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Frode Ringdal (ed.)

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

6.3.1 Introduction

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

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

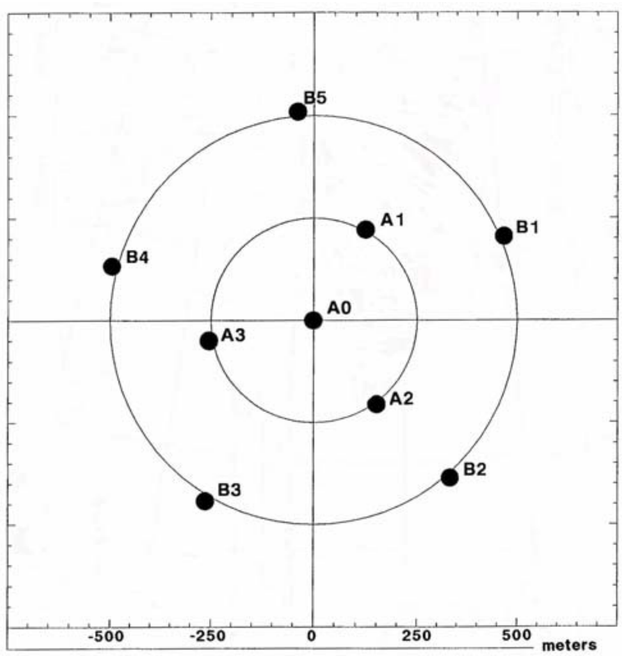

Fig. 6.3.1. Geometry of the Spitsbergen small-aperture array (from Mykkeltveit et al., 1992). The Apatity array has an almost identical geometry.

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

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

6.3.2 Spitsbergen (SPITS) array configurations

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

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

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

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

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

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

* Indicative value

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

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

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

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

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

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

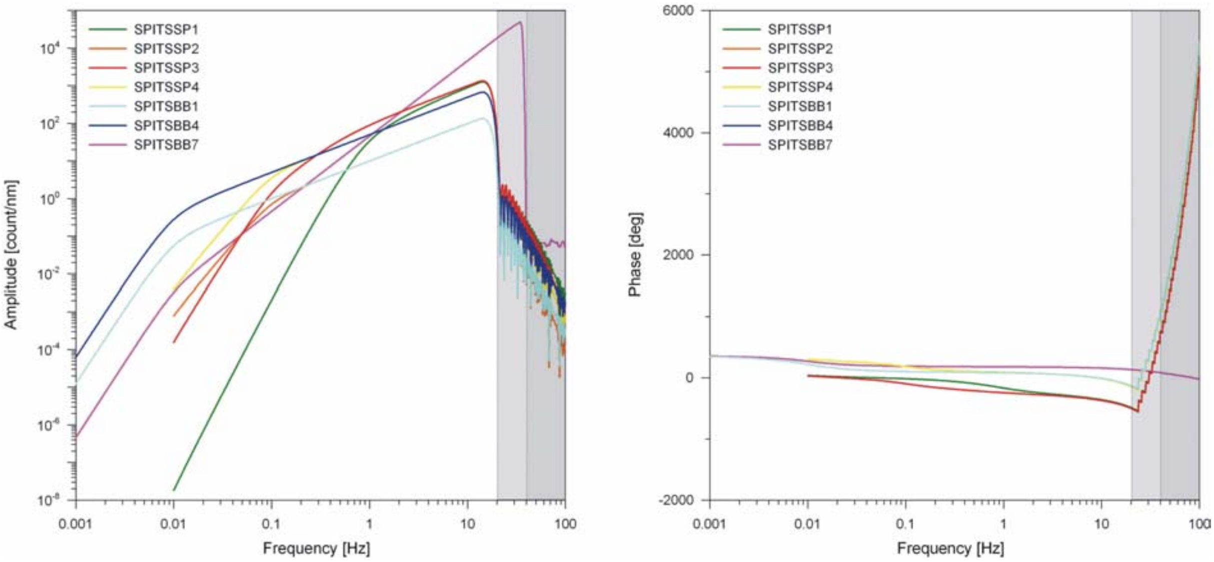

Fig. 6.3.2. Displacement amplitude and phase response for the short-period (SPITSSP1, SPITSSP2, SPITSSP3, SPITSSP4) and broadband (SPITSBB1, SPITSBB4, SPITSBB7) configurations of the SPITS array. The shaded areas represent the range beyond the Nyquist frequency.

6.3.3 Apatity array configurations

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

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

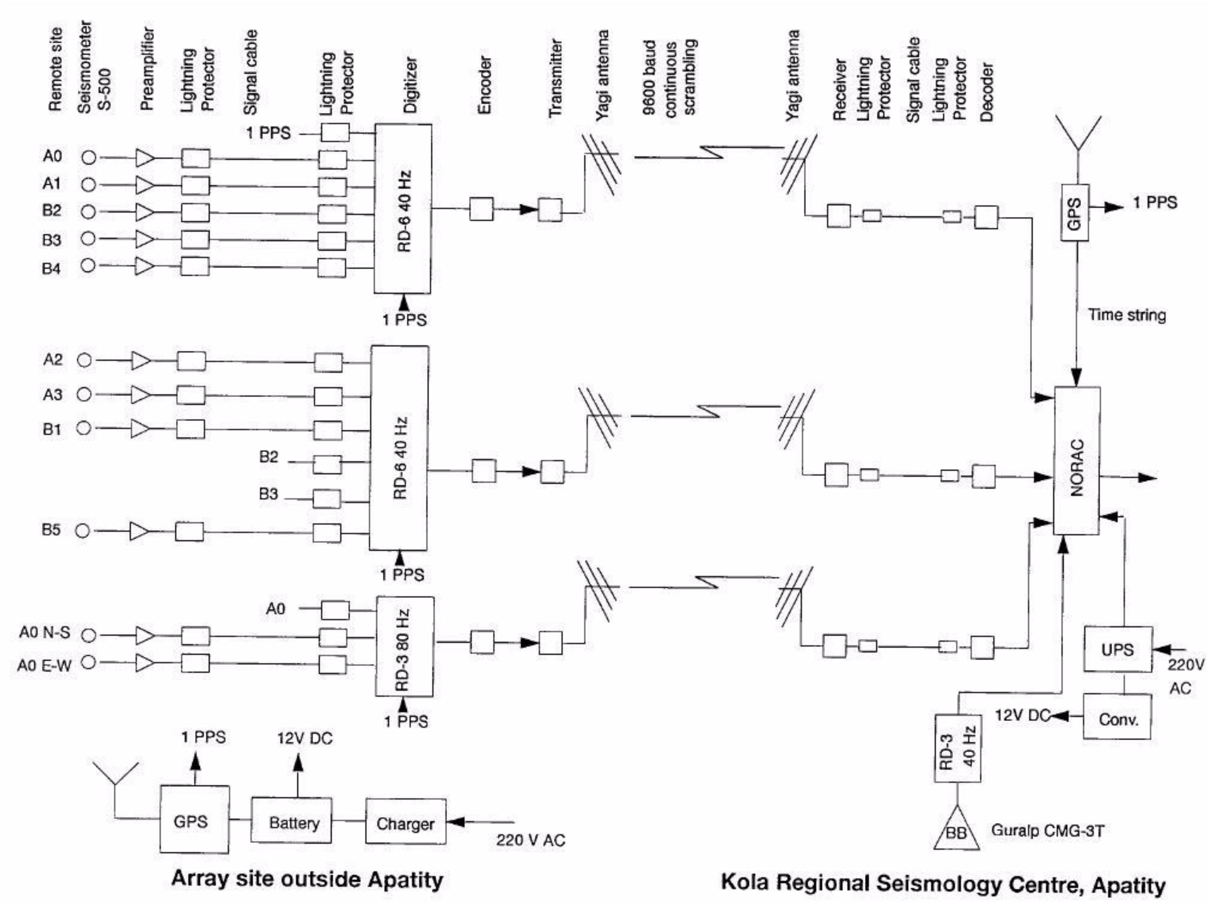

Fig. 6.3.3. Data flow chart for the array and broadband 3-component station in Apatity (from Mykkeltveit et al., 1992). Redundant data acquisition (channels B2 and B3) ensures that data are received even in the case of digitizer or radio channel failure.

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

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

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

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

* Indicative value

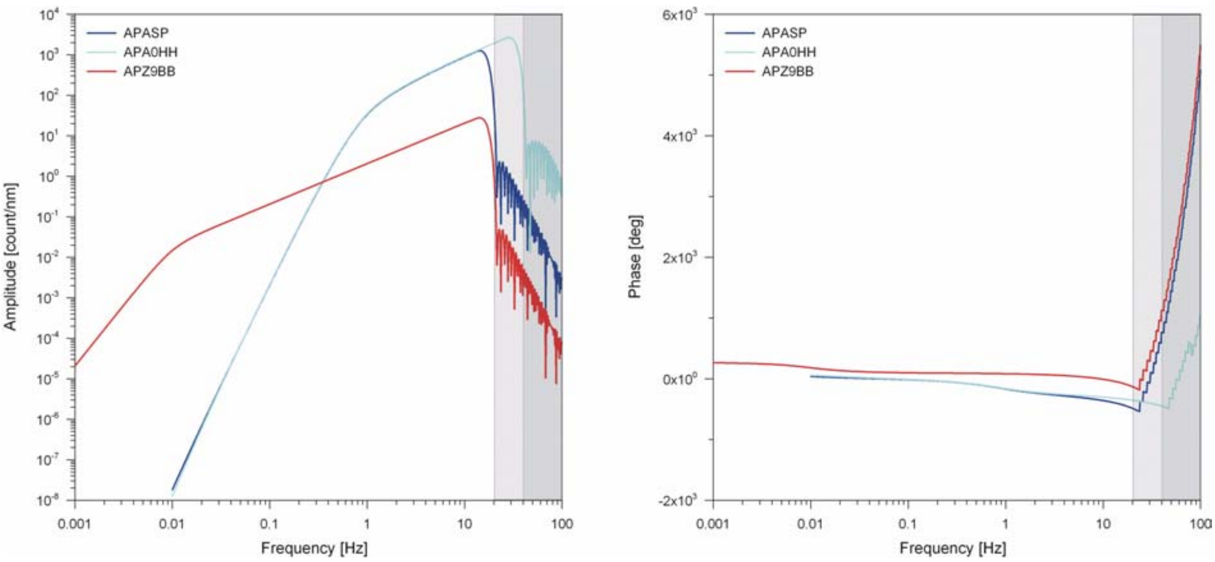

Fig. 6.3.4. Displacement amplitude (left) and phase (right) response for the Apatity array and single 3-component station APZ9 configurations. The short-period array channels (APASP) are noted in blue, the high-frequency APA0 site channel (APA0HH) in cyan and the APZ9 broadband station (APZ9BB) in red.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

6.3.4 Jan Mayen (JMIC) station configurations

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

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

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

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

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

* Indicative value

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

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

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

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

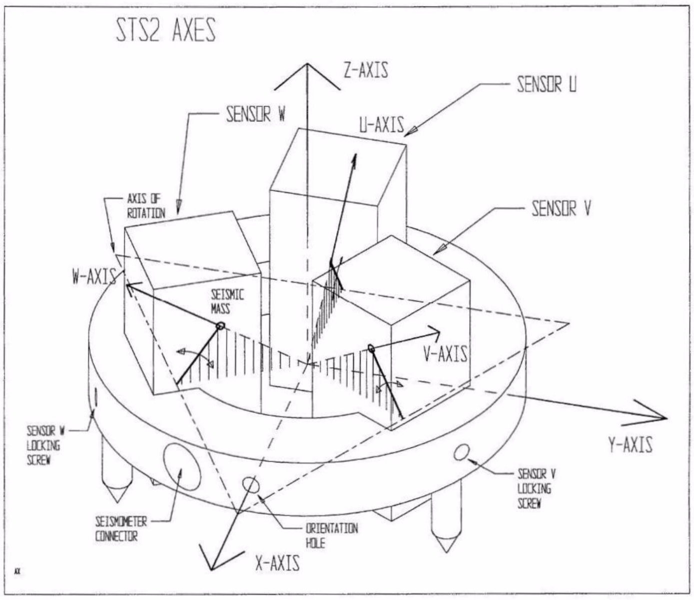

Fig. 6.3.5. A schematic representation of the axes positioning of the STS-2 seismometer (Streckeisen, 2003).

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

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

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

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

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

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

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

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

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

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

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

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

High-frequency end

4 zeros [Hz]:

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

9 poles [Hz]

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

Low-frequency end

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

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

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

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

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

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

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

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

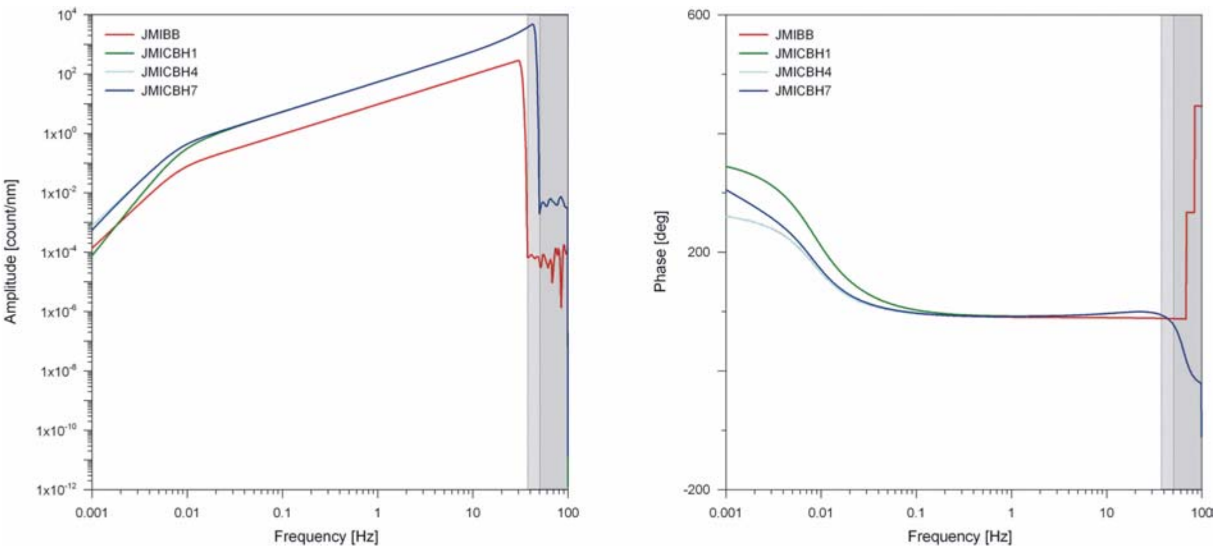

Fig. 6.3.6. Displacement amplitude (left) and phase (right) response for the JMI and JMIC 3-component broadband station configurations. The JMI response (JMIBB) is noted in red, the 10mHz IIR filter version of the JMIC station (JMICBH1) in green, the 1mHz IIR filter version of JMIC (JMICBH7) in blue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

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

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

Myrto Pirli
Johannes Schweitzer

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