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1 January - 30 June 2007

Frode Ringdal (ed.)

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14. ABSTRACT
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Abstract (cont.)

International Monitoring System (IMS) will gradually be transferred to the CTBTO/PTS. The O&M statistics presented in this report are included for the purpose of completeness, and in order to maintain consistency with earlier reporting practice.

The seismic arrays operated by the Norwegian NDC comprise the Norwegian Seismic Array (NOA), the Arctic Regional Seismic Array (ARCES) and the Spitsbergen Regional Array (SPITS). This report presents statistics for these three arrays as well as for additional seismic stations which through cooperative agreements with institutions in the host countries provide continuous data to the NORSAR Data Processing Center (NDPC). These additional stations include the Finnish Regional Seismic Array (FINES) and the Hagfors array in Sweden (HFS).

The NOA Detection Processing system has been operated throughout the period with an uptime of 100%. A total of 2,362 seismic events have been reported in the NOA monthly seismic bulletin during the reporting period. On-line detection processing and data recording at the NDC of data from ARCES, FINES, SPITS and HFS data have been conducted throughout the period. Processing statistics for the arrays for the reporting period are given.

A summary of the activities at the Norwegian NDC and relating to field installations during the reporting period is provided in Section 4. Norway is now contributing primary station data from two seismic arrays: NOA (PS27) and ARCES (PS28), one auxiliary seismic array SPITS (AS72), and one auxiliary three-component station (AS73). These data are being provided to the IDC via the global communications infrastructure (GCI). Continuous data from the three arrays are in addition being transmitted to the US NDC. The performance of the data transmission to the US NDC has been satisfactory during the reporting period.

So far among the Norwegian stations, the NOA and the ARCES array (PS27 and PS28 respectively), the radionuclide station at Spitsbergen (RN49) and the auxiliary seismic stations on Spitsbergen (AS72) and Jan Mayen (AS73) have been certified. Provided that adequate funding continues to be made available (from the PTS and the Norwegian Ministry of Foreign Affairs), we envisage continuing the provision of data from these and other Norwegian IMS-designated stations in accordance with current procedures. The IMS infrasound station at Karasjok (IS37) is expected to be built during 2008, provided that the local authorities grant the permissions required for the establishment of the station.

Summaries of four scientific and technical contributions are presented in Chapter 6 of this report.

Section 6.1 is a paper entitled “Joint seismic-infrasonic processing of recordings from a repeating source of atmospheric explosions in Northern Finland”. 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. 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.

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 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. 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.

Section 6.2 describes the application of array-based waveform correlation techniques to the detection of the 2003 Lefkada Island, Greece, aftershock sequence focusing on the very small aperture TRISAR array. A strong earthquake of Mw = 6.2 occurred on the northern part of the CTFZ Lefkada segment, off the NW coast of Lefkada Island, on 14th August 2003. The mainshock was followed by a vast number of aftershocks, distributed along the Lefkada Island coastline and extending southwards to the northern coasts of Cephalonia Island.

The first two days of this activity were recorded by the very small-aperture Tripoli Seismic Array (TRISAR), which is located in central Peloponnese, southern Greece. TRISAR is a 3-component, 4-site array, operated by the Seismological Laboratory of the University of Athens. Three short-period instruments form an almost equilateral triangle with side length of the order of 250 m, while a reference broadband station is situated in the middle of this deployment. Routine TRISAR data processing involves automatic event detection and location using the DP, EP and RONAPP algorithms developed at NORSAR.

Array-based waveform correlation techniques were applied to the first two days of the Lefkada aftershock sequence. The observed degrees of waveform similarity are consistent with the large extent of the aftershock area and the great diversity of associated waveforms. One limitation of the method applied here appears to be its sensitivity to the time windows used for the template and target waveforms. The cause of these difficulties is that template and target time-windows are defined for single events based upon location estimates; an iterative scheme to modify window definitions according to a matched filter detector would presumably improve the situation.

The mainshock does not appear to correlate highly with any aftershocks, belonging to a larger group of events loosely linked together. This can be attributed to the different rupture process that is associated with the mainshock.In most cases, according to the available bulletins, events populating the same clusters appear scattered on both segments of the CTFZ and even in areas lying outside the fault zone. This suggests that the location estimates used are poorly constrained. Indeed, some events in the ISC On-Line Bulletin with a large separation between epicenters were verified manually to produce highly similar waveforms suggesting a far smaller distance between epicenters than the bulletins suggest.

The obtained cluster pattern appears to be independent of the recording station, supporting the validity of the results. The waveform similarity suggests the possibility of obtaining accurate relocation estimates which, in turn, may be used in the future to explore further the seismicity patterns and characteristics of this seismic sequence. Following a relocation, it would also be interesting to investigate the relation between the obtained event clusters and estimated focal mechanisms.

Section 6.3 is entitled “Single small array regional localization using PMCC (ELOSV2)”. The Progressive Multi-Channel Correlation Method (PMCC) has been developed at the French Commissariat à l’Energie Atomique (CEA) and is used as a real-time detector for low-amplitude coherent waves within non-coherent noise. It works by performing a progressive association of channels for which the cross-correlation functions are consistent with delay-times (closure time relation) corresponding to coherent seismic energy propagating over an array. The detector is only sensitive to an increased degree of semblance between traces and does not detect directly increases in signal amplitudes.

A new module (ELOSV2) has been developed by CEA for single small-array regional event location using the PMCC results. Phase detection, and the estimation of azimuth and apparent velocity within each time-frequency window, is performed by PMCC. ELOSV2 then applies deterministic criteria to identify seismic phases, and associate them in order to create events.

We have tested the ELOSV2 algorithm on several months of ARCES data. The data are filtered between 2.5 Hz and 7 Hz; only the A, B and C rings of ARCES are used for the analysis. The algorithm has also been applied to data observed by the Spitsbergen array. SPITS is located to the north of ARCES and may help to locate the source region of seismic energy reaching ARCES from the north. As a quality check, the ELOSV2 results are compared with the results of a moving window fk-analysis.

We have compared our time-azimuth pattern at ARCES, calculated in the high frequency band 2.5 - 7 Hz, with the pattern at lower frequencies (below 3 Hz). According to previous studies, this low-frequency energy is related to ocean generated microseisms. From our results it appears that there are significant differences between the high and low frequency time-azimuth patterns, suggesting different source mechanisms.

One possible explanation could be that long periodic waves with high amplitudes, which means high kinetic energy, are hitting the coast as a cascade of single forces. Such hits generate compressional waves propagating in the Earth’s crust. The frequency contents of these compressional waves can be much higher than the original period of the oceanic waves. This period is then defining the time interval between two successive hits.

To test this hypothesis, the time differences between the signal pulses observed by the moving window fk-analysis were investigated. There is a dominance of time intervals between 4 and 10 seconds, which corresponds quite well with our hypothesis. However, further investigations are needed to come to consolidate this explanation.

Section 6.4 is entitled “Towards a Nordic Regional Infrasonic Array Network”. An important area of research at NORSAR is to develop methods for joint seismic/infrasonic analysis of events recorded at regional distances. In particular, we wish to apply and evaluate automatic processing techniques for the area comprising northern Fennoscandia and adjacent regions. It is clear that such an approach will require a far denser network of infrasonic arrays than is projected for the International Monitoring System (IMS).

This paper summarizes the currently available infrasound arrays in northern Europe. In particular, we describe the Swedish/Finnish infrasonic network, the data from which will allow a much improved joint seismic/infrasonic regional processing at NORSAR.

We continue our work towards developing and evaluating a joint seismic/infrasonic bulletin for northern Fennoscandia and adjacent regions. This bulletin would be similar to the automatic seismic bulletin that we are currently providing on the NORSAR Web pages, but it would also contain infrasonic phase associations. Furthermore, we will experimentally attempt to generate an infrasonic event bulletin using only the estimated azimuths and detection times of infrasound phases recorded by stations in the nordic network.

The combined seismic/infrasonic database that we plan to develop in the coming years will be highly valuable for various studies related to obtaining improved accuracy in detecting and characterizing seismic events in the European Arctic region using seismic and infrasonic array recordings at local and regional distances.

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The operational activities of the seismic field systems and the Norwegian National Data Center (NDC) are currently jointly funded by the Norwegian Government and the CTBTO/PTS, with the understanding that the funding of appropriate IMS-related activities will gradually be transferred to the CTBTO/PTS.

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1 Summary

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Frode Ringdal

2 Operation of International Monitoring System (IMS) Stations in Norway

2.1 PS27 — Primary Seismic Station NOA

The mission-capable data statistics were 100%, the same as for the previous reporting period. The net instrument availability was 99.572%.

There were no outages of all subarrays at the same time in the reporting period.

Monthly uptimes for the NORSAR on-line data recording task, taking into account all factors (field installations, transmissions line, data center operation) affecting this task were as follows:

2007		Mission Capable	Net instrument availability
January	:	100%	99.480%
February	:	100%	99.998%
March	:	100%	99.999%
April	:	100%	99.999%
May	:	100%	99.991%
June	:	100%	97.966%

B. Paulsen

NOA Event Detection Operation

In Table 2.1.1 some monthly statistics of the Detection and Event Processor operation are given. The table lists the total number of detections (DPX) triggered by the on-line detector, the total number of detections processed by the automatic event processor (EPX) and the total number of events accepted after analyst review (teleseismic phases, core phases and total).

	Total DPX	Total EPX	Accepted Events		Sum	Daily
			P-phases	Core Phases		
Jan	12,951	993	365	45	410	13.2
Feb	10,256	820	248	59	307	11.0
Mar	10,658	1,022	324	89	413	13.3
Apr	9,315	1,004	362	157	519	17.3
May	6,982	799	303	76	379	12.2
Jun	4,858	713	261	73	334	11.1
	55,020	5,351	1,863	499	2,362	13.0

Table 2.1.1. *Detection and Event Processor statistics, 1 January - 30 June 2007.*

NOA detections

The number of detections (phases) reported by the NORSAR detector during day 001, 2007, through day 181, 2007, was 55,020, giving an average of 304 detections per processed day (181 days processed).

B. Paulsen
U. Baadshaug

2.2 PS28 — Primary Seismic Station ARCES

The mission-capable data statistics were 99.846%, as compared to 99.554% for the previous reporting period. The net instrument availability was 97.179%.

The main outages in the period are presented in Table 2.2.1.

Day	Period
Jan 04	00.19-00.25
Jan 08	11.45-11.54
Jan 16	11.45-11.54
Jan 16	20.06-20.29
Jan 31	08.38-20.29
Mar 28	07.42-07.49
Jun 28	14.25-14.39
Jun 28	14.40-14.49
Jun 28	14.49-14.59

Table 2.2.1. *The main interruptions in recording of ARCES data at NDPC, 1 January - 30 June 2007.*

Monthly uptimes for the ARCES on-line data recording task, taking into account all factors (field installations, transmission lines, data center operation) affecting this task were as follows:

2007		Mission Capable	Net instrument availability
January	:	99.192%	96.259%
February	:	100%	88.839%
March	:	99.984%	98.050%
April	:	100%	99.994%
May	:	100%	100%
June	:	99.925%	99.365%

B. Paulsen

Event Detection Operation

ARCES detections

The number of detections (phases) reported during day 001, 2007, through day 181, 2007, was 158,375, giving an average of 875 detections per processed day (181 days processed).

Events automatically located by ARCES

During days 001, 2007, through 181, 2007, 8,493 local and regional events were located by ARCES, based on automatic association of P- and S-type arrivals. This gives an average of 46.9 events per processed day (181 days processed). 56% of these events are within 300 km, and 84 % of these events are within 1000 km.

U. Baadshaug

2.3 AS72 — Auxiliary Seismic Station Spitsbergen

The mission-capable data for the period were 100%, as compared to 96.259% for the previous reporting period. The net instrument availability was 99.940%.

Monthly uptimes for the Spitsbergen on-line data recording task, taking into account all factors (field installations, transmissions line, data center operation) affecting this task were as follows:

2007		Mission Capable	Net instrument availability
January	:	99.999%	99.679%
February	:	100%	99.994%
March	:	100%	99.992%
April	:	100%	99.994%
May	:	100%	99.991%
June	:	100%	99.996%

B. Paulsen

Event Detection Operation

Spitsbergen array detections

The number of detections (phases) reported from day 001, 2007, through day 181, 2007, was 340,227, giving an average of 1,880 detections per processed day (181 days processed).

Events automatically located by the Spitsbergen array

During days 001, 2007, through 181, 2007, 27,623 local and regional events were located by the Spitsbergen array, based on automatic association of P- and S-type arrivals. This gives an average of 152.6 events per processed day (181 days processed). 80% of these events are within 300 km, and 93% of these events are within 1000 km.

U. Baadshaug

2.4 AS73 — Auxiliary Seismic Station at Jan Mayen

The IMS auxiliary seismic network includes a three-component station on the Norwegian island of Jan Mayen. The station location given in the protocol to the Comprehensive Nuclear-Test-Ban Treaty is 70.9˚N, 8.7˚W.

The University of Bergen has operated a seismic station at this location since 1970. A so-called Parent Network Station Assessment for AS73 was completed in April 2002. A vault at a new location (71.0^{o}N, 8.5^{o}W) was prepared in early 2003, after its location had been approved by the PrepCom. New equipment was installed in this vault in October 2003, as a cooperative effort between NORSAR and the CTBTO/PTS. Continuous data from this station are being transmitted to the NDC at Kjeller via a satellite link installed in April 2000. Data are also made available to the University of Bergen.

The station was certified by the CTBTO/PTS on 12 June 2006.

J. Fyen

2.5 IS37 — Infrasound Station at Karasjok

The IMS infrasound network will include a station at Karasjok in northern Norway. The coordinates given for this station are 69.5˚N, 25.5˚E. These coordinates coincide with those of the primary seismic station PS28.

A site survey for this station was carried out during June/July 1998 as a cooperative effort between the CTBTO/PTS and NORSAR. The site survey led to a recommendation on the exact location of the infrasound station. There was, however, a strong local opposition against establishing the station at the recommended location, and two alternative sites were identified. The appropriate applications were sent to the local authorities to obtain the permissions needed to establish the station at one of these alternative locations. Both applications were turned down by the local governing council in June 2007. Discussions are currently underway with local stakeholders, in an attempt to identify a location for the station that will be acceptable to all parties.

A site preparation contract has been signed with the PTS. Due to scarce vegetation, possible high winds and difficult arctic operating conditions, the PTS has accepted our proposal to build a station comprising 9 elements.

J. Fyen

2.6 RN49 — Radionuclide Station on Spitsbergen

The IMS radionuclide network includes a station on the island of Spitsbergen. This station is also among those IMS radionuclide stations that will have a capability of monitoring for the presence of relevant noble gases upon entry into force of the CTBT.

A site survey for this station was carried out in August of 1999 by NORSAR, in cooperation with the Norwegian Radiation Protection Authority. The site survey report to the PTS contained a recommendation to establish this station at Platåberget, near Longyearbyen. The infrastructure for housing the station equipment was established in early 2001, and a noble gas detection system, based on the Swedish “SAUNA” design, was installed at this site in May 2001, as part of PrepCom’s noble gas experiment. A particulate station (“ARAME” design) was installed at the same location in September 2001. A certification visit to the particulate station took place in October 2002, and the particulate station was certified on 10 June 2003. Both systems underwent substantial upgrading in May/June 2006. The equipment at RN49 is being maintained and operated in accordance with a contract with the CTBTO/PTS.

S. Mykkeltveit

3 Contributing Regional Seismic Arrays

3.1 NORES

NORES has been out of operation since lightning destroyed the station electronics on 11 June 2002.

B. Paulsen

3.2 Hagfors (IMS Station AS101)

Data from the Hagfors array are made available continuously to NORSAR through a cooperative agreement with Swedish authorities.

The mission-capable data statistics were 97.877%, as compared to 99.996% for the previous reporting period. The net instrument availability was 97.635%.

The main outages in the period are presented in Table 3.2.1.

Day	Period
Jun 20	00.00-23.59
Jun 21	00.00-23.59
Jun 22	00.00-23.59
Jun 23	00.00-20.00

Table 3.2.1. *The main interruptions in recording of Hagfors data at NDPC, 1 January - 30 June 2007.*

Monthly uptimes for the Hagfors on-line data recording task, taking into account all factors (field installations, transmissions line, data center operation) affecting this task were as follows:

2007		Mission Capable	Net instrument availability
January	:	100%	100%
February	:	99.992%	99.992%
March	:	99.993%	99.993%
April	:	99.986%	99.985%
May	:	100%	100%
June	:	87.223%	87.761%

B. Paulsen

Hagfors Event Detection Operation

Hagfors array detections

The number of detections (phases) reported from day 001, 2007, through day 181, 2007, was 144,645, giving an average of 799 detections per processed day (181 days processed).

Events automatically located by the Hagfors array

During days 001, 2007, through 181, 2007, 3,198 local and regional events were located by the Hagfors array, based on automatic association of P- and S-type arrivals. This gives an average of 17.7 events per processed day (184 days processed). 79% of these events are within 300 km, and 92% of these events are within 1000 km.

U. Baadshaug

3.3 FINES (IMS station PS17)

Data from the FINES array are made available continuously to NORSAR through a cooperative agreement with Finnish authorities.

The mission-capable data statistics were 100%, as compared to 99.991% for the previous reporting period. The net instrument availability was 95.113%.

Monthly uptimes for the FINES on-line data recording task, taking into account all factors (field installations, transmissions line, data center operation) affecting this task were as follows:

2007		Mission Capable	Net instrument availability
January	:	100%	95.238%
February	:	100%	94.845%
March	:	100%	95.255%
April	:	100%	100%
May	:	100%	95.238%
June	:	100%	94.582%

B. Paulsen

FINES Event Detection Operation

FINES detections

The number of detections (phases) reported during day 001, 2007, through day 181, 2007, was 50,159, giving an average of 277 detections per processed day (181 days processed).

Events automatically located by FINES

During days 001, 2007, through 181, 2007, 2,688 local and regional events were located by FINES, based on automatic association of P- and S-type arrivals. This gives an average of 14.9 events per processed day (181 days processed). 81% of these events are within 300 km, and 89% of these events are within 1000 km.

U. Baadshaug

3.4 Regional Monitoring System Operation and Analysis

The Regional Monitoring System (RMS) was installed at NORSAR in December 1989 and has been operated at NORSAR from 1 January 1990 for automatic processing of data from ARCES and NORES. A second version of RMS that accepts data from an arbitrary number of arrays and single 3-component stations was installed at NORSAR in October 1991, and regular operation of the system comprising analysis of data from the 4 arrays ARCES, NORES, FINES and GERES started on 15 October 1991. As opposed to the first version of RMS, the one in current operation also has the capability of locating events at teleseismic distances.

Data from the Apatity array was included on 14 December 1992, and from the Spitsbergen array on 12 January 1994. Detections from the Hagfors array were available to the analysts and could be added manually during analysis from 6 December 1994. After 2 February 1995, Hagfors detections were also used in the automatic phase association.

Since 24 April 1999, RMS has processed data from all the seven regional arrays ARCES, NORES, FINES, GERES (until January 2000), Apatity, Spitsbergen, and Hagfors. Starting 19 September 1999, waveforms and detections from the NORSAR array have also been available to the analyst.

Phase and event statistics

Table 3.5.1 gives a summary of phase detections and events declared by RMS. From top to bottom the table gives the total number of detections by the RMS, the number of detections that are associated with events automatically declared by the RMS, the number of detections that are not associated with any events, the number of events automatically declared by the RMS, and finally the total number of events worked on interactively (in accordance with criteria that vary over time; see below) and defined by the analyst.

New criteria for interactive event analysis were introduced from 1 January 1994. Since that date, only regional events in areas of special interest (e.g, Spitsbergen, since it is necessary to acquire new knowledge in this region) or other significant events (e.g, felt earthquakes and large industrial explosions) were thoroughly analyzed. Teleseismic events of special interest are also analyzed.

To further reduce the workload on the analysts, a new processing scheme was introduced on 2 February 1995. The GBF (Generalized Beamforming) program is used as a pre-processor to RMS, and only phases associated with selected events in northern Europe are considered in the automatic RMS phase association. All detections, however, are still available to the analysts and can be added manually during analysis.

	Jan 07	Feb 07	Mar 07	Apr 07	May 07	Jun 07	Total
Phase detections	156,259	125,636	130,577	142,538	147,430	142,146	844,586
- Associated phases	4,550	4,369	4,737	4,181	4,345	4,547	26,729
- Unassociated phases	151,709	121,257	125,840	138,357	143,085	137,599	817,857
Events automatically declared by RMS	927	798	870	780	824	813	5,012
No. of events defined by the analyst	39	72	60	47	60	56	334

Table 3.5.1. RMS phase detections and event summary 1 January - 30 June 2007.

U. Baadshaug

B. Paulsen

4 NDC and Field Activities

4.1 NDC Activitities

NORSAR functions as the Norwegian National Data Center (NDC) for CTBT verification. Six monitoring stations, comprising altogether 132 field sensors plus radionuclide monitoring equipment, will be located on Norwegian territory as part of the future IMS as described elsewhere in this report. The four seismic IMS stations are all in operation today, and all of them are currently providing data to the CTBTO on a regular basis. PS27, PS28, AS73 and RN49 are all certified. The infrasound station in northern Norway is planned to be established within next year. Data recorded by the Norwegian stations is being transmitted in real time to the Norwegian NDC, and provided to the IDC through the Global Communications Infrastructure (GCI). Norway is connected to the GCI with a frame relay link to Vienna.

Operating the Norwegian IMS stations continues to require significant efforts by personnel both at the NDC and in the field. Strictly defined procedures as well as increased emphasis on regularity of data recording and timely data transmission to the IDC in Vienna have led to increased reporting activities and implementation of new procedures for the NDC. The NDC carries out all the technical tasks required in support of Norway's treaty obligations. NORSAR will also carry out assessments of events of special interest, and advise the Norwegian authorities in technical matters relating to treaty compliance. A challenge for the NDC is to carry 40 years' experience over to the next generation of personnel.

Verification functions; information received from the IDC

After the CTBT enters into force, the IDC will provide data for a large number of events each day, but will not assess whether any of them are likely to be nuclear explosions. Such assessments will be the task of the States Parties, and it is important to develop the necessary national expertise in the participating countries. An important task for the Norwegian NDC will thus be to make independent assessments of events of particular interest to Norway, and to communicate the results of these analyses to the Norwegian Ministry of Foreign Affairs.

Monitoring the Arctic region

Norway will have monitoring stations of key importance for covering the Arctic, including Novaya Zemlya, and Norwegian experts have a unique competence in assessing events in this region. On several occasions in the past, seismic events near Novaya Zemlya have caused political concern, and NORSAR specialists have contributed to clarifying these issues.

International cooperation

After entry into force of the treaty, a number of countries are expected to establish national expertise to contribute to the treaty verification on a global basis. Norwegian experts have been in contact with experts from several countries with the aim of establishing bilateral or multilateral cooperation in this field. One interesting possibility for the future is to establish NORSAR as a regional center for European cooperation in the CTBT verification activities.

NORSAR event processing

The automatic routine processing of NORSAR events as described in NORSAR Sci. Rep. No. 2-93/94, has been running satisfactorily. The analyst tools for reviewing and updating the solutions have been continually modified to simplify operations and improve results. NORSAR is currently applying teleseismic detection and event processing using the large-aperture NOA array as well as regional monitoring using the network of small-aperture arrays in Fennoscandia and adjacent areas.

Communication topology

Norway has implemented an independent subnetwork, which connects the IMS stations AS72, AS73, PS28, and RN49 operated by NORSAR to the GCI at NOR_NDC. A contract has been concluded and VSAT antennas have been installed at each station in the network. Under the same contract, VSAT antennas for 6 of the PS27 subarrays have been installed for intra-array communication. The seventh subarray is connected to the central recording facility via a leased land line. The central recording facility for PS27 is connected directly to the GCI (Basic Topology). All the VSAT communication is functioning satisfactorily. As of 10 June 2005, AS72 and RN49 are connected to NOR_NDC through a VPN link.

Jan Fyen

4.2 Status Report: Provision of data from Norwegian seismic IMS stations to the IDC

Introduction

This contribution is a report for the period January - June 2007 on activities associated with provision of data from Norwegian seismic IMS stations to the International Data Centre (IDC) in Vienna. This report represents an update of contributions that can be found in previous editions of NORSAR's Semiannual Technical Summary. All four Norwegian seismic stations providing data to the IDC have now been formally certified.

Norwegian IMS stations and communications arrangements

During the reporting interval, Norway has provided data to the IDC from the four seismic stations shown in Fig. 4.2.1. PS27 —NOA is a 60 km aperture teleseismic array, comprised of 7 subarrays, each containing six vertical short period sensors and a three-component broadband instrument. PS28 — ARCES is a 25-element regional array with an aperture of 3 km, whereas AS72 — Spitsbergen array (station code SPITS) has 9 elements within a 1-km aperture. AS73 — JMIC has a single three-component broadband instrument.

The intra-array communication for NOA utilizes a land line for subarray NC6 and VSAT links based on TDMA technology for the other 6 subarrays. The central recording facility for NOA is located at the Norwegian National Data Center (NOR_NDC).

Continuous ARCES data are transmitted from the ARCES site to NOR_NDC using a 64 kbits/s VSAT satellite link, based on BOD technology.

Continuous SPITS data were transmitted to NOR_NDC via a VSAT terminal located at Platåberget in Longyearbyen (which is the site of the IMS radionuclide monitoring station

RN49 installed during 2001) up to 10 June 2005. The central recording facility (CRF) for the SPITS array has been moved to the University of Spitsbergen (UNIS). A 512 bps SHDSL link has been established between UNIS and NOR_NDC. Data from the array elements to the CRF are transmitted via a 2.4 Ghz radio link (Wilan VIP-110). Both AS72 and RN49 data are now transmitted to NOR_NDC over this link using VPN technology.

A minimum of seven-day station buffers have been established at the ARCES and SPITS sites and at all NOA subarray sites, as well as at the NOR_NDC for ARCES, SPITS and NOA. In addition, each individual site of the SPITS array has a 14-day buffer.

The NOA and ARCES arrays are primary stations in the IMS network, which implies that data from these stations is transmitted continuously to the receiving international data center. Since October 1999, this data has been transmitted (from NOR_NDC) via the Global Communications Infrastructure (GCI) to the IDC in Vienna. Data from the auxiliary array station SPITS — AS72 have been sent in continuous mode to the IDC during the reporting period. AS73 — JMIC is an auxiliary station in the IMS, and the JMIC data have been available to the IDC throughout the reporting period on a request basis via use of the AutoDRM protocol (Kradolfer, 1993; Kradolfer, 1996). In addition, continuous data from all three arrays is transmitted to the US_NDC.

Uptimes and data availability

Figs. 4.2.2 and 4.2.3 show the monthly uptimes for the Norwegian IMS primary stations ARCES and NOA, respectively, for the reporting period given as the hatched (taller) bars in these figures. These barplots reflect the percentage of the waveform data that is available in the NOR_NDC data archives for these two arrays. The downtimes inferred from these figures thus represent the cumulative effect of field equipment outages, station site to NOR_NDC communication outage, and NOR_NDC data acquisition outages.

Figs. 4.2.2 and 4.2.3 also give the data availability for these two stations as reported by the IDC in the IDC Station Status reports. The main reason for the discrepancies between the NOR_NDC and IDC data availabilities as observed from these figures is the difference in the ways the two data centers report data availability for arrays: Whereas NOR_NDC reports an array station to be up and available if at least one channel produces useful data, the IDC uses weights where the reported availability (capability) is based on the number of actually operating channels.

Use of the AutoDRM protocol

NOR_NDC's AutoDRM has been operational since November 1995 (Mykkeltveit & Baadshaug, 1996). The monthly number of requests by the IDC for JMIC data for the period January - June 2007 is shown in Fig. 4.2.4.

NDC automatic processing and data analysis

These tasks have proceeded in accordance with the descriptions given in Mykkeltveit and Baadshaug (1996). For the reporting period NOR_NDC derived information on 425 supplementary events in northern Europe and submitted this information to the Finnish NDC as the NOR_NDC contribution to the joint Nordic Supplementary (Gamma) Bulletin, which in turn is forwarded to the IDC. These events are plotted in Fig. 4.2.5.

Data access for the station NIL at Nilore, Pakistan

NOR_NDC continued to provide access to the seismic station NIL at Nilore, Pakistan, through a VSAT satellite link between NOR_NDC and Pakistan's NDC in Nilore. On 10 December 2006, the VSAT ground station in Nilore was damaged by lightning. It was brought back into operation on 14 December 2006 through use of spare units stored on-site.

Current developments and future plans

NOR_NDC is continuing the efforts towards improving and hardening all critical data acquisition and data forwarding hardware and software components, so as to meet the requirements related to operation of IMS stations.

The NOA array was formally certified by the PTS on 28 July 2000, and a contract with the PTS in Vienna currently provides partial funding for operation and maintenance of this station. The ARCES array was formally certified by the PTS on 8 November 2001, and a contract with the PTS is in place which also provides for partial funding of the operation and maintenance of this station. The operation of the two IMS auxiliary seismic stations on Norwegian territory (Spitsbergen and Jan Mayen) is funded by the Norwegian Ministry of Foreign Affairs. Provided that adequate funding continues to be made available (from the PTS and the Norwegian Ministry of Foreign Affairs), we envisage continuing the provision of data from all Norwegian seismic IMS stations without interruption to the IDC in Vienna.

U. Baadshaug
S. Mykkeltveit
J. Fyen

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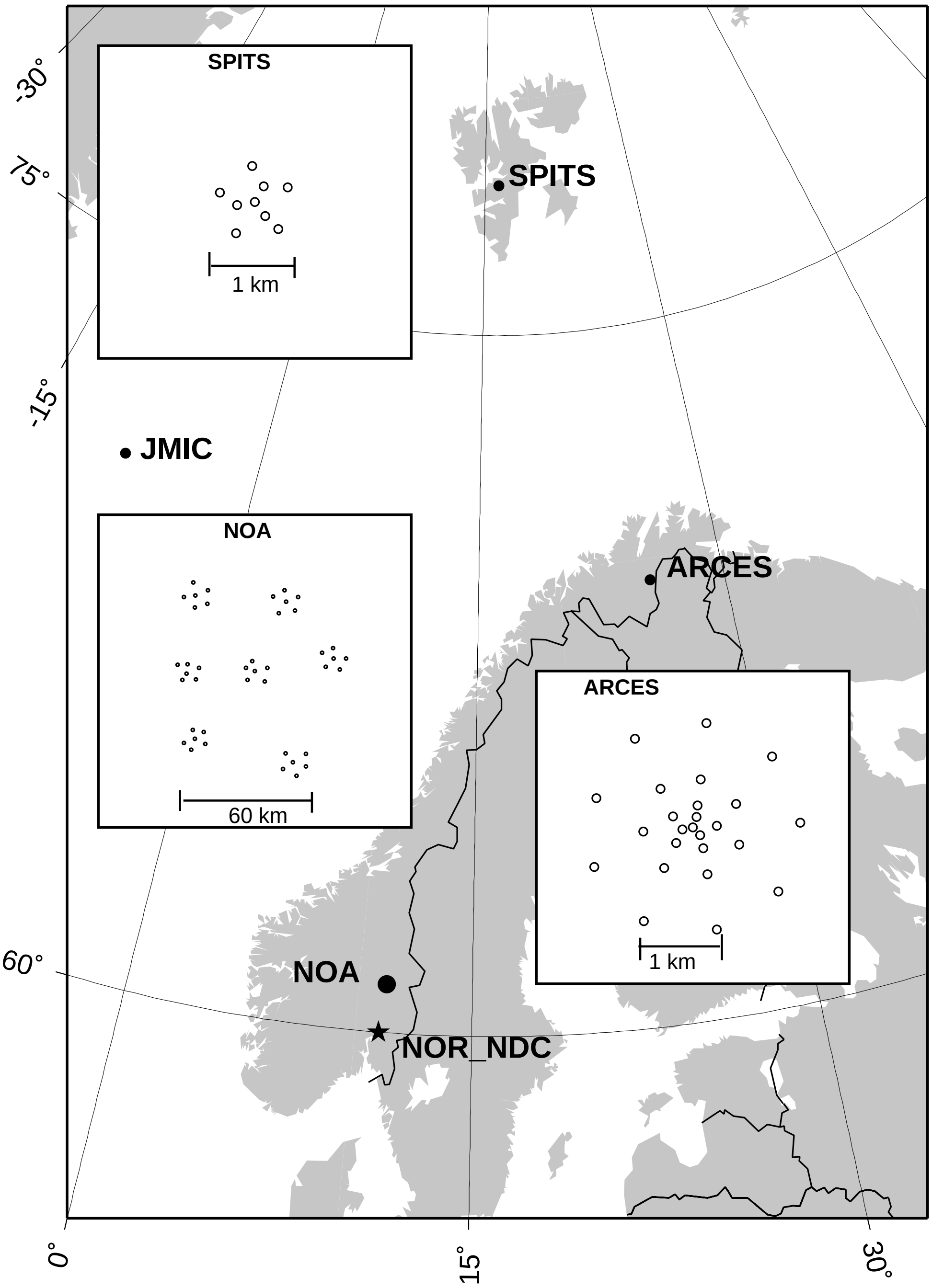

Fig. 4.2.1. The figure shows the locations and configurations of the three Norwegian seismic IMS array stations that provided data to the IDC during the period January - June 2007. The data from these stations and the JMIC three-component station are transmitted continuously and in real time to the Norwegian NDC (NOR_NDC). The stations NOA and ARCES are primary IMS stations, whereas SPITS and JMIC are auxiliary IMS stations.

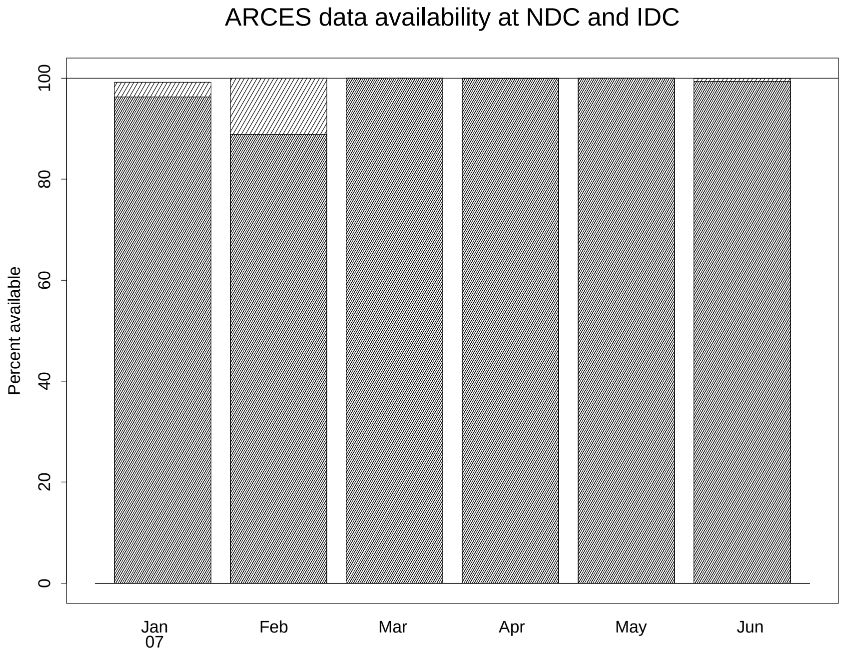

Fig. 4.2.2. The figure shows the monthly availability of ARCES array data for the period January - June 2007 at NOR_NDC and the IDC. See the text for explanation of differences in definition of the term "data availability" between the two centers. The higher values (hatched bars) represent the NOR_NDC data availability.

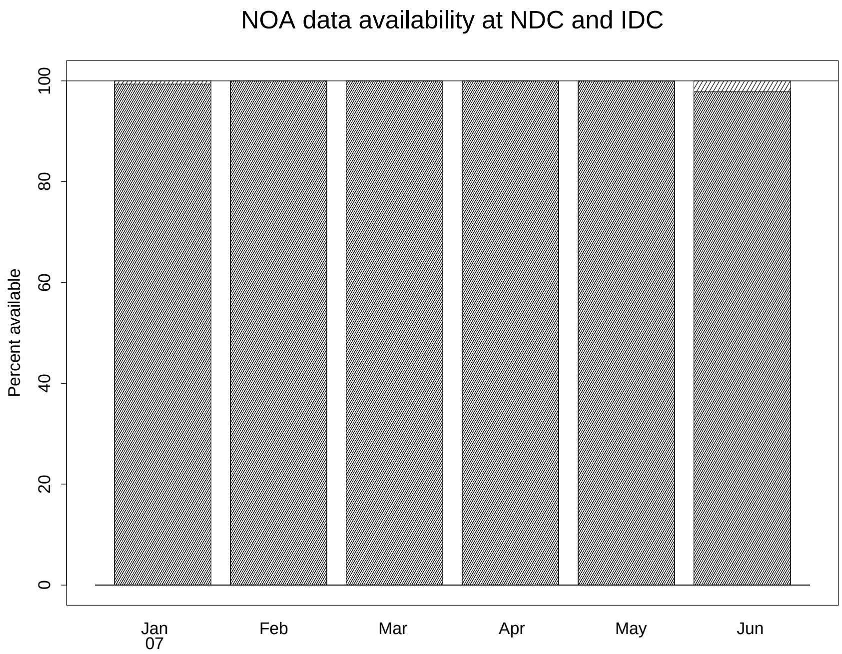

Fig. 4.2.3. The figure shows the monthly availability of NORSAR array data for the period January - June 2007 at NOR_NDC and the IDC. See the text for explanation of differences in definition of the term "data availability" between the two centers. The higher values (hatched bars) represent the NOR_NDC data availability.

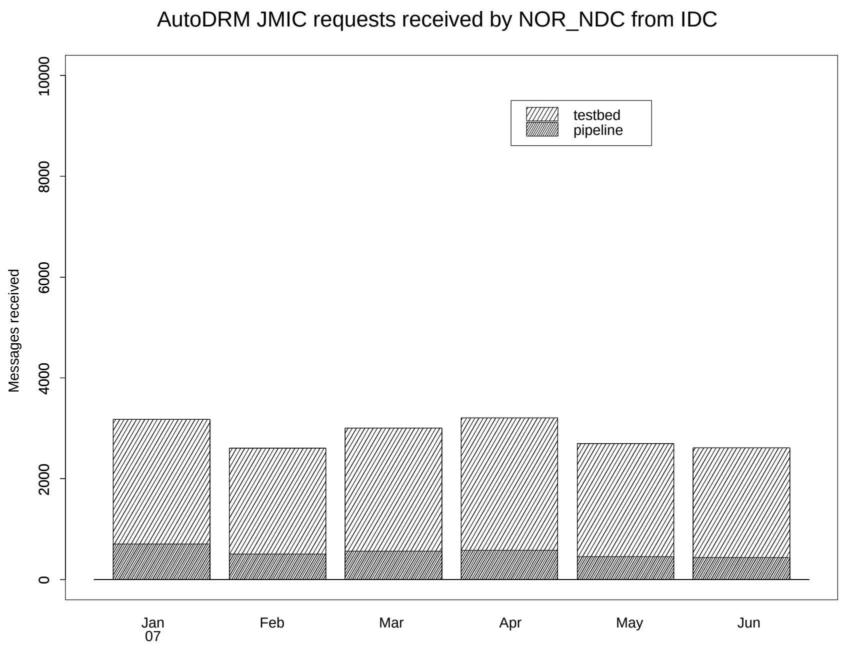

Fig. 4.2.4. The figure shows the monthly number of requests received by NOR_NDC from the IDC for JMIC waveform segments during January - June 2007.

Reviewed Supplementary events

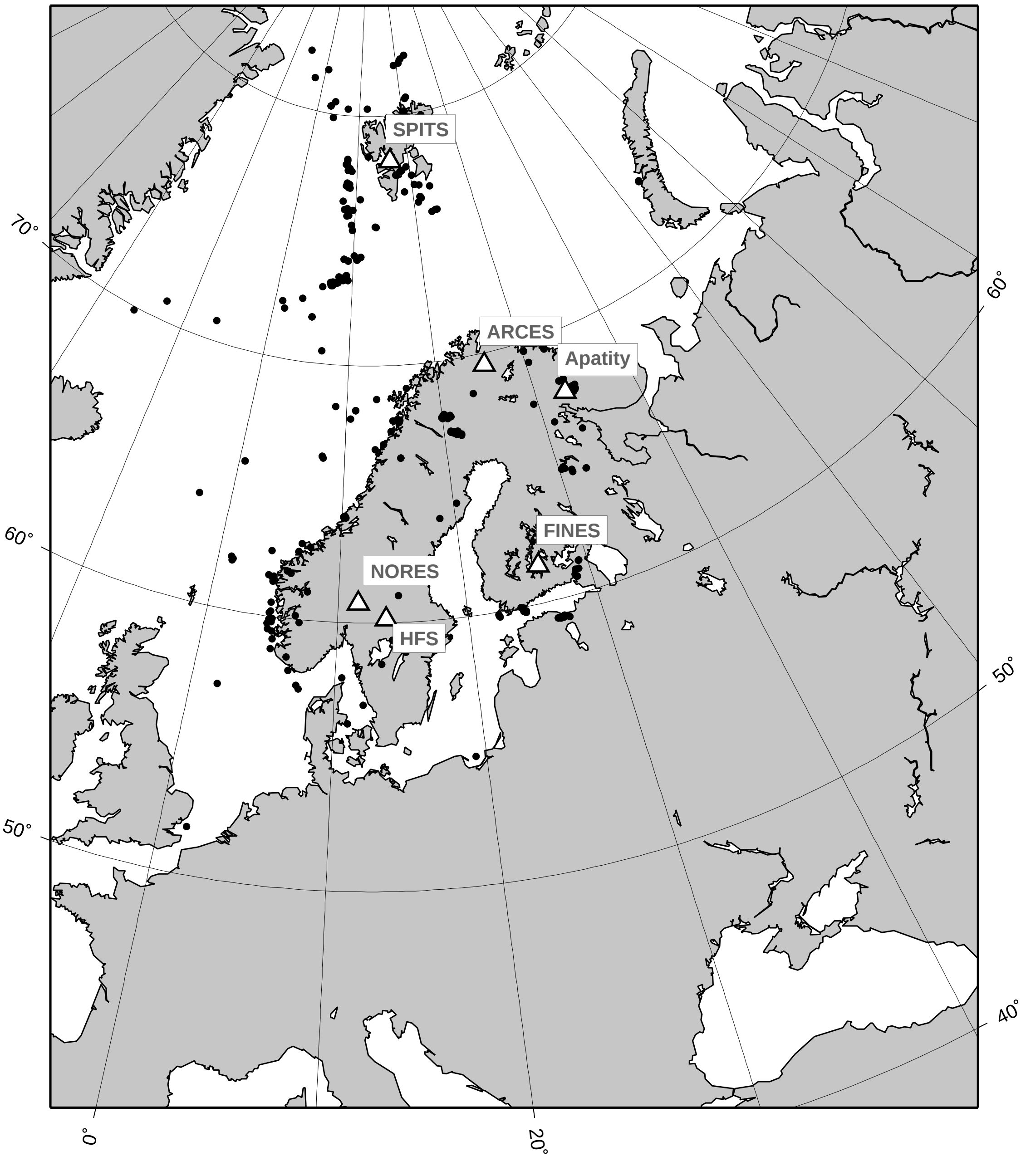

Fig. 4.2.5. The map shows the 415 events in and around Norway contributed by NOR_NDC during January - June 2007 as supplementary (Gamma) events to the IDC, as part of the Nordic supplementary data compiled by the Finnish NDC. The map also shows the main seismic stations used in the data analysis to define these events.

4.3 Field Activities

The activities at the NORSAR Maintenance Center (NMC) at Hamar currently include work related to operation and maintenance of the following IMS seismic stations: the NOA teleseismic array (PS27), the ARCES array (PS28) and the Spitsbergen array (AS72). Some work has also been carried out in connection with the seismic station on Jan Mayen (AS73), the radionuclide station at Spitsbergen (RN49), and preparations for the infrasound station at Karasjok (IS37). NORSAR also acts as a consultant for the operation and maintenance of the Hagfors array in Sweden (AS101).

NORSAR carries out the field activities relating to IMS stations in a manner generally consistent with the requirements specified in the appropriate IMS Operational Manuals, which are currently being developed by Working Group B of the Preparatory Commission. For seismic stations these specifications are contained in the Operational Manual for Seismological Monitoring and the International Exchange of Seismological Data (CTBT/WGB/TL-11/2), currently available in a draft version.

All regular maintenance on the NORSAR field systems is conducted on a one-shift-per-day, five-day-per-week basis. The maintenance tasks include:

- Operating and maintaining the seismic sensors and the associated digitizers, authentication devices and other electronics components.
- Maintaining the power supply to the field sites as well as backup power supplies.
- Operating and maintaining the VSATs, the data acquisition systems and the intra-array data transmission systems.
- Assisting the NDC in evaluating the data quality and making the necessary changes in gain settings, frequency response and other operating characteristics as required.
- Carrying out preventive, routine and emergency maintenance to ensure that all field systems operate properly.
- Maintaining a computerized record of the utilization, status, and maintenance history of all site equipment.
- Providing appropriate security measures to protect against incidents such as intrusion, theft and vandalism at the field installations.

Details of the daily maintenance activities are kept locally. As part of its contract with CTBTO/PTS NORSAR submits, when applicable, problem reports, outage notification reports and equipment status reports. The contents of these reports and the circumstances under which they will be submitted are specified in the draft Operational Manual.

P.W. Larsen
K.A. Løken

5 Documentation Developed

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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.

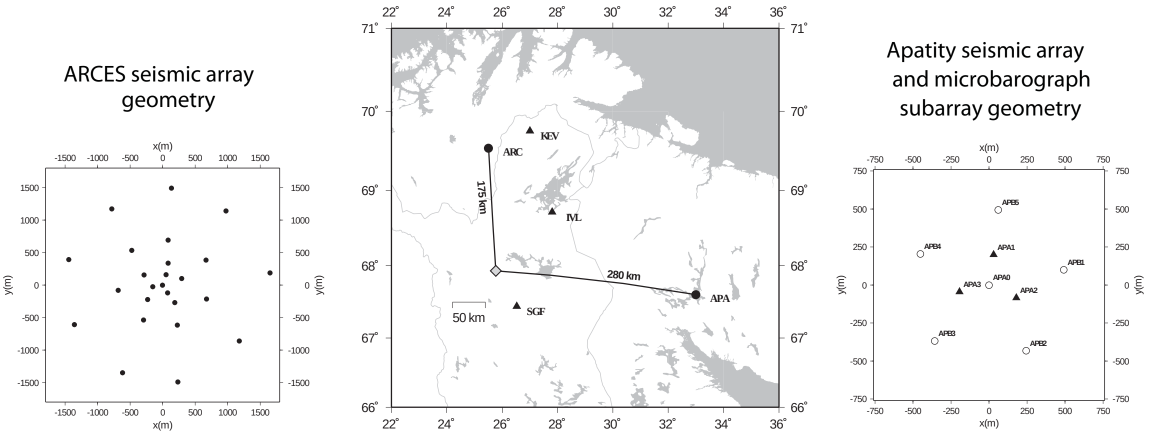

Fig. 6.1.1. Location of explosion site in relation to the arrays as indicated. Sites in the ARCES array contain only seismometers as do sites marked with white circles at Apatity. Black triangles at Apatity indicate both a seismometer and a microbarograph. Data from the SGF, KEV, and IVL 3-component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

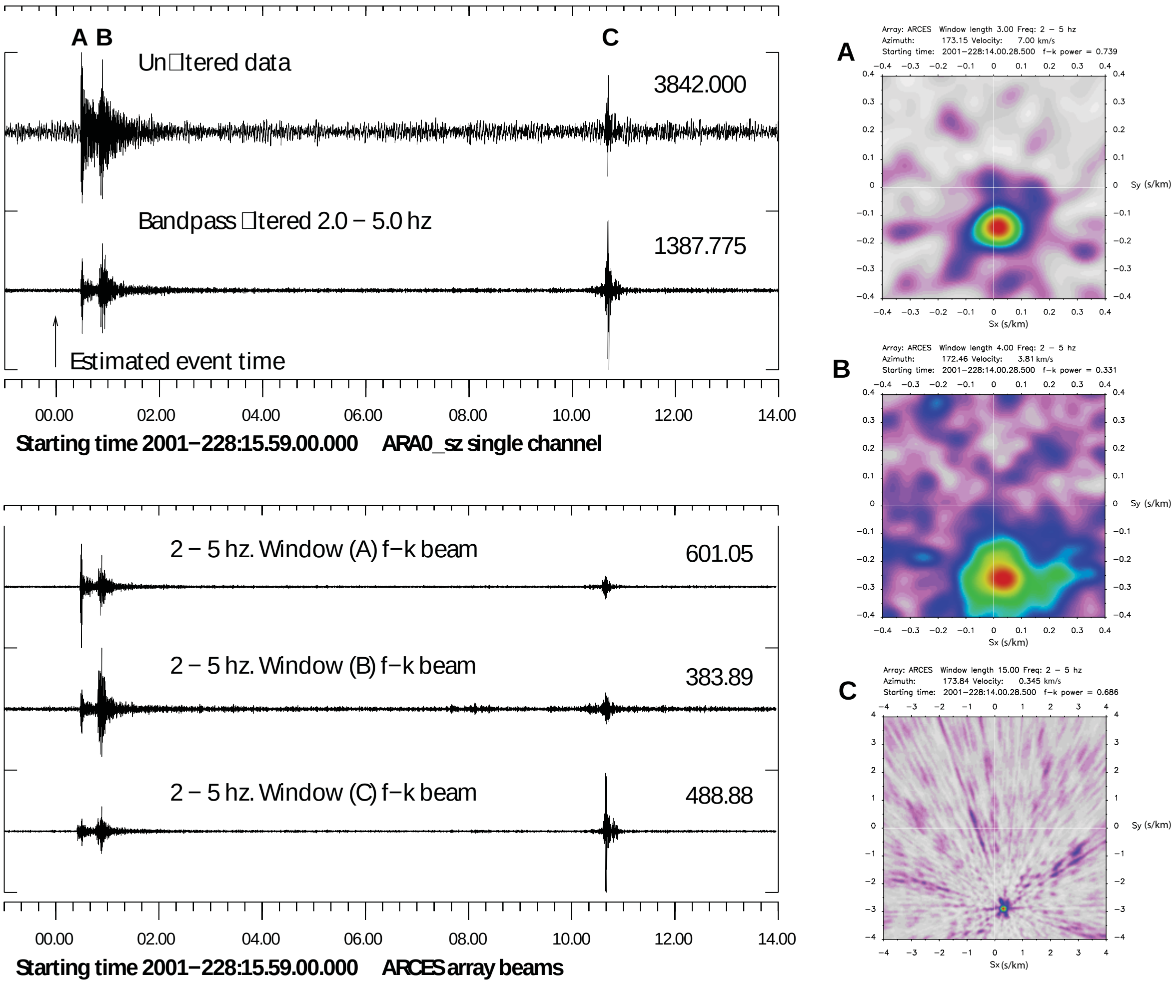

Fig. 6.1.2. Waveform data from the ARCES seismic array one minute prior to and 14 minutes after a surface level explosion in Northern Finland at a distance of approximately 175 km. The top panel shows waveforms on the central seismometer: the seismic P-phase (A), seismic S-phase (B), and an unidentified 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.

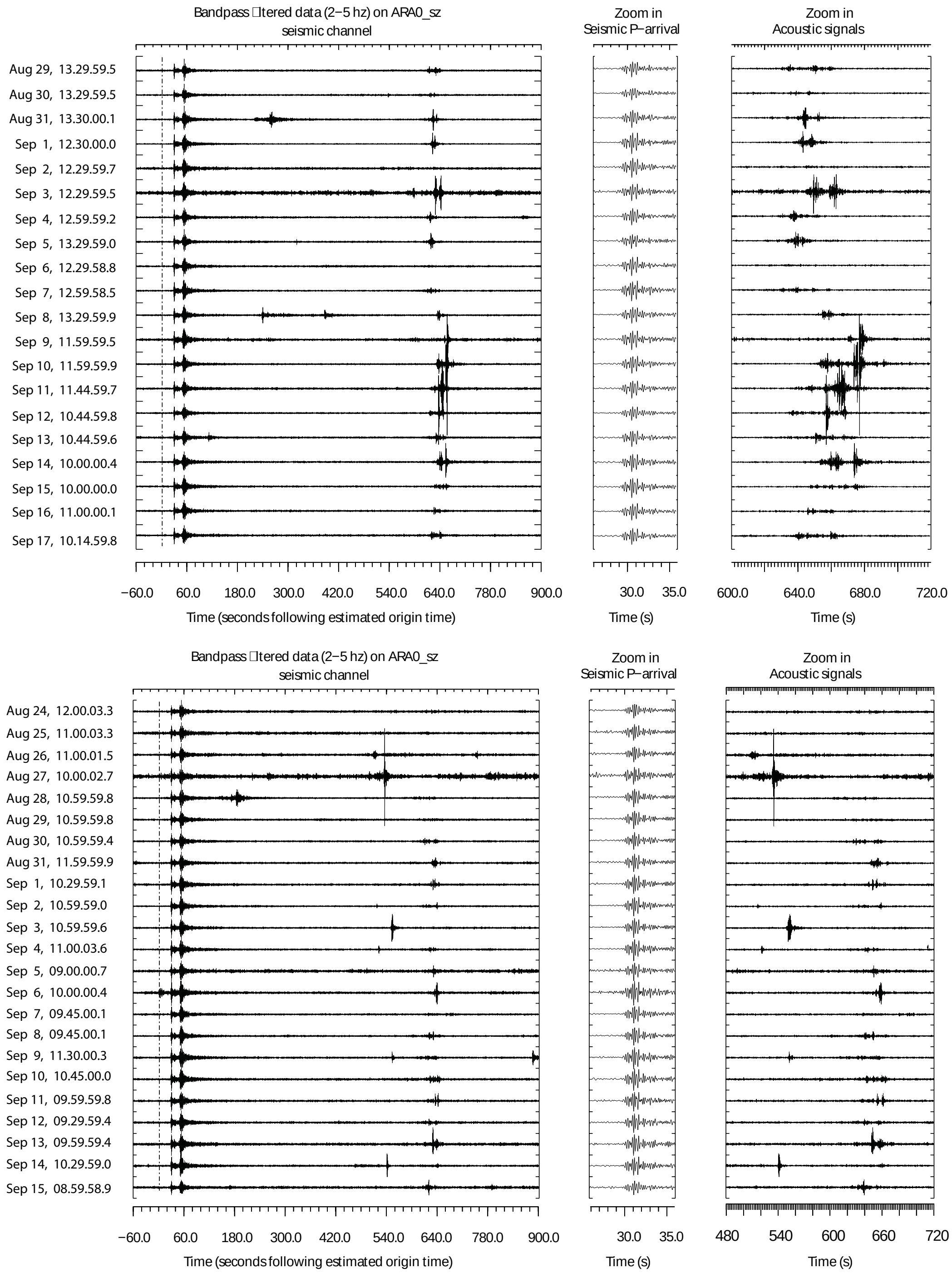

Fig. 6.1.3. Recordings on the ARCES seismic array (channel ARA0_sz) of events at the Finnish explosion site in August and September 2002 (upper panel) and August and September 2005 (lower panel). The time provided to the left is the estimated event UTC origin time. All seismograms are aligned according 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.

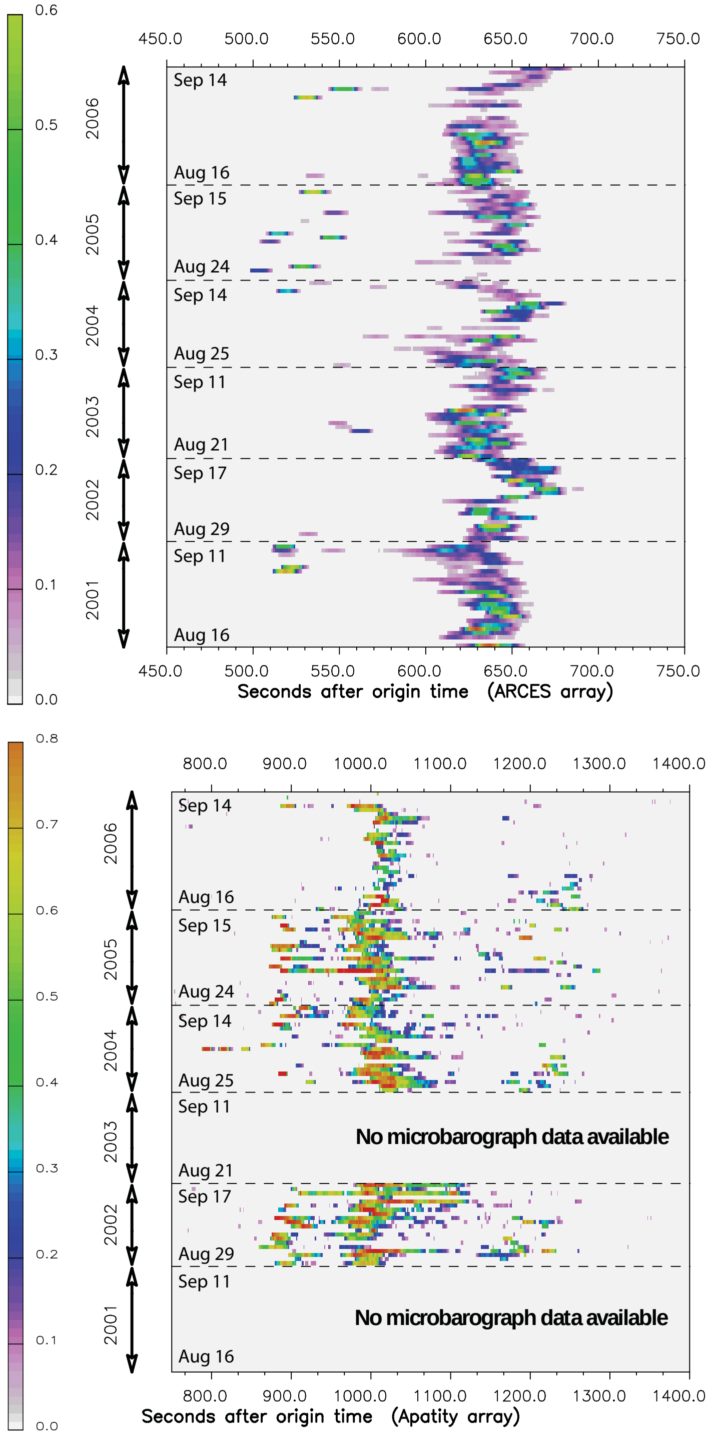

Fig. 6.1.4. Detection statistic over the full ARCES seismic array and the 3-element microbarograph sub-array at Apatity within the time-windows as indicated following each of 141 identified explosions in northern Finland between 2001 and 2006. Events occur one per day between the dates indicated. A pixel 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.

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Disclaimer

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6.2 Application of array-based waveform correlation techniques to the detection of the 2003 Lefkada Island, Greece, aftershock sequence focusing on the very small aperture TRISAR array

6.2.1 Introduction

The Ionian Islands region, depicted in Fig. 6.2.1, is the most seismically active area in Greece. Its most prominent geodynamic feature is the Cephalonia Transform Fault Zone (CTFZ), which terminates the Hellenic subduction zone and comprises of two main segments, the southern Cephalonia segment - CS, and the northern Lefkada segment - LS (e.g., Louvari et al., 1999).

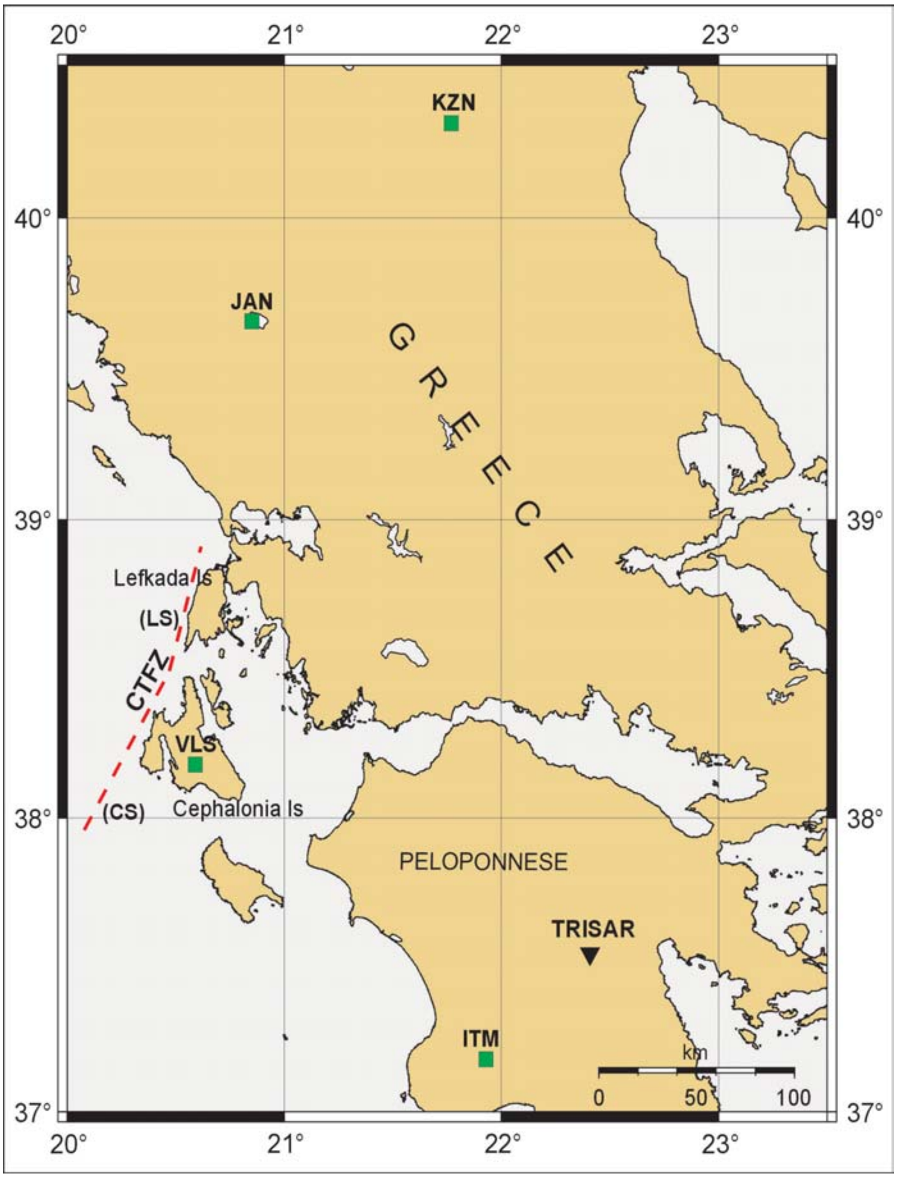

Fig. 6.2.1. Map of the Ionian Islands region and location of the Tripoli Seismic Array (TRISAR - black inverted triangle) and the GI-NOA stations used in this study (green squares). The two segments (CS and LS) of the Cephalonia Transform Fault Zone (CTFZ) are depicted with a dashed, red line.

A strong earthquake of Mw = 6.2 occurred on the northern part of the CTFZ Lefkada segment, off the NW coast of Lefkada Island, on 14th August 2003. The mainshock was followed by a vast number of aftershocks, distributed along the Lefkada Island coastline and extending southwards to the northern coasts of Cephalonia Island (e.g., Karakostas et al., 2004).

The first two days of this activity were recorded by the very small-aperture Tripoli Seismic Array (TRISAR), which is located in central Peloponnese, southern Greece. TRISAR is a 3-component, 4-site array, operated by the Seismological Laboratory of the University of Athens (Pirli et al., 2004). Three short-period instruments form an almost equilateral triangle with side length of the order of 250 m, while a reference broadband station is situated in the middle of this deployment. Routine TRISAR data processing (Pirli, 2005) involves automatic event detection and location using the DP, EP and RONAPP algorithms developed at NORSAR (Fyen, 1987;1989; Mykkeltveit and Bungum, 1984), the results being reviewed by an analyst.

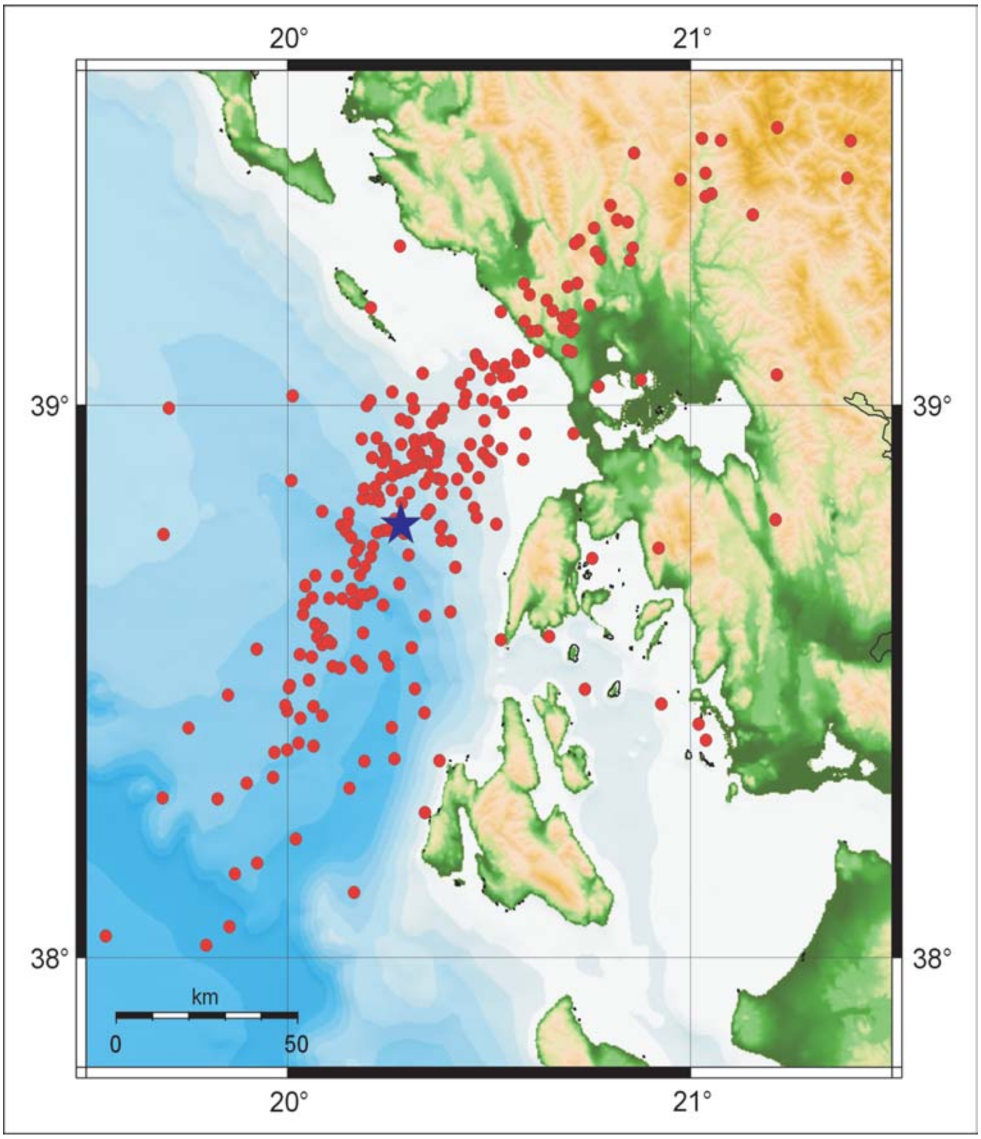

Fig. 6.2.2. Map of single-station TRISAR epicenter location estimates for 254 events of the 2003 Lefkada sequence. The location estimate for the mainshock epicenter is denoted with a blue star.

In the case of the 2003 Lefkada activity, which is located approximately 200 km from TRISAR, single-array locations were obtained for a total of 254 events: a much larger number than has been recorded and analyzed by other networks/agencies. The corresponding single-station epicenter location estimates presented in Fig. 6.2.2 resulted after careful manual review of initial automatic solutions. Even so, the obtained location estimate distribution exhibits significantly larger scatter than regional and local network solutions, due to the limited TRISAR slowness vector resolution and the larger residuals observed in the area of the Ionian Islands (Pirli, 2005; Pirli et al., 2007).

Array-based waveform correlation techniques have been applied to a subset of 244 Lefkada events, which resulted after discarding problematic data, to investigate event spatio-temporal clustering during the initial stages of the seismic sequence. Results obtained are compared with those for single, 3-component local and regional stations, operated by the Geodynamics Institute of the National Observatory of Athens (GI-NOA), and will constitute the basis for a future event relocation exercise applying relative location methods.

Moreover, further interest lies in the assessment of the applicability of full-waveform matching techniques to detect seismicity distributed over a large area.

6.2.2 Method

The 244 Lefkada events recorded by TRISAR are characterized by large variations in signal amplitude and SNR. The provisional epicenter location estimates (Fig. 6.2.2) are distributed over a far larger geographical region than could be anticipated for events resulting in highly correlating waveforms at regional distances (c.f. Geller and Mueller, 1980).

One by one, each event was assigned as a master event with a template waveform being extracted for each available individual trace. For each master event, the template waveforms were correlated against a target time-window of data surrounding each of the other events. Fig. 6.2.3 (top) shows an example of the correlation procedure, with template waveforms coloured blue and corresponding targets black. All waveforms were filtered in a frequency band providing optimal SNR prior to the correlation.

The correlation coefficient channels for the individual traces were then stacked to provide an array correlation beam, as shown in red in the lower part of Fig. 6.2.3 (c.f. Gibbons and Ringdal, 2006). Note that, even on this very small aperture array, the waveforms recorded at the different sites are sufficiently dissimilar for a significant improvement to be made in the correlation coefficient SNR by the stacking process. Note also that correlation coefficient traces from all channels, both vertical and horizontal, are included in the stack.

The array correlation coefficients between the 244 events are displayed in a similarity matrix in Fig. 6.2.4. This matrix is approximately symmetric with asymmetry resulting only from the definitions of the time-windows employed. In the typical cases, the correlation coefficient c_{ij} between events *i* and *j* was simply taken to be the maximum of the two coefficients c_{ij} and c_{ji}. Indeed, a large discrepancy between the measurements of c_{ij} and c_{ji} is a clear indication that the correlation coefficients are not providing an indication of similarity between the same segments of waveform. One such case is event #108, where the asymmetry in many correlation coefficient values was ascribed to a contamination of the waveform template by an unrelated signal.

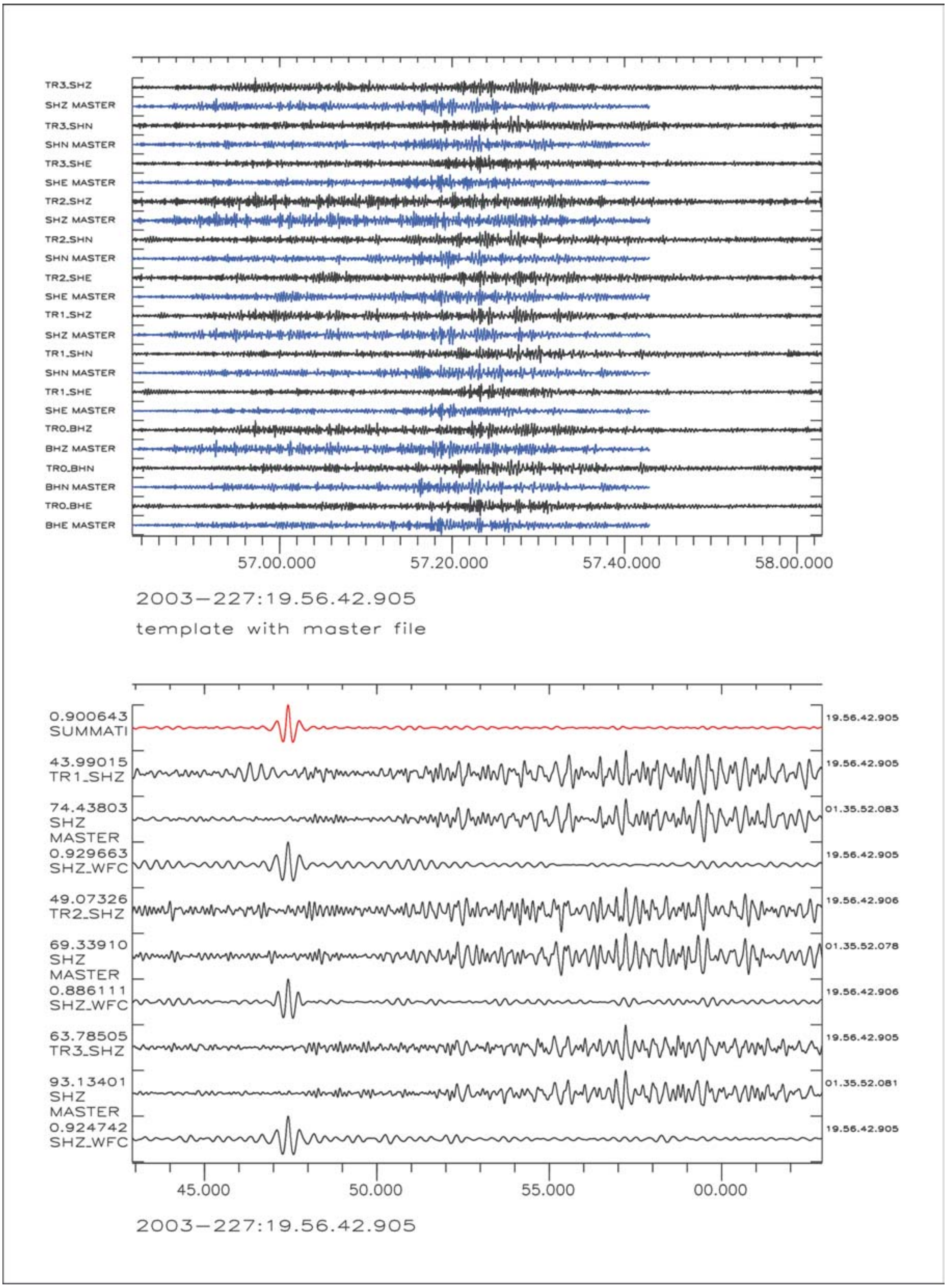

Fig. 6.2.3. Example of the waveform correlation procedure using the 3 component data of all TRISAR elements. The master event waveforms (2003-227:01:35) are coloured blue, while the slightly longer time-windows for the target event (2003-227:19:56) are coloured black (top). Each component of each array element is correlated separately (correlation trace: WFC), the final result being the correlation beam, coloured red (bottom).

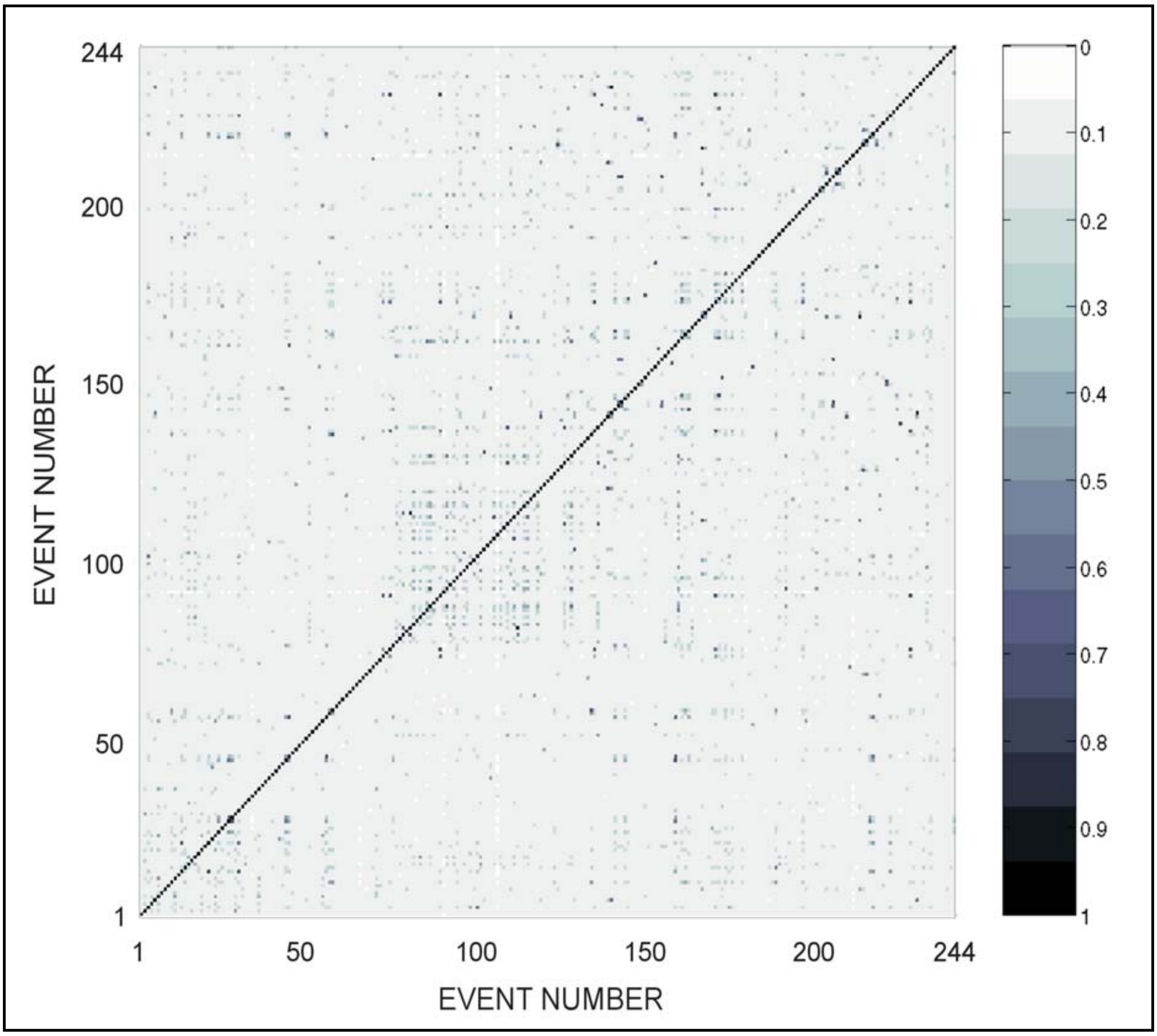

Fig. 6.2.4. Similarity matrix for the 244 Lefkada events analyzed in this study. The colour scale represents waveform correlation coefficient values. The few asymmetric features that can be observed (e.g., event #108) are attributed to overlapping successive aftershocks within the same correlation window.

In order to assess the clustering properties of the events we seek a distance function (i.e. a dissimilarity matrix). An intuitive distance function can be constructed from the correlation coefficients using

$$d_{ij} = \frac{1}{2}\left(1 - \frac{c_{ij}}{2}\right)$$

where c_{ij} and d_{ij} are respectively the fully-normalized maximum array correlation coefficient and the distance function between events i and j. However, there are problems associated with this representation. For example, the correlation coefficient is dependent upon many factors such as the signal to noise ratio and the presence of interfering signals (two events which are exactly co-located may result in a lower correlation coefficient than two events with considerable separation). In addition, the distances d_{ij} will not in general constitute a Euclidean distance matrix. The reader is referred to Saber (1984) for details. In the current application, we used the **cmdscale** function of the commercial package MATLAB to construct a Euclidean dissimilarity matrix from our observations, and additional MATLAB routines to perform the subsequent cluster analysis.

The associations between the 244 events are displayed in Fig. 6.2.5 via a dendrogram constructed using the Ward linkage method for hierarchical cluster analysis (Ward, 1963). Using a cut-off distance of 1.1, ten clusters can be identified and are represented using different colours.

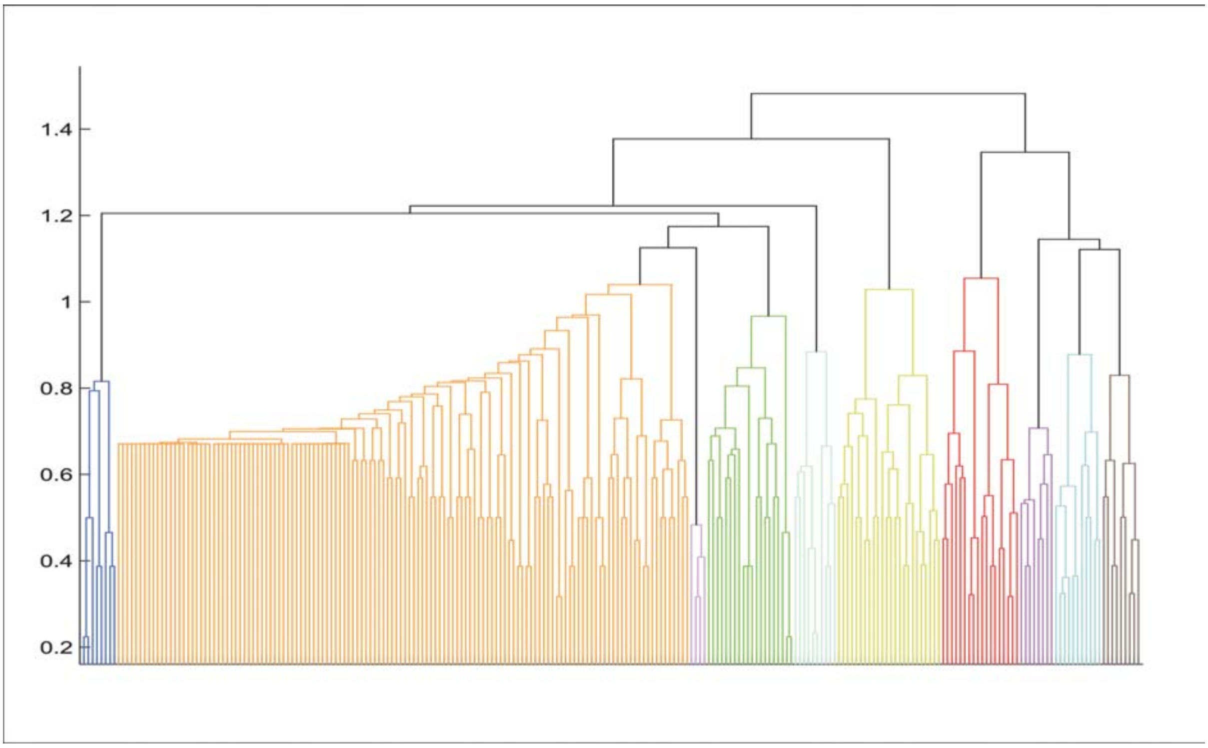

Fig. 6.2.5. Ward linkage dendrogram for the 244 Lefkada events recorded by TRISAR. Using the 1.1 distance value as cut-off level, 10 clusters are identified, represented by different colours.

6.2.3 Discussion

As expected for such a large aftershock area, the correlation coefficient resulting between the waveforms from two randomly chosen events is relatively low (with the given instrumentation and parameters chosen, correlation coefficient values of approximately 0.1 were commonly obtained - this value being quite typical for correlations of randomly chosen data segments). However, there are smaller groups of events characterized by higher degrees of waveform similarity.

Taking into consideration the size of the dataset, and to avoid chaining effects and obtain a more intuitive image of event clustering, Ward linkage was the preferred method for the construction of the dendrogram exhibited in Fig. 6.2.5. Ward clustering is an agglomerative clustering technique that assumes that the total sum of squared deviations of every point from the mean of its cluster represents the loss of information which results from the grouping of individuals into clusters. During each step, the combination of every possible pair of clusters is considered, the resulting clusters being those whose combination exhibits the minimum increase in the error sum of squares.

The cut-off level for cluster identification from the dendrogram of Fig. 6.2.5 was set to the distance value of 1.1, maintaining a balance between the rather low level of minimum similarity and the mean value. According to this, ten event clusters have been identified, noted on the dendrogram with the usage of different colours.

Most of the resulting clusters are populated by a small number of events, reflecting the high diversity of waveforms expected over such a large aftershock area. The largest cluster, consisting of 65 events includes the mainshock, which exhibits relatively low correlation coefficients with the associated aftershocks.

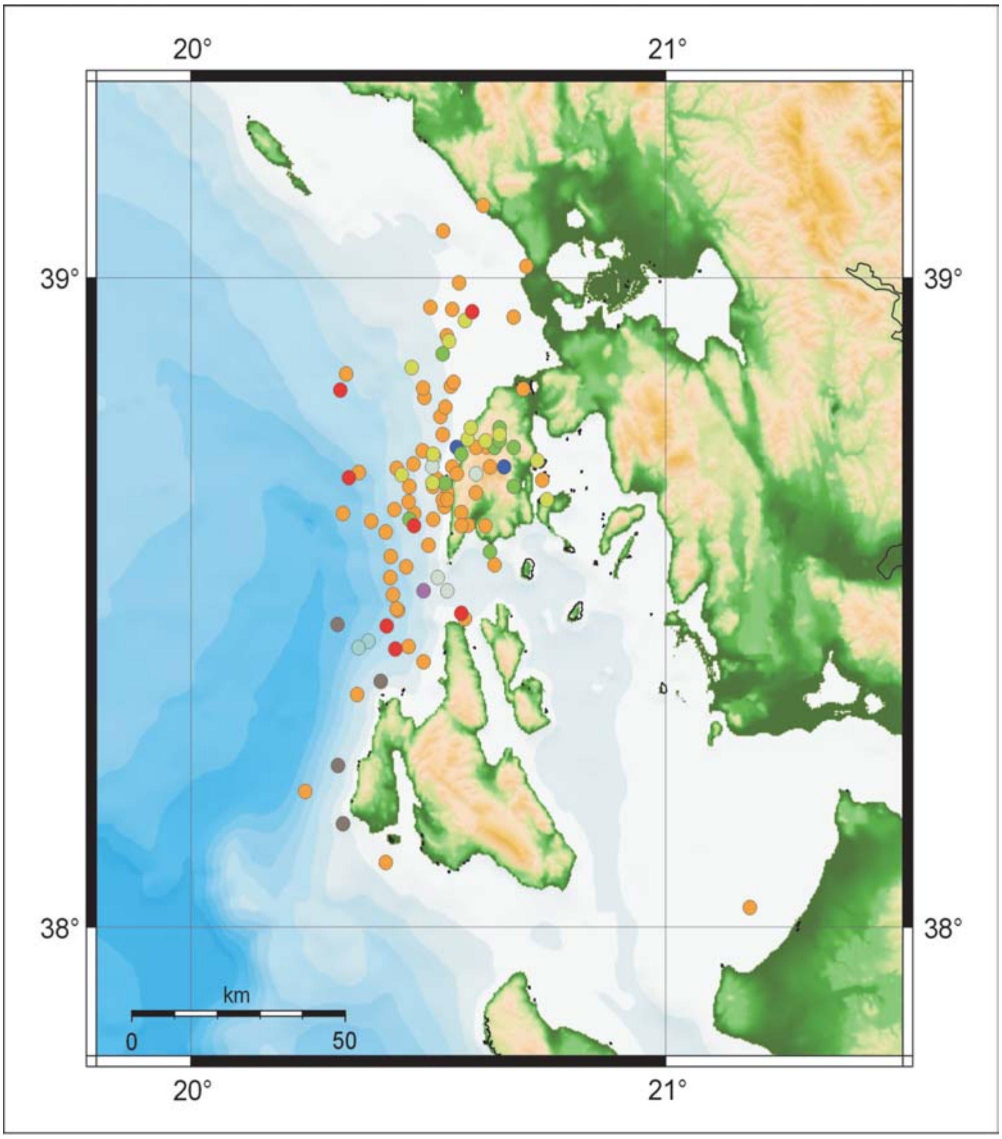

Fig. 6.2.6. Epicenter map for the subset of 108 Lefkada events as located by the ISC. The different colours correspond to those used in the dendrogram of Fig. 6.2.5 to discriminate between the obtained event clusters. Cluster #3 is not represented on this map.

Due to the rather large scatter of TRISAR location estimates apparent in the epicenter map of Fig. 6.2.2, a subset was composed according to the available 108 locations reviewed by the ISC and published in the On-Line Bulletin, to investigate the estimated spatial distribution of the clusters obtained. Fig. 6.2.6 shows a map of these reviewed epicenter solutions, events being sorted according to the clusters of Fig. 6.2.5 by using the same colours as in the dendrogram. The only cluster not represented on the map is cluster #3. Large spatial scatter is observed for events belonging to the same clusters, indicating that epicenter location estimates are inadequately constrained. This suggests that further research, involving the accurate relocation of the sequence with the application of relative location techniques, may provide better insight to the mechanisms controlling the evolution of this sequence.

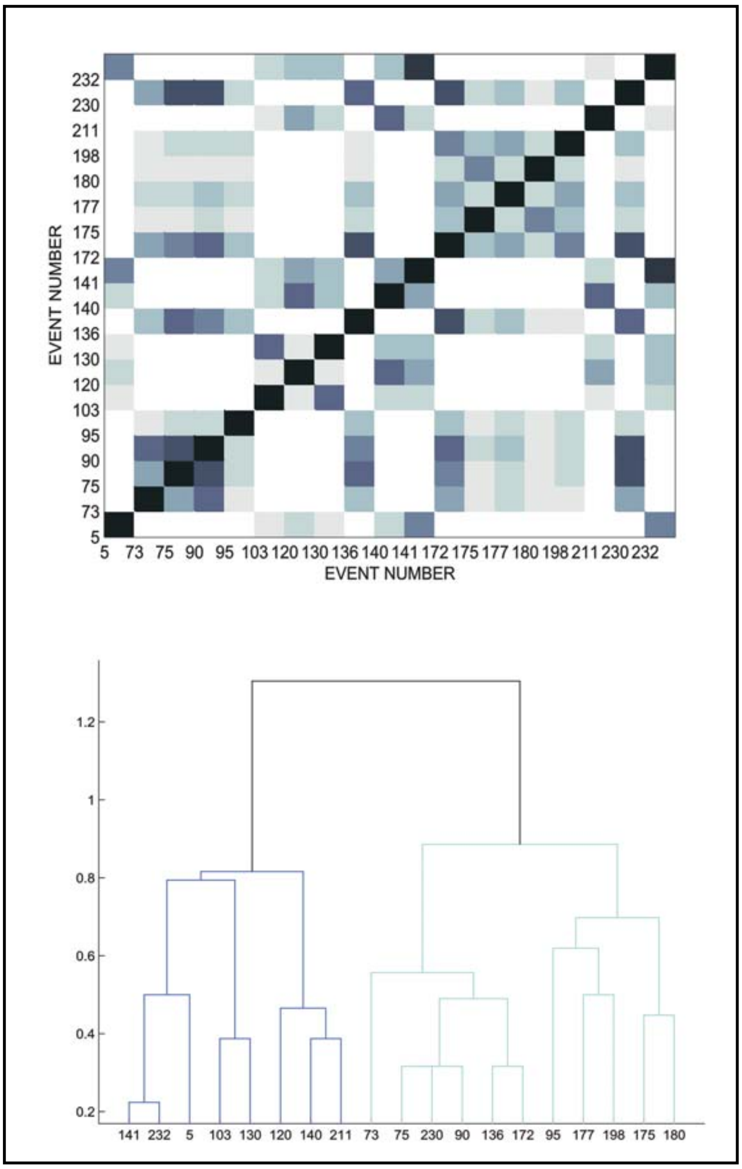

Fig. 6.2.7. Similarity matrix (top) and Ward linkage dendrogram (bottom) for the events belonging to clusters #1 and #9 of the original dataset, as recorded by TRISAR. The matrix colourscale is the same as in Fig. 6.2.4. The 2 clusters are fully consistent with those of Fig. 6.2.5, thereby noted with the same colour.

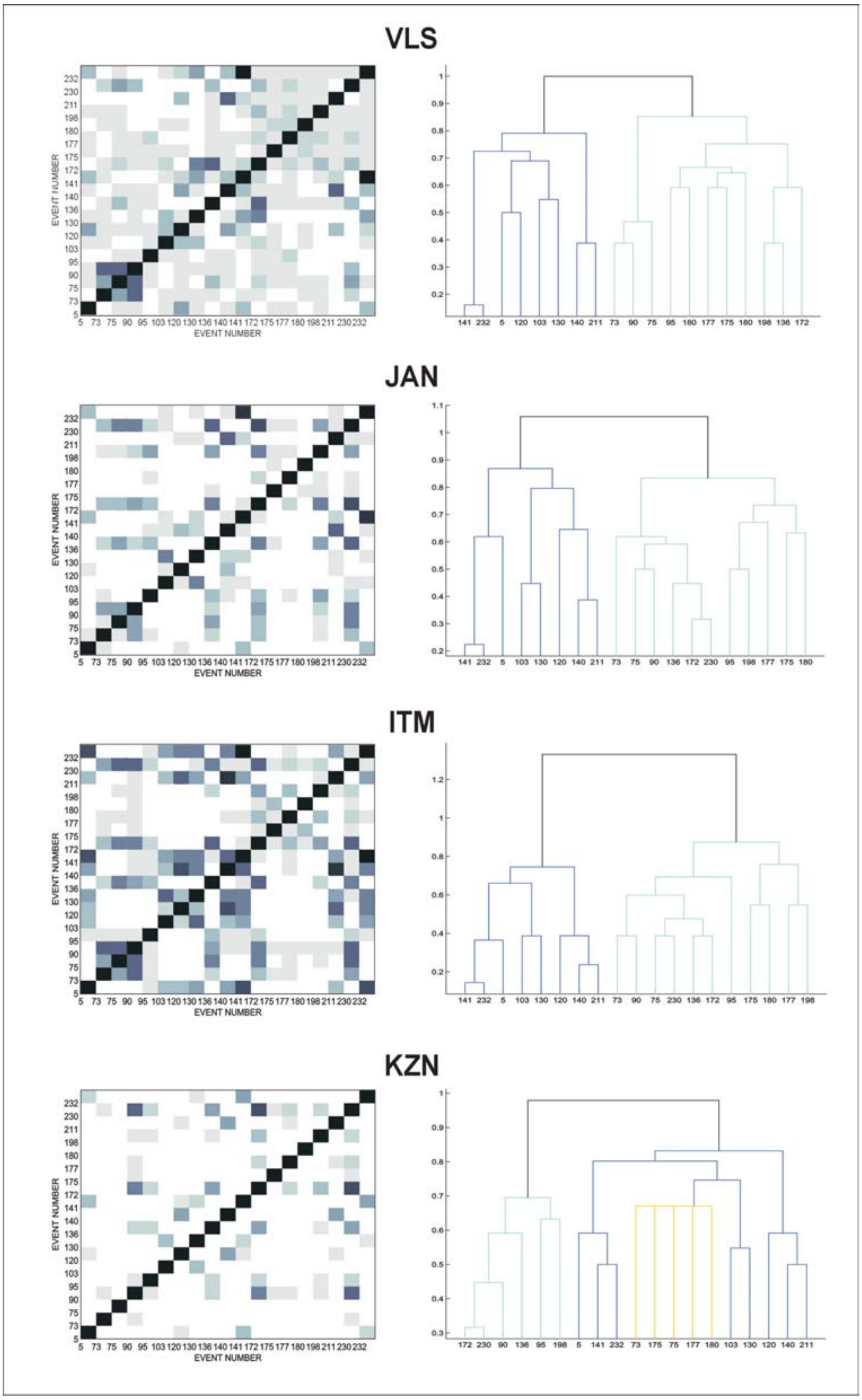

Fig. 6.2.8. Similarity matrices and Ward linkage dendrograms for the events belonging to clusters #1 and #9 (Fig. 6.2.5) for the four GI-NOA single, 3C stations used in this study (VLS, JAN, ITM and KZN), depicted in Fig. 6.2.1. Matrix colourscale is the same as in Fig. 6.2.4. Colouring of resulting clusters corresponds to that of Fig. 6.2.5. In the case of KZN, mis-placed events are depicted in yellow.

In order to assess the validity of the clustering results, two clusters (#1 and #9) were selected to repeat the waveform correlation procedure using data from four single, 3-component GI-NOA stations (VLS, JAN, ITM, and KZN), located at local and regional distances (see Fig. 6.2.1). The clusters were selected so that there is a clear separation between them, according to the dendrogram of Fig. 6.2.5, and they are populated by events with varying SNR levels.

Fig. 6.2.7 (top) displays the resulting similarity matrix for TRISAR, while Fig. 6.2.8 (left) shows the matrix for the four GI-NOA single stations for the two selected clusters. The main features of the similarity matrices appear consistent in all cases. The similarity level varies depending on SNR and path effects, however the most similar events and groups can be easily identified in all cases.

Corresponding Ward linkage dendrograms were constructed for TRISAR (Fig. 6.2.7 - bottom) and the used GI-NOA stations (Fig. 6.2.8). In all cases except for station KZN the two initial clusters are clearly separated and the most similar events within each cluster are linked together, as for example in the case of event #141 and event #232. For intermediate similarity levels, the associations between the different events change for each station. Regarding station KZN, which is characterized by rather low SNR levels and is situated in the most diverse geo-tectonic environment with respect to all other stations, the low levels of correlation affect significantly the linkage results, assigning the events coloured with yellow (Fig. 6.2.8 - bottom right) to the wrong cluster.

6.2.4 Conclusions

Array-based waveform correlation techniques were applied to the first two days of the Lefkada aftershock sequence. The observed degrees of waveform similarity are consistent with the large extent of the aftershock area and the great diversity of associated waveforms. One limitation of the method applied here appears to be its sensitivity to the time windows used for the template and target waveforms. The cause of these difficulties is that template and target time-windows are defined for single events based upon location estimates; an iterative scheme to modify window definitions according to a matched filter detector would presumably improve the situation.

The mainshock does not appear to correlate highly with any aftershocks, belonging to a larger group of events loosely linked together. This can be attributed to the different rupture process that is associated with the mainshock.

In most cases, according to the available bulletins, events populating the same clusters appear scattered on both segments of the CTFZ and even in areas lying outside the fault zone. This suggests that the location estimates used are poorly constrained. Indeed, some events in the ISC On-Line Bulletin with a large separation between epicenters were verified manually to produce highly similar waveforms suggesting a far smaller distance between epicenters than the bulletins suggest (c.f. Geller and Mueller, 1980).

The obtained cluster pattern appears to be independent of the recording station, supporting the validity of the results. The waveform similarity suggests the possibility of obtaining accurate relocation estimates (see, for example, Richards et al., 2006) which, in turn, may be used in the future to explore further the seismicity patterns and characteristics of this seismic sequence. Following a relocation, it would also be interesting to investigate the relation between the obtained event clusters and estimated focal mechanisms.

Acknowledgements

N. Melis kindly provided the Lefkada sequence data from the seismographic network of the Geodynamics Institute of the National Observatory of Athens. Maps included in this study were created using the Generic Mapping Tools software (Wessel and Smith, 1991, 1998).

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6.3 Single small array regional localization using PMCC (ELOSV2)

6.3.1 Introduction - principle of the algorithm and first observations

The Progressive Multi-Channel Correlation Method (PMCC, Cansi, 1995) has been developed at the French Commissariat à l'Energie Atomique (CEA) and is used as a real-time detector for low-amplitude coherent waves within non-coherent noise. It works by performing a progressive association of channels for which the cross-correlation functions are consistent with delay-times (closure time relation) corresponding to coherent seismic energy propagating over an array. The detector is only sensitive to an increased degree of semblance between traces and does not detect directly increases in signal amplitudes.

A new module (ELOSV2) has been developed by CEA for single small-array regional event location using the PMCC results. Phase detection, and the estimation of azimuth and apparent velocity within each time-frequency window, is performed by PMCC. ELOSV2 then applies deterministic criteria to identify seismic phases, and associate them in order to create events.

Firstly, PMCC is run on the recorded data and the time-frequency windows (pixels) are grouped into families under similarity criteria regarding time, frequency, slowness, azimuth, correlation and consistency. The ELOSV2 algorithm then labels the families according to slowness and other criteria, resulting in a seismic phase identification (Pn, Pg, Sn, Lg). Finally, regional events are defined given the detection and association of the appropriate seismic phases. This algorithm has been tested on several months of ARCES data. Fig. 6.3.1 presents a velocity-azimuth histogram of the families detected by ELOSV2 during five months in 2007.

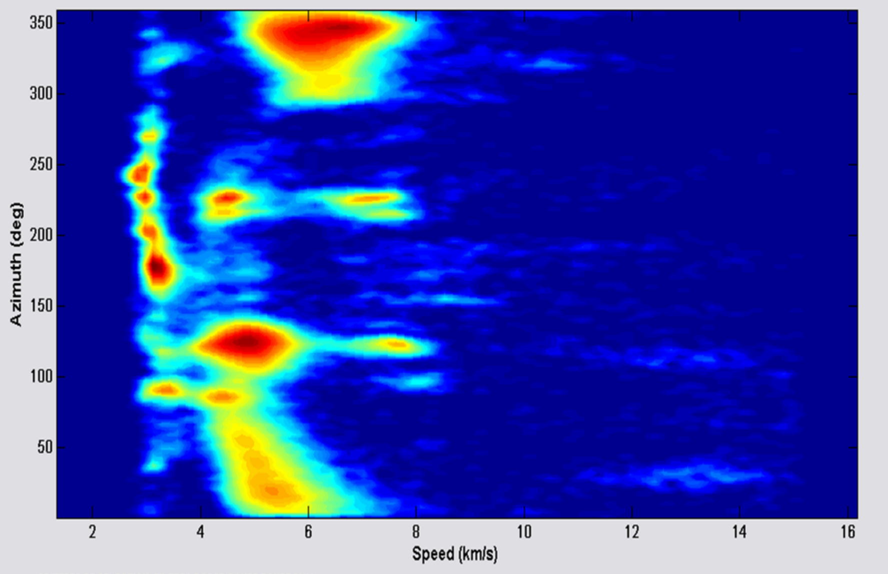


Fig. 6.3.1. Velocity-azimuth histogram of ARCES data between 10 January and 16 May 2007.The data are filtered between 2.5 Hz and 7 Hz, and only the A, B and C rings of ARCES are used for the analysis.

In Fig. 6.3.1, we can identify different kinds of detections. The azimuths around 225˚ and 120˚ are characterized by two distinct groups of energy with different apparent velocities, one around 7.5 km/s and the other around 4.5 km/s. These correspond respectively to P- and S-type regional phases. They cover very distinct azimuth intervals, mostly corresponding to regions of mining activity. The characteristics of detections from the North (backazimuth around 0˚/360˚) in Fig. 6.3.1 are very different; the detections cover a wide azimuth range and a continuum of apparent velocity estimates that cover the range of regional P- and S- type phases. They are almost always characterized by a low SNR and can be considered to be very coherent high-frequency seismic noise. ELOSV2, in the absence of SNR thresholds, is confronted with long lists of PMCC detections of this nature and creates many regional events from these directions according to fairly arbitrary combinations of such PMCC-phases with typical P- and S-velocities. Far fewer of these event hypotheses appear in the GBF (Ringdal and Kværna, 1989) automatic event bulletin at NORSAR. This is because the GBF associates regional phase detections made using an STA/LTA type detector, and most of the PMCC-detected phases corresponded to SNR below the detection threshold. In the current study, the nature of these observations will be investigated in more detail.

The ELOSV2 algorithm is also applied to data recorded by the Spitsbergen array. SPITS is located to the north of ARCES and may help to locate the source region of seismic energy reaching ARCES from this direction. As a quality check, the output from ELOSV2 is compared with the results of a moving window fk-analysis.

6.3.2 Results

A possible source of very coherent seismic noise coming from the North of Norway had already been observed by Friedrich et al. (1998), who linked low-frequency microseisms observed at different seismic stations in Europe to low-pressure systems in the atmosphere near the northern Norwegian coast. Their observations were made for 1995, DOYs 349, 350 and 351. This time period was also chosen for analysis of ARCES and SPITS data.

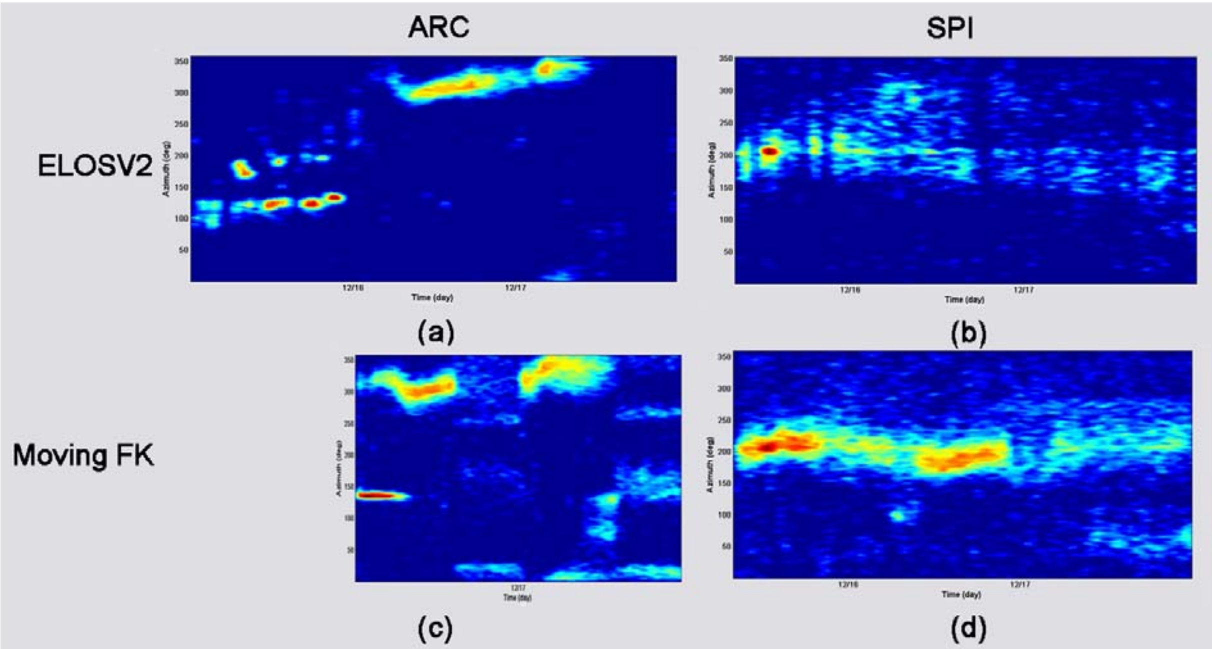


Fig. 6.3.2. Time-azimuth histograms, DOYs 349, 350, and 351 of 1995. (a) ELOSV2, ARCES; (b) ELOSV2, SPITS; (c) Moving fk-analysis, ARCES; (d) Moving fk-analysis, SPITS. The time axes start at about 08 o'clock of DOY 341; due to some data problems, the moving fk-analysis results for ARCES had to be started later (c).

The ELOSV2 processing was performed, together with a moving window fk-analysis, on SPITS and ARCES data from these three days. A “family algorithm” has also been run following the fk-analysis. Fig. 6.3.2 shows the results of this analysis - the time-azimuth histograms obtained for the high frequency (2.5 to 7.0 Hz) calculations of ELOSV2 and moving window fk-analysis.

As we can see in Fig. 6.3.2, the results obtained by the two different methods reveal the same perturbation around the North for ARCES, and from around 200˚ for SPITS. However, the observations begin earlier at SPITS than at ARCES, and the variations of the azimuth are not well correlated.

We have also compared our time-azimuth pattern at ARCES, calculated in the high frequency band 2.5 - 7 Hz, with the pattern at lower frequencies (below 3 Hz). According to Friedrich et al. (1998), this low-frequency energy is related to ocean generated microseisms. It appears that there are significant differences between the high and low frequency time-azimuth patterns, suggesting different source mechanisms.

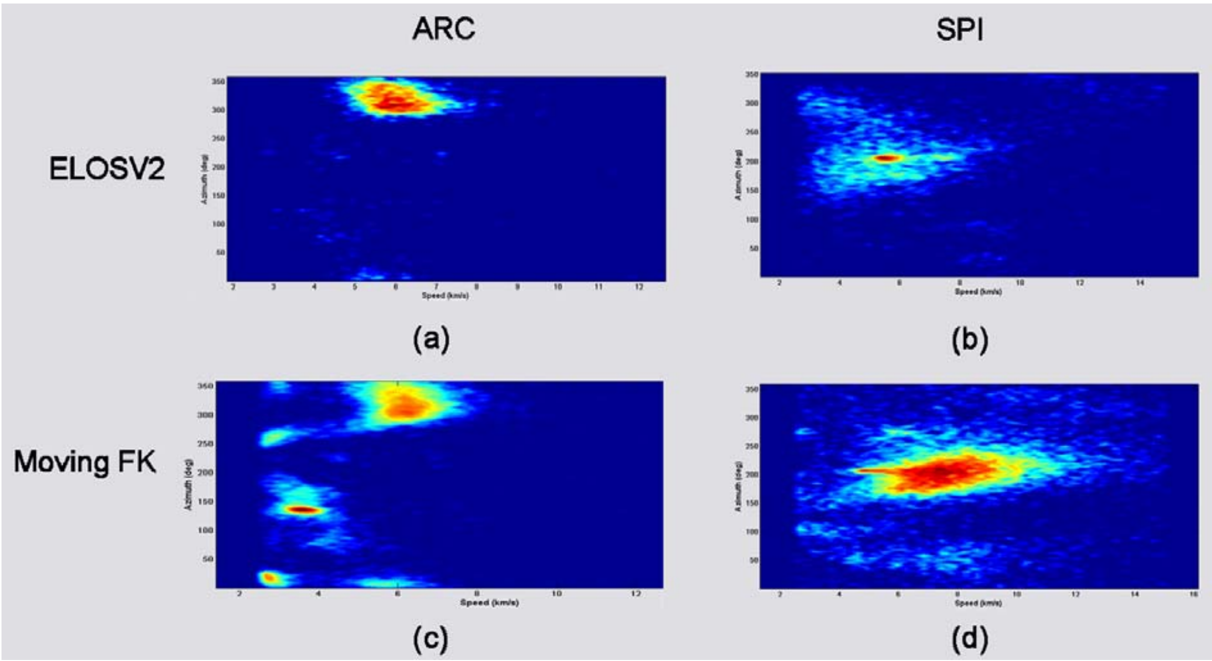


Fig. 6.3.3. Velocity-azimuth histograms, DOYs 349, 350 and 351 of 1995; (a) ELOSV2, ARCES; (b) ELOSV2, SPITS; (c) Moving fk-analysis, ARCES; (d) Moving fk-analysis, SPITS.

The velocity-azimuth histograms are shown in Fig. 6.3.3. Taking into account the frequency range (between 2.5 and 7 Hz) and the velocities measured at the appropriate azimuths (around 6 or 7 km/s), it seems that the observed pulses consist primarily of P-phase type energy.

6.3.3 Discussion

Fig. 6.3.4 shows the evolution (every 6 hours) of three meteorological parameters between DOY 350 at 0 h and 351 at 12 h of 1995, when the higher frequency low amplitude P-wave energy can be observed at ARCES and SPITS. The mean atmospheric air pressure at sea level (on the left, color scale from red/low to blue/high), the mean period of the oceanic waves (in the middle, color scale from green/short to blue/long), and the significant oceanic wave height (on the right, color scale from red/low to blue/high) are displayed.

Fig. 6.3.4 shows a low pressure zone moving between ARCES and SPITS during this period, drawn in red. However, it is difficult to see a direct link with the observations on ARCES or SPITS because the low pressure zone moves too quickly to the East. For example, between DOY 350 at 06 h and DOY 350 at 12 h, the dominant azimuths at ARCES are less than 300°; while the azimuth of the low pressure zone (in red) is already exceeding 0°.

At the same time, as seen from Fig. 6.3.4, long periodic oceanic waves with periods of around 8 seconds, and large amplitudes of almost 4 meters height, reach the Norwegian coast over a large range of azimuths. The ocean waves themselves induce the well-documented microseismic noise by interaction with the ocean floor (see, for example, Friedrich et al., 1998). This relatively low frequency noise is linked to the period of the oceanic waves, and propagates with typical surface wave velocities. This is different from what we observe at high frequencies at ARCES and SPITS, where the energy propagation is with typical body wave velocities.

However, it seems that the high frequency P-phase type energy observed at ARCES and SPITS is somehow linked to the presence of these long period, high amplitude ocean waves, even if the azimuths to these proposed source regions do not correspond exactly to the observed azimuths. Open questions are: Why is not more S-type energy observed? How can long periodic ocean waves generate much higher frequency perturbations?

One possible explanation could be that long periodic waves with high amplitudes (i.e. with high kinetic energy) hit the coast as a cascade of single forces. Like a hammer on the free surface, such hits generate compressional waves which propagate in the Earth's crust. The frequency content of these compressional waves can be much higher than the original period of the oceanic waves. This period is then defining the time interval between two successive hits.

To test this hypothesis, the signal pulses observed by the moving window fk-analysis were investigated. Fig. 6.3.5 shows a histogram of the time interval between two successive pulses observed on day 350 at SPITS (see Fig. 6.3.2, d). It is obvious that there is a dominance of time intervals between 4 and 10 seconds. This corresponds quite well with our hypothesis. However, further investigations are needed to come to consolidate this explanation. The peak for 20 seconds is an artefact of the algorithm that calculates the onset families.

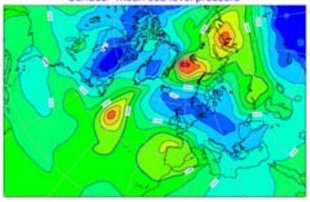
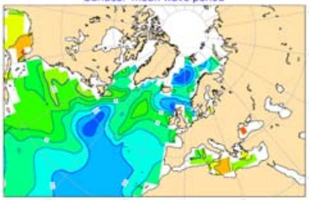
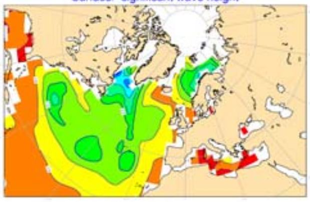
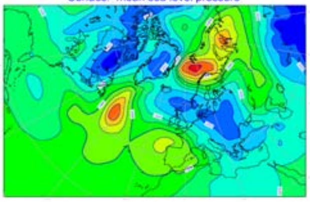
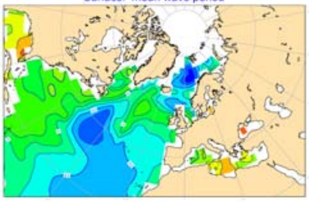
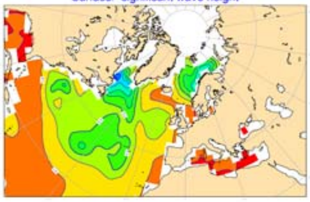
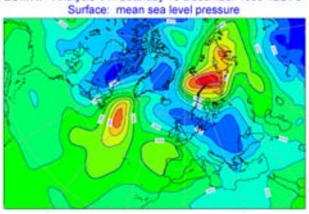
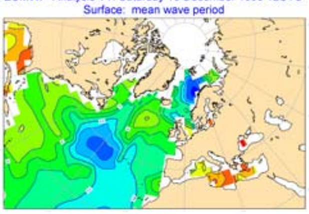
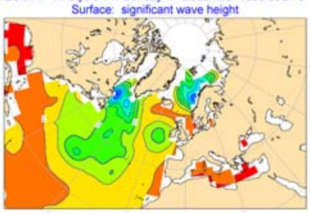
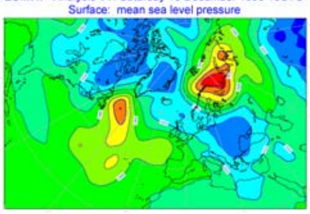
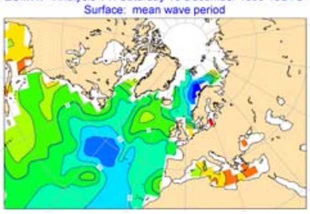
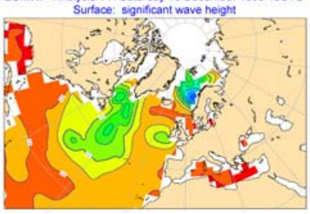
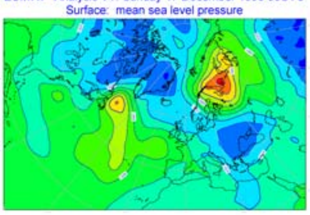
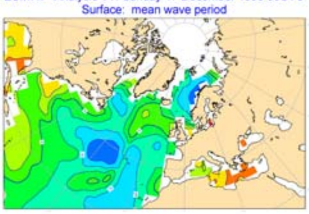
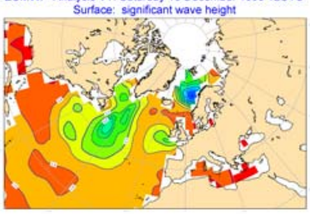
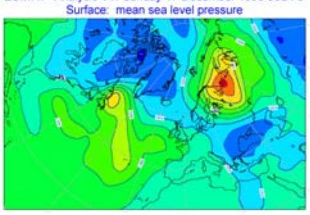
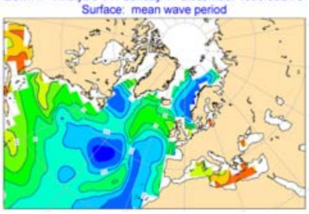
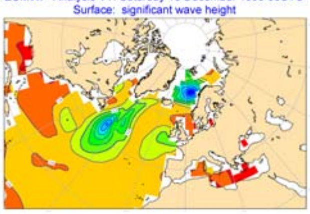
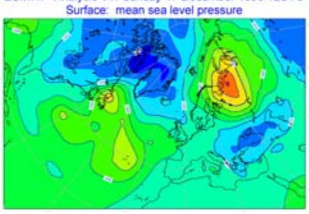
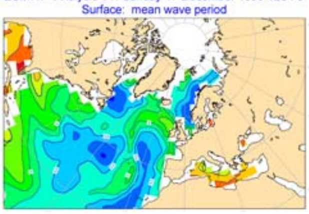
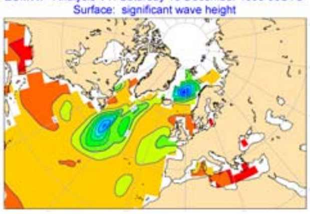
Time	Mean Pressure at Sea Level	Mean Wave Period	Significant Wave Height
0 h			
6 h			
12 h			
18 h			
0 h			
6 h			
12 h			

Fig. 6.3.4. Meteorological data for DOYs 350 and 351 in 1995 in the North Atlantic and Barents Sea Region (from the ECMWF data server)*; for more details see text.*

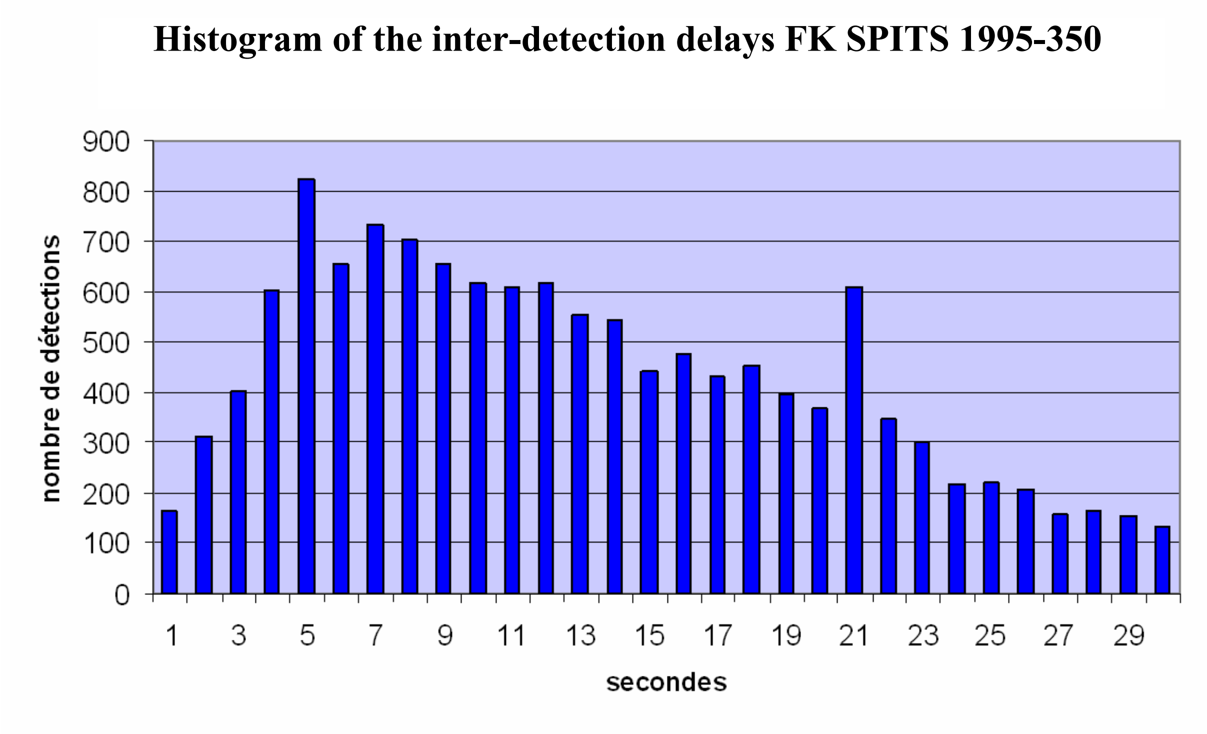


Fig. 6.3.5. Histogram of the time interval between two successive signal pulses applying the moving window fk-analysis for SPITS data on DOY 350 in 1995.

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The ECMWF (European Centre for Medium-Range Weather Forecasts) ERA-40 data (Uppala et al., 2005) used in this study have been obtained from the ECMWF data server (http://data.ecmwf.int/data/d/era40_daily/).

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6.4 Towards a Nordic Regional Infrasonic Array Network

6.4.1 Introduction

The International Monitoring System (IMS) currently being established contains an infrasound component consisting of 60 infrasonic arrays distributed globally. As can be observed from Fig. 6.4.1, only one of the stations in this network (IS37 in Karasjok, northern Norway) is located in the European Arctic region. This station has as of today not yet been established, but is in the planning phase. Another infrasound station, IS18 on Greenland, is en operation, but is located too far away to give any significant contribution to the regional monitoring of low-magnitude events in the European Arctic.

An important area of research at NORSAR is to develop methods for joint seismic/infrasonic analysis of events recorded at regional distances. In particular, we wish to apply and evaluate automatic processing techniques for the area comprising northern Fennoscandia and adjacent regions. It is clear that such an approach will require a far denser network of infrasonic arrays than is projected for the IMS.

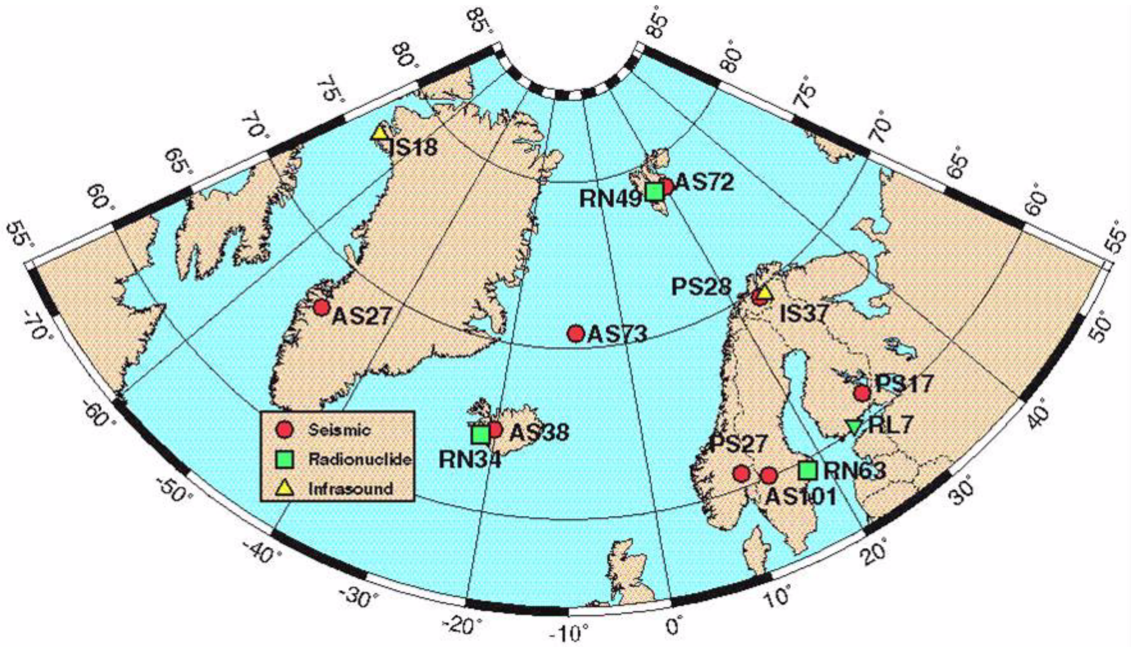

Fig. 6.4.1. Map showing the location of existing and planned IMS stations in the Nordic countries (Norway, Sweden, Finland, Denmark and Iceland). Only two of these stations are infrasonic. The infrasound array IS18 on Greenland is operational, while the infrasound array IS37 in Karasjok, northern Norway, is in the planning phase.

In a number of recent contributions in NORSAR Semiannual Technical Summaries, we have presented infrasonic studies with emphasis on combined seismic-infrasonic observations. The first such study was carried out by Vinogradov and Ringdal (2003), who analyzed seismic and infrasonic signals from a number of mining sites in the Kola Peninsula as well as a site in northern Finland used for ammunition destruction.

In particular, Vinogradov and Ringdal (2003) used data from the Apatity seismic/infrasonic array in their study. The infrasonic component of this array is a small-aperture microbarographic array installed in conjunction with the seismic array near lake Imandra in the Kola Peninsula, with data digitized at the array site and transmitted in real time to a processing center in Apatity. A total of three infrasound sensors are installed in the innermost ring of the array, forming a triangle of approximately 500 m diameter. The sensors are differential microbarographs of model K-304-AM. The frequency working range is 0.01-10Hz, and the sensitivity is 37.5 mV/Pa. The geometry of the combined seismic/infrasound array is shown in Fig. 6.4.2.

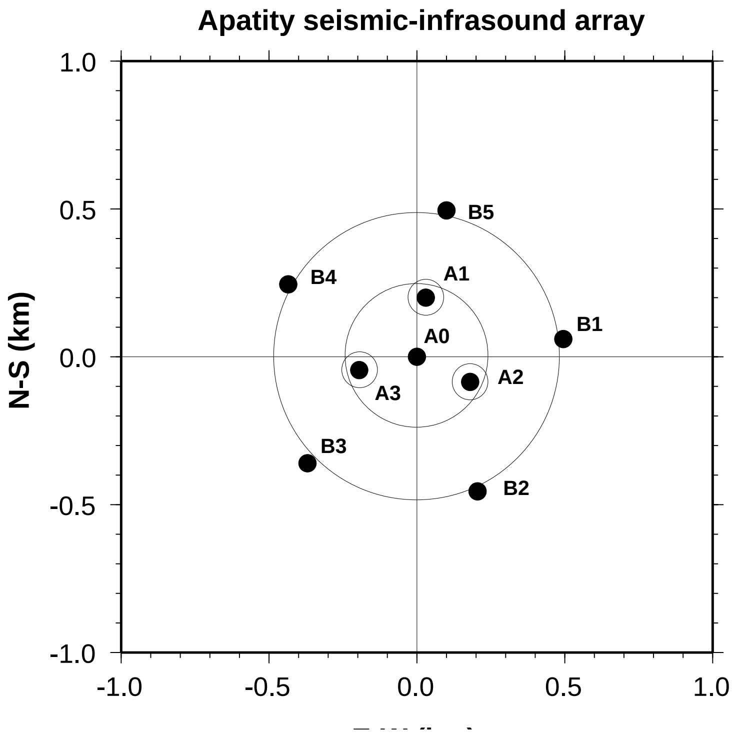

Fig. 6.4.2. Configuration of the Apatity seismic-infrasound array. Seismometers are shown as filled circles, with the location of the three infrasonic sensors (A1, A2 and A3) marked as small circles. The two concentric circles have diameters of 500 m and 1000 m respectively

Although the Apatity array for a long time provided the only infrasonic data available to us, Ringdal and Schweitzer (2005) found that the ARCES seismic array also could be used in infrasonic studies. Although the seismic sensors at ARCES are not by any means as sensitive to sound waves as the microbarographs, they nevertheless provide infrasonic recordings for a number of events at regional distances. The ARCES array (Fig.6.4.3) has the added advantage of comprising as many as 25 sites distributed over an area of 3 km in diameter, and therefore could be used to investigate the spatial characteristics of infrasonic as well as seismic recordings (Ringdal and Gibbons, 2006).

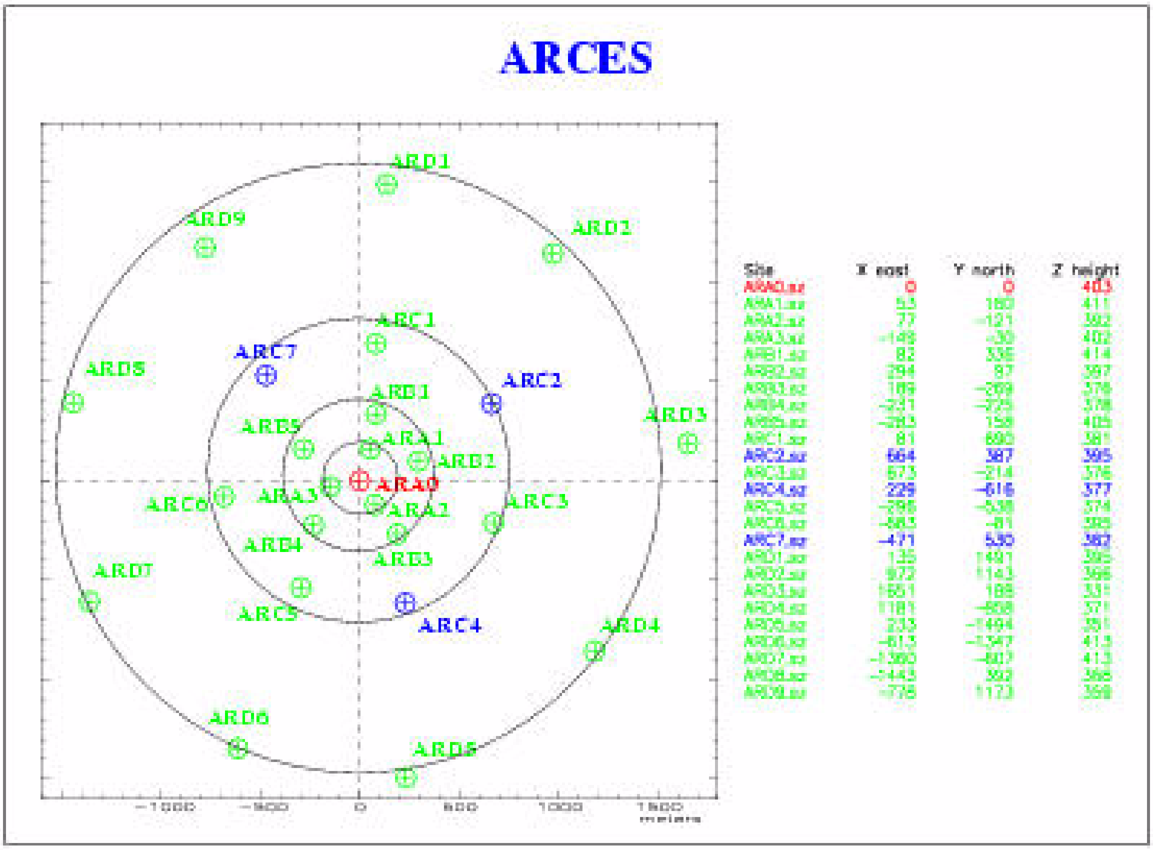

Fig. 6.4.3. ARCES array configuration. The four circles correspond to the A, B, C and D-rings. It turns out that this seismic array is also useful for recording regional infrasonic signals.

6.4.2 The Swedish infrasound network

The Swedish Infrasound Network (Liszka, 2007) has been in operation since the beginning of the 1970s. Operated by the Swedish Institute of Space Physics, the network has until recently comprised four infrasound stations: Kiruna, Jamton, Lycksele and Uppsala. The station in Uppsala was moved to Sodankyla, Finland, during the summer of 2006. The coordinates of these stations are given in Table 6.4.1.

Table 6.4.1 Swedish Infrasound Network

Station	Latitude (N)	Longitude (E)
Kiruna	67.86	20.42
Jamton	65.86	22.51
Lycksele	64.61	18.75
Uppsala	59.85	17.61
Sodankyla	67.42	26.39

Each station consists of a tripartite array of Lidstrom type microphones, with a spacing of 75 meters. Data are digitized at the site and transmitted to a central server. The Swedish Institute of Space Physics makes the recorded data available through the Internet, and also provides software that enables external visitors to locate infrasonic sources and view the recorded time series. Fig. 6.4.4 shows the microphone used in each of the arrays, and the instrument response is shown in Fig. 6.4.5.

Fig. 6.4.4. The Lidstrom infrasonic microphone (After Liszka, 2007).

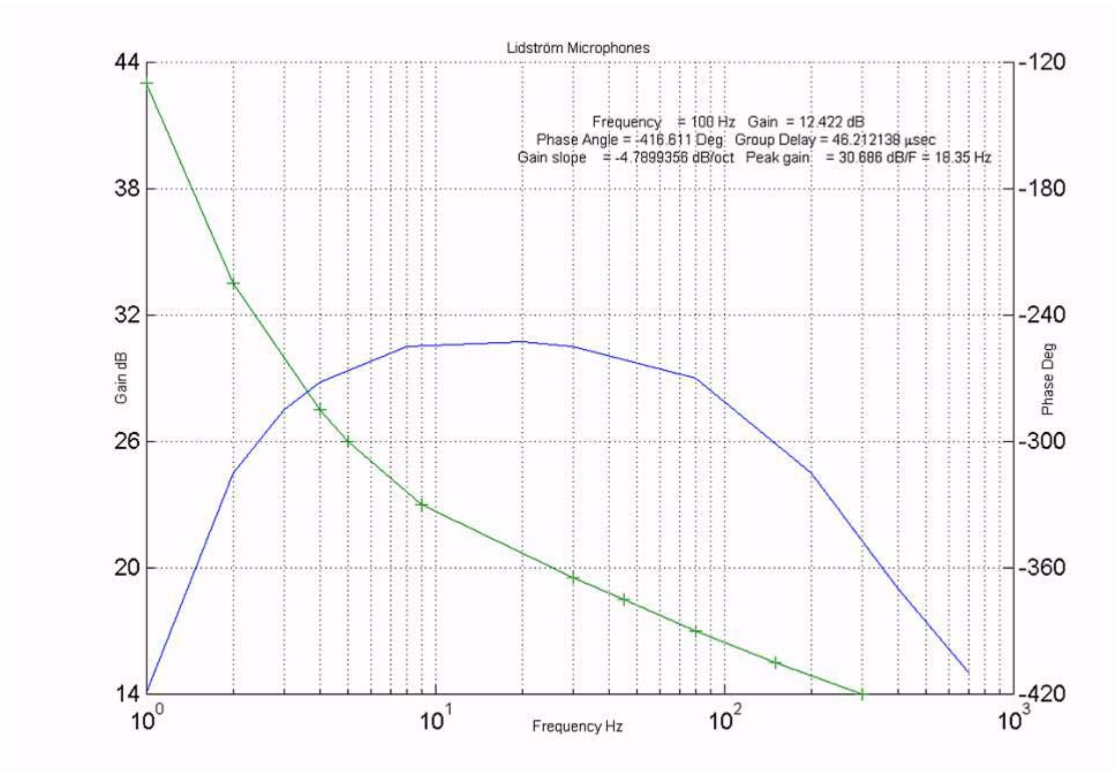

Fig. 6.4.5. The Lidstrom microphone characteristics (After Liszka, 2007).

An important feature of the arrays is the placement of a wind barrier around each microphone. This is in contrast to the spatial filters used at the IMS sites. A schematic picture of a wind barrier is shown in Fig. 6.4.6. It is interesting to note that the use of such wind barriers is now becoming a topic that is creating considerable interest in the international community.

We are grateful to the Swedish Institute of Space Physics for allowing us to use their recorded data in our planned seismic/infrasonic network processing.

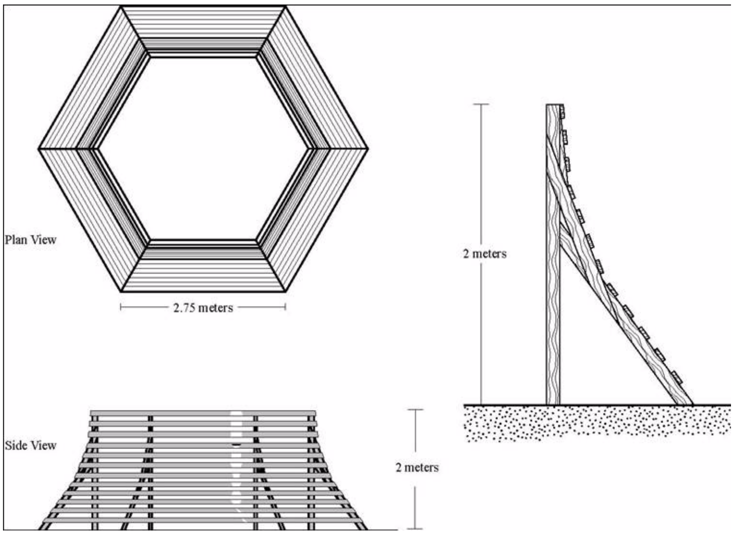

Fig. 6.4.6. A wind barrier of the type used at the recording stations of the Swedish infrasound network (After Liszka, 2007).

6.4.3 Examples of recordings

We present a few examples of infrasonic recordings to illustrate the benefits of the emerging network. We have chosen to use data from the sequence of explosions in NW Russia previously studied by Ringdal and Schweitzer (2005).

Fig. 6.4.7 shows recordings by the four stations in the Swedish network for a two-hour period on 15 March 2005. During this time period, two explosions were carried out, separated in time by approximately 26 minutes. We note that the first explosion shows very strong signals on all four arrays, whereas the second (smaller) explosion is clearly visible on at least two of the arrays.

Fig. 6.4.8 shows a closer view of the Kiruna recordings. Although the signals are clipped due to the limited dynamic range of the digitizer, we have found that reliable azimuths can be easily estimated using either f-k analysis or a cross-correlation technique. The fact that the array is very small does not seem to be a disadvantage at the frequencies of interest for this type of events (2-8 Hz).

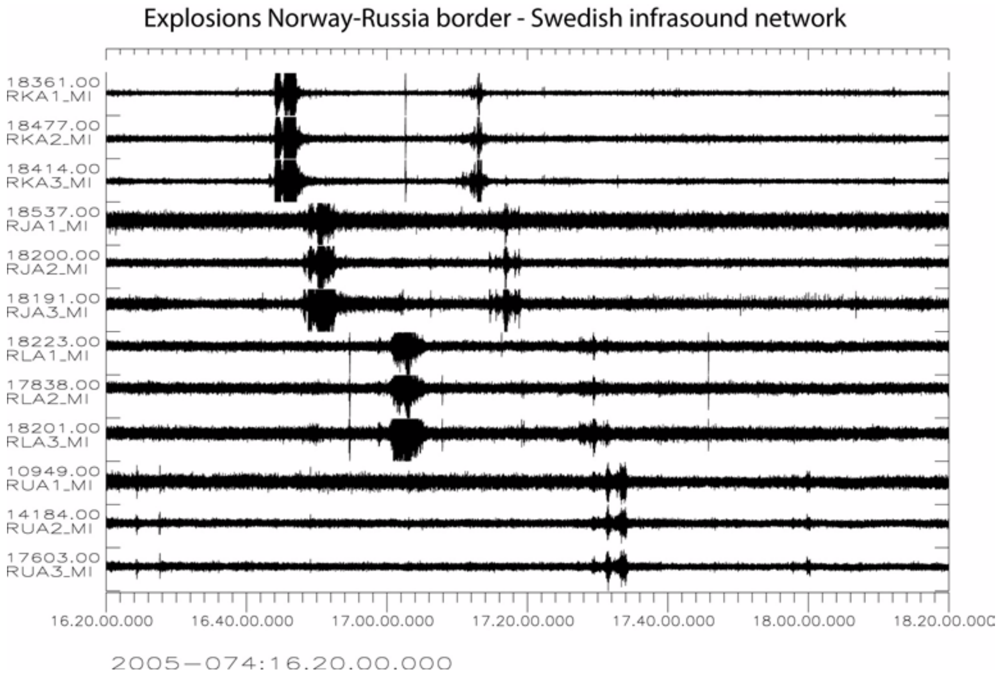

Fig. 6.4.7. Recordings by the Swedish infrasound network of two explosions in NW Russia during 15 March 2005. Three channels for each array are shown. From top to bottom: Kiruna, Jamton, Lycksele, Uppsala.

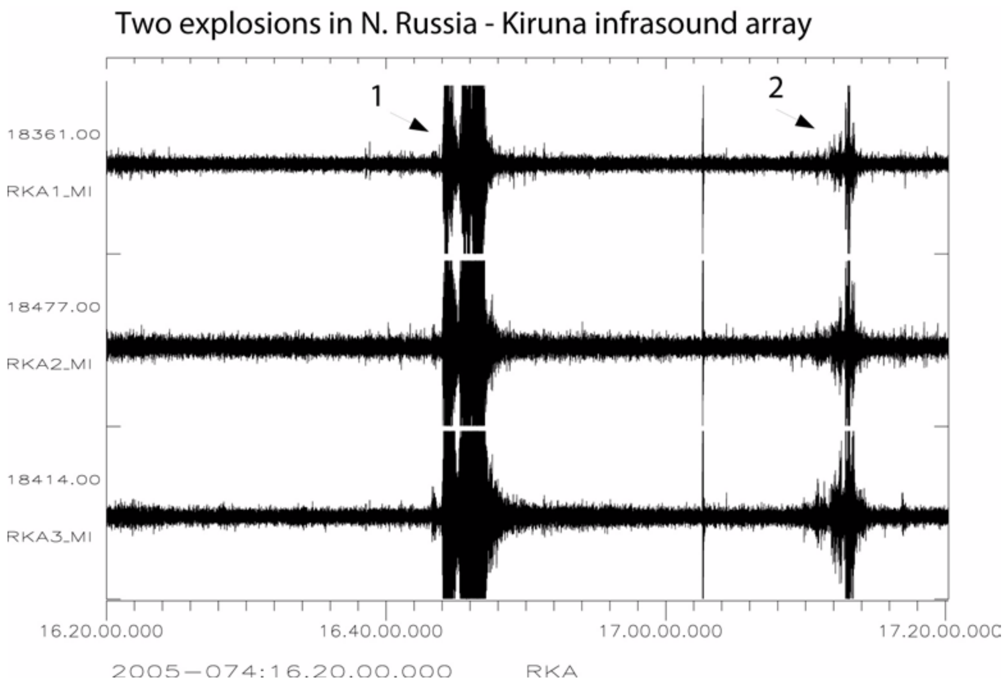

Fig. 6.4.8. Focused view on the two explosions displayed in the preceding figure, showing only the Kiruna station. The onset of the sound waves from the two explosions are marked.

For comparison, the same two explosions, as recorded by the Apatity infrasound array, is shown in Fig. 6.4.9. Here, the dynamic range is much larger, and the true signal can therefore be recorded. It will take time to evaluate the stations in more detail, but it is clear that the Swedish network will provide a valuable addition to the regional seismic/infrasonic monitoring network.

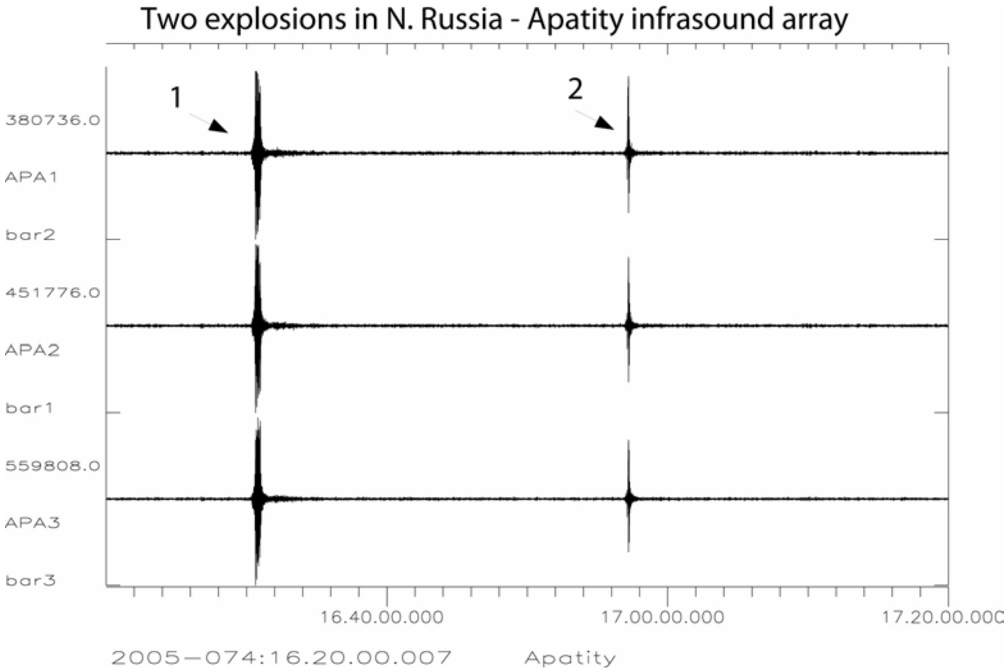

Fig. 6.4.9. The same two explosions as shown in Fig. 6.4.8, but now as recorded by the Apatity infrasound array. See text for details.

Fig. 6.4.10 and 6.4.11 show examples of azimuth estimates for the first of the two explosions using infrasound data recorded by the two arrays (Kiruna and Apatity). In this estimation process we have used the method of Frankel et al. (1991), which comprises pairwise correlations of the individual data channels and a search for maximum energy in the beams formed from time-aligned correlation traces. In both cases (as well as in numerous other cases investigated by us) the azimuth estimates are remarkably accurate. From Fig. 6.4.10 (Kiruna), we note that the azimuth estimate (63.43 degrees) is quite close to the true azimuth (61.87 degrees). The same is also the case for the Apatity estimate (349.56) shown in Figure 6.4.11, which is again close to the true azimuth (348.14).

It is noteworthy that such small arrays are consistently capable of providing reliable azimuths. An especially remarkable observation is that the clipping problem at Kiruna (and also at the other Swedish network stations) has little influence on the quality of the azimuth estimates.

With the inclusion of the Swedish network stations (and the temporary use of ARCES as a substitute infrasound array), we now have available a regional infrasonic array network in northern Europe as shown in Fig. 6.4.12. There are six arrays in this network. When the planned IMS infrasound array near ARCES becomes operational (expected in 2007 or 2008), the quality of this infrasound network will be further improved.

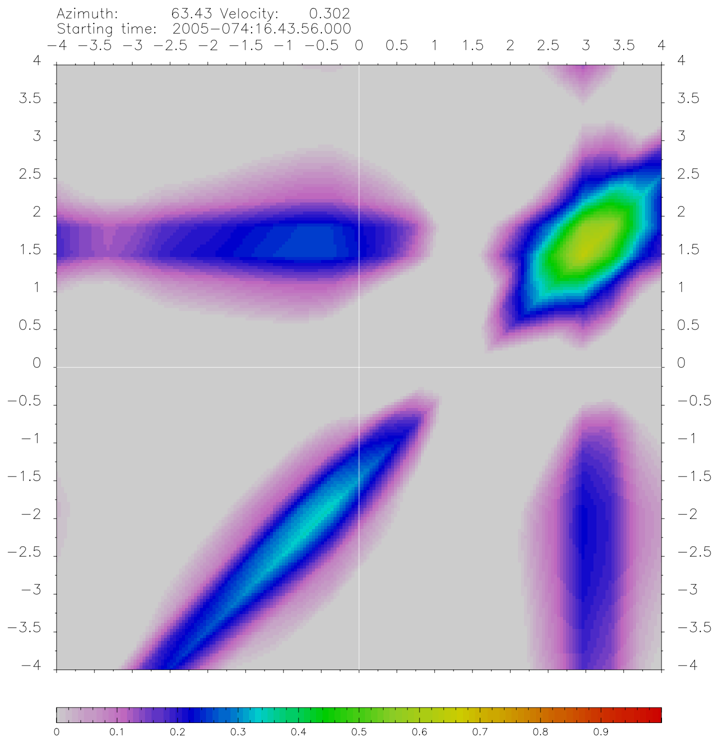

Fig. 6.4.10. Slowness estimate of the Kiruna infrasonic phase for event 1 as shown in Fig. 6.4.8.

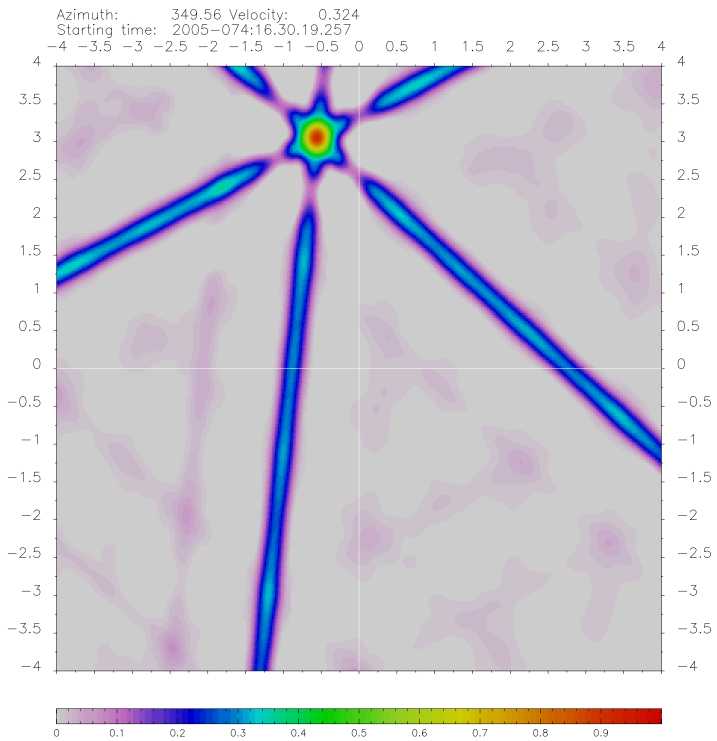

Fig. 6.4.11. Slowness estimate of the Apatity infrasonic phase for event 1 as shown in Fig. 6.4.9.

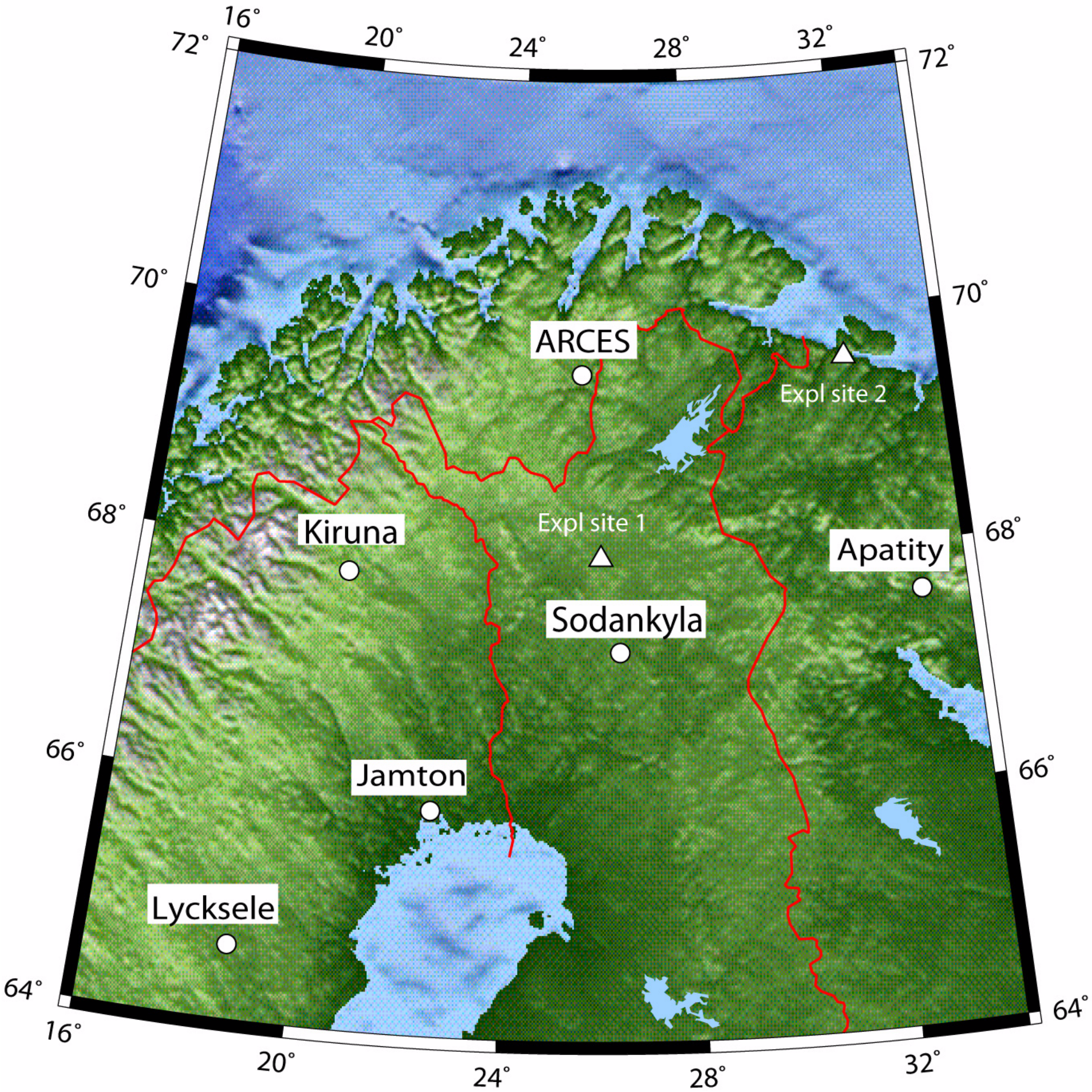

Fig. 6.4.12. Stations in the present Nordic infrasonic array network. Note that the station in Sodankyla, Finland has been moved from Uppsala, Sweden. The two explosion sites in Finland and NW Russia referred to in the text are also marked on the map.

6.4.4 Conclusions

Through the addition of the stations in the Swedish/Finnish infrasonic network, data will be available to allow a much improved joint seismic/infrasonic regional processing at NORSAR. We plan to continue our work on developing automatic phase association techniques for combined seismic and infrasonic phases. We will also follow up our ongoing work on developing two-array and multi-array processing techniques for infrasonic recordings.

Our overall aim is to develop and evaluate a joint seismic/infrasonic bulletin for northern Fennoscandia and adjacent regions. This bulletin would be similar to the automatic seismic bulletin that we are currently providing on the NORSAR Web pages, but it would also contain infrasonic phase associations. Furthermore, we will experimentally attempt to generate an infrasonic event bulletin using only the estimated azimuths and detection times of infrasound phases recorded by stations in the nordic network.

The combined seismic/infrasonic database that we plan to develop in the coming years will be highly valuable for various studies related to obtaining improved accuracy in detecting and characterizing seismic events in the European Arctic region using seismic and infrasonic array recordings at local and regional distances.

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