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PROPAGATION OF INFRASOUND FROM CHEMICAL EXPLOSIONS

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Introduction

The Swedish Institute of Space Physics (IRF) operates—since the early 1970s—four infrasound stations: Kiruna, Jämtön, Lycksele and Uppsala (see Table 1 and Fig. 1). All original time series collected since 1994 are stored in a data base accessible for general public at the Internet home page of the Swedish Institute of Space Physics (http://www.umea.irf.se) together with all standard software needed for data analysis. Each station consists of a tripartite microphone array located in corners of an isosceles triangle, oriented in NS-EW directions. 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.

Name	Latitude (Degrees)	Longitude (Degrees)
Kiruna	67.8°N	20.4°E
Jämtön	65.87°N	22.51°E
Lycksele	64.61°N	18.71°E
Uppsala	59.85°N	17.61°E

Table 1: Stations in the Swedish Infrasound Network (SIN)

Data from all arrays are continuously analysed using a cross-correlation method (Waldemark, 1995). The software: crcorr.exe for data analysis and crview.exe for viewing of result files, may be downloaded from http://www.umea.irf.se when you select: *Locally developed software.*

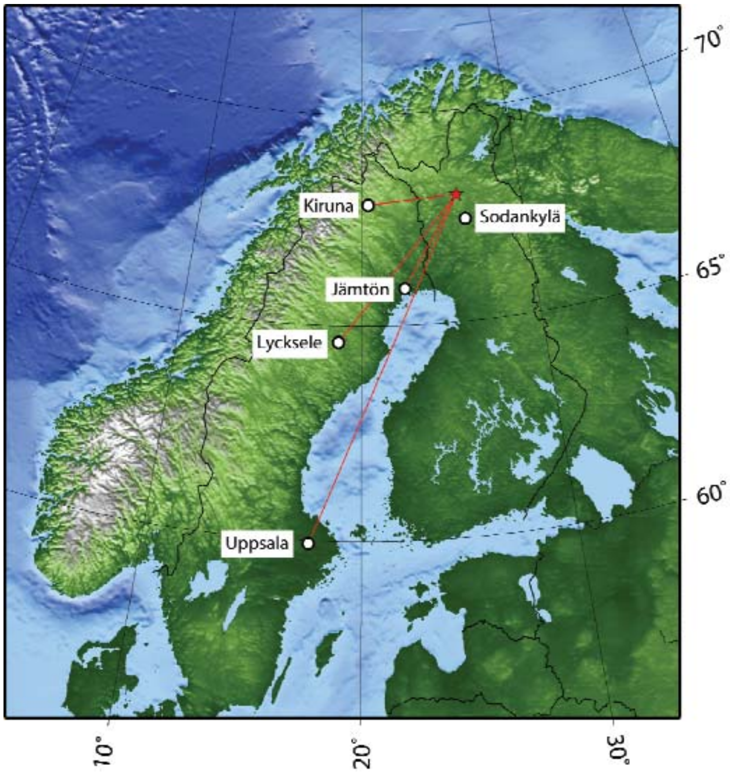

Fig. 1. Location of the infrasound stations in Sweden with respective directions to the explosion site (red star).

Frequency band #	Frequency, Hz	Type of filter	Centre frequency, Hz
1	<1	Low-pass	.75
2	1-2	Band-pass	1.5
3	2-3	"	2.5
4	3-4	"	3.5
5	4-5	"	4.5
6	>5	High-pass	5.5

Table 2: List of wavelet filters

The analysed signals are band-pass-filtered in the frequency range 0.5-6 Hz. Recently, filtered data in six narrow frequency bands have been used. The filtering process is performed using six wavelet filters specified in Table 2. The detection criterion is based on the value of the product, of all three correlation coefficients in the array. Calculated values of the angle-of-arrival, A, and of the horizontal trace velocity, Vp, are assumed significant for 0.02, which corresponds to the average cross-correlation coefficient between two microphones of approximately 0.3.

The infrasonic stations record daily a large amount of infrasonic signals. Unfortunately, usually there is no information about the origin of these signals. A new possibility to study the propagation of infrasound at distances up to 1000 km opened combining seismic data collected by NORSAR, Norway, concerning a long series of chemical explosions (probably destruction of explosives) carried out in Northern Finland during the summers from 2001 to 2006 (Gibbons *et al.,* 2007). The accurate time of origin of each event was determined at NORSAR from seismic recordings at NORSAR stations. It was also possible to establish, by investigating the events' signatures, that each event corresponds to a single explosion (and not to a series of close explosions). All explosions took place during the daytime, at the approximately the same geographical location (68.0°N 25.96°E) on a daily basis between August 15 and September 15, each year. It is estimated that the Finnish explosions, having seismic magnitudes around ML1.3, had yields equivalent to around 10 tons TNT. This estimate is based on the comparison with reported charges of about 20 tons for similar ammunition destruction explosions in Älvdalen, Sweden (Gibbons *et al.,* 2002), which had seismic magnitudes of about ML 1.5.

Table 3 shows the directions to the explosion site from each station and the corresponding distances in kilometers.

Name	Direction (Degrees)	Distance (km)
Kiruna	83.5	231
Jämtön	30.8	280
Lycksele	37.3	492
Uppsala	20.8	978

Table 3: Directions and distances to the explosion site

The present report contains a detailed analysis of infrasonic recordings made during the period August 16-September 14, 2006 and its possible interpretation.

Collected Data

During the period August 16-September 14, 2006 explosions were taking place daily between 0900 and 1330 UT, except for August 30. It was assumed that a signal was recorded at a given station when there was a significant angle-of-arrival measurement within the expected range of azimuth around the true direction to the explosion. That means that the detectability of the signal was considered depending not only on the amplitude of the signal, but also on the cross-correlation across the array. The time-of-arrival/signal duration and the interval of directions around the true directions to the explosion are shown for all stations. All explosions were detected at the Kiruna-array, located only 231 km from the explosion site (Fig. 2).

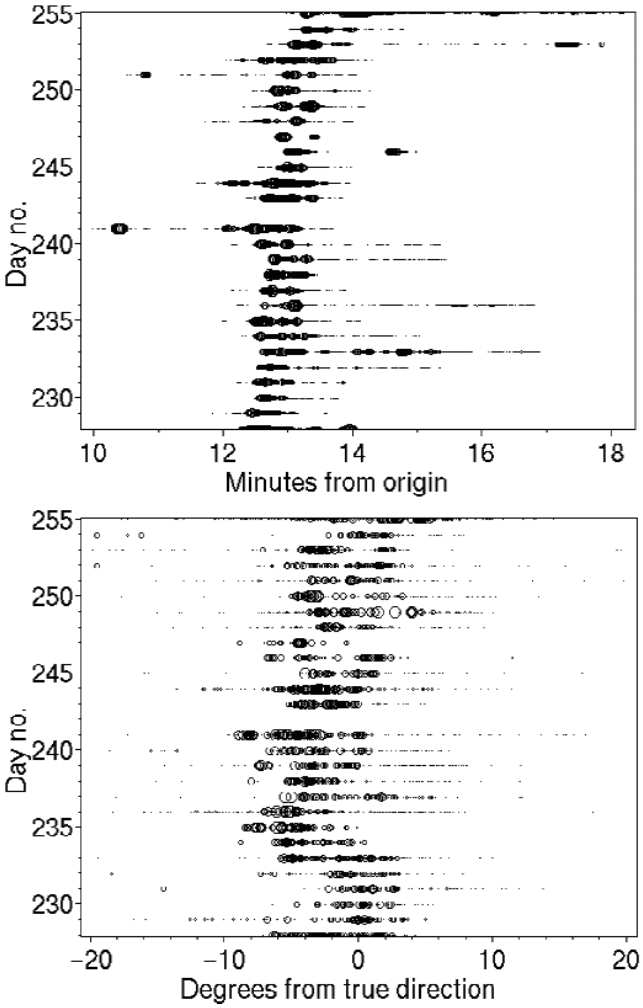

Fig. 2. Explosions observed by the Kiruna-array. The time-of-arrival/signal duration (upper graph) and the interval of directions around the true direction to the explosion (lower graph) are shown. The size of the symbols is proportional to the value of the product ρ of cross-correlation coefficients across the array.

It is interesting that the Jämtön-array, located at a distance of 280 km from the explosion site, does not detect explosions during the last week of August 2006, see Fig. 3.

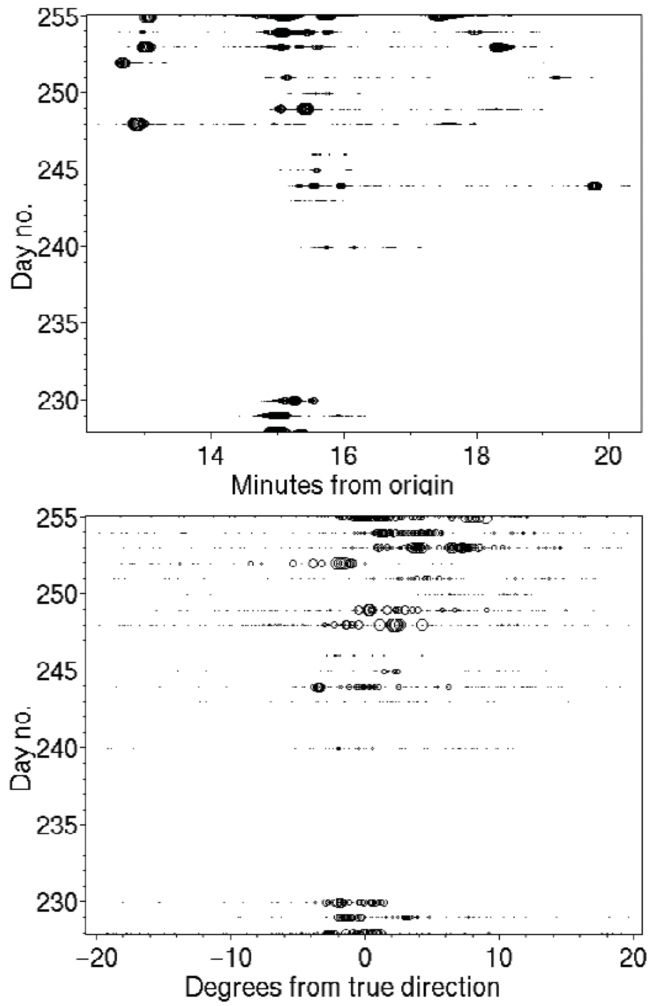

Fig. 3. Explosions observed by the Jämtön-array. The time-of-arrival/signal duration (upper graph) and the interval of directions around the true direction to the explosion (lower graph) are shown. The size of the symbols is proportional to the value of the product ρ of cross-correlation coefficients across the array.

In Lycksele, at a distance of 492 km from the explosion site, only very weak and short signal bursts are observed between August 23 and September 10 (Fig. 4),

In Uppsala, at a distance of 978 km, there is usually no detectable signals. However, during 3 days of August 2006 (August 19-21) weak, intermittent signals were observed also at that station (see Fig. 5).

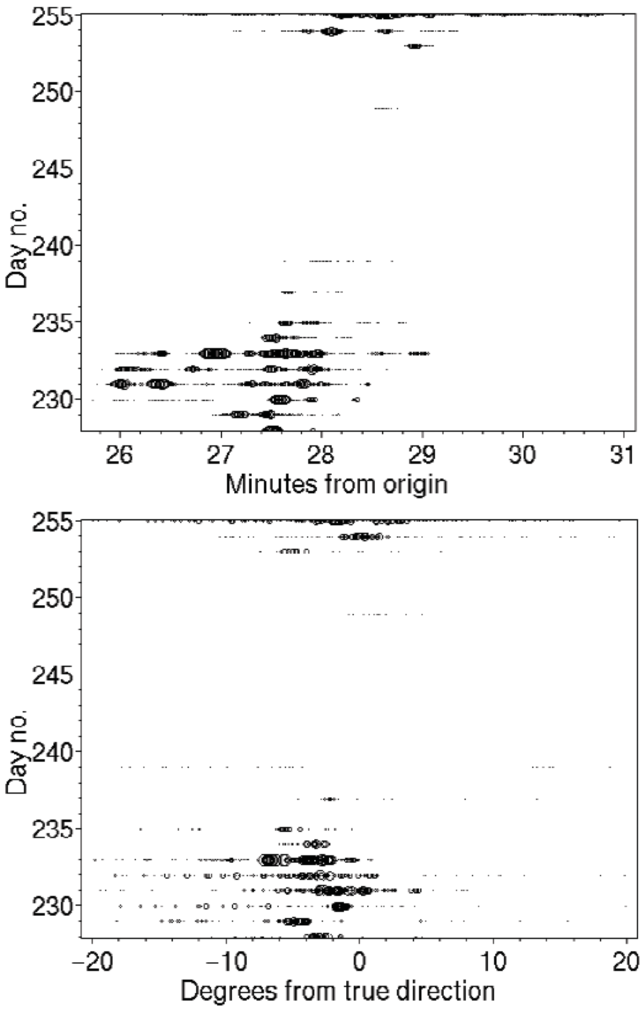

Fig. 4. Explosions observed by the Lycksele-array. The time-of-arrival/signal duration (upper graph) and the interval of directions around the true direction to the explosion (lower graph) are shown. The size of the symbols is proportional to the value of the product ρ of cross-correlation coefficients across the array.

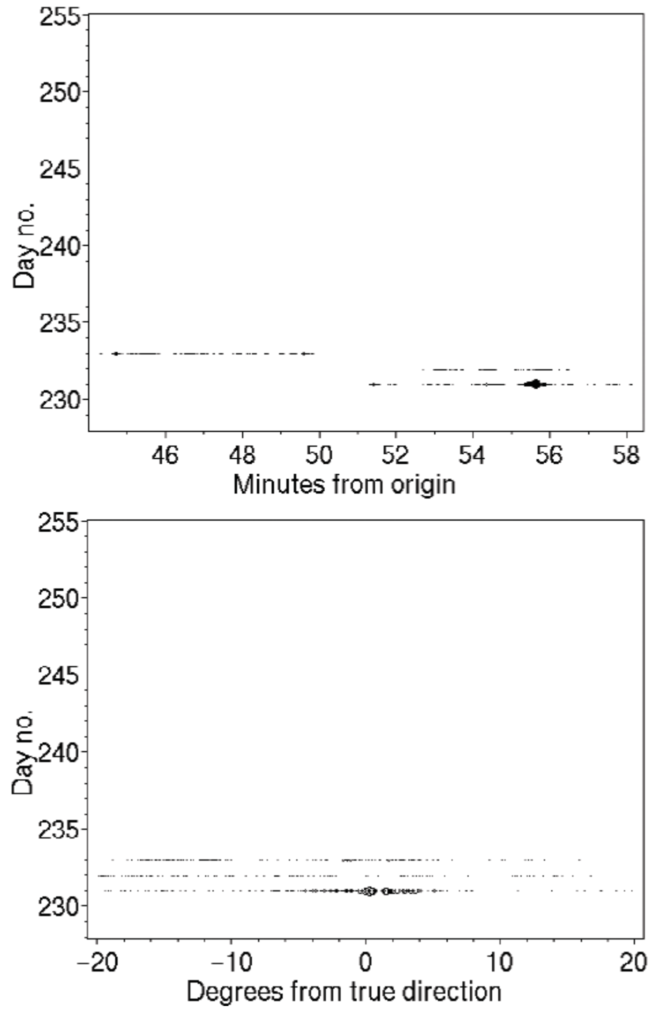

Fig. 5. Explosions observed by the Uppsala-array. The time-of-arrival/signal duration (upper graph) and the interval of directions around the true direction to the explosion (lower graph) are shown. The size of the symbols is proportional to the value of the product ρ of cross-correlation coefficients across the array.

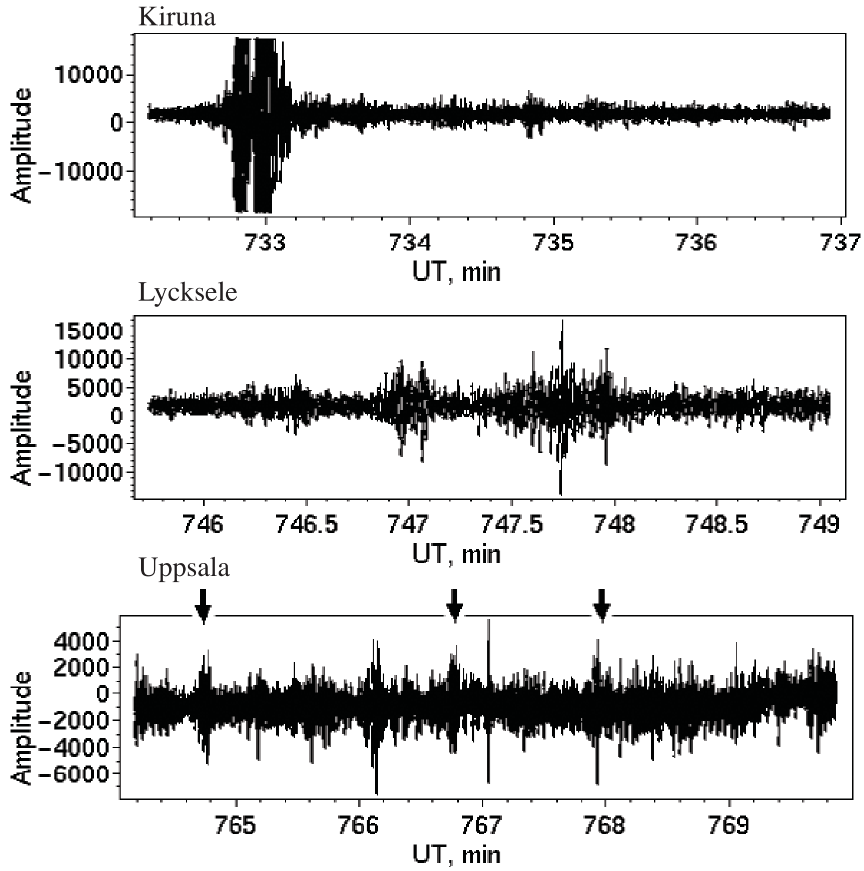

Fig. 6. Amplitude recordings (in A/D-unit) of the explosion on August 21, 2006 at arrays in Kiruna, Lycksele and Uppsala. Arrows on the Uppsala recording indicate arrivals of the explosion signal clearly visible in Fig. 7.

August 21, 2006

On August 21, 2006 (day no. 233), no signals were observed at Jämtön-array (280 km from the explosion site), while Uppsala, at a distance of 978 km, was recording at least three significant bursts of the signal. The amplitude recordings from three arrays, which recorded the explosion, are shown in Fig. 6. In order to demonstrate the complicated nature of the propagation process, detailed graphs of the measured angle-of-arrival as a function of time are shown in Fig. 7 for all three arrays. The size of the symbols is proportional to the value of the product ρ of cross-correlation coefficients across the array. Kiruna and Lycksele show a semi-regular oscillation of the angle-of-arrival, while Uppsala shows only three bursts of the signal.

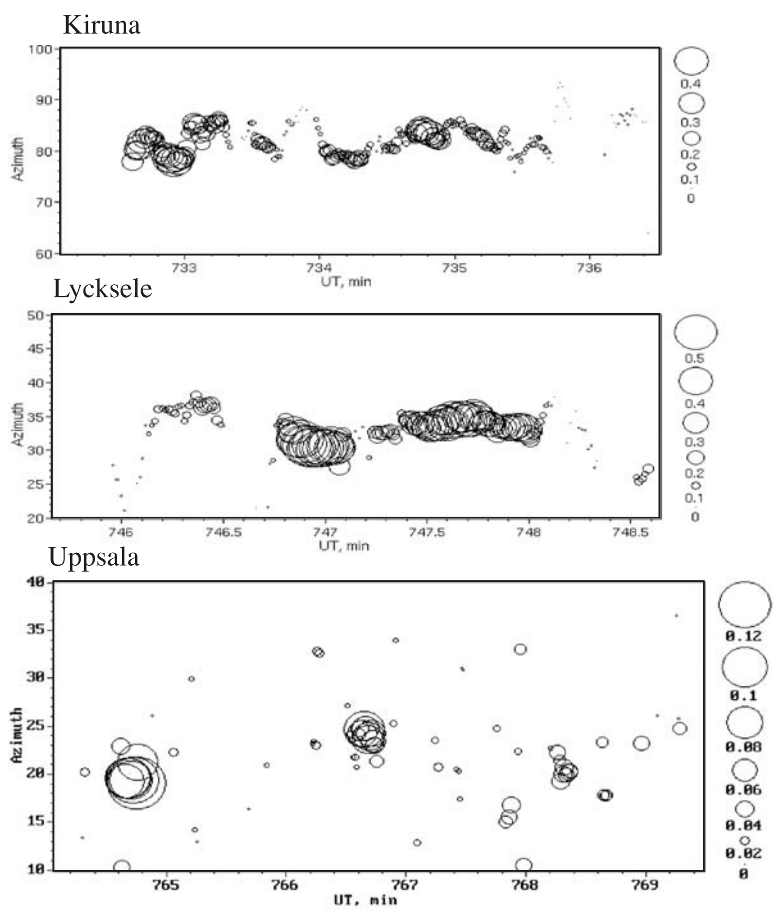

Fig. 7. Angle-of-arrival (clockwise in degrees from N) of signals from the explosion on August 21, 2006 at arrays in Kiruna, Lycksele and Uppsala. The size of the symbols is proportional to the value of the product ρ of cross-correlation coefficients across the array.

The semi-regular variation in properties of the signal is even clearer seen when the product ρ of cross-correlation coefficients across the array is plotted as a function of time. These graphs are shown in Fig. 8.

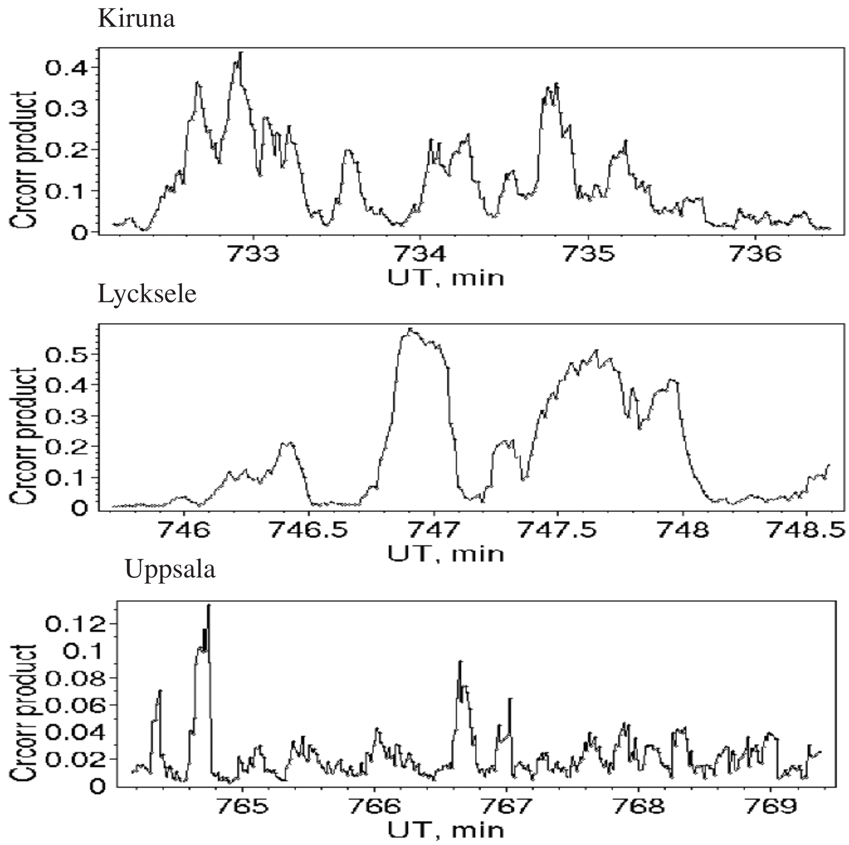

Fig. 8. The product ρ of cross-correlation coefficients across the array plotted as a function of time for arrays in Kiruna, Lycksele and Uppsala. Observe semi-regular variations of the cross-correlation product, ρ , most clearly visible in Kiruna.

Multifrequency Measurements

In order to study the properties of the signal as a function of frequency, the signal recorded in Kiruna in the frequency band 0.5-6 Hz was filtered with 6 wavelet filters. The frequency ranges and corresponding median values of the angle-of-arrival, of the trace velocity and of the cross-correlation product are shown in Table 4.

All frequency bands, except the first one (<1 Hz) show consistent results. The true, geometrical, angle-of-arrival is 83.5 degrees (see Table 3). There are at least two reasons for the deviating result in the first band:

- The effective frequency of the first band is 0.75 Hz. With the array side of 75 meters the accuracy of determination of both variables is very low.
- The S/N ratio in the first band is low since the sensitivity of the microphone drops approximately 3 dB between 1 and 0.5 Hz.

Frequency Range Hz	Median Angle-of-arrival degrees	Median Trace velocity m/sec	Median Cross correlation Product
< 1	107.7	195.7	0.081
1-2	80.8	320.6	0.102
2-3	84.7	320.6	0.109
3-4	86.4	324.6	0.112
4-5	83.6	333.2	0.129
>5	87.7	331.9	0.138

Table 4. Median values from multifrequency measurements

It must be remembered that the microphone was intended for use at frequencies above 1 Hz.

The low trace velocities observed within the entire frequency range indicate that the infrasonic waves from the explosion propagate through reflections in the troposphere and the stratosphere.

The fine structure of both variables and of the cross-correlation product in time- and frequency domain may be studied in Figs. 9-11. Most details are visible, as it could be expected, in the frequency bands 1-2 and 2-3 Hz

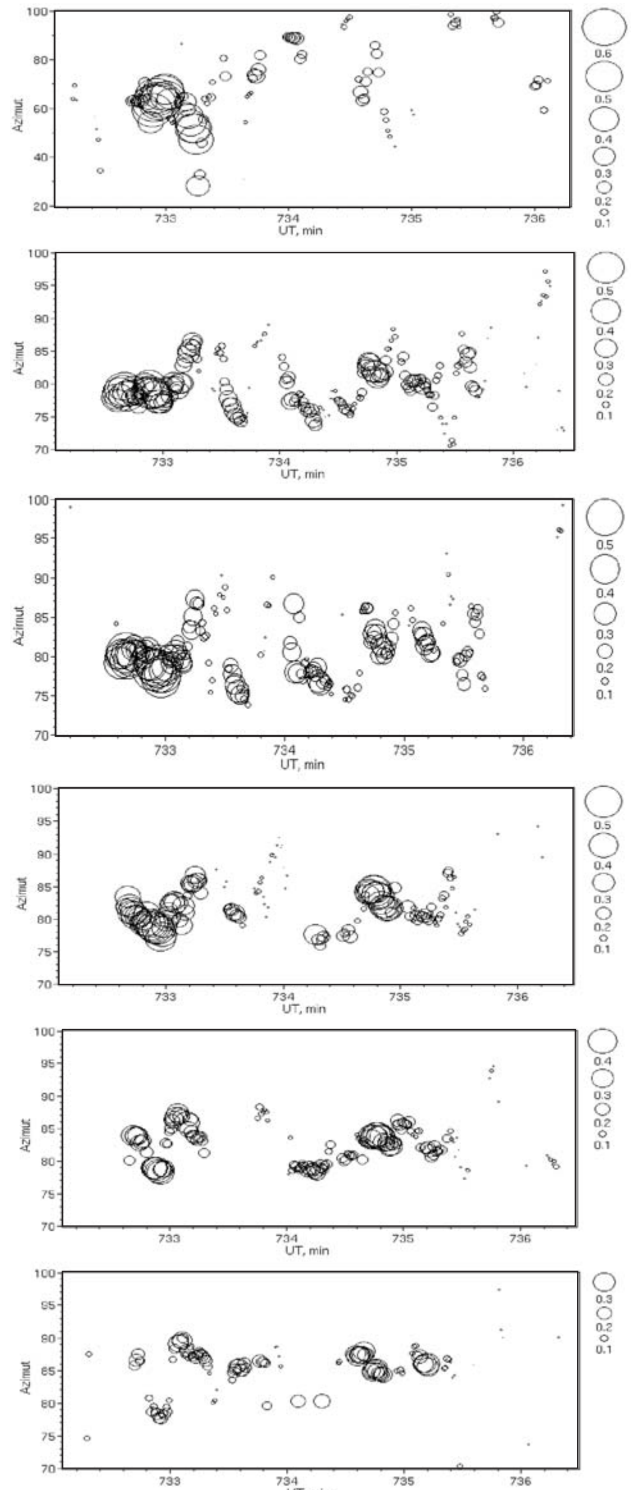

Fig. 9. Time variations of the angle-of-arrival for all six frequency bands for the explosion on August 21, 2006 recorded in Kiruna. The size of the symbols is proportional to the value of the product ρ of cross-correlation coefficients across the array.

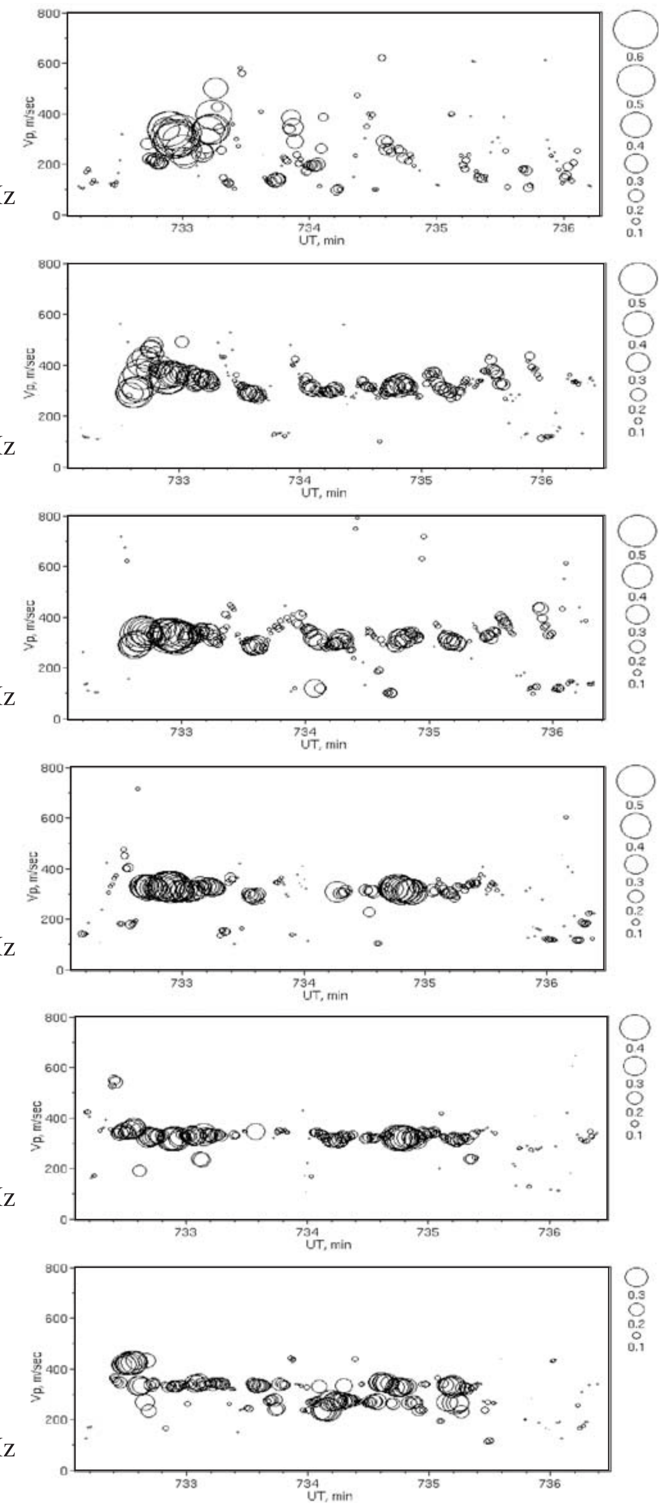

Fig. 10. Time variations of the horizontal trace velocity for all six frequency bands for the explosion on August 21, 2006 recorded in Kiruna. The size of the symbols is proportional to the value of the product ρ of cross-correlation coefficients across the array.

Discussion of Results

A number of interesting conclusions may be drawn from the presented data.

The average signal duration for all arrays and for the days August 16-26 (data taken from Figs. 2-5) is shown in Fig. 12. The above observation, that infrasound from relatively small explosions, may be detected at a distance of 1000 km is astonishing. The signals from the Finnish explosions were observed by the Uppsala-array (see Fig. 5) on August 19, 20 and 21, which corresponds to the weekdays: Saturday, Sunday and Monday. It was already shown in 1974 (Liszka, 1974) that the man-made infrasound background at 2 Hz has a clear minimum during weekends. During the second half of August it was found that the uncorrelated background at the Uppsala array was, on average, 10% lower on Saturdays and Sundays than during weekdays. It must be remembered that the Uppsala-array was located only 10 km from the city of Uppsala and about 40 km from the largest Swedish airport: the Arlanda Airport.

Since the signals from the Finnish explosions were not observed during other weekends during the period August 15-September 15, the observations during August 19-21 must be a result of combination of anomalous propagation conditions and of the lower background, at least on August 19 and 20.

The most important result, shown in Fig. 13, is that the distribution of azimuths of the incoming signal is practically unchanged between 300 and 500 km. Not until distances around 1000 km, if any signal is detected, the distribution broadens and secondary maxima occur.

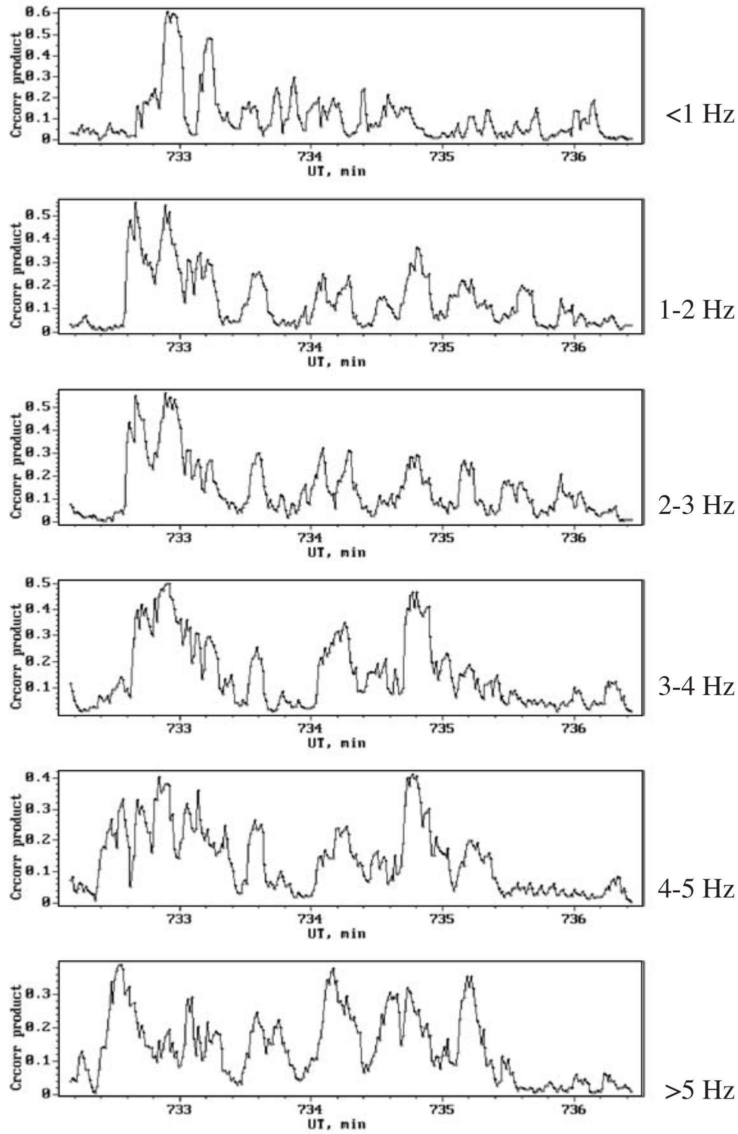

Fig. 11. Time variations of the cross-correlation product for all 6 frequency bands for the explosion on August 21, 2006 recorded in Kiruna.

It could be expected that the width of the distribution should be a linear function of the distance if the spread of angles-of-arrival would be a result of irregularities in the refractive index of the atmosphere. One possibility is that it is mainly the atmospheric structure above, and in the vicinity of the explosion site, which determines the set of possible propagation paths. In fact, it may be seen from radiosonde measurements, that the temperature, and in

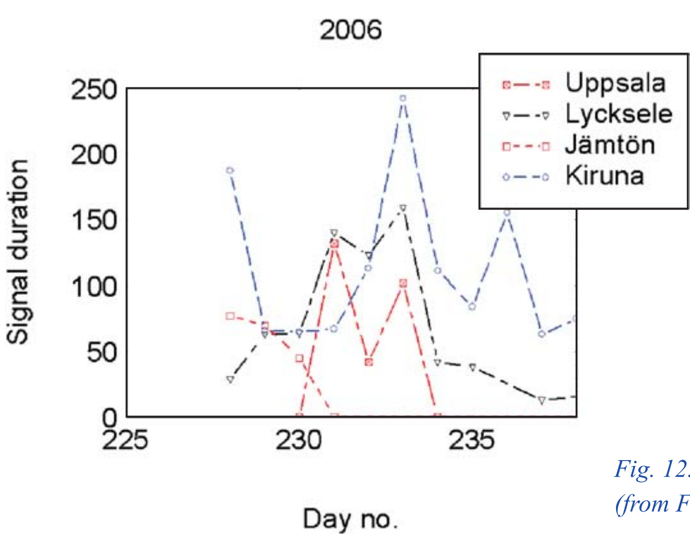

Fig. 12. The average signal duration in seconds (from Figs. 2-5) for all arrays and for days August 16-26.

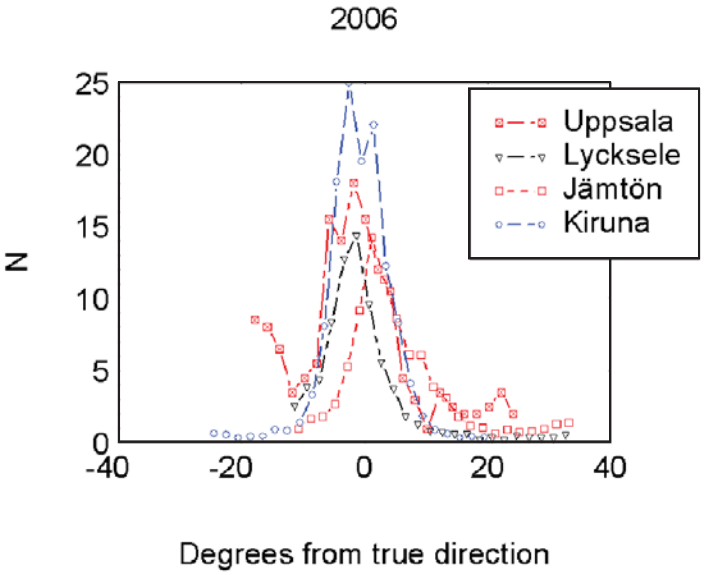

Fig. 13. Average distributions of the angle-of-arrival around the true direction to the source (from Figs. 2-5) for all four arrays.

particular the wind around the tropopause and in the lower stratosphere show a distinct fine structure, see Fig. 14.

These irregularities may extend both in vertical and in horizontal direction, since with a single radiosonde it is not possible to separate vertical and horizontal irregularities.

Effects of atmospheric irregularities on the propagation of infrasound were discussed earlier by Liszka (1997).

When infrasound measurements are made using conventional microbarographs the duration of the recorded signal from an explosion at 200 km distance is usually short. Additional short signals, attributed to different propagation paths, are often observed. When using a high sensitivity free-field microphone, the time between different signal components is often filled with a detectable signal: this may be seen in Fig. 2, showing the signal duration observed by the Kiruna-array. On several occasions signal durations over 4 minutes were observed in spite of the relatively short (231 km) distance to the explosion site. It may be seen that the propagation time can vary between 12 and 17 minutes. To explain that by a distribution of lengths of propagation paths it is necessary to assume that the longest propagation path is about 40% longer than the shortest. It is not obvious how to explain the observed signal duration using a conventional ray-tracing model.

Another possibility is, that there exists a mechanism changing the effective sound velocity, responsible for the observed distribution of propagation times.

It is also possible that these long-lasting infrasonic signals are the effects of the omnipresent fine structure of the atmosphere.

It will be interesting to study the signal characteristics at a closer distance from the explosion site. This will become possible during the summer 2007, since the Uppsala-array has been moved, in November 2006, to Sodankylä, Finland, that is only 67 km from the explosion site.

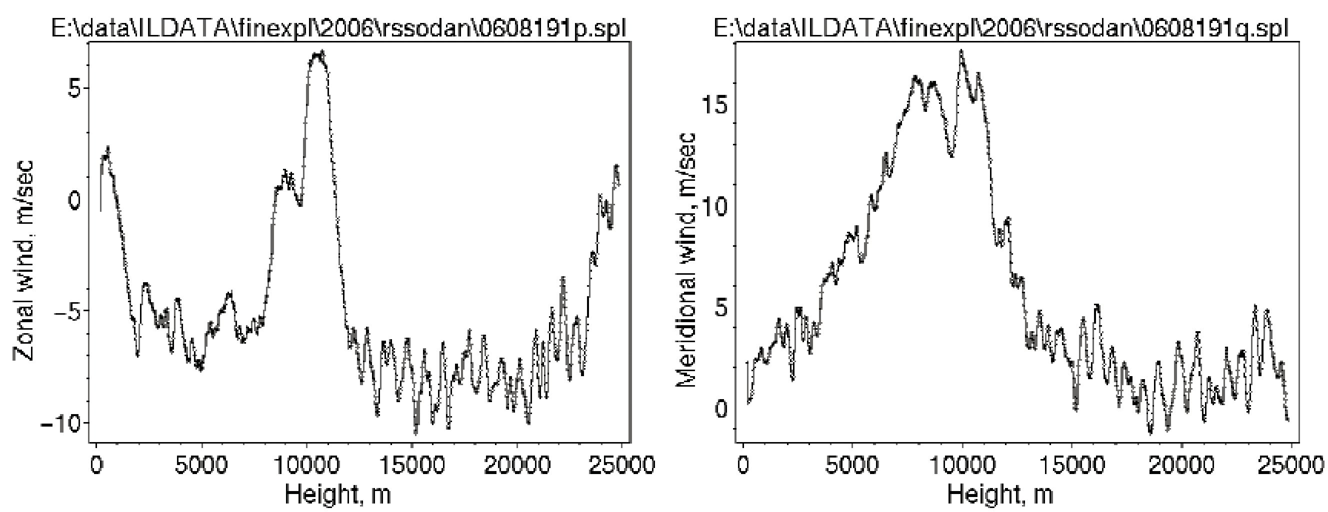

Fig. 14. Zonal (left) and meridional (right) winds over the Northern Finland (source: Finnish Meteorological Institute) up to 25000 m height on August 19, 2006, one of the days when the anomalous propagation was observed, Positive direction of the zonal wind is towards W and of the meridional wind towards S.

Acknowledgements

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