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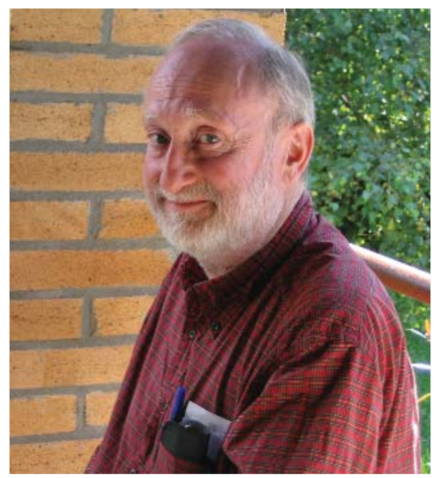
IN MEMORY OF DOUGLAS ORSON REVELLE (1945 - 2010)

Peter Brown, University of Western Ontario



The infrasound science community lost one of its pioneering members on May 2, 2010 when Douglas ReVelle passed away. Doug was trained as an atmospheric scientist with emphasis on aeronomy and planetary atmospheres at the University of Michigan in the late 1960s and early 1970s where he developed a life-long interest in the dual fields of infrasound and meteor science. His doctoral work "Acoustics of Meteors" reflected this combined passion and laid the modern foundations for interpretation and analysis of infrasound from meteors. Doug's early research career as a post doctoral fellow at the National Research Council in Canada and later at the Carnegie Institution in Washington largely focused on meteoroid entry modeling and bolide kinematics. While at the NRC in Canada, Doug helped to build one of the first infrasound arrays in Canada and used it to study diverse sources including meteors and atmospheric pressure waves generated during solar eclipses. However, after moving to Los Alamos in 1994 as a technical staff mem-

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ber in the Earth and Environmental Sciences division, he became heavily involved in the infrasound monitoring group already well established at the lab. With the emergence of the CTBT in the mid-1990's and plans for deployment of infrasound arrays as part of the IMS, Doug's work focused increasingly on modeling infrasound propagation and interpretation of infrasonic measurements. His particular research interests focused on theoretical work related to ray-mode theory, wind shelter modeling and infrasound production from bolides, earthquakes, mining blasts and rockets. Doug retired from Los Alamos in February, 2010 but he continued active research until just before his death. In 2002 asteroid 13358 was named ReVelle in his honor, the citation reading:

"Douglas O. ReVelle, of the Los Alamos National Laboratory is well known for his pioneering theoretical work in meteor physics and astronomy based on theoretical aerodynamics, in meteor acoustics and in the interpretation of infrasonic meteor observations. The name was suggested by Z. Ceplecha."

Doug's energy and enthusiasm for his research was infectious and he served as a mentor to many students and researchers in both the fields of infrasound and meteor research. He will be greatly missed by his many colleagues and friends around the world. Doug is survived by his wife, Ann, of Los Alamos; his son David of Tucson, Arizona, and his son Peter, a student at NM Tech in Socorro, NM.

INFRASONIC OBSERVATIONS OF RECENT METEOROID ENTRIES OVER NORTHERN SCANDINAVIA

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Abstract
Three major bolides recorded during 2008 - 2009 at five infrasonic arrays in Northern Scandinavia are analyzed. It is found that radiants estimated for these events do not conform with radiants of known meteor showers.

Introduction
The Swedish Institute of Space Physics operates, since the beginning of 1970s, four infrasound stations: Kiruna, Jämtön, Lycksele and Uppsala (see Fig. 1 and Table 1). All original time series collected since 1994 are stored in a data base accessible to the general public at the Internet home page of the Swedish Institute of Space Physics together with all standard software needed for data analysis. Each station consists of a tripartite microphone array located in the corners of an isosceles triangle, oriented in the NS-EW directions. The microphones used in the network are unique, high sensitivity Lidström-microphones, manufactured in Sweden. Time series from all three microphones are stored in a compressed binary format, in 30-minutes files.

In October 2006, the Uppsala-array was moved to Sodankylä, Finland. The network became a joint effort of Sweden and Finland.

In March 2008, an experimental 3-site microbarograph mini-array was deployed by NORSAR at sites of the ARCES seismic array near Karasjok, northern Norway (Roth et.al, 2008). Infrasound data from this microbarograph array, called ARCI, are used for analysis of particular events.

That is a first step toward a North-Scandinavian infrasonic network. The coordinates of the five arrays are shown in Table 1.

Among the most interesting phenomena which may be studied with such a network are the entries of meteoroids into the Earth's atmosphere. A meteoroid, entering the atmosphere with a speed of the order of tens of kilometers per second generates a cylindrical shock, which is transformed into infrasound. In the final phase of its descent the meteoroid disintegrates/fragmentates due to the frictional heating. Each fragmentation is a source of a spherical shock wave, which also transforms into infrasound. The mechanism of the meteoroid entry was discussed by ReVelle (1997). Infrasonic observations of a number of meteoroid events, made by the Swedish-Finnish Infrasound Network, were discussed by Liszka (2007).

In the present study, three major meteoroid entries, observed over Northern Scandinavia, during 2008-2009, are described.

Fig. 1: Location of infrasound arrays in Northern Scandinavia.

NAME	LATITUDE (°)	LONGITUDE (°)
ARCI	69.54°N	25.51°E
Kiruna	67.8°N	20.4°E
Sodankylä	67.42N	26.39E
Jämtön	65.87°N	22.51°E
Lycksele	64.61°N	18.71°E

Table 1. Infrasound arrays in Northern Scandinavia

At short distances to the entry (of the order of 100 km) the measured horizontal trace velocity, Vp, may be used as a measure of the apparent height of the source above the ground and both the location and orientation of the trajectory may be determined. Since the time-of-arrival, even at distances around 100 km, is strongly influenced by propagation effects, the velocity of the entry is most difficult to estimate.

At large distances, only the geographical location of the entry may be determined. At distances below 2000 km the heading of trajectory, ***h***, may be calculated. At even shorter distances, well below 1000 km, also the inclination of the trajectory, ***e***, may be determined, see Fig. 2.

Determination of entry trajectory from infrasonic observations

During the final part of the entry the meteoroid is the source of infrasound. Multi-array observations of infrasound from a meteoroid entry may be used for determination of its trajectory. A detailed description of the method may be found in an earlier publication (Liszka, 2007). The method is based on the statistics of observed: angle-of-arrival, AA, horizontal trace velocity, Vp and the corresponding time-of-arrival, TA. The infrasonic arrays providing the data must be located at distances of the order of 100 km over a range of latitudes and longitudes.

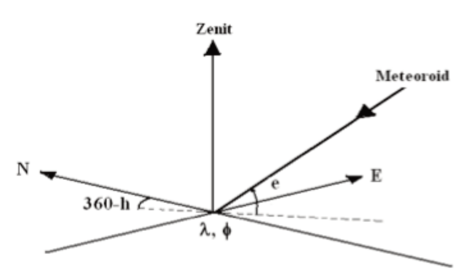

Fig. 2. Geometry of the meteoroid entry.

The determination of wave parameters may be done either for the entire frequency range 1-6 Hz, or for 6 narrow frequency bands within that range. The analysis of narrow-band signals (1 Hz bandwidth) often gives more accurate results.

November 8, 2008

On November 8, 2008, newspapers in Northern Sweden reported a bright bolide observed over the northern part of the country. The bolide was observed as far south as Sunne in Central Sweden (59.86N 13.12E), almost 900 km from the impact area. A low-frequency rumble was reported from places more than 300 km from the impact area. The event coincided in time with the Taurid meteor shower, being the debris from comet 2P/Encke (IMO, *www.imo.net/calendar/2008*). High quality infrasound data were collected during the event at all arrays in Northern Scandinavia, except the Sodankylä-array, having technical problems at that time. Angle-of-arrival, measured at all arrays, is shown in Fig. 3. The size of the symbols is proportional to the cross-correlation product measured across the array.

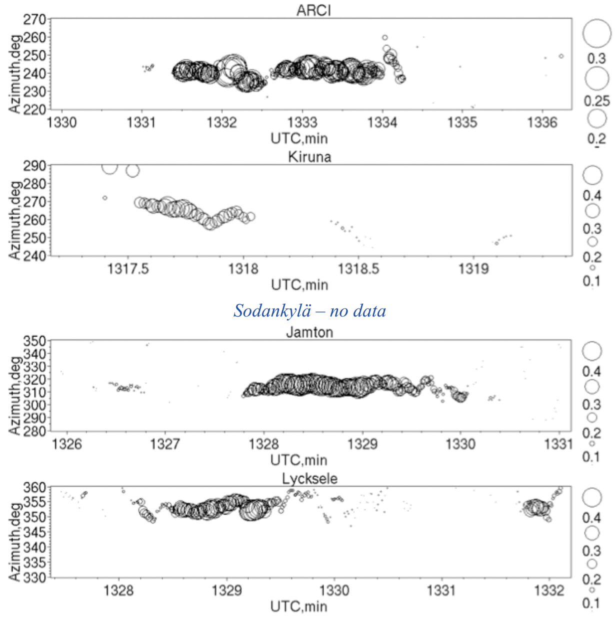

Fig.3: Angle-of-arrival of infrasound from the meteoroid entry on November 8, 2008 as the function of time, recorded at different arrays. Observe different time scales at different arrays. The size of the symbols is proportional to the cross-correlation product measured across the array.

ARRAY	AA AVERAGE	STDEV	AA MEDIAN
ARCI	242.2	1.1	242.0
Kiruna	265.0	3.0	265.8
Sodankylä	Not available	-	-
Jämtön	315.4	1.2	315.6
Lycksele	352.5	0.4	352.4

Table 2. Event 2008-11-08

Kiruna-Jämtön and Kiruna-Lycksele corresponding locations of the event are obtained; see crosses in Fig. 4. The localization error for two arrays depends not only on the accuracy of determination of individual angles-of-arrival, but also on the orientation of the line connecting both arrays with respect to measured angles-of-arrival. A full discussion of localization errors is presented in an earlier work (Liszka, 2007).

A close-up of the localized area of event is shown in Fig. 6 using the corresponding image from Google Earth.

Multifrequency measurements indicate the average heading of the meteoroid was $\boldsymbol{h} = 256.5 \pm 20.7^{\circ}$. The corresponding azimuth of the radiant would be thus $76.5 \pm 20.7^{\circ}$. The inclination angle, $\boldsymbol{e}$, of the impact

The semi-regular variations of the angle-of-arrival are due to atmospheric structure between the source and the array, while the general trend is likely due to orientation of the entry trajectory. Averages, standard deviations and medians of the unweighted angle-of-arrival in frequency range 1-6 Hz are shown in Table 2.

Using median values for three different array combinations with smallest localization errors: ARCI-Kiruna,

Fig. 4. The event localized (red crosses) using median weighted angle-of-arrivals for following array combinations: ARCI-Kiruna, Kiruna-Jämtön and Kiruna-Lycksele.

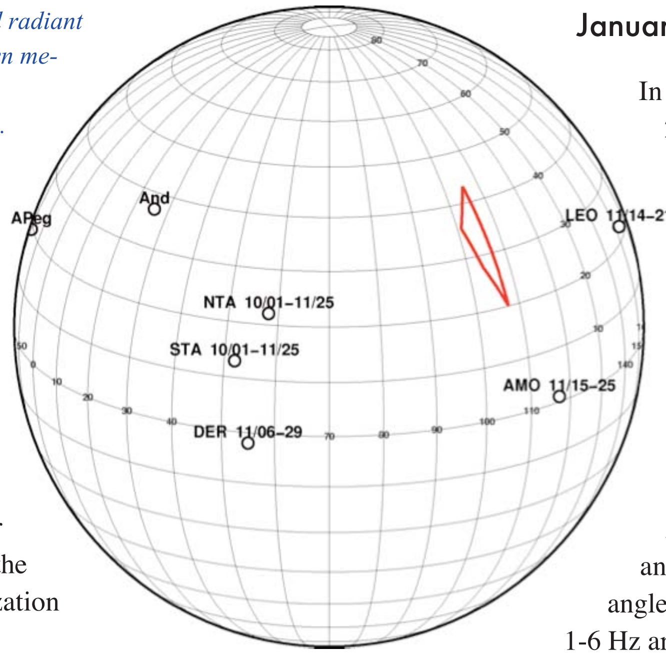

Fig. 5. Position of the determined radiant area on the sky. Radiants of known meteor showers and dates of occurrence (after IMO) are also shown.

trajectory with respect to the horizontal plane was determined to 28.9 ± 4.2°. Position of the determined radiant area on the sky in equatorial coordinates (R.A. - δ) is shown in Fig. 5. In the present study the estimated radiant area is compared with the list of meteor showers published yearly by the International Meteor Organization (*www.imo.net*).

The approximate equatorial coordinates of the Taurid radiant for 2009 are $\alpha = 03h\ 52m$ and $\delta = 22°$. Considering the approximate time of event being 21h 50m UTC the horizontal coordinates of the radiant will be at the horizon of entry area: Az = 152.6 and $e = 42.3°$. The Taurids would thus have, at that time and location, a heading of 152.6 + 180° = 332.6°, which significantly differs from the observed heading.

It may be seen that no known radiants for November may be found within, or close to the determined radiant area.

Fig. 6. The event localized on the Google Earth image using median angle-of-arrivals for following array combinations: ARCI-Kiruna, Kiruna-Jämtön and Kiruna-Lycksele.

January 15, 2009

In the evening of January 15, 2009 numerous inhabitants of Northern Norway reported a bright bolide heading North. Infrasonic signals from the bolide were observed at all arrays in Northern Scandinavia. The angle-of-arrival, as measured at all arrays, is shown in Fig. 7.

Averages, standard deviations and medians of the unweighted angle-of-arrival in frequency range 1-6 Hz are shown in Table 3.

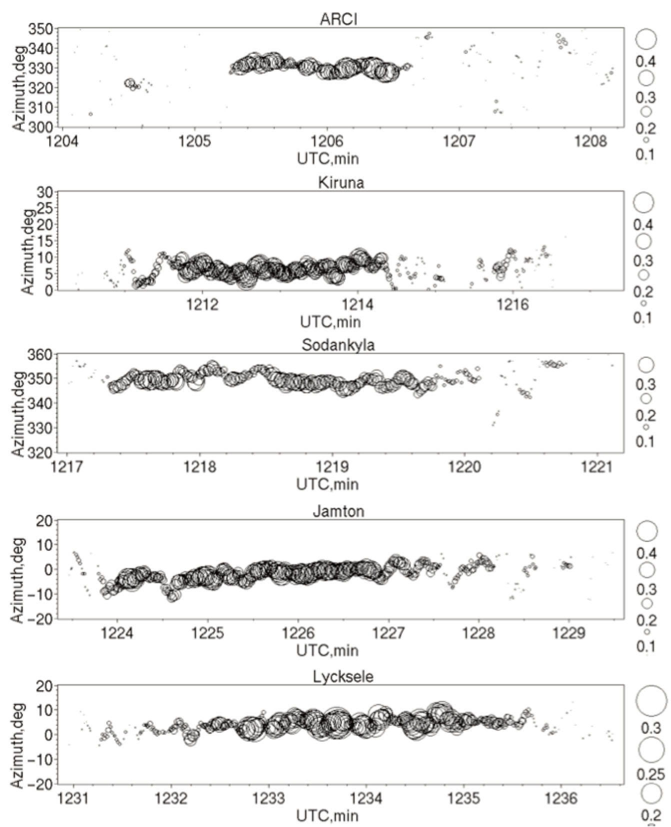

Fig. 7. Angle-of-arrival of infrasound from the meteoroid entry on January 15, 2009 as the function of time, recorded at different arrays. Observe different time scales at different arrays. The size of the symbols is proportional to the cross-correlation product measured across the array.

Using median values for four different array combinations

ARRAY	AA AVERAGE	STDEV	AA MEDIAN
ARCI	329.6	1.9	329.6
Kiruna	6.4	1.9	6.1
Sodankylä	350.0	3.8	349.5
Jämtön	357.4	1.1	357.5
Lycksele	4.2	1.8	4.3

Fig. 8. The event localized (red crosses) using median weighted angle-of-arrivals for following array combinations: ARCI-Kiruna, Kiruna-Jämtön, Kiruna-Lycksele and Kiruna-Jämtön.

with smallest localization errors : ARCI-Kiruna, Kiruna-Jämtön, Kiruna-Lycksele and Kiruna-Jämtön corresponding locations of the event are obtained; see crosses in Fig. 8.

Multifrequency measurements indicate the average heading of the meteoroid was $\boldsymbol{h}$ = 353.0 ± 8.2°. The inclination angle, $\boldsymbol{e}$, of the entry trajectory with respect to the horizontal plane was determined to 23.9 ± 13.0°. Position of the determined radiant area on the sky in equatorial coordinates (R.A. - δ) is shown in Fig. 9. Radiants of known meteor showers and dates of occurrence are also shown. It may be seen that no known radiants for January may be found within, or close to the determined radiant area.

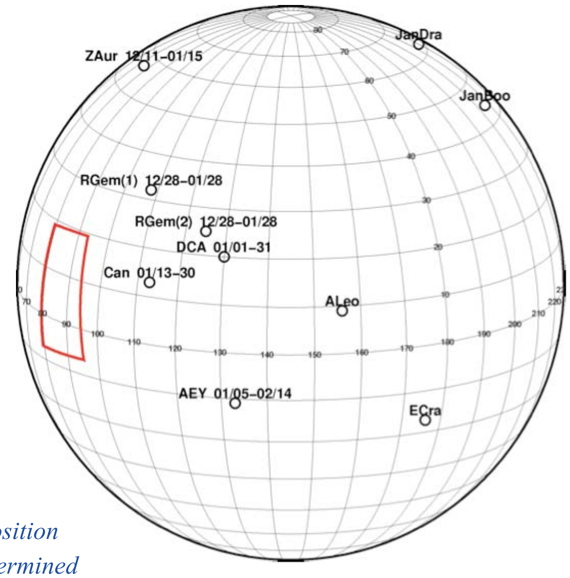

Fig. 9. Position of the determined radiant area on the sky (equatorial coordinates). Radiants of known meteor showers and dates of occurrence (after IMO) are also shown.

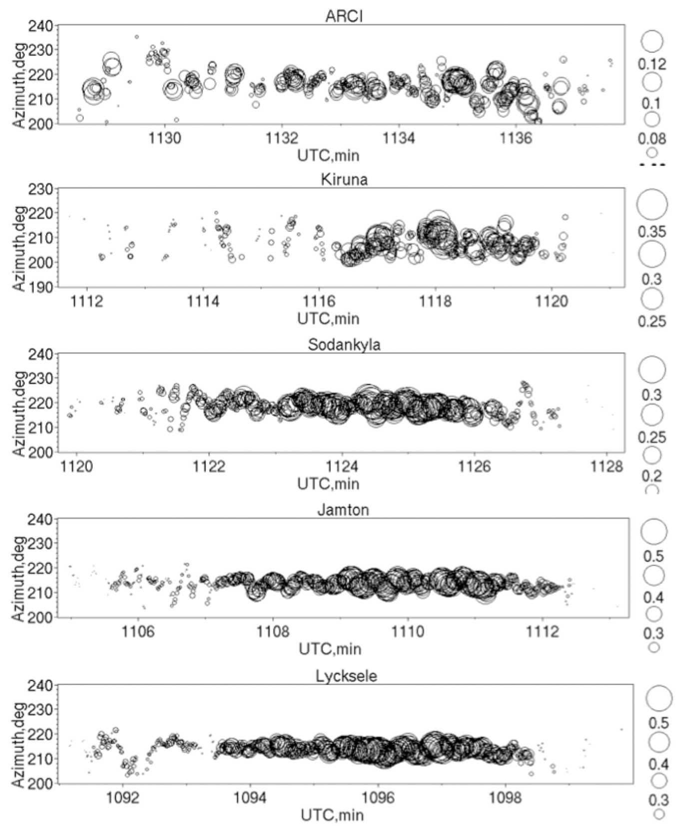

Fig. 10. Angle-of-arrival of infrasound from the meteoroid entry on October 13, 2009 as the function of time, recorded at different arrays. Observe different time scales at different arrays. The size of the symbols is proportional to the cross-correlation product measured across the array.

October 13, 2009

On the evening of October 13, 2009 a bright bolide was observed across Denmark, the Netherlands and Southern Sweden. Low frequency sounds were reported in connection with the event. The infrasound from the event was observed at all arrays in Northern Scandinavia. The angle-of-arrival, as measured at all arrays, is shown in Fig. 10.

Averages, standard deviations and medians of the unweighted angle-of-arrival in frequency range 1-6 Hz are shown in Table 4.

ARRAY	AA AVERAGE	STDEV	AA MEDIAN
ARCI	329.6	1.9	329.6
Kiruna	6.4	1.9	6.1
Sodankylä	350.0	3.8	349.5
Jämtön	357.4	1.1	357.5
Lycksele	4.2	1.8	4.3

Table 4

It may be seen in Table 4, that due to the large distance between the arrays and the event, the differences between the angle-of-arrival, as observed at different arrays, are rather small. For that reason the localization of the event will be inaccurate. Fortunately, there was an accurate visual observation of the bolide made at the west coast of Sweden. Mr. Robert Lundin at Hunnebostrand succeeded, using known landmarks, to locate the bolide trajectory, on a Google Earth image. From that it was possible to find that the meteoroid flew over the point 10.90E 58.427N in northernmost Denmark with an approximate heading of 210°. That part of the bolide trajectory is shown as the solid line in Fig. 11. The line is then extrapolated north of the point of visual observation in Hunnebostrand. The bolide, on its way towards the SSW, apparently passed a few North-Scandinavian arrays, although at so high altitude that any direct infrasonic signals could not be detected. Combining the most significant angle-of-arrival at different arrays a sequence of localizations was obtained. These are indicated in Fig. 11 by crosses. It may be seen that the infrasonic localization of the meteoroid path is about 100 km east from the visual trajectory, which is plausible considering strong high-altitude winds at this time of the year.

Fig. 11. Positions of the infrasound sources (red crosses) during the meteoroid entry on October 13, 2009 (crosses). The dashed line shows the visually determined trajectory of the meteoroid south of the point of visual observation. The line is extrapolated backwards towards NNE.

Because of the distance to the event no significant multi-frequency determinations of the heading and elevation could be obtained. Assuming the visually determined heading to be 210±2° and the probable inclination of the trajectory between 10 and 30°, a possible approximate radiant area may be estimated. This radiant area is shown in Fig. 12.

Again, the visually estimated radiant area does not coincide with any known radiants for October.

Discussion

Estimates of the radiant from infrasonic observations of a single bolide is far less accurate than those determined by photographic methods. Also the inclination of trajectory is determined during the final part of the descent. It may therefore be expected that the true inclination of trajectory is different from the estimated. Since the propagation times of infrasonic signals are strongly influenced by the

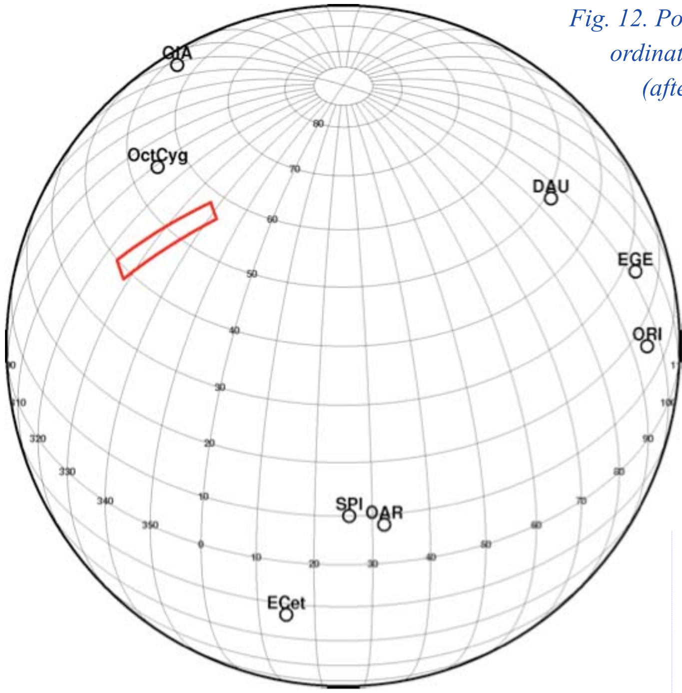

Fig. 12. Position of the determined radiant area on the sky (equatorial co-ordinates). Radiants of known meteor showers and dates of occurrence (after IMO) are also shown.

atmospheric structure, the method does not result in reliable estimates of the meteoroid speed.

However, the infrasonic observations of meteoroid entries do not depend on weather conditions and may also be performed during daylight. The range of infrasonic observations is also in favour of the method.

Although the accuracy of radiants determined for these three major bolides is low, it raises an important question. Apparently, all these events are not conformable with known meteor showers. Is that a rule for large bolides?

It was suggested that some of the large bolides are associated with orbits of certain asteroids or near-earth objects (NEO) (Trigo-Rodrıguez et al., 2007). Infrasonic observations performed with large and dense networks of arrays, like the North-Scandinavian Infrasound Network, could be a complementary source of information about these objects.

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