Detection of Meteor- and Space Object Entries

Using Infrasonic Observations

Ludwik Liszka, Johan Kero, Lars Eliasson
Carl-Fredrik Enell, Tero Raita

IRF Scientific Report 304
October 2014

ISSN 0284-1703

Institutet för rymdfysik
Swedish Institute of Space Physics

Umeå, Sweden

Detection of Meteor- and Space Object Entries

Using Infrasonic Observations

Ludwik Liszka, Johan Kero, Lars Eliasson
Carl-Fredrik Enell, Tero Raita

IRF Scientific Report 304
October 2014

Institutet för rymdfysik
Swedish Institute of Space Physics

Umeå, Sweden

IRF Scientific Report 304
ISSN 0284-1703

Swedish Institute of Space Physics
Box 812
SE-981 28 Kiruna
SWEDEN
www.irf.se

Detection of Meteor- and Space Object Entries Using Infrasonic Observations

Ludwik Liszka, Johan Kero and Lars Eliasson,

Swedish Institute of Space Physics,

Box 812, SE-981 28 Kiruna, Sweden;

Carl-Fredrik Enell and Tero Raita,

Sodankylä Geophysical Observatory,

FIN-99600 Sodankylä, Finland

Abstract

Numerous objects, man-made, such as rockets and satellites, and natural, in the form of meteoroids, continuously enter the Earth's atmosphere. Most of these events occur over unpopulated areas, during unfavourable meteorological conditions or in daylight, without being observed. However all these objects, when passing through the atmosphere, generate infrasound. That infrasound may be detected at long distances, even when optical observations are impossible. The present report shows that it is even possible, by studying the signature of the wave field on the ground, to identify different types of entry events.

Table of contents

Introduction 3

Infrasound arrays in Northern Scandinavia 4

Infrasonic observations of distant sources 5

Identification of infrasound sources – statistical properties of the wave field 6

Neural network tool for source identification 10

Sounding rockets: launch and reentry 11

Recognition of meteoroid entries 13

Recognition of five specific types of event 14

Estimation of meteoroid orbits 16

Future development: a meta-array for space debris/meteoroid detection 19

Acknowledgements 20

References 21

Introduction

The Chelyabinsk meteor event on 15 February 2013 caused a dramatic increase of interest in atmospheric entries of space objects. There are three groups of space objects entering the atmosphere:

- **Meteoroids**
  These objects are fragments of asteroids or comets approaching the Earth with high velocity, greater than 11.2 km/sec, and with sizes ranging from a fraction of a millimetre to hundreds of metres. During entry the object heats up due to the friction and can, if it is large enough, be observed as a bolide. It is well known that bright bolides are usually associated with sound effects. During the past century it was discovered that a large part of the acoustic energy is radiated in the non-audible, low-frequency part of the acoustic spectrum called infrasound, known for its unusual propagation. Already in connection with the giant Tunguska Meteor in 1908, it was found that low-frequency signals generated by the event travelled more than once around the Earth and were detected by barographs worldwide. The presence of infrasound emission from meteoroid entries was furthermore confirmed when infrasound became a common tool for detection of explosions. Several infrasonic observations of meteoroid entries can be found in the literature (e.g. Liszka 2008 and references therein).
- **Earth-orbiting, man-made objects**
  Thousands of man-made objects, such as used rockets and satellites, populate the near-space around the Earth. With gradually changing orbits, due to the atmospheric drag, these objects finally reenter the atmosphere. If the entry velocity is large enough, infrasonic signals, similar to those produced by meteors, will be generated. The infrasound is there a result of the cylindrical shock wave generated in the atmosphere. Since the entry velocity is lower than that of meteoroids, there is usually no detectable infrasound from fragmentation along the trajectory. The acoustic output of these entries is therefore much smaller than from a meteoroid entry with the same mass, where numerous explosions occur along the entry trajectory.
- **Launches of sounding rockets**
  An interesting case is the launch of a sounding rocket. During the launch phase, both the rocket engine and the supersonic shock are responsible for generation of infrasonic signals. During the reentry phase the shock wave is the only source of infrasonic signals. One of the topics of the present study is to compare infrasonic signals during the launch and reentry and to find methods to discriminate between the two types of signal.

1. Infrasound arrays in Northern Scandinavia

The Swedish Institute of Space Physics began operating, at the beginning of 1970s, four infrasound arrays: 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 for the general public on the internet home page of the Swedish Institute of Space Physics together with all the standard software needed for data analysis. Each array consists of three microphones located in the corners of an isosceles triangle, oriented in North-South and East-West directions. Microphones used in the network are unique, highly sensitive Lidström-microphones, manufactured in Sweden. Time series from all three microphones are stored in a compressed binary format, in 30-minute files. In October 2006 the Uppsala array was moved to Sodankylä, Finland, and the network became a joint effort of Sweden and Finland, called the Swedish-Finnish Infrasound Network (SFIN).

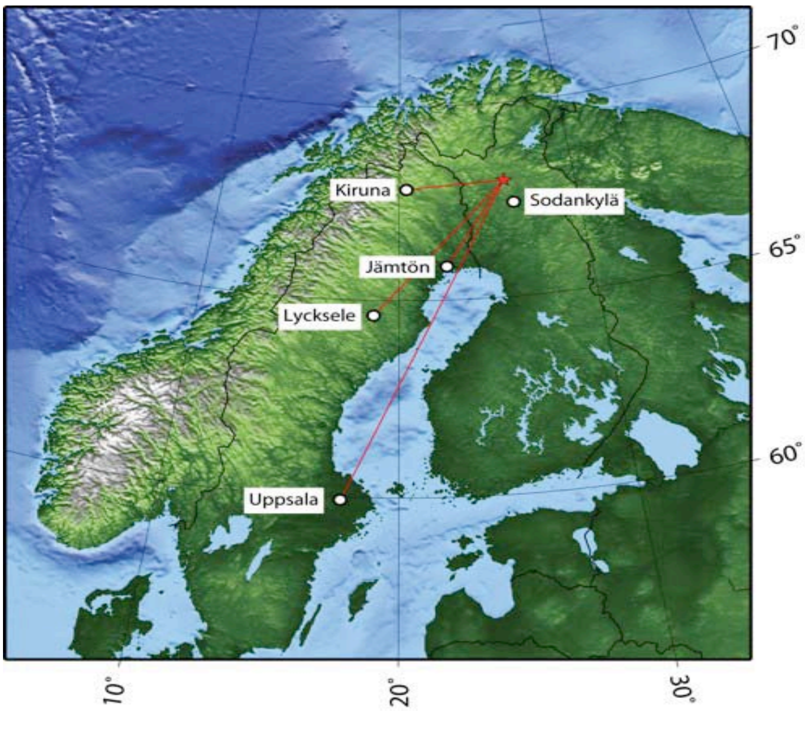


Fig. 1. Swedish-Finnish infrasound network (SFIN). The Sodankylä station replaced the Uppsala station in 2006.

Table 1. Arrays in the Swedish-Finnish Infrasound Network (SFIN)

Name	Latitude (Degrees)	Longitude (Degrees)
Kiruna	67.8˚N	20.4˚E
Sodankylä (since October 2006)	67.42N	26.39E
Jämtön	65.87˚N	22.51˚E
Lycksele	64.61˚N	18.71˚E
Uppsala (until October 2006)	59.85˚N	17.61˚E

2. Infrasonic observations of distant sources

The majority of both meteoroid- and space debris entries take place over oceans and unpopulated regions. In addition to that, visual observations of these events are only possible under clear-sky conditions. So the probability of detection of an entry event is proportional to the product of the population density times the clear-sky probability. Since the entry event cannot be predicted and its duration is usually very short, the probability of detecting it with a scientifically available radar system is also very small. On the other hand, in order to increase our knowledge of the entry events, the probability of detection of these events must be increased.

Thanks to the low attenuation of infrasound in the atmosphere, infrasonic observations provide a unique ground-based method to detect and identify atmospheric entries of objects from space over large distances.

The observational tool is an array of low-frequency microphones, at least three, which records the waveform as a function of time. Since the wind is the main obstacle in infrasound measurements, each microphone must be equipped with a wind noise reduction device. Multi-point measurements of infrasound waves may be used to reconstruct the instantaneous wave field on the ground. Usually, the measurements are aimed at determination of the angle-of-arrival of the wave and the inclination of the wave vector. Also the frequency content of the signal may be of interest. The signal is usually considered as a plane wave with its amplitude quasi-randomly modulated due to diffraction on atmospheric irregularities.

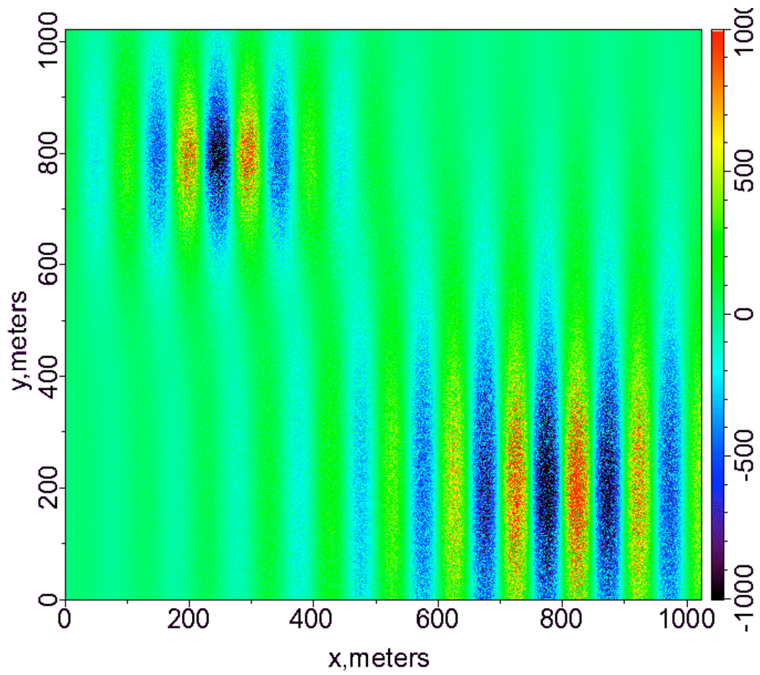


Fig. 2. Reconstructed instantaneous view of the infrasonic wave field on the ground.

3. Identification of infrasound sources – statistical properties of the wave field

At the end of the 1950s and the beginning of the 1960s, the foundations for satellite communication and the global positioning system were created through a worldwide study of the statistical properties of radio wave propagation. Numerous projects (e. g. Liszka, 1963) were aimed at the study of the statistical structure of the wave field at the receiving antenna. That information was necessary to allow appropriate design of the receiving systems, which would take into account the specific properties of the signal.

The wave pattern of infrasound waves on the ground may, like that of radio waves, be described by a correlation ellipse with its major axis along the wave front and its minor axis, approximately, in the direction of propagation.

The size of the major axis is proportional to the dimension of the intensity patch (see Fig. 2), while the size of the minor axis is determined by the dominating frequency of the wave.

Correlation analysis of the wave pattern determines the following parameters:

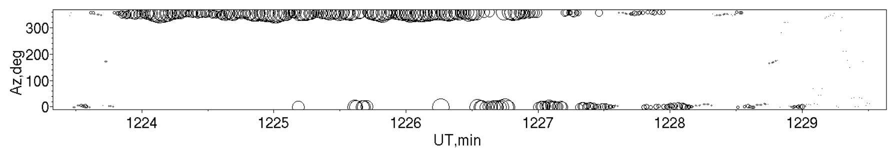
- Major Axis, a, of the ellipse.
- Minor Axis, b.
- Axial Ratio, $(=\sqrt{(a/b)})$.
- Orientation of Minor Axis, ψ, measured clockwise from North (close to the opposite of the angle-of-arrival).
- Deviation from a plane wave, $\varphi=\psi$-Az-90, where Az is the wave's angle-of-arrival.

All these parameters are derived for data points where the product of all cross correlations in the array (for 3 microphones) is greater than 0.05, i. e. when a significant value of the angle-of-arrival is obtained. As an example, parameters for a meteoroid entry between Northern Norway and Spitsbergen on 15 January 2009 are shown in Fig. 3. For comparison, Fig. 4 shows the same parameters for an explosion (destruction of explosives) in Northern Finland.

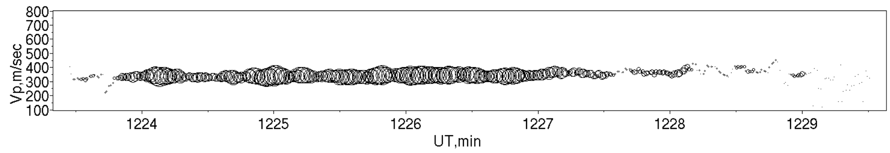
Other useful parameters:

- Period of time during which significant readings of the angle-of-arrival are obtained, N, expressed through total possible number of readings.
- The information density, i. e. ratio, R, between the number of significant readings and the total possible number of readings during the time N.
- The distribution of deviations from plane wave, φ, given through the triad: its lower quartile, the median and the upper quartile.

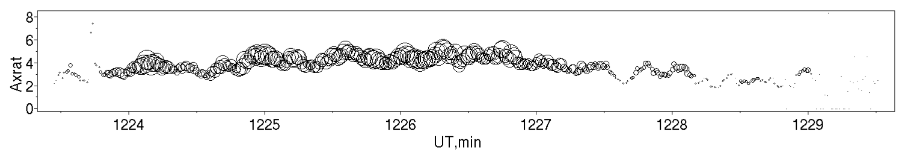
Azimuth



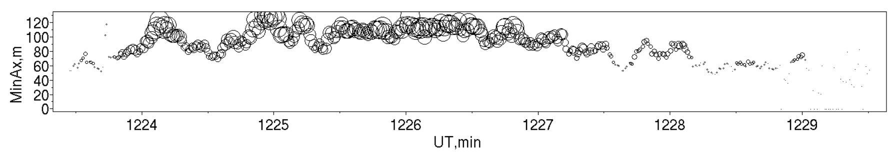
Phase Velocity



Axial Ratio



Minor Axis



Major Axis

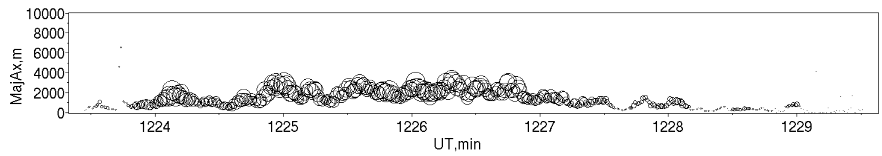
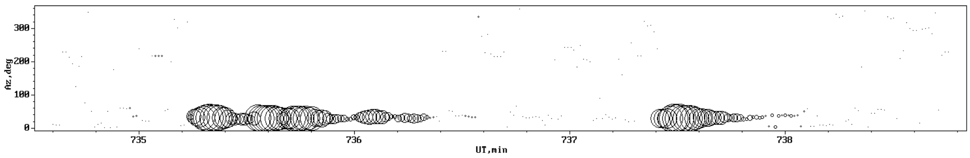
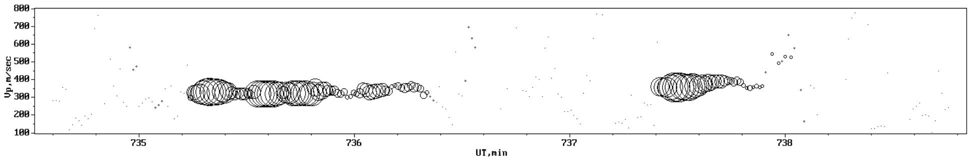


Fig. 3. Meteoroid entry between Northern Norway and Spitsbergen on 15 January 2009 observed at the Jämtön array. The size of the circles is proportional to the product of all 3 cross correlations in the array.

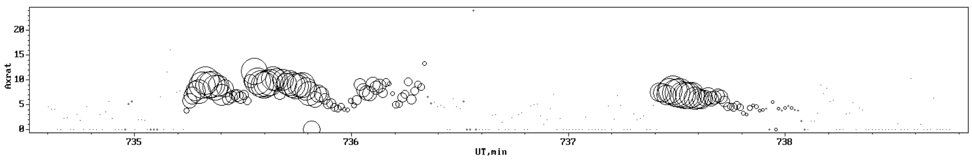
Azimuth



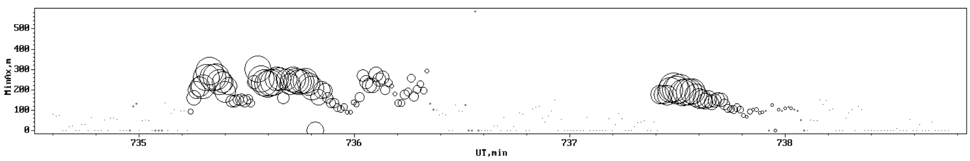
Phase Velocity



Axial Ratio



Minor Axis



Major Axis

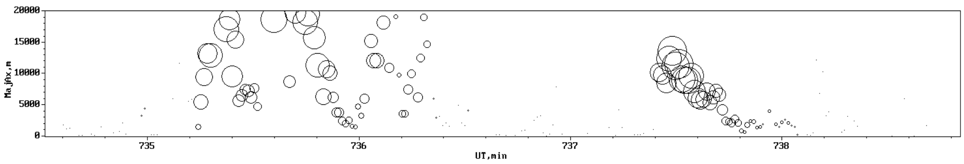


Fig. 4. Ground level explosion (destruction of explosives) in Northern Finland 24 August 2009 observed at the Jämtön array.

It has been found (Liszka et al., 2012) that the distribution of the major axis, b, is the parameter which differs most between three types of sources (meteors, explosions and supersonic jets), see Fig. 5. The differences are smaller for the minor axis distribution (Fig. 6).

Large values of b (≈10 km) for a ground level explosion, and thus also of the intensity patches in the wave field on the ground, are probably the effect of ducting in the lower stratosphere where large, irregular gradients in the temperature and wind frequently occur.

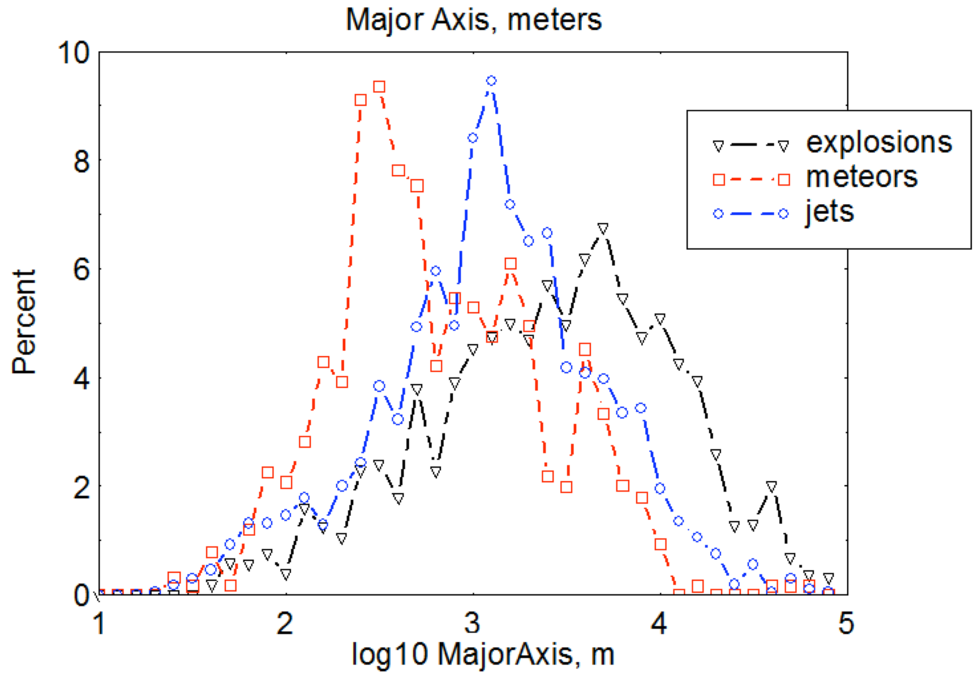


Fig. 5. Statistical distribution of major axis for different infrasound sources: ground level explosions, meteoroid entries and supersonic jets (using logarithmic x-scale).

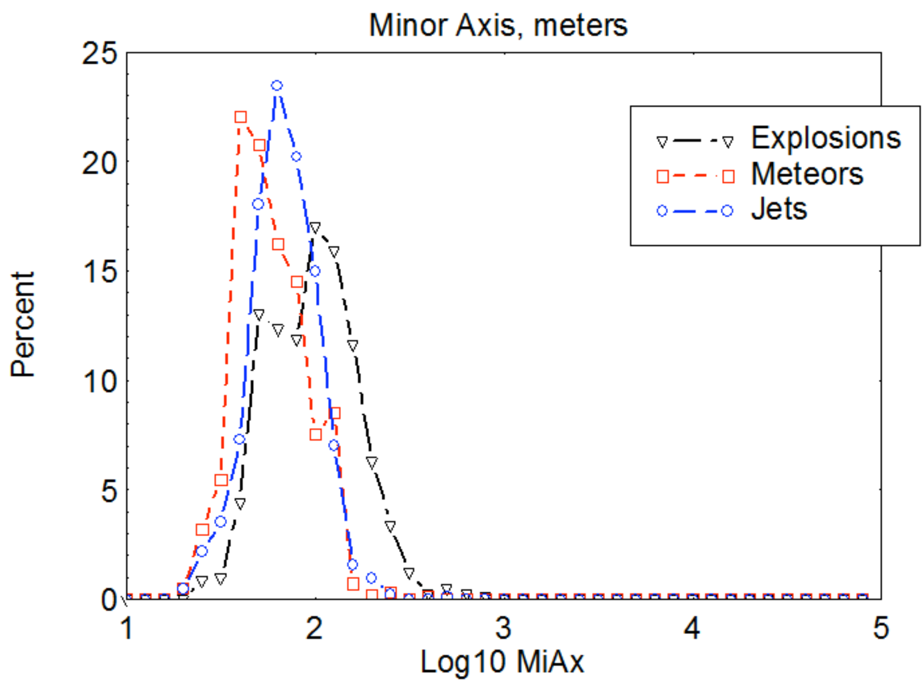


Fig. 6. Statistical distribution of minor axis for different infrasound sources: ground level explosions, meteoroid entries and supersonic jets (using logarithmic x-scale).

Other parameters which have been found useful for source identification are: the total duration of signal (N), the information density (R) and the triad describing the distributions of deviation from a plane wave (φ).

4. Neural network tool for source identification

Infrasound events with a known origin, for which the above parameters were [have been?] calculated, may be used to develop models for different types of events. In the present study a neural network modelling technique is used (cf. e. g. Liszka, 2002).

Each event is described by a vector consisting of the following 61 components:

#	
1 – 18	distribution of minor axis, a,
19 – 56	distribution of major axis, b,
57	total duration of signal expressed through number of possible readings, N,
58	information density, R,
59 – 61	lower quartile, median and upper quartile of the deviation from the plane wave, φ.

The above vector is used as input to a neural network model illustrated in Fig. 7.

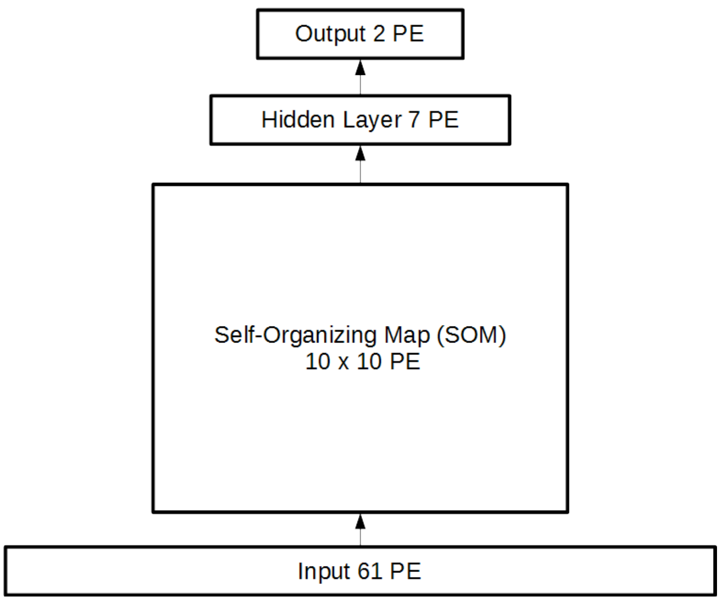


Fig. 7. A neural network model consisting of an input layer with 61 processing elements (PE), a Self-Organizing Map (SOM) consisting of 10 x 10 PEs and a simple back-propagation network consisting of a hidden layer of 7 PEs and of a 2-PE output layer.

During the training phase, when the input vector is loaded into the input layer, two values are loaded into the output layer: the code attributed to the actual type of event (an arbitrary integer: 1, 3, 5, 7…) and the log10 of the distance to the source. The network model is considered trained after a large number of inputs and corresponding outputs have been presented to the network so that network connections, synapses, have been adjusted to an optimum.

During the recall phase, new input vectors are presented and the model estimates the type of event and the log10 of the distance to the source. The model is tested using the vectors for known sources.

5. Sounding rockets: launch and reentry

A useful source of infrasonic events is launches and reentries of medium- and large-sized sounding rockets. In this chapter, high-altitude sounding rockets, especially Castor 4B and Skylark 7/VSB-30, launched from the SSC Esrange Space Center outside Kiruna, Sweden, are analyzed. Observations were performed from all infrasonic arrays belonging to SFIN (Table 1). A detailed description of rocket launch and reentry infrasound analysis has been presented earlier (Liszka, 2008). The present question is whether it is possible, using the model presented in the previous section, to identify if the signal comes from a launch or a reentry and to estimate the approximate distance to the source. Reentries of sounding rockets are interesting, since these are most similar to the reentry of space debris.

An event code 1 was attributed to each launch signal and 3 to each reentry signal. 127 observations of both launch and reentry signals, made at different arrays, were used to construct the model. When testing the trained model, non-integer event codes are obtained. With a known type of tested source it is possible to determine a distribution of obtained codes and thus the probability of correct identification. Distributions of event codes obtained from the model for launches and reentries are shown in Figs. 8 and 9.

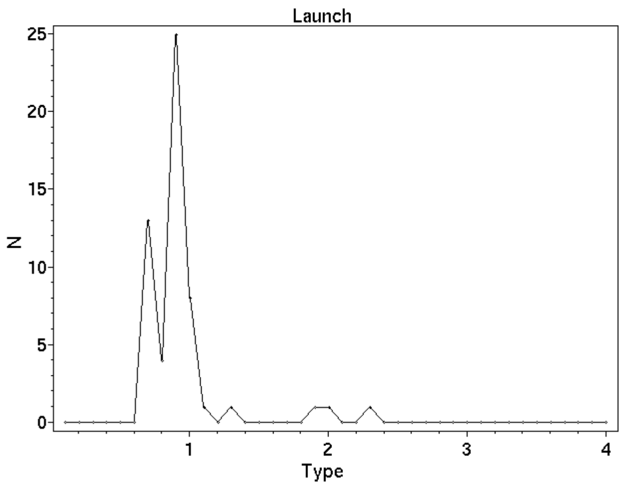


Fig. 8. Distribution of predicted event codes derived from the model when launch signals were presented.

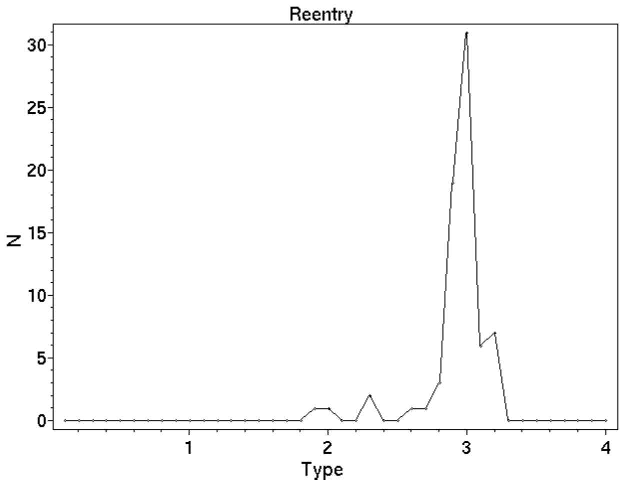


Fig. 9. Distribution of predicted event codes derived from the model when reentry signals were presented.

The sets of predicted event codes are nearly disjoint, which means that the model is able to distinguish between the launch and reentry signals. The correlation coefficient between the actual and predicted event codes is 0.96.

Prediction of the distance to the source is not as efficient as the event code. A scatter plot of the predicted log10 distance versus the true distance is shown in Fig 10.

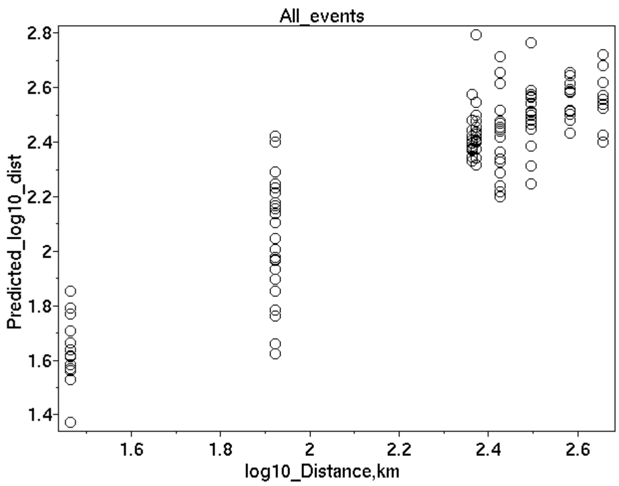


Fig.10. The predicted distance (log10) to the source (launch or reentry) plotted against the true distance.

6. Recognition of meteoroid entries

The simplest solution to try recognizing meteoroid entries is obtained by contrasting meteoroid entry data with the data from all other sources. Unfortunately, the number of meteoroid observations is much smaller than the number of observations of other sources. The configuration of the model is the same as in the previous case. The event code for meteoroid entries is now set to 1 and 3 for all other events. The distribution of event codes obtained from the model for meteoroid entries is shown in Fig. 11.

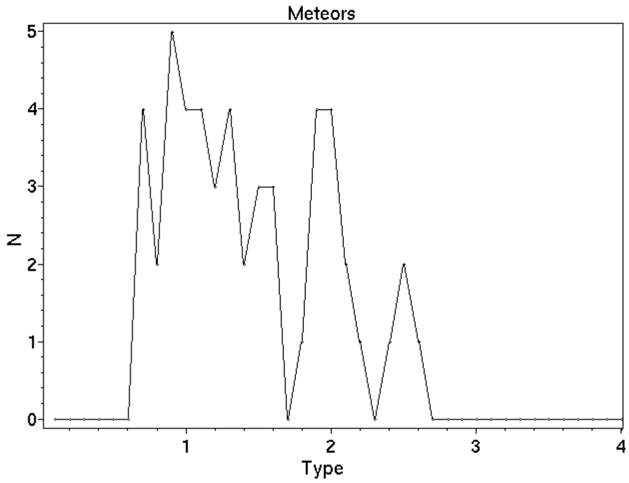


Fig. 11. Distribution of predicted event codes derived from the model when meteoroid entry signals were presented.

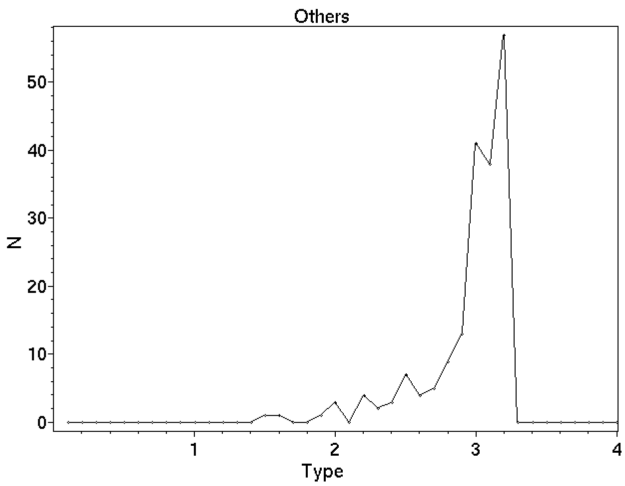


Fig. 12. Distribution of predicted event codes derived from the model when all other signals were presented.

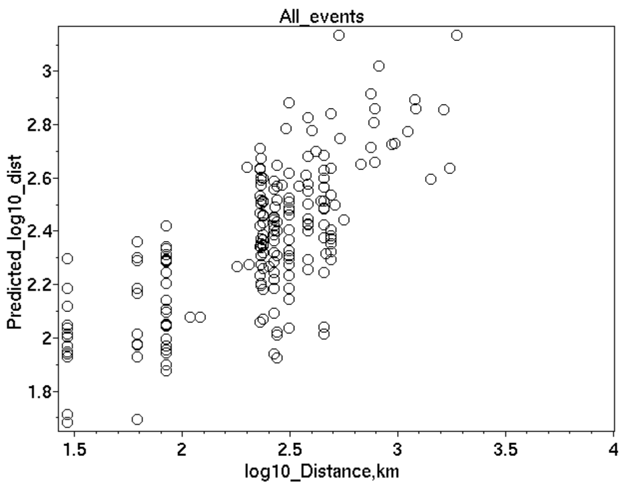


Fig. 13. The predicted distance (log10) to all five types of sources plotted against the true distance.

7. Recognition of five specific types of event

The earlier defined neural network model was also used to distinguish simultaneously between five different types of event with the following event codes:

- Rocket launch 1
- Rocket reentry 3
- Meteoroid entry 5
- Ground level explosion 7
- Supersonic jet 9

Results of recognition of five different types of events by the same network model are shown in Fig. 14. The simultaneous recognition of a number of different events (5-events model) is less efficient than recognition of only one type of event among other, unspecified events (1-event model).

It may be concluded that the 5-events model, in its present form, cannot be used to identify a single signal observed at an array.

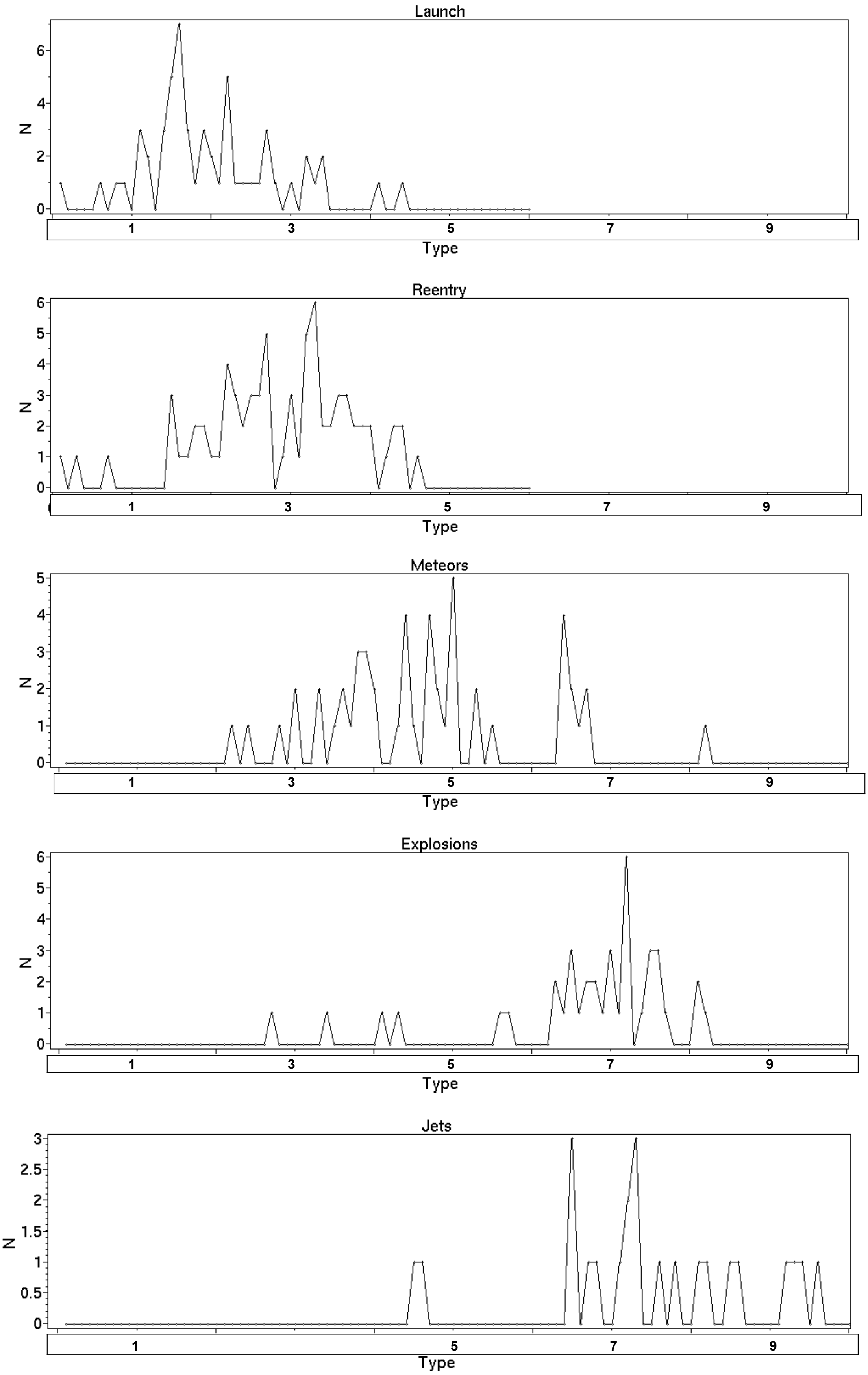


Fig. 14. Recognition of five different types of event using the same network model.

8. Estimation of meteoroid trajectories

Among the most interesting phenomena which may be studied with such a network of infrasound arrays are the entries of meteoroids into the Earth's atmosphere. A meteoroid enters the atmosphere with a speed of the order of tens of kilometres per second and generates a cylindrical shock, which is transformed into infrasound. In the final phase of its descent the meteoroid disintegrates/fragments due to the frictional heating. Each fragmentation is a source of a spherical shock wave, which also transforms into infrasound. The mechanism of meteoroid entries was discussed by ReVelle (1997). Infrasonic observations of a number of meteoroid events, made by SFIN, were discussed by Liszka (2008). Also meteoroid trajectories have been estimated from infrasonic observations (Liszka, 2008 and Liszka et. al., 2010).

During the final part of the entry the meteoroid is a 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 observed statistics of: 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. 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.

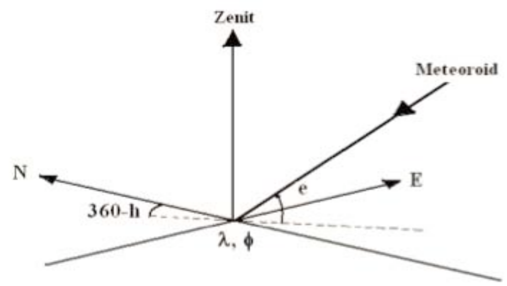


Fig. 15. Geometry of the meteoroid entry: inclination of the trajectory, e, and the heading angle, h.

The inclination of the trajectory and its heading angle may be estimated by comparing the geographical position of the source at different altitudes. The source may be localized at different altitudes by measuring the angle-of-arrival and the elevation angle at different frequencies (Liszka, 2008).

Parameters of the entry trajectory, e and h (see Fig. 15), may be converted into radiant coordinates on the sky. It can then be determined if the observed meteoroid coincides with any known radiants of meteor showers.

It has until now not been possible to make a detailed comparison of infrasonic and optical observations for events detected with SFIN. However on 21 October 2013, at 16:46 UT, a meteoroid entry occurred over Northern Sweden, detected by SFIN and by the URSA, Finnish Fireball Working Group, cameras (Lyytinen, private communication). The accurate optical observations of the event show that the meteoroid entered the atmosphere from an azimuth angle of 300° +/- 1° and on a trajectory with an elevation of 77° +/- 1° degrees. The final disintegration was located to 20.1322°E, 64.5064°N.

A compilation of infrasound data from all four arrays of SFIN results in the angle-of-arrival of the meteoroid of 282.6° +/- 20.1° and in the elevation angle of the trajectory of 81.6° +/- 8.4°. The final point of the trajectory was located, using directions from the two closest arrays, Lycksele and Jämtön, to 20.6376°E, 64.5345°N. The large errors of infrasonic determination of the angle-of-arrival are probably related to the steep entry trajectory of the meteoroid. Both infrasonic and optical locations are shown in Fig. 16. The optical (probably nearly true) location is found west of the infrasonic location. The distance between both points is approximately 24 kilometres. The infrasonic location is not corrected for the atmospheric wind system; this explains its lateral deviation.

Fig. 16. Optical (left) and infrasonic geographical location (right) of the final disintegration point of the meteoroid observed on 21 October 2013 above Northern Sweden.

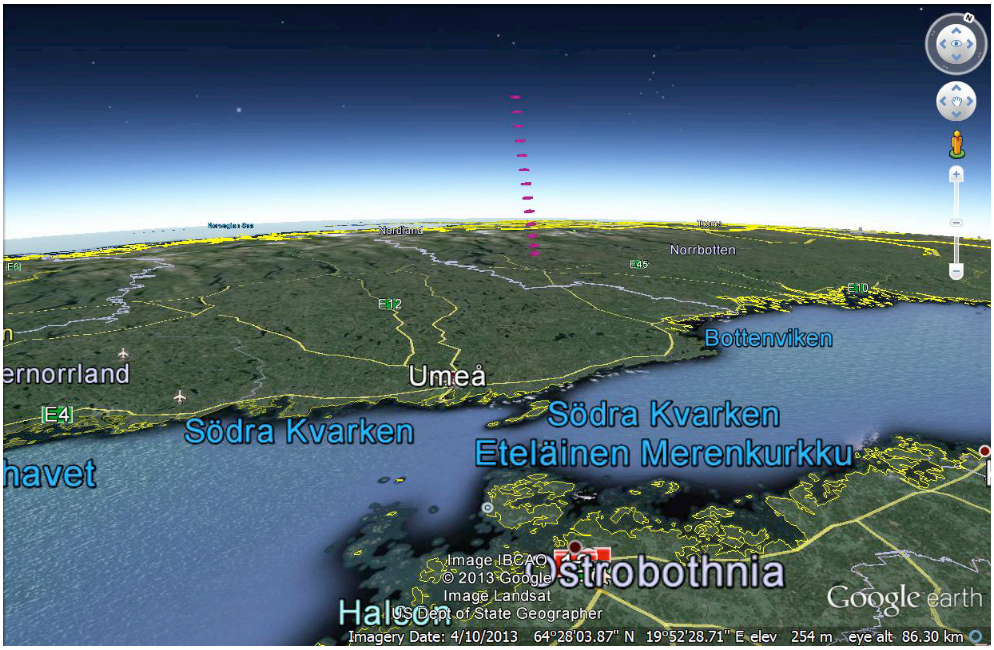


Fig. 17. A 3-D image of the meteoroid trajectory determined by the URSA, Finnish Fireball Working Group, cameras.

The azimuth and elevation of the radiant may be converted to equatorial coordinates (R.A. and δ) and plotted together with radiants of known meteor showers on a sphere, see Fig. 18.

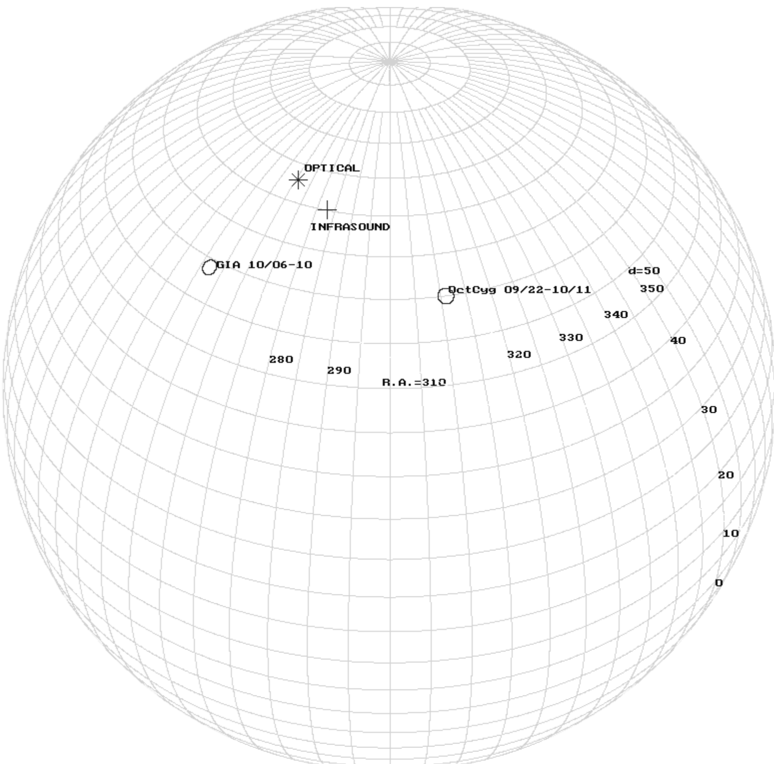


Fig. 18. Radiants of known meteor showers for October plotted on the equatorial coordinate system together with the optical (*) and infrasonic (+) radiant of the meteoroid on 21 October 2013.

9. Future development: a meta-array for space debris/meteoroid detection

It has been shown that infrasound observations can be used as an efficient tool to detect atmospheric entries of space debris and meteoroids. Infrasound is very little dependent on meteorological conditions, unlike optical observation, and can detect events occurring at greater distances, including ones below the local horizon. Infrasound is omnidirectional and, unlike radar observations, not limited to particular measurement directions. Although the accuracy of the trajectory determination and location is rather low, it can still be used to collect a large amount of useful information.

The present SFIN system for data collection and analysis may be further improved:

In the short term the following problems should be addressed:

- The present neural network models can be improved. This may be done by collecting more reference data from known events to improve the training of the models.
- The database of possible meteor entries between 1995 and 2005 will be re-analyzed and completed with possible events after 2005.

In the long term the Scandinavian network of simple tripartite arrays should be modified:

- All arrays should be expanded to four microphones to increase the quality of detections.
- The measuring accuracy (analog-to-digital conversion) should be increased to 24 bits.
- The number of arrays should be increased.

The most efficient distance between arrays seems to be of the order of 100 km. In such a case, the received signals at two (or more) arrays from any nearby source will have propagated through the same atmospheric cell. A typical example of horizontal structures in temperature and wind over Eastern Europe is shown in Fig. 19. These maps were constructed from balloon radiosondes launched simultaneously at different locations, for 10-, 20- and 30-km levels. Fig. 19 shows the 10-km level maps of the speed of sound (temperature), as well as the zonal and the meridional wind components.

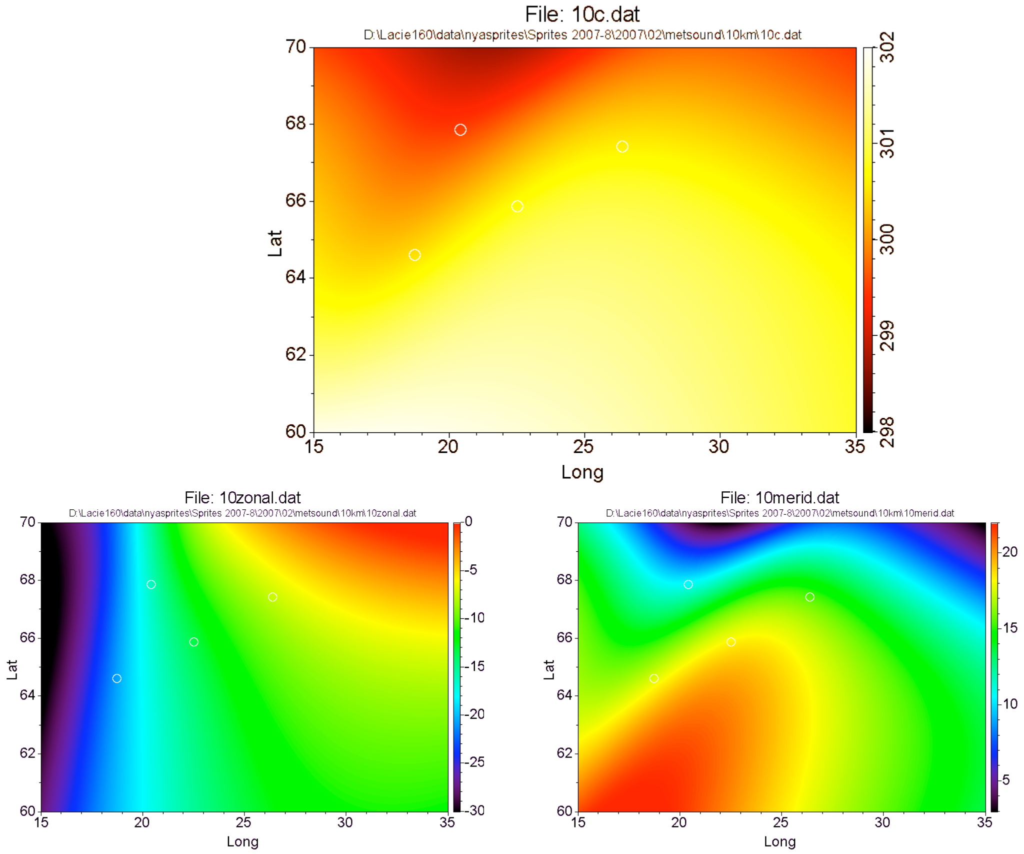


Fig. 19. Upper panel: Sound velocity (m/sec). Lower panels: zonal- (left) and meridional (right) components (m/sec) at the 10-km level above North-Eastern Europe on 23 February 2007 at 12:00 UT.

In the presence of strong horizontal gradients in the atmosphere, it frequently happens that an event cannot be seen at all arrays. For that reason a densification of the network is extremely important, if the system is to be used for routine monitoring of space debris- and/or meteoroid entries. Such a densified network could be considered a **meta-array**.

The meta-array would automatically detect, identify and localize events. It would be most useful to complement the arrays with cameras for supporting information during favourable meteorological conditions.

Acknowledgements

The authors are indebted to Esko Lyytinen for making available his analysis of the URSA, Finnish Fireball Working Group, camera observations of the meteoroid event on 21 October 2013. Rocket launch- and reentry data was kindly provided by the SSC Esrange Space Center in Kiruna, Sweden. The present research is a part of ARISE (Atmospheric dynamics Research InfraStructure in Europe), a collaborative infrastructure Design Study project funded by the FP7 European Commission under the Capacities Programme.

References

Ludwik Liszka: *Auroral zone ionosphere investigations using transmissions from artificial earth satellites* doctoral thesis, Uppsala: Almqvist & Wiksell, 1963.

Ludwik Liszka: *Cognitive Information Processing in Space Physics and Astrophysics*, Tucson, Ariz.: Pachart Publ. House, 2003, ISBN 0-88126-090-8.

Ludwik Liszka: *Listening to Meteors - Infrasonic Observations of Meteors in Northern Sweden*, IRF Scientific Report 295, April 2008, ISBN 978-91-977255-4-5.

L. Liszka, T. Kvaerna, C-F. Enell and T. Raita: Infrasonic Observations of Recent Meteoroid Entries over Northern Scandinavia. *Inframatics Newsletter*, June 2010.

Ludwik Liszka and Lars Eliasson: Source-specific variations of the infrasound intensity pattern on the ground. Paper presented at 1st ARISE Workshop, University of Reading, England, September 2012. (Unpublished.)

ReVelle, D. O.: Historical Detection of Atmospheric Impacts of Large Bolides Using Acoustic-Gravity Waves, in J. L. Remo (ed.), *Annals of the New York Academy of Sciences*, vol. 822, Near-Earth Objects: The United Nations Conference, 1997, pp. 284–302.

Institutet för rymdfysik

Swedish Institute of Space Physics

Swedish Institute of Space Physics
Box 812, SE- 981 28 Kiruna, SWEDEN
tel. +46-980-790 00, fax +46-980-790 50, e-post: irf@irf.se

www.irf.se