon mean free path). These ... also discussed in Ceplecha et. al. (1996). For a sufficiently large Reynolds number and a small Knudsen number (consequently large Mach number), there is an analog between a line source explosion and a meteoroid entry with nearly constant velocity whose radius surrounding the trajectory is the product of the Mach number times the diameter of the body. This assumes for the supersonic and hypersonic flow regimes that the wave drag due to normal stresses (also called form or pressure drag at low Reynolds numbers in continuum flow) dominates completely over the skin friction drag (due to tangential stresses). The blast wave frequency at distances equal to about 10 blast wave radii ... given by:

$$f_m = c_s / 2.81 \cdot R_o = c / 2.81 \cdot (Ma \cdot d_m) \qquad (1)$$

$$R_o = \left(E_o / \left(\pi\, p_o \right) \right)^{0.5} = Ma \cdot d_m \qquad (2)$$

where

E_o = Source energy deposited per unit length of trail

p_o = Ambient pressure at the instantaneous source elevation

At greater range the wave period $\left(1 / f_m \right)$ increases due to nonlinear stretching into an assumed uniform density medium in the manner (ReVelle, 1976):

$$\tau = 0.562 \cdot \tau_o x^{0.25} \qquad (3a)$$

$$\tau_o = 1 / f_m(x) \qquad (3b)$$

Similarly an equation can also be developed for the ratio of the weak shock amplitude to the wave period of n expanding symmetric N wave (equal positive and negative phases) as also shown in ReVelle (1976):

$$\Delta p / \tau = 0.185 \cdot p^* c_s / R \qquad (3c)$$

Equations (3a) and (3c) were utilized in the development of equation (7) below which was used to ubsequently estimate the bolide source energy assuming a line source explosion in the atmosphere.

where

dp = amplitude of the weak shock wave (zero to peak)

p* = $\left(p_s\, p_g \right)^{0.5}$

x = scaled distance from the source = R/Ro

R = total distance from the source

.1.2. Source Efficiency

ReVelle (1980; 1987; 1993) has investigated the fireball energetics, and ReVelle and Whitaker (1995) have ecently analyzed the fireball acoustic efficiency similar to the more well-known luminous efficiency in common use n meteor physics (Ceplecha et. al., 1996). Using their approach for this fireball, we find an associated acoustic fficiency range of from 0.58 0.65 %. For this estimate we used a ground reflection factor of 0.90 as used previously and total slant range of 400 km, as well as skip distances against the prevailing wintertime guiding wind at 50 km of 200 o 400 km, respectively

.2. Audible Sounds and Infrasound from Bolides

.2.1. Historical Summary

ReVelle (1995) recently summarized the historical database of infrasonic recordings from bright fireballs. In ddition, discussions of the possibilities of audible reports of sounds from bright fireballs and their timing relative to the rajectory, etc., were recently summarized in Ceplecha et. al (1996). There are basically three types of possible sounds hat have been reported. 1) a single or multiple boom arriving typically several minutes after the sighting of the bolide traveling at near normal acoustic speeds after an appropriate time delay based on total distance from the bolide and n the temperature and vertical wind structure aloft), 2) single or multiple swishing or clicking noises coincident with he bolide appearance (traveling with apparently no time delay compared to the normal acoustic signals) and 3) hizzing and "thud" type sounds associated with the apparent impact of the meteorites on the ground and its various urface features and for which there may be an associated seismic signal as well.

2.2.2. Other Recent Acoustic Detections of Fireballs

There is at least one other recent recording that deserves mention. On November 17, 1995 at 23:59:33 UT in Andalucia Province in Spain, where video cameras with audible acoustics capability were used by Hans Betlem of the Dutch Meteor Society (DMS) in cooperation with the Spanish Meteor Society (SOMYCE) to record both the acoustical signals from this bright fireball (during the Leonid and the α-Monocerotid meteor shower observing campaign) from two locations: Zafaraya (Marc de Lignie, 1995) and Almedinilla (H. Betlem, 1995), Spain (the two small villages are about 80 km apart). The multiple booms from this event were heard at each of these stations about 4 minutes after the appearance of the fireball. Optical signals were available from three stations in the special Dutch observing network that had been set up during the Leonids. It was also photographed by the European Fireball Network (Spurny and Borovicka, 1995). With a stellar magnitude of -10 (at 100 km altitude in the zenith), it is the brightest object ever photographed by the DMS. The two sonic boom recordings are very impressive and were made at maximum total ranges of about 100-200 km respectively. Work is continuing using these recordings to uncover more details about this very bright fireball entry, especially since detailed photographic information yielding details on mass, velocity, trajectory, orbit, etc., is also available for this event.

3. ACOUSTICS OF THE NOVEMBER 21, 1995 COLORADO BOLIDE

3.1. Audible Recording

A security camera that captured the image of the detonating fireball on the hood of a truck also captured the acoustic signals that arrived with about a 3 1/2 minute delay from one of the major explosions that were identified on the video recording. Although direction can not be determined from a single acoustic channel, the relative amplitude can be determined. This work has been undertaken by Mr. Dan Neafus a technician at the Denver Museum of Natural History with the full support and encouragement of Mr. Jack Murphy, Director of the museum.

3.2. Infrasonic Detection

Arrays operated by Los Alamos National Laboratory include St. George, Utah, the Nevada Test Site (NTS), and Los Alamos, New Mexico. Standard computer searches were made using the infrasound data from all these sites, but signals were only readily discernible at the Los Alamos array. The St. George array was briefly inoperable during this general period, but signals could be detected at NTS, but were not observed. Given propagation against the wind (at this time of year) for the 50 km duct, in retrospect, it is not surprising that a signal from such a small source was not recorded at NTS.

These arrays are all in the shape of rectangles of nominal total size of 112 m and 172 m between sensors (56 and 86 m between the center of the array and each sensor in the N-S and E-W directions). The basic sensors are Globe Universal Sciences Model 100C (now Chaparral Physics, Albuquerque, New Mexico) whose nominal response is from 20 Hz to 0.1 Hz in acoustic amplitude. With a full scale deflection of +/- 10 V combined with a calibration constant of about 0.2 V/microbar (1 microbar = 0.1 Pascals), we can reliably record signals whose amplitude is between about 0.01 microbars to 80 microbars (peak to peak) over the above frequency range. All the pressure sensors are first preceded by noise-reducing, porous-soaker hoses whose properties have been previously documented (Whitaker et. al, 1992). This noise is primarily due to wind-advected turbulence although at times either natural signals of large amplitude (such as microbaroms, etc.) or intermittent signals due to manmade sources can also interfere with the signal detection process.

4. SIGNAL ANALYSES

4.1. The Los Alamos Infrasonic Program

Los Alamos began work on the infrasound from underground tests of nuclear explosions in the early 1980's. This work continued until 1992 with the start of the U.S. moratorium on above-ground testing. In 1994 a new initiative related to the program of infrasound monitoring began within the guidelines of the proposed CTBT (Comprehensive Test Ban Treaty). Some of the success of the early work is detailed in Mutschlecner et al (1990) and in Whitaker et al., (1991; 1994). The current work includes both monitoring as well as theoretical work on infrasound propagation from explosions whose energy exceed about 1 kT (= 4.185·10(12) J). Subjects under consideration are: Expected false alarm rates due to natural and manmade sources other than explosions (ReVelle, 1995), propagation of Lamb waves (ReVelle, 1996), signal processing techniques for event detection and discrimination, normal mode calculations of detailed expectations as a function of range and of atmospheric structural parameters (temperature, winds, etc.) using modifications of the Pierce-Posey-Kinney normal-mode code (Whitaker et. al., 1994), ray tracings with and against the wind as a function of launch angle and atmospheric structure, etc.. In addition, we have also undertaken studies, with the collaboration of Dr. Jack Reed., of the historical microbarograph data available from Sandia National laboratory. The research on this extensive database has allowed us to formulate a number of important new results. These include the influence of stratopause winds on the ducting of the acoustic signal amplitudes, the effective signal velocity of near-surface sources as a function of season and of duct height, etc.

1.2. Signal Analysis Techniques and Results

1.2.1. Cross Correlation and Beam Steering

We use an optimized steered array processor to analyze the arriving signals (assumed to be locally plane propagating waves across our array) using a 60 s Hanning window to reduce aliasing effects. The beam is steered in the slowness plane (21 by 21 points) to search for the maximum cross-correlation of possible acoustic lags from all sensors in the array. For Los Alamos, the array is in the shape of a square with a distance of 106 m between each sensor and the center point of the array across a nearly level ground plane with maximum vertical changes of about ± 2 m (total array size of 212 m by 212 m) . The lobe structure of the array is a function of frequency that can be used to estimate the detectability of a specified source signal. Once the region of largest cross-correlation has been identified, the various properties of the assumed plane wave signal can be ascertained reliably. These include the trace velocity, the azimuth and elevation angle of the arriving wave, the amplitude of the signal within a specialized pass band, etc. These are all summarized in Table I below for the Los Alamos Array detection (over the frequency band from 0.2 to 2.0 Hz), using standardized discrete fast Fourier transform signal analysis techniques.

TABLE I

November 21, 1995 Colorado fireball:
Infrasound detection properties deduced at Los Alamos

Deduced Parameters	Values
Signal Onset Arrival Time	09:39:20 UT (02:39:20 MST) + 2 minutes
Signal Onset Delay Time	21 minutes 20 seconds w.r.t. the Table II value
Total Signal Duration	2 minutes, 10 seconds
Source Bearing	Toward 31 degrees from True North
Trace Velocity	429 meters/second
Signal Velocity	0.293 +/- 0.03 km/sec, assuming a horizontal range of 375 km to the fireball
Dominant Frequency Content	0.25 to 0.84 Hz
Maximum Cross-correlation, r^2	0.97
Maximum Signal Amplitude	2.0 ± 0.1 microbars

We have reproduced the individual channel plots of each of the four sensors (pressure amplitude versus time, with amplitude indicated in voltage units) for this event detection at Los Alamos in Figure 1. On the basis of examination of these plots and on the deduced earliest arrivals of possible signal velocity values, we can conclude that Lamb waves were not present from this event or are very weak in amplitude. Previously, we have determined that a typical Lamb wave signal arrival speed in this period regime to be about 0.34 km/sec, whereas the maximum amplitude signal for this event has a nominal arrival speed of only 0.30 km/sec. Using the recent work of ReVelle (1996) on Lamb wave generation by airborne explosions, we can also limit the magnitude of this event. In this way we have found that the Lamb wave period must be > 130 seconds at a source altitude of 45 km for Lamb waves to be the dominant signal at the observed range. This estimate is based on the fact that a point source (in an isothermal, windless atmosphere) at 45 km altitude should have produced a large amplitude Lamb wave at a period of 130 seconds at a distance of 2*ro of about 407 km from the source. Said another way, for a 45 km source altitude at the observed wave period at maximum amplitude, a dominant Lamb wave arrival is not expected except at enormous ranges, comparable to and > the earth's circumference. The predicted long period Lamb wave can not be readily observed with our current low-frequency microphone array unfortunately and so the above prediction can not be evaluated in a realistic manner. Lamb wave properties computed including Rayleigh friction parameterized viscous effects (work currently in progress) will not significantly change the above results at a period of 130 seconds. Although we can not

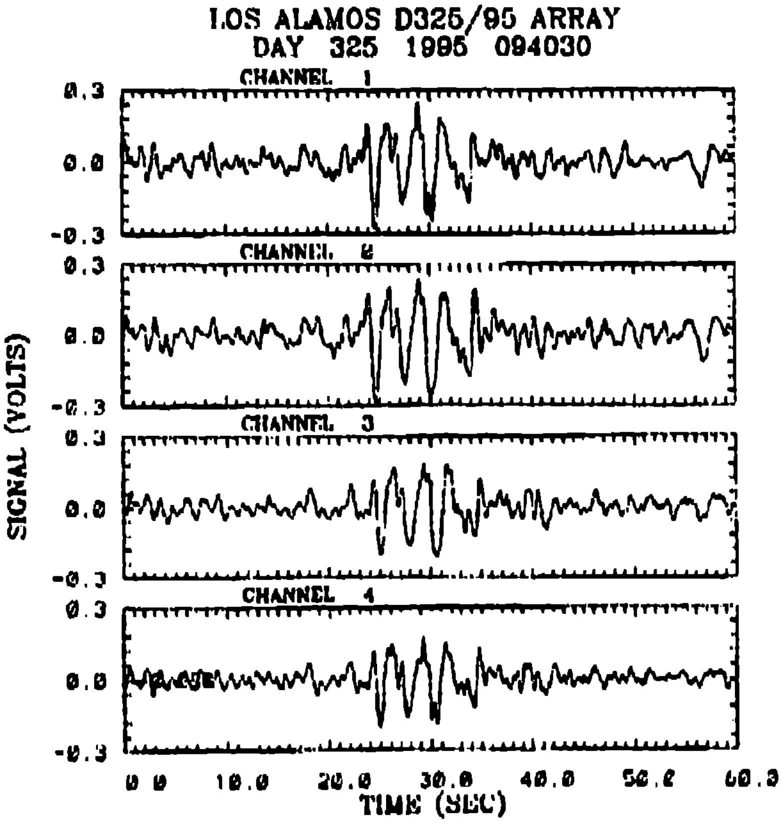

Figure 1. Channel plots of amplitude versus time for each of the four pressure sensors at peak correlation for the Colorado fireball detection

rule out an energetic event with such a long period, based on four independent estimates of source energy described later, we can say that it is unlikely that this event was > 0.2 kt.

We have also plotted the computed trace velocity, azimuth angle of the direction of the wave arrival, and the correlation coefficient for this event and these are given in Figure 2.

4.2.2. Source energetics: Period at maximum amplitude and other relations for calculation of source energy

As presented in ReVelle (1995), the period at maximum amplitude of the signal can be used to infer the yield of an explosion. As indicated in logarithmic form below the yield of an explosion can be related to the observed period at maximum signal amplitude to about the fourth power, contrary to the third power as expected from the simple near-field blast wave scaling law result. Using the equations listed in ReVelle (1995), we can estimate the energy of this event to be between 10-100 tons of TNT (53.0 tons nominal). This was done using a period at maximum amplitude of 0.5 Hz (2 seconds period) for the Colorado fireball signal. The relation used may be written as,

$$log\left(E_s / 2\right) = 3.34 \cdot log\left(P\right) - 2.58; E_s < 100\ kt \qquad (4)$$

where

p = wave period at maximum signal amplitude

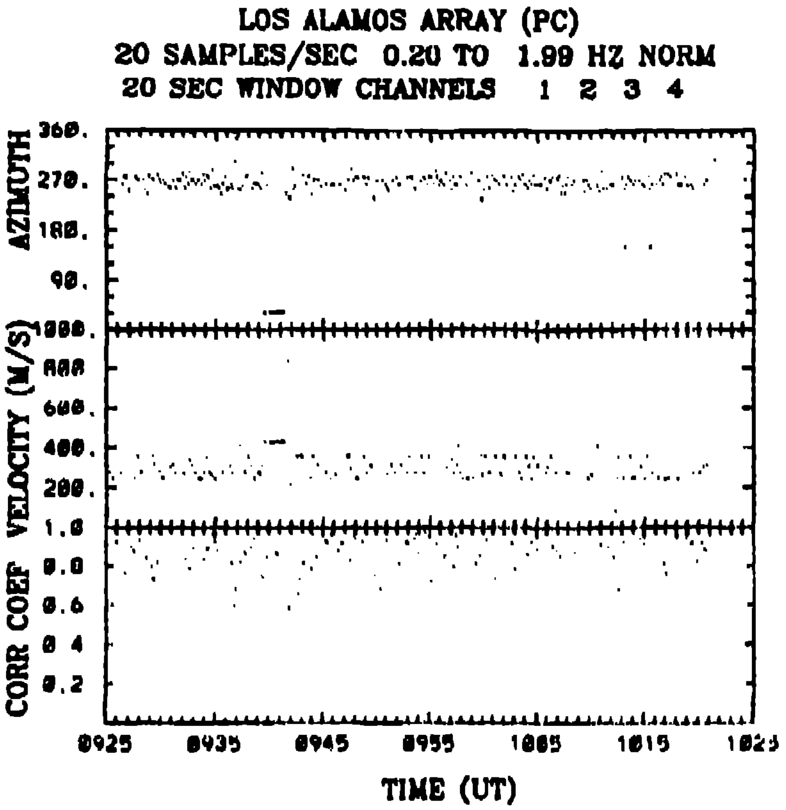

Figure 2. Azimuth arrival angle of the waves, Trace velocity, and the correlation coefficient versus time for the Colorado fireball detection.

Also, using three methods utilized recently in Brown et al. (1996), we can make additional estimates of the source energy for this fireball as well. These methods can be briefly summarized as:

i) Empirical approach
ii) Acoustic efficiency approach
iii) Line source approach

The relevant equations are:

$$E_s = 1.35 \cdot 10(\ 7)\,\Delta p_{p-p}^{1.471} \quad 10^{\,0.0258 W_{50}} R^2 \tag{5}$$

$$E_w = c_a\left(E_s / 2\pi\right) R^{2} \cdot \Delta = \int_0^{\tau_d} \Delta p_{0-p}^2 / \left(\rho c_s\right) dt\,. \tag{6}$$

$$E_s = 11.5\,\pi\,\rho_m R^{1} \quad \left\{\Delta p_{0-p} / \sqrt{p_r p_z}\right\}^{4} \quad c_s^{1} / V \tag{7}$$

where

V_{50}	=	magnitude of the guiding ozonospheric winds (near 50 km in altitude) in m/sec
ε_{ac}	=	acoustic efficiency (ReVelle and Whitaker, 1996)
Δ	=	propagation correction factor due to ground reflection effects, etc.
ρc_s	=	acoustic impedance at the observation location
τ_d	=	total signal duration
ρ_m	=	meteoroid bulk density
V	=	meteoroid velocity in the atmosphere
p_g	=	surface atmospheric pressure
p_z	=	atmospheric pressure at the altitude of the source

Computations using the above equations give the following results using the nominal observed parameters indicated earlier, with additional values indicated in parentheses after each source energy estimate:

i) $6 \cdot 10(-2)$ to 0.197 kt (V_{50} = 0 to -20 m/sec)

ii) $5.84 \cdot 10(-3)$ to 0.1 kt (Δ = 17.1 to 0 (no propagation corrections), ε_{ac} = 0.01, ρ = 1.225, c_s = 340 m/sec)

iii) $6.9 \cdot 10(-4)$ kt (z_s = 55 km, H_p = 7.0 km, p_o = $1.01325 \cdot 10(5)$ Pa, V = 11.2 km/sec, c_s = 340 m/sec, ρ_m = $3.5 \cdot 10(3)$ kg/m^3)

where

z_s	=	source altitude
H_p	=	pressure scale height
p_o	=	surface atmospheric pressure

These source energy values can be compared with the earlier estimate of $5.3 \cdot 10(-2)$ kt made using the period at maximum signal amplitude (see equation (4)). Thus, our four energy estimates range from $6.9 \cdot 10(-4)$ kt to 0.197 kt for this event, depending on the method utilized. Equation (7) requires the largest amount of information to be known about the event. Equation (6) requires information in detail about the propagation and equation (6) assumes a near-surface source. Equation (4) is totally empirical, but is based on a large number of observations of explosion events.

Equation (7) was derived from equations (3a) and (3c) given earlier. In combination with (7) we can also make a self-consistent prediction of the corresponding wave period using (3a). For the conditions given in iii) above we find that τ_d = 0.63 seconds as compared to the observed period at the maximum signal amplitude of 2 seconds. Considering all the uncertainties, the overall self-consistent agreement is quite good..

From the infrasonic data we have also computed the signal power per channel and the predominant peak frequency for this detection versus time is shown in Figure 3.

4.2.3. Ancillary Information

4.2.3.1 Security camera tape (video and audio)

A security camera (Panasonic Model no. PV4514) at a private residence in Colorado Springs was determined to have captured the event in question. The reflection of the fireball's luminous trajectory was seen on the hood of a 1988 Chevrolet pick-up truck parked in the driveway of the residence in southeast Colorado Springs. This camera had both standard visible and audible recording capabilities. The combined audio and video tape is available from Mr. Greg Boyce, News director of KOAA TV in Colorado Springs-Pueblo, Colorado. Unfortunately with only a single sensor no acoustical triangulation of the arriving signals is possible, but some limited amplitude and source altitude timing analysis (see below) is possible using the available instrumental bandpass information. This can be used to estimate the source energy as well although it is not nearly as reliable as the infrasonic techniques discussed earlier above that have been thoroughly documented for numerous low altitude explosions.

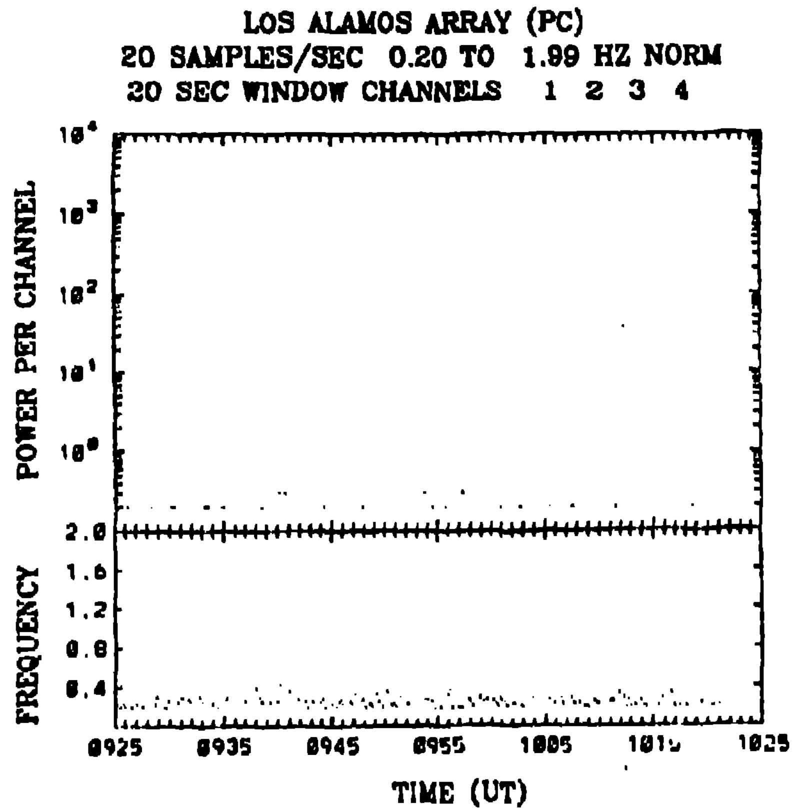

Figure 3. Power per channel and Peak Frequency versus time for the Infrasonic Detection of the November 21, 1995 Colorado Fireball. The fireball event occurs between about 0939 and 0942 UT.

4.2.3.2. Trajectory Analysis

Independent trajectory analyses has been performed by two individuals, namely, Mr. H.B. "Bud" Van Cleef Jr., a retired Air Force Engineer and by Mr. Frank Sanders a Physicist and Electrical Engineer who works for the U.S. Department of Commerce in Boulder (Institute for Telecommunication Sciences) and who is also a volunteer for the Denver Museum of Natural History (see also below). These independent analyses (Van Cleef, 1995; Sanders, 1996) were done using the fireball data available from the brief video recording made in Colorado Springs using the security camera results mentioned above. In addition, the analysis by Sanders utilized the reports of four ground observers as well as the timing of the acoustic (audio) signals at the ground. The acoustic analysis only utilized standard atmosphere temperature data (which were converted to sound speed data), but not the effects of middle atmospheric horizontal winds unfortunately. Both analyses indicate that the fireball trajectory was oriented from Southwest to the Northeast (about 115 deg. from true North) and the trajectory descent entry angle was determined to be about 11 degrees (measured downward from the horizontal). The point of origin was found from the video recording to be about 39 deg N, 106 W at an altitude of about 55 km. The total ground track length was calculated to be about ≥ 150 km. Using the total time and ground path distance, the meteoroid velocity was calculated to be from 56-60 km/sec, using two different methods. Earlier however, Mr Jack Murphy had estimated a speed of 26 miles/sec (41.8 km/sec) for this event. However, these are both extremely large values for such bright (large) fireballs. Bases on results from the U.S. Prairie Network operated by the Smithsonian Institution from 1964-1974, average entry speeds of bright fireballs are all < 31 km/sec., with typical meteorite entry values being < 15-30 km/sec. If the two values estimated above are even close to being correct, the likelihood of meteorites reaching the ground for this event is very poor due to the great ablation expected at such high velocities (ReVelle, 1979)

Using the various assumptions regarding the acoustic propagation path (with winds not having been incorporated) , the altitude of the major explosion burst height was determined to be about 55 km above Colorado Springs, Colorado (This is also fortuitously the height of the first appearance of the fireball in the sky as well). This can be compared to the end point height which was determined to be about 27 km (above mean sea level) or 25 km above mean ground level) for the termination of the visible flight path of the fireball.

4.2.3.3. Space-Based Sensors

Through communications with Dr. Edward Tagliaferri of E.T. Space Systems, Inc. (Los Angeles, Ca.), we have been able to determine that this fireball was also detected by U.S. DOD satellite systems operating in the infrared (IR) part of the electromagnetic spectrum. These data allow us to further constrain the position/trajectory of the fireball, but unfortunately do not allow us to determine either the velocity or any orbital information for this particular event. The results of the IR analysis are indicated in the table below.

TABLE II.

Summary of US DOD Infrared detection of the
November 21, 1995 Colorado fireball

Key Parameters	Values
Date	November 21, 1995
Time	09:18 UT
Latitude	38.6 deg N
Longitude	104.6 deg W
Altitude	45 km

Similar searches in the visible part of the electromagnetic spectrum were performed by Mr. Richard Spalding of Sandia National Laboratory, but these were not successful due presumably to the very low light intensity level for this relatively small event (by satellite light level standards).

4.2.3.4 Airborne Particle Collection Systems

Recently, the authors have also become aware that airborne particulate sampling of the meteoroid debris cloud may also have inadvertently occurred (personal communication with M. Zolensky, NASA-JSC, 1996). Originally this debris cloud was assume to be of volcanic origin since this is a quite common occurrence. This is a very important new development since we have had to assume a bulk density and composition for the body in order to use equation (7) above. Hopefully we will have more useful data on the bolide composition which will be rapidly forthcoming.

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5. PROPERTIES OF THE BOLIDE

5.1 Energy Constraints

On the basis of the very limited satellite data and the single array station infrasound detection, we estimate that the energy release from the bolide did not exceed 0.1 kt, but could have been as low as only about 0.001 kt..

5.2. Location Constraints

On the basis of the discrete detection algorithm used, we estimate a direction to the bolide from Los Alamos of 31 degrees from true North, with an associated uncertainty of ± 1 degree. This estimate confirms the heading of the trajectory determined from the trajectory analysis of the video camera records in Colorado Springs determined by two independent analyses. Had we been able to detect the event at either St. George, Utah or at the Nevada Test Site, we could have found a location ellipse within which the signal was emanated. Due to the counter-wind situation for Los Alamos with respect to Southeastern Colorado (where we anticipate sharply reduced amplitudes compared to the down-wind case), we were very fortunate for such a small event to be so easily detected, and this points out the real power of the acoustical method as a tool for detecting bright fireballs as discussed in ReVelle (1995a) and in ReVelle and Whitaker (1995).

In Figure 4. below we indicate the deduced infrasonic bearing (azimuth) with respect to the observed trajectory obtained by Sanders (1996). Note that the waves emanated nearly perpendicular to the deduced shallow trajectory which is consistent with the source geometry considered in ReVelle (1976). For such shallow trajectories ReVelle (1976) determined that it was far more likely that ray paths could be found that would reach observers or detection instruments on the ground.

Figure 4. A map of the region in which the fireball entered the Earth's atmosphere and the corresponding infrasonic azimuth computed assuming a plane wave across the Los Alamos, New Mexico array.

5.3. Additional Work in Progress

Additional studies of the probable ray paths for the deduced geometry of this fireball (on the basis of constraints provided by the trajectory analyses, the infrasound recording and using other data) will soon be undertaken. These will be used to examine the probable ray path ducting between the source and the location of the video detector in Colorado Springs as well as the infrasonic detection in Los Alamos. The combined detection at two sites will heavily constrain the possible acoustic paths. Also, a detailed normal mode calculation will also be performed for this case assuming a range of 30-50 km in altitude for the elevation of the source. Using the code originally developed by A.D. Pierce and co-workers we will input realistic temperature and wind profiles from the ground to 150 km in order to compute the wave amplitude and period as a function of range from an assumed elevated point source in a range-independent environment. For the expected counter-wind situation for this time of the year with respect to propagation from Southeast Colorado to Los Alamos, N.M., we expect to confirm a decrease in observed amplitude for a source energy in the range from roughly 10 to 100 tons (TNT equivalent), as compared to the zero (neutral) wind case

6. SUMMARY AND CONCLUSIONS

6.1. Fireball Detection

An infrasonic detection was made at an array of pressure sensors operated by the Los Alamos National Laboratory in Los Alamos, New Mexico. The properties of the fireball associated with this detection is consistent with those determined independently in Colorado Springs, Colorado and the surrounding vicinity which indicated a shallow trajectory from NW to SE (about 115 degrees from true North). It is also consistent with US DOD infrared satellite observations which fortuitously covered the region of interest at the time of the bolide as well.

6.2. Deduced Fireball Properties

From the fireball's infrasound we can infer a most probable source energy of from 10 to 100 T (TNT equivalent) for a sea level source. Since the source altitude was 30-50 km above the ground, this may be an overestimate of the real source energy for the bolide. Future work with ray tracing, normal model analysis and other procedures may help to further resolve the present uncertainties.

7. ACKNOWLEDGEMENTS

This work was supported by the U.S. Department of Energy.

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