NORSAR

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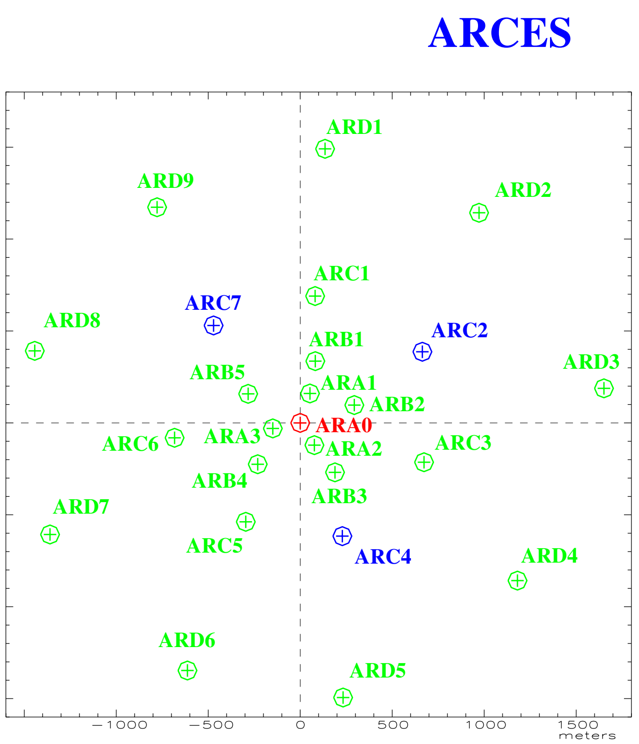
6.4 Continued overview of NORSAR system responses: the NORES and ARCES arrays

6.4.1 Introduction

At the early to mid 1980s, NORSAR began experimenting with the concept of a small-aperture seismic array configuration that would allow detection and location of seismic events at regional distances. This work initiated as a series of test deployments around NORSAR array site NC602 (for details, see Mykkeltveit et al., 1983) and developed into the Norwegian Regional Experimental Seismic System, what is known as the NORES (NORESS) array, whose operation commenced officially on 3rd June 1985 and terminated in July 2002. The array consists of 25 elements, distributed on 4 concentric rings, with one element in the center, and spreads over a diameter of 3 km. During summer and fall of 1987, a second regional array, almost identical to NORES in terms of geometry, instrumentation and data output, was installed in the vicinity of the town of Karasjok, in Finnmark, northern Norway. This is the ARCES (ARCESS) array (ARCtic Experimental Seismic System), which is part of the International Monitoring System for the CTBT (certified in November 2001 under the primary station code PS28). The geometry of ARCES is shown in Fig. 6.4.1.



Site	X east	Y north	Z height
ARA0_sz	0	0	403
ARA1_sz	53	160	411
ARA2_sz	77	−121	392
ARA3_sz	−149	−30	402
ARB1_sz	82	336	414
ARB2_sz	294	97	397
ARB3_sz	189	−269	376
ARB4_sz	−231	−225	378
ARB5_sz	−283	158	405
ARC1_sz	81	690	381
ARC2_sz	664	387	395
ARC3_sz	673	−214	376
ARC4_sz	229	−616	377
ARC5_sz	−296	−538	374
ARC6_sz	−683	−81	395
ARC7_sz	−471	530	362
ARD1_sz	135	1491	395
ARD2_sz	972	1143	366
ARD3_sz	1651	188	331
ARD4_sz	1181	−858	371
ARD5_sz	233	−1494	351
ARD6_sz	−613	−1347	413
ARD7_sz	−1360	−607	413
ARD8_sz	−1443	392	368
ARD9_sz	−778	1173	359

Fig. 6.4.1. Geometry of the ARCES arrays. The NORES array has an identical geometry.

The instrument responses of these two systems will be presented in the following sections, covering their entire operation interval, from installation to present day status. Presentation and methodology follow the scheme initiated in Pirli and Schweitzer (2008) and is part of the ongoing effort to recalculate, organize and document all NORSAR system responses.

6.4.2 NORES array configurations

Although official opening of the NORES array did not take place before summer 1985, the array was equipped with standard instrumentation since late 1984, after the extended test period during which it operated as part of the NORSAR array. 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.

Standard NORES instrumentation is based on GS-13 short-period and KS36000 broadband sensors and Sandia 'Blue Box' digitizers. The central element and three sites on the C-ring (NRA0, NRC2, NRC4, NRC7) are equipped with 3C seismometers. A variation of the short-period channel that existed during a short time interval (September 1985 – September 1986) 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. No further modifications were made to the instrumentation of the array. The installation was struck by lightning in 2002 and has been out of operation since then.

Table 6.4.1. The different instrument configurations of the NORES array.

Time	Installation Name	Components	Calib [nm/count]	Calper [s]
1984-2002	Standard_SP (NORESSP1, NORESSP2, NORESSP3)	GS-13 Couplings Box Seismometer pre-amplifier Short-period filter Distributed filter Sandia 'Blue Box' digitizer	0.0068649	1.00
1985-1986	S-3_SP_variation (NORESSP4, NORESSP5, NORESSP6)	S-3 Couplings Box Seismometer pre-amplifier Short-period filter Distributed filter Sandia 'Blue Box' digitizer	0.0068649	1.00
1984-2002	Standard_IP (NORESIP1, NORESIP2, NORESIP3)	KS36000 Couplings Box Intermediate period bandpass filter Distributed filter Interm. period spectral shaping filter Sandia 'Blue Box' digitizer	0.077364	1.00
1984-2002	Standard_LP (NORESLP1, NORESLP2, NORESLP3)	KS36000 Couplings Box Long period high pass filter Long period bandpass filter Distributed filter Long period spectral shaping filter Sandia 'Blue Box' digitizer	0.13936	25.00

The above mentioned instrumentations for which different instrument responses needed to be calculated are presented in Table 6.4.1. Each case is mentioned together with information about the time interval it could be met, the GSE response file Respid (in parenthesis), which is an identifier for each different calculated response, and the corresponding channel sensitivity (Calib in nm/count) and calibration period (Calper in s).

As shown above, the two different NORES short-period configurations involve a short-period seismometer (Geotech GS-13 or S-3), a Sandia digitizer referred here as ‘Blue Box’ and an interface of pre-amplifier and filters between them. The response of the GS-13 seismometer is described by 2 poles and 2 zeros that can be obtained by the standard seimometer formula (Geotech Instruments, 1999):

$$p_{1,2} = \lambda_0\omega_0 \pm j\omega_0\sqrt{1-\lambda_0^2} ,$$

where $\lambda_0 = 0.75$ and $\omega_0 = 6.283$ rad/s, both of them being nominal values. The gain of the seismometer, normalized at 100 Hz will be equal to 2200 V/m/s. However, all the individual amplifier and filter stages between the seismometer and the digitizer contribute to the overall response of the GS-13, which is expressed by the formula (Durham, 1984b):

$$H_{spv}(s) = H_S(s) \cdot H_{IF}(s) \cdot H_{PA}(s) \cdot H_{SP}(s) \cdot H_{DF}(s) ,$$

expressed in V/m/s, where $H_S(s)$ the response of the seismometer, $H_{IF}(s)$ the response of the seismometer-amplifier interface, $H_{PA}(s)$ the response of the pre-amplifier, $H_{SP}(s)$ the response of the short period filter and $H_{DF}(s)$ the response of the distributed filter. The equations providing each individual response stage and their details can be found in Durham (1984b) and Breding (1986), as well as in the relevant to the NORES system response NORSAR documentation. 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.

The ‘Blue Box’ digitizer, manufactured by Sandia, is a 16 bit gain ranged digitizer with a sensitivity of 100000 count/V.

NORES site E0, which is collocated with site A0, the central array element, hosts a Kinemetrics KS36000-04A broadband borehole seismometer. Two different 3-component channels, a long-period channel (lz, ln, le) and an intermediate-period channel (iz, in, ie), are outputed at this site. For each one of these channels, the system consists of the components (Durham, 1984a) listed in Table 6.4.1 under the names Standard_LP and Standard_IP respectively. The concept of interfacing the seismometer to the digitizer is the same as in the case of the short-period channels, with series of filters that contribute to the overall seismometer response. Individual stage transfer functions can be found in Durham (1984a) and the NORSAR responses documentation.

The displacement response for the different NORES channels is depicted in Fig. 6.4.2. Displacement amplitude is expressed in count/nm and phase in degrees. The short-period (SP) channel response (NORESSP) 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.

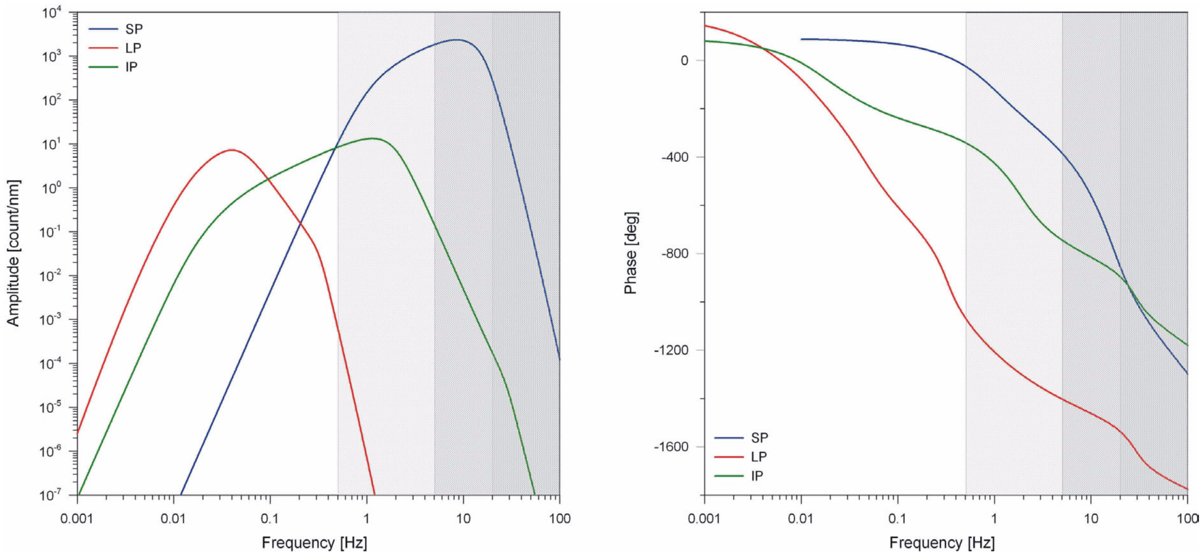


Fig. 6.4.2. Displacement amplitude and phase response for the NORES short period (NORESSP), intermediate period (NORESIP) and long period (NORESLP) configurations. The shaded areas represent the range beyond the Nyquist frequency (20 Hz for the short-period, 5 Hz for the intermediate period and 0.5 Hz for the long period channels).

6.4.3 ARCES array configurations

As already mentioned above, the ARCES array was designed as a duplicate of NORES, both in terms of geometry and instrumentation. So, the status of ARCES responses for the time interval 1987 – 1999 is the same as that described for NORES in the previous section. An extensive refurbishment of the array took place in September 1999, resulting in the replacement of all Sandia digitizers with Nanometrics HRD24 digitizers and the removal of the KS36000 seismometer and their replacement with a Güralp CMG-3T broadband instrument. From October 2003 to July 2004, a high-frequency 3-component channel operated at site ARE0, with a REFTEK 130-01 digitizer connected to the CMG-3T seismometer. Finally, since March 2008, an additional broadband 3-component channel is operating at site ARE0 with a Güralp DM24 digitizer connected to the CMG-3T sensor.

The different ARCES configurations for which separate instrument responses need to be calculated are listed in Table 6.4.2, with information about the time interval they could be met, the GSE response file Respid (in parenthesis), and the corresponding channel sensitivity (Calib in nm/count) and calibration period (Calper in s).

For the initial (Standard_SP/IP/LP) ARCES channels, system response characteristics are identical to those of standard NORES and have been described in the previous section (6.4.2).

Table 6.4.2. The different instrument configurations of the ARCES array.

Time	Installation Name	Components	Calib [nm/ count]	Calper [s]
1987-1999	Standard_SP (ARCESSP1, ARCESSP2, ARCESSP3)	GS-13 Couplings Box Seismometer pre-amplifier Short-period filter Distributed filter Sandia 'Blue Box' digitizer	0.006838	1.00
1987-1999	Standard_IP (ARCESIP1, ARCESIP2, ARCESIP3)	KS36000 Couplings Box Intermediate period bandpass filter Distributed filter Interm. period spectral shaping filter Sandia 'Blue Box' digitizer	0.077313	1.00
1987-1999	Standard_LP (ARCESLP1, ARCESLP2, ARCESLP3)	KS36000 Couplings Box Long period high pass filter Long period bandpass filter Distributed filter Long period spectral shaping filter Sandia 'Blue Box' digitizer	0.139260	25.00
1999-…	Current_SP (ARCESSP4, ARCESSP5, ARCESSP6)	GS-13 HRD24 digitizer	0.037776	1.00
1999-…	Current_BB (ARCESBB1, ARCESBB2, ARCESBB3)	CMG-3T HRD24 digitizer	0.005065	1.00
2003-2004	REFTEK_HH (ARCESHH1, ARCESHH2, ARCESHH3)	CMG-3T DAS 130-01 digitizer	0.000508	1.00
2008-…	Guralp_EH (ARCESEH1, ARCESEH2, ARCESEH3)	CMG-3 DM24 digitizer	4.019100	1.00

The current short-period configuration consists of a GS-13 seismometer and a Nanometrics HRD24 digitizer. The response of the sensor is the same as described in section 6.4.2, but no special interface is required in this case for its connection to the digitizer. The response of the digitizer consists of the following components (Nanometrics communication):

- An analogue lowpass filter with 3 poles and no zeros

- A FIR filter with 34 coeffiecients, decimating by a factor of 5 from an initial input sample rate of 30 kHz
- A FIR filter with 30 coefficients, decimating by a factor of 3
- A FIR filter with 118 coeffiecients, decimating by a factor of 2
- A FIR filter with 36 coefficients, decimating by a factor of 5
- A FIR filter with 256 coefficients, decimating by a factor of 5, down to the desired sample rate of 40 sps, and
- An IIR filter with one pole and one zero

The HRD24 is a 24-bit digitizer with a sensitivity of 6303183.11 count/V.

The same digitizer is connected, in the case of the broadband channels, to a Güralp CMG-3T sensor. The response of the seismometer can be calculated from its poles and zeros, sensitivity and normalization factor provided by the manufacturer in instrument specific calibration sheets.

As mentioned earlier (see also Table 6.4.2), there are two variations of the CMG-3T configuration, one with a REFTEK DAS 130-01 digitizer and one with a Güralp DM24 digitizer.

The REFTEK DAS 130-01 is a 24-bit output word digitizer that employs the Crystal Semiconductor CS5372/5322 chipset. This is the combination of an analog modulator and a series of digital filters that decimate from the frequency of the A/D input clock down to a desired sample rate. However, for some recording sample rates, a combination of CS5322 FIR filters and additional CPU firmware filtering has to take place. The particular ARCES data are recorded with a sample rate of 100 sps, which is achieved by the following combination of filters (REFTEK, 2008):

- CS5322 FIR filter A with 34 coefficients, decimating by a factor of 8 from an input rate of 1024 kHz
- CS5322 FIR filter B with 14 coefficients, decimating by a factor of 2
- CS5322 FIR filter B with 14 coefficients, decimating by a factor of 2
- CS5322 FIR filter B with 14 coefficients, decimating by a factor of 2
- CS5322 FIR filter B with 14 coefficients, decimating by a factor of 2
- CS5322 FIR filter B with 14 coefficients, decimating by a factor of 2
- CS5322 FIR filter C with 102 coefficients, decimating by a factor of 2, down to 200 Hz, and
- CPU firmware filter #3, decimating by a factor of 2, to the desired sample rate of 100 Hz

The sensitivity of the instrument is 62914560 count/V.

Finally, the Güralp DM24 is a 24-bit digitizer, which employs a combination of the Crystal Semiconductor CS5376 chip and internal digital filters to produce the desired data recording sample rate (see Güralp Systems website for product documentation). The filter sequence employed in the case of ARCES to obtain 100 Hz data is the following:

- CS5376 FIR filter Stage 1, Sinc 1, with 36 coefficients, decimating by a factor of 8 from an input rate of 512 kHz
- CS5376 FIR filter Stage 3, Sinc 2, with 6 coefficients, decimating by a factor of 2

- CS5376 FIR filter Stage 4, Sinc 2, with 8 coefficients, decimating by a factor of 2
- CS5376 FIR filter Stage 5, FIR 1, with 48 coefficients, decimating by a factor of 4
- CS5376 FIR filter Stage 5, FIR 2, with 126 coefficients, decimating by a factor of 2
- DM24 FIR Stage 1, SWA-D24-3D08, with 502 coefficients, decimating by a factor of 5, and
- DM24 FIR Stage 2, SWA-D24-3D07, with 502 coefficients, decimating by a factor of 4 to the desired rate of 100 sps

The sensitivity of the digitizer is 312207.306 count/V.

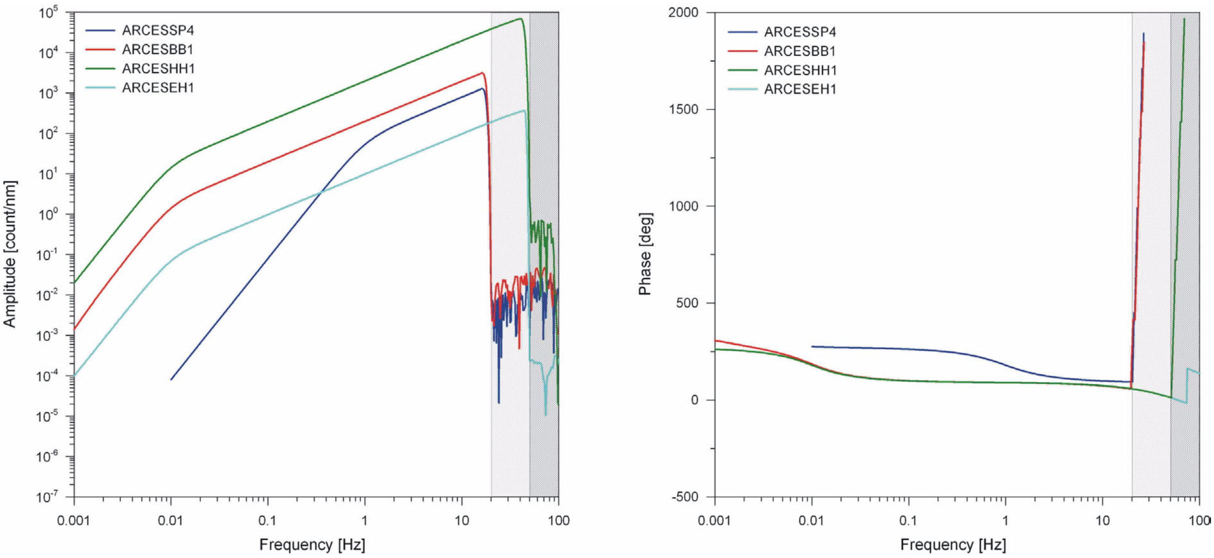


Fig. 6.4.3. Displacement amplitude and phase response of the ARCES short period and broadband installations. The current short period (ARCESSP4), the current broadband (ARCESBB1), the REFTEK high-frequency variation (ARCESHH1) and the Güralp high-frequency variation (ARCESEH1) configurations are depicted. The shaded areas represent the range beyond the Nyquist frequency (20 Hz for short period and broadband and 50 Hz for the high-frequency configurations).

The displacement response for the different ARCES channels is depicted in Fig. 6.4.3. Displacement amplitude is expressed in count/nm and phase in degrees. The initial ARCES configuration response curves are not included in the plot, since they are the same as NORES and are depicted in Fig. 6.4.2. The current short-period (SP) channel response (ARCESSP4) is denoted with a blue line, the current broadband response (ARCESBB1) with a red line, the broadband (high-frequency) REFTEK variation response (ARCESHH1) with a green line and the broadband (high-frequency) Güralp variation (ARCESEH1) with a cyan line. Moreover, shading is used to denote the range beyond the Nyquist frequency, which is equal to 20 Hz for the short-period and broadband channels and 50 Hz for the two high-frequency channels.

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