NORSAR

NORSAR Scientific Report No. 2-2007

Semiannual Technical Summary

1 January - 30 June 2007

Frode Ringdal (ed.)

Kjeller, August 2007

6 Summary of Technical Reports / Papers Published

6.1 Joint seismic-infrasonic processing of recordings from a repeating source of atmospheric explosions in Northern Finland

Abstract

A database has been established of seismic and infrasonic recordings from more than 100 well-constrained surface explosions, conducted by the Finnish military to destroy old ammunition. The recorded seismic signals are essentially identical and indicate that the variation in source location and magnitude is negligible. In contrast, the infrasonic arrivals on both seismic and infrasound sensors exhibit significant variation both with regard to the number of detected phases, phase travel times, and phase amplitudes, which would be attributable to atmospheric factors. This data set provides an excellent database for studies in sound propagation, infrasound array detection, and direction estimation.

6.1.1 Introduction

A major component of the International Monitoring System (IMS) for the verification of compliance with the Comprehensive Nuclear-Test-Ban Treaty (CTBT, www.ctbto.org) is a global network of infrasound sensor arrays deployed to detect atmospheric acoustic signals which could be generated by a nuclear explosion. The processes of detecting and locating events by association of infrasound phases present a very different set of challenges to those involved in the complementary seismic monitoring system. The most significant difference is probably that the propagation path and travel time of a given seismic phase from a given source to a given receiver will remain constant for all subsequent events at that source location over all timescales relevant to current monitoring requirements. In contrast, the travel time and propagation path of an atmospheric sound wave will depend strongly on atmospheric conditions (e.g. Garcés et al., 1998; Georges and Beasley, 1977) which must be accounted for in any conclusions drawn from the detection of an infrasound phase. The modelling and understanding of atmospheric propagation effects needs to be guided by well-constrained events, with mining explosions typically used for this purpose (e.g. Sorrells et al., 1997; Hagerty et al., 2002; Stump et al., 2004; McKenna et al., 2007). In this paper we draw attention to a source of repeating chemical explosions which generate infrasound signals and which are tightly constrained by seismic observations.

6.1.2 Seismic and Acoustic Observations of Finnish Explosions at Regional Distances

A series of seismic events detected by the ARCES array were estimated to have taken place at a distance of approximately 175 km in central Lapland (Fig.6.1.1). They were readily identified as explosions since they occurred systematically in sequences and all were conducted at very characteristic times of day (for example within 1 or 2 seconds of a full-hour or half-hour). Colleagues at the Kola Regional Seismological Center (KRSC) in Russia had installed three microbarograph sensors at sites in the Apatity seismic array and observed very coherent, high amplitude, signals propagating across the infrasound mini-array with speeds characteristic of sound waves from the appropriate direction. In addition, closer examination of the seismic waveforms from ARCES revealed additional high-amplitude signals arriving several minutes after the seismic arrivals which did not correspond to characteristic seismic wave velocities.

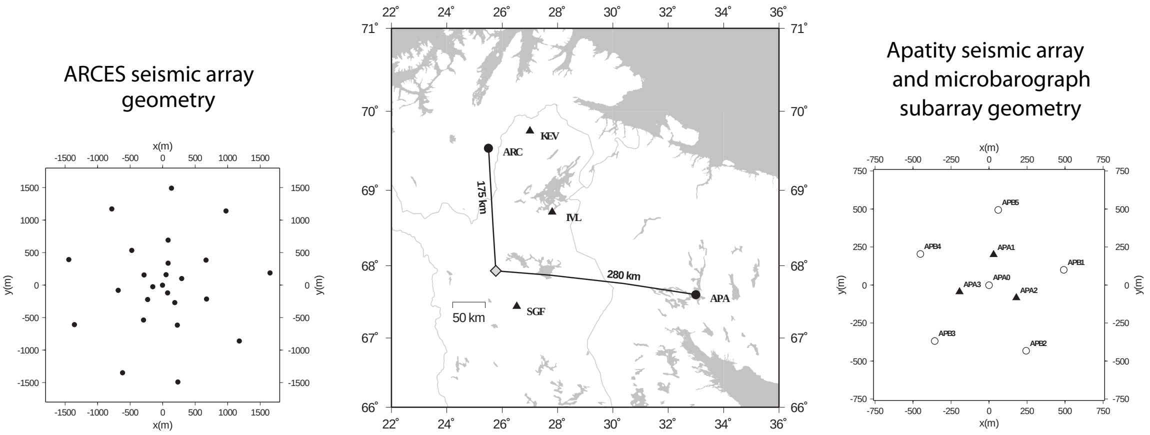

Fig. 6.1.1. Location of explosion site in relation to the arrays as indicated. Sites in the ARCES array contain only seismometers as do sites marked with white circles at Apatity. Black triangles at Apatity indicate both a seismometer and a microbarograph. Data from the SGF, KEV, and IVL 3-component seismometers helped to constrain the absolute location of the events.

An example of such an event is displayed in Fig.6.1.2. The first two pulses on the seismic traces (labelled A and B) correspond to the seismic P-phase and more slowly travelling S-phase. Since our station is an array, we can estimate the direction and velocity of these phases using broadband f-k analysis (based upon the method of Capon, 1969) from which, together with arrival times and velocity model, we can estimate the origin time and location. The ground motion some 10 minutes after the event is dominated by amplitudes comparable to those resulting from the direct seismic arrivals. Performing f-k analysis on a somewhat longer time-segment indicated by C reveals these waves to be very coherent across the array aperture and to fit very well the hypothesis of a plane wave propagating with air sound speed from a very similar direction. Note the higher resolution provided by the array for the slowly propagating sound wavefront (panel C) than for the seismic wavefronts (panels A and B). The lower-left panel of Fig.6.1.2 displays the beams constructed from all sensors in the array using time-delays corresponding to the calculated slowness vectors. Whilst the observation of acoustic signals on seismogram traces is not uncommon (e.g. Cates and Sturtevant, 2002; Stump et al., 2004; Lin and Langston, 2006) it is a useful observation that in this case the seismic response to the pressure changes in the incoming infrasound wavefront is so uniform over the array that standard seismic array processing can be applied to infer accurately a direction of arrival of the atmospheric wave.

The repeatability of measurements for azimuth and velocity for the seismic phases together with the S-P travel time difference provided evidence for a similar source location for the different events. However, the similarity of each individual waveform was so great that a full-waveform multi-channel matched filter detector (Gibbons and Ringdal, 2006) could be applied, taking a single specimen waveform as a template and picking out subsequent events simply from the maxima of the correlation coefficient traces. This procedure fulfilled the multiple aims of

(a) identifying automatically a large number of events,

(b) calculating to sub-sample precision the relative origin times of events, and

(c) confirming that events cannot be separated by more than a few hundred meters (Geller and Mueller, 1980).

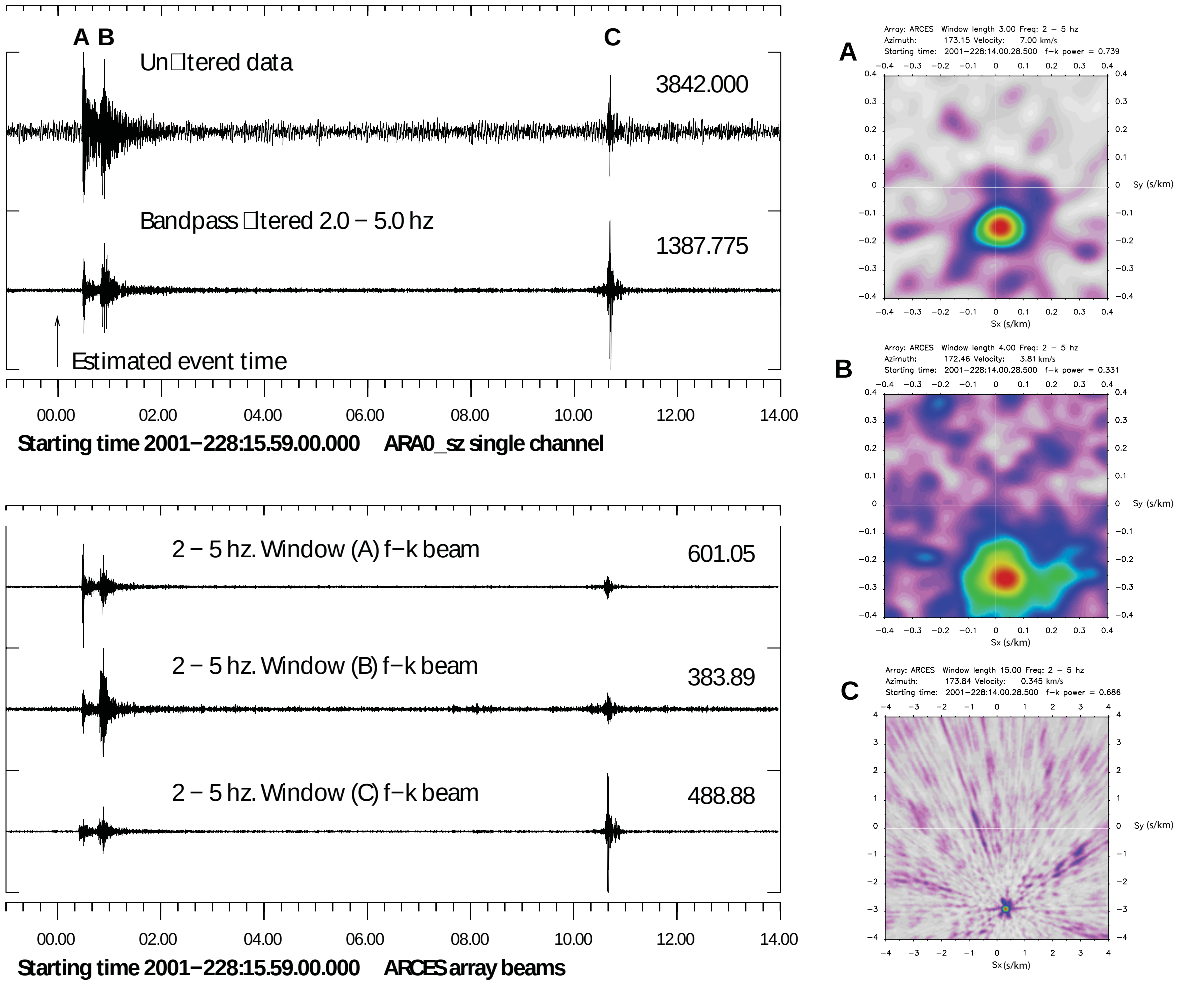

Fig. 6.1.2. Waveform data from the ARCES seismic array one minute prior to and 14 minutes after a surface level explosion in Northern Finland at a distance of approximately 175 km. The top panel shows waveforms on the central seismometer: the seismic P-phase (A), seismic S-phase (B), and an unidentified arrival approximately 640 seconds after the estimated origin time (C). The broadband f-k analysis plots indicate that all of these signals come from a backazimuth of approximately 173^{o}. (Note the different scale for the slowness grid C.) The lower panel shows the beams from the full ARCES array for the slowness vectors indicated. All seismograms show velocity and the numbers above the traces indicate maximum amplitude in counts.

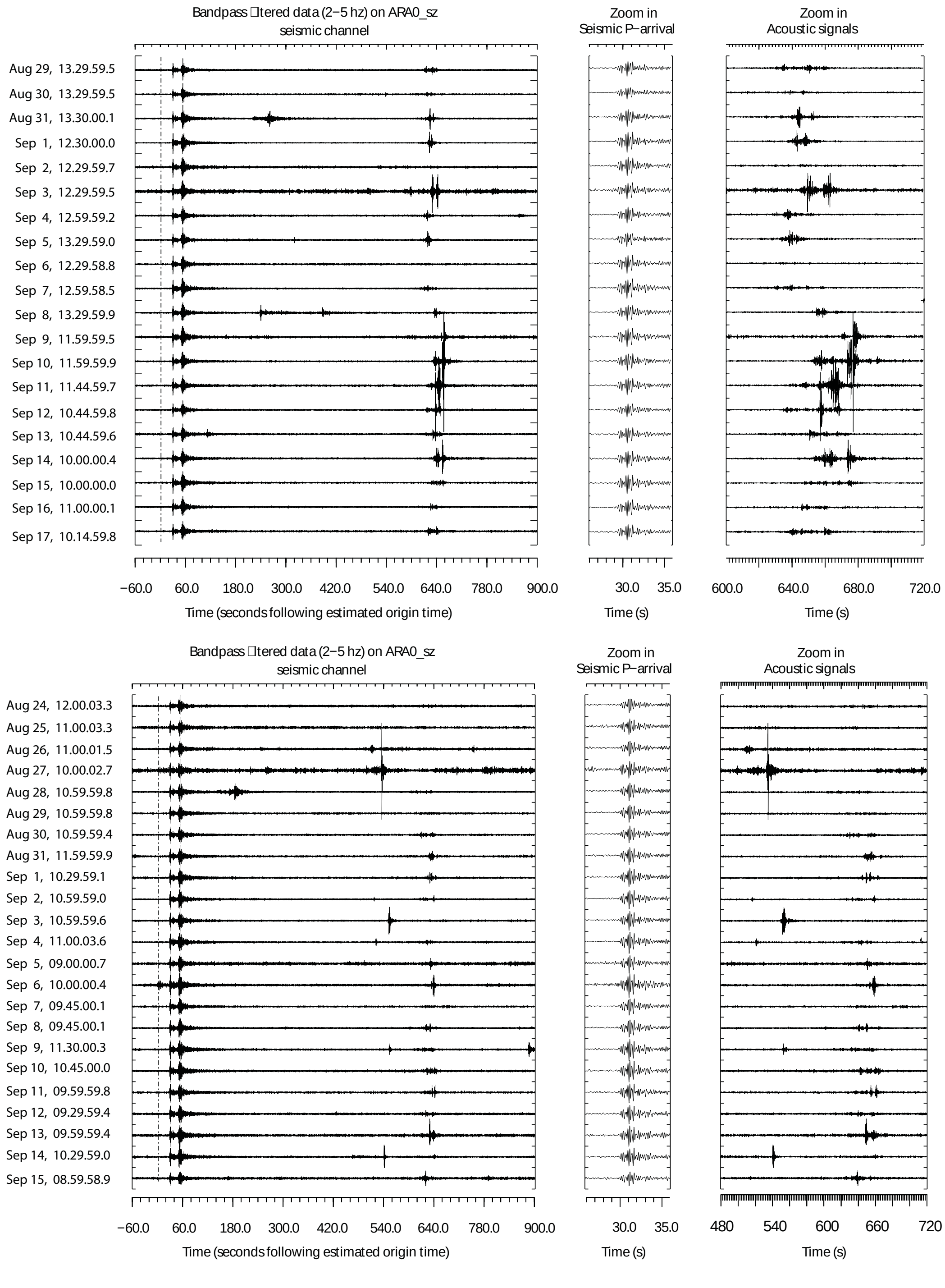

Fig. 6.1.3. Recordings on the ARCES seismic array (channel ARA0_sz) of events at the Finnish explosion site in August and September 2002 (upper panel) and August and September 2005 (lower panel). The time provided to the left is the estimated event UTC origin time. All seismograms are aligned according to the maximum correlation coefficient and have identical vertical scaling such that each division represents ± 1000 *counts. Signal arrivals between 450 and 700 seconds after origin time are demonstrated by array analysis to propagate with sound velocity from an approximate 173*^{o} *backazimuth. All arrivals between 200 and 450 seconds correspond to unrelated seismic events.*

The relative timing of events allows the waveforms from multiple events to be aligned and compared. Fig. 6.1.3 shows signals on the ARA0_sz sensor of the ARCES array for all the events which took place in the years 2002 and 2005, aligned according to the maximum correlation coefficient for the seismic signals. A large amplitude acoustic signal approximately 600 seconds following the origin time is observed for almost all of these events but, unlike the seismic signals which are almost identical for each explosion, the temporal nature and amplitudes differ greatly from event to event. There are clearly some differences between the years 2002 and 2005. For most of the events in 2002, the acoustic signal at ~600 seconds corresponds to a considerably higher amplitude than the associated seismic signals (in the filter band displayed). For the 2005 events, the acoustic signal at 600 seconds is still visible but usually at a smaller amplitude than the corresponding seismic signals. For a small number of events in 2005, an additional infrasonic phase (often with large amplitude) arrives between 500 and 570 seconds after the event origin time, and the observation of this arrival frequently precludes the observation of the arrival after 600 seconds.

On some days no signal is visible and we sought to find all evidence present of atmospheric sound waves following these events. Estimation of marginal coherent signals within a noise field is traditionally achieved using cross-correlation techniques (e.g. Jacobson, 1957) and the main technique used for infrasound processing on the IMS arrays is the Progressive Multichannel Cross-Correlation (P.M.C.C.) method (Cansi, 1995). A comprehensive summary of operational processing of infrasound data in the nuclear explosion monitoring context is provided by Brown et al. (2002) who define a detection statistic based upon the mean of all pair-wise channel correlations with time-delays corresponding to the theoretical plane wavefront models. The statistic Γ defined in Eq. (15) of Brown et al. (2002) was evaluated over successive 10 second time-windows of ARCES data following each of 141 events and Fig. 6.1.4 (top panel) displays the Γ value obtained whenever the maximum-gain slowness vector falls close to the expected value (c.f. Fig. 6.1.2 C). In practice, we required that Γ exceeded *0.01* with velocity in the interval [0.3 km/s, 0.4 km/s] and azimuth between 170 and 180 degrees. A high value of Γ indicates a high correlation between the appropriately delayed channels and, whilst this value is highest for high signal-to-noise ratio (SNR) acoustic signals, significant values can be obtained even when the signal amplitude is smaller than the ambient noise level. Fig. 6.1.4 confirms that evidence of a corresponding infrasound arrival was observed for almost every explosion, with only 5 out of 141 events showing no evidence of sound waves. Over the six years considered, the most common infrasonic arrivals occur between 600 and 680 seconds after origin time with an apparently smooth variation over a several day time-scale (all events displayed in Fig. 6.1.4 are consecutive days between the dates as shown). The more unusual occurrence of earlier infrasonic arrivals from the same direction (as displayed for some events from 2005 in Fig. 6.1.3) is observed for approximately 15% of the events. The days on which these phases are observed are however fairly clustered in time and may indicate some atmospheric property which persists over a timescale of a few days.

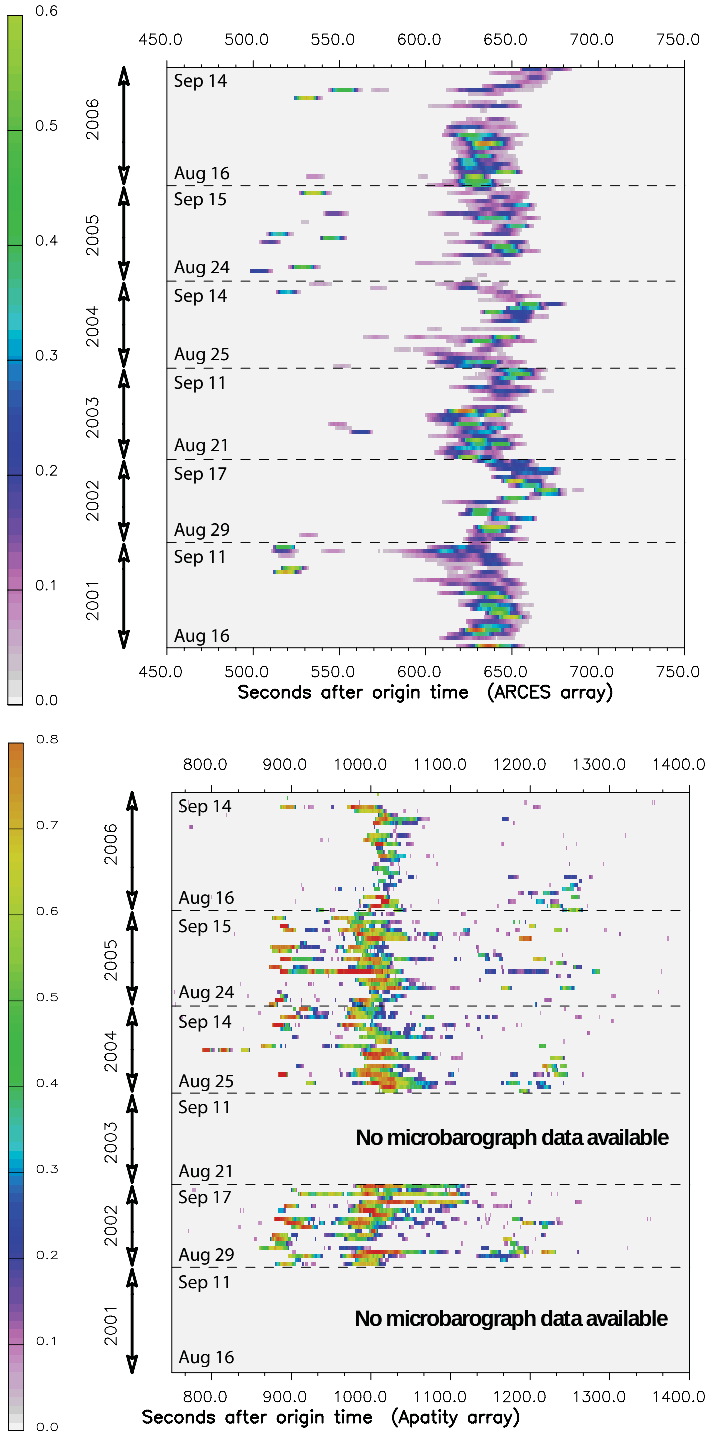

Fig. 6.1.4. Detection statistic over the full ARCES seismic array and the 3-element microbarograph sub-array at Apatity within the time-windows as indicated following each of 141 identified explosions in northern Finland between 2001 and 2006. Events occur one per day between the dates indicated. A pixel is drawn every second, at time t, for each event provided that the preferred slowness and backazimuth evaluated over the 10.0 second long window beginning at time t fall within an acceptable range for acoustic waves from the given source. The color indicates the value of the detection statistic defined in Eq. (15) of Brown et al. (2002).

The same procedure was applied to the microbarograph sub-array at Apatity on data segments provided by colleagues at KRSC and, of the 91 events with available microbarograph data, only 3 provided no indication of signals from the anticipated direction. Many of these recordings are of very high quality and a high SNR frequently results in high correlation coefficients (as indicated by the colors in the lower panel of Fig. 6.1.4. With the minimal configuration of 3 sites, the array gain is far poorer and there is no redundancy. If a single sensor is subjected to an outage or excessive noise, no direction estimate can be made regardless of how well the other sensors perform. This may partly explain the more speckled appearance of the APA panel. The noise levels at Apatity are high due to heavy industry and other local human activity which may hinder the observation of tele-infrasonic signals. Three distinct phases are frequently observed at Apatity approximately 900, 1000, and 1200 seconds following each event. Vinogradov and Ringdal (2003) analyzed waveforms from five such explosions in considerable detail, concluding that these well-observed phases had travel times consistent with the Iw, Is, and It phases as described by Brown et al. (2002).

6.1.3 Summary

We have identified a source of explosions which, in addition to generating seismic signals detected out to distances of several hundred kilometers, result in infrasound signals detected at the microbarograph array in Apatity at a distance of 280 km and on the ARCES seismic array at a distance of 175 km. The seismic signals provide excellent constraints on the source. Waveform similarity from event to event not only constrain the events to be almost co-located but rule out the possibility of multiple events as is common for ripple-fired mining blasts (e.g. Gibbons et al., 2005). We conclude that differences in the occurrence and appearance of infrasonic arrivals from event to event are due to atmospheric conditions alone. The similar amplitude of the seismic signals from event to event imply similar explosion yields and, as observed by McKenna et al. (2007), this does not appear to influence the amplitude of the infrasound signals greatly. For many events, the sound waves observed at the ARCES seismic array did not exceed the ambient noise level. The presence of infrasound arrivals was however confirmed for almost all events by significant values of the Γ statistic defined by Brown et al. (2002).

It would clearly be of considerable interest to apply infrasonic propagation models to attempt to explain the variations in travel times and phase amplitudes documented here. However, such a study is well beyond the scope of the current report. We should only like to note that the horizontal velocities or propagation times versus distance of the infrasonic waves could give an indication of the turning points associated with the various detected phases. For example, Brown et al. (2002) discuss generic travel time information for three main infrasonic phases (Iw, Is, and It, with turning points in the troposphere, stratosphere, and thermosphere respectively) that might be detected at distances similar to those considered for the Apatity array. The observation of infrasound signals at ARCES may provide useful data for subsequent studies of sound propagation at short distances, since the 175 km distance in this case falls within the classical “zone of silence” in which no ray paths predicted by standard atmospheric models return to ground level (see, for example, McKenna et al., 2007). Che et al. (2002) examine infrasonic signals from seismo-acoustic events within 200 km of the Chulwon array on the Korean Peninsula and confirm that local meterological data is required to be able to model these infrasonic arrivals at local-distances.

Whilst the sensitivity to acoustic signals varies from sensor to sensor of the ARCES array, direction estimates for the sound waves are remarkably similar over many different subsets of sensors (Ringdal et al., 2006). The uncertainty associated with direction measurements is of great importance for IMS arrays (Szuberla and Olson, 2004) with signal incoherence (Christie et al., 2005) and strong sidelobes (Kennett et al., 2003) presenting significant challenges for processing over large aperture arrays. Whilst the ARCES seismic array is still only a surrogate for the infrasound array IS37 to be built near Karasjok, the large number of sensors and corresponding wide range of sensor separations make this an ideal laboratory for coherence studies.

The recording of coherent infrasound wavefronts on seismic arrays may be more widespread than is presently assumed and an effort ought to be made to classify their occurrences on, for example, the IMS seismic arrays. The large amplitudes which can be generated (see Fig. 6.1.3) can be problematic in that they can potentially mask out important seismic arrivals. Indeed, one of the few documented descriptions of infrasound on IMS seismic arrays is a description of beams deployed on the GERES array in southern Germany to identify and screen out sound waves generated by nearby military activity (Harjes et al., 1993). However, rather than simply discarding such signals, these waveforms could be analyzed to address topical issues in infrasound array processing such as the discrimination of near- and far-field sound sources (Szuberla et al., 2006).

The current status on the database described can be obtained by contacting the authors and updates are likely to be reported on in future NORSAR technical reports and elsewhere. Use of the waveform correlation detector on ARCES seismic data is being extended back in time and positive identifications have so far been made as far back as August 24, 1988. The picture is not yet complete as many years of data are still in magnetic tape archives and the conversion process is ongoing. We have no reason to believe that the events will not continue into the future and we would advocate passive field experiments to record and interpret both seismic and atmospheric signals from subsequent events.

Acknowledgements

We are grateful to colleagues at the Kola Regional Seismological Center in Apatity, Russia, for providing segments of seismic and infrasound data from the APA array for the requested time-windows. We acknowledge colleagues at the Institute of Seismology at the University of Helsinki who provided us with seismic event bulletins.

Disclaimer

This work was sponsored by Army Space and Missile Defense Command (SMDC) under contract no. W9113M-05-C-0224. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the U.S. Army Space and Missile Defense Command or the U.S. Government.

An edited version of this manuscript has been accepted for publication in the JASA Express Letters section of Journal of the Acoustical Society of America.

References

Brown, D. J., Katz, C. N., Le Bras, R., Flanagan, M. P., Wang, J. and Gault, A. K. (2002): "Infrasonic Signal Detection and Source Location at the Prototype International Data Centre" *Pure appl. geophys.*, **159**, pp. 1081-1125.

Cansi, Y. (1995): "An automatic seismic event processing for detection and location: The P.M.C.C. method" *Geophys. Res. Lett.*, **22**, pp. 1021-1024.

Capon, J. (1969): "High-Resolution Frequency-Wavenumber Spectrum Analysis" *Proc. IEEE*, **57**, pp. 1408-1418.

Cates, J. E. and Sturtevant, B. (2002): "Seismic detection of sonic booms" *J. Acoust. Soc. Am.*, **111**, pp. 614-628.

Che, I.-Y., Jun, M.-S., Jeon, J.-S., and Min, K.D. (2002): "Analysis of local seismo-acoustic events in the Korean Peninsula" *Geophys. Res. Lett.*, **29**, 29-1, 10.1029/2001GL014060.

Christie, D. R., Kennett, B. L. N., and Tarlowski, C. (2005): "Detection of Regional and Distant Atmospheric Explosions at IMS Infrasound Stations" in "Proceedings of the 27th Seismic Research Review, Rancho Mirage, California, September 20-22, 2005. *Ground-based Nuclear Explosion Monitoring Technologies*". LA-UR-05-6407, pp. 817-828.

Garcés, M. A., Hansen, R. A., and Lindquist, K. G. (1998): "Traveltimes for infrasonic waves propagating in a stratified atmosphere" *Geophys. J. Int.*, **135**, pp. 28-34.

Geller, R. J. and Mueller, C. S. (1980): "Four Similar Earthquakes in Central California" *Geophys. Res. Lett.*, **7**, pp. 821-824.

Georges, T. M. and Beasley, W. H. (1977): "Refraction of infrasound by upper-atmosphere winds" *J. Acoust. Soc. Am.*, **61**, pp. 28-34.

Gibbons, S. J., Kværna, T., and Ringdal, F. (2005): "Monitoring of seismic events from a specific source region using a single regional array: a case study" *J. Seismol.*, **9**, pp. 277-294.

Gibbons, S. J., and Ringdal, F. (2006). "The detection of low magnitude seismic events using array-based waveform correlation" *Geophys. J. Int.*, **165**, pp. 149-165.

Hagerty, M. T., Kim, W.-Y., and Martysevich, P. (2002): "Infrasound Detection of Large Mining Blasts in Kazakstan" *Pure appl. geophys.*, **159**, pp. 1063-1079.

Harjes, H.-P., Jost, M. L., Schweitzer, J., Gestermann, N. (1993): "Automatic Seismogram Analysis at GERESS" *Computers and Geosciences*, **19**, pp. 157-166.

Jacobson, M. J. (1957): "Analysis of a Multiple Receiver Correlation System" *J. Acoust. Soc. Am.*, **29**, pp. 1342-1347.

Kennett, B. L. N., Brown, D. J., Sambridge, M., and Tarlowski, C. (2003): "Signal Parameter Estimation for Sparse Arrays" *Bull. Seism. Soc. Am.*, **93**, pp. 1765-1772.

Lin, T.-L. and Langston, C. A. (2006): "Anomalous Acoustic Signals Recorded by the CERI Seismic Network" *Seism. Res. Lett.*, **77**, pp. 572-581.

McKenna, M. H., Stump, B. W., Hayek, S., McKenna, J. R., and Stanton, T. R. (2007): "Tele-infrasonic studies of hard-rock mining explosions" *J. Acoust. Soc. Am.*, **122**, pp. 97-106.

Ringdal, F., Kværna, T., Gibbons, S. J., Mykkeltveit, S., and Schweitzer, J. (2006): "Research On Seismic and Infrasonic Monitoring of the European Arctic" in "Proceedings of the 28th Seismic Research Review, Orlando, Florida, September 19-21, 2006. *Ground-based Nuclear Explosion Monitoring Technologies*." LA-UR-06-5471, pp. 1017-1027.

Sorrells, G. G., Herrin, E. T., and Bonner, J. L. (1997): "Construction of Regional Ground Truth Databases Using Seismic and Infrasound Data" *Seism. Res. Lett.*, **68**, pp. 743-752.

Stump, B., Jun, M.-S., Hayward, C., Jeon, J.-S., Che, I.-Y., Thomason, K., House, S. M., and McKenna, J. (2004): "Small-Aperture Seismo-Acoustic Arrays: Design, Implementation, and Utilization" *Bull. Seism. Soc. Am.*, **94**, pp. 220-236.

Szuberla, C. A. L., Arnoult, K. M., and Olson, J. V. (2006): "Discrimination of near-field infrasound sources based on time-difference of arrival information" *J. Acoust. Soc. Am.*, **120**, pp. EL23-EL28.

Szuberla, C. A. L. and Olson, J. V. (2004): "Uncertainties associated with parameter estimation in atmospheric infrasound arrays" *J. Acoust. Soc. Am.*, **115**, pp. 253-258.

Vinogradov, Y. and Ringdal, F. (2003): "Analysis of infrasound data recorded at the Apatity array" *NORSAR Scientific Report: Semiannual Technical Summary*, No. 1-2003, Kjeller, Norway. pp. 68-77.

S. J. Gibbons
F. Ringdal
T. Kværna