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Frode Ringdal (ed.)

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14. ABSTRACT
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Abstract (cont.)

Government, and the United States also covers the cost of transmission of selected data from the Norwegian NDC to the United States NDC.

The seismic arrays operated by NOR-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 NOR-NDC. 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 2,205 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 NOR-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 JMIC (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 CTBTO/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. As part of NORSAR obsolescence management, a recapitalization plan for PS27 and PS28 has been submitted to CTBTO/PTS in order to prevent severe degradation of the stations due to lack of spare parts.

The IMS infrasound station originally planned to be located near Karasjok (IS37) may need to be moved to another site, since the local authorities have not granted the permissions required for the establishment of the station.

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

Section 6.1 contains a continued study of infrasound recordings from surface explosions in northern Finland. The Finnish military destroy expired ammunition at a site in northern Lapland in a sequence of explosions every year between August and September. Each explosion has a yield of approximately 20000 kg and the seismic signals recorded at the ARCES array in northern Norway indicate a magnitude of approximately 1.5. The events have been of great interest due to the generation of infrasound signals which have been recorded on the seismic traces at ARCES and by both seismic and microbarograph instruments at Apatity. These explosions provide very useful reference events for infrasound sources since the location is known and the origin times are very tightly constrained by the seismic observations. It now appears that infrasound from these events can be observed at far greater distances than previously

assumed with signals likely to come from these sources being observed at the IMS infrasound arrays I18DK (Qaanaaq, Greenland) and I26DE (Freyung, Germany) making the events useful for studies of long-distance sound propagation.

In this contribution we present the origin times of 36 explosions which took place during August and September 2008. The explosions this year are the first to be recorded by the experimental microbarograph mini-array within the ARCES seismic array at a distance of approximately 178 km. Acoustic signals were detected on the microbarograph sensors following every one of the explosions and on the seismic sensors following all but one. The non-detection in this case is attributed to an unrelated seismic signal arriving in the interval in which the acoustic arrival is anticipated.

In addition to the phases identified in previous studies, which all arrive between 500 and 700 seconds after origin time, a number of additional arrivals have now been detected between 800 and 950 seconds. These are associated with considerably higher apparent velocities, consistent with steeper angles of incidence which would be anticipated from thermospheric returns. The travel times are consistent with thermospheric arrivals observed from Nevada Test Site explosions recorded at the comparable distance of 210 km. There were only three such detections on the seismic sensors and all of these were quite marginal. The thermospheric arrivals appear to be of shorter duration and of lower amplitude than the presumed stratospheric returns. This will contribute to their non-detection on the seismic sensors.

Section 6.2 describes an investigation of recorded infrasound signals from a recent meteor explosion north of Norway. In the evening of 15 January 2009, light flashes and a fireball were observed over parts of Northern Norway. Based on visual observations, the object was propagating in a north-northwesterly direction into the Barents Sea, and the time of the event is estimated to 19:40 GMT. The signals from the meteor, recorded at the 4 infrasound arrays operated by the Swedish Institute of Space Physics (IRF) were analyzed within a short time after the event.

In this contribution we provide results from additional analysis of signals at the IRF stations as well as at the infrasound station in Apatity and at an experimental infrasound deployment within the ARCES array.

For each of these stations, we have processed the infrasound data using vespagram analysis. Using a fixed apparent velocity around 0.333 km/s, we have calculated the resulting normalized beam power for a range of back-azimuths, where the maximum represent an estimate of the back-azimuth of the arriving signal. These back-azimuths have then been used to determine an approximate location of the source.

As another approach to source location we have used the reported origin time of the event (19:40 GMT). This gives us the possibility to calculate the travel-time to each station, which again can be scaled with a standard celerity for stratospheric arrivals of 0.29 km/s to obtain distance estimates. In this way, we have estimated the location of the meteorite explosion over the Barents Sea on 15 January 2009 to 72.1^{o} N, 20.3^{o}E. The semi-major axis of the ellipse covering all intersection points between the different distance arcs is approximately 35 km, and indicate the uncertainty of the location estimate. Smaller meteors usually disintegrate at an altitude of around 20 km.

In this paper we have demonstrated that several stations show significant deviations in the back-azimuth estimates as compared to the great-circle path to the source, and it is our plan to compare these deviations with the observed wind field in the region. In this way it may be possible to correct for wind effects when applying the back-azimuths for location purposes. It is also interesting to observe that a standard celerity value of 0.29 km/s provides quite consistent distance estimates to the different stations observing the signals.

This latest meteor explosion supplements two previous such observations in Norway during 2006. Establishing a database of such events will be important for future studies of infrasound wave propagation.

Section 6.3 is a continued overview of system responses, specifically addressing the IMS auxiliary seismic array SPITS, the Apatity seismic array and the IMS three-component auxiliary seismic station on the island of Jan Mayen. This series of contributions is aiming to recalculate and organize all of the system instrument responses of the seismic facilities contributing data to the NORSAR Data Center from the time of the first installation to the present. All sources of information are being catalogued and archived. Furthermore, detailed documentation is being compiled, describing the methodology followed to obtain the necessary information, the calculation of the responses, as well as more practical issues, such as organizing and storing the results for future usage. Therefore, no information such as individual instrument poles and zeroes, serial numbers, sensitivity values, etc. are provided here; instead, the reader is referred to the relevant NORSAR internal documentation.

Section 6.4 is entitled “Seismic arrays in Earthquake Early Warning Systems (EEWS)”. The main parts of this contribution have been compiled during NORSAR’s participation in the SAFER project, which is mainly funded under the Sixth Framework Programme of the European Commission. Within this project, NORSAR has investigated the application of array techniques to EEWS installations.

We begin by briefly discussing the development of event-location techniques with seismic arrays and the contribution of arrays to fast event location. Then we focus on the usage of seismic arrays as EEWSs in general, and in particular on real-time algorithms and discuss the advantages and disadvantages of applying array-analysis techniques as input for any EEWS. Finally, we describe a new quick event-location system which whas been developed at NORSAR with the purpose of providing fast and reliable solutions in the case of strong events: NORSAR’s Event Warning System (NEWS). The whole NEWS system is based on high Signal-to-Noise Ratio (SNR) detections; whenever one of the contributing arrays observes a P-type onset with an SNR larger than a predefined threshold, the NEWS process is initialized. The process calculates basic event parameters based on available detection data from the arrays operated by NORSAR.

On average, NEWS solutions are available between a few and up to about 10 minutes after the first P onsets have been recorded at one of the seismic arrays. Since January 2001, a listing of the most recent NEWS solutions has been available on the web. In the summer of 2002, NORSAR started to send the NEWS solutions to interested data centers, which also work on quick epicenter determinations in Europe, such as the EMSC in Bruyères-le-Châtel, France and the European data center for broadband data ORFEUS in De Bilt, The Netherlands. Since the summer of 2007, NEWS alerts for events observed with magnitudes larger or equal to 6.0 are also automatically reported to World Agency of Planetary Monitoring and Earthquake Risk Reduction in Geneva, Switzerland. From mid-2008, the NEWS alerts are transmitted to the International Seismological Centre (ISC) in Thatcham, UK as well.

Section 6.5 is entitled “Seismometer and digitizer tests at NOA subarray NC6”. It describes an instrument test requested by the CTBTO for several Guralp and Nanometrics broadband sensors and digitizers. NORSAR offered to provide the experimental setup and the data collection for such a test at the NOA subarray NC6. The site has all the necessary infrastructure and is connected via landline and broadband to the NORSAR Data Center. The experiment started in the beginning of August 2008, and lasted until the beginning of December 2008. All waveform data have been delivered to CTBTO, Guralp, and Nanometrics for further detailed analyses. In this section we give a brief overview on the setup and some data examples.

Based on the success of this experiment, we conclude that the NOA subarray NC6 has all necessary infrastructure to perform tests of various types of instrumentation in a controlled environment. The site is remote with low cultural noise and it is suitable for long-term instrument testing.

Frode Ringdal

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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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Based on the success of this experiment, we conclude that the NOA subarray NC6 has all necessary infrastructure to perform tests of various types of instrumentation in a controlled environment. The site is remote with low cultural noise and it is suitable for long-term instrument testing.

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 95.486%.

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:

2008		Mission Capable	Net instrument availability
July	:	100%	95.418%
August	:	100%	87.081%
September	:	100%	96.234%
October	:	100%	97.238%
November	:	100%	97.939%
December	:	100%	99.004%

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		
Jul	6,929	860	346	71	417	13.9
Aug	7,958	954	312	65	377	12.2
Sep	7,977	841	271	64	335	11.2
Oct	11,027	961	345	69	424	13.7
Nov	10,572	824	251	66	317	10.6
Dec	11,044	904	237	98	335	10.8
	55,507	5,344	1,762	433	2,205	12.1

Table 2.1.1. *Detection and Event Processor statistics, 1 July - 31 December 2008.*

NOA detections

The number of detections (phases) reported by the NORSAR detector during day 183, 2008, through day 366, 2008, was 55,507, giving an average of 302 detections per processed day (184 days processed).

B. Paulsen

U. Baadshaug

2.2 PS28 — Primary Seismic Station ARCES

The mission-capable data statistics were 99.939%, as compared to 99.904% for the previous reporting period. The net instrument availability was 99.444%.

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

Day	Period
01 Jul	00.31-00.38
01 Jul	01.16-01.24
01 Jul	06.33-06.39
01 Jul	07.26-07.32
01 Jul	08.50-08.59
01 Jul	15.15-15.23
01 Jul	18.29-18.34
01 Jul	18.59-19.05
02 Jul	05.08-05.13
02 Jul	08.14-08.19
02 Jul	08.32-08.38
18 Jul	07.23-07.28
01 Sep	15.56-16.04
01 Sep	20.22-20.29
01 Sep	21.17-21.24
01 Sep	23.11-23.18
02 Sep	02.27-02.34
02 Sep	04.54-04.58
02 Sep	05.02-05.12
02 Sep	10.04-10.11
04 Sep	16.10-16.19
05 Sep	10.33-10.39
07 Sep	18.50-18.59
29 Sep	13.03-13.10

Table 2.2.1. *The main interruptions in recording of ARCES data at NDPC, 1 July - 31 December 2008.*

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:

2008		**Mission Capable**	**Net instrument availability**
July	:	99.832%	99.831%
August	:	100%	97.222%
September	:	99.801%	99.782%
October	:	100%	100%
November	:	100%	99.968%
December	:	100%	99.859%

B. Paulsen

Event Detection Operation

ARCES detections

The number of detections (phases) reported during day 183, 2008, through day 366, 2008, was 209,013, giving an average of 1136 detections per processed day (184 days processed).

Events automatically located by ARCES

During days 183, 2008, through 366, 2008, 8,696 local and regional events were located by ARCES, based on automatic association of P- and S-type arrivals. This gives an average of 47.3 events per processed day (184 days processed). 62% of these events are within 300 km, and 87 % of these events are within 1000 km.

U. Baadshaug

2.3 AS72 — Auxiliary Seismic Station Spitsbergen

The mission-capable data for the period were 95.736%, as compared to 95.609% for the previous reporting period. The net instrument availability was 81.173%.

The main outages in the period are presented in Table 2.3.1.

Day	Period
30 Jul	13.25-13.38
24 Aug	04.19-05.40
24 Aug	11.38-00.00
25 Aug	00.00-00.00
26 Aug	00.00-04.45
27 Aug	10.38-00.00
28 Aug	00.00-16.43
31 Aug	09.00-10.23
01 Sep	13.25-14.39
06 Sep	19.35-00.00
07 Sep	00.00-00.00
08 Sep	00.00-00.00
09 Sep	00.00-01.41
09 Sep	06.51-07.15
11 Sep	04.42-00.00
12 Sep	00.00-00.00
13 Sep	00.00-12.52
13 Sep	13.01-13.33

Table 2.31. *The main interruptions in recording of Spitsbergen data at NDPC, 1 July - 31 December 2008.*

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:

2008		Mission Capable	Net instrument availability
July	:	99.967%	71.400%
August	:	90.065%	60.063%
September	:	84.383%	59.671%
October	:	100%	99.994%
November	:	100%	100%

2008		Mission Capable	Net instrument availability
December	:	100%	95.908%

B. Paulsen

Event Detection Operation

Spitsbergen array detections

The number of detections (phases) reported from day 183, 2008, through day 366, 2008, was 460,981, giving an average of 2,561 detections per processed day (180 days processed).

Events automatically located by the Spitsbergen array

During days 183, 2008 through 366, 2008, 41,027 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 227.9 events per processed day (180 days processed). 76% of these events are within 300 km, and 92% 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, according to the protocol of the CTBT, 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 several 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. The applications were turned down by the local governing council in June 2007. Investigations are currently underway to identify an alternative site for IS37 outside Karasjok.

J. Fyen

2.6 RN49 — Radionuclide Station on Spitsbergen

The IMS radionuclide network includes a station on the island of Spitsbergen. This station has been selected to be among those IMS radionuclide stations that will monitor 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 under 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 99.979%, as compared to 99.970% for the previous reporting period. The net instrument availability was 99.755%.

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

Day	Period
03 Jul	15.46-15.49
03 Jul	23.04-23.10
11 Jul	05.26-05.29
23 Jul	10.46-10.49
04 Aug	12.26-12.29
13 Aug	05.04-05.06
19 Aug	01.04-01.08
20 Aug	21.44-21.48
05 Sep	04.25-04.28
07 Sep	09.05-09.08
19 Oct	05.45-05.49
31 Oct	19.06-19.09
15 Nov	00.26-00.29
20 Nov	18.26-18.29
02 Dec	00.26-00.29
04 Dec	21.06-21.09
15 Dec	18.26-18.30

Table 3.2.1. *The main interruptions in recording of Hagfors data at NDPC, 1 July - 31 December 2008.*

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:

2008		**Mission Capable**	**Net instrument availability**
July	:	99.969%	99.724%
August	:	99.973%	99.972%
September	:	99.985%	98.891%
October	:	99.985%	99.984%
November	:	99.985%	99.984%
December	:	99.978%	99.977%

B. Paulsen

Hagfors Event Detection Operation

Hagfors array detections

The number of detections (phases) reported from day 183, 2008, through day 366, 2008, was 174,677, giving an average of 949 detections per processed day (184 days processed).

Events automatically located by the Hagfors array

During days 183, 2008, through 366, 2008, 4797 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 26.1 events per processed day (184 days processed). 71% of these events are within 300 km, and 93% 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 99.997%, as compared to 99.986% for the previous reporting period. The net instrument availability was 94.882%.

The main outages in the period are presented in Table 3.3.1.

Day	Period
Jul 15	07.45-07.47
Jul 15	07.50-07.56

Table 3.3.1. *The main interruptions in recording of FINES data at NDPC, 1 July - 31 December 2008.*

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:

2008		Mission Capable	Net instrument availability
July	:	99.982%	95.198%
August	:	100%	95.238%
September	:	100%	95.238%
October	:	100%	95.238%
November	:	100%	92.895%
December	:	99.998%	95.486%

B. Paulsen

FINES Event Detection Operation

FINES detections

The number of detections (phases) reported during day 183, 2008, through day 366, 2008, was 39,641, giving an average of 215 detections per processed day (184 days processed).

Events automatically located by FINES

During days 183, 2008, through 366, 2008, 1842 local and regional events were located by FINES, based on automatic association of P- and S-type arrivals. This gives an average of 10.0 events per processed day (184 days processed). 89% of these events are within 300 km, and 92% 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 and to focus on regional events in preparation for Gamma-data submission during GSETT-3, 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.

	Jul 08	Aug 08	Sep 08	Oct 08	Nov 08	Dec 08	Total
Phase detections	171,338	181,645	138,281	195,823	159.442	173,256	1,019,785
- Associated phases	6,042	7,087	5,645	8,332	5,597	5,864	38,567
- Unassociated phases	165,296	174,558	132,636	187,491	153,845	167,392	981,218
Events automatically declared by RMS	1,198	1,589	1,178	1,713	1,205	1,345	8,228

	Jul 08	Aug 08	Sep 08	Oct 08	Nov 08	Dec 08	Total
No. of events defined by the analyst	78	76	87	96	83	52	472

Table 3.5.1. RMS phase detections and event summary 1 July - 31 December 2008.

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 July - December 2008 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 July - December 2008 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 581 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.

The two stations PS27 and PS28 are both suffering from lack of spare parts. The PS27 NOA equipment was acquired in 1995 and it is now impossible to get spare GPS receivers. The PS28 ARCES equipment was acquired in 1999, and it is no longer possible to get spare digitizers. A recapitilization plan for both arrays was submitted to PTS in October 2008, and discussions with the PTS are being held regarding a future configuraiton of PS27 and PS28.

U. Baadshaug
S. Mykkeltveit
J. Fyen

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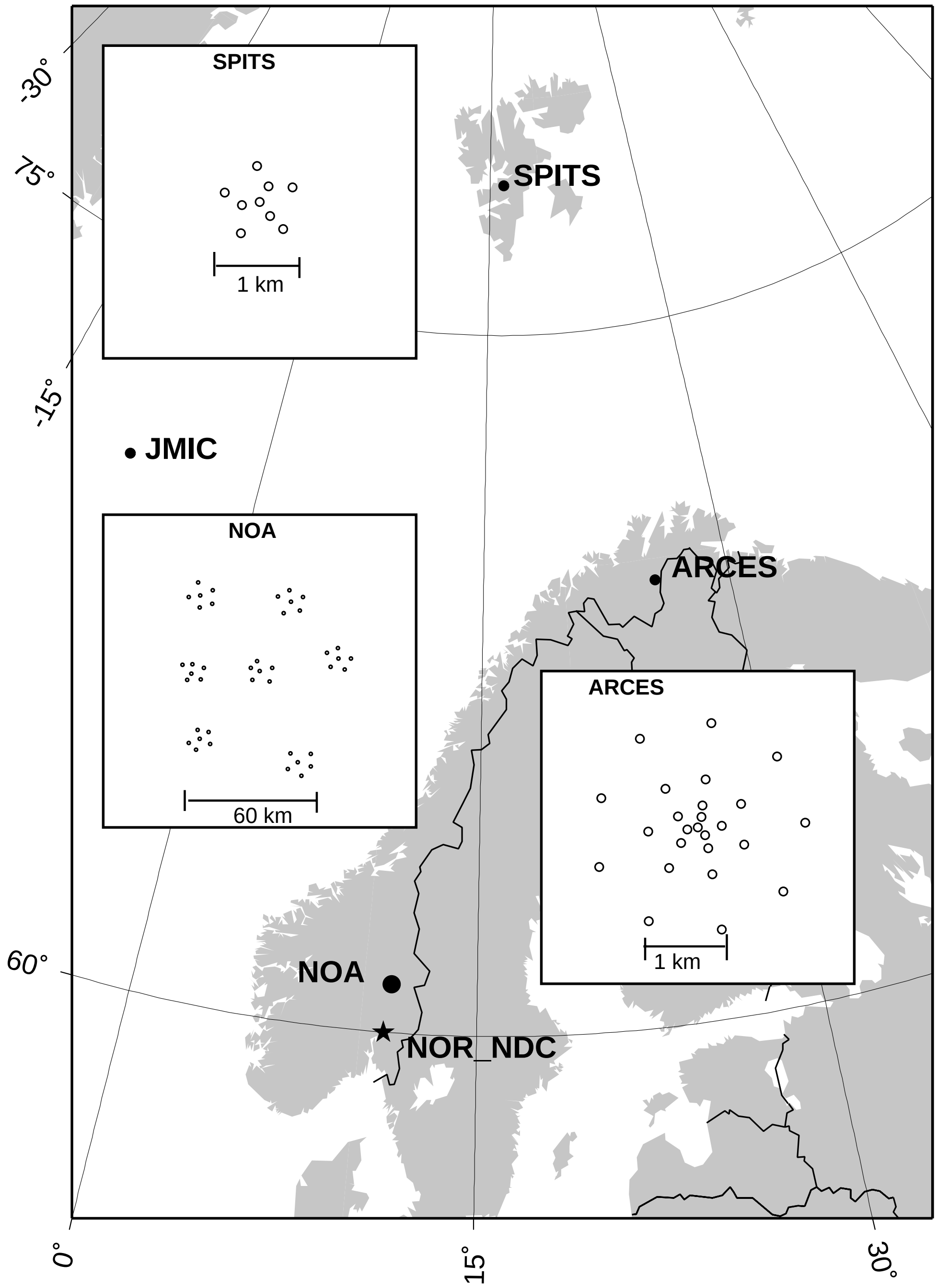

Fig. 4.2.1. The figure shows the locations and configurations of the three Norwegian seismic IMS array stations that provided data to the IDC during the period July - December 2008 The data from these stations and the JMIC three-component station are transmitted continuously and in real time to the Norwegian NDC (NOR_NDC). The stations NOA and ARCES are primary IMS stations, whereas SPITS and JMIC are auxiliary IMS stations.

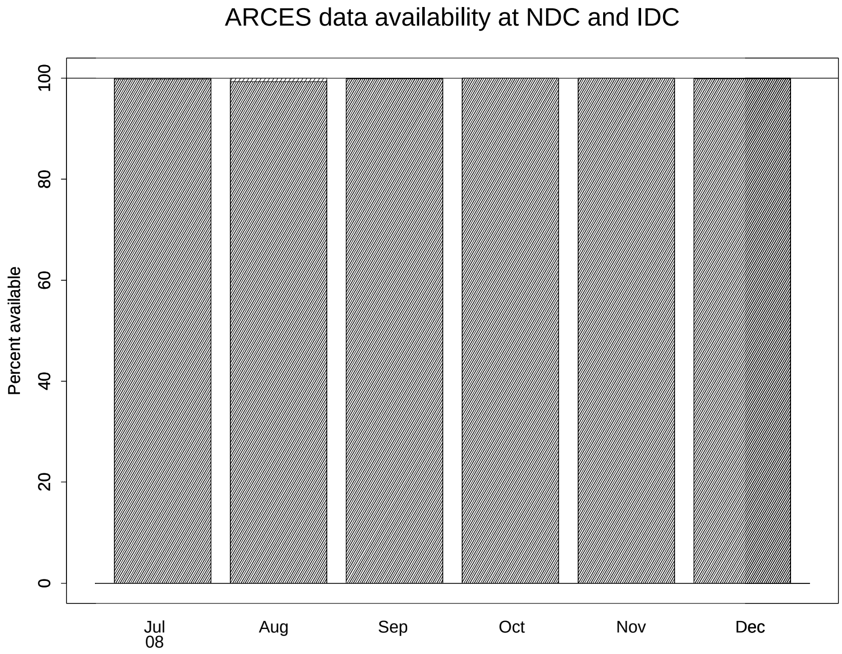

Fig. 4.2.2. The figure shows the monthly availability of ARCES array data for the period July - December 2008 at NOR_NDC and the IDC. See the text for explanation of differences in definition of the term "data availability" between the two centers. The higher values (hatched bars) represent the NOR_NDC data availability.

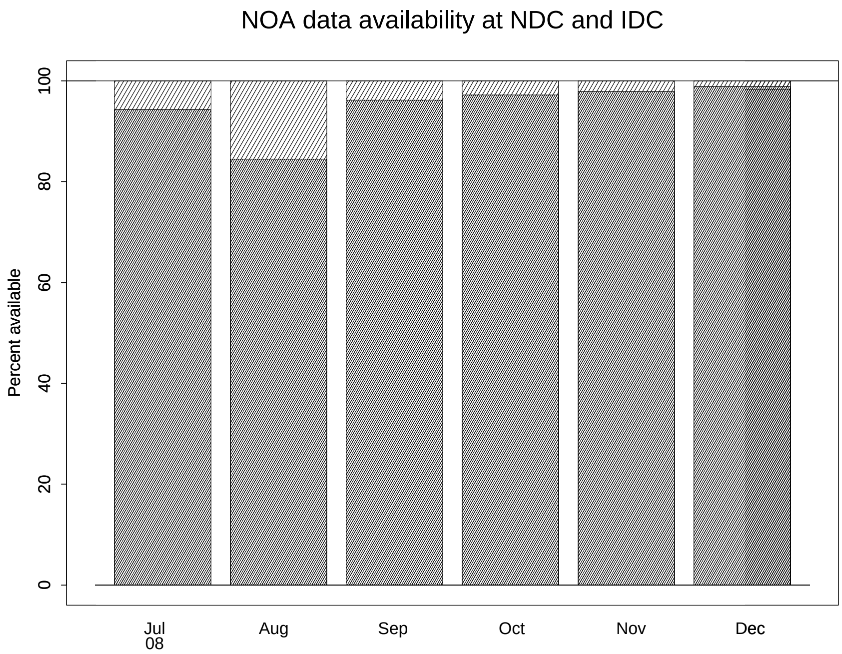

Fig. 4.2.3. The figure shows the monthly availability of NORSAR array data for the period July - December 2008 at NOR_NDC and the IDC. See the text for explanation of differences in definition of the term "data availability" between the two centers. The higher values (hatched bars) represent the NOR_NDC data availability.

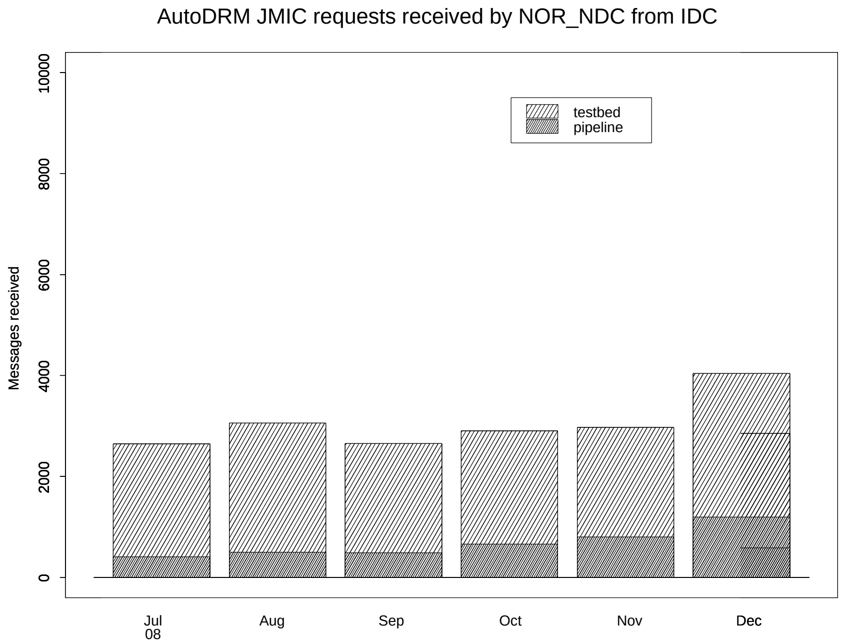

Fig. 4.2.4. The figure shows the monthly number of requests received by NOR_NDC from the IDC for JMIC waveform segments during July - December 2008.

Reviewed Supplementary events

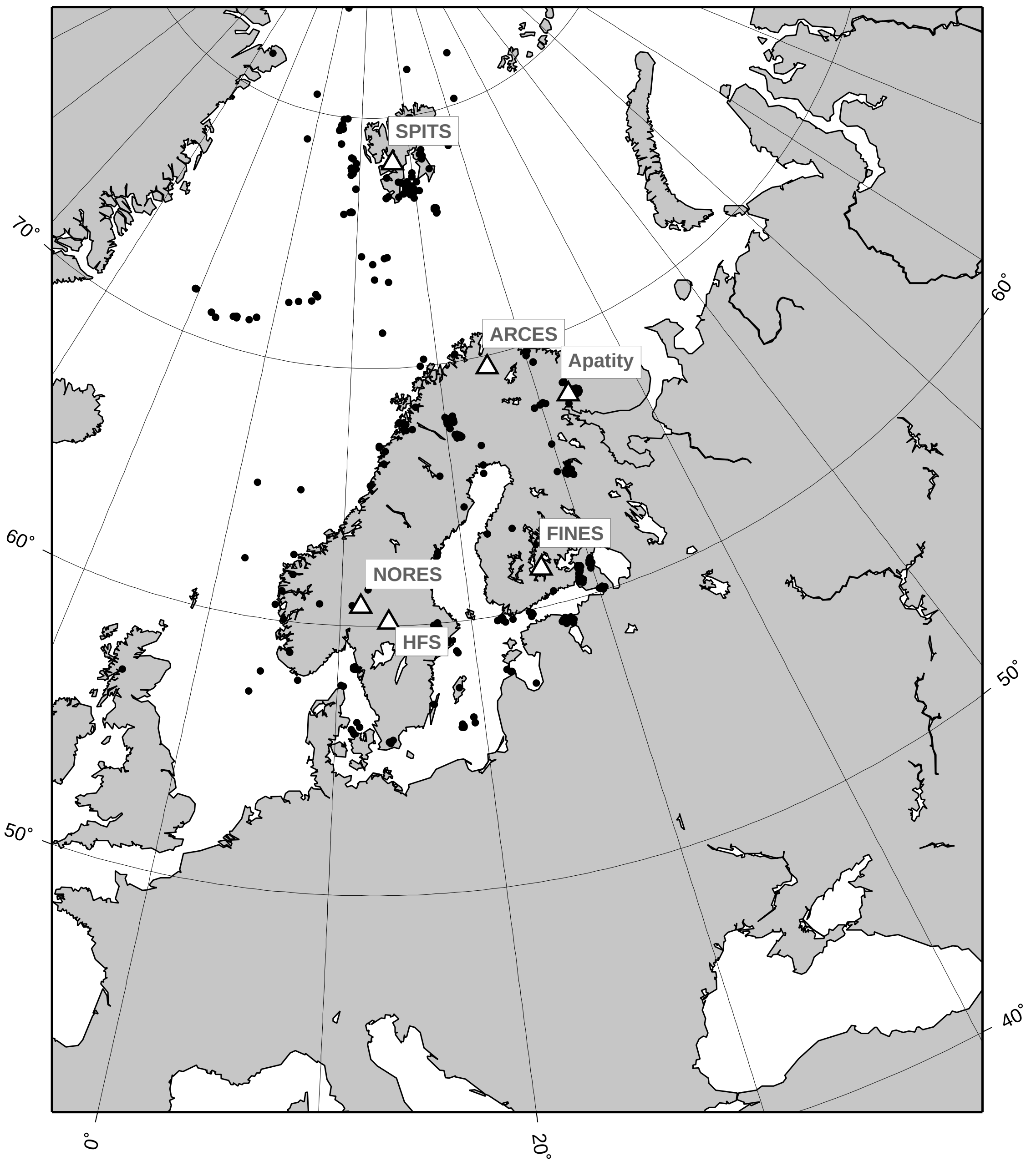

Fig. 4.2.5. The map shows the 581 events in and around Norway contributed by NOR_NDC during July - December 2008 as supplementary (Gamma) events to the IDC, as part of the Nordic supplementary data compiled by the Finnish NDC. The map also shows the main seismic stations used in the data analysis to 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 Infrasound signals generated by atmospheric explosions in Finland as observed at the ARCES seismic array and microbarograph mini-array (sponsored by US Army Space and Missile Defence Command, Contract no. W9113M-05-C-0224)

6.1.1 Introduction

The Finnish military destroys expired ammunition at a site in northern Lapland in a sequence of explosions every year between August and September. Each explosion has a yield of approximately 20000 kg and the seismic signals recorded at the ARCES array in northern Norway indicate a magnitude of approximately 1.5. The events have been of great interest due to the generation of infrasound signals which have been recorded on the seismic traces at ARCES and by both seismic and microbarograph instruments at Apatity (Vinogradov and Ringdal, 2003; Gibbons et al., 2007). These explosions provide very useful reference events for infrasound sources since the location is known (67.934^{o}N, 25.832^{o}E: see Figure 6.1.1) and the origin times are very tightly constrained by the seismic observations. It now appears that infrasound from these events can be observed at far greater distances than previously assumed with signals likely to come from these sources being observed at the IMS infrasound arrays I18DK (Qaanaaq, Greenland) and I26DE (Freyung, Germany) making the events useful for studies of long-distance sound propagation (Bahavar et al., 2008).

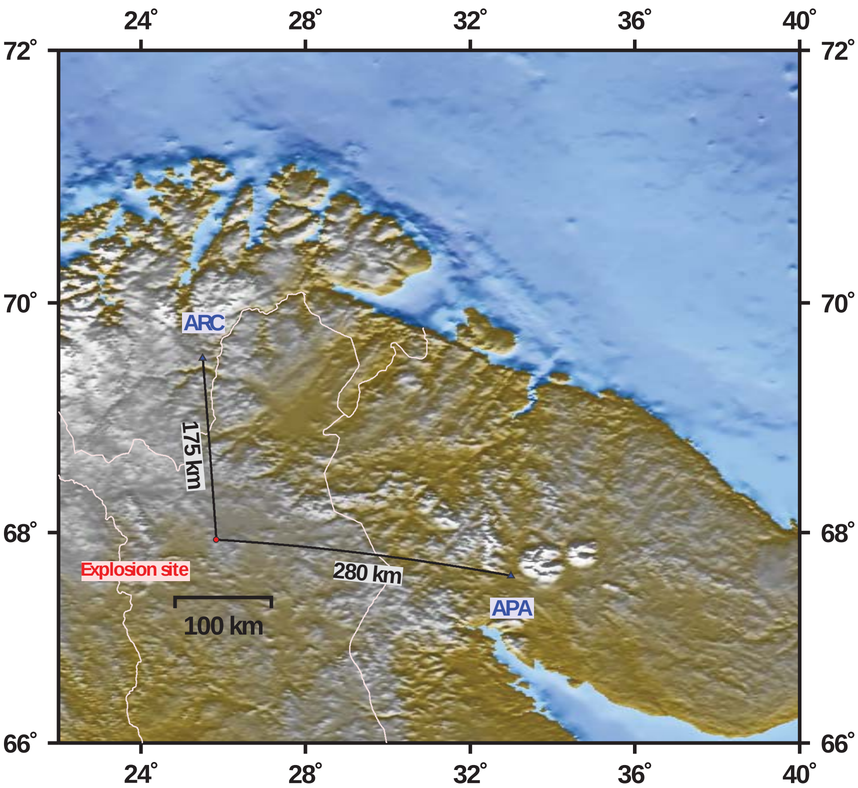

Fig. 6.1.1. Location of the Finnish explosion site (67.934^{o}N, 25.832^{o}E) in relation to the arrays at ARCES and Apatity.

The fall of 2008 was no exception with a total of 36 explosions being conducted between August 13 and September 11 (see Table 6.1.1). As in previous years, a very high degree of similarity was observed between the seismic signals from the events allowing them all to be detected with an essentially zero false alarm rate using a multichannel correlation detector (Gibbons and Ringdal, 2006).

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

Table 6.1.1. Explosions at the Finnish military base in Lapland during 2008. UT Origin time estimates are provided rounded to the nearest second.

Date (day of year)		First event		Second event
13 Aug 2008 (226)	01	09.00.00	02	13.00.00
14 Aug 2008 (227)	03	09.00.00	04	13.00.00
15 Aug 2008 (228)	05	08.30.00	06	11.59.59
16 Aug 2008 (229)	07	08.30.00	08	11.30.00
17 Aug 2008 (230)	09	08.29.58	10	11.30.00
18 Aug 2008 (231)	11	06.59.59	12	13.59.58
19 Aug 2008 (232)	13	10.59.59		
20 Aug 2008 (233)	14	10.59.58		
21 Aug 2008 (234)	15	11.00.00		
22 Aug 2008 (235)	16	11.00.00		
23 Aug 2008 (236)	17	13.15.01		
24 Aug 2008 (237)	18	12.30.00		
25 Aug 2008 (238)	19	11.30.00		
26 Aug 2008 (239)	20	11.00.00		
27 Aug 2008 (240)	21	11.00.00		
28 Aug 2008 (241)	22	10.45.01		
29 Aug 2008 (242)	23	11.00.00		
30 Aug 2008 (243)	24	09.59.59		
31 Aug 2008 (244)	25	11.00.00		
1 Sep 2008 (245)	26	11.30.00		
2 Sep 2008 (246)	27	11.00.03		
3 Sep 2008 (247)	28	11.00.06		
4 Sep 2008 (248)	29	10.30.00		
5 Sep 2008 (249)	30	10.00.00		
6 Sep 2008 (250)	31	11.00.00		
7 Sep 2008 (251)	32	09.29.59		
8 Sep 2008 (252)	33	09.29.59		
9 Sep 2008 (253)	34	09.29.59		

Table 6.1.1. Explosions at the Finnish military base in Lapland during 2008. UT Origin time estimates are provided rounded to the nearest second.

Date (day of year)		First event		Second event
10 Sep 2008 (254)	35	09.29.59		
11 Sep 2008 (255)	36	09.30.00		

6.1.2 Observations

Figure 6.1.2 displays the waveforms observed on co-located seismic and infrasound sensors at the ARA1 site of the ARCES array for each of the 36 events in 2008. The seismic traces in the left panel show the seismic P- and S- phases arriving 29 and 49 seconds respectively after each shot and also acoustic signals between 500 and 700 seconds. Whilst the acoustic phases are generally visible in the filtered data, they are of somewhat smaller amplitude than in some previous years. (Gibbons et al., 2007, display a corresponding plot for 2002 in which the amplitudes of the acoustic phases are frequently greater than those for the seismic phases.) An additional complication which has been particularly problematic for 2008 is the presence of unrelated seismic signals in the interval in which the acoustic phases are anticipated. Signals visible between 500 and 700 seconds after events 14, 15, 16, and 24 are very clearly regional or teleseismic signals unrelated to the explosions in Finland which may make the detection of acoustic phases at these times difficult or impossible.

The right hand panel of Figure 6.1.2 shows microbarograph data from the same site, for the same time intervals. The seismic arrivals are not visible in these waveforms. More often than not, the acoustic phases recorded on the seismic instruments are also visible with a significantly higher amplitude than the background noise. On other days, the background noise is very much higher and matches the amplitudes of the observed signals.

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

We have restricted our analysis to frequency ranges 2.0 - 7.0 Hz for the seismic sensors and between 1.0 - 7.0 Hz for the microbarographs. For the seismic sensors, the limitation to frequencies above 2 Hz is due to the high amplitude microseismic noise at lower frequencies. The frequency range for the infrasound mini-array is the result of the sensor configuration. At low frequencies, there is no resolution in slowness-space and, at high frequencies, aliasing results in an ambiguity of direction estimates.

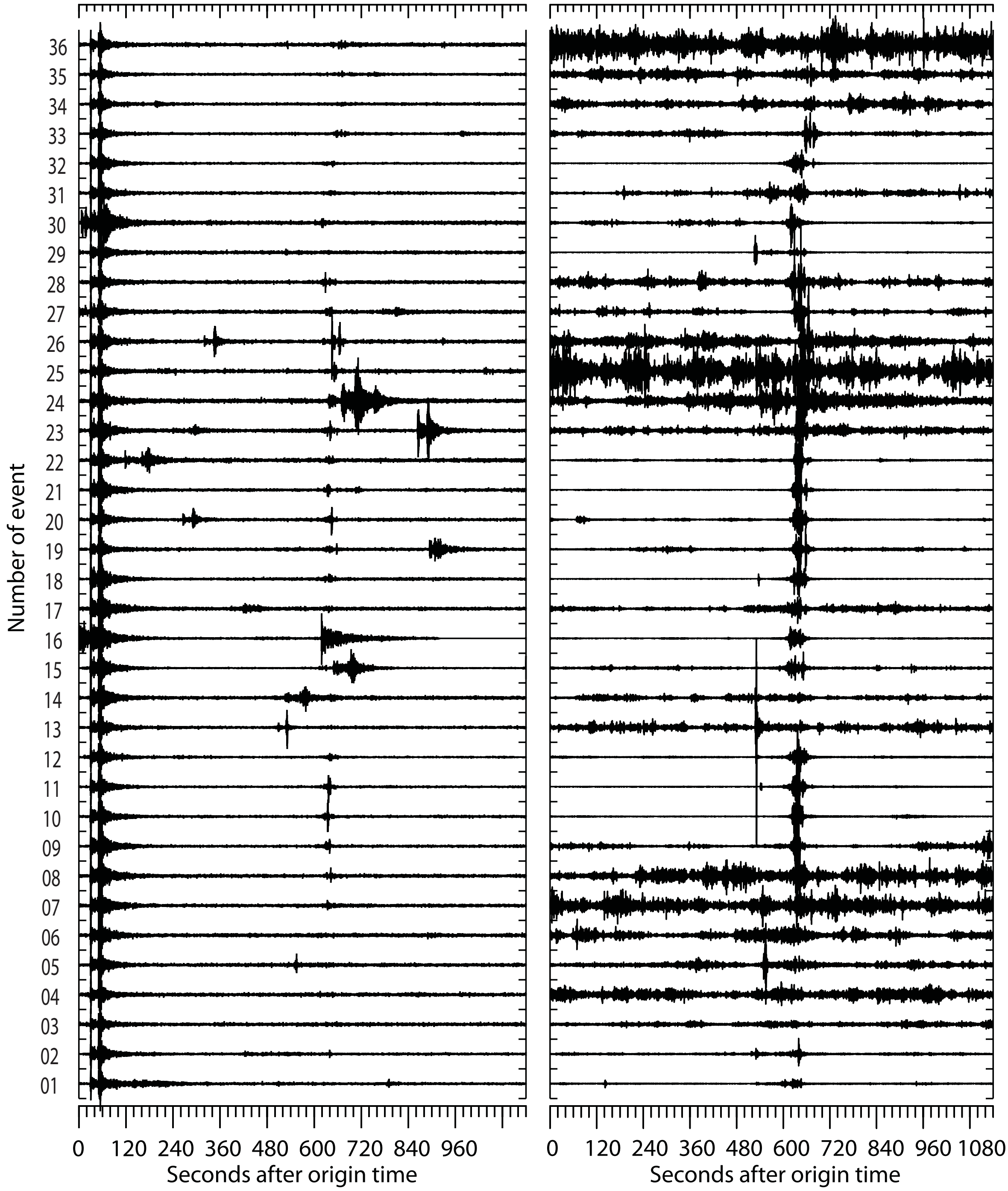

Fig. 6.1.2. Waveforms from the short-period vertical seismic sensor ARA1_sz (left) and the co-located microbarograph sensor ARA1_BDF (right) for the events as listed in Table 6.1.1. The same vertical scale is applied to all of the seismic traces within each panel. All waveforms are bandpass filtered between 2 and 7 Hz.

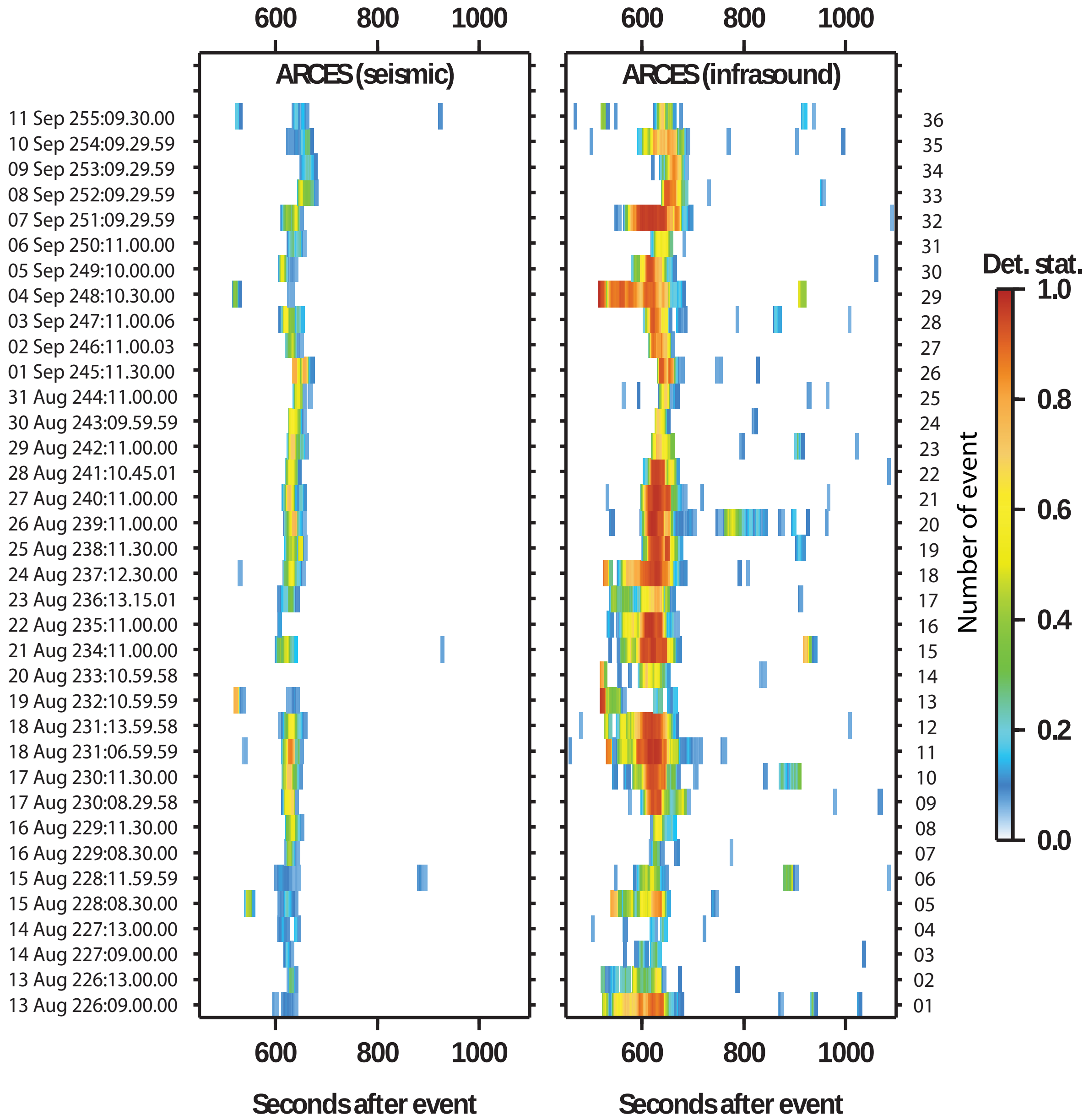

Fig. 6.1.3. Each pixel represents the value of the detection statistic defined in Equation (15) of Brown et al. (2002) for a 10 second long data segment, bandpass filtered between 2.0 and 7.0 Hz, on the condition that the backazimuth and apparent velocity indicated by the cross-correlation analysis fell within the intervals [168^o:190^o] and [0.3 kms^{-1}:0.8 kms^{-1}] respectively. The time provided to the left is the event origin time.

Figure 6.1.3 shows the value of the maximum mean cross-correlation coefficient as a function of time following the explosion on the condition that the preferred slowness-vector is consistent with an anticipated acoustic phase. All events appear to generate infrasound waves which are detected on both the seismic and infrasonic sensors with the exception of event 14 for which no observation is made on the seismometers. There is however a sound signal detected on the infrasound sensors at the anticipated time which suggests that the absence of a detection on the seismic sensors is indeed caused by interference from unrelated seismic signals.

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

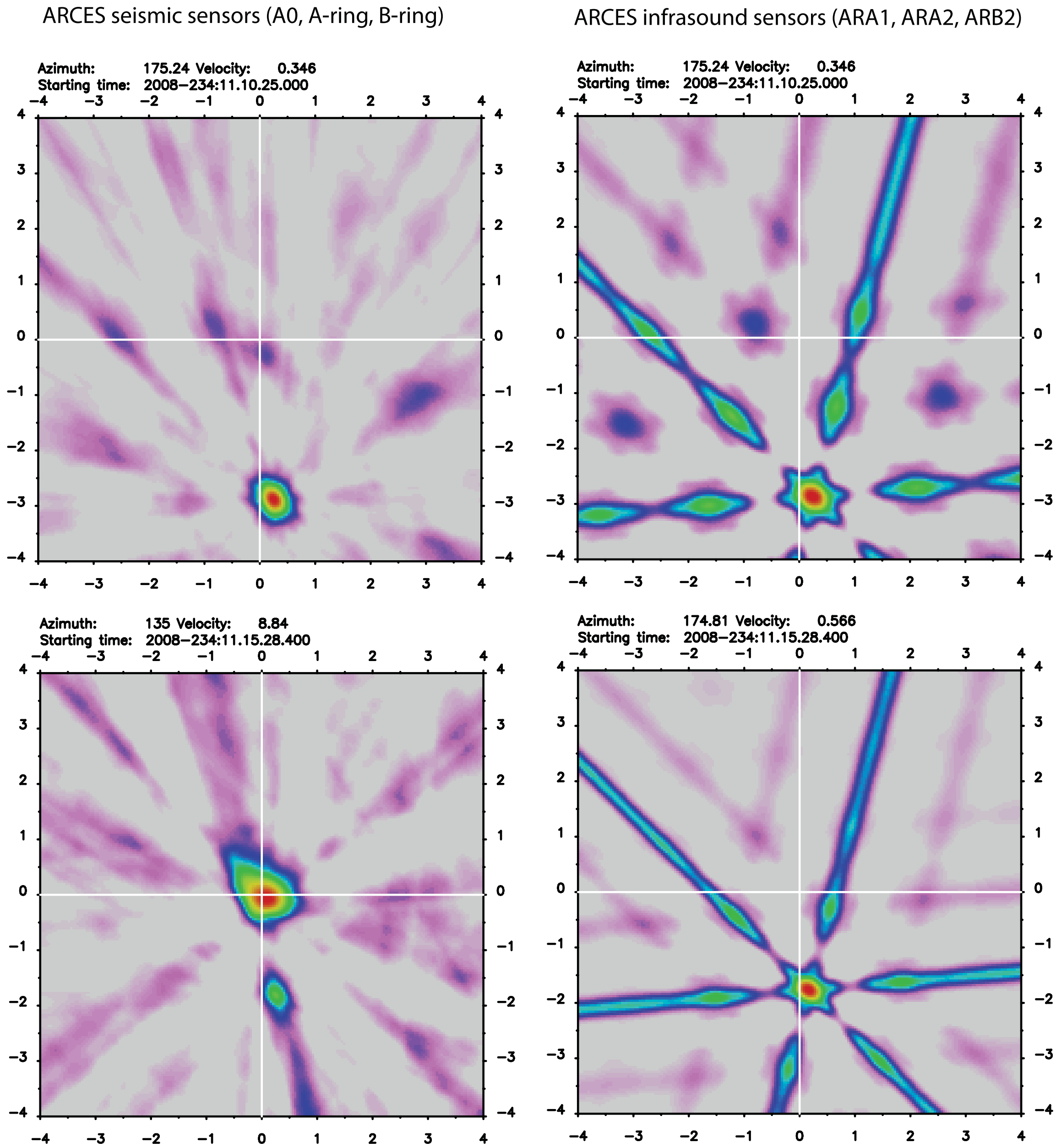

Fig. 6.1.4. Slowness estimates at 625 seconds (above) and 928 seconds (below) after the explosion at 11.00 UTC on August 21, 2008. For the seismic estimates, only the innermost nine sites of the ARCES array are used. The seismic estimate for the later arrival (lower left panel) indicates an apparent velocity consistent with seismic wave speed, although evidence is seen for energy arriving with sound speed.

Examples of direction estimates, both for a typical phase in the 500-700 second interval and for one of the newly observed phases between 800 and 950 seconds, are shown in Figure 6.1.4.

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

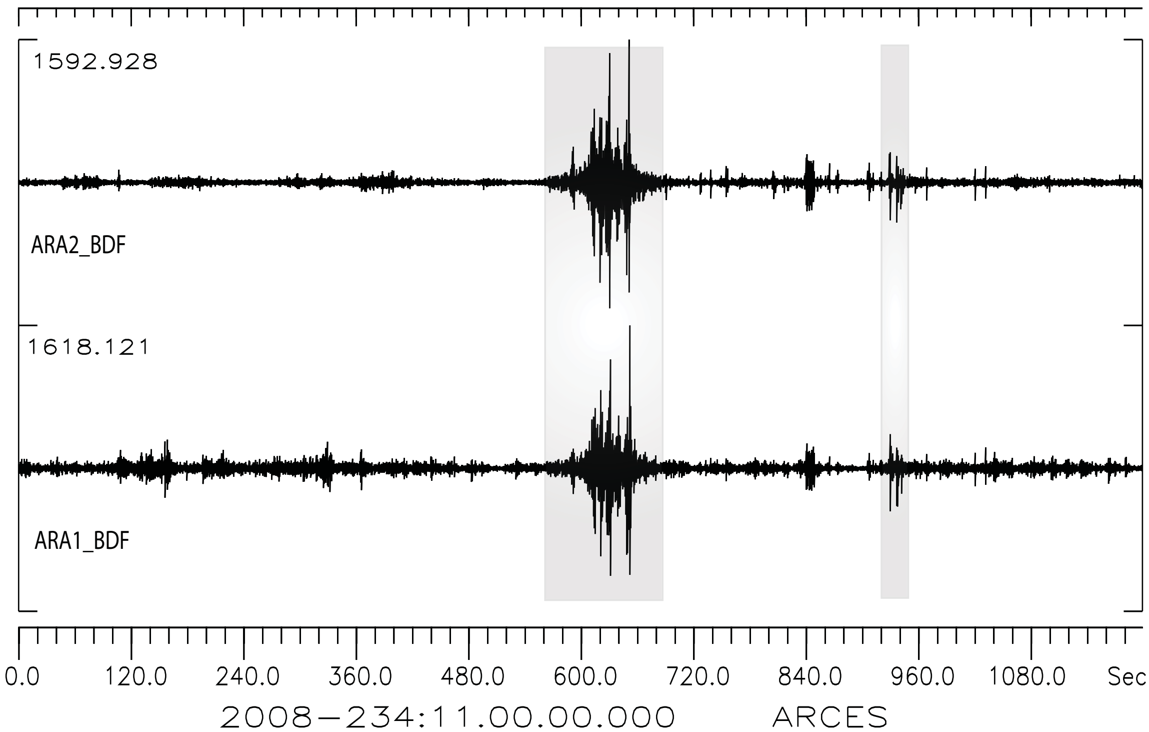

Fig. 6.1.5. Traces of ARCES microbarograph data following the 11.00 UT explosion on August 21, 2008. The grey boxes indicate the time-periods for which the slowness analysis indicates a sound wave from the appropriate direction. All features in this data interval which are not covered by the grey boxes are not consistent with presumed acoustic arrivals from the explosion.

An example of the waveforms corresponding to the two types of arrival is displayed in Figure 6.1.5. In this plot, and in corresponding plots for other events in the sequence, the presumed thermospheric arrival is both of lower amplitude and shorter duration than the presumed stratospheric arrivals. The longer duration signal appears to be rather continuous in nature whereas the presumed thermospheric arrival appears to consist of very short duration bursts. This would also appear to be consistent with the observations of Whitaker and Mutschlecner (2008) and may contribute to the poorer detection rate since the cross-correlation method is best suited to long duration, coherent signals.

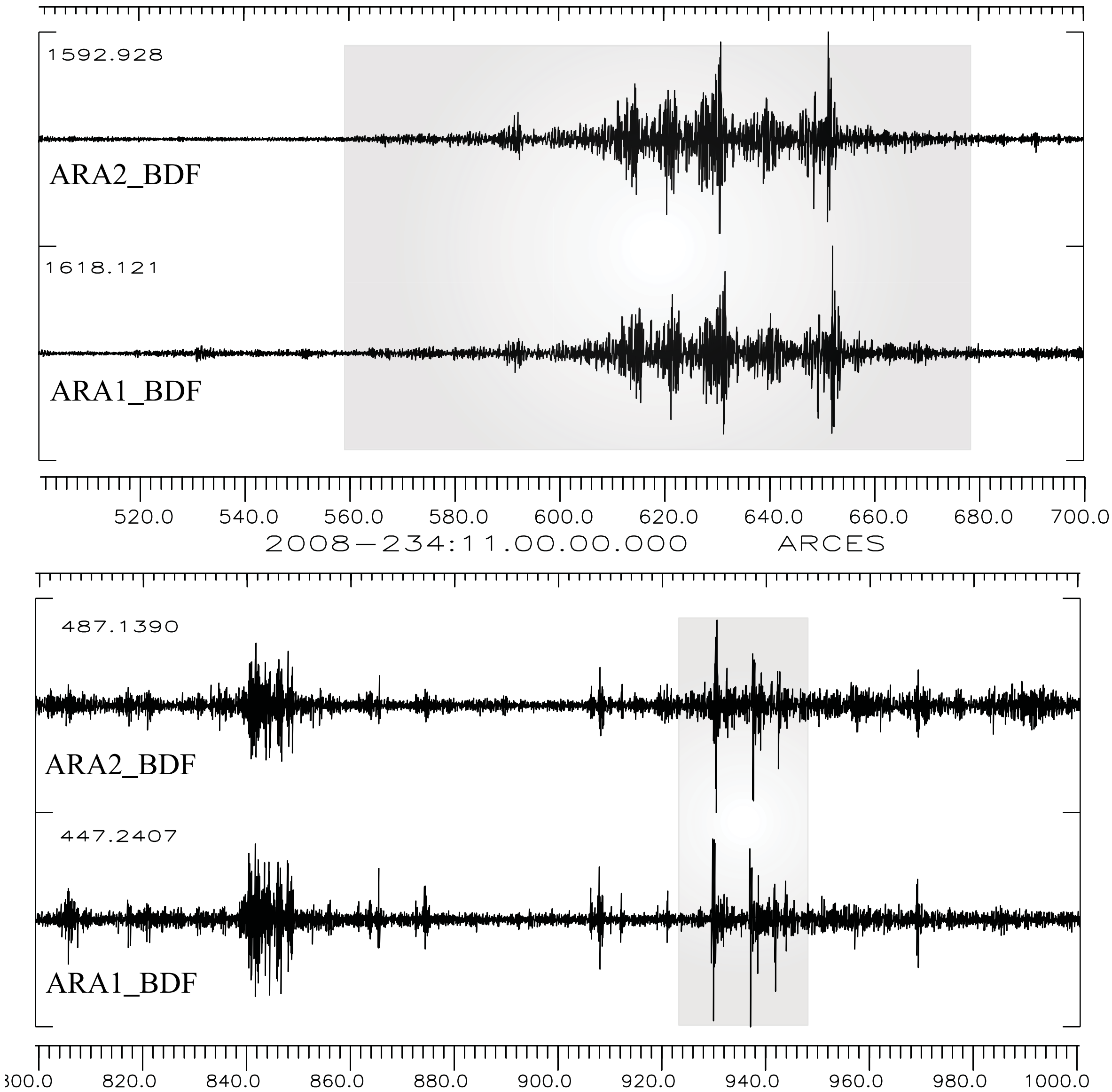

Fig. 6.1.6. Time in seconds following the explosion at 11.00 UT on August 21, 2008, as recorded on the ARA2_BDF and ARA1_BDF microbarograph channels at ARCES. Both panels are 200 second long enlargements of the waveforms displayed in Figure 6.1.5.

6.1.3 Summary

We present the origin times of 36 explosions which took place during August and September 2008 at a site in northern Finland (coordinates 67.934^{o}N, 25.832^{o}E). The explosions this year are the first to be recorded by the microbarograph mini-array within the ARCES seismic array at a distance of approximately 178 km. Acoustic signals were detected on the microbarograph sensors following every one of the explosions and on the seismic sensors following all but one. The non-detection in this case is attributed to an unrelated seismic signal arriving in the interval in which the acoustic arrival is anticipated.

Whilst the seismic array has served well as a surrogate infrasound array for these and other seismo-acoustic and infrasound events, this field deployment has demonstrated that the microbarograph sensors are essential to capture low amplitude infrasound signals which are too weak to be registered on the seismic sensors. Comparing the left and right panels of Figure 6.1.3 it is clear that the onset of the infrasound phases inferred from the microbarograph array is often significantly earlier than for the seismic sensors. A closer inspection of many of the presumed stratospheric returns (c.f. upper panel of Figure 6.1.6) reveals that many of the signals have quite long durations and are quite emergent in nature. This is significant for the validation of models for atmospheric sound propagation since the onset time inferred from the seismic traces (only sensitive to the highest amplitudes) may be 30-60 seconds higher than the onset time estimated from the microbarograph data.

In addition to the phases identified by Gibbons et al. (2007), all arriving between 500 and 700 seconds after origin time, a number of additional arrivals have been detected between 800 and 950 seconds. These are associated with considerably higher apparent velocities, consistent with steeper angles of incidence which would be anticipated from thermospheric returns. The travel times are consistent with thermospheric arrivals observed from Nevada Test Site explosions recorded at the comparable distance of 210 km (Mutschlecner and Whitaker, 1999). There were only three such detections on the seismic sensors and all of these were quite marginal. There were 11 clear detections on the infrasound mini-array. This represents approximately 30% of the events which is similar to the observation rates quoted by Whitaker and Mutschlecner (2008). However, given that only a minimal wind noise reduction system (for noise protection) is available to us within the planning limitations at the ARCES site, it is not clear to what extent this is the result of an absence of the phases and to what extent this is due to excessive background noise[1]. It is clear that very local noise conditions apply and that an increase in the number of sensors would mitigate this problem.

The thermospheric arrivals appear to be of shorter duration and of lower amplitude than the presumed stratospheric returns. This will contribute to their non-detection on the seismic sensors.

The deployment of more infrasound sensors would allow an examination of infrasound over a broader range of frequencies (mitigating the aliasing for high frequency signals and the lack of resolution for low frequency signals) and would make the detection procedure more robust by providing some redundancy among sensors.

1. The thermospheric arrival from the last event in Table 6.1.1 was observed clearly on one channel and barely observed on the other channels and was very nearly missed due to the low correlation values.

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S. J. Gibbons

6.2 Infrasound observations from the meteor north of Norway on 15 January 2009 (sponsored by US Army Space and Missile Defence Command, Contract no. W9113M-05-C-0224)

6.2.1 Introduction

In the evening of 15 January 2009, light flashes and a fireball were observed over parts of Northern Norway. Figure 6.2.1 shows some locations with visual observations of the object, which was reported to propagate in a north-northwesterly direction into the Barents Sea. Based on newspaper reports, the time of the event is estimated to 19:40 GMT.
The signals from the meteor, recorded at the 4 infrasound arrays operated by the Swedish Institute of Space Physics (IRF) were analyzed within a short time after the event. Prof. Liszka of IRF estimated the signals to originate halfway between mainland Norway and Svalbard. For details see *http://www.irf.se/Topical/Other/?newsid=7&group=P2*.

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

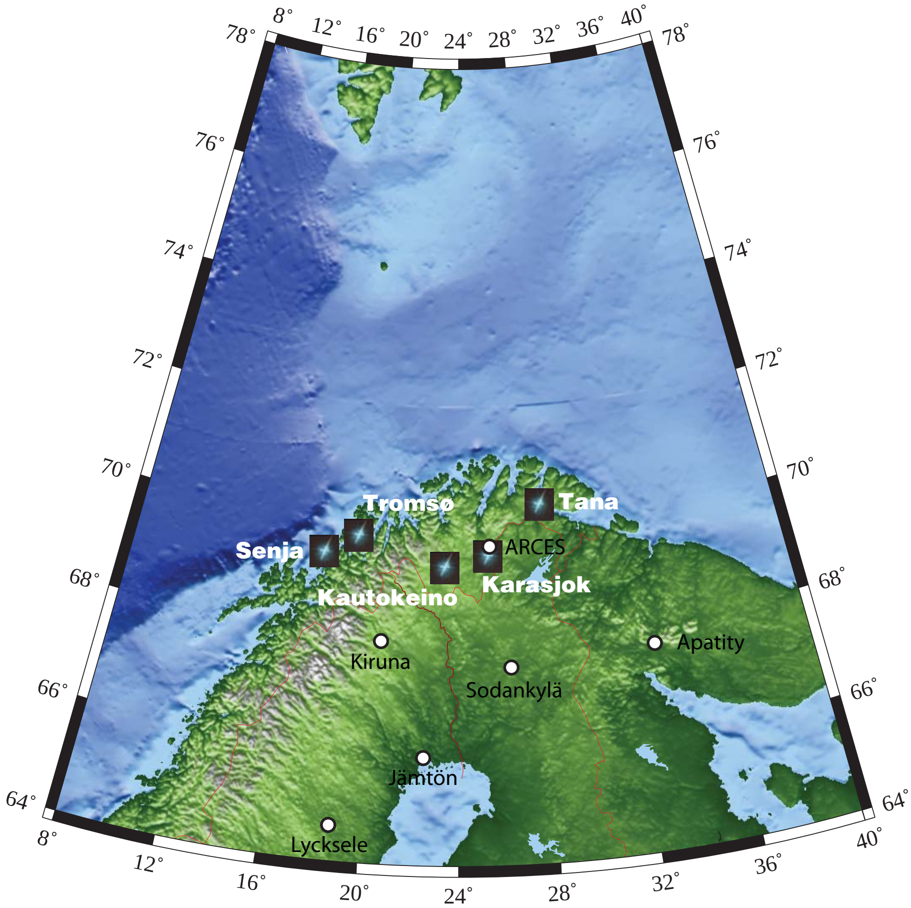

Fig. 6.2.1. The black symbols show some of the locations in Northern Norway (white text) with reported visual observations of the 15 January 2009 meteor. The infrasound stations in Sweden, Finland, NW Russia and Norway are shown as filled white symbols.

6.2.2 Data Processing and Location

For each of the stations (see Figure 6.2.1), we have processed the infrasound data using vespagram analysis. Using a fixed apparent velocity around 0.333 km/s, we have calculated the resulting normalized beam power for a range of back-azimuths, where the maximum represent an estimate of the back-azimuth of the arriving signal. In our calculations we have used a window length of 10 seconds and a window step of 1.0 second. Because of the larger array apertures, the ARCES and Apatity infrasound data were processed in the 1 - 4 Hz frequency band, whereas the stations of the Swedish Infrasound network were all processed in the 2 - 5 Hz band. Figures 6.2.2-6.2.4 show the results from the vespagram analysis together with the raw and bandpass filtered waveforms,

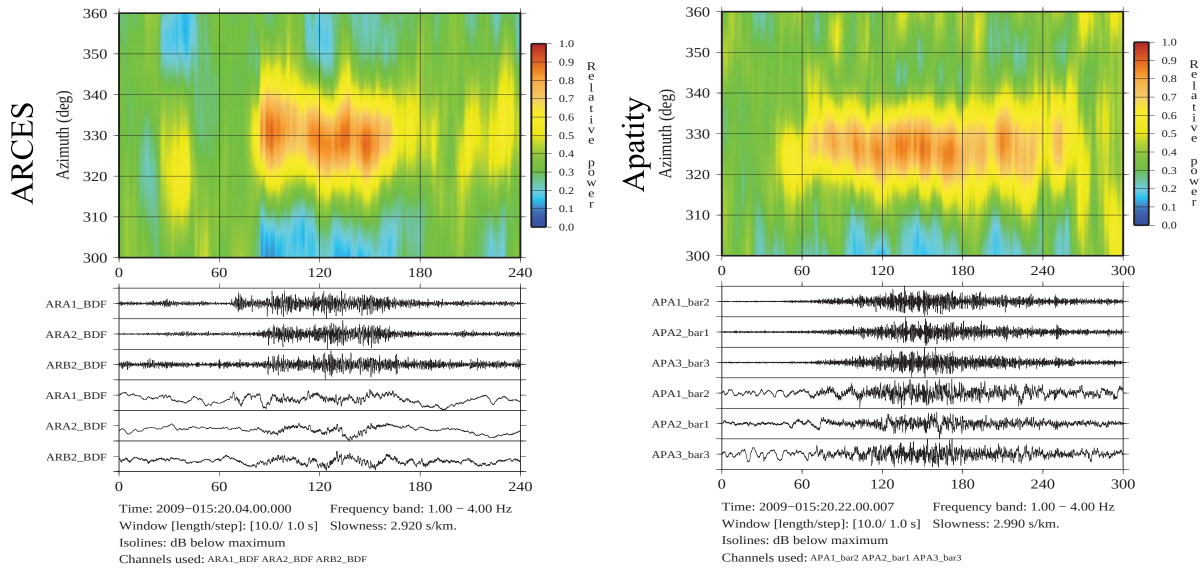

Fig. 6.2.2. Azimuthal vespagrams from analysis of ARCES and Apatity infrasound data for the time interval around the signals from the meteor on 15 January 2009. The upper three traces of each panel show the bandpass filtered waveforms, whereas the three lower traces show the raw data. Notice that different time scales are used for the two stations. A constant slowness close 3 s/km has been used when calculating the azimuthal vespagrams.

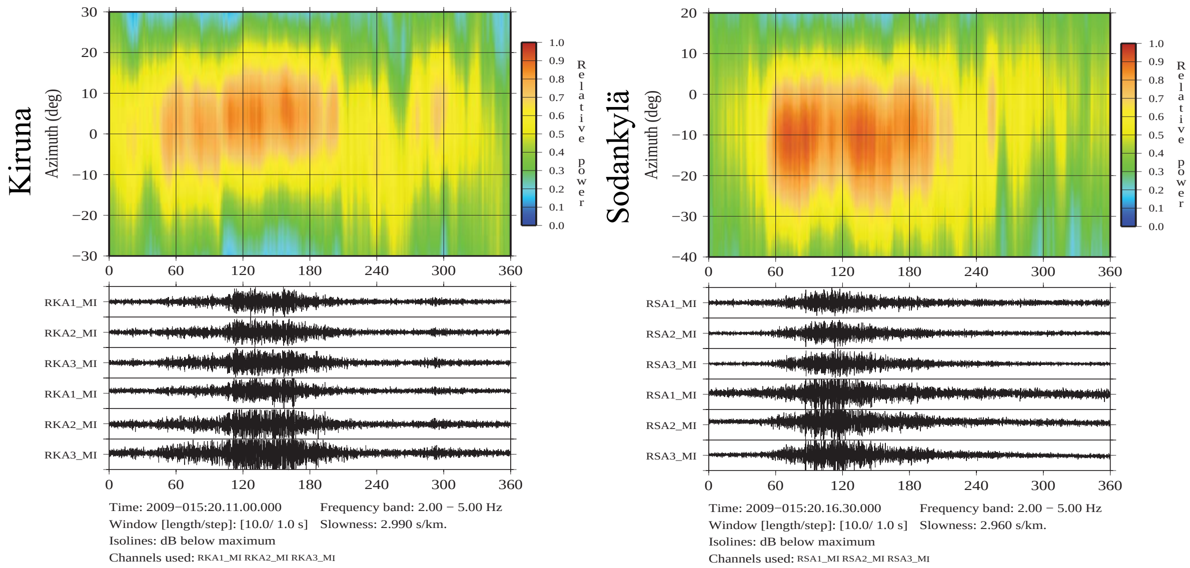

Fig. 6.2.3. Azimuthal vespagrams from analysis of Kiruna and Sodankylä infrasound data for the time interval around the signals from the meteor on 15 January 2009. For these two stations the raw data is clipped. See caption of Figure 6.2.2 for more details.

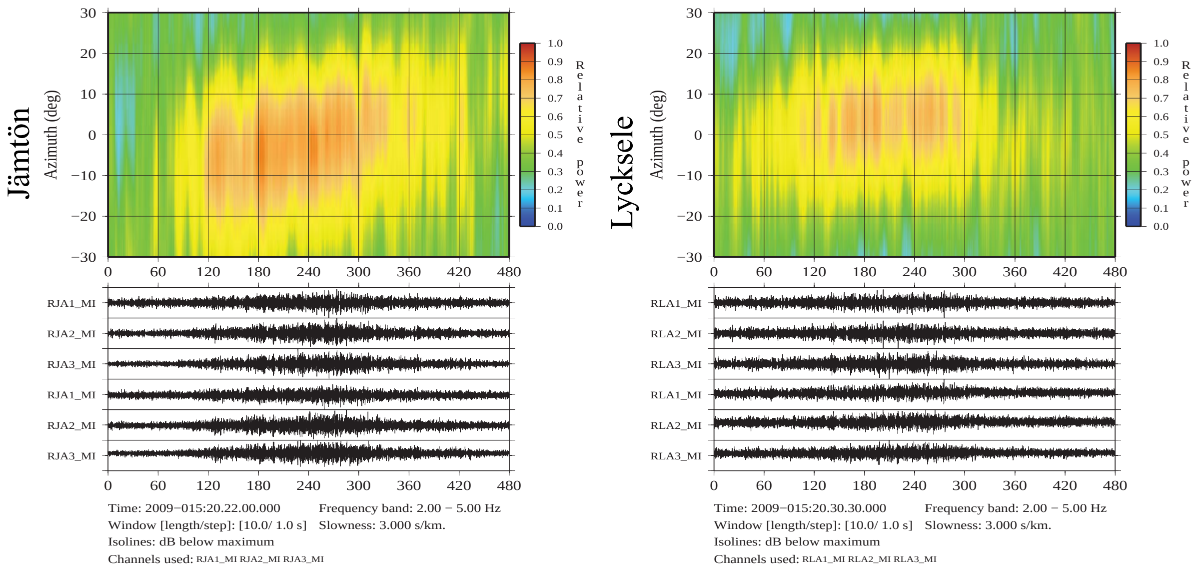

Fig. 6.2.4. Azimuthal vespagrams from analysis of Jämtön and Lycksele infrasound data for the time interval around the signals from the meteor on 15 January 2009. See caption of Figure 6.2.2 for more details.

Table 6.2.1 gives the back-azimuths and apparent velocities for different parts of the infrasound signals, estimated using standard wide-band f-k analysis. The 1 - 4 Hz frequency band was used for ARCES and Apatity, and 2-5 Hz for the IRF arrays. The time windows varied between 10 and 20 seconds.

Table 6.2.1. Estimated back-azimuths and apparent velocities of infrasound signals from the meteor on 15 January 2009

Station	Lat (N)	Lon (E)	Front part of signal			Back part of signal		
			Start time	Baz (^{o})	App. vel (km/s)	Start Time	Baz (^{o})	App. vel (km/s)
ARCES	69.55	25.51	20:05:27	330.88	0.34	20:06.30	329.94	0.35
Kiruna	67.86	20.42	20:11:50	6.18	0.29	20:13:50	8.44	0.30
Sodankylä	67.42	26.39	20:17:30	349.77	0.33	20:19:30	350.06	0.35
Apatity	67.60	32.99	20:23:20	328.05	0.33	20:25:20	327.66	0.34
Jämtön	65.86	22.51	20:24:00	353.54	0.34	20:27:10	0.85	0.35
Lycksele	64.61	18.75	20:32:40	2.43	0.32	20:35:00	5.34	0.33

Compared with analysis of a large number of infrasound signals from a military ammunition demolition site in Finland (Gibbons et. al. 2007), we have found a relatively large variability in back-azimuth estimates. This variability can be caused by several factors, like wind conditions, local noise sources, low SNR or data quality problems. In this study, we have assigned a variability of ± 8 degrees around the average back-azimuth estimates for each station, and the corresponding back-azimuthal sectors from each station are shown in Figure 6.2.5. As indicated in Figure 6.2.5, there is a small area of intersection in the Barents Sea, close to the Finnmark coast.This area is an indication of the source region of the infrasound signals, i.e., where the meteorite exploded.

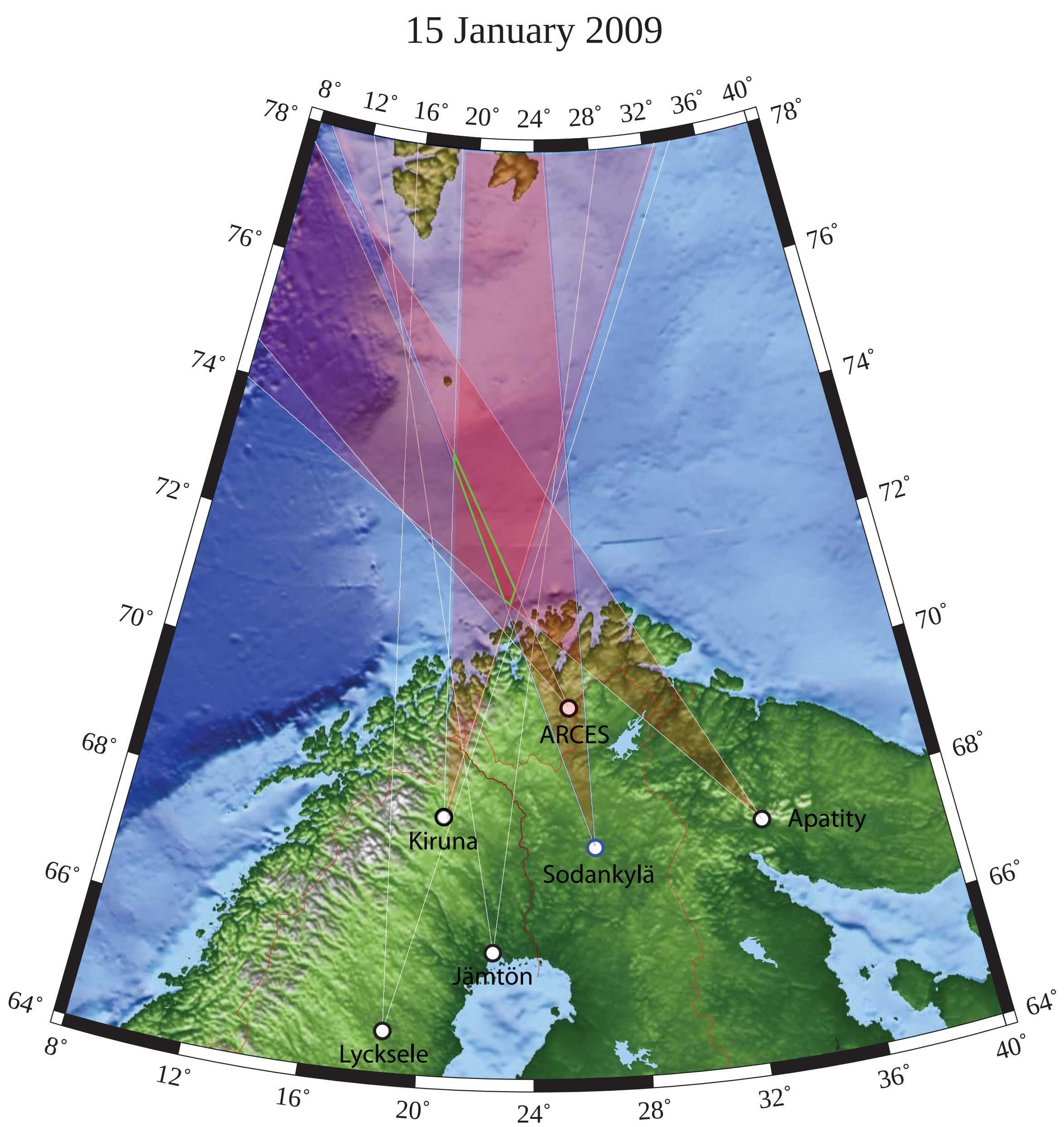

Fig. 6.2.5. Map showing the sectors of back-azimuths of infrasound signals from the meteor as observed at the infrasound stations in Sweden, Finland, NW Russia and Norway. For each station, a sector of ±8 degrees around the average back-azimuth estimate is plotted. The highlighted green polygon shows the area of common intersection. No corrections for the wind field are introduced to the back-azimuth estimates.

Another approach to source location is to use the reported origin time of the event. According to a newspaper report, the origin time of 19:40 GMT was read from the display of a cellular telephone at the time of the meteor observation. This gives us the possibility to calculate the travel-time to each station, which again can be scaled with a standard celerity for stratospheric arrivals of 0.29 km/s to obtain a distance estimate. Table 6.2.2 provide information about the arrival time of the main signal energy at the different stations, the corresponding travel-time and the estimated distance to the source using a standard celerity value of 0.29 km/s.

Table 6.2.2. Distance estimates to the 15 January 2009 meteor explosion at 19:40 GMT

Station	Lat(N)	Lon(E)	Main signal energy	Traveltime (s)	Distance (km) Celerity 0.29 km/s
ARCES	69.55	25.51	20:06:00	1560	452
Kiruna	67.86	20.42	20:13:00	1980	574
Sodankylä	67.42	26.39	20:18:30	2310	670
Apatity	67.60	32.99	20:24:30	2670	774
Jämtön	65.86	22.51	20:26:00	2760	800
Lycksele	64.61	18.75	20:33:30	3210	931

We have in Figure 6.2.6 plotted arcs of the estimated distances from each station, together with the lines of back-azimuth estimates given in Table 6.2.1. The intersection of the distance arcs provide indications of the location of the event, and the white ellipse, with center coordinates 72.1^{o} N, 20.3^{o}E, covers all intersections. In Figure 6.2.6 we have also plotted the area of common azimuthal intersections, also shown in Figure 6.2.5.

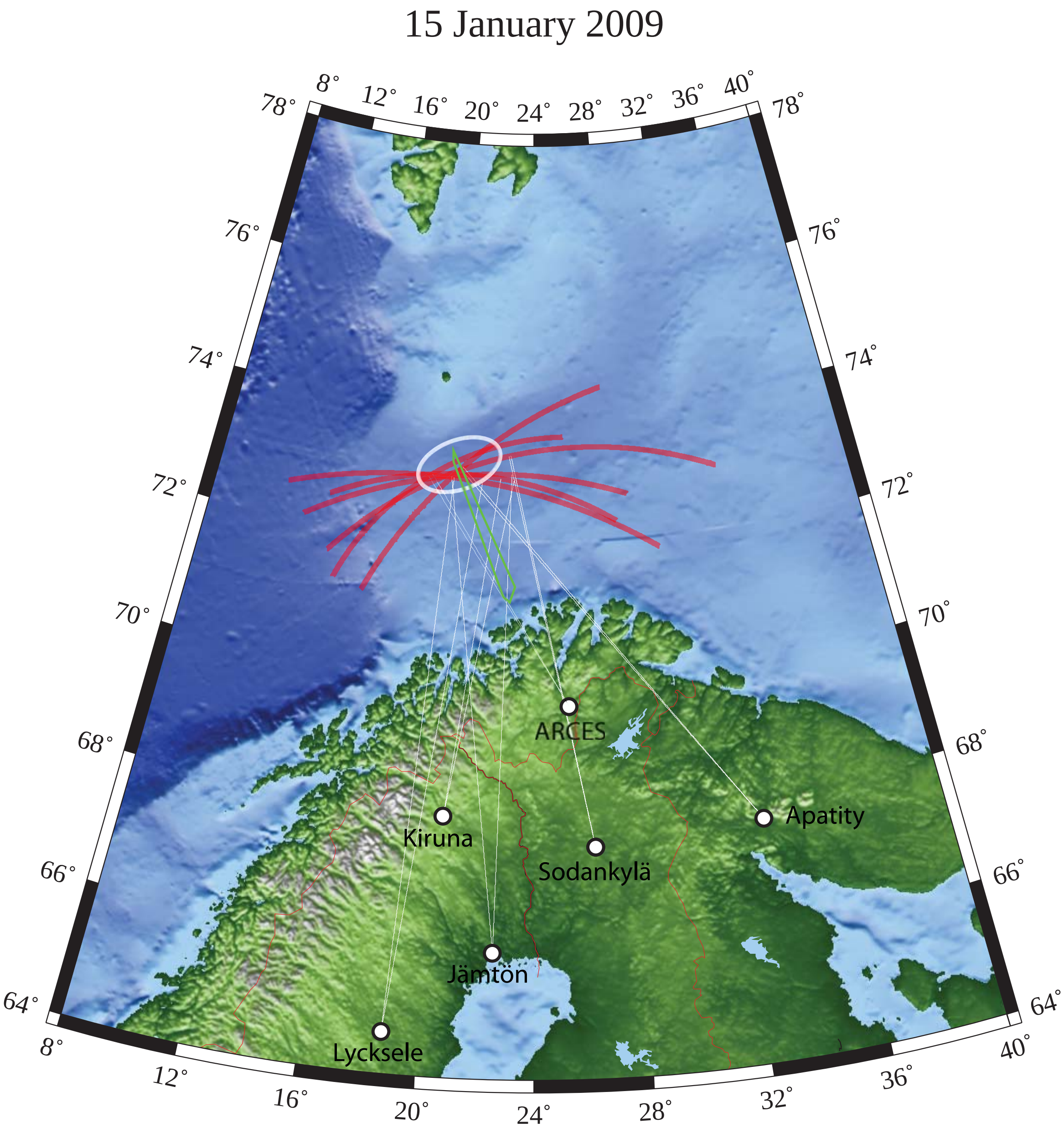

Fig. 6.2.6. Station-source distance estimates are shown as red arcs, and the white ellipse covers all intersection points between the different distance arcs. The center of the ellipse is at 72.1^{o} N, 20.3^{o}E, and indicate the location of the meteor explosion. The green polygon shows the area of common azimuthal intersections, also shown in Figure 6.2.5.

6.2.3 Conclusions

We have estimated the location of the meteorite explosion over the Barents Sea on 15 January 2009 to 72.1^{o} N, 20.3^{o}E. The semi-major axis of the ellipse covering all intersection points between the different distance arcs is approximately 35 km, and indicate the uncertainty of the location estimate. Smaller meteors usually disintegrate at an altitude around 20 km.

We have also demonstrated that several stations show significant deviations in the back-azimuth estimates as compared to the great-circle path to the source, and it is our plan compare these deviations with the observed wind field in the region. In this way it may be possible to correct for wind effects when applying the back-azimuths for location purposes.

It is also interesting to observe that a standard celerity value of 0.29 km/s provides quite consistent distance estimates to the different stations observing the signals.

This latest meteor explosion supplements two previous such observations in Norway during 2006 (Schweitzer and Kværna, 2006). Establishing a database of such events will be important for future studies of infrasound wave propagation.

Acknowledgements

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We thank colleagues at the Kola Regional Seismological Center for providing the infrasound data from the mircobarograph array at Apatity, Russia.

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Tormod Kværna

6.3 Continued overview of system responses for seismic arrays and stations contributing to NORSAR's Data Center

6.3.1 Introduction

This paper continous a series of contributions about system responses of seismic sensors installed by NORSAR (see Pirli and Schweitzer, 2008a; 2008b). As mentioned in these contributions a detailed description of all system responses including copies of the referenced sources is part of a comprehesive documentation available at NORSAR (Pirli, 2009).

In the early 1990s, NORSAR continued its small-aperture array installations by the founding of two new arrays, one situated in Adventdalen on Spitsbergen, Svalbard and one close to Apatity, Kola Peninsula, Russia. The latter is part of an agreement for scientific cooperation between NORSAR and the Kola Science Centre of the Russian Academy of Sciences, represented by the Kola Regional Seismological Centre (KRSC) in Apatity (Mykkeltveit et al., 1992). These two arrays, very similar in design, represent the 'minimum requirement' for an adequate small-aperture installation within the IMS. Their geometry involves 8 sites distributed over 2 concentric rings plus one station in the centre, with an aperture of approximately 1 km. Fig. 6.3.1 shows the geometry of the Spitsbergen array, which is certified as IMS auxiliary station AS72.

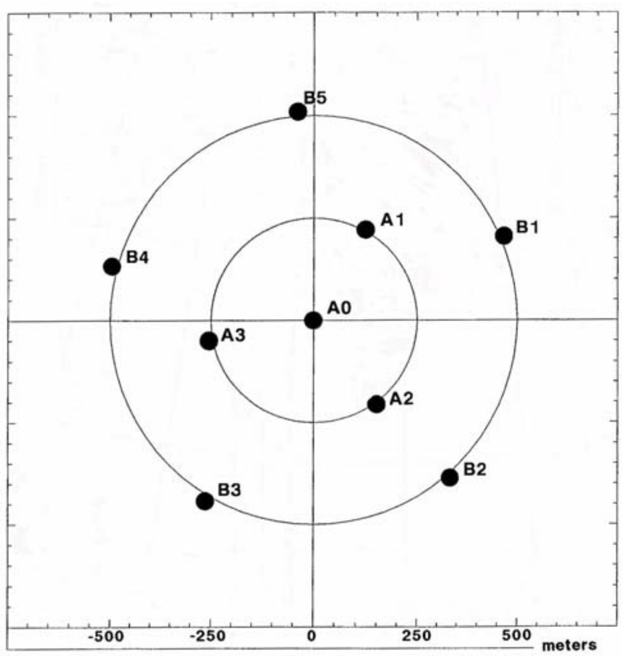

Fig. 6.3.1. Geometry of the Spitsbergen small-aperture array (from Mykkeltveit et al., 1992). The Apatity array has an almost identical geometry.

In 2002, a decision was made for the operation of an IMS auxiliary 3-component station on the island of Jan Mayen. Thus, a broadband station operated by NORSAR (JMIC) 'replaced' the existing Norwegian National Seismic Network station (JMI), which was situated in a nearby location since 1994. The new station was assigned the IMS code AS73 (Fyen, 2003; 2004).

The configurations and instrument responses of the aforementioned systems will be described in the sections that follow, covering their entire operation interval.

6.3.2 Spitsbergen (SPITS) array configurations

The Spitsbergen array was installed in autumn 1992 on the Janssonhaugen plateau, approximately 15 km ESE from the town of Longyearbyen. Initial instrumentation involved Geotech S-500 short-period vertical seismometers, installed in 6 m deep boreholes inside the permafrost (Mykkeltveit et al., 1991), and two Nanometrics RD-6 digitizers (Mykkeltveit et al., 1992; Fyen, 1995). The RD-6 is a gain-ranged, 16-bit, 6 channel A/D converter, with a sensitivity of 610 nV/count. The version installed at the SPITS array employed the following filter sequence:

- 5^{th} order analog low-pass Butterworth filter (f_{3db} = 22.9 Hz)
- Optional 1^{st} order analog high-pass RC filter (f_{3db} = 0.5 Hz)
- Digital low-pass FIR filter (f_{3db} = 16 Hz, N = 68) and
- Digital high-pass IIR filter (f_{3db} = 0.001 Hz)

In August 1994, all S-500 seismometers were replaced with Güralp CMG-3ESP sensors, while the digitizers remained the same. In addition, a 3-component broadband CMG-3TB sensor (borehole version) was placed at site SPB4. Several tests were made by removing and adding the digitizer RC high-pass filter, as well as changing the gain of the channel, resulting in the different configurations listed in Table 6.3.1, each with its identifying Respid flag (see Pirli and Schweitzer, 2008) in parenthesis. The eventually selected configuration for the short-period channels employed a gain of 10x and the analog RC filter, while the broadband channel operated with a gain of 5x (half-gain) and without the RC filter. The CMG-3T sensor was removed in March 2001 and the channel was moved to short-period, continuing to operate with half-gain (5x) and no 0.5 Hz analog filter, as the broadband configuration.

Table 6.3.1. The different instrument configurations of the Spitsbergen array.

Time	Installation Name	Components	Calib [nm/count]	Calper [s]
1992-1994	Initial_SP (SPITSSP1)	S-500 RD-6 digitizer LP Butterworth, analog HP RC, analog LP FIR, digital HP IIR, digital	0.029657	1.00
1994	SP gain 1x (SPITSSP2)	CMG-3ESP RD-6 digitizer LP Butterworth, analog LP FIR, digital HP IIR, digital	0.100410	1.00
1994-2004	SP gain 10x (SPITSSP3)	CMG-3ESP RD-6 digitizer LP Butterworth, analog HP RC, analog LP FIR, digital HP IIR, digital	0.011222	1.00
2001-2004	SP half-gain (5x) at SPB4 (SPITSSP4)	CMG-3ESP RD-6 digitizer LP Butterworth, analog LP FIR, digital HP IIR, digital	0.020081	1.00
1994	BB gain 1x at SPB4 (SPITSBB1, SPITSBB2, SPITSBB3)	CMG-3TB, 3C RD-6 digitizer LP Butterworth, analog LP FIR, digital HP IIR, digital	0.100400	1.00

1994-2004	BB gain 5x at SPB4 (SPITSBB4, SPITSBB5, SPITSBB6)	CMG-3TB, 3C RD-6 digitizer LP Butterworth, analog LP FIR, digital HP IIR, digital	0.020081	1.00
2004-…	Current BB (SPITSBB7, SPITSBB8, SPITSBB9)	CMG-3TB, partly 3C CMG-DM24 digitizer Hardware Sinc filter FIR1 CS5376 FIR2 CS5376 FIR DM24-dec5 FIR DM24-dec5	0.023477*	1.00

* Indicative value

In summer 2004, an extensive refurbishment of the SPITS array took place. Since 13^{th} August, all array sites are equipped with Güralp CMG-3TB broadband seismometers, 6 of them with 3-components (SPA0, SPB1, SPB2, SPB3, SPB4 and SPB5), and CMG-DM24 digitizers. The response of the sensors is flat to acceleration and the parameters describing the transfer function are listed in calibration sheets provided by the manufacturer. Regarding the digitizers, the DM24 (mk3 version) is a full 24-bit A/D converter that employs a 32-bit microprocessor for data storage and manipulation. The system contains the Cirrus Logic CS5376 chipset and TMS320VC33 digital signal processor (DSP) that control data output. The CS5376 chipset (Cirrus Logic, 2001) employs a programmable cascade of digital filters that decimate from an initial input rate of 512 kHz down to 2000 Hz. The exact filter cascade used here is the following:

- A hardware Sinc filter divided into two cascaded sections, Sinc1 and Sinc2:
  - Sinc1 is a fixed 5th order decimate by 8 sinc filter
  - Sinc2 is a multi-stage variable order sinc filter, used here with stages 3 and 4 that both decimate by 2, and are 4th and 5th order filters respectively
- A FIR filter block consisting of two cascaded FIR filters:
  - FIR1 that decimates by 4 and has 48 coefficients
  - FIR2 that decimates by 2 and has 126 coefficients

The outputted 2000 sps data are then forwarded to the DSP that consists of 6 cascaded programmable filter/decimation stages, that can be set individually for decimation factors of 2, 4 and 5 (Güralp Systems, 2006). The filter stages employed in the Spitsbergen array digitizer version are the following:

- FIR filter DM24-dec5, decimating by 5, with 502 coefficients
- FIR filter DM24-dec5, decimating by 5, with 502 coefficients

All filter coefficients are provided in the mentioned documentation, while the sensitivity of the digitizers is equal to 1.7 V/count. It should be noted that the orientation of the horizontal components was corrected on 8^{th} September 2004 and the polarity of the stations on 29^{th} November of the same year (Fyen, 2005).

The displacement amplitude (in count/nm) and phase (in degrees) response for all the SPITS array configurations mentioned above and listed in Table 6.3.1 is depicted in Fig. 6.3.2, according to the corresponding Respid flag. Only vertical component configurations are listed, since the system response is essentially the same for the horizontals, in the case of 3-component instrumentations. Shaded areas represent the range beyond the Nyquist frequency, which is 40 Hz for the current broadband configuration and 20 Hz for all the rest.

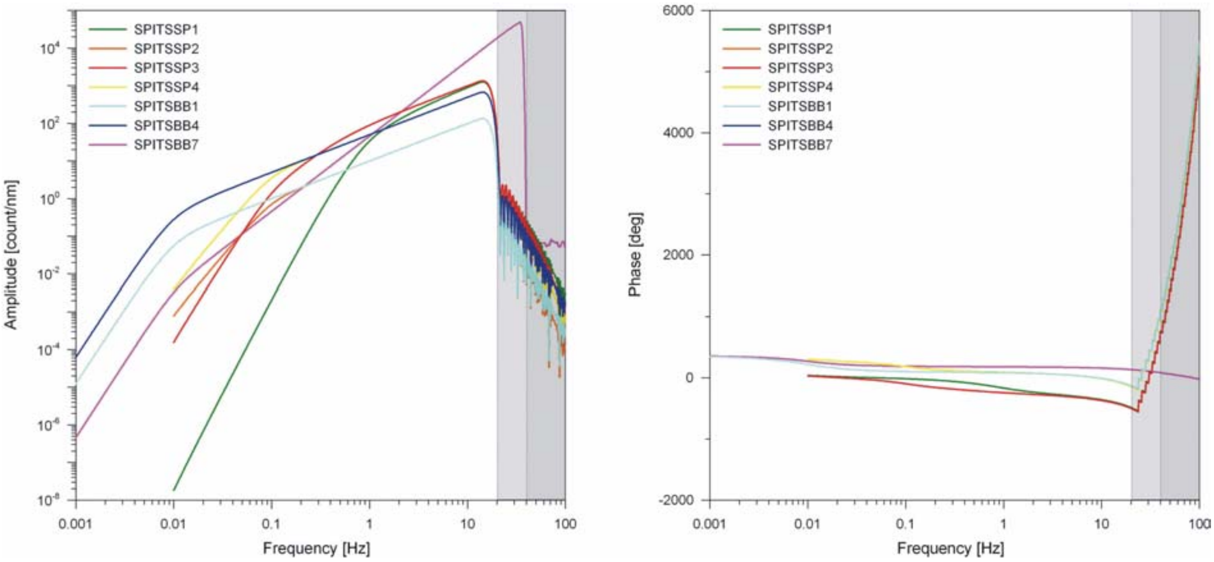

Fig. 6.3.2. Displacement amplitude and phase response for the short-period (SPITSSP1, SPITSSP2, SPITSSP3, SPITSSP4) and broadband (SPITSBB1, SPITSBB4, SPITSBB7) configurations of the SPITS array. The shaded areas represent the range beyond the Nyquist frequency.

6.3.3 Apatity array configurations

The Apatity regional array was installed during fall 1992 on the Kola Peninsula, Russia, approximately 17 km west of the Kola Regional Seismological Centre (KRSC) in Apatity. Like the Spitsbergen array, it consists of 9 sites distributed on two concentric rings, with one element in the centre, covering a diameter of approximately 1 km. All sites are equipped with short-period Geotech S-500 vertical seismometers and Nanometrics RD-3 and RD-6 digitizers, except for the central element, placed in a shallow vault, which additionally carries two horizontal components. All vertical sensors are sampled at 40 sps (short-period channels), while the three seismometers at site A0 are additionally sampled at 80 sps (high-frequent channels). Thus, the vertical sensor of site A0 is sampled both at 40 sps and 80 sps (Mykkeltveit et al., 1992). The S-500 sensors are used with a preamplifier with a gain of 200x.

As already mentioned in the Introduction, the Apatity array was established within the framework of an agreement on scientific cooperation in seismology between NORSAR and the KRSC. This cooperation had actually commenced earlier (June 1991), with the installation of a 3-component station in the basement of the building of the KRSC in Apatity. The original instrumentation involved S-13 seismometers and a Nanometrics RD-3 digitizing unit, but since no data are any longer available this response will not be discussed. Currently, the station is equipped with a Güralp CMG-3T broadband sensor (Mykkeltveit et al., 1992) and the RD-3 digitizer utilizes only the Butterworth low-pass analog filter and the FIR filter (see §6.3.2). Data from this station are routinely used at NORSAR and therefore, since the station is situated far from the Apatity array, it is processed under the name APZ9. A data flow chart that describes the overall Apatity installation is displayed in Fig. 6.3.3.

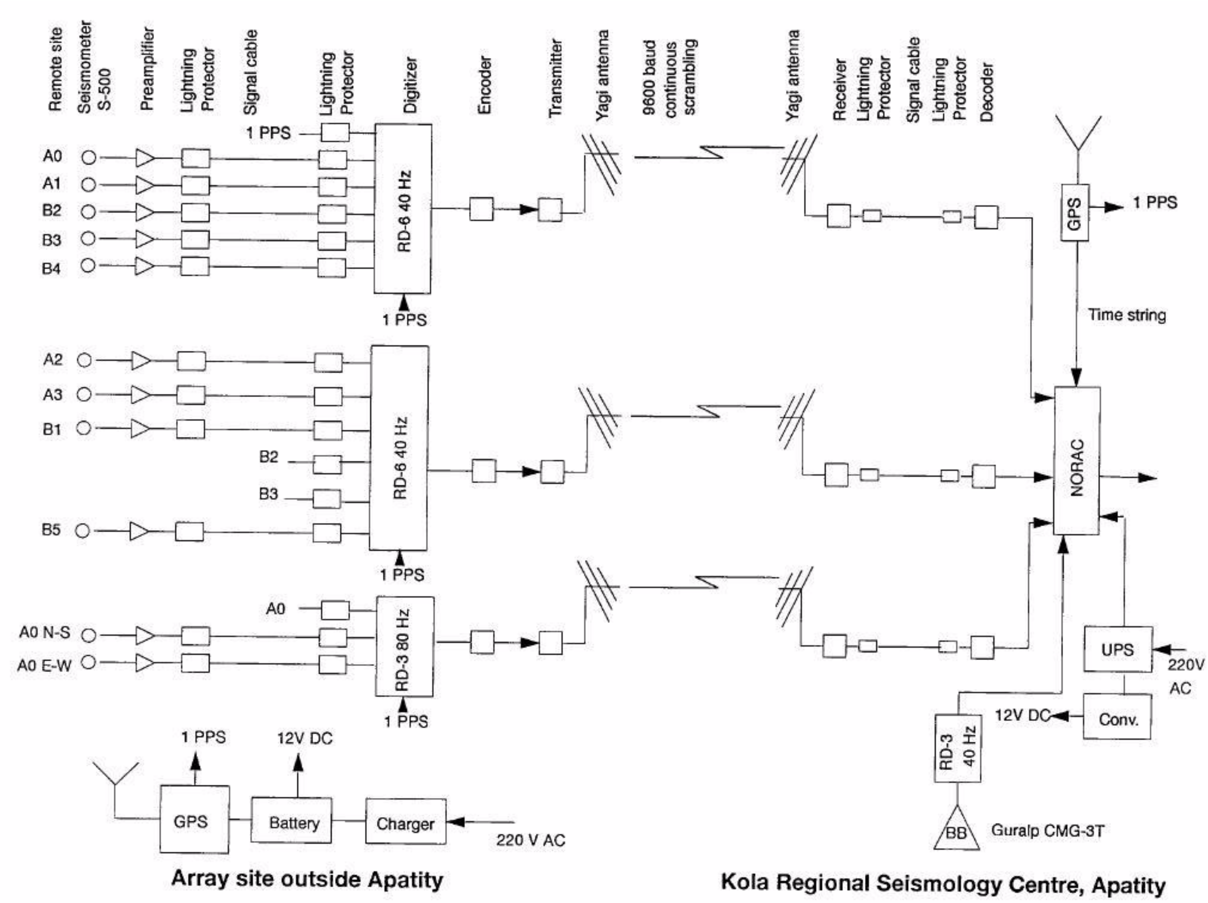

Fig. 6.3.3. Data flow chart for the array and broadband 3-component station in Apatity (from Mykkeltveit et al., 1992). Redundant data acquisition (channels B2 and B3) ensures that data are received even in the case of digitizer or radio channel failure.

The different configurations of the Apatity array and APZ9 station for which the instrument response will be discussed in this contribution are listed in Table 6.3.2, together with their corresponding Respid flags.

The displacement amplitude (in count/nm) and phase (in degrees) response for the Apatity array and APZ9 station configurations listed in Table 6.3.2 is depicted in Fig. 6.3.4. Once again, only the vertical channels are pictured and shaded areas represent the range beyond the Nyquist frequency, which is 20 Hz for the short-period and broadband and 40 Hz for the high-frequency channels.

Table 6.3.2. The different instrument configurations of the Apatity array and APZ9 station.

Time	Installation Name	Components	Calib [nm/count]	Calper [s]
1992-…	Current SP (APASP1)	S-500 RD-6/RD-3 digitizer LP Butterworth, analog HP RC, analog LP FIR, digital 0.008 Hz HP IIR, digital	0.029674	1.00
1992-…	Current HF at APA0 (APA0HH1, APA0HH2, APA0HH3)	S-500, 3C RD-6 digitizer LP Butterworth, analog HP RC, analog LP FIR, digital 0.016 Hz HP IIR, digital	0.028711	1.00
1992-…	Current BB Station APZ9 (APZ9BB1, APZ9BB2, APZ9BB3)	CMG-3T, 3C RD-3 digitizer LP Butterworth, analog LP FIR, digital	0.485280*	1.00

* Indicative value

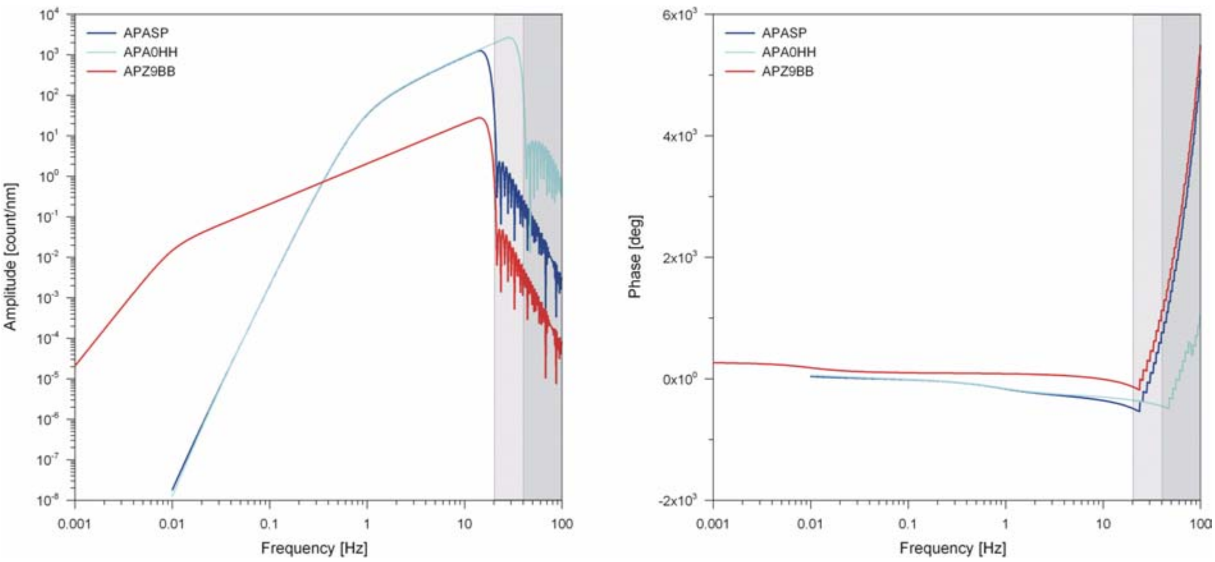

Fig. 6.3.4. Displacement amplitude (left) and phase (right) response for the Apatity array and single 3-component station APZ9 configurations. The short-period array channels (APASP) are noted in blue, the high-frequency APA0 site channel (APA0HH) in cyan and the APZ9 broadband station (APZ9BB) in red. Shaded areas represent the range beyond the Nyquist frequency.

6.3.4 Jan Mayen (JMIC) station configurations

As already mentioned in section 6.3.1, the current JMIC broadband 3-component station on Jan Mayen was installed as part of the IMS in 2003. However, a station (JMI) operated by the University of Bergen (UiB) pre-existed on the island since 1994. From 2000 until its removal in

2004, data were being transmitted to NORSAR, so only a brief reference to its instrument response will be made in this contribution, based on the information provided by UiB.

The JMI station was equipped with a Streckeisen 3-component, broadband STS-2 seismometer and an Earth Data 2433 digitizer, while the current JMIC station also carries an STS-2 sensor and a Europa T digitizer by Nanometrics. These configurations together with the corresponding Respid flags are listed in Table 6.3.3. Details about the differences between the different configurations will be given in the following paragraphs.

Table 6.3.3. The different instrument configurations of the Jan Mayen stations.

Time	Installation Name	Components	Calib [nm/count]	Calper [s]
1994-2004	Old BB, JMI (JMIBB1, JMIBB2, JMIBB3)	STS-2, 3C Earth Data digitizer FIR 1, digital FIR 2, digital	0.106100	1.00
2003	Initial BB, JMIC (JMICBH1, JMICBH2, JMICBH3)	STS-2, 3C Europa T digitizer LP RC filter, analog 3 stage FIR, digital 10 mHz HP IIR, digital	0.018626*	1.00
2004	BB variation, JMIC (JMICBH4, JMICBH5, JMICBH6)	STS-2, 3C Europa T digitizer LP RC filter, analog 3 stage FIR, digital	0.018625*	1.00
2003 2004-…	Current BB, JMIC (JMICBH7, JMICBH8, JMICBH9)	STS-2, 3C Europa T digitizer LP RC filter, analog 3 stage FIR, digital 1 mHz HP IIR, digital	0.018625*	1.00

* Indicative value

The STS-2 is a very broadband triaxial seismometer that uses 3 identical obliquely-oriented mechanical sensors instead of the traditional separate orthogonal vertical and horizontal sensors. This design (Fig. 6.3.5) favors the standardization of manufacturing and guarantees the closest possible matching of the vertical and horizontal components.

Thus, the sensitive axes of the three sensors are inclined against the vertical like the edges of a cube standing on its one corner, by an angle of arctan ($2^{1/2}$) = 54.7°. Most frequently, the Z, N-S and E-W components of the ground motion are desired, so the oblique components W, V and U of the STS-2 are electrically recombined according to the formula:

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \frac{1}{\sqrt{6}} \begin{pmatrix} -2 & 1 & 1 \\ 0 & \sqrt{3} & -\sqrt{3} \\ \sqrt{2} & \sqrt{2} & \sqrt{2} \end{pmatrix} \begin{pmatrix} U \\ V \\ W \end{pmatrix}, \quad (6.3.1)$$

where normally the X axis is oriented towards the East and the Y axis towards the North. The orthogonal output signals are factory-adjusted to represent motions in these geometrical X, Y and Z axes with an accuracy of 1% at a period of 6 s (Streckeisen, 2003; Wielandt, 2002).

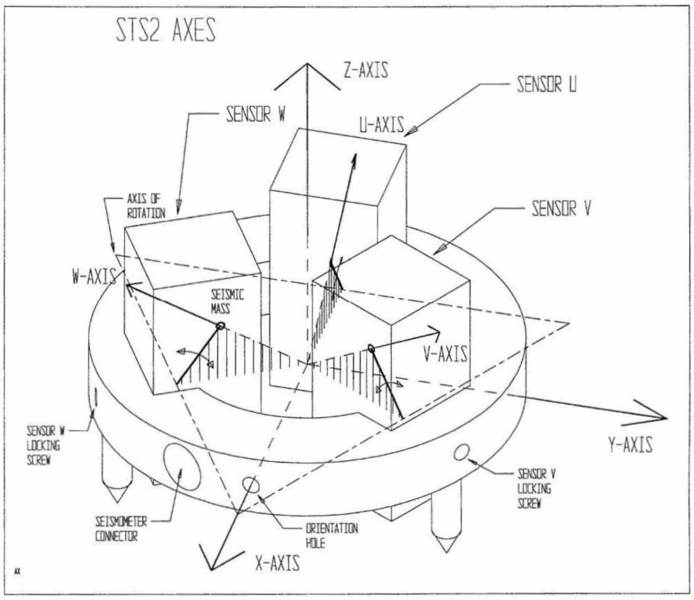

Fig. 6.3.5. A schematic representation of the axes positioning of the STS-2 seismometer (Streckeisen, 2003).

The transfer functions can then only be attributed to the individual U, V and W sensors and not to the X, Y, Z outputs. A method to calibrate the instrument is to calibrate the U, V and W sensors separately, by using for instance the Z output, and then to average the U, V and W transfer functions or parameters with a matrix whose elements are the squares of those of the matrix in equation 6.3.1 (Wielandt, 2002; Wielandt a2d Widmer-Schnidrig, 2002):

$$\begin{pmatrix} T_X \\ T_Y \\ T_Z \end{pmatrix} = \frac{1}{6} \begin{pmatrix} 4 & 1 & 1 \\ 0 & 3 & 3 \\ 2 & 2 & 2 \end{pmatrix} \begin{pmatrix} T_U \\ T_V \\ T_W \end{pmatrix} \quad (6.3.2)$$

Regarding the response of the seismometer to ground motion, at low frequencies below 1 Hz the STS-2 can be considered as a long-period, velocity transducer, 3-component instrument with a free period of 120 s, damping of 0.707 and a generator constant of 2 x 750 V/m/s. In the frequency band between 1 and 10 Hz the velocity response is flat, with a nearly constant group delay of about 3 1 ms. The flat velocity response extends a little bit beyond 50 Hz, however the overall response at high frequencies depends also on the coupling of the seismometer to the ground, which may influence the amplitude and phase of the transfer function, but not the signal delay time. There are 3 different generations of STS-2 seismometers and each has a different high-frequency velocity response both for the amplitude and the phase (Streckeisen, 2006).

In the case of JMIC, a High-Gain, Generation 3 instrument with serial number 30234 is installed. Its particular characteristics are the following:

Generator constant values for X, Y and Z: 20000 200 V/m/s

Poles (10):	Zeros (4):
-1.33×10^4	$-463.1 \pm j\, 430.5$
$-1.053 \times 10^4 \pm j\, 1.005 \times 10^4$	-176.6
-520.3	-15.15

-374.8
-97.34 +/- *j* 400.7
-15.64
-0.037 +/- *j* 0.037

'Mixer pole':
$\omega_{mix} = -2 \pi 40.6$

To obtain the poles and zeros values to be used for each component, the above mentioned information needs to be combined with equation 6.3.2, while instrument specific information are provided by Streckeisen:

The generator constant values and orientations of the three different sensors are:

- Sensor U: G/G0 = 1.0702 theta = 54.397° phi = 179.89°
- Sensor V: G/G0 = 1.0614 theta = 54.375° phi = 59.923°
- Sensor W: G/G0 = 1.0653 theta = 53.975° phi = 299.93°

where G/G0 is the normalized generator constant, which is equal to the actual constant divided by 20000 V/m/s. Regarding the poles and zeros, the response is divided into a high-frequency (1-100 Hz) and a low-frequency (0.00586-0.10547 Hz) end.

High-frequency end

4 zeros [Hz]:

- Sensor U: -73.50 +/- *j*68.29 -29.88 -2.411
- Sensor V: -73.50 +/- *j*68.29 -29.28 -2.411
- Sensor W: -73.50 +/- *j*68.29 -30.02 -2.411

9 poles [Hz]

- Sensor U: -1629.7 +/- *j*433.7 -1514 +/- *j*1825.5 -72.34 -2.46 -14.35 +/- *j*62.65 -74.615
- Sensor V: -1629.7 +/- *j*433.7 -1514 +/- *j*1825.5 -72.34 -2.45 -14.22 +/- *j*63.12 -72.87
- Sensor W: -1629.7 +/- *j*433.7 -1514 +/- *j*1825.5 -72.34 -2.45 -13.67 +/- *j*63.39 -74.494

Low-frequency end

The model fits a 2^{nd}-order high-pass filter with the following corner periods (in s) and damping constants:

- Sensor U: 120.29 s 0.7048
- Sensor V: 120.32 s 0.7030
- Sensor W: 120.33 s 0.7045

Regarding the Earth Data digitizer used at the old JMI station, its response is described by the following succession of digital FIR filters, as reported by UiB:

- FIR filter (asymmetric) with 240 coefficients, decimating by 4 down to 0.75 kHz from an input rate of 3000 Hz
- FIR filter (symmetric, even number of coefficients) with 640 coefficients, decimating by 10 down to the desired sampling rate of 75 Hz.

The sensitivity of the digitizer is reported to be equal to 1000000 count/V.

The Nanometrics Europa T digitizer, employed at the JMIC station, is an A/D converter especially designed for CTBT purposes, to provide authenticated data to the acquisition centre. It is a 3-channel digitizer with 24-bit resolution and a dynamic range of 142 dB. In the case of JMIC, the following filters are employed:

- 1st order RC low-pass analog filter
- Decimating low-pass digital FIR filter in 3 stages
- DC removal digital IIR filter

Details about the filter characteristics can be found in the digitizer's User's Guide and the related GSE response files. It has already been mentioned that several tests were made with the IIR filter, which resulted in the different configurations of Table 6.3.3. Initially, a 10 mHz IIR filter was employed (JMICBH1,2,3), and then two tests were made without using the filter at all (JMICBH4,5,6). Eventually, it was decided to use a 1 mHz IIR filter (JMICBH7,8,9).

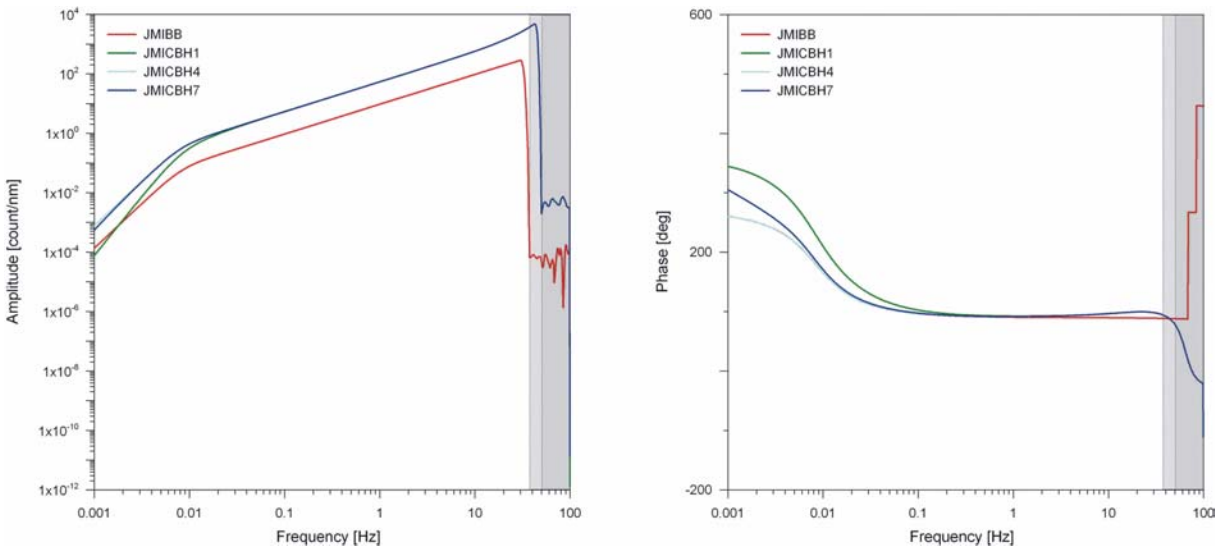

Fig. 6.3.6. Displacement amplitude (left) and phase (right) response for the JMI and JMIC 3-component broadband station configurations. The JMI response (JMIBB) is noted in red, the 10mHz IIR filter version of the JMIC station (JMICBH1) in green, the 1mHz IIR filter version of JMIC (JMICBH7) in blue and the JMIC version without any IIR filter (JMICBH4) in cyan. Shaded areas represent the range beyond the Nyquist frequency.

The Europa T digitizer is used with a gain of 0.4 and the data are sampled at 100 Hz. The sensitivity of the instrument is equal to 1000000 count/V.

The displacement amplitude (in count/nm) and phase (in degrees) response for the configurations of JMI and JMIC described in the previous paragraphs is depicted in Fig. 6.3.6. Only the vertical component case is presented, while shaded areas cover the range beyond the Nyquist frequency (37.5 Hz for JMI and 50 Hz for JMIC).

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6.4 Seismic arrays in Earthquake Early Warning Systems (EEWS)

6.4.1 Introduction

Main parts of the following contribution were compiled during NORSAR's participation in the SAFER project, which is mainly funded under the Sixth Framework Programme of the European Commission (Project Number 036935). Within this project, NORSAR investigated the application of array techniques to EEWS installations. In the following, some results of this study are documented.

A seismic array can be described as a set of seismic sensors with common time base and instrumentation. The data of such an installation are then usually analyzed together by applying the well known algorithms fk-analysis and beamforming. The advantage of applying seismic array techniques in EEWS is connected with the capability of an array not only to observe a seismic signal but also to measure its propagation direction and apparent velocity. Moreover, during the last four decades, arrays also played a very important role in many basic studies about the Earth. However, the capability of an array to measure the backazimuth (BAZ) and apparent velocity with sufficient accuracy and to suppress other than the target signals is very much depending on the array geometry and the number of its sensors. Therefore, not each array is equally suitable for an Earthquake Early Warning System (EEWS). Further details about array geometries and their characteristics can be found *e.g.*, in Douglas (2002), Rost & Thomas (2002) or Schweitzer *et al.* (2002).

In the beginning, we briefly discuss the development of event-location techniques with seismic arrays and the contribution of arrays to fast event location. Then, we will focus on the usage of seismic arrays as EEWSs in general, and in particular on real-time algorithms and discuss the advantages and disadvantages of applying array-analysis techniques as input for any EEWS.

6.4.2 Locating seismic events with arrays

As already mentioned, seismic arrays not only observe amplitudes and onset times of seismic signals, but can also measure their corresponding apparent velocities and BAZs. The latter two parameters are essential in locating the source of observed seismic onsets and thereby locating the seismic event.

Teleseismic event location

Benndorf (1906; 1907) published that in the case of a spherically symmetric Earth model apparent velocities (or the seismic ray parameters) are constant along their whole ray path through the Earth (Benndorf's Law). If the velocities inside the Earth are known, it can easily be shown that the ray parameter of seismic onsets changes with the epicentral distance and that an observed ray parameter (or apparent velocity) can directly be inverted for the epicentral distance. For modern spherically symmetric Earth models and seismic arrays of at least 10 km aperture, this principle works fine for first arriving P-type onsets from seismic events at teleseismic distances (*i.e.*, from about 25° to about 100° epicentral distance). Events at shorter distances are hard to locate because the derivative of the apparent velocity with respect to distance is very small and triplications of the travel-time curve do not allow for a unique correspondence between apparent velocity and distance. At distances beyond the Earth's shadow zone, the interpretation of the different core-phase onsets is also quite difficult and limits the location capabilities of a seismic array. Knowing the epicentral distance, the observed BAZ can then be used to define the epicentral coordinates.

The described event location technique has been in use at least since the 1960s and a quick look in the bulletins of the International Seismological Centre shows the huge amount of reported teleseismic event locations made with e.g., the Large Aperture Seismic Array (LASA) in Montana, USA, the Yellowknife Array (YKA) in Northern Canada, the Gräfenberg Array (GRF) in Bavaria, Germany or the large Norwegian Seismic Array (NOA) in Southern Norway. All results of the automatic array processing of the NOA array can be found at http://www.norsardata.no/NDC/bulletins/dpep.

Regional arrays

As mentioned, the inversion of an apparent velocity into an epicentral distance does not work for local or regional distances, as observed apparent velocities of direct phases are not changing with epicentral distance. However, the apparent velocities are usually different for the different local and regional seismic phase types, Pg, Pn, Sn, or Sg. Therefore, the observed apparent velocity of a seismic onset can be used to characterize the seismic phase.

In the case that different seismic phases from the same seismic event are observed, the travel-time differences between the different phases can be used to determine the epicentral distance and with the observed BAZ the event can be located. This approach was already used by Abt (1907) in the case of teleseismic events. First, he was making apparent velocity and BAZ measurements and then he used the travel-time difference between the first P- and the first S-phase onset, for which the distance dependence was better known, to define the epicentral distance and together with the BAZ he determined the location of the event.

Early seismic arrays were built with an aperture and configuration favorable for teleseismic observations and they were not optimized to handle observations from regional or local events. Therefore, the concept of small-aperture arrays with apertures of only a couple of kilometers was developed in the early 1980s and firstly tested with the NORES array, collocated with one of the NORSAR array sites (Mykkeltveit *et al.*, 1983).

Routine processing of small-aperture array data at NORSAR

For the NORES array, a three step data-analysis and event-location algorithm (called RONAPP) was developed (Mykkeltveit & Bungum, 1984), which utilizes the aforementioned combination of phase identification and travel-time difference measurements and which is in principle the base for many of today's installed small and middle aperture event-location algorithms. This so-called DP/EP automatic array data analysis algorithm was further developed at NORSAR during the last decades (Fyen, 1989; 2001a; 2001b; Kværna & Doornbos, 1986; Kværna & Ringdal, 1986; Mykkeltveit & Bungum, 1984; Ødegaard *et al.*, 1990; Schweitzer, 1994; 1998; 2001b; 2003b; Schweitzer & Kværna, 2006; Schweitzer *et al.*, 2002) and can shortly be described as a three step process:

- Detection Processing (DP), *i.e.*, performing STA/LTA triggering on a number of predefined beams;
- Signal Attribute Processing (SAP), *i.e.*, performing signal feature extraction of detected signals; and

- Event Processing (EP), *i.e.*, performing phase association, event location and event plotting based on the RONAPP processing (Mykkeltveit & Bungum, 1984).

A detailed description of these processing steps can be found in Schweitzer *et al.* (2002) and results of the automated regional array processing at NORSAR can be found at http://www.norsardata.no/NDC/bulletins/dpep.

Network of arrays

It became very soon obvious that the location precision of single small aperture arrays is quite limited. After building up a network of small aperture arrays in Northern and Central Europe during the late 1980s and early 1990s, a joint interpretation of observations from several small-aperture arrays could be tested. One successful approach became the Generalized Beam Forming (GBF) location algorithm. This algorithm developed at NORSAR can automatically utilize the results of several seismic arrays in a common bulletin (Ringdal & Kværna, 1989; Kværna *et al.* 1999). Today, data from the highly sensitive regional arrays ARCES, FINES, HFS, SPITS, and NORES, and the teleseismic NORSAR array (NOA) are automatically processed in on-line mode applying this regional and local event-location process (http://www.norsardata.no/NDC/bulletins/gbf).

6.4.3 Contributions of arrays to fast event locations

Single array results

As already discussed, it is possible to locate seismic events with data observed by one or more seismic arrays. However, in the case of any fast event location algorithm array analysis can only contribute if the whole data processing is automated. On the other hand, the recorded data volume is very large, thus requiring automated data processing techniques. Therefore, array data processing algorithms were as much as possible automated since the 1960s. For example, the program package used for the NORSAR array was mostly developed in the 1970s and 1980s and later adapted to many other array installations (Fyen, 1989; 2001a; 2001b).

After international exchange of emails was becoming more reliable and common in the early 1990s, it became possible to report event locations or strong P-phase observations based on fully automatically data processing algorithms. Thereby, results from the NORSAR, YKA, or the GERES array were automatically sent to *e.g.*, the USGS for its Quick Epicenter Determinations (QEDs), the European-Mediterranean Seismological Center (EMSC), the Swiss Seismological Service (SED), and the wider interested seismological community.

The Fast Earthquake Information Service (FEIS) algorithm

At the University of Bochum a special alert system was developed in the early 1990s, which combined the mentioned single array observations with recordings of the newly at that time installed German Regional Seismological Network (GRSN). The so-called Fast Earthquake Information Service (FEIS) algorithm (Schulte-Theis *et al.*, 1995; Harjes *et al.*, 1996) was triggered by strong local or regional events observed by the GERES array. For this, the data of the regional GERES array were automatically analyzed in real time by applying the DP/EP array software developed at NORSAR (Fyen, 1989; 2001a; 2001b). After each automatic GERES location with a local magnitude above 3.0, the FEIS algorithm was triggered, consisting of the following steps:

- recalculation of an initial location from the GERES data alone;
- calculation of theoretical onset times for regional phases (Pn, Pg, Sn, Sg) at all GRSN stations;
- polling of all GRSN-detection lists via telecommunication lines for a larger time interval around the assumed arrival times;
- searching a small time interval around the theoretical onset times for Pg or Pn detections, depending on the epicentral distance;
- in the case that a P-type phase could be associated, the detection lists were searched for possible S-type detections in a distance-depending predefined time window;
- relocation of the event with the GERES-observation parameters (phase names, onset times, BAZs) and the applicable GRSN detections;
- in the case of a stable location result, the determined location was distributed automatically via email about 30 minutes after the event as FEIS-alert to the EMSC or other interested addresses in Europe.

A comparison with PDE (USGS) locations indicates that the automatic FEIS-relocation procedure significantly improved the automatically achieved location accuracy, in particular for these events which occurred within the GRSN.

NORSAR's Event Warning System (NEWS)

Since 2000, a new quick event-location system was developed at NORSAR to provide fast and reliable solutions in the case of strong events: NORSAR's Event Warning System (NEWS) (Schweitzer, 2003a). The whole NEWS system is based on high Signal-to-Noise Ratio (SNR) detections; whenever one of the contributing arrays observes a P-type onset with an SNR larger than a predefined threshold, the NEWS process is initialising.

Once triggered, the NEWS process searches the automatic result lists of all other available arrays for corresponding onsets. Corresponding in this context means that the other onsets have to come from a backazimuth, and with an apparent velocity, which is consistent with the triggering onset. Formulating robust rules, for which onsets can eventually be associated with the same event, was a quite cumbersome procedure. However, as implemented today, these rules are built on travel-time differences between the onset times at the different stations, measured backazimuth and apparent velocity of the signals, and SNR of the onsets. In the case of a presumably local or regional event, NEWS also searches for S-type onsets in the onset lists of the arrays.

Source location with the NEWS algorithm

After all available lists are searched the NEWS process locates the seismic event. To make this automatic event location as robust as possible, onset times and apparent velocity values are only used from first P and S arrivals. However, to use as much as possible information from the seismic arrays, all onsets in compliance with the selection rules and the measured backazimuth values are used to locate the event. Depending on the mean apparent velocity of all detected P onsets, the program defines the event as probably regional, or as near, far or very far teleseismic. Then, together with the mean backazimuth estimation, an initial source region is chosen. Depending on this initial solution, either a regional or a global velocity model is used to locate the event. The observed P amplitudes can be used to calculate an event magnitude.

For the determination of the source parameters NORSAR's location program HYPOSAT (Schweitzer, 2001a) is used. With the limited amount of data available for locating the event, the event's depth cannot be resolved and has therefore to be fixed to a predefined value. However, until now, such preliminary locations have been sufficient for preliminary information to the public in the case of local or regional events.

In the case of teleseismic events, the NEWS reports are often listed together with only a few other alert-messages from distributing institutes on the Real Time Seismicity Page of the EMSC (http://www.emsc-csem.org/Welcome.html) and thereby help the EMSC to locate such events more accurately.

Although the used network of seismic arrays has an aperture of about 18 degrees in the north-south direction, teleseismic events are usually observed over only a very small azimuth range. Therefore, the small number of available observations produces solutions with limited accuracy and large error bars, and some events are even not locatable. This is in particular true for events in the South Pacific, for which only PKP-type onsets can be observed.

Dissemination of NEWS results

On average, NEWS solutions are available between a few and up to about 10 minutes after the first P onsets have been recorded at one of the seismic arrays. Since January 2001, a listing of the most recent NEWS solutions has been available on the web (http://www.norsar.no/bulletins/alert/). In summer 2002, NORSAR started to send the NEWS solutions to interested data centers, which also work on quick epicenter determinations in Europe, such as the EMSC in Bruyères-le-Châtel, France and the European data center for broadband data ORFEUS in De Bilt, The Netherlands. Since summer 2007, NEWS alerts for events observed with magnitudes larger or equal to 6.0 are also automatically reported to World Agency of Planetary Monitoring and Earthquake Risk Reduction in Geneva, Switzerland and since summer 2008, the NEWS alerts are also going to the International Seismological Centre (ISC) in Thatcham, UK.

The delay of several minutes between the source time and the dissemination of source parameters of regional events by today's NEWS implementation is due to several factors:

- usually, the distance between a seismic event and the closest array recording it is on the order of several hundreds of kilometers
- it takes several additional minutes until other arrays of the sparse network of arrays in Northern Europe can record the event;
- to achieve a more stable solution for the event location the NEWS algorithm is implemented in such a way that it also waits for possible S-type onsets;
- the location algorithm HYPOSAT (Schweitzer, 2001a) used for locating the event is not yet optimized for short computation time.

6.4.4 Usage of seismic arrays to monitor an EEWS relevant site

With its unique capability to measure not only onset times and amplitudes, but also BAZs and apparent velocities of seismic onsets, an array gives us several possibilities to locate an event. The only question is, which algorithm and data processing scheme should be used to provide quick locations for an EEWS. Working with the above mentioned methods and software packages, one can conclude that with today's computer capacities the most critical parameter for using seismic arrays in an EEWS is the epicentral distance to the array installation(s).

All discussed algorithms are on today's computers so fast that the actual calculation times for the different algorithms do not really contribute to EEWS delays. More important are the actual transmission times of seismic signals since all data connections algorithms work with data frames containing a specific amount of data. The delay time between the actual recording of a signal and its arrival at a data center can vary between seconds and minutes and has to be added to the EEWS times achievable by the discussed location algorithms.

The single array case

In the case of single array locations at local or near regional distances, the travel-time difference between source and arrival time of the first P phase is in the order of tens of seconds for local or near regional events. Additional tens of seconds will be needed to record the first S-onset, necessary for calculating the epicentral distance.

Therefore, such an array used as an EEWS tool will most likely need more time to locate the event than a traditional seismic network installed in the area of interest. The situation changes in many cases where several seismic active areas or a longer tectonic fault contribute to seismic hazard. Dense, local networks cannot be installed at all places and in particular if more remote or off-shore located zones contribute to a hazard scenario, single array installations can contribute, within a few minutes, with quite reliable event locations for all events within some hundred kilometers epicentral distance. However, as shown by Gibbons *et al.* (2005), a single array can be tuned for a specific target area and the resulting location precision can become as high as that of a local network, assuming that sufficient calibration information is available. This is in particular of interest in the case of monitoring aftershock sequence of a very large earthquake.

A single array and a sparse national network

In the case that data from an array and additionally a national or local network are available, a FEIS-type algorithm can be used. Knowing the BAZ and apparent velocity of the first P-type onset directly gives information about the direction in which the event occurred and if it was at a local or a regional distance. For regional events, the first P onset should have an apparent velocity typical for Pn phases and for local events typical for Pg onsets, respectively. With this information, the array result for the first P onset directly indicates, which single station records should be added to achieve a fast and reliable event location.

An EEWS based on a single array and a sparse network can provide a first, quick and reliable event location within the first minute after the event occurred as long as one of the network stations is located as close as the array or closer to the event.

Multiple array configuration

In the case of observations from two or more arrays, a GBF- or NEWS-type algorithm can be implemented. Recording one onset from each array with a BAZ estimate is already sufficient to locate the source area. If the target fault zone is located between two arrays, which have a distance of about 200 km from each other, such an installation is sufficient to locate the main shock and the whole aftershock sequence on the fault zone within about 30 seconds. Events, which are not located between the two arrays, will be located within 20 s plus the absolute travel time of the first P onset to one of the arrays.

This scenario of course assumes that the data of the two arrays are available in real time for the automatic array processing software (DP/EP). The location capabilities will increase with a larger number of small-aperture arrays. In such cases, different arrays may be combined to monitor different target areas.

Johannes Schweitzer

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6.5 Seismometer and digitizer tests at NOA subarray NC6

6.5.1 Introduction

CTBTO intended to perform an instrument test for several Guralp and Nanometrics broadband sensors and digitizers. NORSAR offered to provide the experimental setup and the data collection at the NOA subarray NC6. The site has all the necessary infrastructure and is connected via landline and broadband to NORSAR. The experiment started in the beginning of August 2008, and lasted until the beginning of December 2008. We forwarded all data to CTBTO for detailed analyses. In the following we give a brief overview on the setup and some data examples.

6.5.2 Instruments and experimental setup

From CTBTO we received five Guralp CMG-3T seismometers, two Nanometrics Trillium 240 seismometers, seven Nanometrics Europa T digitizers inclusive GPS antennae and one Linux PC for data acquisition. We expanded the instrument pool with one Guralp CMG-3ESPC seismometer, one Streckeissen STS2 seismometer, seven Guralp DM24 digitizers inclusive GPS antennae and one low-power industrial Windows PC (PIP10).

We installed the sensors and digitizers in the long-period vault of NC6. Figure 6.5.1. shows a pit with five CMG-3T, two Trillium 240 and the CMG-3ESPC; the STS2 is in another pit about 1.5 meter away. The pit was covered with a styrofoam lid for thermic insulation. The right hand side of Figure 6.5.1. shows the shelf with the Guralp and Nanometrics digitizers, the DC-power distribution box and the industrial PC. There are no active AC power supplies in the vault during normal operation. The power distribution box is connected to DC and only DC/DC-converters are in use. The DM24s are connected via serial cables to a serial-to-USB module, which in turn is plugged into the fan-less low-power industrial PC. The PC as well as the Europa T digitizers are connected directly via 3 hubs to a local network.

Figure 6.5.1. Left: One of the three pits in the Long-Period Vault (LPV) of the NOA subarray NC6. Right: Shelf with data acquisition equipment.

Data from Guralp digitizers were sent via a Scream server that runs on the PIP10 to a client computer at the NDC, where they are stored in Guralp GCF-format. Additionally we were running Scream2cd1 servers on the PIP10 to forward the data to a cd1.0-receiver at the NDC. CD1.1 data from Europa T digitizers were forwarded to the Linux computer outside of the LPV. On this machine we were running SSI-software to send the data in cd1.1-format to the NDC. At the NDC the cd1.x-data are subsequently converted and integrated into a CSS-database. Due to some performance issues with SSI, we changed the data forwarding to Nanometrics Naqstocd1.1 software after a while.

Figure 6.5.2. shows the transfer functions of the different sensors. The STS-2 is the sensor with the highest sensitivity (20000 V/(m/s)). The STS-2 and the Trillium 240 have a high-frequency amplification, whereas the Guralp sensors have a simpler flat transfer function. The transfer functions and the digitizer-specific sensitivities are used to compute instrument-corrected true ground velocities.

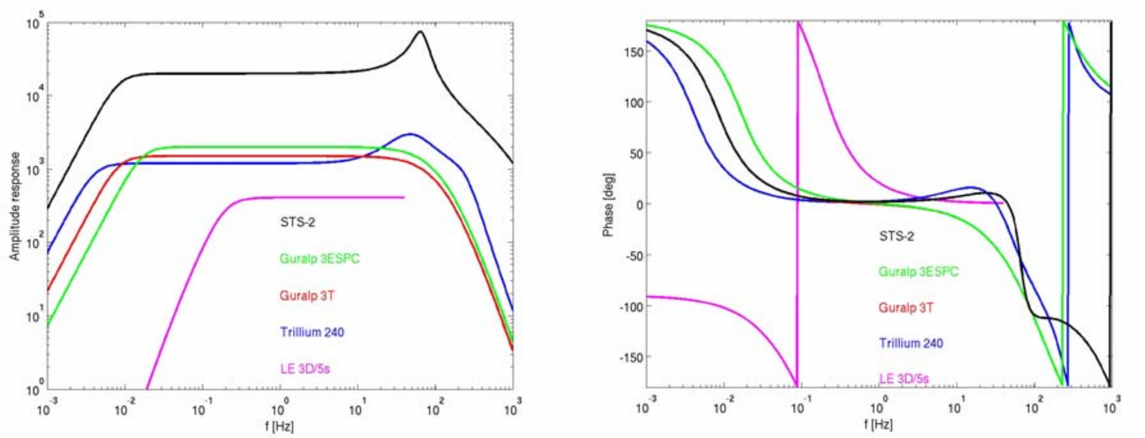

Figure 6.5.2. Transfer functions of the different sensors. Left: Nominal amplitude response in units of V/(m/s). Right: Nominal phase responses.

6.5.3 Determination of instrument noise

In order to determine the instrument noise we are following the approach of Szekely et al. (2007) originally developed by Holcomb (1989). In case of a side-by-side configuration seismic sensors are subjected to the same ground motion. In the frequency domain we have

$$P_{11} = |H_1|^2 \, [X+N_1] \tag{1}$$

$$P_{22}=|H_2|^2 \, [X+N_2] \tag{2}$$

$$P_{12}=H_1 H_2^* \, X \tag{3}$$

where P_{11}, P_{22} and P_{12} are the power spectral densities (PSD) for system 1 and 2 and cross-spectral density between the systems outputs, respectively. H_1 and H_2 are the transfer functions of the systems, X is the power spectral density of the common input to the sensors, and N_1 and N_2 are PSDs of the channel noise. If one assumes equal levels of noise power $N= N_1 = N_2$

(even though statistically independent for the two systems) and introduces the coherence function

$$C^2=|P_{12}|^2/(P_{11}P_{22}), \quad (4)$$

the channel noise can be computed using:

$$N=P_{12}/(H_1H_2)\ (1/C^2-1). \quad (5)$$

6.5.4 Application to selected data examples

Over the experimenting period various sensor/digitizer configurations have been used. Table 6.5.1. shows the configuration for the time period when the following data examples have been recorded.

Table 6.5.1. Station names and associated sensor/digitizer

Station name	Sensor (serial number)	Digitizer (serial number)
NRX6	CMG-3ESPC (T3T15)	Guralp DM24 (A208)
NRX8	Nanometrics Trillium 240 (0447)	Nanometrics Europa T (0748)
NRX9	Nanometrics Trillium 240 (0225)	Nanometrics Europa T (0757)
NRX10	Streckeisen STS2	Guralp DM24 (A091)
NRX11	Guralp CMG-3T (T35348)	Nanometrics Europa T (0727)
NRX12	Guralp CMG-3T (T35437)	Nanometrics Europa T (0762)
NRX13	Guralp CMG-3T (T35345)	Nanometrics Europa T (0708)
NRX14	Guralp CMG-3T (T35349)	Nanometrics Europa T (0764)
NRX15	Guralp CMG-3T (T35347)	Nanometrics Europa T (0699)

Figure 6.5.3. shows the vertical components of the stations for a 5-minute time window. The waveforms are corrected for instrument response and the digitizer scaling factor for a frequency band between 0.01 and 39 Hz (the data are originally sampled with 80 Hz). Figure 6.5.4. shows the traces overlayed for a 90-second time window. The waveforms are practically identical as expected for the colocated sensors.

Figure 6.5.5. and Figure 6.5.6. are power spectral density plots for all stations computed for a 3-hours time window (2008-289 21:00 - 24:00) with relatively low ambient noise level. To obtain these spectra we applied Welch’s method. That means:

- each time series is split up into overlapping segments
- the segments are windowed
- for each segment the periodogram is computed (FFT and squaring the magnitude of the result)
- the periodograms are time-averaged in order to reduce the variance of the individual power measurement

For our PSD results we subdivided the 3-hour time window into 200-s windows with an overlap of 100 s.

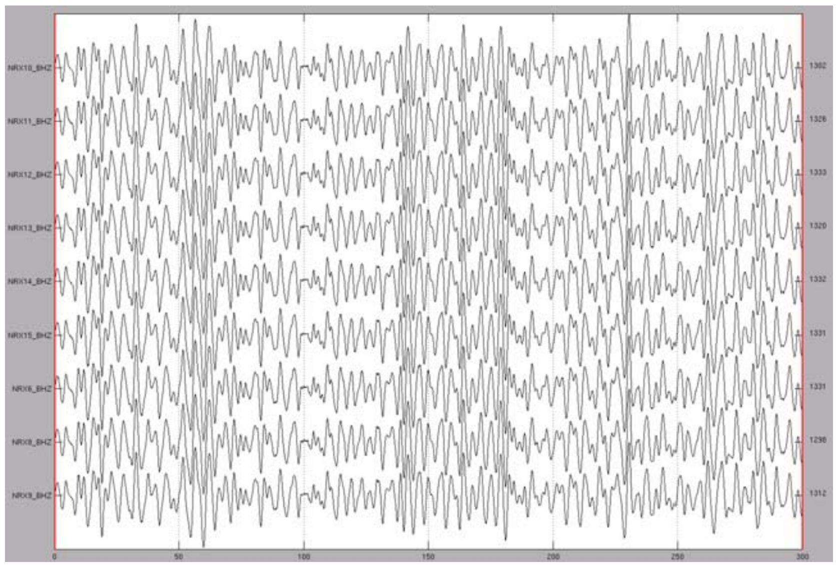

Figure 6.5.3. Instrument-corrected (0.01 - 39 Hz) vertical components (see Table 6.5.1. for station names) for a 5-minute time window.

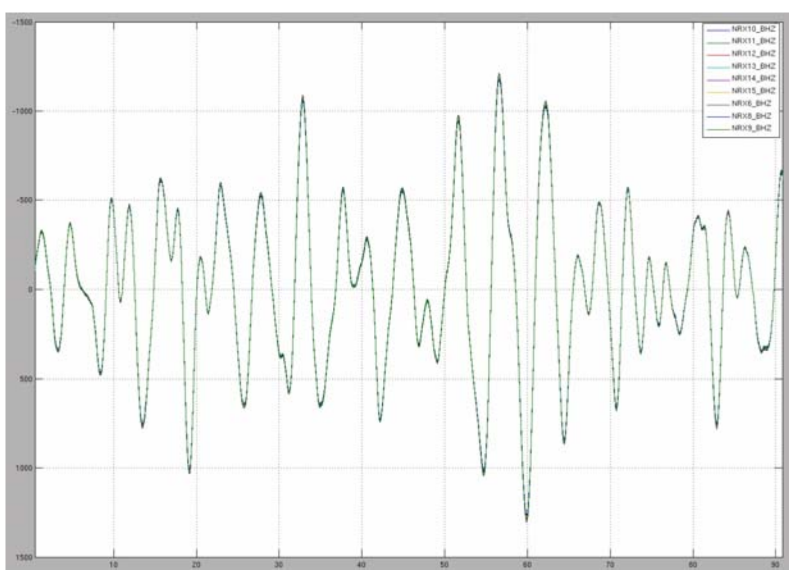

Figure 6.5.4. Overlaid instrument-corrected vertical components (in units of nm/s) for a 90s time window.

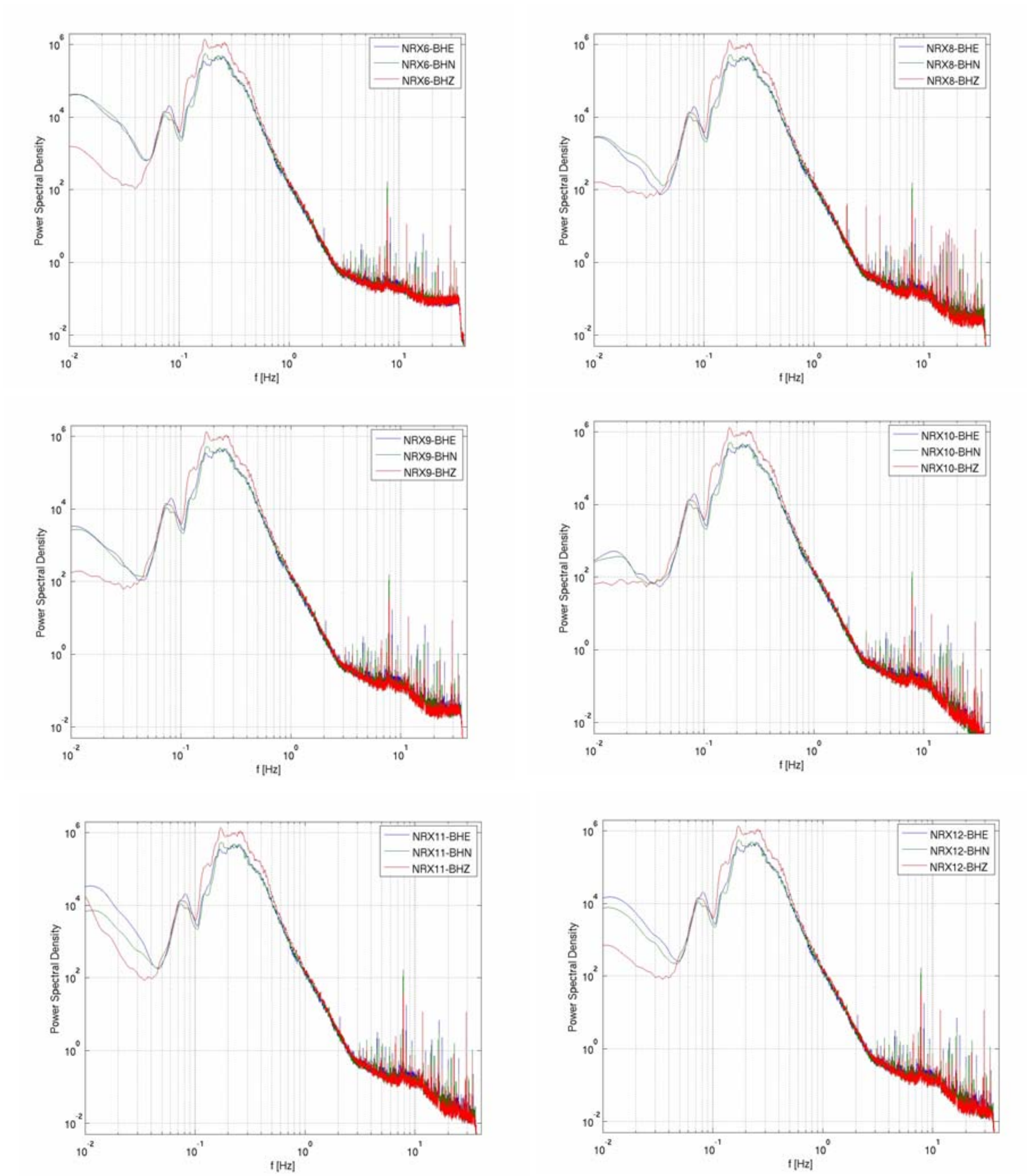

Figure 6.5.5. Power spectral density plots for the East (blue), North (green) and Z (red) components of stations NRX6, NRX8 - NRX12. The units of the PSD is in (nm/s)^2/Hz

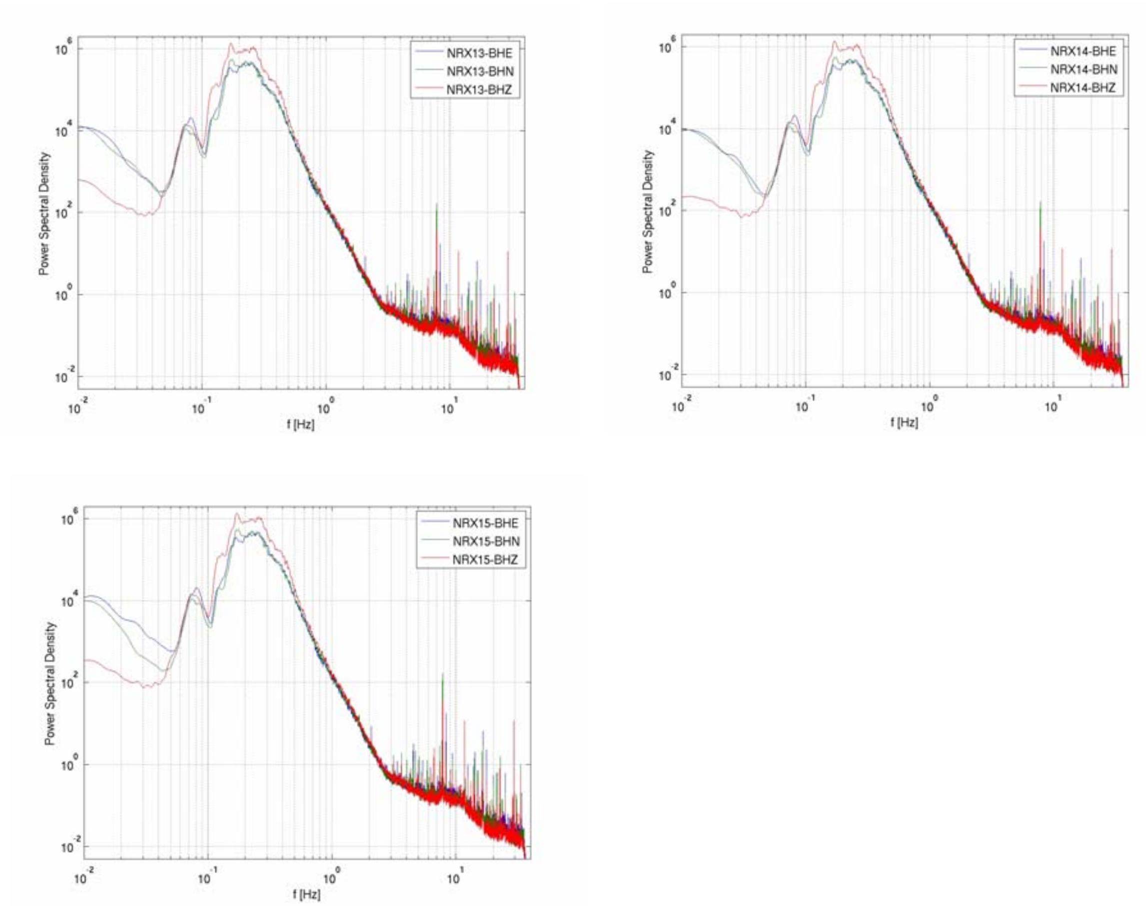

Figure 6.5.6. Power spectral density plots for the East (blue), North (green) and Z (red) components of stations NRX13 - NRX15. The units of the PSD is in (nm/s)^2/Hz

The PSD plots of all instruments and channels have distinct noise peaks above 2 Hz. Most of the noise is probably coupled into the systems over the ground motion, since the amplitudes of the peaks are almost identical for all systems. We would expect that electronic noise that is coupling into the cables, seismometers or digitizers has different peak amplitudes for the different systems. However, a clear electronic noise contamination is present in two stations NRX8 (Trillium 240/Europa T) and NRX10 (STS2/DM14). Both stations are picking up a 1 Hz (and higher harmonics) noise signal, which is most probably a leakage of the GPS signal into the digitizer. This was confirmed, when at a later time we rearranged the GPS cables and the 1 Hz signal dissapeared.

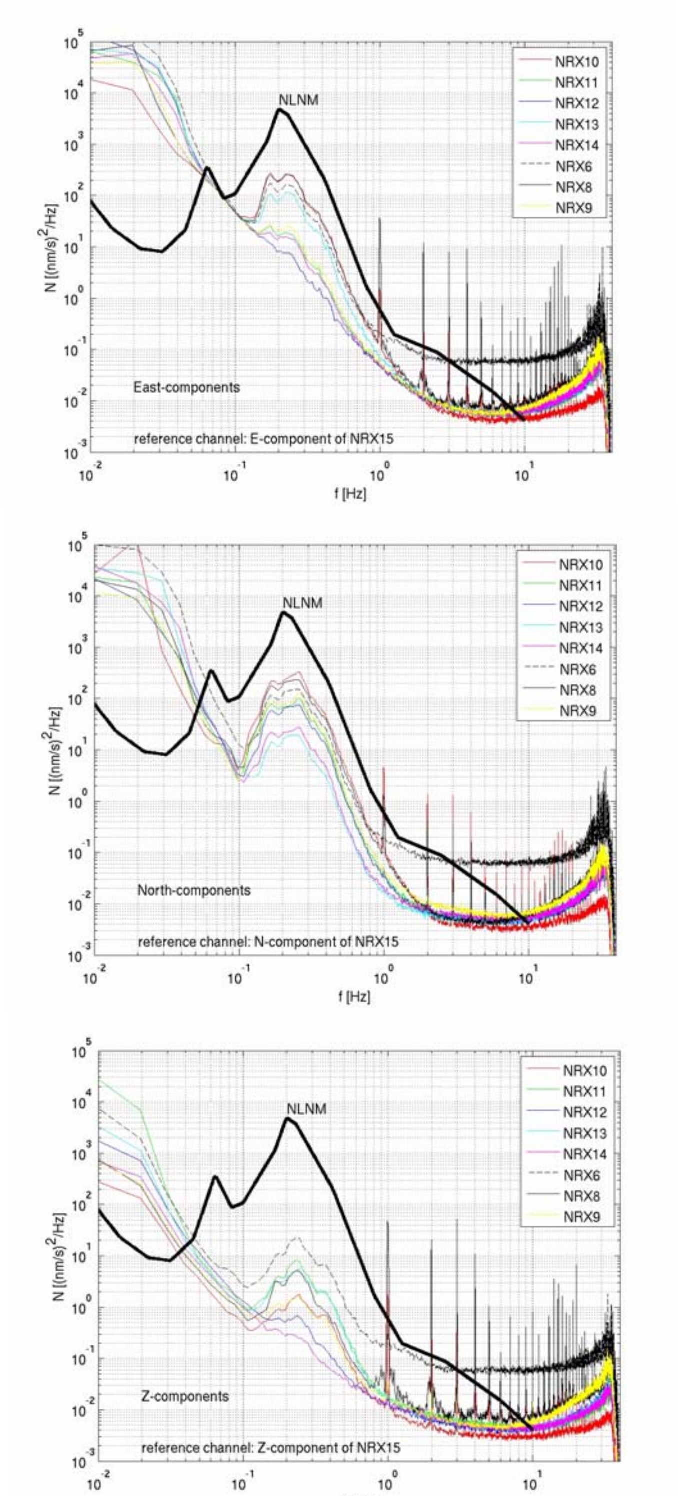

Figure 6.5.7. Instrument noise computed from PSD, cross spectral density and coherence of the instrument-corrected traces (eq.(5)). Top: east components, middle: north components, bottom: vertical components. The reference instrument was NRX15 (i.e. the Guralp GCM-3T (T35347) connected to the Europa T (0699)).

Figure 6.5.7.shows the channel noise of the stations computed with eq. (5) and with NRX15 as reference station. The contamination of stations NRX8 and NRX10 becomes very clear with amplitudes reaching over the New Low Noise Model (NLNM, Peterson, 1993). Generally for all stations the vertical components exhibit lower noise levels than the horizontal components. Station NRX6 (Guralp CMG-3ESPC/DM24) is below the NLNM for frequencies between ~0.6 Hz and 3 Hz, whereas the level for the other stations remains below the NLMN for frequencies up to 10 Hz. The observed high noies level of the CMG-3ESPC with regard to the other instruments is an expected result of the channel noise determination method, as the ESPC is a more narrowband and noisier sensor than the CMG-3T.

6.5.5 Conlusions

The NOA subarray NC6 has all necessary infrastructure to perform instrument tests in a controlled environment. The site is remote with low cultural noise and it is suitable for long-term instrument tests. All waveform data have been delivered to CTBTO, Guralp, and Nanometrics for further detailed analyses.

References

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