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Infrasound and seismic detections associated with the 7 September 2015 Bangkok fireball

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Abstract

A bright fireball was reported at 01:43:35 UTC on September 7, 2015 at a height of ~30 km above 14.5°N, 98.9°E near Bangkok, Thailand. It had a TNT yield equivalent of 3.9 kilotons (kt), making it the largest fireball detected in South–East Asia since the ~50 kt 2009 Sumatra bolide. Infrasonic signals were observed at four infrasound arrays that are part of the International Monitoring System (IMS) and one infrasound array located in Singapore. Acoustic bearings and event origin times inferred from array processing are consistent with the eyewitness accounts. A seismic signal associated with this event was also likely recorded at station SRDT, in Thailand. An acoustic energy equivalent of 1.15 ± 0.24 kt is derived from the Singaporean acoustic data using the period of the peak energy.

Keywords: Bolide, Infrasound, South East Asia, Fireball

Background

Amateur videos in Bangkok (Thailand) and the surrounding towns of Kanchanaburi and Nakhon Ratchasima, captured the fall of a meteor on September 7, 2015. This fireball, with estimated energy of 3.9 kilotons (kt) TNT equivalent (http://neo.jpl.nasa.gov/fireballs/) is the largest meteoritic event recorded in South East Asia since the extraordinary October 8, 2009 bolide over Indonesia, which released energy 50 kt TNT equivalent (1 TNT $= 4.184 \times 10^{12}$ J) (Silber et al. 2011). Previous work has demonstrated that infrasound records can be used to estimate the acoustic wave parameters and blast energy of meteor impacts.

Fireballs have the potential to cause significant damage at the ground level. For example, the 2013 Chelyabinsk airburst shattered thousands of windows in the same named Russian city, with flying glass injuring many residents (Brown et al. 2013). Records of significant impacts are rare and primarily occur over open ocean where much of the energy can be only estimated from satellite data or associated airwaves (Silber et al. 2009). The hypersonic entry of meteroids generates infrasonic waves which are refracted and channelled over long distances by the temperature gradient and the wind structure of the atmosphere (Kulichkov 2004; Silber et al. 2009). In most instances, the atmosphere slows down, breaks up, and even vaporize meteoroids, producing a meteor (Ceplecha and Revelle 2005). A particularly strong shock wave can be generated by explosive fragmentation of the meteoroid in one or several airbursts (Ceplecha and Revelle 2005; Edwards et al. 2008). Infrasound measurements may provide crucial information about trajectory and energy for events [e.g., Brown et al. (2013); Silber et al. (2009); Pichon et al. (2013); Pilger et al. (2015)]. Ultimately, these acoustic waves can couple to the ground producing seismic waves which can be used to reconstruct meteroid trajectories to constrain meteoroid events to obtain source body kinetic energy estimates, and to facilitate the search of meteorites on the ground (Edwards et al. 2008; Heimann et al. 2013; Tauzin et al. 2013).

This work investigates the infrasound and seismic recordings associated with the September 2015 Bangkok fireball. The results include the automatic bulletin produced by the International Data Centre (IDC) of

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the Comprehensive Nuclear Test-Ban Treaty Organization (CTBTO) along with our analysis using the progressive multi channel correlation (PMCC) method (Cansi 1995; Matoza et al. 2013) and Inferno energy estimator (Garces 2013). With the exception of the station in Singapore, infrasound and seismic data used for this study are public.

Methods and results

The IDC detected the fireball signal at five sites using infrasound arrays, the furthest located 9633 km far away. The IDC automatically processes in near real-time continuous infrasound recordings from the IMS stations. The system associates signal detections at distances up to ~7500 km from a source location. The

Table 1 Reviewed Event Bulletin produced by the IDC for this event

Station	Arrival time (UTC)	Azimuth (°)	Azimuth resolution (°)	Trace velocity (m/s)	Celerity (m/s)	Amplitude (Pa)
I06AU	2015/09/07 04:27:30	2.5	0.2	345	301	
I46RU	2015/09/07 05:52:20	160	−0.5	341	309	0.06
I45RU	2015/09/07 06:04:50	235.5	0.7	344	299	0.01
I04AU	2015/09/07 06:59:20	337.5	0.6	337	305	0.06
I53US	2015/09/07 10:45:35	299.5	1.8	345	299	0.01

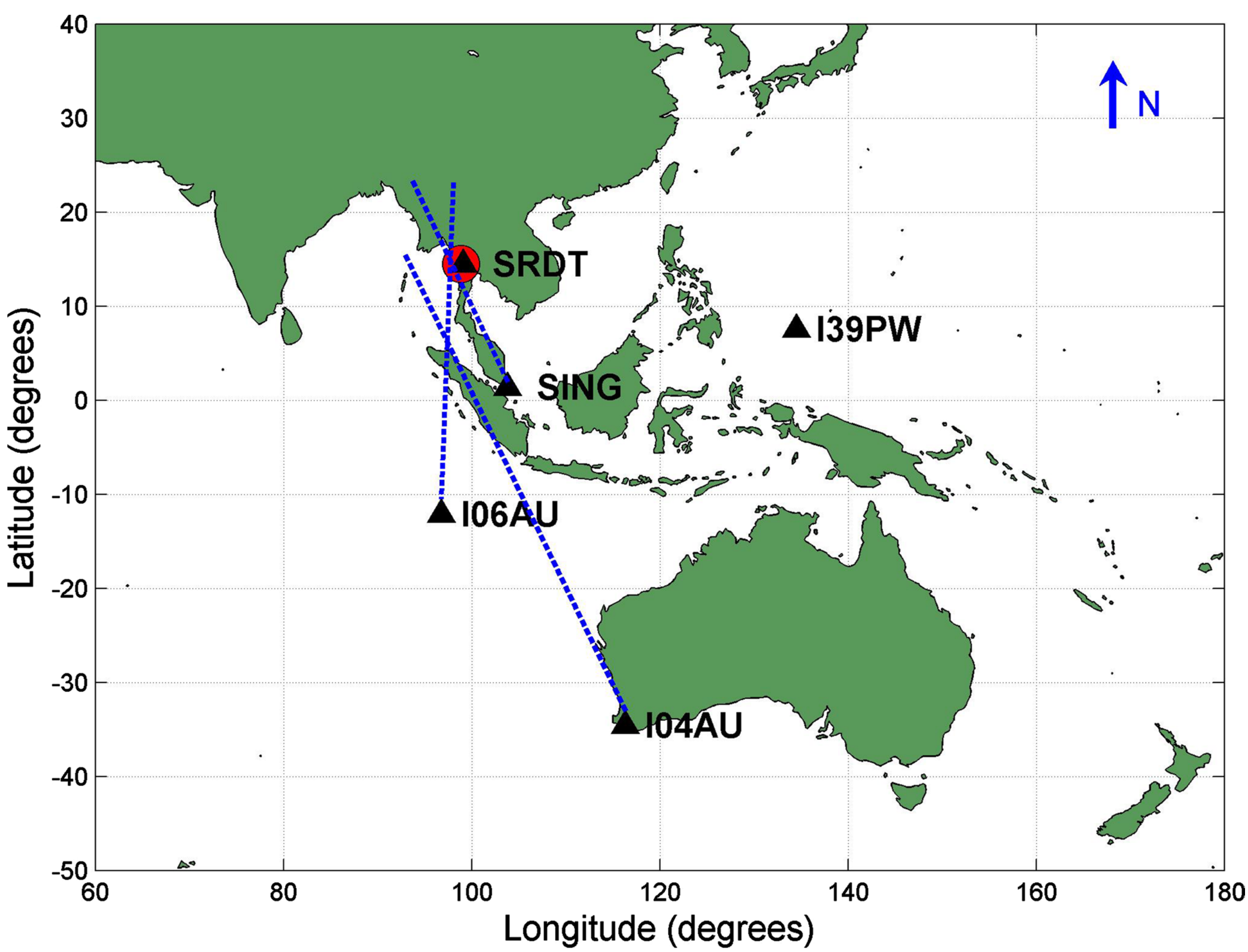

Fig. 1 Map. Regional stations and respective azimuths. Map with the location of the event in *red*, and the region station locations as *black triangles*, not pictured is the IMS station I53US which is located in Fairbanks, Alaska, USA

back azimuths (Table 1), all point toward the region where the fireball was observed (Fig. 1).

The closest infrasound station is located in Singapore, 1414 km away from Bangkok. The array consists of five MB2005 microbarometers which are connected to five Taurus (Nanometrics) data logger. Data are sampled at 80 Hz and transferred in real-time to the Earth Observatory of Singapore. On September 7, 2015, an unusually coherent signal was recorded at 03:07:13 UTC by the array (Fig. 2). The PMCC method was used to estimate the wave parameters, using 30 logarithmic-spaced frequency bands calculated from the Inferno framework (Garces 2013) with the 6th octave bands between 0.0056 and 5.6234 Hz and a 8 Gabor window lengths (MG8), along with second order Chebyshev filters. The time-window length varies in proportion to the period from 12.45 to 1028 s and the window is time-shifted by 25 % of the window length (Garces 2013). We calculate the range, back azimuths and arrival times (Table 2) using the IDC origin time and location provided by the Jet Propulsion Laboratory (JPL, http://neo.jpl.nasa.gov/fireballs/). A beam (Fig. 3) is then calculated from the observed back azimuth and trace velocity calculated from the PMCC results for each station. The multi-resolution Inferno energy estimator (Garces 2013) with the same parameters (6th octave and MG8) was used to determine the location of maximum amplitude by frequency band. The corresponding central period is extracted along with the upper and lower values of the band (Table 2).

We use the maximum intensity frequency to determine the timing. The period is derived from the center frequency of the bin and error bars are calculated from the minimum and maximum 6th octave band edge periods (Table 2).

The same analysis was performed from the publicly available IMS infrasound data downloaded from IRIS (Incorporated Research Institutions for Seismology, http://www.iris.edu/). Compared to the CTBTO bulletin (Table 1), we detected a possible fireball signature at I06AU (Table 2), although the signal is particularly weak at this site. I46RU and I45RU were not openly available and were not reprocessed in this study.

The data from 12 seismic stations located in Thailand were downloaded from IRIS. After deconvolving the sensor responses, an intriguing signal potentially generated by the meteor could only be detected at SRDT (Fig. 4). The station is located to the west of Bangkok where the fireball was observed. The onset of the seismic signal is consistent with the timing of the visual observations (01:43:35 UTC) and energy was radiated in a broad

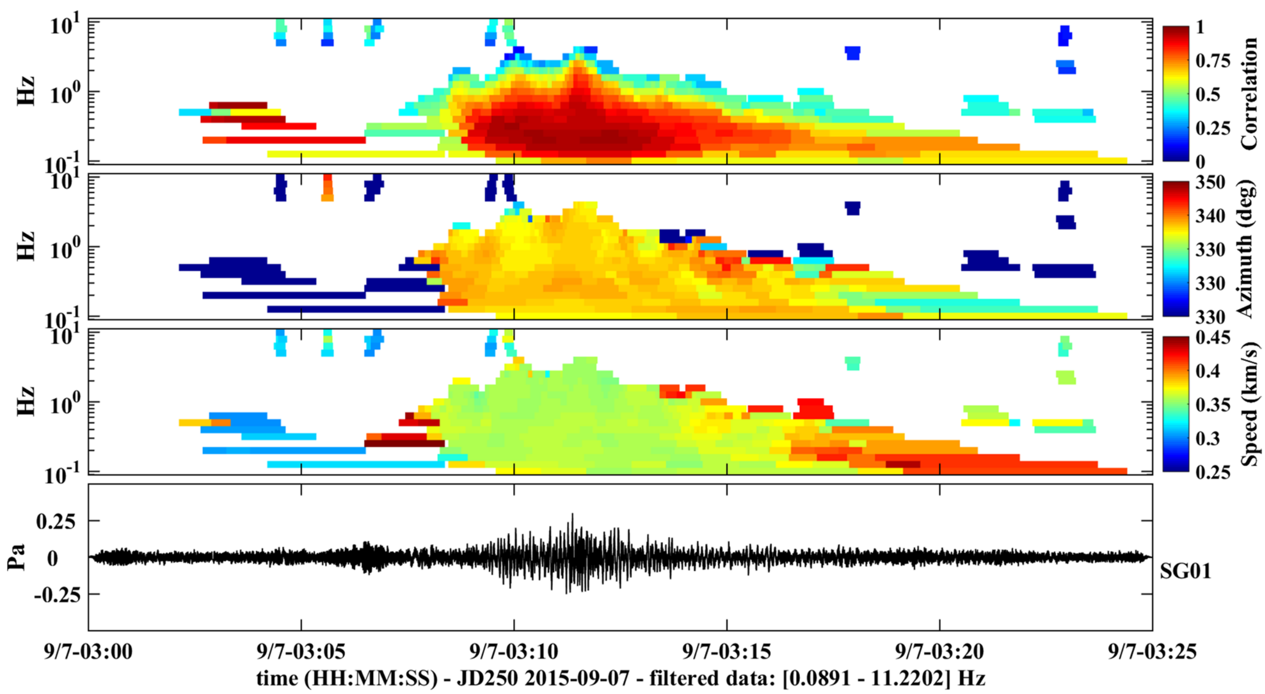

Fig. 2 PMCC results for the infrasound station in Singapore. A 30 logarithmic-spaced frequency bands with Chebyshev filters of order 2 between 0.0056 and 5.6234 Hz was used. The time-window length varies in proportion to the period from 12.45 to 1028 s and the window is time-shifted by 25 % of the window length

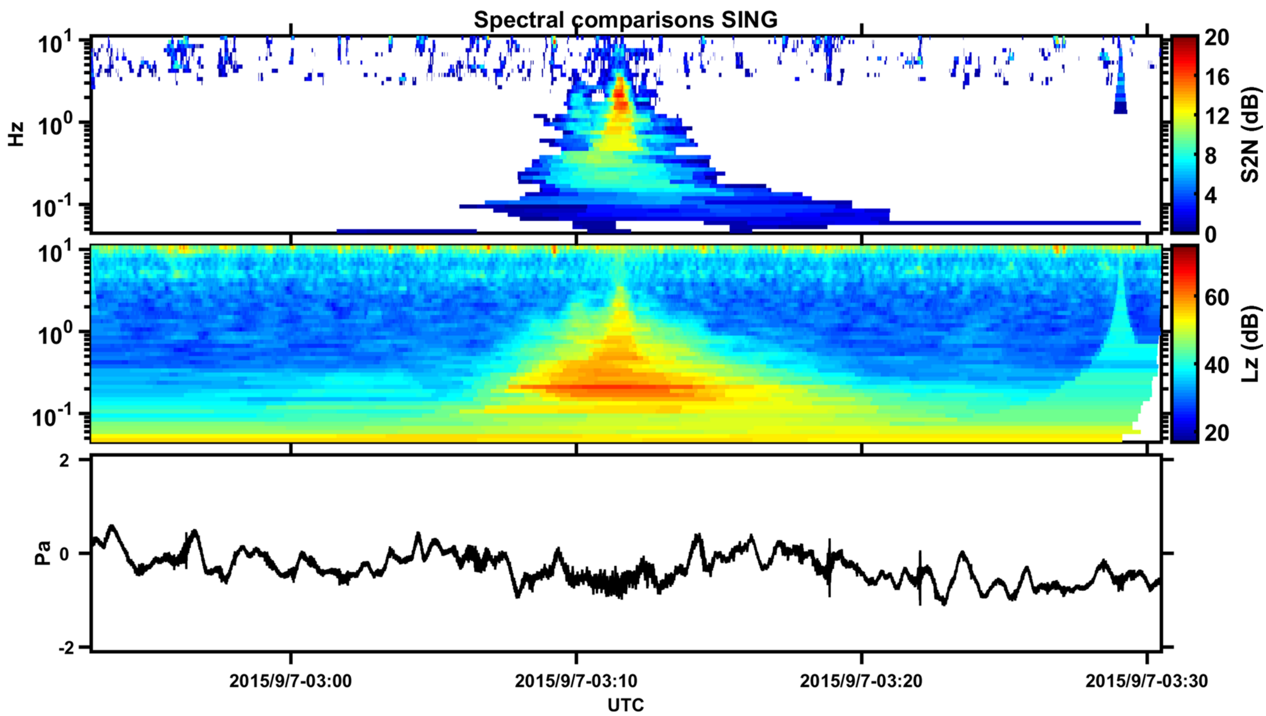

Fig. 3 Beam in Singapore. Beam results for the infrasound station located in Singapore using the Inferno algorithm (Garces 2013). We used the observed back azimuth and trace velocity. The *upper plot* is the spectrogram of signals having a high signal to noise ratio (SNR, in dB, where the noise is considered as the energy averaged over the record at each frequency band). The *plot in the middle* is the raw spectrogram and the *lower plot* corresponds to the raw infrasonic trace

frequency band (0.01–25 Hz) and on each component. Hence, this signal is likely related to the fireball.

Discussion

The analysis of infrasound signals revealed a significant amount of energy at low frequencies (Fig. 2). The acoustic source energy can be approximated from the infrasound recordings using the longest period (Silber et al. 2011). From the available data, the longest period is ~5.01 s (ranging from 4.73 to 5.31 s) and was estimated using the closest station located in Singapore. We derive the energy (E) from the period (P, in seconds) at maximum amplitude using (ReVelle 1997):

$$\log_{10}\left(\frac{E}{2}\right) = 3.34\log_{10}(P) - 2.58 \qquad E/2 \leq 100\,\text{kt} \tag{1}$$

In the period range and distance range in Table 2, the effect of atmospheric absorption is neglected and the peak period becomes independent from distance. The estimated energy of ~1.15 kt ± 0.24 kt is lower than the 3.9 kt reported by the JPL using an empirical relation where the total impact energy is calculated given the optical radiant energy (Brown et al. 2002):

$$E = 8.2508 * E_0^{0.885} \tag{2}$$

where E_0 is the total radiated energy. The discrepancy is not concerning since an infrasonic wave, depending where along the meteor trail it emanates from, might represent only a portion of the total impact energy (Silber et al. 2009; Brown et al. 2002). The stratospheric wind speeds along the great circle for each station suggest a weak influence of these winds on the signal periods (except for I04 AU).

It is difficult to get more insights from the seismic recordings since only one station may have recorded the event. The time, location and frequency content of this event agree well with the reported eyewitness accounts. One could estimate the meteoroid size based on the fundamental frequency, but this would require too many assumptions and unavailable measurements [i.e., site response, source region, meteroid's velocity and density Edwards et al. (2008)]. It is also impossible to resolve the orientation and position in space with a single station. More stations are required to better characterize meteors and constrain the origin of the seismic signal source [e.g., Ishihara et al. (2004);

Table 2 Summarizing table

Station	Calculated range (Km)	Calculated back azimuth (°)	Calculated arrival time UTC (c = 340 m/s)	Observed arrival time (UTC) from PMCC	Observed back azimuth (°) from PMCC	Trace velocity (m/s) from PMCC	Celerity (m/s)	Max amplitude of the beam from Inferno (in dB)	Period at max amplitude from Inferno (beam, in s)	Range for period of max amplitude from Inferno (beam, in s)	Total energy (kt)	Error on total energy estimate (kt)	Stratospheric wind speed (m/s)
SING	1558	335	03:03:02	03:07:13	337.9	365	322	64.85	5.01	5.3088–4.7315	1.15	±0.24	0.93
I06AU	2910	2	04:09:16	04:27:08	3.0	348	298	61.27	3.16	3.3497–2.9854	0.25	±0.05	3.07
I04AU	5738	337	06:27:56	07:06:41	335.7	352	299	69.70	4.47	4.7315–4.2170	0.78	±0.17	10.13
I53US	9703	298	09:42:17	10:40:19	297.4	345	303	39.23	4.47	4.7315–4.2170	0.78	±0.17	3.43

Table summarizing the calculated results for this study for each available infrasound station. The range, back azimuths and arrival times are calculated using the JPL origin time and location (Fig. 1). The trace velocity is calculated using the PMCC results and is the velocity of the signal across the array. The celerity is derived from the arrival time determined using PMCC and the origin time (Fig. 2). The Inferno algorithm, which provides high-resolution multispectral analysis in logarithmic frequency space with time-window auto-scaling, was finally used (Garces 2013) to calculate the maximum amplitude and amplitude period bin from the beam for each station. The period is derived from the center frequency of the bin (Fig. 2). The program was set to 6th octave bands. Our observed arrival times are calculated from the PMCC results and represent the arrival of a coherent signal at the station

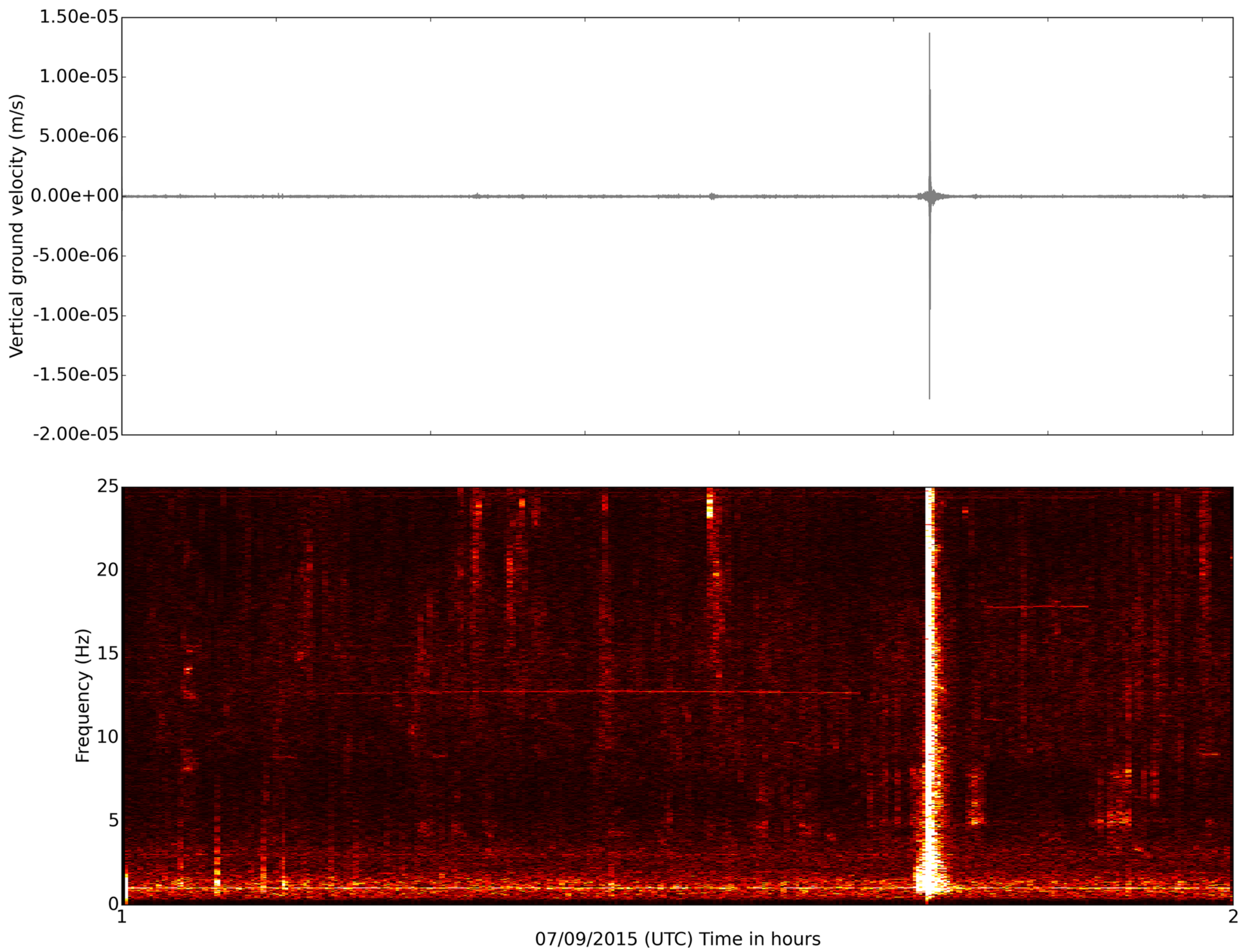

Fig. 4 Seismic recordings. Seismic waveform and spectrogram at TH.SRDT. *Upper* vertical ground velocity (m/s). *Lower* 1-hr spectrogram (between 1:00:00 and 2:00:00 UTC)

Edwards et al. (2008); Heimann et al. (2013); Tauzin et al. (2013)].

Conclusion

An impressive bolide was witnessed in broad daylight over Bangkok (Thailand) and surrounding areas on September 7, 2015. In spite of numerous visual observations, this event remained enigmatic. An infrasound array located in Singapore (~1000 km from the hypothesized source region) detected the acoustic signal along with five other more distal IMS stations. The longest period at maximum amplitude was measured at the closest station in Singapore. Using this period, we estimate the acoustic energy equivalent for this event to $\sim$ 1.15 kt $\pm$ 0.24 kt, which is a bit lower than the 3.9 kt derived from the optical radiant energy. A seismic station located nearby the hypothetical source possibly recorded a seismic event associated with the fireball. Unfortunately, a single seismic recording is insufficient to better characterize the meteor and unravelling the seismic source of this signal. Yet, this study demonstrates the capability of infrasound stations to detect the acoustic fingerprint of significant fireballs in South East Asia. More specifically, the addition of Singapore infrasound array in the region allows a more reliable estimate of the fireball characteristics, such as the TNT yield equivalent.

Authors' contributions

BT and CC performed the initial analyses of infrasound and seismic data. AP significantly improved the initial IMS and EOS data processing. MG and ES helped for the processing and the interpretation. ES shared her knowledge of bolides. PM provided insights of the analysis of this event using the IMS network. All authors read and approved the final manuscript.

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Competing interests
The authors declare that they have no competing interests.

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