Infrasonic detection of a near-Earth object impact over Indonesia on 8 October 2009

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[1] We present analysis of infrasonic signals produced by a large Earth-impacting fireball, believed to be among the most energetic instrumentally recorded during the last century that occurred on 8 October, 2009 over Indonesia. This extraordinary event, detected by 17 infrasonic stations of the global International Monitoring Network, generated stratospherically ducted infrasound returns at distances up to 17 500 km, the greatest range at which infrasound from a fireball has been detected since the 1908 Tunguska explosion. From these infrasonic records, we find the total source energy for this bolide as 8–67 kilotons of TNT equivalent explosive yield, with the favored best estimate near ~50 kt. Global impact events of such energy are expected only once per decade and study of their impact effects can provide insight into the impactor threshold levels for ground damage and climate perturbations. **Citation:** Silber, E. A., A. Le Pichon, and P. G. Brown (2011), Infrasonic detection of a near-Earth object impact over Indonesia on 8 October 2009, *Geophys. Res. Lett.*, *38*, L12201, doi:10.1029/2011GL047633.

1. Introduction

[2] Impacts of medium-sized (meter to 10s of meters in diameter) Near Earth Objects (NEOs) at the Earth may cause physical damage at ground level [e.g., *Chapman and Morrison*, 1994] and could perturb climate on regional scales [*Toon et al.*, 1997]. However, the impactor size at which these effects begin to occur is poorly understood from models [*Artemieva and Bland*, 2003] with little constraining observational data [see *Chapman*, 2008]. Records of significant NEO impacts are rare. *McCord et al.* [1995] reported a ~40 kt impactor detected by satellite over the Pacific on Feb 1, 1994 while *Klekociuk et al.* [2005] and *Arrowsmith et al.* [2008] report multi-instrumental observations of two different impactors with energies of 20–30 kilotons of TNT (1 kt = 4.185×10^{12} J) occurring in the fall of 2004. In all cases these events occurred over open ocean and much of the energetics information was compiled from records of satellite data or the associated airwaves detected by infrasonic stations.

[3] Infrasound is low frequency sound (<20 Hz down to the atmospheric Brunt-Väisälä frequency) which experiences little attenuation during propagation over large distances making it an excellent tool for studying distant explosive sources [*Hedlin et al.*, 2002]. Among the phenomena which have been detected and extensively studied with infrasound are fireballs (bright meteors) [*ReVelle*, 1976, 1997; *P. G. Brown et al.*, 2002b]. Fireballs are produced by large meteoroids which may penetrate deep into the atmosphere and may generate a cylindrical ballistic shock wave and a quasi-spherical ablational shock during their hypersonic passage, which decays to low frequency infrasonic waves that propagate over great distances [*Bronsthen*, 1983; *ReVelle*, 1976; *Edwards*, 2010; *Le Pichon et al.*, 2002; *D. Brown et al.*, 2002; *Brown et al.*, 2003]. Infrasonically detected impacts can provide a valuable tool in estimating and validating of the influx rate of meter sized and larger meteoroids [*P. G. Brown et al.*, 2002a; *Silber et al.*, 2009], as well as trajectory and energetics information for interesting events which otherwise lack such data (e.g., the Carancas crater forming impact in Peru in 2007 [*Brown et al.*, 2008; *Le Pichon et al.*, 2008]). Here we present evidence that a significant NEO impact occurred on 8 October, 2009 over Indonesia based primarily on infrasound recordings of the infrasonic wave detected across the globe; our analysis suggests that this may have been one of the most energetic impactors to collide with the Earth in recent history.

[4] On October 8, 2009 at 2:57 UT (10:57 a.m. local time), thunder-like sounds and ground shaking were reported near the city of Bone, South Sulawesi, Indonesia (Surya News, see auxiliary material).[1] This event was also captured on amateur video (Figure S1). Motivated by these initial reports, we undertook a detailed examination of infrasonic records of all International Monitoring System (IMS) infrasound stations to search for possible signals from the airburst.

2. Data Collection and Analysis

[5] We were able to examine waveform data from 31 infrasound stations in the IMS network, which is operated by the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) and consists in part of 43 globally distributed infrasonic stations to detect nuclear explosions (CTBTO web: http://www.ctbto.org). Infrasonic data were analyzed for probable signals associated with the fireball using the Progressive Multi-Channel Correlation Method (PMCC) [*Cansi*, 1995] (Figure S2). In total 17 positive detections were identified, using the approximate location (4.5°S, 120°E) and timing from media reports and expected typical stratospheric propagation speeds as a guide to isolate the signal arrival on each array. The signal was remarkable in that: (i) it was detected by many infrasonic stations, some at extreme ranges (>17,000 km); and (ii) it had substantial signal energy at very low frequencies, consistent with a source of very high energy. Table 1 summarizes findings of the signal properties from all detecting stations.

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Table 1. Station Details and Signal Measurement Summary[a]

Distance (km)	Station	True Back Azimuth (deg)	Observed Back Azimuth (deg)	Arrival Time	Signal Duration (s)	Minimum Celerity (m/s)	Maximum Celerity (m/s)	Peak-to-Peak Amplitude (Pa)	Period at Max PSD (s)	Period at Max Amplitude (s)
2099	I39PW	230	264	04:39:51	1235	283	340	1.570	18.22	14.87
2291	I07AU	316	318	04:55:46	850	287	320	2.823	7.88	5.79
3350	I04AU	7	9	05:59:18	1370	271	305	0.471	7.31	7.11
4920	I30JP	319	319	07:33:43	1280	280	302	0.642	7.88	7.89
5009	I05AU	210	211	07:37:01	690	280	292	0.542	29.26	25.23
5386	I22FR	284	285	07:45:08	1340	290	312	0.165	20.48	21.07
5543	I45RU	196	197	08:04:54	1450	278	300	1.192	17.07	19.79
7296	I46RU	222	224	09:46:19	1490	281	298	0.803	…	…
7323	I44RU	141	141	09:49:46	2450	268	294	0.363	18.62	18.29
8577	I55US	311	305	10:55:07	1060	289	299	0.168	17.07	17.62
10573	I53US	270	270	12:49:47	830	291	297	0.488	12.80	14.66
11594	I26DE	80	80	14:28:51	185	278	279	0.040	…	…
11900	I18DK	350	340	14:15:26	1100	284	292	0.693	25.60	21.81
12767	I56US	293	322	14:54:45	1520	286	292	0.765	13.65	11.83
13636	I13CL	244	240	16:26:53	1310	273	281	0.618	11.38	11.31
13926	I17CI	91	87	17:05:34	615	270	274	0.128	9.31	8.64
17509	I08BO	203	218	18:54:45	30	…	305	0.933	17.07	16.34

[a]We include results for two methods of dominant period measurements. First, the dominant periods were tabulated by taking an inverse of the frequency at maximum residual power spectral density (PSD), where the latter was obtained by first computing the PSD of the entire signal, then using a series of identically sized windows before and after the signal to establish the background noise PSD and finally subtracting the noise from the total signal PSD. Second, the maximum peak-to-peak amplitude was determined by bandpassing the stacked, raw waveform using a second-order Butterworth filter and then applying the Hilbert Transform [*Dziewonski and Hales*, 1972] to obtain the peak of the envelope. We then computed the period at maximum amplitude by measuring the zero crossings of the stacked waveform at each station [see *ReVelle*, 1997]. Due to sensitivity thresholds and low SNR, it was not possible to reliably calculate the period for I26DE and I46RU.

[6] To ensure robustness of our period estimates, the dominant period was obtained via two independent techniques. The dominant period at maximum frequency was acquired from the residual power spectral density (PSD) of the signal alone, while the period at maximum peak-to-peak amplitude was determined by measuring the zero crossings of the stacked waveform at each station [see *ReVelle*, 1997]. This methodology is robust in itself, as the periods obtained using these two techniques agree to better than 10% in all cases.

[7] Using the nine closest stations it was possible to perform a source geolocation (Figure S3). The location of the signal was computed using an inverse location algorithm based on *Geiger*'s [1910] approach modified in order to also take station azimuth into account (see *Coleman and Li* [1996] for details of this method).

3. Estimating the Blast Radius and Source Energy

[8] There are several empirical relations, relying on either the signal period at maximum amplitude or range and signal amplitude, which can be utilized in estimating source energy for bolides from infrasound measurements [*Edwards et al.*, 2006]. Typically, infrasonic period is less modified during propagation than amplitude [see *Mutschlecner et al.*, 1999; *ReVelle*, 1997, 1974] and thus the period relationship is expected to be more robust. The Air Force Technical Application Centre (AFTAC) period-yield relations which are commonly used for large atmospheric explosions, are given by *ReVelle* [1997], as:

$$\log(E/2) = 3.34\log(P) - 2.58 \qquad E/2 \leq 100kt \qquad (1)$$

$$\log(E/2) = 4.14\log(P) - 3.61 \qquad E/2 \geq 40kt \qquad (2)$$

Here, E is the total energy of the event (in kilotons of TNT), P is the period (in seconds) at maximum amplitude of the waveform. Infrasound for a given bolide event in general shows a large variation in observed periods from different stations [*Silber et al.*, 2009; *ReVelle et al.*, 2008; *Edwards et al.*, 2006]. The exact origin of this variation is not well known; large (Mton) nuclear explosions, for example, do not show period variances as large as we find for bolides [see *Flores and Vega*, 1975]. One possibility is that signals are arriving from different portions of the fireball trajectory. In this interpretation, the period measurement at each station is a 'sample' of the size of the cylindrical blast cavity at that particular segment of the trail [*ReVelle*, 1974] having an acoustically accessible path to the receiver. With this working hypothesis, we have developed a novel technique to correlate the observed period to a most probable source height and compute the equivalent size of the bolide blast cavity at that height and therefore synthesize the blast radius as a function of height from observations across multiple stations.

[9] As an initial step, we performed ray tracing to obtain the most likely source height as observed by the five closest stations, situated within 5,000 km from the event. The InfraMap ray tracing package [*Norris and Gibson*, 2001] was used to find all eigenrays reaching the given station for source heights extending from 15–55 km in 5 km increments at the bolide source location. The eigenray model results were then analyzed by comparing the model predictions to observed parameters, such as the celerity, arrival angle, ray height from the receiver, as well as the number density of the model eigenray population to establish the most likely source height observed by each of the five stations with R < 5,000 km. Once a most probable height is established for each station with this methodology, we

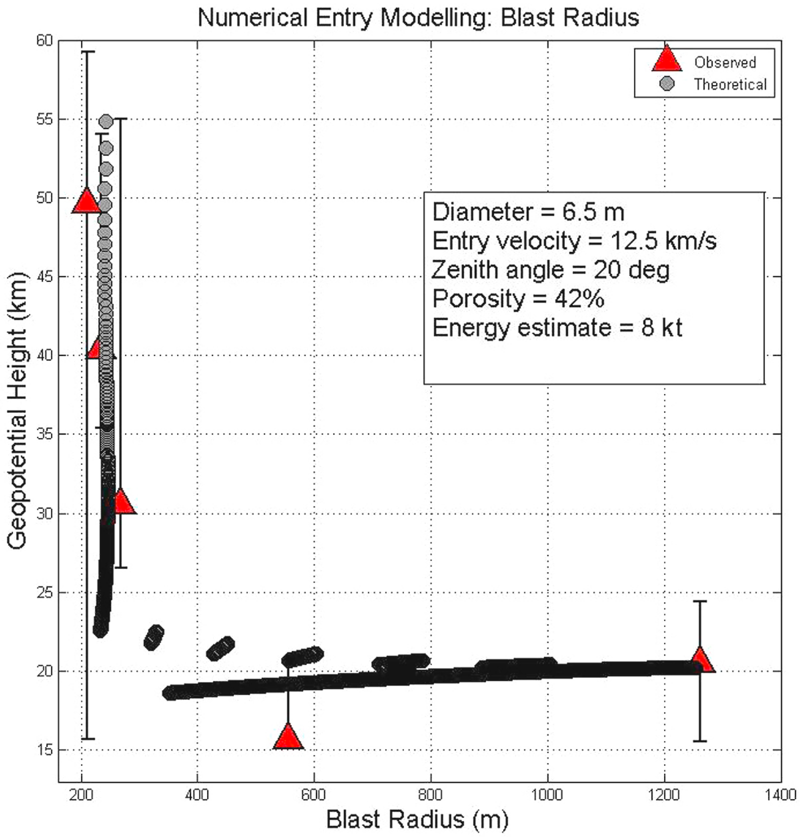

Figure 1. The numerical entry modeling (more details are given by *ReVelle* [2001]) includes full meteoroid ablation and fragmentation in a realistic atmosphere and calculates the meteoroid blast radius as a function of altitude. The model input entry parameters are as follows: initial bolide diameter and velocity, zenith angle, and porosity. As many of these parameters are unknown for the Indonesian bolide, typical values for bolides were chosen in an effort to identify combinations that produce our derived trend in the blast radii as a function of height established using the weak shock treatment. Here we have explored initial bolide radii of 4–10 m, entry velocities from just above Earth's escape (12 km/s) to approximately the mean entry velocity for NEAs colliding with the Earth [*P. G. Brown et al.*, 2002a], zenith angles from 10–60 degrees, while the meteoroid porosity range examined extended from those expected for chondritic bodies to highly porous carbonaceous chondrites [*Britt and Consolmagno*, 2003]. In all, 7000 runs were made using various combinations of these parameters and the resulting model predicted blast radius profile with height compared to Figure S4. From the range of input parameters we found the best fit of the modelled blast radius as a function of height was reproduced using: (i) initial bolide radius = 6.5–10 m; (ii) entry velocity = 12–20 km/s; (iii) zenith angle = 20–40 degrees; (iv) meteoroid porosity = 5–42% (ordinary to carbonaceous chondrites). Using a bulk mass density of 3 300 kg/m^3 [*Wilkison and Robinson*, 2000], we obtain an energy range between 8 and 67 kt.

utilized the bolide weak shock treatment [*ReVelle*, 1974] to determine the fundamental period (τ_0) as well as the blast radius (R_0) at the source for each height using only the observed period at each station and the known range to the source (Figure S4). The blast radius is the region of highly non-linear/strong shock proximal to the propagating meteoroid (given by $R_0 = (E_0/p)^{1/2} \approx Md$, where E_0 is the drag force per unit trail length exerted on the meteoroid by the fluid, p is the ambient hydrostatic pressure, M is the Mach number, and d is the meteoroid diameter). The blast radius is related to the fundamental signal wave period via $\tau_0 = 2.81R_0/C_S$, where C_S is the adiabatic speed of sound. The non-linear shock ultimately transitions into a weak shock (at $x = R_0$) and then decays into a linear wave. In this treatment, once the wave transitions to linear propagation, its period does not significantly change; this is what is recorded by the receiver. Once a series of model estimated blast radii as a function of height were determined, we employed a numerical bolide entry model [*ReVelle*, 2001] to determine limits to the most likely source energy (Figure 1).

4. Results and Discussion

[10] The first bolide - related signal arrived at 04:39:51 UT to I39PW (Palau), the closest detecting station, while the latest signal arrived to I08BO nearly 15 hours later. Average signal celerities (defined by the ratio between the horizontal propagation range and the travel time) are between 0.27 and 0.32 km/s, which is consistent with stratospheric duct signal returns [see *Ceplecha et al.*, 1998]. The geolocation ellipse, computed using azimuths and arrival times points to 4.9°S and 122.0°E with mean residuals of 2.9°. The source time estimated from this location is 02:52:22 UT with a residual of 1320 s (Figure S3).

[11] While recognizing the inherent limitation of combining periods across all stations as discussed earlier, for comparison with earlier bolide energy analyses we found the combined average periods of all phase-aligned stacked waveforms at each station - this produced a global average of 14.8 seconds using zero crossings and 15.3 seconds using PSD analysis. This corresponds to a mean source energy of 43 kt of TNT and 48 kt of TNT, respectively, using the AFTAC period-yield relation (equation (1)). Previous yield estimates using the averaged station period and AFTAC period-yield relation have proven relatively robust [see *Edwards et al.*, 2006] for estimating approximate yield, however, as emphasized earlier, since the periods observed by individual stations show a factor of five variation (Table 1), our new modeling technique has placed more solid constraints on upper and lower bounds beyond this traditional approach to energy estimation. Ray tracing and numerical modeling for the five closest stations reveal a distinctive pattern of the increasing fundamental period, and consequently the blast radius, with decreasing altitude (Figure S4). This implies that the short period signal originates in the upper portions of the fireball trail (30–50 km), while the long period signal emanates from an altitude as low as 15 km. This is consistent with the expected large blast cavity resulting from a terminal detonation/airburst and fragmentation, which typically accompany large bolide events. This gives us confidence that the technique is physically reasonable. We note that inclusion of stations more distant than 5,000 km does not change this basic picture, a finding we did not expect a priori given the large uncertainties in atmospheric propagation over paths in excess of ~5,000 km. This is consistent with the fact that bolides in general exhibit much more variation in the observed period (as much as factor of six), than literature reports of nuclear explosions (factor of ~2). By matching our derived pattern of blast radii with height to entry modeling (Figure 1) we estimate the true total source energy to be between 8–67 kt of TNT, with a nominal best estimate near the upper end of this range at ~50 kt based on average period observed by all stations, corresponding to a chondritic object 6–10 m in diameter.

5. Conclusions

[12] The Indonesian bolide of 8 October, 2009, detected infrasonically on a global scale, was perhaps the most energetic event since the bolide of 1 February, 1994 [*McCord et al.*, 1995] and may have exceeded it in total energy. We have no other instrumental records of this event other than casual video records of the dust trail emphasizing again the value of infrasound monitoring of atmospheric explosive sources. Infrasonic waves from this bolide observed at 17 IMS stations are all characterized by very low frequency content, consistent with a large energy source and a large blast cavity [*ReVelle*, 1976].

[13] Our best estimate for the range of the meteoroid's energy (8–67 kt of TNT) is derived from an inferred blast radius pattern matched to entry modeling and suggests an object 6–10 m in diameter. Based on the flux rate from *P. G. Brown et al.* [2002a], such objects are expected to impact the Earth on average every 2–10 years, while the infrasonic flux rate from *Silber et al.* [2009] suggests an impact every 5 years. Global events of such magnitude can be utilized to calibrate infrasonic location and propagation tools at global scale, evaluate energy yield formula, and event timing. Our large uncertainty in energy for this event can only be refined if additional instrumental records of this unique event become available.

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