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Multi-Station Infrasonic Observations of Two Large Bolides: Signal Interpretation and Implications for Monitoring of Atmospheric Explosions

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Abstract. Observations of two large bolides occurring over the Western Pacific on August 25, 2000 and April 23, 2001 are presented. These large bolides produced infrasonic signals at numerous stations in the Americas and Europe as well as being observed by US Department of Defence satellite sensors. The energy, location and physical characteristics of these bolides is inferred from available infrasound records and compared to satellite data. The infrasonic energy of the events from the observed signal frequencies is estimated to be 3 kT and 1 kT respectively, while the satellite energies are approximately 3 kT and 11kT. The disagreement in energies for the April 23, 2001 (the third largest satellite observed bolide on record) event is significant and indicates acoustic/optical processes not typical of most bolides. The integrated infrasonic acoustic energy of the signals indicates that the percentage of acoustic energy deposited into the atmosphere is a minimum of ~0.1-1% of the total source energy for each event.

Introduction

Observations of large bolides and their associated effects on Earth's atmosphere are now routinely made using several instrumental techniques. Satellite instruments [*Tagliaferri et al.*, 1994], photographs [*Ceplecha et al.*, 1998], video observations [*Brown et al*,. 1994], seismic data [*Qamar*, 1995], and infrasound recordings [*ReVelle et al.*, 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 – 90 km altitude) into the atmosphere and creates a blast wave of sufficiently low frequency to propagate to the Earth's surface [*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 (20 Hz down to the atmospheric waveguide acoustic cut-off frequency) and may be detectable by differential low-frequency microphones on the ground. The global flux of small bolides (kinetic energy ~0.01 tonnes TNT) capable of producing a weak infrasound signal at ground level is estimated to be at least 10^4 per annum [*ReVelle and Whitaker*, 1999], while the influx of larger bodies with energies ~kT TNT (1 kT TNT = 4.185×10^{12} J) is more than 10 per year [*ReVelle*, 1997].

The latter energy range is of practical interest in connection with the Comprehensive Test Ban Treaty (CTBT) which aims to deploy various sensors worldwide to ensure that no nuclear explosion with energy of order one kT or greater can go undetected. The false alarm rate and signal phenomenology associated with natural events releasing kT-class energies is of particular interest for CTBT both as a means to ensure proper interpretation of signals and to estimate the delectability of such signals with each measuring technology. For infrasonic measurements of distant explosions, CTBT calls for deployment of 60 infrasonic arrays of sensors worldwide as part of the International Monitoring System (IMS) of the CTBT. Such a global system will permit regular acoustic detection of large bolides on a scale not possible since the US Air Force global infrasound network ceased operations in the early 1970's [*ReVelle*, 1997].

As of late 2000, significant numbers of IMS stations have begun coming on-line with a particular concentration of IMS and other infrasound stations occurring in western North America. This permits good coverage of bolide detonations over western North America and the eastern Pacific region using instruments with similar design and response characteristics. In connection with this improved coverage, we discuss the detection of two large bolides occurring in the eastern Pacific on August 25, 2000 and April 23, 2001. Both events were in the multi-kT range, were detected optically and in the IR by satellites and demonstrate the utility of infrasound networks for detection, location and estimation of source energies from these large bolides.

Infrasound Generation, Propagation and Energy estimates for Bolides

From infrasound data, the parameters, which may be estimated for a bolide are total kinetic energy, a line of sight direction to the acoustical generation point on the bolide trajectory and an approximate origin time.

From an energy standpoint, 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 [*ReVelle*, 1997]. This is a validated approach, in that observed wave periods could be directly compared to known yields, but is only appropriate for distant, 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]. For distances significantly exceeding the length of the meteor trail this relation is robust since there is an almost exact trade-off between the generally unknown source altitude and the initial kinetic energy of the fireball [*ReVelle*, 1980]. It has also been found to be in reasonable agreement with energy estimates for several bolide events observed infrasonically and with other methods [*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. While numerous processes may modify the period at maximum amplitude [cf. ReVelle, 1974] it tends to be a more robust measure than the maximum amplitude.

Finally we may use the integrated wave energy observed at a station to estimate the source yield or acoustic efficiency of the explosion, if yield is known. For nuclear detonations, the acoustic efficiency is of order 6-7%, while values for bolides range from 0.2 –7 % of the total initial energy, with most typical values near a few percent [*ReVelle and Whitaker*, 1997]. In the simplest construction, the total acoustic wave energy per unit area (W_{Total}) detected at a distance R from a surface source under an inversion is given by [*Cox*, 1958]:

$$W_{Total} = \varepsilon\left(\frac{E}{2\pi R^2}\right)\Delta \qquad (2)$$

where ε is the assumed acoustic efficiency, and Δ is the attenuation, which will be a function of range in general. Alternatively, we may write:

$$W_{total} = \int_0^{\tau} \frac{\Delta P(t)^2}{\rho C_s} dt \qquad (3)$$

where ΔP is the pressure as a function of time observed at the station due to the disturbance, ρ is the mass density of the atmosphere at the receiver, C_s is the local adiabatic sound speed and τ is the duration of the correlated energy from the event. By equating (2) and (3) we may estimate the fraction of total yield (assuming it is known from other sources) going into acoustic energy.

The April 23, 2001 Bolide

The first detection of the 23 April, 2001 event was made during routine processing of the DLIAR infrasound array at Los Alamos National Laboratory on 24 April, 2001. A total of 10 infrasound stations recorded the signal from the event. Table 1 summarizes the stations and signal characteristics observed at each.

The observed trace velocities (apparent signal speeds across the microphone array) are most consistent with stratospheric-type returns [*Ceplecha et al.*, 1998] indicative of relatively shallow received rays. In analyzing this event, we defined the signal to be that interval where the maximum correlation coefficient [*Evers and Haak*, 2001] was at least 2σ above the general noise background. All signals for this event were first filtered from 0.1 – 3 Hz before measurements were made. The correlation coefficients and trace velocities were computed in 30s binning windows. The final trace velocity in table 1 is the mean and one standard deviation for the entire signal at each site. The azimuth value given is the value associated with the signal at the point of maximum cross-correlation. Figure 1 shows the pressure signal from the event.

To determine the likely location for the 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 best fit location using these weighting procedure places the event at 28° 23N and 132° 54'W while the satellite data show 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 order several thousand kilometres.

For the estimated energy of the bolide we applied equation 1 and computed the energies from the periods at maximum amplitude. The results of these energy estimates are summarized in the second column of table 1. Examination of the table shows that the period at maximum amplitude is remarkably similar at all stations over a large spread in range. The satellite data indicate an integrated optical energy (assuming a 6000K blackbody) of 4.6×10^{12} J. From previous events, a typical conversion from integrated optical energy to total event energy [*Brown et al.*, 1996] is ~10%. This implies a total satellite event energy near 11 kT. The values in the table from equation 1 are 10-50 times smaller than the satellite value. This is unusual in that this relation has been applied previously with success to large fireballs [cf. ReVelle *et al.*, 1998]. This suggests that the April 23 fireball was substantially different than previously measured events in that either much less acoustic energy was generated than normal or the satellite optical energy efficiency was much higher than 10% or perhaps both.

To estimate the acoustic energy efficiency we first determined the total signal power measured at each station by performing the numerical integration in equation 3 using the filtered (0.1-3 Hz) signals with windows chosen covering the full signal duration. The summed power in this interval was then computed (as the square of the measured pressure amplitudes) and then the average over all four channels is taken. The average noise for all channels is then computed and a final "best" estimate for the signal-only power computed. We took ρ=1.225 kgm^{-3} and C_s=340 m/s. Using a relationship we found between range and the measured signal power relative to the background in the far-field from 1500<R<4000 km and equations 2 and 3 for all upwind stations we find a minimum acoustic efficiency of 0.32 ± 0.08% for this event.

The August 25, 2000 Bolide

This event was detected at six infrasound arrays in Western North America and South America. The signals all indicate stratospheric returns and are consistent with a relatively large event. The lower portion of table 1 summarizes available acoustic data, using the same procedures described in the previous section and estimated source energy using equation 1. From satellite observations, the optical energy yield of this event was 1.4×10^{12} J, suggesting a total energy of 3.3 kT using a 10% optical-yield conversion. This is in good agreement with infrasonic yield estimates found from equation 1. Only DLIAR had reliable, calibrated amplitude measurements and application of an identical approach as outlined for the April 23, 2001 event for the acoustic efficiency yields a value near 1.2%, some four times greater than for that bolide.

For event location only DLIAR, IS59 and IS25 have sufficiently high signal to noise ratios to reliably determine azimuths. Figure 2 shows the azimuthal intersection for these two stations near the maximum amplitude of the signals. The best-fit intersection point found using the same method as employed for the April 23, 2001 bolide is 13° 12'N, 108° 40'W. The satellite position in 14° 27'N, 106° 6'W, a great-circle distance of 310 km, slightly worse than the April 23 fireball. Additionally, both DLIAR and IS59 show substantial variations in azimuth of arrival for the signals increasing with time from the start of the signal perhaps due to a combination of signals received from different parts of the bolide trail and systematic deviations produced by winds along the different paths.

Conclusions

From observations at multiple stations, the infrasonic signals from two large bolides have been clearly recorded. The source locations found using infrasound bearings are within a few hundred kilometres of satellite determined positions over ranges of several thousand km. The estimated locations for these events were readily determined from infrasound records to within areas of order several 10^4 km^2 with bearings-only information.

The energy estimate for the April 23, 2001 event is not consistent with past estimates of optical satellite energy to absolute yields and/or infrasonic signal periods to energies. The low acoustic efficiencies suggested from records at several sites may be indicative of unusual characteristics for this detonation. Such a low acoustic efficiency is probably indicative of higher luminous output and this may indicate the meteoroid was very porous. This object was third most energetic satellite recorded bolide (out of some 500 events total) since 1972.

The August 25, 2000 fireball showed good agreement between the satellite and acoustically determined energies. Both events demonstrate the capabilities of widely spaced infrasound arrays in robustly locating explosions of order several kT at ranges of many thousands of kilometres. Bolide events, like these two, clearly demonstrate the value of infrasound arrays in monitoring energetic impulsive events in the atmosphere.

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Table 1. Observed signal characteristics associated with the April 23, 2001 and August 25, 2000 bolides. The table gives the station name and location (as latitude,longitude with north and west positive), the equivalent yield using Eq (1), the zzimuth of the received signal (with north 0 and east 90), the period at maximum amplitude (T_{max}), peak-to-peak pressure (in millipascals), and mean signal velocity at maximum amplitude. The duration of the signal is referenced to the levels at which the signal correlation returns to within 2σ of the noise background.

Station	Yield (kt)	Az	Range (km)	Time of Max Amplitude	Duration (seconds)	T_{max} (seconds)	Peak Pres. (mPa)	Signal Velocity (km/s)	Trace Velocity (km/s)
April 23, 2001 :									
IS59 (20,156)	0.61± 0.27	63	2526	08:27:56	740	4.14 ± 0.54	470	0.311	0.340 ± 0.015
DLI (36, 106)	0.56±0.16	259	2626	08:44:43	780	4.05 ± 0.33	400	0.288	0.337 ± 0.018
SGR (37,114)	0.78±0.40	252	2039	08:12:30	1050	4.47 ± 0.68	449	0.282	0.358 ± 0.069
IS26 (49, -14)	-	327	9526	16:26:00	480	-	25	0.259	0.346 ± 0.05
NTS (37,116)	0.22±0.11	240	1833	08:00:58	1440	3.07±0.45	552	0.282	0.305±0.015
IS57 (34,117)	0.50±0.17	247	1666	07:51:46	520	3.90±0.40	-	0.280	0.302±0.016
IS10 (50, 96)	1.25±0.83	244	3931	09:58:47	440	5.14±1.01	-	0.281	-
NV (38,118)	0.85± 0.30	236	1753	07:56:21	420	4.59±0.47	-	0.286	0.341±0.002
FLR (48,0)	-	315	10315	15:45:00	-	-		0.300	0.291
UAF (64,144)	-	151	4183	10:16:00	540	-	-	0.286	0.317
August 25, 2000 :									
IS59 (20,156)	2.1±0.3	90	5304	06:05:25	830	6.04 ± 0.28		0.311	0.339 ± 0.015
DLI (36, 106)	3.7±2.9	185	2381	03:28:00	620	7.20 ± 1.67	125	0.293	0.361 ± 0.055
IS10 (50, 96)	2.9±1.2	-	4079	05:11:00	600	6.68±0.83		0.284	-
IS25 (5,53)	-	283	5925	06:21:55	-	-		0.273	0.338±0.003
PDI (43, 110)	1.1±0.3	-	3171	07:56:21	420	4.59±0.47	200	0.294	-
UAF (64,144)	-	139	6415	07:09:00	-	-		0.297	0.359

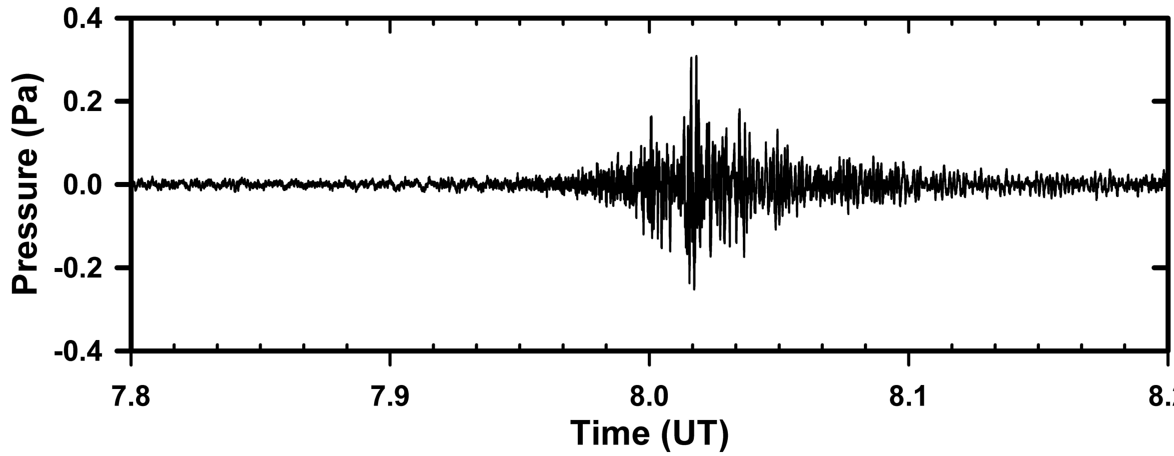

Figure 1. Amplitude record of the April 23, 2001 bolide as recorded on one microphone at the Nevada Test Site array (NTS). The signal has been band-passed from 0.1-3.0 Hz.

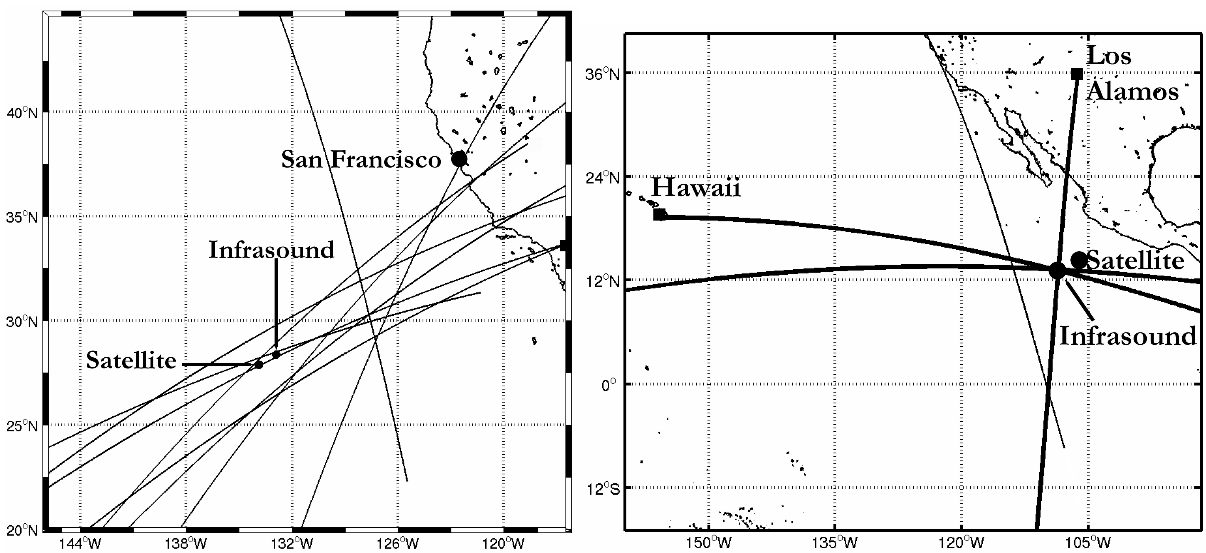

Figure 2. Map showing the intersection of infrasound bearings for the April 23, 2001 event (left) and the August 25, 2000 bolide (right). The intersecting infrasound azimuth solution and the satellite-determined position are labeled on each plot. For the April 23 fireball, the infrasound location was found using intersection locations for all stations except IS26, UAF and NTS and weighting each position by the sine of the intersection angle. For the August 25, 2000 meteor, only Los Alamos (DLI), IS59 (Hawaii) and IS25 (Kourou, Guinea) (bold lines) had accurately determined azimuths.