LA-UR--97-2481

LA-UR-972481

Approved for public release; distribution is unlimited.

CONF-970706--

Title: Infrasonic Observations of Bolides on October 4, 1996

RECEIVED
AUG 27 1997
OSTI

Author(s): Douglas O. ReVelle
Rodney W. Whitaker
William T. Armstrong

Submitted to: Characteristics and Consequences of Orbital Debris and Natural Space Impactors II
SPIE, San Diego, CA, July 28-August 1, 1997

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Los Alamos
NATIONAL LABORATORY

DISCLAIMER

Infrasonic observations of bolides on October 4, 1996

Douglas O. ReVelle[1], Rodney W. Whitaker, and William T. Armstrong

Los Alamos National Laboratory, MS F659, Los Alamos, NM 87545

ABSTRACT

During the evening of October 3, 1996, at least 6 bright fireballs were observed over the western United States with reports from California to Louisiana. The event over California produced tremendous sonic boom reports in the Los Angeles area. This event was also detected locally by 31 seismometers which are part of a network of seismic stations operated by the California Institute of Technology. Subsequent investigations of the data from the four infrasound arrays used by LANL (Los Alamos National Laboratory) and operated for the DOE (Department of Energy) as a part of the CTBT Program (Comprehensive Test Ban Treaty) Research and Development program showed the presence of an infrasonic signal from the proper direction at the correct time for this bolide from two of our four arrays (Nevada Test Site; NTS and Pinedale, WY; PDL). Both the seismic and infrasound recordings indicated that an explosion occurred in the atmosphere, having its epicenter near Little Lake, CA for possible sources heights from 40-60 km.

The infrasonic arrays are each composed of four elements , i.e., low frequency pressure sensors that are in near-continuous operation. The nominal spacing between elements is 150-200 m depending on the specific site. The basic sensor is a Globe Universal Sciences Model 100C microphone whose amplitude response is flat from 0.1 to 300 Hz. Each sensor is connected to 12 porous hoses which act to reduce wind noise.

The signal characteristics, analyzed from 0.1 to 5.0 Hz, includes a total duration of 5 (NTS) to 20 minutes (PDL) for a source directed toward 230-240 degrees from true North. The signal trace velocities ranged from 300-360 m/sec with a signal velocity of 0.30 ± 0.03 km/sec, implying a Stratospheric (S Type) ducted path (with a reflection altitude of from 40-60 km). The dominant signal frequency is from 0.20 to 0.80 Hz, with a peak near 0.2 to 0.25 Hz. These highly correlated signals had a maximum amplitude of 1.0 microbars (0.1 Pa) at PDL and 4.0 microbars (0.4 Pa) at NTS. Our analysis indicates that the bolide had a probable, maximum source energy in the range from 150-390 tons (TNT equivalent).

Keywords: Infrasound; Meteor Acoustics; Blast Waves, Bolides, Long-range Sound Propagation

1. INTRODUCTION AND OVERVIEW

1.1 Large Bolide Entry into the Atmosphere

Large meteor-fireballs or bolides enter the atmosphere quite frequently. ReVelle (1995, 1997) has estimated that about a dozen bolides whose air-coupled explosive energy exceeds 1 kt (TNT equivalent) impact the atmosphere each year, with at about one 15 kt event occurring during the same period. If there is also a terminal explosion during the entry, the source of the waves is no longer a simple line source hypersonic boom, but can also include point source-like effects as well. The quoted influx rate is very similar to that reported by optical and infrared satellite monitoring of the atmosphere (Tagliaferri, et. al., 1994). Only the largest bodies whose kinetic energy at entry exceeds about 0.01 tons of TNT are capable of penetrating the atmosphere deeply enough to reach a condition of near-continuum flow with associated blast wave formation and decay and strong shock radiation effects, etc. also being expected. We estimate that about 10,000 to as many as 30,000 bolides of this energy or greater enter the atmosphere globally in a year.

1.2 Infrasound Detection of Large Bolides

As the strong, ballistic shock wave and/or terminal explosion propagates away from the bolide, it decays in strength and increases its wavelength substantially (ReVelle, 1976). As the shock propagates, the low frequency tail oscillates and grows in strength as the front shock dissipates (Pierce et. al. 1973). As the

[1] Further author information: D.O.R.: Email: dor@vega.lanl.gov

wave propagates its behavior becomes progressively more linear (ReVelle, 1976) and approaches the ordinary acoustic propagation limit at sufficiently high frequencies. For strong shock blast wave radii between 10 m and 20 km, (at continuum flow heights based on small Knudsen number and large Mach number of the flow) which are the rough limits with negligible wave absorption for realistic bolide sources proposed in ReVelle (1976), the corresponding wave frequencies are all sub-audible and hence in the infrasonic or more generally in the acoustic-gravity wave regime. These waves in the near-linear limit can propagate for thousands of kilometers before reaching undetectable amplitudes (ReVelle, 1995, 1997).

2. INFRASOUND OBSERVATIONS ON OCTOBER 4, 1996

2.1 The LANL Infrasound Arrays

The Los Alamos research arrays are located at the Nevada Test Site (NTS), at the Pinedale Seismic Research Facility (PSRF), Pinedale, Wyoming (PDL) operated by the Air Force Technical Applications Center (AFTAC), at St. George, Utah (STG), and on LANL property (LA). The array coordinates are as listed in Table 1. below:

Table 1.- Locations of the LANL Research Infrasound Arrays.

Array	Latitude (deg)	Longitude (deg)	State
Nevada Test Site NTS	**36.706 N**	**-115.963 W**	**Nevada**
St. George STG	**37.0153 N**	**-113.6153 W**	**Utah**
Los Alamos LA	**35.867 N**	**-106.334 W**	**New Mexico**
Pinedale PDL	**42.766 N**	**-109.593 W**	**Wyoming**

2.2 Observed bolide activity during the evenings of October 3-5, 1996

During October 3-5, 1996 a number of bright bolide events occurred over a large area of the Earth. These included multiple reports from California (with an explosion epicenter near Little Lake in Kern County, north of Bakersfield), three from New Mexico, one from Louisiana (possibly a distant sighting of the brightest New Mexico event) and yet another one seen from Cincinnati, Ohio and also possibly observed in Marion, Indiana where two bright meteors were also seen. The New Mexico events were reported on October 4-5, two near the time of the brightest New Mexico event at about 0200 UT on October 4th; the first was reported going from NE to SE as seen from Sante Fe and then 10-15 seconds later the bright bolide videotaped from El Paso appeared going from SW to NE; the third event seen from Albuquerque was almost exactly one day later at 0155 UT October 5th (information from J. Drummond, Philips Lab and sent to us by M. Boslough, SNLA, Albuquerque, 1996). The brightest California bolide was widely seen. Reports from an astronomer (D. Leatart) and his 25 students at Moorpark College just NE of Los Angeles indicated that the bolide was heading to the NNE, and caused significant shadows to be cast. From the U.S. East coast, very long and knotty haze streaks all over the sky, presumed to be dust trails, were observed to be at significant altitudes above the high thin Cirrus clouds observed aloft (information from F. Volz, Philips Lab, Hanscom AFB, MA and sent to us by M. Boslough, 1996). These occurred just before the New Mexico bolide noted above. In addition, a bright bolide (peak absolute, 100 km zenith brightness of -9.7) lasting 4.84 s entered at 02:35 UT on October 4 with an end height of 31.8 km and a velocity of 21.9 km/s which was photographed from 5 widely separated ground cameras of the European Fireball Network (personal communication with P. Spurny, 1996). Using meteor data, this bolide was determined to be of type I (bronzite chondrite) with a photometric mass of 12.4 kg with an aphelion in the asteroid belt (near 3.92 AU). During October 4-5, at least 4 other bolides were observed over California and Oregon as well (personal communication with J. Wasson, 1996). Interestingly a series of swarm-like events also occurred during October 19-24, 1994 during the period when a meteorite was recovered near Coleman, Michigan on October 20th. Three fireballs were detected by US DoD satellites in 6 hours early on October 20 and up to 12 bolides were observed globally (personal communication with P. Brown, 1996).

Because of the large numbers of reports of bolide activity during this period, we did a systematic search of the infrasonic signals from 0000 Z - 0600 Z on October 4, 1996 from all 4 arrays. In addition to doing single station analyses, we also event associated the signals between the various arrays in order to look for events with common wave sources. We used four signal detection methods, including peak cross-correlation of the signal, the f statistic (Blandford, 1974), lag closure and the composite signal power. We found 28 signals using the standard cross-correlation approach when a value of 0.75 was chosen for the detection threshold, cross-correlation coefficient. Of these only three could be connected with signals at other arrays, i.e., with the correct timing, etc. to be consistent with the same wave source. A summary of results is given in Table 2. with associated event "tags" listed in the last column.

Table 2. Event Detection and Association for the four Los Alamos Research Infrasound Arrays: October 4, 1996 from 0000-0600 UT.

Event Number	Wave detection time (UT)	Array Station (*)	r^2 (**)	Azimuth (deg) (***)	Associated events- Travel time delay: hr	Tag ID Number
1	0.100	STG	0.89	234		
2	0.137	LA	0.84	246		
3	0.164	LA	0.86	246		
4	0.507	STG	0.76	216	#5:0.508 **#6:0.533**	1
5	1.015	LA	0.83	261		
6	**1.04**	**LA**	**0.88**	**261**		
7	1.681	STG	0.77	236		
8	1.686	STG	0.94	270		
9	1.700	STG	0.81	018		
10	1.898	STG	0.88	188		
11	2.024	LA	0.79	080		
12	2.124	STG	0.79	210		
13	2.728	NTS	0.86	063		
14	2.839	NTS	0.90	063		
15	2.914	NTS	0.90	063		
16	2.917	NTS	0.92	090	#20: 0.16	2
17	2.939	NTS	0.86	056		
18	3.033	NTS	0.94	090	#22:0.161	
19	3.061	NTS	0.95	090	#23:0.161	
20	3.077	STG	0.90	255		
21	3.108	PDL	0.90	098		
22	3.194	STG	0.92	255		
23	3.222	STG	0.86	255		
24	**3.944**	**NTS**	**0.81**	**240**	#26: 0.70 **#27: 0.72**	3
25	3.964	NTS	0.86	231	#26: 0.68 **#27: 0.70**	
26	4.644	PDL	0.92	225		
27	**4.660**	**PDL**	**0.94**	**218**		
28	4.981	LA	0.77	141		

(*): LA: Los Alamos Array
TG: St. George Array
NTS: Nevada Test Site Array
PDL: Pinedale Array
(**) with r, the cross-correlation coefficient
(***) Measured clockwise from True North (0 deg)
Normal print- First detection for correlation> 0.75
Bold print- First detection for correlation> 0.75, with duration > 60 sec and azimuth deviation < 5 deg.

Tag 1 represents the association of events 4, 5 and 6 and corresponds to a potential explosion over S. California and also, possibly another bolide that may have occurred some 3.5 hours before the brightest bolide event over California. Tag 2 represents the association of events 16, 18, 19, 20, 22 and 23 and corresponds to a source in the Las Vegas, Nevada vicinity, possibly a sonic boom. Tag 3 represents the association of events 24, 25, 26 and 27 and corresponds to the 0344 UTC, bright California bolide.

In addition as noted in Table 2. single array detections were also seen during this period as well, but we have not counted these as possible events unless a minimum of two arrays detected the same signal with an appropriate time delay. For example, a puzzling feature is the possible detection of signals from one of two bolides sighted over New Mexico at 8:00 p.m. MST (0200 UT, October 4th). Unfortunately although the azimuth and its change with time appears correct for this event, there is no corresponding infrasonic propagation time delay, with the time of the infrasound arrivals at LA being almost exactly the time of the appearance of the fireball that was videotaped from El Paso, Texas. Similarly, we also identified an event with very large trace velocity at STG at 0140 UT with an intersecting azimuth from PDL that points to the vicinity of Salt Lake City, UT. The rapidly changing azimuth and elevation angle at STG indicates a relatively near-by event, moving rapidly aloft. The PDL signal, being farther away, only indicates a single, nearly constant azimuth and elevation angle which is more indicative of the observation of a far field, distant bolide or other explosive event. This latter behavior is very commonly observed for most available bolide observations however (ReVelle, 1995, 1997). This is the typical detection situation because most observed events have been of relatively large source energy that can be readily detected far from the event location. For smaller sources at closer ranges, a rapid change in azimuth and elevation of arriving signals can be used as a diagnostic. Unfortunately, this LA and PDL detection is not listed in Table 2. since our subsequent analysis was incomplete due to missing PDL data for part of this period.

2.3 Infrasonic Detections of the Brightest California Bolide

Signals from the 0344 UTC October 4 1996, California bolide were found at two of our 4 research arrays, namely at NTS and at PDL. A marginal detection was also made at the St. George, Utah array. No signals from the event were recorded at the Los Alamos array. A summary of the observed signal characteristics at the NTS and Pinedale arrays for the frequency passband from 0.1 to 5 Hz is given in Table 3. below.

Table 3. LANL infrasound for the 0345 UT California Bolide.

Deduced Parameters	NTS Array	PDL Array
Total signal duration	2 minutes (strongest signals)- Total: 5 minutes	10 minutes (strongest signals)- Total: 20 minutes
Source azimuth	230 deg	220 deg
Range to bolide	160.9 km	1013.9 km
Signal trace speed	300 m/s	380 m/s
Signal velocity	0.30 +/- 0.03 km/s; S Type return	0.30 +/- 0.03 km/s; S Type return
Dominant frequency content	0.20-0.80 Hz (0.25)	0.20-0.80 Hz (0.20)
Maximum cross-correlation, r	0.99	0.99
Maximum signal amplitude	4.0 microbars (0.4 Pa)	1.0 microbars (0.1 Pa)

In Figure 1.a and 1b. below is a plot of the temporal analysis of the signals arriving at NTS array and at PDL from the 0344 UTC California bolide. This includes, respectively a three hour period from the results of our analyses for composite power, cross-correlation and for the f statistic methods. Note the very large spike at the two arrays indicating the arrival of the signal of the bolide well above the background noise level.

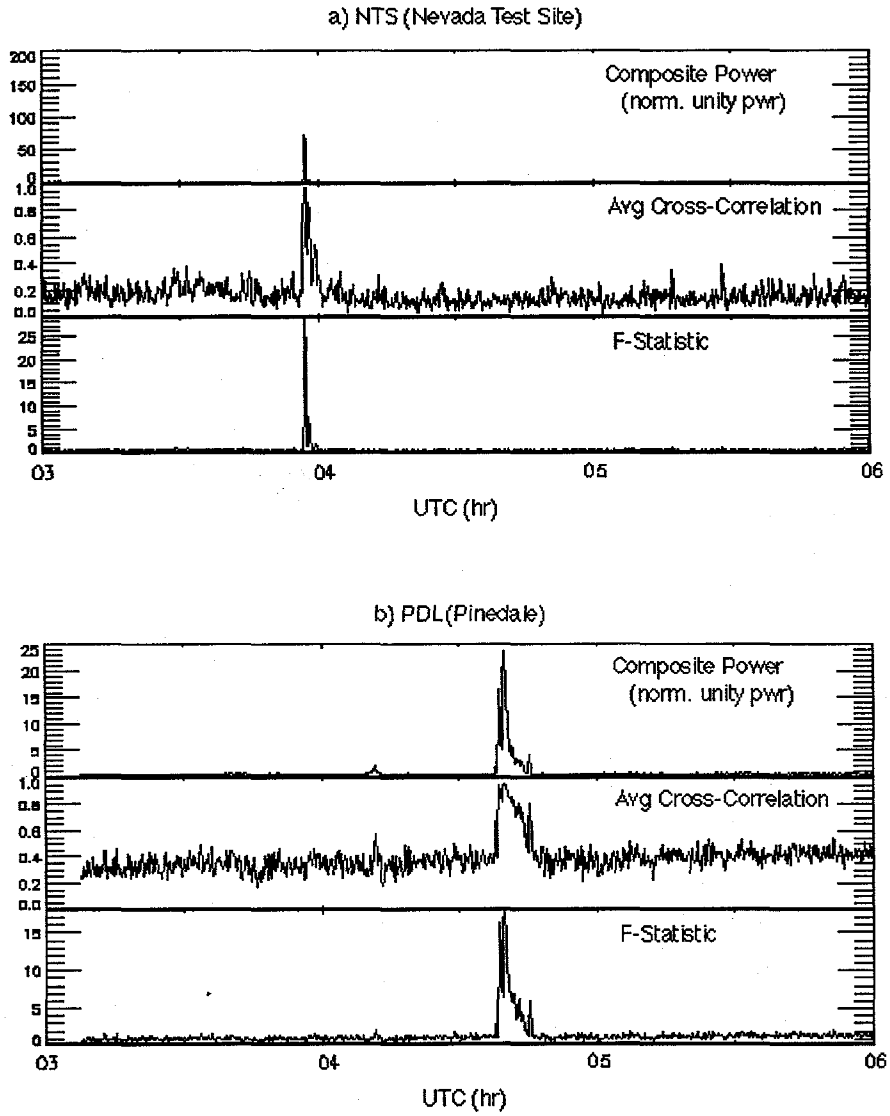

Figure 1a. and 1b. Temporal analysis of the waves arriving at the NTS array (upper panel) and at the PDL array (lower panel) from the 0344 UTC California bolide. The respective methods of detection include composite power, cross-correlation and f statistic.

2.4 Ancillary Information about the California Bolide

Professor John Wasson of the Institute of Geophysics and Planetary Physics (IGPP) at UCLA has personally interviewed over 200 people who witnessed this event (personal communication, 1996). Many individuals reported strong sonic booms as well as electrophonic sounds simultaneous with the flight of the bolide as well. Historically these reports have only been received from observers from very bright fireballs, which are brighter than the full moon (Keay, 1992). The general direction of the fireball heading is from SW to NE, similar to both Peekskill (Brown et. al., 1990) and to the New Mexico fireball on the same night about 105 minutes earlier. In addition, data are available from US DoD satellite monitoring (E. Tagliaferri, personal communication, 1996) and are listed in Table 4. below. Unfortunately, a unique altitude could not be identified for this case and so a reasonable value had to be assumed in order to complete the analysis of the spatial position of the bolide. To be consistent, the value of 55 km was tentatively assigned. Earlier a 40 km source altitude has been used in the analysis of the strongest seismic signals from the bolide. As noted earlier these seismic signals were recorded at 31 stations operated in the Los Angeles area by the California Institute of Technology (K. Hutton, personal communication, 1996). These recordings indicated that two explosions occurred aloft, but that the largest explosion was positioned very nearly over the town of Little Lake, California (just to the west of China Lake Naval Weapons Center). Unfortunately, specification of the height of the explosion is needed for the determination of these spatial coordinates and this in turn depends on the specific nature of the atmospheric sound speed and wind speed model utilized to invert the seismic time of arrival data.

Surface and upper air weather data obtained from the National Weather Service at the time of these events indicated that a very broad and quite strong surface high pressure region was present and moving rapidly southward and eastward into the central part of the United States from Canada. This was quite a well developed system with air at the surface at 0000 Z on October 4 in S. Dakota and Iowa being almost 30-40 degrees F colder than in New Mexico and Arizona for example. This system was strong enough to penetrate as far south as central Texas and managed to even reach the central New Mexico mountains. This can typically happen, but usually much later during the Winter season. From 0Z to 12Z on October 4, the surface front had dissipated over New Mexico and had penetrated into central Florida and into the Gulf of Mexico. Upper air winds at the Tropopause were quite light over the Southwestern region during the period however, with Westerlies over California and more northerly flow over Arizona and then a return to Westerlies over New Mexico. More specifically, a rather strong band of showers and associated winds was moving toward Los Alamos from the West ahead of the moving surface front. This was occurring just 2 hours before the New Mexico bolide of 0200 UT. Thus, as was readily seen in the infrared meteorological satellite data, a large area of Arizona, Utah and Colorado which was heavily cloud covered existed during the bulk of the period from 0000-0060 UT. Strong, gusty surface winds also accompanied the rain showers that were quite evident on radar. In part, this may also explain why the California fireball was not detected at either STG or LA some 1 1/2 hours later, i.e., due to the fact that the strong surface winds created a high noise level. Detailed ray tracings for sources at altitude should be used to investigate the propagation conditions during this period.

Table 4. Summary of Ancillary Observations of the California Bolide

Key Parameters:	Values:
Date and Time	0344 UTC, October 4, 1996
Latitude	36.1 N
Longitude	-117.6 W
Assumed source altitude range	50-60 km: 55 km assigned

3.0 INTERPRETATIONS OF THE INFRASOUND DATA

3.1 Source Location

From our infrasonic bearings we have also determined that Little Lake, California is very near to the site of a major explosion along the fireball trajectory. We can not explicitly determine the source altitude of the infrasonic signals without ray tracing efforts, but the time delay of the arrival of the infrasound is consistent with a waveguide ducting in the sound channel between the ground and about 50 km altitude, similar to what was observed for the November 21, 1995 Colorado Fireball (ReVelle and Whitaker, 1996). The source location of the primary California bolide explosion (called event no. 3 in Table 2.) is indicated in Figure 2. The position of the bolide detonation was determined from seismic intersecting bearings from 31 stations, from our infrasonic intersecting bearings from two distant arrays and from U.S. DoD satellite data. The latter data was kindly provided to us by Dr. Edward Tagliaferri of E.T. Space Systems, Inc., of Los Angeles, California (personal communication, 1996). Note that the intersection of the bearings (back azimuth) from two of our infrasonic arrays occurs within a few km of the town of Little Lake, CA and very near to the location of the intersection of the bearings from 31 seismometers operated by the California Institute of Technology.

Event Association Tag 3

time	site	corr	az	vel
3.944	nts	.81	240	310
4.644	pdl	.92	225	353

Figure 2. Map of the intersection of the mean infrasonic bearings (at maximum correlation) from the NTS and PDL infrasonic arrays for the 0344 UTC California bolide. The intersection occurs very near the town of Little Lake, CA (just to the West of China Lake Naval Weapons Center) and near the location of the intersecting bearings from 31 seismographs operated by the California Institute of Technology in the Los Angeles area.

3.2 Source Energy

Using the four approaches discussed in ReVelle and Whitaker (1996), we can also make estimates of the source energy of the bolide. The four approaches used are:

i) Acoustic efficiency approach: This is an energetics approach originally developed by Cox (1958) to estimate the source energy of the bolide as a function of range, etc. We have assumed an acoustic efficiency of 1 % based on our analyses of the bolide data originally detected by AFTAC (Patrick AFB, Florida). The method assumes that the waves emanate from a near-surface explosive source. Due to the decrease of pressure and air density with increasing height, such source estimates represent an upper limit to the "true" source energy.

ii) Line source model of ReVelle (1976): This is a line source explosion, blast wave model of the hypersonic entry of large bolides into the atmosphere. This method explicitly assumes that the wave behaves as a weak shock during the entire period of propagation from the source to observer. This approach also utilizes both amplitude and wave period data, etc. from the bolide and, unlike the other two approaches, it does not assume, a priori, a near-surface source of explosion waves. The nonlinear relaxation blast radius for a line source is equal to the product of the Mach number of the bolide (entry speed/adiabatic sound speed) and its diameter. This assumes that the continuum flow (sufficiently small Knudsen number) energy deposition per unit length of trail can be equated to the hypersonic aerodynamic wave drag at the stagnation point of the flow around the body and that gross fragmentation effects and deceleration of the body are negligibly small. The properties of the strong and weak shock waves generated are fundamentally related to the blast radius of the interaction between the body and the atmosphere. These properties includes wave amplitude and period, etc. The line source geometry dictates a square root dependence of the energy deposited/trail length divided by the ambient pressure whereas an isolated point source explosion has a blast radius whose magnitude depends on the cube root of the energy deposited divided by the ambient pressure. A bolide with a terminal point source-like explosion will have a blast radius whose length should depend fundamentally on the line source model, but with an isotropic acoustic radiation pattern forward of the terminal explosion and a distinct cylindrical radiation symmetry prior to the terminal explosion.

iii) Empirical explosive yield, wind-corrected amplitude relationship of Mutschlecner and Whitaker (1990): This is a detailed least squares curve fit of near-surface high explosive tests conducted at White Sands Missile Range, New Mexico that have been monitored infrasonically at long range between about 1980-1994 by LANL. As noted above this is an upper limit to the explosive, source energy release.

iv) Period at maximum amplitude approach: This is a method that was developed by AFTAC during the period from 1960-1974. It is based on a curve fit of the acoustic period at maximum signal amplitude as a function of the yield of an explosion (assumed to be the actual explosion source energy/2). The original data that were used to develop these yield-period relationships were long range infrasonic observations of numerous U.S. nuclear, point source explosions conducted primarily at source altitudes below 15,000 feet.

Using the acoustic efficiency approach we find that the source energy is from 1.96e-3 to 1.95e-2 kt, whereas using the line source model of ReVelle (1976), we find a consistent value of the source energy of about 7e-4 kt for a source altitude of 55 km. The acoustic efficiency and line source approach both predict quite small source energy values compared to the other methods used. The efficiency approach would predict substantially larger source energies if either the efficiency was actually lower (which seems unlikely based on our earlier results) or if the reflection coefficient of Cox were lower. For example using a reflection coefficient of 0.7 instead of the nominal value of 0.9 used earlier, the estimate of source energy using PDL data was raised by more than a factor of three from 1.95e-2 kt to 6.54e-2 kt. Also, at a source height of 75 km, the line source approach predicts a source energy of about 0.21 kt of TNT at both NTS and PDL or comparable to values found using the two other methods listed above. In the line source approach, we have used the nominal meteor-fireball parameters used in ReVelle and Whitaker (1996). In addition, the predicted infrasonic wave periods for a source height of 75 km are the correct order of magnitude compared with the observed maximum amplitude signals at NTS and PDL. Using the empirical approach of Whitaker and Mutschlecner we found source energies from 0.0269 kt (NTS) to 0.139 kt (PDL), assuming negligible winds in early October for the Stratospheric duct (V = 0). Finally, using the acoustic period at maximum amplitude relationship given in ReVelle and Whitaker (1996), we have determined that the source energy was in the range from 0.15 to 0.39 kt if the source was no more than two pressure scale heights above the surface. If the source was at a substantial altitude, the actual source energy could be as much as one order of magnitude lower than these values. Clearly, there are differences between the methods that cannot currently be resolved without further modeling efforts. This could include point source modeling using the normal mode analysis developed by Pierce and co-workers, i.e., Pierce et. al., 1973. It could also include a modified, line source modeling effort using the hydrodynamic method of Korobeinikov and co-workers that was developed between the early 1970's through the middle of the 1980's.

In Figure 3a. and 3b. the FFT computed power spectrum of the waves arriving at NTS and PDL is plotted. Note the spectral peaks near 0.25 Hz and 0.20 Hz as previously indicated in Table 3. The peak in Figure 3b. below 0.2 Hz is due to the presence of microbaroms. In Figure 4, a single channel of the arriving infrasound waves and the corresponding spectrograms (spectral power versus frequency and time) for the detections at NTS and PDL are also plotted. Note the extended duration of the signals at PDL as compared to NTS and that the amplitude at PDL is actually about four times smaller than that at NTS.

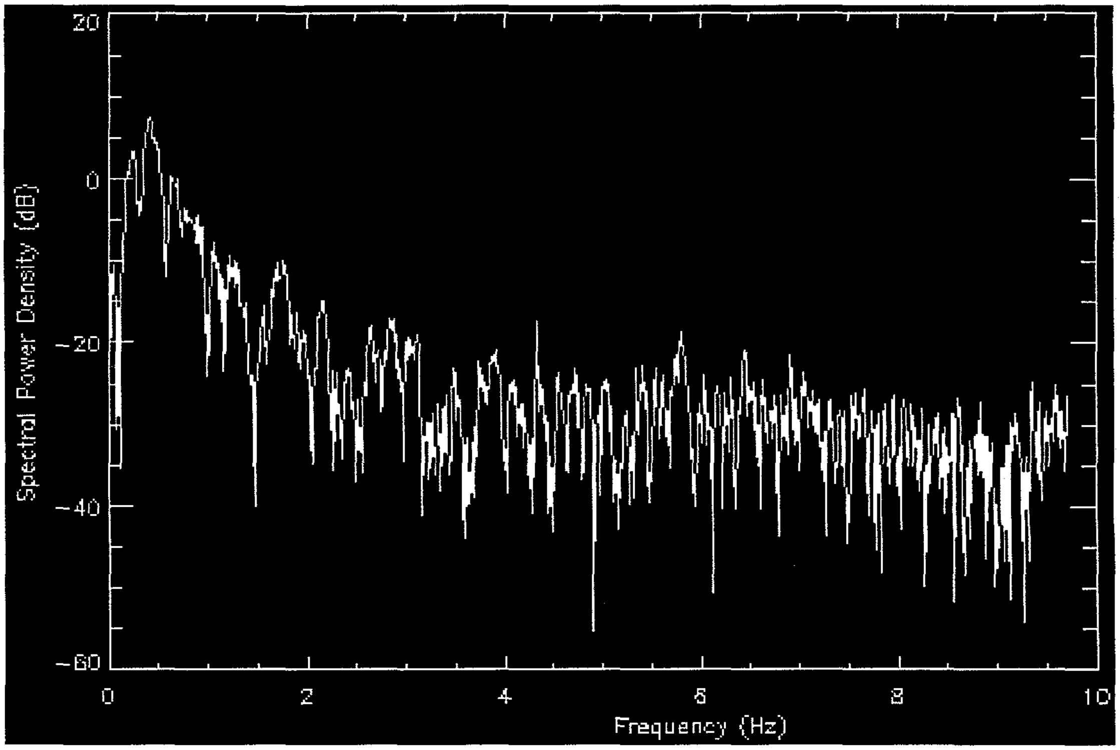

Figure 3a. Power spectrum of infrasonic waves at NTS from the 0344 UTC California bolide.

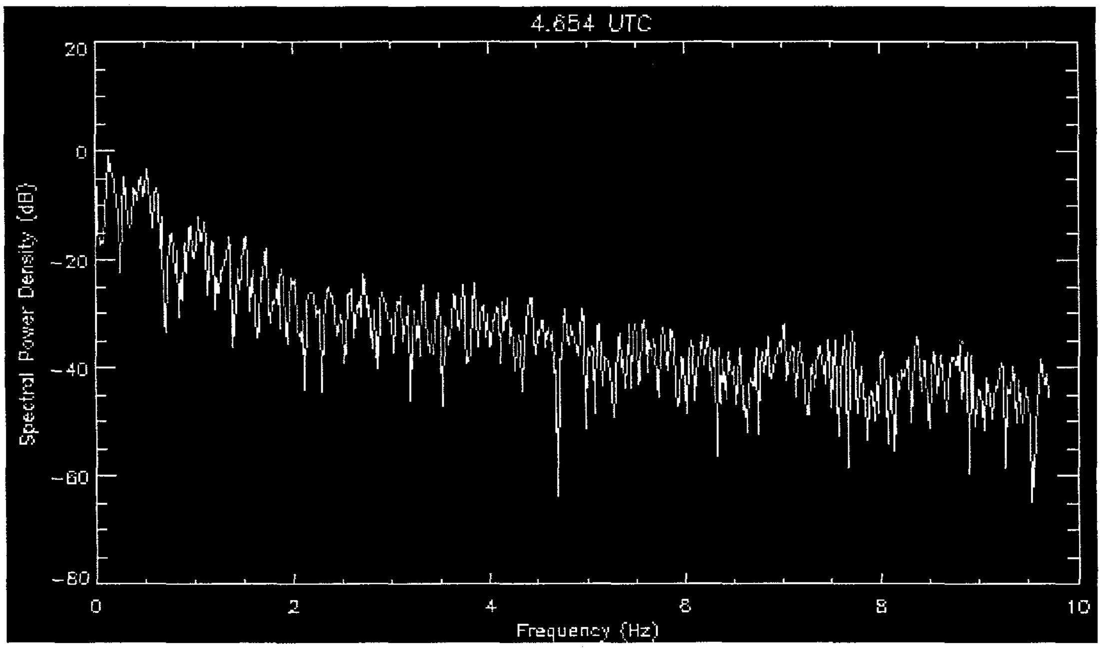

Figure 3b. Power spectrum of infrasonic waves at PDL from the 0344 UTC California bolide.

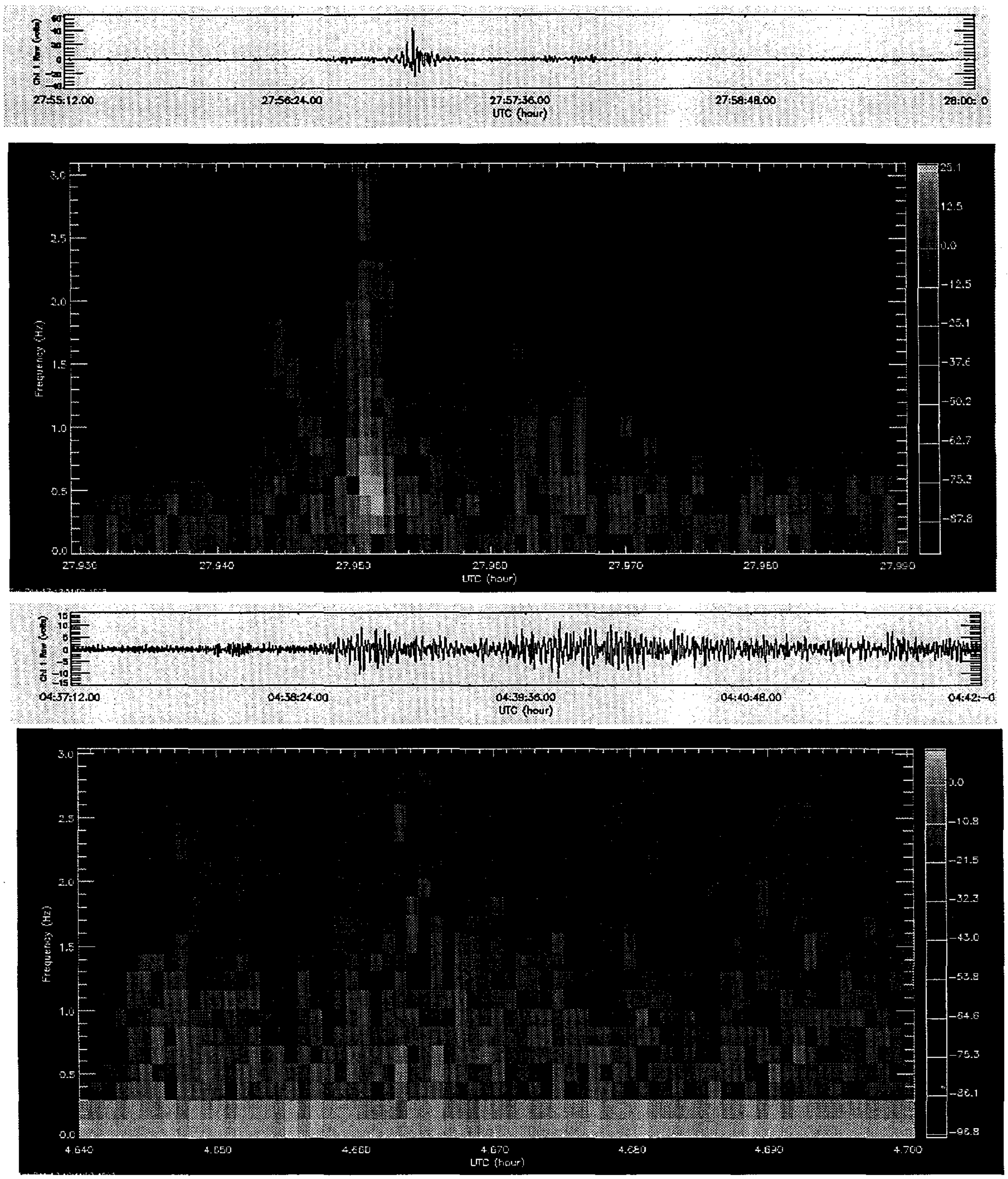

Figure 4. Single channel infrasonic signals and the corresponding spectrograms of these waves from the 0344 UTC, October 4, 1996 California bolide as recorded at the LANL NTS array (upper panel) and at the LANL PDL array (lower panel).

Finally, we will also use the technique developed by ReVelle (1976) and compared in ReVelle (1995; 1997) against the AFTAC period at maximum amplitude approach, i.e., method iv) given above. This line source approach successfully separates calculations of the source energy and the source height associated with using observations of the amplitude and the wave period for a line source explosion in an isothermal, perfectly stratified atmosphere. Unlike method ii) above, only the wave period information is used to calculate the source energy, similar to the approach used by AFTAC. The fundamental equation used in the bolide source energy calculation is:

$$E_s(J) = (\pi/6)\cdot\{1/(1.58)\}^4\cdot(\rho_m c_s^7/V)\cdot(\tau_G^4/R)$$

where

ρ_m = Meteoroid bulk density (= 3.5·10(3) kg/m^3)

c_s = Mean atmospheric sound speed (= 300 m/s)

V = Meteoroid velocity (= 11.2·10(3) m/s)

τ_G = Acoustic wave period at maximum amplitude

R = Total path range from the bolide to the observer

As in ReVelle (1976), we have assumed that the horizontal range can be increased by 10 % to account for the total path between the source and the observer. Thus, the computed value of the source energy at NTS is 1.98 kt and the corresponding value at PDL is 0.769 kt. Previous comparisons (ReVelle, 1995, 1997) have also shown that this method produces results that are larger by about a factor of two than those using the AFTAC, point source approach. Unlike the AFTAC approach however, a ground level source is not assumed and the source height can be calculated separately in an independent manner. A summary of all of our current source energy estimates is given in Table 5.

Table 5.
Summary of Source Energy Estimates for the California Bolide of October 4, 1996 (0344 UTC).

Approach	NTS Data: Source Energy	Pinedale Data: Source Energy
Acoustic efficiency	1.96 t	19.5 t
Line source: Height = 55 km	0.716 t; wave period = 0.51 s	0.70 t; wave period = 0.81 s
Line source: Height = 75 km	217 t; wave period = 2.14 s	212 t; wave period = 3.38 s
Empirical yield-amplitude	27 t	139 t
Period at maximum amplitude	150 t	390 t
Line source: Period only	1980 t; wave period = 4.0 s	769 t; wave period = 5.0 s

4.0. SUMMARY AND CONCLUSIONS

4.1 Large Bolide, Near Earth Object (NEO) Influx Rate

On the basis of the AFTAC upper limit to the source energy of the California bolide (interpreted as a near-surface explosion of 390 tons of TNT equivalent energy release), we should expect that on the average about 14 events of similar energy should be observed over the entire surface of the Earth in the period of 1 year (ReVelle, 1995; 1997). Over an observing region of 1000 km in radius from the event (roughly the distance from PDL to Little Lake, CA), we should only expect about 0.1 bolide/year of similar energy or an event of this magnitude once every 10 years. Thus, taken on this basis, events of this magnitude occur relatively rarely. The techniques used here, as demonstrated earlier in Table 2., can be suitably modified into an automatic event association algorithm that can be effectively used to study the potential false alarm rate associated with the entry of bolides into the atmosphere. These techniques can be then used as a model approach for the regular operation of the CTBT IMS (International Monitoring System) infrasound network.

4.2 Infrasound Detections of Large Bolides

The combination of using infrasound, satellite observations in various spectral regimes, seismic techniques and the possible recovery of fallen meteorites, etc. are very promising tools for the study of solar system debris and their rate of impact on the atmosphere. Future studies should also include Very Low Frequency (VLF) electromagnetic wave emission by very bright bolides as well as ground-based camera systems (including audio and video and spectral capabilities) so that more details about the bolides and their compositions, etc. can be forthcoming. As demonstrated in Table 5., more work is needed to accurately estimate bolide source energies reliably under all circumstances. This could include point source modeling using normal mode type analyses, etc. and also bolide source modeling efforts (modified line source effects, etc.) as well. Our detection of the October 4, 1996 California bolide- similar to our case study for the November 21, 1995 Colorado bolide, but greatly improved by including two very good array detections of the bolide at great range- can be used to help in modeling of the expected false alarm rate for bolides for the operational phase of the CTBT IMS network operations.

ACKNOWLEDGMENTS

This work was supported by the U.S. Department of Energy, Office of Nonproliferation and International Security, NN-20.

REFERENCES

Brown, P., A.R. Hildebrand, D.W.E. Green, D. Page, C. Jacobs, J. Wacker, D.O. ReVelle, E. Tagliaferri and B. Wetmiller, The Fall of the St. Robert Meteorite, J. Meteoritics and Planetary Sci., **31**, 502-517, 1996.

Blandford, R.R., An Automatic Event Detector at the Tonto Forest Seismic Observatory, Geophysics, **39**, 633, 1974.

Cox, E.G., Sound Propagation in Air, Handbuch der Physik, Springer Verlag Pub. Co., Berlin, Vol. XLVIII, Chapter 22, 455-478, 1958.

Keay, C.S.L., Electrophonic Sounds from Large Meteor-fireballs, Meteoritics, **27**, 144-148, 1992.

ReVelle, D.O., On Meteor-Generated Infrasound, J. Geophys. Res., 81, 1217-1237, 1976.

ReVelle, D.O. and R.W. Whitaker, Detection of the Large Meteoroid/NEO Flux: The Detection of the November 21, 1995 Colorado Fireball, SPIE, Denver'96, in *Characteristics and Consequences of Orbital Debris and Natural Space Impactors,* T.D. Maclay and F. A. Allahdadi, Editors, Vol. 2813, Paper 2813-07, pp. 57-68, August 8-9, 1996 and LA-UR-96-2236, 12 pp., 1996.

ReVelle, D.O., Historical Detection of Atmospheric Impacts of Large Bolides Using Acoustic-Gravity Waves, Annals of the New York Academy of Sciences, J. Remo, Editor, New York, 19 pp., June, 1997

Tagliaferri, E, R., R. Spalding, C, Jacobs, S.P. Worden and A. Erlich, Detection of Meteoroid Impacts by Optical Sensors in Earth Orbit, Hazards due to Comets and Asteroids, T. Gehrels Editor, Univ. of Arizona Press, Tucson, 199-220, 1994.

UNPUBLISHED REPORTS

Mutschlecner, J.P. and R.W. Whitaker, The Correction of Infrasound Signals from Upper Atmospheric Winds, Fourth Internat. Sympos. on Long-Range Sound Propagation, NASA Conf. Pub. 3101, Compiled by W.L. Wilshire, NASA Langley Research Center, Hampton, Va., 143-153, 1990.

Pierce, A.D., C.A. Moo and J. W. Posey, Generation and Propagation of Infrasonic Waves, Report No. AFCRL-TR-73-0135, Air Force Cambridge Research Laboratories, Hanscom Air Force Base, Bedford, Mass. 01731, 138 pp., 1973.

ReVelle, D.O., Historical Detection of Atmospheric Impacts of Large Bolides Using Acoustic-Gravity Waves, LA-UR-95-1263, 25 pp., Presented at the NEO Conference at the Explorer's Club/United Nations, N.Y. City, New York, 1995.