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Title: | LARGE METEROID DETECTION USING THE GLOBAL IMS INFRASOUND SYSTEM

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Invited Talk: **Large Meteoroid Detection using the Global IMS Infrasound System**

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Numerous signals will be routinely detected using the 60 array, global IMS (International Monitoring System) infrasound network. Infrasonic signals are sub-audible quasi longitudinal, atmospheric waves in the frequency band from about 10 Hz to ~5 minutes in period (limited by human acoustic audibility in the high frequency limit and by the wave-guide acoustic cut-off frequency and the Brunt Vaisalla frequency in the low frequency limit) These small amplitude waves are a natural subset of the well-known atmospheric acoustic-gravity wave regime which has been identified from the linearized equations of geophysical fluid mechanics in the flat earth approximation, neglecting the earth's rotation, etc. For the IMS network the instrumental pressure sensor response was chosen to range from ~4 to 0.02 Hz. These are ground-based arrays of typically 4 to 9 sensors with separations of about 1-2 km between the array elements. Examples of naturally occurring impulsive sources of infrasound include volcanic eruptions, earthquakes, bolides (large meteor-fireballs entering the atmospheric at very high speeds up to ~300 times faster than ground-level sound waves), microbaroms (the "voice of the sea" due to the interaction of atmospheric storms and surface ocean waves) and the supersonic motion of the auroral electrojet at about 100 km altitude (auroral infrasonic waves), etc. In this paper we will briefly summarize our current state of knowledge of infrasound signals from bolides. This summary will include the generation of the signals at the complex, quasi-cylindrical line source, to the refraction and diffraction of the propagating waves by the middle atmospheric and tropospheric temperature and wind systems and finally, the detection of the signals and their interpretation by inferring the source properties, i.e., source altitude, blast radius (see below) and the source energy, etc. In addition, we will use infrasound from energetic bolides to estimate the expected steady state, global influx rate of these large bodies as a function of the bolide source energy. Further details on this subject can also be found in recent publications by the author (ReVelle; 1997; Ceplecha et. al., 1998; ReVelle and Whitaker, 1999; Brown et. al, 2002, etc.)

We begin with the natural setting of the science of infrasound. In Figure 1 there is a depiction of the realm of infrasound or low frequency atmospheric acoustics as a natural subset of the full dynamical spectrum of atmospheric motions.
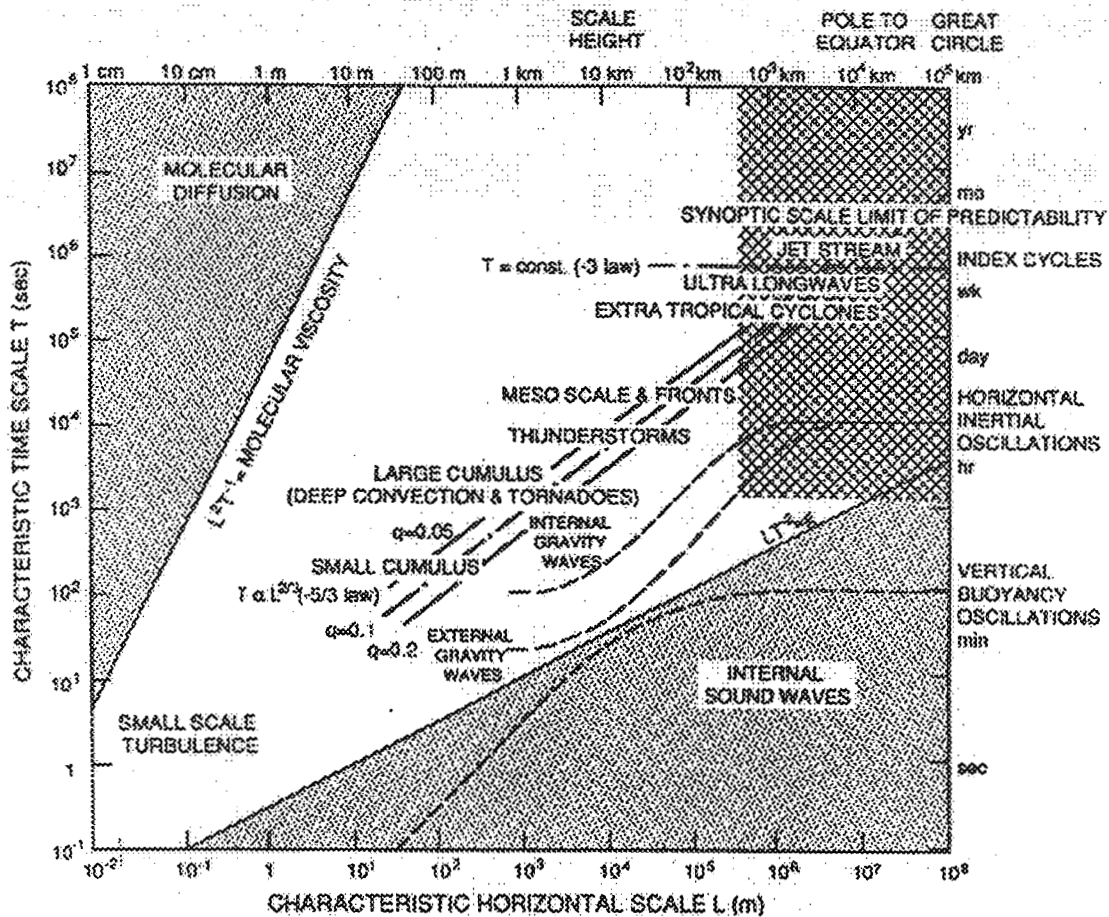

Figure 1. Characteristic time scale versus the characteristic horizontal scale of all types of atmospheric motions. Infrasound occupies the region from timescales < ~2-4 minutes for horizontal scales from ~33 m to ~40-80 km (After Smagorinsky, 1974, based on a figure by H. Fortag as modified by K. Ooyama). The diagonal dark solid line drawn from the lower left side toward the middle right side of the diagram is not the boundary of internal sound waves in the atmosphere, but rather is the ratio of a characteristic atmospheric speed divided by a characteristic time equal to the acceleration due to gravity, g.

As the Earth travels in its orbit about the Sun, it acquires solar system debris (meteoroids) of varying sizes traveling in various characteristic orbits that can intersect our orbit. Typical sources of meteoroids are found with orbits whose aphelion (their furthest distance from the sun) is somewhere within the main asteroid belt, but other sources, including the Amor, Aten and Apollo objects, i.e., the Near-Earth objects (NEOs), in addition to long and short period cometary sources can also occur. Very large meteoroids (generally large r than a few cm across) traveling at hypersonic speeds (very large Mach number compared to the speed of sound waves) can readily create a quasi-line source blast wave of nearly cylindrical symmetry if the meteoroids penetrate the

2

atmosphere deeply enough to reach conditions that resemble those of a continuum fluid. These large bodies are now known to arrive at the Earth's orbit in one of several possible types, including Nickel-iron, ordinary bronzite chondrites (hard rocks), weak stones (carbonaceous chondrites?) or even as very weak cometary material of different types and strengths. On occasion these bodies can travel at subsonic or even at large supersonic speeds down to the Earth's surface to drop meteorites and produce a strewn field of small impact craters or even as an explosion impact crater. Meteor crater, west of Flagstaff in northern Arizona is a good "recent" example of such an event from the fall of a Nickel-iron meteorite. The fall of a giant bolide (~5-10 km) at the geologic time of the Tertiary-Cretaceous boundary in the Yucatan peninsula (very near to where this meeting is being held) is the object that has been scientifically "proven" to be the cause of the famous dinosaur extinction on the Earth.

The interaction of these meteoroids with the atmosphere is very strong due partly to the very high speed of meteoroids at Earth entry and partly due to the compressibility of the atmosphere. The entry speed ratio compared to the speed at which sound waves typically travel can range from 50-300, which we call the Mach number. For comparison a typical Mach number of a commercial or military supersonic jet is < 3. As a direct consequence of this high speed, an atmospheric explosion is generated along a cylindrical path about the entry trajectory. This deposition of energy along the path constitutes a line source explosion whose characteristic radial scale (perpendicular to the entry trajectory) is called the line source blast wave relaxation radius. This scale delineates the very high pressure and high temperature nonlinear region in which an explosion has occurred and is influenced under certain conditions by the break-up of the body. This scale is also of importance for the infrasonic signals generated by the interaction as well. Hydrodynamic simulations of line source explosions have shown that the near-field pressure wave signals have acoustic/infrasonic wavelengths proportional to a constant times the blast radius (where the constant is equal to ~2.81 for a line sources at 10 scaled blast radius from the entry trajectory). For line source blast radii between 10 m and 1 km, this implies near-field wavelengths of ~ 30 m to 3 km. This blast wave range covers the realm of most bolides that have already been observed (where the influx rate of small bodies with smaller blast wave radii occurs far more frequently-see below for details). For comparison, thunder from ordinary lightning discharges has an associated blast radius of~2-3 m.

Within this nonlinear zone significant visible and ultraviolet radiation is generated by the strong interaction between the atmosphere and the bolide that can also be detected by ground and space-based sensors. Prior to bolide fragmentation, this relaxation radius can be calculated theoretically to be the product of the Mach number and the diameter of the bolide. After fragmentation, the blast radius increases, but its increase is ultimately limited by the number of fragments produced and their size distribution and behavior following break-up. Detailed dynamical and energetic theoretical modeling of this behavior is rapidly improving and it is anticipated that soon both optical as well as infrared luminosity predictions will be available as well as spectral models. This progress is due to recent advances in computational power as well as newly developed concepts of bolide fragmentation processes and their effects on bolide luminosity (ReVelle, 2002).

As noted above, for large meteoroids capable of penetrating the atmosphere to heights where a distinct shock wave is formed and which can also be detected at the ground, this

radial length scale can range from about 10 m to kilometers in length. For blast wave radii < 10 m at progressively higher altitudes,, extensive "classical" absorption of sound waves (by both viscous, i.e., frictional and thermal conductive mechanisms) in the middle and upper atmosphere can occur. This can even prevent signals from being recorded above the prevailing background wind-noise levels that can differ significantly from site to site. Signals that emanate from such sources in the atmosphere can have very large amplitudes due to the location of the observation point with respect to the entry trajectory (range effect on acoustical spreading losses) or also due to differences in the intrinsic source strength at various altitudes) or by the formation of caustic surfaces or focusing regions at a point or along a linear region. At times such signals can be significant enough to even break glass windows at relatively close range from the explosion, typically near the end height (where the bolide luminosity ceases). Dominant wave frequencies of such sources can be low enough so that the peak energy is well below the range of human audibility for sound waves. As the blast wave radius increases for larger kinetic energy sources, we find that these frequencies generally become progressively lower due to the combined effects of dispersion, weak non-linearity distortion propagation effects, etc. For the famous Great Siberian Tunguska event of June 30, 1908, quasi-longitudinal, sound waves with a period at maximum amplitude of about 1 minute were observed at great distances from the entry trajectory within a long enduring dispersive wave train which also included internal atmospheric gravity waves with periods of several tens of minutes to ~ one hour (transverse waves similar to shallow water waves breaking on the beach as they approach the shore). This bolide source was so large that even the fundamental atmospheric mode was excited, the so-called Lamb wave, and it was detected at numerous locations in Great Britain very far away from the bolide which entered the atmosphere in Siberia in northern Russia.

As these signals propagate through the atmosphere, significant bending of the sound waves (refraction) can be produced by the ambient temperature (equivalently by the thermodynamic sound speed) and by the horizontal winds aloft. We know from acoustics that in a steady state (time independent) atmosphere that there are two geometric constants of the wave motion in a perfectly stratified, range-independent atmosphere (stratification paralleling the vertical height axis just as in layered rock formations in the Earth). These conserved quantities are called the characteristic velocity and the wave normal heading (azimuth direction) at the source (ReVelle, 1976). The characteristic (or trace) velocity is the speed with which waves travel horizontally across a line that is parallel to the ground plane. For vertical arrivals the trace speed is very large, while for horizontal arrivals this speed is equal to the local sound speed plus the wind speed in the direction of the arriving waves.

These waves can also be diffracted and scattered as well under suitable conditions. We can now use ray-mode theory (which provides a geometrical interpretation of a propagating normal mode) as developed by the author to understand this propagation in detail in a steady state, range independent atmosphere. The arriving signals in the counter-wind case (where Stratospheric arrivals are forbidden to occur using the high frequency limit, geometrical acoustics Snell's law constant) are diffracted by regions of turbulence or internal gravity waves at heights of 40-60 km which allows weak signals to reach the ground at a range of one or more "hops" up-wind from a source.

4

We also now know semi-empirically at large ranges how to relate the period at maximum amplitude of the recorded infrasonic signals from bolides to the source energy. At closer range we can use also line source blast wave theory as developed by the author to estimate the source energy, blast radius and source altitudes, etc. For the blast wave radius values quoted earlier, detected source energies occur over an enormous range, i.e., from ~0.00001 kt (0.001 tons, TNT equivalent energy release) to 10 Mt (1 kt = $4.186 \cdot 10^{12}$ Joules).

Over the past few years we have observed a number of these very large events over a very large energy range (more than 40 events have now been detected with a significant number also detected by orbiting satellites). From some of these, we have been able to uniquely locate the source region with respect to its latitude, longitude and in some cases altitude. We have also been able (using about half of this data) to calculate the steady state, statistically averaged probability of these large bolides at the Earth in a year (see below).

Infrasonic observations are made at ground-based arrays of pressure detectors utilizing wind-noise reduction devices to aid in reducing wind-advected turbulence, etc. These sensors are typically very sensitive differential, low frequency microphones (or relatively high frequency microbarographs). Standard FFT cross-correlation, digital data processing in the slowness plane (back azimuth of arriving plane waves versus the inverse trace velocity of signals as a function of the largest cross-pair-wise cross-correlations) can be used to determine both the arrival direction as well as the elevation angle of the arriving signals as a function of time across the wave train. In addition, spectral properties of the signals can be examined. The directional properties also allow us to locate the bolide in three-dimensional space within certain errors. For example at a range of 3000 km we have already readily recorded a bolide whose source energy was only about 0.10 kt.

Also, as noted above, from such data we can estimate that the probability of occurrence of meteoroids whose source energy is ~8-12 kt is about one per year somewhere over the globe. At the energy of the Great Siberian bolide of 1908, i.e., Tunguska (~10 Mt), it is estimated that a reoccurrence interval is about once every 125 years. Corresponding to an energy of 0.10 kt, we find a value of about 30 ± 9 large bolides/year (including standard statistical counting errors). The number of bolides continues to increase as the source energy decreases in a power law fashion. In Figure 2, we have plotted the predicted influx rate of these large bolides based on 19 infrasonic detections. In all of these cases, satellite or ground-based photographic data or both were also used to corroborate the origin of the infrasonic signals. The full details of this approach are given in ReVelle (2001).
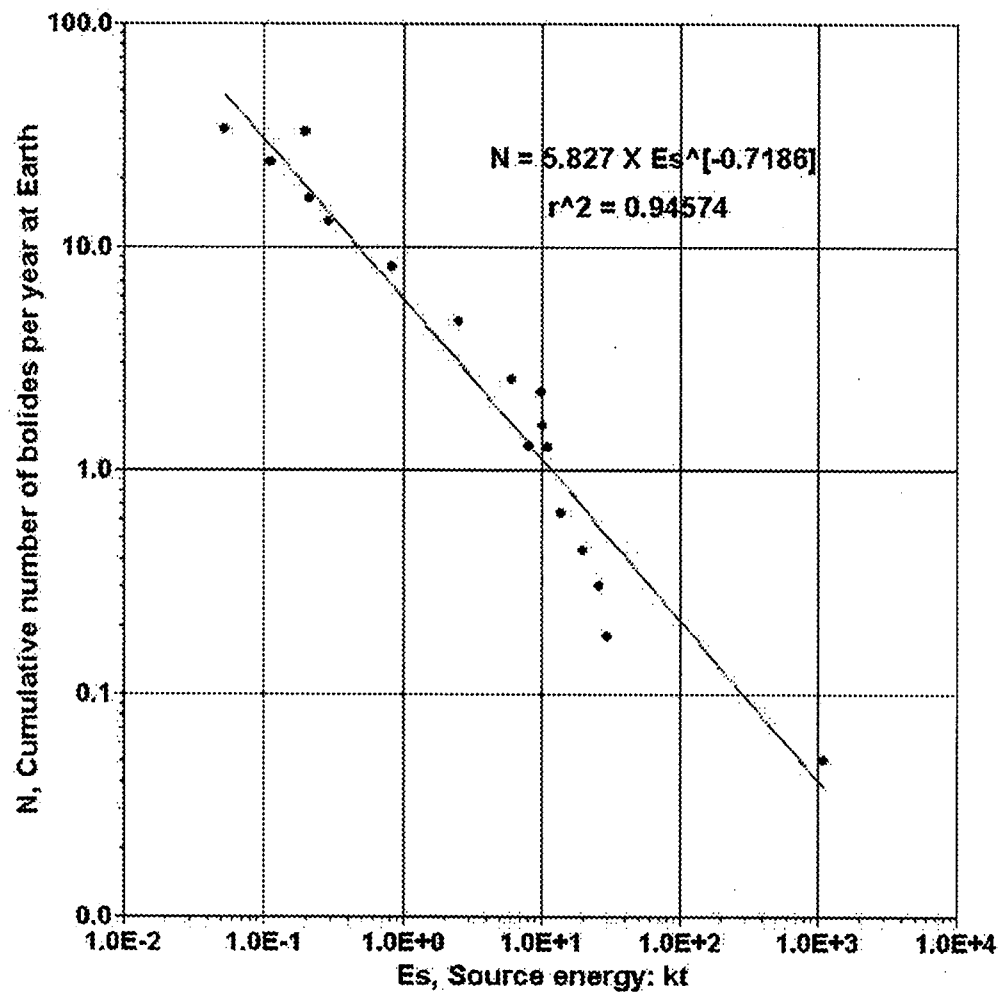
Figure 2: The global influx rate that is predicted using infrasound from bolides at earth (using 19 large bolides from 1960-1974 and 1995-2001) (N is the number per year over the earth versus the source energy in kt TNT equivalent (where 4.186e12 J = 1 kt TNT).

Examples of infrasonic signals from two recent bolides that were also detected by satellite or by ground-based radiometers or video cameras and by multiple ground-based infrasound arrays is included below in Figures 3- 4.
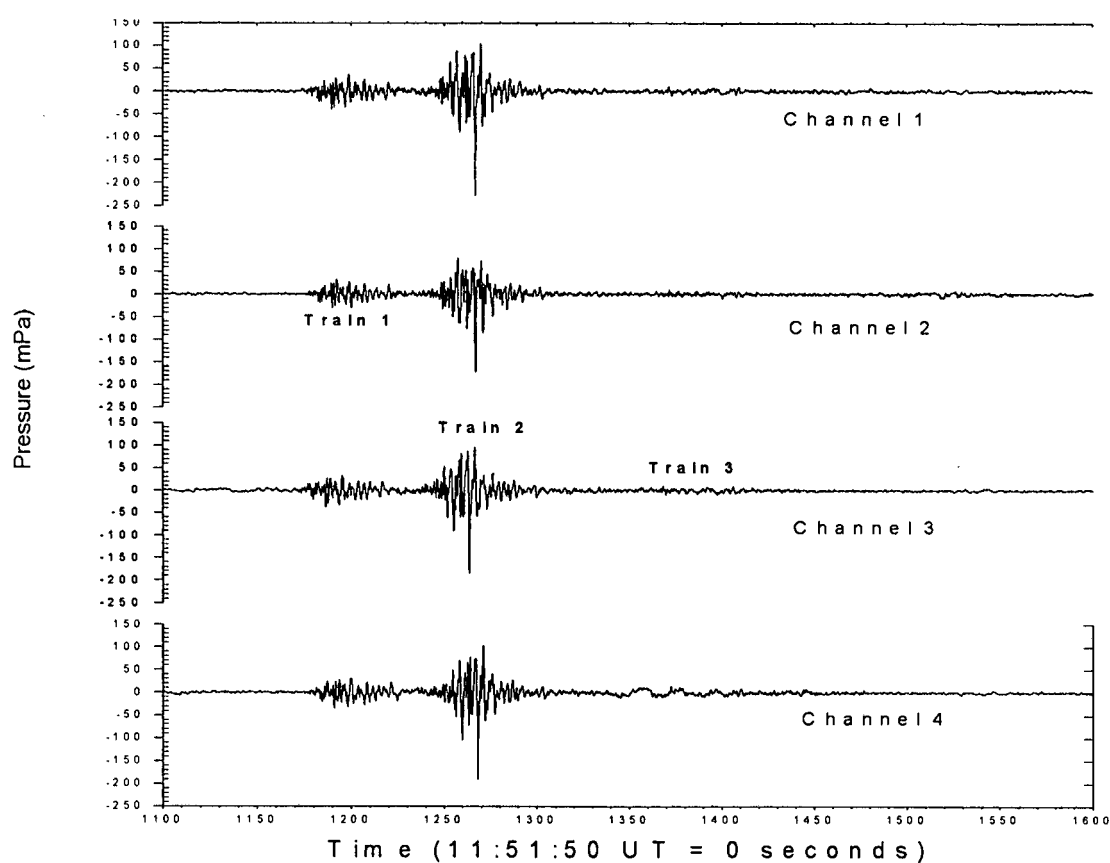
Figure 3. Absolute amplitude (mPa) versus time (s) of infrasonic signals from the Moravka bolide over the Czech Republic detected at IS26 (Freyung, Germany) on May 6, 2000 (band-passed from 0.3 -0 9 Hz). Signals arrive 1182s after the event (12:11:32 UT) ceasing approximately 308s later at 12:16:38 UT.
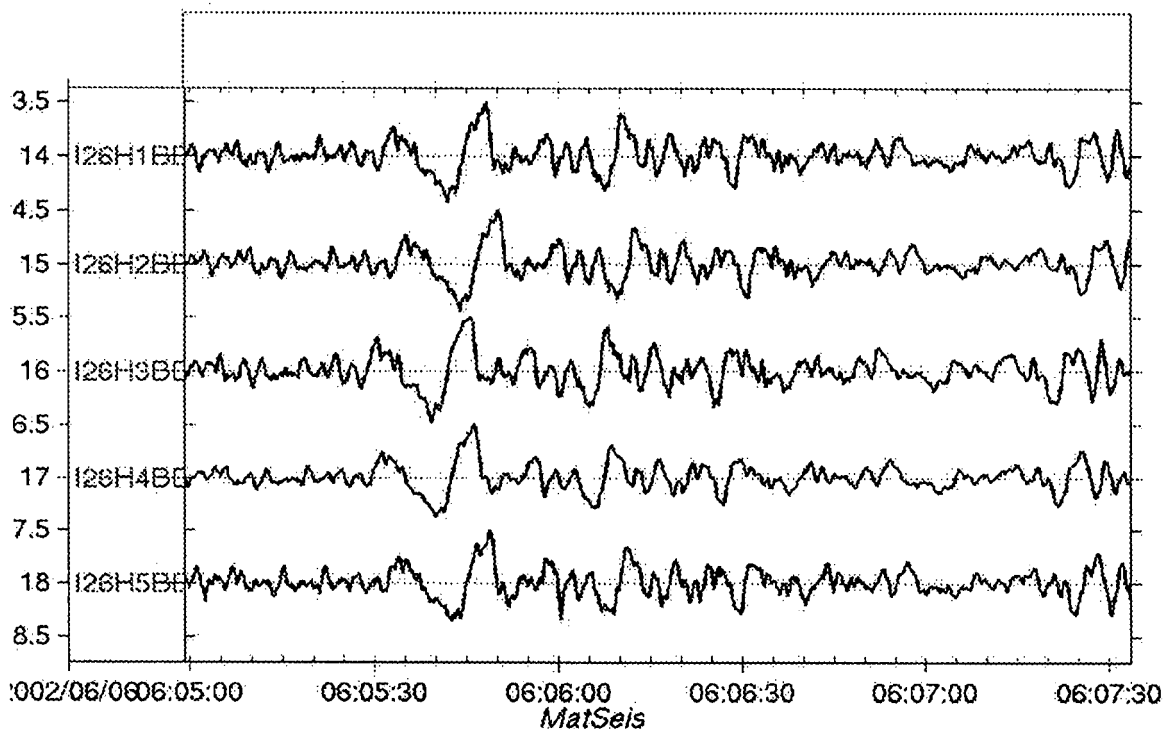

Figure 4. Relative amplitude versus time (minutes) of infrasonic signals from the June 6, 2002 bolide over the Mediterranean Sea detected at IS26 (Freyung, Germany).

Figure 3-4 illustrate some of the properties of infrasonic wave arrivals from two recent bolides over Europe recorded at Freyung, Germany (IMS array, IS 26). The deduced infrasonic back azimuths from IS-26 for Moravka and at both the Deelen infrasound array-DIA, Netherlands operated by KNMI in De Bilt, Evers and Haak, 2001) and at IS26 resulted in a source location very near the Moravaka bolide and for the location of the June 6, 2002 Mediterranean bolide. These figures illustrate the interesting and complex nature regarding the global monitoring of atmospheric explosions in general and of bolides in particular.

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