BOLIDES AND OTHER INFRASOUND EVENTS

Rodney W. Whitaker, Peter G. Brown, Douglas O. ReVelle, Thomas D. Sandoval,
J. Paul Mutschlecner, and Nicole M. Bueck

Los Alamos National Laboratory

Sponsored by National Nuclear Security Administration
Office of Nonproliferation Research and Engineering
Office of Defense Nuclear Nonproliferation

Contract No. W-7405-ENG-36

ABSTRACT

During the past year, we have processed infrasound data from at least 13 bolide events, including the important recent events of 23 April 2001 and 25 August 2000. Bolides represent a source of significant natural impulsive signals that can be detected by infrasound arrays and networks and may not have detections by other technologies. As more International Monitoring System (IMS) infrasound stations come online, detections of these events will increase. Analysis of these multiple-station event detections will allow tuning of detection and location algorithms. Work by various groups on the April 2001 event already has shown this. We will present data from all 13 events, detected by one to eight stations (not all of which are IMS); however, more detailed results will be made for the 4/23/01 and 8/25/00 events for which some space-based data have been released. Some results on the bolide events will illustrate the features of Infra_tool, an infrasound analysis tool for use within MATSEIS.

We will also review some recent work and analysis of infrasound from earthquakes observed with Los Alamos National Laboratory (LANL) arrays. This data set illustrates the value of using wind-corrected amplitudes in the analysis. These natural impulsive events have many of the characteristics of interest to the IMS. Such data will be essential for exercising and refining detection and location algorithms and thus calibrating the infrasound network.

KEY WORDS: infrasound, bolide, location, earthquake, wind correction

OBJECTIVE

We discuss data from recent bolide events detected infrasonically on various infrasound arrays, including newly established ones as part of the International Monitoring System (IMS). Recent results on infrasonic signals from earthquakes are also presented.

Observations of large bolides and their associated effects on Earth's atmosphere are now available from several instrumental techniques. Satellite instruments [Tagliaferri et al*,* 1994], photographs [Ceplecha et al. 1993], video observations [Brown et al. 1994], seismic data [Qamar, 1994], and infrasound recordings [ReVelle, 1998] all contribute to our observational understanding of these rare events. The latter technique, in particular, can be used when a meteoroid penetrates deeply enough (50- to 90-km altitude) into the atmosphere and creates a blast wave of sufficiently low frequency to propagate to the Earth's surface [eg. ReVelle, 1976]. For large bolide events, the blast wave created by the hypersonic passage of the meteoroid may propagate to very large distances at infrasonic frequencies and be detectable by differential low-frequency microphones on the ground, if meteorological conditions are favorable. The global flux of larger bodies with energies ~ 1kT TNT (1 kT TNT = 4.185×10^{12} J) is more than 10 per year [ReVelle, 1997].

RESEARCH ACCOMPLISHED

Bolides

Table 1 gives recent bolide events detected by various infrasound arrays. Included in this table, by each event, are the stations detecting the event. Of particular interest are the events of 8/25/00 and 4/23/01 in the eastern and east-central Pacific for which more detailed data are given.

Table 1: Recent bolides detected on various infrasound arrays.

Date	Time (UT)	Source lat	Source long	Energy (kt)	Stations
February 18, 2000	9:29	0.864N	109.151E	15	WRAI
August 25, 2000	1:12	14.45N	106.1W	8	DLIAR, PDIAR, ISM, IS59
January 18, 2000	16:43	60N	225.29E	5	PDIAR
July 19, 2000	17:40	17.7S	94E	0.5	WRAI
August 16, 1999	5:18	35.02N	107.17W	0.1	DLIAR, LA
August 14, 1999	7:16				DLIAR
November 21, 1995	9:18	38.2N	103.9W	0.05?	LA
October 4, 1996	0:00	36.1N	117.6W	0.05?	SGAR, NTS, PDIAR, LA
June 13, 1998	13:30	34.2N	103.3W	0.1	SGAR
October 9, 1997	18:47	31.8N	106.1W	0.25	DLIAR, LA
August 11, 1998	9:30	20S	128E	9.3	WRAI, ALICE SPRINGS
August 11, 2000	18:45	35.1N	106.4W	?	DLIAR
April 23, 2001	6:12	28.38N	132.90W	11	SGAR, DLIAR, NVIAR, IS10, NTS,IS57, IS59, IS26

where: Alice Springs was a temporary array near Alice Springs, Australia.
DLIAR is the Los Alamos, NM, prototype array.
ISM or IS10 is the Canadian array near Lac du Bonnet, Manitoba.
IS26 is the array in Freyung, Germany.
IS57 is the Pinon Flat, CA, array.
IS59 is the Hawaii array.
LA is the small scale Los Alamos array.
NTS is a small-scale Los Alamos array at the Nevada Test Site.
NVIAR is the array near Mina, NV.
PDIAR is a small scale Los Alamos array at the Pinedale Seismic Research Facility near Pinedale, WY.
SGAR is a Los Alamos array near St. George ,UT.
WRAI is the array at Warramunga, Australia.

Correlation analysis summary plots are shown in Figure 1 for three of the events. These were done with the Infra_tool.m tool within Matseis. (See notes on Figure.)

Tables 2 and 3 provide analysis details for the August and April events. Analysis was done in part with the Matseis software package from Sandia National Laboratories. We did not have calibration data for some arrays and not all stations have physical pressure units. Most headings are self-explanatory. Durations were based on the time during which the cross-correlation coefficient was two sigma above the pre-event background noise values.

To estimate source energy, the observed period at maximum amplitude of the signal may be related (with numerous assumptions) to an empirical formulation derived from Air Force recorded infrasound data of near surface nuclear tests in the 1960's [cf. ReVelle, 1997]. This is a validated approach, in the sense that observed wave periods could be directly compared to known yields, but suffers from the drawback that it is only appropriate for low-altitude spherical nuclear detonations. It must thus be considered an approximation only for higher altitude bolide line-source explosions and short (<400 km) ranges, particularly since a number of effects may change the period at maximum amplitude during propagation [ReVelle, 1974]. However, it has been found to be in reasonable agreement with energy estimates for several bolide events observed infrasonically and with other methods [eg. ReVelle et al. 1998]. This empirical energy relation is given as :

$$Log(E/2) = 3.34 - \log(P) - 2.58 \qquad (1)$$

where E is the total energy of the event (in kT), and P is the period at maximum amplitude in seconds of the stratospheric arrival, also known as the main acoustic arrival.

Table 2. Observed signal characteristics associated with the April 23, 2001, bolide. The table gives the period at maximum amplitude (T_{maxamp}), peak-to-peak pressure (in millipascals) and trace velocity (in km/s). The duration of the signal is referenced to the levels at which the signal correlation returns to within 2σ of the noise background.

Station	**Location**	**Azimuth of Arrival**	**Range (km)**	**Time of Max Amplitude**	**Duration (seconds)**
IS59	19.6N, 155.9W	62.5	2526	08:27:56	740
DLIAR	35.9N, 106.3W	259.3	2626	08:44:43	780
SGAR	37.0N, 113.6W	252.0	2039	08:12:30	1050
IS26	48.9N, 13.7E	327.3	9526	16:26:00	480
NTS	36.7N, 116.0W	240.3	1833	08:00:58	1440
IS57	33.6N, 116.5W	247.1	1666	07:51:46	520
IS10	50.2N, 96.0W	244.2	3931	09:58:47	440
NVIAR	38.4N, 118.3W	236.1	1753	07:56:21	420
FLRS	48.8N, 0.48E	314.6	10315	15:45:00	-
UAF	64.8N,147.7W	151.0	4183	10:16:00	540

Station	**T_{maxamp} (seconds)**	**Peak Pres. (mPa)**	**Trace Velocity**	**Yield (Eq (1))**
IS59	4.14 ± 0.54	470	0.340 ± 0.015	0.61± 0.27
DLIAR	4.05 ± 0.33	400	0.337 ± 0.018	0.56±0.16
SGAR	4.47 ± 0.68	449	0.358 ± 0.069	0.78±0.40
IS26	-	25	0.346 ± 0.05	-
NTS	3.07±0.45	552	0.305±0.015	0.22±0.11
IS57	3.90±0.40	-	0.302±0.016	0.50±0.17
IS10	5.14±1.01	-	-	1.25±0.83
NVIAR	4.59±0.47	-	0.341±0.002	0.85±0.30
FLRS	-		0.291	
UAF	-	-	0.317	

Table 3. Observed signal characteristics associated with the August 25, 2000, bolide. The table values are the same as given in Table 1. Note that as many stations had not been calibrated at this time, few peak pressure measurements are available. PDIAR was experiencing complex instrumental noise problems and thus the period and amplitude measurements are suspect and array processing was not possible. Microphone alignment problems with IS10 prevented reliable array processing.

Station	Location	Azimuth of Arrival	Range (km)	Time of Max Amplitude (UT)	Duration (seconds)	T_{maxamp} (seconds)
IS59	19.6N, 155.9W	90.2	5304	06:05:25	830	6.04 ± 0.28
DLIAR	35.9N, 106.3W	185.1	2381	03:28:00	620	7.20 ± 1.67
IS10	50.2N, 96.0W	-	4079	05:11:00	600	6.68±0.83
IS25	5.21N, 52.73W	282.6	5925	06:21:55	-	-
PDIAR	42.8N, 109.8W	-	3171	07:56:21	420	4.59±0.47
UAF	64.8N,147.7W	139	6415	07:09:00	-	-

Station	Yield (Eq(1))	Peak Pressure	Trace Velocity
IS59	2.1±0.3	-	0.339 ± 0.015
DLIAR	3.7±2.9	125	0.361 ± 0.055
IS10	2.9±1.2	-	-
IS25	-	-	0.338±0.003
PDIAR	1.1±0.3	200	-
UAF	-	-	0.359

To determine the likely location for the April event, we used the best infrasound bearings (determined at maximum amplitude of the signal) and found their individual intersections (see Figure 2). To determine the most probable location, all bearing intersections were weighted by the sine of the angle of intersection, following [Greene and Howard, 1975], and then a weighted average position for the most probable location for the event determined. The bearings from NTS and UAF are most uncertain and these are excluded for our location determination. The best fit location using these weighting procedure places the event at 28° 23N and 132° 54'W. For comparison, the satellite data indicate a location near 27° 54'N and 133° 53'W. This represents a linear difference of 110 km in ground location. Given the poor azimuthal distribution in station coverage for the event and the fact that we have applied no wind corrections to these bearings, this is remarkably good agreement over baselines of the order of several thousand kilometers. Using an observed time for the event from satellite records of 06:12 UT, we derive mean signal speeds from 0.26-0.31 km/s with most signals between 0.28-0.29 km/s. These are typical stratospherically ducted returns.

It is clear that as more infrasound stations come on line, data on bolides will begin to accumulate. These natural impulsive events have many of the characteristics of interest to the IMS. These data will be quite valuable for exercising and refining detection and location algorithms.

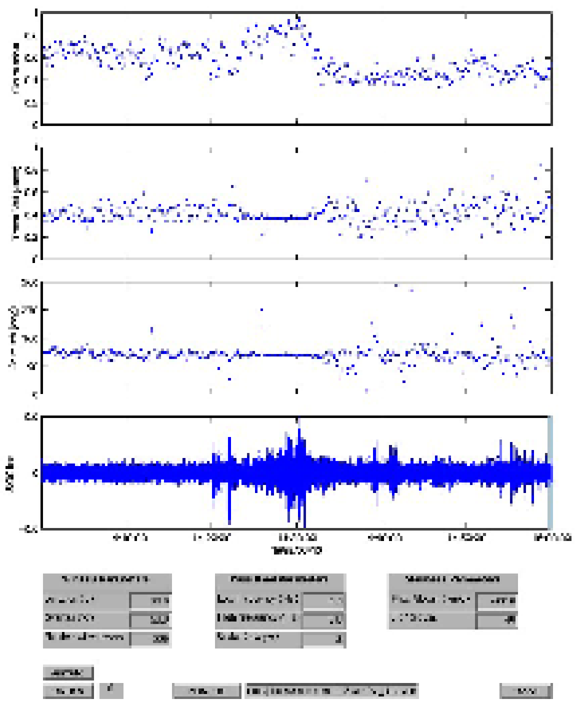
Earthquakes

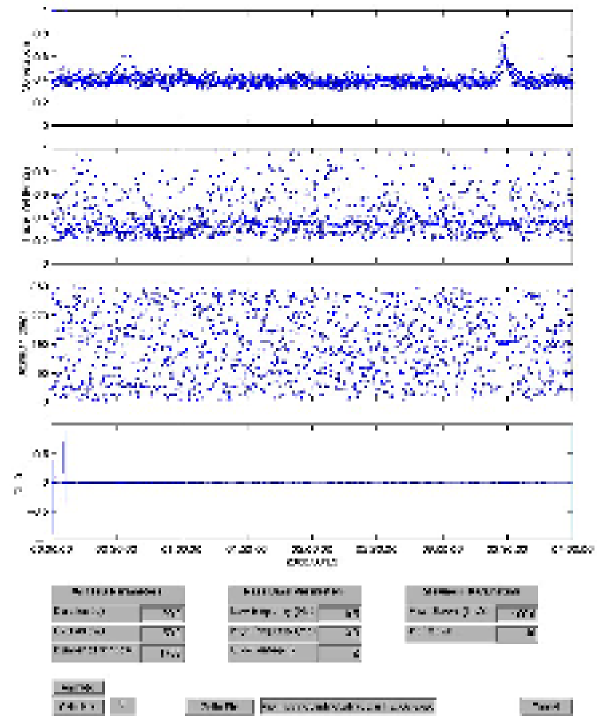
Recently we have re-examined our data on infrasound from earthquakes, obtained mostly during the time of the Los Alamos infrasound program for detecting underground nuclear tests at the Nevada Test Site. The data and results are being reviewed for consistency, etc. We present results in Figure 3, where infrasound amplitudes are plotted against the body wave magnitude, Mb. Two normalizations are used. In the upper plot we normalize raw amplitudes to a distance of 250 km by assuming amplitude is proportional to $R^{-1.2}$, where R is the range in km. The lower plot retains this but uses wind-corrected amplitude, Mutschlecner and Whitaker (1999). In the upper right corner of each plot, the regression equation is given along with the correlation coefficient of the fit. The improvement in correlation is obvious.

SUMMARY AND CONCLUSIONS

The two bolide events discussed in detail here show how well such events can be detected by arrays of infrasound sensors. Given the azimuthal coverage and number of stations, the location of the 4/23/01 event, using only infrasound data, is really quite good. These events clearly demonstrate the ability of these arrays to detect and locate impulsive atmospheric events. Bolide detections will increase as more IMS infrasound station become operational and will provide excellent test beds for refining detection and location software, as well as exercising the ways in which systematic wind effects can be incorporated to improve analysis results.

Some care needs to be used in comparisons of processing results from different researchers and organizations. If processing parameters are not the same, or nearly the same, then differences in results can be expected. For example, source bearings from slowness planes or FK planes with different number of points in the search space cannot be expected to yield the same results or to agree. Results with different band pass filters can also yield different results. Perhaps it is time to begin discussion, within the community of infrasound researchers, of what a standard set of such parameters should be. This would help to ensure that results for different organizations can be compared on an equal footing and add confidence to the results.





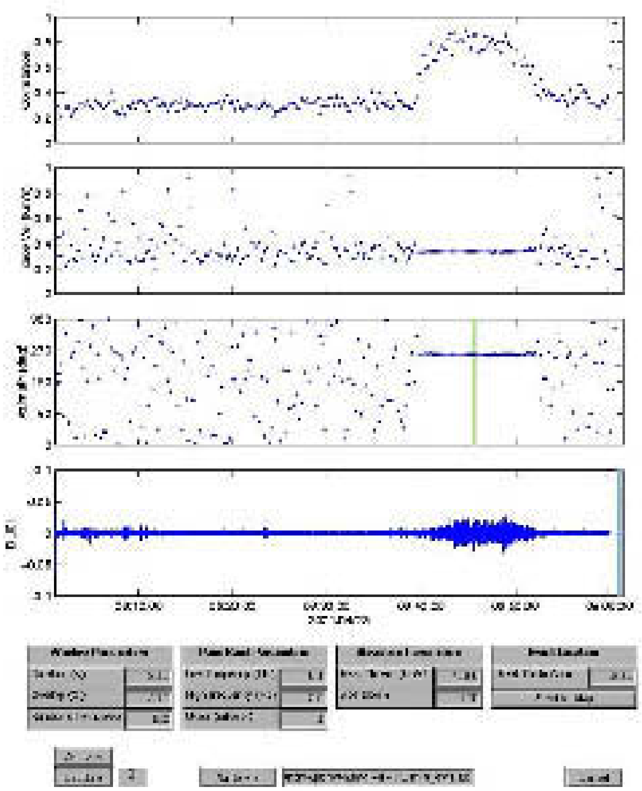


Figure 1: Summary processing data for three events. Clockwise from the upper left – 6/13/98 near Portales, NM, using the St. George, UT array; the 8/25/01 event off the west coast of Mexico , with DLIAR data; and the 4/23/01 event with DLIAR data.

In each set values are shown as a function of time. The first panel is the correlation coefficient, the second is the trace velocity, the third is the azimuth and the fourth is one channel of data.

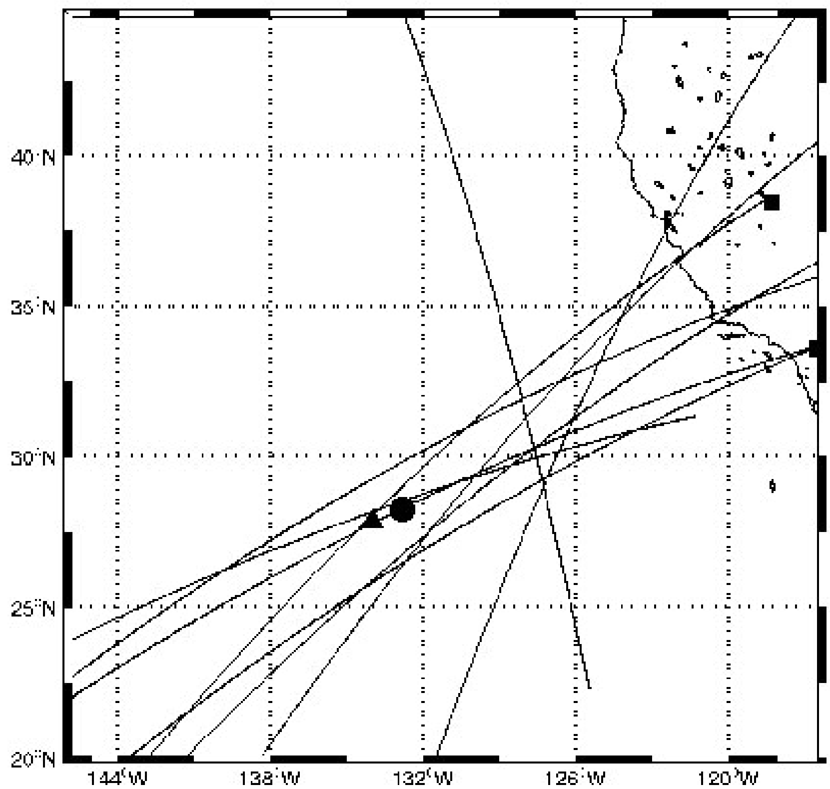
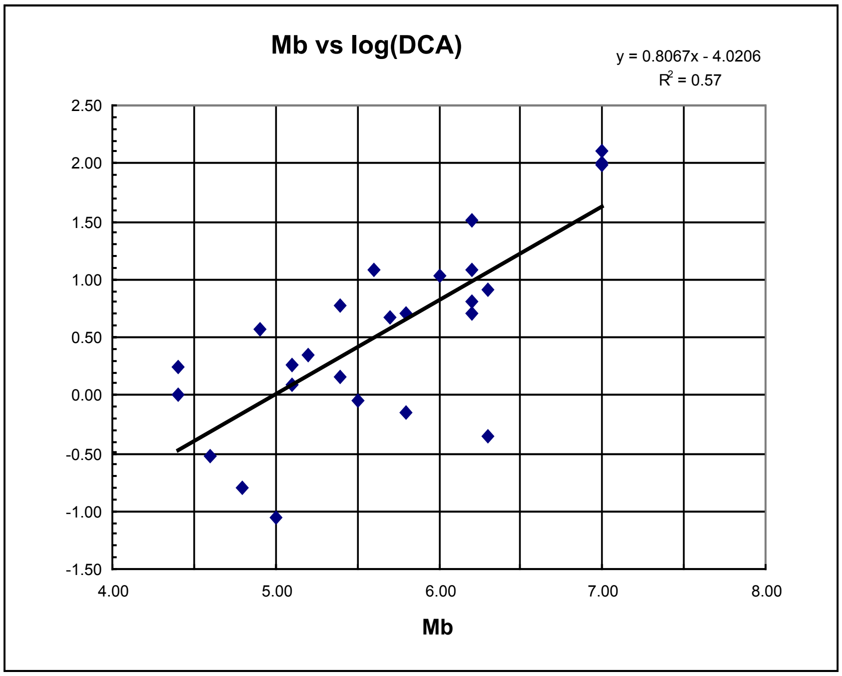


Figure 2: A plot of the various azimuths for the arrays detecting the 4/23/01 event. The circle is the location determined from the weighting of the individual intersections. The triangle is the announced location from satellite data.



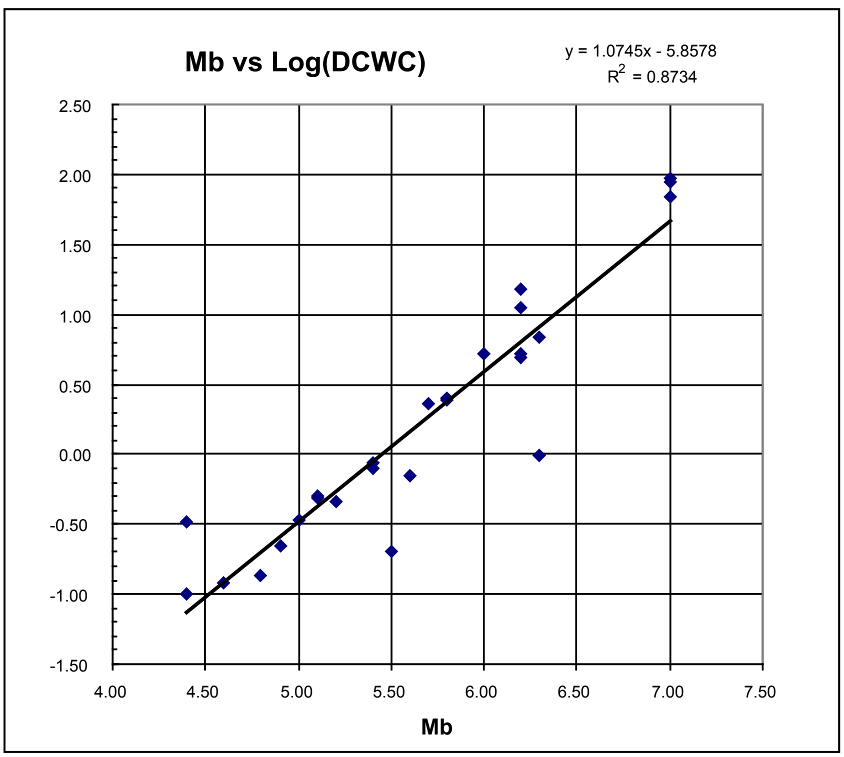


Figure 3: Infrasonic earthquake amplitude data as a function of Mb.

REFERENCES

Brown, P., Z. Ceplecha, R.L. Hawkes, G.W. Wetherill, M. Beech, and K. Mossman (1994), The Orbit and Atmospheric Trajectory of the Peekskill meteorite from video records, *Nature, 3*67, 624-626.

Ceplecha, Z., J. Borovica, W.G. Elford, D.O. ReVelle, R.L. Hawkes, V. Porubcan, and M. Simek (1998), Meteor Phenomena and Bodies, *Sp. Sci. Rev., 84*, 327-471.

Greene, G.E. and J. Howard (1975), Natural Infrasoun : A one Year Global Study, *NOAA Tech. Report ERL 317-WPL 37*, Boulder CO.

Mutschlecnet, J.P., R.W. Whitaker and L.H. Auer (1999), An Empirical Study of Infrasonic Propagation, LA-13620-MS, Los Alamos National Laboratory.

Qamar A. (1995), Space shuttle and meteroid (sic) - tracking supersonic objects in the atmosphere with seismographs. *Seismological Research Letters 66*, 6 – 12.

ReVelle, D.O. (1974), Acoustics of Meteors, PhD Dissertation, University of Michigan.

ReVelle D.O. (1976), On Meteor-Generated Infrasound. *J. Geophys. Res. 8*1, 1217-1240.

ReVelle, D.O. (1997), Historical detection of atmospheric impacts of large super-bolides using acoustic-gravity waves, *Ann. N.Y. Acad. Swci., 822*, 284-302.

ReVelle, D.O., R.W. Whitaker and W.T. Armstrong (1998), Infrasound from the El Paso Superbolide of October 9, 1997, in *Proceeding of SPIE*, edited by C.B. Johnson, T.D. Maclay and F.A. Allahdadi, pp. 66-78, The international society for optical engineering v.3434, Washington.

Tagliaferri, E., R. Spalding, C. Jacobs, S.P. Worden, and A. Erlich (1994), Detection of meteoroid impacts by optical sensors in Earth orbit, in *Hazards due to Comets and Asteroids*, edited by T. Gehrels, pp. 199-220, Univ. of Arizona Press, Tucson, Arizona.