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6.2 Infrasound observations of two recent meteor impacts in Norway

6.2.1 Introduction

During the summer of 2006, a large number of people observed sound and light phenomena from two meteor impacts in Norway. The first impact was on 7 June at about 00:07 GMT in northern Norway (Finnmark) and the second impact was on 14 July at about 08:18 GMT in southern Norway (Oslo Fjord area). The observations indicate that the first event was larger than the second. Fragments of the meteors have up to now only been found for the second event in Rygge and Moss (see e.g., Aftenposten, 17 & 18 July 2006).

After NORSAR was informed by interested or frightened people about their meteor observations, a detailed data analysis was started to search for infrasonic or seismic signals of these explosive events in the atmosphere. In both cases, we were able to find such signals and to define a location of the probable explosions. This contribution reports on these preliminary results.

6.2.2 The impact of 7 June 2006

Observations on the ARCES seismic array

As known from former studies, the seismic sensors of the ARCES array are quite sensitive to infrasound signals (Ringdal & Schweitzer, 2005; Ringdal & Gibbons, 2006; Schweitzer et al., 2006). The meteor itself most probably exploded in the atmosphere at approximately 10 to 20 km above the ground. Until now, no fragments were found. The explosion was heard over a large area of northern Norway, and although the sky was quite bright due to the midnight sun, the explosion was also observed visually, and pictures are available from its smoky trace (e.g., Aftenposten, 9 June 2006).

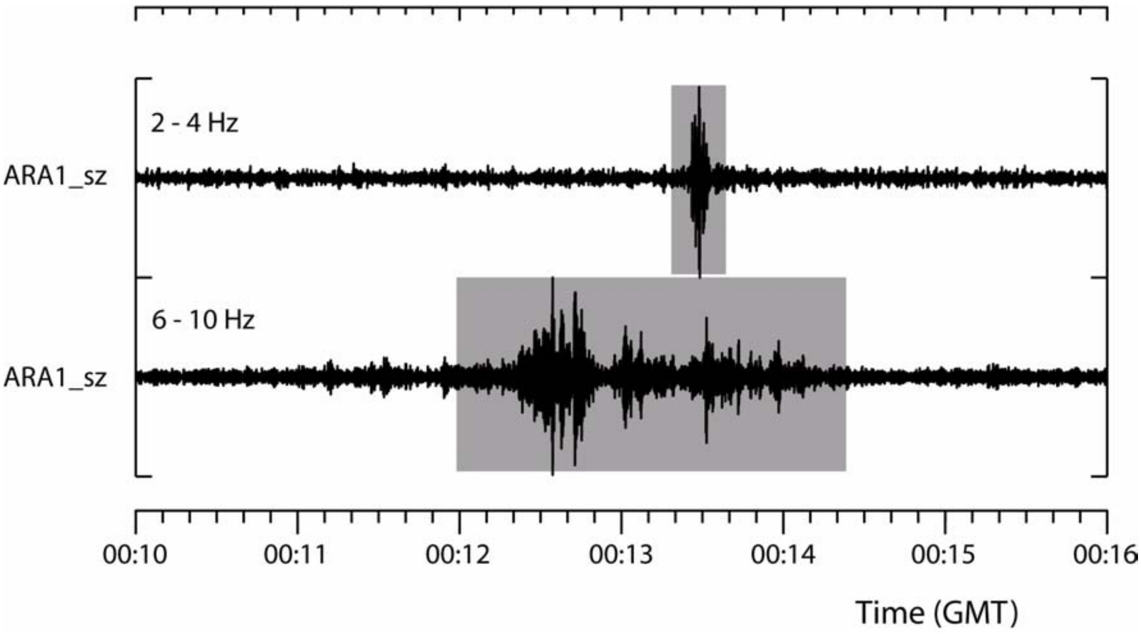

Fig. 6.2.1. The two different signals observed at the ARCES site A1. The upper trace shows the infrasound signal of the meteor explosion on 7 June 2006 and the lower trace higher frequency Rg waves observed at the same time.

The ARCES array is located east of the presumed explosion and, some minutes after the reported explosion time, a strong signal was recorded crossing the array from west to east with an apparent velocity of about 330 m/s. The upper trace in Fig. 6.2.1 shows this signal at the ARCES array site ARA1 after Butterworth bandpass filtering between 2 and 4 Hz. The lower trace in Fig. 6.2.1 shows a higher frequency signal (filtered between 6 and 10 Hz) that reached the array during the same time window from the west but with varying backazimuth (BAZ) and an apparent velocity of about 2.5 km/s, which is typical for Rg phases. In a first interpretation it was assumed that these signals were generated by the same source but the varying BAZ of the Rg-type energy was impossible to explain with the single explosion of a meteor.

To investigate these two signals in more detail, vespagrams were calculated in different frequency ranges and for different apparent velocities. The left panel of Fig. 6.2.2 shows a vespagram for a 20 minute long time window and a constant BAZ of 260 degrees. Two different signals are clearly visible: one with an apparent slowness of about 0.4 s/km (the Rg signal) followed by a signal with an apparent slowness of about 3 s/km (the infrasound signal). The right hand panel of Fig. 6.2.2 shows the time dependence of the infrasound signal (i.e., for energy with a constant apparent slowness of 3 s/km) with respect to the observed BAZ. The vespagram shows that the infrasound signal was generated during one single event and that its BAZ is quite stable at about 259 degrees.

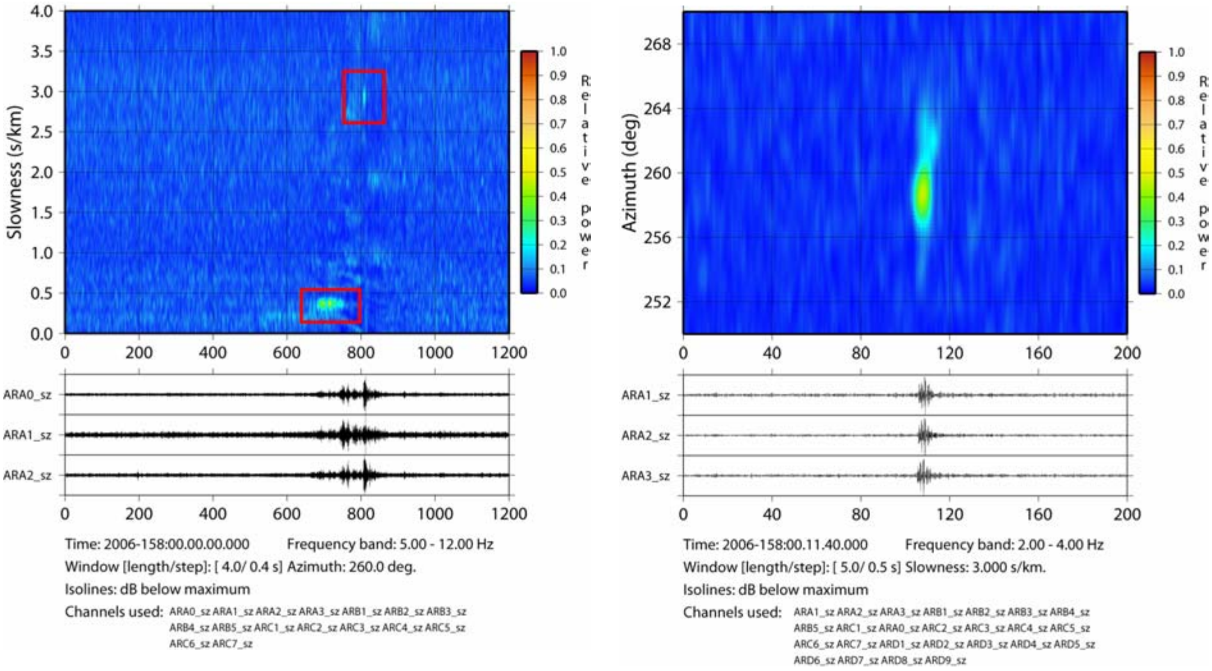

Fig. 6.2.2. Vespagrams of the data recorded at ARCES, see text for details.

Fig. 6.2.3 shows on the left the vespagram of the Rg signal recorded with the infrasound signal. In this case the constant apparent velocity was 2.5 km/s. As can be seen, the Rg signal starts earlier and ends later than the infrasound signal, which would be visible at about 200 s after the start of the vespagram. The spread of the BAZ values is quite remarkable and can only be explained by a moving source, active for more than 3 minutes. However, detailed calculations of theoretical travel time differences between the infrasound signal and an eventually ground coupled Rg energy could not be matched with the observations, and in addition the quite high signal frequency of the Rg energy indicates that the source may be located quite close to the array. Some hours later a similar signal could be observed and its vespagram is shown on the right panel of Fig. 6.2.3. It is obvious that the two vespagrams are almost the mirror of each other: once the source moves from north to south (left) and once from south to north (right). Already in earlier times it was observed that heavy vehicles driving on a road at about 1 km west of the array can be seen on seismograms whenever they crossed significant bumps in the road. One can project the observed BAZ range of about 195 to 265 degrees onto this road, which give a road length of about 5 km. Driving with an assumed velocity of 90 km/h, a car will need about 200 s to drive these 5 km. Therefore, it is clear that the Rg signal observed in parallel with the infrasound signal from the meteor explosion was caused by a heavy vehicle driving on this road.

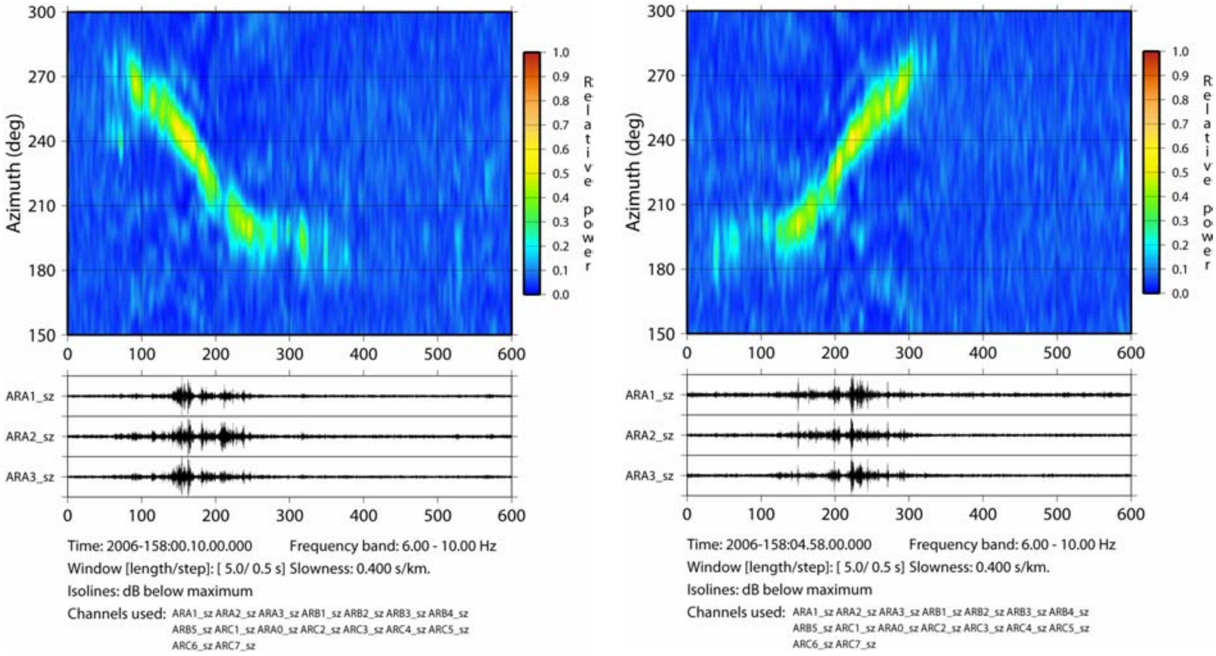

Fig. 6.2.3. Vespagram of the Rg signal as recorded at ARCES in parallel to the infrasound signal on the left and on the right a similar Rg signal recorded approximately 5 hours later.

Observations at the Apatity infrasound array

Many infrasound signals observed at ARCES are also detected by the infrasound array collocated with the Apatity seismic array on the Kola peninsula (Ringdal & Schweitzer, 2005; Ringdal & Gibbons, 2006). Therefore, we searched the infrasound data recorded at Apatity for a signal from this meteor explosion. Unfortunately, the infrasound data were quite noisy during the expected arrival time window and no clear signal is visible on the records. Fig. 6.2.4 shows on the left side the search vespagram for the BAZ range of 180 to 360 degrees during one hour after the event. On this vespagram two signals become visible (blue box) indicating coherent energy arriving the array from a BAZ of about 300 degrees. On the right side of Fig. 6.2.4 a more detailed vespagram is shown for the time and BAZ range around the detected signals.

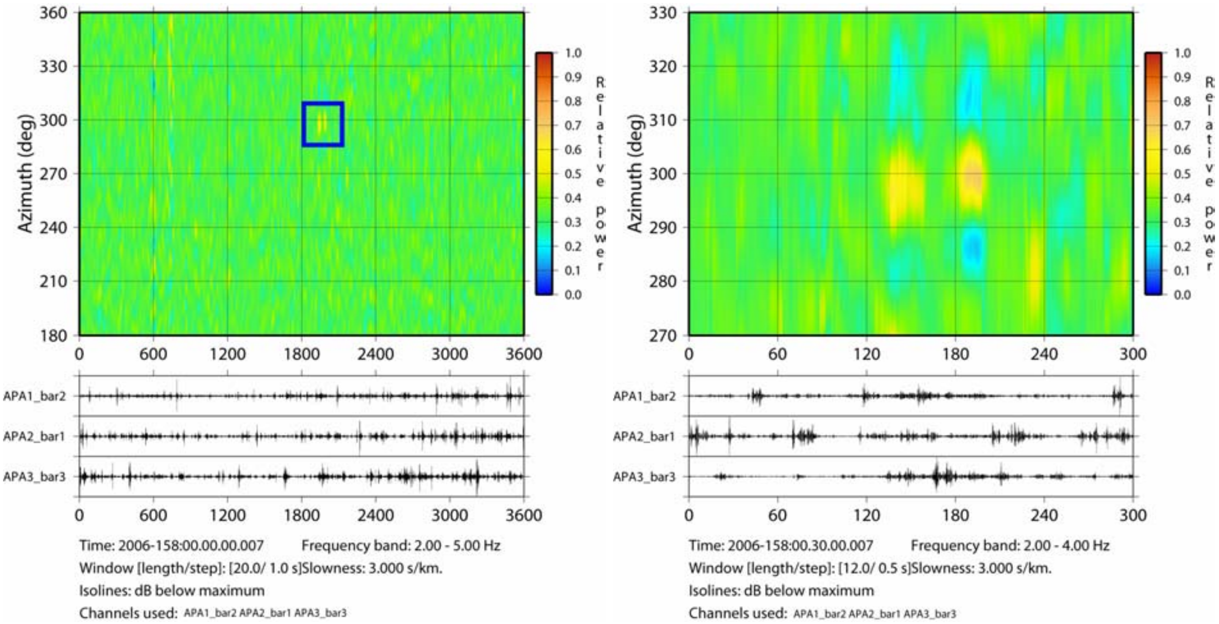

Fig. 6.2.4. Vespagrams showing the signals of the meteor explosion recorded with the Apatity infrasound array. The figure shows to the left the search vespagram with the two detected signals (blue box) and on the right a more detailed vespagram around these signals, respectively.

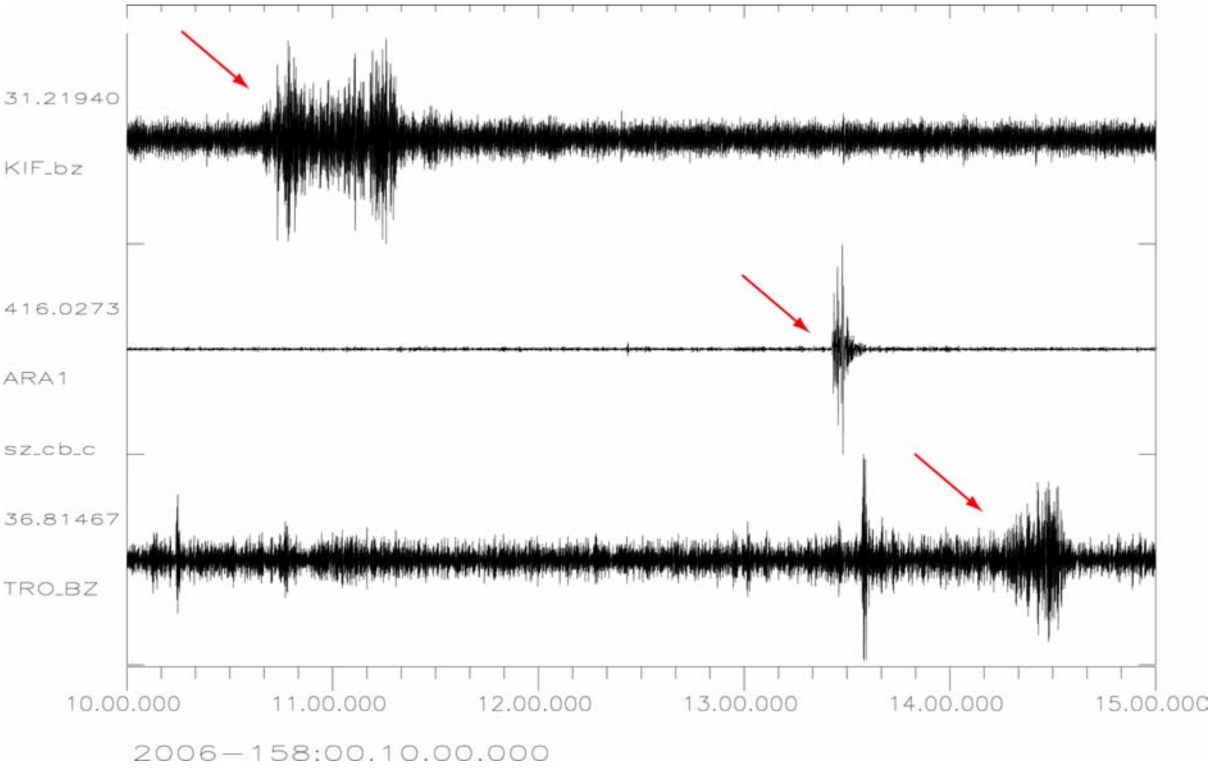

Fig. 6.2.5. Seismograms of the infrasound signal (red arrows) as recorded at the 3C stations KIF and TRO and with the ARCES array (ARA1, array beam). The data were Butterworth bandpass filtered between 2 and 5 Hz (ARA1), 5 and 10 Hz (TRO), and 8 and 16 Hz (KIF).

Additional observations at other stations

The two seismic broadband 3C stations KIF and TRO and the short period station KTK are located in the vicinity of the presumed location of the meteor explosion. We retrieved all available data from these stations and could identify signals at both broadband stations, which can be associated with the meteor event; KTK had unfortunately not triggered during the time period of interest.

In Sweden, a network of infrasound arrays is operated by the Swedish Institute of Space Physics. Some of theses arrays observed the event and signals could be analyzed. We received the measured BAZ values as parameter data from the infrasound arrays Jämtön and Lycksele (Ludwik Liszka, pers. communication).

Also the infrasound arrays in the Netherlands observed infrasound signals for which the observed BAZs, arrival times and apparent velocities fit with the meteor event (Läslo Evers, pers. communication).

Source parameters of the 7 June 2006 meteor explosion

Combining all observations and using them as input to a traditional event location program (HYPOSAT (Schweitzer, 2001)) a presumed location of the meteor explosion could be determined. To locate the event, the BAZ observations from the arrays (ARCES, Apatity, Jämtön, and Lycksele) could be used. The observations at the arrays in the Netherlands were too weak and the estimated onset parameters were too uncertain to be used for locating the event (Laslo Evers, pers. communication). The atmosphere as propagation medium of the infrasound waves was modelled by a simple halfspace with a constant velocity of 0.33 km/s. With this model the onset times of the infrasound signals at nearby stations (KIF, TRO, and ARCES) could also be used to locate the event (see Table 6.3.1).

Table 6.3.1. List of parameter data used to locate the meteor explosion of 7 June 2006

Station	Arrival Time	dt	BAZ	dBAZ
KIF	00:10:39.7	0.5	46.3	5.0
ARCES	00:13:25.8	0.2	259.16	0.3
TRO	00:14:16.5	0.5	48.9	5.0
Apatity	00:32:15.0	2.0	295.0	3.0
Apatity	00:33:01.5	1.0	299.32	2.0
Jämtön	?		1.08	2.0
Jämtön	?		0.96	2.0
Jämtön	?		351.01	2.0
Lycksele	?		13.6	2.0
Lycksele	?		12.82	2.0
Lycksele	?		12.39	2.0

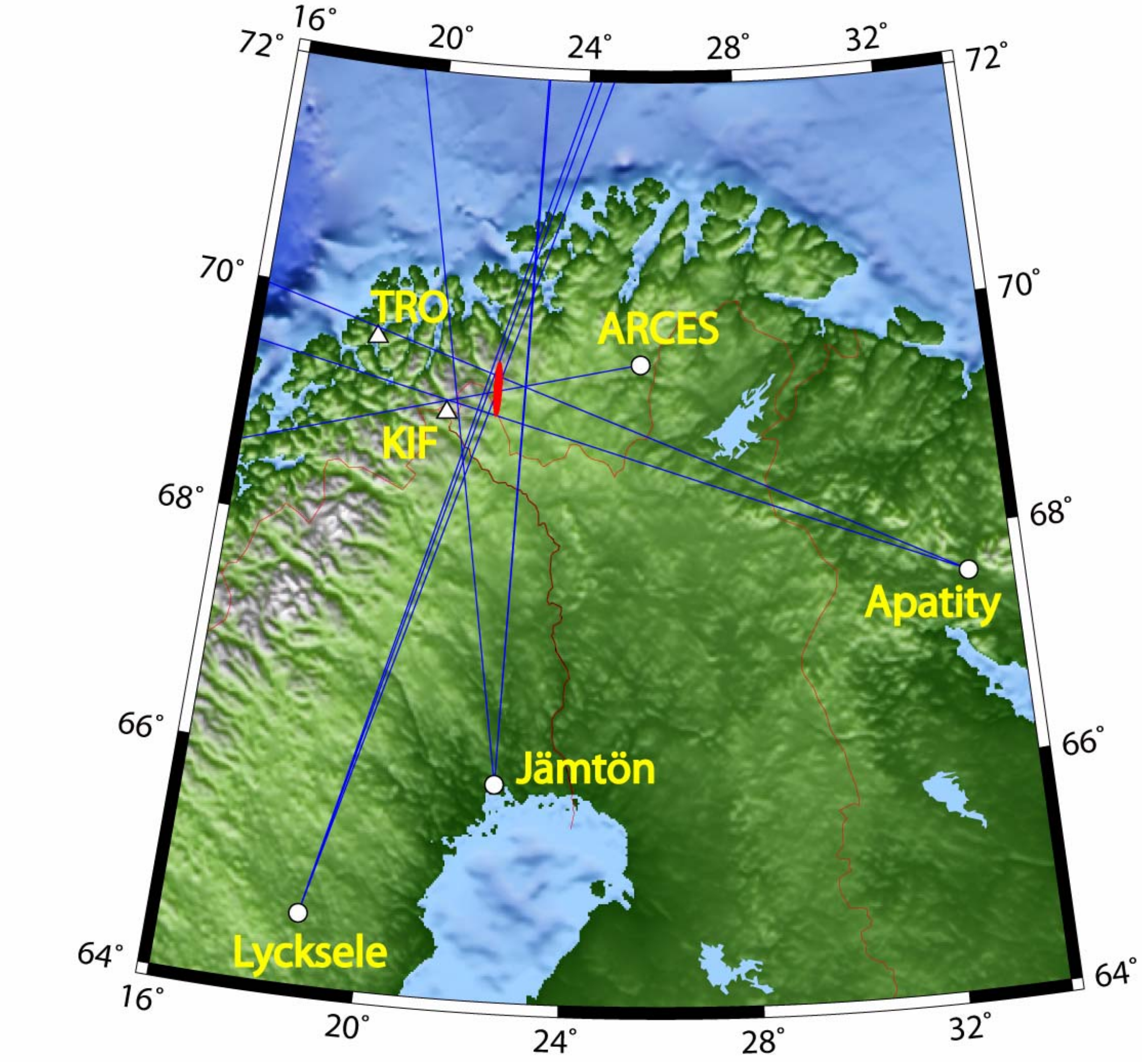

Fig. 6.2.6. Map with arrays (circles) and 3C stations (triangles) which observed the meteor explosion in northern Norway. The blue lines show the BAZ directions of the observed signals and the red ellipse shows the source region (+/- one standard deviation) calculated from these BAZ observations.

Table 6.3.2. List of locations for the meteor explosion above northern Norway on 7 June 2006

Location	Latitude	Longitude	Source Time
BAZ observations only, no height	69.28 +/- 0.23	22.17 +/- 0.09	-
BAZ and onset times, height fixed at 7 km	69.26 +/- 0.01	22.11 +/- 0.01	00:07:05.9 +/- 0.7
Closest people observing the event	69.279	22.383	-

However, our location is biased by the unknown 3D velocity structure of the atmosphere and the unmodelled influence of wind on the observed BAZ values. Two of our location results are listed in Table 6.3.2: one result for a location based on the BAZ observations only with its corresponding uncertainty of +/- one standard deviation and one result for a location based on the BAZ observations and the onset times at KIF, ARCES, and TRO. For the latter location the height was fixed at 7 km, which gives the smallest residuals in the chosen halfspace model with a constant velocity of 0.33 km/s. In addition, Table 6.3.2 also lists the position of two persons reporting that they observed the meteor explosion on the sky directly above them. Their position was slightly east of the presumed source region. Despite intensive search, remains of the meteor have yet to be found (Knut Jørgen Røed Ødegaard, pers. communication). A map showing the observing stations together with the presumed source region based on the BAZ observations only (in red) is shown in Fig. 6.2.6.

The observed infrasound signals are related to the size of the meteor explosion. Following ReVelle (1975; 1997), the explosion size of a meteor can be calculated with the formula

$$\log\left(\frac{E}{2}\right) = 3.34 \cdot \log(P) - 2.58$$

where E is the explosion yield in kilotons TNT equivalent and P the dominant period of the infrasound signal. The signal at ARCES has a dominant period of about 1 s and at KIF of about 0.6 s. From this the yield can be calculated as 5.3 tons for ARCES and as 1 ton for KIF. How significant the difference is in yield between the two measurements cannot be decided because contrary to ARCES the seismometer at KIF is installed in a small cabin, which may filter out parts of the infrasound signal and thereby change the observable dominant period.

6.2.3 The impact of 14 July 2006

About five weeks later another meteor was observed during its impact and explosion. This time the observations came from the border region between southern Norway and Sweden. The explosion of the meteor was heard in Rygge and at least 2 fragments were found on ground in the Rygge - Moss area. After we were informed about this new event, data from nearby located seismic stations were searched for corresponding signals. No related signal could be found in records of the broadband station KONO and of the Hagfors array in Southern Sweden. Moreover, on the traces of the short period sensors of the large NORSAR array, a signal was detected crossing the array from south to north with sound velocity. Fig. 6.2.7 shows a seismogram section of all available short period traces of the NORSAR array. The seismograms are plotted with respect to the estimated event location. The infrasound wave can clearly be identified. Unfortunately the signal itself is quite incoherent so that no standard tool to analyze array data could be applied.

To measure the onset time of the infrasound energy, all traces were transformed into short-term-average (STA) traces using a 2 s long moving window with 0.25 s steps. On 28 of the transformed traces the time of the maximum STA value was measured as ‘onset’ time of the infrasound signal. Fig. 6.2.8 shows a section of these STA traces. The measured ‘onset’ times were used as input parameter for HYPOSAT, which again used a halfspace model with a constant velocity of 0.33 km/s.

Using such approximate onset time readings, a very simple velocity model and only observations from one main direction makes the resulting location of the event quite inaccurate. As already mentioned some meteorite fragments were found after the event (Aftenposten, 17 & 18 July 2006, Knut Jørgen Røed Ødegaard, pers. communication). Fig. 6.2.9 shows a map with the location of the event, its corresponding error ellipse, and two of the sites where meteorite fragments were collected. However, the location of the infrasound signal is sufficiently precise to be connected with the observed meteor explosion and the area where its fragments were found.

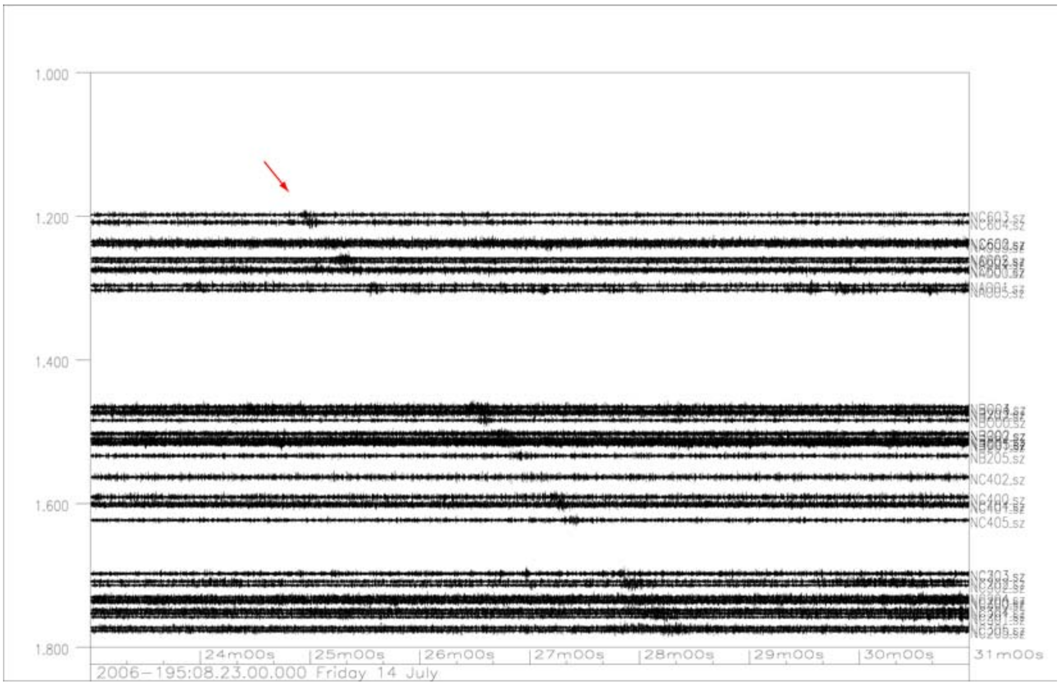

Fig. 6.2.7. Seismogram section with the observed infrasound signal (see red arrow). The data for the short period sensors of the large NORSAR array are 3 - 7 Hz bandpass filtered and plotted with respect to the estimated location of the explosion of the meteor. The vertical axis shows the distance in degrees.

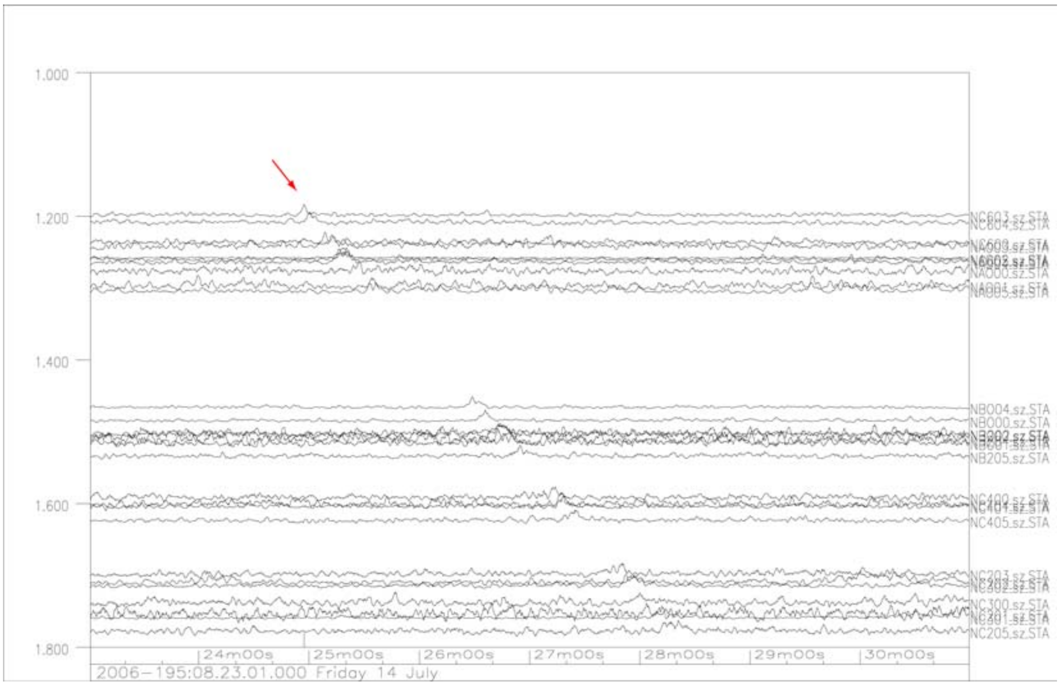

Fig. 6.2.8. Seismogram section as in Fig. 6.2.7, here for the STA traces used to locate the meteor explosion on 14 July 2006.

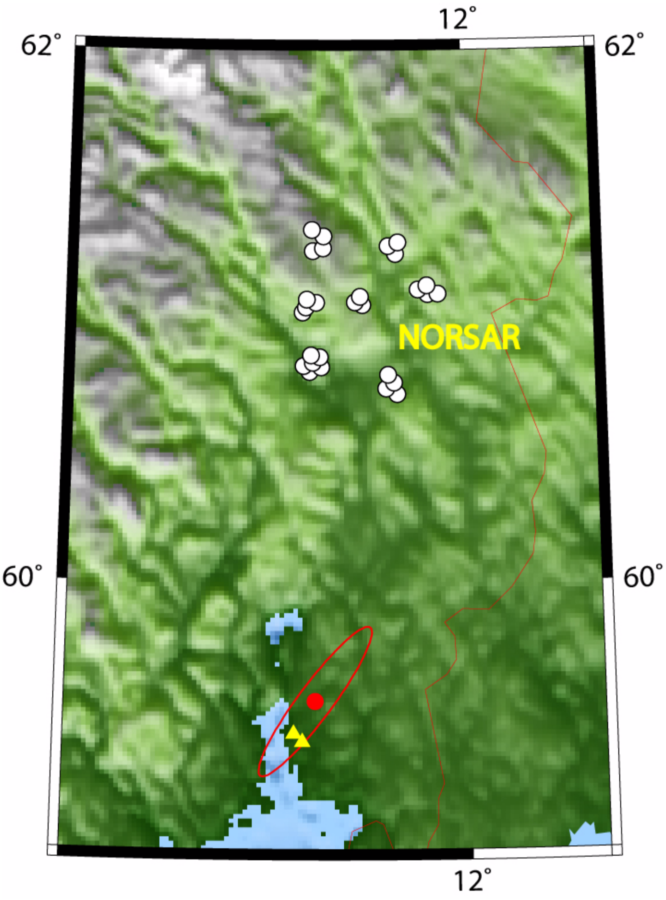

Fig. 6.2.9. Map of the estimated location of the 14 July 2006 meteor explosion in red, estimated using data recorded at the shown NORSAR sites. The yellow triangles show sites where meteorite fragments had been found.

Acknowledgements

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Tormod Kværna

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