Exploring the Earth

NORSAR Scientific Report No. 2-2013

Semiannual Technical Summary

1 July – 31 December 2013

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Kjeller, June 2014

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1 Summary

This report provides summary information on operation and maintenance (O&M) activities at the Norwegian National Data Center (NOR-NDC) for CTBT verification during the period 1 July – 31 December 2013, as well as scientific and technical contributions relevant to verification in a broad sense. The O&M activities, including operation of monitoring stations and transmission links within Norway and to Vienna, Austria are being funded jointly by the CTBTO/PTS and the Norwegian Government, with the understanding that the funding of O&M activities for primary stations in the International Monitoring System (IMS) will gradually be transferred to the CTBTO/PTS. The O&M statistics presented in this report maintain consistency with long-standing reporting practices. Research activities described in this report are mainly funded by the Norwegian Government, with other sponsors acknowledged where appropriate.

A summary of the activities at NOR-NDC relating to field installations, data acquisition, data forwarding and processing during the reporting period is provided in chapters 2 – 4 of this report. Norway contributes data from two primary seismic arrays: the Norwegian Seismic Array NOA (IMS code PS27) and the Arctic Regional Seismic Array ARCES (IMS code PS28), one auxiliary seismic array on Spitsbergen (SPITS, IMS code AS72), and one auxiliary three-component station at Jan Mayen (JMIC, IMS code AS73). In addition, NORSAR provides data from one infrasound array in northern Norway (IMS code IS37), and one radionuclide monitoring station on Spitsbergen (IMS code RN49). These data are provided to the International Data Centre (IDC) in Vienna via the Global Communications Infrastructure (GCI).

This report presents operational statistics for NOA, ARCES, SPITS and JMIC, as well as for additional seismic stations which through cooperative agreements with institutions in the host countries provide continuous data to the NOR-NDC. These additional stations include the Finnish Regional Seismic Array (FINES, IMS code PS17) and the Hagfors array in Sweden (HFS, IMS code AS101). Operational statistics for the reestablished NORES array and two other three-component stations operated by NORSAR are also provided. These two stations are Åknes (AKN) and TROLL in Antarctica.

By the end of this reporting period, all Norwegian IMS stations, the NOA and the ARCES arrays (PS27 and PS28, respectively), the radionuclide station at Spitsbergen (RN49), the auxiliary seismic stations on Spitsbergen (AS72) and Jan Mayen (AS73), as well as the infrasound array at Bardufoss (IS37) have been certified by the CTBTO/PTS. 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's obsolescence management, a recapitalization plan for PS27 and PS28 was submitted to CTBTO/PTS in October 2008, with the purpose of preventing severe degradation of the stations due to lack of spare parts. The recapitalization of PS27 was concluded in 2012. In parallel the recapitalization of P28 has started with development and testing of particular equipment for PS28, like a central timing system and a hybrid sensor for surface vaults.

The installation of IMS infrasound station IS37 was completed during the autumn of 2013. IS37, having coordinates 69.10° N, 18.60° E, is located close to the small town of Bardufoss in the municipality of Målselv, northern Norway.

IS37 started sending continuous data to NOR-NDC on 16 October 2013, and was certified by the CTBTO/PTS on 19 December 2013.

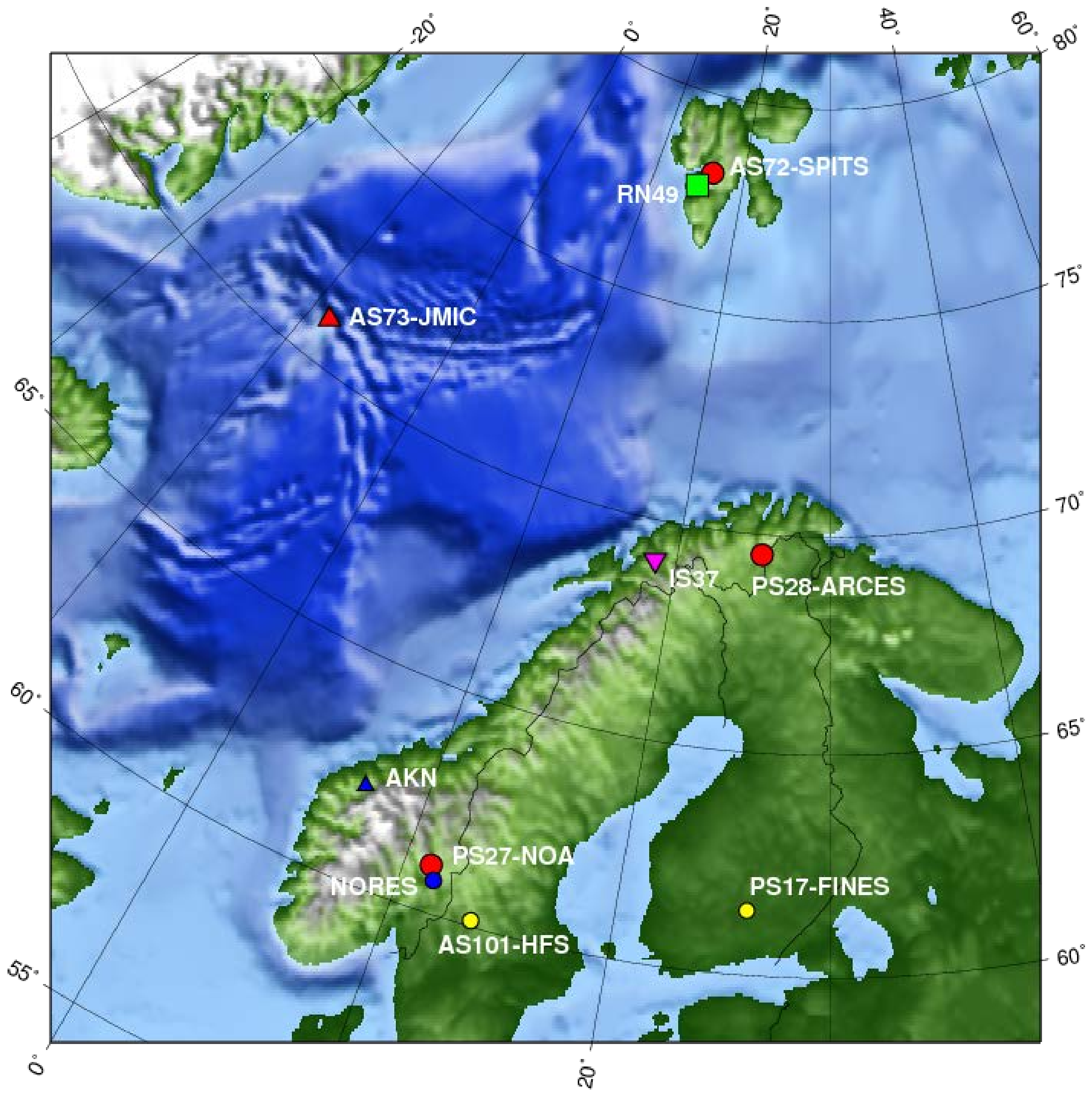

Fig. 1.1 *Locations for stations covered in this report (except TROLL in Antarctica, see Fig. 3.5.1). Norwegian seismic IMS stations are shown in red. Other Norwegian seismic stations are shown by blue symbols. Contributing IMS seismic stations in other countries are yellow. Circles indicate seismic arrays and triangles indicate single 3-component seismic stations. The IMS infrasound station IS37 is shown by a purple inverted triangle, and the IMS radionuclide station RN49 is shown by a green square.*

Three scientific and technical contributions presented in chapter 6 of this report are provided as follows:

Section 6.1 summarizes the 15 years history of constructing infrasound station IS37. Highlights from the many years of planning work in the vicinity of PS28 – ARCES are given. However, these locations were rejected by local authorities, and the station was moved to Bardufoss in northern Norway. The section gives a report on the technical installations of IS37. The station started operation in October 2013, and was certified on 19 December 2013.

Section 6.2 considers infrasound registrations and modeling related to the accidental explosion which took place close to Drevja, north east of Mosjøen, Nordland, Norway on December 17, 2013. The event was due to an exploding lorry carrying 15 tons of slurry. We present signals received at the newly installed IS37 array close to Bardufoss, the ARCI array (Karasjok), and the NRSI array (Løten). In addition, signals from other Fennoscandian infrasound stations and a Russian infrasound array are displayed. For the NORSAR-operated arrays, we apply ray-trace modelling through an atmospheric model describing winds and temperature conditions up to around 120 km altitude. This work results from our recently commenced effort to build up capacity in infrasound propagation modelling through the atmosphere and the incorporation of this into localization and yield estimation procedures for registered events.

In Section 6.3, we present observations both on the NORES infrasound array and the large aperture NOA seismic array which result from low frequency atmospheric sound generated by a bolide explosion which was both seen and heard over extensive parts of southern and eastern Norway on November 6, 2013. The resulting infrasound was detected clearly on the microbarometers of the NORES infrasound array and this allowed for a high confidence estimate of the backazimuth from NORES at which the explosion occurred. In the absence of other infrasound arrays in southern Norway, this information alone is not sufficient to estimate the location of the event. Inspection of the seismic data from the NORSAR teleseismic array (NOA) revealed a large number of high frequency bursts of energy, the timing of which was consistent with an atmospheric signal from the west. These high frequency infrasound-to-seismic converted signals are not coherent between sensors of the array, precluding classical array processing methods for estimating the direction of arrival. However, estimating the delay between the energy pulses on the different sensors simply by picking the times at which the maximum amplitudes occur, it is possible to estimate an approximate direction and distance using a simplified constant slowness circular wavefield model. The observations on the seismic and infrasonic sensors indicate a source location some 25 kilometers WSW of the town on Fagernes, consistent with estimates obtained from visual eye-witness reports.

Tormod Kværna

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

2.1 PS27 — Primary Seismic Station NOA

The mission-capable data statistics were 99.998%, as compared to 99.997% for the previous reporting period. The net instrument availability was 94.921%

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:

	Mission Capable	Net instrument availability
July 2013:	99.999	95.992
August 2013:	100.000	89.299
September 2013:	99.999	94.902
October 2013:	99.987	93.410
November 2013:	100.000	97.436
December 2013:	100.000	98.486

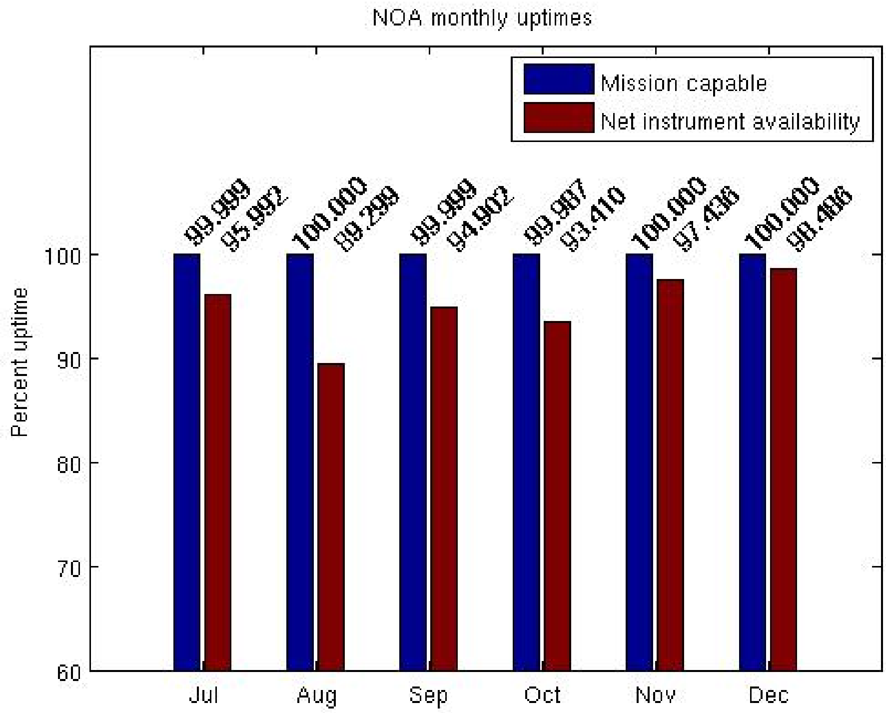

Fig. 2.1.1 Monthly uptimes for NOA for the period July – December 2013.

B. Paulsen

2.1.1 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 P-phases	Core Phases	Sum	Daily average
Jul 13	6289	1001	311	97	408	13.2
Aug	8624	1538	302	61	363	11.7
Sep	6426	1064	320	66	386	12.9
Oct	6416	818	266	63	329	10.6
Nov	6884	784	230	62	292	9.7
Dec	7208	698	219	41	260	8.4
	41847	5903	1648	390	2038	11.1

Table 2.1.1. Detection and event processor statistics, 1 July – 31 December 2013.

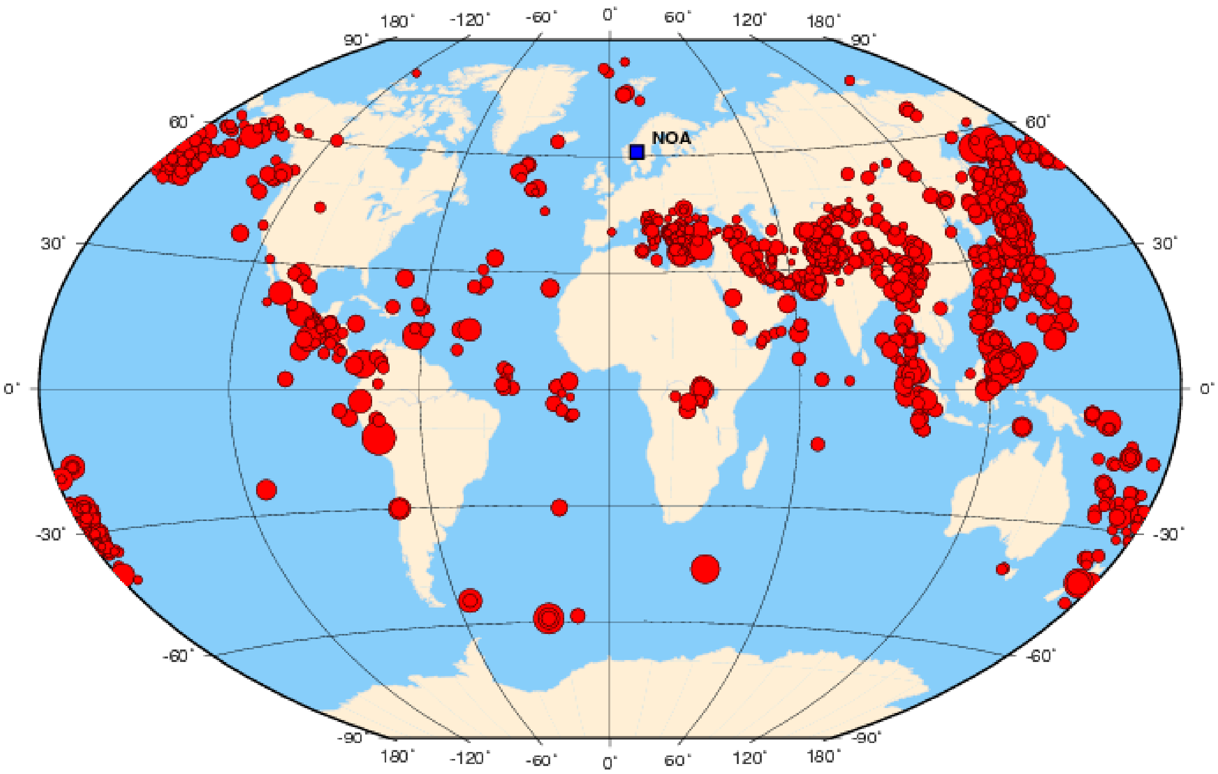

Fig. 2.1.2 Distribution of events in NORSAR's teleseismic reviewed bulletin for the time interval 1 July – 31 December 2013. Event symbols are scaled proportionally to event magnitude. The location of NOA is noted with a blue square. All locations are based on phase interpretation and inversion of slowness and backazimuth into a location, using the NOA array alone.

NOA detections

The number of detections (phases) reported by the NORSAR detector during day 182, 2013, through day 365, 2013, was 41,847, giving an average of 227 detections per processed day (184 days processed).

B. Paulsen
U. Baadshaug

2.2 PS28 — Primary Seismic Station ARCES

The mission-capable data statistics were 99.986%, as compared to 99.977% for the previous reporting period. The net instrument availability was 96.784%.
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:

	Mission Capable	Net instrument availability
July 2013:	99.988	91.656
August 2013:	99.979	99.296
September 2013:	99.999	99.999
October 2013:	99.985	99.891
November 2013:	99.994	99.897
December 2013:	99.968	89.967

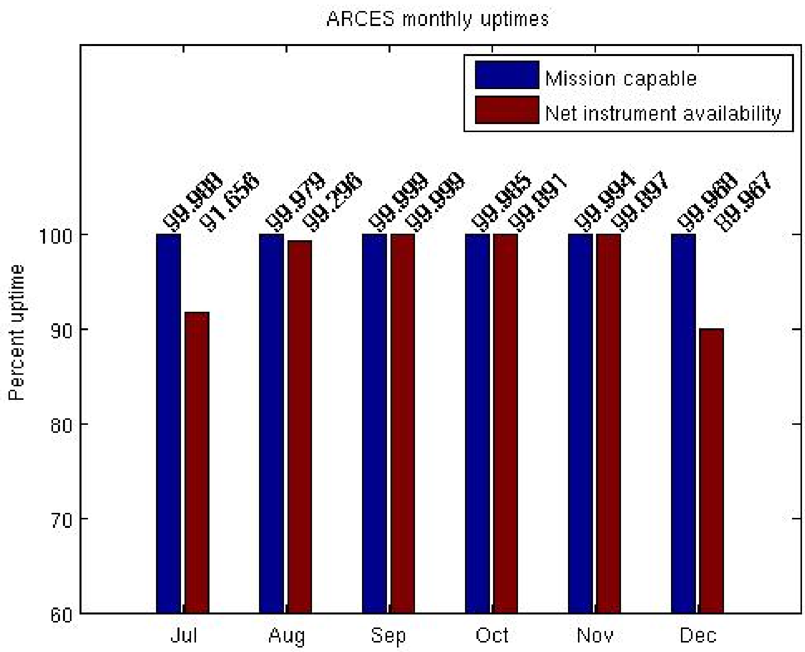

Fig. 2.2.1 Monthly uptimes for ARCES for the period July - December 2013.

B. Paulsen

2.2.1 Event detection operation

ARCES detections

The number of detections (phases) reported during day 182, 2013, through day 365, 2013, was 221,567, giving an average of 1204 detections per processed day (184 days processed).

Events automatically located by ARCES

During days 182, 2013, through day 365, 2013, 9,195 local and regional events were located by ARCES, based on automatic association of P- and S-type arrivals. This gives an average of 50.0 events per processed day (184 days processed). 75% of these events are within 300 km, and 92% of these events are within 1000 km.

U. Baadshaug

2.3 AS72 — Auxiliary Seismic Station on Spitsbergen

The mission-capable data for the period were 98.356%, as compared to 99.058% for the previous reporting period. The net instrument availability was 85.396%.

The low net instrument availability is mainly caused by an outage of the site SPB1 which was out of operation from 13 July 2013 to the end of the reporting period because of modem problems.

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:

	Mission Capable	Net instrument availability
July 2013:	99.962	91.001
August 2013:	99.923	85.642
September 2013:	99.992	85.702
October 2013:	95.108	80.549
November 2013:	95.176	83.793
December 2013:	99.975	85.689

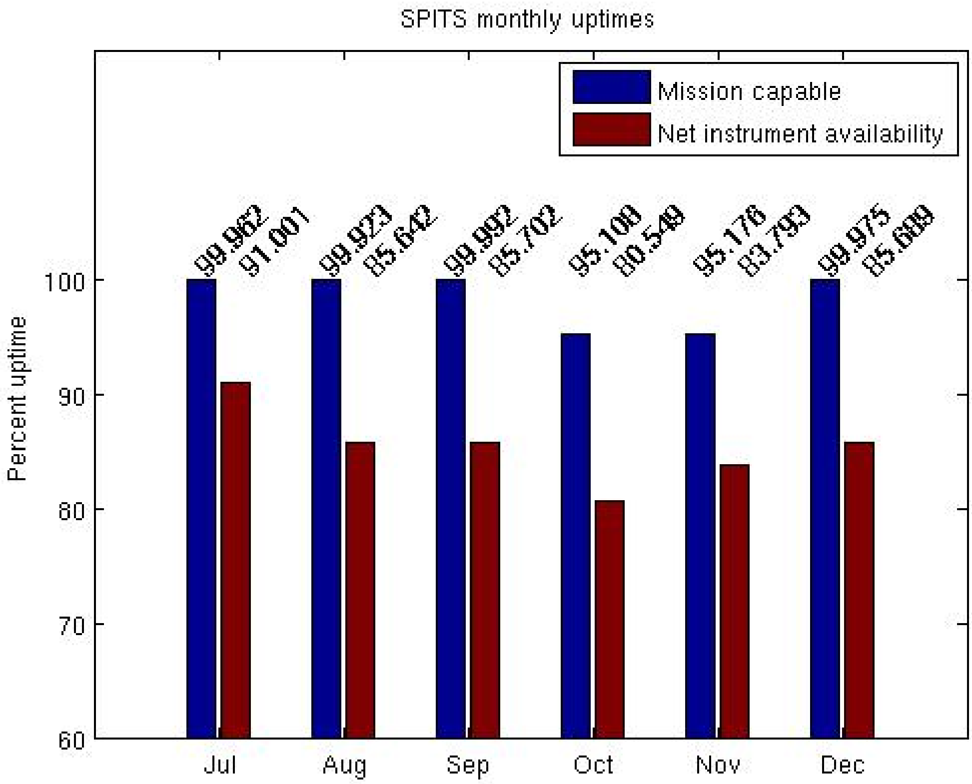

Fig. 2.3.1 Monthly uptimes for SPITS for the period July - December 2013.

B. Paulsen

2.3.1 Event detection operation

Spitsbergen array detections

The number of detections (phases) reported from day 182, 2013, through day 365, 2013, was 520,824, giving an average of 2,862 detections per processed day (182 days processed).

Events automatically located by the Spitsbergen array

During days 182, 2013, through day 365, 2013, 45,143 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 248.0 events per processed day (182 days processed). 83% of these events are within 300 km, and 93% of these events are within 1000 km.

U. Baadshaug

2.4 AS73 — Auxiliary Seismic Station at Jan Mayen

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

The University of Bergen has operated a seismic station at this location since 1970. A so-called Parent Network Station Assessment for AS73 was completed in April 2002. A vault at a new location (71.0°N, 8.5°W) was prepared in early 2003, after its location had been approved by the CTBTO 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.
Monthly uptimes for the Jan Mayen on-line data recording task, taking into account all factors (field installations, transmissions line, data center operation) affecting this task were as follows:

	Mission Capable	Net instrument availability
July 2013:	98.869	98.875
August 2013:	98.971	98.978
September 2013:	98.100	98.108
October 2013:	97.324	97.331
November 2013:	95.835	95.875
December 2013:	92.515	92.633

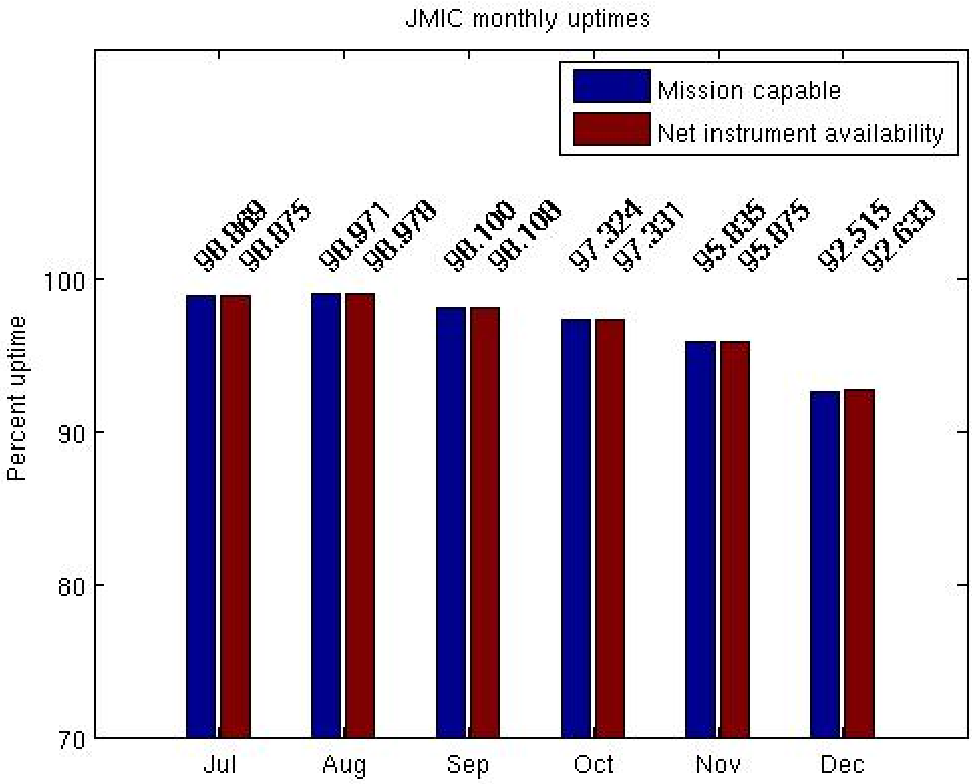

Fig. 2.4.1 Monthly uptimes for JMIC for the period July - December 2013.

B. Paulsen

2.5 IS37 — Infrasound Station at Bardufoss

The IMS infrasound network should, 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.

It proved, however, impossible to obtain the necessary permits for use of land for an infrasound station at Karasjok. Various alternatives for locating the station at Karasjok were prepared, but all applications to the local authorities to obtain the permissions needed to establish the station were turned down by the local governing council in June 2007.

In 2008, investigations were initiated to identify an alternative site for IS37 outside Karasjok. A site at Bardufoss, at 69.1°N, 18.6°E, was approved in December 2012 by landowners and the municipal authorities for installation of IS37. The CTBTO preparatory Commission approved the corresponding coordinate change for the station, and during the reporting period, IS37 was installed at the designated Bardufoss location.

IS37 started sending continuous data to NOR-NDC on 16 October 2013.

The station was certified by the CTBTO/PTS on 19 December 2013.

Monthly uptimes for the IS37 on-line data recording task, taking into account all factors (field installations, transmissions line, data center operation) affecting this task were as follows:

	Mission Capable	Net instrument availability
July 2013:	0.000	0.000
August 2013:	0.000	0.000
September 2013:	0.000	0.000
October 2013:	51.182	50.663
November 2013:	99.984	99.986
December 2013:	99.999	99.999

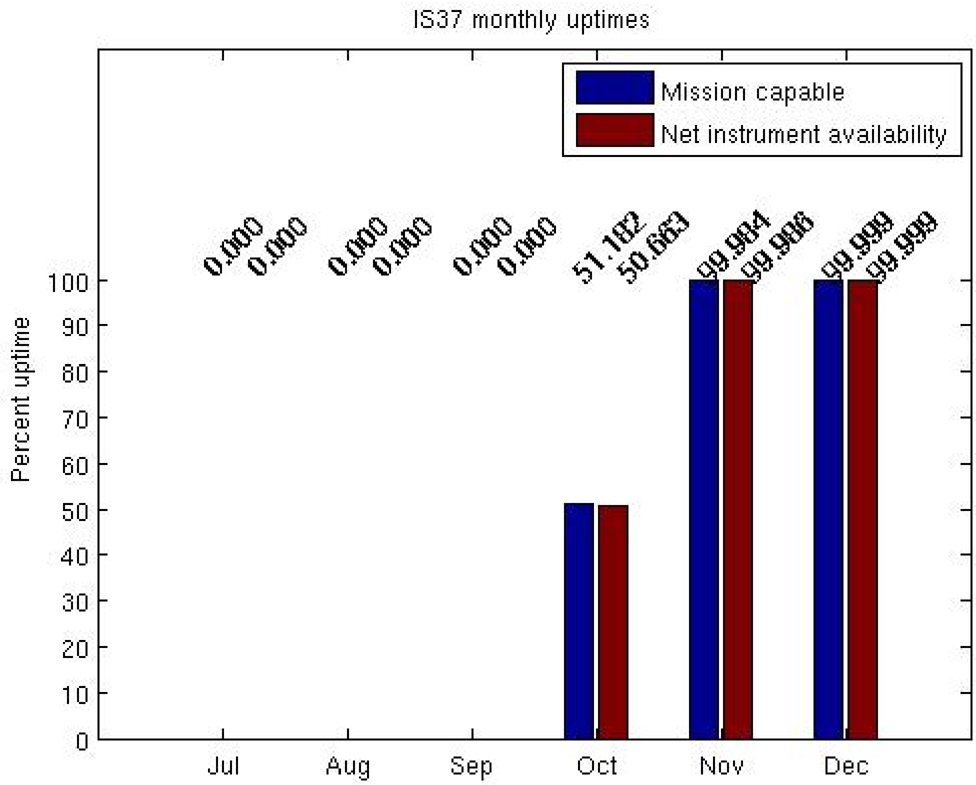

Fig. 2.5.1 Monthly uptimes for IS37 for the period July - December 2013.

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 CTBTO 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 upgrades in May/June 2006. The noble gas system was certified on 21 December 2012. The equipment at RN49 is being maintained and operated under a contract with the CTBTO/PTS.

S. Mykkeltveit

3 Contributing Regional Arrays and Three-Component Stations

3.1 NORES

The NORES array went out of operation on 11 June 2002, when lightning destroyed the station electronics. In December 2011 the array was rebuilt and again became operational in an experimental mode where the 9 inner sites were instrumented with three-component sensors.

Monthly uptimes for the NORES on-line data recording task, taking into account all factors (field installations, transmission lines, data center operation) affecting this task are given in the following table:

	Data availability
July 2013:	99.987
August 2013:	100.000
September 2013:	100.000
October 2013:	100.000
November 2013:	100.000
December 2013:	100.000

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 98.749%, as compared to 99.776% for the previous reporting period. The net instrument availability was 99.277%.

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

	Mission Capable	**Net instrument availability**
July 2013:	98.174	99.430
August 2013:	94.321	96.234
September 2013:	100.000	100.000
October 2013:	100.000	100.000
November 2013:	99.999	100.000
December 2013:	99.998	99.999

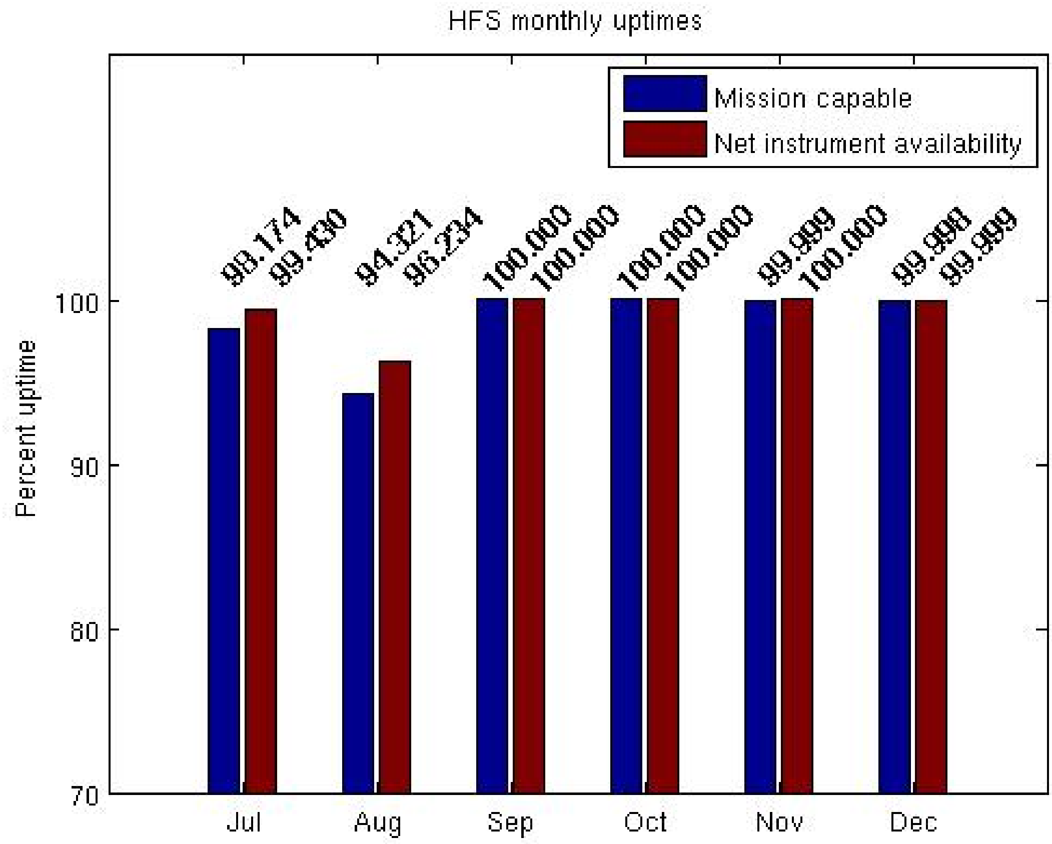

Fig. 3.2.1 Monthly uptimes for HFS for the period July - December 2013.

B. Paulsen

3.2.1 Hagfors event detection operation

Hagfors array detections

The number of detections (phases) reported from day 182, 2013, through day 365, 2013, was 132,731, giving an average of 725 detections per processed day (183 days processed).

Events automatically located by the Hagfors array

During days 182, 2013, through 365, 2013, 5,873 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 32.1 events per processed day (183 days processed). 77% 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 99.067%, as compared to 99.833% for the previous reporting period. The net instrument availability was 97.296%.

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:

	Mission Capable	Net instrument availability
July 2013:	100.000	100.000
August 2013:	99.997	99.997
September 2013:	99.988	99.986
October 2013:	99.999	99.999
November 2013:	94.661	92.819
December 2013:	99.758	90.974

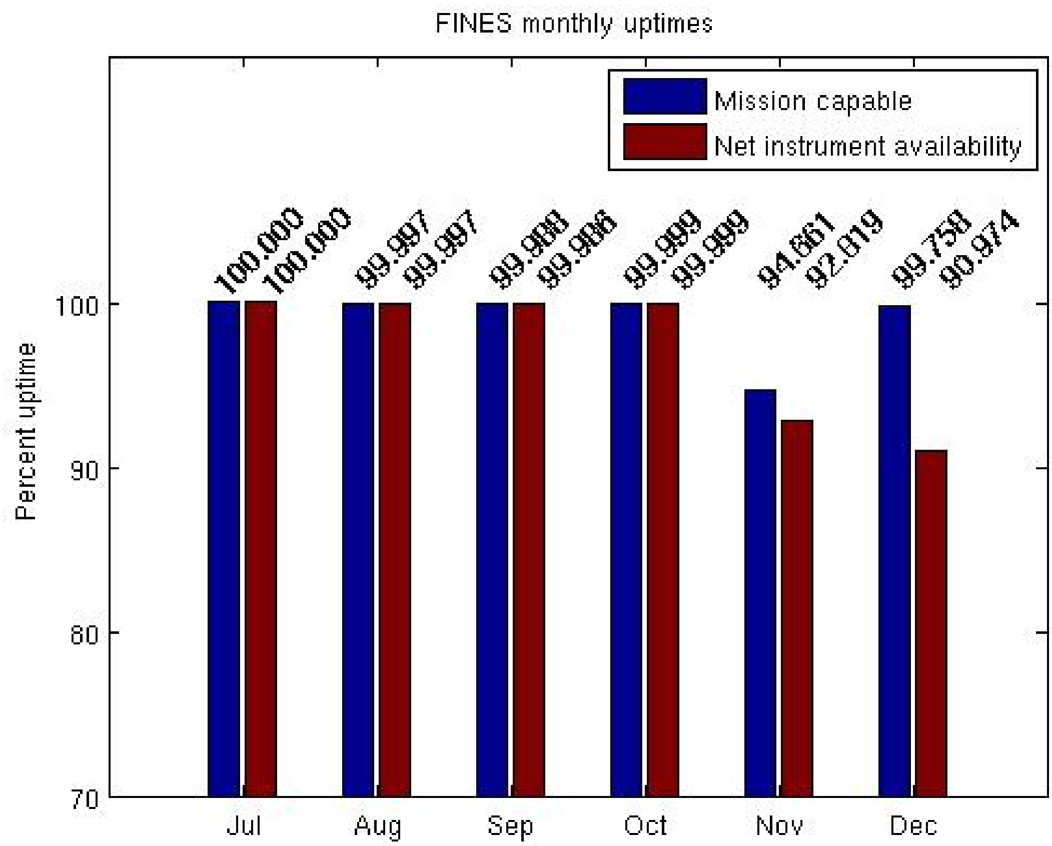

Fig. 3.3.1 Monthly uptimes for FINES for the period July - December 2013.

B. Paulsen

3.3.1 FINES event detection operation

FINES detections

The number of detections (phases) reported during day 182, 2013, through day 365, 2013, was 39,894, giving an average of 217 detections per processed day (184 days processed).

Events automatically located by FINES

During days 182, 2013, through 365, 2013, 1,827 local and regional events were located by FINES, based on automatic association of P- and S-type arrivals. This gives an average of 9.9 events per processed day (184 days processed). 84% of these events are within 300 km, and 92% of these events are within 1000 km.

U. Baadshaug

3.4 Åknes (AKN)

The seismic broadband station AKN was installed in October 2009 on top of the unstable rock slope site Åknes, Møre og Romsdal. Its primary purpose is the monitoring of local seismic activity related to the movement of the slope, but due to the relatively low ambient noise conditions it also provides excellent data of local, regional and global seismic events. The station has been sending continuous real-time data (200 Hz sampling rate) to NORSAR since 27 October 2009. On 17 January 2013 we added a 40 Hz data tap in order to facilitate data distribution to the seismologic community.

Monthly uptimes for the AKN on-line data recording task, taking into account all factors (field installations, transmission lines, data center operation) affecting this task are given in the following table:

	Data availability
July 2013:	99.979
August 2013:	100.000
September 2013:	100.000
October 2013:	99.442
November 2013:	100.000
December 2013:	99.997

U. Baadshaug

3.5 TROLL, Antarctica

The seismic station at the Norwegian Research Base Troll in Dronning Maud Land, Antarctica, became operational and started sending continuous data to NORSAR on 5 February 2012. On 4 February 2013 the Q330HR digitizer gain was increased by a factor of 20, and on 9 February 2013, the TROLL station was upgraded with additional thermal insulation. An additional low-gain data stream with a sampling rate of 40 Hz was retained by using the auxiliary 24-bit input and a gain factor of 1.

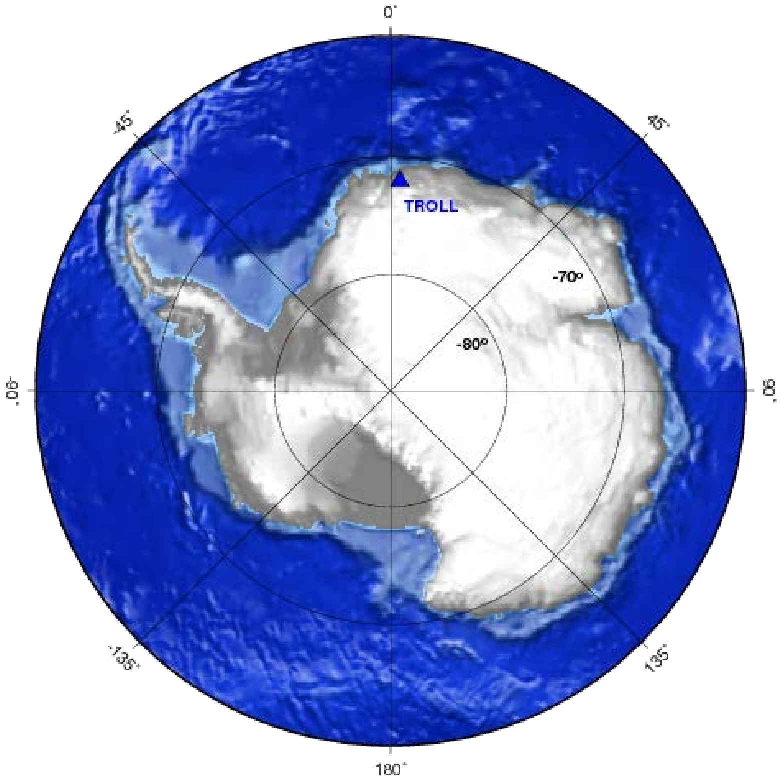

Fig. 3.5.1
Location of the 3-component seismic station TROLL in Antarctica.

Monthly uptimes for the TROLL on-line data recording task, taking into account all factors (field installations, transmission lines, data center operation) affecting this task are given in the following table:

	Data availability
July 2013:	100.000
August 2013:	100.000
September 2013:	100.000
October 2013:	100.000
November 2013:	100.000
December 2013:	100.000

U. Baadshaug

3.6 Regional Monitoring System Operation and Analysis

The Regional Monitoring System (RMS) was installed at NORSAR in December 1989 and has been operated 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. In contrast 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 NOA array have also been available to the analyst.

3.6.1 Phase and event statistics

Table 3.6.1 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 13	Aug 13	Sep 13	Oct 13	Nov 13	Dec 13	Total
Phase detections	144024	160270	189572	177725	149127	168171	988889
- Associated phases	6683	8604	9066	7862	7048	7886	47149
- Unassociated phases	137341	151666	180506	169863	142079	160285	941740
Events automatically declared by RMS	1425	1786	1990	1736	1421	1626	9984
No. of events defined by the analyst	49	64	49	41	53	89	345

Table 3.6.1. RMS phase detections and event summary 1 July – 31 December 2013.

U. Baadshaug
B. Paulsen

4 The Norwegian National Data Center and Field Activities

4.1 NOR-NDC Activities

NORSAR functions as the Norwegian National Data Center (NOR-NDC) for CTBT verification. Six monitoring stations, comprising altogether 87 seismic and infrasound waveform sensor sites plus radionuclide monitoring equipment, are located on Norwegian territory as part of the 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/PTS on a regular basis. PS27, PS28, AS72, AS73, RN49 and IS37are all certified. Data recorded by the Norwegian stations are being transmitted in real time to the NOR-NDC, and provided to the IDC through the Global Communications Infrastructure (GCI). Norway is connected to the GCI with an MPLS link to Vienna.

Operating the Norwegian IMS stations continues to require significant efforts by personnel both at the NOR-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 NOR-NDC. The NOR-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 NOR-NDC is to carry 40 years' experience over to the next generation of personnel.

4.1.1 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 NOR-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.

4.1.2 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.

4.1.3 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.

4.1.4 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.

4.1.5 Communication topology

Norway has implemented an independent subnetwork, which connects the IMS stations AS72, AS73, PS28, RN49 and IS37 operated by NORSAR to the GCI at the NOR-NDC. VSAT is used for communication for PS28 and AS73. 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 VSAT communication is functioning satisfactorily. Since 10 June 2005, AS72 and RN49 have been connected to the NOR-NDC through a VPN link.

Jan Fyen

4.2 Status Report: Provision of Data from Norwegian Seismic IMS Stations to the IDC

4.2.1 Introduction

This contribution is a report for the period July – December 2013 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 been formally certified.

4.2.2 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, comprising of 7 subarrays, each containing five vertical broadband sensors and one three-component hybrid 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 iDirect 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 the NOR-NDC using the same iDirect network as NOA.

Continuous SPITS data are transmitted to NOR-NDC via the central recording facility (CRF) for the SPITS array at the University Centre in Svalbard (UNIS). Data from the array elements to the CRF are transmitted via a 2.4 Ghz radio link (Wilan VIP-110). A 512 Kbps SHDSL link has been established between UNIS and NOR-NDC. Both AS72 and RN49 data are now transmitted to NOR-NDC over this link using VPN technology.

A minimum of 14-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 are transmitted continuously to the receiving International Data Centre. Since October 1999, these data have 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 also this station is transmitted in continuous mode to the IDC. In addition, continuous data from all three arrays are transmitted to the US_NDC under a bi-lateral agreement.

NORSAR also provides broadband data from Norwegian IMS stations to ORFEUS and IRIS.

4.2.3 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 red (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.

4.2.4 NOR-NDC automatic processing and data analysis

These tasks have proceeded in accordance with the descriptions given in Sci. Rep. No. 2-95/96 (Mykkeltveit and Baadshaug). For the reporting period NOR-NDC derived information on 337 events and submitted this information to the Finnish NDC as the NOR-NDC contribution to the Bulletin of seismic events in northern Europe. These events are plotted in Fig. 4.2.4.

4.2.5 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 PS27 - NOA equipment was recapitalized during 2010-2012, and has been revalidated. The PS28 - ARCES equipment was acquired in 1999, and it is no longer possible to get spare digitizers. A recapitalization plan for the array was submitted to the PTS in October 2008, and development and testing of specific equipment for that array are ongoing.

U. Baadshaug
S. Mykkeltveit
J. Fyen

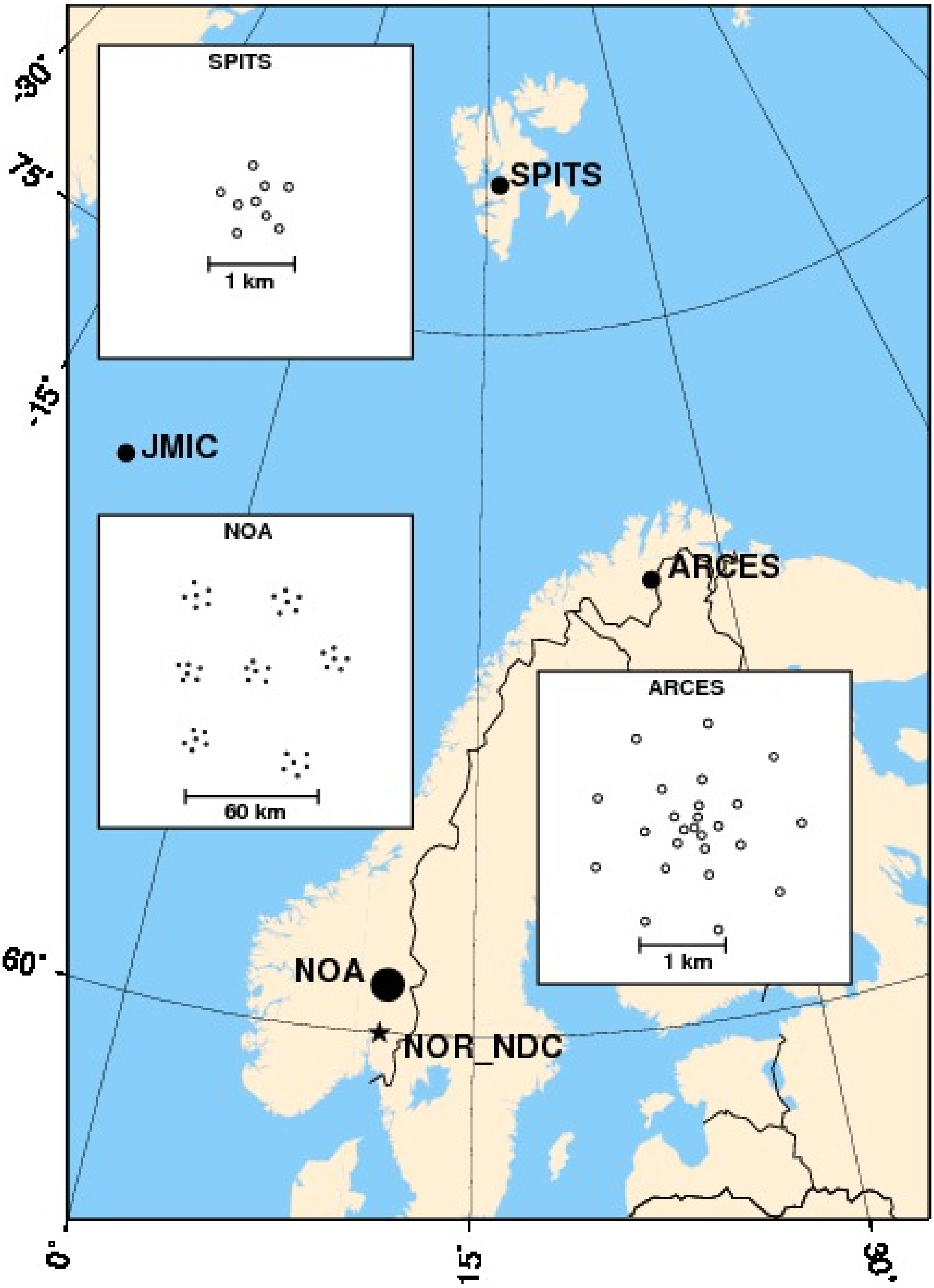

Fig. 4.2.1. The figure shows the locations and configurations of the three Norwegian seismic IMS array stations that provided data to the IDC during the period July - December 2013. The data from these stations and the JMIC three-component station are transmitted continuously and in real time to the Norwegian NDC (NOR-NDC). The stations NOA and ARCES are primary IMS stations, whereas SPITS and JMIC are auxiliary IMS stations.

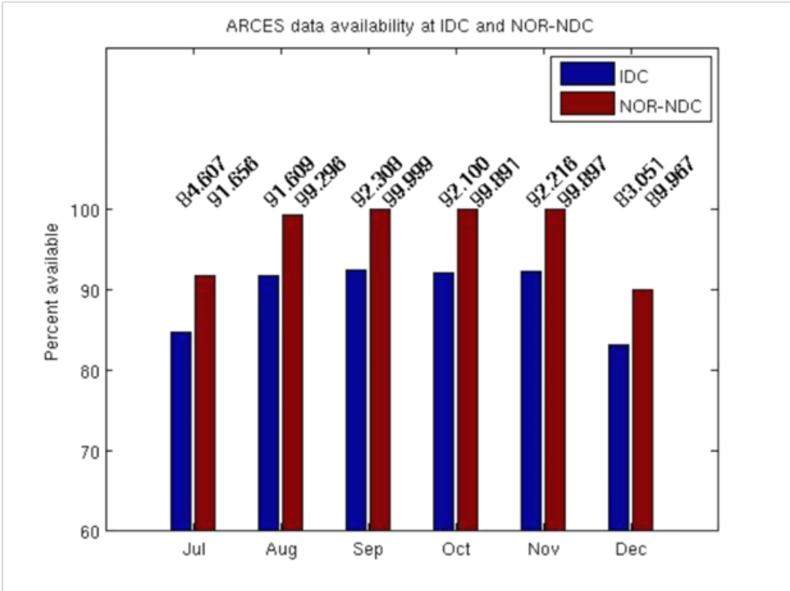

Fig. 4.2.2 The figure shows the monthly availability of ARCES array data for the period July – December 2013 at NOR-NDC and the IDC.

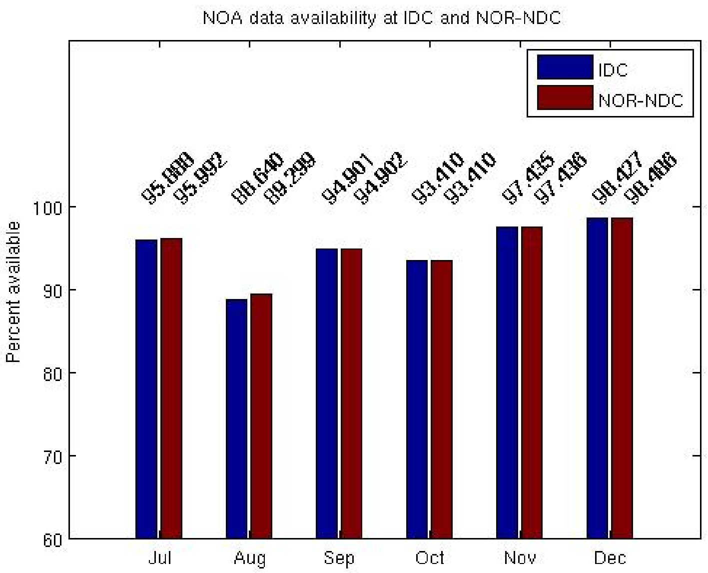

Fig. 4.2.3 The figure shows the monthly availability of NORSAR array data for the period July – December 2013 at NOR-NDC and the IDC.

Reviewed Supplementary events

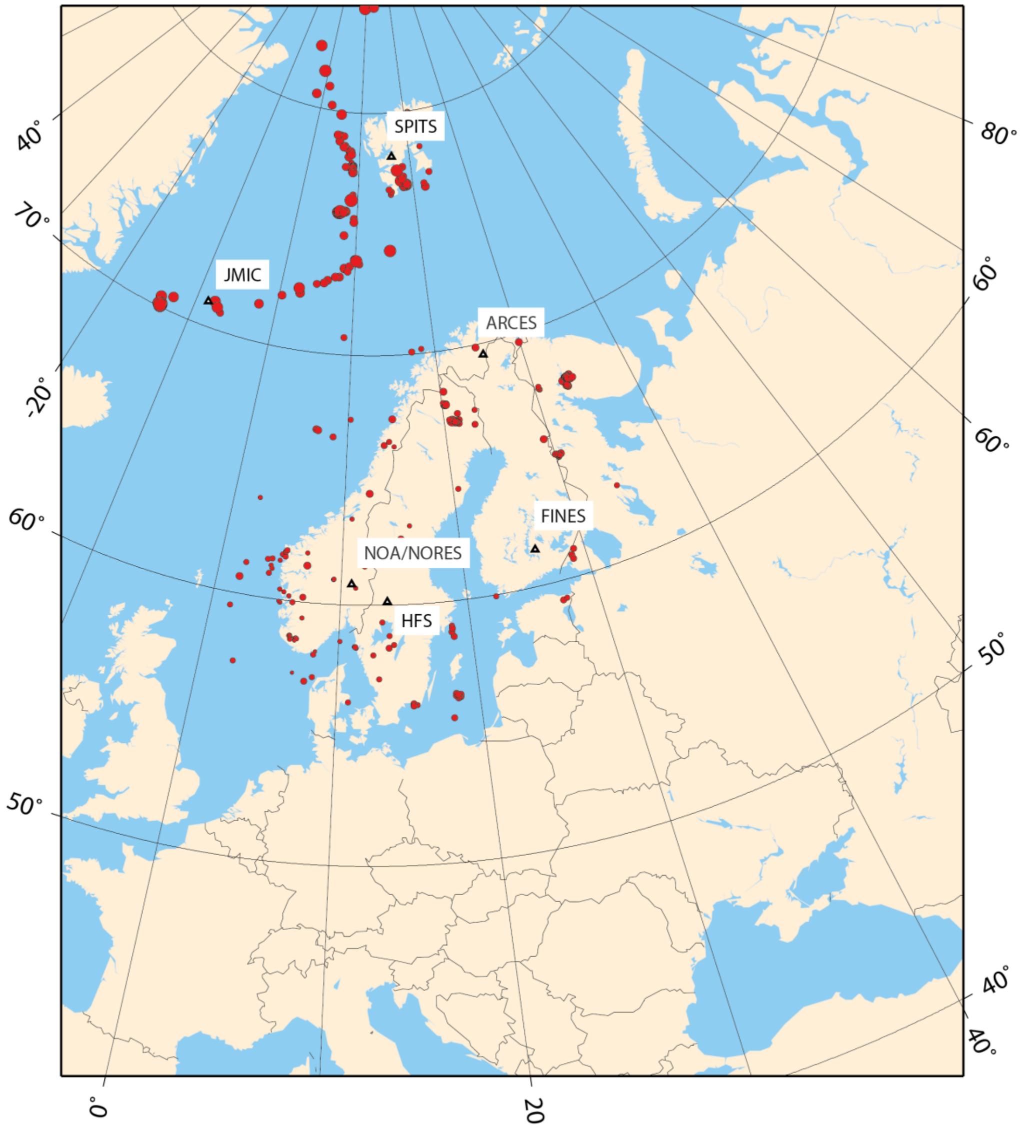

Fig. 4.2.4 The map shows the 337 events in and around Norway contributed by NOR-NDC during July - December 2013 to the Bulletin of seismic events in northern Europe compiled by the Finnish NDC. The map also shows the main seismic stations used in the data analysis to define these events.

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 installation of the infrasound station 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

Fyen, J., M. Roth and P.W. Larsen (2014). I37NO Infrasound Station in Bardufoss, Norway. In: NORSAR Scientific Report 2-2013, Semiannual Technical Summary, 1 July – 31 December 2013.

Gibbons, S.G. (2014). Location of the November 6, 2013, Valdres/Hallingdal Bolide from Infrasound Signals on the NORES Infrasound Array and the NORSAR Seismic Array. In: NORSAR Scientific Report 2-2013, Semiannual Technical Summary, 1 July – 31 December 2013.

Näsholm, S. P. (2014). Infrasound signal detection from the Drevja accidental explosion. In: NORSAR Scientific Report 2-2013, Semiannual Technical Summary, 1 July – 31 December 2013.

6 Technical Reports / Papers Published

6.1 IS37 Infrasound Station in Bardufoss, Norway

The IS37 infrasound array was initially planned to be collocated with PS28-ARCES in Karasjok, northern Norway, to gain synergy between seismic and infrasound observations. A site survey for the planned station was carried out during June/July 1998 as a cooperative effort between CTBTO/PTS and NORSAR. The site survey report proposed a 4 element array with an 18 meter diameter, 4 rosettes pipe array as Wind Noise Reduction Pipe Array (WNRPA) at each element.

During the years 2000-2006, NORSAR and the CTBTO/PTS continued discussions and planning of the array and the whole infrasound community discussed and experimented with different array configurations and different wind noise reduction systems. As a result of this a 9 element array with 18 meters pipe arrays placed within 20x20 meter fences was designed. However, the construction of fences in the area was not permitted by the municipal authorities because of possible obstruction of frequently used reindeer migration paths.

Consequently, alternative sites close to PS28 were investigated, and the municipal authorities gave positive signals for an approval. Hence, NORSAR and the CTBTO/PTS concluded a contract for the construction of IS37 in Karasjok in July 2006. However, despite intense efforts by NORSAR, permission to establish IS37 in Karasjok was rejected in a final formal meeting of the municipal community board on 14 June 2007.

NORSAR continued the work to obtain access/use of a new site for IS37. This work led to an alternative location. A promising location was found in Bardufoss, in the municipality of Målselv (Målselv Kommune), Norway, 280 km WSW of Karasjok. Several reconnaissance as well as site survey measurements were performed during 2007-2010, which resulted in a preferred location at Brannmoen, close to the small town of Bardufoss. The change of location was approved by the CTBTO PrepCom in June 2009. See Figures 6.1.1 and 6.1.2 showing the location of IS37 together with other IMS monitoring stations, and together with experimental infrasound stations in Fennoscandia.

Målselv Kommune proved to be very cooperative, and NORSAR undertook the task of developing a regulatory plan for the area (Reguleringsplan). This is a mandatory document, describing in detail the installation/construction and its consequences for the environment and society at large, and is the basis for the consideration by the authorities, prepared with the intent of leading to an approval of the proposed plans, in this case the installation of IS37. NORSAR succeeded in obtaining the final permission for the construction of IS37 at Brannmoen in December 2012.

So finally, in May 2013, after the snow had melted, NORSAR and its subcontractor started the civil works at IS37. First, the CRF (Central Recording Facility) building was constructed. Soon after a transformer and the power cable connecting the transformer with the CRF were installed. In parallel, a total length of 5.2 km of trenches from the CRF to the element sites were excavated for deployment of the power and fiber optic cables. The installation of the power and fiber optic cables was finished in August 2013. The preparations for the element sites started in June 2013 with the installation of the equipment vaults, the GPS and meteorological masts and the installation of the fences. Figure 6.1.3 shows a map of the Brannmoen site, with marks for the trenches and the 10 sites H0 – H9.

The construction work at the station continued until the end of August 2013. Soon after the construction works were finished, NORSAR started to install the station equipment at the CRF and at each element and by the end of the second week in October 2013 most of the equipment was installed and configured.

On October 19 the station started sending data from each element to Vienna (IMS-Lab) and several certification tests were performed. This resulted in the formal acceptance and certification of the station on December 19, 2013.

Figures 6.1.4 – 6.1.7 illustrates in more details the pipe arrays and the cabling of IS37.

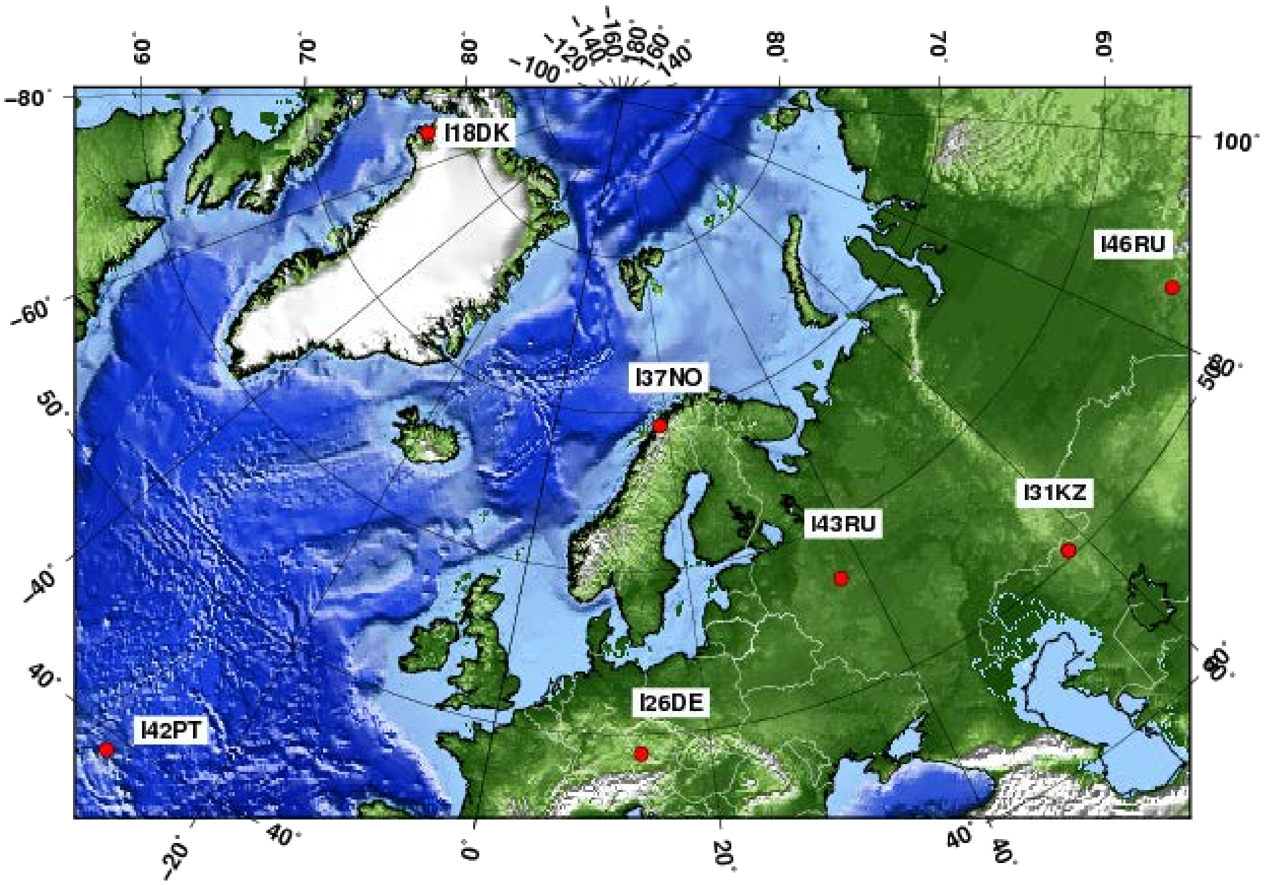

Fig. 6.1.1 The map above shows the location of IS37 together with other operating infrasound stations in the IMS network. Although we were not able to co-locate IS37 with the seismic station PS28, the move of the station will not affect the overall coverage and performance of the IMS network. The separation from other stations in the network shown in the map is still from 1700 km to 4300 km.

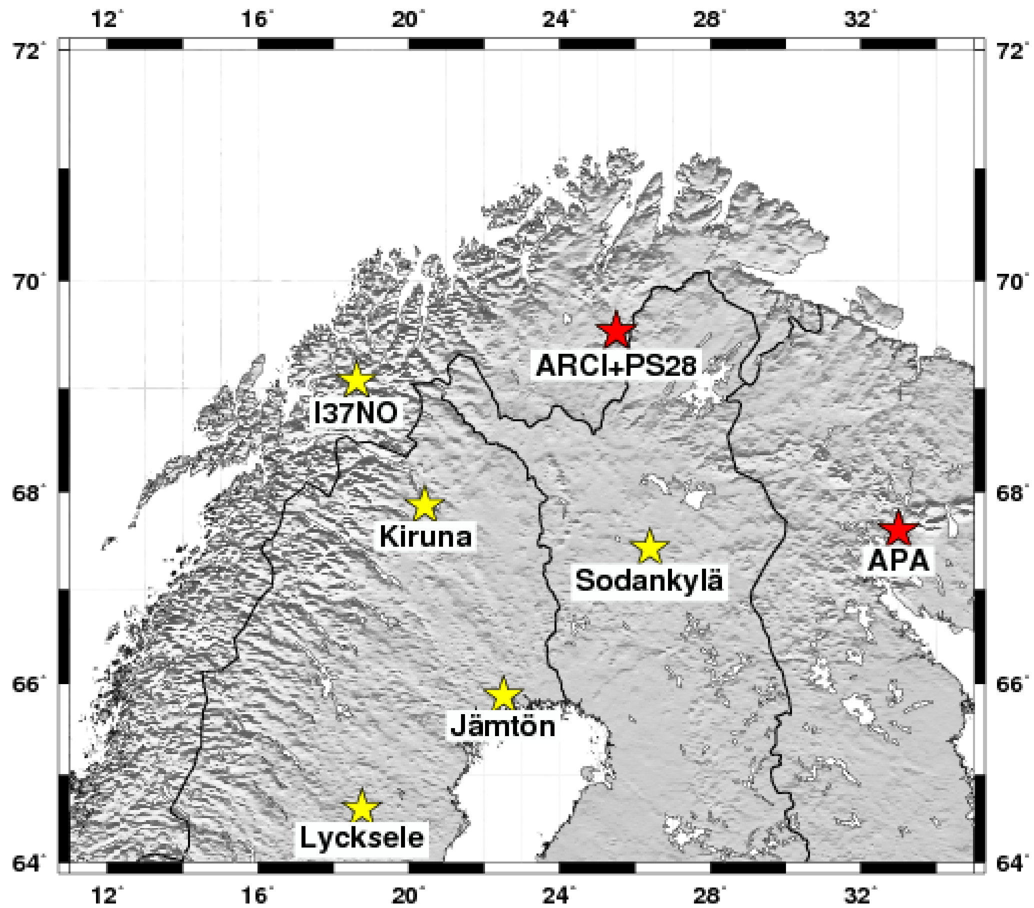

Fig. 6.1.2 The above map shows IS37 along with other cooperating infrasound stations in northern Fennoscandia. Red diamonds indicate both seismic and infrasound sensors in an array. NORSAR cooperates with the host institutions of several permanent and experimental infrasound stations in northern Europe and exchange data for processing of interesting events. Within PS28, NORSAR operates a 4 element infrasound array with porous hoses as the noise reduction filter.

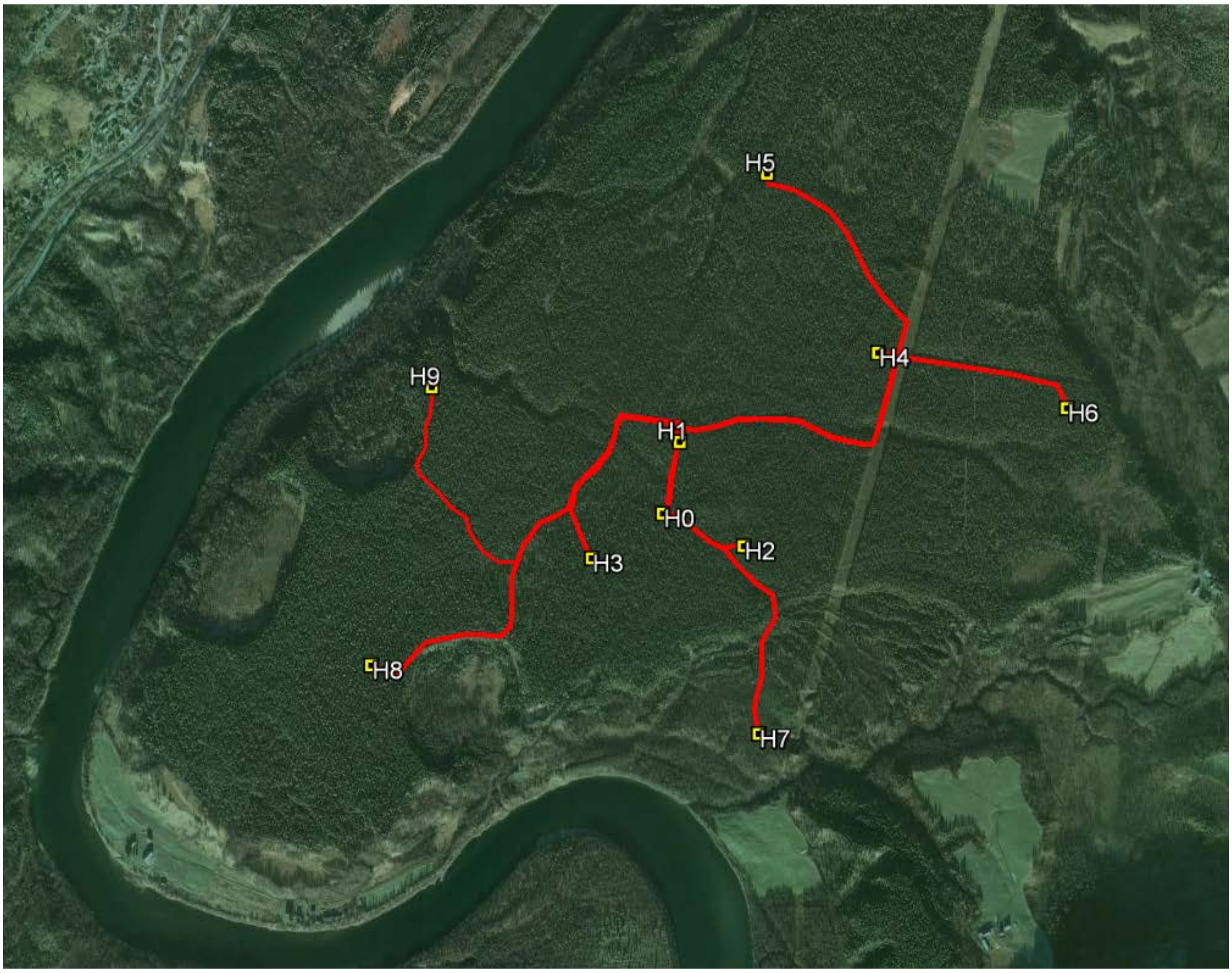

Fig. 6.1.3 The above picture shows an aerial view of IS37. As can be seen from the picture, the area is forested with pine trees of height about 14 meters. The density of the forest varies across the area, but all sites are in places that are well protected from wind by trees. The "reguleringsplan" prevents landowners from cutting trees in an area with diameter 50 meters surrounding each of the 10 sites.

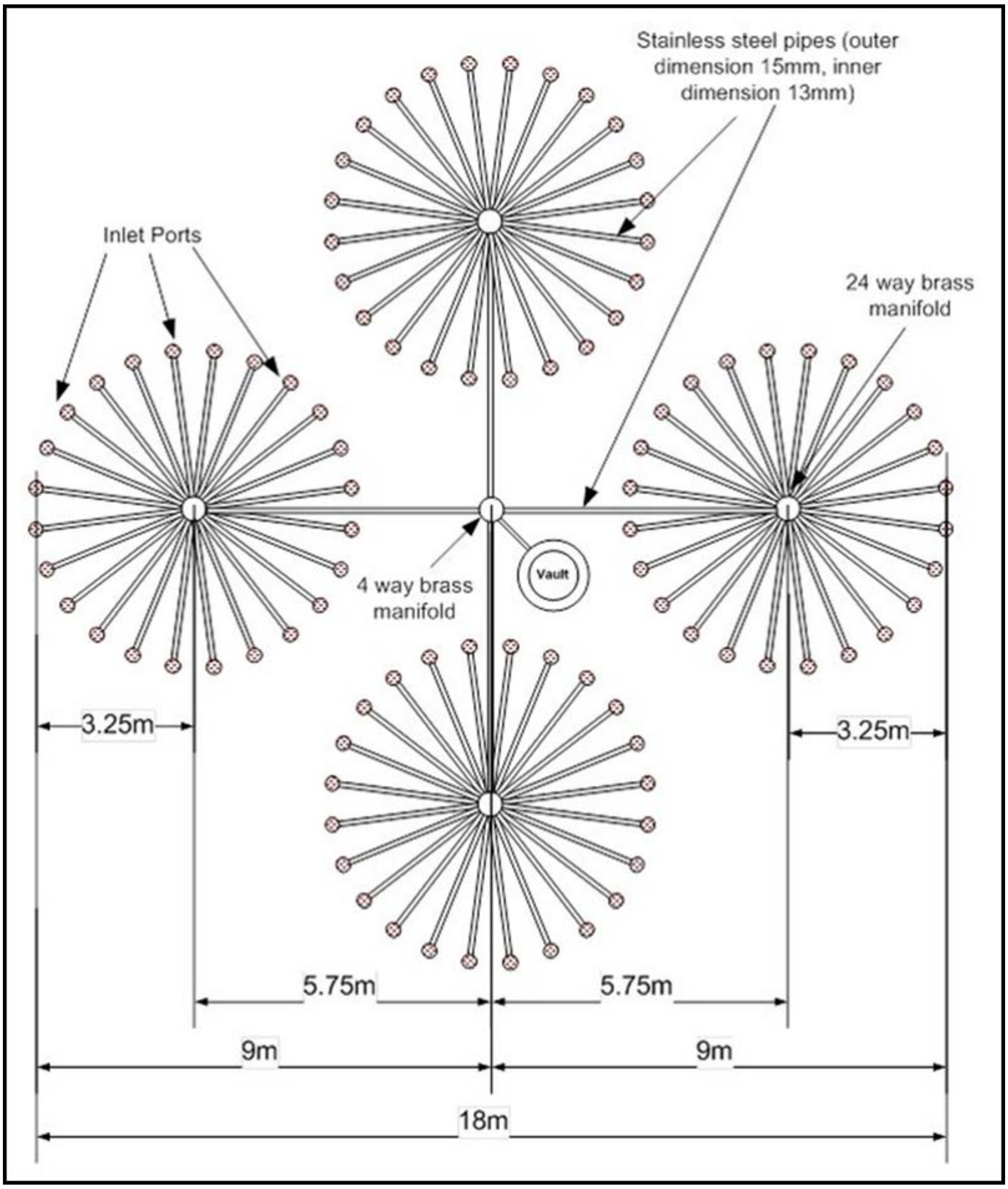

Fig. 6.1.4 Each of the 10 sites has a 18 meter wide wind noise reduction system consisting of stainless steel pipes with diameter 15 mm. The figure above shows the layout of the pipes and the 96 inlet ports. The MB2005 microbarometer is inside a shallow vault in the center of the site. All the 10 sites are protected by a 2 meter high fence of dimension 20 by 20 meters.

Fig. 6.1.5 The picture shows the pipe array system during installation.

Fig. 6.1.6 The picture above shows the pipe array system, the fence and the CRF in the background.

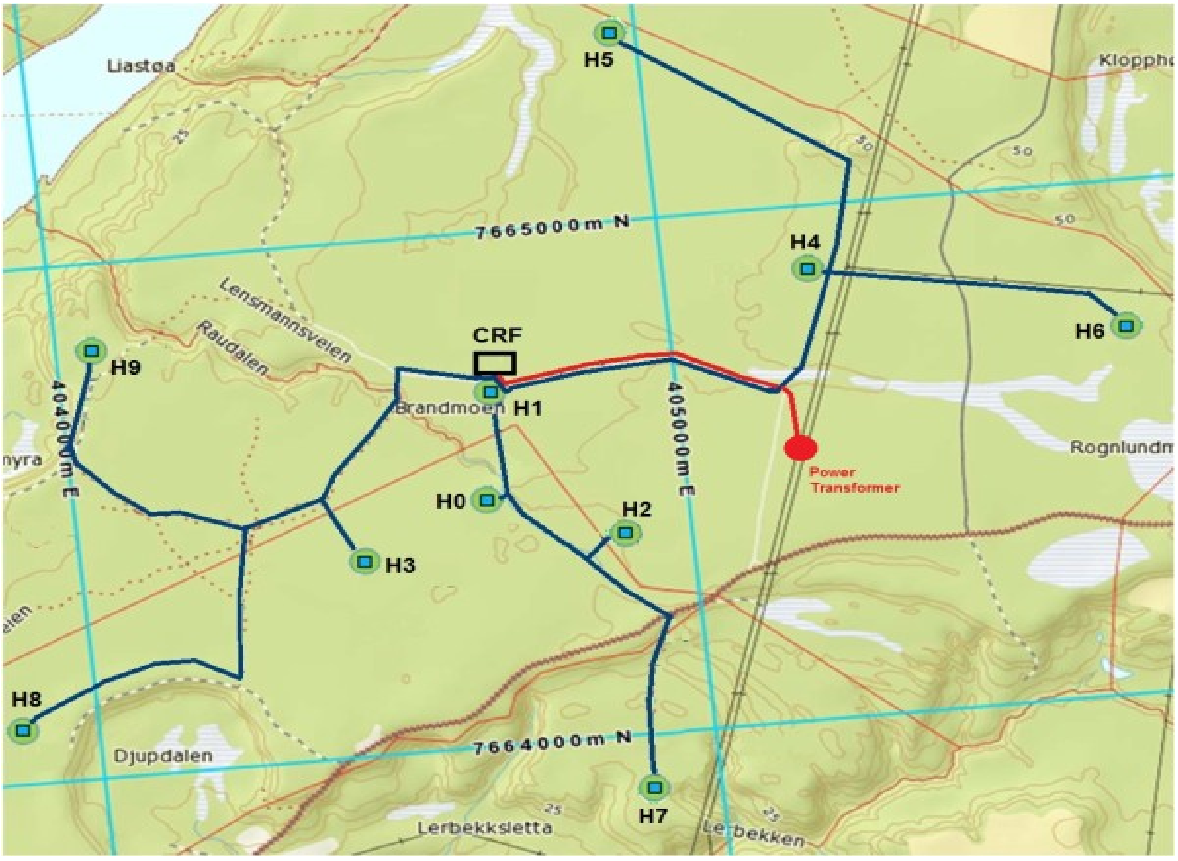

Fig. 6.1.7 The station receives mains power from a 22 kVAC to 415 VAC transformer indicated with a red dot. Power lines on poles connect the station CRF to mains power. At the CRF a UPS provides 230 VAC to a central cabinet, where AC/DC converters give 48 VDC to each of the 10 remote sites. Approximately 5200 meters of trenches connect the 10 sites to the CRF. In the trenches are one copper cable for each of the sites, and one PVC pipe for fiber optic cable. So there is one power cable and one fiber cable to each of the points. Each site has power cable and fiber connected directly to the CRF, not via any other site. For H1, there is additionally one extra power cable for heating of the meteorological equipment.

From the CRF to each of the 10 sites there are at least 60 cm deep trenches which house continuous PVC conduits and armored power cables; one conduit and one power cable for each site. Fiber cables with 12 fibers were blown from the CRF to each of the sites through the conduits. Six of the fibers have connectors, so 4 fibers are available as backup.

Figures 6.1.8 and 6.1.9 show schematic and photo views of the remote sites H0 – H9, and give an explanation to the pit installations. Each pit has an Uponor manhole which houses major electronic equipment.

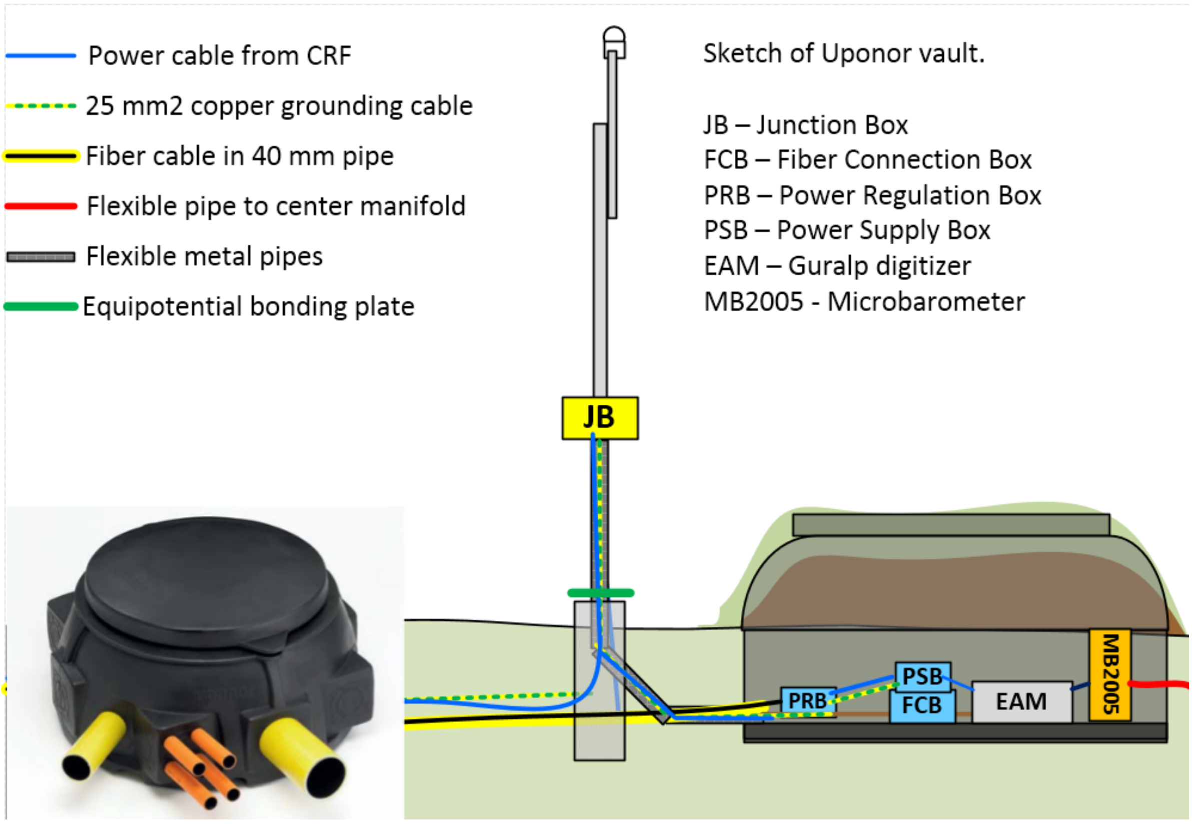

Fig. 6.1.8 The figure above is a principle sketch of the Uponor cable well that contains pit equipment. The manhole is 60 cm high, and about 20 cm is above surface. A 5 cm layer of concrete is added in the bottom for additional weight, and covered by epoxy.

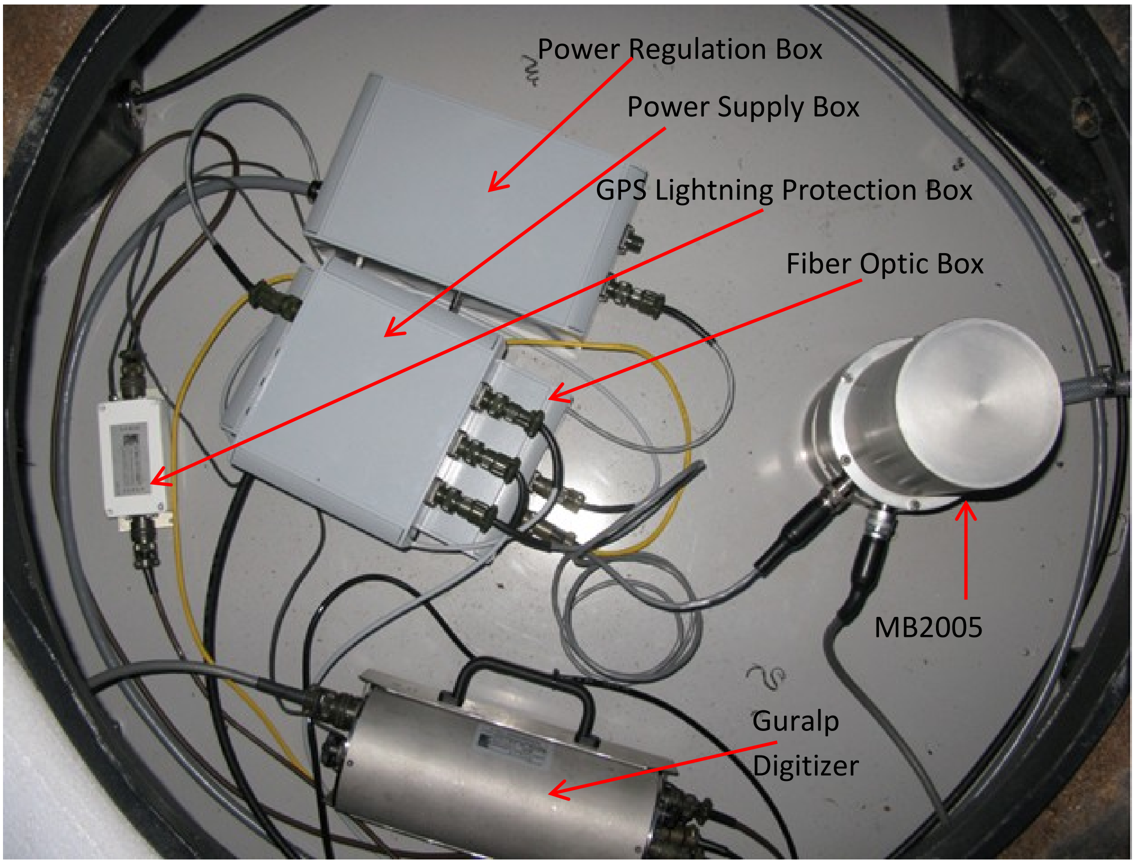

Fig. 6.1.9 Equipment installed inside IS37 vaults. The inside bottom of the tank has a 5 cm layer of concrete topped with epoxy coating. The vault houses a MB2005 microbarometer, a Güralp digitizer model CMG-DM24S3AM, and a Güralp GPS lightning protection box. The two power boxes with power conditioning and lightning protection and a fiber optic communication box are NORSAR custom made products. The fiber optic communication has the Luxcom OM-101 Ethernet converter and the fiber splice assembly.

Figure 6.1.10 show a block diagram of the IS37 power system. The UPS contains an Eltek Flatpack 2 power system with Smartpack 2 controller and 12*77Ah SAFT Evolion batteries. For each of the 10 remote sites, the CRF has a web controlled power switch, AC/DC converters and lightning protection. There is one buried power cable to each of the 10 remote sites, which again have lightning protection and DC/DC converters.

The length of the buried cables ranges from 100 to 1500 meters. The cable is of type Nexans EKKJ 1 kV 4x6/6 mm2 shielded cable. 25 mm2 grounding wires are connected to 2 meter deep copper spears in each end, as well as to the shield of the power cable.

A test showed that the UPS provided power to the whole system for 87 hours, including two large PCs used for data acquisition. The UPS sends e-mail alarms to operators, so that the PCs can optionally be switched off using the web controlled power switch. The rest of the system can then be operated for 5-6 days. The test also showed that the batteries reached full capacity after 7 hours of charging. Each of the 12 batteries can be monitored, and one battery can be exchanged with new, without interruption of the system. Each battery delivers 56 Volts when fully charged, and the system automatically shuts down if voltage drops below 43 Volts.

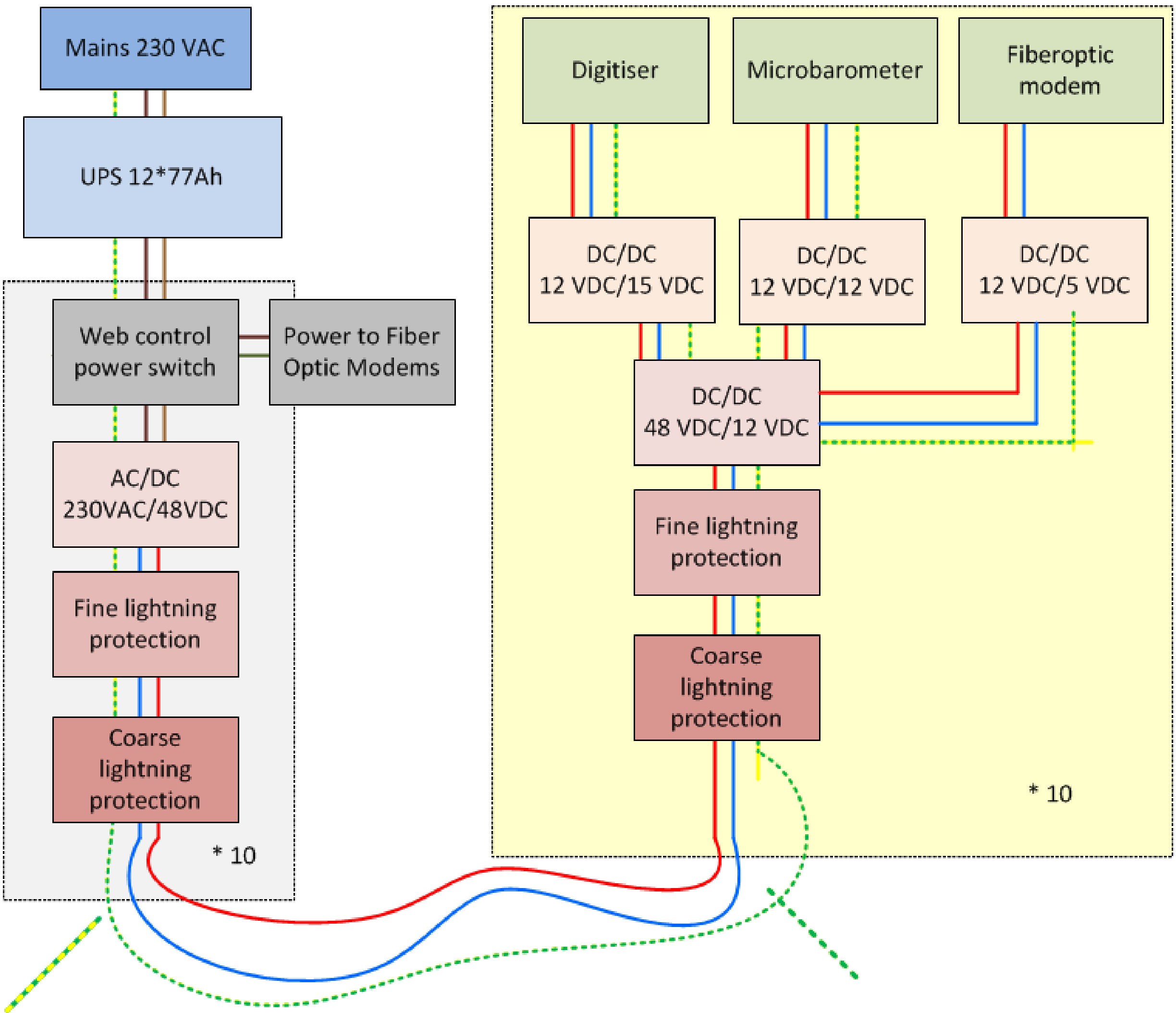

Fig 6.1.10 Block diagram for the power system at IS37.

The communication between the CRF and the remote pits is over single mode fiber cables with Luxcom OM-101 Ethernet converters in each end. Between the CRF and the NDC is a VPN connection over internet provided by DirectConnect. See Figure 6.1.11. The internet connection is utilized at site H7. Between H7 and CRF we use one pair of fibers from the fiber cable and Luxcom OM-101 Ethernet converters in each end. The VPN connection is handled by a CISCO ASA router at the CRF. All IP based units in the CRF are connected to this link via the Ethernet switch. The two PCs have two Ethernet interfaces. One of them is connected to the Ethernet switch. The other is connected to a GSM router, NetModule NB1600, which provides VPN connection to the NDC.

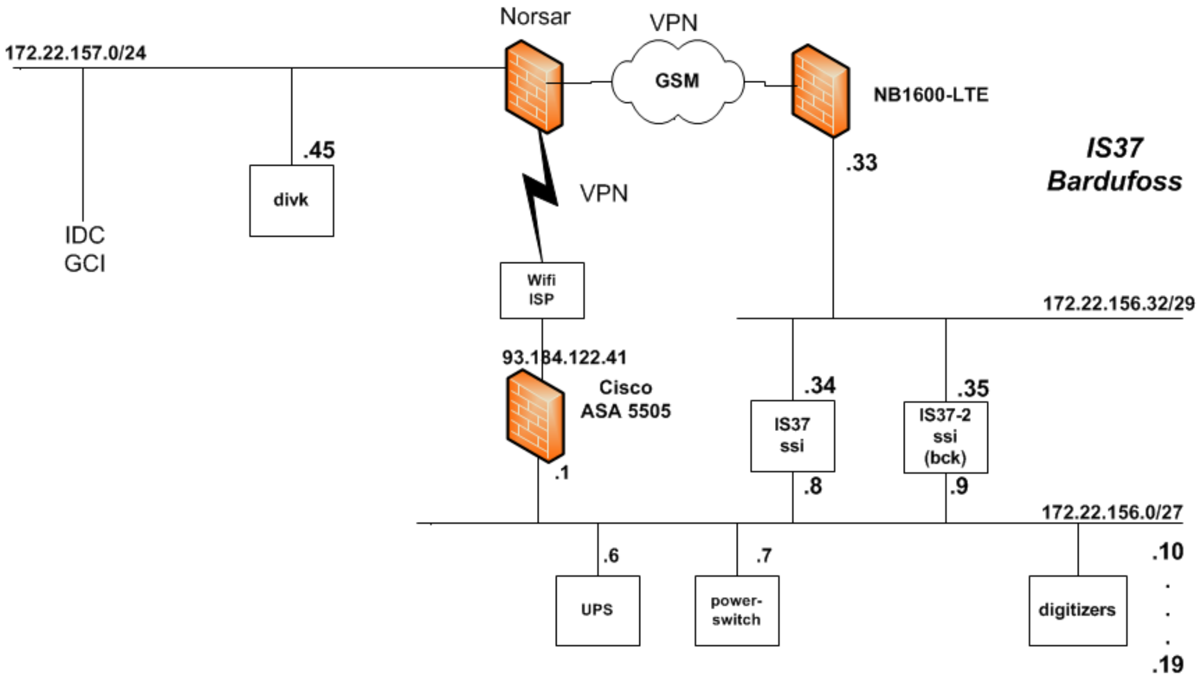

Fig. 6.1.11 The figure above shows a schematic of the IP configuration of IS37.

NORSAR is utilizing the feature of multiple sample rates from the Güralp digitizer. The sensors are thus sampled with 20 Hz for CD1.1 data to the IDC. Additionally, we collect data with 40 Hz sample rate for NDC use. All data are transmitted to the NDC and from there, only 20 Hz data are forwarded to the IDC.

We plan to change all sensor cables of the array to be able to additionally record absolute pressure.

Data received at the NDC are stored in an easily accessible data base of Unix files, and NORSAR keeps all its seismic and infrasound array data online on disk storage. In the same data base are also all data from all arrays, since the start of digital data acquisition from the large aperture NORSAR array in 1970.

Jan Fyen, NORSAR
Michael Roth, NORSAR
Paul W. Larsen, NORSAR

6.2 Infrasound signal detection from the Drevja accidental explosion

6.2.1 Background

We have undertaken an initial modelling effort in order to predict travel times for infrasound phases recorded at the new IS37 array. We are still in the knowledge build-up stage and more work needs to be done for us to establish a more robust arrival-time prediction framework.

In the following preliminary results, a ray-tracing engine was applied to the atmospheric conditions along the great circle path from the Drevja accidental explosion on December 17, 2013 to the new IS37 array. For comparison, we also made similar simulations for the two other Norwegian infrasound arrays ARCI and NRSI.

This analyzed ground-truth event was due to an exploding lorry carrying 15 tons of slurry. It took place at 65.988°N, 13.343°E at around 14h26 (UTC). The great circle distances from the event to the operating Fennoscandian infrasound arrays are listed in Table 6.2.1, while the sizes and geographic locations of these arrays are illustrated in Figure 6.2.1. Signals recorded at the Fennoscandian infrasound arrays as well as the Apatity infrasound array in northwest Russia are shown in Figure 6.2.2.

Table 6.2.1 – Great circle distances [km] from the Drevja event to all operating Fennoscandian infrasound arrays. Stations where ray-trace modelling is performed are typed in boldface.

LYC	Lycksele	294
KIR	Kiruna	368
IS37	**Bardufoss**	**399**
JAM	Jämtön	418
NRSI	**NORES**	**590**
SDK	Sodankylä	594
ARCI	**ARCES**	**639**

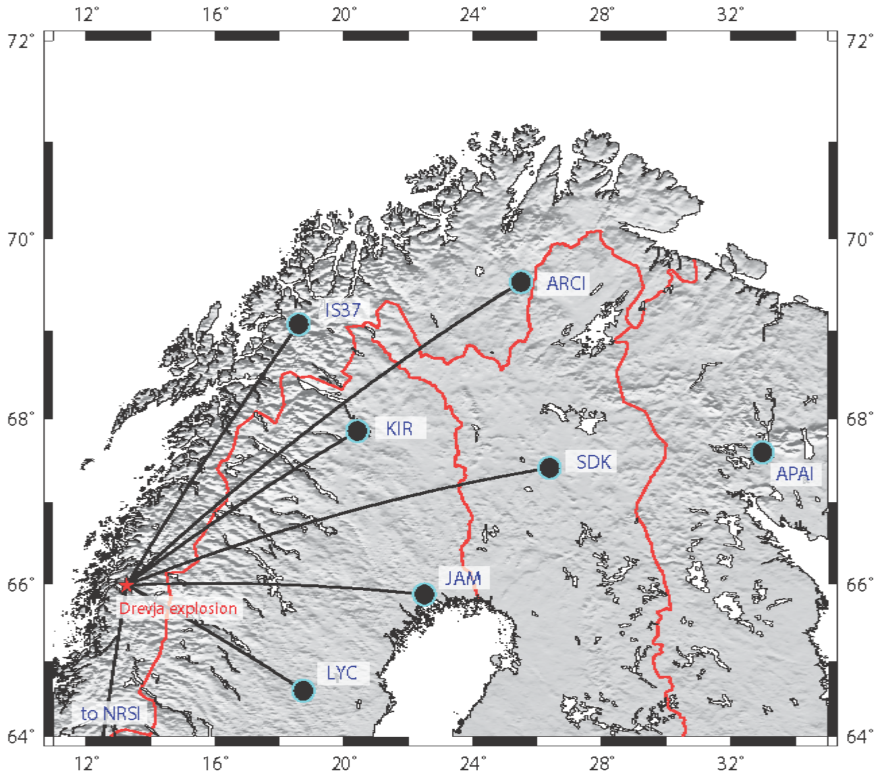

Fig. 6.2.1 The location 65.988°N, 13.343°E of the Drevja accidental explosion event in relation to the closest infrasound arrays.

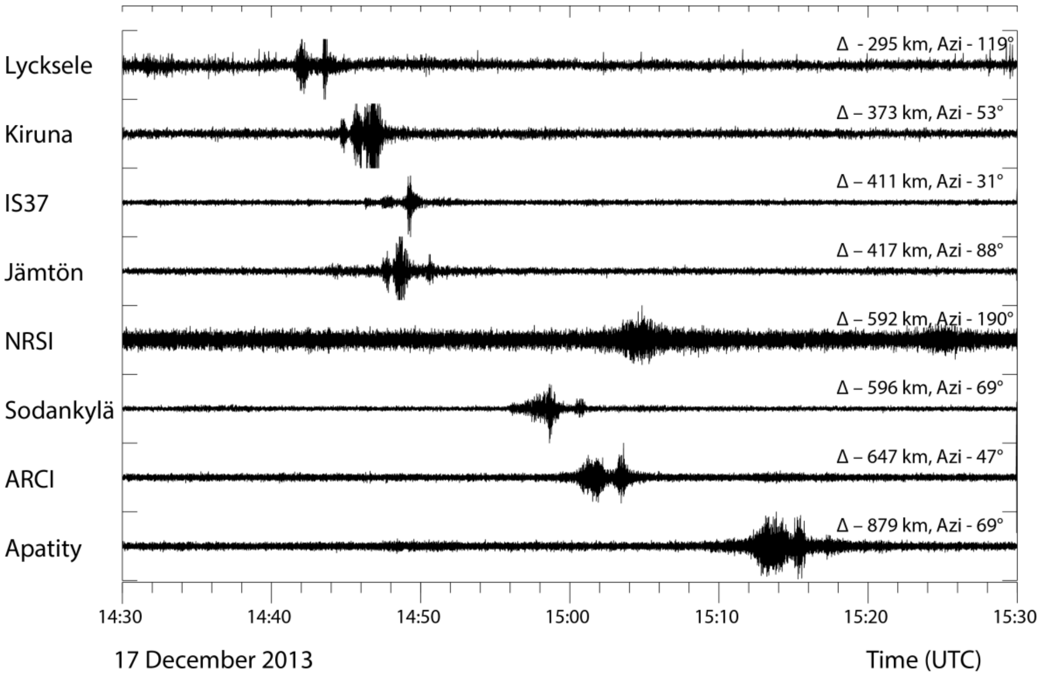

Fig. 6.2.2 Signals associated with the Drevja explosion recorded at the Fennoscandian infrasound arrays as well as the Apatity infrasound array in northwest Russia. The event-station distances and the event-station azimuth estimates are given in the right-hand side of the panel.

6.2.2 Methods

We used the Ground to Space (G2S) atmospheric model to extract wind and adiabatic sound speed profiles (Drob and Picone, 2003). This G2S model is based on the public National Oceanic and Atmospheric Administration (NOAA) global analysis fields from 0 to 45 km altitude. For altitudes between 35 and 75 km, it uses the GEOS5/MERRA public profiles published by NASA. In the overlap region, between 35 and 45 km altitude, the fields are included in the G2S profile by weighted averaging. Above 75 km, the G2S profiles are compiled from the empirical NRLMSISE-00 (temperature, see Picone et al., 2002) and HWM07 (wind, see Drob et al., 2008 and Emmert et al., 2008) models. The ray-tracing was carried out using the ART2D public code written by K. Walker at University of California, San Diego (Walker, 2012).

We refer to the different predicted infrasonic phase arrivals as tropospheric, stratospheric, and thermospheric depending on the highest altitude of the turning ray.

6.2.3 Results

For the signals recorded at the IS37 array, the signal to noise ratio (SNR) below 2 Hz is very low; it is far superior in the 2–5 Hz band. Such events demonstrate the usefulness of the array geometry with its innermost ring of closely spaced elements allowing the direction and apparent velocity of higher frequency signals to be estimated.

Figure 6.2.3 shows modelling results for the IS37 array location. Here, the ray-tracing predicts three distinct infrasound phase arrivals at ground level. Adding the corresponding travel times to the time when the explosion took place (14h26 UTC) yields: first a tropospheric arrival at around 14:46:30, then a stratospheric arrival at around 14:49:15, and finally a thermospheric arrival at around 14h50.

Looking at Figure 6.2.4, where the phase arrivals estimated by ray-tracing are indicated by vertical lines, we note that the first arrival estimate agrees with a received low-amplitude signal. The corresponding apparent velocity and back-azimuth from f-k analysis suggest that this is a tropospheric or stratospheric arrival from the direction of the event.

Similarly, the second predicted arrival corresponds well with an observed high-amplitude signal. In contrast, the third predicted arrival, which is a thermospheric phase, neither corresponds with a signal visible in the traces, nor with an increase in coherence between the element signals. The received signals also reveal a phase arrival at around 14h47. This is not directly predicted by the ray-tracing model. However, it is known that “head waves” are badly represented in ray-tracing and by using finer sampling of the ray angles, we see that the maximum range of the stratospheric first-bounce ground hit is extended. The tag “Extrapolated” in Figure 6.2.3 corresponds to such anticipated stratospheric first bounce arrivals at greater ranges than the ones shown by the plotted rays.

The apparent velocities estimated from f-k analysis looking only at correlation values exceeding 0.2 suggest that the observed phases are either stratospheric or tropospheric returns. However, as framed in green in the bottom panel of figure 6.2.4, when lowering the correlation threshold the backazimuth and apparent velocity estimates indicate a possible weak thermospheric arrival at around 14:51:30. This is around 1 minute later than what is predicted by the ray-tracing.

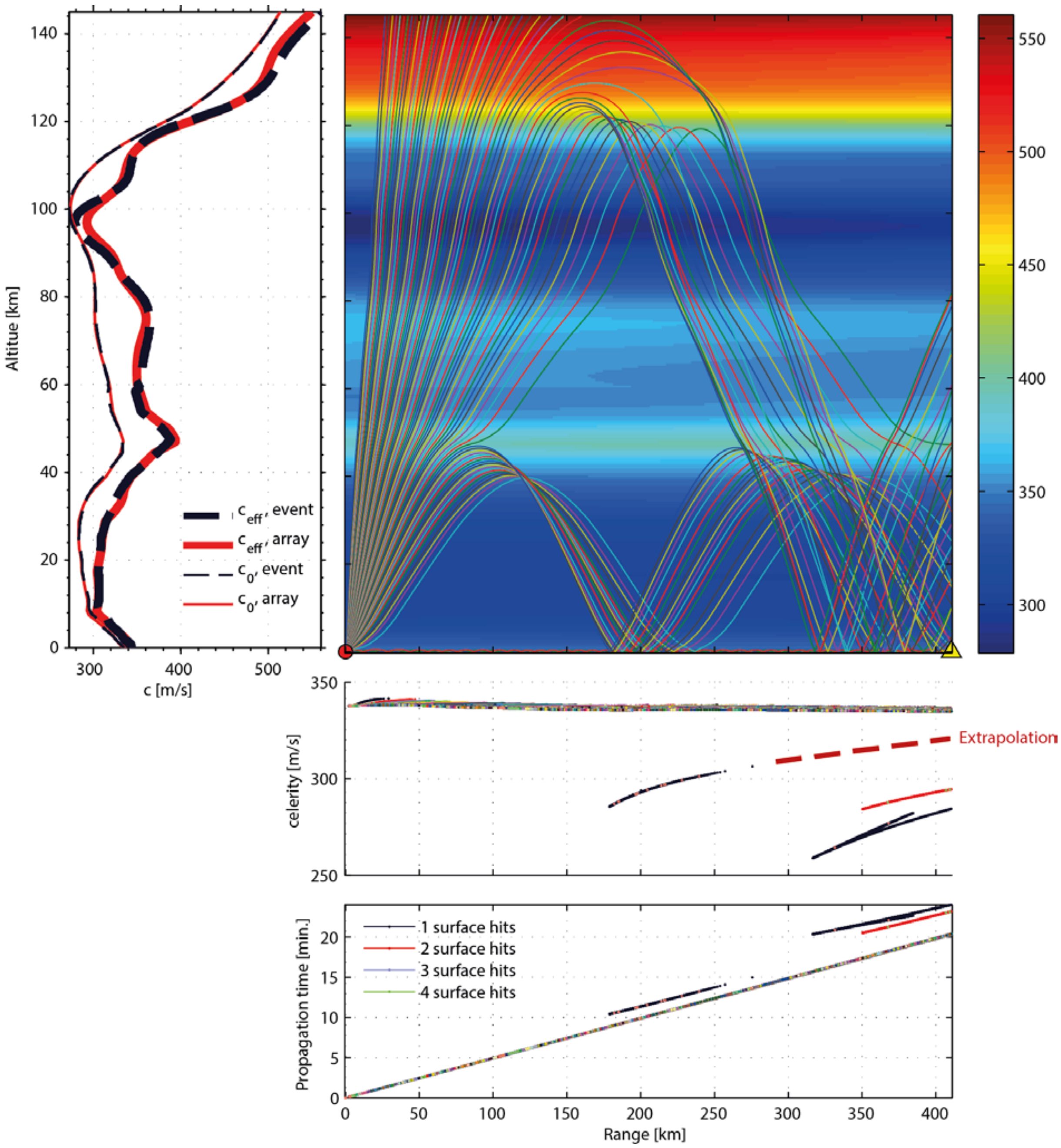

Fig. 6.2.3 Ray-trace modelling from the Drevja event to the IS37.
Top right panel: infrasound ray paths overlaid on a map of the effective sound speed $c_{eff} = c_0 + v_x$, where c_0 is the adiabatic temperature-dependent sound speed and v_x is the wind component in the direction of the great circle between the event and the array. For the predicted ground hits, the middle panel shows the corresponding celerity, while the bottom panel shows the propagation time estimate.
The tag "Extrapolated" corresponds to anticipated stratospheric first bounce arrivals at greater ranges than the ones shown by the plotted rays.
The upper left panel shows c_0 and c_{eff} profiles at the source and receiver end of the propagation path.

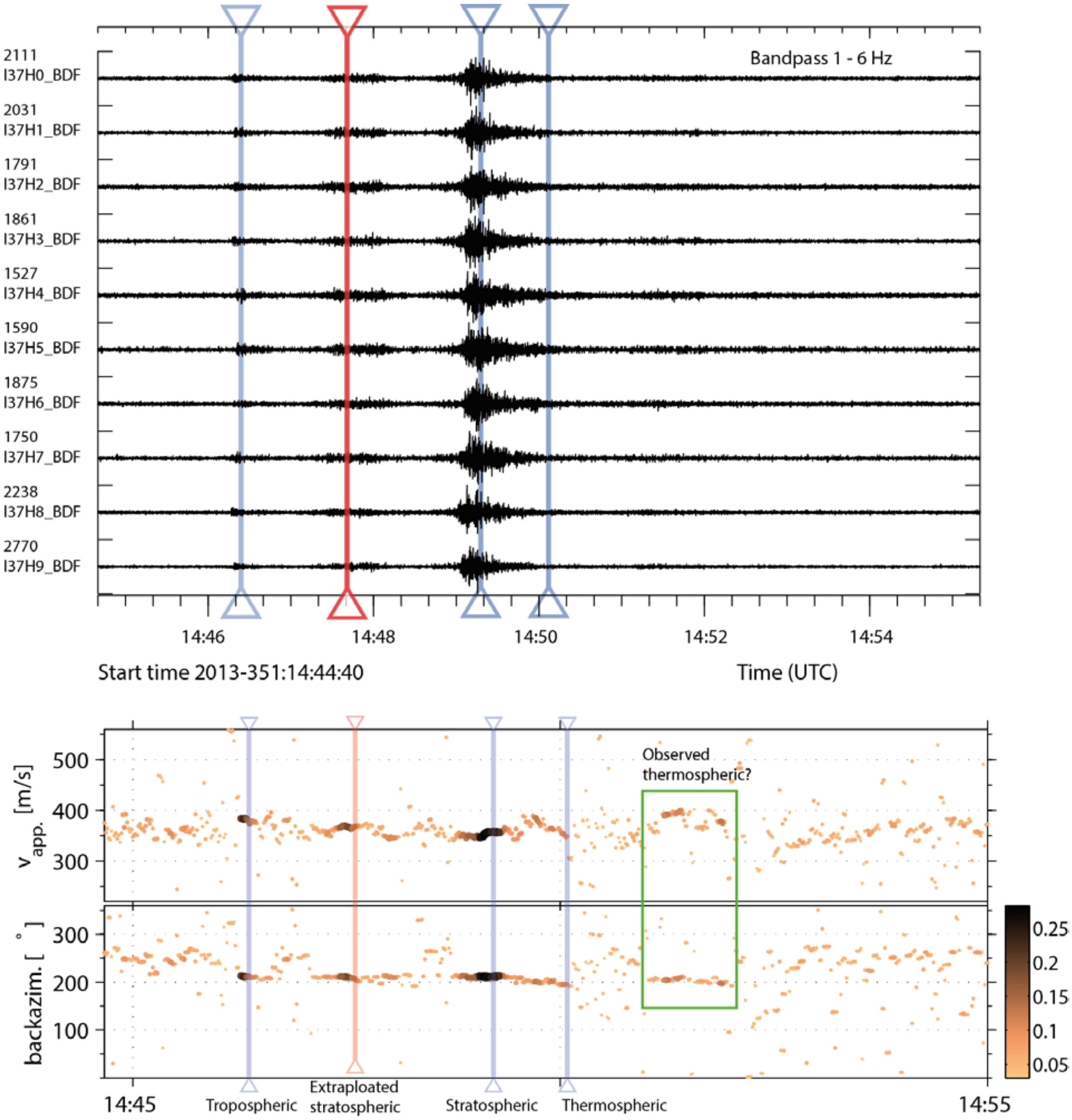

Fig. 6.2.4 The upper panel shows observations of the Drevja event at IS37, bandpass filtered between 1 and 6 Hz. Vertical lines are introduced at times when the ray-tracing predicts array arrivals (see Figure 6.2.3), where the red line represents the extrapolated stratospheric first bounce. The bottom panel shows the estimated apparent velocity and the back-azimuth from f–k analysis of the filtered received signals. The data point coloring is based on the correlation coefficient between the element signals which can be read from the colorbar. Recordings of possible thermospheric arrivals are framed in green.

For the ARCI array, the ray-tracing and signal analysis results are shown in Figures 6.2.5 and 6.2.6. Here we notice that the simulation predicts two arrivals: a tropospheric and a "double-bounce" stratospheric one. The collected data also reveals two distinct pulses. However, these are seen around 3 minutes after the predictions from ray-tracing while on the other hand the separation between them is in accordance with the simulations.

While the IS37 and ARCI arrays are located approximately north-east of the Drevja event, the NRSI array is south of it, hence making the wind along the acoustic propagation direction differ significantly. Therefore the conditions for the arrival of infrasound phases can be significantly different although the great circle distance is quite similar. Looking in Figures 6.2.7 and 6.2.8 for signals received from the event, no such are visible in the time-signal plots. But in the f-k analysis plot at around 15h05 we see a back-azimuth estimate which approximately corresponds to the direction to Drevja.

6.2.4 Conclusion

To conclude, we note that the ray-trace modelling corresponds best to the observed phase arrivals for the IS37 array. There, both a tropospheric and a stratospheric arrival are in accordance with the simulations. We need to examine whether the deviations between the model and the collected signals are mostly due to shortcomings of the ray-tracing method (which is a high-frequency approximation), or if it has more to do with the inherent inaccuracy of the atmospheric specification model.

We also plan to make similar analyses for the other infrasound arrays in the region.

Acknowledgements

We wish to thank Douglas P. Drob of the United States Naval Research Laboratory for provision of the G2S atmospheric specifications for this case study. The GEOS-5 data used in this study/project for the G2S specifications have been provided by the Global Modeling and Assimilation Office (GMAO) at NASA Goddard Space Flight Center through the online data portal in the NASA Center for Climate Simulation. The NOAA Global Forecast System (GFS) analyses fields, also for this study in the G2S specifications, are from NOAA's National Operational Model Archive and Distribution System (NOMADS), which is maintained at NOAA's National Climatic Data Center (NCDC).

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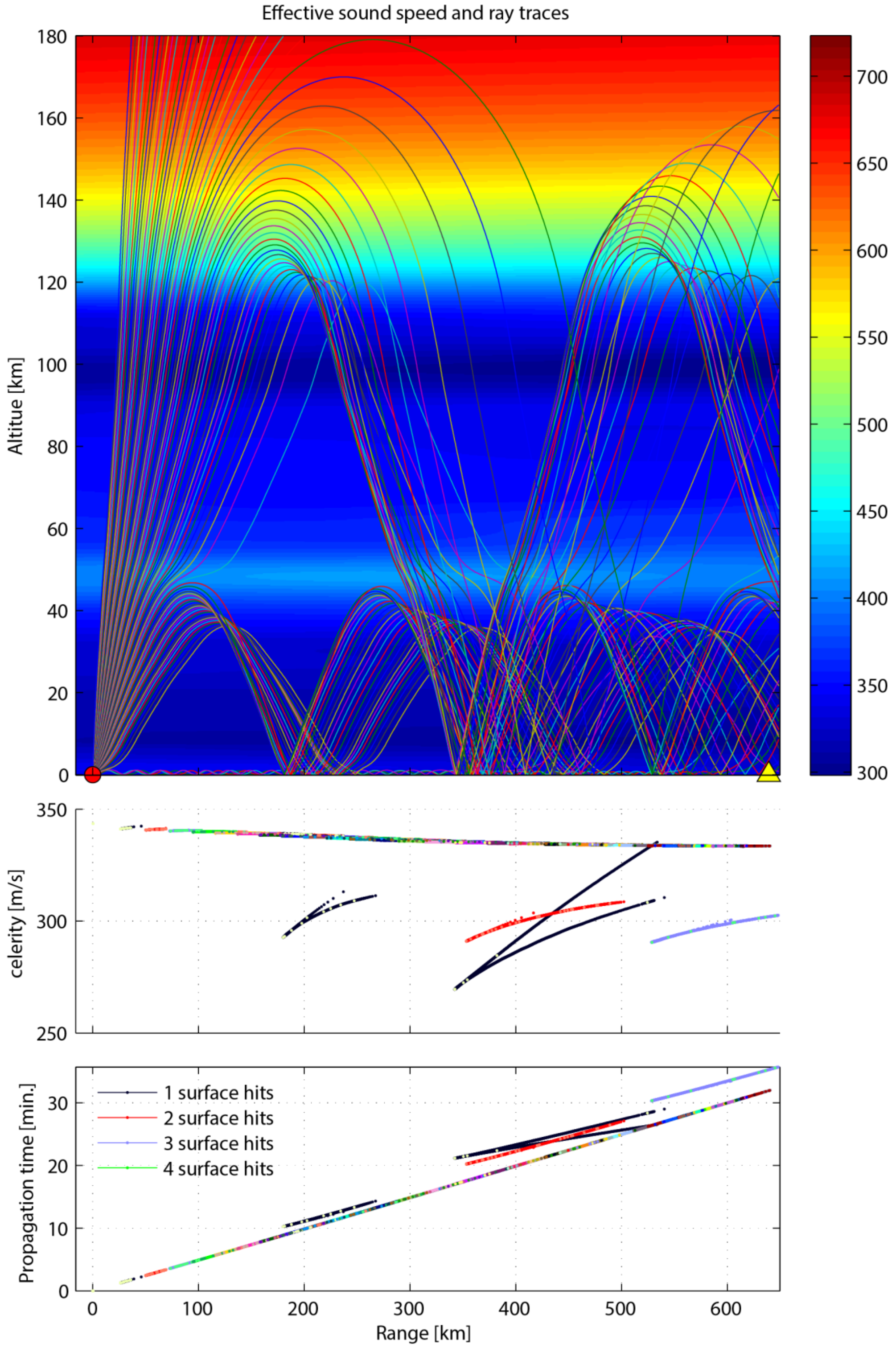

Fig. 6.2.5 Ray-trace modelling from the Drevja event to the ARCI array.
Top panel: infrasound ray paths overlaid on a map of the effective sound speed $c_{eff} = c_0 + v_x$, where c_0 is the adiabatic temperature-dependent sound speed and v_x is the wind component in the direction of the great circle between the event and the array. For the predicted ground hits, the middle panel shows the corresponding celerity, while the bottom panel shows the propagation time estimate.

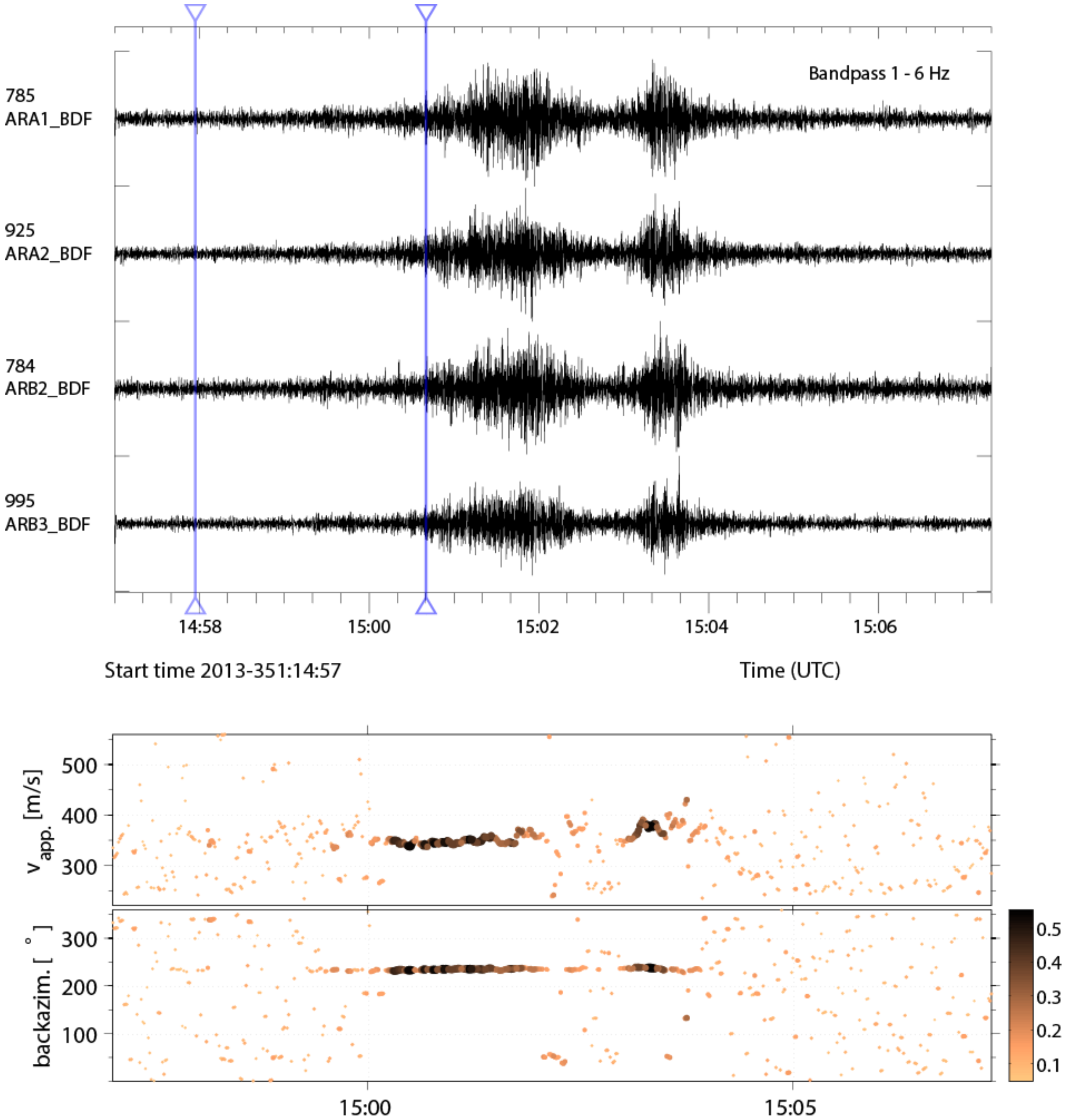

Fig. 6.2.6 The upper panel shows observations of the Drevja event at ARCI, bandpass filtered between 1 and 6 Hz. Vertical lines are introduced at times when the ray-tracing predicts array arrivals (see Figure 6.2.5).
The bottom panel shows the estimated apparent velocity and the back-azimuth from f–k analysis of the filtered received signals. The data point coloring is based on the correlation coefficient between the element signals which can be read from the colorbar.

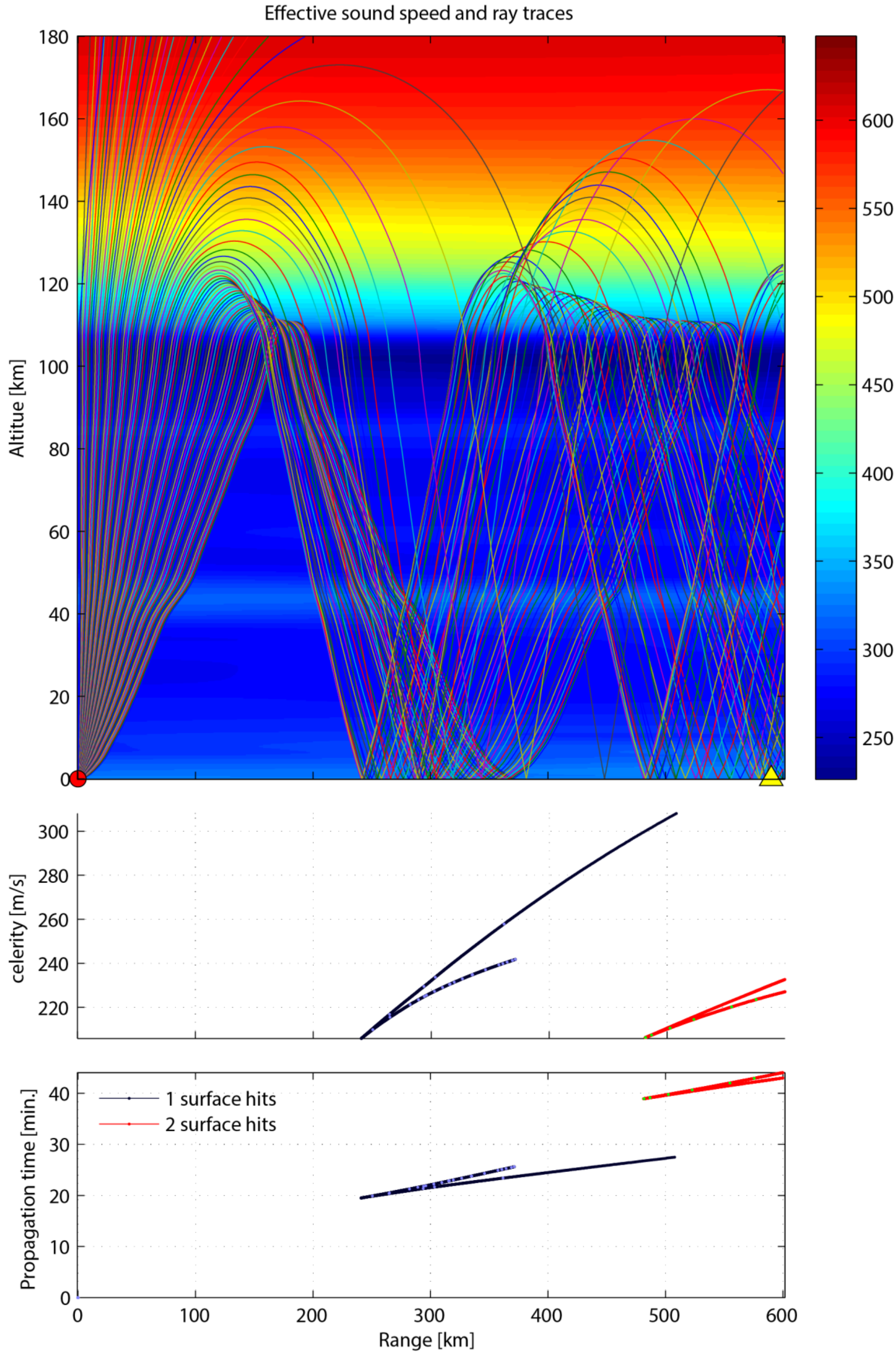

Fig. 6.2.7 Ray-trace modelling from the Drevja event to the NRSI array.
Top panel: infrasound ray paths overlaid on a map of the effective sound speed $c_{eff} = c_0 + v_x$, where c_0 is the adiabatic temperature-dependent sound speed and v_x is the wind component in the direction of the great circle between the event and the array. For the predicted ground hits, the middle panel shows the corresponding celerity, while the bottom panel shows the propagation time estimate.

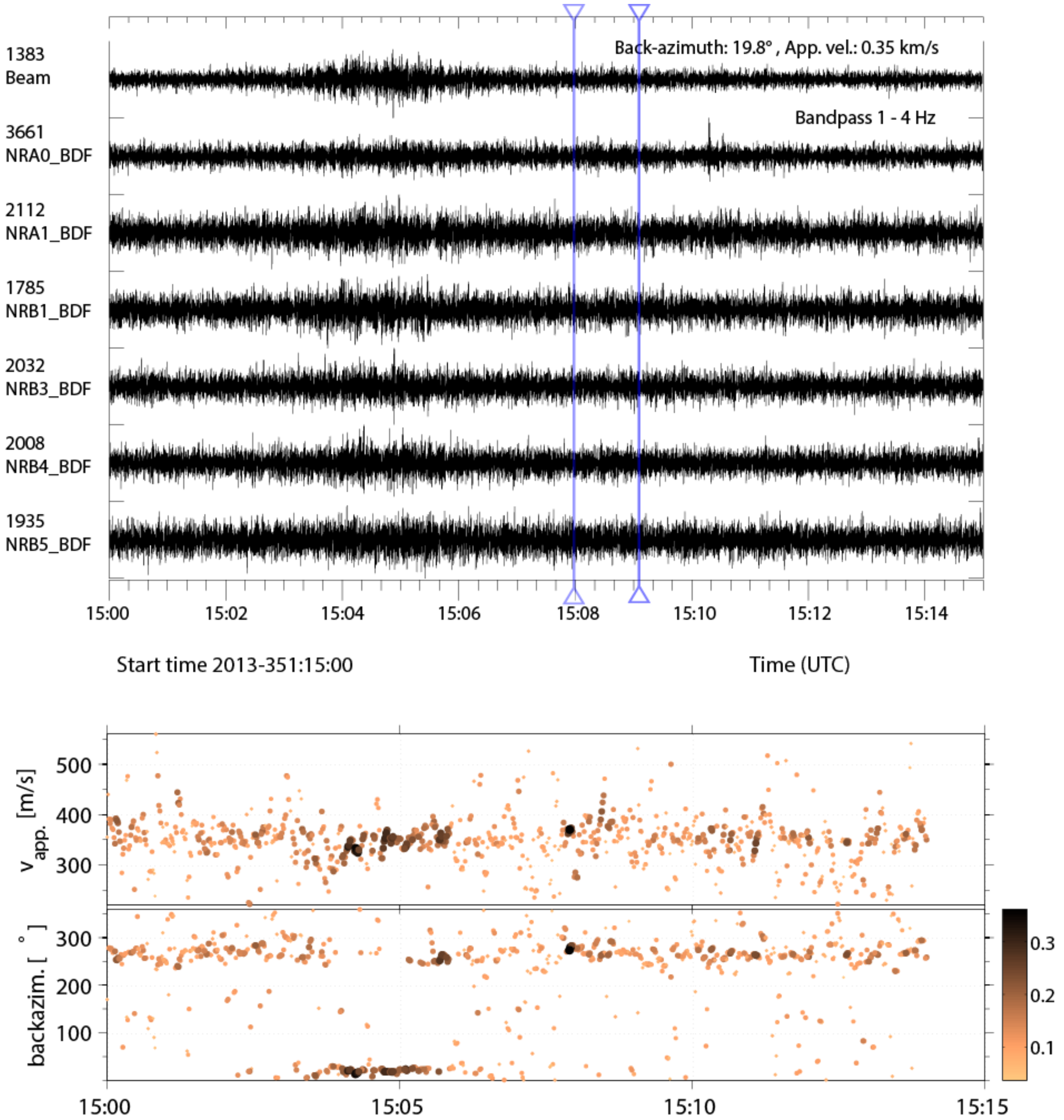

Fig. 6.2.8 The upper panel shows observations of the Drevja event at NRSI, bandpass filtered between 1 and 4 Hz. Vertical lines are introduced at times when the ray-tracing predicts array arrivals (see Figure 6.2.7).
The bottom panel shows the estimated apparent velocity and the back-azimuth from f–k analysis of the filtered received signals. The data point coloring is based on the correlation coefficient between the element signals which can be read from the colorbar. Note the increase in signal correlation and the stabilization of the back-azimuth estimate at ≈15°, corresponding to the direction of Drevja, for a couple of minutes around 15h05.

6.3 Location of the November 6, 2013, Valdres/Hallingdal Bolide from Infrasound Signals on the NORES Infrasound Array and the NORSAR Seismic Array

6.3.1 Introduction

On November 6, 2013, a fireball was both seen and heard over much of Southern Norway with an estimated time of 19.18.17 UT. The Norwegian Meteor Network (Norsk Meteornettverk, http://norskmeteornettverk.no/) collected large numbers of eye-witness accounts and, based upon directions provided by these observers, provided a location estimate somewhat to the West of the town of Fagernes. A preliminary search of the automatic detection list for the NORES infrasound array in Hedmark indicated strong signals shortly after this time coming from the West. An inspection of the seismic traces from the large aperture NORSAR array indicates that many of the seismic sensors also recorded converted acoustic signals. In this short report, I present the observations on these instruments together with an evaluation of how directional estimates from these signals can constrain the location of the event.

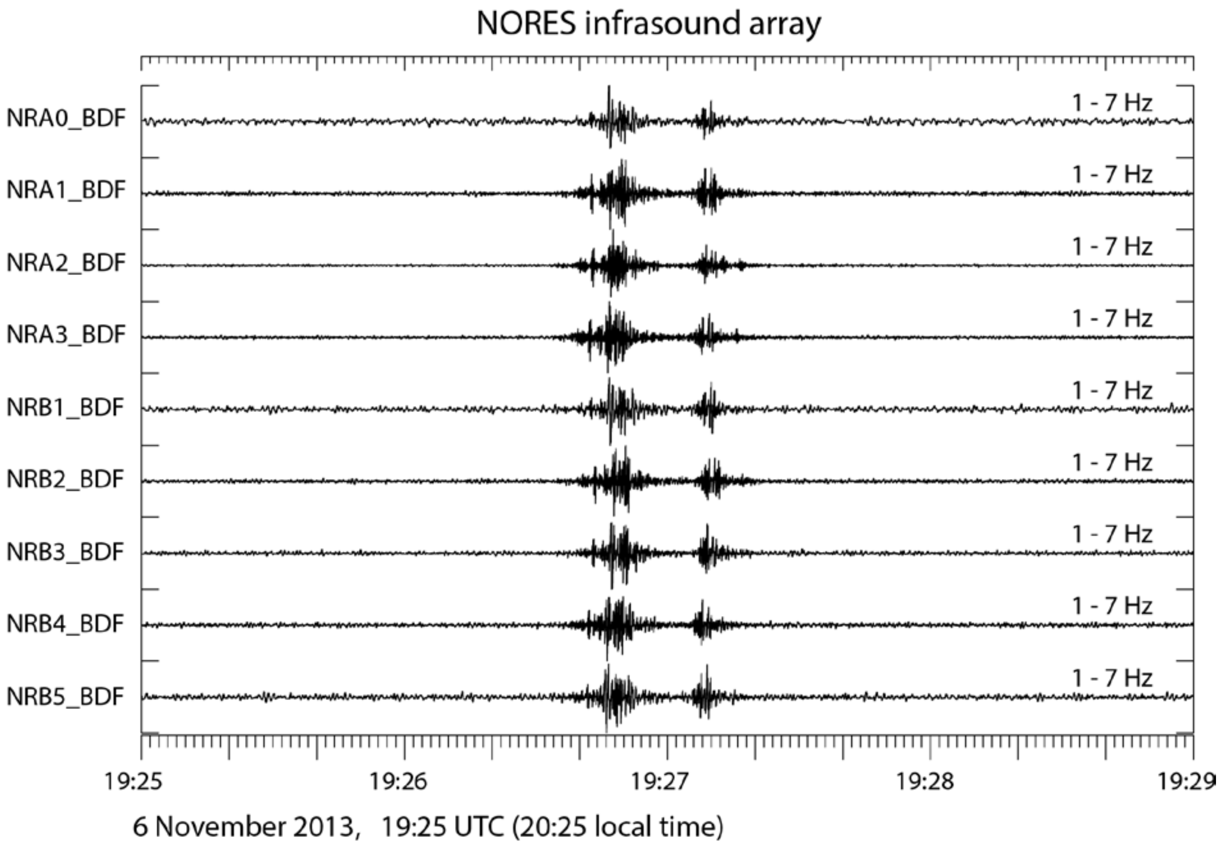

Fig. 6.3.1 Four minutes of microbarograph data from the 9 sensors of the NORES infrasound array bandpass filtered in the 1-7 Hz band.

6.3.2 Observation on the NORES infrasound array

The innermost 9 sites of the NORES seismic array have had infrasound sensors placed in the vaults since April 2013. (A 4-element infrasonic subarray had been running since February 2013.) Details of the array geometry and instrument responses are provided by Roth and Pirli (2013). A four minute data segment, including the signal assumed to be associated with the presumed bolide explosion, is displayed in Figure 6.3.1. The signal-to-noise ratio (SNR) is good over quite a large range of frequencies (1-10 Hz). There appear to be two major pulses of energy at NORES separated by approximately 25 seconds. The identification of this signal is non-trivial as most of the background noise in the 1-4 Hz band (in which the data is routinely processed) also comes from a similar direction. However, processing overlapping data segments (each of which being 10 seconds long) resulted in the detection of exceptionally coherent signals for a duration of approximately one minute starting at a time 2013-310:19.26.25 with backazimuth estimates between 274 degrees and 279 degrees, and apparent velocity estimates in the range [340 m/s:395 m/s]. A typical slowness grid for this time window is displayed in Figure 6.3.2.

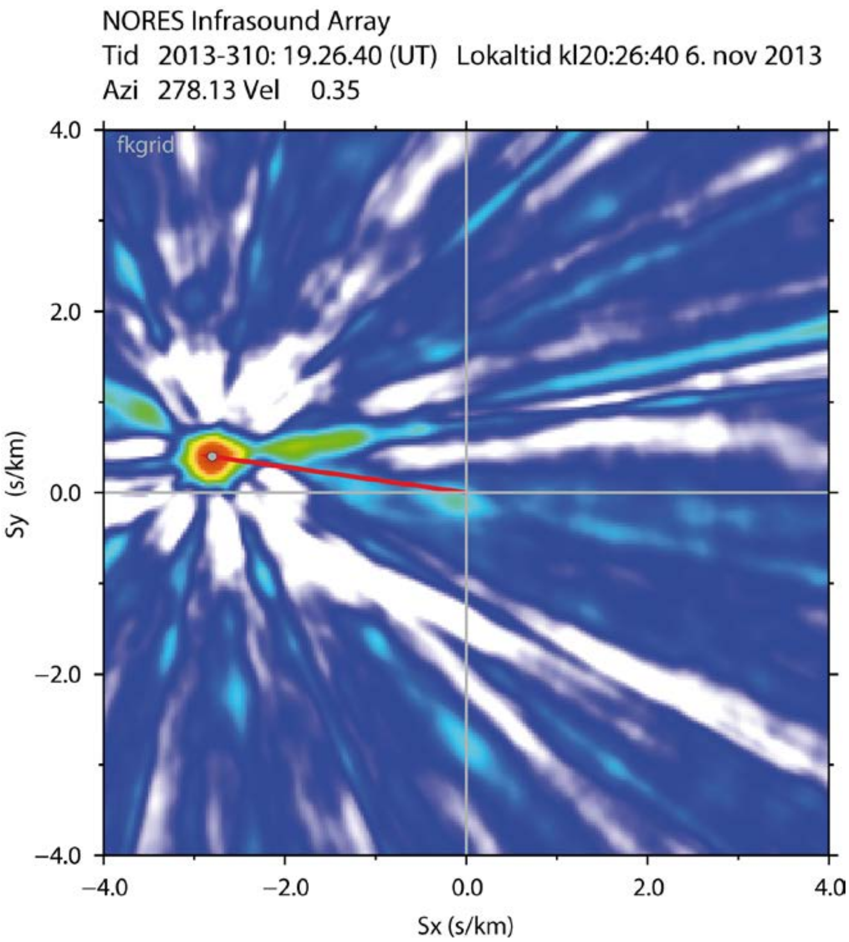

Fig. 6.3.2 Slowness estimate for the infrasound arrival at NORES at the time indicated. The 9 waveforms are bandpass filtered 1-4 Hz prior to parameter estimation, then all pairs of signals are cross-correlated, then the resulting 36 cross-correlation traces are stacked according to the predicted time-delays for a dense grid of slowness vectors. The method is described in more detail by Brown et al. (2002).The coordinates of the center element of the NORES array are 60.7353°N, 11.5414°E.

6.3.3 Observation of Converted Infrasonic to Seismic Signals on the NORSAR Seismic Array

It has long been acknowledged that infrasound can generate a response in seismic sensors. Gibbons et al (2007) demonstrated that the ARCES seismic array in northern Norway had acted as a surrogate infrasound array for almost 20 years - providing excellent records of the acoustic signatures from mining and military explosions in the region - without any of these signals having been classified correctly at the time. The ARCES array has properties that make it quite amenable to the recording of acoustic signals. Firstly, the instruments are all placed in surface vaults, and secondly, the inter-site spacings are small - meaning that acoustic waves above 2 Hz are coherent from sensor to sensor. (Below 2 Hz, the noise generated by ocean waves is usually too high at stations in Fennoscandia for acoustic signals to have an appreciable SNR.) In contrast, the NORSAR array has very large inter-site spacings (with a typical distance of around 5 km between adjacent seismometers) leading to incoherence in the frequency band of interest. The instruments in the NORSAR array are also placed either in boreholes or very large underground vaults, which reduces the possibility of recording atmospheric sound.

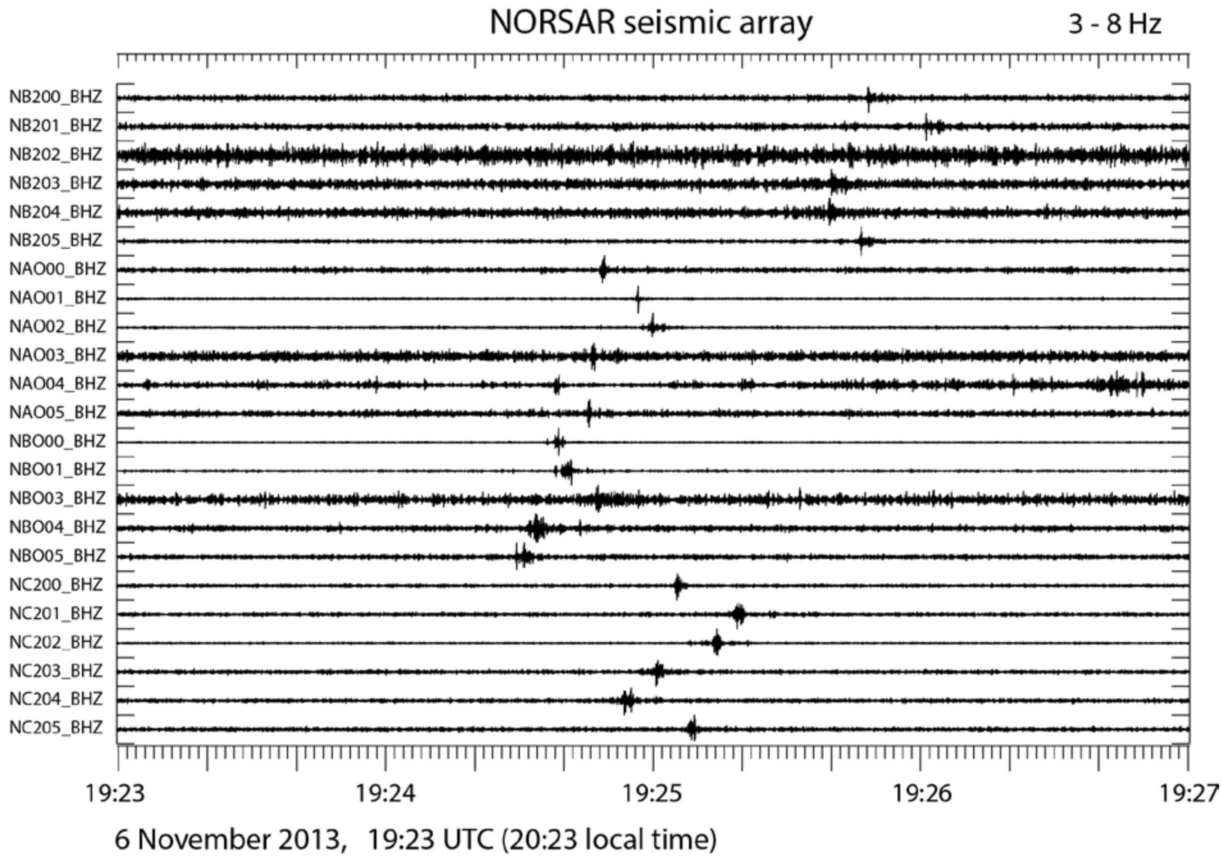

Fig. 6.3.3 Four minutes of waveform data from four subarrays of the large aperture NORSAR (or NOA) seismic array. All waveforms are bandpass filtered 3-8 Hz.

On four of the seven subarrays of NOA short bursts of high frequency energy were well observed, the best signals being observed on the three most westerly subarrays (Figure 6.3.3). The time delay between the acoustic signals on adjacent seismometers is typically longer than the duration of the signals themselves and a rapid inspection of the signals demonstrates that there is not enough waveform similarity for a classical array-processing direction estimator to be applied.

The infrasound community is now realizing that dense deployments of seismometers may provide a far greater spatial representation of the infrasonic wavefield than the limited number of available infrasound arrays (see, for example, Hedlin et al., 2010). This is in spite of the poorer SNR and fidelity to the atmospheric sound signal that the seismometer provides relative to a microbarograph. Hedlin and Walker (2013) advocate the use of reverse time migration (RTM) to be able to locate the sources of infrasound observed over a dense seismic network.

Table 6.3.1 Elements of the NORSAR array at which a time of maximum amplitude for the converted infrasound signal was measured. The times are given in UT in the format ddd:hh.mm.ss.sss where ddd is the Julian day (310 for November 6, 2013), hh, mm, and ss.sss are the hours, minutes and seconds.

Station	Latitude	Longitude	Picked Time of Max. Energy
NB200	61.0397	11.2148	310:19.25.48.168
NB201	61.0495	11.2939	310:19.26.01.580
NB202	61.0069	11.2778	310:19.25.44.815
NB203	61.0107	11.1677	310:19.25.39.599
NB204	61.0498	11.1581	310:19.25.40.530
NB205	61.0710	11.1977	310:19.25.46.677
NAO00	60.8237	10.8324	310:19.24.48.744
NAO01	60.8442	10.8865	310:19.24.56.382
NAO02	60.8057	10.8971	310:19.24.59.921
NAO03	60.7881	10.8084	310:19.24.46.695
NAO04	60.8105	10.7625	310:19.24.38.685
NAO05	60.8507	10.8193	310:19.24.45.578
NBO00	61.0307	10.7774	310:19.24.38.871
NBO01	61.0616	10.7834	310:19.24.41.479
NBO03	61.0129	10.8371	310:19.24.47.440
NBO04	61.0119	10.7524	310:19.24.33.656
NBO05	61.0597	10.7219	310:19.24.29.930
NC200	61.2807	10.8354	310:19.25.05.509
NC201	61.2988	10.9138	310:19.25.18.922
NC202	61.2545	10.9110	310:19.25.14.265
NC203	61.2438	10.8318	310:19.25.00.852
NC204	61.2759	10.7629	310:19.24.54.333
NC205	61.3231	10.8227	310:19.25.09.235

In this case study, it is likely that the size of the observing network, relative to the distance from the source, is sufficiently small that the spread of the wavefield can be approximated well using a circular wavefront model (see Almendros et al., 1999). Given the difference in forms from signal to signal, and the long time needed to propagate over the array (surrogate infrasound network), it appeared that simply estimating the times of the maximum energy on each trace was a sufficient time indicator. Table 6.3.1 provides a list of all of the stations on NOA for which a signal was well observed, together with an estimate of the time of maximum acoustic energy. Setting the reference station to NB200 (the central element of the current NORSAR array) and assuming that the waves all propagate with a horizontal slowness of 2.85 s/km (i.e. 350 m/s) then the iteration prescribed by Almendros et al. with the information provided in Table 6.3.1, results in a backazimuth of 265 degrees and with a distance of approximately 120 km.

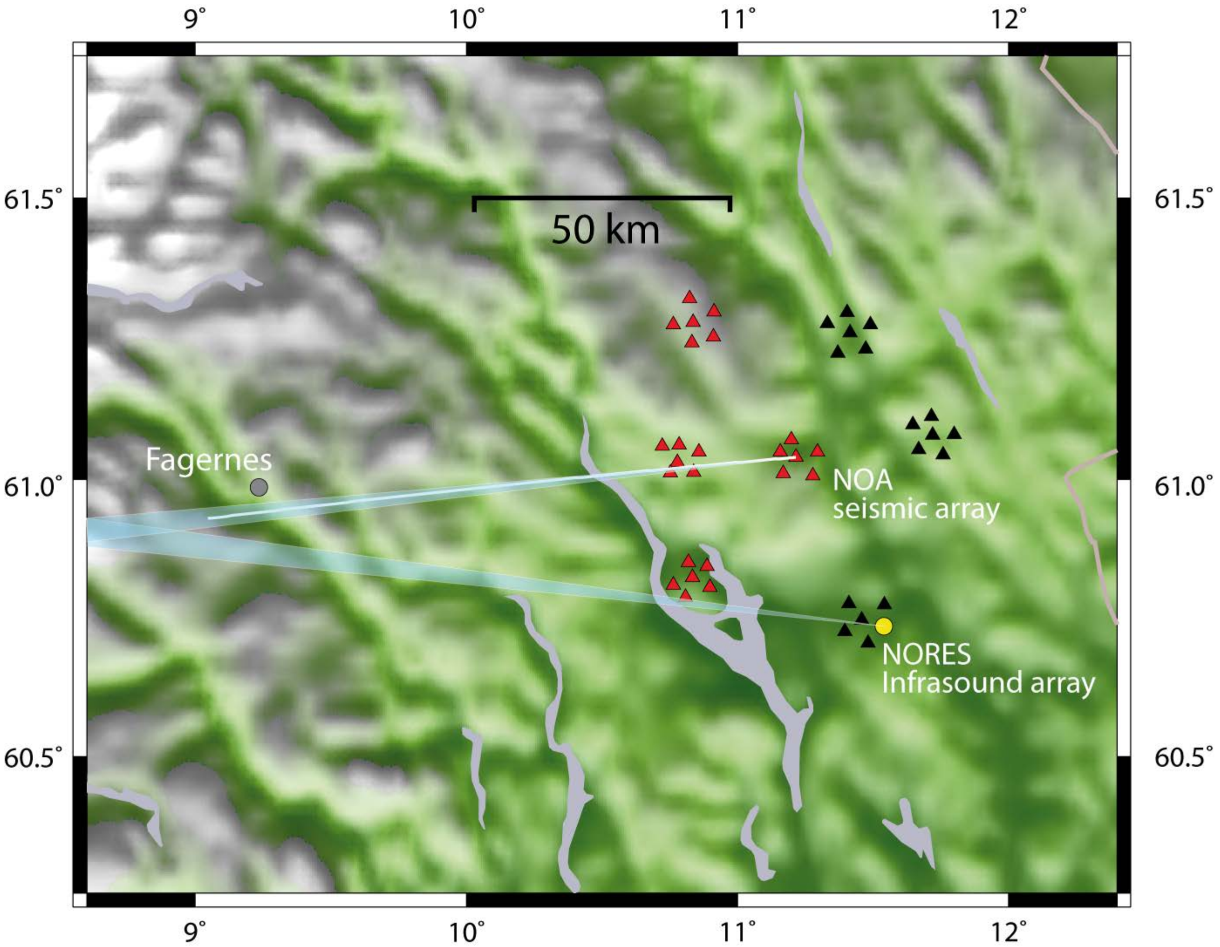

Fig. 6.3.4 Map displaying the location of the NORES infrasound array together with the sites of the NOA (NORSAR) seismic array. Sites with red symbols are those displayed on Figure 6.3.3 which recorded a visible acoustic signal (with the exception of site NBO02 which was not in operation) – the black symbols indicate sites at which no acoustic signals were clearly visible. The blue ray from NORES is a projection of a backazimuth of 278 degrees, and the blue ray from site NB200 of the NOA array is projection of a backazimuth of 265 degrees. The white line marked along this projection has a length of 120 km, the distance from source indicated by the simple curved-wavefield model of Almendros et al. (1999).

6.3.4 Summary

The geometry of the stations, together with the inferred bearings towards the source of the presumed bolide explosion are displayed in Figure 6.3.4. While the station geometry with respect to the source region is poor (the azimuthal gap is very large), the location obtained using a simple bearing between the two different arrays appears to provide a location estimate that is very similar to that inferred from the visual observations (see http://norskmeteornettverk.no/wordpress/?p=867 - In Norwegian).

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All plots were generated using the GMT software (Wessel and Smith, 1998).

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NORSAR

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