BASIC RESEARCH ON SEISMIC AND INFRASONIC MONITORING OF THE EUROPEAN ARCTIC

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ABSTRACT

This project is a research effort aimed at improving seismic and infrasonic monitoring tools at regional distances, with emphasis on the European Arctic region, which includes the former Novaya Zemlya test site. The project has three main components: a) to improve seismic processing in this region using the regional seismic arrays installed in northern Europe, b) to investigate the potential of using combined seismic/infrasonic processing to characterize events in this region and c) to carry out experimental operation, evaluation and tuning of the seismic threshold monitoring technique.

We have continued our studies of a sequence of surface explosions in northern Finland, carried out for the purpose of destroying old ammunition. These explosions are taking place in August and September each year, and provide very useful reference events for infrasound sources since the location is known and the origin times are very tightly constrained by seismic observations. Previously, we have studied recordings mainly at the ARCES seismic array (at a distance of about 175 km) and the Apatity seismic/infrasound array (at a distance of about 280 km). However, in early 2008 an experimental 3-site array of microbarographs was installed within the ARCES seismic array, thus providing additional data for studying the 36 explosions which took place in the fall of 2008. Acoustic signals were detected on the microbarograph sensors following every one of the explosions, and on the seismic sensors following all but one. The non-detection was due to an interfering (unrelated) seismic signal.

While the seismic array has served well as a surrogate infrasound array in the past, our results show that microbarograph sensors are essential to capture very weak infrasound signals. Moreover, the onset of the infrasound phases inferred from microbarograph recordings are often significantly earlier (by up to 60 seconds) than for the seismic sensors. In our previous studies of the Finnish explosions, using ARCES seismic sensors, we have noted acoustic signals arriving 500-700 seconds after the origin time. By studying the experimental microbarograph recordings, we have now detected a number of arrivals occurring between 800 and 950 seconds after origin time. These are associated with considerably higher apparent velocities than the earlier arrivals, consistent with the steeper angles of incidence which would be anticipated from thermospheric returns. Such presumed thermospheric arrivals were observed for 11 of the 36 explosions.

We have continued using the current array network of infrasound stations in northern Europe for studying a variety of infrasonic sources. On 15 January 2009, a meteor was observed over parts of northern Norway. We have used available recordings from the experimental infrasound deployment within the ARCES array, the Apatity infrasound array and the stations of the Swedish Infrasound Network to analyze this event. We have made a location estimate using backazimuths from the stations within the network. We have confirmed the location by making distance estimates from each station using a standard celerity value of 0.29 km/s and traveltimes obtained by calculating the difference between the time of the main signal energy observed at each station and the (reportedly accurate) origin time of the event. This latest meteor observation supplements two previous such observations in Norway during 2006. Establishing a database of such events will be important for future studies of infrasound wave propagation.

As part of our ongoing study of regional monitoring, we are investigating the notorious difficulties in obtaining accurate slowness estimates from the Spitsbergen array. The complex geology of Spitsbergen influences the incoming wavefield in such a way that the apparent phase velocity varies greatly with azimuth. In the future we plan to address this problem by making more extensive use of the three-component seismometers in the array.

OBJECTIVE

The objective of the project is to carry out research to improve the current capabilities for monitoring small seismic events in the European Arctic, which includes the former Russian test site at Novaya Zemlya. The project has three main components: a) to improve seismic processing in this region using the regional seismic arrays installed in northern Europe, b) to investigate the potential of using combined seismic/infrasonic processing to characterize events in this region and c) to carry out experimental operation, evaluation and tuning of the seismic threshold monitoring technique, with application to various regions of monitoring interest.

RESEARCH ACCOMPLISHED

Study of Infrasound Signals Generated by Atmospheric Explosions in Finland

The Finnish military destroys expired ammunition at a site in northern Lapland in a sequence of explosions every year between August and September. Each explosion has a yield of approximately 20000 kg and the seismic signals recorded at the ARCES array in northern Norway indicate a magnitude of approximately 1.5. The events have been of great interest due to the generation of infrasound signals which have been recorded on the seismic traces at ARCES and by both seismic and microbarograph instruments at Apatity (Vinogradov and Ringdal, 2003; Gibbons et al., 2007). These explosions provide very useful reference events for infrasound sources since the location is known (67.934^{o}N, 25.832^{o}E: see Figure 1) and the origin times are very tightly constrained by the seismic observations. It now appears that infrasound from these events can be observed at far greater distances than previously assumed with signals likely to come from these sources being observed at the International Monitoring System (IMS) infrasound arrays I18DK (Qaanaaq, Greenland) and I26DE (Freyung, Germany) making the events useful for studies of long-distance sound propagation (Bahavar et al., 2008).

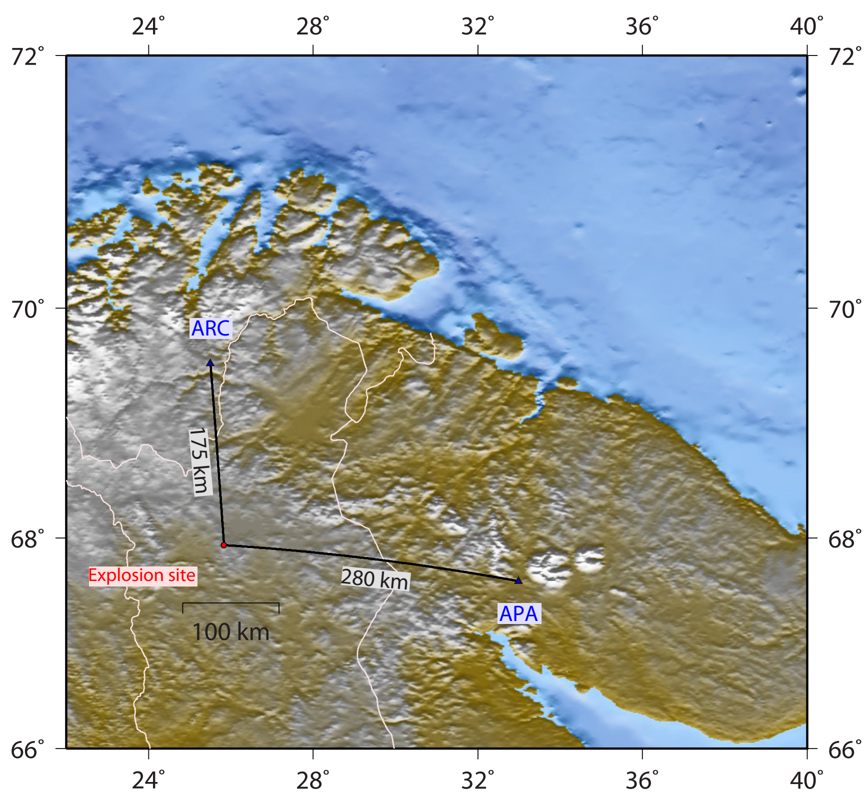

Figure 1. Location of the Finnish explosion site (67.934^{o}N, 25.832^{o}E) in relation to the arrays at ARCES and Apatity.

During 2008 a total of 36 such explosions were conducted between August 13 and September 11. As in previous years, a very high degree of similarity was observed between the seismic signals from the events allowing them all to be detected with an essentially zero false alarm rate using a multichannel correlation detector (Gibbons and Ringdal, 2006).

The 2008 explosion sequence has been of special interest since an experimental 3-site array of microbarographs deployed within the ARCES array (Roth et al., 2008) has allowed for a direct comparison of the infrasound signals recorded on the seismometers and those recorded on co-located microbarographs. Due to local environmental restrictions (which have also delayed indefinitely the deployment of the IMS infrasound array IS37) no wind noise reduction system has been allowed other than the use of porous hoses. A full description of the installation, including instrumentation and data samples, is provided by Roth et al. (2008), and preliminary data analysis is provided by Ringdal et al. (2008).

Figure 2 displays the waveforms observed on co-located seismic and infrasound sensors at the ARA1 site of the ARCES array for each of the 36 events in 2008. The seismic traces in the left panel show the seismic P- and S- phases arriving 29 and 49 seconds respectively after each shot and also acoustic signals between 500 and 700 seconds. Whilst the acoustic phases are generally visible in the filtered data, they are of somewhat smaller amplitude than in some previous years. (Gibbons et al., 2007, display a corresponding plot for 2002 in which the amplitudes of the acoustic phases are frequently greater than those for the seismic phases.) An additional complication which has been particularly problematic for 2008 is the presence of unrelated seismic signals in the interval in which the acoustic phases are anticipated. Signals visible between 500 and 700 seconds after events 14, 15, 16, and 24 are very clearly regional or teleseismic signals unrelated to the explosions in Finland which may make the detection of acoustic phases at these times difficult or impossible.

The right hand panel of Figure 2 shows microbarograph data from the same ARCES site, covering the same time intervals. The seismic arrivals are not visible in these waveforms. More often than not, the acoustic phases recorded on the seismic instruments are also visible on the microbarograph traces, with a significantly higher amplitude than the background noise. On other days, the background noise is very much higher and matches the amplitudes of the observed signals.

The only way to identify which parts of the waveforms truly correspond to acoustic signals from the direction of interest is to perform slowness analysis. We calculate cross-correlation coefficient traces between pairs of signals and then loop around a grid of slowness vectors and calculate the mean values for the corresponding time delays (c.f. Brown et al., 2002). If the slowness vector corresponding to the maximum average cross-correlation coefficient does not fall within limits appropriate for a wavefront propagating with air-sound speed from a plausible backazimuth then we have to assume that the observed signal is probably not an acoustic phase from one of our events. With the seismic sensors, we have traces from 25 sites and so can perform slowness analysis either with the full array or with one of many possible subsets of sensors. There are only three sensors in the infrasound subarray. Whilst it is possible to obtain reasonable slowness estimates if all three sensors record a signal well, there is no redundancy and should a single one of the sensors fail, or be subject to excessive noise, no direction estimate is possible.

One feature which has not previously been observed in recordings from these events is the presence of acoustic phases with higher apparent velocities between around 800 and 950 seconds. They are detected only marginally for three events (6, 15, and 36) on the seismic sensors, but are clearly visible on the microbarograph data for several more. We will illustrate these observations by using event 15 as an example.

Slowness estimates for event 15, both for a typical phase in the 500-700 second interval and for one of the newly observed phases between 800 and 950 seconds, are shown in Figure 3. The two plots at the left side of this figure are based on the seismic recordings (innermost nine sites of ARCES) whereas the two plots to the right are generated from the three microbarographs. The leftmost plots (based on seismic data) show a clear infrasound signal at 625 seconds, whereas an interfering seismic signal obscures the sound wave at 928 seconds. The rightmost plot (based on microbarograph data) show two clear infrasound signals, with the signal at 928 seconds having a significantly higher phase velocity than the signal at 625 seconds.

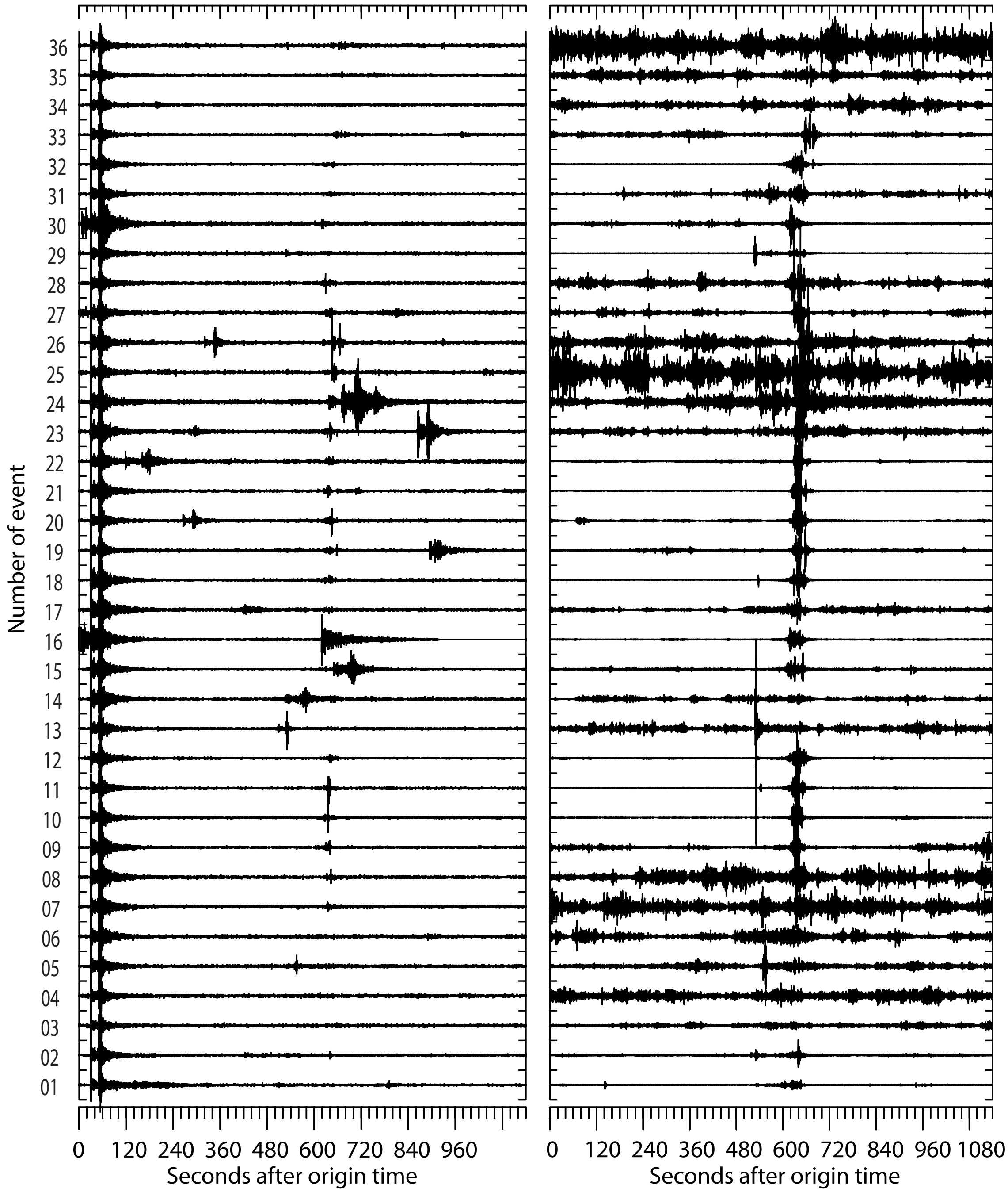

Figure 2. Waveforms from the short-period vertical seismic sensor ARA1_sz (left) and the co-located microbarograph sensor ARA1_BDF (right) for the Finnish explosions during 2008. The same vertical scale is applied to all of the traces within each panel. All waveforms are bandpass filtered between 2 and 7 Hz.

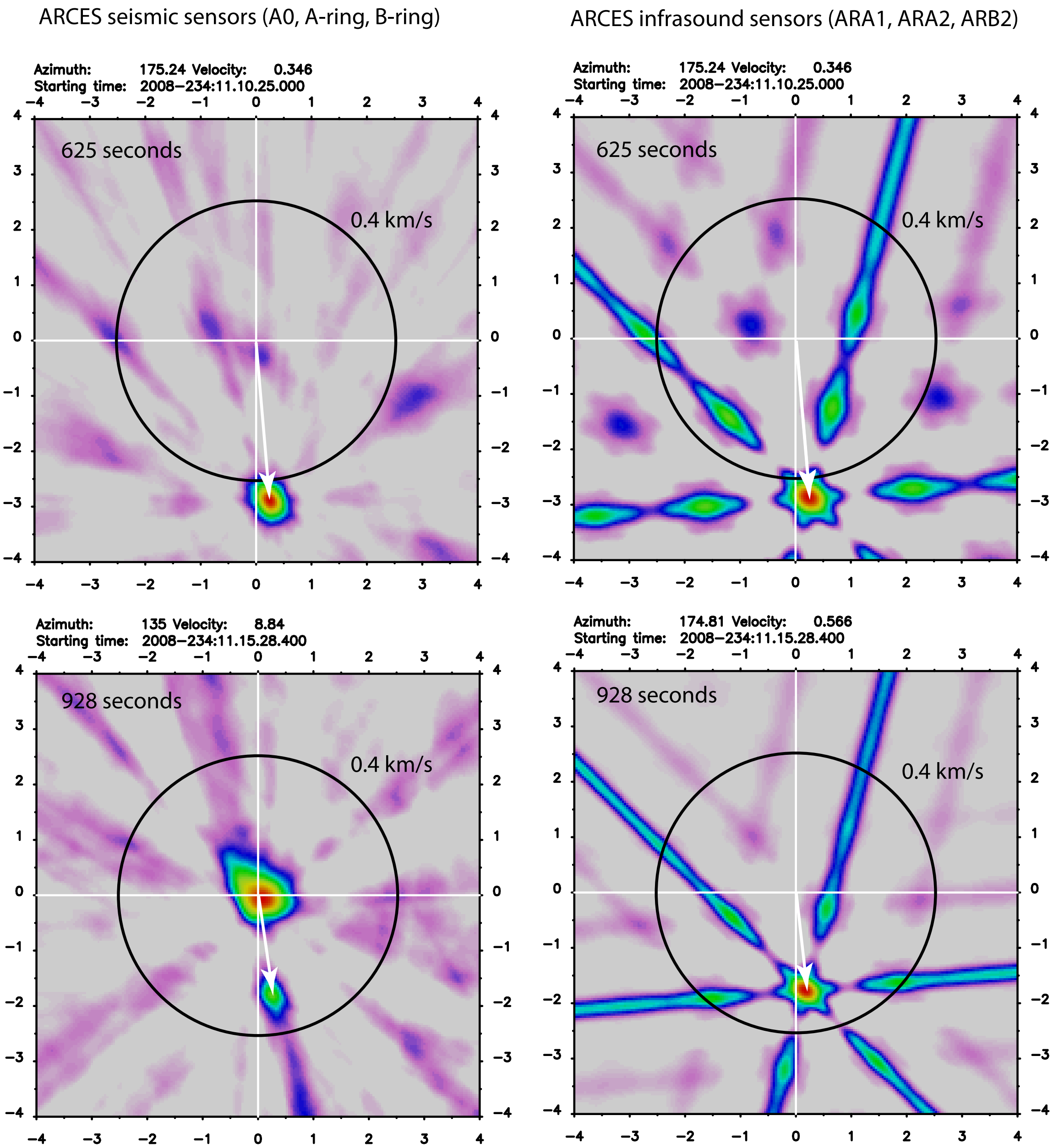

Figure 3. Slowness estimates at 625 seconds (above) and 928 seconds (below) after the explosion at 11.00 UTC on August 21, 2008. For the seismic estimates (the two plots to the left), only the innermost nine sites of the ARCES array are used. The seismic estimate for the later arrival (lower left panel) indicates an apparent velocity consistent with seismic wave speed, although evidence is seen for energy arriving with sound speed. The circles correspond to an apparent velocity of 0.4 km/s.

The significantly higher apparent velocity for the later arrival (lower right panel of Figure 3) is consistent with a steeper angle of incidence as would be anticipated for a thermospheric arrival. At a distance of 178 km, the range of travel times 800 to 950 seconds corresponds to celerities between 0.187 kms^{-1} and 0.223 kms^{-1}, which is comparable with the values plotted by Mutschlecner and Whitaker (1999) for thermospheric arrivals observed from explosions at the Nevada Test Site, observed at a distance of approximately 210 km.

Infrasound Recordings of the Meteor North of Norway on 15 January 2009

In the evening of 15 January 2009, light flashes and a fireball were observed over parts of northern Norway. The object was reported to propagate in a north-northwesterly direction into the Barents Sea. Based on newspaper reports, the time of the event is estimated to 19:40 GMT.

The signals from the meteor, recorded at the 4 infrasound arrays operated by the Swedish Institute of Space Physics (IRF) were analyzed within a short time after the event. Prof. Liszka of IRF estimated the signals to originate halfway between mainland Norway and Svalbard. For details see *http://www.irf.se/Topical/Other/?newsid=7&group=P2*.

We will here provide results from additional analysis of signals at the IRF stations (Liszka and Kværna, 2008), as well as at the infrasound station in Apatity (Vinogradov and Ringdal, 2003) and at an experimental infrasound deployment within the ARCES array (Roth et. al., 2008).

For each of the stations we have processed the infrasound data using vespagram analysis. Using a fixed apparent velocity around 0.333 km/s, we have calculated the resulting normalized beam power for a range of back-azimuths, where the maximum represents an estimate of the back-azimuth of the arriving signal. In our calculations we have used a window length of 10 seconds and a window step of 1.0 second. Because of the larger array apertures, the ARCES and Apatity infrasound data were processed in the 1 - 4 Hz frequency band, whereas the stations of the Swedish Infrasound network were all processed in the 2 - 5 Hz band. Figure 4 shows the results from the vespagram analysis of ARCES and Apatity data together with the raw and bandpass filtered waveforms.

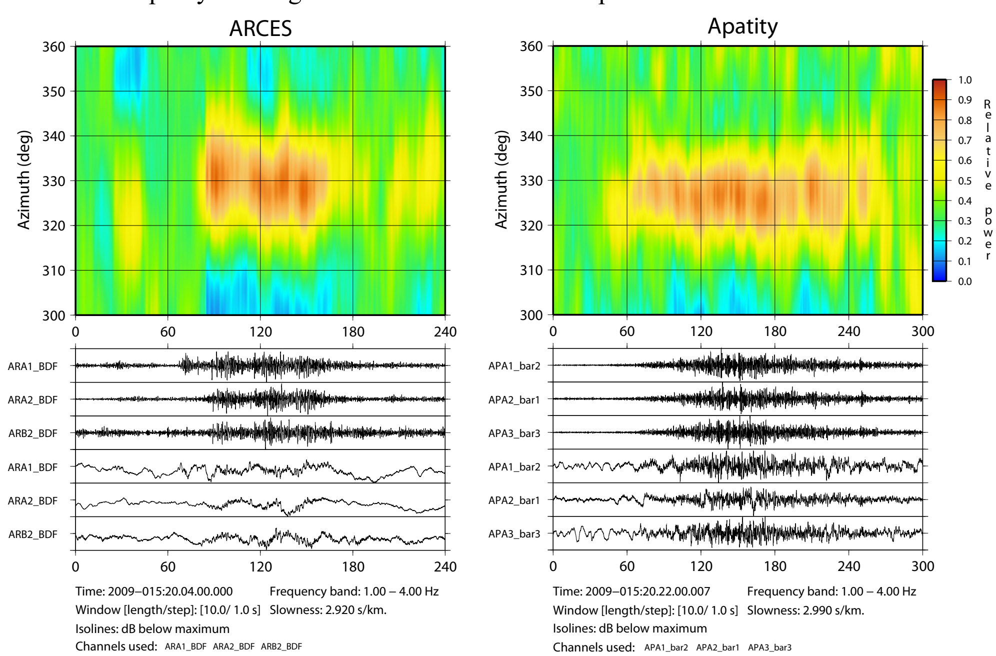

Figure 4. Azimuthal vespagrams from analysis of ARCES and Apatity infrasound data for the time interval around the signals from the meteor on 15 January 2009. The upper three traces of each panel show the bandpass filtered waveforms, whereas the three lower traces show the raw data. Notice that different time scales are used for the two stations. A constant slowness close to 3 s/km has been used when calculating the azimuthal vespagrams.

Compared with analysis of a large number of infrasound signals from the previously described military ammunition destruction site in Finland (Gibbons et. al. 2007), we have found a relatively large variability in back-azimuth estimates. This variability can be caused by several factors, like wind conditions, local noise sources, low SNR or data quality problems. In this study, we have assigned a variability of ± 8 degrees around the average back-azimuth estimates for each station, and the corresponding back-azimuthal sectors from each station are shown in Figure 5. As indicated in Figure 5, there is a small area of intersection in the Barents Sea, close to the Finnmark coast.This area is an indication of the source region of the infrasound signals, i.e., where the meteorite exploded.

Another approach to source location is to use the reported origin time of the event. According to a newspaper report, the origin time of 19:40 GMT was read from the display of a cellular telephone at the time of the meteor observation. This gives us the possibility to calculate the travel-time to each station, which again can be scaled with a standard celerity for stratospheric arrivals of 0.29 km/s to obtain a distance estimate. The intersection of the distance arcs provide indications of the location of the event, and we thereby obtain an estimate of 72.1^{o} N, 20.3^{o}E, which is consistent with the intersections of the sectors in Figure 5.

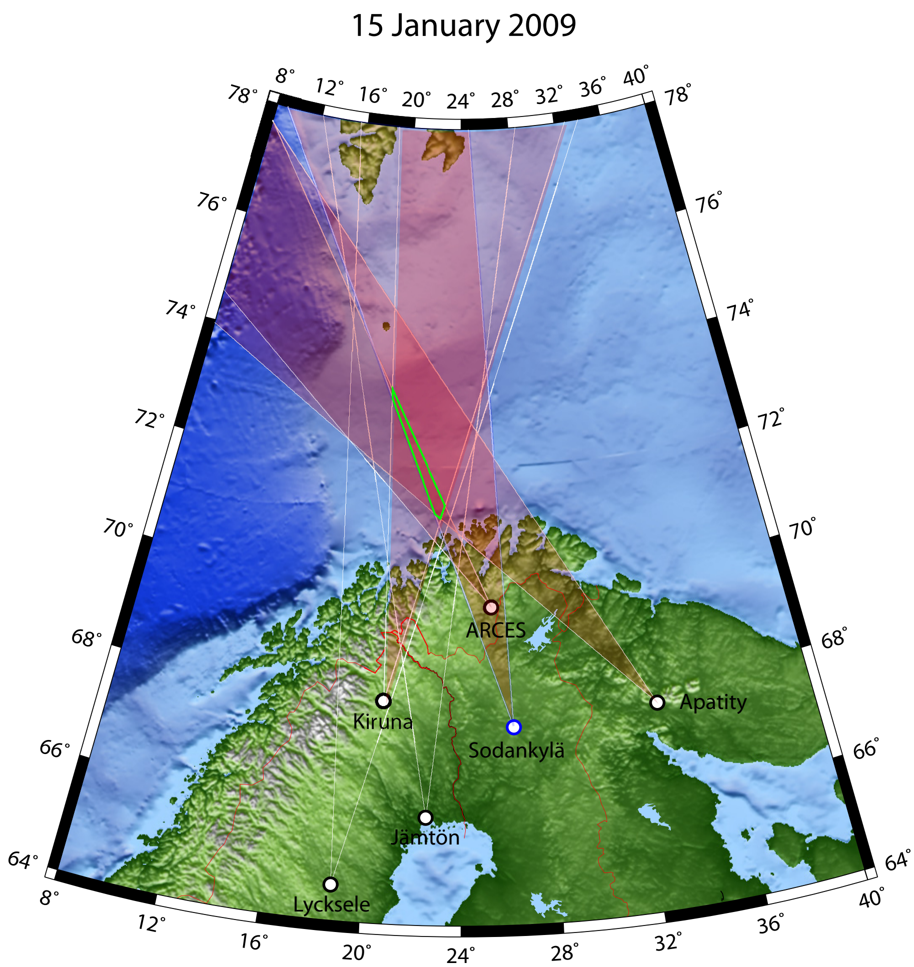

Figure 5. Map showing the sectors of back-azimuths of infrasound signals from the meteor as observed at the infrasound stations in Sweden, Finland, NW Russia and Norway. For each station, a sector of ± 8 degrees around the average back-azimuth estimate is plotted. The highlighted green polygon shows the area of common intersection. No corrections for the wind field are introduced to the back-azimuth estimates.

Resolving Ambiguity in Slowness Estimates

The SPITS and ARCES arrays are crucial to the seismic monitoring of small events in the European Arctic. Small events (lower than magnitude 3) on or close to Novaya Zemlya are not usually detected by any additional IMS stations. With so few observations, good recordings of S-phases are essential for accurate event location - especially given the large azimuthal gap to the North and East. If S-phases are not detected automatically, there is an increased risk that detected P-phases will remain unassociated and that the event will be missed.

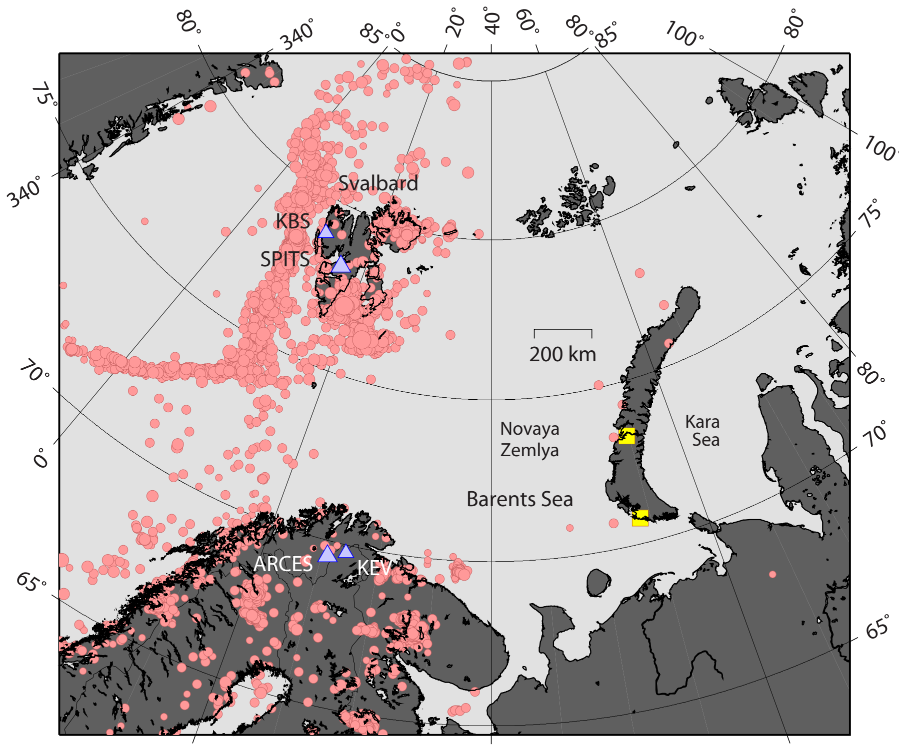

Figure 6. Seismicity of the European Arctic (1998-2009) from the NORSAR reviewed regional seismic bulletin. Yellow squares indicate the sites of former Soviet nuclear test sites on Novaya Zemlya.

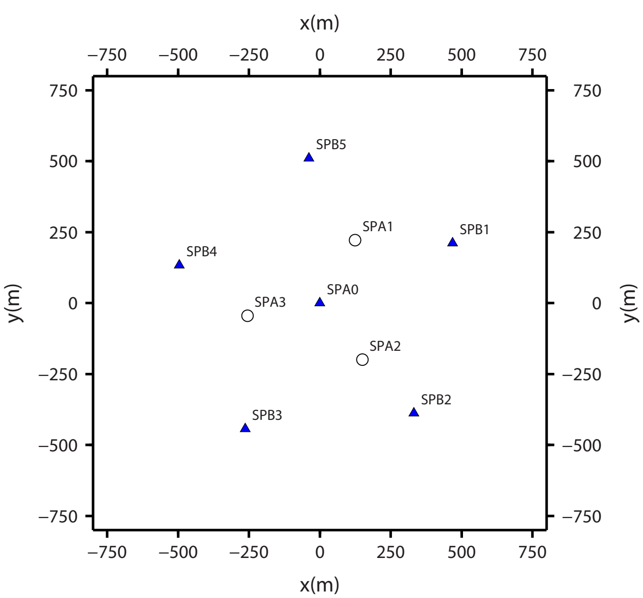

Figure 7. Map showing the configuration of the Spitsbergen array (SPITS). The blue triangles are three-component stations.

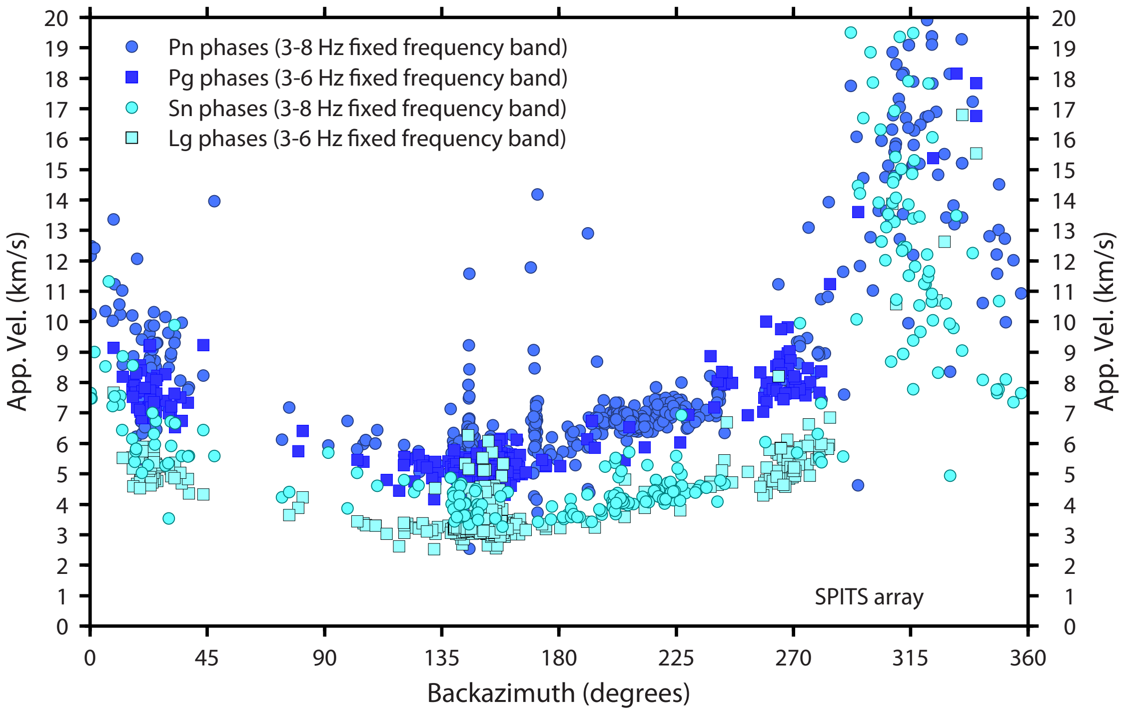

Figure 8. Apparent velocity of regional phases recorded by the SPITS array as a function of geographical backazimuth. The backazimuths are based on the solutions in the NORSAR analyst-reviewed regional bulletin. The slowness estimates have been made by fixed band f-k analysis as indicated, using only the vertical seismometers. The plot does not take into account epicentral distance and does not show SPITS backazimuth deviations relative to the reference backazimuth.

Large amplitude Lg phases are often observed for continental propagation paths which are well-recorded on vertical sensors. Lg propagation is blocked in the Barents Sea and we rely on good recordings of Sn-phases. As demonstrated in many situations, the amplitude of the S-phases on the horizontal components is greater than on the vertical. In previous studies we have documented that only a modest improvement in SNR for the Sn-phase is obtained by beamforming on the vertical components. The achievable improvement using 3-component data is far greater. A more extensive use of the 3-C array for processing secondary phases would significantly improve SNR and at the same time allow more reliable azimuth and slowness estimates to be made.

Geological structure below the SPITS array influences the incoming wavefield such that the apparent velocity measured varies greatly as a function of backazimuth (see Figure 8). This can to some degree be corrected for by applying a sinusoidal correction term. However, there is a significant overlap between regional P and S apparent velocities which is problematic for phase identification. The problem is most acute for the region to the northwest with regional phases (both P and S) often having very high apparent velocities (frequently in the range 15-20 km/s). It is hoped that 3-C processing will help to resolve issues in phase identification.

CONCLUSIONS AND RECOMMENDATIONS

The infrasound database that has been developed based on the explosions in northern Finland provides a unique resource for studies of infrasonic propagation under controlled conditions. One of the main topics to be studied is the surprising observations of various infrasound phases in what is often denoted as a “quiet” zone (less than 200 km distance). The observation of apparently thermospheric phases as indicated in this paper is particularly interesting. We plan to carry out various modelling exercises in order to further investigate the propagation of infrasound phases at local distances. At the same time, we will continue to accumulate ground truth data of a variety of infrasound sources.

This study has revealed significant ambiguity in regional phase identification and slowness estimation for the Spitsbergen array. In view of the important role of this array in monitoring the European Arctic, it is essential to resolve this problem We recommend that further studies be undertaken, using three-component array processing, to attempt to improve upon this situation.

Previous studies, documented in various NORSAR Semiannual Technical Summaries, have shown a remarkably efficient seismic wave propagation from events near Novaya Zemlya across the Barents Sea to the Spitsbergen array. By analyzing data from a newly installed high-frequency element in the ARCES array in northern Norway, we have found that similar propagation characteristics are observed for this array as well. We consider that there is still much to be gained by making improved use of the high-frequency recordings in the European Arctic, and we recommend that a systematic mapping of the high-frequency propagation characteristics of this region be undertaken.

We note that the available high-frequency data so far does not include events to the east and north-east of the ARCES array, and the high-frequency propagation from the Novaya Zemlya region to ARCES is therefore still unknown. As more data is accumulated, we recommend that a detailed study of the high frequency propagation characteristics for various paths in the region be carried out. We also recommend that data from temporary seismic stations installed as part of the International Polar Year be fully exploited in such a study.

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