NORSAR

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6.4 Overview of NORSAR system response

6.4.1 Introduction

Since the end of the 1960s, when it was first installed, to the current installation, the NORSAR array has been repeatedly reconfigured, once by reducing its size and numerous times by modifying the instrumentation. Consequently, the instrument response of the array stations has changed many times during the 40 years of its operation. However, the detailed knowledge of a seismographic system instrument response is critical for the correct interpretation of its recordings, since it affects both the amplitude and the phase of the recorded waveforms.

An attempt is under way to recalculate and organize all NORSAR system instrument responses, from the time of the first installation to the present. All sources of information are being catalogued and archived. Furthermore, detailed documentation is being compiled, describing the methodology followed to obtain the necessary information, the calculation of the responses, as well as more practical issues, such as organizing and storing the results for future usage. Therefore, no information such as individual instrument poles and zeroes, serial numbers, sensitivity values, etc. are provided here, the reader being referred to the relevant NORSAR internal publication.

6.4.2 NORSAR array configurations

A brief history of the development of the NORSAR array is necessary in order to catalogue the different instrumentations employed since the first installation of the array. This took place in 1968 and involved 22 subarrays (Fig. 6.4.1), comprising as a total 132 short-period and 22 long-period instruments.

In the short-period vaults (SPVs), the sensors (Hall-Sears HS-10-1 vertical seismometers) were connected to an amplifier (Texas Instruments RA-5) and via a several kilometer long cable to the Central Terminal Vault (CTV), where the SLEM (Short and Long Period Electronic Module by Philco-Ford) unit was residing. The main components of the latter, relevant to instrument response calculations, were the Line Terminating Amplifier (LTA), which included two analog filters, a high-pass RC filter and a low-pass Chebyshev filter, and the SLEM A/D converter, a gain-ranged digitizer of 14-bit resolution. The standard instrumentation chain was different for the long-period instruments (Geotech 7505B vertical and 8700C horizontal seismometers). The sensors were connected to an Ithaco amplifier, which was directly connected to the LTA, without the latter employing any low-pass filter.

Several minor modifications, mainly concerning the LTA filter cards were made until 1976, when a large number of sites from the original configuration were shut down. 7 subarrays remained in operation (Fig. 6.4.1), each one of them consisting of six elements. These modifications resulted in a series of ‘alternate versions’ of the standard NORSAR instrumentation and are tabulated, together with the instrumentations to be discussed next, in Table 6.4.1. Some more drastic modifications involving test configurations with S-13 or S-500 triaxial seismometers, took place in the late 1970s.

From 1979 on, a small-aperture seismic array (NORESS) started being tested on subarray 06C of the NORSAR array. The initial configuration employed 6 sites, including NORSAR site 06C02 under the name NRA0, whereas since the end of October 1980 a ‘new’ NORESS consisted of 12 sites equipped with vertical sensors (Mykkeltveit and Ringdal, 1980). The final

NORESS installation came in operation in 1984. Employed instrumentation during the test phase was standard NORSAR however, the NORESS tests required changes in data channel assignment for the NORSAR array (Nilsen, 1980).

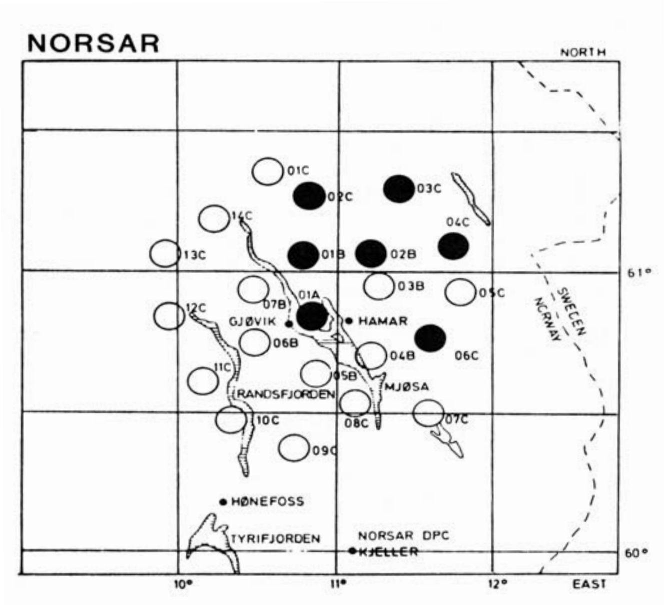

Fig. 6.4.1. Location and naming of the NORSAR subarrays. Still operating subarrays are noted with filled circles and closed down subarrays with open circles (Ringdal, 1981).

The 1976 instrumentation continued until the end of 1993, beginning of 1994, when the NORSAR Backup System came in operation. It employed 7 Nanometrics RD6 (6-channel) digitizers to backup the entire system, after extensive problems with the communications system. The rest of the equipment remained unmodified.

At the end of 1994, the RD6 were exchanged with Science Horizons AIM24 digitizers. A general refurbishment took place in 1995, when the array became equipped with the instrumentation it's carrying today. A Geotech 20171A short-period sensor is installed at each site, while each subarray also has a 3-component, broadband KS54000 sensor. Finally, the broadband instrument installed at site 06C02 was replaced in 2000 with a broadband Güralp CMG-3T seismometer, in order to acquire CTBT certification for the NORSAR array as IMS primary station PS27.

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, the corresponding channel sensitivity (Calib in nm/count) and the calibration period (Calper in s). It should be noted that a large number of exchanges between the different variations of the standard configuration took place in numerous channels, and that precise documentation of these modifications with respect to array site and time interval is outside the scope of this contribution. Furthermore, NORESS test configurations are not specifically mentioned here, unless the instrumentation itself differs from listed NORSAR configurations.

Table 6.4.1. The different instrument configurations of the NORSAR array from its installation to the present. Calib values are in nm/count and Calper in seconds.

Time	Installation Name	Components	Calib	Calper
1968-1994	Standard_SP (SPSLEM1)	HS-10-1 RA-5 LTA 4.75 Hz Chebyshev low-pass SLEM	0.042722	1.00
1977-1994	SP_var1 (SPSLEM2)	HS-10-1 RA-5 LTA 8.00 Hz Chebyshev low-pass SLEM	0.042722	1.00
1986	SP_var2 (SPSLEM6)	HS-10-1 RA-5 LTA Unknown filter SLEM	0.042722	1.00
1986-1989	SP_var3, SVZ, NRA0 (SPSLEM5)	HS-10-1 RA-5 LTA 'prototype' Butterworth bandpass SLEM	0.042722	1.00
1968-1994	SP_var4 (SPSLEM3)	HS-10-1 RA-5 LTA no low-pass SLEM	0.042722	1.00
1976-1994	SP_var5, attenuat. SLZ (SPSLEM4)	HS-10-1 RA-5, attenuated -30 db LTA 4.75 Hz Chebyshev low-pass SLEM	1.351000	1.00
1976, 1978, 1980	SP_var7, S-13 (SPSLEM7)	S-13 RA-5 LTA 4.75 Hz Chebyshev low-pass SLEM	0.042722	1.00
1978	SP_var8, S-500 (SPSLEM8)	S-500 RA-5 LTA 8.00 Hz Chebyshev low-pass SLEM	0.099500	1.00

1968-1994	Standard_LP (LPSLEM1, LPSLEM2)	7505B/8700C Ithaco LTA SLEM	2.4700	25.0
1975-1976	LP_var1, attenuat. (LPSLEM3, LPSLEM4)	7505B/8700C Ithaco, attenuated -30 db LTA SLEM	2.4700	25.00
1994	NB2_SP (RDSP1)	HS-10-1 RA-5 LTA no low-pass RD6	4.2717e-04	1.00
1994	NB2_SP, attenuat. (RDSP2)	HS-10-1 RA-5, attenuated -30 db LTA no low-pass RD6	1.3508e-02	1.00
1994	NB2_LP (RDLP1)	7505B/8700C Ithaco LTA RD6, auxiliary SOH channel	0.95	25.0
1994-1995	old_AIM_SP_CTV (AIM1)	HS-10-1 RA-5 LTA AIM24-1 in CTV, gain 1x	1.669e-04	1.00
1994-1995	old_AIM_SP_SPV 06C sites (AIM2)	HS-10-1 AIM24-1 in SPV, gain 100x	0.006529	1.00
1994-1995	old_AIM_SP_CTV attenuated (AIM3)	HS-10-1 RA-5, attenuated -30 db LTA AIM24-1, gain 1x	0.0052773	1.00
1995	old_AIM_LP (AIM4, AIM5)	7505B/8700C RA-5 LTA AIM24-3BB	0.01543	1.00
1995-…	current_SP (AIM0SP)	20171A Brick AIM24-1	0.006430*	1.00
1995-…	current_BB (AIM0BB)	KS54000 AIM24-3BB	0.019325	1.00
2000-…	current_BBG (AIM0BBG)	CMG-3T AIM24-3BB	0.12009*	1.00

* Indicative value. The sensitivity is site specific.

The Calib values presented in Table 6.4.1 can all be considered as ‘nominal’ channel sensitivity values, except for the cases marked with an asterisk, where the values are indicative. As will be explained in further detail later, for all configurations prior to 1995, the whole system was being tuned to a predetermined sensitivity value, by adjusting the voltage at the output of the amplifier components. This approach is not followed in the current installation, where each channel has an own sensitivity value.

There have also existed some experimental configurations, from which no data are available today and thus these are not mentioned in Table 6.4.1. Such cases are for instance the NORSAR short-period analog station and the broadband analog (KIRNOS) station (e.g. Bungum et al., 1974; Dahle, 1975).

In the following section, a brief description will be made of the methodology applied to calculate the responses of the 20 different configurations listed in Table 6.4.1.

6.4.3 Methodology

The approach to NORSAR system response calculation initially involved the validation of all information necessary for the calculations. This meant gathering all available information, either in the form of published material, instrumentation manuals, datasheets, etc. or derived from related macros and subroutines or information obtained directly from NORSAR staff. According to this information, a ‘history’ of modifications in array development was compiled and used as a guide for the identification and categorization of the different cases for which a new response had to be determined, similar to the listing of Table 6.4.1.

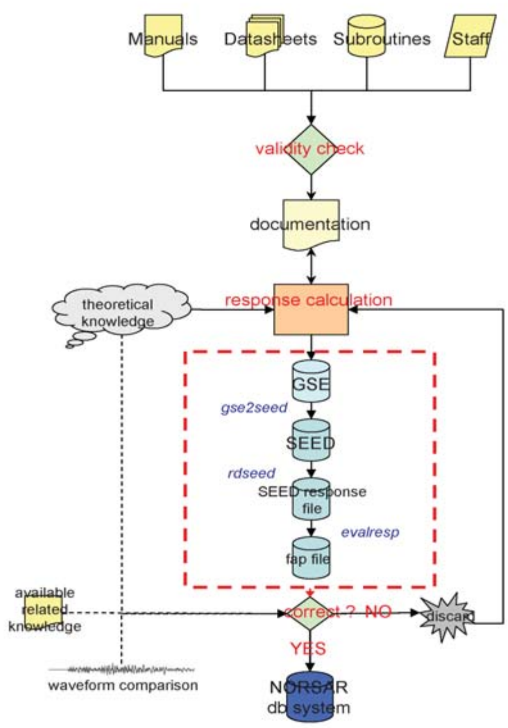

Fig. 6.4.2. Flowchart describing the NORSAR systems instrument response calculation procedure followed in this study.

The responses were 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. SEED response files and corresponding fap tables (frequency-amplitude-phase triplets) were constructed from the GSE files and the validity of the results was 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 responses. Finally, validated calib and calper values were introduced in the NORSAR db system. A schematic description of the methodology mentioned above is provided in the flowchart of Fig. 6.4.2.

6.4.4 Results

For all NORSAR configurations until the refurbishment of the array in 1995, a common instrument sensitivity for all channels was ensured by constantly tuning the system to a predetermined value. For the NORSAR short-period channels, this value was set to 0.0427 nm/qu +/-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). Similarly, such ‘nominal’ channel sensitivity values exist for the long-period channels, as well as the configurations involving the combination of HS-10-1 and long-period sensors with RD6 and AIM24 digitizers (see Table 6.4.1, field Calib). The task was achieved by measuring and appropriately adjusting the circuits in the amplifiers that were part of the array configuration. The amount of adjustment varies significantly for each channel, since a rather wide spread is observed in individual instruments parameter values (NORSAR, 1969a,b; Johansen, 1970; Dalland, 1971; Steinert and Nilsen, 1973). It is noteworthy that observed variations in seismometer damping ratios and natural frequencies were so large, that is was deemed necessary to review and modify tolerance limits to a wider acceptable value range (Steinert and Nilsen, 1972).

In this respect, the different NORSAR instrumentations were divided into two main groups. The one included cases for which a ‘generic’ response could be used for all array elements, since the channel sensitivity had been adjusted to be the same in all cases and the instrument-specific group, which includes cases where a different response is calculated for each array site. Thus, the first group includes almost all configurations prior to the NORSAR 1995 refurbishment, while the second group includes the current instrumentations.

Regarding the first group of responses, recalculation was a demanding task, mostly due to the fact that a lot of the original information sources are not available any longer and the existing ones were not archived in an organized way. As obvious from Table 6.4.1, a larger number of configurations existed, where the system was being tuned to the same channel sensitivity value of 0.0427 nm/count. This essentially ascertains that all sites have comparable amplitudes, but leaves open the question of different phase responses, in the case that different filters were employed (i.e., some sites with a 4.75 Hz Chebyshev filter and some with a 8.00 Hz Chebyshev filter or no low-pass filter at all). These responses were calculated separately and were introduced and stored in the system under different file names. The careful documentation of the various modifications in the GSE files ensures the correct linking between each different configuration and the appropriate response file (fap table).

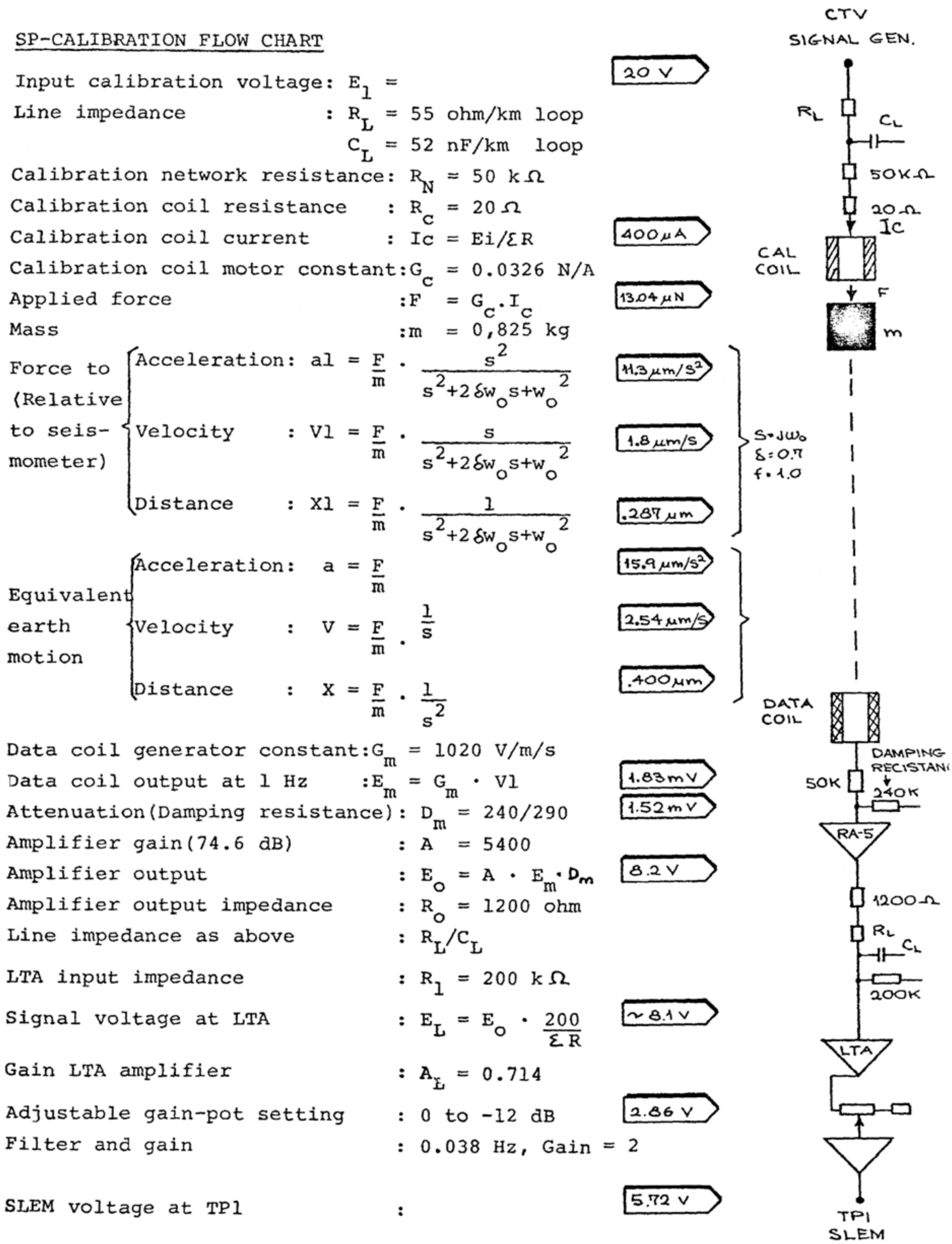

Fig. 6.4.3. Short-period calibration flowchart for the standard NORSAR configuration (Dalland, 1971).

A description of the most important points for the calculation of system responses will be provided in the following paragraphs, sorted by different digitizer, since this makes the greatest difference in each configuration. For a detailed description of system components and variations, Table 6.4.1 should be consulted.

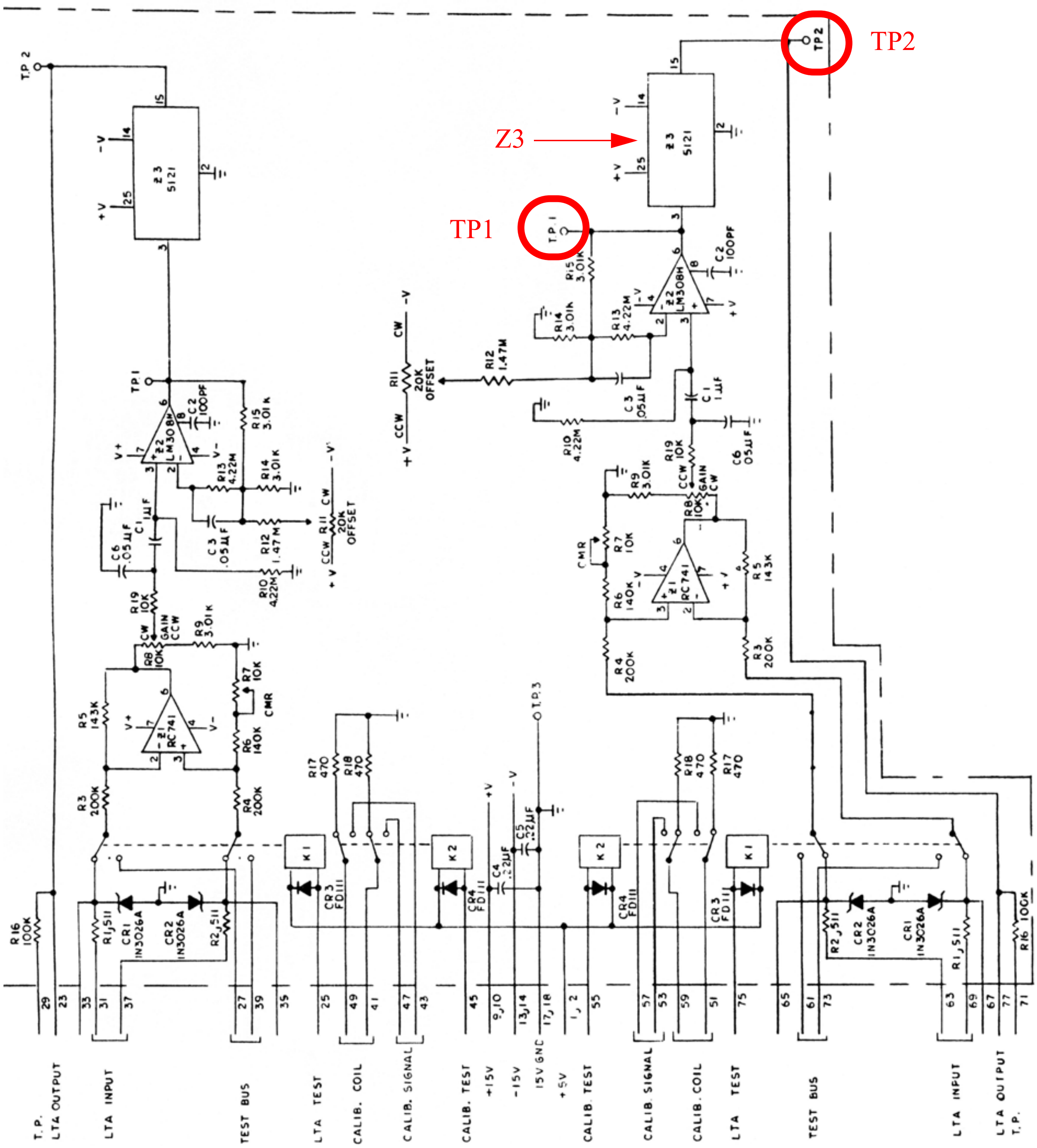

Fig. 6.4.4. Schematic diagram of the short-period Line Terminating Amplifier (Philco-Ford, 1970). Z3 is the low-pass, 24 dB/octave Chebyshev filter and TP1, TP2 are two voltage measuring/ adjusting points.

Standard NORSAR - SLEM

The standard NORSAR instrumentation chain is presented in Fig. 6.4.3, where the short-period instrument calibration chain is described.

The calibration procedure for the short-period sites initiates with a 20 V peak-to-peak, 1 Hz sinusoidal signal, generated at the CTV and going out to the sensors. The resistances of the calibration network are arranged so that the calibration current I_c is in the order of 400 μA. This current produces a force F on the moving mass of the seismometer, which depends on the calibration coil motor constant G_c and the current I_c. The applied force is converted into motion according to the sensor transfer function (see Fig. 6.4.3 for actual values). The equivalent ground motion in this case is equal to 0.400 μm and the actual amplitude of the induced voltage is 1.83 mV. This is however reduced to 1.52 mV by the resistance attenuator, consisting of the seismometer internal resistance and the external damping resistance. This voltage is the input to the RA-5 amplifier, which has a gain of 5400 (= 74.6 db), thus amplifying the output voltage to 8.2 V peak-to-peak. When reaching the CTV, this voltage is actually slightly attenuated due to the RA-5, line and LTA impedance. Finally, the gain setting of the LTA is adjusted to a voltage of 5.72 V peak-to-peak at test point TP2 in the SLEM, so that the overall system scaling is set to 0.0427 nm/count (Dalland, 1971), taking into consideration that the SLEM A/D converter is a 14-bit digitizer with a least significant bit of 0.61 mV/count. In the case that the low-pass filter card of the LTA is omitted, the voltage adjustment is made at test point TP1 (Fig. 6.4.4). In accordance to this, the short-period standard instrumentation response calculation is made using the nominal values and the appropriate adjustments to obtain a channel sensitivity of 0.0427 nm/count. The displacement amplitude and phase responses, up to 100 Hz, for this configuration as well as two of its variations are depicted in Fig. 6.4.5. Responses are coded according to the Respid included in Table 6.4.1 (SPSLEM1, SPSLEM2 and SPSLEM4).

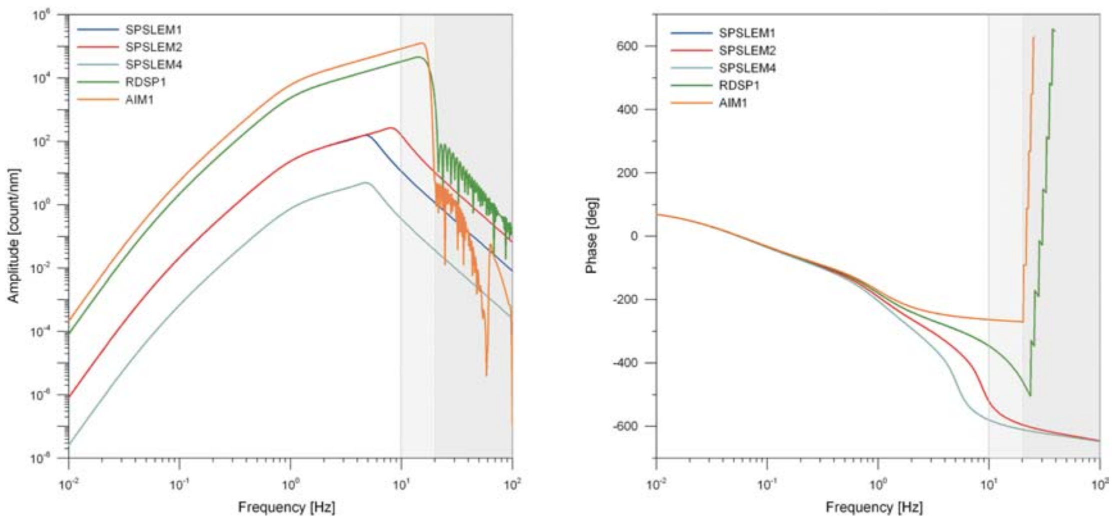

Fig. 6.4.5. Displacement amplitude and phase response for the NORSAR short-period configurations employing an HS-10-1 seismometer. The standard NORSAR (SPSLEM1), the 8.00 Hz Chebyshev filter LTA variation (SPSLEM2), the attenuated channel (SPSLEM4), the RD6 installation (RDSP1) and the first AIM24-1 installation in the CTVs (AIM1) are depicted. The shaded areas represent the range beyond the Nyquist frequency (10 Hz for the SLEM and 20 Hz for the RD6 and AIM24 configurations).

Regarding the long-period instruments, a similar calibration procedure is followed to the one described in the previous paragraph, with a 20 V peak-to-peak, 0.04 Hz sinusoidal signal being used. Part of an unknown document provides a schematic description of the procedure, which was unfortunately impossible to reconstruct with the scarce information available. Therefore, the long-period instrument response will be described here according to information assembled from documents NORSAR Report 40 and 58 (Steinert and Nilsen, 1972; Falch, 1973) and the Ithaco amplifier manual (Ithaco, 1968). As already mentioned, the overall channel sensitivity was being adjusted to a predetermined value for all original NORSAR installations, which in this case equaled 2.47 nm/count. To achieve this, a first adjustment was made in the output of the Ithaco amplifier. The final adjustment was made after the LTA amplifier, for a calibration period of 25 s. The long-period version of the LTA amplifier employed only a high-pass RC filter, with a cut-off frequency at 0.00373 Hz. The adjustments were thereby made at test point TP1, as in the case of no low-pass anti-alias filter for the short-period channels (Z3 in Fig. 6.4.4). The displacement amplitude and phase response for the standard NORSAR long-period configuration (LPSLEM1) is depicted in Fig. 6.4.6.

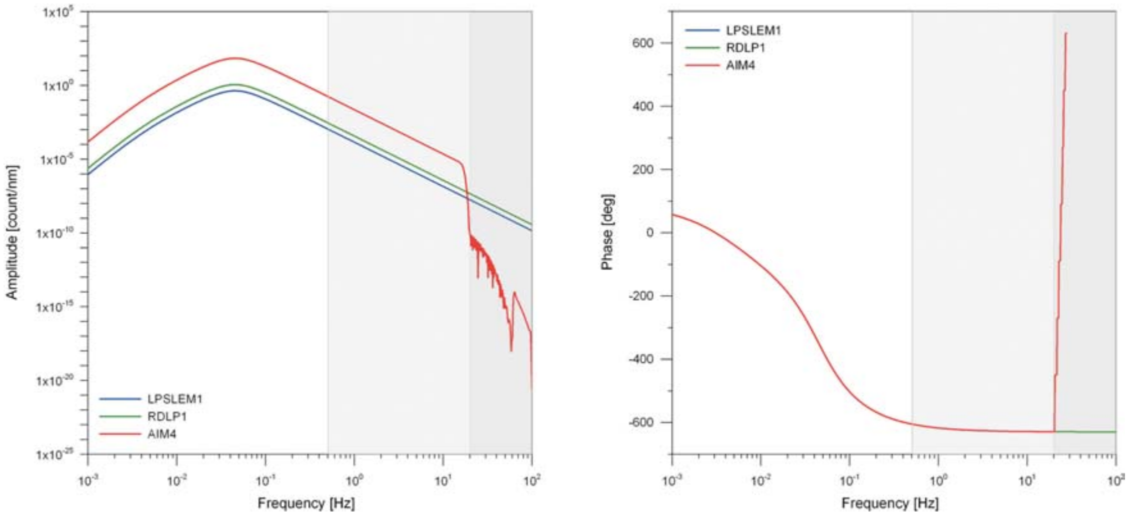

Fig. 6.4.6. Displacement amplitude and phase response of the NORSAR long-period installations. The standard NORSAR (LPSLEM1), the RD6 (RDLP1) and the AIM24-3BB (AIM4) configurations are depicted. The shaded areas represent the range beyond the Nyquist frequency (0.5 Hz for SLEM and RD6 and 20 Hz for AIM24 configurations).

RD6 configurations

The same instrumentation as the standard NORSAR has been employed also for the NORSAR Backup System, except for the digitizer that was a Nanometrics RD6 model, a gain-ranged, 16-bit, 6-channel A/D converter, with a sensitivity of 6103.5 nV/bit (Nanometrics, 1992). The version installed at the NORSAR array employs an analog 5th-order low-pass Butterworth anti-alias filter, with cut-off frequency at 23 Hz and a digital low-pass FIR filter with -3 db point at 40 Hz and 68 coefficients. The displacement amplitude and phase response for the short-period channels is depicted in Fig. 6.4.1 (RDSP1), and for the long-period channels in Fig. 6.4.6 (RDLP1).

AIM24 configurations

The third digitizer to be installed at the NORSAR array, and the one that is still in use today, is the Science Horizons AIM24. It is a 24-bit A/D converter, with a seismometer dependent gain. There are two versions installed at NORSAR, the AIM24-1, which is used with the short-period, vertical seismometers and the AIM24-3BB, used with the 3-component broadband sensors. The unit consists 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).

Regarding the short-period installations, the AIM24-1 digitizer was first installed in the Central Terminal Vaults (CTVs) together with the old, standard NORSAR instrumentation, except for subarray 06C, where it was installed in the Short Period Vaults (SPVs). The displacement amplitude and phase response for the CTV version is depicted in Fig. 6.4.5 (AIM1).

The current short-period installation, which came in operation in 1995, employs a 20171A seismometer by Geotech. The desired relative damping value of the sensor can be achieved by applying the appropriate combination of resistances, since

$$R_t = \frac{R_{CDR}}{\lambda_0} ,$$

where R_t is the total circuit resistance, R_{CDR} the critical damping resistance and λ_0 the relative damping. The generator constant for the data coil can be determined from the following formula:

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

where f_0 is the natural frequency and λ_x the open-circuit damping. The resulting constant however is not the sensitivity value to be used for calculating the instrument's response. That is obtained by the formula (Teledyne-Brown, 1995):

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

All necessary values are either provided by the manufacturer or can be measured in the lab, so a different set of values is available for each individual seismometer, sorted by serial number. This means that a different response is calculated for each array site.

The AIM24 digitizer version (AIM24-1) installed with the 20171A short-period seismometers and the Brick amplifier has a 32 V peak-to-peak full scale dynamic range and a selectable gain of 1 V/V, 10 V/V or 100 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).

The AIM24-1 employs the Crystal Semiconductor CS5322/5323 chipset (Cirrus Logic, 1995). 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 it the following succession of FIR filters was selected:

FIR1, decimating by 8, 33 coefficients
FIR2, decimating by 64, 13 coefficients
FIR3, decimating by 2, 101 coefficients

FIR2 consists of a succession of 6 equal FIR filters, each of them decimating by a factor of 2. The overall digitizer response can be constructed with the following sequence of FIR filters:

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

The least significant bit of the AIM24-1 unit equals to:

$32V/(2^{24}-1)counts = 1907{,}734\ nV/count$ or $sensitivity$ = 524288 $counts/V$.

Taking into consideration the 10 V/V gain, then the total sensitivity of the unit at 1 Hz is equal to 5242880 counts/V. The displacement amplitude and phase response for the current short-period channels is depicted in Fig. 6.4.7 (AIM0SP).

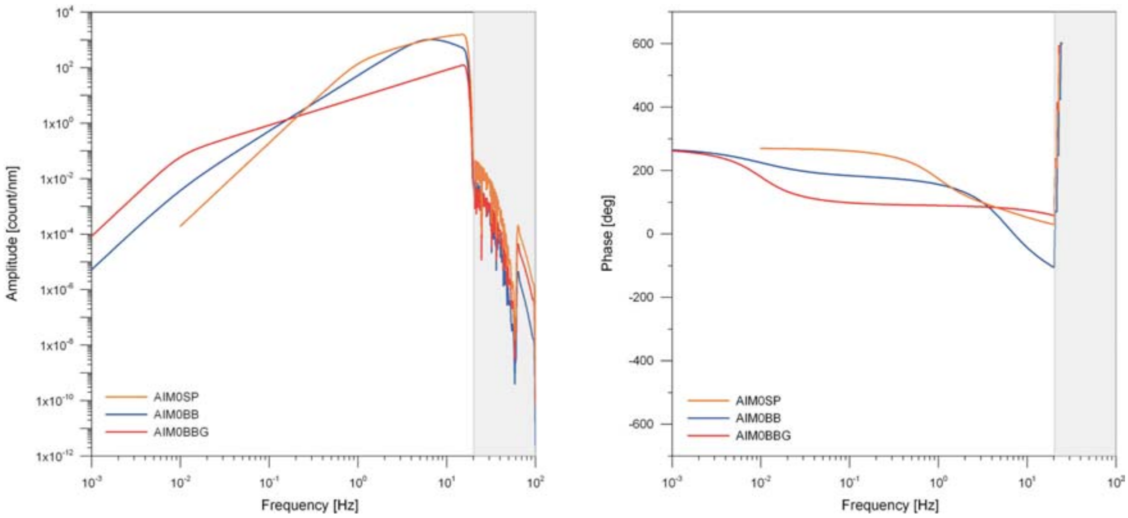

Fig. 6.4.7. Displacement amplitude and phase response for the current short-period 20171A (AIM0SP) and broadband NORSAR installations (KS54000 = AIM0BB, CMG-3T = AIM0BBG). The shaded area represents the range beyond the Nyquist frequency (=20 Hz).

Regarding the broadband installations, the AIM24-3BB version connected to the 3-component broadband seismometers has a gain of 1 V/V and a full-scale dynamic range of 64 V. It employs the Crystal Semiconductor CS5321/5322 chipset. The least significant bit is equal to: $64V/(2^{24}-1)counts = 3.81469\ \mu V/count$ and sensitivity equals 262144.5 $counts/V$.

Initially, AIM24-3BB digitizers were connected to the old NORSAR long-period instruments. The displacement amplitude and phase response for this installation is depicted in Fig. 6.4.6 (AIM4).

Currently, the AIM24-3BB units are employed together with 3-component broadband sensors. The amplitude and phase response for displacement for the KS54000 (AIM0BB) and CMG-3T (AIM0BBG) broadband configurations is depicted in Fig. 6.4.7.

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