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Global Detection of Infrasonic Signals from Three Large Bolides

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Abstract We present the infrasonic observations of three large bolides that were observed at numerous International Monitoring System (IMS) infrasound arrays on a global scale. First, a simple procedure for the global association of infrasound detections from large infrasound events is outlined. Infrasound signals are associated with large events based on arrival time, backazimuth and uniqueness at a given IMS array. Next, we apply the algorithm to three bolides and investigate some of the factors affecting the detectability of infrasound from large events. Our findings suggest that site-noise effects significantly degrade the capability of the IMS infrasound network, suggesting that more effort is required to reduce ambient site noise. These results have implications for the use of infrasound measurements (in particular those from IMS stations) as a tool for evaluating the global flux of near-Earth objects.

Keywords Bolide infrasound · Meteor detection · International Monitoring System

1 Introduction

Infrasound is acoustic energy that propagates at frequencies below the 20 Hz hearing threshold of the human ear. Unlike audible sound, infrasound can travel for long distances with relatively little attenuation. Large meteors generate infrasound as they enter Earths atmosphere (ReVelle 1976), which can propagate across the globe. The purpose of this paper is to outline a simple method for identifying infrasonic signals from large events on a global scale, and to apply the method to three superbolides. Following Docobo et al. (1998), a "superbolide" has a peak optical luminosity that exceeds -17 stellar magnitudes (referenced to an elevation of 100 km in the zenith). We also provide an assessment of the

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effect of site noise on the detectability of these large events. There have been relatively few studies of multi-station infrasound signals from large events on a global scale. Long before the advent of the present-day IMS, Wexler and Hass (1962) documented the global detection of infrasound signals from a large Soviet nuclear test. More recently, Brown et al. (2002) present the observations of infrasound at numerous IMS stations from two large bolides. Finally, Garces et al. (2005) and Le Pichon et al. (2006) document multi-station infrasonic signals from the 2004 Sumatra earthquake and tsunami and the 2005 Chilean earthquake respectively. In contrast with earlier studies, this study focuses on the more general problem of associating infrasound signals with global events, and on an assessment of factors that affect the global detectability of large events. We report on the global detection of three superbolides which entered Earths atmosphere on September 3rd, 2004 over Antarctica; on October 7th, 2004 over the Indian Ocean; and on December 9th, 2006 over North Africa.

2 Global Infrasound Event Association

The problem of associating an infrasound signal with a known event is non-trivial. The challenge can be phrased as follows: How can we confidently associate a large event (with

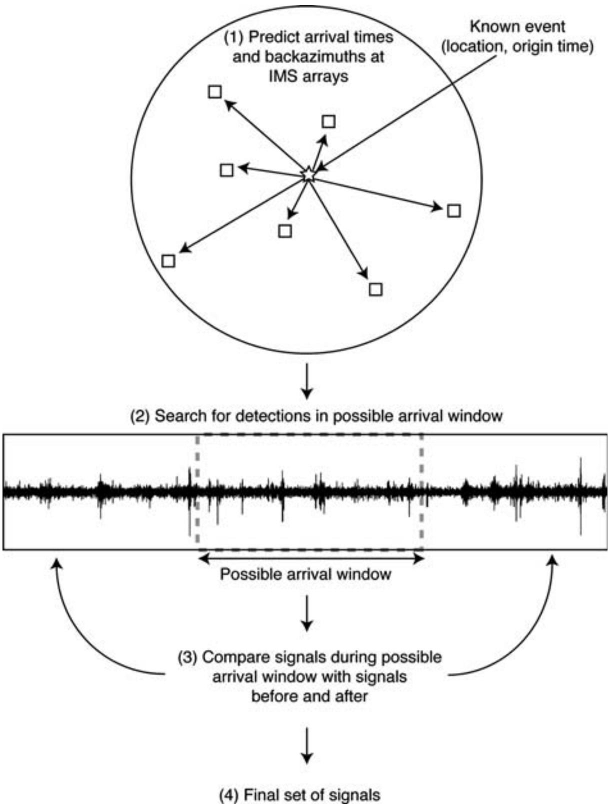

Fig. 1 Flowchart illustrating the event-based global association procedure (schematic diagram for illustration purposes only)

known event location and origin time) with an infrasound signal at a range of 100s to 10,000s of kilometers? Typically, event-based association utilizes the consistency of arrival-time and backazimuth at a given array with predicted values based on the known event location and origin time. However, standard detection algorithms can generate large numbers of coherent infrasonic signals with low signal-to-noise ratios (e.g., Brachet and Coyne 2006). This results in a significant risk of incorrectly associating an infrasonic signal with a given event. To mitigate against the possibility of mis-association, we introduce an additional requirement that a signal associated with a large bolide must be “unique” for a given array in a time window before and after the signal. Subsequently, we have developed a three-stage procedure for associating infrasound signals with large bolides (Fig. 1). First, for a known event location and origin time, we compute predicted arrival times and backazimuths at all IMS arrays located around the globe. Second, we apply an array-based signal detection algorithm to the data—the PMCC algorithm (Cansi 1995). The basis of the PMCC method, in common with other array-based detectors, is that signals are spatially coherent—arriving as plane waves, whereas noise is incoherent between the different elements in an array. By time-aligning arrivals at the different elements in an array, PMCC provides backazimuths and trace velocities for the incoming wave—useful information for event association. We search for PMCC detections in a time-window encompassing the range of all possible infrasonic arrivals (where the earliest possible signal propagates with a horizontal group velocity of 0.34 km/s, and the latest signal propagates with a group velocity of 0.22 km/s, Ceplecha et al. 1998). We then consider detections within an allowed backazimuth deviation of the true great-circle path, occuring within the predicted time window, to be “potential associations”. The allowed backazimuth deviations are based on an empirical relation calculated by the U.S. Air Force for known explosions. Finally, we remove potential associations that are: (a) short-duration and narrow-band (and

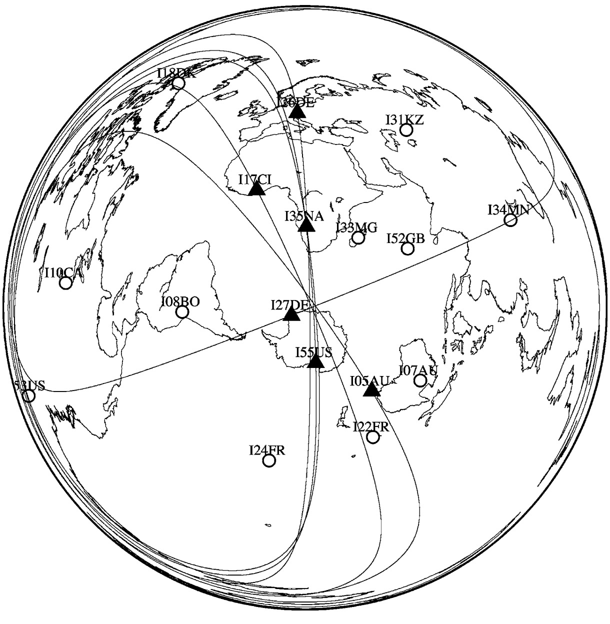

Fig. 2 Map showing stations that detected the September 3rd, 2004 Antarctic bolide (black triangles) and stations that did not (white circles). The event location is at the center of the map

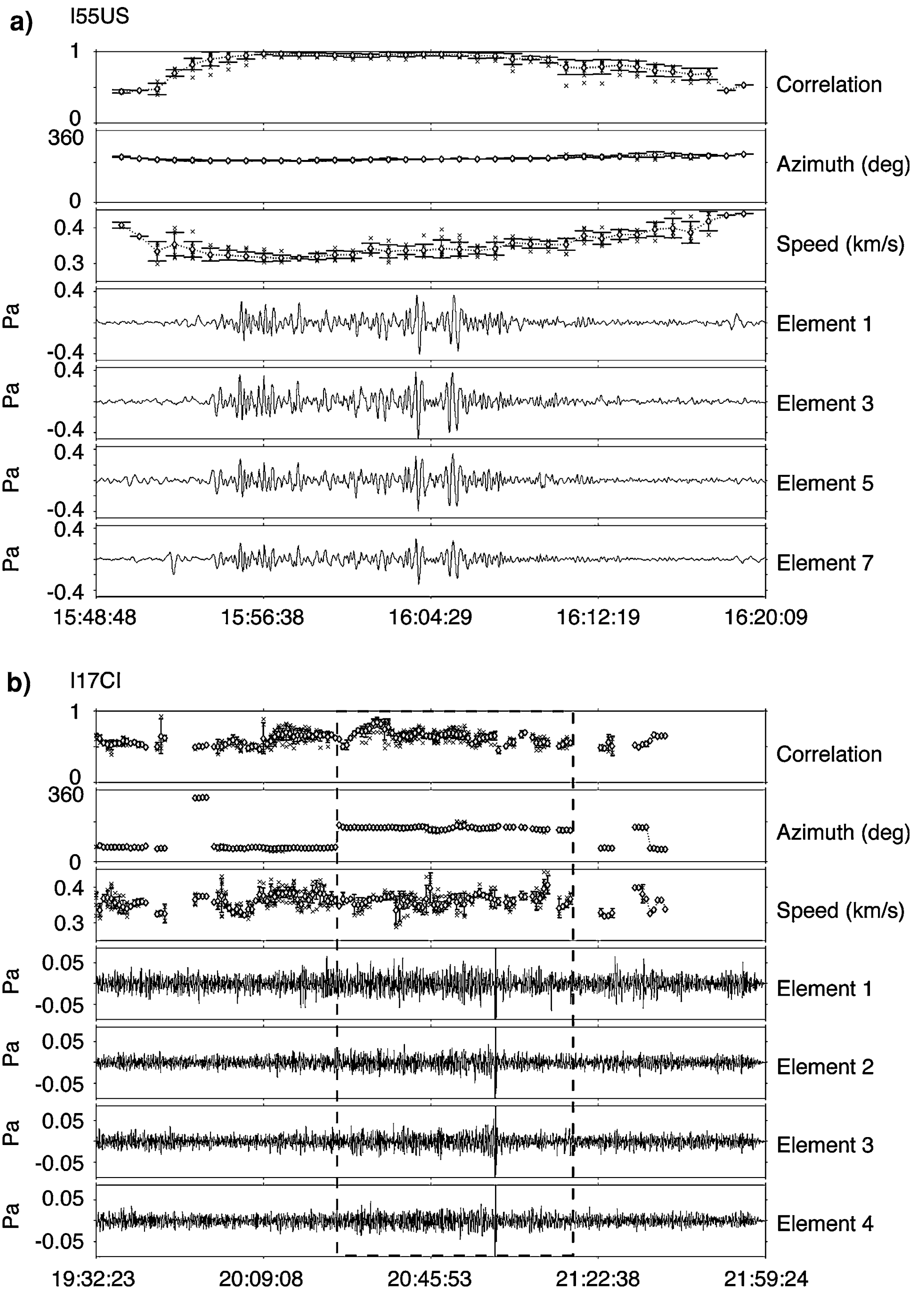

Fig. 3 Example signals from the September 3rd, 2004 Antarctic superbolide at (**a**) the I55US array at Windless Bight, Antarctica; and (**b**) the I17CI array in the Ivory Coast. In (**b**), the signal from the superbolide is outlined by the dashed lines

Table 1 Summary of associated detections at IMS infrasound arrays for the three superbolide events

Event	Array	Range (km)	Arrival time (UT)	Duration (s)	Peak amplitude (Pa)	Back-azimuth (°)
09/03/04	I27DE	1044	13:15:25	1300	0.25	92.0
09/03/04	I55US	3743	15:50:03	1565	0.44	208.4
09/03/04	I35NA	5390	17:20:45	1650	0.10	172.2
09/03/04	I05AU	7114	18:47:55	1900	0.06	204.8
09/03/04	I17CI	8423	20:26:15	2550	0.05	168.0
09/03/04	I26DE	12,918	00:27:45 (on 09/04)	2000	0.10	175.6
10/07/04	I52GB	2201	15:50:50	540	0.33	186.3
10/07/04	I32KE	4679	17:38:50	80	0.04	131.0
10/07/04	I55US	7204	20:01:15	1250	0.14	260.7
10/07/04	I17CI	9001	21:45:50	100	0.04	110.0
10/07/04	I26DE	10182	23:02:55	6150	0.10	127.6
10/07/04	I10CA	17241	06:17:55 (on 10/08)	1700	0.57	27.3
12/09/06	I26DE	2727	06:08:43	750	0.53	158.3
12/09/06	I35NA	5094	11:40:30	1360	0.47	12.2
12/09/06	I30JP	10320	15:13:30	70	0.07	301.2
12/09/06	I41PY	10632	16:05:20	110	0.40	63.2
12/09/06	I56US	10979	20:11:20	70	0.23	43.1
12/09/06	I04AU	11629	16:57:50	150	0.17	294.1

Note: The signal durations observed for these three superbolides do not increase as a function of range, as would be predicted theoretically. We speculate that the reason for this discrepancy is due to site noise

therefore unlikely to be associated with a large, distant source), and (b) similar to other detections obtained before and/or after the signal time window (Fig. 1). Test (b) reduces the likelihood of incorrectly associating an unrelated signal with the event of interest, since detections from coherent noise at a given station (which are typically highly repetitive) will be removed. The criteria used for measuring the similarity with other detections include backazimuth, frequency and trace velocity. The threshold constraints for matching two detections are set as follows: Maximum deviation in backazimuth = 5°, Maximum deviation in frequency = 1.2 Hz, Maximum deviation in trace velocity = 0.1 km/s. These constraints increase the likelihood that the signal is unique to a given event, i.e. it does not occur before or after the possible arrival window for an event of interest (Fig. 1).

3 Results and Conclusions

The event-based association algorithm described above is applied to three superbolides, which occurred from 2004 to 2006. Figure 2 shows the locations of arrays that detected one of the three events, a superbolide that entered over Antarctica on September 3rd, 2004 (for further details on this event, see Klekociuk et al. 2005). The event was detected by six IMS arrays. As shown in Fig. 2, the distribution of observations is strongly asymmetrical, suggesting that detectability is not a simple function of range. An example signal, recorded at the I55US infrasound array (which is located at Windless Bight in

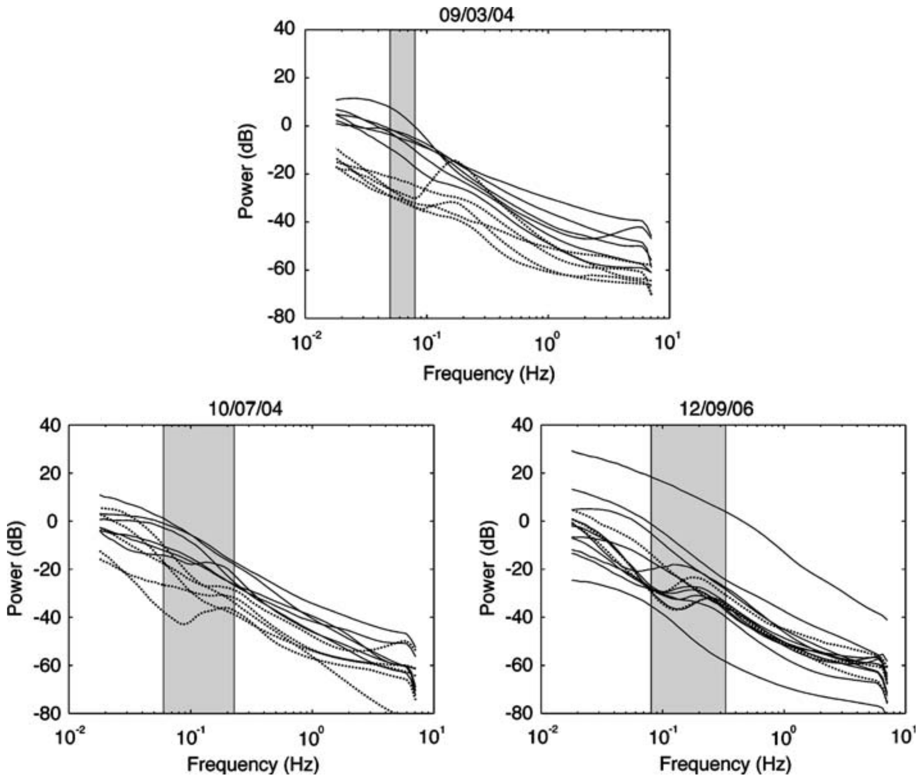

Fig. 4 Noise spectra for each of the three bolides. Solid black lines denote spectra for stations that detected the events and gray dashed lines denote spectra for stations that did not (for stations at ranges less than $\sim$10,000 km). Regions shaded gray denote the frequency band over which detections were observed for each bolide

Antarctica), is shown in Fig. 3a. A long duration ($\sim$10 min long) signal is observed, with a backazimuth of 209 ± 4.8°. The relatively fixed backazimuth and trace velocity indicate the signal is from a single event. The clear signal correlation between the separate array elements can be observed. Signals at greater ranges are typically lower in amplitude and harder to pick out from the ambient noise, requiring array-processing techniques to extract their full extent. An example of such a signal from the September 3rd, 2004 Antarctic bolide is shown in Fig. 3b, which was recorded at the I17CI infrasound array in the Ivory Coast (see map in Fig. 2). Similar patterns of observations were observed for the two other events, with six detections, and an asymmetric distribution of observations observed in each case. A summary of the observations from all three bolides is provided in Table 1.

Whether or not a given station detects an event appears to be strongly governed by factors other than range. In particular, two factors that influence the detectability of infrasound from an event are: (1) ambient noise levels at a given station, and (2) propagation effects. In order to assess the importance of ambient noise levels on the signal detection, we have computed pre-event noise spectra for each station. Each power spectrum was computed for a beamformed waveform at each array using a time window of $\sim$ 1 h (i.e., 2^{16} data points), and smoothed by averaging the power spectrum over

1/8 octave intervals. The resultant power spectra for stations at ranges <10,000 km are plotted in Fig. 4. The plot demonstrates that for two events there is a clear separation between noise-levels at stations that detected the event and stations that did not detect the events. In fact, for these two events the difference in noise levels between stations that detected the events, and stations that did not, is approximately 20 dB on average. This suggests that site-noise effects play a dominant role on the detectability of infrasound from such large events. We note that such a separation is not observed for more distant stations (>10,000 km), suggesting that propagation effects may dominate noise effects at larger ranges.

We have not performed detailed propagation modeling in this study but plan to do so for a future publication. As discussed previously, both site noise and propagation effects will affect the detectability of infrasound. However, our present results clearly suggest that site noise effects are a significant factor on the global detectability of the three superbolides.

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