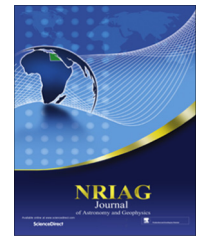


National Research Institute of Astronomy and Geophysics NRIAG Journal of Astronomy and Geophysics

www.elsevier.com/locate/nrjag



Assessment of the accuracy and stability of ENSN sensors responses



Hamed Nofal, Omar Mohamed ^{*}, Mahmoud Mohanna, Mohamed El-Gabry

National Research Institute of Astronomy and Geophysics (NRIAG), Helwan, Egypt

Received 26 November 2014; revised 24 March 2015; accepted 15 April 2015

Available online 13 May 2015

KEYWORDS

Calibration;
Seismometer;
Transfer function;
Seismology

Abstract The Egyptian National Seismic Network (ENSN) is an advanced scientific tool used to investigate earth structure and seismic activity in Egypt. One of the main tasks of the engineering team of ENSN is to keep the accuracy and stability of the high performance seismic instruments as close as possible to the international standards used in international seismic network. To achieve this task, the seismometers are routinely calibrated. One of the final outcomes of the calibration process is a set of the actual poles and zeros of the seismometers. Due to the strategic importance of the High Dam, we present in this paper the results of the calibrating broad band (BB) seismometers type Trillium-40 (40 second). From these sets we computed both amplitude and phase responses as well as their deviations from the nominal responses of this particular seismometer type. The computed deviation of this sub-network is then statistically analyzed to obtain an overall estimate of the accuracy of measurements recorded by it. Such analysis might also discover some stations which are far from the international standards. This test will be carried out regularly at periods of several months to find out how stable the seismometer response is. As a result, the values of the magnitude and phase errors are confined between 0% and 2% for about 90% of the calibrated seismometers. The average magnitude error was found to be 5% from the nominal and 4% for average phase error. In order to eliminate any possible error in the measured data, the measured (true) poles and zeroes are used in the response files to replace the nominal values.
© 2015 Production and hosting by Elsevier B.V. on behalf of National Research Institute of Astronomy and Geophysics.

1. Introduction

The Sumatra–Andaman earthquake of 26 December 2004 provides a special opportunity to validate the accuracy of sensor sensitivities reported for the IRIS Global Seismic Network (GSN) [Butler et al., 2004](#). A goal of the GSN is to publish instrument responses to an accuracy of 1% in amplitude and 1° in phase [Park et al., 2005](#). This earthquake, the largest in forty years, excited long-period free oscillations well above the ambient noise level at all GSN stations [Berger et al.,](#)

^{*} Corresponding author.

Peer review under responsibility of National Research Institute of Astronomy and Geophysics.



Production and hosting by Elsevier

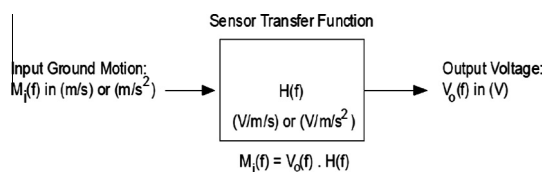


Figure 1 Transfer function of seismometers.

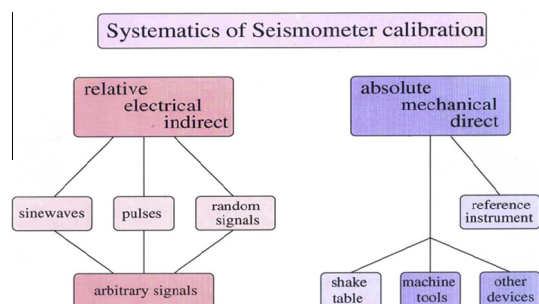


Figure 2 Different types of calibration.

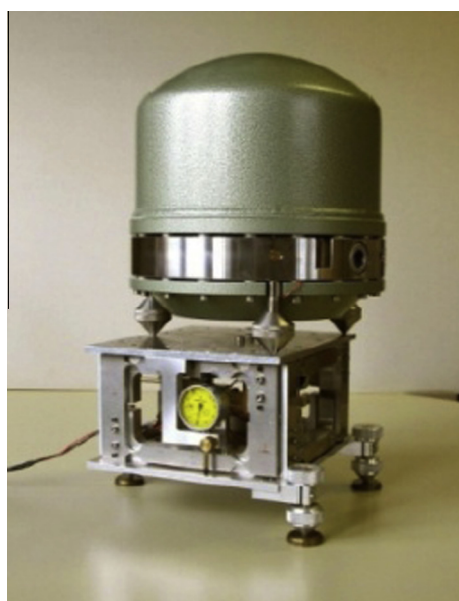


Figure 3 Mechanical calibration.

2004). The lowest frequency radial oscillations are only weakly coupled to other modes by rotation and laterally varying Earth structure, so their amplitudes and phases should be approximately uniform globally (Park, 1990). Seismometers (velocity) or accelerometers (acceleration), are transducers that convert ground motion into an electric signal. Typically, calibration serves two main purposes (Wielandt, 2002). First, it is used to derive the frequency response of a seismometer when this information is missing. In most cases, however, the transfer function of the seismometer in Fig. 1 is known as it is usually provided by the manufacturer (Nanometrics Inc., 2003). The second and most important motive behind calibration consists of periodically checking the operation of the seismometer, and

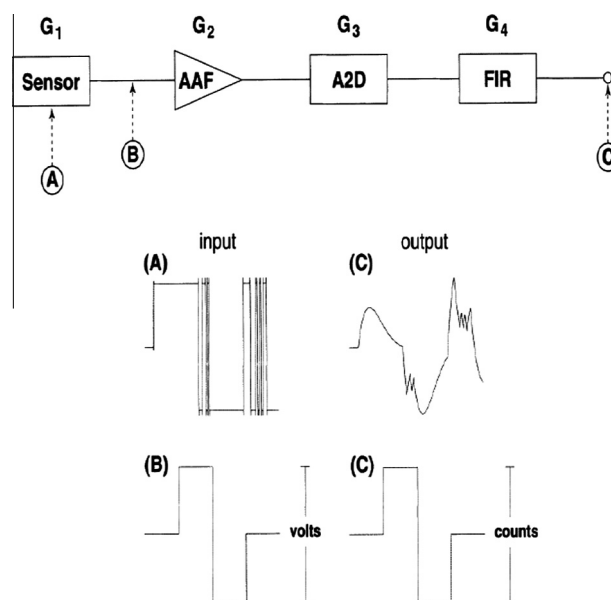


Figure 4 Calibration scheme for ENSN systems. To determine the shape of the seismometer's response, a random binary or other broadband, white-noise signal is fed into the calibration circuit of the seismometer at A and the output is recorded at C.

Table 1 Specification for Trillium-40.

Parameter	Specification
Midband generator constant	1500 V s/m
Clip level	16 V peak-to-peak differential
Lower corner frequency	0.025 Hz
Upper corner frequency	50 Hz
Lower corner damping relative to critical	0.707

detecting any changes to its known sensitivity and transfer function with temperature and time. Fig. 2 shows the two types of calibration process. First type is mechanical calibration, seismometer is attached to test bench to apply to the seismometer a known input signal and record the corresponding output in order to determine the relationship between the two to get the sensitivity of the seismometer. Fig. 3 shows the test bench bar. Second the electrical calibration which can be done by using various signal types (sinusoidal, pulses and pseudo random binary (PRB)). In these techniques we can get the amplitude for each single frequency and comparing to the nominal, in addition, we can get the sensitivity. Pulses and sine waves can be used to extract the parameters of the second order system, namely, the natural frequency (canonical frequency) and the damping ratio. These parameters are, then, utilized to construct the transfer function. Alternatively, broadband signals such as pseudorandom binary signals and white Gaussian noise could also be used. In this case, both the input and the corresponding output waveforms should be simultaneously digitized; therefore, two digital channels are required. Their frequency domain spectrum is derived through the Fast Fourier Transform (FFT) algorithm.

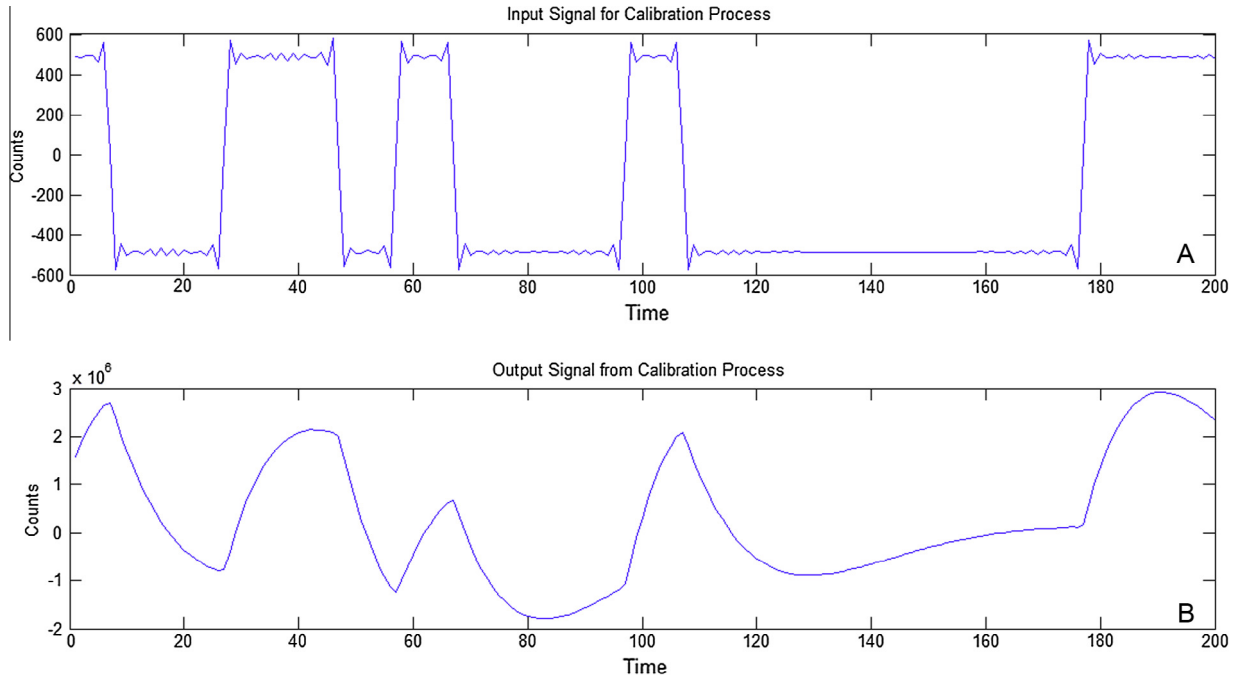


Figure 5 A segment of real PRB input signal (A) and the corresponding output signal (B).

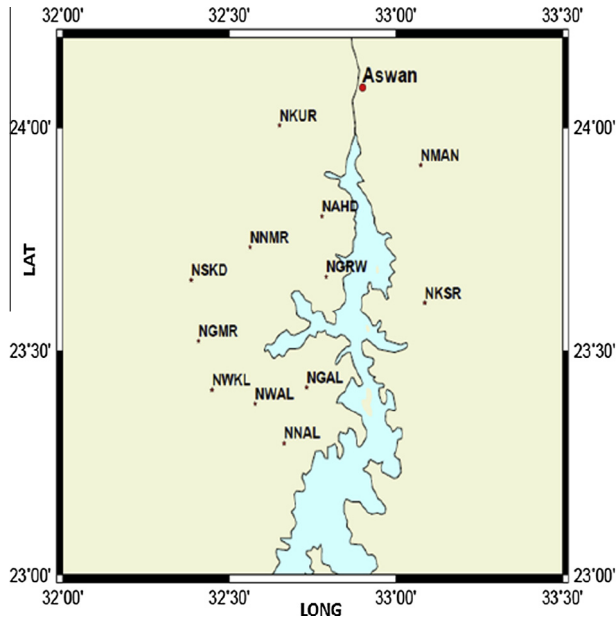


Figure 6 Twelve three-component BB stations (Trillium-40) in ASWAN.

2. Calibration process in ENSN

System calibration of an ENSN station is accomplished by applying a well-known calibrating signal through the digitizer to the calibrating coil in the seismometer, and then measuring the response of the seismometer to it. This process is generally done during installation, upgrade, or repair. ENSN systems

employ a standard pole-zero formats (according to seismometer manual) to represent the analog stages, which consist of the seismometer and front end unit of the digitizer. The transfer function of the seismometer is expressed in Eqs. (1) and (2) [Trillium 40 Seismometer User Guide](#).

$$G(s) = SA_0 \frac{\prod_{n=1}^N (s - z_n)}{\prod_{m=1}^M (s - p_m)} \quad (1)$$

$$A_0 = \frac{1}{\frac{\prod_{n=1}^N (i2\pi f_0 - z_n)}{\prod_{m=1}^M (i2\pi f_0 - p_m)}} \quad (2)$$

where p_m and z_n represent the poles and zeros, respectively. By convention, the normalization factor A_0 is chosen to normalize the seismometer sensitivity at a given frequency, so the scalar S expresses the flat-response sensitivity to ground velocity. [Fig. 4](#) shows the applied seismometer response to the digitizer and taken in counts at its output counts. A random binary or other broadband, white-noise signal is fed into the calibration circuit of the seismometer at A or of the digitizer at B and the output is recorded at C. This test yields the combined gain of the anti-aliasing filter (G2) and the digitizer sensitivity (G3). Given the sensitivity of the digitizer in counts/volt we obtain the seismometer analog response to the applied calibrating signal.

A random binary signal or other broadband white-noise process is fed to the calibration coils of the seismometer, and the output is recorded for analysis at the network operator's data collection center. The shape of the seismometer frequency response is found by fitting a perturbed function of the nominal system to the cross-spectrum of the output and the (known) input [Berger et al., 1979](#). ENSN network seismologists use the nominal pole, zeroes and generator constant values provided by the manufacturer in the process of analyzing events. It is essential to regularly calibrate the seismometer to test the stability of these nominal values.

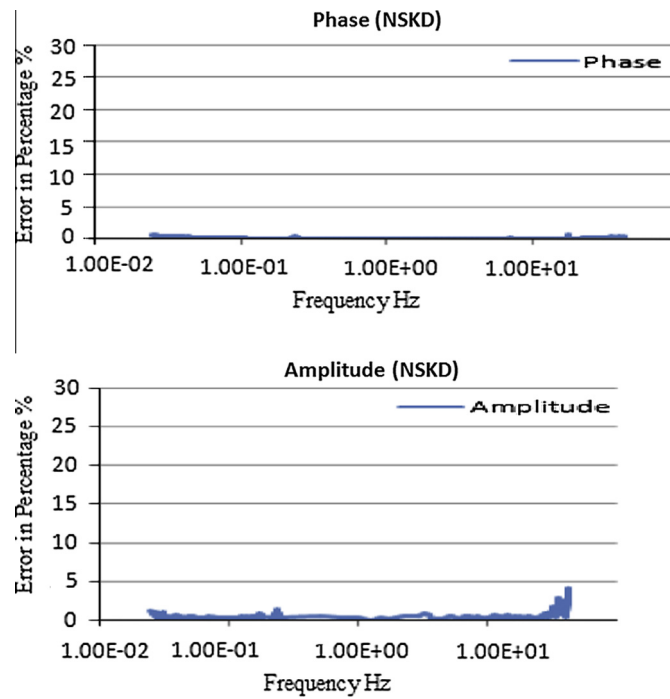


Figure 7 Frequency against percentage error in amplitude and phase from the nominal (NSKD station).

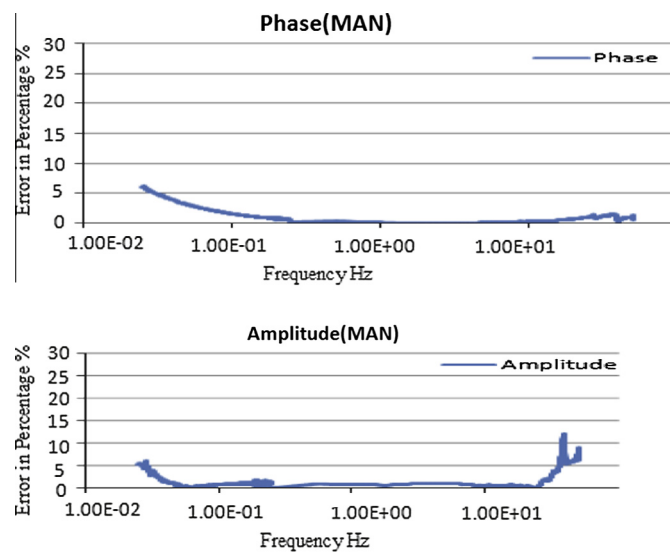


Figure 8 Frequency against percentage error in amplitude and phase from the nominal (NMAN station).

The specification for Trillium-40 is shown in Table 1. In the calibration process a 500 s/s digitized PRB calibrating signal is sent to the seismometer calibration coil. The duration of the pattern and the amplitude of each pulse inside the pattern are determined according to the frequency band under calibration. Fig. 5a shows a segment of the pattern we used for calibrating the frequency band above 1 Hz. Fig. 5b shows the response of Trillium-40 to this calibrating signal. It is to be observed that due to the limited band width of the instrument indicated in Table 1, the response is no longer sharp as the input signal.

3. Evaluation of calibration results

Due to the strategic importance of the High Dam, Aswan sub-network is based on twelve three-component BB Trillium-40 seismometers as shown in Fig. 6.

Nanometrics calibration program can be used to calibrate all these seismometers (the same circumstances and the same thermal isolations) for both low frequency band (below 1 Hz) and high frequency band (above 1 Hz) provided us with a complete knowledge about the amplitude and phase responses as well as their deviations from the nominal

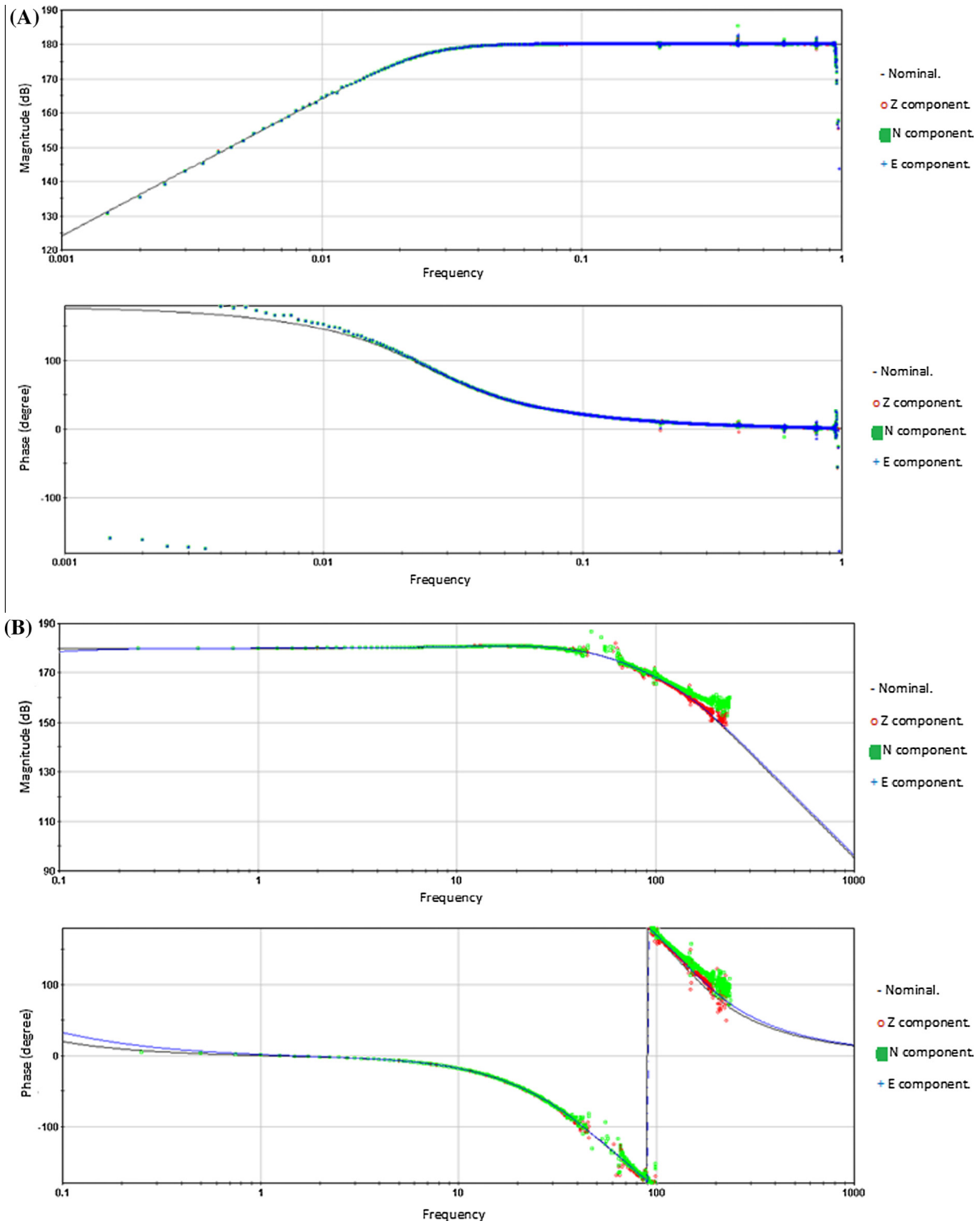


Figure 9 Low frequency (A) and high frequency (B) Transfer Function (TF) (NSKD station).

responses provided by the manufacturer. Fig. 7 shows the calibration results of the E-W component of seismometer in NSKD station as an example of a good station, while Fig. 8 shows the same for NMAN station as an example of unreliable station. The upper figure for Figs. 7 and 8 is

the error in phase, while the lower figure is the error in amplitude. The amplitude deviation ($\frac{\text{Measured} - \text{Nominal}}{\text{Nominal}} * 100\%$) of NSKD did not exceed 2% while the phase deviation was found to be 1% from the nominal response along the frequency band 40 second–42.5 Hz. On the contrary to

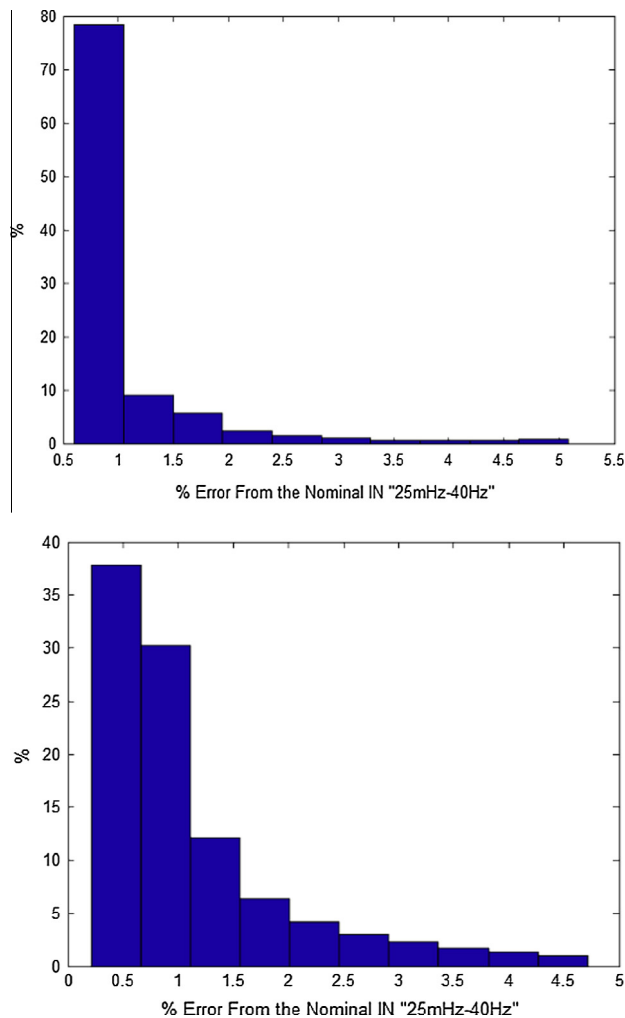


Figure 10 The average percentage error for phase (upper figure) and magnitude (lower figure) responses for 12 station-3 components each.

NSKD, NMAN station showed a deviation of 6% for amplitude and phase responses in the same frequency band. Fig. 9 shows the measured transfer function of NSKD station at low and high frequency (A is the low frequency and B is the high frequency). The upper figure in Fig. 9A and B is the magnitude response, while the lower figure is the phase response. As an assessment of the complete Aswan sub-network, we calculated the average amplitude and phase deviations from the nominal values of three components of all twelve stations for both low and high frequency bands. Fig. 10 shows that components in magnitude and phase responses are 5% and 4.5% respectively.

The upper figure in Fig. 10 represents the error in phase, while the lower figure is the error in magnitude. We noticed the appearance of a weird result at 0.2041 Hz (4.9 second) in amplitude and phase deviations. Fig. 11 shows the statistical distribution of the amplitude and phase deviations of the twelve calibrated seismometers. The upper figure in Fig. 11 represents the distribution of the amplitude, while the lower

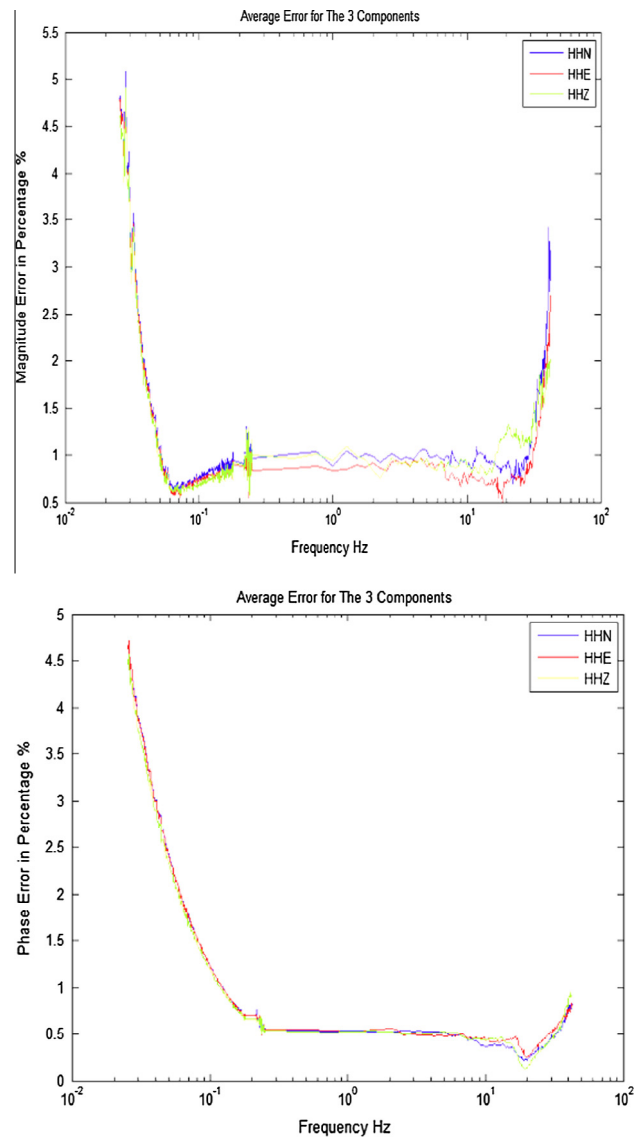


Figure 11 Distribution of the percentage error for magnitude (upper figure) and phase (lower figure) in the set we have.

figure is the distribution of the phase. For about 90% of seismometers, amplitude and phase deviations are found to be confined between 0% and 2%.

4. Conclusion and future work

From a total of 12 stations, we found 9 of them can be accepted compared with the reference given in [Trillium 40 Seismometer User Guide](#). The other 3 stations need to be tested to realize how to improve its performance. Also we found that the actual performance of most of the studied stations is reliable and their measured amplitude and phase responses are acceptable. Unfortunately, the measured responses of few of the studied stations (e.g. NMAN station) do not fall within accepted limits and need to be investigated. This study showed some unaccepted and not understood deviations even in most accepted stations at frequency 0.204 Hz. This phenomenon has to be investigated to reveal its source.

References

- Berger, Jon, Agnew, Duncan Carr, Parker, Robert L., Farrell, William E., 1979. Seismic system calibration: 2. Cross-spectral calibration using random binary signals. *Bull. Seismol. Soc. Am.* 69 (1), 271–288.
- Berger, Jonathan, Davis, Peter, Ekström, Göran, 2004. Ambient earth noise: a survey of the global seismographic network. *J. Geophys. Res.: Solid Earth* (1978–2012) 109 (B11).
- Butler, Rhett, Lay, Thome, Creager, Ken, Earl, Paul, Fischer, Karen, Gaherty, Jim, Laske, Gabi, et al, 2004. The Global Seismographic Network surpasses its design goal. *Eos, Trans. Am. Geophys. Union* 85 (23), 225–229.
- Nanometrics Inc., 2003. *Seismological Instruments*, “Nanometrics Sensor Calibration”, September 18, 2003, Revision 5.
- Park, Jeffrey, 1990. Radial mode observations from the 5/23/89 Macquarie Ridge earthquake. *Geophys. Res. Lett.* 17 (7), 1005–1008.
- Park, Jeffrey, Song, Teh-Ru Alex, Tromp, Jeroen, Okal, Emile, Stein, Seth, Roullet, Genevieve, Clevede, Eric, et al, 2005. Earth’s free oscillations excited by the 26 December 2004 Sumatra-Andaman earthquake. *Science* 308 (5725), 1139–1144.
- Trillium 40 Seismometer User Guide. <http://www.passcal.nmt.edu/webfm_send/948> (last access 26.11.14).
- Wielandt, Erhard, 2002. *Seismic sensors and their calibration*. New Manual Seismol. Observatory Practice 1.