NORSAR System Responses Manual

3rd Edition

Myrto Pirli

NORSAR, Kjeller, Norway

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INTRODUCTORY NOTES

to the 3rd Edition

This is the 3rd Edition of the NORSAR System Responses Manual. Apart from minor revisions to previously composed chapters and additions of new systems to already described arrays/stations (*e.g.*, the new, hybrid NORSAR array configuration, the new NORES, *etc.*), this edition has been re-structured to include response information of Norwegian National Seismic Network (NNSN) stations and other permanent stations in the region, as well as temporary, project-specific installations. In addition, responses for NORSAR's and other institutions' infrasound arrays are described. Thus, the documentation is now divided into four Parts (1, 2, 3 and 4), the first one describing the system responses of NORSAR seismic arrays and stations, the second of NNSN seismic stations and other permanent stations, the third of temporary seismic installations, and the fourth of infrasound arrays.

Part 1 includes Chapters 1 to 13. Except for seismic arrays and stations owned and operated exclusively by NORSAR, this compilation of Chapters includes systems where NORSAR has a year-long involvement and cooperation. New NORSAR and collaborative stations will be listed in this part, as well as upgrades and refurbishments of existing systems.

Part 2 includes Chapters 1 to 6. As already mentioned, NNSN, permanent regional network stations and stations owned and operated by third parties contributing regularly to NORSAR's database will be covered in this Part.

Part 3 includes temporary and project-specific installations. It describes the responses of the broadband ocean-bottom seismometer deployment (Chapter 1) and the seismic array BJOA on Bjørnøya (Chapter 2) realized within the International Polar Year 2007-2008 (IPY) project "The Dynamic Continental Margin Between the Mid-Atlantic-Ridge System (Mohns Ridge, Knipovich Ridge) and Bear Island".

Part 4 includes Chapters 1 to 4. There, the responses of the infrasound arrays operated by NORSAR are described, following a similar presentation as for the seismic channels.

As with the previous editions, the principal aim of this documentation is to concentrate and organize the significant volume of information on NORSAR systems' responses, and to make the information available to future users, with varying degrees of familiarity either with the systems themselves or the procedure of system response determination. Shorter and maybe easier to follow descriptions of each system response are published in several NORSAR Scientific Reports. However, in the case one needs to recalculate the responses, the usage of this documentation is strongly advised instead.

Part 1, Chapter 1: Initially, the problem of recalculating NORSAR systems' responses is addressed, and a brief description of the adopted procedure is provided. Links to a citation list (§ References) for further reading and original information sources are provided within this chapter, as well as in the rest of the documentation, with a separate list for each chapter. No specific examples of response determination are provided in this chapter, since actual responses are discussed in Section x.2 of each chapter.

Part 1, Chapter 2: The first section consists of a brief description and development history for the NORSAR array. This includes a more general subsection with the timeline of the development of the different configurations and instrumentations, as well as a listing of available information necessary for the determination of each system component's response. Moreover, a short description of each component is provided. The following section focuses on the calculation of the response of each configuration. Each subsection corresponds to a different configuration for the system under discussion (*e.g.*, a separate subsection for the original NORSAR array short period configuration and a separate subsection on the current short period configuration). The components of each configuration are presented, as well as the way to calculate each response by means of transfer function poles and zeros and gain. In the case that overall channel response depends strongly on system components (*e.g.*, digitizer gain is seismometer driven, as in the case of the AIM24), more detailed information is provided regarding the calculation of the overall system response. Examples of numerical computations are also included where deemed necessary. The sources of information used throughout this chapter are listed in the References section.

Part 4, Chapter 1: Some aspects of calculating responses for infrasound stations are discussed, highlighting the differences to response estimates for seismic channels.

The remaining chapters in this documentation are structured in the same logic as Chapter 2 (Part 1), independently of the Part they belong to.

Additional information that would decrease the readability of the text is provided in the Appendices that follow. References to them are made in the related text.

Digital copies of the complete documentation in PDF format and individual sections in PDF and Microsoft Word format are stored under /ndc/programs/dpep/dbtables/2008/ documentation/.

Finally, but most significantly, a few words of acknowledgement. This work would never have come so far without the indispensable help of the NORSAR staff. Most of all, the contributions (in the form of information, relevant literature, help with the implementation and a lot more) of Jan Fyen, Johannes Schweitzer, Paul W. Larsen, Svein Mykkeltveit and Michael Roth are gratefully acknowledged. Jan Fyen, Michael Roth and Johannes Schweitzer reviewed this edition of the manual, while previous versions were reviewed also by Frode Ringdal, Tormod Kværna and Steven J. Gibbons. Regarding the Hagfors and FINES array responses, Nils-Olov Bergkvist, FOI, and Jari Kortström, University of Helsinki, provided a great wealth of information. Jan Wiszniowski from the Institute of Geophysics of the Polish Academy of Sciences provided crucial information regarding the current instrumentation of the HSPB station and reviewed the corresponding chapter. Crucial information to reconstruct the latest Apatity array response was provided by Vladimir Asming, KRSC. Information about NNSN stations responses was provided by Lars Ottemöller, UiB. Frank Krüger, University of Potsdam, and Mechita Schmidt-Aursch, AWI, provided information about the IPY land and ocean-bottom temporary installation instrumentation. I am grateful to Reinoud Sleeman at the ORFEUS Data Centre for his kind help with issues regarding response formats, for providing feedback and an invaluable quality control of the calculated responses.

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Myrto Pirli

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PART 1

CHAPTER 1: CALCULATION OF NORSAR SYSTEM RESPONSES

1.1 Methodology

1.1.1 Response calculation procedure

Information about NORSAR system responses can be obtained from numerous sources, such as instrument manuals and datasheets, NORSAR publications, available macros and subroutines, as well as directly from the staff.

The approach followed here to calculate system responses and update the information inside the NORSAR system, presented schematically in the flowchart of Fig. 1.1, is the following:

1. All available information about the instrumentation, modifications and development in time of a specific array/station are gathered together. A short description of the instrumentation is compiled, followed by a list of relevant parameter values (*e.g.*, instrument sensitivity, natural frequency, *etc.*).
2. From the total volume of information, a 'history' of system modifications is compiled and documented (see *e.g.*, *GSE* response file /ndc/programs/dpep/dbtables/2008/NOA/cal2_noa for the NORSAR array).
3. System responses are initially calculated and organized in *GSE2.0* format (GSETT-3, 1997). Corresponding *GSE* response files include short descriptions of each system component (*e.g.*, sensor, amplifier, A/D converter), mainly referring to instrument model, used parameter values and normalization information. Moreover, in the case that only nominal values are available, this is clearly stated and the response is described as 'nominal' or 'theoretical', otherwise instrument serial numbers are listed in the *GSE* files. Information is inserted in the *GSE* files manually. Finally, the *GSE* response file format has been modified, to enable easier usage of response information (see §1.1.2, this Chapter). All computed *GSE* response files are stored under the path /ndc/programs/dpep/dbtables/2008/ARRAY/GSE/, where ARRAY should be substituted with each array/station name.
4. *GSE* response files are then converted to *DATALESS.SEED* volumes, using the *gse2seed* conversion tool (Sleeman, 2003) and *SEED* response files (*RESP.SEED*) are generated from the *DATALESS.SEED* volumes using the *rdseed* program (O'Neill *et al.*, 2004). Using the utility *evalresp* (IRIS, 2006), *FAP* files are created. Obtained *RESP.SEED* files reside under the path /ndc/programs/dpep/dbtables/2008/ARRAY/RESP/.
5. The validity of obtained response results can be assessed based on theoretical considerations (*e.g.*, expected form of the amplitude and phase graphs), available information (*e.g.*, accordance in gain with previously reported results and calculated magnitudes) and comparison against waveforms of known instrument response.
6. Final *FAP* tables were named according to network name, *GSE* file *Respid* (see §1.1.2), site and channel name, and are stored under the path /ndc/programs/dpep/dbtables/2008/ARRAY/FAP. Details on the naming convention for *FAP* files are provided in paragraph 1.2.2.
7. Finally, a system of scripts/macros has been compiled to introduce calculated *GSE Calib*, *Calper* values in the corresponding NORSAR db system *CSS3.0* tables, taking into consideration the time interval described by the *Ondate*, *Ontime* and *Offdate*, *Offtime* fields in the *GSE* response files. The *GSE Calib* and *Calper* values are appointed as *ncalib* and *ncalper* values in the db system .instrument file, respectively.

Then, *ncalper* is appointed equal to *calper* in the .sensor and .wfdisc files, while the *calratio* field in the .sensor file is set to 1.0 (Anderson *et al.*, 1990).

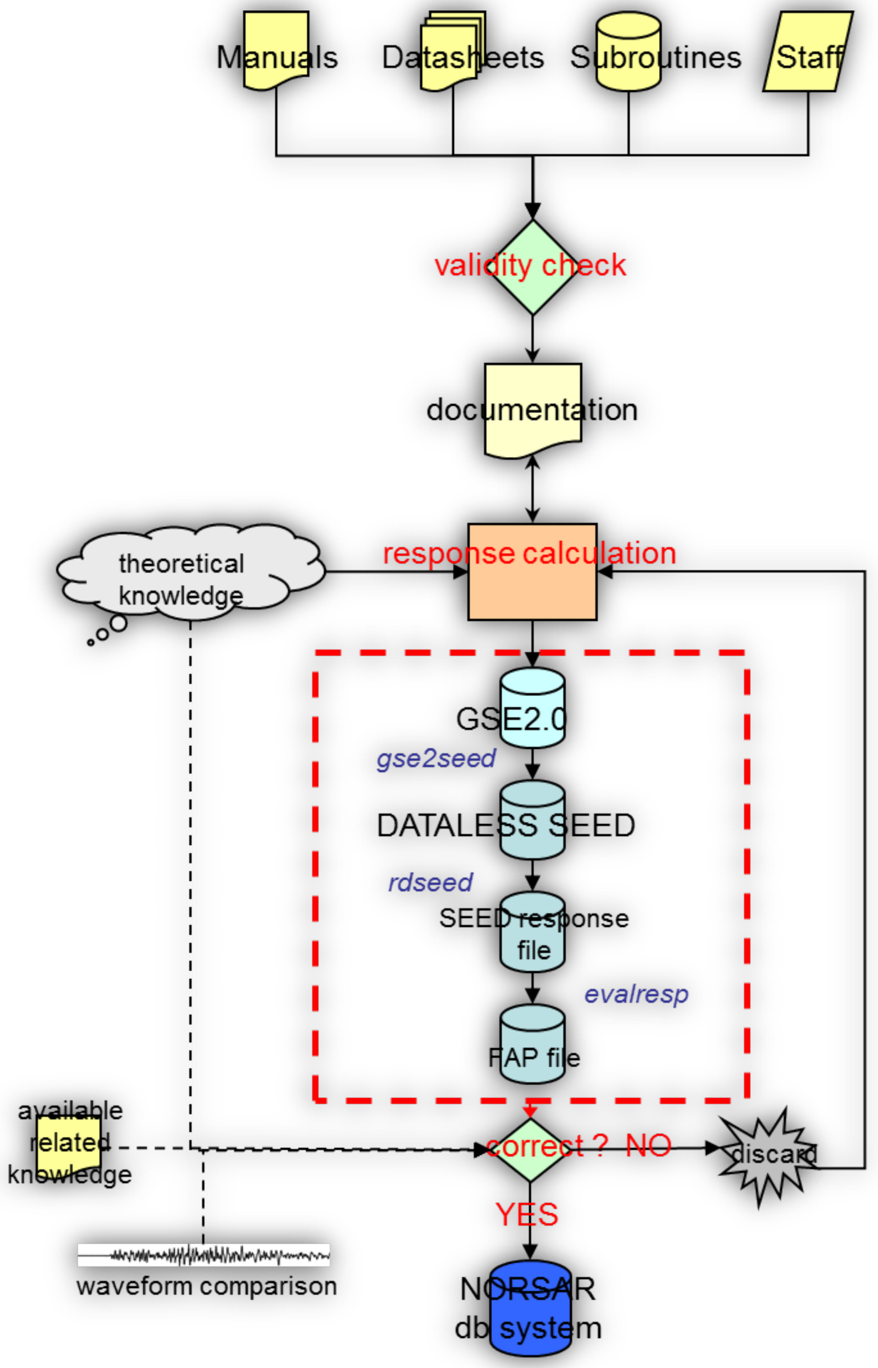


Fig. 1.1. Flowchart of the NORSAR systems response calculation procedure described in the present documentation.

1.1.2 <u>Conversions between different response formats</u>

As already discussed in the previous section, the procedure followed to update NORSAR's response database involves the calculation of system responses in different formats. This conversion line will be described briefly in this section.

Starting with a *GSE2.0* response file, the overall response of a system (sensor, digitizer, digital and/or analog filters, *etc.*) for a particular time period is summarized in the file's CAL2 line as the overall channel gain in nm/count at a particular calibration period (s).

The next response format in the chain is *DATALESS.SEED* volume, out of which *RESP.SEED* files can be extracted for particular stations/channels. Overall channel sensitivity is expressed in count/m/s for the declared calibration frequency (Hz).

Then, *FAP* files can be obtained for each configuration. Note that the employed utility *evalresp* used to produce the *FAP* response files outputs channel sensitivity in count/m. However, due to the fact that the *CSS3.0* schema requires *ncalib* to be in count/nm, a modified *evalresp* version is in use at NORSAR, writing *FAP* files with amplitude values in count/nm.

The corresponding command chain is the following:

GSE2.0 → *DATALESS.SEED*:	*gse2seed* –i ####.gse –o ###_DATALESS.SEED
DATALESS.SEED → *RESP.SEED*:	*rdseed* –R –f ###_DATALESS.SEED
RESP.SEED → *FAP*:	*evalresp* SSS CCC 2011 001 f1 f2 N –u dis –s log –r fap –v

where: ####.gse = *GSE2.0* file name,
###_DATALESS.SEED = *DATALESS.SEED* file name,
-R = make *RESP.SEED ascii* file with response data (*e.g.*, RESP.NO.ARA1.SZ.SHZ),
-f = input file name,
SSS = station name,
CCC = channel (*e.g.*, SHZ),
2011 001 = a time point when a particular response is valid,
f1, f2 = desired frequency range,
N = number of frequency samples in the *FAP* file,
-u = units (dis = displacement),
-s = spacing (log = logarithmic),
-r = response type (fap = frequency-amplitude-phase triplets),
-v = verbose output

During the conversion process and the review of resulting response volumes, but also during the transfer of information from original sources (*i.e.*, data sheets, calibration sheets, manuals, *etc.*) to the *GSE* response files, it is extremely important to be aware of and have control over employed units and unit conversions, *e.g.*, whether provided pole-zero sets are expressed in Hz or rad/s, *etc*.

1.1.3 Modified GSE response file

In order to extract from the *GSE* response files (GSETT-3, 1997) the necessary parameters for introduction into the *CSS3.0* database system (Anderson *et al.*, 1990), some extra fields were added to the former, to operate as identifiers, linking the corresponding responses to the different sites. The modifications made are the following:

- The Datatype channel lines were extended to include ontime and offtime information additionally to ondate and offdate.

- The Auxid field (a4) was filled with the original channel code, namely the one used initially at NORSAR, independently of any international naming convention. This was deemed necessary, as *GSE* format does not accept 2-letter Chan codes (a3), which was the case for old, standard NORSAR array channels (e.g., sz, sn, lz, etc.).
- An extra field corresponding to *CSS3.0* chanid (i8) was added in each channel entry, after the end of valid *GSE* format fields. This addition will be treated as comment from *GSE* related software, but will be read from the conversion/extraction tool developed to introduce response information in the *CSS3.0* database.
- An identifier flag (*Respid*, a8) was added both to each channel entry and each response CAL2 line to correctly link each different configuration modification to its corresponding response. This was necessary particularly in the case of the old NORSAR array *GSE* response files, where 11 different variations of the standard configuration are present in one file and have to be linked to the correct channels and time intervals. As an example, the definition of each identifier flag for the NORSAR array is provided in Table 1.1. In the case of the newer AIM24 NORSAR installation, where each channel has a different sensitivity and thereby a slightly different overall amplitude response, the *Respid* field remains the same for all the sites with the same instrumentation and is read, but essentially not being used in the same context. It points to a 'nominal' response used to describe the system.
- Any other extra information, e.g., a brief reference to a modification in the instrumentation or alternative station naming, can follow as simple comment after the *Respid* field.

An example of such a modified *GSE* response file is provided in Appendix I, while all *GSE* response files can be found under /ndc/programs/dpep/dbtables/2008/ARRAY/GSE/.

1.2 Extraction and storage of response information

1.2.1 Information from GSE files

The information that needs to be 'transferred' from the *GSE* response files to the *CSS3.0* database system is the following:

- System or channel sensitivity, which is stored under field *Calib* (f10.2) in the *GSE* file and should be linked to field *ncalib* in the .instrument table.
- Calibration period, stored under field *Calper* (f7.3) in the *GSE* file, to be linked to *calper* in .sensor, .wfdisc and *ncalper* in .instrument.
- Sampling rate, stored under *Samprat* (f11.5) in the *GSE* file, to be linked to *samprate* in .instrument, .wfdisc.
- Channel identifier, stored as extra information under *Chanid* (i8) in the *GSE* file, to be linked to *chanid* in .sensor, .sitechan, .wfdisc.
- Time interval of channel operation under the instrumentation characterized by a particular response. This is defined by fields *Ondate* (i4,a1,i1,a1,i2), *Ontime* (i2,a1,i2), *Offdate* (i4,a1,i1,a1,i2), *Offtime* (i2,a1,i2) in the *GSE* file, to be linked to *time*, *endtime* in .sensor, in epoch time form.
- The response identifier flag *Respid* (a8), which links the correct response entry to the corresponding channels. As already mentioned, it is used only in the cases where a 'nominal' response is applied to more than one sites. It is also used to link each response entry to the corresponding *FAP* file eventually produced by the *evalresp*

code (IRIS, 2006). The name of each *FAP* file is then written in the *dfile* (a32) field of .instrument. In the case of current NORSAR array configurations, where a separate *FAP* file is produced for each site and channel, a nominal *FAP* table is calculated and the name which appears in Table 1.1 is written in the .instrument file.

Table 1.1: *Respid* codes and name of corresponding *FAP* files for the NORSAR array.

instrumentation	**Respid**	***FAP*-file**
standard SP SLEM (4.75 Hz LP @ LTA)	SPSLEM1	NOASPSLEM1-NOA-SHZ.fap
SP SLEM, 8 Hz LP @ LTA	SPSLEM2	NOASPSLEM2-NOA-SHZ.fap
SP SLEM, no LP @ LTA	SPSLEM3	NOASPSLEM3-NOA-SHZ.fap
SP SLEM, -30 db (slz)	SPSLEM4	NOASPSLEM4-NOA-SLZ.fap
SP SLEM, prototype BU BP (NRA0, svz)	SPSLEM5	NOASPSLEM5-NC602-SVZ.fap
SP SLEM, unknown filter	SPSLEM6	NOASPSLEM6-NC602-SVZ.fap
SP SLEM, 4.75 Hz, S-13 sensor	SPSLEM7	NOASPSLEM7-NOA-SHZ.fap*
SP SLEM, 8 Hz, S-500 sensor	SPSLEM8	NOASPSLEM8-NC602-SHZ.fap**
standard LP SLEM	LPSLEM1	NOALPSLEM1-NAO00-LHZ.fap*
LP SLEM, -30 db	LPSLEM2	NOALPSLEM3-N1403-LHZ.fap*
SP RD6	RDSP1	NOARDSP1-NOA-SHZ.fap
SP RD6, -30 db (slz)	RDSP2	NOARDSP2-NAO01-SLZ.fap
LP RD6	RDLP1	NOARDLP1-NOA-LHZ.fap*
old SP AIM in CTV	AIM1	NOAAIM1-NOA-SHZ.fap
old SP AIM in SPV	AIM2	NOAAIM2-NOA-SHZ.fap
old SP AIM, -30 db (slz)	AIM3	NOAAIM3-NAO01-SLZ.fap
LP AIM	AIM4	NOAAIM4-NOA-LHZ.fap*
SP AIM, 20171A sensors	AIM0SP	NOAAIM0SP-NAO00-SHZ.fap
BB AIM, KS54000 sensors	AIM0BB	NOAAIM0BB-NAO01-BHZ.fap*
BB AIM, Güralp sensor	AIM0BBG	NOAAIM0BBG-NC602-BHZ.fap*

* 3-component instrument (*e.g.*, lz, ln, le).
** Only components sz, sn.

Corresponding tables for the rest of arrays/stations operated by NORSAR are given in Appendix II.

1.2.2 Naming convention of FAP files

The name of the file containing the *FAP* table of each calculated response is written in field *dfile* of the .instrument *CSS3.0* table. This restricts the name of the *FAP* file to maximum 32 characters.

The *FAP* file is created from previously generated *RESP.SEED* files using program *evalresp*. The name suggested here for the *FAP* file (see also Table 1.1) consists of the *GSE Respid*, the station and channel name: Respid-STA-CHA.fap
This suggestion is made on the basis of applying a unified approach to *FAP* file generation and naming, both for ‘nominal’ and actual (channel specific) responses. Keeping this under consideration, station (site) name and channel are included in the ‘nominal’ case names, although they seem to be redundant, since they are only necessary in the case of individual channel responses.

1.3 References

Anderson, J., W.E. Farrell, K. Garcia, J. Given and H. Swanger, 1990. Center for Seismic Studies version 3 database: schema reference manual. *Techn. Rep. C90-01*, DARPA, Arlington, Viriginia, 61 pp.

GSETT-3, 1997. Provisional GSE 2.1 Message Formats and Protocols. Operations Annex 3, May 1997, 123 pp.

IRIS, 2006. EVALRESP Manual Pages (V3.2.35). http://www.iris.edu/manuals//evalresp.htm, *Incorporated Research Institutions for Seismology*, May 2006.

O' Neill, D., A. Nance, C. Laughbon and S. Stromme, 2004. RDSEED 4.6 Manual. http://www.iris.edu/manuals/rdseed.htm, *Incorporated Research Institutions for Seismology*, July 2004.

Sleeman, R., 2003. GSE2SEED version 2.23. ftp://orfeus.knmi.nl/pub/software/conversion//GSE2SEED/README, *ORFEUS Data Center*, August 2003.

CHAPTER 2: DEVELOPMENT OF NORSAR ARRAY SYSTEMS: INSTRUMENTATION AND RESPONSES

A brief description of the development over time of the NORSAR array is provided in this chapter. Furthermore, each different configuration is listed with its components and the validated parameter values necessary to calculate system response are catalogued. The values listed here are mostly mean or nominal values, however references to Appendices and publications containing actual values by instrument serial number are provided.

2.1 NORSAR ARRAY (CTBT IMS station PS27 – NOA)

2.1.1 Short description

- 1968-1978:

Original (standard) instrumentation involves HS-10-1 SP and 7505B/8700C LP seismometers with RA-5 amplifier, LTA and SLEM. SP sites are operating with a sample rate of 20 Hz and LP with 1 Hz. However, from 24.11.1976 LP output is being attenuated by 40 dB and fed through an Ithaco amplifier and an LTA amplifier with a sampling rate of 0.5 Hz. Moreover, channels 14C02 1, 2 and 6 were Z, NS, EW with S-13 seismometer (see S-13 related paragraph).

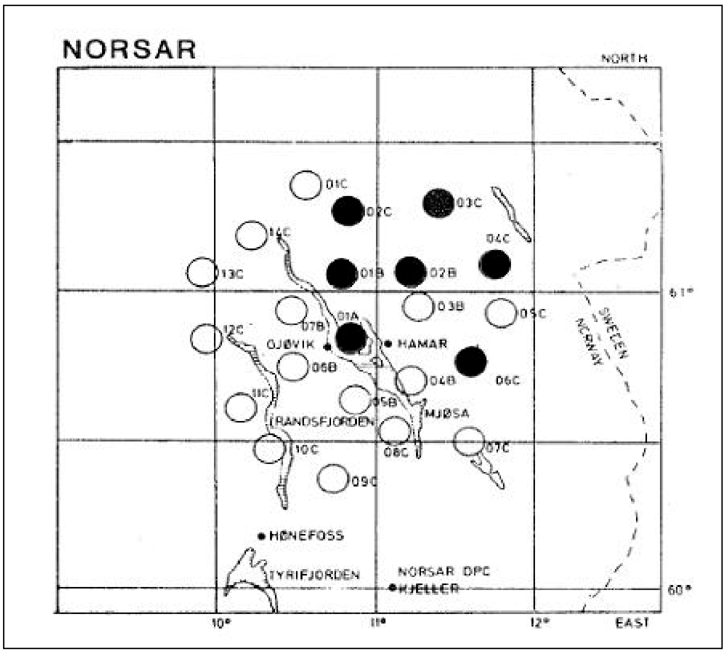


Fig. 2.1. Geographic location and numbering of the 22 NORSAR array subarrays. Open circles denote subarrays closed down in 1976, while filled circles denote subarrays still in operation.

Between 1969 and 1976, the gain of the RA-5 amplifier was reduced by -30 dB at site 01A00. The f_c=4.75 Hz low-pass Chebyshev filter was exchanged with an f_c=8 Hz Chebyshev filter at sites 03C and 08C in 1971, at channels 14C01 and 14C02 in 1974, and at channels 01A06, 02B06, 02C06, 04C06 and 06C06 on November 1977. All filters were removed from site 04B in 1974, as well as from channels 14C03 and 14C04. Filters were removed from channels

14C02 and 14C04 in 1976. However, on March 1977, a new LTA with upper 3 dB point at 8 Hz was installed in the NORSAR Analog SP station, channel 04B05 (Nilsen, 1979). It should be noted here that the naming convention mentioned previously, which utilizes a '06' site numbering is not typical and is only reported by Nilsen (1979).
A large percentage of the original configuration is closing down in 1976 (Fig. 2.1).

-1978-1994:
S-13 and S-500 seismometers tested on certain array sites (05.04.78 at 01A01,02,03 and 15.03.78 at 06C02 respectively).
From 1979 on, a small-aperture seismic array (NORESS) is being tested on subarray 06C of the NORSAR array. The initial configuration employs 6 sites, whereas since end October 1980 the 'new' NORESS consists of 12 sites equipped with vertical sensors (Mykkeltveit and Ringdal, 1980). Employed instrumentation is standard NORSAR, however the tests with this small-aperture array require changes in data channel names for the NORSAR array (Nilsen, 1980b).

Timing system: during the period 1968 – 1994, the array timing system was based on a central clock at the NDC. Timing control was transmitted to each subarray SLEM unit over telephone line, with a 2400 bps modem. The development of telecommunication systems made this array time synchronization system obsolete.

- 1994-1995:
Standard NORSAR instrumentation during 1994: NB2 Backup System (NBS).
The NB2 Backup System employs 7 Nanometrics RD6 (6-channel) digitizers to backup the entire system, after problems having occurred by using the communications system for the timing of the array (Fyen, 1996). At the end of 1994, the system was changed to AIM24 digitizers (Larsen and Løken, 1995).

- 1995-2011:
Refurbishment of the array. 42 Teledyne-Geotech 20171B SP seismometers in all remaining sites and 7 KS54000 3C BB seismometers in one element of each subarray, with AIM24 digitizers; AIM24-1 and AIM24-3BB respectively (Fyen, 1995a; Larsen and Løken, 1995, 1996). A Güralp CMG-3T seismometer is installed at site 06C02, in the place of a KS54000 instrument, in 2000, for the NORSAR array to acquire CTBT certification, as primary station PS27 (Larsen and Løken, 2000).
As of 01.09.1996, NORSAR array sites follow a new naming convention, in preparation for the data to be continuously transmitted to the IDC in Vienna, with the subarray names being registered as ISC codes (Fyen, 1995b; Fyen and Kværna, 1996).

- 2011-present:
Recapitalization of the NORSAR array, with plans to extend the same concept to ARCES and potentially also in the future to SPITS. For this reason, the proper response was sought that fits the different records/targets of these systems. A hybrid response was designed at NORSAR (Roth et al., 2011), which was to be implemented by Güralp Systems, Ltd. In reality, some discrepancies exist between designed and delivered instrument response (see section 2.2.12). The new instrumentation involves CMG-3T hybrid sensors and three-channel EAM acquisition modules with authentication, equipped with CMG-DM24 digitizers (CMG-DM24S3EAMS (SS)). There are two versions of the seismometer; a 3-component broadband one, which will occupy one site per subarray, and a vertical, less broadband version for the rest of the stations.

2.1.2 Main sources of information

- NORSAR.systems in /ndc/stations/…/response.
- NOA_COO in /ndc/programs/dpep/libdata.
- Usage of db query macros residing in /ndc/programs/dpep/dbtables.
- Already existing response files residing in various paths, mostly under /ndc/programs/dpep.
- Manuals, instrument datasheets, notes and related documentation.
- Information derived directly from NORSAR staff.

2.1.3 Instrumentation

I. Configurations

- Standard (original) configuration (1968-1976):

HS-10-1 seismometer (SP)	7505B (z) / 8700C (h) seismometer (LP)
RA-5 amplifier	Ithaco amplifier
Long SPV-CTV cable	Long cable
LTA amplifier	LTA amplifier
SLEM	SLEM

- Test configurations (1976-1994):

Variation of original configuration with a few S-13 and S-500 seismometers as sz, sn, se channels.

- Variations of original configuration (1994-1995):

Several variations of the original configuration existed, mainly involving changes in digitizer.

HS-10-1 seismometer (LP version: 7505)	seismometer
RA-5/Ithaco amplifier	RA-5 amplifier/Ithaco amplifier
Long cable	cable
LTA	LTA
RD-6 digitizer (NB2 Backup System)	AIM24 digitizer

- Refurbishment (1995-2011):

The remaining array sites were refurbished with 42 vertical SP and 7 3C BB seismometers.

20171B seismometer (SP)	KS54000 seismometer (3C BB)
Brick amplifier	or CMG-3T seismometer (site 06C02)
AIM24-1 digitizer	AIM24-3BB digitizer

In order for the NORSAR array to acquire CTBT certification (IMS station PS27), a KS54000 seismometer was exchanged with a CMG-3T in 2000 – site 06C02, channels gz, gn, ge.

- Recapitalization (2011-present):

Refurbishment with hybrid sensors, 7 3C BB ones and 42 vertical SP.

CMG-3T HYBRID	CMG-3V HYBRID
CMG-DM24S3EAMS	CMG-DM24S3EAMS

II. Configuration codes

SP	LP/BB
HS-10-SLEM	7505B/8700C-SLEM
HS-10-RD6 (NBS)	7505B-RD6mux (NBS)
HS-10-AIM24	7505B/8700C-AIM
HS-10AC24	
HS-10AR24	
S-13-SLEM	
S-500-SLEM	
20171B-AIM24	KS54000-AIM24-3BB
	CMG-3T-AIM24-3BB
CMGEAMHYB1V	CMGEAMHYB3T

III. Instrument specifications

HS-10-1:
Short period, vertical Hall-Sears seismometer by GeoSpace Corp. The specifications of the version installed at the NORSAR array are the following:

Natural frequency	fo	1 Hz (nominal)	1.02 Hz (mean)
Damping	λ	0.707 (nominal)	0.69 (mean)
Generator constant	Gm	1020 V/m/s	
DC resistance	Rdc	50 kohms	
Calibration coil motor constant	Gc	0.0326 N/A	
Total moving mass	M	0.825 kg	

7505B / 8700C:
Long period, vertical and horizontal Teledyne-Geotech seismometers, respectively. The specifications of the version installed at the NORSAR array are the following:

Natural period	To	20 s
Damping	λ	0.64
Generator constant	Gm	750 V/m/s nominal, 761.3 V/m/s mean
DC resistance	Rdc	50 kohms
Calibration coil motor constant	Gc	0.028 N/A nominal, 0.0316 N/A mean

20171B:
Short period, vertical Teledyne-Geotech (TG) seismometer, flat to velocity. The general specifications* of the version installed at the NORSAR array are the following:

Natural frequency	fo	1 Hz
Damping	λ	0.707
Generator constant	Gm	650 V/m/s (by TG for Rc=6.5 kohms)
DC resistance	Rdc	7640 ohms
Calibration coil motor constant	Gc	0.1976 N/A

* General specifications refer to the mean values used in response and configuration references. Instrument specific values are provided in Appendix I.

KS54000:

Broadband, 3-component Teledyne-Geotech posthole seismometer. Instrument flat to acceleration between 0.01 – 5.2 Hz. The specifications of the version installed at the NORSAR array are the following:

Calibration period	To	1 s
Sensitivity	G	5000 Vs^2/m (0.019325 nm/count) @calper
Coil resistance	Rc	25 Ohms

S-13:

Portable, short period Teledyne-Geotech tri-axial seismometer, model 18300. Installed at site 14C02 of the NORSAR array as of 30 June 1976. The seismometers are directed towards the Hunderfoss power plant, so that channel 01 is vertical, channel 02 horizontal at 137° and channel 03 horizontal at 47°. Low-pass filters on the LTA cards are removed, but the rest of the instrumentation is the same with the standard NORSAR equipment (Nilsen, 1976). The specifications of the three channels are the following:

Natural frequency	fo	0.958 0.968 0.986 Hz
Inertial mass	M	5 kg
Generator constant	Gm	629 V/m/s nominal
Critical damping resistance	R_o	71100 72100 73900 ohms
Calibration coil motor constant	Gc	z: 0.1973 N/A, n/e: 0.1975 N/A
Channel output at LTA		5.71 V p-p
Damping ratio	λ_0	0.705 0.687 0.688

On April 1978 a Geotech S-13 seismometer was installed in the LPV at site 01A01 to operate as a 3-C instrument, with channel names sz, sn, se. The S-13 was connected to standard NORSAR array equipment (Nilsen, 1978b).

Natural frequency	f_o	1.0 Hz
Generator constant	Gm	629 V/m/s nominal
Weight of inertial mass	M	5 kg
Input calibration voltage		20.0 V p-p
Calibration network resistance	R_n	50 kohms
Calibration coil resistance	R_c	23 ohms
Calibration coil current	I_c	400μA
Calibration coil motor constant	Gc	0.1975 N/A 0.1973 N/A for vertical
Equivalent ground motion p-p		0.400 μm
Channel resolution @ 1 Hz		42.73 pm/qu for all components

On March 1980 a Geotech S-13 seismometer was installed in the LPV at subarray 06C, with channels 06C02 and 04 operating as horizontal NS and EW components (Nilsen, 1980a). The horizontal seismometers were exchanged back to standard vertical HS-10-1 instruments on 16 June 1980 (Nilsen, 1980b). The S-13 is used with standard coil, the RA-5 amplifier, LTA and SLEM.

Natural frequency	f_o	1.0 Hz
Damping ratio	λ_0	0.7
Generator constant	Gm	629 V/m/s
Equivalent ground motion p-p		0.400 μm
Channel output		6800 qu p-p
Channel resolution @ 1 Hz		58.8 pm/qu

S-500:
Portable, short period Teledyne-Geotech seismometer. May be used either as vertical or horizontal or at any other inclination. Tested at site 06C, channel 02 of the NORSAR array between 15 March and 12 April 1978, initially (until 30/03/78) as vertical and then as horizontal component (sn). It was connected to the SLEM via an RA-5 amplifier and the 8Hz LP filter LTA version (Larsen, 1978). The specifications of the version installed at the NORSAR array are the following:

Mass	M	1 kg
Natural frequency	f_o	1.0 Hz
Calibration factor	K(Gc)	3.046 m/(s^2A)
Channel resolution @ 1 Hz		99.5 pm/qu
Equivalent ground motion p-p		0.930 µm

Although a seismometer pre-amplifier gain of 200 is employed in future installations (*e.g.*, SPITS, Apatity array – see Chapters 2.IV, 2.V and 3.IV, 3.V), no reference to such a feature has been documented by any author regarding the test with the NORSAR array (Larsen, 1978, Nilsen, 1978a,b).

CMG-3T:
3-component, broadband Güralp seismometer. The specifications of the model (S/N T3720) installed at the NORSAR array are the following (for the vertical):

Velocity output	2x2527.9 V/m/s (differential)
Acceleration output	1711 V/m/s^2
Feedback coil constant	0.02592 A/m/s^2
Power consumption	69 mA @ + 12 V input
Calibration resistor	51 K
Poles (Hz)	$-7.07 \times 10^{-3} \pm j\ 7.07 \times 10^{-3}$
	$-80.5 \pm j\ 30.8$
Zeros (Hz)	0 0 -150.5
Normalizing factor	-49.5 @ 1 Hz

CMG-3T HYBRID:
3-component, broadband (360s) Güralp seismometer, with hybrid response. The specifications for the vertical component of instrument with S/N T36188, installed at the NORSAR array, are listed below. Note that a wrong pole is given in the calibration sheet ($-30.0 \pm j\ 31.0$ instead of $-24.0 \pm j\ 21.0$).

Velocity output	2x19804 V/m/s (differential) @ 5 Hz
Acceleration output	5705 V/m/s^2
Feedback coil constant	0.02377 A/m/s^2
Power consumption	90 mA @ + 12 V input
Calibration resistor	51 K
Poles (Hz)	-2.0
	$-1.964 \times 10^{-3} \pm j\ 1.964 \times 10^{-3}$
	$-24.0 \pm j\ 21.0$
	$-41.0 \pm j\ 114.0$
Zeros (Hz)	0 0 -333.33×10^{-3}
Gain @ 1 Hz	2 x 10000 V/m/s

CMG-3V HYBRID:
Vertical-only, short-period (120s) Güralp seismometer, with hybrid response. The specifications of the model (S/N V3I46) installed at the NORSAR array are as shown below. Note that the same error as for the CMG-3T HYBRID exists in the calibration sheet for pole/zero listings.

Velocity output	2x19962 V/m/s (differential) @ 5 Hz
	2x3556 V/m/s (differential) @ 0.03 Hz
Acceleration output	7778 V/m/s^2
Feedback coil constant	0.02357 A/m/s^2
Power consumption	68 mA @ + 12 V input
Calibration resistor	51 K
Poles (Hz)	-2.0
	$-5.89 \times 10^{-3} \pm j\, 5.89 \times 10^{-3}$
	$-24.0 \pm j\, 21.0$
	$-41.0 \pm j\, 114.0$
Zeros (Hz)	0 0 -333.33×10^{-3}
Normalizing factor	29000000 @ 5 Hz

RA-5:
Amplifier by Texas Instruments. The specifications are the following:

Gain (amplification)	G	74.68 dB (= 5400 x)
Output	E_o	8.2 V
Output impedance	R_o	1200 ohm
Upper 3 dB frequency limit		230 Hz
Lower 3 dB frequency limit		0.1 Hz

A special version of the RA-5 with a gain reduction of -30 dB was employed at site 01A00 for the time period 1976-1994 (attenuated channel slz). This amounts to a gain of 44.68 dB.
It should be noted that initially the RA-5 was running with an amplification of 7070 times, this was however modified in 1970, as it seemed to cause instability to SLEM performance. No data are still available from that original configuration.

Ithaco amplifier:
Model 6083-82 Long Period Seismic Amplifier by Ithaco Inc. The specifications are the following:

Gain	G	80 dB
Upper 3 dB frequency limit		12 dB/octave @ 0.033 Hz
Lower 3 dB frequency limit		6 dB/octave @ 0.005 Hz
Output		min 60 V p-p into 100 kohms load

The system consists of the following filters:

2xRC low-pass filters	20 dB gain, -12 dB/oct above 0.033 Hz
Low-pass Butterworth filter	2 poles, 0 gain, -12 dB/oct above 0.04 Hz
High-pass RC filter	-6 dB/oct @ 0.005 Hz

Brick amplifier:
Short-period Brick amplifier, model 990-57010-0107, by Teledyne-Geotech. The specifications are the following:

Gain	G	39.8 = 32.0 dB

Dynamic range	> 140 dB
Response	single pole low pass, corner @ 9.7 Hz

SPV – CTV long cable:
A long, buried cable, connecting the short-period instrument vaults with the central terminal vault. A standard attenuation value of 0.935 is applied for 3.7 km of cable (NORSAR, 1969a).

SLEM:
The Short and Long Period Electronic Module by Philco-Ford is an 8-bit A/D converter. Gain ranging increases the dynamic range to 14 bits. Each unit provides for 21 seismometer inputs, 18 of them being SP channels and 3 of them being LP channels.
The SP channels consist of a Surge Protection circuit, a Test Relay, a Line Terminating Amplifier (LTA) and a Chebyshev low-pass filter.
The LP channels consist only of the Test Relay and the LTA.
The outputs of the SP and LP channels go to an analog multiplexer which selects only one signal to be converted to a digital value by the A/D Converter.
The specifications are the following:

Dynamic range	14 bit = +/- 8192 counts maximum
Analog input	+/- 5.0 V (10 V p-p) ≈ 0.61035 mV/count
Calibration output (nominal)	5.7 V p-p for 8.0 V p-p in LTA @ 1 Hz
Calibration gain (nominal)	0.7143

LTA:
Line Terminating Amplifier at the central terminal vault: The unit consists of the following filters:

- Analog, one-pole, high-pass RC filter: at 0.038 Hz, 6 dB RC 1-order.
- 4th-order Tschebyshev, low-pass filter: Burr-Brown, Model 5121. Analog filter at 4.75 Hz, 0.15 dB ripple, 24 dB/octave roll-off.
  A version of this filter with a cutoff frequency of 8 Hz (Burr-Brown, Model 5237) was used at certain channels (see page 6), with corresponding ripple 0.25 dB.

Information on other filter versions of the LTA can be found in Chapter 3, Section 1.3.

Overall voltage gain 0.714±6 dB

Timing: timing synchronization was provided by a control word transmitted to each subarray from the NDC 20 times per second over telephone line.

RD6:
RD6 16-bit A/D converter by Nanometrics. The 6-channel version installed at the NORSAR Backup System employs autogain and a series of filters described below (Software Filter Type 5.18). 7 units were ordered, with s/n: A160, A161, A162, A163, A165, A167 and A168.
The specifications are the following:

Analog input level	+/- 20.0 V
Dynamic range	24 bit
Sensitivity	ranges between 6020-6210 nV/bit
Sampling rate	160 Hz
Decimation	4
Output	40 Hz
Analog low-pass filter (F2): 5th-order Butterworth	$\omega_{3db} = 2\pi\ 23$ Hz
	Q_1=1.61803, Q_2=0.618034
Analog high-pass filter (F3): optional	not used
Digital FIR filter (F4): low-pass	f_{3db} = 40 Hz, N = 68

Digital IIR filter (F5): high-pass not used
F1 in the filter sequence above is the seismometer.
Timing: each RD6 was time synchronized using a GPS clock.

AIM24:
AIM24 A/D converter by Science Horizons, Inc. It employs a Crystal semiconductor CS5321/22 chipset with an input bitstream clocking of 40960 Hz, where CS5321 is a 4th order modulator and CS5322 is a linear phase FIR decimation filter with the following sets of coefficients:
FIR1, decimating by 8, 33 coefficients
FIR2, decimating by 64, 13 coefficients, in 6 steps with decimation by 2
FIR3, decimating by 2, 101 coefficients
Normalizing coefficients to SUM=1, the digitizer response can be constructed with the following sequence of FIR filters:
$$40960Hz \xrightarrow{FIR1(8)} 5120Hz \xrightarrow{6xFIR2(2)=64} 80Hz \xrightarrow{FIR3(2)} 40Hz$$
Gain is seismometer driven, so specifications will be presented according to array element configuration.
In the case of AIM24-1, the A/D converter unit comes with the CS5323 digitizer that has a full scale input of 32.0 V p-p, and a selectable gain of 1.0 V/V, 10.0 V/V or 100.0 V/V (according to Th. Cherry of Science Horizons, Inc.).
Output coding for the two chipsets described above is presented in tables I and II. Reference voltage, VREF, for the CS5321/22 chipset is ± 4.5 V full-scale (Cirrus Logic, 2003) and ± 10.0 V for the CS5322/23 chipset (Cirrus Logic, 1995).

Table I. Output Coding for the CS5321 and CS5322 Combination

Modulator Input Signal	CS5322 Filter Output Code	
	HEX	Decimal
> (+VREF + 5%)	Error Flag Possible	
≈ (+VREF + 5%)	53FFFF(H)	+5505023
+VREF	4FFFFF(H)	+5242879
0V	000000(H)	0
-VREF	B00000(H)	-5242880
≈ - (+VREF +5%)	AC0000(H)	-5505024
> - (+VREF +5%)	Error Flag Possible	

(Cirrus Logic, Inc., 2003)

Table II. Output Coding for the CS5322 and CS5323 combination

Modulator Input Signal	Digital Filter Output Code	
	HEX	Decimal
approx. +16V†	7FEFFF	+8384511
approx. +11V	57FFFF	+5767167
approx. +10V	4FFFFF	+5242879
0V	000000	0
approx. -10V	B00000	-5242880
approx. -11V	A00000	-5767168
approx. -16V†	800000	-8388608

† This is an overrange condition
(Cirrus Logic, Inc., 1995)

AIM24 employs an internal front-end preamplifier (*e.g.*, Ingate, 1995, Kromer *et al.*, 1995) that outputs the full-scale voltage of the attached seismometer to a range suitable for the Crystal chipset. In the case of the broad-band KS54000 instruments installed at the NORSAR array, input voltage is decimated by a factor of ≈ 4.44, while no amplification takes place in the case of the 20171B instruments.

- KS54000-AIM24-3BB:
    - Remote in LPV:
        - Sampling rate 40 sps
        - Full scale dynamic range +/- 32.0 V
        - Gain G 1 V/V
        - Sensitivity 262144 counts/V
        - LSB 3814.6 nV/count
    - Central in CTV: RA-5 amplifier
        - Sampling rate 40 sps
        - Pre-amplifier gain 74 dB
        - Full scale dynamic range +/- 32.0 V
        - Gain G 1 V/V
        - Sensitivity 262151 counts/V
        - LSB 3814.6 nV/count
- 20171B-AIM24-1:
    - Sampling rate 40 sps
    - Pre-amplifier gain 39.8 V/V (32 dB)
    - Gain 10 V/V (set)
    - Full scale dynamic range +/- 16.0 V
    - Sensitivity 524288 counts/V
    - LSB 190.73 nV/count
- HS-10-1-AIM24:
    - AC24: remote HS-10-1 with RA-5 and AIM24-1 in CTV
        - Pre-amplifier gain 74 dB
        - Full scale dynamic range +/- 16.0 V
        - Gain G 10 V/V
        - Sensitivity 524288 counts/V
        - LSB 190.73 nV/count
    - AR24: remote HS-10-1 with remote AIM24-1 in SPV
        - Gain G 100 V/V
        - Full scale dynamic range +/- 16.0 V
        - Sensitivity 524288 counts/V
        - LSB 190.73 nV/count
- CMG-3T-AIM24-3BB: in LPV
    - Sampling rate 40 sps
    - Full scale dynamic range +/- 32.0 V
    - Gain G 10 V/V
    - Sensitivity 2621440 counts/V
    - LSB 381.46 nV/count

Timing: each AIM24 is time synchronized using GPS clock.

CMG-DM24S3EAMS:

The Güralp Systems Enhanced Acquisition Module (EAM) is a data recording, communications and control module, used here in combination with a CMG-DM24 digitizer.

The exact model employed at the NORSAR array, the CMG-DM24S3EAMS (SS), in stainless steel, supports three channels and authentication for CTBTO purposes. The CMG-DM24 is a full 24-bit digitizer that employs the Cirrus Logic CS5376 digital filtering chipset and the TMS320VC33 digital signal processor (DSP). The DSP software consists of 6 cascaded programmable filter/decimation stages that allow the selection of multiple data output rates simultaneously (Güralp Systems, 2006). The specifications are the following:

Input Voltage range	+/- 10 V differential
Dynamic range	137 dB @ 40 sps
DSP sampling rate	32 kHz
Sensitivity	3.2 μV/count

2.2 INSTRUMENT RESPONSE CALCULATION FOR NORSAR ARRAY SYSTEMS

This chapter focuses on the main considerations to be taken into account for the calculation of the instrument response of the NORSAR array. Although some examples of calculation are provided, neither the precise procedure for obtaining the final response or any general, theoretical considerations are discussed here.

The GSE response file *Respid* flag(s) covered by the description of each response are provided in the beginning of each section.

2.2.1 <u>HS-10-SLEM</u> (1968/01/01 - 1994/12/31)

Respid: SPSLEM1
SPSLEM2
SPSLEM3
SPSLEM4
SPSLEM5
SPSLEM6

Original SP NORSAR configuration, consisting of the following components:

- HS-10-1 short-period seismometers
- RA-5 amplifier
- Cable connecting SPV and CTV
- LTA amplifier
- Chebyshev low-pass filter
- SLEM

According to documents NORSAR-PHASE 2, DOC. IV, PART1 and 2, eight of the 132 original SP instrument locations (on the A- and B- ring) were equipped with two seismometers, one on the surface and one at a borehole of 60 m depth (*e.g.*, 02B11). Data from the borehole placed instruments do not longer exist, except for the case of channel sbz of site 01A01, which operated until the end of October 1982.

Regarding total system response, the system had been normalized, based on a series of measurements, so that the output at the end of the LTA was the same for all channels. Thereby, individual constants for each seismometer were not being used, and system sensitivity was being equalized by the gain setting of the SLEM LTA (NORSAR-PHASE 2, DOC. IV, PART 1).

The following sections describe the calculation of individual instrument response functions.

2.2.1.1 *HS-10-1*

The data (or main) coil generator constant, G_m, can be calculated by the following formula:

$$G = \sqrt{4\pi f_0 m R_{CDR} \cdot (1-\lambda_0)} \text{ , in V/m/s} \tag{2.2.1}$$

In the above written formula, f_0 is the natural frequency in Hz,

m the weight of inertial mass in kg,
R_{CDR} or R_o the critical damping resistance in ohms and
λ_o the relative damping.

All the above listed parameters were being measured according to the procedures described in Document IV, Part 1 of NORSAR-PHASE 2.

HS-10 transfer function for ground velocity is the typical damping seismometer equation:

$$H(s) = \frac{s^2}{s^2 + 2\lambda_o \omega_o s + \omega_o^2}, \qquad (2.2.2)$$

where $\omega_o = 2\pi f_o$.

The above transfer function has two zeros and two poles, obtained by the following formulas:

Zeros: 0.0, 0.0

Poles: $-\lambda_o \omega_o \pm j\omega_o \sqrt{1-\lambda_o^2}$. For λ_o = 0.7 and ω_o = 2 π 1.06 rad/s, the two complex poles are: - 4.66212349 ± j 4.75631732.

2.2.1.2 *RA-5*

The RA-5 amplifier has a response that is described by a 1st-order bandpass filter. Nominal values for cut-off frequencies are 0.115 and 230 Hz, however instrument specific values can be obtained from data-sheets included in NORSAR-PHASE 2, DOC. IV, PART 2. The values actually used for system response calculation are mean values derived from NORSAR Rep. 40 (Steinert and Nilsen, 1972) and are equal to 0.1 and 230 Hz:

Regarding amplifier gain, total achieved amplification is equal to 77 dB (= 7070 x). Theoretically, this can be increased by 3 dB to 1010 x and can be reduced by any amount by inserting an attenuator in front of the amplifier. Initially, the amplifier was being run with maximum gain however this was changed in 1970, as it seemed to cause instabilities in SLEM performance. In the case of the NORSAR array original configuration, overall system instrumentation causes a reduction of this value down to approximately 5400 x (74.64 dB). The main contributors to this reduction are attenuation caused by voltage drop in the internal impedance of the data coil, when this is loaded with the damping network (D_D = 240/290 = 0.826 = -1.68 dB), and attenuation due to 3.7 km of cable (D_T = 0.935). The latter is a mean value since cable length varies. The system is thus tuned that an output voltage of 8.2 V is achieved (NORSAR, 1969a; Dalland, 1971). A flow-chart of the short-period system calibration procedure is presented in Fig. 2.2.

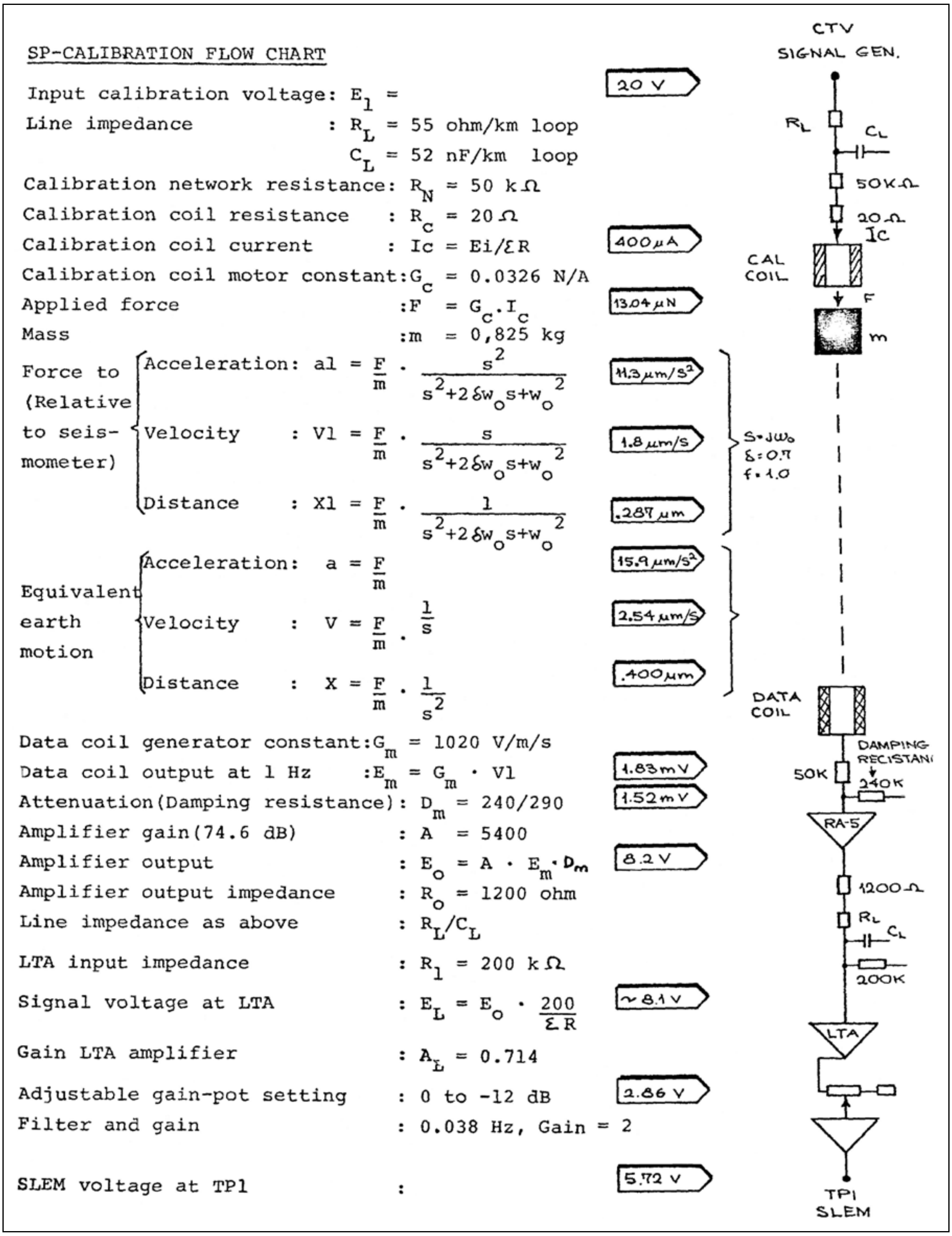


Fig. 2.2. Short-period standard NORSAR array configuration calibration flowchart. The instrumentation chain is presented up to the test point after the Line Terminating Amplifier (LTA), just before the SLEM A/D converter. The second triplet of equations on the left provides equivalent ground motion for a 1 Hz sinusoidal calibration signal of 20 V peak to peak (Dalland, 1971).

It should be noted that all values reported here are either nominal or mean values, since individual instrument parameter values exhibited a rather wide spread. Indeed, this lead in the early 1970s to the review and modification of tolerance values to a wider acceptable range than initially employed (Steinert and Nilsen, 1972). The values provided in the same report are the ones used for response calculation since they are representative of the widest time period of NORSAR array operation and the whole system was being tuned to the same channel sensitivity value as with previous reports (see §2.1.3). Reported mean and/or nominal values do not vary significantly among the different report versions and it should be noted that a lot of these values are artifacts resulting from incorrect parameter rounding and approximations (*e.g.*, in the case of Dalland, 1971).

A 'modified' version of the RA-5 amplifier was used from 1976 on, for the attenuated channel slz at NORSAR array site NAO01. The amplification was reduced by 30 dB, resulting in an overall channel sensitivity different from the one corresponding to standard NORSAR array configuration and its variations (*Respid*: SPSLEM4). In array maintenance logs (Hansen, 1983a;b;c), a different version with a -40 dB attenuation can be found documented, however this appears to be a mistype (Larsen, pers. comm.).

2.2.1.3 *LTA*

The Line Terminating Amplifier (LTA) is part of the SLEM unit. Its response can be described by the total contribution of one or several filters that were inserted in the form of cards. The typical LTA configuration consisted of the following components:

- An analog 1st-order, HP RC filter, of 2x gain and a cut-off frequency at 0.038 Hz.
- An analog 4th-order, LP Chebyshev filter, of 0.25 dB ripple and -3 dB frequency at 4.75 Hz (Burr-Brown, 1969).

The total gain of the LTA was regulated so that with an input of 8.1 V, an output of 5.72 V was obtained however, the nominal value of 0.7143 is reported (Dalland, 1971) and used for response calculation. The whole system was tuned so, that at the TP2 measuring point (TP1 in Fig. 2.2) a value of 5.72 V was obtained. In order to achieve this, an adjustable gain potentiometer was used, which could correct LTA gain up to ± 6 dB from nominal (Philco-Ford, 1970; Dalland, 1971). The desirable voltage value is compatible with an overall channel sensitivity of 0.0427 nm/count ± 10% at 1 Hz, in accordance to the overall scaling put forward by IBM/SAAC in their Proposed Composite Specification for Array Instrumentation System, dated 27.02.70 (Dalland, 1971). As already mentioned in section 2.1.1, lots of the values reported regarding the tuning of the system are approximations and an important point to be taken into account is the inability to measure in the lab the calibration coil motor constant value.

Several more LTA configurations were used in the NORSAR array, resulting from the replacement of filter cards. These alternative options are listed below, while the corresponding *Respid* is given in parenthesis:

- Analog 4th-order Chebyshev filter (Burr-Brown, 1971), of 0.25 dB ripple and -3 dB frequency at 8.00 Hz (SPSLEM2).
- No LP filter employed (SPSLEM3).
- A 'prototype', Butterworth bandpass filter (Hansen, 1986a; Larsen, pers. comm.) was used at channel SVZ at NC602 to simulate the NRA0 response (Fig. 2.3). The filter consists of a 3 pole high-pass component, with -3 dB point at 1.3 Hz, and an 8 pole low-pass component, with -3 dB point at 7.7 Hz. The total roll-off is 48 dB/octave. The relatively large attenuation was decided to avoid clipping, since data from the particular sub-array was widely used for CTBT monitoring purposes (SPSLEM5).

- An unknown filter with a reported roll-off of 12 dB/octave had been installed at channel SVZ prior to the ‘prototype’ Butterworth filter (NOA_COO.xls; NOA.xls). The existence of the filter has been confirmed by waveform comparison, it was impossible however to retrieve information about its characteristics (SPSLEM6).

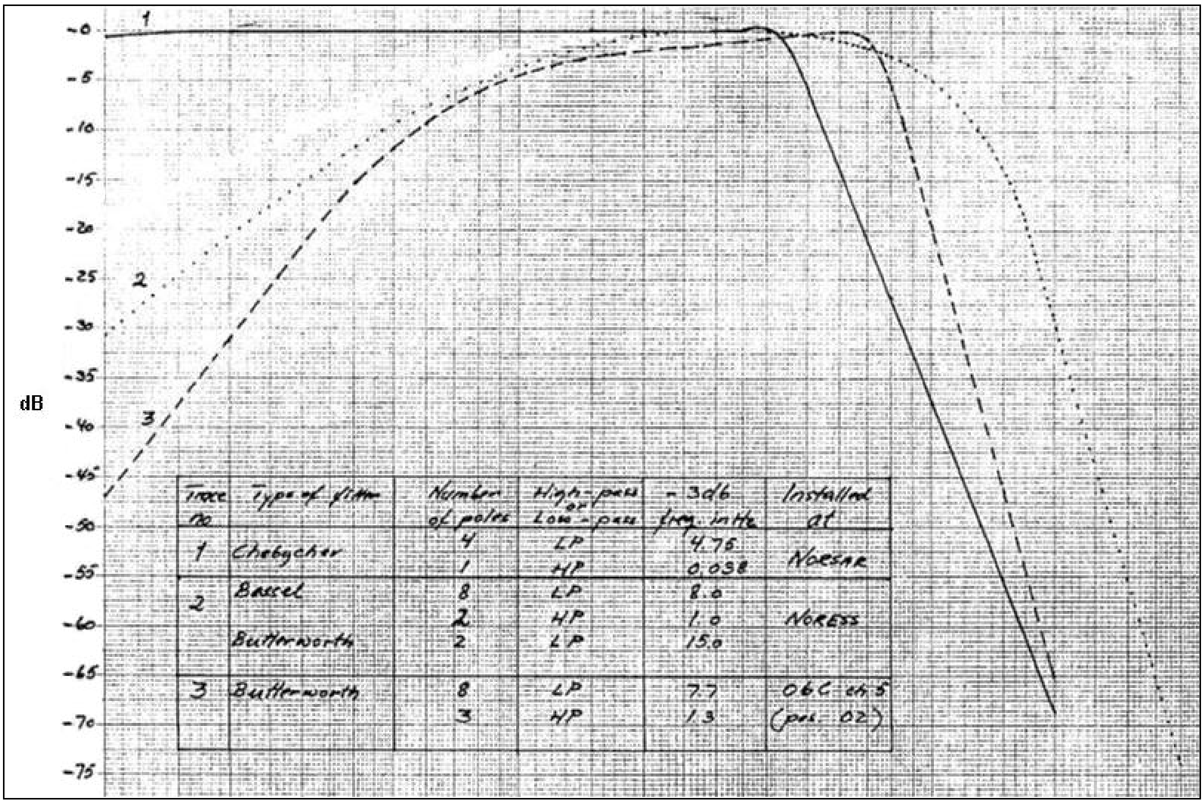


Fig. 2.3. Response graphs of different filters (Larsen, pers. comm..). Filter no. 1 is the standard NORSAR array short-period LTA arrangement, with the 24 dB/octave Chebyshev low-pass filter and RC high-pass filter, while filter no. 3 is the ‘prototype’ Butterworth bandpass filter, designed at the NMC to replace existing filters on short-period LTA cards and tested at site NC602 (Hansen, 1986).

In the case that the LTA low-pass filter (Z3 in Figure 2.4) was bypassed, output voltage measurements were made at TP1 (see Figure 2.4).

The poles and zeros (in rad/s) of the typical LTA filter cards are:
RC HP filter
1 pole: -0.23876104
1 zero: 0.0

LP Chebyshev filter 4.75 Hz
4 poles: $-6.3426323 \pm j31.5397979$
$-15.312469 \pm j13.0642120$
No zeros

For the rest of the filters used, the poles and zeros (in rad/s) are:
LP Chebyshev filter 8.00 Hz
4 poles: $-10.6823281 \pm j53.1196596$
$-25.7894214 \pm j22.0028834$

'Prototype' BP Butterworth filter

11 poles: $-47.4504 \pm j9.4385$
$-40.2265 \pm j26.8785$
$-26.8785 \pm j40.2265$
$-9.4385 \pm j47.4504$
$-4.0840 \pm j7.0737$
-8.1680

3 zeros: 0.0
0.0
0.0

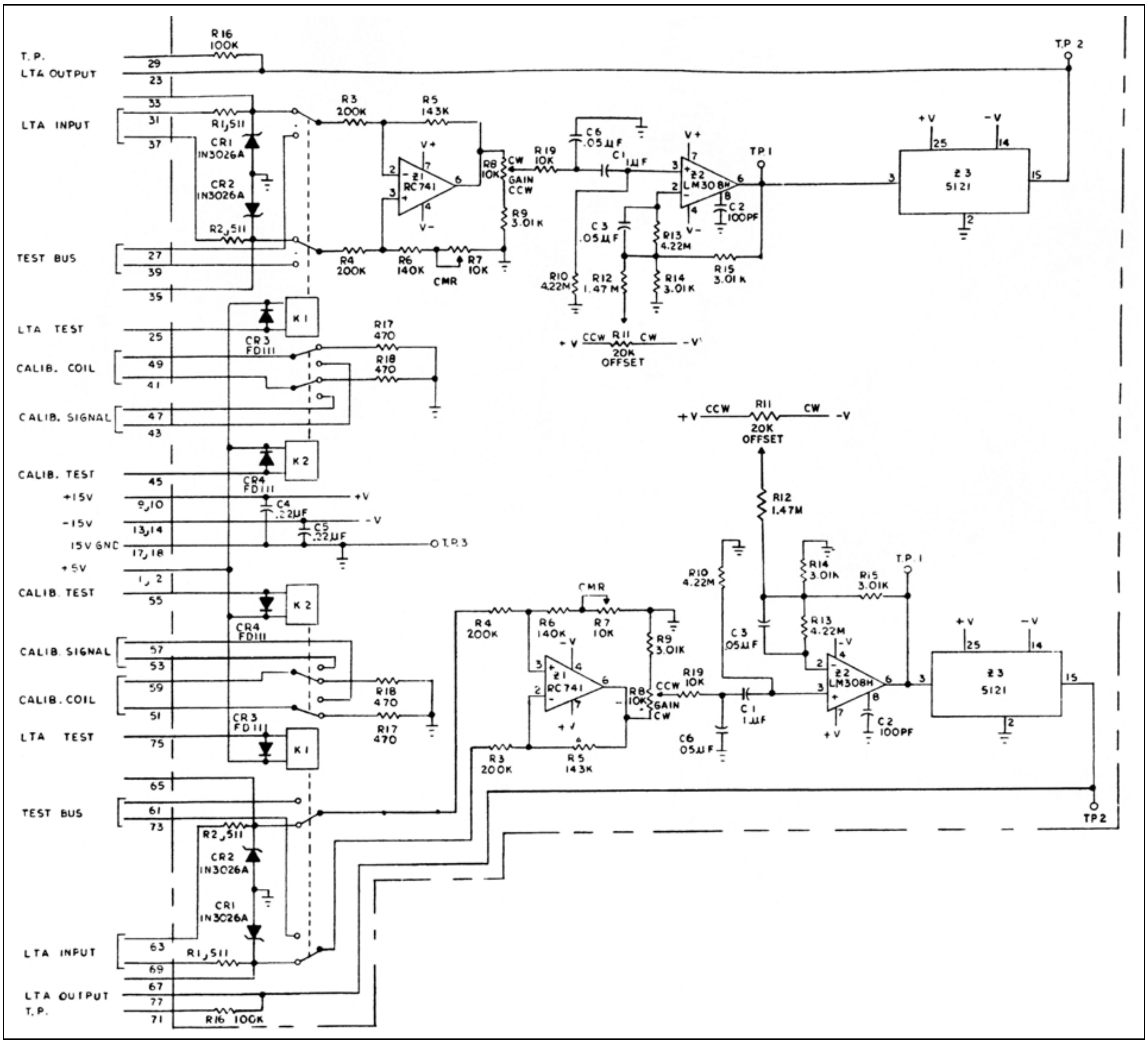


Fig. 2.4. Schematic diagram of the short-period Line Terminating Amplifier (LTA) version (Philco-Ford, 1970). TP1 and TP2 are the two measuring/adjusting points and Z3 the low-pass Chebyshev filter card (Larsen and Nilsen, 1974).

2.2.1.4 *SLEM A/D converter*

The SLEM interfaces seismometers to a remote computer through a digital data service. A variety of modes is available to support different seismometer configurations. The mode employed at the NORSAR array supports up to 6 SP and 1 3-component LP seismometer per subsystem, with a sample rate of 20 Hz and 2400 bps transmission service (Philco-Ford, 1970).

The system consists of an Analog Unit (AU), a Versatile Common Digital Unit (VCDU) and an External Power Unit (EPU). The latter provides DC voltages to the rest of the equipment and the SLEM subsystem for all operation modes.

Short period input has already been described in section 2.2.1.3 about the LTA amplifier.

The resolution of the A/D converter is 12 bits and full scale input equals ± 5.00 V. Gain-ranging with an option of x4 gain, provides 2 extra bits (IBM, 1969), least significant bit thus being equal to:

$$LSB = \pm 5.0 \text{ V} / \pm 2^{13}\text{-1 counts} = 610.426 \ \mu\text{V/count}$$

The sensitivity of this system is equal to: 1638.2 counts/V

The displacement amplitude and phase response for the standard NORSAR array short-period configuration (SPSLEM1), its variation with the 8 Hz low-pass Chebyshev filter (SPSLEM2) and the short-period attenuated channel slz (SPSLEM4) is depicted in Fig. 2.5.

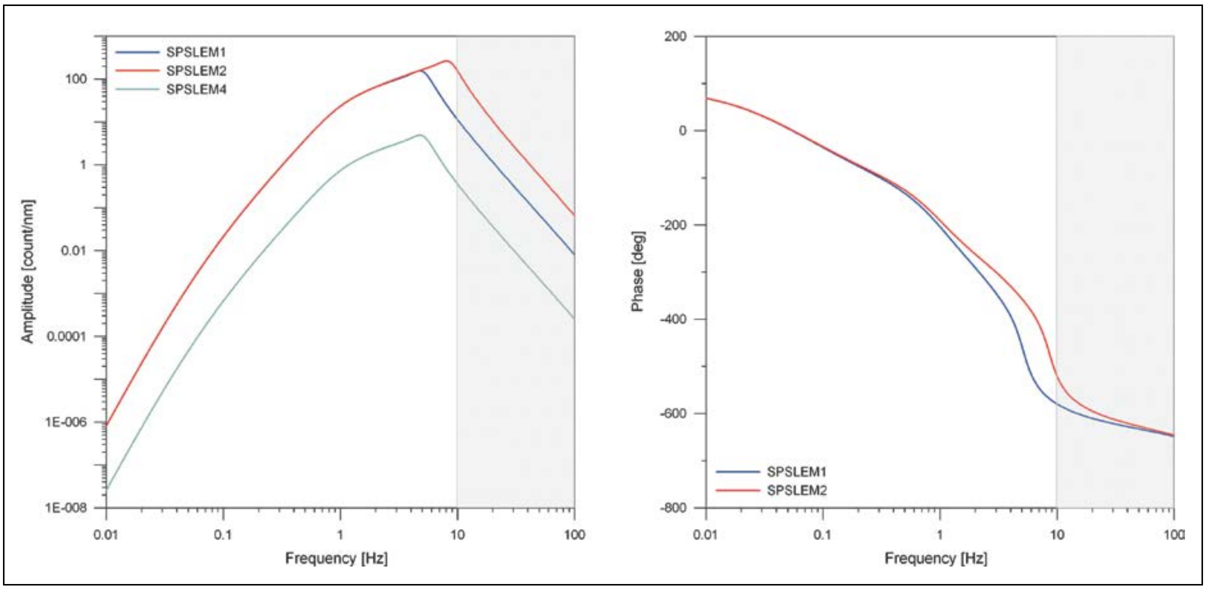


Fig. 2.5. Displacement amplitude (left) and phase (right) response for the SPSLEM1, SPSLEM2 and SPSLEM4 NORSAR configurations. The phase response of SPSLEM1 and SPSLEM4 are identical and therefore no separate response was plotted for SPSLEM4. The shaded area represents the range beyond the Nyquist frequency (=10 Hz).

2.2.2 <u>7505B/8700C-SLEM</u> (1968/01/01 – 1994/12/31)
Respid: LPSLEM1
LPSLEM2

Original LP NORSAR array configuration, consisting of the following components:
- 7505B/8700C long-period seismometers
- Ithaco amplifier
- Cable connecting LPV and CTV
- LTA amplifier
- SLEM

Except for the manuals of the different components of the system, as well as some old publications regarding initial NORSAR array installation and procedures, it is almost impossible to retrieve any other documentation on the long-period NORSAR array installations. Some information in the form of a calibration chain has been found, this however is part of an unknown document and it was not possible to reconstruct the system response according to this information. Therefore, the response was constructed according to documents NORSAR Rep. 40 (Steinert and Nilsen, 1972), NORSAR Rep. 58 (Falch, 1973) and the Ithaco amplifier manual (Ithaco, 1968), taking into consideration that all long-period channels were tuned to an overall sensitivity of 2.47 nm/count (see §2.2.2.3).

The following sections describe the calculation of individual instrument response functions.

2.2.2.1 *7505B/8700C*

The sensitivity of the LP 7505B/8700C seismometers can be obtained by the following formula:

$$G = \frac{395}{Gc \cdot i} \cdot \frac{A}{T^2}, \qquad (2.2.3)$$

where Gc = 0.028 N/A,
i = 450 μA and
A and T are expressed in mV and s respectively, and can be found in the frequency calculation sheets of NORSAR Phase 2, Document IV, Part 2.

In the same document, frequency response diagrams for the effect of the sensor and the Ithaco amplifier are provided for each site and LP channel, but only for the amplitude. Moreover, for a more accurate calculation of each individual LP seismometer, datasheets are provided in the same publication. However, as already mentioned, for the original NORSAR array configuration all amplitudes were normalized at the end of the LTA amplifier, so that a uniform amplitude response was obtained for all array elements.

The seismometer parameter values used to reconstruct the system response are (Steinert and Nilsen, 1972):
T_o = 1.0 s
λ_o = 0.64 and
G_m = 750 V/m/s.

The 7505B/8700C sensors' transfer function is the typical damping seismometer equation:

$$H(s) = \frac{s^2}{s^2 + 2\lambda_o \omega_o s + \omega_o^2}, \tag{2.2.4}$$

where $\omega_o = 2\pi f_o$.

The above transfer function for ground velocity has two zeros and two poles, obtained by the following formulas:

Zeros: 0.0, 0.0

Poles: $-\lambda_o \omega_o \pm j\omega_o \sqrt{1-\lambda_o^2}$. For λ_o = 0.64 and ω_o = 2 π 0.05 rad/s, the two complex poles are: -0.201061930 ± *j* 0.241392097.

2.2.2.2 *Ithaco*

The frequency response of the Ithaco, model 6083-82 long-period seismic amplifier can be constructed from the following filter succession (Ithaco, 1968):

- 2 low-pass RC filters with overall effect of a -3 dB frequency at 0.033 Hz (≈ 30.3 s) and a -12 dB/octave roll-off,
- 1 low-pass, 2nd order Butterworth filter with cut-off frequency at 0.04 Hz (= 25 s) and a -12 dB/octave roll-off and
  (2 poles: -0.177715318 ± *j* 0.177715318)
- 1 high-pass RC filter with cut-off frequency at 0.005 Hz (= 200 s) and -6 dB/octave roll-off
  (1 pole: -0.031415926, 1 zero: 0.0)

The information provided regarding the double RC filter stage of the amplifier is unclear on the characteristics of the two filters, *i.e.*, whether these filters are identical or not and which are their -3 dB frequencies. Since no implication whatsoever is made suggesting that the two filters differ, the approach followed for the construction of the response of this instrument was to consider two identical low-pass filters that result in the overall response described above. The characteristics of these filters will be:

-1.5 dB at 0.0286 Hz, resulting in a cut-off frequency of 0.0444997 Hz (22.47 s) and a 6 dB/octave roll-off .
(1 pole each: -0.2796)

The Ithaco amplifier operated with an overall nominal gain of 80 dB (10000 x). This value is the result of the various instrument components, including the filters mentioned above. Since the system was being tuned, the output of the Ithaco amplifier was being adjusted. A reported mean value of its output is equal to 505 mV/μm at 23 s (NORSAR, 1969b).

NORSAR array site N1403 long-period channels were attenuated by -30 dB as of September 1975, in order to receive unsaturated seismic signals from events up to M_b = 7.0, at a 30° distance (NORSAR, 1976). A separate response with a reduced Ithaco amplifier gain is calculated in this case.

The theoretical (solid line) and measured amplitude response of the Ithaco amplifier (Leichliter, 1968) is depicted in Fig. 2.6, for three different units that were later installed at NORSAR array site 03C03, with the long-period vertical and horizontal seismometers.

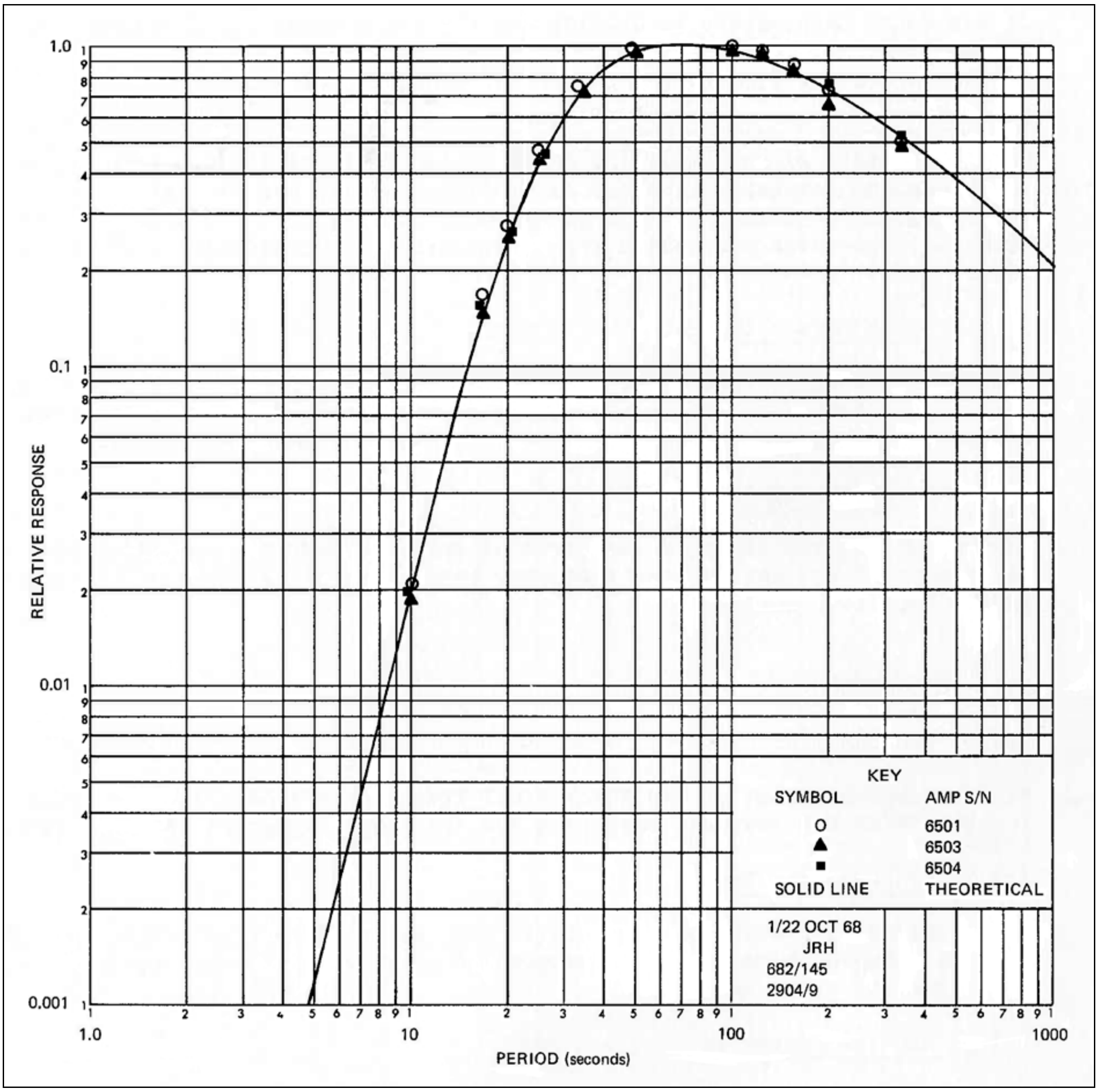


Fig. 2.6. Theoretical and measured response of the Ithaco seismic amplifiers with serial number 6501, 6503 and 6504 (Leichliter, 1968).

2.2.2.3 *LTA*

The response of the long-period version of the LTA amplifier does not differ essentially from the one described in section 2.2.1.3. However, the LP version employs only one 1^{st}-order HP filter with cut-off frequency at 0.00372 Hz (≈ 269 s). The frequency response can therefore be constructed using the following information: 1 pole: -0.0233734493, 1 zero: 0.0

In the case of the LTA long-period version, which lacks any low-pass filter, all measurements and adjustments are made at TP1 (see Fig. 2.4). The adjustment was such that an overall channel sensitivity of 2.47 nm/count was obtained at 25 s.

It should be noted here that although in existing response related macros the calibration period of the long-period channels is reported to be equal to 20 s, this is not supported either by the existing documentation or measurements made on calibration pulses. Thus, the response calculated here considers a calibration period of 25 s. In any case, a comparison was performed between the responses resulting from these two different calibration period values, and these were found to vary by approximately 1 %. Taking into consideration the much wider tolerance limits for all parameters used to calculate the system response, such a variation can be considered negligible.

2.2.2.4 *SLEM*

The response of the SLEM unit is described in detail in section 2.2.1.4.

The overall response for displacement amplitude and phase is depicted in Fig. 2.7, for the standard NORSAR long-period configuration (LPSLEM1) and the attenuated channel test at subarray 14C (LPSLEM3). The two configurations have an identical phase response, but differ in sensitivity.

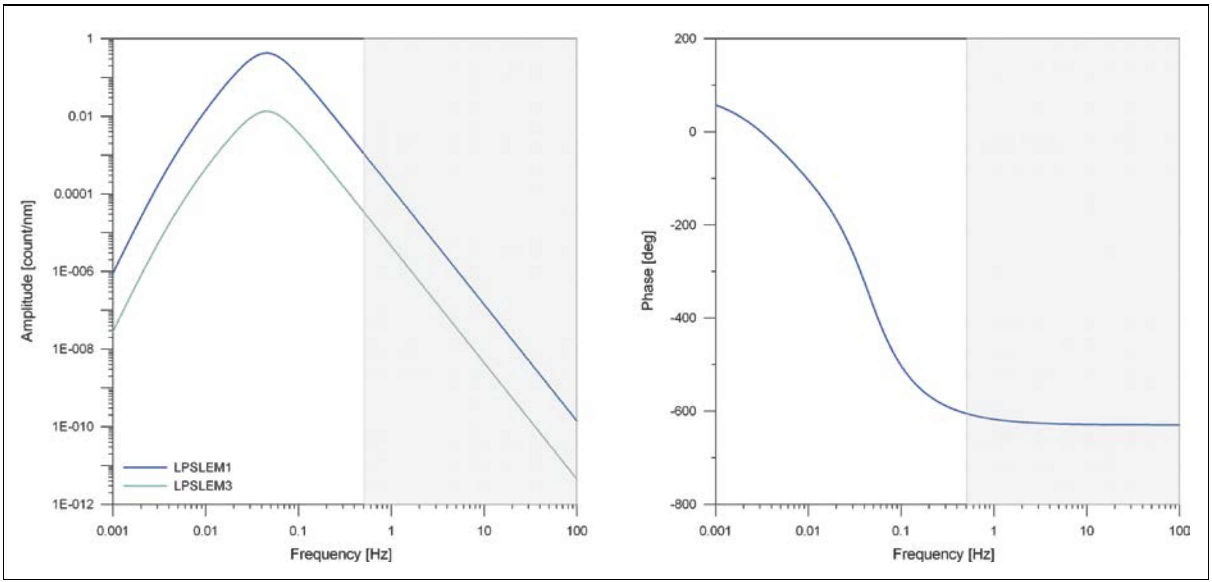


Fig. 2.7. Displacement amplitude (left) and phase (right) response for NORSAR array long-period configurations LPSLEM1 and LPSLEM3. The phase response is identical for both cases and therefore has been plotted only once. The shaded area represents the range beyond the Nyquist frequency (=0.5 Hz).

2.2.3 HS-10-RD6 (1994/01/01 – 1994/12/20)
Respid: RDSP1
RDSP2

The system consists of the following units:
- HS-10-1 short-period seismometer
- RA-5 amplifier
- LTA amplifier
- RD6 digitizer

The following sections describe the calculation of individual instrument response functions.

2.2.3.1 *HS-10-1*

The response of this instrument has been described in section 2.2.1.1.

2.2.3.2 *RA-5*

The response of this instrument has been described in section 2.2.1.2.

2.2.3.3 *LTA*

The response of this instrument has been described in section 2.2.1.3.

2.2.3.4 *RD6*

The RD6 is a 16-bit, 6-channel A/D converter manufactured by Nanometrics. The version installed at the NORSAR array (model 1625) employs autogain and the following filters:

- Analog 5^{th} order low-pass Butterworth anti-alias filter, with f_c = 23 Hz.
- Digital low-pass FIR filter, with $f_{3\mathrm{dB}}$ = 40 Hz and 68 coefficients.

- The transfer function of the above mentioned Butterworth filter is described in the s-plane by the equation:

$$F(s) = \frac{\omega^5}{(s^2 + \frac{s\omega}{Q_1} + \omega^2)(s^2 + \frac{s\omega}{Q_2} + \omega^2)(s + \omega)}, \qquad (2.2.5)$$

where Q_1 = 1.61803 and Q_2 = 0.618034.

The poles of this filter in the s-plane will then be the roots of the equations:

$$s^2 + 89.31 \cdot s + 20880.25 = 0$$
$$s^2 + 233.81 \cdot s + 20880.25 = 0$$
$$s + 144.5 = 0$$

So, the above listed Butterworth filter has 5 poles and no zeros, expressed in rad/s:

$-0.4465\text{x}10^2 \pm j\ 1.3743\text{x}10^2$,
$-1.1690\text{x}10^2 \pm j\ 0.8493\text{x}10^2$ and
$-1.4450\text{x}10^2$.

The scale factor equals: $k = 6.3\text{x}10^{10}$.

- The transfer function of the digital FIR filter is described in the time domain by the equation:

$$y[n] = \sum_{i=0}^{N-1} c(i) \times (n-i)\,, \tag{2.2.6}$$

where N is the number of coefficients and c_i are the coefficient values.

The employed FIR filter is symmetric and the values of the $N/2$ coefficients can be found in file NOARDSP1-NOA-SHZ.gse. It is decimating by a factor of 4, from the initial sampling rate of 160 sps down to the output rate of 40 sps.

Regarding digitizer sensitivity, the RD6 unit is a gain-ranged instrument, with gain ranging providing an extra 40 dB gain. Oversampling with a factor of 4 gives (theoretically) 2 extra bits of resolution. In the case of 6 active channels, each sample consists of 6 16-bit mantissas followed by a byte containing all exponent bits. The exponent base equals 8 in the case that any software filters have been selected (Nanometrics, 1992). This amounts to a resolution of 20-bit which results in an additional gain factor of 100 (= $10^{(40\text{ dB} / 20\text{ bit})}$).

Then, the sensitivity is in the order of:

$$\frac{\pm 20V}{2^{15} bit \cdot 100} = \frac{\pm 20V}{3276800 bit} = 6103.5 nV / bit\,, \tag{2.2.7}$$

as stated also in the actual instrument datasheets.

The displacement amplitude and phase response for the NB2 short-period configurations with *Respid* RDSP1 and RDSP2 are depicted in Fig. 2.8. RDSP2 response is essentially the same as RDSP1, except for the 30 dB attenuation. Therefore, the phase response is identical in both cases. The system has a sampling rate of 40 sps.

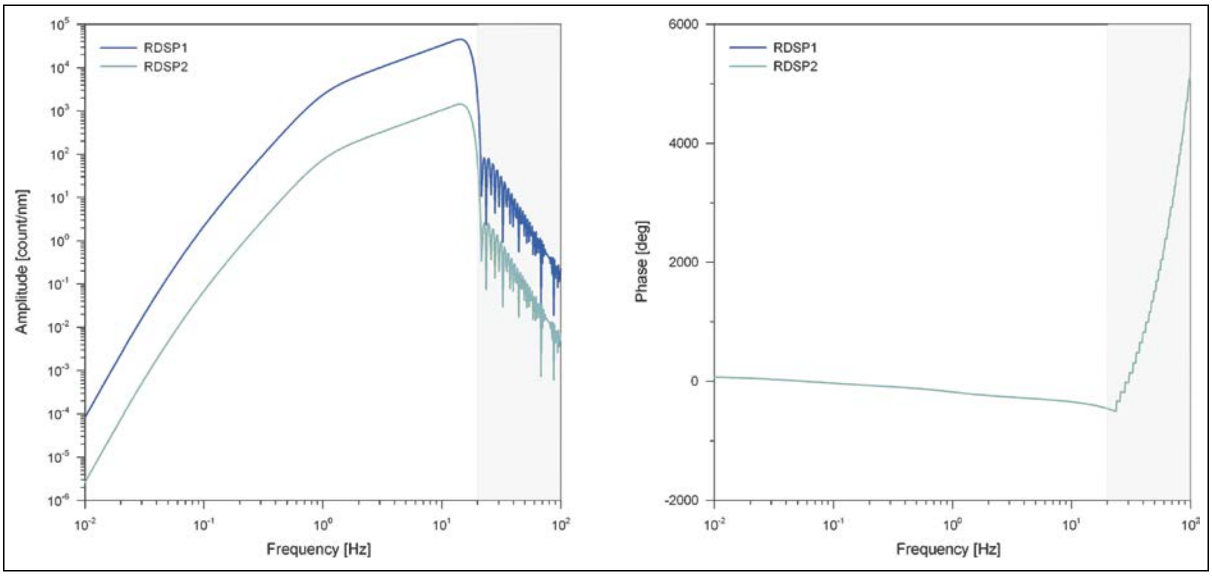


Fig. 2.8. Displacement amplitude (left) and phase (right) response for NORSAR array short-period configurations RDSP1 and RDSP2. The shaded area represents the range beyond the Nyquist frequency (= 20 Hz).

2.2.4 7505B-RD6 (1994/01/01 – 1994/12/20)

Respid: RDLP1

The system consists of the following units:

- 7505B long-period seismometer
- Ithaco amplifier
- LTA amplifier
- RD6 digitizer

Only data from the vertical long-period seismometer are available. The data were assigned to the auxiliary digitizer channel that is typically used for instrument state-of-health (SOH) information, as well as wind measurements, *etc*. No 3-component data are available in this case.

The following sections describe the calculation of individual instrument response functions.

2.2.4.1 *7505B/8700C*

The response of this instrument has been described in section 2.2.2.1.

2.2.4.2 *Ithaco*

The response of this instrument has been described in section 2.2.2.2.

2.2.4.3 *LTA*

The response of this instrument (long-period version) has been described in section 2.2.2.3.

2.2.4.4 *RD6*

The response of this instrument has been described in section 2.2.3.4. However, the employment of the digitizer auxiliary channel excludes the application of any of the filters described in the above mentioned section. Moreover, the channels have a sensitivity of 4259.84 count/V, as reported within FORTRAN routine lv2isc.f, residing under ~/ndc/programs/dpep/ver2/lsys/arrman/. There, it is stated that the sensitivity of the RD6 auxiliary channels is 2.6 times smaller, compared to original SLEM configuration.

The displacement amplitude and phase response curves for the NB2 long-period configuration with *Respid* RDLP1, are displayed in Fig. 2.9. Since no RD6 filters are being employed, the response curve strongly resembles the SLEM configuration curves of Fig. 2.7. For the RD6 auxiliary channel employed here, the sampling rate is set to 1 sample/s.

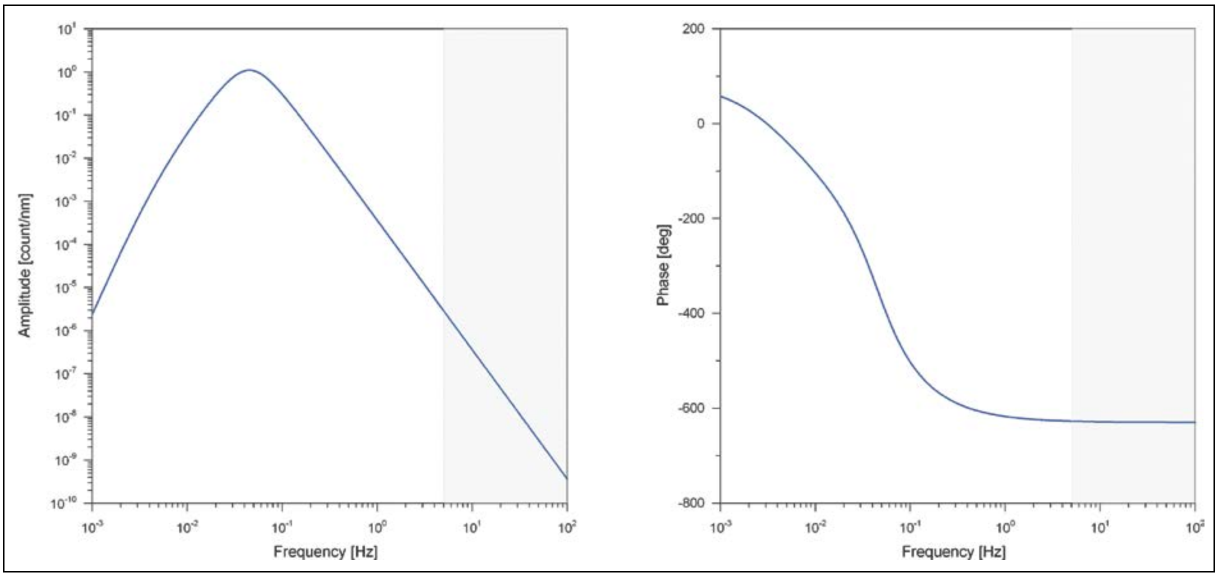


Fig. 2.9. Displacement amplitude (left) and phase (right) response for NB2 long-period configuration RDLP1. The shaded area represents the range beyond the Nyquist frequency (= 0.5 Hz).

2.2.5 HS-10-AIM24-1 (1994/12/20 – 1995/10/29)

Respid: AIM1
AIM2
AIM3

There have been two combinations for an HS-10 seismometer and an AIM24-1 digitizer. Either the AIM24-1 is residing in the CTV (AIM1, AIM3) or both seismometer and digitizer are residing in the SPV (AIM2) and are connected without the interference of any other unit. An RA-5 preamplifier and LTA amplifier with no low-pass filter are used in the first case. The initial plan was to have one AIM24-1 in the CTV and the rest in the SPVs of each subarray however, the inaccessibility of the SPVs during wintertime resulted in all the AIM24 units being placed in the CTVs, except for the ones in subarray 06C (Fyen, 1995a).

Thus, the system consists of the following units:

- *HS-10-1 short-period seismometer*
- RA-5 amplifier
- LTA amplifier
- *AIM24-1 digitizer*

Lines in italics denote the only components of the system employed with the AIM residing in the SPV.

2.2.5.1 *HS-10-1*

System response is described in section 2.2.1.1.

2.2.5.2 *RA-5*

The response of this instrument has been described in section 2.2.1.2.

2.2.5.3 *LTA*

Details regarding the response of this instrument are given in section 2.2.1.3. It should be noted however, that the LTA amplifier version installed at the NORSAR array Backup System employs only a high-pass 1st-order RC filter, with a cut-off frequency at 0.038 Hz and a 6 dB/octave roll-off.

2.2.5.4 *AIM24-1*

The response of the AIM24-1 unit will be described in Section 2.2.9.3. It should be noted that for units placed in the short period vaults a gain of 40 dB (x 100) was employed.

The displacement amplitude and phase response curves for the short-period configurations AIM1, AIM2 and AIM3 discussed above are presented in Fig. 2.10. For AIM1 and AIM3 the instruments reside in the CTVs, while AIM2 represents the case of array site NC602, where the instruments were installed in the SPV. Configuration AIM3 is the attenuated version (by 30 dB) of AIM1, therefore the phase response is identical for both cases. Sample rate equals 40 samples/s.

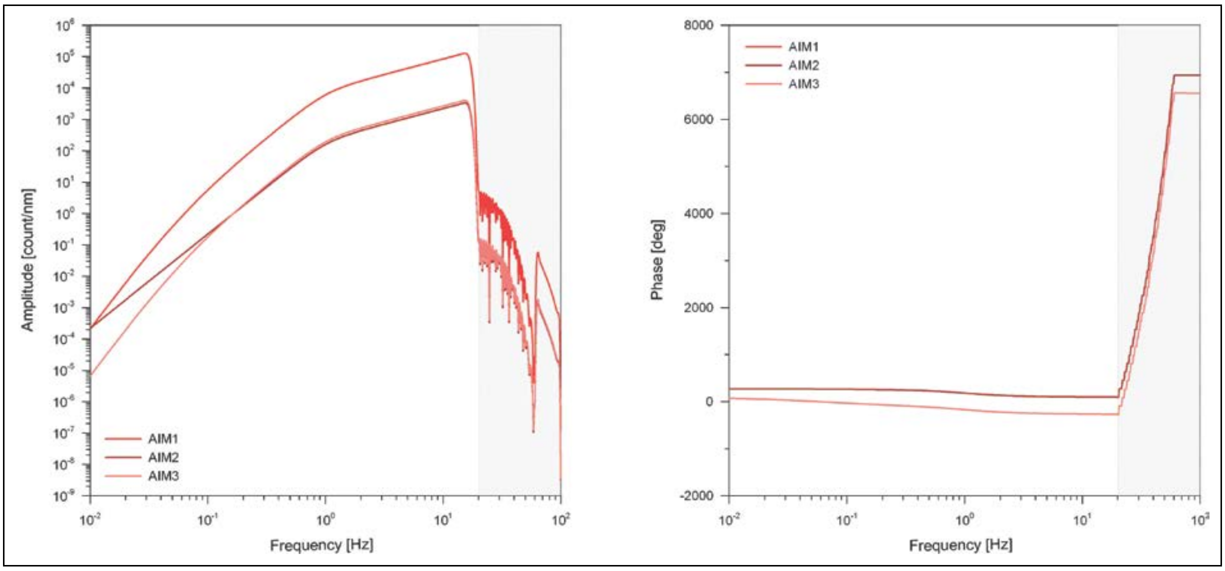


Fig. 2.10. Displacement amplitude (left) and phase (right) response for NORSAR array short-period configurations AIM1, AIM2 and AIM3. The shaded area represents the range beyond the Nyquist frequency (= 20 Hz).

2.2.6 7505B/8700C-AIM24-BB (1995/07/31 – 1995/10)
Respid: AIM4 (vertical)
AIM5 (horizontals)

The system consists of the following units:
- 7505B/8700C long-period seismometer
- Ithaco amplifier
- LTA amplifier
- AIM24-3BB digitizer

The following sections describe the calculation of individual instrument response functions.

2.2.6.1 *7505B/8700C*

The response of this instrument is described in section 2.2.2.1.

2.2.6.2 *Ithaco*

The response of this instrument is described in section 2.2.2.2.

2.2.6.3 *LTA*

The response of the long-period version of the LTA amplifier is described in section 2.2.2.3.

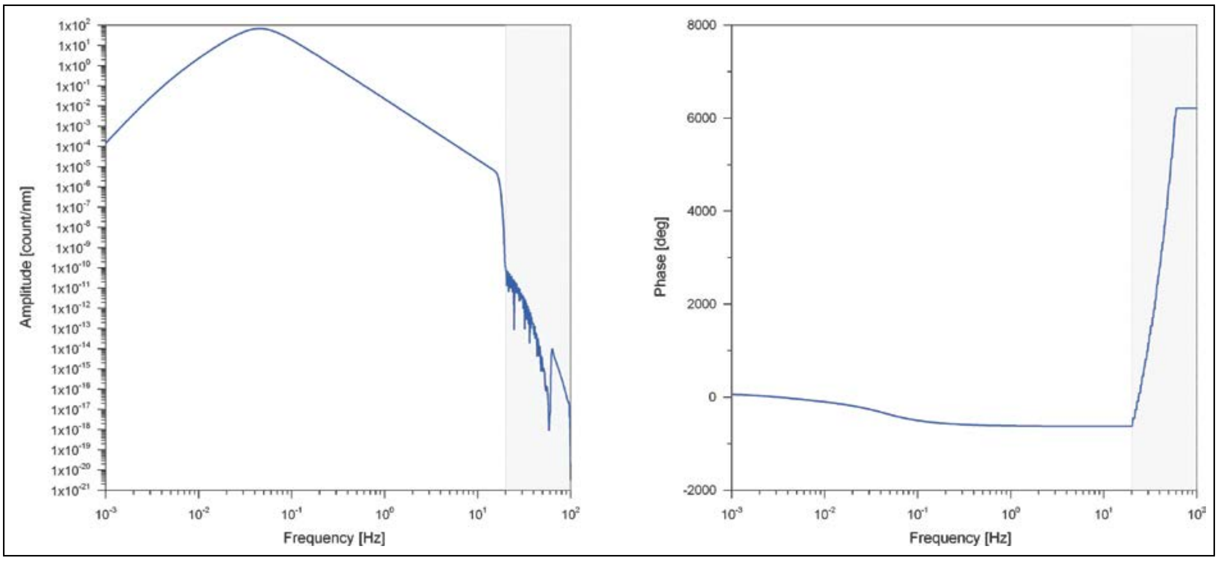


Fig. 2.11. Displacement amplitude (left) and phase (right) response for NORSAR array long-period configuration RDLP1. The shaded area represents the range beyond the Nyquist frequency (=20 Hz).

2.2.6.4 *AIM24-3BB*

The response of this instrument is described in detail in section 2.2.10.2. It should be noted however that this had been a temporary installation, part of the general NORSAR array refurbishment, until the old long-period sensors were replaced by the broadband KS54000 instruments (see also §2.2.10.1).

The displacement amplitude and phase response curves for the long-period configuration discussed here (RDLP1) are depicted in Fig. 2.11. System sampling rate is set to 40 samples/s.

2.2.7 <u>S-13-SLEM</u> (short intervals within 1976, 1978 and 1980)
Respid: SPSLEM7

The system consists of the following units:
- S-13 short-period seismometer
- RA-5 amplifier
- LTA amplifier
- SLEM A/D converter

The following sections describe the calculation of individual instrument response functions.

2.2.7.1 *S-13*

The transfer function of the S-13 seismometer for displacement is expressed by the following formula:

$$F(s) = \frac{s^2}{s^2 + 2\lambda_o \omega_o s + \omega_o^2}. \tag{2.2.8}$$

In the case of the instruments installed at the NORSAR array, the following values can be used:

$\lambda_o = 0.707$ and
$\omega_o = 2\pi 1$ rad/s.

The above function has two poles and two zeros,
$z_{1,2} = 0.0$
and
$p_{1,2} = \lambda_o \omega_o \pm \omega_o \sqrt{1-\lambda_o^2}$.

To calculate the response function of a short-period S-13 seismometer, the following information, provided by the manufacturer or calculated in the lab, is needed (Nilsen, 1978b):

- calibration frequency, f_c, in Hz
- calibration coil motor constant, G_c, in N/A
- calibration coil current, i, in A
- weight of intertial mass, m, in kg

Equivalent ground motion is calculated by the formula:

$$y = \frac{G_c \cdot i \cdot 10^6}{4\pi^2 f_c^2 m}, \text{ in } \mu\text{m}. \tag{2.2.9}$$

Then, sensitivity can be calculated by the following formula:

$$G = \frac{y}{quantum\_units\_p - p\_at\_channel\_output}, \text{ in nm/qu.} \tag{2.2.10}$$

Example:

For the seismometer installed in 1978 on channel 01A01 of the NORSAR array, the above listed parameters receive the following values (Nilsen, 1978b):

- f_c = 1.0 Hz
- G_c = 0.1975 N/A (0.1973 N/A for the vertical)
- i = 400 µA
- m = 5.0 kg

Applying formula (2.2.9) we obtain a value of y = 0.4 µm and finally, applying formula (2.2.10) we get a sensitivity value of G = 42.73 pm/qu.

However, in all three S-13 installations at the NORSAR array, the system was tuned to the channel sensitivity value of 0.0427 nm/count, as in the case of the HS-10-1 seismometers.

2.2.7.2 *RA-5*

The response of this instrument has been described in section 2.2.1.2.

2.2.7.3 *LTA*

The response of this instrument has been described in section 2.2.1.3.

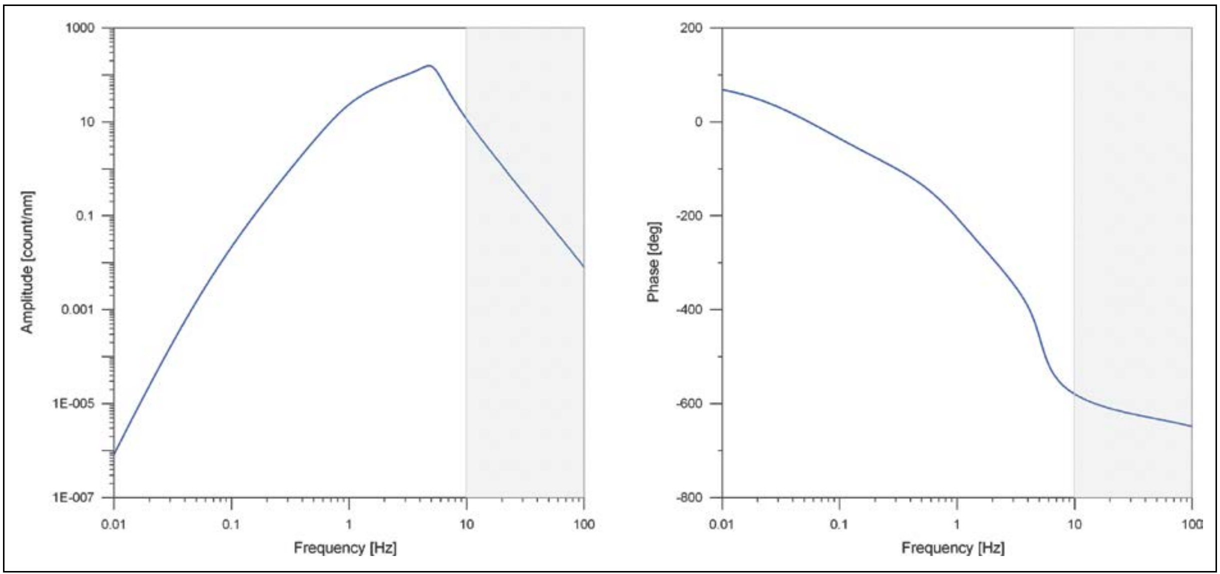


Fig. 2.12. Displacement amplitude (left) and phase (right) response for NORSAR array short-period configuration SPSLEM7. The shaded area represents the range beyond the Nyquist frequency (= 10 Hz).

2.2.7.4 *SLEM*

The response of this instrument has been described in section 2.2.1.4. All S-13 configurations were being tuned to the standard short-period channel sensitivity value of 0.0427 nm/count.

The overall system response (SPSLEM7) for displacement amplitude and phase is depicted in Fig. 2.12.

2.2.8 S-500-SLEM (1978/03/15 – 1978/04/12)
Respid: SPSLEM8

The channel configuration consists of the following components:

- S-500 short-period seismometer
- RA-5 amplifier
- Short-period LTA with a 8 Hz low-pass filter
- SLEM

In this case, the system was not tuned to any predetermined sensitivity value. Channel sensitivity for the above mentioned configuration equals 0.0995 nm/count. The following sections describe the calculation of individual instrument response functions.

2.2.8.1 *S-500*

To calculate the response function of a short-period S-500 seismometer, the following information, provided by the manufacturer or calculated in the lab, is needed (Larsen, 1978, Nilsen, 1978a,b):

- calibration frequency, f_c, in Hz
- calibration coil factor, K, in m/(s^{2}A)
- calibration coil current, i, in A
- weight of intertial mass, m, in kg

Equivalent ground motion p-p is calculated by the formula:

$$y = \frac{K \cdot i}{4\pi^2 f_c^2}\text{, in meters.} \qquad (2.2.11)$$

Then, sensitivity can be calculated by the following formula:

$$G = \frac{y}{quantum\_units\_p-p\_at\_channel\_output}\text{, in m/qu.} \qquad (2.2.12)$$

Example:

For the seismometer installed on channel 06C02 of the NORSAR array, the above listed parameters receive the following values (Larsen, 1978):

- f_c = 1.0 Hz
- K = 3.046 m/(s^{2}A)
- i = 12.05 μA p-p
- m = 1.0 kg

Applying formula (2.2.11) we obtain a value of y = 0.930 μm and finally, applying formula (2.2.12) we get a sensitivity value of G = 99.5 pm/qu.

The velocity response of the S-500 instrument is described by the following equations (Geotech, 1995, fax info):

$$V_{I,k} = \frac{K_V \cdot f_{I,k} \cdot \left|(f_{I,k} + z_a)(f_{I,k} + z_i)\right|}{\left|(f_{I,k} + p_{s1})(f_{I,k} - p_{s2})(f_{I,k} + p_{L1})(f_{I,k} - p_{L2})(f_{I,k} + p_a)(f_{I,k} + p_{i1})(f_{I,k} - p_{i2})\right|} ,(2.2.13)$$

where $K_V = 2\pi K \cdot$ 0.14325 Hz (6.4) = 5.457x10^{10} V/m/s^3,

I is the number of decades (= 1, 2, … *ndec*) and k the number of points (= 1, 2, … *np*), *np*=100.

For $f_{3,1}$ = 10 Hz, $V_{3,1}$ equals 450.1 V/m/s.

The transfer function of equation (2.2.13) has the following poles and zeros, in Hz (frequency domain):

$p_{s1,2} = 60 \pm j103.9$	mechanical poles
$p_a = 0.965$	preamplifier pole
$p_{L1,2} = 66.3 \pm j\ 57{,}2$	low pass poles
$p_{i1,2} = 0.662 \pm j\ 0.662$	integrator poles
$z_a = 0.0$	preamplifier pole
$z_i = 0.0$	integrator pole

To obtain the poles and zeros in the s-domain, equation (2.2.13) has to be multiplied by $j2\pi$.

2.2.8.2 *RA-5*

The response of the RA-5 unit is described in section 2.2.1.2.

2.2.8.3 *LTA*

The response of the LTA unit is described in section 2.2.1.3.

2.2.8.4 *SLEM*

The response of the digitizer is described in section 2.2.1.4. In this case, the system was not being tuned to the standard short-period channel sensitivity value.

Displacement amplitude and phase response for this configuration (SPSLEM8) is depicted in Fig. 2.13.

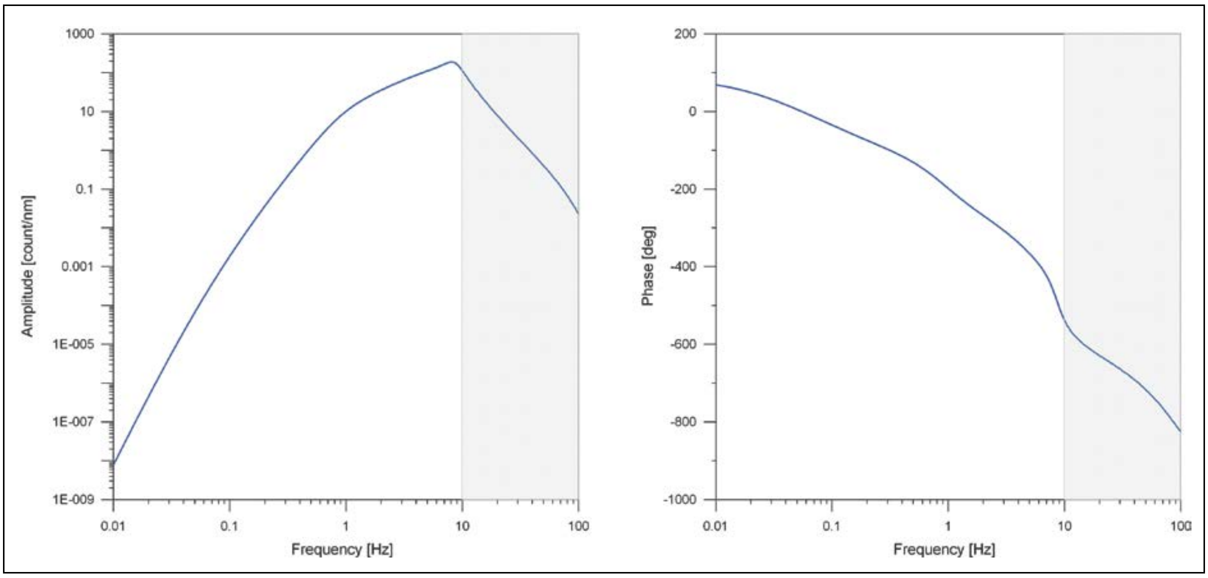


Fig. 2.13. Displacement amplitude (left) and phase (right) response for NORSAR array short-period configuration SPSLEM8. The shaded area represents the range beyond the Nyquist frequency (= 10 Hz).

2.2.9 <u>20171B-AIM24-1</u> (1995/10/29 – 2011)
Respid: AIM0SP

The system consists of the following units (Figure 2.14):
- 20171B short-period seismometer
- Brick amplifier
- AIM24-1 A/D converter

The following sections describe the calculation of individual instrument response functions.

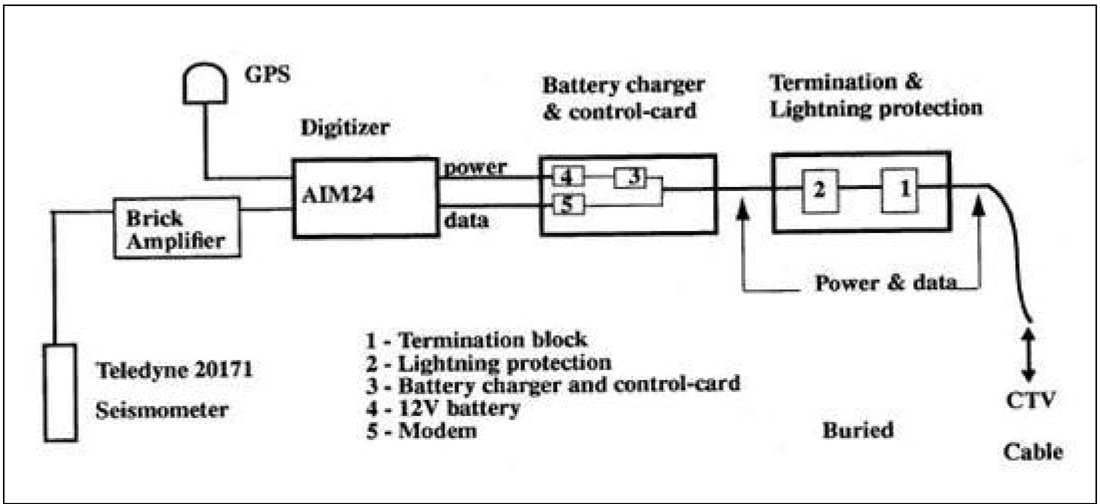


Fig. 2.14. Schematic illustration of NORSAR array remote SPV electronics (Fyen, 1995).

2.2.9.1 *20171B*

To calculate the response function of a short-period 20171B seismometer, the following information, provided by the manufacturer or calculated in the lab, is needed (Teledyne Brown, 1995):

- weight of inertial mass, M
- total circuit resistance, R_t
- open-circuit damping, λ_x
- relative damping, λ_0
- critical damping resistance, R_{CDR}
- natural frequency, f_0
- coil resistance, R_c
- generator constant, G
- external load resistance, R_0 or R_D

Depending on the desired relative damping value, circuit resistance values have to be calculated in the lab, so that:

$$R_t = \frac{R_{CDR}}{\lambda_0}. \tag{2.2.14}$$

The generator constant for the data coil can be determined from the following formula:

$$G = \sqrt{4\pi f_0 M R_{CDR}(1-\lambda_x)}\text{, in V/m/s} \tag{2.2.15}$$

The resulting constant however, is not the sensitivity value to be used for calculating instrument response. This will be the 'effective' sensitivity resulting from the formula:

$$w = G\frac{R_0}{R_c + R_0}. \tag{2.2.16}$$

For the NORSAR array, this information is tabulated in Appendix III, and the final 'effective' sensitivity factor, which will be used for the system response determination, is calculated for each element. It is quite clear from Fig. 2.15 that the spread in seismometer sensitivity values is reflected on overall channel sensitivity values.

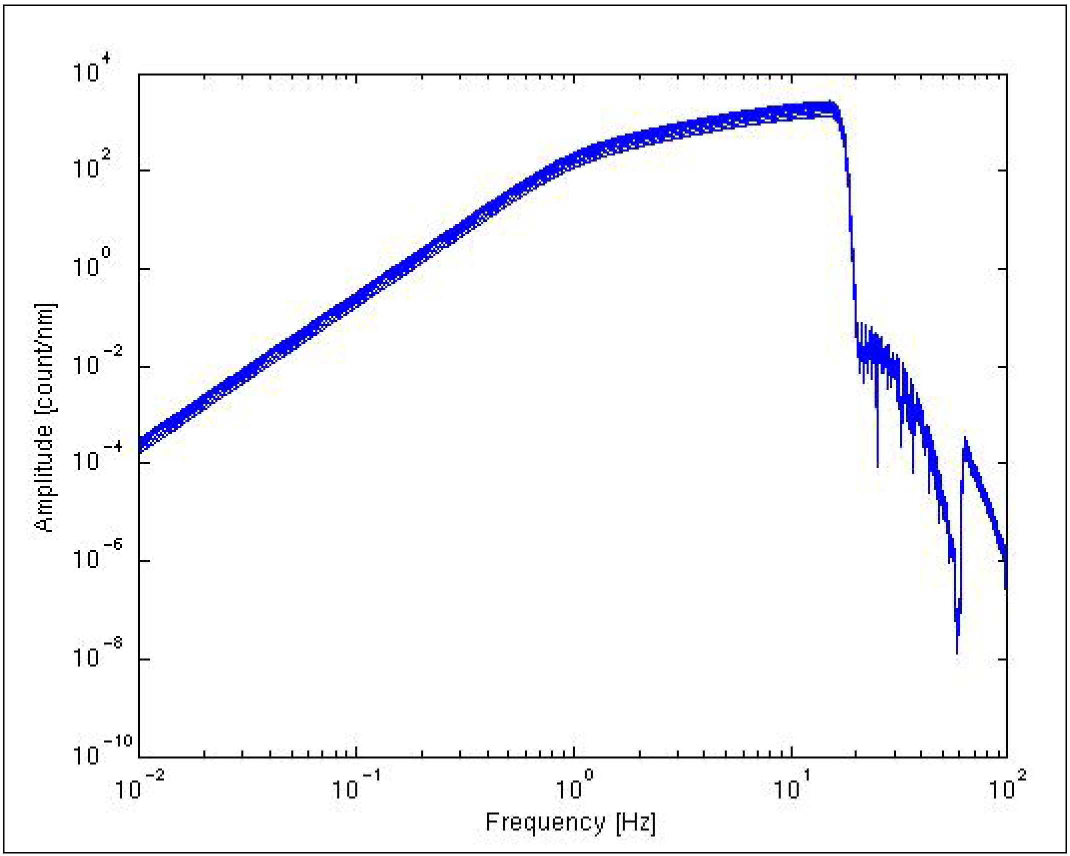


Fig. 2.15. Displacement amplitude response for the 42 Geotech 20171A seismometer installations of the NORSAR array. A significant spread in sensitivity levels is obvious.

The theoretical transfer function for ground velocity of the seismometer, which is a second-order system, is:

$$H(s) = \frac{s^2}{s^2 + 2\lambda_o\omega_o s + \omega_o^2}, \tag{2.2.17}$$

where $\omega_0 = 2\,\pi\, f_0$.
Then, the system has 2 zeros and 2 poles:

$z_{1,2}$ = 0.0

and

$p_{1,2} = \lambda_o \omega_o \pm \omega_o \sqrt{1-\lambda_o^2}$.

Example:

For the 20171B seismometer with S/N 226, installed at element NC602, the above mentioned quantities receive the following values:

- f_0 = 1.0 Hz
- M = 5.0 kg
- λ_0 = 0.707
- λ_x = 0.027
- R_t = 9383.3 ohms
- R_{CDR} = 6634 ohms
- R_c = 7222 ohms
- R_0 = 2160 ohms

Applying formula (2.2.15) for G calculation, we obtain: 636.8 V/m/s

Finally, with the application for formula (2.2.16), the factor *w* equals 146.609 V/m/s.

Regarding the transfer function, it will look like:

$$H(s) = \frac{s^2}{s^2 + 8.8844 \cdot s + 39.4784} . \qquad (2.2.18)$$

Then, the poles are:

$p_{1,2}$ = -4.4422 ± j 4.4436.

2.2.9.2 *Brick amplifier*

The Brick amplifier response is described by the following transfer function:

$$F(s) = \frac{39.8}{\sqrt{1+(0.103 \cdot f_c)^2}} \text{ or } F = \frac{39.8 \cdot \omega_c}{(s+\omega_c)} ,$$

where $\omega_c = 2\pi f_c$ (rad/s),
f_c = 9.7 Hz and
$s = j\omega = 2\pi f$ (rad/s)

It has only one real pole: $-2\pi f_c$ = -60.946897.

2.2.9.3 *AIM24-1*

The AIM24 is a 24-bit A/D converter by Science Horizons Inc., consisting of a preamplifier front end, a 24-bit delta sigma A/D converter chipset, digital signal processor, a very stable clock source and a microprocessor which controls the entire operation (Ingate, 1995).

The version installed with the 20171B short-period seismometers at the NORSAR array has a 32.0 V peak-to-peak full scale dynamic range and a selectable gain of 1.0 V/V, 10.0 V/V or 100.0 V/V. For the short-period channels of the NORSAR array, gain was set to 10 V/V after testing various combinations with the Brick amplifier, since this provided the best SNR for frequencies above 2 Hz (Fyen, 1995).

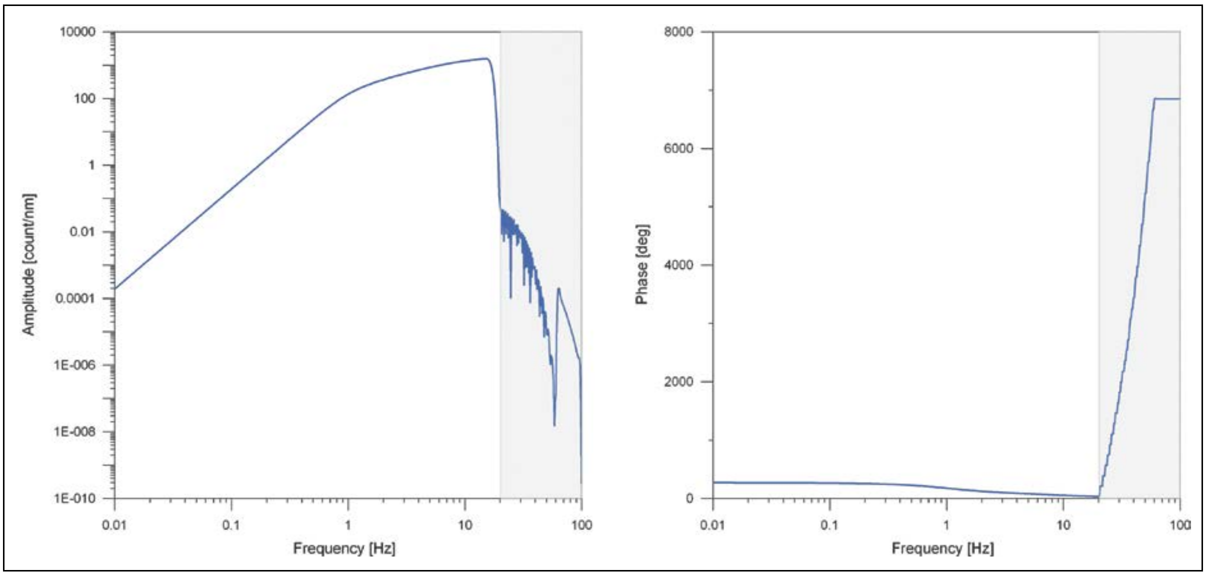


Fig. 2.16. Displacement amplitude (left) and phase (right) response for the current short-period NORSAR array configuration (AIM0SP). The shaded area represents the range beyond the Nyquist frequency (= 20 Hz).

Regarding the Crystal semiconductor, the CS5323 chip is an analog modulator with an input bitstream clocking of 40960 Hz, while the CS5322 chip employs 3 successive linear phase FIR filters, which decimate down to the desired sampling rate. The first filter applies a decimation factor of 8, the second one can decimate by 4, 8, 16, 32, …, 256, and the third filter by a factor of 2. The sampling rate used for the NORSAR array is 40 sps and in order to achieve the following succession of FIR filters was selected:

FIR1, decimating by 8, 33 coefficients
FIR2, decimating by 64, 13 coefficients, 6 stages with decimation factor of 2
FIR3, decimating by 2, 101 coefficients

FIR2 in the above mentioned list consists of a succession of 6 equal FIR filters, each of them decimating by a factor of 2. So, normalizing coefficients to SUM=1, the digitizer response can be constructed with the following sequence of FIR filters:

$$40960Hz \xrightarrow{FIR1(8)} 5120Hz \xrightarrow{6xFIR2(2)=64} 80Hz \xrightarrow{FIR3(2)} 40Hz\,.$$

Note that in the case of FIR2, the use of a single FIR filter decimating by 64 does not provide the same response as the succession of the 6 FIR filters described above.

Regarding the sensitivity of the AIM24-1 unit, the least significant bit equals

$$LSB = 32V/(2^{24} - 1)counts = 32V/16777215counts = 1907{,}734\ nV/count.$$

or

$$sensitivity = 524288\ counts/V.$$

Taking into consideration the 10V/V gain, then total sensitivity of the unit at 1.0 Hz equals 5242880 counts/V.

The overall short-period channel response (AIM0SP) for displacement is depicted in Fig. 2.16, for NORSAR array site NC602.

2.2.10 KS54000-AIM24-3BB (1995/12/11 – 2011/11)
Respid: AIM0BB

The system consists of the following units:
- KS54000 broadband seismometer
- AIM24-3BB digitizer

The following sections describe the calculation of individual instrument responses.

2.2.10.1 *KS54000*

The transfer function for ground acceleration of the KS54000 tri-axial, broadband seismometer is described by the following poles and zeros, provided by the manufacturer (Teledyne-Geotech):

CHANNEL	**POLES (HZ)**	**ZEROS (HZ)**	**SCALE FACTOR**
Closed loop output	-3.6147454 ± *j* 4.3141396	-135.82144	-155740 $V/m/s^2$
	-9.4587884	-680.74475	
	-136.71430	-15579.31817	
	-680.73611		
	-15579.31812		
Loop output filter stage	-0.0099239296	0.0	-254450 Vrms/Vrms
	-10.936363	-72343.156	
	-1507.7381		
	-230127.33		
Line driver stage	-1591.5494	-1591.5574	1.0 Vrms/Vrms
	-795774.72	-1591549.4	
Mass position monitor output stage	-79577		-79577 Vrms/Vrms

Instrument sensitivity is equal to 5000 $V/m/s^2$ between 0.01 and 5.2 Hz.

2.2.10.2 *AIM24-3BB*

The AIM24 version installed with the 3-component broadband seismometers has a gain of 1.0 V/V and has a full-scale dynamic range of 64.0 V.

The unit employs the Crystal Semiconductor CS5321/5322 chipset, with CS5321 being an analog modulator with an input bitstream clocking of 40960 Hz, while the CS5322 chip employs 3 successive linear phase FIR filters, which decimate down to the desired sampling rate of 40 Hz (see section 2.2.9.3 for details).

The least significant bit equals:

$$LSB = 64V/(2^{24}-1)counts = 64V/16777215counts = 3.81469\,\mu V/count$$

and the sensitivity is: 262144.49929 *counts*/*V*

The overall broadband channel displacement response is depicted in Fig. 2.17, for NORSAR array site NC602.

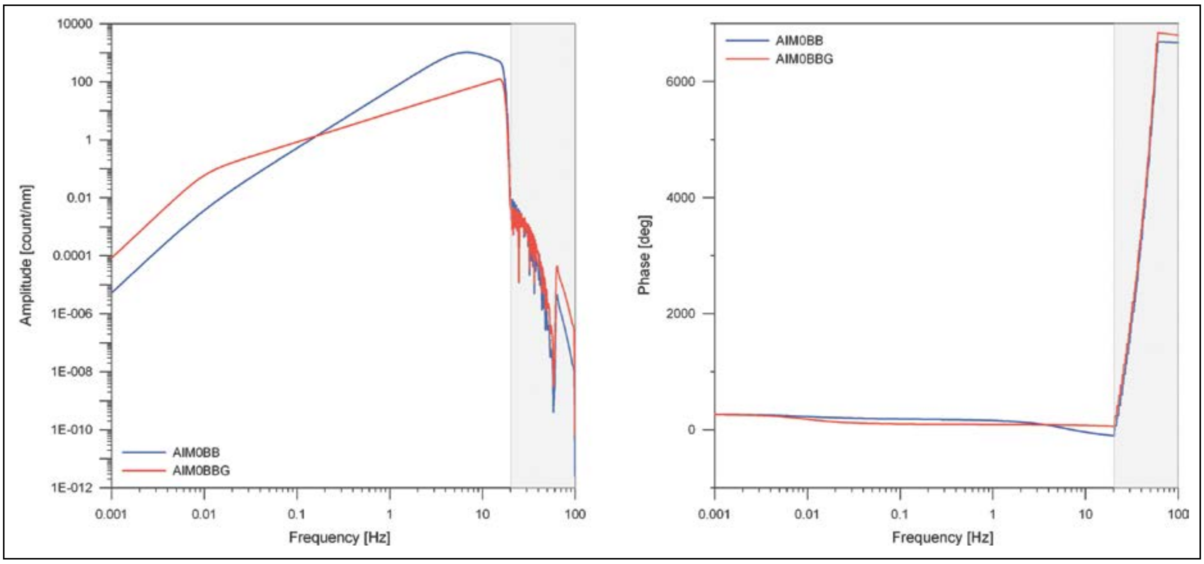


Fig. 2.17. Displacement amplitude (left) and phase (right) response for the broadband configurations of the NORSAR array. The AIM0BB configuration is employing the KS54000 sensor and the AIM0BBG the CMG-3T Güralp sensor (see §2.2.11, this Chapter). The shaded area represents the range beyond the Nyquist frequency (= 20 Hz).

2.2.11 CMG-3T-AIM24-3BB (2000/03/16 – 2011/11/25)
Respid: AIM0BBG(a)

The system consists of the following units:
- CMG-3T broadband, 3-component seismometer
- AIM24-3BB digitizer

This configuration is found only at NORSAR site NC602 and was adopted to ensure the array's compatibility with CTBTO requirements. Initially, the new seismometer was operating in parallel to the old broadband channel with the KS54000 sensor, described in section 2.2.10, and was therefore assigned the channel code gz, gn, ge for the vertical, N-S and E-W component, respectively. The old broadband channel was closed in June 2000 (05/06/2000) and since then the channel codes bz, bn, be have replaced the 'g' codes for the current configuration. To differentiate between the two cases that have identical responses but different channel codes, an additional response file (see also Appendix II), with an 'a' appended to the file name, is used.

The following sections describe the calculation of individual instrument responses.

2.2.11.1 *CMG-3T*

Instrument response information is provided by the manufacturer (Güralp Instruments, Ltd.) in the form of poles and zeros, while sensitivity values are provided on a calibration sheet shipped together with the equipment.

For the instrument with serial number T3720, installed on site 06C02 of the NORSAR array, the above listed information receives the following values:

Velocity response output, Vertical Sensor:

POLES (HZ)	ZEROS HZ
$-7.07 \times 10^{-3} \pm j7.07 \times 10^{-3}$	0
$-80.5 \pm j\,30.8$	0
	150.5

Normalizing factor at 1 Hz: A = -49.5

Sensor Sensitivity: 2 x 2527.9 V/m/s

Velocity response output, Horizontal Sensors:

POLES (HZ)	ZEROS (HZ)
$-7.07 \times 10^{-3} \pm j7.07 \times 10^{-3}$	0
$-80.5 \pm j\,30.8$	0
	150.5

Normalizing factor at 1 Hz: A = -49.5

Sensor Sensitivity:	2 x 2521.3 V/m/s	N-S
	2 x 2537.3 V/m/s	E-W

The factor of 2 in the sensitivity estimate is used because of sensor outputs being used differentially.

Regarding poles and zeros, values are listed in units of Hz. They need to be multiplied with 2π to be converted to rad/s. The same change applies for the normalizing factor.
Total sensor sensitivity will then be equal to:

$$G = \text{(sensitivity)} \times \text{(norm. factor)} \tag{2.2.19}$$

Example:

After application of formula 2.2.19 and converting the poles and zeros to rad/s, the paz table for the vertical component of instrument T3720 will be:

$-1.57244312\text{x}10^{-3}$ V/nm/s
poles
$-505.796417 \pm j\ 193.522107$
$-0.04442212 \pm j\ 0.04442212$
zeros
945.619389
0.0
0.0

2.2.11.2 *AIM24-3BB*

The response of the AIM24-3BB unit is described in section 2.2.10.2.

Overall channel displacement response is depicted in Fig. 2.17 (red lines) at the end of the previous section. From the comparison, it is clear that the CMG-3T sensor is not as sensitive as the KS54000 instrument. This has also been confirmed by waveform comparisons.

2.2.12 CMG-3T HYBRID – EAM24 (2011/06/20 – present)
Respid: CMGEAMHYB3T

The system consists of the following units:
- CMG-3T HYBRID hybrid, three-component, broadband seismometer
- CMG-DM24S3EAMS data acquisition unit (EAM24 is used partly in this documentation for brevity)

The following sections describe the calculation of individual instrument responses.

2.2.12.1 *CMG-3T HYBRID*

The velocity response output for the CMG-3T HYBRID broadband seismometer is described by the following poles and zeros, provided by the manufacturer (Güralp Systems, Ltd.):

POLES (HZ)	ZEROS HZ
-2.0	-333.33×10^{-3}
$-1.964 \times 10^{-3} \pm j\ 1.964 \times 10^{-3}$	0.0
$-24.0 \pm j\ 21.0$	0.0
$-41.0 \pm j\ 114.0$	

Attention should be given to an error that exists in the calibration sheets distributed by Güralp Systems, Ltd., and which has not been corrected. The listed pole/zero set is the one that was designed at NORSAR and requested from the manufacturer, who, however, delivered a modified one. Instead of the double, complex pole $-30.0 \pm j\ 31.0$ that was requested, the double pole $-24.0 \pm j\ 21.0$ was delivered.

For instrument T35728, works order 5685, the sensitivity of the three components is as follows, according to the calibration sheet:

	Velocity Output V/m/s (Differential) **@ 5Hz**	Mass Position Output (Acceleration output) V/m/s^2	Feedback Coil Constant Amp/m/s^2
VERTICAL	2 x 19,634	6835	0.02848
NORTH/SOUTH	2 x 19,985	7354	0.03064
EAST/WEST	2 x 20,081	7668	0.03195

2.2.12.2 *CMG-DM24S3EAMS*

The digitizers employed at the NORSAR array are the Güralp CMG-DM24S3EAMS (SS), consisting of a three-channel CMG-EAM acquisition module with authentication and a CMG-

DM24 digitizer, in stainless steel. The digitizing unit, which is the part relevant to system response, is described in detail in section 5.2.4.2 on the SPITS array. The unit currently installed at NBO00, with S/N A2196 works order 5242, has the following sensitivity, according to the calibration sheet, provided by Güralp Systems, Ltd.:

<u>VELOCITY CHANNELS</u>

Channel:	2196Z2	Vertical	2.867 µV/Count
	2196N2	North/South	2.867 µV/Count
	2196E2	East/West	2.867 µV/Count

For the hybrid channels of the NORSAR array, the digitizers are used with a gain of 2.0.

NORSAR array data are sampled at 40 sps. The entire FIR filter cascade employed to achieve this sampling rate (TTL = 31) is the following (Cirrus Logic, 2001; Güralp Systems, 2006):

- FIR filter CS5376 Stage 1, Sinc 1 (symmetric), 18 coefficients, decimating by 8 from the 512 kHz input clock
- FIR filter CS5376 Stage 3, Sinc 2 (symmetric), 3 coefficients, decimating by 2
- FIR filter CS5376 Stage 4, Sinc 2 (symmetric), 7 coefficients, decimating by 2
- FIR filter CS5376 Stage 5, FIR1 (symmetric), 24 coefficients, decimating by 4
- FIR filter CS5376 Stage 5, FIR2 (symmetric), 63 coefficients, decimating by 2
- FIR filter DM24 Stage 1, SWA-D24-3D06 (symmetric), 501 coefficients, decimating by 2 from 2 kHz
- FIR filter DM24 Stage 2, SWA-D24-3D08 (symmetric), 501 coefficients, decimating by 5, from 1 kHz
- FIR filter DM24 Stage 3, SWA-D24-3D08 (symmetric), 501 coefficients, decimating by 5

The displacement amplitude and phase response of the three-component, broadband, hybrid elements of the NORSAR array is shown in Fig. 2.18, at the end of section 2.2.13.2 (dark blue line).

2.2.13 <u>CMG-3V HYBRID – EAM24</u> (2011/06/20 – present)

Respid: CMGEAMHYB1V

The system consists of the following units:

- CMG-3V HYBRID hybrid, vertical, broadband seismometer
- CMG-DM24S3EAMS data acquisition unit

The following sections describe the calculation of individual instrument responses.

2.2.13.1 *CMG-3V HYBRID*

The velocity response output for the CMG-3V HYBRID broadband seismometer is described by the following poles and zeros, provided by the manufacturer (Güralp Systems, Ltd.):

POLES (HZ)	ZEROS HZ
-2.0	-333.33×10^{-3}
$-5.89 \times 10^{-3} \pm j\ 5.89 \times 10^{-3}$	0.0
$\mathbf{-24.0 \pm j\ 21.0}$	0.0
$-41.0 \pm j\ 114.0$	

Attention should be given to an error that exists in the calibration sheets distributed by Güralp Systems, Ltd., and which has not been corrected. The listed pole/zero set is the one that was designed at NORSAR and requested from the manufacturer, who, however, delivered a modified one. Instead of the double, complex pole $-30.0 \pm j\ 31.0$ that was requested, the double pole $-24.0 \pm j\ 21.0$ was delivered.

For instrument V3I25, works order 5947, the sensitivity is as follows, according to the calibration sheet:

	Velocity Output V/m/s (Differential) **@ 5Hz**	Velocity Output V/m/s (Differential) **@ 0.03Hz**	Mass Position Output (Acceleration output) $V/m/s^2$	Feedback Coil Constant $Amp/m/s^2$
VERTICAL	2 x 20,381	2 x 3,583	7831	0.02373

2.2.13.2 *CMG-DM24S3EAMS*

The digitizer currently employed at the NORSAR array is described in section 2.2.12.2.

As for the three-component elements, the digitizers are used with a gain of 2.0.

The vertical-only NORSAR array site data are also sampled at 40 sps, so the digital filter cascade is the same as the one described in section 2.2.12.2.

The displacement amplitude and phase response of the vertical hybrid elements of the NORSAR array is shown in Fig. 2.18 (light blue line).

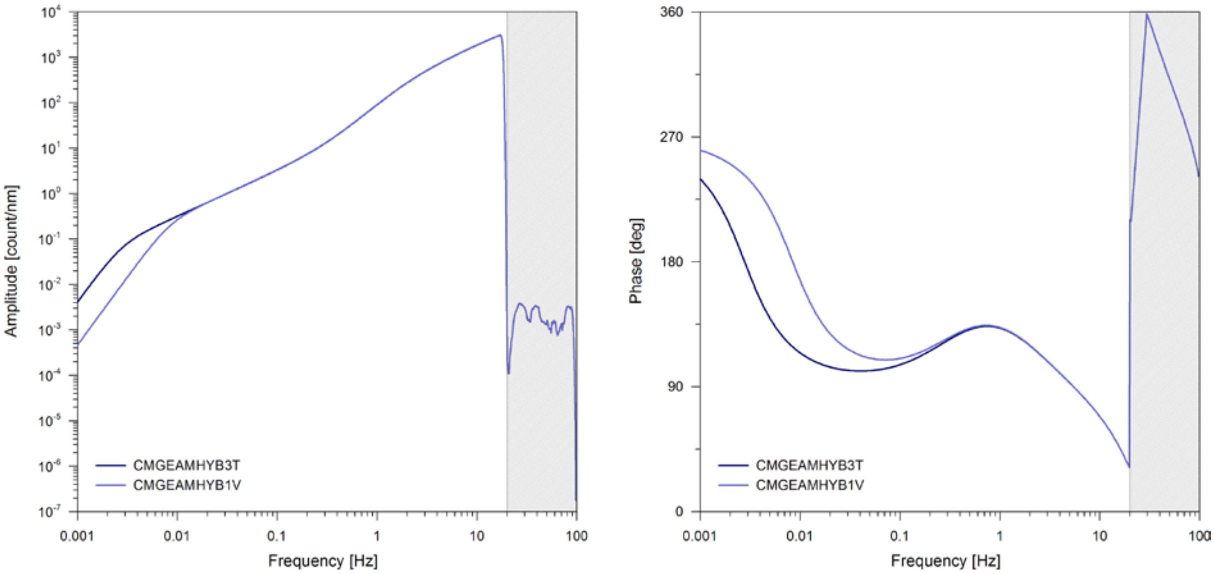


Fig. 2.18. Displacement amplitude (left) and phase (right) response for the hybrid configurations of the NORSAR array. One example of vertical component is shown for each case; the NAO00 element for the vertical-only configuration (CMGEAMHYB1V) and the NAO01 element for the three-component, broadband configuration (CMGEAMHYB3T). The shaded area represents the range beyond the Nyquist frequency (= 20 Hz).

2.3 References

NOTE:

The following References section aims to make all primary information available to future users. Lots of information on NORSAR array systems could be obtained from different sorts of publications, such as manuals, data-sheets, internal reports and publications, as well as some scientific papers. There was however a large volume of crucial information to be found only within facsimile communication between NORSAR and instrument selling companies. In order to make also this information easily available, two different subsections are compiled:

I. Publications: containing publications in all the above mentioned forms and
II. Information received by facsimile: all facsimile communications that contain important information. They are filed under the name of the trading company and date of transmission.

References to the latter are also made wherever relevant to the NORSAR array Systems' Response Documentation, adding the index 'fax info' after the author and date field. Both sources of information (publications and fax-sheets) have been sorted and archived, and may be retrieved from the Archive.

REFERENCES LIST

I. Publications

Bungum, H., 1983. Description of NORSAR recording system. *NORSAR Semiann. Techn. Summ. 2-82/83*, Kjeller, Norway, p. 14-20.

Bungum, H., E.S. Husebye and F. Ringdal, 1971. The NORSAR array and preliminary results of data analysis. *Geophys. J. R. astr. Soc.*, vol. 25, p. 115-126.

Bungum, H., A.K. Nilsen and O. Steinert, 1974. Experimental analog stations at NORSAR. *NORSAR Sci. Rep. 4-73/74*, Kjeller, Norway, p. 60-65.

Bungum, H. and A.K. Nilsen, 1974. Experimental analog stations at NORSAR. *NORSAR Sci. Rep. 6-73/74*, Kjeller, Norway, p. 82-86.

Bungum, H., T. Risbo and E. Hjortenberg, 1977. Precise continuous monitoring of seismic velocity variations and their possible connection to solid Earth tides. *J. Geophys. Res.*, vol. 82, no. 33, p. 5365-5373.

Burr-Brown Research Corp., 1969. Instruction manual, model 5121 active filter. In *DC offset trim modification of NORSAR short period Line Terminating Amplifier, Larsen and Nilsen, 1974, Internal Report 8-73/74*, Burr-Brown Research Corp., Tucson, Arizona, 5pp.

Burr-Brown Research Corp., 1971. Instruction manual, model 5237 active filter. Attached to *DC offset trim modification of NORSAR short period Line Terminating Amplifier, Larsen and Nilsen, 1974, Internal Report 8-73/74*, Burr-Brown Research Corp., Tucson, Arizona, 1pp.

Cirrus Logic, Inc., 1995. CS5322/5323 24-bit variable bandwidth A/D converter. *Cirrus Logic, Inc. DS70F1, March '95*, Austin, Texas, 40 pp.

Cirrus Logic, Inc., 2001. Crystal CS5376 Low Power Multi-Channel Decimation Filter. *DS256PP1*, Cirrus Logic, Inc., Austin, Texas, 122 pp.

Cirrus Logic, Inc., 2003. CS5321/22 24-bit variable bandwidth A/D converter chipset. *Cirrus Logic, Inc. DS454PP3, October '03*, 24 pp.

Dahle, A., 1975. A KIRNOS seismograph in the NORSAR seismic array. *NORSAR Internal Rep. 4-74/75*, Kjeller, Norway, 25 pp.

Dalland, L.J., 1971. NORSAR SP seismometer instrumentation chain. *A/S Tele-plan*, Lysaker, Norway, 14 pp.

Falch, K., 1973. Technical description and operational instruction Ithaco amplifier and test panel. *NORSAR Techn. Rep. 58*, Kjeller, Norway., 18 pp.

Fyen, J., 1986. Improvements and modifications. *NORSAR Semiann. Techn. Summ. 1-86/87*, Kjeller, Norway, p. 12-22.

Fyen, J., 1994. Improvements and modifications. *NORSAR Semiann. Techn. Summ. 2-93/94*, Kjeller, Norway, p. 62-73.

Fyen, J., 1995a. Improvements and modifications. *NORSAR Semiann. Techn. Summ. 2-94/95*, Kjeller, Norway, p. 75-80.

Fyen, J., 1995b. Improvements and modifications. *NORSAR Semiann. Techn. Summ. 1-95/96*, Kjeller, Norway, p. 69-72.

Fyen, J., 1996. Improvements and modifications. *NORSAR Semiann. Techn. Summ. 1-96/97,* Kjeller, Norway, p. 64-65.

Fyen, J. and T. Kværna, 1996. Status and plans for implementing algorithms at the GSETT-3 IDC. *NORSAR Semiann. Techn. Summ. 1-96/97,* Kjeller, Norway, p. 80-83.

Güralp Systems, 2006. CMG-DM24 Operator's Guide. *MAN-D24-0004,* Güralp Systems Ltd., Aldermaston, England, 113 pp.

Hansen, O.A., 1983a. Field instrumentation. *NORSAR Semiann. Techn. Summ. 1-82/83,* Kjeller, Norway, p. 21-31.

Hansen, O.A., 1983b. Field instrumentation and maintenance activities. *NORSAR Semiann. Techn. Summ. 2-82/83,* Kjeller, Norway, p. 21-29.

Hansen, O.A., 1983c. Field instrumentation and maintenance activities. *NORSAR Semiann. Techn. Summ. 1-83/84,* Kjeller, Norway, p. 12-21.

Hansen, O.A., 1984a. Maintenance activities. *NORSAR Semiann. Techn. Summ. 2-83/84,* Kjeller, Norway, p. 14-19.

Hansen, O.A., 1984b. Maintenance activities. *NORSAR Semiann. Techn. Summ. 1-84/85,* Kjeller, Norway, p. 14-15.

Hansen, O.A., 1985a. Maintenance activities. *NORSAR Semiann. Techn. Summ. 2-84/85,* Kjeller, Norway, p. 16-20.

Hansen, O.A., 1985b. Maintenance activities. *NORSAR Semiann. Techn. Summ. 1-85/86,* Kjeller, Norway, p. 16-19.

Hansen, O.A., 1986a. Maintenance activities. *NORSAR Semiann. Techn. Summ. 2-85/86,* Kjeller, Norway, p. 15-19.

Hansen, O.A., 1986b. Maintenance activities. *NORSAR Semiann. Techn. Summ. 1-86/87,* Kjeller, Norway, p. 23-27.

Husebye, E.S., 1971. NORSAR Research and Development, 1 July 1970 – 30 June 1971. *NORSAR Rep. 23,* NORSAR, Kjeller, Norway, 42 pp.

IBM, 1969. Integrated array electronics maintenance manual. *REF 20, Integrated Seismic Research Signal Processing System,* Federal Systems Division, International Business Machines Corp., Gaithersburg, Maryland.

Ingate, S.F., 1995. Validating the frequency response of the Science Horizons, Inc. AIM24 high-resolution 24-bit digitizers. *Science Horizons Report #IR-95-0001,* Encinitas, California,15 pp.

Ithaco Inc., 1968. Instruction and maintenance manual Ithaco long period seismic amplifier model 6083-82. *Ithaco Inc.,* Ithaca, New York, 25 pp.

Johansen, T., 1970. Preliminary report on the spread in natural frequencies of HS-10-1 ARPA seismometer. *A/S Tele-plan,* Lysaker, Norway, 22 pp.

Johnson, J., 1996. The CS5322 digital filter. *AN53REV2, Crystal Semiconductor Corp.,* Austin, Texas, 30 pp.

Kromer, R.P., T.S. McDonald and J.W. Walkup, 1995. Report on the test and evaluation of the Science Horizons Incorporated AQUINAS Digital Field Station (ADFS) digitizer elements for the Pinedale Seismic Research Facility (PSRF) experimental array. *Test* *and Evaluation Report – SHI Pinedale Array*, Sandia National Laboratories, Albuquerque, New Mexico, 40 pp.

Larsen, P.W., 1978. Test of Teledyne-Geotech S-500 seismometer. *NORSAR Internal Report 1-78/79*, Kjeller, Norway, 8 pp.

Larsen, P.W. and A.K. Nilsen, 1981. Array instrumentation and facilities. *NORSAR Semiann. Techn. Summ. 2-80/81*, Kjeller, Norway, p. 15-22.

Larsen, P.W. and K.A. Løken, 1995. Maintenance activities. *NORSAR Semiann. Techn. Summ. 2-94/95*, Kjeller, Norway, p. 81-87.

Larsen, P.W. and K.A. Løken, 1996. Maintenance activities. *NORSAR Semiann. Techn. Summ. 2-95/96*, Kjeller, Norway, p. 75-77.

Larsen, P.W. and K.A. Løken, 2000. Field activities. *NORSAR Semiann. Techn. Summ. 1-2000/2001*, Kjeller, Norway, p. 46-49.

Leichliter, B.B., 1968. Results of tests on long-period seismographs, contract F19628-68-C-0321. *Techn. Report no 68-63*, Geotech, Garland, Texas, 22 pp.

Mykkeltveit, S. and F. Ringdal, 1980. Further development of the NORESS small-aperture array. *NORSAR Semiann. Techn. Summ. 1-80/81,* Kjeller, Norway, p. 33-36.

Nanometrics, Inc., 1992. NORSAR RD3 User Guide, Version 3 Software & Version 5 Software. *Nanometrics, Inc.,* Ontario, Canada, 70 pp.

Nilsen, A.K., 1975. Array monitoring and field maintenance. *NORSAR Sci. Rep. 5-74/75,* Kjeller, Norway, p. 99-108.

Nilsen, A.K., 1976a. Array instrumentation. *NORSAR Semiann. Techn. Summ. 4-75/76,* Kjeller, Norway, p. 27-28.

Nilsen, A.K., 1976b. Array instrumentation. *NORSAR Semiann. Techn. Summ. 1-76/77,* Kjeller, Norway, p. 22.

Nilsen, A.K., 1978a. Array instrumentation and facilities. *NORSAR Semiann. Techn. Summ. 2-77/78,* Kjeller, Norway, p. 15-18.

Nilsen, A.K., 1978b. Array instrumentation and facilities. *NORSAR Semiann. Techn. Summ. 1-78/79,* Kjeller, Norway, p. 23-27.

Nilsen, A.K., 1979. NORSAR defective signal channel status as of 22 August 1979, including description of nonstandard channels and modifications. Temporary modifications on instruments no longer in the NORSAR array. *NORSAR*, Kjeller, Norway, 2 pp.

Nilsen, A.K., 1980a. Array instrumentation and facilities. *NORSAR Semiann. Techn. Summ. 2-79/80,* Kjeller, Norway, p. 17-23.

Nilsen, A.K., 1980b. Array instrumentation and facilities. *NORSAR Semiann. Techn. Summ. 1-80/81*, Kjeller, Norway, p. 20-26.

Nilsen, A.K., 1981. Improvements and modifications. *NORSAR Semiann. Techn. Summ. 1-81/82*, Kjeller, Norway, p. 14-18.

Nilsen, A.K., 1982. Field instrumentation and facilities. *NORSAR Semiann. Techn. Summ. 2-81/82*, Kjeller, Norway, p.16-18.

NORSAR, 1969a. The 1968 installation program. *NORSAR PHASE 2, Interim Technical Report*, 101 pp.

NORSAR, 1969b. Check-out of short and long period field instrumentation – Procedures. *NORSAR PHASE 2, 1968-1969 PROGRAM, DOCUMENT IV, PART 1*, 50 pp.

NORSAR, 1969c. Check-out of short and long period field instrumentation – Collected data. *NORSAR PHASE 2, 1968-1969 PROGRAM, DOCUMENT IV, PART 2*.

NORSAR, 1974. Array monitoring and field maintenance. *NORSAR Sci. Rep. 6-73/74*, Kjeller, Norway, p. 87-95.

NORSAR, 1976. Improvements and modifications. *NORSAR Semiann. Techn. Summ. 1-75/76*, Kjeller, Norway, p. 18-24.

Philco-Ford, 1970. Seismic Short and Long Period Electronic Modules (SLEM). *Philco-Ford, Corp.*, December 1970, 3 volumes.

Ringdal, F., 1981. Location of regional events using travel time differentials between P arrival branches. *NORSAR Semiann. Techn. Summ. 2-80/81*, Kjeller, Norway, p. 60-69.

Roth, M., J. Fyen, P.W. Larsen and J. Schweitzer, 2011. Test of new hybrid seismometers at NORSAR. *NORSAR Sci. Rep. 1-2011*, Kjeller, Norway, p. 61-71.

Steinert, O. and A. Nilsen, 1972. Array monitoring and field maintenance report. *NORSAR Rep. 40*, NORSAR, Kjeller, Norway, 89 pp.

Steinert, O. and A. Nilsen, 1973. Array monitoring and field maintenance report. *NORSAR Rep. 60*, NORSAR, Kjeller, Norway, 45 pp.

Steinert, O. and A.K. Nilsen, 1974. Array monitoring and field maintenance. *NORSAR Sci. Rep. 4-73/74*, Kjeller, Norway, p. 66-73.

Teledyne Brown Engineering, 1995a. Operation and maintenance manual of the posthole seismometer system, model 54000-0105 – Part I. *54000D51.W60*, 79 pp.

Teledyne Brown Engineering, 1995b. Operation and maintenance manual of the shallow-hole seismometer, model 990-20171-0104. *20171D4_.W60*, Dallas, Texas, 85 pp.

Teledyne Geotech, 1987. Operation and maintenance manual of the short-period seismometer, model S-500. *M-S-500*, Garland, Texas, 27 pp.

Teledyne Industries, 1966. Operation and maintenance manual of the portable short-period seismometer, model 18300 (S-13). *M-18300*, Dallas, Texas, 49 pp.

II. Information received by facsimile

Geotech Instruments, 07.09.1994. Proposed changes to the NORSAR KS54000-Posthole seismometers. F. Kissinger to F. Ringdal, 2pp. + 2 attached reports.

Geotech Instruments, 04.07.1995. S-500 seismometer response function, poles and zeros. F. Kissinger to J. Fyen, 3pp.

Internal, 12.2007. LP-calibration flow chart. P. Larsen to J. Schweitzer, 1 pp.

Nanometrics Inc., 08.01.1993. RD6 response information. M. Collum to J. Fyen, 6 pp.

Nanometrics Inc., 10.03.1993. RD6 Remote Digitiser as-shipped specifications and final test data. Nanometrics Inc. to P. Larsen, 7 pp.

CHAPTER 3: NORES

3.1 Development of NORES systems: instrumentation and responses

3.1.1 Short description

- 1983 – 1984:

From 23 July 1983 until the spring of 1984, a 21-element vertical sensor only array was operated at the NORES site, as a 'last-minute' check of the validity of the proposed NORES array design. This system was independent of the NORSAR array data acquisition system (Mykkeltveit, 1985). However, data from this system are unavailable and no discussion of its response will be made.

- 1984 – 1986:

The NORES regional array was equipped with the standard instrumentation in late 1984, after an extended test period, as part of the NORSAR array and within its data acquisition system. The test configurations have been already described in section 2.1 (see §2.1.1). Official opening of the NORES array however, took place on June 3rd 1985. The array consisted of 25 elements, distributed on 4 concentric rings, with one element in the center, and spreads over a diameter of 3 km. NORES seismic data cover a variety of frequency bands, the result of maintaining in operation short-, long- and intermediate-period channels, as well as high-frequency channels. No data are available any longer from the latter configuration and therefore the high-frequency response will not be discussed in this documentation. Standard NORES instrumentation is based on GS-13 short-period and KS36000 broadband sensors and Sandia 'Blue Box' digitizers. Due to the erroneous assignment of the same CID to both array sites A3 and B5 (February 1985), available data are problematic. The error was initially identified in file /ndc/programs/dpep/libdata/NRS_COO. Since the response is the same for both sites, the corresponding time intervals were corrected in the *GSE* response file, by assuming site A3 to be the correct entry. A variation of the short-period channel existed during this time interval (September 1985 – September 1986) that employed a 3-component S-3 short-period sensor, installed in a 60 m borehole. The site coincided with site NRA0 and was assigned the name NRF0.

- 1986 – 2002:

No modification in array instrumentation, with only exception the removal of the S-3 seismometers. Following the closing of the borehole site (September 1986), the E-W channel of site A0 was reassigned for short intervals to components Z and N-S (see Mykkeltveit, 1987), without however changing the component name in the database system. This was taken into consideration in the *GSE* response file, by appropriately correcting fields *Hang, Vang*. Comments have been included in the *GSE* response file for both this case and the one regarding the erroneous channel IDs mentioned above. The array was struck by lightning in 2002 and has been out of operation for a long time. Extensive repair work begun in 2009 to make the array operational.

- 2010 – …:

New NORES configuration. Old Sandia units are replaced by Güralp CMG-DM24 digitizers, while sensors remain the same, as with the previous configuration (GS-13). All array sites (A- and B-ring only, 9 elements) are now equipped with three-component stations.

A note should be made here regarding changes in the construction of the NORES response database, starting January 2012. As mentioned in the previous paragraphs and in Chapter 1, only one array-wide response is produced in the case that all channels have an identical response, which is linked to the corresponding channels by the introduction of the *Respid*. This approach was followed in the case of NORES, for *Respids* NORESSP1, NORESSP2 and NORESSP3. Since this seems to create managing problems for some applications (*e.g.*, AutoDRM), separate response files were created for each channel, although they all describe an identical response. In the case of NORES, there was an additional problem with erroneous CID entries. Since the CIDs are no longer used to manage and update the response database, the channel section of the NORES *GSE* file has been updated and all multiple channel entries (identical response, but changing CID) were merged into one, with a new CID. Only the orientation changes of NRA0_se mentioned in Mykkeltveit (1987) justify the use of multiple response entries, and this was taken care of by appending short tags to the name of the *GSE* and *FAP* response files to denote each different case (see Appendix II for file names and the NORES *GSE* file for times).

3.1.2 Instrumentation

I. Configurations

- Standard SP configuration (1984 – 2002):
  - GS-13 seismometer
  - Pre-amplifier
  - Short-period filter
  - Distributed filter
  - Sandia 'Blue Box' digitizer

- SP variation (1985 – 1986):
  - S-3 seismometer (in 60 m borehole)
  - Pre-amplifier
  - Short-period filter
  - Distributed filter
  - Sandia 'Blue Box' digitizer

- Standard LP configuration (1984 – 2002):
  - KS36000 seismometer
  - Long period high-pass filter
  - Long period bandpass filter
  - Distributed filter
  - Long period spectral shaping filter
  - Sandia 'Blue Box' digitizer

- Standard IP configuration (1984 – 2002):
  - KS36000 seismometer
  - Intermediate period bandpass filter
  - Distributed filter
  - Intermediate period spectral shaping filter
  - Sandia 'Blue Box' digitizer

- Current configuration (2010 – …):
    - GS-13 seismometer
    - CMG-DM24 digitzer

II. Respids

NORESSP1,2,3
NORESSP4,5,6
NORESSP7,8,9
NORESLP
NORESIP

III. Instrument specifications

GS-13:
Short-period seismometer by Geotech Instruments, that can be operated either as vertical or horizontal sensor. The specifications of the version installed at the NORES array are the following (nominal values according to Geotech Instruments, 1999):

Total moving mass	M	5 kg
Natural frequency	f_0	1 Hz
Damping ratio	λ_0	0.75
Coil resistance	R_c	9100 ± 700 ohm
Generator constant	Gm	2180 ± 545 V/m/s
Calibration coil motor constant	Gc	4.5 ± 0.9 N/A

S-3:
Short-period triaxial seismometer by Geotech Instruments. The specifications of the version installed at NORES are the following, according to Durham (1984b):

Natural frequency	f_0	1 Hz
Damping ratio	λ_0	0.75
Generator constant	Gm	2200 V/m/s

KS36000:
Broadband, triaxial seismometer by Geotech Instruments. The specifications of the version installed at NORES are the following (Durham, 1984a):

Gain constant	3224.5 V/m/s @ 1.0 Hz
	129 V/m/s @ 0.04 Hz

'Blue Box':
A/D converter by Sandia. The unit has a resolution of 14-bit and 2 gain bits with a step of 8, 16, 32, 128, which provide a dynamic range of 20 bits. Few other information can be retrieved about the instrument. As documented as a note in several documents:

Sensitivity	100000 count/V

CMG-DM24 mk3
Digitizer by Güralp Systems Ltd. Detailed reference can be found in sections 2.1 and 5.1.

3.2 Instrument response calculation for NORES systems

This chapter focuses on the major considerations to be taken into account for the calculation of the instrument response of the different systems operating at the NORES regional array.

As with the NORSAR array, GSE file response *Respid* flags for each configuration are provided at the beginning of each section.

3.2.1 GS-13-BlueBox (1984/10/03 – 2002/06/11)

Respid:	NORESSP1	Z
	NORESSP2	N-S
	NORESSP3	E-W

Standard NORES short-period channel configuration consists of the following components:

- GS-13 short-period seismometers
- Seismometer pre-amplifier
- Short-period filter
- Distributed filter
- Sandia 'Blue Box'

3.2.1.1 *GS-13*

The GS-13 short-period velocity related seismometer transfer function is expressed by the following equation (Durham, 1984b):

$$H_S(s) = \frac{G_S \cdot \frac{s^2}{\omega_0^2}}{1 + 2\frac{\lambda}{\omega_0}s + \frac{1}{\omega_0^2}s^2} \text{ in V/m/s.} \qquad (3.2.1)$$

This has two poles and two zeros, which are the roots of the denominator and numerator respectively, which results to (Geotech Instruments, 1999):

$$p_{1,2} = \lambda_0\omega_0 \pm j\omega_0\sqrt{1-\lambda_0^2}\,. \qquad (3.2.2)$$

The nominal values for the parameters to be used in equations (3.2.1) and (3.2.2) are the following:

G_S = 2200 V/m/s
ω_0 = 6.283 rad/s (f_0 = 1 Hz)
λ_0 = 0.75

The gain of the seismometer will be equal to 2200 V/m/s.

The GS-13 sensor is used together with an amplifier, and their *interface* is described by the formula:

$$H_{IF}(s) = \frac{Z_t(s)}{Z_t(s) + Z_s(s)} \text{ in V/V,} \tag{3.2.3}$$

where $Z_t(s)$ is the seismometer termination impedance and $Z_s(s)$ the seismometer source impedance. They are expressed by the following equations:

$$Z_t(s) = \frac{R_t}{1 + sR_tC_t} \text{ and} \tag{3.2.4}$$

$$Z_s(s) = R_s + sL_s\,. \tag{3.2.5}$$

By substituting relations (3.2.4) and (3.2.5) in equation (3.2.3), we obtain the equation:

$$H_{IF}(s) = \frac{R_t}{(R_t + R_s) + (R_tR_sC_t + L_s)\cdot s + (R_tC_tL_s)\cdot s^2}\,. \tag{3.2.6}$$

The values of R_t, C_t, R_s, and L_s are either provided by the manufacturer or can be measured in the lab. The nominal values are the following:

R_t = 100000 ohm
C_t = 0.010 μfd
R_s = 9000 ohm
L_s = 80 henry

Equation (3.2.6) has two poles and essentially describes a low-pass filter, with cut-off frequency at around 250 Hz. The gain of this filter will be equal to 0.9174 V/V, for normalization at 1.0 Hz.

The seismometer *pre-amplifier* itself has a response that can be described by equation:

$$H_{PA}(s) = 2G_{PA}\frac{Z_2}{Z_1} \text{ in V/V,} \tag{3.2.7}$$

where 2 G_{PA} = 13.62 for the case of NORES and

$$Z_1 = \frac{1 + sR_1C_1}{sC_1} \text{ and} \tag{3.2.8}$$

$$Z_2 = \frac{R_2}{1 + sR_2C_2}\,. \tag{3.2.9}$$

Substituting relations (3.2.8) and (3.2.9) in equation (3.2.7), the mathematical formula providing the response of the pre-amplifier obtains the following form:

$$H_{PA}(s) = \frac{2G_{PA}\cdot sR_2C_1}{(1 + sR_2C_2)(1 + sR_1C_1)}\,. \tag{3.2.10}$$

The above written equation contributes to the sensor's total response with one zero and two poles. Nominal values of the parameters found in formula (3.2.10) are as follows:

R_1 = 340000 ohm
C_1 = 0.470 μfd
R_2 = 866000 ohm
C_2 = 0.0018 μfd

Regarding the gain of the pre-amplifier, this has to be set to match the associated seismometer parameters so, that an output of 70000 V/m/s is achieved. This condition is satisfied by the formula:

$$G_s \cdot \frac{R_t}{R_t + R_s} \cdot 2G_{PA} \cdot \frac{R_2}{R_1} = 70000 \text{ (V/m/s)}. \tag{3.2.11}$$

The pre-amplifier is a bandpass filter with cut-off frequency points at about 1 Hz and 102 Hz. This system can be normalized at 10 Hz, receiving at this frequency a gain value of 34.35812 V/V.

The next stage in the seismometer response is the *short-period filter* stage, which consists of three sub-stages, (i) the input stage, (ii) the low pass filter stages and (iii) the output stage.

(i) Input stage: The response of this stage is described by equation:

$$H_i(s) = \frac{R_2}{R_1} \cdot \frac{1}{1 + sR_2C_2}. \tag{3.2.12}$$

This equation provides a single pole, while nominal values of the different parameters are equal to:

R_1 = 53000 ohm
R_2 = 53000 ohm
C_2 = 0.015 μfd

(ii) Low pass filter stages: A series of five successive low-pass filters described by the following equations, each one of them featuring two poles.

$$\left.\begin{aligned}
H_1(s) &= \frac{1}{1 + 0.0221 \cdot s + 0.000125 \cdot s^2} \\
H_2(s) &= \frac{1}{1 + 0.0195 \cdot s + 0.000119 \cdot s^2} \\
H_3(s) &= \frac{1}{1 + 0.0143 \cdot s + 0.000104 \cdot s^2} \\
H_4(s) &= \frac{1}{1 + 0.00739 \cdot s + 0.000082 \cdot s^2} \\
H_5(s) &= \frac{1}{1 + 0.0150 \cdot s + 0.000113 \cdot s^2}
\end{aligned}\right\} \tag{3.2.13}$$

(iii) Output stage: The response of this stage is described by equation:

$$H_0(s) = \frac{Z_2}{Z_1} \ , \tag{3.2.14}$$

where $Z_1 = \dfrac{1 + sR_1C_1}{sC_1}$ (3.2.15) and $Z_2 = \dfrac{R_2}{1 + sR_2C_2}$. (3.2.16)

Substituting relations (3.2.15) and (3.2.16) in formula (3.2.14), provides us with:

$$H_0(s) = \frac{sR_2C_1}{(1 + sR_1C_1)(1 + sR_2C_2)} \ . \tag{3.2.17}$$

Equation (3.2.17) has one zero and two poles and the nominal parameter values are:

R_1 = 590000 ohm
C_1 = 0.270 μfd
R_2 = 1180000 ohm
C_2 = 0.0012 μfd

While stages (i) and (ii) have no gain, gain (iii) has a gain of 1.9822262 V/V, when normalized at 10 Hz, as a bandpass filter with cut-off frequency points around 1 Hz and 112 Hz.

The total response of the short period filter will then be equal to:

$$H_{SP}(s) = -G_0 \cdot H_i(s) \cdot H_1(s) \cdot H_2(s) \cdot H_3(s) \cdot H_4(s) \cdot H_5(s) \cdot H_0(s) \text{ in V/V,} \tag{3.2.18}$$

where factor G_0 is the short period filter nominal gain. For seismic data, this can be selected to equal either 50.0 (high gain) or 5.0 (low gain). In the case of NORES, the low gain option was selected, so G_0 = 5.0 (Durham, 1984b; Breding, 1986).

The final stage in the seismometer's response is the distributed filter, whose transfer function is expressed by formula:

$$H_{DF}(s) = \frac{-1.0}{1.0 + 1.592 \times 10^{-3} s} \ . \tag{3.2.19}$$

This filter is described by one single real pole and has no gain.

The overall response function for the GS-13 seismometer will be equal to (Durham, 1984b):

$$H_{spv}(s) = H_S(s) \cdot H_{IF}(s) \cdot H_{PA}(s) \cdot H_{SP}(s) \cdot H_{DF}(s), \text{ expressed in V/m/s.} \tag{3.2.20}$$

From the equations of the individual transfer functions of the system, mentioned previously, it becomes clear that the overall seismometer displacement response for the short period NORES channels can be reconstructed using the 20 poles and 5 zeros provided below, in rad/s.

Poles:	Zeros:	
-4.711804185 ± *j* 4.156654920	0.0	
-5.562746965 ± *j* 1026.227032	0.0	
-641.4368185	0.0	
-6.257822278	0.0	
-1257.861635	0.0	for displacement
-88.40000000 ± *j* 13.61763563		
-81.93277310 ± *j* 41.11425589		
-68.75000000 ± *j* 69.92011240		
-45.06097561 ± *j* 100.8197919		
-66.37168140 ± *j* 66.66601405		
-6.277463905		
-706.2146893		
-628.1407035		

A value of A_0 = 1.62901265 x 10^{32} is provided by Hardin and Breding (1989) for the overall normalization factor. This value is the product of all individual stage gain factors at 1 Hz, with individual filter gains appropriately normalized.

3.2.1.2 *Blue Box*

The 'Blue Box' digitizer manufactured by Sandia has a 14-bit resolution, while gain ranging by 2 gain bits (representing a step of 1, 8, 32, 128) results to a total dynamic range of 20 bits.

The sensitivity of the digitizer equals 100000 count/V.

According to an alternative approach, the appropriate form of the overall system complex transfer function is (Hardin and Breding, 1989):

$$H(s) = A_0 \cdot DS \cdot \frac{(s - Z01)(s - Z02)\cdots(s - ZM)}{(s - P01)(s - P02)\cdots(s - PN)}, \qquad (3.2.21)$$

where $s = j\omega$, A_0 is the overall normalizing constant (see §3.2.1.1), M the number of complex poles, N the number of complex zeros and DS the digital sensitivity in count/μm. The latter is channel sensitivity at normalization frequency, provided that all individual filter stages have been appropriately normalized. For the previously described configuration (§3.2.1.1), the digital sensitivity equals 146249.8804 count/μm at 1.0 Hz.

3.2.2 S-3-BlueBox (1985/09/27 – 1986/09/24)

Respid:	NORESSP4	Z
	NORESSP5	N-S
	NORESSP6	E-W

A variation of the short-period NORES channels, installed at site F0, employs a Geotech S-3 seismometer (3-components). Site F0 is the borehole version (60 meters depth) of the A0 central site. The components of the system are the following:

- S-3 short-period seismometer
- Seismometer pre-amplifier
- Short-period filter
- Distributed filter
- Sandia 'Blue Box'

3.2.2.1 *S-3*

The response of the S-3 short-period seismometer is identical to that of the GS-13 instrument, including the pre-amplifier and filter stages (Durham, 1984b) and is therefore described by the same transfer function(s), poles and zeros (see §3.2.1.1).

3.2.2.2 *Blue Box*

The response of this unit is described in section 3.2.1.2.

3.2.3 KS36000-BlueBox (1984/10/03 – 2002/06/11)

Respid: NORESLP1 Z
NORESLP2 N-S
NORESLP3 E-W
NORESIP1 Z
NORESIP2 N-S
NORESIP3 E-W

A Kinemetrics KS36000-04A broadband seismometer is installed at NORES site E0, collocated with site A0, the central array element. Two different channels, each one with 3 components operate on this site, a long-period channel (lz, ln, le) and an intermediate-period channel (iz, in, ie). For each one of these channels, the system consists of the following components (Durham, 1984a):

LP:	IP:
- KS36000 broadband seismometer	KS36000 broadband seismometer
- Long period high-pass filter	Intermediate period bandpass filter
- Long period bandpass filter	Distributed filter
- Distributed filter	Intermediate period spectral shaping filter
- Long period spectral shaping filter	Sandia 'Blue Box' digitizer
- Sandia 'Blue Box' digitizer	

3.2.3.1 *KS36000*

The KS36000 seismometer transfer function for ground velocity is expressed by the formula:

$$H_S(s) = 100.0 \cdot H_{KA}(s) \cdot s \text{ in V/m/s,} \tag{3.2.22}$$

where $H_{KA}(s)$ is expressed in V/cm/s^2 and is described from equation:

$$H_{KA}(s) = \frac{H_T(s) \cdot H_A(s)}{1 - H_T(s) \cdot H_A(s) \cdot H_B(s) \cdot K_B} . \tag{3.2.23}$$

K_B is equal to 1.370 x 10^3 (cm/s^2)/A, while the rest of the functions appearing in equation (3.2.23) are provided by the following formulas:

$$H_T(s) = \frac{12.66}{1.0 + 0.02256 \cdot s + 0.6333 \cdot s^2} \text{ in V/cm/s}^2 \qquad (3.2.23)$$

$$H_A(s) = \frac{-3.360 \times 10^3}{1.0 + 3.789 \times 10^{-3} s} \text{ in V/V} \tag{3.2.24}$$

$$H_B(s) = 1.421 \times 10^{-4} \frac{1.0 + 1.394 \times 10^{-2} s}{1.0 + 9.936 \times 10^{-4} s} \text{ in A/V.} \tag{3.2.25}$$

Thus, the seismometer has two zeros and four poles, for velocity. An extra zero at s = 0 should be added for displacement response.

The response of the series of filters that interface the seismometer to the digitizer is described in the following sections, both for the long (LP) and intermediate period (IP) channels. The overall seismometer response is provided in the end of each section.

- *LP*:

The response of the *long period high-pass filter* has one zero and two poles, and is described from the following equation:

$$H_{HP1}(s) = \frac{-390.6s}{1.0 + 7.813s + 0.4505s^2} \text{ in V/V.} \tag{3.2.26}$$

The filter, which is a bandpass between 0.0204 Hz and 2.76 Hz has a gain of 49.9936 V/V at 0.238 Hz.

The *long period bandpass filter* has also one zero and two poles, while its response is provided by equation:

$$H_{BP1}(s) = \frac{324.0s}{1.0 + 16.90s + 113.1s^2} \text{ in V/V.} \tag{3.2.27}$$

The bandpass of this filter is between 0.0072 Hz and 0.031 Hz, while its gain equals 19.1708 V/V at 0.015059 Hz.

The response of the *distributed filter*, which has only one pole, is described by equation:

$$H_{DF}(s) = \frac{-1.0}{1.0 + 1.592 \times 10^{-3} s} \text{ in V/V.} \tag{3.2.28}$$

Finally, the *long period spectral shaping filter*'s response is described by the following formula (in V/V):

$$H_{LPF}(s) = G_{KLP} \cdot H_A(s) \cdot H_B(s) \cdot H_C(s) \cdot H_D(s) \cdot H_E(s) \cdot H_F(s) \cdot H_G(s) \cdot H_H(s), \tag{3.2.29}$$

where G_{KLP} = 6589.6 and the rest of the functions appearing in equation (3.2.29) are provided by formulas:

$$H_A(s) = \frac{1.0}{1.0 + 0.00159s}, \tag{3.2.30}$$

$$H_B(s) = \frac{1.0}{1.0 + 4.576s + 11.66s^2}, \tag{3.2.31}$$

$$H_C(s) = \frac{s}{(1.0 + 0.1504s)(1.0 + 32.02s)}, \tag{3.2.32}$$

$$H_D(s) = \frac{1.0}{1.0 + 4.576s + 11.66s^2}, \tag{3.2.33}$$

$$H_E(s) = \frac{1.0}{1.0 + 9.477s + 0.2428s^2}, \tag{3.2.34}$$

$$H_F(s) = \frac{1.0}{1.0 + 0.6927s + 0.2399s^2}, \tag{3.2.35}$$

$$H_G(s) = \frac{1.0}{1.0 + 0.2524s + 0.2403s^2} \text{ and} \tag{3.2.36}$$

$$H_H(s) = \frac{s}{(1.0 + 0.1913s)(1.0 + 32.02s)}. \tag{3.2.37}$$

Thus, the long period spectral shaping filter has 2 zeros and 15 poles. An overall gain of 4.5388 V/V is achieved at 0.04 Hz.

The overall seismometer response in V/m/s, for the long period channels is provided by the formula:

$$H_{LPV}(s) = H_S(s) \cdot H_{HP1}(s) \cdot H_{BP1}(s) \cdot H_{DF}(s) \cdot H_{LPF}(s). \tag{3.2.38}$$

The response for displacement is constructed by the following 24 poles and 7 zeros, expressed in rad/s. The normalizing constant in this case equals A_0 = 2.838611768 x 10^{10} at 0.04 Hz (= 25 s) (Hardin and Breding, 1989), provided that all individual filter-gain stages are appropriately normalized.

Poles:	Zeros:
-1059.923907	0.0
-104.0526481	0.0
-53.21108539 ± *j* 169.3412870	0.0
-0.128950600	0.0
-17.21400168	0.0
-0.074580759 ± *j* 0.005712999	0.0
-628.1407035	-1006.441224
-628.9308176	
-0.196226415 ± *j* 0.217390173	
-0.196226415 ± *j* 0.217390173	
-6.648936170	
-0.031230481	
-1.951606261 ± *j* 0.556640953	
-1.443726553 ± *j* 1.443626386	
-0.525176863 ± *j* 1.971206255	
-5.227391532	
-0.031230481	

- *IP*:

The response of the *intermediate period bandpass filter* is expressed by the following equation, which has two zeros and two poles:

$$H_{BP2}(s) = \frac{-10.17s \cdot (127.8 + s)}{1.0 + 16.9s + 113.1s^2} \text{ in V/V} \tag{3.2.39}$$

The filter has a gain of 76.9046 V/V at 0.01506 Hz.

The *distributed filter* is again expressed by equation (3.2.28), as in the case of the long period channels, its response having only one pole.

Finally, the *intermediate period spectral shaping filter* has a transfer function that is provided by the formula:

$$H_{IPF}(s) = G_{KIP} \cdot H_A(s) \cdot H_B(s) \cdot H_C(s) \cdot H_D(s) \cdot H_E(s) \cdot H_F(s) \text{ in V/V,} \tag{3.2.40}$$

where G_{KIP} = 129.5, while the rest of the functions appearing in equation (3.2.40) are provided by the following formulas:

$$H_A(s) = \frac{1.0}{1.0 + 0.00159s}, \tag{3.2.41}$$

$$H_B(s) = \frac{1.0}{1.0 + 0.195s + 0.0099s^2}, \tag{3.2.42}$$

$$H_C(s) = \frac{s}{(1.0 + 0.00153s)(1.0 + 5.11s)}, \tag{3.2.43}$$

$$H_D(s) = \frac{1.0}{1.0 + 0.154s + 0.00888s^2}, \tag{3.2.44}$$

$$H_E(s) = \frac{1.0}{1.0 + 0.0817s + 0.0069s^2} \text{ and} \tag{3.2.45}$$

$$H_F(s) = \frac{s}{(1.0 + 0.00419s)(1.0 + 5.11s)}. \tag{3.2.46}$$

Thus, the filter has two zeros and eleven poles. An overall gain of 4.783811 V/V is achieved at 0.2326 Hz.

The overall response of the intermediate period NORES channels is described by the following formula:

$$H_{IPV}(s) = H_S(s) \cdot H_{BP2}(s) \cdot H_{DF}(s) \cdot H_{IPF}(s) \text{ in V/m/s.} \tag{3.2.47}$$

For displacement, this response is constructed by the 7 zeros and 18 poles listed below, expressed in rad/s. The overall normalizing constant is reported being equal to A_0 = 6.209179297 x 10^{15} (Hardin and Breding, 1989). This value can be achieved provided that individual filter stages have been appropriately normalized.

Poles:	Zeros:
-1059.923907	0.0
-104.0526481	0.0
-53.21108539 ± *j* 169.3412870	0.0
-0.074712644 ± *j* 0.057094254	0.0
-628.1407035	-1006.441224
-628.9308176	-127.8000000
-9.848484848 ± *j* 2.004357042	
-653.5947712	
-0.195694716	
-8.671171171 ± *j* 6.117467055	
-5.920289855 ± *j* 10.48225664	
-238.6634845	
-0.195694716	

Attention should be paid to the fact that poles and zeros are listed wrongly in the Hardin and Breding (1989) document for the intermediate period channel. A correction is made on the document, the correct values being the ones listed above.

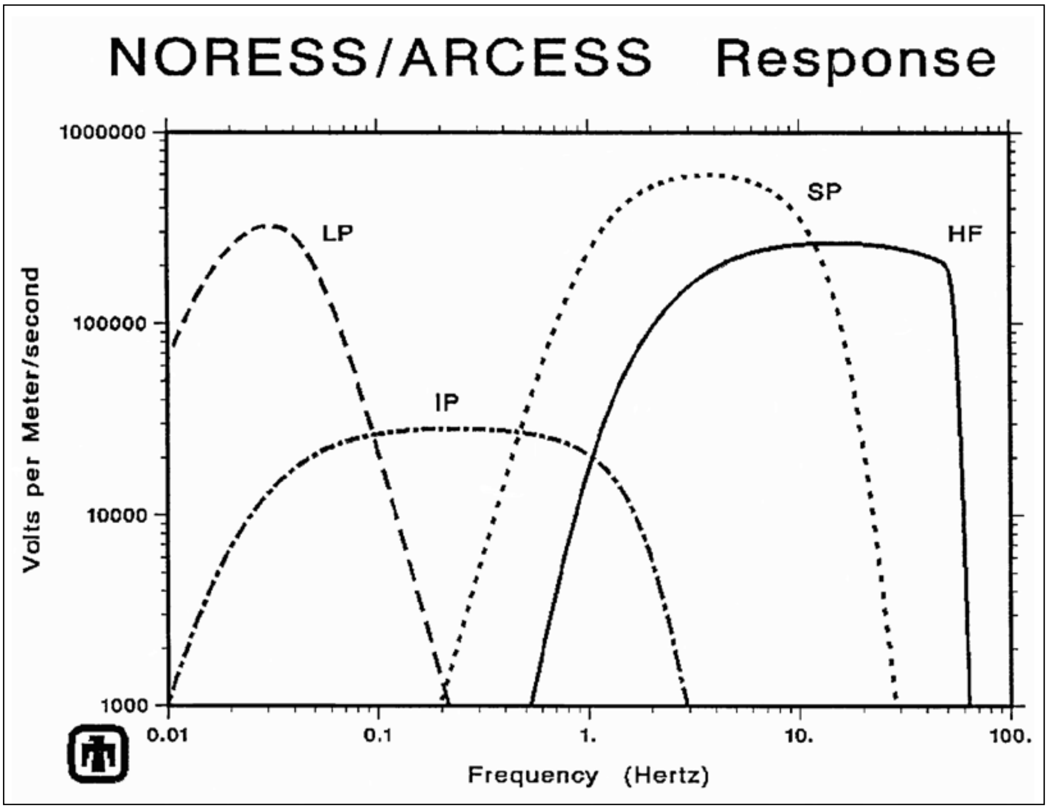


Fig. 3.17. Velocity amplitude response in V/m/s for the short period (SP), long period (LP), intermediate period (IP) and high frequency (HF) channels of the NORES array (Hardin and Breding, 1989). The response is identical to that of the initial ARCES array configuration (see section 2.3.1).

3.2.3.2 *Blue Box*

Information about the Sandia 'Blue Box' digitizer can be found in section 3.2.1.2.

In the case of the LP NORES channels, the digital sensitivity is equal to 7180.688085 count/μm, while for the IP channels it is equal to 12934.45398 count/μm (Hardin and Breding, 1989).

The velocity amplitude response, as calculated by Sandia (Hardin and Breding, 1989) for the NORES channels is depicted in Fig. 3.17. The solid line curve represents the response of the high-frequency channel. This response was not recalculated here due to lack of data.

The displacement response, as calculated in this project, is depicted in Fig. 3.18. Displacement amplitude is expressed in count/nm and phase in degrees. The short-period (SP) channel response (NORESSP1) is denoted with a blue line, the intermediate-period (IP) response (NORESIP) with a green line and the long-period (LP) response (NORESLP) with a red line. Moreover, shading is used to denote the range beyond the Nyquist frequency, which is equal to 20 Hz for the short-period channels, 5 Hz for the intermediate-period channels and 0.5 Hz for the long-period channels.

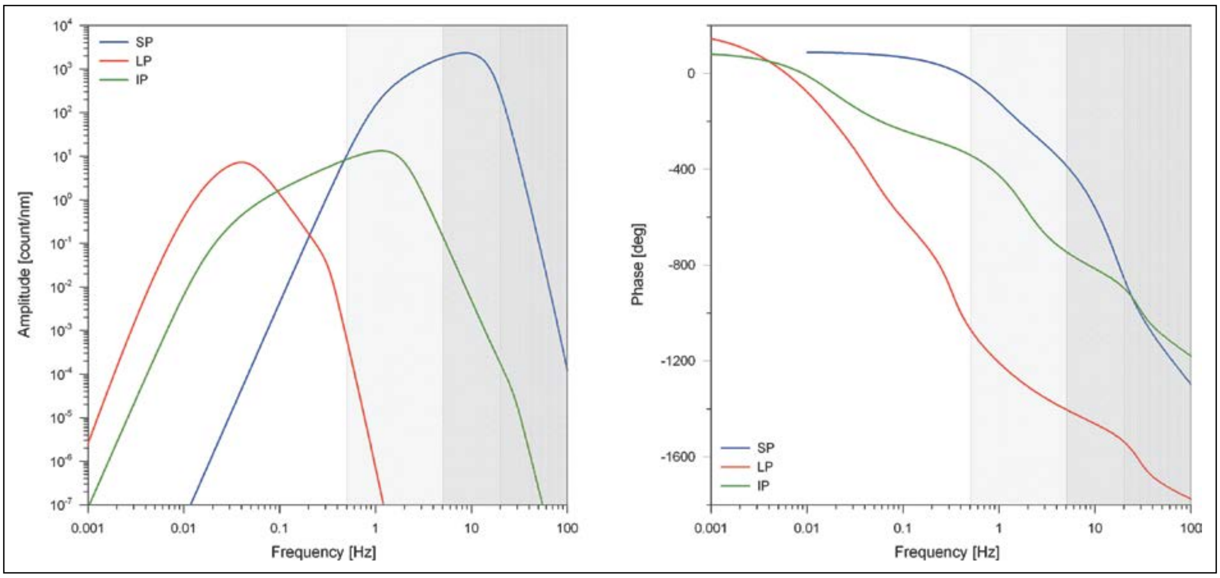


Fig. 3.18. Displacement amplitude and phase response for the short-period (SP), long-period (LP) and intermediate-period (IP) channels of the NORES array. Shaded areas represent range beyond the Nyquist frequency for each configuration.

3.2.4 GS-13 – DM24 (2010/12/20 – …)

Respid:	NORESSP7	Z
	NORESSP8	N-S
	NORESSP9	E-W

Current NORES configuration consists of the following components:

- GS-13 short-period seismometer
- Seismometer pre-amplifier
- CMG-DM24 mk3 digitizer

3.2.4.1 *GS-13*

For a detailed description of the GS-13 seismometer, see section 3.2.1.1.

At this new configuration, the GS-13 is used together with the pre-amplifier, but without the short-period filter and the distributed filter.

3.2.4.2 *DM24*

The CMG-DM24 mk3 digitizer by Güralp Systems Ltd. is extensively described in section 5.2.4.2.

Instrument specific information, *e.g.*, channel sensitivity values, is provided by the manufacturer. For example, for the instrument with serial number A085, which is operating at NORES site NRA2, the velocity channels have the following sensitivity values, according to the corresponding calibration sheet, works order 3039:

Channel:	A085Z2	Vertical	3.177 µV/Count
	A085N2	North/South	3.174 µV/Count
	A085E2	East/West	3.183 µV/Count

The employed digital filter cascade, which is used here at decimate down to the sampling rate of 80 sps, can be retrieved by accessing the raw data header information. A TTL value of 91 is used at this NORES configuration, which corresponds to the following FIR cascade:

- CS5376 SINC1, decimating by 8 from 512 kHz to 64 kHz
- CS5376 SINC2-stage-3, decimating by 2 → 32 kHz
- CS5376 SINC2-stage-4, decimating by 2 → 16 kHz
- CS5376 FIR-1-set0, decimating by 4 → 4 kHz
- CS5376 FIR-2-set0, decimating by 2 → 2 kHz
- DM24 FIR 1, decimating by 5 → 400 Hz
- DM24 FIR 2, decimating by 5 → 80 Hz

The filter coefficients can be found in the corresponding *GSE* response files (see Appendix II for names).

An example of the displacement amplitude and phase response of the current NORES configuration is depicted in Fig. 3.19.

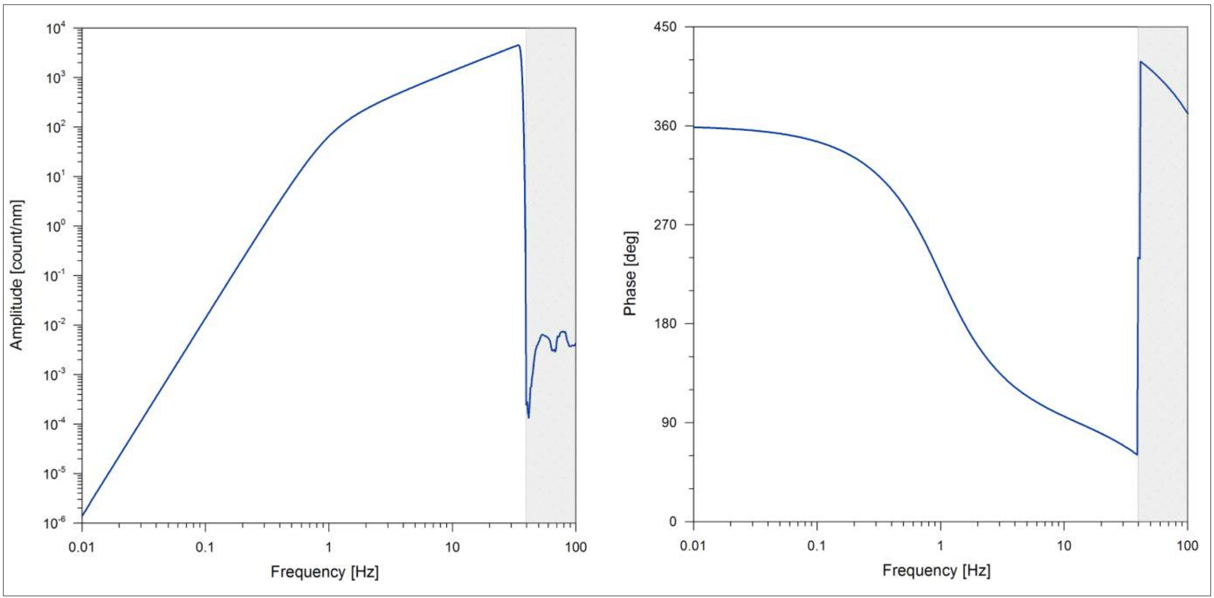


Fig. 3.19. Displacement amplitude and phase response for the current configuration of the NORES array, here for the vertical channel of site NRA0. Shaded areas represent range beyond the Nyquist frequency (40 Hz).

3.3 References

Breding, D., 1986. NSEIS subroutine. Currently contained in */ndc/programs/dpep/lsrc/ /resp/nrsyst.f*.

Durham, H.B., 1984a. NRSA broad band channel response functions. *Sandia National Laboratories*, Albuquerque, New Mexico, 4 pp.

Durham, H.B., 1984b. NRSA short period response functions. *Sandia National Laboratories*, Albuquerque, New Mexico, 6 pp.

Geotech Instruments, 1999. Operation and maintenance manual portable short-period seismometer, model GS-13. *55400D0A.WFW*, Geotech Instruments, Dallas, Texas, 50 pp.

Hansen, O.A., 1985a. Maintenance activities. *NORSAR Semiann. Techn. Summ. 2-84/85*, Kjeller, Norway, p. 16-20.

Hansen, O.A., 1985b. Maintenance activities. *NORSAR Semiann. Techn. Summ. 1-85/86*, Kjeller, Norway, p. 16-19.

Hardin, T.L. and Breding, D.R., 1989. Poles and zeros of the NORESS/ARCESS system responses. *Sandia National Laboratories*, Albuquerque, New Mexico, 12 pp.

Mykkeltveit. S., 1985. A new regional array in Norway: design work and results from analysis of data from a provisional installation. In A. U. Kerr (ed.) *The VELA Program, A Twenty-Five Year Review of Basic Research*, DARPA, p. 546-553.

Mykkeltveit, S. (ed.), 1987. *Annual Report 01 December 1985 – 30 November 1986 for project 'Development and evaluation of a regional seismic array in Norway'*. NORSAR, Kjeller, Norway, 17 pp.

CHAPTER 4: ARCES

4.1 Development of ARCES systems: instrumentation and responses

4.1.1 Short description

- 1987-1999:

The ARCES regional array was installed during the summer and fall of 1987 in the vicinity of the town of Karasjok, Finnmark, northern Norway. ARCES was designed to be almost identical to NORES, both in terms of geometry, instrumentation and data output. Thus, initial ARCES instrumentation consists of GS-13 short-period and KS36000 broadband sensors and Sandia 'Blue Box' digitizers (see also §3.2.1). Data transmission to NORSAR commenced on 16th October 1987, while data are available in the NORSAR database system since 1st November 1987 (Mykkeltveit et al., 1987, Torstveit et al., 1988).

- 1999-…:

Extensive refurbishment of the array in September 1999. All Sandia digitizers were replaced with Nanometrics HRD24 digitizers and the long- and intermediate-period channels were closed. The KS36000 seismometer was replaced by a Güralp CMG-3T broadband sensor, data being assigned to a broadband (BB) channel. Within this time interval, a high-frequency variation of the broadband channel existed for a few months (October 2003 – July 2004), with a REF TEK 130-01 DAS unit connected to the CMG-3T seismometer. Moreover, another broadband variation with a Güralp DM24 digitizer is in operation since March 2008. The CMG-3T sensors were exchanged several times due to malfunction however this has not seriously affected the response of the configuration. Initially, the instrument response provided by the manufacturer contained a negative normalization factor, which proved to be incompatible with IDC software. Thus, the manufacturer provided a different expression of the same response, approximated by a different combination of poles and zeros and a positive normalization factor. Both versions are listed in section 4.2.4.1. ARCES was certified as IMS station PS28 on 8th November 2001 (Fyen, 2003).

4.1.2 Instrumentation

I. Configurations

- Standard SP configuration (1987-1999):
  - GS-13 seismometer
  - Pre-amplifier
  - Short-period filter
  - Distributed filter
  - Sandia 'Blue Box' digitizer

- Standard LP configuration (1987-1999):
  - KS36000 seismometer
  - Long period high-pass filter
  - Long period bandpass filter
  - Distributed filter
  - Long period spectral shaping filter
  - Sandia 'Blue Box' digitizer

- Standard IP configuration (1987-1999):
  - KS36000 seismometer
  - Intermediate period bandpass filter
  - Distributed filter
  - Intermediate period spectral shaping filter
  - Sandia ‘Blue Box’ digitizer

- Current SP configuration (1999-…):
  - GS-13 seismometer
  - HRD24 digitizer

- Current BB configuration (1999-…):
  - CMG-3T seismometer
  - HRD24 digitizer

- High-frequency HH broadband variation (2003-2004):
  - CMG-3T seismometer
  - REF TEK DAS 130-01 digitizer

- Current high-frequency EH variation (2008-…):
  - CMG-3T seismometer
  - DM24 digitizer

II. Respids

ARCESSP1,2,3
ARCESLP1,2,3
ARCESIP1,2,3
ARCESSP4,5,6
ARCESBB1,2,3
ARCESHH1,2,3
ARCESEH1,2,3

III. Instrument specifications

GS-13:
See §2.2.2.

KS36000:
See §2.2.2.

CMG-3T:
3-component, broadband Güralp seismometer. The ground velocity specifications of the model (S/N T3890) installed at ARCES are the following (for the vertical):

Velocity output	2x2486 V/m/s (differential)
Acceleration output	1576 V/m/s^2
Feedback coil constant	0.02388 A/m/s^2
Power consumption	60 mA @ + 12 V input
Calibration resistor	51 K

Poles (Hz)	$-7.07 \times 10^{-3} \pm j7.07 \times 10^{-3}$ (in Hz)
	-180
	-160
	-80
Zeros (Hz)	0.0 0.0
Normalizing factor	2304000 Hz @ 1 Hz

Sandia 'Blue Box':
See §2.2.2.

Nanometrics HRD24:
A 24-bit digitizer with 132 dB dynamic range. Data are oversampled at 256 kHz per channel and then filtered and decimated down to the desired sample rate. Employs the following filters:
- Analogue low pass anti-alias filter
- Digital FIR filter with 34 coefficients, decimating the sampling rate by 5
- Digital FIR filter with 30 coefficients, decimating the sampling rate by 3
- Digital FIR filter with 118 coefficients, the sampling rate decimating by 2
- Digital FIR filter with 36 coefficients, the sampling rate decimating by 5
- Digital FIR filter with 256 coefficients, the sampling rate decimating by 5
- Optional digital IIR high pass filter

Summarizing, the specifications of the instrument are the following:

Resolution	24 bit
Dynamic range	132 dB
Sensitivity	6303183.11 count/V

REF TEK 130-01:
The REF TEK 130-01 DAS is an A/D converter that provides a 24-bit output word. It employs the Crystal Semiconductor CS5372/5322 chipset that uses a delta-sigma modulation and digital filtering to produce a 24-bit output word for each data sample (REF TEK, 2008). Depending on the desired data recording sampling rate, the CS5322 FIR filters and a combination with CPU firmware filters may be needed to decimate down to the proper value (see §2.1.3 for details). The specifications of this instrument are the following:

Full scale input voltage	20 V p-p
Bit weight	1.5895 µV/count
Sensitivity	62914560 count/V

Güralp DM24:
Full 24-bit digitizer employing the Cirrus Logic CS5376 digital filtering chipset and TMS320VC33 digital signal processor (DSP). The DSP software consists of 6 cascaded programmable filter/decimation stages that allow the selection of multiple data output rates simultaneously (Güralp Systems, 2006). The specifications are the following:

Input voltage range	+/- 10 V differential
Dynamic range	137 dB @ 40 sps
DSP sampling rate	32 kHz
Sensitivity	3.2 µV/count

4.2 Instrument response calculation for ARCES systems

This chapter focuses on the major considerations to be taken into account for the calculation of the instrument response of the different systems operating at the ARCES regional array.

As with the NORSAR and NORES arrays, GSE file response *Respid* flags for each configuration are provided at the beginning of each section.

4.2.1 <u>GS-13-BlueBox</u> (1987/10/03 – 1999/09/14)

Respid:	ARCESSP1	Z
	ARCESSP2	N-S
	ARCESSP3	E-W

Standard ARCES short-period channel configuration consists of the following components:

- GS-13 short-period seismometers
- Seismometer pre-amplifier
- Short-period filter
- Distributed filter
- Sandia 'Blue Box'

4.2.1.1 *GS-13*

The GS-13 short-period seismometer transfer function for ground velocity is expressed by the following equation (Durham, 1984b):

$$H_S(s) = \frac{G_S \cdot \dfrac{s^2}{\omega_0^2}}{1 + 2\dfrac{\lambda}{\omega_0}s + \dfrac{1}{\omega_0^2}s^2} \text{ in V/m/s.} \qquad (4.2.1)$$

This has two poles and two zeros, which are the roots of the denominator and numerator respectively.

The poles can also be calculated according to formula (Geotech Instruments, 1999):

$$p_{1,2} = \lambda_0\omega_0 \pm j\omega_0\sqrt{1-\lambda_0^2}\,. \qquad (4.2.2)$$

The nominal values for the parameters to be used in equations (4.2.1) and (4.2.2) are the following:

G_S = 2200 V/m/s
ω_0 = 6.283 rad/s (f_0 = 1 Hz)
λ_0 = 0.75

The gain of the seismometer will be equal to 2200 V/m/s.

The GS-13 sensor is used together with an amplifier, and their *interface* is described by the formula:

$$H_{IF}(s) = \frac{Z_t(s)}{Z_t(s) + Z_s(s)} \text{ in V/V,} \tag{4.2.3}$$

where $Z_t(s)$ is the seismometer termination impedance and $Z_s(s)$ the seismometer source impedance. They are expressed by the following equations:

$$Z_t(s) = \frac{R_t}{1 + sR_tC_t} \text{ and} \tag{4.2.4}$$

$$Z_s(s) = R_s + sL_s\,. \tag{4.2.5}$$

By substituting relations (4.2.4) and (4.2.5) in equation (4.2.3), we obtain the equation:

$$H_{IF}(s) = \frac{R_t}{(R_t + R_s) + (R_tR_sC_t + L_s)\cdot s + (R_tC_tL_s)\cdot s^2}\,. \tag{4.2.6}$$

The values of R_t, C_t, R_s, and L_s are either provided by the manufacturer or can be measured in the lab. The nominal values are the following:

R_t = 100000 ohm
C_t = 0.010 μfd
R_s = 9000 ohm
L_s = 80 henry

Equation (4.2.6) has two poles and essentially describes a low-pass filter, with cut-off frequency at around 250 Hz. The gain of this filter will be equal to 0.9174 V/V, for normalization at 1.0 Hz.

The seismometer *pre-amplifier* itself has a response that can be described by equation:

$$H_{PA}(s) = 2G_{PA}\frac{Z_2}{Z_1} \text{ in V/V,} \tag{4.2.7}$$

where 2 G_{PA} = 13.62 for the case of ARCES and

$$Z_1 = \frac{1 + sR_1C_1}{sC_1} \text{ and} \tag{4.2.8}$$

$$Z_2 = \frac{R_2}{1 + sR_2C_2}\,. \tag{4.2.9}$$

Substituting relations (4.2.8) and (4.2.9) in equation (4.2.7), the mathematical formula providing the response of the pre-amplifier obtains the following form:

$$H_{PA}(s) = \frac{2G_{PA} \cdot sR_2C_1}{(1+sR_2C_2)(1+sR_1C_1)}\,. \tag{4.2.10}$$

The above written equation contributes to the sensor's total response with one zero and two poles. Nominal values of the parameters found in formula (4.2.10) are as follows:

R_1 = 340000 ohm
C_1 = 0.470 μfd
R_2 = 866000 ohm
C_2 = 0.0018 μfd

Regarding the gain of the pre-amplifier, this has to be set to match the associated seismometer parameters so, that an output of 70000 V/m/s is achieved. This condition is satisfied by the formula:

$$G_s \cdot \frac{R_t}{R_t + R_s} \cdot 2G_{PA} \cdot \frac{R_2}{R_1} = 70000 \text{ (V/m/s).} \tag{4.2.11}$$

The pre-amplifier is a bandpass filter with cut-off frequency points at about 1 Hz and 102 Hz. This system can be normalized at 10 Hz, receiving at this frequency a gain value of 34.35812 V/V.

The next stage in the seismometer response is the *short-period filter* stage, which consists of three sub-stages, (i) the input stage, (ii) the low pass filter stages and (iii) the output stage.

(i) Input stage: The response of this stage is described by equation:

$$H_i(s) = \frac{R_2}{R_1} \cdot \frac{1}{1+sR_2C_2}\,. \tag{4.2.12}$$

This equation provides a single pole, while nominal values of the different parameters are equal to:

R_1 = 53000 ohm
R_2 = 53000 ohm
C_2 = 0.015 μfd

(ii) Low pass filter stages: A series of five successive low-pass filters described by the following equations, each one of them featuring two poles.

$$\left.\begin{aligned}
H_1(s) &= \frac{1}{1+0.0221\cdot s+0.000125\cdot s^2}\\
H_2(s) &= \frac{1}{1+0.0195\cdot s+0.000119\cdot s^2}\\
H_3(s) &= \frac{1}{1+0.0143\cdot s+0.000104\cdot s^2}\\
H_4(s) &= \frac{1}{1+0.00739\cdot s+0.000082\cdot s^2}\\
H_5(s) &= \frac{1}{1+0.0150\cdot s+0.000113\cdot s^2}
\end{aligned}\right\} \tag{4.2.13}$$

(iii) Output stage: The response of this stage is described by equation:

$$H_0(s) = \frac{Z_2}{Z_1} \ , \tag{4.2.14}$$

where $Z_1 = \dfrac{1+sR_1C_1}{sC_1}$ (4.2.15) and $Z_2 = \dfrac{R_2}{1+sR_2C_2}$. (4.2.16)

Substituting relations (4.2.15) and (4.2.16) in formula (4.2.14), provides us with:

$$H_0(s) = \frac{sR_2C_1}{(1+sR_1C_1)(1+sR_2C_2)} \ . \tag{4.2.17}$$

Equation (4.2.17) has one zero and two poles and the nominal parameter values are:

R_1 = 590000 ohm
C_1 = 0.270 μfd
R_2 = 1180000 ohm
C_2 = 0.0012 μfd

While stages (i) and (ii) have no gain, gain (iii) has a gain of 1.9822262 V/V, when normalized at 10 Hz, as a bandpass filter with cut-off frequency points around 1 Hz and 112 Hz.

The total response of the short period filter will then be equal to:

$$H_{SP}(s) = -G_0 \cdot H_i(s) \cdot H_1(s) \cdot H_2(s) \cdot H_3(s) \cdot H_4(s) \cdot H_5(s) \cdot H_0(s) \text{ in V/V}, \tag{4.2.18}$$

where factor G_0 is the short period filter nominal gain. For seismic data, this can be selected to equal either 50.0 (high gain) or 5.0 (low gain). In the case of ARCES, the low gain option was selected, so G_0 = 5.0 (Durham, 1984b; Breding, 1986).

The final stage in the seismometer's response is the distributed filter, whose transfer function is expressed by formula:

$$H_{DF}(s) = \frac{-1.0}{1.0 + 1.592 \times 10^{-3} s} \ . \tag{3.3.19}$$

This filter is described by one single real pole and has no gain.

The overall response function for the GS-13 seismometer will be equal to (Durham, 1984b):

$$H_{spv}(s) = H_S(s) \cdot H_{IF}(s) \cdot H_{PA}(s) \cdot H_{SP}(s) \cdot H_{DF}(s) \text{, expressed in V/m/s.} \tag{4.2.20}$$

From the equations of the individual transfer functions of the system, mentioned previously, it becomes clear that the overall seismometer displacement response for the short period ARCES channels can be reconstructed using the 20 poles and 5 zeros provided below, in rad/s.

Poles:	Zeros:	
-4.711804185 ± *j* 4.156654920	0.0	
-5.562746965 ± *j* 1026.227032	0.0	
-641.4368185	0.0	
-6.257822278	0.0	
-1257.861635	0.0	for displacement
-88.40000000 ± *j* 13.61763563		
-81.93277310 ± *j* 41.11425589		
-68.75000000 ± *j* 69.92011240		
-45.06097561 ± *j* 100.8197919		
-66.37168140 ± *j* 66.66601405		
-6.277463905		
-706.2146893		
-628.1407035		

A value of $A_0 = 1.62901265 \times 10^{32}$ is provided by Hardin and Breding (1989) for the overall normalization factor. This value is the product of all individual stage gain factors at 1 Hz, with individual filter gains appropriately normalized.

4.2.1.2 *Blue Box*

The 'Blue Box' digitizer manufactured by Sandia has a 14-bit resolution, while gain ranging by 2 gain bits (representing a step of 1, 8, 32, 128) results to a total dynamic range of 20 bits.

The sensitivity of the digitizer equals 100000 count/V.

According to an alternative approach, the appropriate form of the overall system complex transfer function is (Hardin and Breding, 1989):

$$H(s) = A_0 \cdot DS \cdot \frac{(s - Z01)(s - Z02)\cdots(s - ZM)}{(s - P01)(s - P02)\cdots(s - PN)}, \qquad (4.2.21)$$

where $s = j\omega$, A_0 is the overall normalizing constant (see §4.2.1.1), M the number of complex poles, N the number of complex zeros and DS the digital sensitivity in count/μm. The latter is channel sensitivity at normalization frequency, provided that all individual filter stages have been appropriately normalized. For the previously described configuration (§4.2.1.1), the digital sensitivity equals 146249.8804 count/μm at 1.0 Hz.

4.2.2 KS36000-BlueBox (1987/10/03 – 1999/09/14)

Respid: ARCESLP1 Z
ARCESLP2 N-S
ARCESLP3 E-W
ARCESIP1 Z
ARCESIP2 N-S
ARCESIP3 E-W

A Kinemetrics KS36000-04A broadband seismometer is installed at ARCES site E0, collocated with site A0, the central array element. Two different channels, each one with 3 components operate on this site, a long-period channel (lz, ln, le) and an intermediate-period channel (iz, in, ie). For each one of these channels, the system consists of the following components (Durham, 1984a):

LP:	IP:
- KS36000 broadband seismometer	KS36000 broadband seismometer
- Long period high-pass filter	Intermediate period bandpass filter
- Long period bandpass filter	Distributed filter
- Distributed filter	Intermediate period spectral shaping filter
- Long period spectral shaping filter	Sandia 'Blue Box' digitizer
- Sandia 'Blue Box' digitizer	

4.2.2.1 *KS36000*

The KS36000 seismometer transfer function for ground velocity is expressed by the formula:

$$H_S(s) = 100.0 \cdot H_{KA}(s) \cdot s \text{ in V/m/s,} \tag{4.2.22}$$

where $H_{KA}(s)$ is expressed in V/cm/s^2 and is described from equation:

$$H_{KA}(s) = \frac{H_T(s) \cdot H_A(s)}{1 - H_T(s) \cdot H_A(s) \cdot H_B(s) \cdot K_B}. \tag{4.2.23}$$

K_B is equal to 1.370 x 10^3 (cm/s^2)/A, while the rest of the functions appearing in equation (4.2.23) are provided by the following formulas:

$$H_T(s) = \frac{12.66}{1.0 + 0.02256 \cdot s + 0.6333 \cdot s^2} \text{ in V/cm/s}^2 \tag{4.2.24}$$

$$H_A(s) = \frac{-3.360 \times 10^3}{1.0 + 3.789 \times 10^{-3} s} \text{ in V/V} \tag{4.2.25}$$

$$H_B(s) = 1.421 \times 10^{-4} \frac{1.0 + 1.394 \times 10^{-2} s}{1.0 + 9.936 \times 10^{-4} s} \text{ in A/V.} \tag{4.2.26}$$

Thus, the seismometer has two zeros and four poles, for velocity. An extra zero should be added for displacement response.

The response of the series of filters that interface the seismometer to the digitizer is described in the following sections, both for the long (LP) and intermediate period (IP) channels. The overall seismometer response is provided in the end of each section.

- *LP*:

The response of the *long period high-pass filter* has one zero and two poles, and is described from the following equation:

$$H_{HP1}(s) = \frac{-390.6s}{1.0 + 7.813s + 0.4505s^2} \text{ in V/V.} \tag{4.2.27}$$

The filter, which is a bandpass between 0.0204 Hz and 2.76 Hz has a gain of 49.9936 V/V at 0.238 Hz.

The *long period bandpass filter* has also one zero and two poles and its response is provided by equation:

$$H_{BP1}(s) = \frac{324.0s}{1.0 + 16.90s + 113.1s^2} \text{ in V/V.} \tag{4.2.28}$$

The bandpass of this filter is between 0.0072 Hz and 0.031 Hz, while its gain equals 19.1708 V/V at 0.015059 Hz.

The response of the *distributed filter*, which has only one pole, is described by equation:

$$H_{DF}(s) = \frac{-1.0}{1.0 + 1.592 \times 10^{-3} s} \text{ in V/V.} \tag{4.2.29}$$

Finally, the *long period spectral shaping filter*'s response is described by the following formula (in V/V):

$$H_{LPF}(s) = G_{KLP} \cdot H_A(s) \cdot H_B(s) \cdot H_C(s) \cdot H_D(s) \cdot H_E(s) \cdot H_F(s) \cdot H_G(s) \cdot H_H(s), \tag{4.2.30}$$

where G_{KLP} = 6589.6 and the rest of the functions appearing in equation (4.2.30) are provided by formulas:

$$H_A(s) = \frac{1.0}{1.0 + 0.00159s}, \tag{4.2.31}$$

$$H_B(s) = \frac{1.0}{1.0 + 4.576s + 11.66s^2}, \tag{4.2.32}$$

$$H_C(s) = \frac{s}{(1.0 + 0.1504s)(1.0 + 32.02s)}, \tag{4.2.33}$$

$$H_D(s) = \frac{1.0}{1.0 + 4.576s + 11.66s^2}, \tag{4.2.34}$$

$$H_E(s) = \frac{1.0}{1.0 + 9.477s + 0.2428s^2}, \tag{4.2.35}$$

$$H_F(s) = \frac{1.0}{1.0 + 0.6927s + 0.2399s^2}, \tag{4.2.36}$$

$$H_G(s) = \frac{1.0}{1.0 + 0.2524s + 0.2403s^2} \text{ and} \tag{4.2.37}$$

$$H_H(s) = \frac{s}{(1.0 + 0.1913s)(1.0 + 32.02s)}. \tag{4.2.38}$$

Thus, the long period spectral shaping filter has 2 zeros and 15 poles. An overall gain of 4.5388 V/V is achieved at 0.04 Hz.

The overall seismometer response in V/m/s, for the long period channels is provided by the formula:

$$H_{LPV}(s) = H_S(s) \cdot H_{HP1}(s) \cdot H_{BP1}(s) \cdot H_{DF}(s) \cdot H_{LPF}(s). \tag{4.2.39}$$

The response for displacement is constructed by the following 24 poles and 7 zeros, expressed in rad/s. The normalizing constant in this case equals A_0 = 2.838611768 x 10^{10} at 0.04 Hz (= 25 s) (Hardin and Breding, 1989), provided that all individual filter-gain stages are appropriately normalized.

Poles:	Zeros:
-1059.923907	0.0
-104.0526481	0.0
-53.21108539 ± *j* 169.3412870	0.0
-0.128950600	0.0
-17.21400168	0.0
-0.074580759 ± *j* 0.005712999	0.0
-628.1407035	-1006.441224
-628.9308176	
-0.196226415 ± *j* 0.217390173	
-0.196226415 ± *j* 0.217390173	
-6.648936170	
-0.031230481	
-1.951606261 ± *j* 0.556640953	
-1.443726553 ± *j* 1.443626386	
-0.525176863 ± *j* 1.971206255	
-5.227391532	
-0.031230481	

- *IP*:

The response of the *intermediate period bandpass filter* is expressed by the following equation, which has two zeros and two poles:

$$H_{BP2}(s) = \frac{-10.17s \cdot (127.8 + s)}{1.0 + 16.9s + 113.1s^2} \text{ in V/V} \tag{4.2.40}$$

The filter has a gain of 76.9046 V/V at 0.01506 Hz.

The *distributed filter* is again expressed by equation (4.2.29), as in the case of the long period channels, its response having only one pole.

Finally, the *intermediate period spectral shaping filter* has a transfer function that is provided by the formula:

$$H_{IPF}(s) = G_{KIP} \cdot H_A(s) \cdot H_B(s) \cdot H_C(s) \cdot H_D(s) \cdot H_E(s) \cdot H_F(s) \text{ in V/V,} \tag{4.2.41}$$

where G_{KIP} = 129.5, while the rest of the functions appearing in equation (4.2.41) are provided by the following formulas:

$$H_A(s) = \frac{1.0}{1.0 + 0.00159s}, \tag{4.2.42}$$

$$H_B(s) = \frac{1.0}{1.0 + 0.195s + 0.0099s^2}, \tag{4.2.43}$$

$$H_C(s) = \frac{s}{(1.0 + 0.00153s)(1.0 + 5.11s)}, \tag{4.2.44}$$

$$H_D(s) = \frac{1.0}{1.0 + 0.154s + 0.00888s^2}, \tag{4.2.45}$$

$$H_E(s) = \frac{1.0}{1.0 + 0.0817s + 0.0069s^2} \text{ and} \tag{4.2.46}$$

$$H_F(s) = \frac{s}{(1.0 + 0.00419s)(1.0 + 5.11s)}. \tag{4.2.47}$$

Thus, the filter has two zeros and eleven poles. An overall gain of 4.783811 V/V is achieved at 0.2326 Hz.

The overall response of the intermediate period ARCES channels is described by the following formula:

$$H_{IPV}(s) = H_S(s) \cdot H_{BP2}(s) \cdot H_{DF}(s) \cdot H_{IPF}(s) \text{ in V/m/s.} \tag{4.2.48}$$

For displacement, this response is constructed by the 7 zeros and 18 poles listed below, expressed in rad/s. The overall normalizing constant is reported being equal to A_0 = 6.209179297 x 10^{15} (Hardin and Breding, 1989). This value can be achieved provided that individual filter stages have been appropriately normalized.

Poles:	Zeros:
-1059.923907	0.0
-104.0526481	0.0
-53.21108539 ± *j* 169.3412870	0.0
-0.074712644 ± *j* 0.057094254	0.0
-628.1407035	-1006.441224
-628.9308176	-127.8000000
-9.848484848 ± *j* 2.004357042	
-653.5947712	
-0.195694716	
-8.671171171 ± *j* 6.117467055	
-5.920289855 ± *j* 10.48225664	
-238.6634845	
-0.195694716	

Attention should be paid to the fact that poles and zeros are listed wrongly in the Hardin and Breding (1989) document for the intermediate period channel. A correction is made on the document, the correct values being the ones listed above.

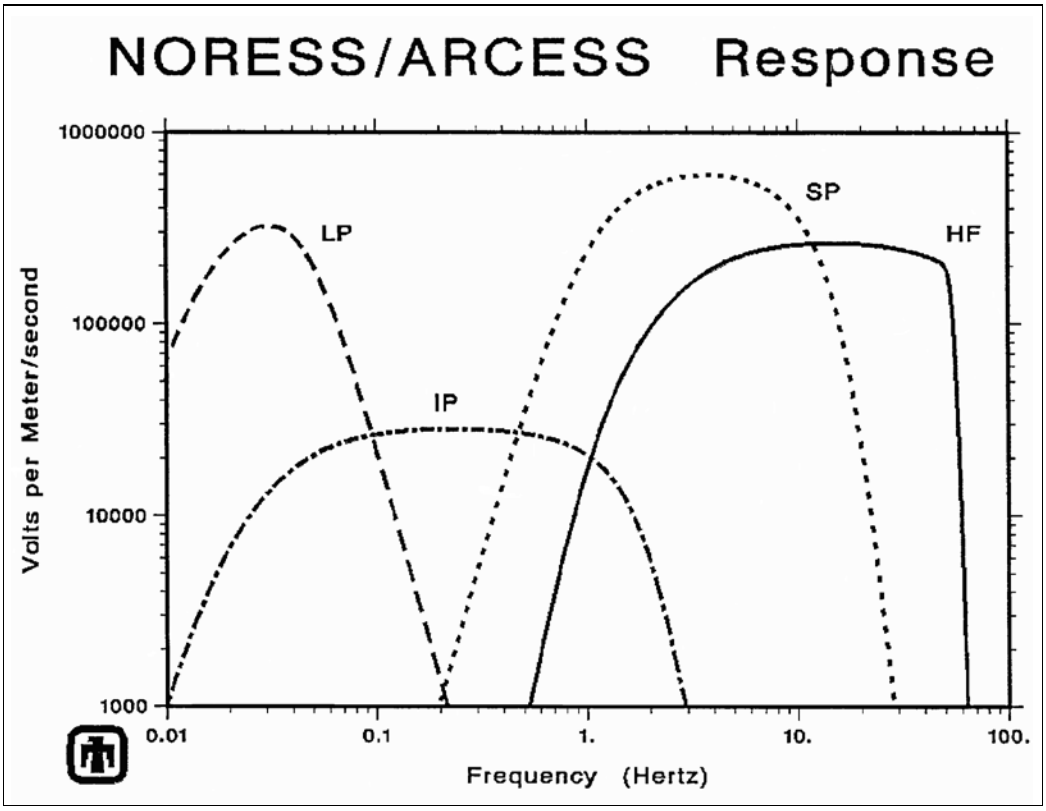


Fig. 4.1. Velocity amplitude response in V/m/s for the short period (SP), long period (LP), intermediate period (IP) and high frequency (HF) channels of the ARCES array (Hardin and Breding, 1989).

4.2.2.2 Blue Box

Information about the Sandia 'Blue Box' digitizer can be found in section 4.2.1.2.

In the case of the LP ARCES channels, the digital sensitivity is equal to 7180.688085 count/µm, while for the IP channels it is equal to 12934.45398 count/µm (Hardin and Breding, 1989).

The velocity amplitude response, as calculated by Sandia (Hardin and Breding, 1989) for the ARCES channels is depicted in Fig. 4.1. The solid line curve represents the response of the high-frequency channel. This response was not recalculated here due to lack of data.

The displacement response, as calculated in this project, is depicted in Fig. 4.2. Displacement amplitude is expressed in count/nm and phase in degrees. The short-period (SP) channel response (ARCESSP1) is denoted with a blue line, the intermediate-period (IP) response (ARCESIP) with a green line and the long-period (LP) response (ARCESLP) with a red line. Moreover, shading is used to denote the range beyond the Nyquist frequency, which is equal to 20 Hz for the short-period channels, 5 Hz for the intermediate-period channels and 0.5 Hz for the long-period channels.

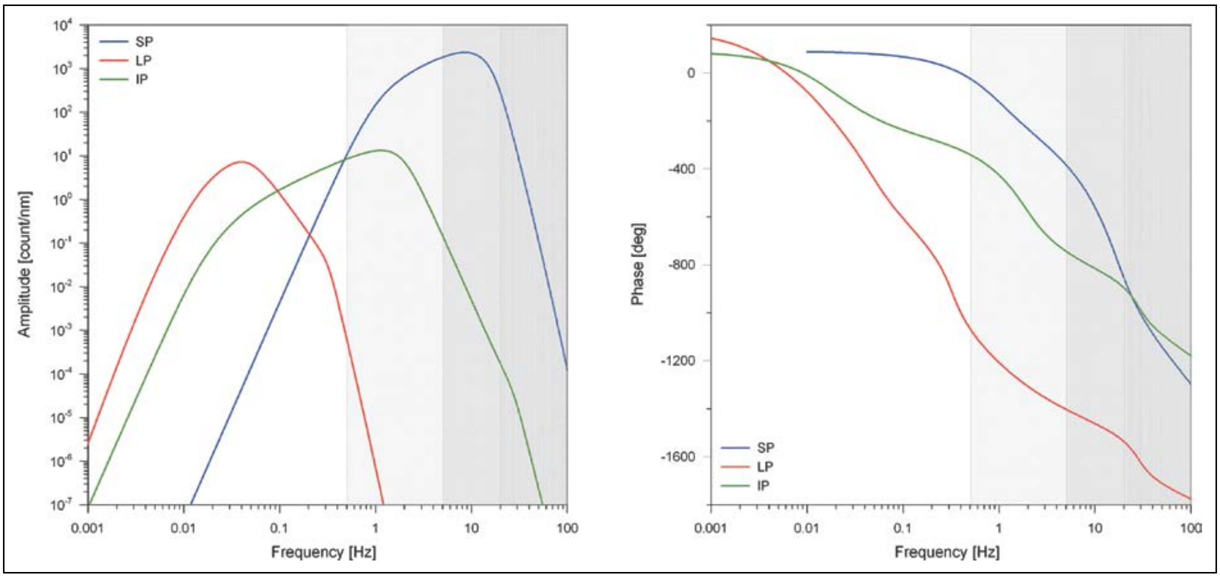


Fig. 4.2. Displacement amplitude and phase response for the short-period (SP), long-period (LP) and intermediate-period (IP) channels of the ARCES array. Shaded areas represent range beyond the Nyquist frequency for each configuration.

4.2.3 GS-13 – HRD24 (1999/09/14 - …)

Respid: ARCESSP4,5,6 Z, N-S, E-W
ARCESSP7,8,9 Z, N-S, E-W

The new ARCES short-period channel configuration consists of the following components:
- GS-13 seismometers
- Nanometrics HRD24 digitizers

4.2.3.1 *GS-13*

For a detailed description of the GS-13 seismometer instrument response see section 4.2.1.1. It should be taken into consideration however that when the sensor is connected to an HRD24 digitizer, no amplifier is employed. Thereby, the poles and zeros will be provided by the standard seismometer formula expressed by equation 2.2.8. Nominal values are the same as in section 4.2.1.1.

Attention should be paid to the fact that for approximately one month in 1999 (14 September – 7 October), the GS-13 seismometers operated with a damping of 1.5 instead of the typical value of 0.75 that was adopted afterwards. Thus, the highly damped version is assigned *Respids* ARCESSP4,5,6, while the current version *Respids* ARCESSP7,8,9. The corresponding poles and zeros can be found in the related *GSE* response files.

4.2.3.2 *HRD24*

The Nanometrics High Resolution Digitizer (HRD24) is a 24-bit A/D converter designed for short period and broadband seismic monitoring, which connects directly to most seismometers, without requiring additional preamplification. It has 24-bit resolution after digital filtering and provides a typical dynamic range of 132 dB.

The analog signals connected to the HRD24 are low-pass filtered using an analogue 3rd order Bessel low-pass filter of the following specifications (Nanometrics, 1999):
- f_{3dB} = 1500 Hz
- $\omega_1 = 2\pi f_{3dB} = 9424.8$
- 3 poles: -9904.799805 ± 3786.000000 [rad/s]
  -12507.00000 [rad/s]
- no zeros

The desired data recording sample rate is achieved by filtering and decimating by a series of digital FIR filters. In the case of ARCES, the data are being recorded at 40 sps, and the FIR filter sequence employed is the following:
- FIR 1 filter: 34 coefficients, decimation factor of 5 from an initial input rate of 30 kHz
- FIR 2 filter: 30 coefficients, decimation factor of 3
- FIR 3 filter: 118 coefficients, decimation factor of 2
- FIR 7 filter: 36 coefficients, decimation factor of 5
- FIR 10 filter: 256 coefficients, decimation factor of 5 down to the desired rate of 40 Hz

Finally, a DC removal IIR filter is employed. Its characteristics are the following:

- f_{3dB} = 0.001 Hz
- Gain K = 0.9999215218041547
- 1 pole: 0.9998430436083094
- 1 zero: 1.0000000000000000

The poles and zeros are expressed in the Z domain.

The sensitivity of the HRD24 digitizer is equal to 6303183.11 count/V.

The displacement amplitude (in count/nm) and phase (in deg) response of the two short-period configurations discussed in this section (*Respids* ARCESSP4 and ARCESSP7) are depicted with blue and cyan lines respectively in Fig. 4.3, at the end of the chapter. A shaded rectangle represents the frequency range beyond the Nyquist frequency of 20 Hz.

4.2.4 CMG-3T – HRD24 (1999/09/14 - …)

Respid:	ARCESBB1(a),4	Z
	ARCESBB2(a),5	N-S
	ARCESBB3(a),6	E-W

Current ARCES broadband channel configuration consists of the following components:
- CMG-3T seismometer
- Nanometrics HRD24 digitizer

4.2.4.1 *CMG-3T*

Since September 1999 the broadband channel of ARCES has been equipped with a Güralp CMG-3T sensor. Until today, the instrument has been exchanged due to malfunction several times. Unfortunately, no detailed tracking of the sensor serial numbers was taking place during the exchanges, but the following can be mentioned:

Response information are derived by the instrument specific Calibration Sheets provided by the manufacturer together with the instrument. These documents contain channel sensitivity and pole-and-zero values (see also §2.2.11.1) as an expression of the instrument response. Although initial values are different than the ones contained in the Calibration Sheets for the same instruments today, this poses no problems regarding the response, since Güralp Systems modified the way they are expressing the response of their sensors, but not the response itself. The modification was deemed necessary due to the fact that original response information contained negative normalization factors that could not be handled by several software packages, including those of the IDC.

Initial sensitivity and poles-and-zeros information are the following, *e.g.*, for # T3890:

Velocity response output, Vertical Sensor:

POLES (HZ)	**ZEROS HZ**
$-7.07 \times 10^{-3} \pm j7.07 \times 10^{-3}$	0
$-80.5 \pm j\,30.8$	0
	150.5

Normalizing factor at 1 Hz: A = -49.5

Sensor Sensitivity: 2 x 2490 V/m/s

Velocity response output, Horizontal Sensors:

POLES (HZ)	**ZEROS (HZ)**
$-7.07 \times 10^{-3} \pm j7.07 \times 10^{-3}$	0
$-80.5 \pm j\,30.8$	0
	150.5

Normalizing factor at 1 Hz: A = -49.5

Sensor Sensitivity:	2 x 2513 V/m/s	N-S
	2 x 2521 V/m/s	E-W

Current information for # T3890 is the following:

Velocity response output, Vertical Sensor:

POLES (HZ)	**ZEROS HZ**
$-7.07 \times 10^{-3} \pm j7.07 \times 10^{-3}$	0
-180	0
-160	
-80	

Normalizing factor at 1 Hz: A = 2304000

Sensor Sensitivity: 2 x 2486 V/m/s

Velocity response output, Horizontal Sensors:

POLES (HZ)	**ZEROS (HZ)**
$-7.07 \times 10^{-3} \pm j7.07 \times 10^{-3}$	0
-180	0
-160	
-80	

Normalizing factor at 1 Hz: A = 2304000

Sensor Sensitivity:	2 x 2507 V/m/s	N-S
	2 x 2508 V/m/s	E-W

The factor of 2 in the sensitivity estimate is used because of sensor outputs being used differentially.

Regarding poles and zeros, values are listed in units of Hz. They need to be multiplied with 2π to be converted to rad/s. The same change applies to the normalizing factor.
Total sensor sensitivity will then be equal to: G = (sensitivity) x (norm. factor)

Although the exact history of seismometer exchanges is not documented, the following can be said and is followed in the calculation of ARCES responses. The instrument originally installed at ARCES was # T3781, which had exactly the same poles/zeros with # T3890 and velocity output sensitivity values:

Z 2 x 2503.8 N-S 2 x 2493.9 E-W 2 x 2532.2

This instrument was exchanged due to malfunction with # T3890 on 19.05.2005 and back on 12.01.2006. An a is appended to the *Respids* to denote the instrument exchanges, since the overall sensitivity of the channels changes. The final exchange between them was made on

28.07.2006, with # T3890 operating still at ARCES. Although, as already mentioned, the instrument response has not changed, the *Respids* ARCESBB4, ARCESBB5 and ARCESBB6 are given to the vertical, N-S and E-W component of the current configuration, to denote the usage of the latest pole-zero set for sensor # T3890.

4.2.4.2 *HRD24*

The response of this unit is described in detail in section 4.2.3.2.

The displacement amplitude (in count/nm) and phase (in deg) response of the current ARCES broadband configuration (ARCESBB1) is depicted in Fig. 4.3, at the end of the chapter, with the red line.

4.2.5 CMG-3T – REF TEK 130-01 (2003/10/02 – 2004/07/01)
Respid: ARCESHH1,2,3 Z, N-S, E-W

A high-frequency variation of the ARCES broadband channel configuration, which operated for a few months in 2003/2004, consists of the following components:

- CMG-3T seismometer
- REF TEK 130-01 digitizer

4.2.5.1 *CMG-3T*

The response of this instrument is described in detail in section 4.2.4.1.

4.2.5.2 *130-01*

The REF TEK 130-01 DAS is a 24-bit output word A/D converter that employs the Crystal Semiconductors CS5372/CS5322 chipset. The chipset outputs a limited digital count range of +/- 6291456 counts for the specific analog full scale input range, which in this case is +/- 10 V. Taking this into consideration, bit weight is equal to: V_{fs} / 6291456 = 1.58945 μV /count, where V_{fs} the full scale input voltage. It should be noted that this is a nominal value and slight variations may occur for each different instrument, as well as that these data are accurate only if the channel is set for unity gain (which is the case for ARCES).

The A/D output sample rate is a combination of the frequency of the A/D input clock (MCLK), the A/D power mode and the selection of an A/D decimation rate (A/D entry). The CS5372 converts the samples at a rate (SCLK) of either ½ or ¼ of the MCLK, depending on the power mode. Then, it outputs the data to the CS5322 chip, which filters and decimates to the desired recording sample rate. Some sample rates however can only be achieved by additional filtering, employing CPU firmware. The firmware filters are the 'hard' or 'sharp' filters used in the REF TEK 72A-02/08 DAS. In the case of the ARCES high-frequency (HH) channel, the data recording rate is 100 sps. This can be achieved by the following succession (REF TEK, 2008): YGHHHHHI3, where:

- Y represents an SCLK of 102.4 kHz,
- G is CS5322 FIR filter A with 34 coefficients, decimating by a factor of 8
- H is CS5322 FIR filter B with 14 coefficients, decimating by a factor of 2
- I is CS5322 FIR filter C with 102 coefficients, decimating by a factor of 2 down to 200 Hz, and
- 3 represents CPU firmware filter F2-95.DAT with 95 coefficients, decimating by a factor of 2 to the desired rate of 100 Hz.

The firmware filter coefficients are listed in REF TEK (2008), while the coefficients of the CS5322 filters can become available upon request at REF TEK and can now be found in the corresponding GSE response file.

The sensitivity of the digitizer is equal to 62914560 count/V.

The displacement amplitude (in count/nm) and phase (in deg) response curves for this configuration (ARCESHH1) are depicted with the darker green line in Fig. 4.3, at the end of this chapter.

4.2.6 CMG-3T – DM24 (2008/03/13 – 2012/07/30)

Respid:	ARCESEH1	Z
	ARCESEH2	N-S
	ARCESEH3	E-W

Another variation of the high-frequency channels of the ARCES broadband channel configuration consists of the following components:

- CMG-3T seismometer
- CMG-DM24 digitizer

4.2.6.1 *CMG-3T*

The response of this instrument is described in detail in section 4.2.4.1. The instrument installed at this configuration of ARE0 has serial number # T3890.

4.2.6.2 *CMG-DM24*

The Güralp CMG-DM24 A/D converter is a 24-bit digitizer. It employs the Crystal Semiconductor CS5376 chipset and the TMS320VC33 digital signal processor (DSP) to achieve the desired output rate. The DSP software consists of 6 cascaded programmable filter/decimation stages that allow the selection of multiple data output rates simultaneously (Güralp Systems, 2006). In the case of the current ARCES high-frequency version of the broadband channel, the data recording sample rate is set to 100 sps. This is obtained by the following digital filter cascade:

- CS5376 FIR filter Stage 1, Sinc 1, with 36 coefficients, decimating by 8 from an input rate of 512 kHz
- CS5376 FIR filter Stage 3, Sinc 2, with 6 coefficients, decimating by 2
- CS5376 FIR filter Stage 4, Sinc 2, with 8 coefficients, decimating by 2
- CS5376 FIR filter Stage 5, FIR 1, with 48 coefficients, decimating by 4
- CS5376 FIR filter Stage 5, FIR 2, with 126 coefficients, decimating by 2
- DM24 FIR Stage 1, SWA-D24-3D08, with 502 coefficients, decimating by 5, and
- DM24 FIR Stage 2, SWA-D24-3D07, with 502 coefficients, decimating by 4 down to 100 sps.

The sensitivity of the digitizer for each channel can be found in the instrument specific Calibration Sheet provided by the manufacturer. The digitizer installed at ARCES has serial number # A290 and the following sensitivity values:

VELOCITY CHANNELS

Channel:	A290Z2	Vertical	3.180 μV/Count
	A290N2	North/South	3.192 μV/Count
	A290E2	East/West	3.172 μV/Count

The displacement amplitude and phase response for this configuration (ARCESEH1) is depicted with light green lines in Fig. 4.3, at the end of this chapter.

4.2.7 CMG-3T – DM24 (2012/07/30 - …)

Respid: ARCESBH1 Z
ARCESBH2 N-S
ARCESBH3 E-W

Since July 2012, ARE0 outputs 40 sps data streams, without changing the instrumentation, which consists of the following components:

- CMG-3T seismometer
- CMG-DM24 digitizer

4.2.7.1 *CMG-3T*

The response of this instrument is identical to that described in § 4.2.6.1.

4.2.7.2 *CMG-DM24*

The response of this unit (# A290) was described in § 4.2.6.2. However, a different digital filter cascade is used to output 40 sps:

- CS5376 FIR filter Stage 1, Sinc 1, with 36 coefficients, decimating by 8 from an input rate of 512 kHz
- CS5376 FIR filter Stage 3, Sinc 2, with 6 coefficients, decimating by 2
- CS5376 FIR filter Stage 4, Sinc 2, with 8 coefficients, decimating by 2
- CS5376 FIR filter Stage 5, FIR 1, with 48 coefficients, decimating by 4
- CS5376 FIR filter Stage 5, FIR 2, with 126 coefficients, decimating by 2
- DM24 FIR Stage 1, SWA-D24-3D08, with 502 coefficients, decimating by 5
- DM24 FIR Stage 2, SWA-D24-3D08, with 502 coefficients, decimating by 5, and
- DM24 FIR Stage 3, SWA-D24-3D06, with 502 coefficients, decimating by 2 down to 40 sps.

The displacement amplitude and phase response for this configuration (ARCESBH1) is depicted with yellow lines in Fig. 4.3, where the corresponding curves for the responses discussed in sections 4.2.3, 4.2.4, 4.2.5 and 4.2.6 of this chapter are also plotted. The shaded areas represent the frequency range beyond the Nyquist frequency, which is 20 Hz for the short-period and broadband channels and 50 Hz for the high-frequency variations of the broadband channel (ARE0).

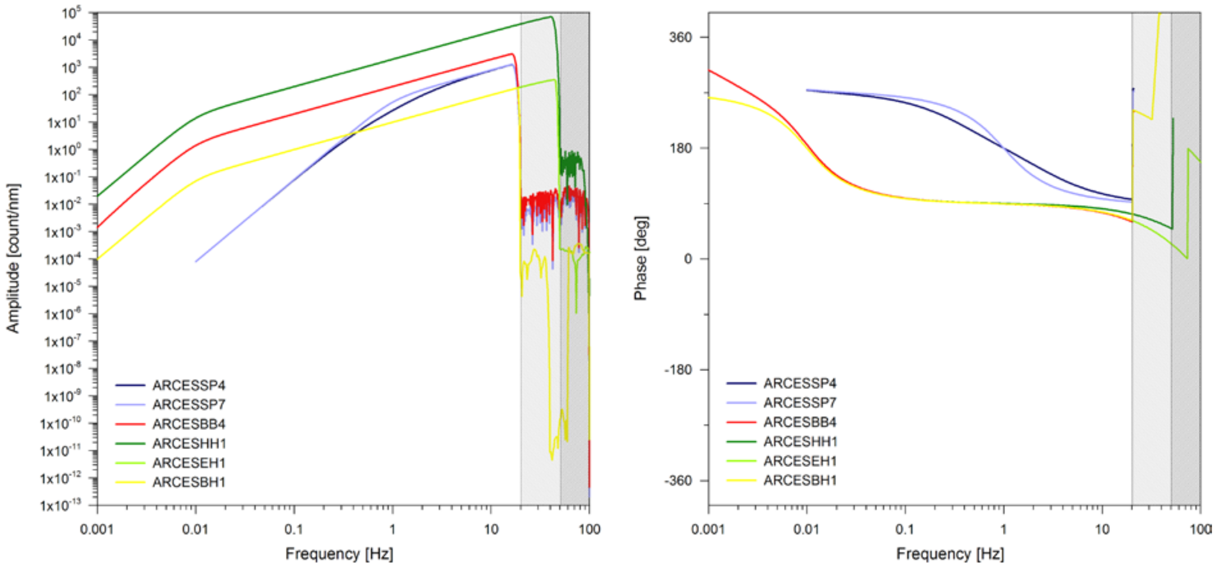


Fig. 4.3. Displacement amplitude and phase response for the damped (ARCESSP4) and current short-period (ARCESSP7) configurations, the broadband (ARCESBB1) configuration, as well as the two high-frequency variations (ARCESHH1 & ARCESEH1) of the ARCES broadband channel, plus the current 40 sps channels at ARE0 (ARCESBH1). Shaded areas represent range beyond the Nyquist frequency (20 Hz for ARCESSP1, ARCESSP7 and ARCESBH1, and 50 Hz for ARCESHH1 and ARCESEH1).

4.3 References

Fyen, J., 2000. NDC Activities. *NORSAR Semiann. Techn. Summ. 1-2000/2001*, Kjeller, Norway, p. 36-38.

Fyen, J., 2002. NDC Activities. *NORSAR Semiann. Techn. Summ. 1-2002*, Kjeller, Norway, p. 36-37.

Fyen, J., 2003. NDC Activities. *NORSAR Semiann. Techn. Summ. 1-2003*, Kjeller, Norway, p. 17-18.

Güralp Systems, 2006. CMG-DM24 Operator's Guide. *MAN-D24-0004*, Güralp Systems Ltd., Aldermaston, England, 113 pp.

Mykkeltveit, S., Ringdal, F., Fyen, J. and Kværna, T., 1987. Initial results from analysis of data recorded at the new regional array in Finnmark, Norway. *NORSAR Semiann. Techn. Summ. 1-87/88*, Kjeller, Norway, p. 61-82.

Nanometrics, 1999. *Custom configuration guide*. Nanometrics, Inc., Kanata, Ontario, Canada, 26 pp.

REF TEK, 2008. 130 Theory of Operations. *Doc-130-Theory-J*, Refraction Technology, Inc., Plano, Texas, 106 pp.

Torstveit, J., Hansen, O.A. and Mykkeltveit, S., 1988. Recording of ARCESS data at Kjeller. *NORSAR Semiann. Techn. Summ. 2-87/88*, Kjeller, Norway, p. 18-21.

CHAPTER 5: SPITS

5.1 Development of SPITS systems: instrumentation and responses

5.1.1 Short description

- 1992-1994:

The SPITS regional array was installed during fall 1992 on the plateau of the Janssonhaugen hill in the area of the Adventdalen valley, approximately 15 km ESE of the town of Longyearbyen, Spitsbergen. The Spitsbergen array consists of 9 sites distributed on two concentric rings, with one element in the centre. The whole deployment, which is shown in Fig. 5.1, has a diameter of 1 km. Initial SPITS instrumentation consists of Geotech S-500 short-period, vertical seismometers and Nanometrics RD-6 digitizers (Mykkeltveit et al., 1992, Fyen, 1995). The sensors were installed in 6 m boreholes inside the permafrost (Mykkeltveit et al., 1991).

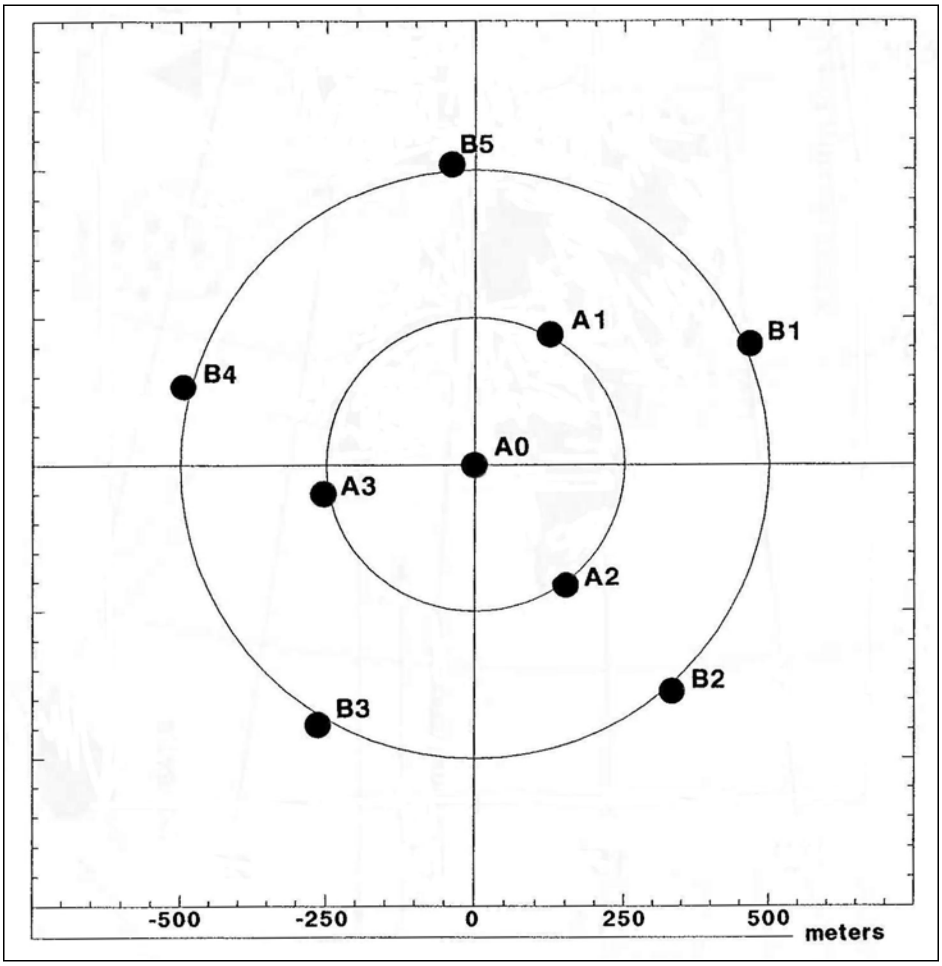


Fig. 5.1. Geometry of the Spitsbergen array.

- 1994-2004:

In August 1994, all S-500 seismometers were replaced with Güralp CMG-3ESP sensors, while the digitizers remained the same. In addition, a broadband 3-component CMG-3T seismometer was installed at site SPB4. The configurations were initially operating with a gain of 1x and no analog 0.5 Hz high-pass filter for the RD6. 2 RD6 digitizers were supporting a total of 12 channels. The same sensors were reinstalled on 18th October 1994, this time with a gain of 10x and the analog high-pass 0.5 Hz filter. The broadband channel was changed to gain 5x, still without the 0.5 Hz filter. The CMG-3T sensor was replaced due to malfunction in May 1995 and was finally removed in March 2001, due to digitizer problems. The channel was moved to short-period, continuing to operate with half-gain (5x) and no 0.5 Hz analog filter.

- 2004-2014:
Extensive refurbishment of the Spitsbergen array took place in August 2004. Since 13th August 2004, all array sites are equipped with Güralp CMG-3TB broadband seismometers, 6 of them with 3-component versions (SPA0, SPB1, SPB2, SPB3, SPB4 and SPB5), and CMG-DM24 digitizers after testing several different sensors (short-period and broadband) to decide on the optimum choice for SPITS. The sensors' response is flat to acceleration. The orientation of the horizontal components was corrected on 8th September 2004 and the polarity of the stations on 29th November of the same year (Fyen, 2003, 2005). SPITS is certified as auxiliary station AS72 of the IMS.

- 2014-…:
In summer 2013 new digitizers for the SPITS array were delivered by Güralp Systems, Ltd. The units match the digitizers installed during the last refurbishment of the NORSAR array (see § 2.1.1) and are three-channel EAM acquisition modules with authentication, equipped with CMG-DM24 digitizers (CMG-DM24S3EAMS (SS)). They are employed with a gain of 2x. The sensors remain the same. The new equipment will be installed at SPITS in 2014. Data channel names will be changed to HHZ/N/E.

5.1.2 Instrumentation

I. Configurations

- Original SP configuration (1992-1994):
  S-500 seismometer
  Nanometrics RD-6 digitizer

- Initial SP configuration with Güralp sensors (~1.5 months in 1994):
  CMG-3ESP seismometer
  Nanometrics RD-6 digitizer

- SP configuration with Güralp sensors (1994-2004):
  CMG-3ESP seismometer with a gain of 10x
  Nanometrics RD-6 digitizer

- SP configuration (special case, SPB4 only) with Güralp sensors (~9 months in 2001):
  CMG-3ESP seismometer with a gain of 5x
  Nanometrics RD-6 digitizer, without the 0.5 Hz filter

- Initial BB configuration, site SPB4 (~1.5 months in 1994):
  CMG-3T seismometer
  Nanometrics RD-6 digitizer

- BB configuration, site SPB4 with 5x gain (1994-2001):
  CMG-3T seismometer
  Nanometrics RD-6 digitizer

- BB configuration (2004-2014):
  CMG-3TB sensor
  CMG-DM24 digitizer

- HH configuration (2014-…):
  CMG-3TB sensor
  CMG-DM24S3EAMS

II. Respids

SPITSSP1
SPITSSP2
SPITSSP3
SPITSSP4
SPITSBB1,2,3
SPITSBB4,5,6
SPITSBB7,8,9
SPITSHH1,2,3

III. Instrument specifications

S-500:
See §2.1.3 for details.

CMG-3ESP:
Vertical, short-period Güralp seismometer. The specifications of the model installed at SPITS (serial numbers V3135-V3144, work order 0356) are the following:

Velocity output	2x5000 V/m/s (differential)	
Poles (Hz)	$-70.7 \times 10^{-3} \pm j70.7 \times 10^{-3}$ (in Hz)	
		$-43.2 \pm j30.8$
		-150
		-190
Zeros (Hz)	0.0	0.0
Normalizing factor	95480000 @ 1 Hz	

CMG-3TB:
This is a borehole version of the 3-component, broadband Güralp CMG-3T sensor. See §2.3.2 for details. The response of this sensor is flat to acceleration with a sensitivity value of 2x938 V/m/s^2.

Nanometrics RD-6:
See §2.1.3 for details. The version installed at the Spitsbergen array employs the following filter sequence:

Analog low-pass filter (F2): 5th-order Butterworth	$\omega_{3db} = 2\ \pi\ 22.9$
	Q_1=1.61803, Q_2=0.618034
Analog high-pass filter (F3): optional	1st order, f_{3db} = 0.5 Hz
Digital FIR filter (F4): low-pass	f_{3db} = 16 Hz, N = 68
Digital IIR filter (F5): high-pass	f_{3db} = 0.001 Hz
Sensitivity	610 nV/count

F1 in the filter sequence above is the seismometer. It should be noted that the above sequence is valid for the S-500 and CMG-3ESP seismometers, but that in the case of the CMG-3T sensor no highpass RC filter is used and the sensitivity is 1220 nV/count.

Güralp DM24:
Full 24-bit digitizer employing the Cirrus Logic CS5376 digital filtering chipset and TMS320VC33 digital signal processor (DSP). The DSP software consists of 6 cascaded programmable filter/decimation stages that allow the selection of multiple data output rates simultaneously (Güralp Systems, 2006). The specifications of this instrument are the following:

Input voltage range	+/- 10 V differential
Dynamic range	137 dB @ 40 sps
DSP sampling rate	32 kHz
Sensitivity	1.7 µV/count

CMG-DM24S3EAMS:
The Güralp Systems Enhanced Acquisition Module (EAM) is a data recording, communications and control module, used here in combination with a CMG-DM24 digitizer. The exact model employed at the SPITS array, the CMG-DM24S3EAMS (SS), in stainless steel, supports three channels and authentication for CTBTO purposes. See § 2.1.2 for further details and nominal values.

5.2 Instrument response calculation for SPITS systems

This chapter focuses on the major considerations to be taken into account for the calculation of the instrument response of the different systems operating at the Spitsbergen regional array.

As with the NORSAR, NORES and ARCES arrays, GSE file response *Respid* flags for each configuration are provided at the beginning of each section.

5.2.1 S-500 – RD6 (1992/11/06 – 1994/08/30)
Respid: SPITSSP1 Z

Standard SPITS short-period channel configuration consists of the following components:

- S-500 short-period, vertical seismometers
- Nanometrics RD6 digitizers

5.2.1.1 *S-500*

The response of the Geotech S-500 seismometer is described in detail in section 2.2.8.1. Poles and zeros, as well as the gain value can be taken from there.

However, in the case of the Spitsbergen array, the S-500 seismometers are used with a preamplifier with a gain of 200.

5.2.1.2 *RD6*

The response of the Nanometrics RD6 digitizer is described in detail in section 2.2.3.4.

At Spitsbergen however, the RD6 model 1625 operate with additional filters than what was installed at the NORSAR array. Thus, the filter cascade is the following:

- Analog 5th-order Butterworth low-pass filter at 22.9 Hz
- Analog 1st order RC high-pass filter at 0.5 Hz
- Digital low-pass FIR filter at 16 Hz with 68 coefficients
- Digital high-pass IIR filter at 0.008 Hz

The equations for the filters common to the NORSAR RD6 configuration can be found in section 3.1.3.4. Regarding the 1st order high-pass RC filter, it has one real pole:
$2\,\pi\, 0.5 = 3.14159265$
and one zero: 0.0

The IIR filter, which has only one pole, is described by the following formula in the Z domain (Nanometrics, 1991):

$$u(z) = \frac{a(1 - z^{-1})}{1 + bz^{-1}}, \qquad (5.2.1)$$

where *a* and *b* the filter coefficients. In the case of the Spitsbergen array, where the required sampling rate is 40 sps, the characteristics of the IIR filter are the following:

f_{3db} = 0.008 Hz
a = -0.998749
b = 1.0
gain = 0.999374

The sensitivity is equal to 610 nV/count and the output sample rate is set to 40 sps.

The displacement amplitude and phase response of this instrumentation (SPITSSP1) is depicted, noted in green, in Fig. 5.3 at the end of this chapter.

5.2.2 CMG-3ESP – RD6 (1994/08/01 – 2004/08/13)

Respid: SPITSSP2 Z (gain 1x)

SPITSSP3 Z (gain 10x)

SPITSSP4 Z (half-gain, 5x)

In August 1994, the S-500 seismometers were replaced with Güralp CMG-3ESP vertical seismometers. The same instruments were reinstalled on 18th October 1994 with a gain of 10x. Further changes in this configuration are the removal/utilization of the digitizer analog high-pass 0.5 Hz filter (see §5.2.2.2 for details). Regardless of the employed gain and filters, the system consists of the following components:

- CMG-3ESP short-period seismometer
- Nanometrics RD6 digitizer

5.2.2.1 *CMG-3ESP*

Instrument response information for ground velocity is provided by the manufacturer (Güralp Instruments, Ltd.) in the form of poles and zeros, while sensitivity values are provided on a calibration sheet shipped together with the equipment.

Poles and zeros for the shipment with serial numbers V3135 – V3144 (work order 0356) are listed in the following table:

POLES (HZ)	**ZEROS HZ**
$-70.7 \times 10^{-3} \pm j70.7 \times 10^{-3}$	0
$-43.2 \pm j38.6$	0
-150	
-190	

Normalizing factor at 1 Hz: A = 95480000

Instrument sensitivity is equal to 2x5000 V/m/s.

The factor of 2 in the sensitivity estimate is used because of sensor outputs being used differentially.

Regarding poles and zeros, values are listed in units of Hz. They need to be multiplied with 2π to be converted to rad/s. The same change applies for the normalizing factor.
Total sensor sensitivity will then be equal to: G = (sensitivity) x (norm. factor)

5.2.2.2 *RD6*

Information about the RD6 digitizer can be found in section 5.2.1.2 of the current chapter and section 2.2.3.4 on the NORSAR array. As mentioned earlier, a difference between the responses corresponding to this configuration is the utilization or not of the digitizer analog high-pass 0.5 Hz filter. A summarization of one this was employed and not is as follows, sorted by corresponding *Respid*:

- SPITSSP2:	gain 1 x	no 0.5 Hz filter
- SPITSSP3:	gain 10 x	0.5 Hz filter
- SPITSSP4:	gain 5 x (half-gain)	no 0.5 Hz filter

The displacement amplitude and phase responses for the above mentioned configurations (SPITSSP2, SPITSSP3, SPITSSP4) are plotted in Fig. 5.3 at the end of the chapter, in orange, red and yellow respectively.

5.2.3 CMG-3TB – RD6 (1994/10/18 – 2001/03/28)
Respid: SPITSBB1,2,3 Z, N-S, E-W
SPITSBB4,5,6 Z, N-S, E-W

A 3-component broadband Güralp seismometer, model CMG-3TB was installed additionally to the short-period vertical instrument at the Spitsbergen array site SPB4 on 18th October 1994. The CMG-3TB was removed from the site on 28th March 2001. The configuration of this channel is equipped with the following components:

- CMG-3TB broadband seismometer
- Nanometrics RD6 digitizer

5.2.3.1 *CMG-3TB*

The instrument installed at the Spitsbergen array has a serial number of T321. The poles and zeros describing the velocity response of this instrument are provided by the manufacturer and are the following:

POLES (HZ)	**ZEROS (HZ)**
$-7.07 \times 10^{-3} \pm j7.07 \times 10^{-3}$	0
$-80.5 \pm j30.8$	0
-150	150.5

Normalizing factor at 1 Hz: A = -49.5

The sensitivity is equal to: 2x5000 V/m/s.

The factor of 2 in the sensitivity estimate is used because of sensor outputs being used differentially.

Regarding poles and zeros, values are listed in units of Hz. They need to be multiplied with 2π to be converted to rad/s. The same change applies for the normalizing factor.
Total sensor sensitivity will then be equal to: G = (sensitivity) x (norm. factor)

5.2.3.2 *RD6*

Information about the RD6 digitizer can be found in section 5.2.1.2 of the current chapter and section 2.2.3.4 on the NORSAR array. Here it was used without the analog high-pass 0.5 Hz filter and the channel operated initially with a gain of 1x and after 18th October 1994 with a gain of 5x.

The displacement amplitude and phase responses for these broadband channels (SPITSBB1 and SPITSBB4) are depicted in Fig. 5.3 at the end of the chapter, noted in cyan and blue respectively.

5.2.4 CMG-3TB – DM24 (2004/08/13 – 2014)

Respid:	SPITSBB7	Z
	SPITSBB8	N-S
	SPITSBB9	E-W

Upgraded SPITS broadband channel configuration consists of the following components:

- CMG-3TB seismometers
- CMG-DM24 digitizers

5.2.4.1 *CMG-3TB*

Since August 2004, the 3-component broadband channels of SPITS have been equipped with Güralp CMG-3TB sensors, with a response flat to acceleration. Three of the array sites (SPA1, SPA2 and SPA3) are still equipped only with vertical component.

Response information are derived by the instrument specific Calibration Sheets provided by the manufacturer together with the instruments. These documents contain channel sensitivity and pole-and-zero values as an expression of the instrument response.

Sensitivity and poles-and-zeros information are the following, *e.g.*, for # T3H76 at site SPA0:

Acceleration response output, Vertical Sensor:

POLES (HZ)	**ZEROS (HZ)**
-7.07 x 10-3 ± j 7.07 x 10-3	0
-30.0529 ± j 31.1211	0
-41.2564 ± j 114.535	

Normalizing factor at 1 Hz: A = 27.7 x 106

Sensor Sensitivity: 2 x 937.4 V/m/s^2

Acceleration response output, Horizontal Sensors:

POLES (HZ)	**ZEROS (HZ)**
-7.07 x 10-3 ± j 7.07 x 10-3	0
-30.0529 ± j 31.1211	0
-41.2564 ± j 114.535	

Normalizing factor at 1 Hz: A = 27.7 x 106

Sensor Sensitivity:	2 x 1057.9 V/m/s^2	N-S
	2 x 1000.4 V/m/s^2	E-W

The factor of 2 in the sensitivity estimate is used because of sensor outputs being used differentially.

Regarding poles and zeros, values are listed in units of Hz. They need to be multiplied with 2π to be converted to rad/s. The same change applies for the normalizing factor.

Total sensor sensitivity will then be equal to: G = (sensitivity) x (norm. factor)

5.2.4.2 *CMG-DM24*

The digitizers are the Güralp CMG-DM24 mk3 instruments. Officially, the DM24 mk3 version did not start being distributed before 2005, however from the digital filters employed in the instruments received from Güralp Systems, it becomes clear that this is the version installed at the Spitsbergen array. Moreover, the digitizers belonged to a special works order arranged for NORSAR and thereby their serial numbers are not included in the Güralp automatic calibration information retrieval system.

The DM24 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 cascade of filters employed by the CS5376 chipset is depicted in Fig. 5.2. Stages that are used in the Güralp DM24 configuration discussed here are noted with red colour.

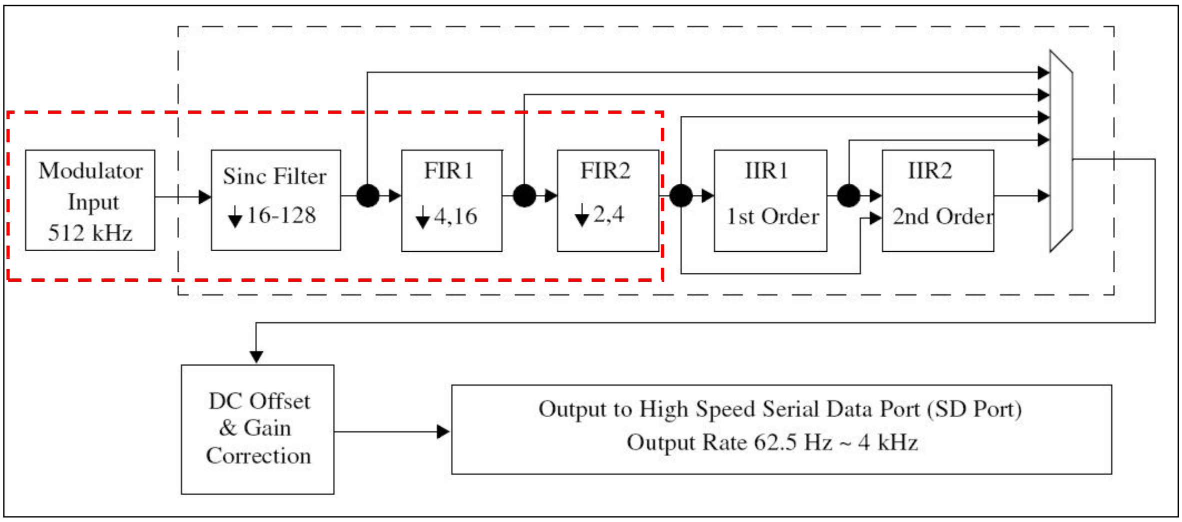


Fig. 5.2. CS5376 digital filter stages (Cirrus Logic, 2001). Downwards pointing arrows represent the selectable decimation factors, while the dashed red frame includes the components employed in the DM24 digitizer.

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 501 coefficients
- FIR filter DM24-dec5, decimating by 5, with 501 coefficients

All filter coefficients are provided in the mentioned documentation and can also be found in the corresponding GSE response files.

The sensitivity of the digitizers is equal to 1.7 μV/count (Fyen, 2005).

A table with sensor and digitizer serial numbers per site, as well as instrument specific sensitivity values is provided in Appendix IV.

The displacement amplitude (in count/nm) and phase (in degrees) response of this configuration (SPITSBB7,8,9) is depicted in magenta in Fig. 5.3, at the end of this chapter, together with the rest of the instrumentations described in this chapter. In the case of 3-component configurations, the vertical channel has been selected as a representative example, while shaded areas denote the range beyond the Nyquist frequency.

Finally, it should be noted that because of the fact that a _COO file for SPITS existed only for the old configurations, the values in the field *Chanid* of the *GSE* response files had to be filled up with 'invented' numbers for the new configuration. Thus, the _COO file *Chanid* entries are used and additionally to them entries between 4 and 21 are assigned to the current channels, in a way that no conflict occurs (see also Chapter 1 regarding GSE response files and introducing response information to the NORSAR database system).

5.2.5 CMG-3TB – EAM24 (2014 - …)

Respid: SPITSHH1 Z
SPITSHH2 N-S
SPITSHH3 E-W

The eventual, new SPITS broadband channel configuration will consist of the following components:

- CMG-3TB seismometers
- CMG-DM24S3EAMS data acquisition unit

Data channels will be renamed to HHZ, HHN and HHE and have a sampling rate of 80 sps.

5.2.5.1 *CMG-3TB*

See § 5.2.4.1 for a detailed description.

5.2.5.2 *CMG-DM24S3EAMS*

The digitizers to be employed at the Spitsbergen array are the Güralp CMG-DM24S3EAMS (SS), consisting of a three-channel CMG-EAM acquisition module with authentication and a CMG-DM24 digitizer, in stainless steel. Details can be found in § 2.2.12.2 on the NORSAR array and § 5.2.4.2 earlier in this chapter.

The digitizers will be employed with a gain setting of 2x. To achieve the desired sampling rate of 80 sps, the selected filter cascade corresponds to a TTL value of 79 and is as follows (Cirrus Logic, 2001; Güralp Systems, 2006):

- FIR filter CS5376 Stage 1, Sinc 1 (symmetric), 18 coefficients, decimating by 8 from the 512 kHz input clock
- FIR filter CS5376 Stage 3, Sinc 2 (symmetric), 3 coefficients, decimating by 2
- FIR filter CS5376 Stage 4, Sinc 2 (symmetric), 7 coefficients, decimating by 2
- FIR filter CS5376 Stage 5, FIR1 (symmetric), 24 coefficients, decimating by 4
- FIR filter CS5376 Stage 5, FIR2 (symmetric), 63 coefficients, decimating by 2
- FIR filter DM24 Stage 1, SWA-D24-3D08 (symmetric), 501 coefficients, decimating by 5 from 2 kHz
- FIR filter DM24 Stage 2, SWA-D24-3D08 (symmetric), 501 coefficients, decimating by 5, from 400 Hz

The displacement amplitude (in count/nm) and phase (in degrees) response of this configuration (SPITSHH1,2,3) is depicted in magenta in Fig. 5.3 together with the rest of the instrumentations described in this chapter. In the case of 3-component configurations, the vertical channel has been selected as a representative example, while shaded areas denote the range beyond the Nyquist frequency.

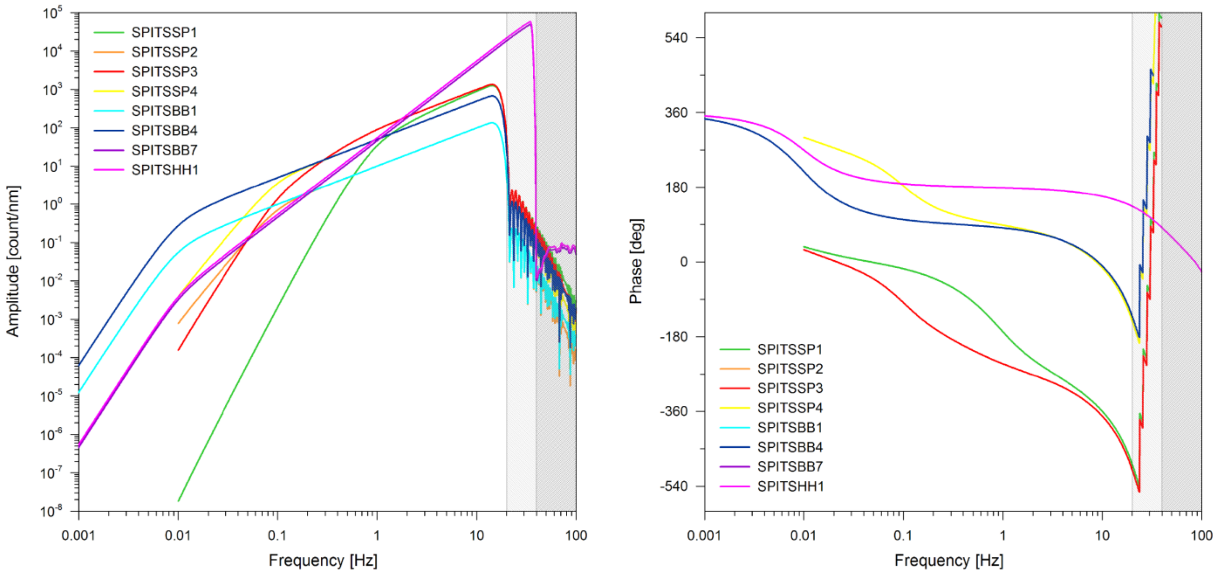


Fig. 5.3. Displacement amplitude and phase response for the short-period (SPITSSP1, SPITSSP2, SPITSSP3, SPITSSP4) and broadband (SPITSBB1, SPITSBB4, SPITSBB7, SPITSHH1) configurations of the SPITS array. Only vertical component cases are displayed. The shaded areas represent the range beyond the Nyquist frequency (40 Hz for the current broadband configuration SPITSHH1 and SPITSBB7, and 20 Hz for all the rest).

5.3 References

Cirrus Logic, 2001. Crystal CS5376 Low Power Multi-Channel Decimation Filter. *DS256PP1*, Cirrus Logic, Inc., Austin, Texas, 122 pp.

Fyen, J., 1995. System response for the Spitsbergen array. *NORSAR Semiann. Techn. Summ. 2-94/95*, Kjeller, Norway, p. 69-74.

Fyen, J., 2003. System responses. *NORSAR Techn. Report*, Kjeller, Norway, 26 pp.

Fyen, J., 2005. Spitsbergen array refurbishment. *NORSAR Semiann. Techn. Summ. 1-2005*, Kjeller, Norway, p. 24-33.

Güralp Systems, 2006. CMG-DM24 mk3 Operator's Guide. *MAN-D24-0004*, Güralp Systems Ltd., Aldermaston, England, 113 pp.

Mykkeltveit, S., Dahle, A., Fyen, J., Kværna, T., Larsen, P.W., Paulsen, R., Ringdal, F., and Kremenetskaya, E.O., 1991. Extensions of the Northern Europe Regional Array Network – a new three-component station at Apatity, USSR, and a planned array at Spitsbergen. *NORSAR Semiann. Techn. Summ. 1-91/92*, Kjeller, Norway, p. 100-111.

Mykkeltveit, S., Dahle, A., Fyen, J., Kværna, T., Larsen, P.W., Paulsen, R., Ringdal, F., and Kuzmin, I., 1992. Extensions of the Northern Europe Regional Array Network – New small-aperture arrays at Apatity, Russia, and on the Arctic island of Spitsbergen. *NORSAR Semiann. Techn. Summ. 1-92/93*, Kjeller, Norway, p. 58-71.

Nanometrics, 1991. *1608 System Transfer Functions*. Fax from Jennifer McKenzie to Jan Fyen, 30 October 1991, 7 pp.

CHAPTER 6: APATITY ARRAY

6.1 Development of Apatity array systems: instrumentation and responses

6.1.1 Short description

- 1992-2010:

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 (Fig. 6.1). The Apatity array consists of 9 sites distributed on two concentric rings, with one element in the centre. The whole deployment, which is shown in Fig. 6.2, has a diameter of approximately 1 km. All sites were 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 carried two horizontal components. All vertical sensors were sampled at 40 sps (short-period channels), while the three seismometers at site A0 were additionally sampled at 80 sps (high-frequent channels). Thus, the vertical sensor of site A0 was sampled both at 40 sps and 80 sps (Mykkeltveit et al., 1992). Installation work was completed on 3rd October 1992 (Hansen, 1993).

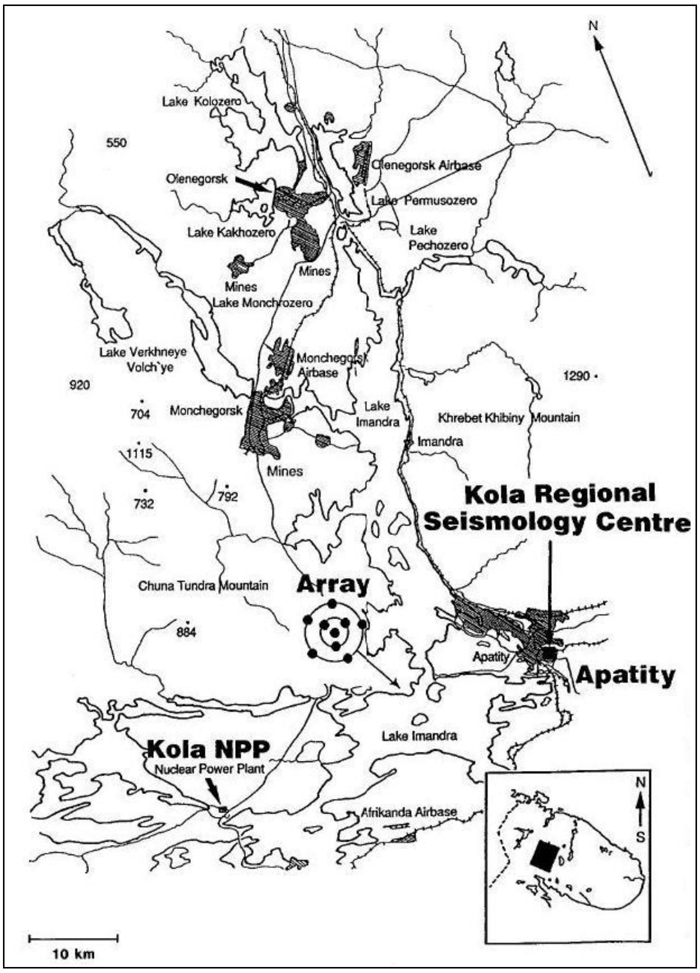


Fig. 6.1. Schematic map of the broader Apatity region, Kola Peninsula, Russia, showing the location of the Kola Regional Seismology Centre and the Apatity array (from Mykkeltveit et al., 1992).

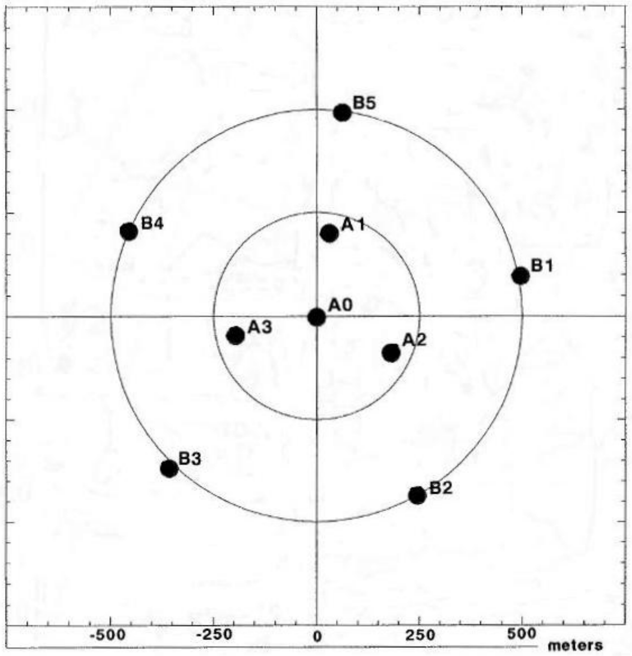


Fig. 6.2. Geometry of the Apatity array (Mykkeltveit et al., 1992).

The displacement amplitude response for the vertical typical short-period channels as presented in Mykkeltveit et al. (1992) is depicted in Fig. 6.3.

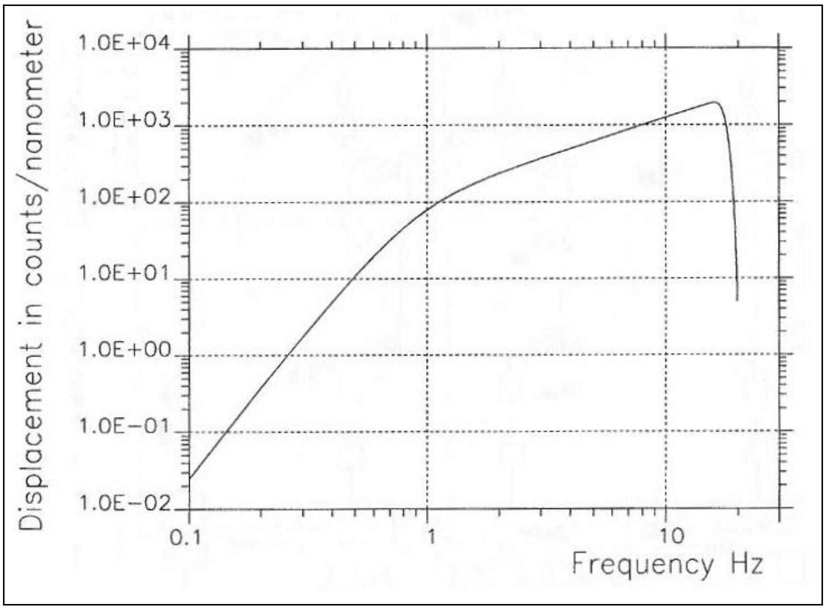


Fig. 6.3. Displacement amplitude response in count/nm for the short-period channels of the Apatity array (from Mykkeltveit et al., 1992).

The Apatity array was established within the framework of an agreement on scientific cooperation in seismology between NORSAR and the KRSC of the USSR Academy of Sciences (today, Russian Academy of Sciences). 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.

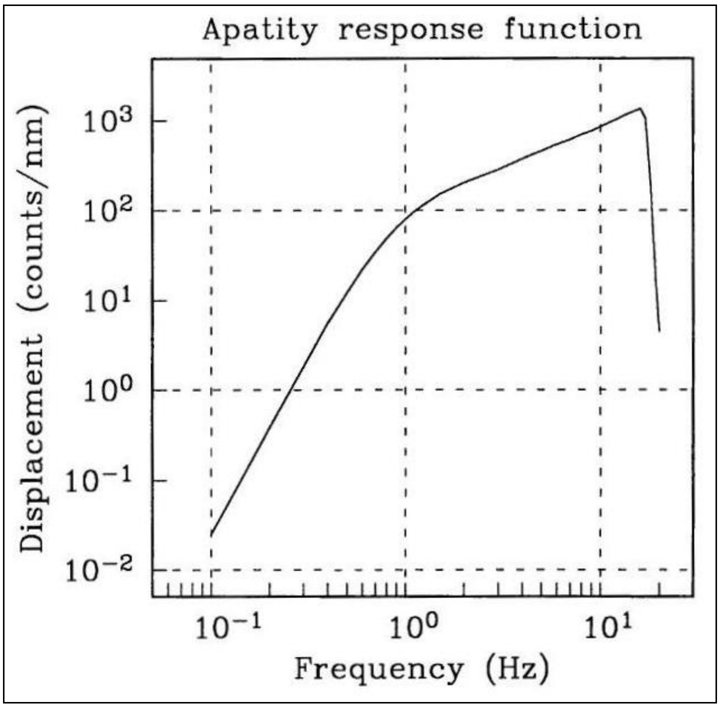


Fig. 6.4. Displacement amplitude response in count/nm for the original 3-component station installed at the KRSC building in Apatity (from Mykkeltveit et al., 1991).

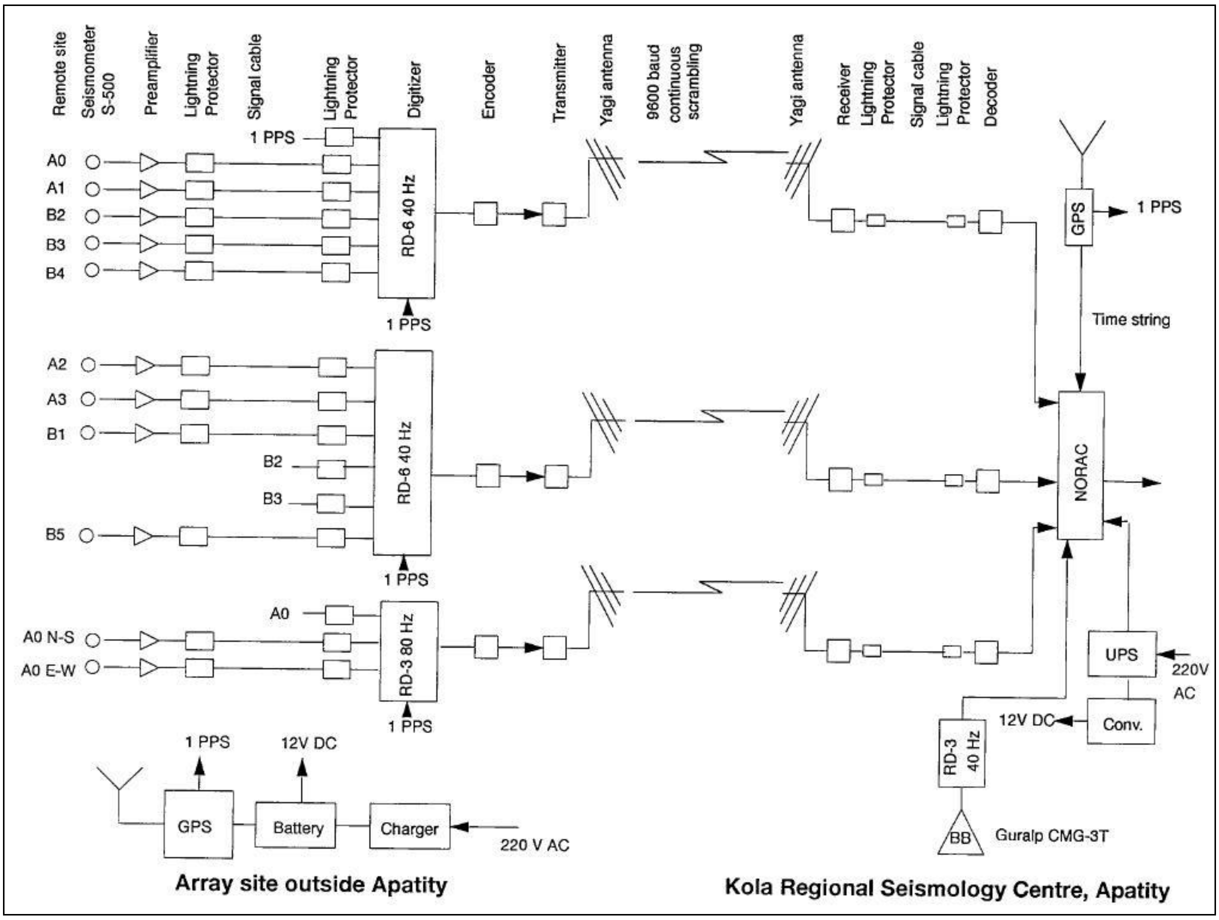


Fig. 6.5. Data flow chart for the array and broadband 3-component station in Apatity (from Mykkeltveit et al., 1992). Redundant data acquisition (channels B2 and B3) ensures that data are received even in the case of digitizer or radio channel failure.

The displacement amplitude response of this system is depicted in Fig. 6.4 (Mykkeltveit et al., 1991). However, during summer and autumn 1992, together with the design and installation of the Apatity array, the 3-component station at the KRSC was refurbished by exchanging the S-13 seismometers with a Güralp CMG-3T broadband sensor (Mykkeltveit et al., 1992). 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. 6.5 (Mykkeltveit et al., 1992).

Initial configuration data from the 3-component APZ9 station are not available and therefore its response will not be discussed further in this documentation.

- 2010-present:

A refurbishment of the Apatity array and the APZ9 station took place in spring 2010. The new instrumentation for the array involves GS-1 geophones by OYO Geospace and the Russian-made E-24 digitizers, while a CMG-3ESP seismometer and an E-24 are now installed at APZ9. Data from these configurations can be found in NORSAR's database since 1st June 2010.

6.1.2 Instrumentation

I. Configurations

- Original SP configuration (1992-2010):
    S-500 seismometer
    Nanometrics RD-6/RD-3 digitizer

- Original HF configuration (1992-2010):
    S-500 seismometer
    Nanometrics RD-6 digitizer

- Current SP configuration (2010-present):
    GS-1 geophone
    E-24 digitizer

- Current HF configuration (2010-present):
    GS-1 geophone
    E-24 digitizer

- Original 3-component BB configuration (1992-2010):
    CMG-3T seismometer
    Nanometrics RD-3 digitizer

- Original 3-component BB configuration (2010-present):
    CMG-3ESP seismometer
    E-24 digitizer

II. Respids

APASP1
APA0HH1,2,3
APZ9BB1,2,3
APASP2
APA0HH4,5,6
APZ9BB4,5,6

III. Instrument specifications

S-500:
See §2.1.3 for details.

CMG-3T:
See §3.1.2 for details.
The sensitivity of the instrument is 2 x 1000 V/m/s.

Nanometrics RD-6/RD-3:
See §2.1.3 for details. The RD-3 is the 3-channel version, while the RD-6 is the 6-channel version of this Nanometrics digitizer. Two RD-6 digitizers, model 1625 are employed in the Apatity array, supporting a total of 12 channels. The version of the digitizers installed at the Apatity array and 3-component station employs the following filter sequence:

Analog low-pass filter (F2): 5th-order Butterworth	$\omega_{3db} = 2\,\pi\,22.9$
	Q_1=1.61803, Q_2=0.618034
Analog high-pass filter (F3): optional	1st order, f_{3db} = 0.5 Hz
Digital FIR filter (F4): low-pass	f_{3db} = 16 Hz, N = 68
Digital IIR filter (F5): high-pass	f_{3db} = 0.001 Hz
Sensitivity	610 nV/count

F1 in the filter sequence above is the seismometer. It should be noted that the above sequence is valid for the S-500 seismometers, but that in the case of the CMG-3T sensor at the KRSC building basement no highpass RC and IIR filters are used and the sensitivity is 1220 nV/count.

GS-1:
Geophone by OYO Geospace. The instruments installed in Apatity are the GS1-4550 model. Some nominal values are the following:

DC resistance	4550 Ohms @ 25°C
Natural undamped frequency	1 Hz
Intrinsic sensitivity	3, 7 or 15 V/in/s
Open-circuit damping	0.54

E-24:
Data acquisition module produced by Л-КАРД, Moscow (L-card, Ltd). It employs the AD7714 microchip (24-bit delta-sigma modulator with programmable gain front end) by

Analog Devices, Inc. and can support 4 data channels. Some nominal values are the following (Analog Devices, 1998; L-card Ltd., 1998):

Resolution	24-bit
Input voltage	±2.5 V for gain 1 in bipolar mode for E-24
Input clock (AD7114)	2.4576 MHz
Selectable gain	1, 2, 4, 8, 16, 32, 64, 128

6.2 Instrument response calculation for the Apatity array systems

This chapter focuses on the major considerations to be taken into account for the calculation of the instrument response of the different systems operating at the Apatity regional array.

As with the NORSAR, NORES, ARCES arrays *etc.*, GSE file response *Respid* flags for each configuration are provided at the beginning of each section.

6.2.1 <u>S-500 – RD6</u> (1992/10/03 – 2010/06/01)
Respid: APASP1 Z

Initial Apatity short-period channel configuration consists of the following components:

- S-500 short-period, vertical seismometers
- Nanometrics RD-6 digitizers

6.2.1.1 *S-500*

The response of the Geotech S-500 seismometer is described in detail in section 2.2.8.1. Poles and zeros, as well as the gain value can be taken from there.

However, in the case of the Apatity array, the S-500 seismometers are used with a preamplifier with a gain of 200 x. Thereby, the total sensitivity is:

$$450 \text{ V/m/s} * 200\text{x} = 9000 \text{ V/m/s}$$

6.2.1.2 *RD6*

The response of the Nanometrics RD-6 digitizers is described in detail in section 2.2.3.4.

At Apatity however, the digitizers operate with additional filters than what was installed at the NORSAR array, just as in the case of SPITS (see §5.2.1.2). Thus, the filter cascade is the following:

- Analog 5^{th}-order Butterworth low-pass filter at 22.9 Hz
- Analog 1st order RC high-pass filter at 0.5 Hz
- Digital low-pass FIR filter at 16 Hz with 68 coefficients
- Digital high-pass IIR filter at 0.001 Hz

The equations for the filters common to the NORSAR RD6 configuration can be found in section 3.1.3.4. Regarding the 1^{st} order high-pass RC filter, it has one real pole:
$2\,\pi\,0.5 = 3.14159265$
and one zero: 0.0

Information about the IIR filter can be found in section 5.2.1.2. The characteristics for the configuration described here, which operates with a sampling rate of 40 sps, are the following (Nanometrics, 1993):

f_{3db} = 0.008 Hz
a = -0.998749
b = -1.0
gain = 0.999374

The sensitivity of the digitizer is equal to 610 nV/count and the output sample rate is set to 40 sps.

6.2.2 S-500 – RD3 (1992/10/03 – 2010/06/01)

Respid: APA0HH1 Z
APA0HH2 N-S
APA0HH3 E-W

An extra high-frequency channel with a sampling rate of 80 Hz operates at the central element APA0 of the Apatity array. This is a 3-component channel (3 seismometers), additional to the typical 40 Hz sampled vertical channel. However, the instrumentation is the same as in the previous section, so the system consists of the following components:

- S-500 short-period seismometers
- Nanometrics RD3 digitizer

6.2.2.1 *S-500*

The response of the Geotech S-500 seismometer is described in detail in section 2.2.8.1. Poles and zeros, as well as the gain value can be taken from there.

However, in the case of the Apatity array, the S-500 seismometers are used with a preamplifier with a gain of 200.

6.2.2.2 *RD3*

Information about the RD3 digitizer (same instrument with RD6, but with only 3 channels) can be found in section 6.2.1.2 of the current chapter, section 2.2.3.4 on the NORSAR array and section 5.2.1.2 on the SPITS array.

In the case of this higher sampling rate channel, the employed filters are different from those of the RD6 configuration:

- An analog 5^{th} order low-pass filter at 68.6 Hz is used and
- the IIR filter has a 3db frequency of 0.016 Hz (Nanometrics, 1993)

6.2.3 CMG-3T – RD3 (1992/10/03 – 2010/06/01)

Respid: APZ9BB1 Z
APZ9BB2 N-S
APZ9BB3 E-W

A 3-component broadband Güralp seismometer, model CMG-3T was installed at the basement of the KRSC building in Apatity on June 1992, replacing the S-13 seismometers previously installed there in 1991. The configuration of this channel is equipped with the following components:

- CMG-3T broadband seismometer
- Nanometrics RD-3 digitizer

6.2.3.1 *CMG-3T*

The instrument installed at the Apatity APZ9 station has a serial number of T389. The poles and zeros describing the velocity response of this instrument are provided by the manufacturer and are the following:

POLES (HZ)	ZEROS (HZ)
$-7.07 \times 10^{-3} \pm j7.07 \times 10^{-3}$	0
$-80.5 \pm j30.8$	0
	150.5

Normalizing factor at 1 Hz: A = -49.5

The sensitivity is equal to: 2x1004 V/m/s.

The factor of 2 in the sensitivity estimate is used because of sensor outputs being used differentially.

Regarding poles and zeros, values are listed in units of Hz. They need to be multiplied with 2π to be converted to rad/s. The same change applies for the normalizing factor.
Total sensor sensitivity will then be equal to: G = (sensitivity) x (norm. factor)

6.2.3.2 *RD-3*

Information about the RD-3 digitizer can be found in section 6.2.1.2 of the current chapter, section 2.2.3.4 on the NORSAR array and section 5.2.1.2 on the SPITS array. The version installed in the basement of the KRSC building in Apatity also utilizes software version 1625, but employs only the following filters:

- Analog 5^{th} order low-pass Butterworth filter at 22.9 Hz
- Digital FIR filter (low-pass) with f_{3db} at 16 Hz and 68 coefficients, decimating by 4

The analog high-pass and digital IIR filter mentioned in other cases (*e.g.*, §6.2.1.2) are not used here.

The displacement amplitude (in count/nm) and phase (in degrees) responses for all three configurations (APASP1, APA0HH1,2,3 and APZ9BB1,2,3) described in this and the two previous sections (6.2.1, 6.2.2) are depicted in Fig. 6.6. As always, shaded areas represent the range beyond the Nyquist frequency.

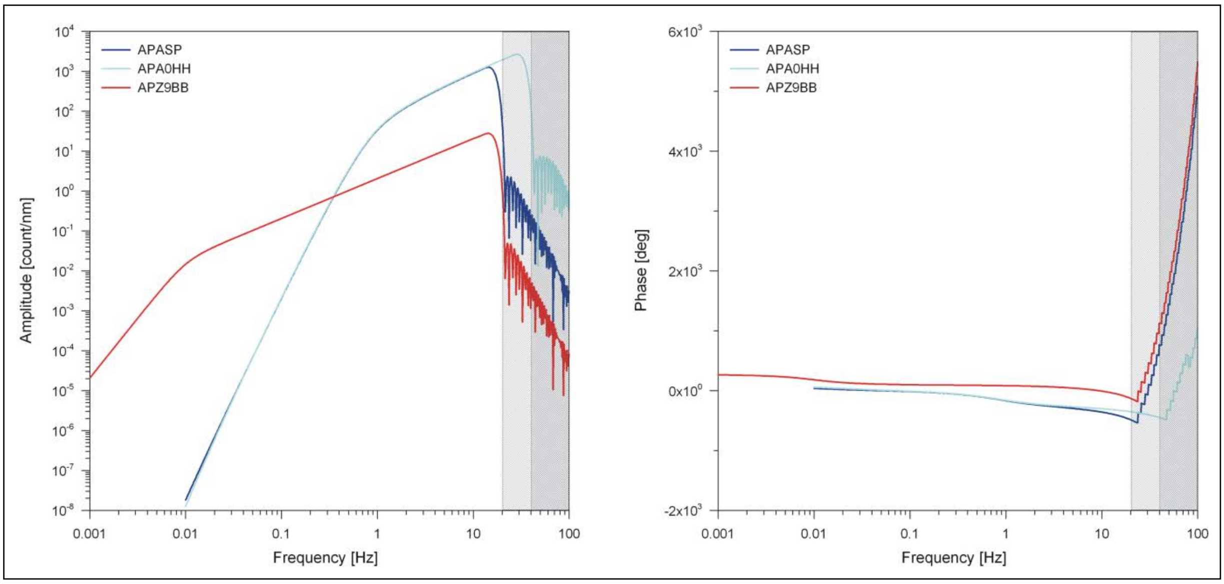


Fig. 6.6. Displacement amplitude (left) and phase (right) response for the Apatity array and single 3-component station APZ9 configurations. The short-period array channels (APASP) are noted in blue, the high-frequency APA0 site channel (APA0HH) in cyan and the APZ9 broadband station (APZ9BB) in red. The curves plotted here correspond to the vertical component of each case. Shaded areas represent the range beyond the Nyquist frequency (20 Hz for SP and BB and 40 Hz for HH configurations).

6.2.4 GS-1 – E-24 (2010/06/01 – …)
Respid: APASP2 Z

The current Apatity short-period channel configuration consists of the following components:

- GS-1 geophones
- E-24 digitizers

6.2.4.1 *GS-1*

The GS-1 geophone of OYO Geospace is a damping seismometer, with two damping options, depending on whether an open circuit is used or not. The 4450 Ohm DC resistance at 25°C model is used in Apatity. A nominal value for open-circuit damping is 54%, whereas the alternative is 70%. The typical damping seismometer equation (Eq. 2.2.2) could be used to obtain the pole-zero set of the instrument if we knew which damping option is applied. The difference between the responses of the two options can be seen in Fig. 6.7, for the sensor with serial number 1782.

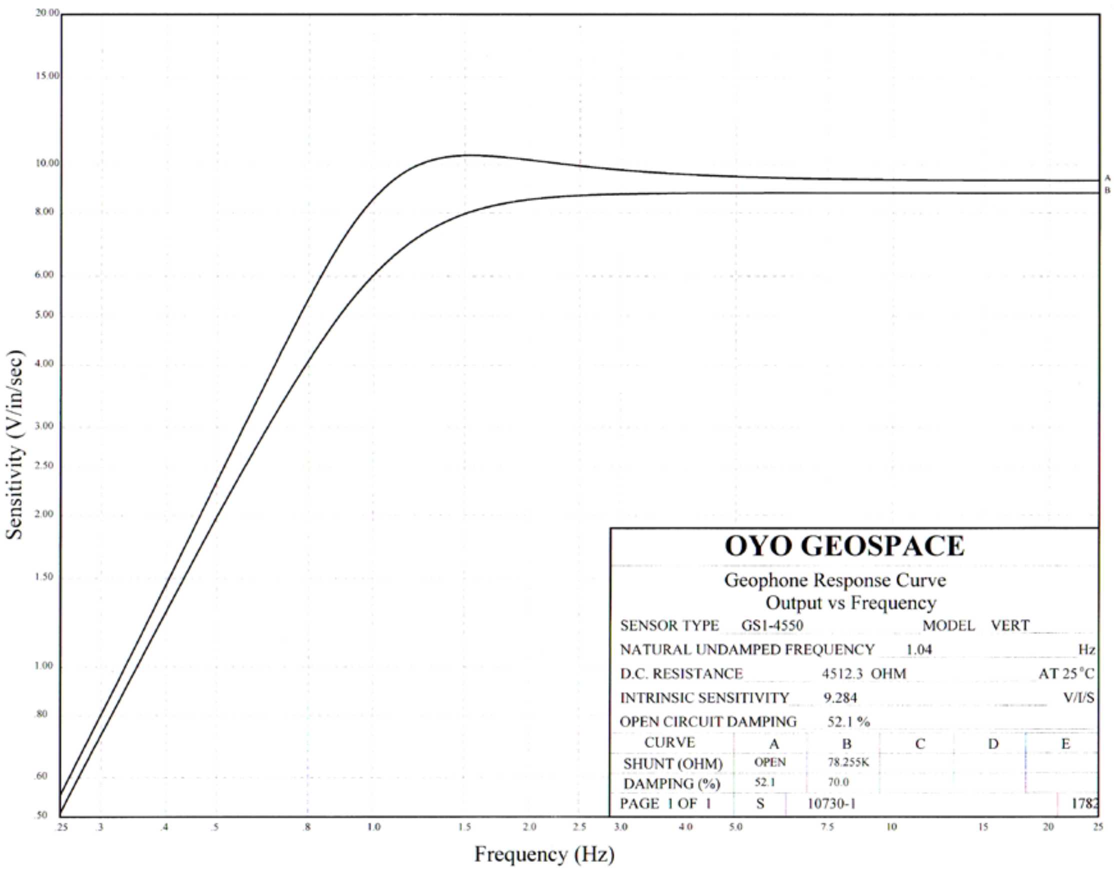


Fig. 6.7. Response curves for the GS1-4550 sensor with S/N 1782 (provided by V. Asming, KRSC).

The sensitivity of the sensors is in the order of 9 V/in/s. A sensitivity value of 9.284 V/in/s = 365.5 V/m/s (1 V/in/s = 39.3700787 V/m/s) can be seen is Fig. 6.7 for sensor with S/N 1782.

6.2.4.2 *E-24*

The E-24 data acquisition module of L-card, Ltd. employs the AD7714 24-bit A/D converter of Analog Devices (L-card, 1998). The AD7714-5 model is used, which needs a full-scale input voltage of 5V (Analog Devices, 1998).

The AD7714 is a complete analog front end for low-frequency measurement applications. The device accepts low level signals directly from a transducer and outputs a serial digital word. It employs a sigma-delta conversion technique to realize up to 24 bits of no missing codes performance. The input signal is applied to a proprietary programmable gain front end based around an analog modulator. The modulator output is processed by an on-chip digital filter. The first notch of this digital filter can be programmed via the on-chip control register allowing adjustment of the filter cutoff and settling time. The part features three differential analog inputs (which can also be configured as five pseudo-differential analog inputs) as well as a differential reference input. It operates from a single supply (+5 V for the E-24). The AD7714 thus performs all signal conditioning and conversion for a system consisting of up to five channels (Analog Devices, 1998).

The master clock input frequency of MCLK = 2.4576 MHz is employed at the E-24 (L-card, 1998). Selectable gain settings between 1 and 128 are supported.

The modulator sample frequency for the AD7714 remains at $f_{CLK\ IN}/128$ (19.2 kHz @ $f_{CLK\ IN}$ = 2.4576 MHz) regardless of the selected gain. However, gains greater than 1 are achieved by a combination of multiple input samples per modulator cycle and a scaling of the ratio of reference capacitor to input capacitor. As a result of the multiple sampling, the input sample rate of the device varies with the selected gain, as seen in Table 6.1 (Analog Devices, 1998).

Table 6.1. Input sampling frequency vs. gain (Table XIV in Analog Devices, 1998)

Gain	Input sampling frequency (f_s)
1	$f_{CLK\ IN}/64$ (38.4 kHz @ $f_{CLK\ IN}$ = 2.4576 MHz)
2	$2 \times f_{CLK\ IN}/64$ (76.8 kHz @ $f_{CLK\ IN}$ = 2.4576 MHz)
4	$4 \times f_{CLK\ IN}/64$ (153.6 kHz @ $f_{CLK\ IN}$ = 2.4576 MHz)
8	$8 \times f_{CLK\ IN}/64$ (307.2 kHz @ $f_{CLK\ IN}$ = 2.4576 MHz)
16	$8 \times f_{CLK\ IN}/64$ (307.2 kHz @ $f_{CLK\ IN}$ = 2.4576 MHz)
32	$8 \times f_{CLK\ IN}/64$ (307.2 kHz @ $f_{CLK\ IN}$ = 2.4576 MHz)
64	$8 \times f_{CLK\ IN}/64$ (307.2 kHz @ $f_{CLK\ IN}$ = 2.4576 MHz)
128	$8 \times f_{CLK\ IN}/64$ (307.2 kHz @ $f_{CLK\ IN}$ = 2.4576 MHz)

The AD7714 contains an on-chip low-pass digital filter which processes the output of the sigma-delta modulator (Analog Devices, 1998). The AD7714's digital filter is a low-pass filter with a $(\sin x/x)^3$ response (also called sinc^3). The transfer function for this filter is described in the frequency domain by:

$$|H(f)| = \left| \frac{1}{N} \times \frac{\sin(N\pi \frac{f}{f_s})}{\sin(\pi \frac{f}{f_s})} \right|^3 \quad (6.2.1)$$

It is unfortunately unclear how all the different options mentioned above are set in the case of the Apatity array, and the same applies for the GS-1 geophones (see previous section). Thus, instead of calculating the channel response based on this information, we approximate the response. This has been facilitated by the parallel operation of the old and new configuration for a very short time interval. The corresponding data was kindly provided by V. Asming, KRSC, who also reported an amplification factor of 8.2 between the two different configurations. In practice, this means that the *GSE* response files still describe the previous instrumentation (section 6.2.1), but adjusted with an additional gain component of 8.2, to level with the current configuration's amplitudes.

6.2.5 GS-1 – E-24 (2010/06/01 – …)

Respid:	APA0HH4	Z
	APA0HH5	N-S
	APA0HH6	E-W

The high-frequency channel of the Apatity array employs the same instrumentation as in section 6.2.4:

- GS-1 geophones
- E-24 digitizers

6.2.5.1 *GS-1*

The GS-1 geophone of OYO Geospace was presented in section 6.2.4.1.

6.2.5.2 *E-24*

The E-24 data acquisition module of L-card, Ltd. was presented in section 6.2.4.2.

The same problems mentioned therein apply for the high-frequency channel and we have resorted to the same solution as for the short-period channels to acquire the system response, namely using the old response and adjusting it so that the amplitudes are correct.

In the case that further information becomes available in future, so that the actual response can be calculated, an addendum to this documentation will be produced.

6.2.6 CMG-3ESP – E-24 (2010/06/01 – …)

Respid: APZ9BB4 Z
APZ9BB5 N-S
APZ9BB6 E-W

At the same time with the refurbishment of the Apatity array (sections 6.2.4 and 6.2.5), the 3-component, broadband station APZ9 was also equipped with new instrumentation. The station is now equipped with the following components:

- CMG-3ESP broadband seismometer
- E-24 digitizer

6.2.6.1 *CMG-3ESP*

The CMG-3ESP instrument currently installed at the Apatity APZ9 station has a serial number of T36281. The poles and zeros describing the velocity response of this instrument are provided by the manufacturer and are the following:

POLES (HZ)	**ZEROS HZ**
$-5.89 \times 10^{-3} \pm j5.89 \times 10^{-3}$	0
-180	0
-160	
-80	

Normalizing factor at 1 Hz: A = 2304000

The sensitivity is equal to:

VERTICAL	2 x 981 V/m/s
NORTH/SOUTH	2 x 978 V/m/s
EAST/WEST	2 x 985 V/m/s

The factor of 2 in the sensitivity estimate is used because of sensor outputs being used differentially.

Regarding poles and zeros, values are listed in units of Hz. They need to be multiplied with 2π to be converted to rad/s. The same change applies for the normalizing factor.
Total sensor sensitivity will then be equal to: G = (sensitivity) x (norm. factor)

6.2.6.2 *E-24*

The E-24 unit is described in section 6.2.4.2. In the case of the APZ9 station we used the sensitivity of the digitizer for a gain of 1:

$\pm$ 2.5V / 2^{24} count/V = 3.3554795×10^{6} count/V

Still, we have no information on the settings that would help us reconstruct the employed digital filter. Thus, the digitizer was used only as a sensitivity stage. However, the extensive use of the station in event magnitude calculations in the area of the European Arctic indicates that the above sensitivity value is correct.

Fig. 6.8 shows the displacement amplitude and phase response for the current Apatity array and APZ9 configurations. Shaded areas denote frequency range beyond the Nyquist.

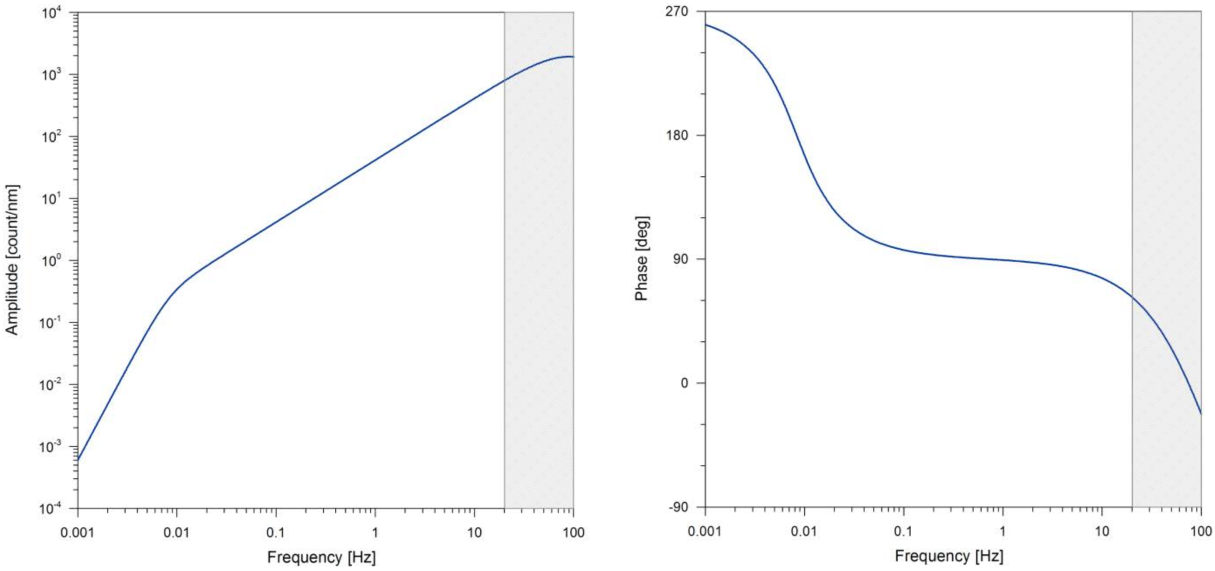


Fig. 6.8. Displacement amplitude and frequency response curves for the vertical component of the new configuration of station APZ9. No digital filters are used, since the cascade is not known. The shaded area represents the range beyond the Nyquist frequency (20 Hz).

6.3 References

Analog Devices, Inc., 1998. *3 V/5 V, CMOS, 500 μA, Signal Conditioning ADC AD7714**. Analog Devices, Inc., Norwood, USA, 40 pp.

Cirrus Logic, 2001. Crystal CS5376 Low Power Multi-Channel Decimation Filter. *DS256PP1*, Cirrus Logic, Inc., Austin, Texas, 122 pp.

Fyen, J., 2003. System responses. *NORSAR Techn. Report*, Kjeller, Norway, 26 pp.

Güralp Systems, 2006. CMG-DM24 mk3 Operator's Guide. *MAN-D24-0004*, Güralp Systems Ltd., Aldermaston, England, 113 pp.

Hansen, O.A., 1993. Maintenance activities. *NORSAR Semiann. Techn. Summ. 2-92/03*, Kjeller, Norway, p. 55-58.

L-card, Ltd., 1998: *Модуль E-24 – Техническое описание и инструкция по эксплуатации.* ЗАО «Л-КАРД», Москва, 19 pp.

Mykkeltveit, S., Dahle, A., Fyen, J., Kværna, T., Larsen, P.W., Paulsen, R., Ringdal, F., and Kremenetskaya, E.O., 1991. Extensions of the Northern Europe Regional Array Network – a new three-component station at Apatity, USSR, and a planned array at Spitsbergen. *NORSAR Semiann. Techn. Summ. 1-91/92*, Kjeller, Norway, p. 100-111.

Mykkeltveit, S., Dahle, A., Fyen, J., Kværna, T., Larsen, P.W., Paulsen, R., Ringdal, F., and Kuzmin, I., 1992. Extensions of the Northern Europe Regional Array Network – New small-aperture arrays at Apatity, Russia, and on the Arctic island of Spitsbergen. *NORSAR Semiann. Techn. Summ. 1-92/93*, Kjeller, Norway, p. 58-71.

Nanometrics, 1991. *1608 System Transfer Functions.* Fax from Jennifer McKenzie to Jan Fyen, 30 October 1991, 7 pp.

Nanometrics, 1993. *Response RD3 1626 Digitiser.* Fax from Robin Hayman to Jan Fyen, 8 February 1993, 12 pp.

CHAPTER 7: JAN MAYEN BROADBAND STATION

7.1 Development of JMIC broadband station systems: instrumentation and responses

7.1.1 <u>Short description</u>

- 1994-2004:

A broadband seismic station on Jan Mayen Island, in mid north Atlantic, was initially installed and operated by the University of Bergen, as part of the Norwegian National Seismic Network in October 1994. The station was equipped with a 3-component, broadband STS-2 seismometer and an Earth Data digitizer. Data were being transmitted also to the Norwegian National Data Centre (NORSAR) for CTBT related issues since 2000 and stored in the NDC database under station code JMI until April 2004, when the station was closed.

- 2003-…:

In 1996, it was included in the CTBT that an IMS auxiliary 3-component station should be installed on the island of Jan Mayen, and the implementation of this decision began in 2002. The installation was completed in October 2003 at a slightly different location than the old University of Bergen JMI station. The new 3-component broadband station to be operated by NORSAR was assigned the auxiliary IMS station code AS73 (Fyen, 2003, 2004). Thus, JMI was closed in April 2004. The new station is operating under the name JMIC and is equipped with an STS-2 broadband seismometer and a Nanometrics Europa T digitizer. The only change made to this configuration were tests regarding the digitizer IIR DC removal filter. A version with no filter at all, a version with a 10 mHz IIR filter and a version with a 1 mHz IIR filter (the currently employed one) were tested.

7.1.2 <u>Instrumentation</u>

I. Configurations

- JMI BB configuration (1994-2004):
    - STS-2 seismometer
    - Earth Data digitizer

- JMIC BB configurations (2003-…):
    - STS-2 seismometer
    - Nanometrics Europa T digitizer with
        - 10 mHz IIR filter
        - 1 mHz IIR filter
        - no IIR filter

II. Respids

JMIBB1,2,3
JMICBH1,2,3
JMICBH4,5,6
JMICBH7,8,9

III. Instrument specifications

STS-2:
Streckeisen very broadband triaxial seismometer. 3 identical obliquely-oriented mechanical sensors are employed, instead of the traditional arrangement of separate orthogonal vertical and horizontal sensors. The versions installed at Jan Mayen have the following characteristics (nominal values; Streckeisen, 2003):

Seismic output (flat velocity)	8.33 mHz – 50 Hz
Mass	0.3 Kg
Gain	2 x 750 V/m/s (JMI), 20000 V/m/s (JMIC)
Damping	0.707 (low frequencies, < 1 Hz)
Feedback coil	50 N/A

Earth Data digitizer:
Earth Data A/D converter (possibly type 2433). The version installed at the JMI station employed the following succession of digital filters:

Digital FIR filter: low-pass	N = 240, decimating by 4
Digital FIR filter: low-pass	N = 640, decimating by 10

Europa T digitizer:
A Nanometrics A/D converter, manufactured especially for CTBT monitoring purposes. The version installed at the JMIC station has the following characteristics:

Resolution	24-bit
Maximum differential input voltage range	40 V p-p @ gain 0.4
Nominal sensitivity	1 count/µV for gain 1
Software selectable gain	0.4, 1, 2, 4, 8
Dynamic range	142 dB for 100 Hz output sample rate
Output sample rates	10, 20, 40, 50, 100 sps

The digitizer employs the following digital filters:

A decimating FIR filter (low-pass) and
An optional IIR filter (high-pass for DC offset removal), first order, 1 mHz to 1 Hz

7.2 Instrument response calculation for the Jan Mayen broadband station systems

This chapter focuses on the major considerations to be taken into account for the calculation of the instrument response of the different systems operating at the Jan Mayen broadband station.

As with the rest of the NORSAR systems, *GSE* file response *Respid* flags for each configuration are provided at the beginning of each section.

7.2.1 STS-2 - EarthData	(1994/10/01 – 2004/04/03)
Respid: JMIBB1	Z
JMIBB2	N-S
JMIBB3	E-W

Old JMI (University of Bergen) broadband configuration consists of the following components:

- STS-2 broadband 3-component seismometer
- Earth Data 2433 digitizer

7.2.1.1 *STS-2*

The Streckeisen STS-2 very broadband triaxial seismometer uses 3 identical obliquely-oriented mechanical sensors instead of the traditional separate orthogonal vertical and horizontal sensors. This design (Fig. 7.1) favors the standardization of manufacturing and guarantees the closest possible matching of the vertical and horizontal components.

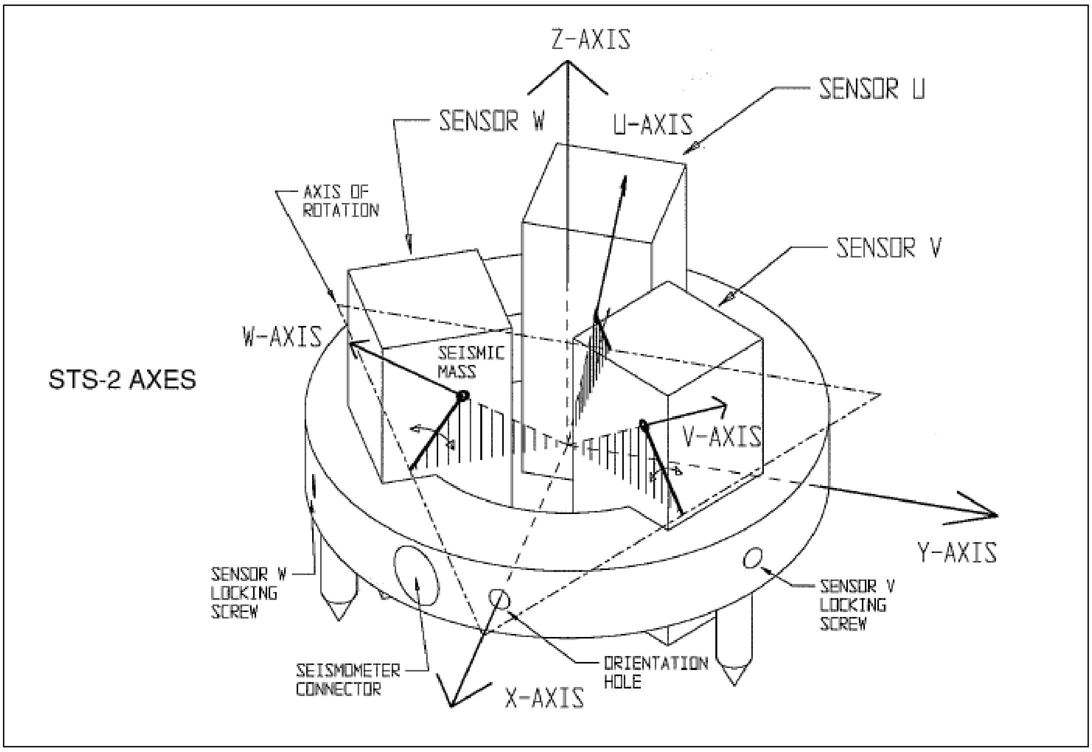


Fig. 7.1. A schematic representation of the axes positioning of the STS-2 seismometer (Streckeisen, 2003).

So, 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:

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \frac{1}{\sqrt{6}} \begin{pmatrix} -2 & 1 & 1 \\ 0 & \sqrt{3} & -\sqrt{3} \\ \sqrt{2} & \sqrt{2} & \sqrt{2} \end{pmatrix} \begin{pmatrix} U \\ V \\ W \end{pmatrix}, \tag{7.2.1}$$

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).

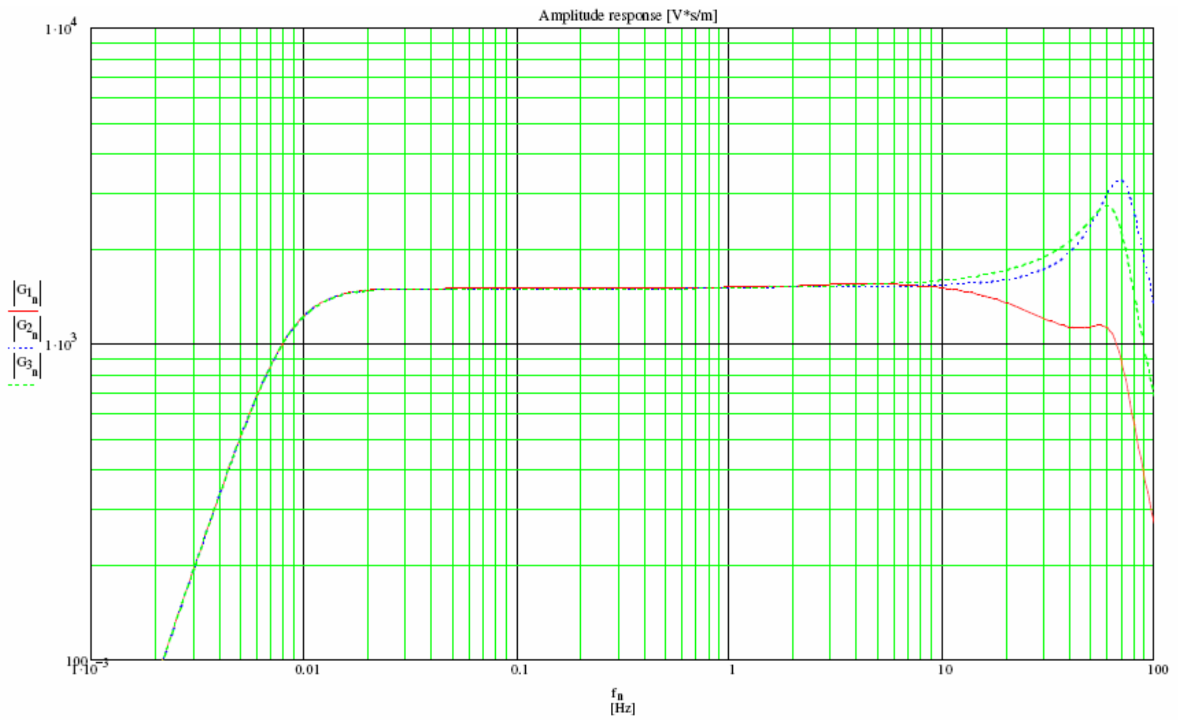
The transfer functions can then only be attributed to the individual U, V and W sensors and not to the X, Y, Z outputs. A method to calibrate the instrument is to calibrate the U, V and W sensors separately, by using for instance the Z output, and then to average the U, V and W transfer functions or parameters with a matrix whose elements are the squares of those of the matrix in equation 7.2.1 (Wielandt, 2002, Wielandt and Widmer-Schnidrig, 2002):

$$\begin{pmatrix} T_X \\ T_Y \\ T_Z \end{pmatrix} = \frac{1}{6} \begin{pmatrix} 4 & 1 & 1 \\ 0 & 3 & 3 \\ 2 & 2 & 2 \end{pmatrix} \begin{pmatrix} T_U \\ T_V \\ T_W \end{pmatrix}. \tag{7.2.2}$$

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 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 seismometer's coupling to the ground. This 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 (the mechanical part has been the same since 1990, but the electronics part has been redesigned twice) and each has a different high-frequency velocity response, as shown in Fig. 7.2 both for the amplitude and the phase (Streckeisen, 2006).

For the JMI Bergen station the only information available is that provided by the University of Bergen (UiB). Therefore, it will only be reproduced within these chapters without the possibility to verify it. For a more detailed description on how to actually obtain the poles and zeros of the transfer function see section 7.2.2.1.

Only 2 poles and 2 zeros are reported by UiB, inconsistently to all pole-zero reports by Streckeisen (*e.g.,* Streckeisen, 2006). Since Streckeisen is describing their instrument as a velocity transducer for frequencies less than 1 Hz, it can only be assumed that the typical damping seismometer formula (equation 2.2.2 in section 2.2.1.1) was used by UiB to derive the poles and zeros. Indeed, when tried for a period value of 120 s, the reported pole values return a damping value of 0.7, which is consistent with what was reported two paragraphs earlier. The generator constant is reported equal to 1500 V/m/s.



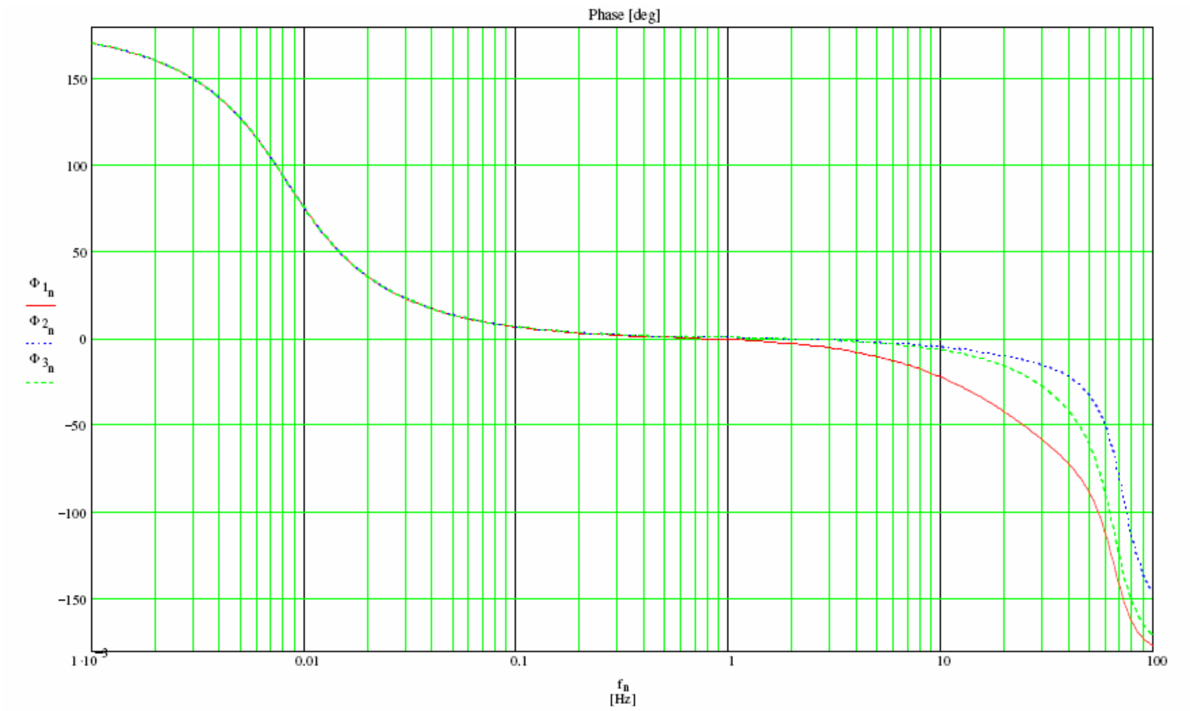


Fig. 7.2. STS-2 velocity amplitude (top) and phase (bottom) response for Generations 1, 2 and 3 (Streckeisen, 2006).

7.2.1.2 *Earth Data*

The response of the Earth Data digitizer (probably a 2433 model instrument) is described by the following succession of digital FIR filters:

- 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 is reported to be equal to 1000000 count/V.

The displacement amplitude and phase response of the above described configuration are depicted in red in Fig. 7.4 in the end of section 7.2.2.

7.2.2 STS-2 – EuropaT (2003/10/01 – …)

Respid:	JMICBH1,2,3	Z, N-S, E-W
	JMICBH4,5,6	Z, N-S, E-W
	JMICBH7,8,9	Z, N-S, E-W

The current JMIC broadband configuration consists of the following components:

- STS-2 broadband 3-component seismometer
- Nanometrics Europa T digitizer

No changes were made to the above mentioned instrumentation, except for several tests with different versions of the digitizer IIR filter (see §7.2.2.2 for details).

7.2.2.1 *STS-2*

The velocity response of the STS-2 broadband seismometer is described in detail in section 7.2.1.1. For the JMIC version, the serial number of the seismometer is 30234, which according to the 'Detailed list of STS-2 Generations' document to be found on the ORFEUS website (last update April 2004), corresponds to a High-Gain, Generation 3 instrument (see also Fig. 7.3). The particular characteristics of the transfer function of this type of STS-2 sensor are listed below:

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	
$-97.34 \pm j\ 400.7$	
-15.64	
$-0.037 \pm j\ 0.037$	

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

The generator constant values for X, Y and Z are equal to 20000 ± 200 V/m/s.

The equations describing the velocity amplitude (in V/m/s) and phase response are the following (Streckeisen, 2006):

$$G_{3n} = (j\omega_n)^2 \cdot \frac{5.2107 \cdot 10^{20} \left[\prod_{k=0}^{3} (j\omega_n - Z_k) \right]}{\prod_{l=0}^{9} (j\omega_n - P_1) \cdot (j\omega_n - \omega_{mix})} \quad \text{and} \qquad (7.2.3)$$

$$\Phi_{3n} = \frac{180}{\pi} \cdot \arg(G_{3n}), \qquad (7.2.4)$$

where $\omega_n = 2\ \pi\ f_n$ and $f_n = 0.001 \times 10^{(n/96)}$, for a logarithmic scale frequency with n ranging from 0 to 480.

To obtain the poles and zeros values for each component, the above mentioned information needs to be combined with equation 7.2.2.

From the ‘Laboratory Data of the Seismometer No. 30234’ document, which was faxed from Streckeisen in 2003, we obtain the following instrument specific information:

The orientation of the U, V, W axes that are relative to X, Y, Z, is shown in the ‘cube corner’ schematic representation of Fig. 7.3.

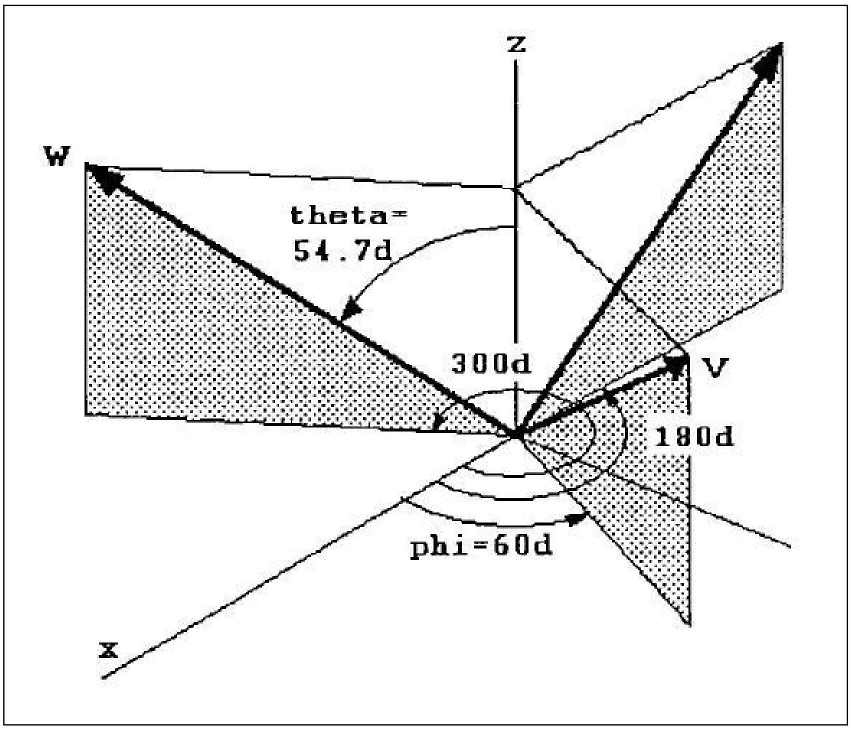


Fig. 7.3. Schematic representation of the U, V, W and X, Y, Z axes for the STS-2 seismometer with serial number 30234, according to the instrument specific information provided by Streckeisen.

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

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.

However, as communicated by Streckeisen (personal communication), the differences in the generator constant for the three sensors (U, V and W) are compensated for in the mixing process to produce components Z, N-S and E-W. Thus, for the flat part of the response the sensitivity is equal to the nominal value (*i.e.*, 20000 V/m/s for High-Gain, Generation 3 instrument in this case). The frequency of 0.5 Hz (2 s) is used for this, since this is the frequency at which all measurements are made by the manufacturer. Thereby, all *GSE* response files are normalized at 2 s, even if the response is eventually calculated for a different calibration period.

Regarding the poles and zeros, the response is divided to a high-frequency (1-100 Hz) and a low-frequency (0.00586-0.10547 Hz) end.

i) High-frequency end

4 zeros [Hz]:

Sensor U:	$-73.50 \pm j68.29$	-29.88	-2.411
Sensor V:	$-73.50 \pm j68.29$	-29.28	-2.411
Sensor W:	$-73.50 \pm j68.29$	-30.02	-2.411

9 poles [Hz]

Sensor U:	$-1629.7 \pm j433.7$	$-1514 \pm j1825.5$	-72.34	-2.46	$-14.35 \pm j62.65$	-74.615
Sensor V:	$-1629.7 \pm j433.7$	$-1514 \pm j1825.5$	-72.34	-72.87	$-14.22 \pm j63.12$	-2.457
Sensor W:	$-1629.7 \pm j433.7$	$-1514 \pm j1825.5$	-72.34	-2.45	$-13.67 \pm j63.39$	-74.494

ii) Low-frequency end

The model fits a 2^{nd}-order high-pass filter. The corner periods in s and damping constant values are the following:

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

Finally, an example is provided on how to combine the above mentioned information and equation 7.2.2 to obtain the pole-zero values to be used in the *GSE* response file.

<u>*Example*</u>

To calculate the third zero listed above for the Z component in rad/s, using equation 7.2.2 and taking into consideration that this corresponds to sensor W, we get:

$$z_{3,Z} = \{[(-29.88 \times 2\pi \times 2) + (-29.28 \times 2\pi \times 2) + (-30.02 \times 2\pi \times 2)] / 6\} = -186.778155.$$

It should be noted that a spare STS-2 seismometer assigned to JMIC exists, with serial number 120216. The poles, zeros and sensitivity values have been calculated and can be found in a specially edited *GSE* response file (cal2_spare).

7.2.2.2 *Europa T*

The Europa T digitizer is a Nanometrics A/D converter, based on the Trident digitizer, especially designed for CTBT purposes, to provide authenticated data to the acquisition centre. It is a 3-channel digitizer with a 24-bit resolution and a 142 dB dynamic range. Available software filters are the following:

- A decimating FIR filter (low-pass) and
- An optional IIR filter (high-pass for DC offset removal)

Actually, the analog signals are first being filtered by a first order low-pass antialias filter and then sampled at 30 kHz. This data is further low-pass filtered and decimated using the FIR filter mentioned above, which consists of 3 to 4 FIR stages, depending on the desired output sampling rate. The low frequency response can be configured by employing the DC removal IIR filter, which can set this response to a number of predetermined frequencies. If no IIR is employed, low frequency response is set to DC. The equations describing the filters mentioned above are the following (Europa T User Guide):

Analog 1st-order low-pass filter: $$F(s) = \frac{A}{s \cdot r \cdot c + 1}, \tag{7.2.5}$$

where $A = \frac{\alpha}{\beta + Z}$, $r = \frac{1}{\frac{1}{\alpha} + \frac{1}{\gamma + Z}}$ and Z is the sensor impedance. The coefficients mentioned here receive the following values: c = 1.0 x 10^{-8}, α = 33600, β = 43250, γ = 9650, and the complex frequency response is obtained by $s = -j\omega$.

Digital FIR low-pass filters: $$y(n) = \sum_{i=0}^{N-1} c(i) \cdot x(n-i), \tag{7.2.6}$$

where $y(n)$ is the output sample, $x(n-i)$ is an input sample, $c(i)$ is a FIR coefficient and N is the number of coefficients. Since an output sampling rate of 100 sps is requested, only 3 FIR stages are employed:

- FIR stage 1: 165 coefficients, decimating by 15
- FIR stage 2: 187 coefficients, decimating by 10 and
- FIR stage 3: 223 coefficients, decimating by 2

The cumulative filter delay is 0.604233 s. The coefficient values can be found either in the Europa T User Guide or the corresponding *GSE* response file.

Digital IIR high-pass filter: $$y(n) = K \cdot [x(n) - x(n-1)] + F_1 \cdot y(n-1), \tag{7.2.7}$$

where $y(n)$ is the current output sample, K is the filter gain, $x(n)$ is the current input sample, $x(n-1)$ is the previous input sample, F_1 is the filter coefficient and $y(n-1)$ is the previous output sample. The IIR filter is implemented as a 1st-order IIR filter using the following coefficients calculated at runtime:

$$F_1 = \frac{1 - \left(\frac{\pi \cdot f}{F_S}\right)}{1 + \left(\frac{\pi \cdot f}{F_S}\right)} \text{ and} \tag{7.2.8}$$

$$K = \frac{1}{1 + \left(\frac{\pi \cdot f}{F_S}\right)}, \tag{7.2.9}$$

where F_S is the output sample rate and f the 3-dB corner frequency of the filter. The time constant (TC) of the filter can be calculated by the formula:

$$TC = \frac{1}{2\pi \cdot f}. \tag{7.2.10}$$

As mentioned earlier, several test configurations of the IIR filter existed. The current version, with *Respids* JMICBH7,8,9 employs the typical 1 mHz IIR filter. Initially, a version with a 10 mHz filter was installed (*Respids* JMICBH1,2,3), and then two tests were made without using the filter at all (digitizer optional feature). These were assigned the *Respids* JMICBH4,5,6. See corresponding *GSE* response file for actual time intervals of operation.
The digitizer is used with a gain of 0.4 and a nominal sensitivity of 1000000 count/V, resulting in a sensitivity of 400000 count/V. The data are sampled at 100 sps.

The displacement amplitude (in count/nm) and phase (in degrees) response of the configurations described in this section are depicted in Fig. 7.4, in green (JMICBH1,2,3), cyan (JMICBH4,5,6) and blue (JMICBH7,8,9). The shaded areas represent the range beyond the Nyquist frequency. It is very obvious that as expected, all JMIC configuration responses differ only in the low-frequency area affected by the existence and shape of the digitizer IIR filter.

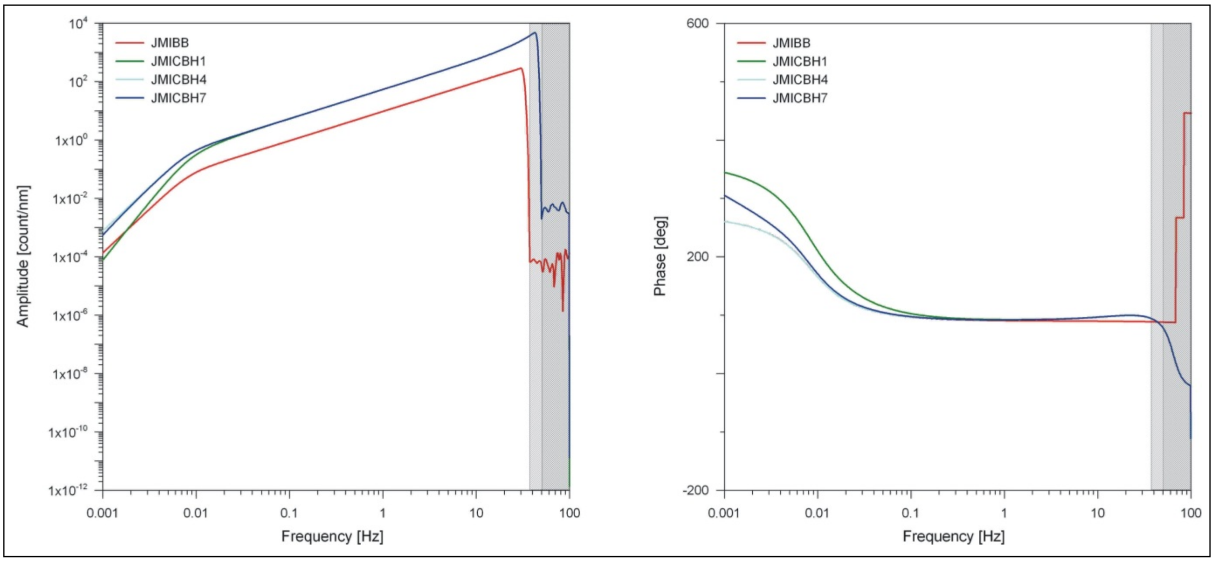


Fig. 7.4. Displacement amplitude (left) and phase (right) response for the JMI and JMIC 3-component broadband station configurations. The JMI response (JMIBB) is noted in red, the 10mHz IIR filter version of the JMIC station (JMICBH1) in green, the 1mHz IIR filter version of JMIC (JMICBH7) in blue and the JMIC version without any IIR filter (JMICBH4) in cyan. Only the vertical component is depicted here. Shaded areas represent the range beyond the Nyquist frequency (37.5 Hz for JMI and 50 Hz for JMIC).

7.3 References

I. Publications

Fyen, J., 2003. AS73 – Auxiliary Seismic Station at Jan Mayen. *NORSAR Semiann. Techn. Summ. 2-2003*, Kjeller, Norway, p. 10.

Fyen, J., 2004. AS73 – Auxiliary Seismic Station at Jan Mayen. *NORSAR Semiann. Techn. Summ. 1-2004*, Kjeller, Norway, p. 10.

Nanometrics. Europa T Digitizer User Guide. 50 pp.

Streckeisen, 2003. STS-2 portable bery-broad-band triaxial seismometer. *sts2-1.pdf*, G. Streckeisen AG Messgeräte, Pfungen, Switzerland, 12 pp.

Streckeisen, 2004. Detailed list for STS-2 generations. *sts_list.pdf*, G. Streckeisen AG, Pfungen, Switzerland, 2 pp.

Streckeisen, 2006. Pole-zero representation of the STS-2 transfer function from 0.001 to 100 Hz. *sts.pdf*, G. Streckeisen AG, Pfungen, Switzerland, 14 pp.

Wielandt, E., 2002. Seismic sensors and their calibration. Chapter 5 in *IASPEI New Manual of Seismological Observatory Practice*, Bormann, P. (Ed.), GeoForschungsZentrum Potsdam, Vol. 1, 46 pp.

Wielandt, E. and Widmer-Schnidrig, R., 2002. Seismic sensing and data acquisition in the GRSN. In *Ten Years of German Regional Seismic Network (GRSN)*, Deutsche Forschungsgemeinschaft, Senate Commission for Geosciences, Report 25, Wiley-VCH, p. 73-83.

II. Information received by facsimile

Streckeisen, 11.12.2003. ‘*Certificate of Calibration*’ & ‘*Laboratory Data of the Seismometer No. 30234*’. 2pp.

CHAPTER 8: HAGFORS ARRAY

8.1 Development of Hagfors (HFS) array systems: instrumentation and responses

The Hagfors array and contributes on a regular basis to NORSAR's Data Center as the result of years-long collaboration with FOI (the Swedish Defense Research Agency) in Stockholm, Sweden.

8.1.1 Short description

- 1969-1994:

The HFS seismic array, located in central Sweden, operated initially as one of the four sub-stations (HFS, APO, SLL and TBY) of a larger installation called at that time the Hagfors array station (*e.g.*, GSE, 1989, 1990) or Hagfors Observatory (FOI, 2005). Each sub-station except for TBY was a 1 km aperture array with five equally-spaced, short-period vertical sensors, installed in shallow boreholes. HFS had in addition two horizontal component short-period seismometers and a full 3-component long-period station. A modernization of the system took place in 1989. Later, the HFS sub-array became known as Hagfors array instead of the larger installation. Since no data from this system are available at NORSAR prior to June 1994, no further mention will be made to this system.

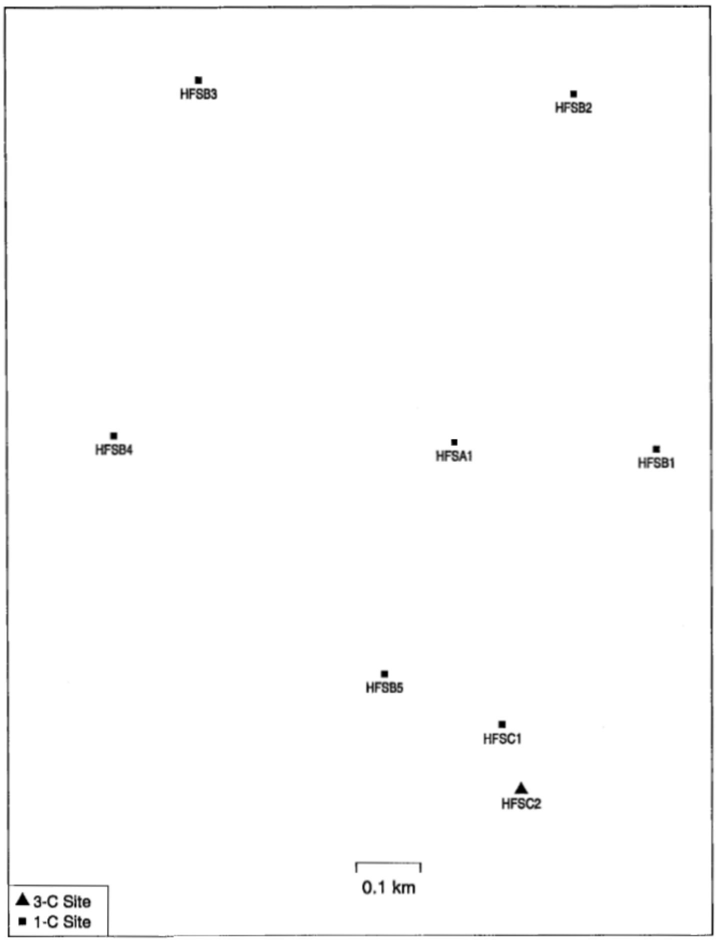


Fig. 8.1. Geometry of the initial Hagfors array (GSETT3, 1995).

- 1994-2003:
Since 8th June 1994 (and 1995 via satellite link), NORSAR has been collecting data from the Hagfors (HFS - IMS auxiliary station AS101, certified 17/12/2002) seismic array (*e.g.*, Baadshaug *et al.*, 1995; Nedgård, 2005). The initial configuration consisted of 8 sites, distributed over an aperture of approximately 900 m. All sites were equipped with short-period S-13 or 20171A vertical seismometers and RD-3 digitizers. Additionally, site HFSC2 had a 3-C long-period and a vertical broadband channel, equipped with a 7505A/8700C sensor combination and an STS-1 respectively. The short-period channel of site HFSC2 also carried a 3-component instrument. Detailed information about each channel can be found in Appendix V (GSETT3, 1995; Lund and Lennartsson, 2005). The initial geometry of the Hagfors array can be seen in Fig. 8.1.

- 2001-2003:
During this time interval, and while the initial Hagfors array was still under operation, a new configuration was tested. The new array comprised 10 sites, nine of which carried only vertical, short-period GS-13 sensors, while the tenth was equipped with a 3-component broadband STS-2 seismometer. All sites carried Nanometrics Europa (HRD-24/authentication) digitizers. For the particular time interval, the old array data were stored in the NORSAR database under the db entry HFS, while the new configuration data under SVE. All available resources within NORSAR directories suggest that this dual system commenced on 19 August 2001, however no data can be found stored under database entry /db/2001/ for SVE prior to DOY 270 (27 September 2001). The short-period configuration recommended by the instrument manufacturers includes a preamplifier between the seismometer and digitizer (Bergkvist and Lennartsson, 2004; Nanometrics, 2001). However, during the time period 2001 – April 2002, the preamplifier was not yet delivered, resulting in rather small amplitudes and a decision was made to keep the old and new configuration operating in parallel.

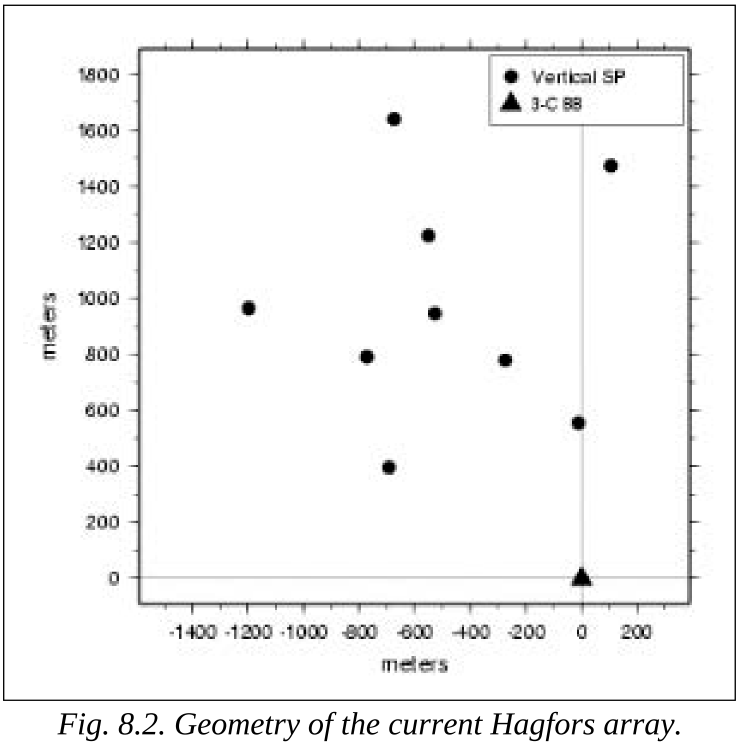


Fig. 8.2. Geometry of the current Hagfors array.

- 2003-2012:
The current geometry of the Hagfors array is displayed in Fig. 8.2. The instrumentation remains the same, as described in the previous section for the new Hagfors. Only one change took place in 2004, when the 10 mHz IIR filter of the Europa T digitizer at the broadband channel was replaced with a 1 mHz IIR filter. Since the old array was closed, Hagfors data are again stored at NORSAR under db entry HFS.

- 2012-…:
A defective digitizer at HFA1 was replaced with the digitizer of the broadband element HFC2. HFC2 was equipped with a Europa T, with the optional 1 mHz IIR filter. No other changes were performed.

8.1.2 Instrumentation

I. Configurations

- Initial SP configuration (1995-2003):
  S-13 seismometer
  Nanometrics RD-3 digitizer

- Initial SP configuration (1995-2003):
  20171A seismometer (vertical only)
  Nanometrics RD-3 digitizer

- Initial LP configuration (1995-2003):
  7505A/8700C seismometers (3-component)
  Nanometrics RD-3 digitizer

- Initial BB configuration (1995-2003):
  STS-1 seismometer (vertical only)
  Nanometrics RD-3 digitizer

- Current SP configuration (2003-…):
  GS-13 seismometer (vertical only)
  Nanometrics Europa digitizer

- Current broadband configuration (2003-…):
  STS-2 seismometer (3-component)
  Nanometrics Europa digitizer

II. Respids

HFSSP1,2,3
HFSSP4
HFSSP5
HFSSP6
HFSLP1,2,3
HFSBB1
HFSBB2,3,4

HFSBB5,6,7
HFSBB8,9,10

III. Instrument specifications

S-13:
See §2.1.3 for details.
20171A:
See §2.1.3 for details.
The sensitivity of the instrument is 2 x 1000 V/m/s.

GS-13:
See §3.1.2 for details.
The sensitivity of the instrument is 2000 V/m/s.

7505A/8700C:
See §2.1.3 for details.

STS-1:
The Streckeisen STS-1, designed in 1976, is a VBB seismometer, mainly dedicated to global seismology and strong earthquakes. Its low frequency corner is at 360 s (0.0028 Hz) and its high frequency corner at 10 Hz, making it unsuitable for local (even regional) studies. Some technical specifications of this instrument are the following (Trnkoczy, 1997; Wielandt and Streckeisen, 1982):

Sensitivity	2400 V/m/s
Dynamic range	> 140 dB between 0.0001 and 10 Hz
Clipping level	8 mm/s signal over 0.1 to 360 s period

STS-2:
See §7.1.2 for details.

Generator constant	20000 +/- 200 V/m/s for X,Y,Z

Nanometrics RD-3:
See §2.2.3.4 for details. The RD-3 is a 3-channel 16-bit A/D converter. The version of the digitizers installed at the Hagfors array employs the following filter sequence:

Analog low-pass filter (F2): 5th-order Butterworth	$\omega_c = 2\,\pi\,20$ rad/s
	Q_1=1.61803, Q_2=0.618034
Digital FIR filter (F4): low-pass	f_c = 17 Hz, N = 150, symmetric
Digital IIR filter (F5): high-pass	f_c = 0.08 Hz

F1 in the filter sequence above is the seismometer.

Dynamic range (gain-ranged)	136 dB

In Hagfors, the acquisition computer was synchronized to GPS timing and transmitted a synchronization character to the remote RD3s.

Nanometrics Europa (HRD-24/Authentication):
See §4.1.2 for details.

LSB	874.082 nV/count for BB channel
GPS timing	

Nanometrics Europa T (Trident/Authentication):
See §7.1.2 for details. Some nominal values are the following (Nanometrics, 2004):

Maximum input voltage range	40 Vp-p differential at gain 0.4
Nominal sensitivity	1 count/microV for gain 1.0
Gain selection	0.4, 1, 2, 4, 8 software selectable

8.2 Instrument response calculation for the Hagfors array systems

This chapter focuses on the major considerations to be taken into account for the calculation of the instrument response of the different systems operating at the Hagfors array (HFS).

As with the rest of the systems discussed in this documentation, *GSE* file response *Respid* flags for each configuration are provided at the beginning of each section.

8.2.1 S-13 – RD-3 (1994/12/06 – 2003/09/21)

Respid:	HFSSP1	Z
	HFSSP2	N-S
	HFSSP3	E-W

One variation of the old Hagfors short-period channel configuration consists of the following components:

- S-13 short-period seismometers (horizontals only at HFSC2)
- Nanometrics RD-3 digitizers

8.2.1.1 *S-13*

The response of the Geotech S-13 seismometer is described in detail in section 2.2.7.1 on the NORSAR array. Very little information is available about the old Hagfors instrumentation. Some pole/zero sets provided by FOI (*e.g.*, Bergkvist, pers. comm.) are inconsistent with the standard damping seismometer formula (equation 2.2.2) and when plotted they appear either to correspond to instruments flat to displacement, which is not the case, or produce response curves that do not fit with any documented ones (*e.g.*, FOI, 2001 in Fig. 8.3).

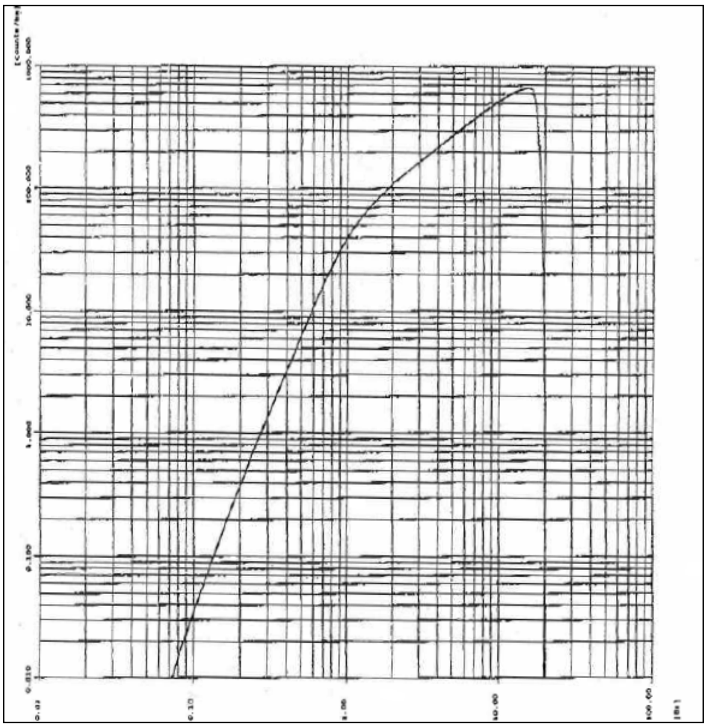


Fig. 8.3 System response for a short-period channel (from FOI, 2001).

No information is provided regarding the seismometer gain either. After several trials with different pole/zero sets, we adopted the same response information as used for the NORSAR array (see §2.2.7.1). Since the overall channel sensitivity is known (Lund and Lennartsson, 2005), the sensor sensitivity varies slightly and the final value is obtained by assuming the required combination of gain in the digitizer amplifiers to achieve the reported values (see next section).

8.2.1.2 *RD-3*

The response of the Nanometrics RD-3 digitizers is described in detail in section 2.2.3.4 on the NORSAR array and sections 5.2.1.2 and 6.2.1.2 on the SPITS and Apatity arrays respectively. As already mentioned in these chapters, the RD-3 is a 16-bit A/D converter. The version employed here has 3 gain steps, which result in a dynamic range of 136 dB. The initial sampling rate is set to 160 sps, while digitized data are filtered and decimated down to 40 sps.

The filters employed in this case are:
- the analog low-pass filter
- the digital low-pass FIR filter and
- the digital high-pass IIR filter

The analog filter used is a 5th order Butterworth low-pass filter with a 3db frequency of 20 Hz. Its transfer function is expressed by the following formula (FOI, 2005):

$$F_2(s) = \frac{\omega_1^5}{(s^2 + \frac{s\omega_1}{Q_1} + \omega_1^2)(s^2 + \frac{s\omega_1}{Q_2} + \omega_1^2)(s + \omega_1)}, \qquad (8.2.1)$$

where $\omega_1 = \omega_{3db} = 2\,\pi\,20$ rad/s,
$Q_1 = 1.61803$ and
$Q_2 = 0.618034$

The digital FIR low-pass filter used to decimate down to the desired sampling rate is a symmetric filter with 150 coefficients and a 3db frequency of 17 Hz. The coefficients can be found listed in the related *GSE* response files.

The high-pass IIR filter that is used together with the above mentioned FIR filter and for a sampling rate of 40 sps has a corner frequency of 0.08 Hz (Nanometrics, 1992), while its characteristics are the following:

$f_c = 0.008$ Hz
a = -0.998749
b = 1.0
gain = 0.999374

The IIR filters employed by Nanometrics are based on a 1st order Butterworth highpass filter converted to digital by applying the bilinear transform for the channel specific sampling rate.

The sensitivity of the short-period channel is reported to be in the order of 0.025 nm/bit at 1 Hz (Lund and Lennartsson, 2005) and is channel specific. Since no information could be obtained either from FOI or NORSAR about the exact settings, a combination of gains was used to achieve these values, taking into account the relevant information in the RD3 User Guide (Nanometrics, 1992). Thus, the Butterworth low-pass filter has been assigned a gain of 2, while an additional gain stage of 30 is introduced to fix the overall sensitivity to the reported levels.

The displacement amplitude and phase response of this configuration is presented in Fig. 8.5 at the end of section 8.2.4.

8.2.2 20171A – RD-3 (1994/12/06 – 2003/09/21)
Respid: HFSSP4 Z

This variation of the old Hagfors short-period system utilizes 20171A vertical sensors, without any other changes to the instrumentation. Thus, the system consists of the following components:

- 20171A short-period seismometers
- Nanometrics RD3 digitizer

8.2.2.1 *20171A*

The response of the Teledyne-Geotech 20171A seismometer is described in detail in section 2.2.9.1 about the NORSAR array. For transfer function and poles and zeros see section 8.2.1.1 of the current chapter.

8.2.2.2 *RD-3*

Information about the RD3 digitizers can be found in section 8.2.1.2 of the current chapter, section 2.2.3.4 on the NORSAR array and section 5.2.1.2 on the SPITS array.

As mentioned also in the previous section, the sensitivity of the short-period channels is in the order of 0.025 nm/count, according to FOI (Lund and Lennartsson, 2005), slightly varying from station to station. As in the previous case, a gain of 2 is assumed for the RD3 Butterworth low-pass filter (Nanometrics, 1992), as well as an additional gain of 30.

The response is identical to that of the previous configuration (with the S-13 seismometer) and will not be plotted separately.

8.2.3 7505A/8700C – RD-3 (1994/12/06 – 2003/09/21)

Respid: HFSLP1 Z
HFSLP2 N-S
HFSLP3 E-W

The 3-component long-period channel of the old Hagfors array is equipped with a vertical 7505A and two horizontal 8700C long-period sensors. So, the system consists of the following components:

- 7505A & 8700C long-period seismometers
- Nanometrics RD-3 digitizer

8.2.3.1 *7505A/8700C*

Detailed information about these instruments can be found in section 2.2.4.1 about the NORSAR array.

As with the short-period channels, the pole-zero information provided by FOI (Bergkvist, pers. comm.) is not consistent with the result of the typical damping seismometer formula (see §2.2.2.1, equation 2.2.4) or any of the available response curves. J. Schweitzer had used calibration information provided by FOI (2005) and reconstructed the curves by using f_0 ~ 0.05 Hz and λ_0 ~ 0.406 and applying equation 2.2.4. The calibration curve for the vertical channel is shown in Fig. 8.4.

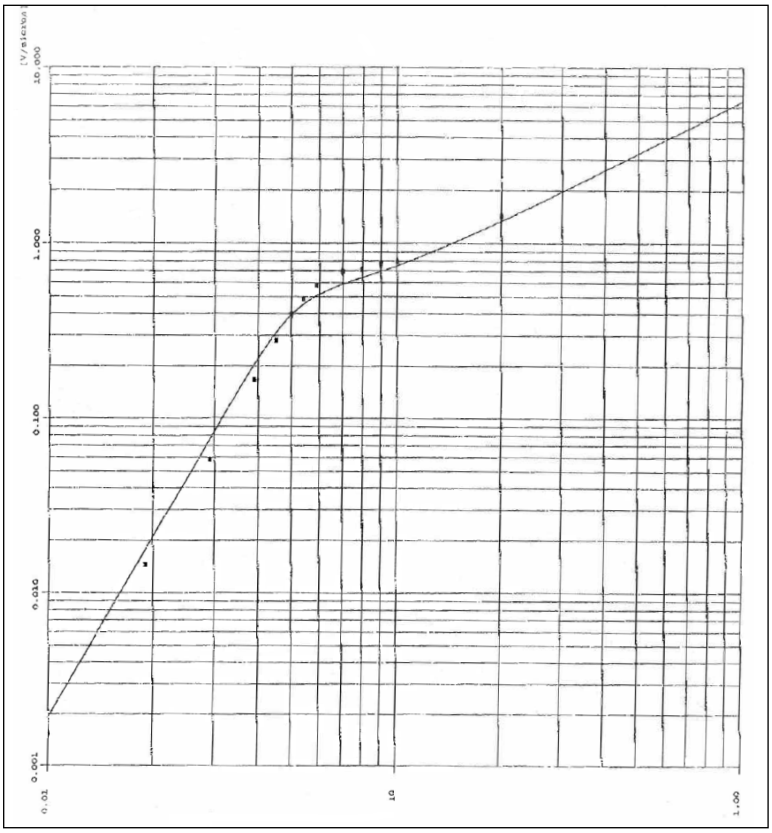


Fig. 8.4 Seismometer displacement amplitude response for the reported and calculated by equation 2.2.4 pole-zero set.

Regarding the seismometer gain, this was again adjusted in the same way as for the short-period channels (§8.2.1.1, this chapter).

8.2.3.2 *RD-3*

Information about the RD-3 digitizer can be found in section 8.2.1.2 of the current chapter, section 2.2.3.4 on the NORSAR array and section 5.2.1.2 on the SPITS array.

The overall sensitivity at 20 s is reported to be equal to 0.34544 nm/count for the vertical channel, 0.32523 nm/count for the N-S channel and 0.35787 nm/count for the E-W channel (Lund and Lennartsson, 2005). Since no information exists on the exact configuration of the system, and following the description in the RD3 User Guide (Nanometrics, 1992), a combination of gains is used internally in the digitizer to achieve the reported sensitivity. A gain of 2 is assigned to the Butterworth low-pass filter, while an additional gain of 30 is attributed to the RD3 differential amplifier.

The displacement amplitude and phase response of this configuration is shown in Fig. 8.5 in the end of section 8.2.4.

8.2.4 STS-1 – RD-3 (1994/12/06 – 2003/09/21)
Respid: HFSBB1 Z

The vertical component broadband channel of the old Hagfors array is equipped with an STS-1 seismometer. So, the system consists of the following components:

- STS-1 broadband seismometer
- Nanometrics RD-3 digitizer

8.2.4.1 *STS-1*

The STS-1V/VBB seismometer is a highly sensitive, remotely controlled sensor for wide-band and long-period recording. The basic response of the instrument is that of a long-period seismometer with 360 s free period and 0.707 critical damping. The response is flat to ground velocity from 0.1 to 360 s period. The entire spectrum of teleseismic signals from 0.1 s to about 1 h period is resolved in the VBB output signal and can be recorded in a single digital data stream when a suitable digitizer is used. However, the version installed at Hagfors is not as broadband, with the response being flat to ground velocity from 0.1 to 28 s period.

The seismometer transfer function for velocity is expressed by the following formula (FOI, 2005, Streckeisen, 1986):

$$T(\omega) = \frac{-\omega^2 S}{-\omega^2 + 2i\omega\omega_1 h_1 + \omega_1^2} \frac{\omega_2^2}{-\omega^2 + 2i\omega\omega_2 h_2 + \omega_2^2}, \qquad (8.2.2)$$

where $\omega_1 = 2\pi/360$ rad/s,
$h_1 = 1/\sqrt{2}$,
$\omega_2 = 2\pi/0.1$ rad/s,
$h_2 = 0.6235$ and
$S = 2400$ V/m/s

The instrument installed at Hagfors has serial number # 28729. Poles and zeros can be found in the corresponding *GSE* response file.

8.2.4.2 *RD-3*

Information about the RD-3 digitizer can be found in section 8.2.1.2 of the current chapter, section 2.2.3.4 on the NORSAR array and section 5.2.1.2 on the SPITS array.

The overall sensitivity for the broadband channel is reported equal to 0.006 nm/bit at 1 Hz (Lund and Lennartsson, 2005). As in the previous cases (§8.2.1, §8.2.2 and §8.2.3), a combination of internal gains in the RD3 has been used to achieve the above mentioned sensitivity value.

The displacement amplitude and phase response for the different channels of the old Hagfors array is shown in Fig. 8.5.

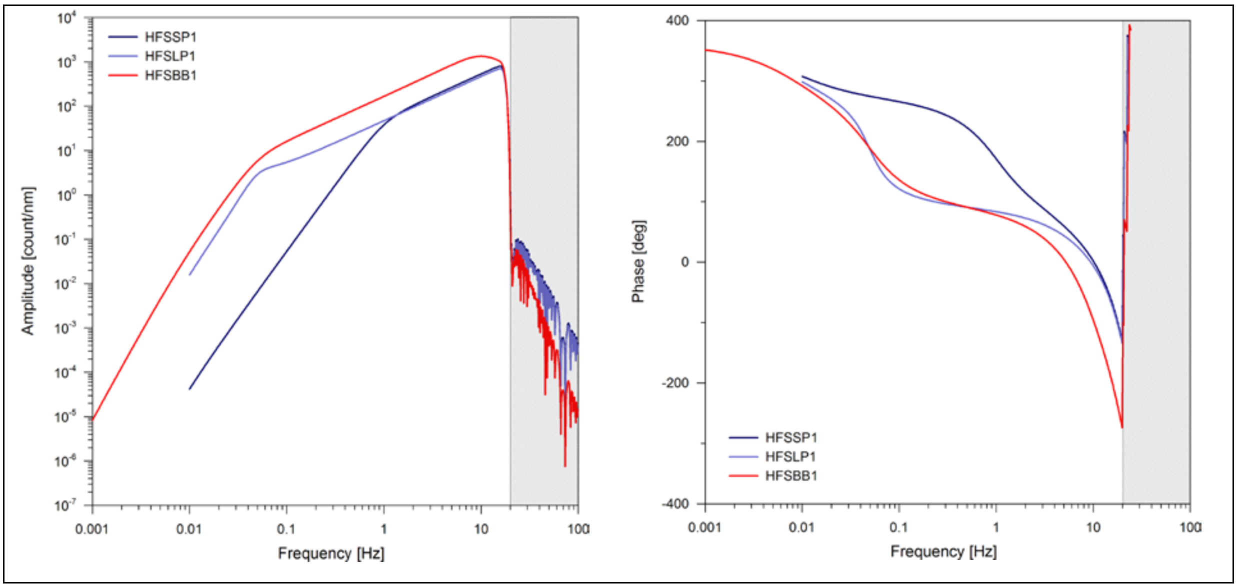


Fig. 8.5. Displacement amplitude (left) and phase (right) response for the old Hagfors array configurations. The short-period array channels (HFSSP1) are noted in blue, the long-period HFSC2 site channel (HFSLP1) in cyan and the old HFSC2 broadband channel (HFSBB1) in red. The curves plotted here correspond to the vertical component of each case, while the short-period response HFSSP4 is identical to HFSSP1 and is not plotted. Shaded areas represent the range beyond the Nyquist frequency (40 Hz for all channels).

8.2.5 GS-13 – Europa (2001/08/24 – …)

Respid: HFSSP5	Z	non amplified
HFSSP6	Z	amplified

The short-period channels of the current Hagfors array have only a vertical component and are equipped with GS-13 seismometers. The system consists of the following components (Nanometrics, 2001):

- GS-13 short-period seismometers
- Preamplifier (for HFSSP6)
- Nanometrics Europa digitizers

8.2.5.1 *GS-13*

Detailed information about these instruments can be found in section 3.2.1.1 about the NORES array and section 4.2.3.1 about the ARCES array.

All sensors have a sensitivity of 2000 V/m/s. The seismometers were to be installed since the beginning with a preamplifier, which was however not delivered at the time by Nanometrics. It was on 4th April 2004 that preamplifiers with a gain factor of 30.23, were installed at all short-period sites, so that the overall channel sensitivity is in the order of 23 count/nm/s (Bergkvist and Lennartsson, 2004; CTBTO, 2004).

8.2.5.2 *Europa*

The Nanometrics Europa digitizer is an HRD-24 digitizer which includes in addition data authentication. Information about the HRD-24 digitizer can be found in section 4.2.3.2 on the ARCES array.

The version installed at Hagfors employs the following filters:

- 3rd order analog low-pass Bessel anti-alias filter with f_{3db} = 1500 Hz (CTBTO, 2004)
- 4 FIR filter stages to achieve a sampling rate of 80 sps:
    - FIR 1: decimating by 5, 34 coefficients
    - FIR 2: decimating by 3, 30 coefficients
    - FIR 7: decimating by 5, 36 coefficients
    - FIR 10: decimating by 5, 256 coefficients
- High-pass digital IIR filter with corner frequency at 10 mHz.

The sensitivity of the digitizer is channel specific and is provided by Lund and Lennartsson (2004).

The displacement amplitude and phase response is shown in Fig. 8.6 at the end of this chapter.

8.2.6 STS-2 – Europa (2001/09/27 – 2012/03/02)

Respid: HFSBB2,3,4 Z, N-S, E-W

HFSBB5,6,7 Z, N-S, E-W

The broadband channel of the current Hagfors array has 3-components and is equipped with an STS-2 seismometer. The system consists of the following components:

- STS-2 broadband seismometer
- Nanometrics Europa digitizer

8.2.6.1 *STS-2*

Detailed information about this instrument can be found in sections 7.2.1.1 and 7.2.2.1 about the Jan Mayen broadband station.

The seismometer installed at HFS has serial number 110042. Instrument specific response information is the following (see also §7.2.2.1 for details):

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

Sensor U:	G/G0 = 0.96996	theta = 54.364°	phi = 180.10°
Sensor V:	G/G0 = 0.99997	theta = 54.973°	phi = 59.979°
Sensor W:	G/G0 = 0.98638	theta = 53.550°	phi = 300.02°

where G/G0 is the normalized generator constant, which is equal to the actual constant divided by 20000 V/m/s. As explained in §7.2.2.1, a sensor sensitivity of 20000 V/m/s at 2 s is used.

Regarding the poles and zeros, the response is divided to a high-frequency (1-100 Hz) and a low-frequency (0.00586-0.10547 Hz) end, as already mentioned in §7.2.2.1.

i) High-frequency end

4 zeros [Hz]:

Sensor U:	-73.50 ± *j*68.29	-31.67	-2.411
Sensor V:	-73.50 ± *j*68.29	-30.29	-2.411
Sensor W:	-73.50 ± *j*68.29	-32.33	-2.411

9 poles [Hz]

Sensor U:	-1629.7 ± *j*433.7	-1514 ± *j*1825.5	-72.34	-76.72	-11.95 ± *j*66.10	-2.451
Sensor V:	-1629.7 ± *j*433.7	-1514 ± *j*1825.5	-72.34	-76.20	-13.01 ± *j*65.12	-2.446
Sensor W:	-1629.7 ± *j*433.7	-1514 ± *j*1825.5	-72.34	-83.55	-11.94 ± *j*65.08	-2.439

ii) Low-frequency end

The model fits a 2^{nd}-order high-pass filter. The corner periods in s and damping constant values are the following:

Sensor U:	119.97	0.7067
Sensor V:	120.03	0.7077
Sensor W:	120.27	0.7084

8.2.6.2 *Europa*

Information on the Europa digitizer can be found in section 8.2.5.2 of the current chapter and section 4.2.3.2 on the ARCES array.

Two different responses are found for the broadband channel of the new Hagfors array. The initial one, corresponding to the time interval autumn 2001 – 29th June 2004, employs a digitizer IIR filter of 10 mHz (HFSBB2,3,4), while the current configuration has an IIR filter of 1 mHz (HFSBB5,6,7).

According to information by FOI (e-mail to Jan Fyen), the digitizer in this configuration is used with unity gain and an LSB of 874.082 nV/count, achieving an overall channel sensitivity of approximately 23 count/nm/s. A value of 864 nV/count is reported by Lund and Lennartsson (2004) and for consistency reasons this will be the value used in the *GSE* response file.

The displacement amplitude (in count/nm) and phase (in degrees) response for this channel is shown in Fig. 8.6 at the end of this chapter.

8.2.7 STS-2 – Europa T (2012/03/02 – …)
Respid: HFSBB8,9,10 Z, N-S, E-W

The broadband channel of the current Hagfors array has 3-components and is equipped with an STS-2 seismometer. The system consists of the following components:

- STS-2 broadband seismometer
- Nanometrics Europa T digitizer

8.2.7.1 *STS-2*

Detailed information about this instrument can be found in sections 7.2.1.1 and 7.2.2.1 about the Jan Mayen broadband station. Regarding the sensor installed at HFS, see section 8.2.6.1.

8.2.7.2 *Europa T*

Information on the Europa T digitizer can be found in section 7.2.2.2 on the JMIC station.

An input voltage of 40 V peak-to-peak combined with a software gain of 2.86 result in a sensitivity of 1.144 count/μV, so that the overall system sensitivity remains comparable throughout the entire Hagfors array (CTBTO, 2012). The chosen configuration has an IIR filter at 1 mHz.

The displacement amplitude (in count/nm) and phase (in degrees) responses for all the different configurations of the vertical componenet of the new Hagfors array described above (HFSSP5, HFSSP6, HFSBB2, HFSBB5 and HFSBB8) are depicted in Fig. 8.6. As always, shaded areas represent the range beyond the Nyquist frequency.

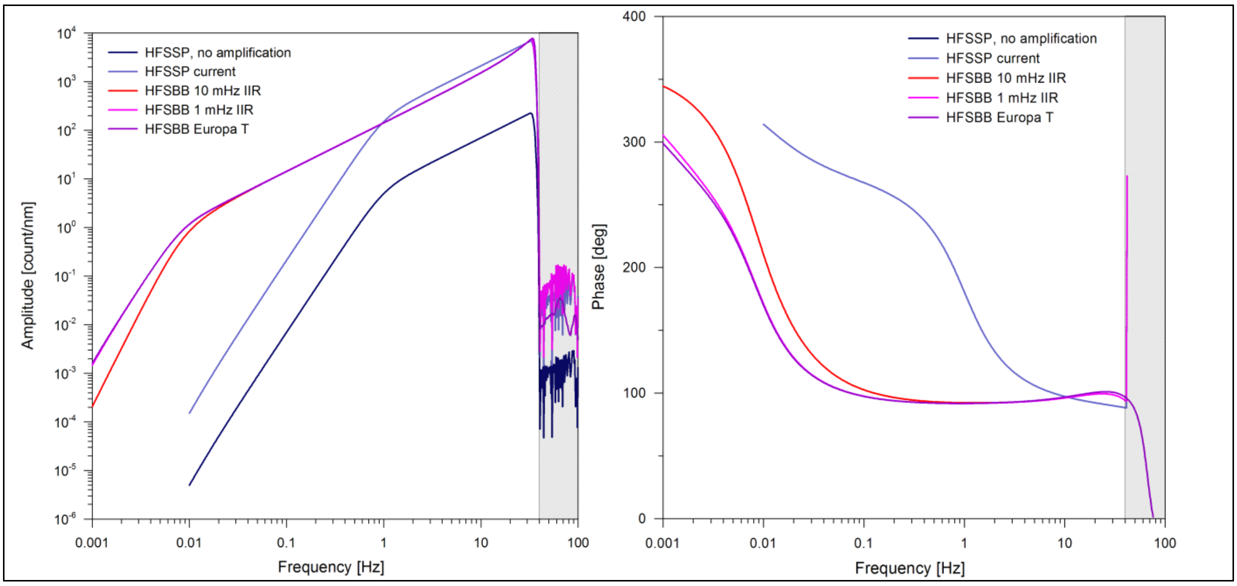


Fig. 8.6. Displacement amplitude (left) and phase (right) response for the new Hagfors array configurations. The short-period array channels (HFSSP) are noted in blue and cyan, while the broadband channels (HFSBB) in red and magenta. The curves plotted here correspond to the vertical component of each case. Shaded areas represent the range beyond the Nyquist frequency (80 Hz for all new Hagfors channels).

8.3 References

Baadshaug, U., Ferstad, B., Hokland, B.Kr., Loughran, L.B., and Paulsen, B., 1995. IMS operation. *NORSAR Semiann. Techn. Summ. 1-95/96*, Kjeller, Norway, p. 67-68.

Bergkvist, N.-O., and Lennartsson, M., 2004. Upgrade of Auxiliary Seismic Stations AS101, Hagfors, Sweden. *Technical Report FOI-R—1310—SE*, 14 pp.

CTBTO, 2004. *Displacement response for Hagfors short-period channels*. Information received via AUTODRM from CTBTO on 08 June 2004.

CTBTO, 2012. *Email exchange between Jan Fyen at NORSAR and support@CTBTO.ORG, 23/03/2012 and previous associated messages*.

FOI, 2005. *Fax transmittions from FOI SYSTEMTEKNIK*, 10 pp.

GSE, 1989. Sourcebook for International Seismic Data Exchange, Description of Seismic Stations, Appendix Three. *Conference Room Paper No. 167/Rev. 1*, May 1989, p. A.121-A.124.

GSE, 1990. Sourcebook for International Seismic Data Exchange, Description of Seismic Stations, Appendix Three. *Conference Room Paper /167/Rev. 2*, April 1991, p. SWE.1-SWE.4.

GSETT3, 1995. Station Information. Chapter 2 under Sweden in Volume Three, Facilities, *Conference Room Paper /243 of GSETT3 Documentation*, p. 3-8.

Lund, B., and Lennartsson, M., 2005. Hagfors Seismic Array Performance Analysis. *Technical Report FOI-R—1309—SE*, 48 pp.

Nanometrics, Inc., 1992. *NORSAR RD3 User Guide. RD3 – 1625, Revision 1.1*, Nanometrics, Inc., Kanata, Ontario, Canada, 61 pp.

Nanometrics, Inc., 2001. System response for CTBTO short period array elements. *Document Number: 13858 Revision 1*, Kanata, Ontario, Canada, 20 pp.

Nanometrics, Inc., 2004. *Europa T Digitizer User Guide.* Nanometrics, Inc., Kanata, Ontario, Canada, 54 pp.

Nedgård, I., 2005. Hagforsobservatoriet, seismologisk verksamhet. *Systemteknik Teknisk rapport FOI-R—1651—SE*, 55 pp.

Streckeisen, 1986. *VBB.MAN, 08-JUL-86 version*, 45 pp.

Trnkoczy, A., 1997. STS-1 and STS-2 sensors in National Seismic Networks. *Application Note #40*, Kinemetrics SA, 4 pp.

Wielandt, E. and Streckeisen, G., 1982. The leaf-spring seismometer: design and performance. *Bull. Seismol. Soc. Am.*, vol. 72, no. 6, p. 2349-2367.

CHAPTER 9: FINES

9.1 Development of FINES systems: instrumentation and responses

Data from the FINES array in Finland contribute regularly to NORSAR's Data Center under a cooperation agreement with the University of Helsinki.

9.1.1 Short description

- 1985-1987:

The small-aperture Finnish Experimental Seismic Array (FINESA) was installed in November 1985 at Sysmä, about 100 km NE of Helsinki, as a cooperative project between the Institute of Seismology of the University of Helsinki and NORSAR (*e.g.*, Ringdal *et al.*, 1987; Uski, 1990). The initial array geometry (Fig. 9.1) comprised 10 short-period elements, with a maximum intersensor separation of about 1.5 km. All sites were equipped with vertical seismometers only, except for FIA1 that had also two horizontal sensors. The instrumentation includes Geotech S-13 seismometers, RA-5 and LTA amplifiers, and 12 bit Kinemetrics DDS-1105 A/D converters (Korhonen *et al.*, 1987).

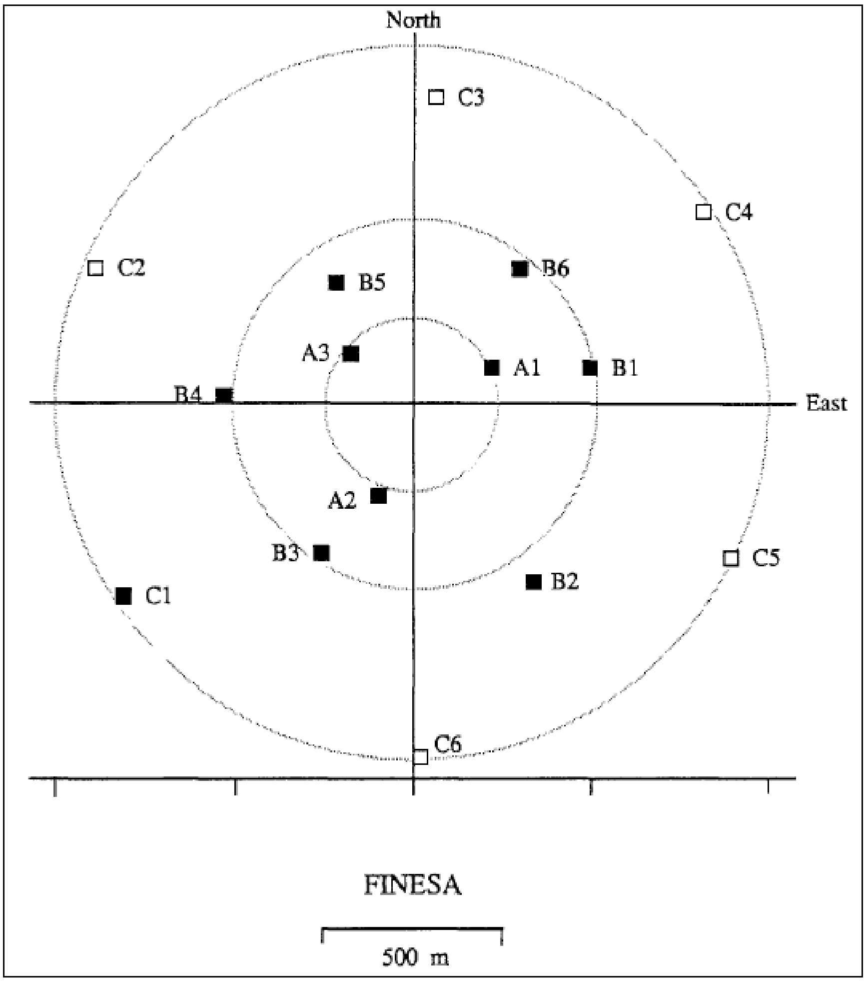


Fig. 9.1. Geometry of the FINESA array (from Uski, 1990). Open squares denote elements added in autumn 1987. The central recording unit is at site A1.

- 1987-1989:
Five additional elements were installed in the FINESA array in autumn 1987 (Mykkeltveit *et al.*, 1988; Uski, 1990). This resulted in three concentric rings of sites, the outer of which had a diameter of approximately 2 km (Fig. 9.1, open squares). The instrumentation remained the same as prior to the addition of the new sites. However, the horizontal sensors at site FIA1 were removed (Paulsen *et al.*, 1989; Uski, 1990).

- 1989-1990:
Seismometers remained the same, but the LTA amplifier was removed and the digitizer was changed to a Motorola based Data Translation A/D converter.

- 1990-1993:
A larger upgrade of the array was underway. One additional site (A0), whose location can be seen in Fig. 9.2, was added to the array in August 1990. Hansen (1990a) reports a change in the array's acquisition system in late 1989, but no further change in instrumentation since a more general refurbishment was planned. The only change appears to be an additional low-gain channel (sl) with an attenuation of -30 dB, operating at the new site and re-opening the horizontal channels at site FIA1 (Hansen, 1990b).

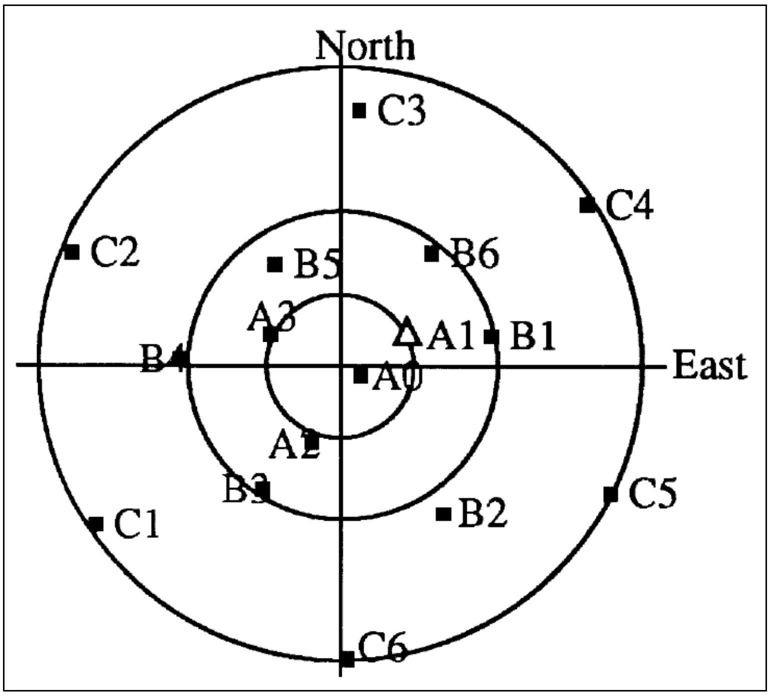


Fig. 9.2. Geometry of the upgraded FINESA array (from Tarvainen, 1994). The 3-component element is denoted with an open triangle.

- 1993-2000:
The upgrade of the array was completed and the system was renamed to FINESS (*e.g.*, Tarvainen, 1994; Tiira *et al.*, 1995). The name FINES will be used instead throughout this document, so that a uniform convention is applied for all regional arrays (ARCES and NORES). As mentioned in the previous paragraph, one element was added including a low-gain channel (sl), while two elements were moved. Horizontal channels were moved to site FIA0. The equipment was modernized, exchanging the old 16-bit digitizers with 24-bit

AIM24 A/D converters (Tiira *et al.*, 1995). It looks like amplifiers were used, although it is unclear which model this was, since it is not documented anywhere.

- 2000-2007:
A 3-component broadband CMT-3T seismometer was added to site FIA1. The final geometry of the FINES array can be seen in Fig. 9.3, where triangles are used to denote the 3-component elements. No amplifier was used for the broadband channel, while the short-period channel instrumentation remained the same.

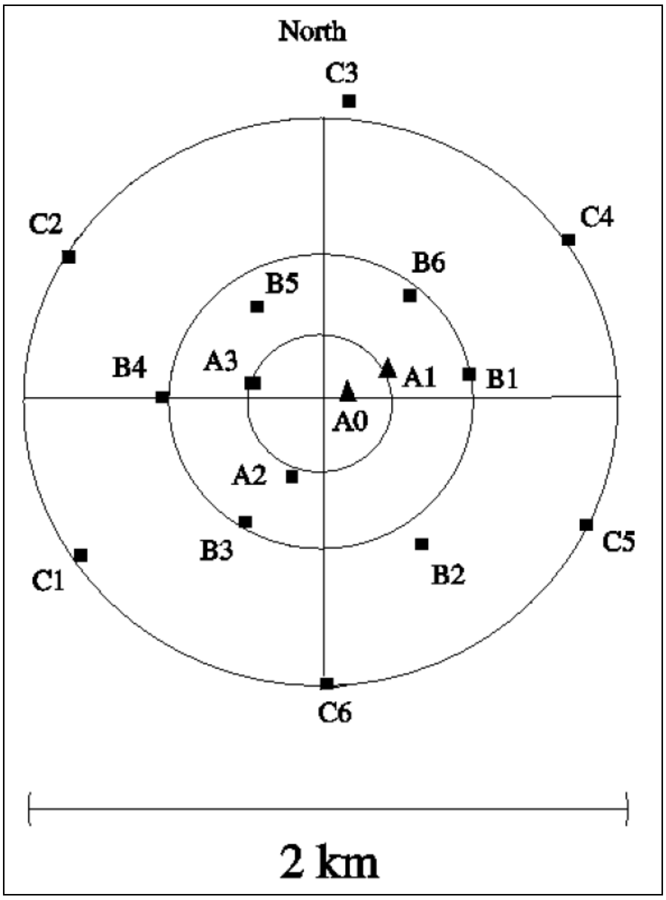


Fig. 9.3. Geometry of the FINES array (from Heikkinen, 2003). 3-component elements are denoted with a triangle. Site FIA1 carries a broadband seismometer.

- 2007-present:
The old digitizers were exchanged with Nanometrics Europa T models. This took place initially for sites FIA0 through FIB4, while the remaining sites were equipped with Europa T digitizers in spring 2009. The CMG-3T sensor was changed in November 2010 to a new one with a slightly different response.

6.1.2 <u>Instrumentation</u>

I. Configurations

- Original SP configuration (1985-1989):

S-13 seismometer
RA-5 amplifier
LTA amplifier
Kinemetrics DDS-1105 digitizer

- 1st Upgraded SP configuration (1989-1993):
  S-13 seismometer
  RA-5 amplifier
  Motorola A/D converter

- Low-gain SP configuration (1990-1993):
  S-13 seismometer
  RA-5 amplifier
  Motorola A/D converter with -30 dB attenuation @ FIA0 (channel sl)

- 2nd Upgraded SP configuration (1993-2007):
  S-13 seismometer
  Amplifier
  SHI AIM24 digitizer

- Current Nanometrics SP configuration (2007-present):
  S-13 seismometer
  Nanometrics preamplifier
  Nanometrics Europa T

- Initial BB configuration (2000-2007):
  CMG-3T seismometer
  SHI AIM24 digitizer

- Upgraded BB configuration (2007-2010):
  CMG-3T seismometer
  Nanometrics Europa T

- Current BB configuration (2010-present):
  CMG-3T seismometer
  Nanometrics Europa T

II. Respids

FINSP1,2,3
FINSP4,5,6
FINSP7,8,9
FINSP10,11,12
FINSL1
FINBB1,2,3
FINBB4,5,6
FINBB7,8,9

S-13:
See §2.1.3 for details. Some nominal values are the following (Laporte, 2006):

Sensitivity:	636.4 V/m/s
Coil resistance:	3704 Ohm
Damping ratio λ_0:	0.707
Critical damping resistance:	6.64 kOhm
Critical damping:	1.0
Open circuit (internal) damping:	0.029
Total damping resistance:	9.509 kOhm

CMG-3T:
See §3.1.2 for details.
The nominal sensitivity of the instrument is 2 x 750 V/m/s.

RA-5 amplifier:
See also §2.1.3.
The reported gain for FINES is 82.7 dB.

LTA amplifier:
See also §2.1.3.
Reported gain is 0.625.

Nanometrics preamplifier:
A gain of 51.236 (= 34.259 dB) is reported for this instrument. It also includes an external damping resistor to be used with the S-13's damping circuit. The following nominal values apply (Laporte, 2006):

Damping resistance:	5.805 kOhm
Standard damping resistance:	5.76 kOhm
Gain-set resistor:	438.13 Ohm

Kinemetrics DDS-1105:
A 12-bit, non gain-ranged A/D converter by Kinemetrics Inc. Some nominal values are the following (Kinemetrics, 1974 in Bungum, 1977):

Input voltage:	± 5 V
Gain:	unity (fixed)

Motorola based A/D converter:
A 16-bit A/D converter card by Data Translation that replaced the DDS-1105.

AIM24 digitizer:
The AIM24 digitizer by Science Horizons Inc. is a 24-bit A/D converter. Details can be found in §2.1.3.

Nanometrics Europa T:
See also §7.1.3 for information. According to documents by PTS (Laporte, 2006) the Europa T in this case carries a Nanometrics Trident digitizer, which is a proprietary high order sigma-delta digitizer. The digital filters employed in the Trident are linear phase filters, which provide a 140 dB attenuation at the output Nyquist frequency. Some nominal values are the following (Nanometrics, 2009):

Input voltage range:	20 V p-p
Input impedance:	43 kOhm
Sensitivity:	5 count/µV for gain 1
Gain selection:	0.4, 1, 2, 4, 8
Dynamic range:	142 dB
Output channels:	1, 2, 3
Output sampling rates:	10, 20, 40, 50, 100, 200, 500 sps
Optional DC removal filter:	1 mHz to 1 Hz, first order

The version of the digitizers installed at FINES employs the following filter sequence:

Digital FIR filter 1:	decimation by 15, N = 177
Digital FIR filter 2:	decimation by 5, N = 71
Digital FIR filter 3:	decimation by 5, N = 113
Digital FIR filter 4:	decimation by 2, N = 223
Gain:	1
Sampling rate:	40 sps

9.2 Instrument response calculation for the FINES systems

This chapter focuses on the major considerations to be taken into account for the calculation of the instrument response of the different systems operating at the FINES array.

As with the NORSAR, NORES, ARCES arrays *etc.*, *GSE* file response *Respid* flags for each configuration are provided at the beginning of each section.

9.2.1 S-13 – DDS-1105 (1985/10/11 – 1989/11/22)

Respid: FINSP1	Z
FINSP2	N-S
FINSP3	E-W

It is unclear whether data from this initial FINES configuration exist at NORSAR, however the response will be discussed, since it helps to understand later configurations. The initial short-period channel configuration consists of the following components:

- S-13 short-period seismometers
- RA-5 amplifiers
- LTA amplifiers
- Kinemetrics DDS-1105 digitizers

9.2.1.1 *S-13*

The response of the Geotech S-13 seismometer is described in detail in section 2.2.7.1. Poles and zeros are provided by the standard damping seismometer formula (equation 2.2.8). Related values are the same as for the NORSAR array, so the poles and zeros are the same.

Regarding the seismometer gain, Fig. 9.4 (Korhonen *et al.*, 1987) displays the succession of components is the FINES instrumentation chain, where the sensor's data coil generator constant is equal to 629 V/m/s.

9.2.1.2 *RA-5*

The response of the RA-5 amplifier is described in detail in section 2.2.1.2. It can be seen in Fig. 9.4 that the gain used at FINES was equal to 82.7 dB, while the system was tuned so that an output of 8.1 V was achieved (Korhonen *et al.*, 1987). There is no information however on the amplifier's filters if any. In section 2.2.1.2 the RA-5 is described as a 1st-order bandpass filter, which should thereby have 2 poles and 1 zero. Since this is inconsistent with the filter information existing in the report by Korhonen *et al.*, the amplifier will be treated as a gain-only stage in the response calculation, while the filter will occupy a separate stage.

9.2.1.3 *LTA*

The response of the Line Terminating Amplifier (LTA) amplifier is described in detail in section 2.2.1.3. In the case of FINES, an input of 8.1 V produced an output of 5.0 V, which was then fed into the digitizer (Fig. 9.4). The same applies for the LTA as for the RA-5 amplifier in terms of possible poles and zeroes. Korhonen *et al.* (1987) report an analog anti-alias filter with 3dB points at 0.7 and 14.5 Hz and slopes of 6 and 30 dB/octave at the low and high ends, respectively, directly before the digitizer, so one could assume this to be part of the LTA amplifier. The existence of such a filter was verified by comparing the resulting displacement amplitude curves (Fig. 9.5) to curves obtained by calibration measurements.

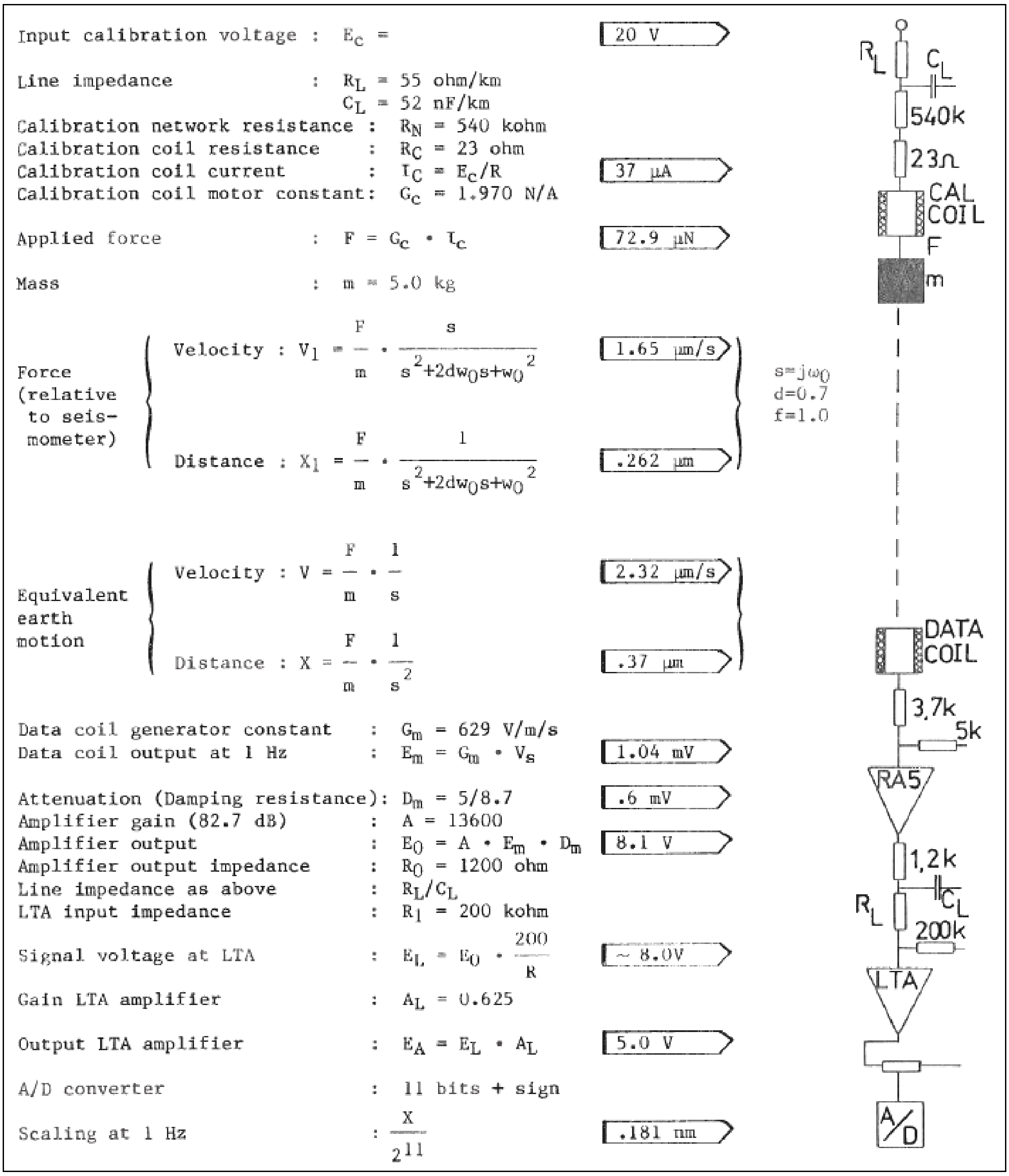


Fig. 9.4. Initial FINES array configuration calibration flowchart (from Korhonen et al., 1987). The entire instrumentation chain is presented, including the A/D converter. The second triplet of equations on the left provides equivalent ground motion for a 1 Hz sinusoidal signal of 20 V peak to peak.

In the corresponding *GSE* response file, the mentioned filter will occupy a separate entry and will not be treated as part of one of the amplifiers (see also previous section on the RA-5).

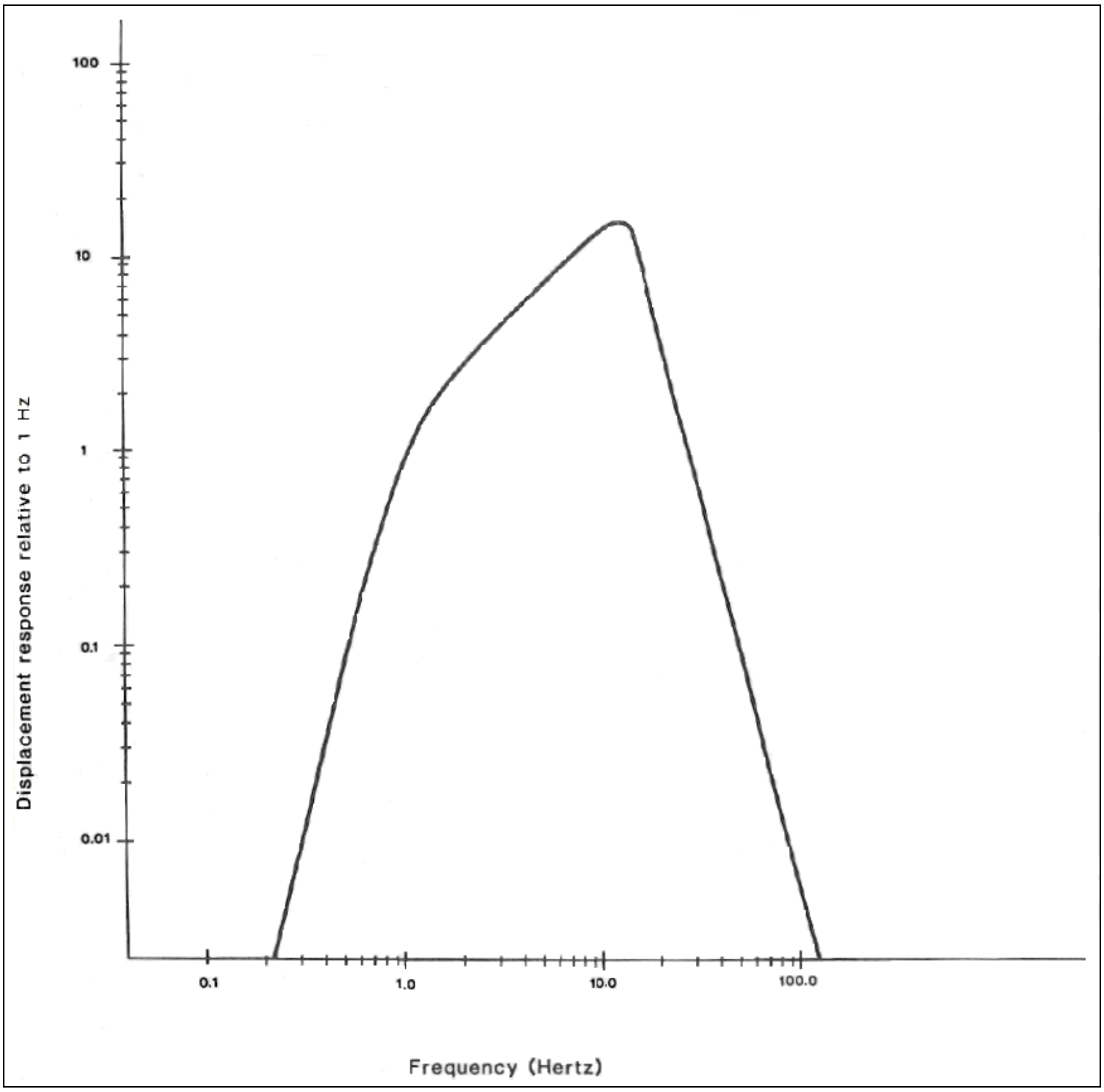


Fig. 9.5. Initial FINES array configuration displacement amplitude response relative to 1 Hz (from Korhonen et al., 1987).

9.2.1.4 *DDS-1105*

Not much information is available regarding the Kinemetrics DDS-1105 A/D converters used with the initial FINES installation. Korhonen *et al.* (1987) report that each recording unit comprises a 12-bit linear A/D converter, a radio receiver for timing, a drum recorder and a magnetic tape transport. As shown in Fig. 9.4, the digitizer scaling at 1 Hz is equal to 0.181 nm/count. The system is not gain-ranged, thus providing data values in the range -2048 to +2048.

The same equipment was used, prior to their deployment in Finland, at the Stiegler's Gorge Seismic Network (*e.g.*, Bungum, 1977) in Tanzania. A data sheet from Kinemetrics describing the DDS-1105 can be found there, confirming the nominal values given above. It also clarifies that the input voltage for the standard system is equal to +/- 5 V.

The displacement amplitude and phase response of this, as well as the other short-period configurations is presented in Fig. 9.8 at the end of section 9.2.4.

9.2.2 S-13 – Motorola A/D (1989/11/22 – 1993/11/18)

Respid: FINSP4	Z
FINSP5	N-S
FINSP6	E-W
FINSL1	Z

The system consists of the following components:

- S-13 short-period seismometers
- RA-5 amplifiers
- Motorola base A/D converters

An attenuated by 30 dB version of the short-period channel (sl) operated at site FIA0 in addition to the standard short-period channels.

9.2.2.1 *S-13*

The response of the Geotech S-13 seismometer is described in detail in section 2.2.7.1 and section 9.2.1.1 of the current chapter. Poles and zeros are taken from Teikari and Suvilinna (1994) and correspond to $\lambda_0 = 0.625$ and $f_0 = 1$ Hz.

9.2.2.2 *RA-5*

Information about the RA-5 amplifier can be found in section 9.2.1.2 of the current chapter and section 2.2.1.2 on the NORSAR array. Again, no information is provided about any filters in the RA-5 that is consistent with what it known from the NORSAR array. However, Teikari and Suvilinna (1994) report poles and zeros for a bandpass filter that fits the description of the one mentioned by Korhonen *et al.* (see section 9.2.1). An amplifier gain of 57.91 dB is used in this case, while a 30 dB reduction is made for the attenuated channel (sl).

9.2.2.3 *Motorola A/D*

Not much information exists on this digitizer, which replaced the DDS-1105, however we know from documents proposing an upgrade of the array instrumentation and corresponding order forms, as well as from Paulsen et al. (1989) that a 16-bit digitizer was ordered. This was a VME-based system manufactured by Force Computers (Motorola), which employed 16-bit A/D cards by Data Translation (model DT1405/5716A). No information is longer available from the manufacturer about their VME compatible products, so the reconstruction of the system's response has been based exclusively on Teikari and Suvilinna (1994). The displacement amplitude response they are reporting and which corresponds to a channel sensitivity of 40.72 count/nm at 1 Hz can be seen in Fig. 9.6.

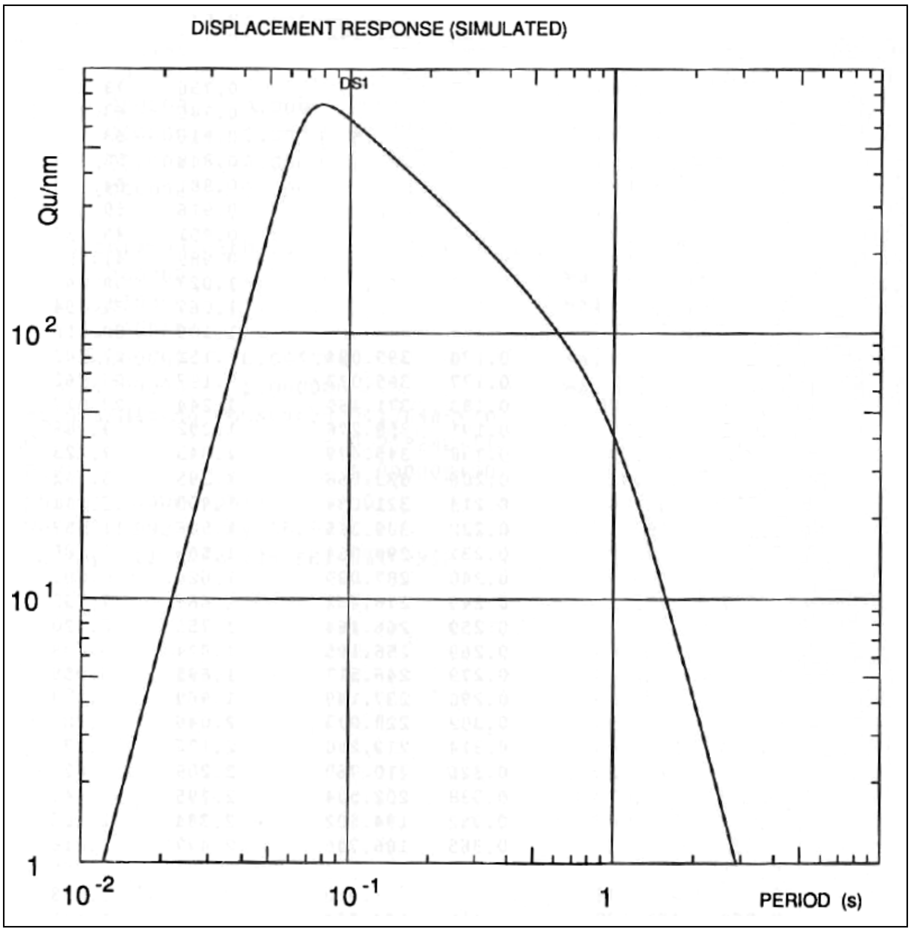


Fig. 9.6. S-13 and Motorola based A/D FINES displacement amplitude response (from Teikari and Suvilinna, 1994).

9.2.3 S-13 – AIM24 (1993/11/18 – 2007/08/17)

Respid: FINSP7	Z
FINSP8	N-S
FINSP9	E-W

The configuration of these channels is equipped with the following components:
- S-13 seismometers
- Amplifiers
- SHI AIM24 digitizers

9.2.3.1 *S-13*

The response of the Geotech S-13 seismometer is described in detail in section 2.2.7.1 and section 9.2.1.1 of the current chapter. For this configuration, Teikari and Suvilinna (1994) are reporting poles and zeros corresponding to $\lambda_0 = 0.69$ and $f_0 = 1$ Hz.

9.2.3.2 *Amplifier*

It is unclear what kind of amplifier was employed with this particular configuration. Teikari and Suvilinna are not providing any extra poles and zeros except from those of the seismometer and no extra normalization factors. However, with our knowledge of the AIM digitizer from the NORSAR array (see §2.2.9.3), an additional gain factor of about 10.5 has to be used in order to achieve the reported channel sensitivity. Thus, a gain-only amplifier stage is added to the response.

9.2.3.3 *AIM24*

The AIM24 digitizer by Science Horizons Inc. is described in detail in §2.2.9.3 about the NORSAR array. No information can be found on FINES-specific settings, so the NORSAR settings will be duplicated for the calculation of the response, tuning the system by the help of an amplifier stage (see previous paragraph) to the channel sensitivity of 0.01 nm/count at 1 Hz reported by Teikari and Suvilinna (1994). The displacement amplitude response, normalized at 5 Hz, which they are describing, can be seen in Fig. 9.7. It is evident that their response calculations do not account for the digital filters of the AIM24 unit.

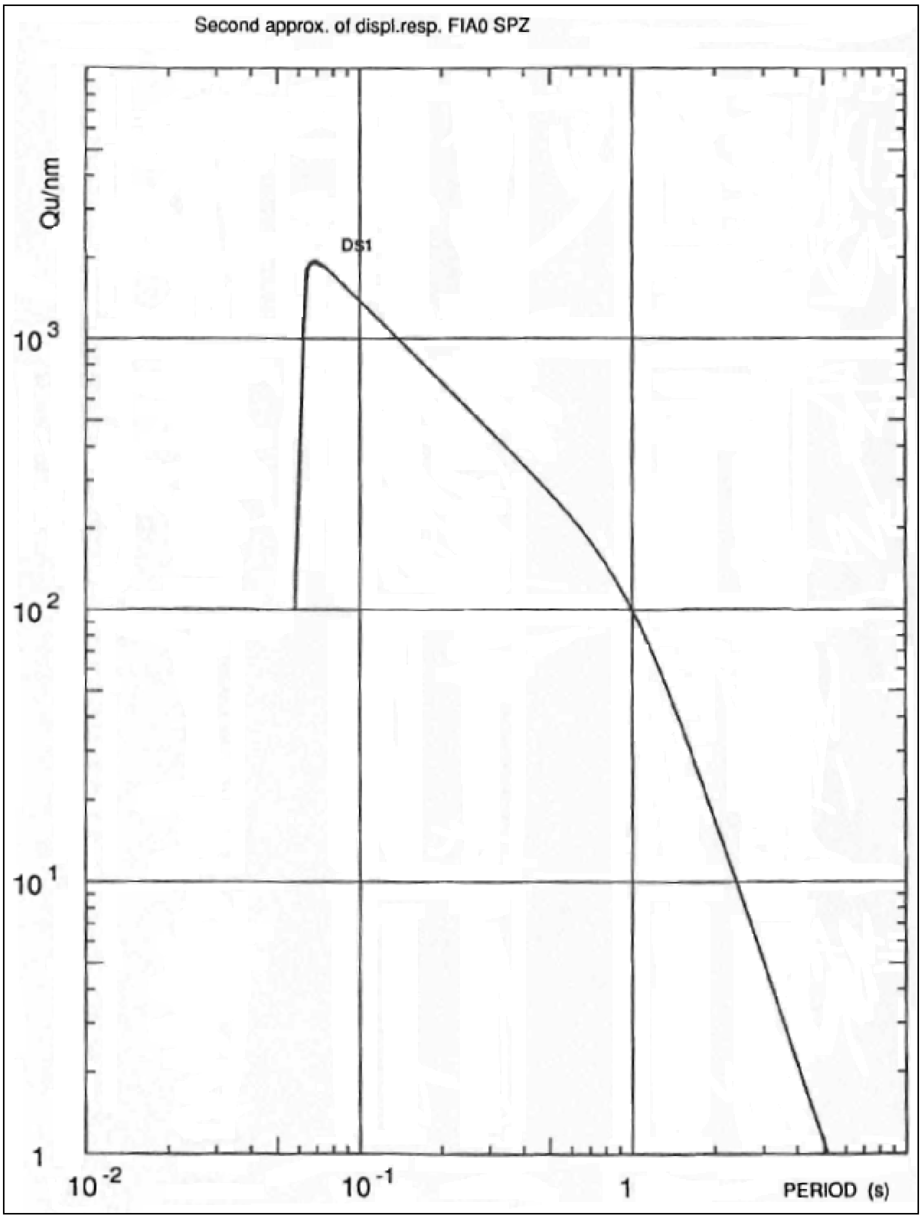


Fig. 9.7. S-13 and AIM24 FINES displacement amplitude response (from Teikari and Suvilinna, 1994).

9.2.4 S-13 – Europa T (2007/08/17 – …)

Respid: FINSP10	Z
FINSP11	N-S
FINSP12	E-W

The configuration of these channels is equipped with the following components:
- S-13 seismometers
- Nanometrics preamplifiers
- Nanometrics Europa T digitizers

Not all sites of the array where upgraded to the Europa T digitizer in 2007, this resulting in a time interval when this configuration was operating in parallel with that of section 9.2.3. Sites FIB5, FIB6, FIC1, FIC2, FIC3, FIC4, FIC5 and FIC6 were upgraded in spring 2009 (J. Korström, pers. comm.).

9.2.4.1 *S-13*

The response of the Geotech S-13 seismometer is described in detail in section 2.2.7.1 and section 9.2.1.1 of the current chapter.

9.2.4.2 *Nanometrics preamplifiers*

A preamplifier by Nanometrics is used together with the S-13 seismometers. The gain is equal to 51.236. The preamplifier includes an external damping resistor to be used with the S-13's damping circuit (Laporte, 2006; J. Kortström, pers. comm.).

9.2.4.3 *Europa T*

The Nanometrics Europa T digitizer has been previously described in §7.2.2.2 about the JMIC station. However, the version installed at the FINES array does not contain an HRD-24, but a Trident A/D converter.

In the case of the short-period channels, the Europa T has a sensitivity of 1.0078 count/μV.

The digitizer employs a series of digital FIR filters to decimate from the frequency of 30 kHz to the desired sampling rate of 40 sps. The filters, which can be found described in detail in the corresponding *GSE* response file, are the following:

FIR 1:	decimation by 15, 177 coefficients, symmetric
FIR 2:	decimation by 5, 71 coefficients, symmetric
FIR 3:	decimation by 5, 113 coefficients, symmetric
FIR 4:	decimation by 2, 223 coefficients, symmetric

An inspection of FINES data shows that they are characterized by high DC-offsets, which means that no IIR DC-offset removal filter is in use.

The displacement amplitude and phase response of all FINES short-period configurations is shown in Fig. 9.8 that follows. Configurations are identified by the corresponding *Respid*, presenting only the vertical channel for each case. As earlier in this manual, the shaded area represents the frequency range beyond the Nyquist frequency.

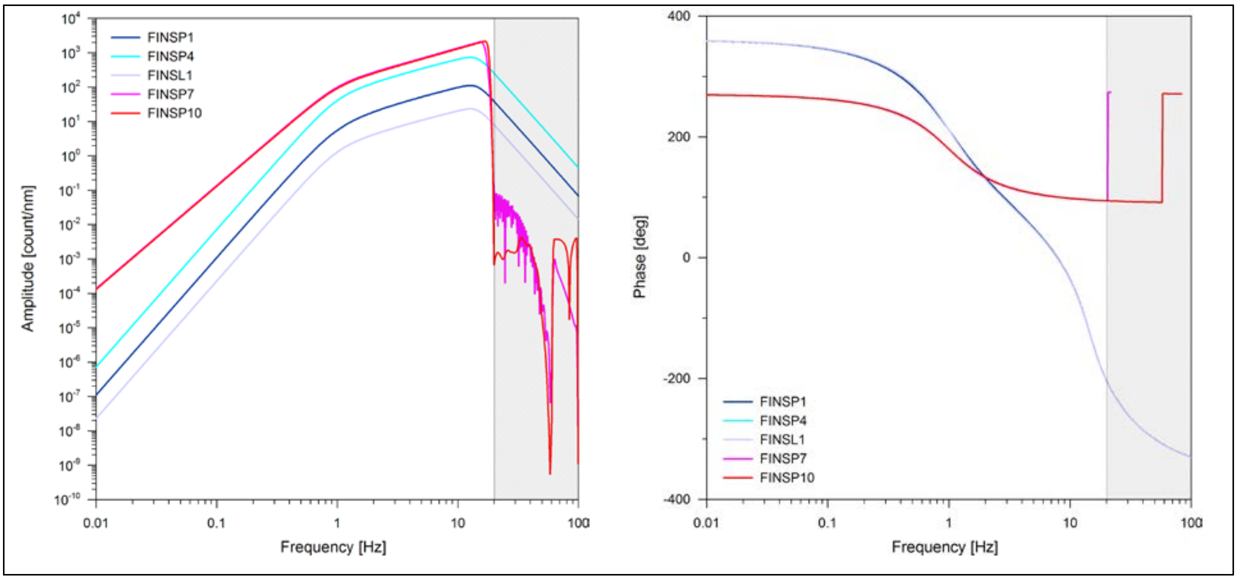


Fig. 9.8. Displacement amplitude (left) and phase (right) response for the FINES array short-period configurations. The initial FINESA configuration is plotted in blue, the second one in cyan and the attenuated by 30 dB channel in light blue. The first FINES configuration is plotted in magenta, while the current in red. The curves correspond to the vertical component of each case. Shaded areas represent the range beyond the Nyquist frequency (20 Hz).

9.2.5 CMG-3T – AIM24 (2000/06/06 – 2007/08/17)

Respid: FINBB1	Z
FINBB2	N-S
FINBB3	E-W

The configuration of the broadband channel is equipped with the following components:

- CMG-3T seismometer
- AIM24 digitizer

9.2.5.1 *CMG-3T*

The instrument installed at the site FIA1 of the FINES array has a serial number of T3474. The poles and zeros describing the velocity response of this instrument are provided by the manufacturer and are the following:

POLES (HZ)	**ZEROS (HZ)**
$-7.07 \times 10^{-3} \pm j7.07 \times 10^{-3}$	0
$-80.5 \pm j30.8$	0
	150.5

Normalizing factor at 1 Hz: A = -49.5

Regarding poles and zeros, values are listed in units of Hz. They need to be multiplied with 2π to be converted to rad/s. The same change applies for the normalizing factor.

The sensor sensitivity is reported by Güralp equal to:

Z	2x769 V/m/s
N-S	2x746 V/m/s
E-W	2x740 V/m/s

9.2.5.2 *AIM24*

The AIM24 digitizer by Science Horizons Inc. is described in detail in §2.2.9.3 about the NORSAR array and §9.2.3.3 of the current chapter.

The displacement amplitude and phase response is shown in Fig. 9.9 at the end of the chapter.

9.2.6 CMG-3T – Europa T (2007/08/17 – 2010/03/11)

Respid: FINBB4	Z
FINBB5	N-S
FINBB6	E-W

The configuration of the broadband channel is equipped with the following components:

- CMG-3T seismometer
- Nanometrics Europa T digitizer

9.2.6.1 *CMG-3T*

The response of the Güralp CMG-3T sensor installed at FINES is described in the previous section (§9.2.5.1).

The following sensitivity values at 1 Hz are reported according to a system calibration performed in May 2009 (J. Kortström, pers. comm.):

Z	1212.91 V/m/s
N-S	1647.09 V/m/s
E-W	1489.79 V/m/s

9.2.6.2 *Europa T*

The response of the Europa T digitizer by Nanometrics Inc. installed at FINES is described in section §9.2.4.3 of the current chapter.

For the broadband channel, the digitizer is used without preamplifier or external damping resistor and has a sensitivity of 4.8 count/µV, according to a system calibration performed in May 2009 (J. Kortström, pers. comm.).

9.2.7 CMG-3T – Europa T (2010/03/11 – …)

Respid: FINBB7 Z
FINBB8 N-S
FINBB9 E-W

The configuration of the broadband channel is equipped with the following components:

- CMG-3T seismometer
- Nanometrics Europa T digitizer

Seemingly, this response is the same with the one described in section 9.2.6, however the CMG-3T sensor needed to be replaced, and the new one has both a different pole-zero set and sensitivity.

9.2.7.1 *CMG-3T*

The Güralp CMG-3T sensor currently installed at FINES has serial number T36311. The poles and zeros for this particular instrument are the following, as provided by the manufacturer:

POLES (HZ)	**ZEROS HZ**
$-5.89 \times 10^{-3} \pm j5.89 \times 10^{-3}$	0
-180	0
-160	
-80	

Normalizing factor at 1 Hz: A = 2304000

As usual, the pole and zero values are listed in units of Hz. They need to be multiplied with 2π to be converted to rad/s. The same change applies for the normalizing factor.

The sensor sensitivity is reported by the same source equal to:

Z	2x744 V/m/s
N-S	2x747 V/m/s
E-W	2x747 V/m/s

9.2.7.2 *Europa T*

The response of the Europa T digitizer by Nanometrics Inc. installed at FINES is described in section §9.2.4.3 of the current chapter.

The digitizer settings are the same as those for the previous system response, described in section 9.2.6.2.

Fig. 9.9 shows the displacement amplitude and phase response for the current and earlier FINES broadband channels. Note the change in phase response introduced by the pole-zero set of the new CMG-3T seismometer.

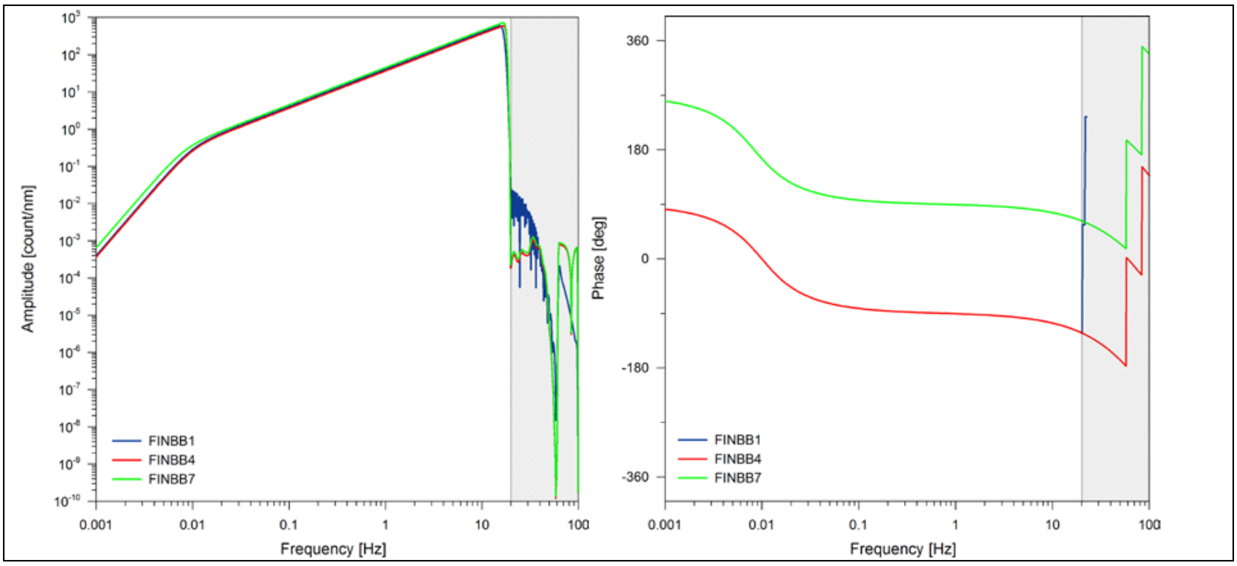


Fig. 9.9. Displacement amplitude (left) and phase (right) response for the FINES array broadband configurations. The first broadband configuration is plotted in blue, the second in red and the current in green. The curves correspond to the vertical component of each case. Shaded areas represent the range beyond the Nyquist frequency (20 Hz).

9.3 References

Bungum, H., 1977. Stiegler's Gorge Seismic Network. *NORSAR Techn. Report 2/77*, Kjeller, Norway, 140 pp.

Hansen, O.A., 1990a. Maintenance activities. *NORSAR Semiann. Techn. Summ. 2-89/90*, Kjeller, Norway, p. 43-47.

Hansen, O.A., 1990b. Maintenance activities. *NORSAR Semiann. Techn. Summ. 1-90/91*, Kjeller, Norway, p. 50-54.

Heikkinen, P. (Ed.), 2003. *Annual Report 2002.* Institute of Seismology, University of Helsinki, Helsinki, Finland, 35 pp.

Korhonen, H., Pirhonen, S., Ringdal, F., Mykkeltveit, S., Kværna, T., Larsen P.W., and Paulsen, R., 1987. The FINESA array and preliminary results of data analysis. *Univ. Helsinki, Institute of Seismology, Report S – 16*, 69 pp.

Laporte, M., 2006. System noise study, CTBTO – PS17 FINES, Lahti, Finland, Short Period Element. *Document EC16003R1.mcd, Initial Release*, 31 pp.

Mykkeltveit, S., Fyen, J., Kværna, T., and Uski, M., 1988. Analysis of regional seismic events using the NORESS/ARCESS/FINESA arrays. *NORSAR Semiann. Techn. Summ. 1-88/89*, Kjeller, Norway, p. 74-87.

Nanometrics Inc., 2009. Trident digitiser. *Trident.pdf*, Nanometrics Inc., Kanata, Ontario, Canada, 4 pp.

Paulsen, R., Fyen, J., Larsen, P.W., and Mykkeltveit, S., 1989. A new data acquisition system for FINESA. *NORSAR Semiann. Techn. Summ. 1-89/90*, Kjeller, Norway, p. 74-82.

Ringdal, F., Mykkeltveit, S., Kværna, T., Paulsen, R., Korhonen, H., and Pirhonen, S., 1987. Initial results from data analysis using the FINESA experimental small aperture array. *NORSAR Semiann. Techn. Summ. 2-86/87*, Kjeller, Norway, p. 59-83.

Tarvainen, M., 1994. The capability of three-component substation FIA1 at local and regional distances. Comparisons with FINESA and Helsinki bulletins. *Annali di Geofisica*, vol. 37, no. 3, p. 267-285.

Teikari, P., and Suvilinna, I., 1994. Seismic stations in Finland 1993. *Univ. Helsinki, Institute of Seismology, Report T – 58*.

Tiira, T., Tarvainen, M., and Tuppurainen, A., 1995. Noise characteristics of the upgraded FINESS array. *Geophysica*, vol. 31, p. 71-84.

Uski, M., 1990. Event detection and location performance of the FINESA array in Finland. *Bull. Seismol. Soc. Am.*, vol. 80, no. 6, part B, p. 1818-1832.

CHAPTER 10: ÅKNES BROADBAND STATION

10.1 Development of AKN broadband station systems: instrumentation and responses

10.1.1 Short description

- 2009-2013:

In the end of October 2009 a broadband 3-C station (AKN) was installed on the rockslope at Åknes, close to Stranda, Møre og Romsdal, to complement the rockslide monitoring network. The station is equipped with a Güralp CMG-3ESPC seismometer and a CMG-DM24S6DCM unit, which combines a DM24 digitizer and EAM data communications module (Güralp, 2009).

The location of the station is shown in Fig. 10.1

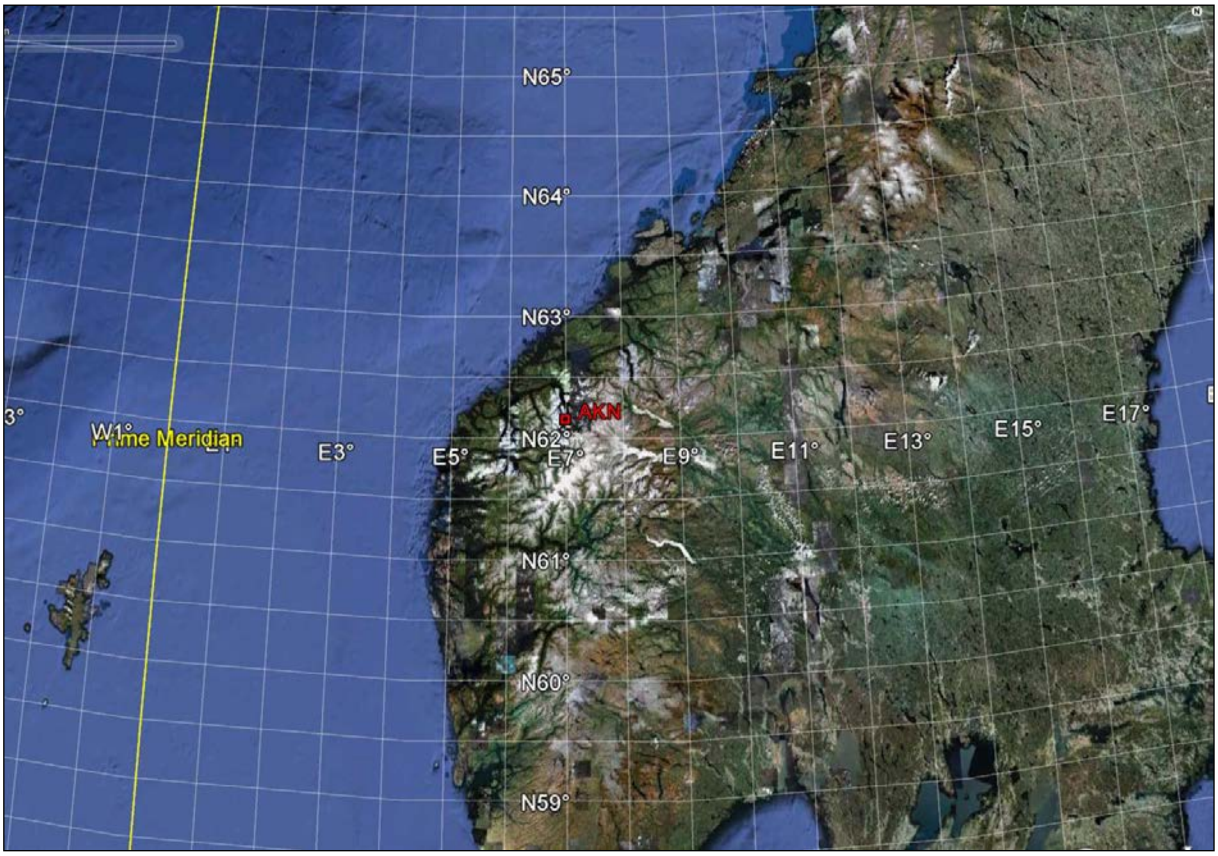


Fig. 10.1. Map showing the location of the AKN station (satellite image from GoogleEarth).

- 2013-…:

In January 2013, an additional data stream, with a lower sampling rate (40 sps in addition to 200 sps) started to be acquired. The channel names were changed and consequently the *Respids*, but the response of the high sampling rate channels remains the same.

10.1.2 Instrumentation

I. Configurations

- AKN BB configuration (2009-…):
  CMG-3ESPC seismometer
  DM24 digitizer

II. Respids

AKNBH1,2,3
AKNHH1,2,3
AKNBH4,5,6

III. Instrument specifications

CMG-3ESPC:
Three-component, compact version, broadband seismometer by Güralp. The specifications for the vertical channel of the instrument installed at Åknes (serial number T35812, work order 4813) are the following:

Velocity output	2x962 V/m/s (differential)
Poles (Hz)	0.074 ± j 0.074
	1005.31
	502.655
	1130.973
Zeros (Hz)	0.0 0.0
Normalizing factor	2304000 @ 1 Hz

CMG-DM24 digitizer:
Detailed information on the DM24 digitizer can be found in section 5.1.2 about the SPITS array. The instrument installed at the AKN station (serial number B729) is part of a CMG-DM24S6DCM digitizer and data acquisition unit. Some nominal values are the following (Güralp, 2009):

Resolution	24-bit
Number of channels	7 (6 primary, 1 auxiliary)
Input voltage range	± 10 V differential
Velocity channel sensitivity	3.194 µV/count (vertical component)

10.2 Instrument response calculation for the Åknes broadband station systems

This chapter focuses on the major considerations to be taken into account for the calculation of the instrument response of the different systems operating at the Åknes broadband station.

As with the rest of the NORSAR systems, GSE file response *Respid* flags for each configuration are provided at the beginning of each section.

10.2.1 CMG-3ESPC – DM24 (2009/11/01 – 2013/01/17)

Respid:	AKNBH1	Z
	AKNBH2	N-S
	AKNBH3	E-W

The Åknes station configuration consists of the following components:

- CMG-3ESPC broadband 3-component, compact seismometer
- DM24 digitizer

10.2.1.1 *CMG-3ESPC*

Instrument response information for ground velocity is provided by the manufacturer (Güralp Systems, Ltd.) in the form of poles and zeros, while sensitivity values are provided on a calibration sheet shipped together with the equipment.

Poles and zeros for the shipment with serial number T35812 (work order 4813) are listed in the following table:

POLES (HZ)	ZEROS HZ
$-11.78 \times 10^{-3} \pm j11.78 \times 10^{-3}$	0
-160	0
-80	
-180	

Normalizing factor at 1 Hz: A = 2304000

Instrument output is equal to:

	Velocity Output V/m/s (Differential)	Mass Position Output (Acceleration output) $V/m/s^2$	Feedback Coil Constant $Amp/m/s^2$
VERTICAL	2 x 962	738	0.01571
N-S	2 x 973	758	0.01613
E-W	2 x 973	761	0.0162

The factor of 2 in the sensitivity estimate is used because of sensor outputs being used differentially.

Poles and zeros are listed in units of Hz. They need to be multiplied with 2π to be converted to rad/s which is the accepted unit in the *GSE* response file. The same change applies for the normalizing factor.
Total sensor sensitivity at 1 Hz will then be equal to: G = (sensitivity) x (norm. factor)

10.2.1.2 *CMG-DM24*

The AKN station is equipped with a Güralp CMG-DM24S6DCM digitizer and communications unit, which consists of a DM24 digitizer and an EAM data acquisition module. Only the digitizer response is relevant and will be discussed further in this section.

Detailed information about the DM24 digitizer (mk3) can be found in section 5.2.4.2 about the SPITS array. In the case of Åknes, the output sample rate is 200 sps, so the digitizer filter chain is the following (Güralp, 2006) for TTL = 39:

- FIR filter SINC-1 (symmetric) with 18 coefficients, decimating by 8 down to 64 kHz from an input rate of 512 kHz.
- FIR filter SINC-2-stage-3 (symmetric) with 3 coefficients, decimating by 2
- FIR filter SINC-2-stage-4 (symmetric) with 7 coefficients, decimating by 2
- filter FIR-1-set0 (symmetric) with 24 coefficients, decimating by 4
- filter FIR-2-set0 (symmetric) with 63 coefficients, decimating by 2
- filter DM24-tap0 (symmetric) with 501 coefficients, decimating by 2
- filter DM24-tap1 (symmetric) with 501 coefficients, decimating by 5 down to the desired sampling rate of 200 sps

All filter coefficients can be found in the corresponding *GSE* response file.

According to the calibration sheet provided by Güralp Systems, Ltd., the sensitivity of the digitizer (serial number B729, work order 5100) is equal to:

VELOCITY CHANNELS

Channel:	B729Z2	Vertical	3.194 µV/Count
	B729N2	North/South	3.201 µV/Count
	B729E2	East/West	3.197 µV/Count

The displacement amplitude and phase response of the above described configuration are displayed in Fig. 10.2 at the end of the chapter, under *Respid* AKNHH1 (deep blue), since the two responses are identical. The plotted response corresponds to the vertical channel and is shown up to the Nyquist frequency, which is equal to 100 Hz.

10.2.2 CMG-3ESPC – DM24 (2013/01/17 – …)

Respid: AKNHH1	Z
AKNHH2	N-S
AKNHH3	E-W
AKNBH4	Z
AKNBH5	N-S
AKNBH6	E-W

The Åknes station configuration consists of the following components:

- CMG-3ESPC broadband 3-component, compact seismometer
- DM24 digitizer

From January 2013 on, data streams of 40 sps started to be acquired, in addition to the 200 sps data streams. Thus, the higher sampling rate channels were renamed to HHZ, HHN, HHE, in accordance to international standards, and the BHZ, BHN, BHE channels names were assigned to the 40 sps data streams.

10.2.2.1 *CMG-3ESPC*

The instrument response of this sensor is described in section 10.2.1.1.

10.2.2.2 *CMG-DM24*

The response of the digitizer is described in detail in section 10.2.1.2.

In the case of the HH-channels (200 sps), the digitizer filter chain is the same as described in section 10.2.1.2, while for the 40 sps sampling rate an additional tap was installed. The cascade is the following (Güralp, 2006) for TTL = 39:

- FIR filter SINC-1 (symmetric) with 18 coefficients, decimating by 8 down to 64 kHz from an input rate of 512 kHz.
- FIR filter SINC-2-stage-3 (symmetric) with 3 coefficients, decimating by 2
- FIR filter SINC-2-stage-4 (symmetric) with 7 coefficients, decimating by 2
- filter FIR-1-set0 (symmetric) with 24 coefficients, decimating by 4
- filter FIR-2-set0 (symmetric) with 63 coefficients, decimating by 2
- filter DM24-tap0 (symmetric) with 501 coefficients, decimating by 2
- filter DM24-tap1 (symmetric) with 501 coefficients, decimating by 5 down to the desired sampling rate of 200 sps (HH-channels)
- filter DM24-tap2 (symmetric) with 501 coefficients, decimating by 5 down to the desired sampling rate of 40 sps (BH-channels)

All filter coefficients can be found in the corresponding *GSE* response file.

The displacement amplitude and phase response of the above described configurations are displayed in Fig. 10.2. The plotted response corresponds to the vertical channel and is shown up to the Nyquist frequency, which is equal to 100 Hz, for the 200 sps channel, while the range beyond the Nyquist for the 40 sps channel is noted with a shaded rectangle.

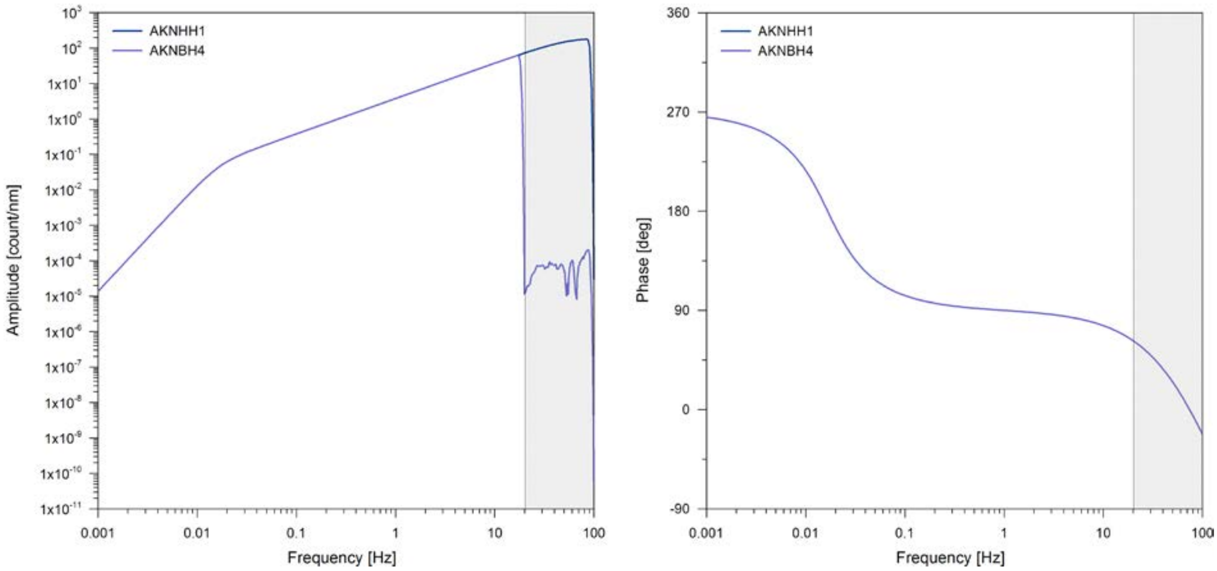


Fig. 10.2. Displacement amplitude (left) and phase (right) response for the vertical component of the AKN broadband station. The response for the 200 sps channel (AKNHH1) is plotted only up to the Nyquist frequency (100 Hz), while the range beyond the Nyquist for the 40 sps channel (AKNBH4) is noted with the shaded rectangle. Response AKNBH1 (section 10.2.1) is identical to AKNHH1, so it is not shown in an own plot.

10.3 References

Güralp Systems, 2006. CMG-DM24 Mk3 Digitizer Operator's Guide. *MAN-D24-0004*, Güralp Systems Ltd., Aldermaston, England, 122 pp.

Güralp Systems, 2009. CMG-DM24S6DCM Digitizer and Communications Module. *DAS-D24-0009*, Güralp Systems Ltd., Aldermaston, England, 11 pp.

CHAPTER 11: HORNSUND BROADBAND STATION

11.1 Development of HSPBB & HSPB broadband station systems: instrumentation and responses

11.1.1 <u>Short description</u>

- 2007-2009:

A new broadband seismic station with the provisional name HSPBB was installed at Hornsund, Spitsbergen, in September 2007, within the frame of the IPY project “The dynamic continental margin between the Mid-Atlantic-Ridge system (Mohns Ridge, Knipovich Ridge) and the Bear Island region”. The station, which is a collaborative effort between NORSAR and the Institute of Geophysics of the Polish Academy of Sciences, is located close to the Polish Polar Station Hornsund. Original instrumentation involved an STS-2 3-C broadband seismometer and a Güralp DM24 digitizer. The station outputted three different channels with sampling rates of 100 (HH), 10 (BH) and 1 (LH) sps (Wilde-Piórko *et al.*, 2009).

Fig. 11.1. The STS-2 seismometer installed at the Hornsund station and the location of the station on an outcrop of bedrock (photos by J. Schweitzer).

- 2009-…:

In August 2009, the digitizer was changed to an MK-6 A/D converter designed and manufactured at the Institute of Geophysics of the Polish Academy of Sciences. Only the 100 sps channels are supported. The station name was changed to HSPB, as registered at ISC and NEIC.

11.1.2 <u>Instrumentation</u>

I. Configurations

- HSPBB configuration (2007-2009):
  - STS-2 seismometer
  - DM24 digitizer

- HSPB configuration (2009-…):
  - STS-2 seismometer
  - MK-6

II. Respids

HSPHH1,2,3
HSPBB1,2,3
HSPLP1,2,3
HSPBB4,5,6

III. Instrument specifications

STS-2:
Streckeisen very broadband triaxial seismometer. 3 identical obliquely-oriented mechanical sensors are employed, instead of the traditional arrangement of separate orthogonal vertical and horizontal sensors. The version installed at Hornsund has the following characteristics (nominal values; Streckeisen, 1995, 2003):

Seismic output (flat velocity)	8.33 mHz – 50 Hz
Mass	0.3 Kg
Gain	1500 V/m/s @ 2 s
Damping	0.707 (low frequencies, < 1 Hz)
Feedback coil	50 N/A

DM24 digitizer:
Güralp DM24 Mk3 digitizer. Detailed information can be found in section 5.1.2 on the SPITS array and section 10.1.2 on the Åknes station. The instrument installed at the Hornsund station (serial number B794, work order 4007) has the following sensitivity for the velocity channels:

Sensitivity (vertical)	3.203 µV/count
Sensitivity (N-S)	3.200 µV/count
Sensitivity (E-W)	3.197 µV/count

MK-6 digitizer:
A/D converter designed and manufactured at the Institute of Geophysics of the Polish Academy of Sciences. The version installed at the HSPB station has the following characteristics:

Resolution	26-bit
Sensitivity	298.02 nV/count
Input sampling rate	12.8 kHz

The digitizer employs the following filters:

An analog low-pass filter (pac12anf)
A series of FIR filters decimating down to the desired output sampling rate

11.2 Instrument response calculation for the Hornsund broadband station systems

This chapter focuses on the major considerations to be taken into account for the calculation of the instrument response of the different systems operating at the Hornsund broadband station.

As with the rest of the NORSAR systems, *GSE* file response *Respid* flags for each configuration are provided at the beginning of each section.

11.2.1 STS-2 – DM24		(2007/09/22 – 2009/08/19)
Respid:	HSPHH1,2,3	Z, N-S, E-W
	HSPBB1,2,3	Z, N-S, E-W
	HSPLP1,2,3	Z, N-S, E-W

The initial Hornsund station (HSPBB) configuration consists of the following components:

- STS-2 broadband 3-component seismometer
- DM24 digitizer

Three different sampling rates were outputted: 100 sps (HH channel), 10 sps (BB channel) and 1 sps (LP channel). Output of 1 sps data commenced a day later, on 23/09/2007. Only the digitizer FIR filters changed between these different data streams and the corresponding filter sequences will be provided in section 11.2.1.2.

11.2.1.1 *STS-2*

Detailed information regarding the response of the Streckeisen STS-2 very broadband triaxial seismometer is provided in sections 7.2.1.1 and 7.2.2.1 on the Jan Mayen broadband station.

For the Hornsund station, the serial number of the seismometer is 60702, which according to information by the manufacturer, corresponds to a Generation 3 instrument (see also Fig. 7.3). The particular characteristics of the transfer function of this type of STS-2 sensor are listed below (Streckeisen, 1995, 2003):

The generator constant values for X, Y and Z are equal to: 1500 ± 15 V/m/s

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

Sensor U:	G/G0 = 1.0486	theta = 54.544°	phi = 179.79°
Sensor V:	G/G0 = 1.0525	theta = 54.458°	phi = 59.844°
Sensor W:	G/G0 = 1.0516	theta = 54.311°	phi = 299.73°

where G/G0 is the normalized generator constant, equal to the actual constant divided by 1500 V/m/s. The employed sensitivity is 1500 V/m/s at 2 s, as explained in §7.2.2.1.

Following the procedure described in sections 7.2.1.1 and 7.2.2.1, resulting generator constant values for the three components are the following:

Z:	1576.3 V/m/s
N-S:	1578.1 V/m/s
E-W:	1574.6 V/m/s

The poles and zeros in Hz for this particular instrument, calculated as described in sections 7.2.1.1 and 7.2.2.1, are the following:

Poles (11)	Zeros (4)
-4.55×10^{2}	$-461.8 \pm j\ 429.1$
$-1.024 \times 10^{4} \pm j\ 2.725 \times 10^{3}$	-191.1
-424.5	-15.15
$-99.7 \pm j\ 391.5$	
$-9.513 \times 10^{3} \pm j\ 1.147 \times 10^{4}$	
-15.46	
$-0.037 \pm j\ 0.037$	

11.2.2.2 *DM24*

The Güralp DM24 digitizer is described in detail in section 5.2.4.2 on the SPITS array. The unit installed at Hornsund with serial number B794 has the following sensitivity for the velocity channels:

Z: 3.203 µV/count
N-S: 3.200 µV/count
E-W: 3.197 µV/count

As already mentioned, three different sampling rates were outputted for the initial configuration at Hornsund, which means that a particular cascade of digitizer filters with different taps for each case is employed. Fig. 11.2 (Güralp Systems, 2009) shows the standard and variable parts of the FIR filter cascade for a DM24 Mk3 unit.

The TTL (tap table lookup) value contained in HSPBB GCF data header provides the needed information for the actual cascade used to output the desired sampling rates (FIR Stages 1 – 6 in Fig. 11.2). Initially (see also beginning of §11.2.1), only the 100 sps and 10 sps data streams were outputted, and for this the TTL value was equal to 76. From 23rd September 2007, the 1 sps tap was also installed, this time with a TTL value of 77. This does not change the FIR filter cascade for the two earlier taps, since only the two last stages differ between cascade 76 and cascade 77. Thus, the entire FIR filter cascade employed for the three different data streams of HSPBB is the following (Cirrus Logic, 2001; Güralp Systems, 2006):

- FIR filter CS5376 Stage 1, Sinc 1 (symmetric), 18 coefficients, decimating by 8 from the 512 kHz input clock
- FIR filter CS5376 Stage 3, Sinc 2 (symmetric), 3 coefficients, decimating by 2
- FIR filter CS5376 Stage 4, Sinc 2 (symmetric), 7 coefficients, decimating by 2
- FIR filter CS5376 Stage 5, FIR1 (symmetric), 24 coefficients, decimating by 4
- FIR filter CS5376 Stage 5, FIR2 (symmetric), 63 coefficients, decimating by 2
- FIR filter DM24 Stage 1, SWA-D24-3D08 (symmetric), 501 coefficients, decimating by 5 from 2 kHz
- FIR filter DM24 Stage 2, SWA-D24-3D07 (symmetric), 501 coefficients, decimating by 4, tap for 100 sps
- FIR filter DM24 Stage 3, SWA-D24-3D08 (symmetric), 501 coefficients, decimating by 5
- FIR filter DM24 Stage 4, SWA-D24-3D06 (symmetric), 501 coefficients, decimating by 2, tap for 10 sps

- FIR filter DM24 Stage 5, SWA-D24-3D08 (symmetric), 501 coefficients, decimating by 5
- FIR filter DM24 Stage 6, SWA-D24-3D06 (symmetric), 501 coefficients, decimating by 2, tap for 1 sps

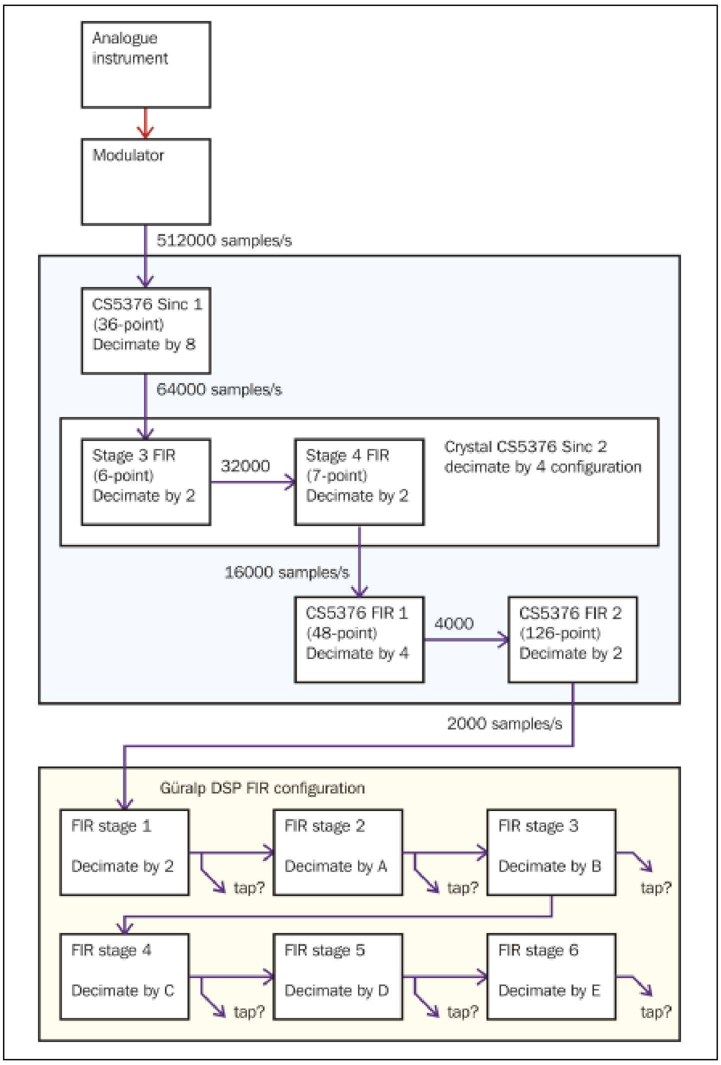


Fig. 11.2. The digital filter cascade employed by the Güralp DM24 Mk3 digitizer, to decimate from the 512 kHz input clock of the CS5376 chipset to the desired data sampling rate (from Güralp Systems, 2009b). In the case of the HSPBB station, a decimation of 5 from the sampling rate of 2 kHz occurs (FIR stage 1), omitting the decimation by 2 stage shown in the figure.

The displacement amplitude and phase responses for the configurations described above are shown in Fig. 11.4 at the end of this chapter.

11.2.2 <u>STS-2 – MK-6</u> (2009/08/19 – …)
Respid: HSPHH4,5,6 Z, N-S, E-W

The current Hornsund station (HSPB) configuration consists of the following components:

- STS-2 broadband 3-component seismometer
- MK-6 digitizer

Only the 100 sps data stream is outputted. The digitizer has been exchanged with the MK-6 model designed and constructed at the Polish Academy of Sciences (Wiszniowski, 2002), while data from the station are now transferred to Warsaw in real time. A duplicate system for power supply, data acquisition and timing has been set up at the station, to secure operability even in the case of equipment malfunction, taking into consideration the remoteness of the location. This system is shown in Fig. 11.3.

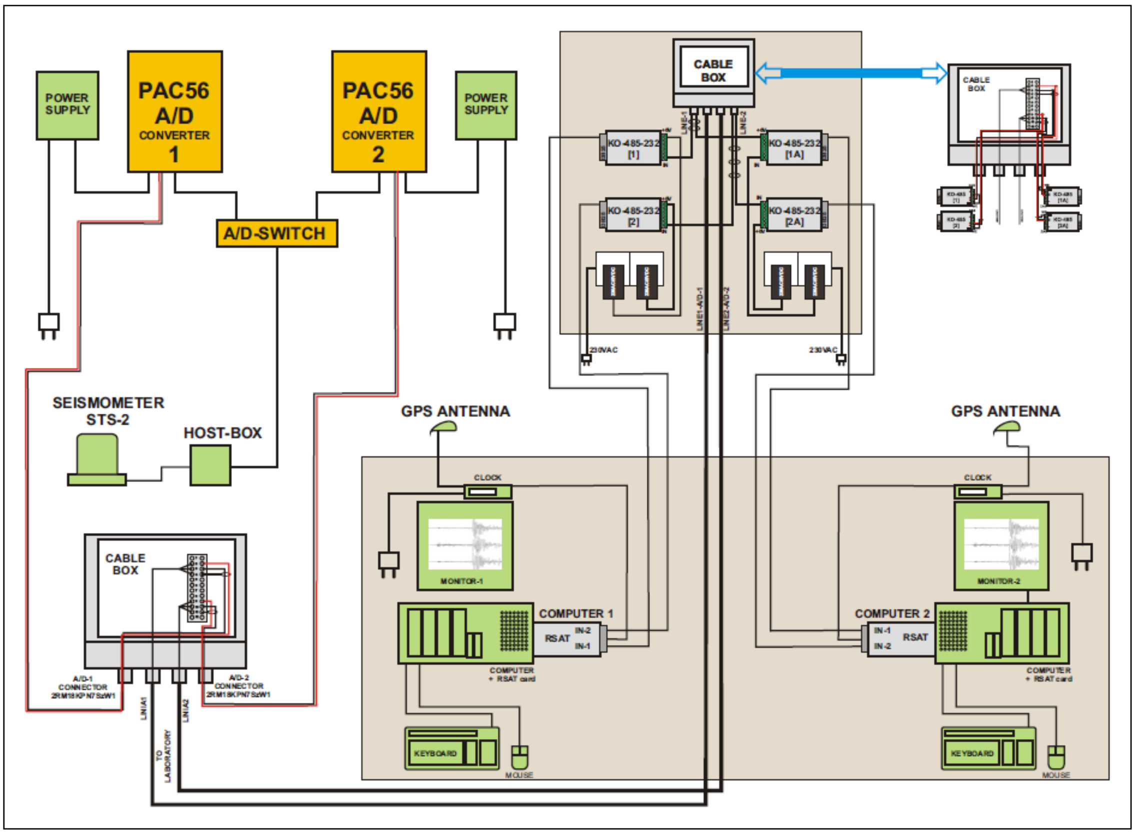


Fig. 11.3. Schematic representation of the duplicate system that supports power supply and data acquisition and timing at the HSPB station at Hornsund (courtesy of Andrzej Skrzynski, Institute of Geophysics, Polish Academy of Sciences) .

11.2.2.1 *STS-2*

Detailed information regarding the response of the Streckeisen STS-2 very broadband triaxial seismometer installed at Hornsund is provided in section 11.2.1.1 of the current chapter.

11.2.2.2 *MK-6*

The Polish-made broadband seismic data acquisition system MK-6 (Wiszniowski, 2002) uses a PAC56 digitizer, which employs the Motorola DSP56 Sigma-Delta signal processors for filtration (Motorola, 1992). The signal is transmitted from the PAC56 unit to the central unit controlled by a computer, where timing, recording and further processing takes place. The PAC56 employs oversampling to 12.8 kHz to achieve a resolution of 26 bit.

Prior to sampling, the signal is low-pass filtered to prevent aliasing. This analogue filter has three poles and is described by the following transfer function (Temes and Mitra, 1973):

$$T_f(s) = \frac{K_f}{\prod_{j=1}^{3}(s - p_j)}, \tag{11.1}$$

where p_1, p_2 and p_3 are the three poles and $K_f = |p_1.p_2.p_3|$. The values of the poles are listed in the corresponding *GSE* response file.

For response calculation we are using the information provided by the Polish Academy of Sciences. According to this, the MK-6 unit at Hornsund has a sensitivity of 298.02 nV/count, while the employed filter cascade is the following:

- Analogue anti-alias filter (pac12anf)
- FIR filter (b2d6n), symmetric, 20 coefficients, decimating by 2 from 12.8 kHz
- FIR filter (b4d6n), symmetric, 20 coefficients, decimating by 4
- FIR filter (b2d8n), symmetric, 10 coefficients, decimating by 2
- FIR filter (b2d12nn), symmetric, 14 coefficients, decimating by 2
- FIR filter (pac56lin), symmetric, 512 coefficients, decimating by 4

The displacement amplitude and phase response of the HSPB station is displayed in Fig. 11.4. As usual, the shaded areas represent the frequency range beyond the Nyquist.

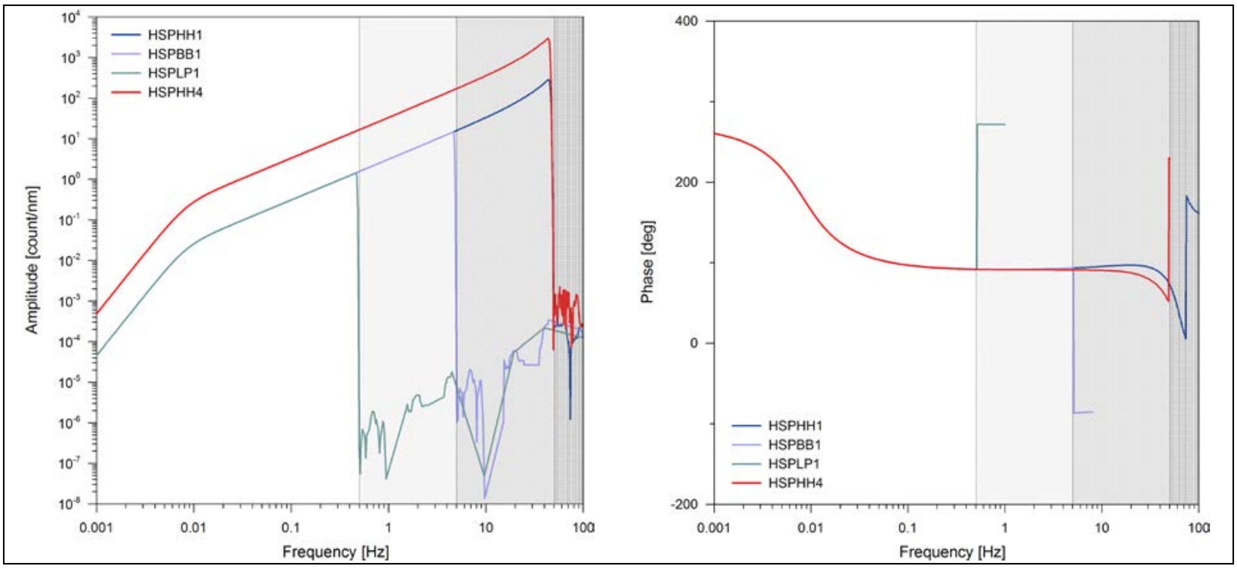


Fig. 11.4. Displacement amplitude (left) and phase (right) response for the vertical component of the HSPBB and HSPB 3-component Hornsund station configurations. HSPHH1 is the initial 100 sps channel, HSPBB1 the 10 sps channel and HSPLP1 the 1 sps channel. The current 100 sps channel is displayed in red under the entry HSPHH4. Shaded areas represent the range beyond the Nyquist frequency (50, 5 and 0.5 Hz for the HH, BB and LP data streams of HSPBB respectively, and 50 Hz for HSPB).

11.3 References

Cirrus Logic, 2001. Crystal CS5376 Low Power Multi-Channel Decimation Filter. *DSA0072869.pdf*, Cirrus Logic Inc., Austin, Texas, 122 pp.

Güralp Systems, 2006. CMG-DM24 mk3 Operator's Guide. *MAN-D24-0004*, Güralp Systems Ltd., Aldermaston, England, 113 pp.

Güralp Systems, 2009. *FIR filter configuration of the CMG-DM24 mk3*. Güralp Systems Ltd., Aldermaston, England, http://www.guralp.com/articles/20060410-technical-filter-DM24mk3/ /support.

Motorola, 1992. *DSP56000 Digital Signal Processor Family Manual*. Motorola Inc., Chicago, Illinois.

Streckeisen, 1995. *Portable very-broad-band tri-axial seismometer STS-2 manual*. G. Streckeisen AG Messgeräte, Pfungen, Switzerland, 50 pp.

Streckeisen, 2003. STS-2 portable very-broad-band triaxial seismometer. *sts2-1.pdf*, G. Streckeisen AG Messgeräte, Pfungen, Switzerland, 12 pp.

Temes, G.C. and Mitra, S.K., 1973. *Modern Filters Theory and Design*. John Wiley and Sons, New York.

Wilde-Piórko, M., Grad, M., Wiejacz, P. and Schweitzer, J., 2009. HSPB seismic broadband station in Southern Spitsbergen: First results on crustal and mantle structure from receiver functions and SKS splitting. *Polish Polar Research*, vol. 30, no. 4, p. 301-316.

Wiszniowski, J., 2002. Broadband Seismic System: Effect of transfer band on detection and recording of seismic waves. *Publications of the Institute of Geophysics Polish Academy of Sciences, Monographic Volume B-27* (339), Polish Academy of Sciences, Institute of Geophysics, Warsaw, 180 pp.

CHAPTER 12: BARENTSBURG BROADBAND STATIONS

12.1 Development of the Barentsburg broadband station systems: instrumentation and responses

12.1.1 Short description

- 2010-2012:

In September 2010, a new broadband 3-C station was installed in Barentsburg, Spitsbergen, to replace the old, Russian station BRBA, in collaboration between the Kola Regional Seismological Centre (KRSC) and NORSAR, within the framework of the POLRES project "Cooperative seismological studies on Spitsbergen" (RCN contract no. 196157/S30). The station is equipped with a Güralp CMG-3ESP seismometer (Fig. 12.1) and a CMG-DM24 digitizer. Data of two sampling rates are obtained through different digitizer filter taps; 3-C 80 sps HH channels and 3-C 1 sps LH channels. 4 sps data (MH channels) were obtained instead of the LH during the first hours of operation of the station.

Fig. 12.1. The new BRBA station sensor (Photo by J. Schweitzer). The 3-C, broadband CMG-3ESP seismometer (metal cylinder) is installed on a concrete block shielded in a small, wooden cabin which also houses the old Kirnos station (rectangular boxes).

- 2012/10-2012/11:

In October 2012, a second broadband 3-C station (BRBB) was installed at a distance of approximately 4 km from BRBA, outside the Barentsburg settlement. The new station has similar equipment to BRBA (Güralp CMG-3ESP seismometer and CMG-DM24 digitizer) and outputs 80 sps HH channels (*Respid* BRBBHH1a,2a,3a). The configuration of BRBA has remained unchanged.

- 2012/11-2013:

Station BRBB was moved to a different, nearby location on 25/11/2012. Instrumentation remained the same, thus having no effect on the response of the system (*Respid* BRBBHH1b,2b,3b).

- 2013-…:

In September 2013, station BRBB was moved again to a new location, with coordinates 78.095°N, 14.215°E. The instrumentation was not changed, resulting in an identical response with that of the initial location (*Respid* BRBBHH1,2,3). The configuration and location of BRBA are unchanged.

12.1.2 Instrumentation

I. Configurations

- BRBA configuration (2010-…):
    - CMG-3ESP seismometer
    - DM24 digitizer

-BRBB configuration (2012-…):
    - CMG-3ESP seismometer
    - DM24 digitizer

II. Respids

BRBAHH1,2,3
BRBAMH1,2,3
BRBALH1,2,3
BRBBHH1(a/b),2(a/b),3(a/b)

III. Instrument specifications

CMG-3ESP:

Three-component, broadband seismometer by Güralp Systems Ltd. The specifications for the vertical channel of the instrument installed at Barentsburg (serial number T35444, work order 5679) are the following:

Velocity output	2x988 V/m/s (differential)	
Poles (Hz)	$-11.78\times10^{-3} \pm j\ 11.78\times10^{-3}$	
		-160
		-80
		-180
Zeros (Hz)	0.0	0.0
Normalizing factor	2304000 @ 1 Hz	

CMG-DM24 digitizer:

Detailed information on the DM24 digitizer can be found in section 5.1.2 about the SPITS array. The instrument installed at the BRBA station has serial number A212. Some nominal values are the following:

Resolution	24-bit
Number of channels	7 (6 primary, 1 auxiliary)
Input voltage range	± 10 V differential
Velocity channel sensitivity	3.176 µV/count (vertical component)

12.2 Instrument response calculation for the Barentsburg broadband station systems

This chapter focuses on the major considerations to be taken into account for the calculation of the instrument response of the different systems operating at the BRBA and BRBB broadband stations, in Barentsburg, Spitsbergen.

As with the rest of the NORSAR systems, GSE file response *Respid* flags for each configuration are provided at the beginning of each section.

12.2.1 CMG-3ESP – DM24 (2010/09/13 – …)

Respid:	BRBAHH1	Z	
	BRBAHH2	N-S	
	BRBAHH3	E-W	
	BRBAMH1	Z	(2010/09/13 – 2010/09/14)
	BRBAMH2	N-S	
	BRBAMH3	E-W	
	BRBALH1	Z	(2010/09/14 – …)
	BRBALH2	N-S	
	BRBALH3	E-W	
	BRBBHH1(a/b)	Z	(2012/10/01 – …)
	BRBBHH2(a/b)	N-S	
	BRBBHH3(a/b)	E-W	

The two Barentsburg station (BRBA and BRBB) configurations consist of the following components:

- CMG-3ESP broadband 3-component, compact seismometer
- DM24 digitizer

Letters a and b appended to the *Respid* of BRBB denote different earlier locations of the station, with identical response. See §12.1.1 for details.

12.2.1.1 *CMG-3ESP*

Instrument response information for ground velocity is provided by the manufacturer (Güralp Systems, Ltd.) in the form of poles and zeros, while sensitivity values are provided on a calibration sheet shipped together with the equipment.

Poles and zeros for the shipment with serial number T35444 (work order 5679), which is in place at BRBA, are listed in the following tables:

POLES (HZ)	ZEROS HZ
$-11.78 \times 10^{-3} \pm j11.78 \times 10^{-3}$	0
-160	0
-80	
-180	

Normalizing factor at 1 Hz: A = 2304000

Instrument output is equal to:

	Velocity Output V/m/s (Differential)	Mass Position Output (Acceleration output) $V/m/s^2$	Feedback Coil Constant $Amp/m/s^2$
VERTICAL	2 x 988	732	0.01557
N-S	2 x 988	772	0.01643
E-W	2 x 991	789	0.01678

The corresponding information for instrument T36866 (work order 6228), installed at BRBB, is found below:

POLES (HZ)	**ZEROS HZ**
$-11.78 \times 10^{-3} \pm j11.78 \times 10^{-3}$	0
-160	0
-80	
-180	

Normalizing factor at 1 Hz: A = 2304000

	Velocity Output V/m/s (Differential)	Mass Position Output (Acceleration output) $V/m/s^2$	Feedback Coil Constant $Amp/m/s^2$
VERTICAL	2 x 987	790	0.01681
NORTH/SOUTH	2 x 979	827	0.01759
EAST/WEST	2 x 981	828	0.01762

The factor of 2 in the sensitivity estimates is used because of sensor outputs being used differentially.

Poles and zeros are listed in units of Hz. They need to be multiplied with 2π to be converted to rad/s which is the accepted unit in the *GSE* response file. The same change applies for the normalizing factor.

Total sensor sensitivity at 1 Hz will then be equal to: G = (sensitivity) x (norm. factor)

12.2.1.2 *CMG-DM24*

The BRBA and BRBB stations are equipped with Güralp CMG-DM24 digitizers.

Detailed information about the DM24 digitizer (mk3) can be found in section 5.2.4.2 about the SPITS array. In the case of BRBA, the output sample rates are 80 sps (HH channels) and 1 sps (LH channels), while for the first hours of station operation a 4 sps rate (MH channels) was outputted instead of 1 sps. Since outputted sampling rates are controlled by taps on different filter cascades (see also §11.2.2.2), two different cascades were used, with TTL values 86 (for 80 and 4 sps) and 90 (for 80 and 1 sps). These two cascades are identical down to the 80 sps tap, so the response of the HH channels has not changed at all and thereby no separate *Respid* will be used. The digitizer filter chain for a TTL value of 90 is the following (Cirrus Logic, 2001; Güralp Systems, 2006):

- FIR filter SINC-1 (asymmetric) with 18 coefficients, decimating by 8 down to 64 kHz from an input rate of 512 kHz.
- FIR filter SINC-2-stage-3 (asymmetric) with 3 coefficients, decimating by 2
- FIR filter SINC-2-stage-4 (symmetric) with 7 coefficients, decimating by 2
- filter FIR-1-set0 (asymmetric) with 24 coefficients, decimating by 4
- filter FIR-2-set0 (asymmetric) with 63 coefficients, decimating by 2
- filter DM24-tap0 (symmetric) with 501 coefficients, decimating by 5
- filter DM24-tap1 (symmetric) with 501 coefficients, decimating by 5 down to the desired sampling rate of 80 sps (HH channels)
- filter DM24-tap0 (symmetric) with 501 coefficients, decimating by 4
- filter DM24-tap0 (symmetric) with 501 coefficients, decimating by 2
- filter DM24-tap0 (symmetric) with 501 coefficients, decimating by 5
- filter DM24-tap2 (symmetric) with 501 coefficients, decimating by 2 down to the desired sampling rate of 1 sps (LH channels)

All filter coefficients can be found in the corresponding *GSE* response file.

According to the calibration sheet provided by Güralp Systems, Ltd., the sensitivity of the digitizer for BRBA (serial number B212, works order 3039) is equal to:

VELOCITY CHANNELS

Channel:	A212Z2	Vertical	3.176 µV/Count
	A212N2	North/South	3.190 µV/Count
	A212E2	East/West	3.175 µV/Count

BRBB outputs only 80 sps channels, with the same TTL value as BRBA, so the FIR cascade is the same as above.

Unit B794 (work order 4007), which is installed at BRBB, has the following sensitivity, according to the calibration sheet:

VELOCITY CHANNELS

Channel:

	B794Z2	Vertical	3.203 µV/Count
	B794N2	North/South	3.200 µV/Count
	B794E2	East/West	3.197 µV/Count

The displacement amplitude and phase response of the above described configurations are displayed in Fig. 12.2. The plotted responses correspond to the vertical channels and are shown up to the Nyquist frequency for each outputted sampling rate, which is equal to 40 Hz for the HH channel, 2 Hz for the MH channel and 0.5 Hz for the LH channel. BRBA and BRBB HH channel responses are very similar, with only very minor differences in overall sensitivity and thereby cannot be distinguished from each other.

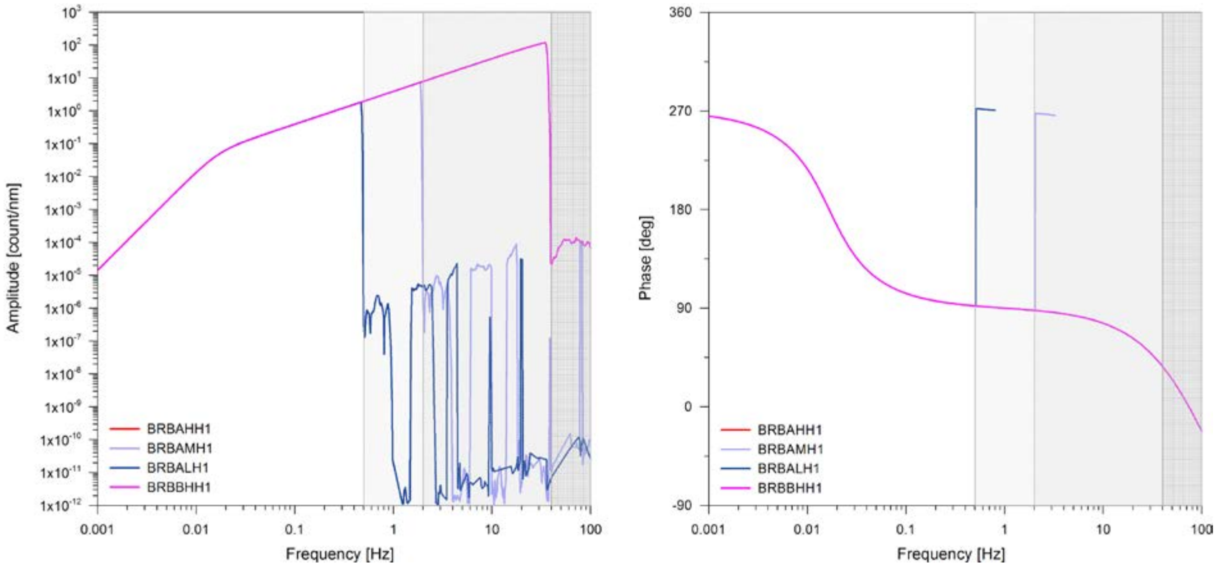


Fig. 12.2. Displacement amplitude (left) and phase (right) response for the different sampling rates of the vertical component of the Barentsburg broadband stations. Shaded areas represent the range beyond the Nyquist frequency (80 Hz for BRBAHH1 and BRBBHH1, 2 Hz for BRBAMH1 and 0.5 Hz for BRBALH1). The responses of the HH channel of BRBA and BRBB are essentially identical and cannot be told apart in the plot.

12.3 References

Cirrus Logic, 2001. Crystal CS5376 Low Power Multi-Channel Decimation Filter. *DSA0072869.pdf*, Cirrus Logic Inc., Austin, Texas, 122 pp.

Güralp Systems, 2006. CMG-DM24 Mk3 Digitizer Operator's Guide. *MAN-D24-0004*, Güralp Systems Ltd., Aldermaston, England, 122 pp.

CHAPTER 13: TROLL BROADBAND STATION

13.1 Development of TROLL broadband station systems: instrumentation and responses

13.1.1 Short description

- 2011-2012:

In 2011, NORSAR succeeded in achieving funding for the installation of a permanent seismic station at the Norwegian research base Troll, in Dronning Maud Land, Antarctica, within the framework of the Norwegian Antarctic Research Expedition (NARE) program and in collaboration with the Norwegian Polar Institute (NPI). Aiming to establish a very high quality, broadband station, the instrumentation selected was the Streckeisen STS-2.5 very broadband seismometer and the Q330HR digitizer by Quanterra. The equipment was installed for an interval of approximately one month (December 2011 – January 2012) at NORSAR's testing site in Stendammen for testing purposes, before it was transported to Antarctica in the end of January 2012. The test installation ran under the same configuration as was planned for Antarctica (digitizer gain 1x), but outputting only one data sampling rate, 100 sps.

- 2012-2013:

The station, registered as TROLL, was installed by NORSAR scientists and in collaboration with the NPI staff at Troll on a bedrock outcrop on the Jutulsessen nunatak. For installation details, see Schweitzer et al. (2012). As mentioned, system response relevant components are the tri-axial STS-2.5 very broadband seismometer and the Q330HR digitizer, initially employed with a gain of 1x. The following sampling rates were outputted: 100 sps (HH channels), 40 sps (BH), 1 sps (LH), 0.1 sps (VH) and 0.01 sps (UH channels).

- 2013-…:

In February 2013, the NPI staff at TROLL performed, under instructions from NORSAR, some maintenance work at the station, aiming primarily in better thermal insulation. The main response relevant adjustment was the change of digitizer gain to 20x for all channels (HH, BH, LH, VH and UH), while at the same time outputting an additional, low gain channel (BL) for the case that the high gain ones become clipped. This was achieved by obtaining from Streckeisen a customized split cable for the connection of the STS-2.5 with the digitizer.

13.1.2 Instrumentation

I. Configurations

- TROLL test HH configuration (2011-2012):
  - STS-2.5 seismometer
  - Q330HR digitizer gain 1x

- TROLL initial configurations (2012-2013):
  - STS-2.5 seismometer
  - Q330HR digitizer gain 1x
- TROLL current configurations (2013-…):

STS-2.5 seismometer
Q330HR digitizer gain 20x, plus additional low gain channel (BL)

II. Respids

TROLLHH1a,2a,3a
TROLLHH1,2,3
TROLLBH1,2,3
TROLLLH1,2,3
TROLLVH1,2,3
TROLLUH1,2,3
TROLLHH4,5,6
TROLLBH4,5,6
TROLLLH4,5,6
TROLLVH4,5,6
TROLLUH4,5,6

III. Instrument specifications

STS-2.5:
Streckeisen very broadband triaxial seismometer. The 2.5 version constitutes a compromise that installs the new generation STS-3 sensor in the casing of STS-2. As with STS-2, 3 identical obliquely-oriented mechanical sensors are employed, instead of the traditional arrangement of separate orthogonal vertical and horizontal sensors. Some nominal values are the following (Streckeisen, 2011a):

Seismic output (flat velocity)	8.33 mHz (120 s) – 50 Hz
Generator constant	2 x 750 V/m/s ± 1 %

Q330HR digitizer:
The Q330 High-Resolution (Q330HR) is a broadband data acquisition system, manufactured by Quanterra, Inc., a Kinemetrics, Inc. subsidiary, ensures ultrahigh resolution recording at low power (Kinemetrics, 2005). Some nominal values are the following (Kinemetrics, 2005, Q330Response-v1_0.pdf):

Resolution	26-bit
Input voltage range	40 V p-p at gain 1x
Nominal sensitivity	1677721.6 count/V
Selectable gain	1x , 20x
Dynamic range	148 dB at < 2 W power consumption
Output sample rates	200, 100, 50, 40, 20, 10, 1 sps
	software filters provide rates below 1 sps
Filtering	linear or minimum phase FIR

13.2 Instrument response calculation for the TROLL broadband station systems

This chapter focuses on the major considerations to be taken into account for the calculation of the instrument response of the different systems operating at the TROLL broadband station.

As with the rest of the NORSAR systems, *GSE* file response *Respid* flags for each configuration are provided at the beginning of each section.

13.2.1 STS-2.5 – Q330HR (2011/12/07 – 2013/02/04)

Respid:	TROLLHH1a,2a,3a	Z, N-S, E-W (2011/12/07 – 2012/01/13)
	TROLLHH1,2,3	Z, N-S, E-W (2012/02/05 – 2013/02/04)
	TROLLBH1,2,3	Z, N-S, E-W (2012/02/05 – 2013/02/04)
	TROLLLH1,2,3	Z, N-S, E-W (2012/02/05 – 2013/02/04)
	TROLLVH1,2,3	Z, N-S, E-W (2012/02/05 – 2013/02/04)
	TROLLUH1,2,3	Z, N-S, E-W (2012/02/05 – 2013/02/04)

Test and initial TROLL configurations involve the following components:
- STS-2.5 broadband seismometer
- Q330HR digitizer, gain 1x

13.2.1.1 *STS-2.5*

As with the STS-2, the Streckeisen STS-2.5 very broadband tri-axial seismometer uses 3 identical obliquely-oriented mechanical sensors instead of the traditional separate orthogonal vertical and horizontal sensors (see a detailed discussion in Part 1, § 7.2.1.1).

The transfer function of the STS-2.5 (G_G) can be represented as the combination of an upper frequency band (> 1 Hz) and a lower frequency band (< 1 Hz) transfer function (Streckeisen, 2011b). The former is expressed by the combination of a pole-zero fit to the measured calibration curve (GU_{fit}) and an inverse filter for conversion to ground excitation (IF), while the latter (GL_{fit}) can be expressed as a 2nd-order high-pass filter for $\omega_0=\frac{2\pi}{120}$ and $h_0=\frac{1}{\sqrt{2}}$ damping. Thus, the combined transfer function to represent the STS-2.5's response to ground motion will be:

$$G_{G_n} = GU_{fit_n} GL_{fit_n} IF_n,$$

with the amplitude response being equal to: $A_{G_n}=\left|G_{G_n}\right|$ and the phase response equal to: $\Phi_{G_n}=\frac{180}{\pi}\arg\left(G_{G_n}\right)$.

The upper frequency band transfer function is as follows:

$$GU_{fit_n}=\frac{1500\cdot p_1^2\cdot\left(pre_2^2+pim_2^2\right)}{z_1^2}\cdot\frac{(i\cdot\omega_n+z_1)^2\cdot\left(i\cdot\omega_n-zp_{ph}\right)}{(i\cdot\omega_n+p_1)^2\cdot(i\cdot\omega_n+pre_2+i\cdot pim_2)\cdot(i\cdot\omega_n+pre_2-i\cdot pim_2)\cdot\left(i\cdot\omega_n+zp_{ph}\right)}$$

In this equation, z_1 is a double real zero, zp_{ph} is the phase shifter zero/pole, p_1 is a double real pole, and pre_2 and pim_2 are the real and imaginary part of a double pole.

The inverse filter for conversion to ground excitation is described by equation:

$$IF_n = \frac{(i \cdot \omega_n + zre_1 + i \cdot zim_1) \cdot (i \cdot \omega_n + zre_1 - i \cdot zim_1) \cdot (i \cdot \omega_n + zre_2)}{\left(zre_1^2 + zim_1^2\right) \cdot zre_2}$$

In this equation, zre_1 and zim_1 are the real and imaginary part of a zero, while zre_2 is a real zero.

The lower frequency part of the response is described by the damping seismometer formula (see equation 2.2.2 and its solutions in Part 1, § 2.2.1.1). For the STS-2.5, this equation has a double zero, z_0 = 0.03702 and a double pole with real and imaginary parts pre_0 = 0.03702 and pim_0 = 0.03702.

For the sensor with serial number 110644 that is installed at TROLL, the poles, zeros, T_0 and damping factor for the three components U, V and W are provided by the manufacturer (Streckeisen, 2011c):

High-Frequency Poles and Zeroes. Sensor Component U [1/s]										
Zero1	Zero2	Zero3	Zero4 Real	Zero4 Imag	Zero5	Pole1	Pole2	Pole3 Real	Pole3 Imag	Pole4
15.71	15.71	630.2	556.1	936.2	-960.2	16.07	16.07	333.6	113.93	960.2

High-Frequency Poles and Zeroes. Sensor Component V [1/s]										
Zero1	Zero2	Zero3	Zero4 Real	Zero4 Imag	Zero5	Pole1	Pole2	Pole3 Real	Pole3 Imag	Pole4
15.71	15.71	630.2	556.1	936.2	-955.8	16.06	16.06	334.9	113.98	955.8

High-Frequency Poles and Zeroes. Sensor Component W [1/s]										
Zero1	Zero2	Zero3	Zero4 Real	Zero4 Imag	Zero5	Pole1	Pole2	Pole3 Real	Pole3 Imag	Pole4
15.71	15.71	630.2	556.1	936.2	-959.5	16.06	16.06	339.8	113.92	959.5

Zero5, Pole1, Pole2, Pole3 and Pole4 are evaluated by least-square-minimizing residuals between measured and modeled transfer function (TF). Zero3 and Zero4 are modeled using PSPICE© in order to account for the difference between coil-excited TF and ground-excited TF. The amplitude and phase residuals after optimization are limited to 1% of the 1-Hz-value and 1°, resp., from 0.75 Hz to 50 Hz.

Low-Frequency Corner Period and Damping Constant.											
Sensor Component U				Sensor Component V				Sensor Component W			
T0 [s]	h0	σT0 [%]	σh0 [%]	T0 [s]	h0	σT0 [%]	σh0 [%]	T0 [s]	h0	σT0 [%]	σh0 [%]
119.911	0.709	0.036	0.046	119.670	0.707	0.029	0.038	119.894	0.708	0.034	0.044

σT0 [%]: Standard deviation of least-square-optimized corner period in percent; σh0 [%]: Standard deviation of least-square-optimized damping constant in percent.

The generator constant at 2 s for the three components is provided in the same document (Streckeisen, 2011c) and is reported equal to 1500 V/m/s with an accuracy of 1 %.

13.2.1.2 *Q330HR*

The Q330HR digitizer by Quanterra, Inc. has a resolution of 26-bit. Taking in account the 40 V peak-to-peak input voltage range, the sensitivity of the digitizer equals 1677721.6 count/V. At its initial installation at the TROLL station (serial number 4629), the digitizer was employed with a gain of 1x.

Except for the test installation in Norway that was set up to provide only 100 sps data (HH channels), data with lower sampling rates are acquired in addition from the permanent installation in Antarctica. These include 40 sps (BH), 1 sps (LH), 0.1 sps (VH) and 0.01 sps (UH) data streams. Digital filter cascades employed to output the desired sampling rates are provided by the manufacturer in the form of "composite filters", converged into one FIR filter stage, with corresponding delays given in the table shown below (from Q330Response-v1_0.pdf):

	200 sps	100 sps	50 sps	40 sps	20 sps	10 sps	1 sps
Linear at All Freq.	0.090000 FLinear-200	0.330000 FLinear-100	0.820000 FLinear-50	0.500000 FLinear-40	1.700000 FLinear-20	4.100000 FLinear-10	16.000000 FLinear-1
Linear Below 100 sps	0.020462 FLbelow100-200	0.041607 FLbelow100-100	0.531607 FLbelow100-50	0.430462 FLbelow100-40	1.630462 FLbelow100-20	4.030462 FLbelow100-10	15.930462 FLbelow100-1
Linear Below 40 sps	0.020462 FLbelow40-200	0.041607 FLbelow40-100	0.084847 FLbelow40-50	0.082972 FLbelow40-40	1.282972 FLbelow40-20	3.682972 FLbelow40-10	15.582972 FLbelow40-1
Linear Below 20 sps	0.020462 FLbelow20-200	0.041607 FLbelow20-100	0.084847 FLbelow20-50	0.082972 FLbelow20-40	0.188697 FLbelow20-20	2.588697 FLbelow20-10	14.488697 FLbelow20-1

TABLE 1: COMPOSITE FILTER DELAY IN SECONDS.
Blue indicates the ouput sample rate was filtered with Linear Phase filter in the last stage (and possibly earlier stages).
Red indicates the output sample rate was filtered with Minimum Phase Filters.

The filters used to output the above listed sampling rates can be identified using the Willard software utility and are the following:

- 100 sps: FLbelow100-100, decimating by 1, asymmetric, 65 coefficients
- 40 sps: FLbelow100-40, decimating by 1, asymmetric, 39 coefficients
- 1 sps: FLbelow100-1, decimating by 1, asymmetric, 31 coefficients

To obtain sampling rates below 1 Hz, software filters are used in addition. For the VH and UH channels of TROLL, the resulting cascades are the following:

- 0.1 sps: FLbelow100-1, decimating by 1, asymmetric, 31 coefficients and
  FIR DEC 10, decimating by 10, symmetric even, 400 coefficients
- 0.01 sps: FLbelow100-1, decimating by 1, asymmetric, 31 coefficients,
  FIR DEC 10, decimating by 10, symmetric even, 400 coefficients and
  FIR DEC 10, decimating by 10, symmetric even, 400 coefficients

Filter coefficients can be found in the corresponding *GSE* response files.

The displacement amplitude and phase response of the above described configuration (HH channel) is depicted in dark blue in Fig. 13.1, at the end of section 13.2.2.

13.2.2 STS-2.5 – Q330HR (2013/02/04 – …)

Respid: TROLLHH4,5,6 Z, N-S, E-W
TROLLBH4,5,6 Z, N-S, E-W
TROLLLH4,5,6 Z, N-S, E-W
TROLLVH4,5,6 Z, N-S, E-W
TROLLUH4,5,6 Z, N-S, E-W
TROLLBL1,2,3 Z, N-S, E-W

The current TROLL broadband configuration consists of the following components:

- STS-2.5 broadband seismometer
- Q330HR digitizer, gain 20x, plus additional low gain channel (BL) with gain 1x

13.2.2.1 *STS-2.5*

The response of the STS-2.5 seismometer installed at TROLL has been discussed in § 13.2.1.1 of this chapter.

13.2.2.2 *Q330HR*

The general response relevant characteristics of the Q330HR digitizer have been discussed in § 13.2.1.2 of this chapter.

The only difference between the current and the initial configuration at TROLL is that the digitizer gain was switched to 20x for channels HH, BH, LH, VH and UH, while a low gain and 24-bit channel (BL, gain 1x) was set up in addition to secure non-clipped data in case of very strong signals.

To achieve the high and low gain data streams, a customized, split cable by Streckeisen is used to connect the STS-2.5 to the digitizer.

The displacement amplitude (in count/nm) and phase (in degrees) response of the high sampling rate (100 sps) and the low gain, 24-bit TROLL station configurations described in this chapter are depicted in Fig. 13.1. The current, high gain configuration is noted in light blue, while the current low gain configuration in red. The shaded areas represent the range beyond the Nyquist frequency (50 Hz and 20 Hz).

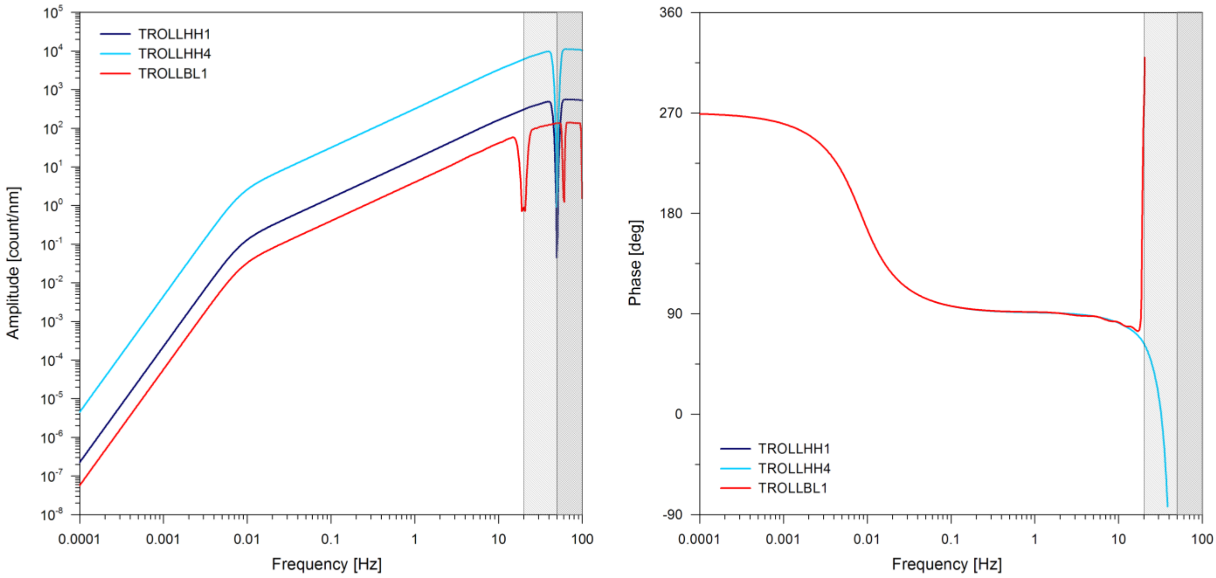


Fig. 13.1. Displacement amplitude (left) and phase (right) response for TROLL station 100 sps configurations (HH) and the low gain, 24-bit channels (BL). The shaded areas represent the range beyond the Nyquist frequency (50 Hz for the high sampling rate channels and 20 Hz for the BL channel).

13.3 References

Kinemetrics, Inc., 2005. Quanterra Q330HR Data Acquisition System. *Seismol. Res. Lett.*, 76(1), 84.

Quanterra, Inc., –. Q330 Response Description, Guidelines for SEED Data. *Q330Response-v1_0.pdf*, 19 pp.

Schweitzer, J., Roth, M., and Pirli, M., 2012. The new three-component very broadband seismic station at Troll, Antarctica. *NORSAR Sci. Rep. 1-2012*, 39-46.

Streckeisen, 2011a. *Velocity-Broadband Seismometer STS-2.5 Short instruction.* Revision 0.9, 01.11.2011. Streckeisen GmbH, Switzerland, 12 pp.

Streckeisen, 2011b. STS-2.5/STS-3 poles & zeros representation of the transfer function. *Zeroes-Poles-STS2_5-STS3-improved.xmcd*, 16.03.2011, 3 pp.

Streckeisen, 2011c. Certificate of Calibration, Type: STS-2.5, Serial No: 110644, Date November 23, 2011. *CAL110644.doc*, Streckeisen GmbH, Switzerland, 2 pp.

PART 2

CHAPTER 1: KINGSBAY BROADBAND STATION

1.1 Development of KBS broadband station systems: instrumentation and responses

1.1.1 Short description

The KBS broadband station at Kingsbay, west Spitsbergen, is a station owned and operated jointly by IRIS (GSN), GFZ Potsdam (GEOFON), AWI and UiB. The station is also part of the Norwegian National Seismic Network and NORSAR receives data routinely. System response information is obtained by IRIS, and responses will be considered only for those configurations found in NORSAR's database. The responses are re-organized, following the schema described previously in this documentation.

NORSAR's database contains data from two different, co-located station configurations, which can be partly found in parallel. These two configurations are distinguished by the use of a location ID, which is 00 in the case of an STS-1 sensor and 10 in the case of an STS-2 sensor. Since location ID does not feature in the CSS3.0 schema used in NORSAR's database, the two configurations were distinguished by renaming the channels of the 00 configuration to BZ, BN, BE from BHZ, BHN, BHE respectively.

This information will be now introduced as auxiliary channel names for the corresponding system responses. An overview of the instrumentation and corresponding *Respids* can be found in the following paragraph.

1.1.2 Instrumentation

I. Configurations

- KBS 00 configurations (1994-2009):
  STS-1 seismometer
  Quanterra Q380 digitizer

- KBS 10 configurations (1994-2010):
  STS-2 seismometer
  Quanterra Q380 digitizer

- KBS 10 configurations (2010-…):
  STS-2 seismometer
  Quanterra Q330HR digitizer

II. Respids

KBS00BB1,2,3(a)
KBS00LH1,2,3
KBS10SH1,2,3
KBS10BB1,2,3
KBS10BB4,5,6
KBS10LH1,2,3

III. Instrument specifications

STS-1:
The Streckeisen STS-1, designed in 1976, is a VBB seismometer, mainly dedicated to global seismology and strong earthquakes. Its low frequency corner is at 360 s (0.0028 Hz) and its high frequency corner at 10 Hz, making it unsuitable for local (even regional) studies. Some technical specifications of this instrument are the following (Trnkoczy, 1997; Wielandt and Streckeisen, 1982):

Sensitivity	2400 V/m/s
Dynamic range	> 140 dB between 0.0001 and 10 Hz
Clipping level	8 mm/s signal over 0.1 to 360 s period

STS-2:
Streckeisen very broadband triaxial seismometer. 3 identical obliquely-oriented mechanical sensors are employed, instead of the traditional arrangement of separate orthogonal vertical and horizontal sensors. Some nominal values are the following (Streckeisen, 2003):

Seismic output (flat velocity)	8.33 mHz – 50 Hz
Mass	0.3 Kg
Gain	2 x 750 V/m/s
Damping	0.707 (low frequencies, < 1 Hz)
Feedback coil	50 N/A

Q380 digitizer:
Digitizer by Quanterra Inc. For response related values, see SEED response file distributed by IRIS or GSE response files under /ndc/programs/dpep/dbtables/2008/KBS. Some aspects of Q380 digitizer response (*e.g.*, FIR cascade and delays) can be found at http://www.iris.edu//NRL/dataloggers/quanterra/qx80/quanterra_Qx80_dataloggers.html.

Q330HR digitizer:
Digitizer by Quanterra Inc. Some nominal values, obtained from document q330-HRRevB.pdf, are the following:

Resolution	maximum 26-bit
Number of channels	6 (3 26-bit, 3 24-bit)
Dynamic range	144-145 dB
Input voltage range	40 V p-p at gain 1

1.2 Instrument response calculation for the Kingsbay broadband station systems

This chapter focuses on the major considerations to be taken into account for the calculation of the instrument response of the different systems operating at the Kingsbay broadband station (KBS).

As with the rest of the systems discussed in this documentation, *GSE* file response *Respid* flags for each configuration are provided at the beginning of each section.

All information presented in the following paragraphs is based on the SEED response files distributed by IRIS and instrument manufacturers.

It should be noted that although IRIS is distributing several response files for each configuration, they all describe the same response and have probably been produced more than once for book-keeping purposes. All these cases have been grouped together for the NORSAR database and are presented as one configuration, provided that no changes occur in channel names.

1.2.1 STS-1 – Q380 (1994/11/05 – …)

Respid:	KBS00BB1(a)	Z
	KBS00BB2(a)	N-S
	KBS00BB3(a)	E-W
	KBS00LH1	Z
	KBS00LH2	N-S
	KBS00LH3	E-W

The KBS station version with locationID 00 is equipped with an STS-1 seismometer. So, the system consists of the following components:

- STS-1 broadband seismometer
- Quanterra Q380 digitizer

Due to the fact that there is no way to discriminate in NORSAR's db system between two station versions with a different locationID, but same channel name, channels for this configuration were renamed to BZ, BN, BE, when data was stored in parallel to data from the configuration with locationID 10 (see section 1.2.2). When organizing the system response information, channels retained their original naming (BHZ, BHN, BHE), and the names BZ, BN, BE were introduced as auxiliary channel names. Details for the time interval when this renaming is relevant can be found in the corresponding *GSE*-file. In this case, the *Respid* remains unchanged since the response is identical, but an .a is appended to the response file names (see Appendix II).

This configuration can be found in NORSAR's database with two different sampling rates; 20 sps (BB channels) and 1 sps (LH channels).

1.2.1.1 *STS-1*

The STS-1V/VBB seismometer is a highly sensitive, remotely controlled sensor for wide-band and long-period recording. The basic response of the instrument is that of a long-period seismometer with 360 s free period and 0.707 critical damping. The response is flat to ground velocity from 0.1 to 360 s period. The entire spectrum of teleseismic signals from 0.1 s to about 1 h period is resolved in the VBB output signal and can be recorded in a single digital data stream when a suitable digitizer is used.

The seismometer transfer function for velocity is expressed by the following formula (Streckeisen, 1986):

$$T(\omega) = \frac{-\omega^2 S}{-\omega^2 + 2i\omega\omega_1 h_1 + \omega_1^2} \frac{\omega_2^2}{-\omega^2 + 2i\omega\omega_2 h_2 + \omega_2^2}\ , \tag{1.2.2}$$

where $\omega_1 = 2\pi/360$ rad/s,
$h_1 = 1/\sqrt{2}$,
$\omega_2 = 2\pi/0.1$ rad/s,
$h_2 = 0.6235$ and
$S = 2400$ V/m/s

Poles and zeros can be found in the corresponding *GSE* response file.

1.2.1.2 *Q380*

The KBS configuration discussed in this section is equipped with a Quanterra Q380 digitizer. All relevant information was obtained from the corresponding SEED response file and can be found therein or in the corresponding *GSE* file.

The displacement amplitude and phase response for the different channels of the locationID 00 KBS configuration can be found in Fig. 1.1 at the end of section 1.2 of Part II.

1.2.2 STS-2 – Q380 (1994/11/05 – 2010/06/07)

Respid:	KBS10BB1	Z
	KBS10BB2	N-S
	KBS10BB3	E-W
	KBS10SH1	Z
	KBS10SH2	N-S
	KBS10SH3	E-W
	KBS10LH1	Z
	KBS10LH2	N-S
	KBS10LH3	E-W

The earlier configurations of the locationID 10 of the KBS station were equipped with an STS-2 seismometer. The system consisted of the following components:

- STS-2 broadband seismometer
- Quanterra Q380 digitizer

Data with sampling rates of 40 and 1 sps can be found in NORSAR’s database system. The earliest of these 40 sps configurations (1994 – 1999) has a channel naming of SHZ, SHN, SHE, while afterwards it continues as BHZ, BHN, BHE. Channel names LHZ, LHN, LHE correspond to the 1 sps channels.

1.2.2.1 *STS-2*

Detailed information about this instrument can be found in sections 7.2.1.1 and 7.2.2.1 about the Jan Mayen broadband station.

Details about the actual instrument characteristics used at KBS can be found in the SEED response files distributed by IRIS and the corresponding *GSE* files. It should be noted that IRIS is distributing only the simplified sensor response (pole-zero set) that describes adequately the low-frequency end (< 1 Hz) of the response.

1.2.2.2 *Q380*

Information on this component can be found in section 1.2.1.2.

The displacement amplitude and phase response is shown in Fig. 1.1 at the end of this chapter.

1.2.3 STS-2 – Q330HR (2010/06/08 – …)

Respid:	KBS10BB4	Z
	KBS10BB5	N-S
	KBS10BB6	E-W

The 40 sps channels of the current KBS station locationID 10 configuration are equipped with the following components:

- STS-2 broadband seismometer
- Quanterra Q330HR digitizer

IRIS has adopted a new channel nomenclature for horizontal components, naming them BH1 and BH2. By analyzing data (rotating components and comparing between rotated horizontals and vertical) it has become clear that BH1 corresponds to N-S and BH2 to E-W. In the *Channel*-block of the *GSE* response file these channel names are attributed the appropriate *Hang*- and *Vang*-field values to allow correct channel definition within NORSAR's database system.

1.2.3.1 *STS-2*

See section 1.2.2.1.

1.2.3.2 *Q330HR*

Some information on the Quanterra Q330 High-Reslution Data Acquisition System can be found in the document q330-HRRevB.pdf and Kinemetrics (2005), while actual values for the KBS station are distributed by IRIS and can be found both in the corresponding SEED and *GSE* response files.

The displacement amplitude (in count/nm) and phase (in degrees) responses for all the different configurations of the KBS broadband station described above (locationID 00 and 10) are depicted in Fig. 1.1. As always, shaded areas represent the range beyond the Nyquist frequency.

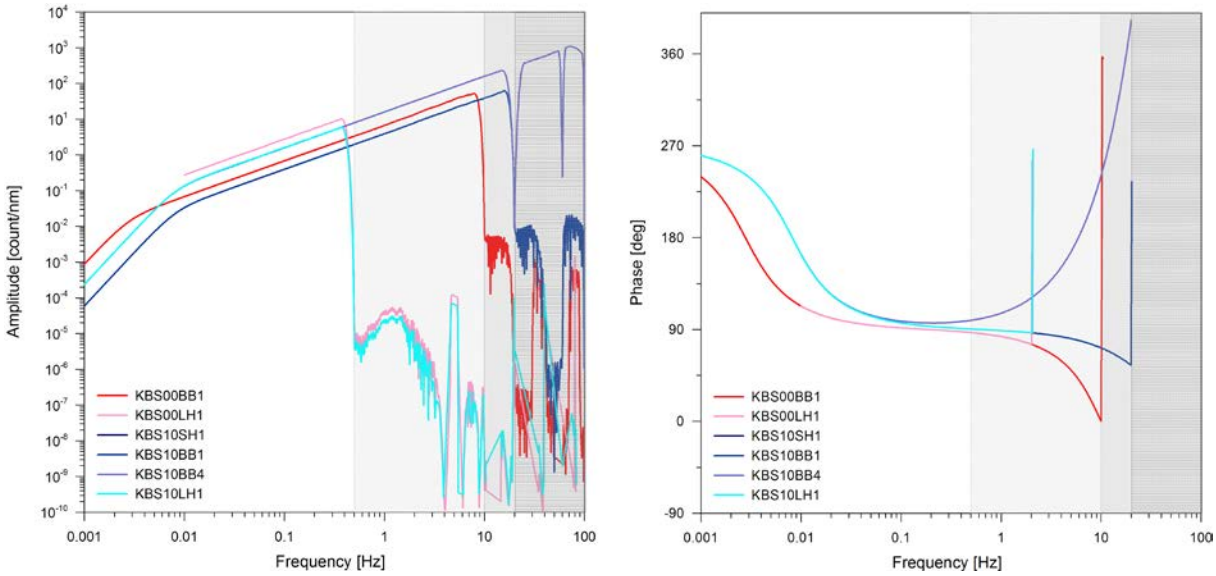


Fig. 1.1. Displacement amplitude (left) and phase (right) response for the KBS broadband station configurations. LocationID 00 configurations are noted in red and pink, while locationID 10 configurations appear in shades of blue and cyan. The curves plotted here correspond to the vertical component of each case. Shaded areas represent the range beyond the Nyquist frequency (20 Hz for 00 BB-channels, 10 Hz for 10 BB- and SH-channels and 0.5 Hz for all LH-channels).

1.3 References

Kinemetrics, Inc., 2005. Quanterra Q330HR Data Acquisition System. *Seismol. Res. Lett.*, vol. 76, no. 1, p. 84.

Streckeisen, 1986. VBB.MAN, 08-JUL-86 version., 45 pp.

Streckeisen, 2003. STS-2 portable very-broad-band triaxial seismometer. *sts2-1.pdf, G. Streckeisen AG Messgeräte*, Pfungen, Switzerland, 12 pp.

Trnkoczy, A., 1997. STS-1 and STS-2 sensors in National Seismic Networks. *Application Note #40*, Kinemetrics SA, 4 pp.

Wielandt, E. and Streckeisen, G., 1982. The leaf-spring seismometer: design and performance. *Bull. Seismol. Soc. Am.*, vol. 72, no. 6, p. 2349-2367.

CHAPTER 2: HOPEN BROADBAND STATION

2.1 Development of HOPEN broadband station systems: instrumentation and responses

2.1.1 <u>Short description</u>

The seismic station (HOPEN) on Hopen Island, Svalbard Archipelago, is a station owned and operated by UiB and constitutes part of the Norwegian National Seismic Network. In 2007, within the framework of the International Polar Year 2007-2008 project “The dynamic continental margin between the Mid-Atlantic-Ridge System (Mohns Ridge, Knipovich Ridge) and the Bear Island Region” (Schweitzer *et al.*, 2008) the station was upgraded to broadband, in cooperation with NORSAR, with the installation of an STS-2 seismometer. Since no HOPEN data were stored prior to this in NORSAR’s database, no earlier responses will be discussed in this documentation. The station is in addition equipped with an EarthData digitizer and data is collected with a sampling rate of 100 sps.

2.1.2 <u>Instrumentation</u>

I. Configurations

- HOPEN broadband configuration (2007-present):
  - STS-2 seismometer
  - EarthData digitizer

II. Respids

HOPENHH1,2,3

III. Instrument specifications

STS-2:
Streckeisen very broadband triaxial seismometer. 3 identical obliquely-oriented mechanical sensors are employed, instead of the traditional arrangement of separate orthogonal vertical and horizontal sensors. Some nominal values are the following (Streckeisen, 2003):

Seismic output (flat velocity)	8.33 mHz – 50 Hz
Mass	0.3 Kg
Gain	2 x 750 V/m/s
Damping	0.707 (low frequencies, < 1 Hz)
Feedback coil	50 N/A

EarthData digitizer:
The EarthData A/D converter has been discussed also in section 7.1.2 of Part I, on the Jan Mayen station. The version installed at the HOPEN station employs the following succession of digital filters:

Digital FIR filter: low-pass	N = 360, asymmetric, decimating by 6
Digital FIR filter: low-pass	N = 320, asymmetric, decimating by 5

2.2 Instrument response calculation for the HOPEN broadband station systems

This chapter focuses on the major considerations to be taken into account for the calculation of the instrument response of the broadband configuration currently in operation at the Hopen Island broadband station (HOPEN).

As with the rest of the systems discussed in this documentation, *GSE* file response *Respid* flags for each configuration are provided at the beginning of each section.

Digitizer response information was provided by UiB.

2.2.1 STS-2 – EarthData (2007/10/02 – …)

Respid:	HOPENHH1	Z
	HOPENHH2	N-S
	HOPENHH3	E-W

The HOPEN station is equipped with the following components:

- STS-2 broadband seismometer
- EarthData digitizer

2.2.1.1 *STS-2*

Detailed information about this instrument can be found in sections 7.2.1.1 and 7.2.2.1 of Part I about the Jan Mayen broadband station.

The instrument installed at HOPEN has serial number # 60703. Poles and zeros were calculated according to the formula 7.2.2 (Wielandt, 2002, Wielandt and Widmer-Schnidrig, 2002) in section 7.2.1.1 and are listed in the corresponding *GSE* response files. Sensitivity is equal to 1500 V/m/s at 2 s.

2.2.1.2 *EarthData*

The response of the Earth Data digitizer is described by the following succession of digital FIR filters, according to information from UiB:

- FIR filter (asymmetric) with 360 coefficients, decimating by 6 down to 500 Hz from an input rate of 3000 Hz
- FIR filter (asymmetric) with 320 coefficients, decimating by 5 down to the desired sampling rate of 100 sps.

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

The displacement amplitude and phase response of the above described configuration are depicted in Fig. 2.1.

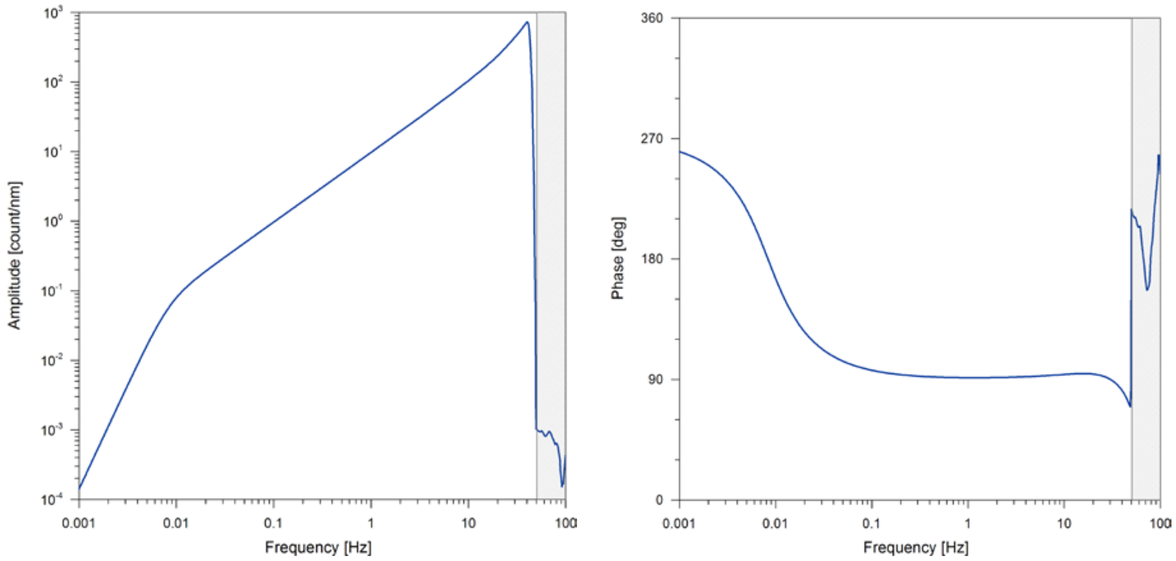


Fig. 2.1. Displacement amplitude (left) and phase (right) response for the vertical component of the HOPEN broadband station configuration. Shaded areas represent the range beyond the Nyquist frequency (50 Hz).

2.3 References

Schweitzer, J. and the IPY Project Consortium Members, 2008. The International Polar Year 2007-2008 Project "The Dynamic Continental Margin between the Mid-Atlantic-Ridge System (Mohn's Ridge, Knipovich Ridge) and the Bear Island Region". *NORSAR Sci. Rep.*, 1-2008, p. 53-63.

Wielandt, E., 2002. Seismic sensors and their calibration. Chapter 5 in *IASPEI New Manual of Seismological Observatory Practice*, Bormann, P. (Ed.), GeoForschungsZentrum Potsdam, Vol. 1, 46 pp.

Wielandt, E. and Widmer-Schnidrig, R., 2002. Seismic sensing and data acquisition in the GRSN. In *Ten Years of German Regional Seismic Network (GRSN)*, Deutsche Forschungsgemeinschaft, Senate Commission for Geosciences, Report 25, Wiley-VCH, p. 73-83.

CHAPTER 3: BJØRNØYA BROADBAND STATION

3.1 Development of BJO1 broadband station systems: instrumentation and responses

3.1.1 Short description

The seismic station BJO1 on Bjørnøya (Bear Island), western Barents Sea, is a station owned and operated by UiB and constitutes part of the Norwegian National Seismic Network. Since its first installation, several equipment changes have taken place at the station, resulting in several different configurations. Only those for which data can be found in NORSAR's database will be discussed herein. The first one of these two configurations was installed in 2005 and involves a combined seismometer and digitizer (CMG-6TD) by Güralp Systems, Ltd., while the current configuration, installed in October 2011, is equipped with a Trillium 120P sensor and a CMG-DM24 mk3 digitizer. Both configurations were sampled at 100 sps.

3.1.2 Instrumentation

I. Configurations

- BJO1 broadband configuration (2005-2011):
  CMG-6TD seismometer & digitizer

- BJO1 current configuration (2011-present):
  Trillium 120P seismometer
  CMG-DM24 mk3 digitizer

II. Respids

BJO1HH1,2,3
BJO1HH4,5,6

III. Instrument specifications

CMG-6TD:
The CMG-6TD is a three-component, digital, broadband seismometer for medium-noise sites. Some nominal values are the following (Güralp Systems, 2011):

Seismic output (flat velocity)	30 s (optionally 10 s) – 100 Hz
Gain	2 x 1200 V/m/s
Linearity	> 95 dB
Digitizer resolution at 1 sps	21-bit
Sampling rates	1000 – 1 sps

T120P:
The Trillium 120P broadband seismometer by Nanometrics, Inc. is built around a classic symmetric triaxial force feedback design with axis orientation in UVW. Some nominal values are the following (Nanometrics, 2011):

Sensitivity	1200 V/m/s ± 0.5% precision

Bandwidth	-3 dB points @ 120 s and 145 Hz
Clip level	> 15 mm/s up to 1.5 Hz
Velocity output	40 V peak-to-peak, differential

CMG-DM24 mk3:
The CMG-DM24 mk3 digitizer by Güralp Systems, Ltd. has been extensively discussed at Chapter 11 of Part 1 (sections 11.1.2 and 11.2.1.2) about the HSPB station.

3.2 Instrument response calculation for the BJO1 broadband station systems

This chapter focuses on the major considerations to be taken into account for the calculation of the instrument response of the broadband configuration currently in operation at the Bjørnøya broadband station (BJO1).

As with the rest of the systems discussed in this documentation, *GSE* file response *Respid* flags for each configuration are provided at the beginning of each section.

3.2.1 CMG-6TD	(2005/09/20 – 2011/10/10)
Respid: BJO1HH1	Z
BJO1HH2	N-S
BJO1HH3	E-W

This BJO1 configuration is equipped with the following components:

- CMG-6TD seismometer & digitizer

Due to a channel renaming in NORSAR's database (from BZ/N/E to HHZ/N/E), the same *Respid* is applied to two combinations of *GSE*, *SEED* and *FAP* files (see Appendix II).

3.2.1.1 *CMG-6TD*

The CMG-6TD is a three-component, digital, broadband seismometer. The model installed at BJO1 was built in 2003 and consequently – according to Güralp Systems, Ltd. (http://www.guralp.com/fir-filter-configuration-of-older-cmg-6td-instruments/, http://www.guralp.com/fir-filter-configuration-of-the-cmg-cd24/) – has an inbuilt digitizing unit.

The instrument installed at BJO1 has serial number # T6303. Sensitivity values for sensor (V/m/s) and digitizer (μV/count), as well as poles and zeros (Hz) are provided by the manufacturer in the corresponding datasheet, works order 2169, 27 January 2003:

	Velocity Response V/m/s	Digitiser Output uV/count	Digital Output m/s/count
VERTICAL	1183.90	0.2639	2.229E-10
NORTH/SOUTH	1182.12	0.2574	2.177E-10
EAST/WEST	1258.83	0.2605	2.069E-10

Velocity response output:

POLES (HZ)	**ZEROS HZ**
-23.65e-3 + 23.65e-3j	-5.03207
-23.65e-3 - 23.65e-3j	0
-393.011	0
-7.4904	
-53.5979 - 21.7494j	
-53.5979 + 21.7494j	

Normalizing factor at 1 Hz: A =$1.983*10^6$

As usual with Güralp instruments, pole/zero values and the normalization factor need to be multiplied by 2π to convert to rad/s.

The form of the amplitude and frequency response of the CMG-6TD is also provided in the datasheet:

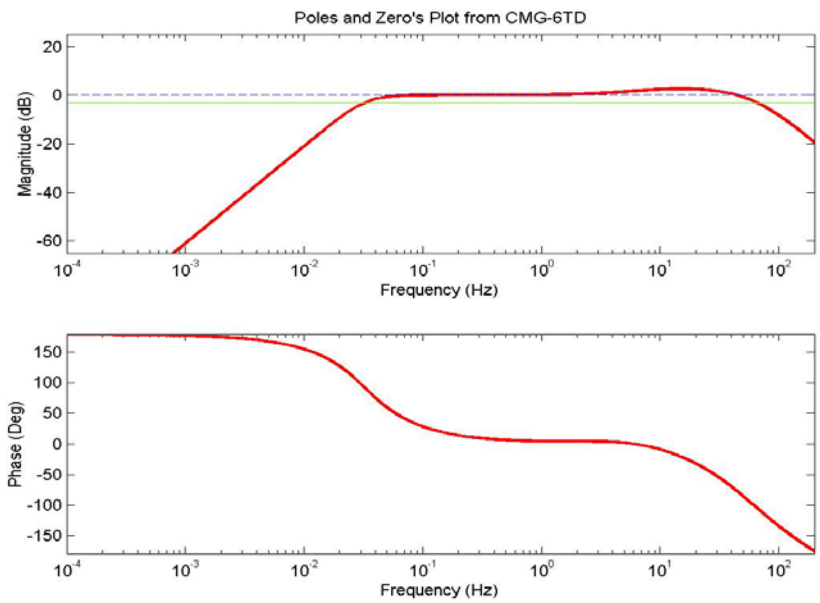


Fig. 3.1. Amplitude (top) and phase (bottom) response for CMG-6TD according to the datasheet of instrument # T6303 (Güralp Systems, 2003).

An alternative pole/zero set was distributed later by Güralp Systems to avoid the negative normalization factor introduced by the original set, that some software tools at the time were unable of handling. Since this problem is no longer actual, we will use the original pole/zero set, since it describes better the form of the response curve, as seen in Fig. 3.1.

Regarding decimation down to the sampling rate of 100 sps at BJO1, detailed information is provided by Güralp Systems on their webpage (http://www.guralp.com/fir-filter-configuration-of-older-cmg-6td-instruments/) and is summarized in Fig. 3.2.

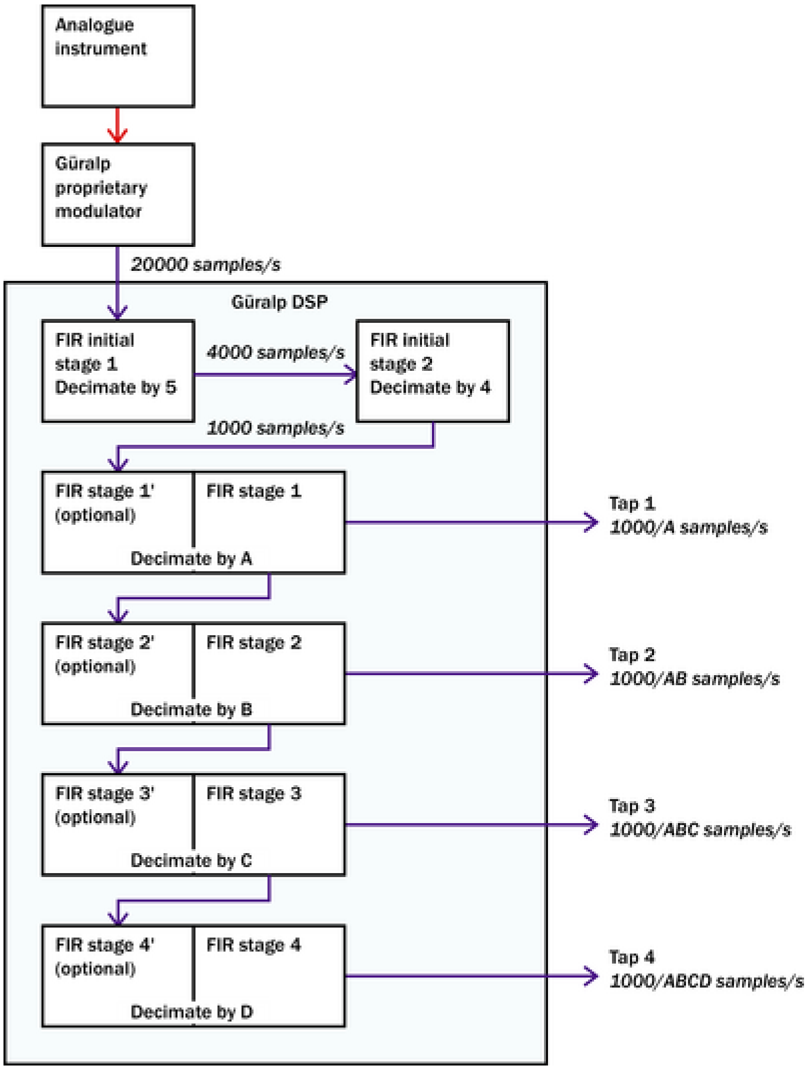


Fig. 3.2. The digital filter cascade employed by the old version (prior to 2005) of the CMG-6TD digital seismometer (from http://www.guralp.com/fir-filter-configuration-of-older-cmg-6td-instruments/).

Data from the modulator (20000 sps) is decimated within the DSP to 1000 Hz. This is done using cascaded ÷5 and ÷4 filters, both of them symmetric, with 501 coefficients.

After this, four further sets of FIR filters are used to decimate the data. ÷2, ÷4 and ÷5 filters are available; however, up to two FIR filters may be applied at each tap, allowing the user to choose decimation factors up to 10. The CMG-6TD allows the selection of a decimation factor for all four taps. However, the hardware does not support a 500 samples/s output rate, so the first tap must be set to a factor of ÷4 or ÷5. Decimation by 8 and 10 is achieved with the following combinations:

- Decimation by 8 = decimation by 4, then decimation by 2
- Decimation by 10 = decimation by 5, then decimation by 2

In the case of BJO1, the entire cascade is the following:

- FIR initial stage 1, symmetric, 501 coefficients, decimating by 5 → 4000 sps
- FIR initial stage 2, symmetric, 501 coefficients, decimating by 4 → 1000 sps

- FIR stage 1, symmetric, 501 coefficients, decimating by 5 → 200 sps
- FIR stage 2, symmetric, 501 coefficients, decimating by 2 → 100 sps

The coefficients of all FIR filters are listed in the corresponding *GSE* response file.

The displacement amplitude and frequency response of this configuration is plotted in Fig. 3.3 at section 3.2.2.2.

3.2.2 T120P – DM24 (2011/10/11 – …)

Respid: BJO1HH4 Z

BJO1HH5 N-S

BJO1HH6 E-W

The BJO1 station is currently equipped with the following components:

- Trillium 120P seismometer
- CMG-DM24 mk3 digitizer

3.2.2.1 *T120P*

The Trillium 120P seismometers by Nanometrics, Inc. are three-component, very broadband, low-noise seismometers suitable for both portable and fixed applications involving teleseismic, regional, and local studies. The symmetric triaxial arrangement of the sensing elements in Trillium 120P ensures uniformity between vertical and horizontal outputs (Nanometrics, 2009).

Regarding the instrument's response, information about the nominal response can be obtained from the sensor's manual (Nanometrics, 2009), and this is the information provided also by UiB. It is summarized in Table 3.1:

Table 3.1: Velocity response nominal values for the Trillium 120P sensor (from Nanometrics, 2009).

Symbol	Parameter	Nominal Values	Units
z_n	Zeros	0 0 –90.0 –160.7 –3108	rad/s
p_n	Poles	–0.03852 ±0.03658i –178 –135 ±160i –671 ±1154i	rad/s
k	Normalization factor	3.080×10^5	$(\mathrm{rad/s})^2$
f_0	Normalization frequency	1	Hz
S	Ground motion sensitivity at f_0	1201	V·s/m

Attention should be paid to the fact that in the instrument's manual (Nanometrics, 2009) the term "ground motion" is used, however this should not misinterpreted as displacement, since (i) the corresponding sensitivity is expressed in V/m/s and (ii) it is mentioned that the seismometer's passband is flat to velocity. This can be seen in Fig. 3.3, also extracted from the same source.

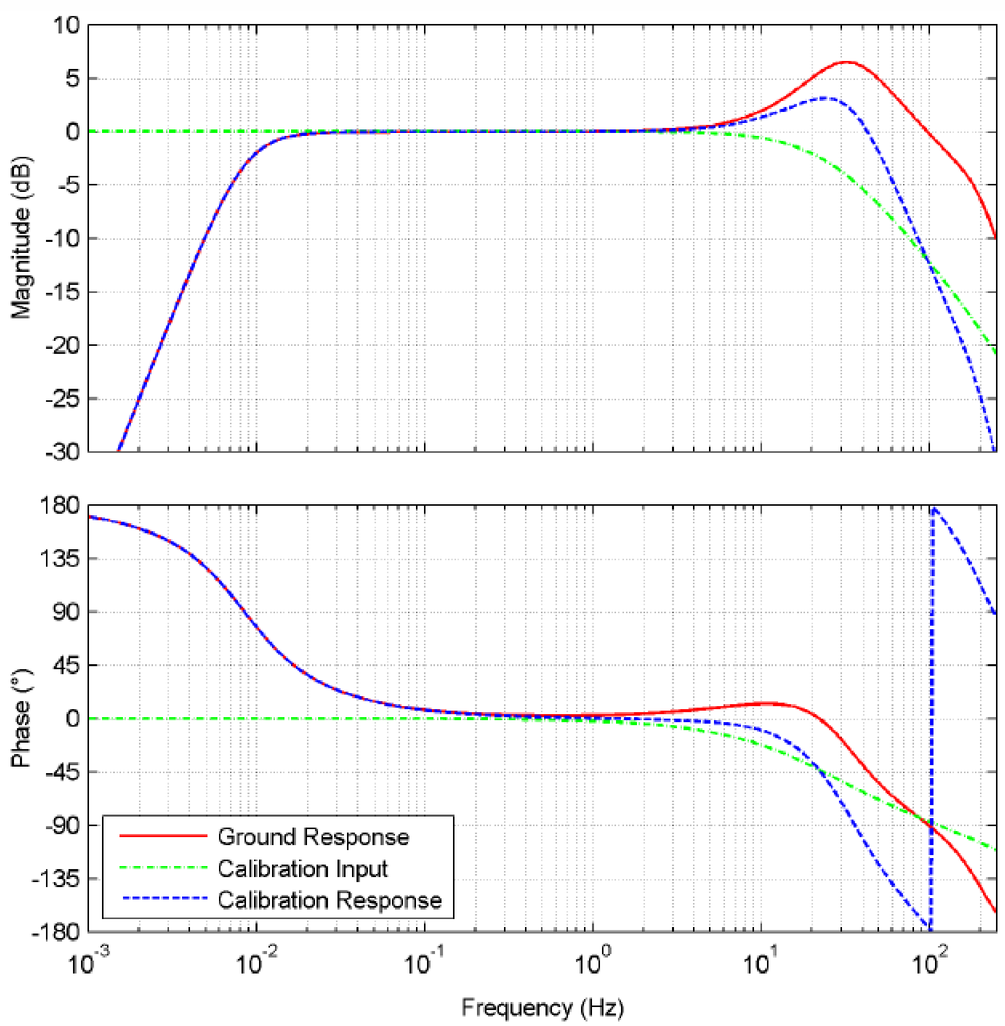


Fig. 3.3. Bode plot for the Trillium 120P (Fig. 10-1 in Nanometrics, 2009).

The transfer function $F(s)$ and the normalization factor k are provided by the following equations (Nanometrics, 2009), with employed notation explained in Table 3.1:

$$F(s) = S \cdot k \cdot \frac{\prod_n (s - z_n)}{\prod_n (s - p_n)}$$

and

$$k = \frac{1}{\dfrac{\prod_n (i \cdot 2 \cdot \pi \cdot f_0 - z_n)}{\prod_n (i \cdot 2 \cdot \pi \cdot f_0 - p_n)}}$$

3.2.2.2 *CMG-DM24*

The CMG-DM24 mk3 has been extensively discussed in sections 10.2.1.2 and 11.2.1.2 of Part 1 about the AKN and HSPBB stations respectively.

The sensitivity is provided by the manufacturer in the corresponding datasheets (here for serial number A3009). UiB uses the digitizer with a TTL value of 23, to output 100 sps, which means that the following FIR filter cascade is employed:

- CS5376 SINC1, decimating by 8
- CS5376 SINC2-stage-3, decimating by 2
- CS5376 SINC2-stage-4, decimating by 2
- CS5376 FIR-1-set0, decimating by 4
- CS5376 FIR-2-set0, decimating by 2
- DM24 FIR 1, decimating by 2
- DM24 FIR 2, decimating by 5
- DM24 FIR 3, decimating by 2

The filter coefficients can be found in the corresponding *GSE* response files (see Appendix II for names).

The displacement amplitude and phase response of the above described configurations are depicted in Fig. 3.4.

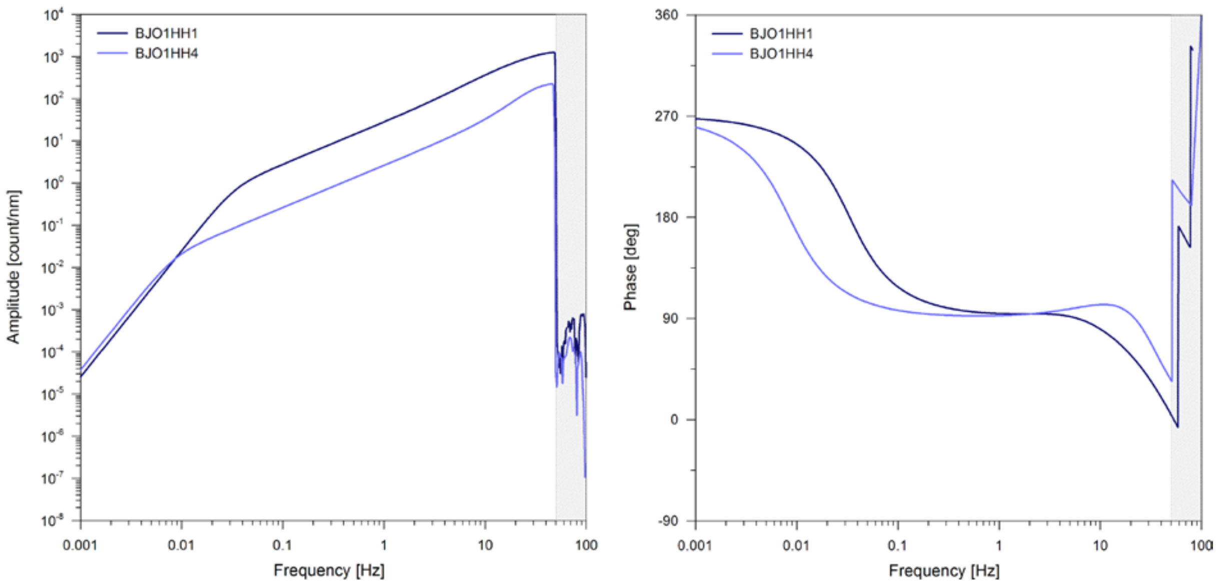


Fig. 3.4. Displacement amplitude (left) and phase (right) response for the vertical component of the BJO1 broadband station configurations. BJO1HH1 is the CMG-6TD configuration and BJO1HH4 the T120P and CMG-DM24 configuration. Shaded areas represent the range beyond the Nyquist frequency (50 Hz).

3.3 References

Güralp Systems, 2003. *CMG-6TD Calibration Sheet, # T6303*. Güralp Systems, Ltd., Aldermaston, Reading, UK, 2 pp.

Güralp Systems, 2011. CMG-6TD Broadband Seismometer and Digitiser. *DAS-040-0001 Issue A*, Güralp Systems, Ltd., Aldermaston, Reading, UK, 2 pp.

Nanometrics Inc., 2009. *Trillium 120P/PA Seismometer User Guide*. Nanometrics, Inc., Kanata, Ontario, Canada, 79 pp.

Nanometrics Inc., 2011. Trillium Broadband Seismometer. *NMX-Trillium.pdf*. Nanometrics, Inc., Kanata, Ontario, Canada, 6 pp.

CHAPTER 4: BERGEN BROADBAND STATION

4.1 Development of BER broadband station systems: instrumentation and responses

4.1.1 Short description

The Bergen seismic station (BER) is a station owned and operated by UiB and constitutes part of the Norwegian National Seismic Network. Since its first installation, several equipment changes have taken place at the station, resulting in several different configurations. Only those for which data can be found in NORSAR's database will be discussed herein. The first one of these two configurations was installed in 2007 and involves an STS-2 seismometer and an EarthData P2400 digitizer, while the current configuration, installed in February 2011, is equipped with an STS-2 seismometer and a Güralp Systems CMG-DM24 mk3 digitizer. The digitizer was exchanged with another one of the same type in June 2012. Both configurations (EarthData and Güralp digitizer) were sampled at 100 sps.

4.1.2 Instrumentation

I. Configurations

- BER broadband configuration (2007-2011):
    - STS-2 seismometer
    - EarthData P2400 digitizer

- BER current configuration (2011-present):
    - STS-2 seismometer
    - CMG-DM24 mk3 digitizer

II. Respids

BERHH1,2,3
BERHH4,5,6/a

III. Instrument specifications

STS-2:
Streckeisen very broadband triaxial seismometer. 3 identical obliquely-oriented mechanical sensors are employed, instead of the traditional arrangement of separate orthogonal vertical and horizontal sensors. Information available only from UiB.

EarthData P2400:
24-bit digitizer by EarthData. Information available only from UiB.

CMG-DM24 mk3:
The CMG-DM24 mk3 digitizer by Güralp Systems, Ltd. has been extensively discussed at Chapter 11 of Part 1 (§ 11.1.2 and 11.2.1.2) about the HSPB station.

4.2 Instrument response calculation for the BER broadband station systems

This chapter focuses on the major considerations to be taken into account for the calculation of the instrument response of the broadband configuration currently in operation at the Bergen broadband station (BER).

As with the rest of the systems discussed in this documentation, *GSE* file response *Respid* flags for each configuration are provided at the beginning of each section.

4.2.1 STS-2 – EarthData P2400 (2007/02/26 – 2011/02/16)

Respid: BERHH1	Z
BERHH2	N-S
BERHH3	E-W

This BER configuration is equipped with the following components:

- STS-2 seismometer
- EarthData P2400 digitizer

4.2.1.1 *STS-2*

The STS-2 tri-axial, broadband seismometer is discussed in detail in Part 1, § 7.2.1.1 about the Jan Mayen seismic station. In the case of station BER we are restricted to information provided by UiB, which described only the lower end of the instrument's frequency response. They model the STS-2 as a 120 s sensor with 0.7 damping (see Eq. 2.2.2 and its solution in Part 1, § 2.2.1.1 about obtaining poles and zeros).

4.2.1.2 *EarthData P2400*

The only information in our disposal about this digitizer is what is provided by UiB. They report a sensitivity of 10^6 count/V and a cascade of two linear-phase FIR filters that are employed to decimate from a rate of 3000 Hz down to 100 sps:

- FIR 1, asymmetric, with 360 coefficients, decimating by 6 and
- FIR 2, asymmetric, with 320 coefficients, decimating by 5 down to 100 sps.

The displacement amplitude and frequency response of this configuration is plotted in Fig. 4.1 at § 4.2.2.2 at the end of this chapter.

4.2.2 STS-2 – DM24 (2011/02/17 – …)

Respid:	BERHH4(a)	Z
	BERHH5(a)	N-S
	BERHH6(a)	E-W

The BER station is currently equipped with the following components:

- STS-2 seismometer
- CMG-DM24 mk3 digitizer

A digitizer change was made in June 2012, which resulted in a slight difference in overall channel sensitivity. The configuration with the first DM24 digitizer is denoted as BERHH4/5/6a.

4.2.2.1 *STS-2*

See § 4.2.1.1 of the same chapter.

4.2.2.2 *CMG-DM24*

The CMG-DM24 mk3 has been extensively discussed in Part 1, § 10.2.1.2 and 11.2.1.2 about the AKN and HSPBB stations respectively.

The sensitivity is instrument specific and is provided by the manufacturer in the corresponding datasheets. UiB uses the digitizer with a TTL value of 23, to output 100 sps, which means that the following FIR filter cascade is employed:

- CS5376 SINC1, decimating by 8
- CS5376 SINC2-stage-3, decimating by 2
- CS5376 SINC2-stage-4, decimating by 2
- CS5376 FIR-1-set0, decimating by 4
- CS5376 FIR-2-set0, decimating by 2
- DM24 FIR 1, decimating by 2
- DM24 FIR 2, decimating by 5
- DM24 FIR 3, decimating by 2

The filter coefficients can be found in the corresponding *GSE* response files (see Appendix II for names).

The displacement amplitude and phase response of the above described configurations are depicted in Fig. 4.1.

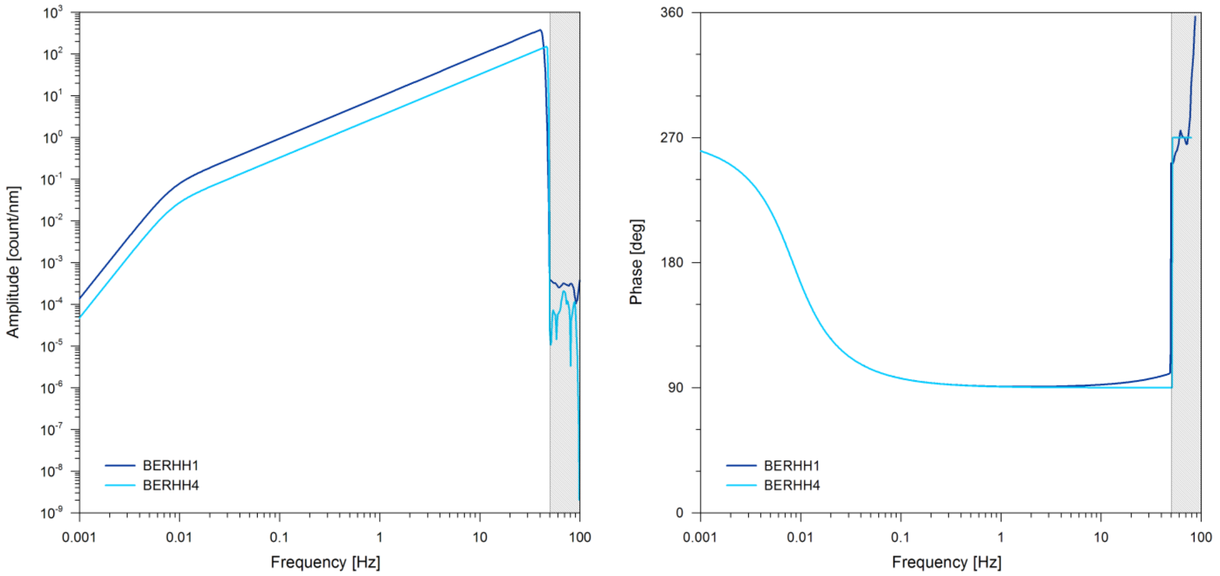


Fig. 4.1. Displacement amplitude (left) and phase (right) response for the vertical component of the BER broadband station configurations. BERHH1 is the EarthData configuration and BERHH4 the CMG-DM24 configuration. Shaded areas represent the range beyond the Nyquist frequency (50 Hz).

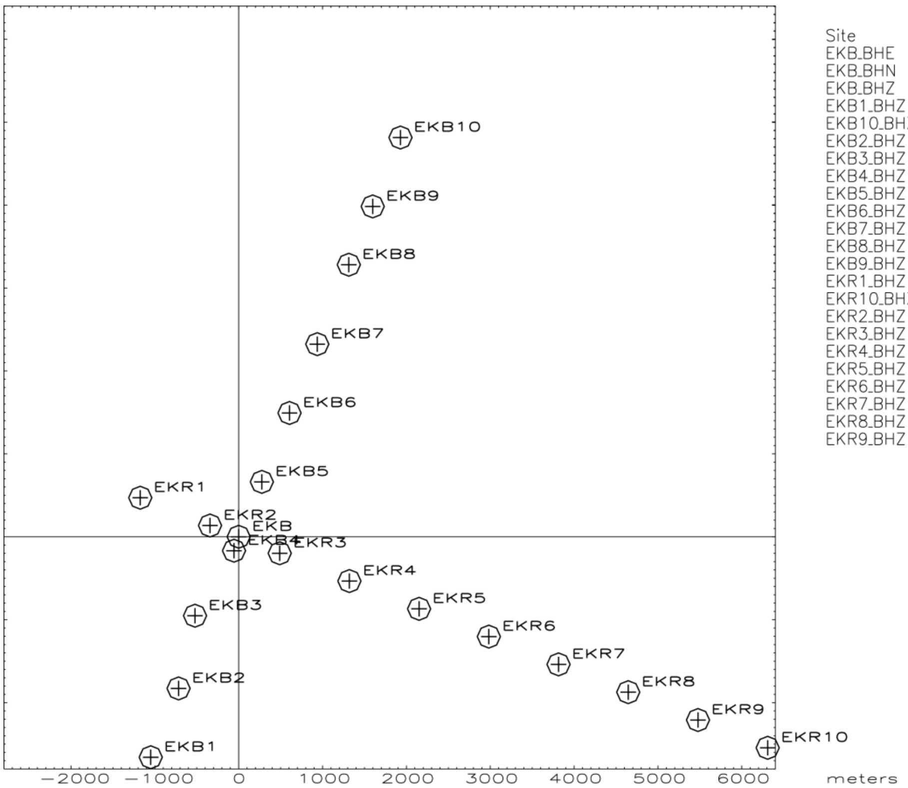
CHAPTER 5: ESKDALEMUIR SEISMIC ARRAY – EKA

5.1 Development of EKA systems: instrumentation and responses

5.1.1 Short description

- 2008-…:

Since November 2012, NORSAR began receiving and archiving data from the Eskdalemuir seismic array (EKA) in UK. The array is cross shaped (Fig. 5.1), with only one three-component site (EKB) at the crossing of the two branches (EKB and EKR), which is used as array reference point. The array has been since 2008 equipped with a CMG-3T seismometer at the 3-C site and CMG-3V seismometers at the vertical-only elements, together with CMG-DM24 digitizers, all manufactured by Güralp Systems.



Site	X east	Y north	Z height
EKB_BHE	0	0	307
EKB_BHN	0	0	307
EKB_BHZ	0	0	307
EKB1_BHZ	−1049	−2659	275
EKB10_BHZ	1929	4815	327
EKB2_BHZ	−717	−1829	313
EKB3_BHZ	−521	−952	312
EKB4_BHZ	−56	−168	299
EKB5_BHZ	276	662	310
EKB6_BHZ	606	1493	338
EKB7_BHZ	937	2323	436
EKB8_BHZ	1313	3281	405
EKB9_BHZ	1598	3984	398
EKR1_BHZ	−1174	471	356
EKR10_BHZ	6308	−2545	383
EKR2_BHZ	−342	136	350
EKR3_BHZ	489	−199	322
EKR4_BHZ	1320	−534	338
EKR5_BHZ	2151	−869	307
EKR6_BHZ	2983	−1204	396
EKR7_BHZ	3814	−1539	349
EKR8_BHZ	4645	−1874	420
EKR9_BHZ	5477	−2210	429

Fig. 5.1. Geometry of the Eskdalemuir seismic array (EKA). Array element distances based on the position of the central site EKB are listed in meters.

5.1.2 Instrumentation

I. Configurations

- BB 3-C configuration (2008-…):
  - CMG-3T sensor
  - CMG-DM24 digitizer

- BB 1-C configuration (2008-…):
  - CMG-3V sensors
  - CMG-DM24 digitizers

II. Respids

EKABH1,2,3
EKABH4

III. Instrument specifications

CMG-3V:
Vertical seismometer by Güralp Systems, with response that is flat to acceleration. Response specifications for the sensor with serial number V3I26, work order 2616, are the following:

Velocity output	2 x 370 V/m/s^2 @ 1 Hz

CMG-3T:
Three-component, broadband sensor by Güralp Systems. The response of this sensor is flat to velocity.

Nominal velocity output	2 x 2000 V/m/s (differential) @ 1 Hz

CMG-DM24:
Full 24-bit digitizer employing the Cirrus Logic CS5376 digital filtering chipset and TMS320VC33 digital signal processor (DSP). The DSP software consists of 6 cascaded programmable filter/decimation stages that allow the selection of multiple data output rates simultaneously (Güralp Systems, 2006). The specifications of this instrument are the following:

Input voltage range	+/- 10 V differential
Dynamic range	137 dB @ 40 sps
DSP sampling rate	32 kHz
Sensitivity	1.7 µV/count

5.2 Instrument response calculation for the EKA array systems

This chapter focuses on the major considerations to be taken into account for the calculation of the instrument response of the different systems operating at the Eskdalemuir array (EKA).

As with the rest of the systems discussed in this documentation, *GSE* file response *Respid* flags for each configuration are provided at the beginning of each section.

5.2.1 CMG-3T – DM24 (2008/11/24 – …)

Respid:	EKABH1	Z
	EKABH2	N-S
	EKABH3	E-W

The reference element (EKB) of the EKA array is the only three-component site and carries the following instrumentation:

- CMG-3T broadband seismometer
- CMG-DM24 digitizer

5.2.1.1 *CMG-3T*

The response characteristics of the CMG-3T broadband seismometer installed at site EKB at the Eskdalemuir array are provided by the manufacturer (Güralp Systems) in the instrument specific calibration sheet.

The poles and zeros for instrument with serial number T3442 (works order 1246) are the following:

POLES (HZ)	**ZEROS HZ**
$-35.35 \times 10^{-3} \pm 35.35 \times 10^{-3}j$	180.076
-133.115	0
-72.0764	0

The reported normalization factor at 1 Hz is A = -53.52.

To convert to rad/s, pole and zero values need to be multiplied by 2π.

The gain values for the three components of this instrument are:

	Velocity Output V/m/s (Differential)	Mass Position Output (Acceleration output) $V/m/s^2$	Feedback Coil Constant $Amp/m/s^2$
VERTICAL	2 x 1993.7	1163	0.02475
NORTH/SOUTH	2 x 1983.8	1366	0.02906
EAST/WEST	2 x 2005.6	1637	0.03483

5.2.1.2 *CMGD-DM24*

The response of the CMD-DM24 digitizer, mk3, of Güralp Systems has been described in detail in several instances in this documentation (see *e.g.*, Part 1, § 11.2.1.2). Sensitivity values are instrument specific and are provided by the manufacturer in the instrument calibration sheet. In this case, for digitizer with serial number C690, the values for each channel are the following:

VELOCITY CHANNELS

Channel:	BNEKBZ2	Vertical	3.200 µV/Count
	BNEKBN2	North/South	3.193 µV/Count
	BNEKBE2	East/West	3.196 µV/Count

The digital filter cascade employed to decimate down to the desired sampling rate of 40 sps corresponds to a value of TTL = 31 in the Güralp Systems tabulated, decimation cascade look-up system and is as follows:

- CS5376 FIR filter Stage 1, Sinc 1, with 36 coefficients, decimating by 8 from an input rate of 512 kHz
- CS5376 FIR filter Stage 3, Sinc 2, with 6 coefficients, decimating by 2
- CS5376 FIR filter Stage 4, Sinc 2, with 8 coefficients, decimating by 2
- CS5376 FIR filter Stage 5, FIR 1, with 48 coefficients, decimating by 4
- CS5376 FIR filter Stage 5, FIR 2, with 126 coefficients, decimating by 2,
- DM24 FIR Stage 1, SWA-D24-3D06, with 502 coefficients, decimating by 2,
- DM24 FIR Stage 2, SWA-D24-3D08, with 502 coefficients, decimating by 5 and
- DM24 FIR Stage 3, SWA-D24-3D08, with 502 coefficients, decimating by 5 down to 40 sps.

The displacement amplitude and phase response of this configuration is presented in Fig. 5.2 at the end of section 5.2.2 with the dark blue line.

5.2.2 CMG-3V – DM24 (2008/11/24 – …)

Respid: EKABH4 Z

The vertical only sites of the Eskdalemuir seismic array are equipped with the following instrumentation:

- CMG-3V sensors
- CMG-DM24 digitizers

5.2.2.1 *CMG-3V*

The response characteristics of the CMG-3V sensors installed at the vertical only sites of the Eskdalemuir array are provided by the manufacturer (Güralp Systems) in the instrument specific calibration sheets.

The response of these sensors is flat to acceleration and is described by the following pole-zero set:

POLES (HZ)	**ZEROS HZ**
-50×10^{-3}	0
-250	
-68.802	
$-27.656 \pm j41.738$	

Normalizing factor at 1 Hz: A = 43.22×10^{6}

Pole and zero values need to be multiplied by 2π to convert to rad/s. The normalization factor would also need to be recalculated.

The sensor gain values are instrument specific. An example, for sensor with serial number V3I33 (works order 2616) installed at site EKB1, is shown below.

	Acceleration Output V/ms^{-2}	Mass Position Output (Acceleration output) V/ms^{-2}	Feedback Coil Constant Amp/ms^{-2}
VERTICAL	2 x 371	1575	0.02386

5.2.2.2 *CMG-DM24*

The response of the Güralp Systems DM24 digitizer, as employed at EKA has been discussed in § 5.2.1.2 of this chapter.

Site specific sensitivity values can be found in the corresponding *GSE* response files.

The displacement amplitude and phase response of the vertical only sites (EKABH4) of the Eskdalemuir array is shown in Fig. 5.2 in light blue. The shaded area represents the response range beyond the Nyquist frequency.

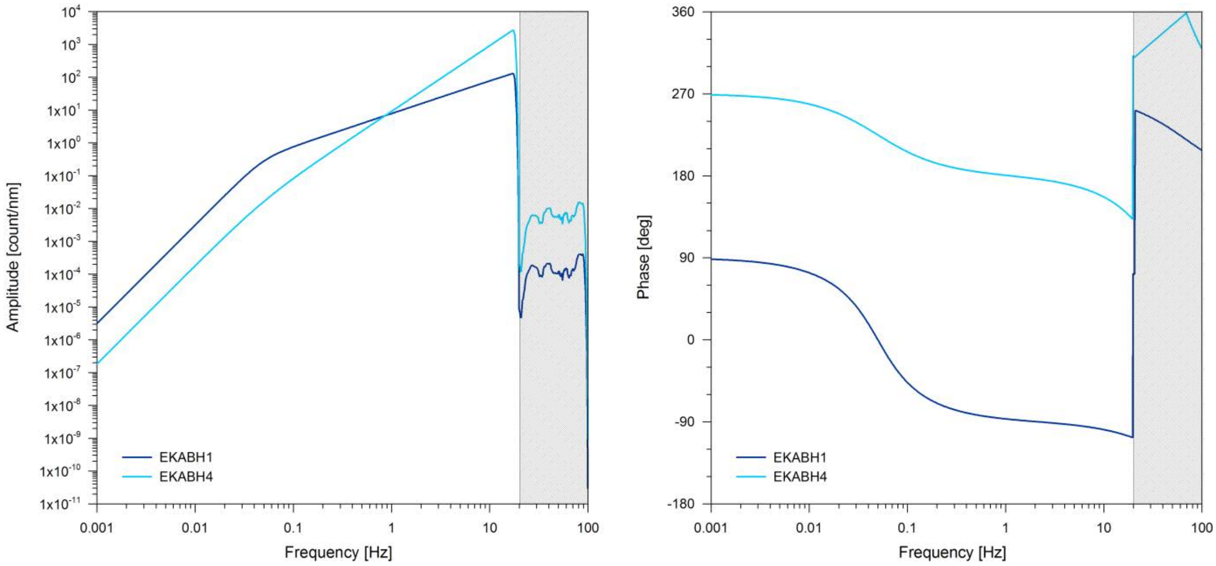


Fig. 5.2. Displacement amplitude (left) and phase (right) response for the EKA seismic array configurations. The three-component site EKB response (here represented by the vertical component with Respid EKABH1) is noted in dark blue, while that of the vertical only sites (EKABH4) in light blue. Shaded areas represent the range beyond the Nyquist frequency (20 Hz for the EKA array).

5.3 References

Güralp Systems, 2006. CMG-DM24 Operator's Guide. *MAN-D24-0004*, Güralp Systems Ltd., Aldermaston, England, 113 pp.

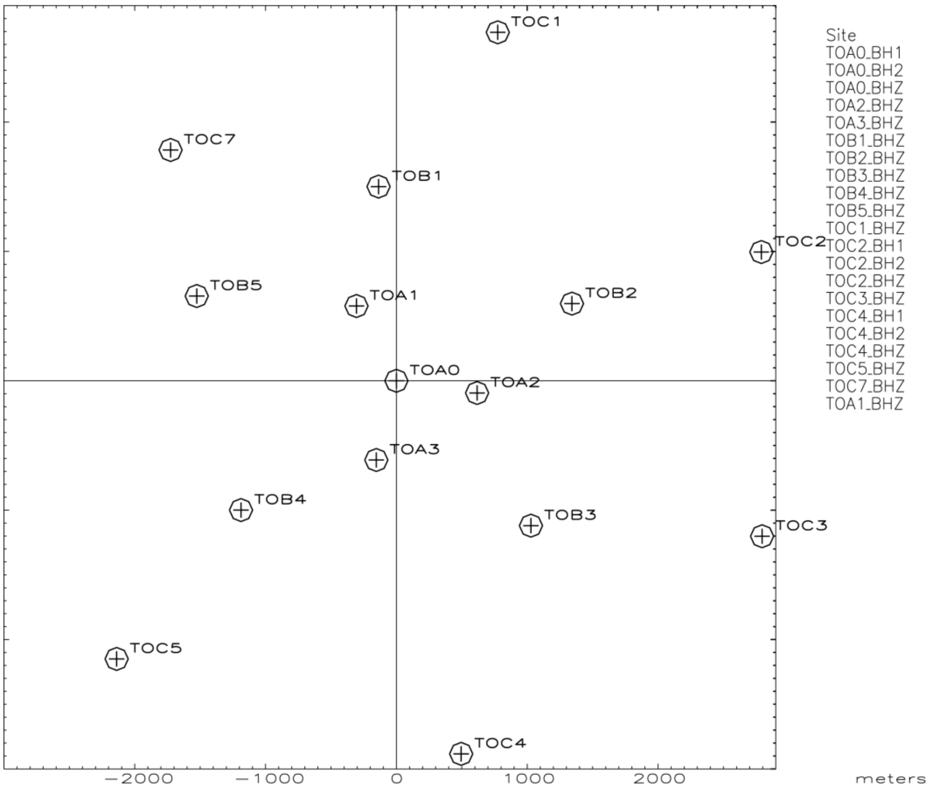
CHAPTER 6: TORODI SEISMIC ARRAY – TORD

6.1 Development of TORD systems: instrumentation and responses

6.1.1 Short description

- 2009-…:

Since 2013, NORSAR has been retrieving from the IDC and store continuous data from the Torodi seismic array (TORD), which is part of the IMS (primary station PS26). A Memorandum of Understanding between NORSAR and the Abdou Moumouni University of Niamey, Niger, who owns TORD, is under preparation. The geometry of the TORD array is shown in Fig. 6.1. The array has been since February 2009 equipped with a CMG-3TB seismometers and Europa T digitizers.



Site	X east	Y north	Z height
TOA0_BH1	0	0	214
TOA0_BH2	0	0	214
TOA0_BHZ	0	0	214
TOA2_BHZ	617	−94	216
TOA3_BHZ	−154	−612	217
TOB1_BHZ	−137	1501	231
TOB2_BHZ	1342	597	216
TOB3_BHZ	1028	−1120	216
TOB4_BHZ	−1188	−999	226
TOB5_BHZ	−1526	655	219
TOC1_BHZ	775	2694	233
TOC2_BH1	2789	995	222
TOC2_BH2	2789	995	222
TOC2_BHZ	2789	995	222
TOC3_BHZ	2795	−1202	214
TOC4_BH1	495	−2884	232
TOC4_BH2	495	−2884	232
TOC4_BHZ	495	−2884	232
TOC5_BHZ	−2138	−2150	232
TOC7_BHZ	−1726	1784	225
TOA1_BHZ	−305	578	220

Fig. 6.1. Geometry of the Torodi seismic array (TORD, PS26). Array element distances based on the position of the central site TOA0 are listed in meters. The latter together with sites TOC2 and TOC4 are the only three-component sites of the array.

6.1.2 Instrumentation

I. Configurations

- Current BB configuration (2009-…):
  CMG-3TB sensors
  Europa T digitizers

II. Respids

N/A

III. Instrument specifications

CMG-3TB:
Borehole broadband sensor by Güralp Systems.

Europa T:
A Nanometrics A/D converter, manufactured especially for CTBT monitoring purposes (Trident with authentication). Some nominal values are the following (see also Part 1, chapters 7 and 8):

Resolution	24-bit
Maximum differential input voltage range	40 V p-p @ gain 0.4
Nominal sensitivity	1 count/μV for gain 1
Software selectable gain	0.4, 1, 2, 4, 8
Dynamic range	142 dB for 100 Hz output sample rate
Output sample rates	10, 20, 40, 50, 100 sps

The digitizer employs the following digital filters:

A decimating FIR filter (low-pass) and

An optional IIR filter (high-pass for DC offset removal), first order, 1 mHz to 1 Hz

6.2 Instrument response calculation for the TORD array systems

This chapter touches briefly upon some aspects of the Torodi seismic array (TORD, IMS station PS26) system response.

Response information for TORD is retrieved solely from response files provided by the IDC. The information has not been organized following the scheme described in Chapter 1 of Part 1 of this documentation and consequently no *Respid* flag has been assigned to the response described in this section.

According to the IDC, the current TORD array configuration consists of the following components:

- CMG-3TB borehole seismometers
- Nanometrics Europa T digitizers

As mentioned in § 6.1.1 of this chapter, apart from three array sites with three-component instrumentation, the rest of the array has vertical only elements. Vertical channels are denoted BHZ and horizontal BH1 and BH2. Data are sampled at 40 sps.

6.2.1.1 *CMG-3TB*

The response of these instruments is according to the IDC described by the following pole-zero set (rad/s):

Poles (6)
-0.03701 ± *j* 0.03701
-188.8279 ± *j* 195.5396
-259.2216 ± *j* 719.6446
Zeros (3)
0.0 0.0 0.0

In the brief comments within the *paz* file provided by the IDC, it is implied that the sensors are flat to acceleration, by mentioning that two additional zeros are contained in the pole-zero set above to convert from acceleration to displacement.

A sensitivity of 10000 V/m/s is reported in *RESP.SEED* format (see Part 1, Chapter 1 for more details).

6.2.1.2 *Europa T*

The Europa T digitizer is a Nanometrics A/D converter, based on the Trident digitizer, especially designed for CTBT purposes, to provide authenticated data to the acquisition centre. A detailed discussion of its response can be found in Part 1, § 7.2.2.2. From the information available to us from the IDC, the following digital filters are reported to being used at the Torodi array:

- A decimating FIR filter (low-pass) and
- An optional IIR filter (high-pass for DC offset removal)

Filter coefficients can be found in the *paz* file TORD_bb_response_20090202, residing under /ndc/programs/dpep/dbtables/2008/TORD/response.

In the same file, the sensitivity of the Europa T units at TORD is reported to be equal to 2000000 count/V.

The overall channel sensitivity is thus equal to 20 count/nm/s at 1 Hz.

PART 3

CHAPTER 1: IPY BROADBAND OBS/H DEPLOYMENT

1.1 Development of IPY broadband OBS/H systems: instrumentation and responses

1.1.1 Short description

- 2007-2008:

A deployment of 12 broadband ocean-bottom seismometers and hydrophones (OBS/H) belonging to the German Pool for Amphibian Seismology (DEPAS) was installed in the region between the mid-Atlantic ridge and the western Barents Sea margin within the International Polar Year (IPY) project “The dynamic continental margin between the Mid-Atlantic-Ridge System (Mohns Ridge, Knipovich Ridge) and the Bear Island Region” (Schweitzer *et al.*, 2008). The positions of the stations, which were watered in September 2007 and recovered in August 2008, are shown in Fig. 1.1. Some instrument and data loss took place: station OBS04 got fished out in April 2008 by a Russian trawler, but the data could be retrieved albeit without possibilities for skew correction; station OBS03 was lost during recovery, sinking back to the water after hitting the ship’s propeller; OBS10 was not found at the time and ended up on the northern coast of Iceland, without recording any data.

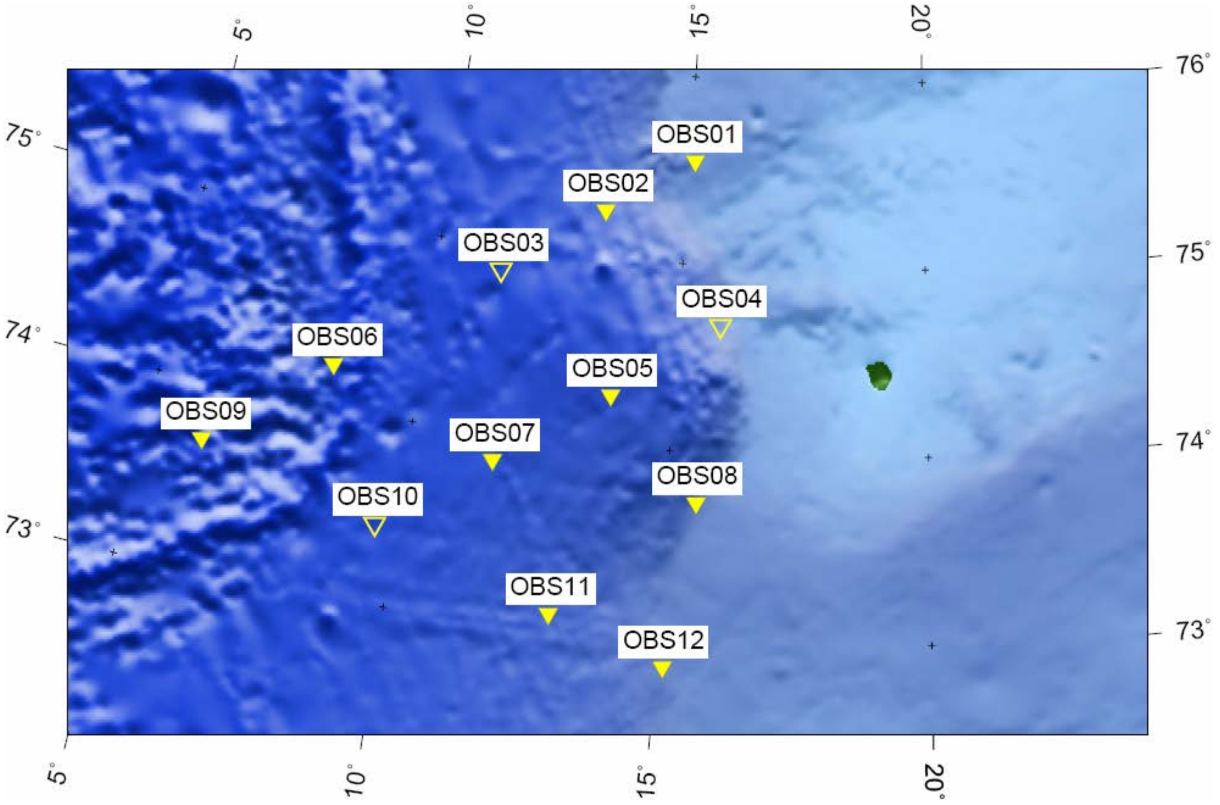


Fig. 1.1. The IPY broadband OBS/H deployment. Open symbols are used for stations will partial (OBS04) or total data loss. Minimum interstation distance is in the order of 60 km.

The particular station type (Fig. 1.2), known as LOBSTER (Long-term OBS for Tsunami and Earthquake Research), is designed and manufactured for the Alfred-Wegener-Institute for Polar and Marine Research, Bremerhaven, Germany by Umwelt- und Meerestechnik Kiel GmbH (K.U.M. GmbH).

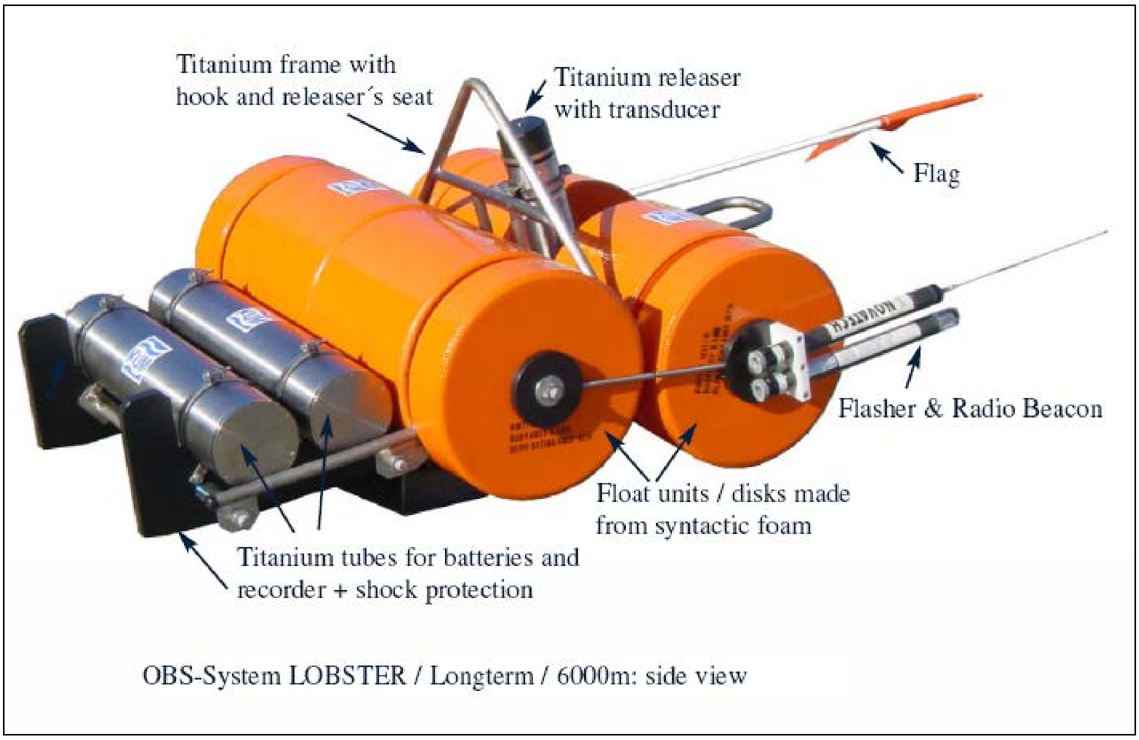


Fig. 1.2. The LOBSTER OBS/H system (picture taken from K.U.M. GmbH LOBSTER brochure).

The station has three seismic channels, BHZ, BHX and BHY, which under correct orientation would correspond to Z, N-S and E-W and a hydrophone channel, BHH. The seismic data are provided by a Güralp Systems CMG-40T broadband sensor incorporated in Titanium pressure housing and the pressure data by a HTI-04-PCA/ULF hydrophone (High Tech Inc., USA), with acquisition being performed by a GEOLON-MCS recorder in a Titanium tube, manufactured by SEND Off-Shore Electronics GmbH.

1.1.2 Instrumentation

I. Configurations

- IPY OBS configuration (2007-2008):
  CMG-40T broadband seismometer
  GEOLON-MCS recorder

- IPY OBH configuration (2007-2008):
  HTI-04-PCA/ULF hydrophone
  GEOLON-MCS recorder

II. Respids

OBSBH1,2,3
OBSBHH

III. Instrument specifications

CMG-40T:

Three-component, broadband seismometer, by Güralp Systems Ltd, incorporated in Titanium pressure housing for OBS usage (Güralp Systems, 2005). Some nominal values are the following:

Frequency response	0.033 Hz (30 s) – 50 Hz,
Optional response	60 s – 50 Hz
Velocity output	2000 V/m/s
Poles (Hz)	$-11.78 \times 10^{-3} \pm j\ 11.6932 \times 10^{-3}$
	$-80.0 \pm j\ 95.0$
Zeros (Hz)	0.0 0.0
Normalizing factor	15.41 K @ 1 Hz

HTI-04-PCA/ULF:

Hydrophone manufactured by High Tech, Inc., USA for SEND Off-Shore Electronics GmbH. Some nominal values are the following (High Tech, Inc., 2005):

Sensitivity	-195 dB relative to 1 V/μPa
Nominal capacitance	60 nF

GEOLON-MCS recorder:

The GEOLON Marine Compact Seismocorder, manufactured by SEND Off-Shore Electronics GmbH, is a seismic exploration data logger optimized for the marine environment. It can record 4 channels (3 seismic and hydrophone), with software selectable pre-amplification. Timing signals are produced by a high-performance microprocessor-controlled crystal oscillator and are synchronized before deployment by using GPS time signals (SEND, 2009). Some nominal values are the following:

Resolution	24-bit
Number of channels	4 (3 seismic, 1 pressure)
Pre-amplification	seven 6 dB steps from 0 dB to 36 dB
Input sensitivity	software selectable 5 Vp-p – 80 mVp-p

1.2 Instrument response calculation for the IPY broadband OBS/H deployment

This chapter focuses on the major considerations to be taken into account for the calculation of the instrument response of the different systems operating at the IPY broadband OBS/H deployment.

As with the rest of the systems described in this documentation, *GSE* file response *Respid* flags for each configuration are provided at the beginning of each section.

1.2.1 <u>CMG-40T – GEOLON</u> (2007/09/19 – 2008/08/19)

Respid:	OBSBH1	Z
	OBSBH2	N-S
	OBSBH3	E-W

The IPY broadband OBS/H deployment's seismic channel configuration consists of the following components:

- CMG-40T broadband 3-component, seismometer in Titanium pressure housing
- GEOLON-MCS recorder

1.2.1.1 *CMG-40T*

Instrument response information for ground velocity is provided by the manufacturer (Güralp Systems, Ltd.) in the form of poles and zeros, while sensitivity values are provided on a calibration sheet shipped together with the equipment.

The correspondence between sensor serial number and OBS/H station can be found in the corresponding *GSE* response files.

Poles and zeros for the instrument with serial number T4L91 (works order 3305), at station OBS01, are listed in the following table:

POLES (HZ)	**ZEROS HZ**
$-11.78 \times 10^{-3} \pm j11.78 \times 10^{-3}$	0
$-80.0 \pm j\,95.0$	0

Normalizing factor at 1 Hz: A = 15.41 K

For the same case, instrument output is equal to:

	Velocity Output V/m/s	Mass Position Output (Acceleration output) V/m/s^2	Feedback Coil Constant Amp/m/s^2
VERTICAL	1957	14.6	0.004421
N-S	1987	14.1	0.004286
E-W	1993	14.0	0.004242

Poles and zeros are listed in units of Hz. They need to be multiplied with 2π to be converted to rad/s which is the accepted unit in the *GSE* response file. The same change applies for the normalizing factor.

Total sensor sensitivity at 1 Hz will then be equal to: G = (sensitivity) x (norm. factor). Sensor and channel specific sensitivity values can be found in the corresponding *GSE* files.

1.2.1.2 *GEOLON-MCS*

The IPY broadband OBS/H deployment was equipped with SEND GEOLON-MCS recorders.

The GEOLON-MCS is a seismic exploration data logger optimized for the marine environment. The GEOLON-MCS has four differential input channels for 4C recordings. Channel 1 has a very high impedance of 30 MOhm (MCS12) or 150MOhm (MCS20 and 30) as well as a guard output to directly connect to a hydrophone. Channels 2 - 4 have an input impedance of 200 kOhm for connecting to geophones. One Hydrophone, one 3-component geophone or all 4 components may be recorded. The pre-amplification is software selectable in seven 6 dB steps from 0 dB - 36 dB. Then each channel is digitized using a high-performance 24-bit sigma-delta A/D-converter that produces software selectable sample rates needed for seismic exploration. A high-performance microprocessor-controlled crystal oscillator (MCXO) produces timing signals that are synchronized before deployment using GPS time signals (SEND GmbH, 2009).

The preamplifier gain for each channel may be set using the **GAIN** command. The minimum amplification factor is 1 and the maximum is 64 in 7 discrete steps of 6 dB each.

The input sensitivity $\mathbf{UIN}_{0dB}$ can be determined using the following formula (SEND GmbH, 2009):

$$\mathbf{UIN}_{0dB} = \mathbf{5\ V / GAIN}\ [V_{pp\ differential}]$$

and $\mathbf{1 \leq GAIN \leq 64}$ in seven steps (powers of two: 1, 2, 4, 8, 16, 32, 64). In the case of the IPY deployment, a GAIN of 1 was used for the seismic channels.

Apart from the already mentioned pre-amplifier, the GEOLON-MCS A/D converter consists of a sigma-delta modulator and a digital filter, which decimates down to the desired data sampling rate (SEND GmbH, 2007). The Cirrus Logic CS5378 low-power, single-channel, digital filter is used for this purpose (Cirrus Logic, 2010). A cascade of a multi-staged SINC filter with variable decimation stages and two FIR filters (Fig. 1.3(a) – (c)) are employed to decimate from the 512 kHz of the modulator to a diversity of sampling rates. In the case of the IPY OBS/H deployment, 50 sps data was outputted. Tables 1.1 and 1.2 (Cirrus Logic, 2010) show the different possible sub-stages of the SINC filter and the different combinations of SINC sub-stages used to achieve a particular sampling rate, respectively. Thus, to achieve a sampling rate of 50 sps, a digital filter cascade consisting of SINC1, SINC2 stages 2, 3 and 4, SINC3 stages 3, 5 and 7, and FIR filters FIR1 and FIR2 is employed. The characteristics, decimation factors and number of coefficients for each employed sub-stage of the SINC filter can be found in Table 1.1, while the decimation factors of FIR1 and FIR2 can be seen in Fig. 1.3(c).

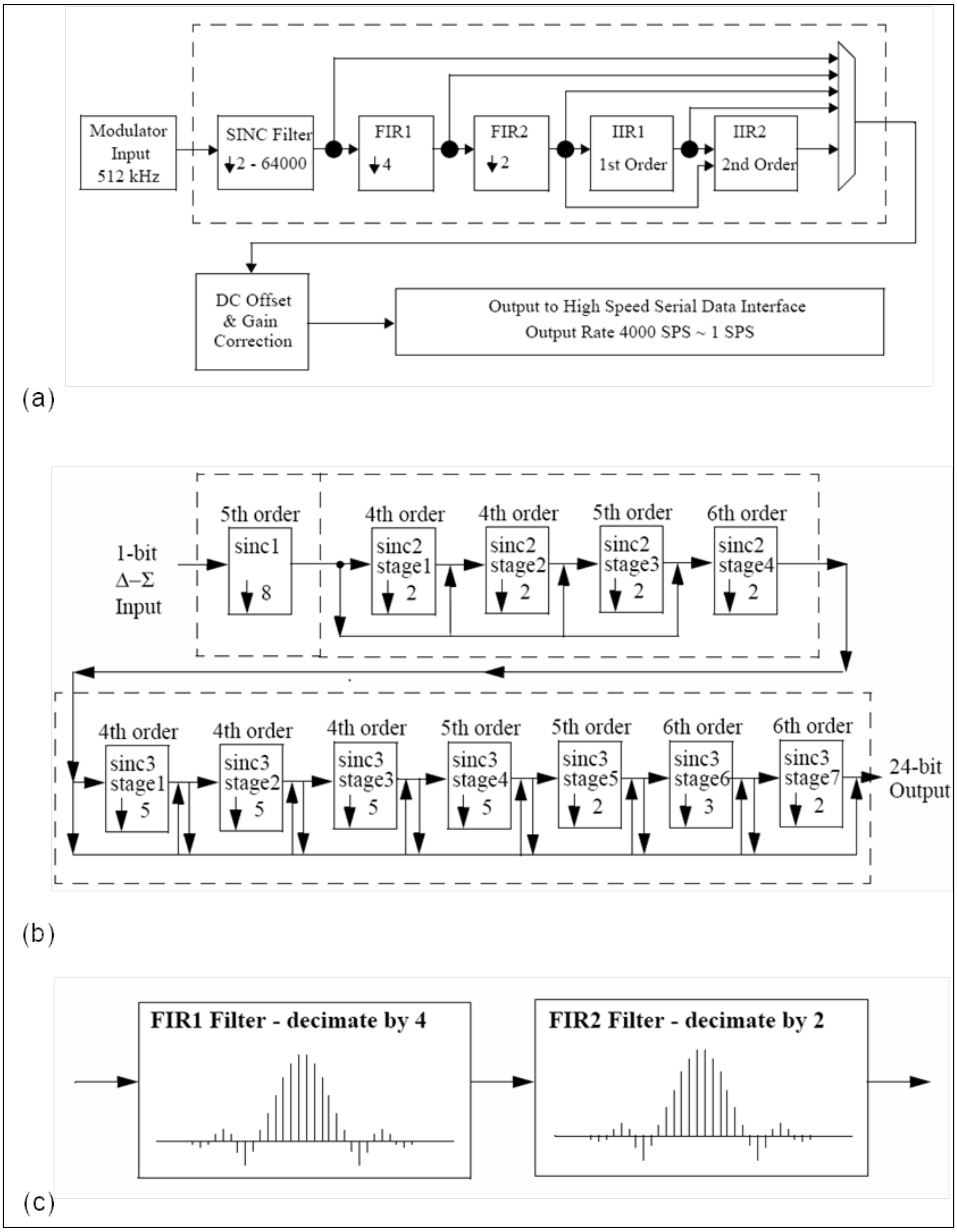


Fig. 1.3. (a) The different CS5378 digital filter stages. In the case of the IPY broadband OBS/H deployment, no IIR filter is employed. (b) The CS5378 SINC filter block diagram. The SINC filter has three cascaded sections, SINC1, SINC2 and SINC3, each made up from smaller stages. (c) The CS5378 FIR filter block diagram. The FIR filter consists of two cascaded stages, FIR1 and FIR2. All information taken from Cirrus Logic, 2010.

The two stages FIR1 and FIR2 of the FIR filter come with two different sets of coefficients, one for a linear-phase filter character (set 0) and another for a minimum-phase character (set 1). In the case examined here, the linear-phase option is employed (SEND GmbH, 2007). Both FIR1 and FIR2 are symmetric, the first having 48 and the second 126 coefficients.

All filter coefficients (SINC and FIR) can be found in the corresponding *GSE* response files.

Table 1.1. CS5378 SINC filter stages (Cirrus Logic, 2010).

SINC1 - Single stage, fixed decimate by 8

5^{th} order decimate by 8, 36 coefficients

SINC2 - Multi-stage, variable decimation

Stage 1: 4^{th} order decimate by 2, 5 coefficients
Stage 2: 4^{th} order decimate by 2, 5 coefficients
Stage 3: 5^{th} order decimate by 2, 6 coefficients
Stage 4: 6^{th} order decimate by 2, 7 coefficients

SINC3 - Multi-stage, variable decimation

Stage 1: 4^{th} order decimate by 5, 17 coefficients
Stage 2: 4^{th} order decimate by 5, 17 coefficients
Stage 3: 4^{th} order decimate by 5, 17 coefficients
Stage 4: 5^{th} order decimate by 5, 21 coefficients
Stage 5: 5^{th} order decimate by 2, 6 coefficients
Stage 6: 6^{th} order decimate by 3, 13 coefficients
Stage 7: 6^{th} order decimate by 2, 7 coefficients

Table 1.2. CS5378 SINC filter configurations (Cirrus Logic, 2010).

SINC filters

FIR2 Output Word Rate	DEC Bit Setting	SINC1 Deci-mation	SINC2 Deci-mation	SINC2 Stages	SINC3 Deci-mation	SINC3 Stages
4000	0111	8	2	4	-	-
2000	0110	8	4	3,4	-	-
1000	0101	8	8	2,3,4	-	-
500	0100	8	16	1,2,3,4	-	-
333	0011	8	8	2,3,4	3	6
250	0010	8	16	1,2,3,4	2	7
200	0001	8	4	3,4	10	4,7
125	0000	8	16	1,2,3,4	4	5,7
100	1111	8	4	3,4	20	3,5,7
50	1110	8	8	2,3,4	20	3,5,7
40	1101	8	4	3,4	50	3,4,7
25	1100	8	16	1,2,3,4	20	3,5,7
20	1011	8	4	3,4	100	2,3,5,7
10	1010	8	8	2,3,4	100	2,3,5,7
5	1001	8	16	1,2,3,4	100	2,3,5,7
1	1000	8	16	1,2,3,4	500	1,2,3,5,7

The displacement amplitude and phase response of the above described configuration is displayed in Fig. 1.4. The plotted response corresponds to the vertical channel of OBS01 and is shown up to the Nyquist frequency, which is equal to 25 Hz.

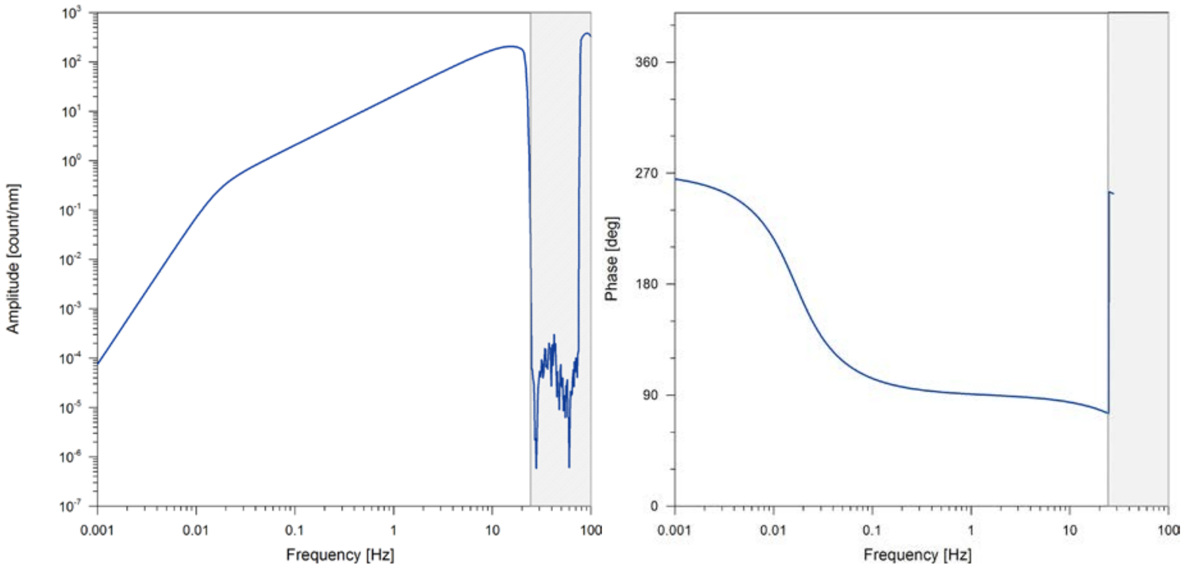


Fig. 1.4. Displacement amplitude (left) and phase (right) response for the vertical component of station OBS01. The shaded area represents the range beyond the Nyquist frequency (25 Hz).

1.2.2 HTI-01-PCA/ULF – GEOLON (2007/09/19 – 2008/08/19)
Respid: OBSBHH hydrophone

The IPY broadband OBS/H deployment's pressure channel configuration consists of the following components:

- HTI-01-PCA/ULF hydrophone
- GEOLON-MCS recorder

1.2.2.1 *HTI-01-PCA/ULF*

The sensitivity of each of the hydrophones is provided by the manufacturer in the brief documentation accompanying the shipped instruments (High Tech, Inc., 2005). There it is mentioned that the sensitivity was measured by comparing each instrument to a reference hydrophone.

All hydrophones listed within the document are reported to have the same polarity response, but no further response related information is provided, except for the curve of Fig. 1.5. There, it becomes evident that the sensitivity is frequency dependent and no clarification is provided whether the reported values correspond to a plateau or not. We therefore forego calculating a response for the pressure channel. By a search in the relevant literature, we have observed that the same practice was followed by several others researchers using the HTI-01-PCA/ULF hydrophone (*e.g.*, Tilmann *et al.*, 2008). An addendum will be composed in the case that more information becomes available in the future.

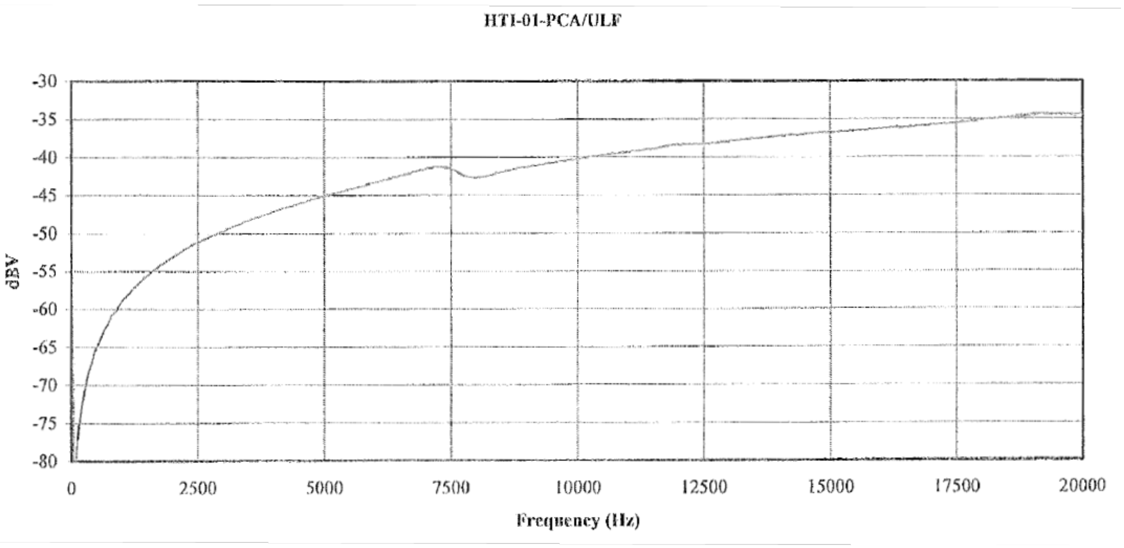


Fig. 1.5. Response curve for the HTI-01-PCA/ULF hydrophone (High Tech, Inc., 2005).

1.2.2.2 *GEOLON-MCS*

For details on the GEOLON-MCS recorder, see section 1.2.1.2 of current Chapter.

The pressure data channel is used with a gain of 4.

As mentioned in section 1.2.2.1, no response is calculated for this channel, due to lack of information regarding the response of the pressure sensor.

1.3 References

Cirrus Logic, 2010. Crystal CS5378 Low-Power Single-Channel Decimation Filter. *CS5378_F3.pdf*, Cirrus Logic Inc., Austin, Texas, 88 pp.

Güralp Systems, Ltd., 2005. *CMG-40T OBS Seismometer of Güralp.* 4 pp.

High Tech, Inc., 2005. *HTI-01-PCA/ULF Hydrophones 31205605 – 31208505.* High Tech, Inc., Gulfport, Mississippi, 4 pp.

Schweitzer, J. and the IPY Project Consortium Members, 2008. The International Polar Year 2007-2008 Project "The Dynamic Continental Margin between the Mid-Atlantic-Ridge System (Mohn's Ridge, Knipovich Ridge) and the Bear Island Region". *NORSAR Sci. Rep.*, 1-2008, p. 53-63.

SEND GmbH, 2007. Application Note: Geolon-MCS Digital Filtering. *Digital_filtering_mcs.doc*, SEND GmbH, Hamburg, Germany, 8 pp.

SEND GmbH, 2009. GEOLON-MCS Marine Compact Seismocorder, User Manual. *MCS1.09.mnl.doc*, SEND GmbH, Hamburg, Germany, 38 pp.

Tilmann, F.J., I. Grevemeyer, E.R. Flueh, T. Dahm and J. Gossler, 2008. Seismicity in the outer rise offshore southern Chile: Indication of fluid effects in crust and mantle. Supplementary material. *Earth Planet. Sci. Lett.*, 269, p. 41-55.

CHAPTER 2: IPY BJØRNØYA ARRAY (BJOA)

2.1 Development of IPY BJOA array systems: instrumentation and responses

2.1.1 Short description

- May – September 2008:

A small-aperture seismic array (BJOA) of 13 elements was installed in May 2008 on Bjørnøya (Bear Island) by the University of Potsdam within the International Polar Year (IPY) project "The dynamic continental margin between the Mid-Atlantic-Ridge System (Mohns Ridge, Knipovich Ridge) and the Bear Island Region" (Schweitzer *et al.*, 2008). The geometry of the array is shown in Fig. 2.1.

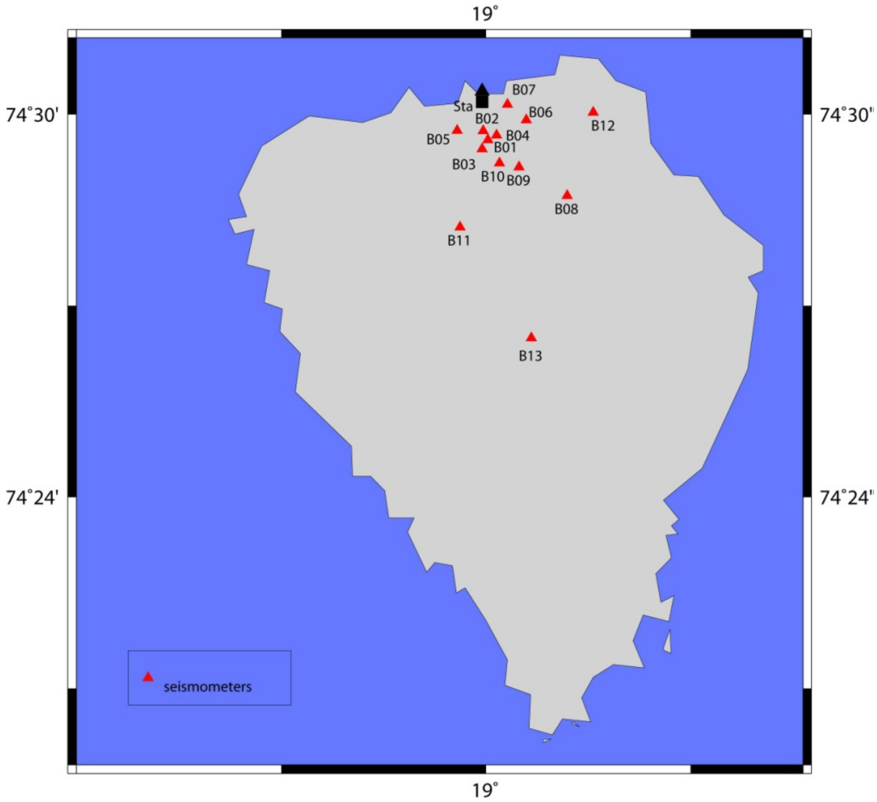


Fig. 2.1. The IPY BJOA array. Array sites are noted with red triangles, while the black symbol notes the location of the Bjørnøya Meteorological Station.

The array remained in operation throughout the summer and was demobilized in the end of September 2008 by a team from NORSAR and the University of Potsdam. The array stations were equipped with Lennartz seismometers (LE-3D/5s) and digitizers (MARSlite), and received power from a combination of solar panel and battery. Fig. 2.2 shows such a station, with all of the instrumentation, except for the solar panels and seismometer, closed in a weatherproof bag.

Fig. 2.2. A site of the BJOA array. The station receives power from solar panels that are feeding a battery located inside the protective yellow bag. All instrumentation except for the seismometer that is buried beside it is in the bag.

Each array site has three channels, SHZ, SHN and SHE, sampled at 125 sps.

Exactly the same station configuration was used for the MASI-1999 field experiment, in Finnmark, northern Norway, in summer 1999 (Schweitzer, 1999).

2.1.2 Instrumentation

I. Configurations

- IPY BJOA configuration (summer 2008):
  - LE-3D/5s seismometer
  - MARSlite digitizer

II. Respids

BJOASP1,2,3

III. Instrument specifications

LE-3D/5s:
Three-component, portable, 5 s seismometer by Lennartz electronic GmbH. Some nominal values are the following (Lennartz, 2011a):

Dynamic range	> 120 dB
Frequency response	5 s – 50 Hz

RMS noise @ 1 Hz	< 1 nm/s
Velocity output	400 V/m/s on all components
Damping	0.707 critical
Eigenfrequency	0.2 Hz
3 Poles	-0.888 ± *j* 0.888, -0.290 ± *j* 0.000
3 Zeros	0.000, 0.000, 0.000

MARSlite digitizer:
3 channel, portable data acquisition system by Lennartz electronic GmbH, with software selectable pre-amplification. Some nominal values are the following (Lennartz, 1998):

Resolution	20-bit
Pre-amplification	4 user selectable sensitivities
Full scale voltage	± 4.1 V, ± 1 V, ± 250 mV, ± 65 mV
Maximum sampling rate	250 sps
Digital filters	zero-phase FIR filters
FIR filter passband	0.4 x *sampling frequency* (100 Hz max)

2.2 Instrument response calculation for the IPY BJOA array

This chapter focuses on the major considerations to be taken into account for the calculation of the instrument response of the different systems operating at the IPY BJOA array.

As with the rest of the systems described in this documentation, *GSE* file response *Respid* flags for each configuration are provided at the beginning of each section.

2.2.1 <u>LE-3D/5s – MARSlite</u> (2008/05/25 – 2008/09/30)

Respid:	BJOASP1	Z
	BJOASP2	N-S
	BJOASP3	E-W

The IPY BJOA array configuration consists of the following components:

- LE-3D/5s 3-component seismometer
- MARSlite digitizer

2.2.1.1 *LE-3D/5s*

The instrument response of the LE-3D/5s seismometer of Lennartz electronic GmbH is described in documents distributed by the manufacturer (Lennartz 2011a,b). There, the sensitivity is reported to be equal to 400 V/m/s, and accurately adjusted for all components, while the shape of the amplitude response is provided both graphically (see Fig. 2.3) and in the form of poles and zeros.

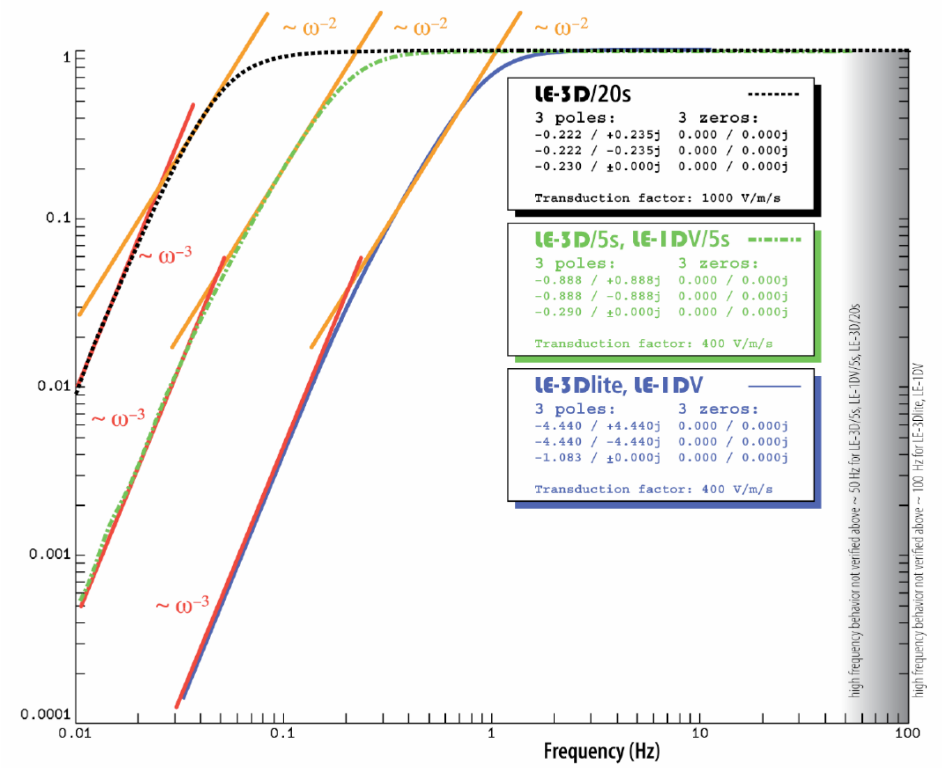


Fig. 2.3. Amplitude transfer functions and numerical poles and zeros for the different members of the LE-xD family. The LE-3D/5s is shown in green (from Lennartz, 2011b).

Regarding the high-frequency behavior of this sensor (gray-shaded part of graph in Fig. 2.3), it is shaped by an intrinsic lowpass filter. The exact characteristics of the filter are not provided, but it should start to have effect at about 50 Hz for the LE-3D/5s (Lennartz, 2011b). The provided poles and zeros do not describe this high-frequency part, but only the low-frequency rolloff. The two complex poles and two zeros are actually derived using the standard damping seismometer formula (see *e.g.*, section 2.2.1.1 of Part 1) for 0.707 relative damping and eigenperiod of 5 s. The third, real pole and third zero describe a highpass, first order RC-type filter, used to shape the transfer function, according to the Lippmann method (Lennartz, 2011a).

In the case of the instrument deployed at BJOA, information obtained from the University of Potsdam suggests that the "Lippmann filter" has different characteristics to those described in Lennartz, 2011a,b, so the pole/zero set for the LE-3D/5s sensors of BJOA is the following:

Poles [rad/s]	Zeros [rad/s]
$-0.888442401 \pm j\, 0.888710752$	0.00 0.00
-0.4272566 (at 0.068 Hz)	0.00

The above shown pole/zero set is also found in the corresponding *GSE* response files (see Appendix II for *Respids* and filenames), where it is actually represented as two separate PAZ2 stages.

2.2.1.2 *MARSlite*

The IPY BJOA array was equipped with MARSlite digitizers, also by Lennartz electronic GmbH, which were providing data with a sampling rate of 125 sps.

At this point, not much is known regarding the response of the digitizer, apart from the scant information provided in Lennartz, 1998 and information via e-mail by the University of Potsdam, in connection to data processing for the MASI-1999 experiment (Schweitzer, 1999).

According to the draft version of Chapter 6 of the New Manual of Seismological Observatory Practice (Asch, 2000 at http://seismo.um.ac.ir/education/Seismic%20Recorders.htm), the MARSlite is built around the CS5323 chipset, however no further mention could be found on this (*e.g.*, in the finalized version of the NMSOP), and it was not possible to verify this information.

The MARSlite is reported to be a 20-bit A/D converter, with user-selectable preamplification (Lennartz, 1998). Information from the University of Potsdam suggests that the digitizer has a resolution of 16-bit, which would mean that the 20-bit performance is a result of gain ranging. From the same source it is reported that both during the MASI-1999 experiment and the IPY BJOA deployment, a gain of 1 was used for the digitizer. Furthermore, the software employed to convert raw data seems to introduce a scaling factor, so at this point it is impossible to reconstruct the true sensitivity of the digitizer.

Consequently, we are using the MARSlite without any digital filter, and scaling it so that the channel sensitivity is equal to 0.024868 nm/s at 1 Hz. This corresponds to a total digitizer gain of 1.59999582×10^7 count/V. This scaling factor is the result of waveform comparison, facilitated by the co-location of one of the temporary stations with site ARE0 of the ARCES array during the MASI-1999 experiment. These results were also verified by comparing waveform data from the closest BJOA element (operating only shortly) to those of the BJO1 permanent station of the NNSN, operated by UiB (see Chapter 3 of Part 2).

The displacement amplitude and phase response of the above described configuration is displayed in Fig. 2.4. The shaded area represents the range beyond the Nyquist frequency, which is equal to 62.5 Hz.

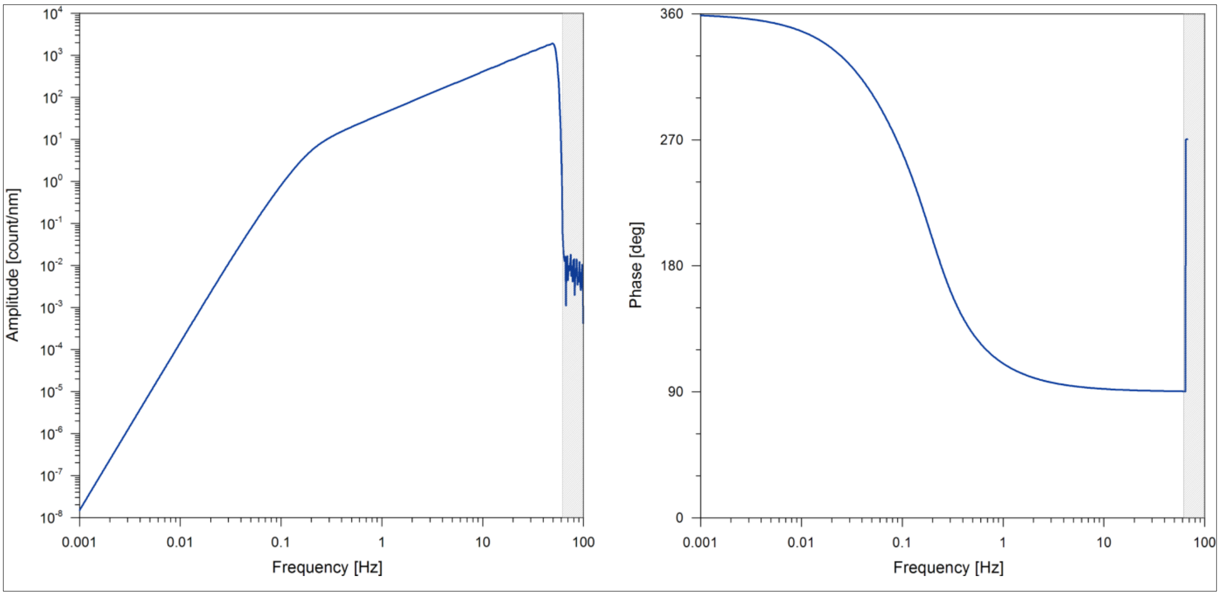


Fig. 2.4. Displacement amplitude (left) and phase (right) response for the channels of the BJOA array. The shaded area represents the range beyond the Nyquist frequency (62.5 Hz).

2.3 References

Asch, G., 2000. Seismic Recording Systems. Chapter 6 in draft version of *New Manual of Seismological Observatory Practice*, http://seismo.um.ac.ir/education/Seismic%20 Recorders.htm.

Lennartz, 1998. *Reliable Measurements. MARSlite/HD Portable digital seismograph with up to 4.3 gigabytes hard disk.* Lennartz electronic GmbH, Tübingen, Germany, 2 pp.

Lennartz, 2011a. *Reliable Measurements. Seismometers General Description.* Lennartz electronic GmbH, Tübingen, Germany, 25 pp.

Lennartz, 2011b. *LE-xD Seismometer Family. Document Number: 990-0003.* Lennartz electronic GmbH, Tübingen, Germany, 30 pp.

Schweitzer, J., 1999. The MASI-1999 field experiment. *NORSAR Sci. Rep.*, 1-1999/2000, p. 91-101.

Schweitzer, J. and the IPY Project Consortium Members, 2008. The International Polar Year 2007-2008 Project "The Dynamic Continental Margin between the Mid-Atlantic-Ridge System (Mohn's Ridge, Knipovich Ridge) and the Bear Island Region". *NORSAR Sci. Rep.*, 1-2008, p. 53-63.

PART 4

CHAPTER 1: CALCULATION OF INFRASOUND STATION RESPONSES

1.1 Methodology

1.1.1 <u>Response calculation procedure</u>

It is considered necessary to discuss briefly the calculation of the system response for the infrasound stations, as performed at NORSAR, taking in account that it is subject to different assumptions and needs than the responses of the seismic channels.

The approach followed to calculate the infrasound system responses and update the information inside the NORSAR db system, is essentially the same as for the seismic channels (Part 1, Chapter 1), however, changes had to be introduced in the utility programs used to convert one response format to the other, so that pressure measurements are treated accordingly. Below, the different steps are presented, as in Part 1, § 1.1.1 and § 1.1.2, highlighting the differences between the seismic and infrasound channels.

1. Using all available information, a 'history' of system modifications is compiled and documented (see *e.g.*, *GSE* response file /ndc/programs/dpep/dbtables/ 2008/NOA/cal2_noa for the NORSAR array) and organized initially in *GSE2.0* format (GSETT-3, 1997). Corresponding *GSE* response files include short descriptions of each system component (*e.g.*, sensor, A/D converter, other components such as amplifiers), mainly referring to instrument model, used parameter values and normalization information. Moreover, in the case that only nominal values are available, this is clearly stated and the response is described as 'nominal' or 'theoretical', otherwise instrument serial numbers are listed in the *GSE* files. Information is inserted in the *GSE* files manually. Finally, the *GSE* response file format has been modified, to enable easier usage of response information (see Part 1, §1.1.3). All computed *GSE* response files are stored under the path /ndc/programs/dpep/dbtables/2008/ARRAY/GSE/, where ARRAY should be substituted with each array/station name.
2. However, although both *GSE* and *SEED* standards have been adjusted to include pressure measurements (GSETT-3, 1997, IRIS, 2010), the conversion tool *gse2seed* needed to be adapted so that this is handled correctly. The problem focused on the conversions between acceleration, velocity and displacement performed by the software for the handling of seismic channels. In the case of pressure sensors, no such conversion is needed and therefore no additional zeros should be included in the *GSE* response file and consequently removed later when converting to *SEED* format. Since pressure channels have an own nomenclature (Channel Instrument Code D denotes pressure sensor, Channel Orientation Code F denotes infrasonic pressure sensor and H hydrophone, see, *e.g.*, GSETT-3, 1997), it was possible to alter the code to avoid same treatment of seismic and infrasonic channels. The utilities supporting pressure measurements have "_infra" appended to their name. UNIX precompiled binary executables can be found under /ndc/programs/dpep/bin, while for the code or versions for other operating systems, please contact Johannes Schweitzer.
3. *GSE* response files are then converted to *DATALESS.SEED* volumes, using the *gse2seed_infra* conversion tool (Sleeman, 2003 and modifications by J. Schweitzer) and *SEED* response files (*RESP.SEED*) are generated from the *DATALESS.SEED* volumes using the *rdseed* program (O'Neill *et al.*, 2004). Using the utility *evalresp_infra* (IRIS, 2006 and modifications by J. Schweitzer), *FAP* files are created.

Obtained *RESP.SEED* files reside under the path /ndc/programs/dpep/dbtables/2008/ARRAY/ RESP/.

4. Final *FAP* tables were named according to network name, *GSE* file *Respid* (see §1.1.3), site and channel name, and are stored under the path /ndc/programs/dpep/ dbtables/2008/ARRAY/FAP. Details on the naming convention for *FAP* files are provided in Part 1, § 1.2.2.
5. Finally, a system of scripts/macros is used to introduce calculated *GSE Calib*, *Calper* values in the corresponding NORSAR db system *CSS3.0* tables, taking into consideration the time interval described by the *Ondate*, *Ontime* and *Offdate*, *Offtime* fields in the *GSE* response files. The *GSE Calib* and *Calper* values are appointed as *ncalib* and *ncalper* values in the db system .instrument file, respectively. Then, *ncalper* is appointed equal to *calper* in the .sensor and .wfdisc files, while the *calratio* field in the .sensor file is set to 1.0 (Anderson *et al.*, 1990).

1.1.2 Conversions between different response formats

As already discussed in § 1.1.1, this chapter, the procedure followed to update NORSAR's response database involves the calculation of infrasound system responses in different formats. This conversion line will be described briefly in this section.

Starting with a *GSE2.0* response file, the overall response of a system (sensor, digitizer, digital and/or analog filters, *etc.*) for a particular time period is summarized in the file's CAL2 line as the overall channel gain in Pa/count at a particular calibration period (s).

The next response format in the chain is *DATALESS.SEED* volume, out of which *RESP.SEED* files can be extracted for particular stations/channels. Overall channel sensitivity is expressed in count/Pa for the declared calibration frequency (Hz).

Then, *FAP* files can be obtained for each configuration, with amplitude values in count/Pa.

The corresponding command chain is the following:

GSE2.0 → *DATALESS.SEED*: *gse2seed_infra* –i ####.gse –o ###_DATALESS.SEED
DATALESS → *RESP.SEED*: *rdseed* –R –f ###_DATALESS.SEED
RESP.SEED → *FAP*: *evalresp_infra* SSS CCC 2011 001 f1 f2 N –u vel –s log –r fap –v

where: ####.gse = *GSE2.0* file name,
###_DATALESS.SEED = *DATALESS.SEED* file name,
-R = make *RESP.SEED ascii* file with response data (*e.g.*, RESP.NO.ARA1..BDF),
-f = input file name,
SSS = station/array name (*e.g.*, ARCI),
CCC = channel (*e.g.*, BDF),
2011 001 = a time point when a particular response is valid,
f1, f2 = desired frequency range,
N = number of frequency samples in the *FAP* file,
-u = units (vel = velocity, to ensure correct treatment of pressure measurements),
-s = spacing (log = logarithmic),
-r = response type (fap = frequency-amplitude-phase triplets),
-v = verbose output

1.2 References

Anderson, J., W.E. Farrell, K. Garcia, J. Given and H. Swanger, 1990. Center for Seismic Studies version 3 database: schema reference manual. *Techn. Rep. C90-01*, DARPA, Arlington, Viriginia, 61 pp.

GSETT-3, 1997. Provisional GSE 2.1 Message Formats and Protocols. Operations Annex 3, May 1997, 123 pp.

IRIS, 2006. EVALRESP Manual Pages (V3.2.35). http://www.iris.edu/manuals/evalresp.htm, *Incorporated Research Institutions for Seismology*, May 2006.

IRIS, 2010. SEED Reference Manual, SEED Format Version 2.4. *SEEDManual_V2.4.pdf*. Incorporated Research Institutions for Seismology, May 2010, 212 pp.

O' Neill, D., A. Nance, C. Laughbon and S. Stromme, 2004. RDSEED 4.6 Manual. http://www.iris.edu/manuals/rdseed.htm, *Incorporated Research Institutions for Seismology*, July 2004.

Sleeman, R., 2003. GSE2SEED version 2.23. ftp://orfeus.knmi.nl/pub/software/conversion//GSE2SEED/README, *ORFEUS Data Center*, August 2003.

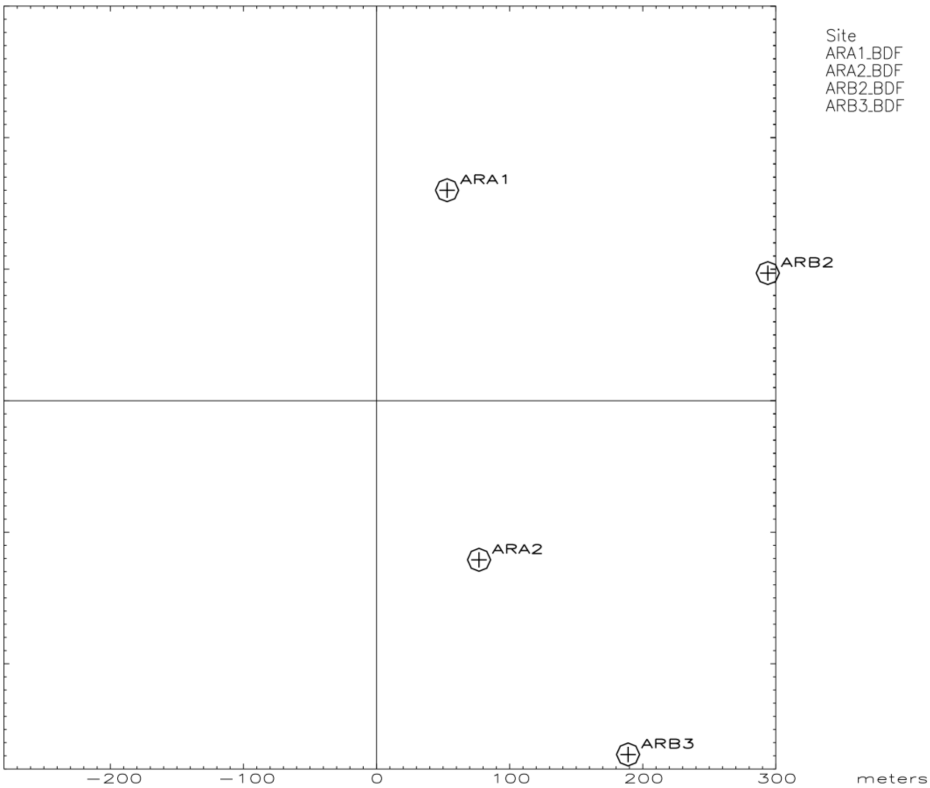
CHAPTER 2: ARCES INFRASOUND ARRAY - ARCI

2.1 Development of the ARCI infrasound systems: instrumentation and responses

2.1.1 Short description

- 2008-…:

In 2008, the ARCES array was supplemented with an experimental infrasound array by installing Martec MB2005 microbarometers together with Güralp CMG-DM24 digitizers at sites ARA1, ARA2 and ARB2 (Roth et al., 2008). One more site (ARB3) was installed in 2010 (Roth and Pirli, 2013). A map of the resulting ARCI geometry is shown in Fig. 2.1, with infrasound sites presented relatively to the central element ARA0 of the ARCES seismic array, positioned at the crossing of the two axes. The equipment for the infrasound channels shares the same pit as the seismic sensors.



Site	X east	Y north	Z height
ARA1_BDF	53	160	411
ARA2_BDF	77	−121	392
ARB2_BDF	294	97	397
ARB3_BDF	189	−269	376

Fig. 2.1. Map of the infrasound sites ARA1, ARA2, ARB2 and ARB3 of the ARCI array. Site distances from the ARCES seismic array central element (axes crossing point) are given in meters.

2.1.2 Instrumentation

I. Configurations

- Current configuration (2008-…):
    - MB2005 microbarometer
    - CMG-DM24 digitizer

II. Respids

ARCIBD1

III. Instrument specifications

MB2005:

The MB2005 microbarometer, developed to detect air nuclear explosions, measures small variations in atmospheric pressure. Some nominal values are the following (Martec, 2007):

Filtered output passband	0.01 – 27.0 Hz (modifiable)
Electronic noise level	2 mPa rms between 1 – 10 Hz
Mechanical sensitivity	35 nm/Pa
Sensitivity in 0.01 – 27 Hz passband	20 mV/Pa (± 10 V for ± 5 hPa)

CMG-DM24:

Full 24-bit digitizer employing the Cirrus Logic CS5376 digital filtering chipset and TMS320VC33 digital signal processor (DSP). The DSP software consists of 6 cascaded programmable filter/decimation stages that allow the selection of multiple data output rates simultaneously (Güralp Systems, 2006). The specifications are the following:

Input voltage range	+/- 10 V differential
Dynamic range	137 dB @ 40 sps
DSP sampling rate	32 kHz
Sensitivity	3.2 μV/count

2.2 Instrument response calculation for the ARCI infrasound array

This chapter focuses on the major considerations to be taken into account for the calculation of the instrument response of the different systems operating at the ARCI infrasound array.

GSE file response *Respid* flags for each configuration are provided at the beginning of each section.

2.2.1 MB2005 – DM24 (2008/05/13 – …)
Respid: ARCIBD1 BDF

ARCI infrasound channel configuration consists of the following components:

- MB2005 microbarometers
- CMG-DM24 digitizers

2.2.1.1 *MB2005*

The transfer function of the Martec MB2005 microbarometer is provided by the manufacturer (Martec, 2007) and is the following:

With $p=j\omega$

$$H(p) = \frac{b1 * p + b0}{a6 * p^6 + a5 * p^5 + a4 * p^4 + a3 * p^3 + a2 * p^2 + a1 * p + 1}$$

b1=2.133 E-9
b0=1 E-3a6=1.89 E-17

a6=1.89 E-17
a5=7.03 E-15
a4=3.757 E-11
a3=1.321 E-8
a2=1.823 E-5
a1=5.645 E-3

$$Hs(p) = \frac{318.31 * p}{0.077 * p^2 + 15.92 * p + 1}$$

This equation describes a function with two poles and one zero, which are shown in rad/s in the table below:

	Real part	Imaginary part
Poles (2)		
Real pole	-0.03141593	0
Real pole	-99.9968941	0
Zeros (1)		
Zero	0	0

The sensitivity of the sensor is 20 mV/Pa. The shape of the amplitude response as provided by the manufacturer (Martec, 2007) is shown in Fig. 2.2.

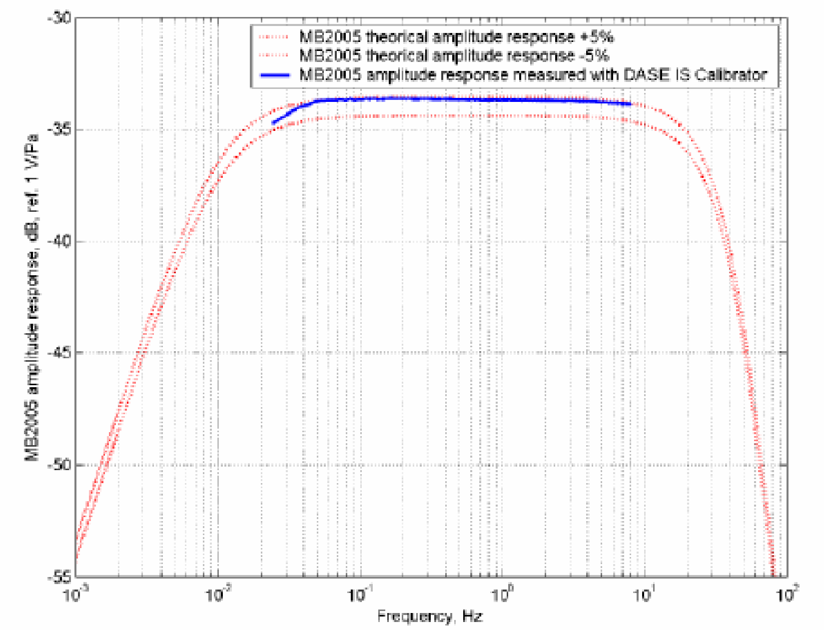


Fig. 2.2. MB2005 microbarometer amplitude response (Martec, 2007).

2.2.1.2 *CMG-DM24*

The Güralp CMG-DM24 A/D converter is a 24-bit digitizer. It employs the Crystal Semiconductor CS5376 chipset and the TMS320VC33 digital signal processor (DSP) to achieve the desired output rate. The DSP software consists of 6 cascaded programmable filter/decimation stages that allow the selection of multiple data output rates simultaneously (Güralp Systems, 2006). In the case of the ARCI infrasound channels, the data recording sample rate is set to 80 sps. This is obtained by the following digital filter cascade (TTL = 79 in the Güralp Systems tabulated, decimation cascade look-up system):

- CS5376 FIR filter Stage 1, Sinc 1, with 36 coefficients, decimating by 8 from an input rate of 512 kHz
- CS5376 FIR filter Stage 3, Sinc 2, with 6 coefficients, decimating by 2
- CS5376 FIR filter Stage 4, Sinc 2, with 8 coefficients, decimating by 2
- CS5376 FIR filter Stage 5, FIR 1, with 48 coefficients, decimating by 4
- CS5376 FIR filter Stage 5, FIR 2, with 126 coefficients, decimating by 2,
- DM24 FIR Stage 1, SWA-D24-3D08, with 502 coefficients, decimating by 5, and
- DM24 FIR Stage 2, SWA-D24-3D08, with 502 coefficients, decimating by 5 down to 80 sps.

Channel	Digitizer serial number	sensitivity
ARA1 BDF	A087	3.185 μV/count
ARA2 BDF	A222	3.189 μV/count
ARB2 BDF	A093	3.170 μV/count
ARB3 BDF	A216	3.178 μV/count

The sensitivity of the digitizer for each channel can be found in the instrument specific Calibration Sheet provided by the manufacturer. The digitizers installed at ARCI have serial numbers and the sensitivity values as listed in the table above.

The pressure amplitude and phase response for this configuration (ARCIBD1) is depicted in Fig. 2.3. The shaded area represents the frequency range beyond the Nyquist frequency, which is 40 Hz.

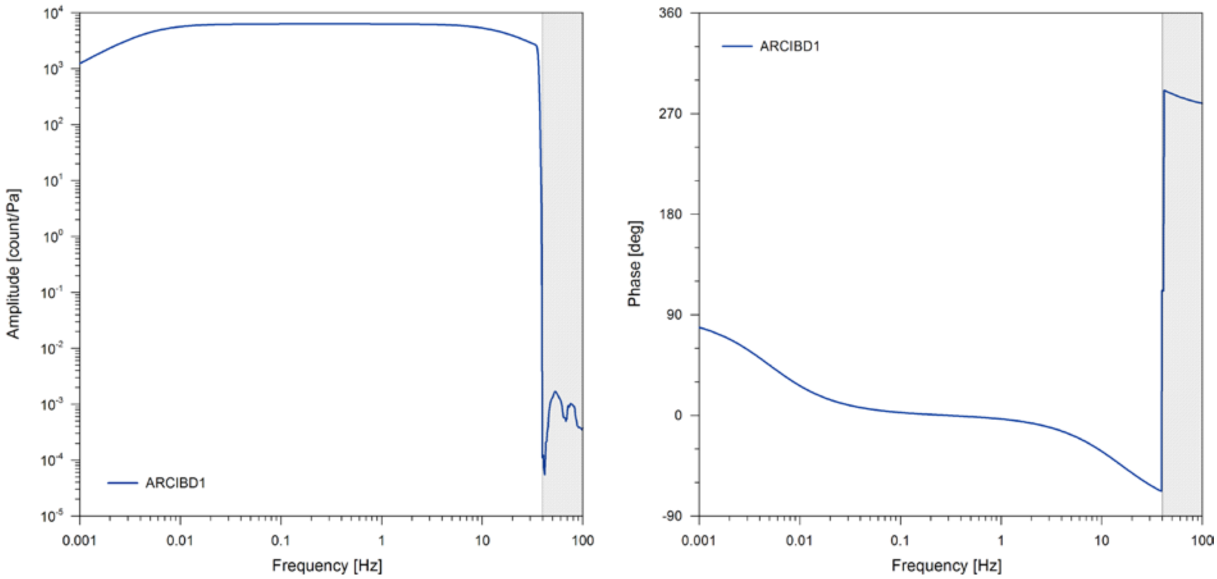


Fig. 2.3. Pressure amplitude and phase response for the infrasound (ARCIBD1) channels of the ARCI array. Shaded areas represent range beyond the Nyquist frequency (40 Hz in this case).

2.3 References

Güralp Systems, 2006. CMG-DM24 Operator's Guide. *MAN-D24-0004*, Güralp Systems Ltd., Aldermaston, England, 113 pp.

Martec, 2007. MB2005 User Manual. *14643-C, Edition 17/01/2007*, Martec, CEA, 20 pp.

Roth, M., and Pirli, M., 2013. Responses of the infrasound channels of ARCES and NORES. *NORSAR Sci. Rep. 2-2012*, NORSAR, Kjeller, Norway, 59-66.

Roth, M., Fyen, J., and Larsen, P.W., 2008. Setup of an experimental infrasound deployment within the ARCES array. *NORSAR Sci. Rep. 2-2008*, NORSAR, Kjeller, Norway, 52-59.

CHAPTER 3: NORES INFRASOUND ARRAY

3.1 Development of the NORES infrasound systems: instrumentation and responses

3.1.1 <u>Short description</u>

- 2013-…:

In 2013, a 9 element infrasound array was established at the NORES array by installing Hyperion IFS-3000 sensors together with the Güralp CMG-DM24 digitizers of the seismic channels at the A- and B-rings of the seismic array. Sites NRA1, NRA2 and NRA3 were installed in February 2013, while sites NRA0, NRB2, NRB3, NRB4 and NRB5 were completed in April of the same year. Finally, infrasound site NRB1 came in operation on May 6, 2013. The infrasound channel employs the calibration signal monitor channel (X-channel) of the DM24 (Roth and Pirli, 2013). Fig. 3.1 shows the geometry of the NORES array.

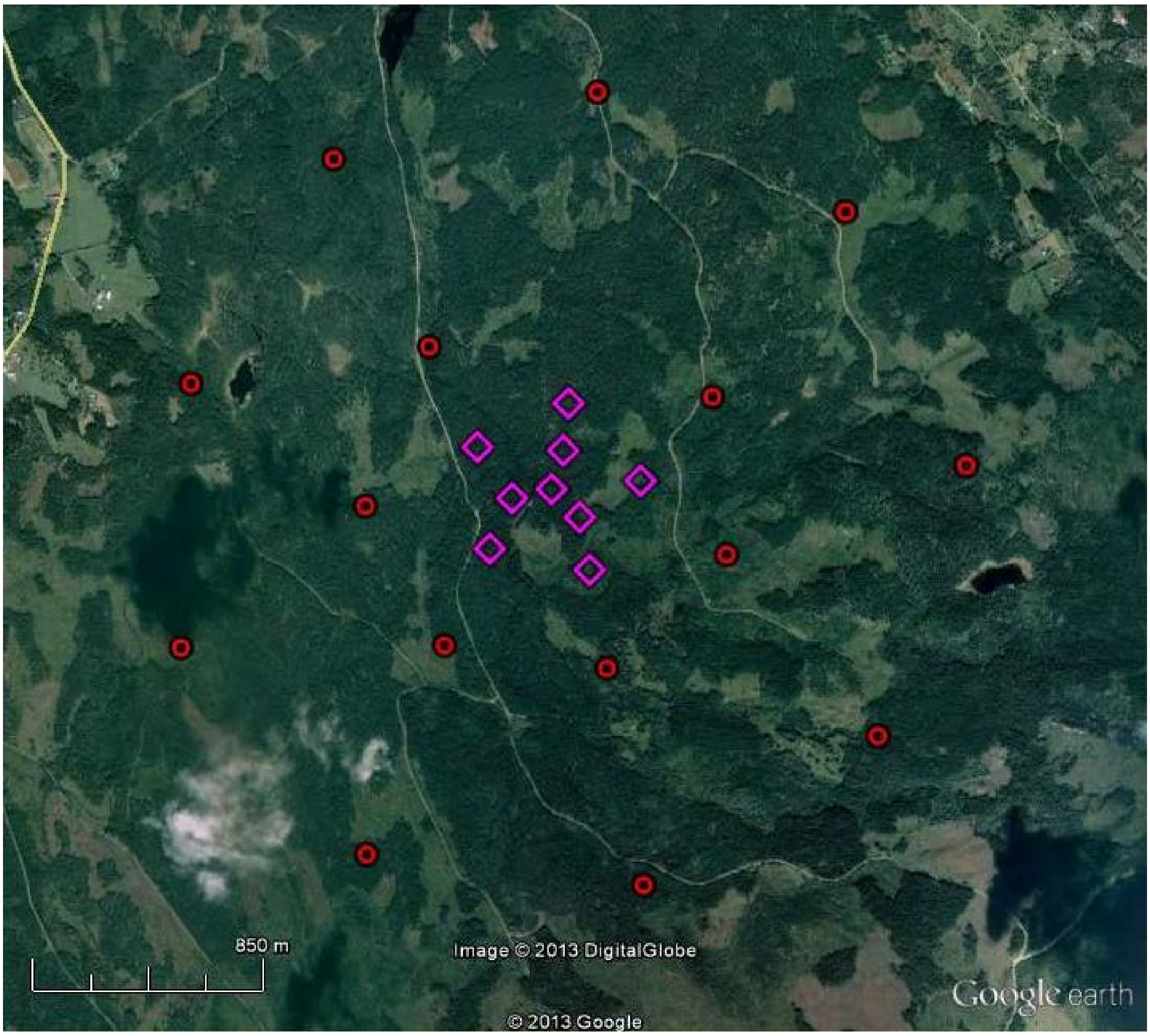


Fig. 3.1. Google™Earth image of the currently operating (rhombuses) and future elements (circles) of the NORES array. All sites in operation carry both seismic and infrasound sensors, sharing the same digitizers.

3.1.2 Instrumentation

I. Configurations

- Current configuration (2013-…):

  IFS-3000 microbarometer

  CMG-DM24 digitizer

II. Respids

NORESBD1

III. Instrument specifications

IFS-3000:

The IFS-3000 infrasound sensor is manufactured by Hyperion Technology Group, Inc., with some nominal values being the following (Hyperion Technology Group, 2012):

Maximum differential output	15 Vp-p
Noise floor	≤ 10^{-4} Pa between 0.01 – 100 Hz
Dynamic range	120 dB
Nominal sensitivity	150 mV/Pa @ 1 Hz

CMG-DM24:

Full 24-bit digitizer employing the Cirrus Logic CS5376 digital filtering chipset and TMS320VC33 digital signal processor (DSP). The DSP software consists of 6 cascaded programmable filter/decimation stages that allow the selection of multiple data output rates simultaneously (Güralp Systems, 2006). The specifications are the following:

Input voltage range	+/- 10 V differential
Dynamic range	137 dB @ 40 sps
DSP sampling rate	32 kHz
Sensitivity	3.2 µV/count

3.2 Instrument response calculation for the NORES infrasound array

This chapter focuses on the major considerations to be taken into account for the calculation of the instrument response of the different systems operating at the NORES infrasound array.

GSE file response *Respid* flags for each configuration are provided at the beginning of each section.

3.2.1 IFS-3000 – DM24 (2013/02/06 – …)
Respid: NORESBD1 BDF

NORES infrasound channel configuration consists of the following components:

- IFS-3000 infrasound sensors
- CMG-DM24 digitizers

3.2.1.1 *IFS-3000*

The transfer function of the IFS-3000 infrasound sensor, manufactured by Hyperion Technology Group, Inc., is reportedly described by equation (Hyperion Technology Group, 2012):

$$|H(f)| = \left|\frac{f^3}{(f - if_1)(f - if_2)(f - if_3)}\right|$$

with three real poles at frequencies f_1 = 1.483 mHz, f_2 = 3.387 mHz and f_3 = 29.49 mHz and three zeros at 0.0. The frequency response is shown in Fig. 3.2.

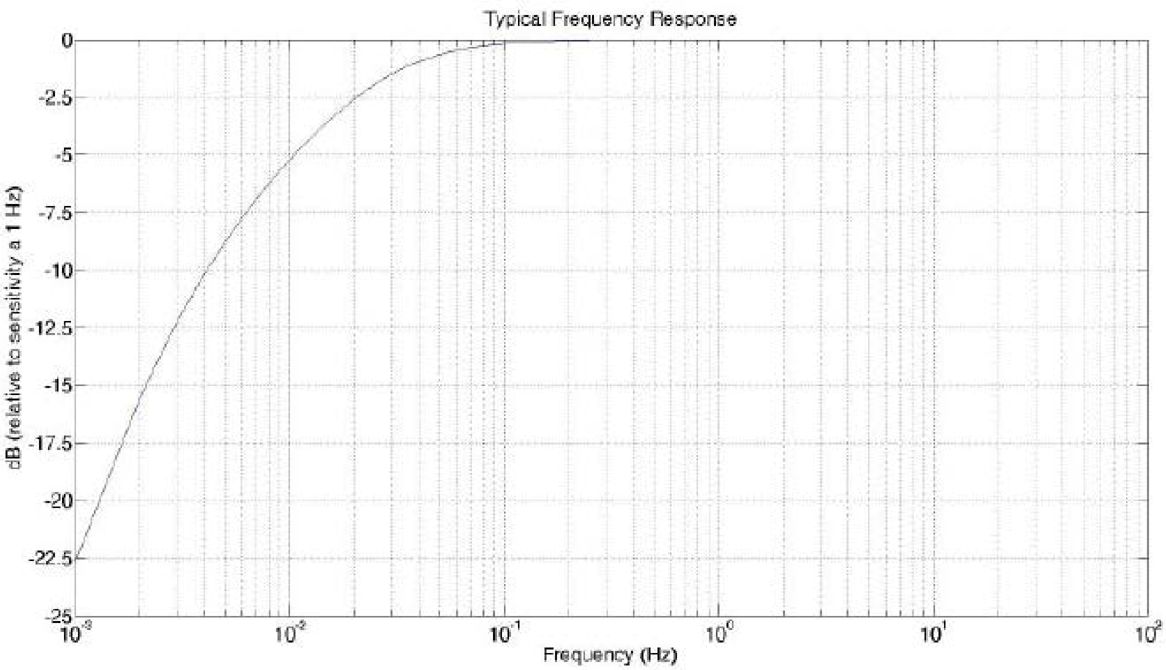


Fig. 3.2. IFS-3000 infrasound sensor typical response (Hyperion Technology Group, 2012).

Attention should be given to the fact that this transfer function does not describe the higher frequency end of the sensor's response. That part is affected strongly by the acoustic port and shrouding geometry (Hyperion Technology Group, 2012).

The sensitivity of the sensors is equal to 150 mV/Pa at 1 Hz.

3.2.1.2 *CMG-DM24*

The Güralp CMG-DM24 A/D converter is a 24-bit digitizer. It employs the Crystal Semiconductor CS5376 chipset and the TMS320VC33 digital signal processor (DSP) to achieve the desired output rate. The DSP software consists of 6 cascaded programmable filter/decimation stages that allow the selection of multiple data output rates simultaneously (Güralp Systems, 2006). In the case of the NORES infrasound channels, the data recording sample rate is set to 80 sps. This is obtained by the following digital filter cascade (TTL = 91 in the Güralp Systems tabulated, decimation cascade look-up system):

- CS5376 FIR filter Stage 1, Sinc 1, with 36 coefficients, decimating by 8 from an input rate of 512 kHz
- CS5376 FIR filter Stage 3, Sinc 2, with 6 coefficients, decimating by 2
- CS5376 FIR filter Stage 4, Sinc 2, with 8 coefficients, decimating by 2
- CS5376 FIR filter Stage 5, FIR 1, with 48 coefficients, decimating by 4
- CS5376 FIR filter Stage 5, FIR 2, with 126 coefficients, decimating by 2,
- DM24 FIR Stage 1, SWA-D24-3D08, with 502 coefficients, decimating by 5 and
- DM24 FIR Stage 2, SWA-D24-3D08, with 502 coefficients, decimating by 5 down to 80 sps.

The sensitivity values for channel X (see Part 4, §3.1; Roth and Pirli, 2013) of the digitizers installed at NORES and employed for the infrasound channels are listed below:

Channel	**Digitizer serial number**	**sensitivity**
NRA0 BDF	A203 (A203X2)	3.185 µV/count
NRA1 BDF	A098 (A098X2)	3.177 µV/count
NRA2 BDF	A085 (A085X2)	3.171 µV/count
NRA3 BDF	A253 (A253X2)	3.180 µV/count
NRB1 BDF	A309(A309X2)	3.173 µV/count
NRB2 BDF	A247 (A247X2)	3.173 µV/count
NRB3 BDF	A287 (A287X2)	3.184 µV/count
NRB4 BDF	A217 (A217X2)	3.182 µV/count
NRB5 BDF	A313 (A313X2)	3.162 µV/count

The pressure amplitude and phase response for this configuration (NORESBD1) is depicted in Fig. 3.3. The shaded area represents the frequency range beyond the Nyquist frequency, which is 40 Hz.

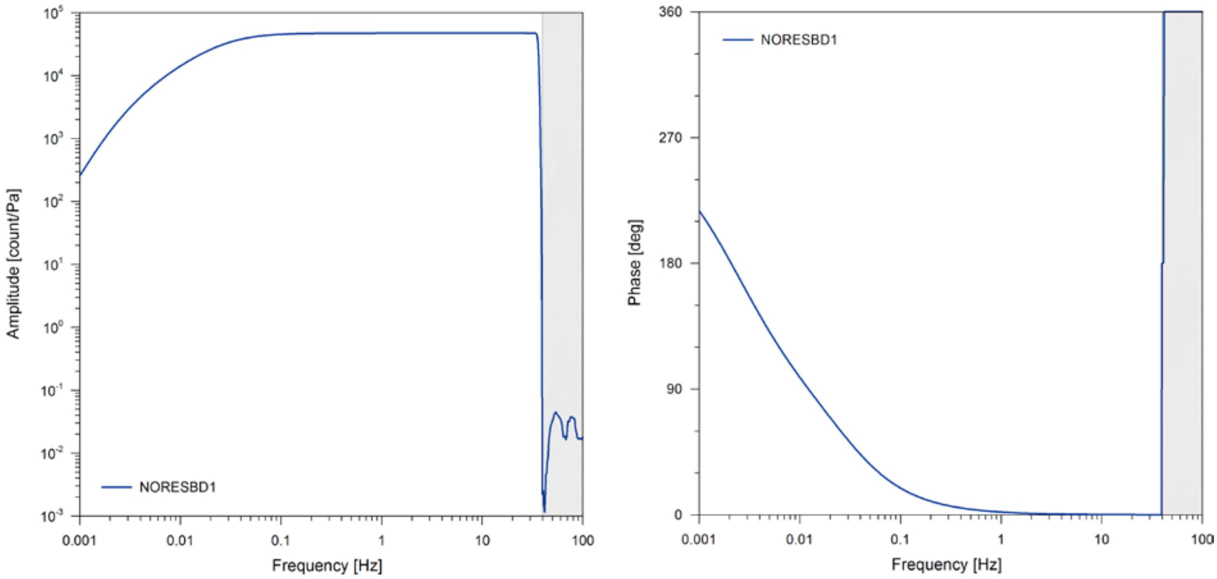


Fig. 3.3. Pressure amplitude and phase response for the infrasound (NORESBD1) channels of the NORES array. Shaded areas represent range beyond the Nyquist frequency (40 Hz in this case).

3.3 References

Güralp Systems, 2006. CMG-DM24 Operator's Guide. *MAN-D24-0004*, Güralp Systems Ltd., Aldermaston, England, 113 pp.

Hyperion Technology Group, 2012. *IFS-3000 series infrasound sensor user manual.* Hyperion Technolog Group, Inc., Tupelo, Mississippi, 11 pp.

Roth, M., and Pirli, M., 2013. Responses of the infrasound channels of ARCES and NORES. *NORSAR Sci. Rep. 2-2012*, NORSAR, Kjeller, Norway, 59-66.

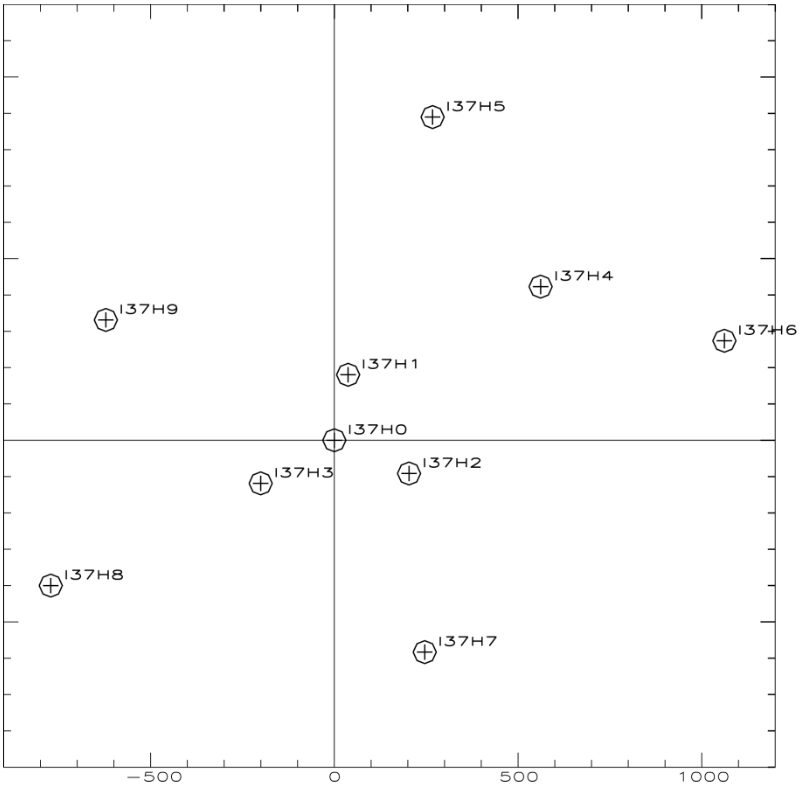
CHAPTER 4: INFRASOUND ARRAY IS37

4.1 Development of the IS37 infrasound systems: instrumentation and responses

4.1.1 <u>Short description</u>

- 2013-…:

Infrasound array IS37, located in Bardufoss, northern Norway, is a 10-element array, equipped with MB2005 microbarometers and CMG-DM24S3EAM digitizers. At the moment (September 2013), the array is not fully operational and certification is pending. Fig. 4.1 shows the geometry of IS37.



Site	X east	Y north	Z height
I37H0_BDF	0	0	200
I37H1_BDF	38	180	200
I37H2_BDF	203	−92	200
I37H3_BDF	−201	−119	200
I37H4_BDF	561	423	200
I37H5_BDF	267	890	200
I37H6_BDF	1062	274	200
I37H7_BDF	246	−583	200
I37H8_BDF	−772	−400	200
I37H9_BDF	−622	331	200

Fig. 4.1. Map of the infrasound array IS37.

4.1.2 <u>Instrumentation</u>

I. Configurations

- Current configuration (2013-…):

    MB2005 microbarometer
    CMG-EAM24 digitizer

II. Respids

    IS37BD1
    IS37HD1

III. Instrument specifications

MB2005:

The MB2005 microbarometer, developed to detect air nuclear explosions, measures small variations in atmospheric pressure. Some nominal values are the following (Martec, 2007):

Filtered output passband	0.01 – 27.0 Hz (modifiable)
Electronic noise level	2 mPa rms between 1 – 10 Hz
Mechanical sensitivity	35 nm/Pa
Sensitivity in 0.01 – 27 Hz passband	20 mV/Pa (± 10 V for ± 5 hPa)

CMG-EAM24:

Full 24-bit digitizer employing the Cirrus Logic CS5376 digital filtering chipset and TMS320VC33 digital signal processor (DSP). The DSP software consists of 6 cascaded programmable filter/decimation stages that allow the selection of multiple data output rates simultaneously (Güralp Systems, 2006). Some specifications are the following:

Input voltage range	+/- 10 V differential
Dynamic range	137 dB @ 40 sps
DSP sampling rate	32 kHz
Nominal sensitivity	3.2 µV/count

4.2 Instrument response calculation for the IS37 infrasound array

This chapter focuses on the major considerations to be taken into account for the calculation of the instrument response of the different systems operating at the IS37 infrasound array.

GSE file response *Respid* flags for each configuration are provided at the beginning of each section.

4.2.1 MB2005 – EAM24 (2013/10/16 – …)

Respid:	IS37BD1	BDF
	IS37HD1	HDF

Two different sampling rates are outputted, since the IDC is interested in receiving 20 sps data, but for non-CTBT related purposes, a higher sampling rate channel is stored locally. Following strictly the GSE and SEED standards (GSETT-3, 1997, IRIS, 2010), both channels should be noted with code 'B', thus requiring an auxiliary channel name to distinguish between them. To avoid this, code 'H' is assigned to the 40 sps channel, *i.e.*, it is coded HDF. The IS37 infrasound array configuration consists of the following components:

- MB2005 microbarometers
- CMG-EAM24 digitizers

4.2.1.1 *MB2005*

Response information about the MB2005 microbarometer can be found in Part 4, §2.2.1.1 on the ARCI infrasound array.

4.2.1.2 *CMG-EAM24*

The Güralp CMG-DM24S3EAM A/D converter is a 24-bit digitizer. It employs the Crystal Semiconductors CS5376 chipset and the TMS320VC33 digital signal processor (DSP) to achieve the desired output rate. The DSP software consists of 6 cascaded programmable filter/decimation stages that allow the selection of multiple data output rates simultaneously (Güralp Systems, 2006). In the case of the IS37 infrasound channels, the data recording sample rate is set to 40 and 20 sps. These rates are obtained by the following digital filter cascade (TTL = 31 in the Güralp Systems tabulated, decimation cascade look-up system):

- CS5376 FIR filter Stage 1, Sinc 1, with 36 coefficients, decimating by 8 from an input rate of 512 kHz
- CS5376 FIR filter Stage 3, Sinc 2, with 6 coefficients, decimating by 2
- CS5376 FIR filter Stage 4, Sinc 2, with 8 coefficients, decimating by 2
- CS5376 FIR filter Stage 5, FIR 1, with 48 coefficients, decimating by 4
- CS5376 FIR filter Stage 5, FIR 2, with 126 coefficients, decimating by 2,
- EAM24 FIR Stage 1, SWA-D24-3D06, with 502 coefficients, decimating by 2,
- EAM24 FIR Stage 2, SWA-D24-3D08, with 502 coefficients, decimating by 5,
- EAM24 FIR Stage 3, SWA-D24-3D08, with 502 coefficients, decimating by 5 down to 40 sps, and
- EAM24 FIR Stage 4, SWA-D24-3D06, with 502 coefficients, decimating by 2 down to 20 sps.

The sensitivity of the digitizer for each channel can be found in the instrument specific Calibration Sheet provided by the manufacturer.

The pressure amplitude and phase response for these configurations (IS37HD1, IS37BD1) is depicted in Fig. 4.2. The shaded areas represent the frequency range beyond the Nyquist frequency, which is 20 Hz for the HDF channels and 10 Hz for the BDF channels.

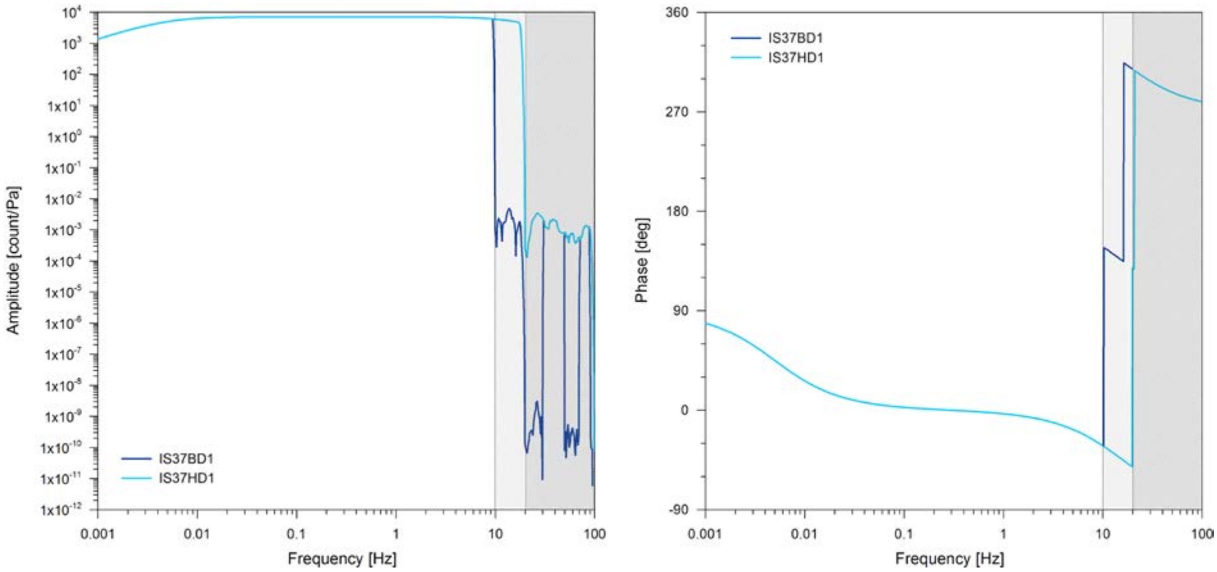


Fig. 4.4. Pressure amplitude and phase response for the HDF (IS37HD1) and BDF (IS37BD1) channels of the IS37 infrasound array. Shaded areas represent range beyond the Nyquist frequency for each channel (20 Hz and 10 Hz respectively).

4.3 References

GSETT-3, 1997. *Provisional GSE 2.1, Message Formats & Protocols.* Operations Annex 3, 132, pp.

Güralp Systems, 2006. CMG-DM24 Operator's Guide. *MAN-D24-0004*, Güralp Systems Ltd., Aldermaston, England, 113 pp.

IRIS, 2010. *SEED Reference Manual, SEED Format Version 2.4.* Incorporated Research Institutions for Seismology, 212 pp.

Martec, 2007. MB2005 User Manual. *14643-C, Edition 17/01/2007*, Martec, CEA, 20 pp.

CHAPTER 5: ESKDALEMUIR INFRASOUND ARRAY – EKAI

5.1 Development of the EKAI infrasound systems: instrumentation and responses

5.1.1 Short description

- 2013-…:

In June 2013, NORSAR begun acquiring data from the Eskdalemuir infrasound array (EKAI) in UK, operated by Blacknest since February 2013. The infrasound channels of the array are equipped with Chaparral 50A infrasound sensors and Güralp CMG-DM24 digitizers and are installed at sites EKB3, EKB5, EKR3 and EKR4 (see Fig. 5.1), in the same pits as the seismic sensors of EKA (see Part 2, § 5.1). An acoustic conditioner manufactured by Güralp (D. Green, personal communication) is used between sensor and digitizer.

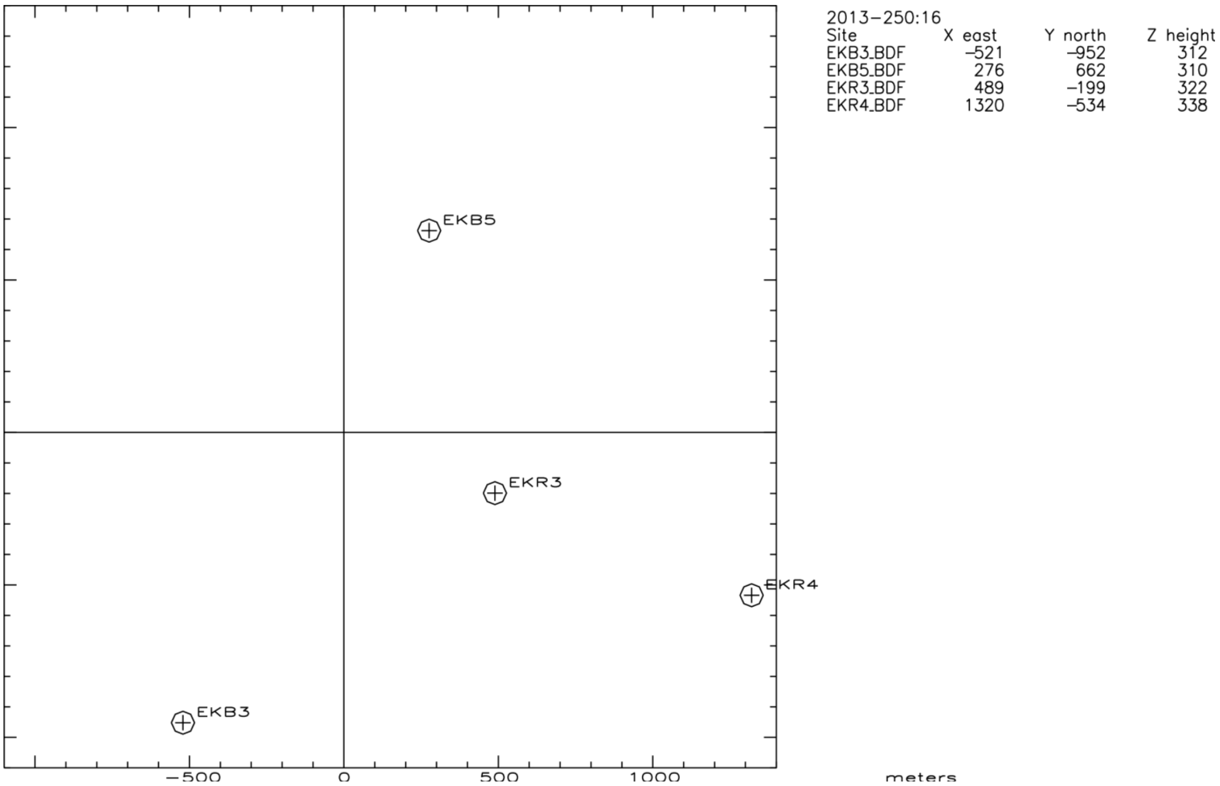


Fig. 5.1. Map of the infrasound sites EKB3, EKB5, EKR3 and EKR4 of the EKAI array. Site distances from the EKA seismic array (see Part 2, §5.1) central element (axes crossing point) are given in meters.

5.1.2 Instrumentation

I. Configurations

- Currently acquired configuration (2013-…):

Chaparral 50A infrasound sensor
Acoustic conditioner
CMG-DM24 digitizer

II. Respids

EKABD1

III. Instrument specifications

Chaparral 50A:

The Chaparral 50A infrasound sensor, developed by Chaparral Physics at the University of Alaska, covers the full infrasound band from 0.02 to 50 Hz. Some nominal values are the following (Chaparral Physics, 2010):

Output type	differential
Maximum output	36 Vp-p
Self-noise	less than -76 dB Pa2/Hz, rel to 1 Pa
Dynamic range	99 dB high, 113 dB low gain @ 0.5-2 Hz
Nominal sensitivity (high)	2 V/Pa @ 1 Hz, 18 Pa full scale range
Nominal sensitivity (low)	0.4 V/Pa @ 1 Hz, 90 Pa full scale range

Acoustic conditioner:

Interfacing units between infrasound sensor and digitizer, manufactured upon request by Güralp Systems (D. Green, personal communication). Gain values range between x 1.04 and 1.09.

CMG-DM24:

Full 24-bit digitizer employing the Cirrus Logic CS5376 digital filtering chipset and TMS320VC33 digital signal processor (DSP). The DSP software consists of 6 cascaded programmable filter/decimation stages that allow the selection of multiple data output rates simultaneously (Güralp Systems, 2006). The specifications are the following:

Input voltage range	+/- 10 V differential
Dynamic range	137 dB @ 40 sps
DSP sampling rate	32 kHz
Sensitivity	3.2 µV/count

5.2 Instrument response calculation for the EKAI infrasound array

This chapter focuses on the major considerations to be taken into account for the calculation of the instrument response of the different systems operating at the EKAI infrasound array.

GSE file response *Respid* flags for each configuration are provided at the beginning of each section.

5.2.1 Chaparral 50A – DM24 (2013/06/27 – …)
Respid: EKABD1 BDF

According to information received from Blacknest, EKAI infrasound channel configuration consists of the following components:

- Chaparral 50 A infrasound sensors
- Acoustic conditioners
- CMG-DM24 digitizers

5.2.1.1 *Chaparral 50A*

Response information about the Chaparral Model 50A infrasound sensor is provided by the manufacturer (Chaparral Physics, 2010) in the form of nominal frequency response and poles and zeros. Fig. 5.2 shows the frequency response roll-off at the upper and lower end of the nominal passband 0.02 – 50 Hz for Model 50 A.

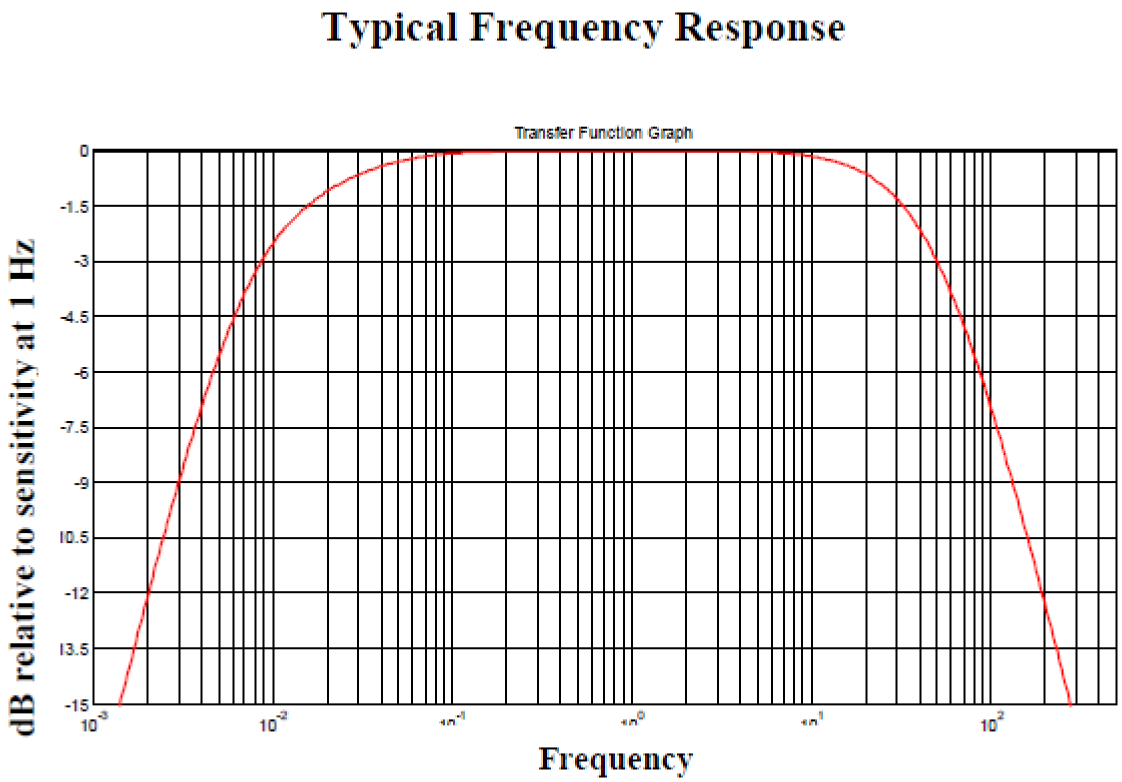


Fig. 5.2. Chaparral Model 50A typical frequency response (Chaparral Physics, 2010).

The poles, zeros and scaling factor of the transfer function that describes the response curve of Fig. 5.2 are listed below in rad/s (Chaparral Physics, 2010):

Poles	Zeros	K
0	0	314.1
-314.0	0	
-0.188	-0.17	
-0.044		

Note that this transfer function is only valid below 500 Hz (Chaparral Physics, 2010).

The manufacturer instructs that when connecting the Model 50A sensor to a 24-bit digitizer, low gain should be used exclusively (Chaparral Physics, 2010). The nominal sensitivity for low gain is 0.4 V/Pa @ 1 Hz, however, actual values are instrument-specific. The sensitivity values for the sensors installed at EKAI can be found in the table of Fig. 5.3, provided by Blacknest (see §5.2.1.3, this chapter).

5.2.1.2 *Acoustic Conditioner*

An acoustic conditioner (A.C.) is used between sensor and digitizer at EKAI channels. The units have been manufactured by Güralp Systems upon request from Blacknest and have a gain that ranges between x 1.04 and 1.09 (D. Green, personal communication). Particular gain values for each channel are also provided in the table of Fig. 5.3.

5.2.1.3 *CMG-DM24*

The Güralp CMG-DM24 A/D converter is a 24-bit digitizer. It employs the Crystal Semiconductors CS5376 chipset and the TMS320VC33 digital signal processor (DSP) to achieve the desired output rate. The DSP software consists of 6 cascaded programmable filter/decimation stages that allow the selection of multiple data output rates simultaneously (Güralp Systems, 2006). In the case of the EKAI infrasound channels, the data recording sample rate is set to 100 sps. This is obtained by the following digital filter cascade (TTL = 6 in the Güralp Systems tabulated, decimation cascade look-up system):

- CS5376 FIR filter Stage 1, Sinc 1, with 36 coefficients, decimating by 8 from an input rate of 512 kHz
- CS5376 FIR filter Stage 3, Sinc 2, with 6 coefficients, decimating by 2
- CS5376 FIR filter Stage 4, Sinc 2, with 8 coefficients, decimating by 2
- CS5376 FIR filter Stage 5, FIR 1, with 48 coefficients, decimating by 4
- CS5376 FIR filter Stage 5, FIR 2, with 126 coefficients, decimating by 2,
- DM24 FIR Stage 1, SWA-D24-3D06, with 502 coefficients, decimating by 2,
- DM24 FIR Stage 2, SWA-D24-3D06, with 502 coefficients, decimating by 2, and
- DM24 FIR Stage 3, SWA-D24-3D08, with 502 coefficients, decimating by 5 down to 100 sps.

The sensitivity of the digitizer for each channel can be found in the instrument specific Calibration Sheet provided by the manufacturer. The digitizers installed at EKAI have serial numbers and the sensitivity values as listed in the table of Fig. 5.3.

Table A-2: The instrument and digitiser codes for the four Chaparral 50A microbarometers installed in the permanent EKAI array in February 2013, with the corresponding calibration information. The counts value of the digitised data is converted to the differential pressure (Pa) by multiplying by the 'counts to pressure' value. This value is generated by dividing the 'counts to voltage' value by the product of the 'pressure to voltage at 1 Hz' value and the 'acoustic conditioner gain'. 'Pit no.' is the code of the corresponding seismic pit at the EKA seismometer array.

Pit No.	Instrument Code	Digitiser Code	Counts to Voltage (μV/count)	Acoustic Conditioner	A.C. gain	Pressure to Voltage (V/Pa)		Counts to Pressure ($\times 10^{-6}$Pa/count)
						at 0.1 Hz	at 1 Hz	
R3	102210	4567/A3823	2.986	G13553	1.090	0.382	0.400	6.85
R4	102219	4568/A3824	2.966	G13550	1.040	0.382	0.401	7.11
B3	102211	4566/A3822	2.879	G13552	1.090	0.376	0.395	6.69
B5	102217	4565/A3821	2.875	G13551	1.090	0.383	0.404	6.53

Fig. 5.3. Table with site-specific instrumentation and response-related information for the EKAI infrasound array, provided by Blacknest. "Pressure to Voltage" field refers to the sensitivity of the Chaparral 50A sensors, while "Counts to Pressure" to overall response sensitivity for each EKAI channel.

The pressure amplitude and phase response for this configuration (EKABD1) is depicted in Fig. 5.4. The shaded area represents the frequency range beyond the Nyquist frequency, which is 50 Hz.

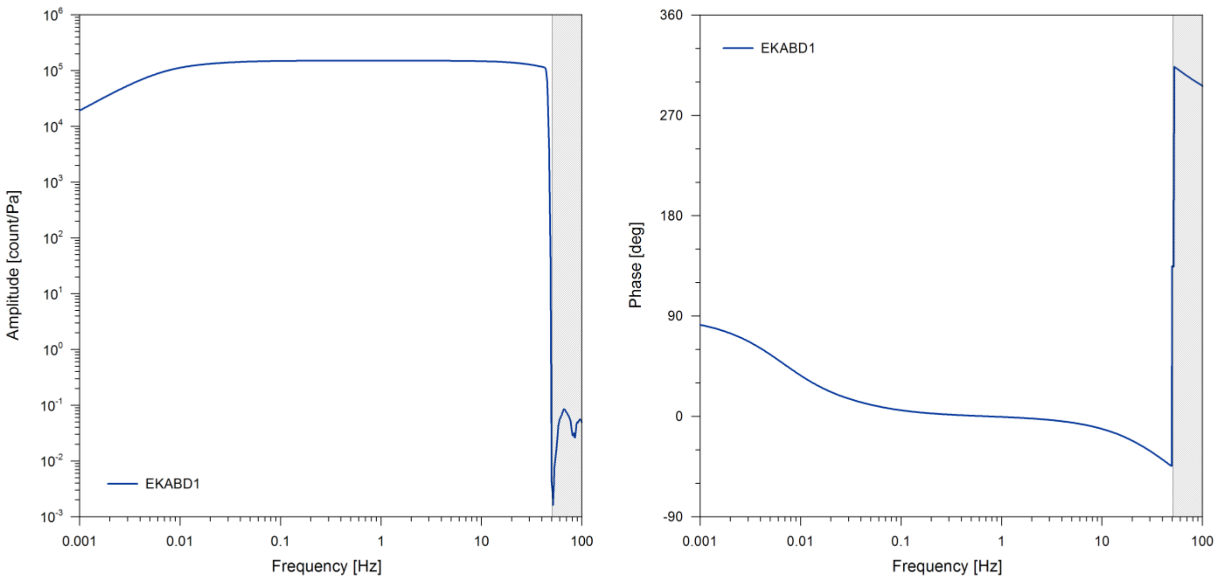


Fig. 5.4. Pressure amplitude and phase response for the infrasound (EKABD1) channels of the EKAI array. Shaded areas represent range beyond the Nyquist frequency (50 Hz in this case).

5.3 References

Chaparral Physics, 2010. Operation manual for the Model 50A Infrasound Sensor. *Manual Revision 1 (5/13/2010)*, Chaparral Physics, Fairbanks, Alaska, 18 pp.

Güralp Systems, 2006. CMG-DM24 Operator's Guide. *MAN-D24-0004*, Güralp Systems Ltd., Aldermaston, England, 113 pp.

APPENDICES

APPENDIX I

```
DATA_TYPE station GSE2.0
Sta   Type  Latitude  Longitude    Elev   On Date   Off Date
NAO00 1C    60.82372   10.83236   0.379 1968/01/01               01A00

DATA_TYPE channel GSE2.0
Sta  Chan Aux   Latitude  Longitude    Elev  Depth   Hang  Vang Sample_Rate Inst       On Date    Off Date                   Chanid   Respid
NAO00 SHZ sz     60.82372    10.83236    0.379  0.000    -1.0    0.0    20.000000 HS-10   1968/01/01 00:00 1977/11/06 23:59          6  SPSLEM1 01A00
4.75 Hz
NAO00 SHZ sz     60.82372    10.83236    0.379  0.000    -1.0    0.0    20.000000 HS-10   1977/11/07 00:00 1979/10/22 23:59          6  SPSLEM2 01A00
8.00 Hz
NAO00 SHZ sz     60.82372    10.83236    0.379  0.000    -1.0    0.0    20.000000 HS-10   1979/10/23 00:00 1981/01/07 23:59          6  SPSLEM1 01A00
4.75 Hz
NAO00 SHZ sz     60.82372    10.83236    0.379  0.000    -1.0    0.0    20.000000 HS-10   1981/01/08 00:00 1982/10/28 23:59          6  SPSLEM2 01A00
8.00 Hz

DATA_TYPE response GSE2.0
CAL2 NAO00 SHZ sz   HS-10  4.2722e-02 1.00000   20.00000 1968/01/01 00:00 1977/11/06 23:59  SPSLEM1
PAZ2   1 V  1.02000000e-06                    2    3 Hall-Sears, for 1020 V/m/s (plateau), for eigenfrequency 1.02 Hz & damping ratio 0.69, both
median values from NORSAR Report # 40
 -4.42210582e+00  4.54782838e+00
 -4.42210582e+00 -4.54782838e+00
  0.00000000e+00  0.00000000e+00
  0.00000000e+00  0.00000000e+00
  0.00000000e+00  0.00000000e+00             extra zero for displacement
PAZ2   2 V  8.27586207e-01                0   0 Attenuation due to damping network
PAZ2   3 V  7.88991474e+06                 2   1 RA-5 amplifier(nominal x 5432.5, 74.7 db), 3dB down @ 0.1 and @ 230 Hz, normalized @ 1Hz, NORSAR
Report #40
 -6.28318531e-01  0.00000000e+00
 -1.44513260e+03  0.00000000e+00
  0.00000000e+00  0.00000000e+00
PAZ2   4 V  9.35000000e-01                0   0 Attenuation due to 3.7 km cable (standard value)
PAZ2   5 V  7.14300000e-01                0   0 LTA amplifier: gain 0.7143
PAZ2   6 V  5.22561557e-01                0   0 Gain-potentiometer, adjustable 0 to -12 db that the cal-output gives 2.86 V, here used -5.64 db
PAZ2   7 V  2.00144000e+00                1   1 LTA: 1st order RC filter, HP @ 0.038 Hz and gain 2x
 -2.38761040e-01  0.00000000e+00
  0.00000000e+00  0.00000000e+00
PAZ2   8 V  4.12666000e+05                4   0 LTA: Analog LP 4th order Chebyshev, ripple 0.25 dB @ 4.75 Hz
 -6.34263230e+00  3.15397979e+01
 -6.34263230e+00 -3.15397979e+01
 -1.53124690e+01  1.30642120e+01
 -1.53124690e+01 -1.30642120e+01
DIG2   9  1.63840000e+03     20.0000 SLEM A/D converter, 13 bit per 5 V (gain ranging) (= 0.610351563 mV/count)
```

Respid

APPENDIX II

SEISMIC CHANNELS

Respid codes and names of corresponding fap files for the NORSAR array.

instrumentation	**Respid**	**fap-file**
standard SP SLEM (4.75 Hz LP @ LTA)	SPSLEM1	NOASPSLEM1-NOA-SHZ.fap
SP SLEM, 8 Hz LP @ LTA	SPSLEM2	NOASPSLEM2-NOA-SHZ.fap
SP SLEM, no LP @ LTA	SPSLEM3	NOASPSLEM3-NOA-SHZ.fap
SP SLEM, -30 db (slz)	SPSLEM4	NOASPSLEM4-NOA-SLZ.fap
SP SLEM, prototype BU BP (NRA0, svz)	SPSLEM5	NOASPSLEM5-NC602-SVZ.fap
SP SLEM, unknown filter	SPSLEM6	NOASPSLEM6-NC602-SVZ.fap
SP SLEM, 4.75 Hz, S-13 sensor	SPSLEM7	NOASPSLEM7-NOA-SHZ.fap[*]
SP SLEM, 8 Hz, S-500 sensor	SPSLEM8	NOASPSLEM8-NC602-SHZ.fap[**]
standard LP SLEM	LPSLEM1	NOALPSLEM1-NAO00-LHZ.fap[*]
LP SLEM, -30 db	LPSLEM2	NOALPSLEM3-N1403-LHZ.fap[*]
SP RD6	RDSP1	NOARDSP1-NOA-SHZ.fap
SP RD6, -30 db (slz)	RDSP2	NOARDSP2-NAO01-SLZ.fap
LP RD6	RDLP1	NOARDLP1-NOA-LHZ.fap[*]
old SP AIM in CTV	AIM1	NOAAIM1-NOA-SHZ.fap
old SP AIM in SPV	AIM2	NOAAIM2-NOA-SHZ.fap
old SP AIM, -30 db (slz)	AIM3	NOAAIM3-NAO01-SLZ.fap
LP AIM	AIM4	NOAAIM4-NOA-LHZ.fap[*]
SP AIM, 20171A sensors	AIM0SP	NOAAIM0SP-NAO00-SHZ.fap
BB AIM, KS54000 sensors	AIM0BB	NOAAIM0BB-NAO01-BHZ.fap[*]
BB AIM, Güralp sensor	AIM0BBG	NOAAIM0BBG-NC602-BHZ.(a.)fap[*,‡]
BB CMG-EAM24, CMG-3T HYBRID	CMGEAM HYB3T	CMGEAMHYB3T-NC602-BHZ.fap[*]
"SP" CMG-EAM24, CMG-3V HYBRID	CMGEAM HYB1V	CMGEAMHYB1V-NC600-BHZ.fap

[*] 3-component instrument (*e.g.*, sz, sn, se).
[**] Only components sz, sn.
[‡] a appended after regular file name: identical response, different channel code (gz,gn,ge vs bz,bn,be).

Respid codes and names of corresponding fap files for the NORES array.

instrumentation	**Respid**	**fap-file**
standard SP, GS-13 'Blue-Box'	NORESSP1	NORESSP1-NRA0-SHZ.fap
standard SP, GS-13 'Blue-Box'	NORESSP2	NORESSP2-NRA0-SHN.fap
standard SP, GS-13 'Blue-Box'	NORESSP3	NORESSP3-NRA0-SHE.(a./na./z./nb.)fap[♠]
SP borehole variation, S-3 'Blue-Box'	NORESSP4,5,6	NORESSP4-NRF0-SHZ.fap[*]
LP channels, KS36000 'Blue-Box'	NORESLP1,2,3	NORESLP1-NRE0-LHZ.fap[*]
IP channels, KS36000 'Blue-Box'	NORESIP1,2,3	NORESIP1-NRE0-MHZ.fap[*]
current NORES, GS-13 CMG-DM24	NORESSP7,8,9	NORESSP7-NRA0-SHZ.fap[*]

♠ Identical response, differences in orientation (Mykkeltveit, 1987).
SHE.fap and SHE.a.fap: two different time intervals with correct EW orientation.
SHE.na.fap and SHE.nb.fap: two different time interval with NS orientation.
SHE.z.fap: time interval as vertical (Z) channel.
See *GSE* file for time definitions.
* 3-component instrument (*e.g.*, sz, sn, se).

Respid codes and names of corresponding fap files for the ARCES array.

instrumentation	**Respid**	**fap-file**
standard SP, GS-13 'Blue-Box'	ARCESSP1,2,3	ARCESSP1-ARCES-SHZ.fap*
LP channels, KS36000 'Blue-Box'	ARCESLP1,2,3	ARCESLP1-ARE0-LHZ.fap*
IP channels, KS36000 'Blue-Box'	ARCESIP1,2,3	ARCESIP1-ARE0-MHZ.fap*
Highly damped SP, GS-13 HRD-24	ARCESSP4,5,6	ARCESSP4-ARCES-SHZ.fap*
Current SP, GS-13 HRD-24	ARCESSP7,8,9	ARCESSP7-ARCES-SHZ.fap*
BB channel, CMG-3T HRD-24	ARCESBB1,2,3	ARCESBB1(a)-ARE0-BHZ .fap*,†
BB channel, new PAZ CMG-3T HRD-24	ARCESBB4,5,6	ARCESBB4-ARE0-BHZ.fap*
Initial HF, CMG-3T RefTek 130-01	ARCESHH1,2,3	ARCESHH1-ARE0-HHZ.fap*
HF variation, CMG-3T DM-24	ARCESEH1,2,3	ARCESEH1-ARE0-EHZ.fap*
Current BH channel, CMG-3T DM-24	ARCESBH1,2,3	ARCESBH1-ARE0-BHZ.fap*

* 3-component instrument (*e.g.*, sz, sn, se).
† a appended to regular *Respid*: identical response shape, but different sensor (serial number).

Respid codes and names of corresponding fap files for the SPITS array.

instrumentation	**Respid**	**fap-file**
standard SP, S-500 RD-6	SPITSSP1	SPITSSP1-SPI-SHZ.fap
SP variation, CMG-3ESP RD-6 gain 1x	SPITSSP2	SPITSSP2-SPI-SHZ.fap
standard SP, CMG-3ESP RD-6 gain 10x	SPITSSP3	SPITSSP3-SPI-SHZ.fap
SP variation, CMG-3ESP RD-6 gain 5x	SPITSSP4	SPITSSP4-SPB4-SHZ.fap
3C BB @ SPB4, CMG-3T RD-6 gain 1x	SPITSBB1,2,3	SPITSBB1-SPB4-BHZ.fap*
3C BB @ SPB4, CMG-3T RD-6 gain 5x	SPITSBB4,5,6	SPITSBB4-SPB4-BHZ.fap*
current BB, CMG-3T DM-24	SPITSBB7,8,9	SPITSBB7-SPA0-BHZ.(a.)fap*,†

* 3-component instrument (*e.g.*, BHZ, BHN, BHE).
† a appended after regular file name: identical response shape, but different sensor (serial number).

Respid codes and names of corresponding fap files for the Apatity array (APA) and APZ9.

instrumentation	**Respid**	**fap-file**
standard SP, S-500 RD-6	APASP1	APASP1-APA-SHZ.fap
HF variation, S-500 RD-6, 80 sps	APA0HH1,2,3	APA0HH1-APA0-HHZ.fap*
BB APZ9, CMG-3T RD-3	APZ9BB1,2,3	APZ9BB1-APZ9-BHZ.fap*

* 3-component instrument (*e.g.*, BHZ, BHN, BHE).

Respid codes and names of corresponding fap files for the Jan Mayen (JMI/JMIC) broadband stations.

instrumentation	**Respid**	**fap-file**
old BB (UiB), STS-2 Earth Data	JMIBB1,2,3	JMIBB1-JMI-BHZ.fap*
new BB, STS-2 Europa T, 10 mHz IIR	JMICBB1,2,3	JMICBB1-JMIC-BHZ.fap*
new BB, STS-2 Europa T, no IIR	JMICBB4,5,6	JMICBB4-JMIC-BHZ.fap*
current BB, STS-2 Europa T, 1 mHz IIR	JMICBB7,8,9	JMICBB7-JMIC-BHZ.fap*

* 3-component instrument (*e.g.*, BHZ, BHN, BHE).

Respid codes and names of corresponding fap files for the Hagfors array (HFS).

instrumentation	**Respid**	**fap-file**
old SP, S-13 RD-3	HFSSP1,2,3	HFSSP1-HFSA1-SHZ.fap*,**
old SP, 20171A RD-3	HFSSP4	HFSSP4-HFSB1-SHZ.fap**
old LP, 7505A/8700C RD-3	HFSLP1,2,3	HFSLP1-HFSC2-LHZ.fap*,**
old BB, STS-1 RD-3	HFSBB1	HFSBB1-HFSC2-BHZ.fap
new SP, GS-13 Europa T, non amplified	HFSSP5	HFSSP5-HFA0-SHZ.fap**
current SP, GS-13 Europa T, amplified	HFSSP6	HFSSP6-HFA0-SHZ.fap**
new BB, STS-2 Europa T, 10 mHz IIR	HFSBB2,3,4	HFSBB2-HFC2-BHZ.fap*
current BB, STS-2 Europa T, 1 mHz IIR	HFSBB5,6,7	HFSBB5-HFC2-BHZ.fap*

* 3-component instrument (*e.g.*, BHZ, BHN, BHE).

** Sensitivity is channel specific, channel name included in fap-file name.

Respid codes and names of corresponding fap files for the FINES array.

instrumentation	**Respid**	**fap-file**
original FINESA SP, S-13 DDS1105	FINSP1,2,3	FINSP1-FIN-SHZ.fap*
old SP, S-13 Motorola based A/D	FINSP4,5,6	FINSP4-FIN-SHZ.fap*
old SP, -30 dB channel, S-13 Motorola	FINSL1	FINSL1-FIA0-SLZ.fap
first FINES SP, S-13 AIM24	FINSP7,8,9	FINSP7-FIN-SHZ.(a.)fap*,‡
current FINES SP, S-13 Europa T	FINSP10,11,12	FINSP10-FIA0-SHZ.fap*,**
first BB, CMG-3T AIM24	FINBB1,2,3	FINBB1-FIA1-BHZ.fap*,**
upgraded BB, CMG-3T Europa T	FINBB4,5,6	FINBB4-FIA1-BHZ.fap*,**
current BB, CMG-3T Europa T	FINBB7,8,9	FINBB7-FIA1- BHZ.fap*,**

* 3-component instrument (*e.g.*, SHZ, SHN, SHE).

‡ a appended after regular file name: identical response but no auxiliary channel name (sz) used.

** Sensitivity is channel specific, channel name included in fap-file name.

Respid codes and names of corresponding fap files for the Åknes (AKN) broadband station.

instrumentation	**Respid**	**fap-file**
standard BB, CMG-3ESP DM24	AKNBH1,2,3	AKNBH1-AKN-BHZ.fap*

* 3-component instrument (BHZ, BHN, BHE).

Respid codes and names of corresponding fap files for the Hornsund broadband station (HSPBB/HSPB).

instrumentation	Respid	fap-file
initial HH, 100 sps, STS-2 DM24	HSPHH1,2,3	HSPHH1-HSPBB-HHZ.fap*
initial BB, 10 sps, STS-2 DM24	HSPBB1,2,3	HSPBB1-HSPBB-BHZ.fap*
initial LP, 1 sps, STS-2 DM24	HSPLP1,2,3	HSPLP1-HSPBB-LHZ.fap*
current HH, STS-2 MK-6	HSPHH4,5,6	HSPHH4-HSPB-HHZ.fap*

* 3-component instrument (*e.g.*, BHZ, BHN, BHE).

Respid codes and names of corresponding fap files for the Barentsburg broadband stations (BRBA & BRBB).

instrumentation	Respid	fap-file
current HH, 80 sps, CMG-3ESP DM24	BRBAHH1,2,3	BRBAHH1-BRBA-HHZ.fap*
initial MH, 4 sps, CMG-3ESP DM24	BRBAMH1,2,3	BRBAMH1-BRBA-MHZ.fap*
current LH, 1 sps, CMG-3ESP DM24	BRBALH1,2,3	BRBALH1-BRBA-LHZ.fap*
current HH, 80 sps, CMG-3ESP DM24	BRBBHH1,2,3	BRBBHH1(a/b)-BRBB-HHZ.fap*,†

* 3-component instrument (*e.g.*, HHZ, HHN, HHE).
† a, b appended to *Respid*: indentical response, different station locations

Respid codes and names of corresponding fap files for the Troll broadband station (TROLL).

instrumentation	Respid	fap-file
initial HH, STS-2.5 Q330HR gain 1x	TROLLHH1,2,3	TROLLHH1(a)-TROLL-HHZ.fap*,†
initial BH, STS-2.5 Q330HR gain 1x	TROLLBH1,2,3	TROLLBH1-TROLL-BHZ.fap*
initial LH, STS-2.5 Q330HR gain 1x	TROLLLH1,2,3	TROLLLH1-TROLL-LHZ.fap*
initial VH, STS-2.5 Q330HR gain 1x	TROLLVH1,2,3	TROLLVH1-TROLL-VHZ.fap*
initial UH, STS-2.5 Q330HR gain 1x	TROLLUH1,2,3	TROLLUH1-TROLL-UHZ.fap*
current HH, STS-2.5 Q330HR gain 20x	TROLLHH4,5,6	TROLLHH4-TROLL-HHZ.fap*
current BH, STS-2.5 Q330HR gain 20x	TROLLBH4,5,6	TROLLBH4-TROLL-BHZ.fap*
current LH, STS-2.5 Q330HR gain 20x	TROLLLH4,5,6	TROLLLH4-TROLL-LHZ.fap*
current VH, STS-2.5 Q330HR gain 20x	TROLLVH4,5,6	TROLLVH4-TROLL-VHZ.fap*
current UH, STS-2.5 Q330HR gain 20x	TROLLUH4,5,6	TROLLUH4-TROLL-UHZ.fap*
current BL, STS-2.5 Q330HR gain 1x	TROLLBL1,2,3	TROLLBL1-TROLL-BHZ.fap*

* 3-component instrument (*e.g.*, HHZ, HHN, HHE).
† a appended to *Respid*: identical response, different station location

Respid codes and names of corresponding fap files for the Kingsbay broadband station (KBS).

instrumentation	Respid	fap-file
locationID 00, STS-1 Q380, 20 sps	KBS00BB1,2,3	KBS00BB1-KBS-BHZ. (a.)fap*,‡
locationID 00, STS-1 Q380, 1 sps	KBS00LH1,2,3	KBS00LH-KBS-LHZ.fap*
locationID 10, STS-2 Q380, 40 sps	KBS10BB1,2,3	KBS10BB1-KBS-BHZ.fap*
locationID 10, STS-2 Q330HR, 40 sps	KBS10BB4,5,6	KBS10BB4-KBS-BHZ.fap*
locationID 10, STS-2 Q380, 40 sps	KBS10SH1,2,3	KBS10SH1-KBS-SHZ.fap*
locationID 10, STS-2 Q380, 1 sps	KBS10LH1,2,3	KBS10LH1-KBS-LHZ.fap*

* 3-component instrument (*e.g.*, BHZ, BHN, BHE).
‡ a appended after regular file name: identical response shape, auxiliary channel name (BZ) used.

Respid codes and names of corresponding fap files for the Hopen broadband station (HOPEN).

instrumentation	Respid	fap-file
current HH, 100 sps, STS-2 EarthData	HOPENHH1,2,3	HOPENHH1-HOPEN-HHZ.fap[*]

[*] 3-component instrument (HHZ, HHN, HHE).

Respid codes and names of corresponding fap files for the Bjørnøya broadband station (BJO1).

instrumentation	Respid	fap-file
previous HH, 100 sps, CMG-6TD	BJO1HH1,2,3	BJO1HH1-BJO1-BZ.fap[*]
previous HH, 100 sps, CMG-6TD	BJO1HH1,2,3	BJO1HH1-BJO1-HHZ.fap[*]
current HH, 100 sps, T120P DM24	BJO1HH4,5,6	BJO1HH4-BJO1-HHZ.fap[*]

[*] 3-component instrument (*e.g.*, HHZ, HHN, HHE).

Respid codes and names of corresponding fap files for the Eskdalemuir seismic array (EKA).

instrumentation	Respid	fap-file
3-C BH, CMG-3T DM24	EKABH1,2,3	EKABH1-EKB-BHZ.fap[*]
Vertical only BH, CMG-3V DM24	EKABH4	EKABH4-EKB1-BHZ.fap[**]

[*] 3-component instrument (BHZ, BHN, BHE).
[**] Sensitivity is channel specific, channel name included in fap-file name.

Respid codes and names of corresponding fap files for the Bergen broadband station (BER).

instrumentation	Respid	fap-file
previous HH, 100 sps, STS-2 P2400	BERHH1,2,3	BERHH1-BER-HHZ.fap[*]
current HH, 100 sps, STS-2 DM24	BERHH4,5,6	BERHH4(a)-BER-HHZ.fap[*,†]

[*] 3-component instrument (HHZ, HHN, HHE).

Respid codes and names of corresponding fap files for the IPY broadband OBS/H stations.

instrumentation	Respid	fap-file
50 sps, CMG-40T GEOLON-MCS	OBSBH1	OBSBH1-OBS01-BHZ.fap[*]
50 sps, CMG-40T GEOLON-MCS	OBSBH2	OBSBH2-OBS01-BHY.fap[*,†]
50 sps, CMG-40T GEOLON-MCS	OBSBH3	OBSBH3-OBS01-BHX.fap[*,‡]
50 sps, HTI-01-PCA/ULF GEOLON-MCs	OBSHH	NaN

[*] Corresponding component at all stations (OBS01, OBS02, …, OBS12).
[†] Unknown true orientation, theoretically EW.
[‡] Unknown true orientation, theoretically NS.

Respid codes and names of corresponding fap files for the IPY BOA array.

instrumentation	Respid	fap-file
125 sps, LE-3D/5s MARSlite	BJOASP1,2,3	BJOASP1-BJO01-SHZ.fap[*,**]

[*] 3-component instrument (SHZ, SHN, SHE)
[**] Sensitivity is channel specific, channel name included in fap-file name.

ACOUSTIC CHANNELS

Respid codes and names of corresponding fap files for the ARCES infrasound array (ARCI).

instrumentation	Respid	fap-file
current BD, MB2005 DM24	ARCIBD1	ARCIBD1-ARA1-BDF.fap**

** Sensitivity is channel specific, channel name included in fap-file name.

Respid codes and names of corresponding fap files for the NORES infrasound array.

instrumentation	Respid	fap-file
current BD, IFS-3000 EM24	NORESBD1	NORESBD1-NRA0-BDF.fap**

** Sensitivity is channel specific, channel name included in fap-file name.

Respid codes and names of corresponding fap files for the IS37 infrasound array.

instrumentation	Respid	fap-file
planned BD, MB2005 EAM24, 20 sps	IS37BD1	IS37BD1-I37H0-BDF.fap**
planned HD, MB2005 EAM24, 40 sps	IS37HD1	IS37HD1-I37H0-HDF.fap**

** Sensitivity is channel specific, channel name included in fap-file name.

Respid codes and names of corresponding fap files for the Eskdalemuir infrasound array (EKAI).

instrumentation	Respid	fap-file
current BD, Chaparral 50A DM24	EKABD1	EKABD1-EKB3-BDF.fap**

** Sensitivity is channel specific, channel name included in fap-file name.

Appendix III

Site	S/N	Freq	λ_x	Rc	R_{CDR}	G	Motor	R_0	w
NAO00	213	1.0	0.027	7085	6786	644.0	0.1972	2513	168.62
NAO01	223	1.0	0.026	7202	7425	674.0	0.1975	3300	211.79
NAO02	225	1.0	0.027	7110	6804	645.0	0.1960	2513	168.44
NAO03	221	1.0	0.022	7054	6726	642.8	0.1972	2459	166.16
NAO04	250	1.0	0.0227	7225	6861	649.0	0.1970	2480	165.84
NAO05	206	1.0	0.021	7054	6702	642.0	0.1974	2425	164.24
NBO00	204	1.0	0.024	7194	7409	674.0	0.1974	3285	211.29
NBO01	240	1.0	0.025	7200	6357	624.0	0.1975	1791	124.30
NBO02	214	1.0	0.026	7129	7669	685.0	0.1978	3718	234.80
NBO03	229	1.0	0.026	7030	6988	654.0	0.1976	2854	188.84
NBO04	207	1.0	0.021	7114	6765	645.0	0.1972	2455	165.48
NBO05	236	1.0	0.021	7061	6723	643.0	0.1971	2448	165.53
NB200	209	1.0	0.026	7385	7012	655.0	0.1977	2533	167.28
NB201	246	1.0	0.028	7222	7640	683.0	0.1976	3584	226.53
NB202	234	1.0	0.030	7136	6347	621.9	0.1966	4086	226.44
NB203	203	1.0	0.026	7053	6736	642.0	0.1975	2474	166.72
NB204	201	1.0	0.024	7047	6733	642.5	0.1976	2476	167.05
NB205	217	1.0	0.024	7117	6828	645.0	0.1978	2540	169.65
NC200	211	1.0	0.025	7210	7134	661.0	0.1976	2880	188.67
NC201	242	1.0	0.026	6932	7491	677.0	0.1977	3663	234.06
NC202	222	1.0	0.025	7047	7461	676.0	0.1976	3506	224.59
NC203	202	1.0	0.023	7212	6842	648.0	0.1978	2466	165.11
NC204	238	1.0	0.029	7074	6789	643.5	0.1971	2529	169.47
NC205	220	1.0	0.025	7131	7594	682.0	0.1974	3610	229.22
NC300	212	1.0	0.022	7049	6709	642.0	0.1974	2440	165.08
NC301	237	1.0	0.026	7206	7197	663.6	0.1972	2974	193.87
NC302	231	1.0	0.023	7066	6251	619.0	0.1960	1775	124.28
NC303	247	1.0	0.022	7119	6286	621.0	0.1960	1772	123.77
NC304	205	1.0	0.025	6936	6646	638.0	0.1960	2464	167.24
NC305	208	1.0	0.027	7377	7277	667.0	0.1977	2915	188.91
NC400	239	1.0	0.029	7133	6837	645.8	0.1963	2537	169.43
NC401	248	1.0	0.027	7149	6828	646.0	0.1960	2508	167.77
NC402	200	1.0	0.026	7201	7141	661.0	0.1962	2899	189.73
NC403	234	1.0	0.030	7136	6347	621.9	0.1966	1841	127.54
NC404	228	1.0	0.026	7138	7099	659.0	0.1975	2903	190.53
NC405	216	1.0	0.028	7048	7843	692.0	0.1975	4045	252.33
NC600	235	1.0	0.023	7071	6740	643.0	0.1972	2462	166.06
NC601	210	1.0	0.026	7113	7119	660.0	0.1976	2956	193.76
NC602	226	1.0	0.027	7222	6634	636.8	0.1975	2160	146.61
NC603	232	1.0	0.026	7079	6772	643.7	0.1960	2499	167.95
NC604	241	1.0	0.026	7106	7359	671.0	0.1975	3302	212.88
NC605	219	1.0	0.023	7064	6740	643.0	0.1972	2469	166.53
NC405bb	230	1.0	0.028	7042	6750	642.0	0.1974	2505	168.45

Appendix IV

Station	Chan	Sensor	S/N	ADC #	Offset Val	μV/count Dif	V/m/s^2 Dif	A/m/s^2 Feedback	Comment
SPA0	BHZ	CMG-3T	T3H76	DD25-35	-903	1.7110	937.4	0.02422	
SPA0	BHN				-342	1.7033	1057.9	0.02572	
SPA0	BHE				-425	1.7138	1000.4	0.02571	
SPA1	BHZ	CMG-3V	V3310	DD26-36	-1049	1.7092	997.9	0.02297	Vertical only
SPA1	BHN				-222	1.6936			
SPA1	BHE				-1060	1.7103			
SPA2	BHZ	CMG-3V	V3309	DD27-37	-271	1.7014	989.3	0.02327	Vertical only
SPA2	BHN				-54	1.7100			
SPA2	BHE				346	1.7059			
SPA3	BHZ	CMG-3V	V3311	DD28-38	-338	1.6903	998.9	0.02322	Vertical only
SPA3	BHN				-863	1.7072			
SPA3	BHE				90	1.7040			
SPB1	BHZ	CMG-3T	T3J19	DD29-39	-541	1.7050	1000.3	0.02295	
SPB1	BHN				-585	1.7058	997.6	0.02541	
SPB1	BHE				-369	1.7000	1001.4	0.02448	
SPB2	BHZ	CMG-3T	T3J03	DD30-40	-346	1.6977	1003.6	0.02473	
SPB2	BHN				-732	1.7019	1009.6	0.02620	
SPB2	BHE				-89	1.7056	1024.0	0.02564	
SPB3	BHZ	CMG-3T	T3J56	DD31-41	-493	1.7052	996.8	0.02286	
SPB3	BHN				-868	1.7051	1006.3	0.02463	
SPB3	BHE				-731	1.7074	1003.4	0.02508	
SPB4	BHZ	CMG-3T	T3H65	DD32-42	-378	1.7030	999.7	0.02449	
SPB4	BHN				-904	1.7037	1005.2	0.02525	
SPB4	BHE				-647	1.6902	999.8	0.02509	
SPB5	BHZ	CMG-3T	T3J67	DD33-43	50	1.7135	1000.8	0.02306	
SPB5	BHN				-86	1.6982	1003.2	0.02477	
SPB5	BHE				-498	1.7010	994.9	0.02498	
SPX1	BHZ	CMG-3T		DD34-50	-454	1.7038			Spare digitiser
SPX1	BHN				-292	1.7007			
SPX1	BHE				-712	1.7046			
SPX2	BHZ	CMG-3T	T3J37	DD35-51	-939	1.7020	1001.6	0.02288	Spare digitiser & sensor
SPX2	BHN				-447	1.7077	999.6	0.02481	
SPX2	BHE				-375	1.7028	993.8	0.02497	
SPX3	BHZ	CMG-3T		DD36-52	-117	1.7025			Spare digitiser
SPX3	BHN				-251	1.7048			
SPX3	BHE				-904	1.7066			
SPB2	BHZ	CMG-3T	T3J37	DD30-40	-346	1.6977	1001.6	0.02288	From 2005-229:11
SPB2	BHN				-732	1.7019	999.6	0.02481	
SPB2	BHE				-89	1.7056	993.8	0.02497	

NOTE: Acceleration output is differential, *e.g.*, 2 x 937.4

APPENDIX V

Old Hagfors array channel information
(according to GSETT3, 1995; Lund and Lennartsson, 2004)

Site code	Chan code	Sampling rate	Channel sensitivity	Sensor
HFSA1	sz	40 sps	0.02655 nm/count @ 1 s	S-13
HFSB1	sz	40 sps	0.02623 nm/count @ 1 s	20171A
HFSB2	sz	40 sps	0.03068 nm/count @ 1 s	20171A
HFSB3	sz	40 sps	0.02866 nm/count @ 1 s	S-13
HFSB4	sz	40 sps	0.02929 nm/count @ 1 s	S-13
HFSB5	sz	40 sps	0.02394 nm/count @ 1 s	S-13
HFSC1	sz	40 sps	0.02561 nm/count @ 1 s	20171A
HFSC2	sz	40 sps	0.02500 nm/count @ 1 s	S-13
HFSC2	sn	40 sps	0.02500 nm/count @ 1 s	S-13
HFSC2	se	40 sps	0.02500 nm/count @ 1 s	S-13
HFSC2	lz	40 sps	0.34544 nm/count @ 20 s	7505A
HFSC2	ln	40 sps	0.32524 nm/count @ 20 s	8700C
HFSC2	le	40 sps	0.35787 nm/count @ 20 s	8700C
HFSC2	bz	40 sps	0.00600 nm/count @ 1 s	STS-1V

Current Hagfors array channel & instrumentation information

Site code	Chan code	Sampling rate	Sensor #	Digitizer #
HFA0	sz	80 sps	GS-13 553	HRD-24 173
HFA1	sz	80 sps	GS-13 559	HRD-24 177
HFA2	sz	80 sps	GS-13 563	HRD-24 172
HFA3	sz	80 sps	GS-13 555	HRD-24 176
HFB1	sz	80 sps	GS-13 564	HRD-24 178
HFB2	sz	80 sps	GS-13 556	HRD-24 174
HFB3	sz	80 sps	GS-13 561	HRD-24 180
HFB4	sz	80 sps	GS-13 560	HRD-24 175
HFB5	sz	80 sps	GS-13 554	HRD-24 181
HFC2	bz, bn, be	80 sps	STS-2 110042	HRD-24 183
HFC2	bz, bn, be	80 sps	STS-2 110042	Trident 709, since 2012/03/02
reserves				
-			GS13 557	HRD-24 179
-			GS13 562	HRD-24 182