Technical Requirements to Signal Detection at Seismic Stations of the International Monitoring System
- Test Method -

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Abstract

Seismic stations planned for monitoring of nuclear explosions banned under the Comprehensive Nuclear-Test-Ban Treaty (CTBT) should meet certain special technical requirements, established for the International Monitoring System (IMS) of the Preparatory Commission of the CTBT Organization. For verification of compliance with such stringent requirements extensive testing of the equipment instrumental noise is required. This paper presents the testing and results of seismometers and digitizers used or planned to be used in the IMS network.

I. Introduction

The technical requirements for the equipment of an IMS seismic station have been developed by the policy making organs of the Commission and are included in the Manual of Stations Operation as quantitative criteria. These requirements are somewhat special, customized for explosion monitoring and contain several items which reflect the capability of the seismic system to resolve the minimum background seismic noise with a predefined margin of Signal-to-Noise Ratio (SNR) in the pass-band of interest. The requirements relate, particularly, to the digitizer noise and self-noise of seismometer to be respectively 20 and 10 dB below the minimum seismic background at the measurement site. Other requirements with the same importance include those referring to resolution, dynamic range and timing accuracy. Table 1. describes a subset of these requirements.

Table 1. Some technical requirements for the primary and auxiliary seismic station:

Parameter	Requirement
Seismometer self noise, dB	>= 10 below minimum earth seismic background noise at the station location over the passband
Resolution, dB	>= 18 below the minimum local background noise
System self noise, dB	>= 10 below the seismometer self noise over the passband
Dynamic range, dB	>= 120
Absolute timing accuracy, ms	=< 10
Relative timing accuracy, ms	=< 1 between the array elements

CTBTO has been carrying out intensive testing of digitizers and seismometers proposed for the IMS stations. Firstly all brands of digitizers which are already used or are planned to be used in the IMS network have been tested in cooperation with Sandia National Laboratory (SNL), in New Mexico (USA). In SNL a customized, adequate testing procedure was designed for IMS purposes [4]. As for the seismometers, the instrumental noise was estimated based on manufacturer's specifications found in the User's Manual of the respective seismometer. However this information is not sufficient and sometimes inadequately reflects the actual level of instrumental noise, because improper integration of seismometers with digital waveform recording systems (in some cases with front-end amplifier or pre-amplifier) might result in additional instrumental noise. Therefore, additional noise and resolution tests (field measurements) were performed on complete systems (seismometer + digitizer) in a side-by-side setup using a seismometer-to-seismometer comparison method.

II. Digitizer Testing

Test procedures applied in digitizer testing included as a first step analysis of the manufacturer's specifications in view of the IMS requirements. If the published specifications fell short of the IMS requirements recommendations or requests were provided to the manufacturer for quality and performance improvement of the respective digitizer. Representative samples of the final hardware and firmware release of the digitizer were, then, extensively tested in SNL. SNL is well equipped with all necessary instruments and test systems, such as low-distortion signal generators, filters, power supply sets, etc.

The main parameters tested in SNL for all digitizers are:

1) LSB (lest significant bit): determination the resolution or in other words the information content of the least significant bit. The results of the least significant bit determination for some digitizers' models are shown in the Table 2.

Table 2. LSB test results for some digitizers

Nr.	Model	LSB [microV]	Remarks
1	HRD24 (Nanometrics)	2.58	Adjustable
2	Reftek 72-07A (Refraction Technologies)	1.92	Adjustable
3	Quanterra 4120	2.41	Fixed

2) ITN (input terminated noise): estimation of the electronic self-noise. The digitizer self-noise is defined by the shorted input method. The digitizer self-noise with shorted input is the resolution threshold, which is provided by this digitizer for the seismic signals records. A sample of input data and its spectrogram of Nanometrics HRD24 digitizer recorded having the digitizer's input terminated with 50 Ohms resistor are shown in Figure 1a. Figure 1b shows the self-noise power spectral density in the pass band 0.01 to 20 Hz for the same fragment of data. This is the pass band of interest of this digitizer for IMS applications.
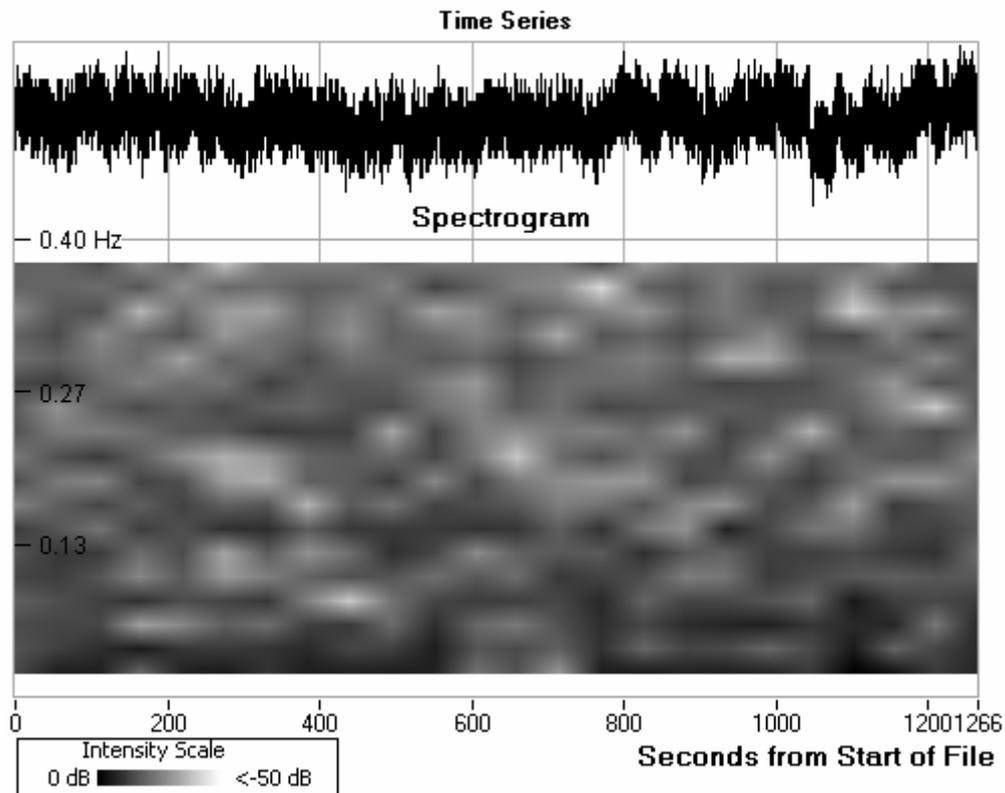

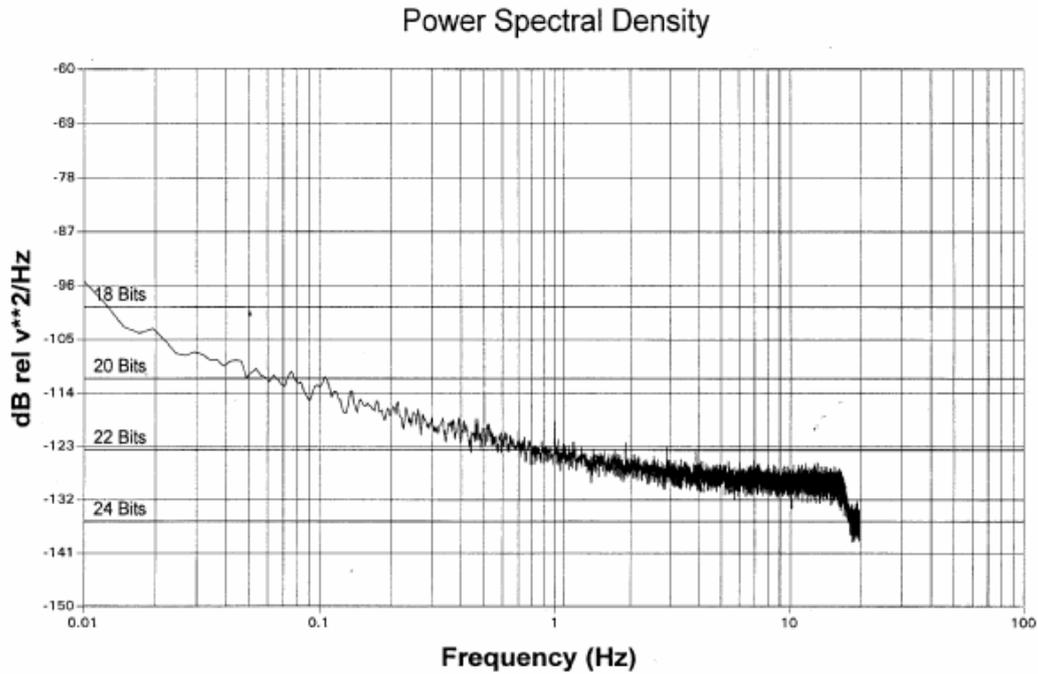Figure 1a. Digitizer terminated noise time series and its spectrogram

Figure 1b. Power Spectral Density for the data shown in Figure 1a.

3) MPDR (maximum potential dynamic value): estimation of the dynamic range of the digitizer.

4) TTA (time-tag accuracy): estimation of the accuracy of sample timing relative to Coordinated Universal Time (UTC). Figure 2 shows the results of the time-tag accuracy test. The GPS minute marks are digitized and time stamped with UTC time acquired from another reference GPS used to synchronize the timing system of the digitizer. The recorded data consist of individual samples and the digitized minute mark on a time axes synchronized to UTC. Figure 2 shows, that the sample corresponding to the minute mark is located in the central part of the GPS signal, which means that recorded signals are accurately timed (with accuracy of 46.19 us, which is in accordance with the Table 1, 5th row requirements).
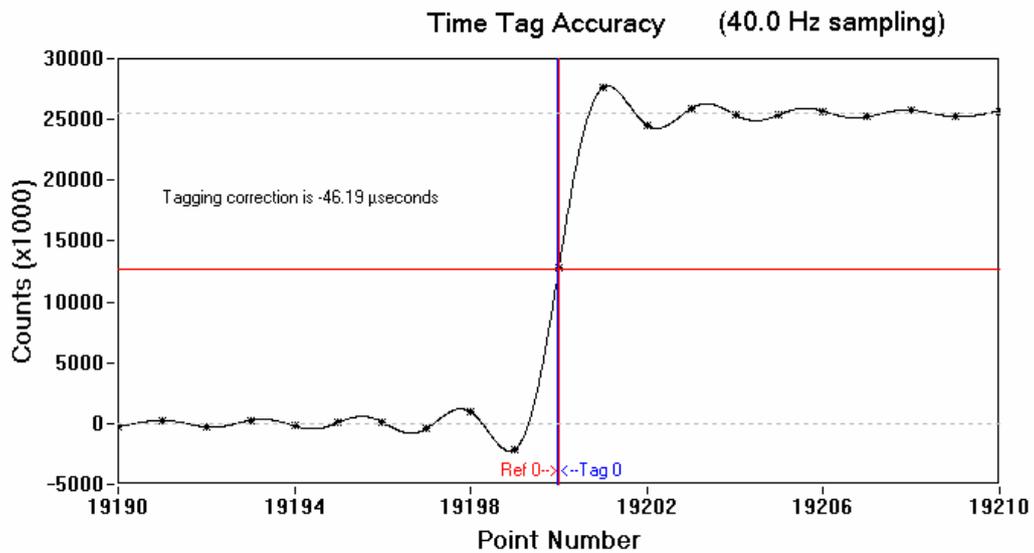

Figure 2 The result of the time tag accuracy test

5) Harmonic distortion test determines and verify the linearity and identify the sources of non-

linearities of the digitizer under the test. Figure 3 shows an example of the results of Total Harmonic Distortion (THD) test. The main harmonic (frequency 1.666 Hz), as well as the second and the third harmonics are clearly seen. The non-linearity distortion level is 125.85 dB in this case.
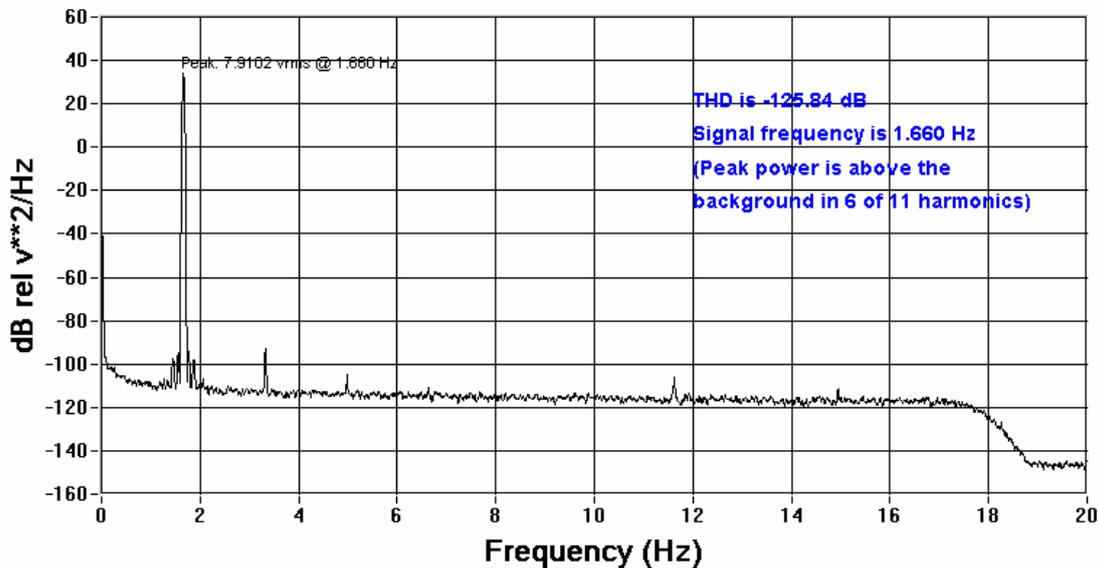

Figure 3. An example of THD test result for digitizer.

The digitizers tested in SNL and approved for deployment in the IMS network include GD2 from the Canadian Geological Survey, HRD24 and Trident from Nanometrics Inc. (Canada), Alpillines from DASE (France), SAN2003 from SAIC (USA), Reftec 72-07A from Refraction Technologies (USA) and DM from Guralp Systems (UK).

III. Seismometer Testing

The main part of seismometer testing was conducted either in the manufacturer's facility or in Albuquerque Seismological Laboratory (ASL) in the USA. The parallel seismometers installation method was used. The block-diagram of the testing algorithm is shown in Figure 5 below. The algorithm is based on the use of 3 equations, which allow estimating the auto-spectrum of each channel and the cross-spectrum of each two channels. Supposing, that the noise parameters of each channel are equal, the solution of the equations' system allows getting seismometer's self noise estimation. Figure 6 shows fragments of the records of two short-period seismic sensors installed on the same pillar with identical frequency responses. The signals seem to be identical, at least at the first glance. Then the fragments were tested by the described method, which, after the solution of the equations has given the seismometers' noise level, shown in Figure 7. It can be seen, that the difference between the station seismic noise and the estimated seismic sensors' self noise is not lees 10 dB.

The list of seismometers tested and deployed so far in the IMS network includes the broadband seismometer STS-2 manufactured by Streckeisen (Swiss), CMG3TB manufactured by Guralp Systems Ltd (UK), KS-54000, GS-13, and GS-21, GS13 manufactured by Teledyn Geotech (USA), as well as CMG-3ESP, CMG-40T by Guralp Systems Ltd (UK).

IV. Complete System Testing in Field Conditions

Selection of the Test Site

Testing of a complete seismic system requires conditions with low level of background seismic noise. Such places are in general remote areas with no industrial, human induced, volcanic or geothermal seismicity. However, for successful and professional completion of tests these sites have to be equipped with all equipment and facilities required to perform the testing. CTBTO benefited from the geographical proximity to CTBTO offices in Vienna, Austria, of the Conrad Observatory at Trafelberg, built by Central Institute of Meteorology and Geodynamics in Vienna [2]. Officially opened on 23

May, 2002 the Conrad Observatory is located relatively far (as far as possible in Central Europe) from potential sources of man-made seismic and electromagnetic noise [2]. Pilot estimation of seismic noise level has demonstrated that this site has a relatively low level of seismic background from 1 to 20 Hz, unusual for Europe. Moreover this facility is modern, state-of-the-art geophysical laboratory, which has an outstanding capability to conduct different type of equipment testing as well as permanent seismic, gravimetric and magnetic observations.

The Conrad Laboratory, extremely well designed, constructed and equipped for experimental testing of modern seismic equipment, includes seismic chambers with stable temperature [3]. Pillars constructed for seismic seismometers are well connected to the hard rock and have sufficient surface for deployment of different brand of vault seismometers. The Conrad Observatory also has two pairs of co-located seismic boreholes. A cable system with a large number of conduits allow for signal transmission in both digital and analog forms as well as for conversion to different communication media, such as fiber optic cable, Ethernet link etc. There is a satellite communication link from Trafelberg to CTBTO offices Vienna, allowing for an easy data transmission to as well as command and control of equipment from the IMS Laboratory.

Methodology

Testing of new seismic equipment followed the accepted and time-proven conception in seismological practice to use side-by-side deployed seismometers for estimation of the channel self-noise [1]. Note that this method actually allows to estimate not only a seismometer noise but to get an estimation of the overall self-noise of the seismic channel when digitizer and amplifier also contribute to the self-noise.
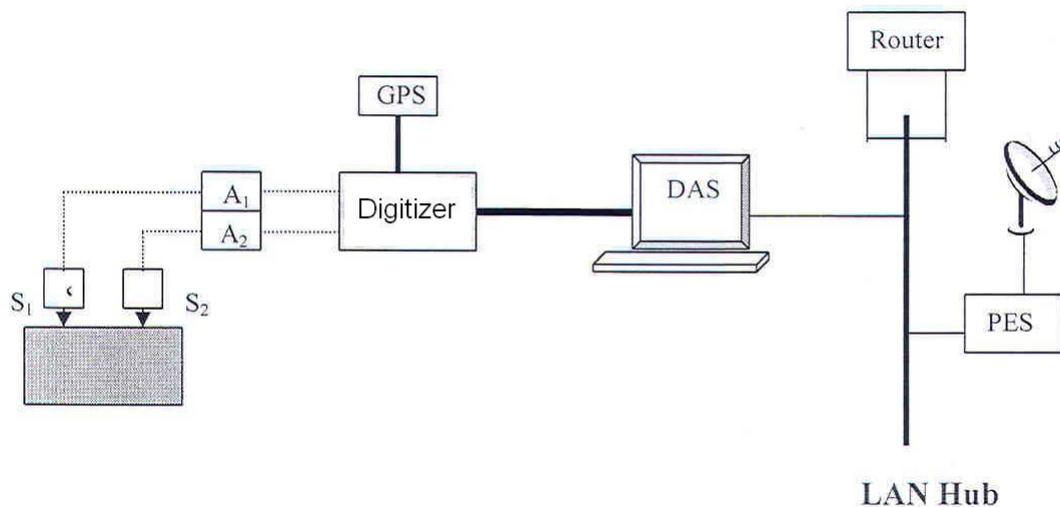

Figure 4. Block diagram of a typical seismometer self-noise test setup using two vault seismometers located on the same pillar. Solid lines represent digital data flow while dotted lines analog data flow.

For example equipment set up as depicted in Figure 4 comprises two broadband seismometers co-located in the same pillar and a data acquisition system based on a 24-bit digitizer. Data are being recorded by standard data acquisition software (DAS) and output in IMS1.0/CD1 format to a satellite link part of the Global Communication Interface (GCI) of the IMS network. Data is transmitted via GCI link to IMS laboratory for further analysis. Any active or passive seismometers as well as seismic digitizer from any manufacturer could be used in this equipment configuration. Sometimes a preamplifier (A1 and A2 in Figure 4) is used for achieving specified sensitivity level in the channel output. It should be noted that equipment in the above setup are selected as an example and during testing of various sensors and digitizers other equipment could be used
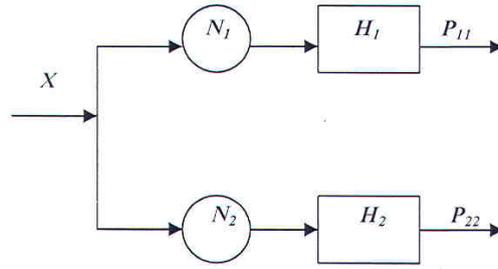
Figure 5. Block diagram of side-by-side technique of seismic channels testing.

Ground motion X on Figure 5 assumes the same input for both systems. N1 and N2 are incoherent noise powers not necessarily equal. The relationships between noise power at various points of the diagram could be written as a system of equation in the following form [1]:

$$P_{11} = |H_1|^2 \cdot [X + N_1]$$
(1)

$$P_{22} = |H_2|^2 \cdot [X + N_2]$$
(2)

$$P_{12} = H_1 \cdot H_2^* \cdot X$$
(3)

Where P_{11}, P_{22}, and P_{12} are power spectral densities for systems 1 and 2 and cross-spectral density between the outputs of two systems, respectively. The two system are assumed to have known transfer functions H_1 and H_2.

This system of equations allows direct estimation of N_1 and N_2. Equation (1) yields to:

$$N_1 = \frac{P_{11}}{|H_1|} - X$$
(4)

Substituting of X from equation (3) gives:

$$N_1 = \frac{P_{11}}{|H_1|^2} - \frac{P_{12}}{H_1 \cdot H_2^*}$$
(5)

Similar solution can be obtained for N_2.

Equation (4) demonstrates that channel noise power can be expressed in terms of directly measurable quantities at the output of the two test systems and the system transfer functions. Since an assumption regarding the incoherence of the channels noises N_1 and N_2 was made, equation (5) simply demonstrates that noise power, P_{noise}, is equal to the total system output power, P_{total}, minus the coherent power, $P_{coherent}$. Introducing the frequently used coherence function to the above analysis as:

$$\gamma^2 = \frac{|P_{12}|^2}{P_{11} \cdot P_{22}}$$
(6)

and assuming:

$$N_1 = N_2 = N$$
(7)

allows to come to a simpler estimation of the channel noise:

$$N = X \cdot \left(\frac{1}{\gamma^2} - 1 \right) \qquad (8)$$

Substitution of *X* from equation (3) yields to the final formula for *N*:

$$N = \frac{P_{12}}{H_1 \cdot H_2} \cdot \left(\frac{1}{\gamma^2} - 1 \right) \qquad (9)$$

The last equation can also be used to estimate the absolute upper power limit for the noise in both seismic channels involved in the test.
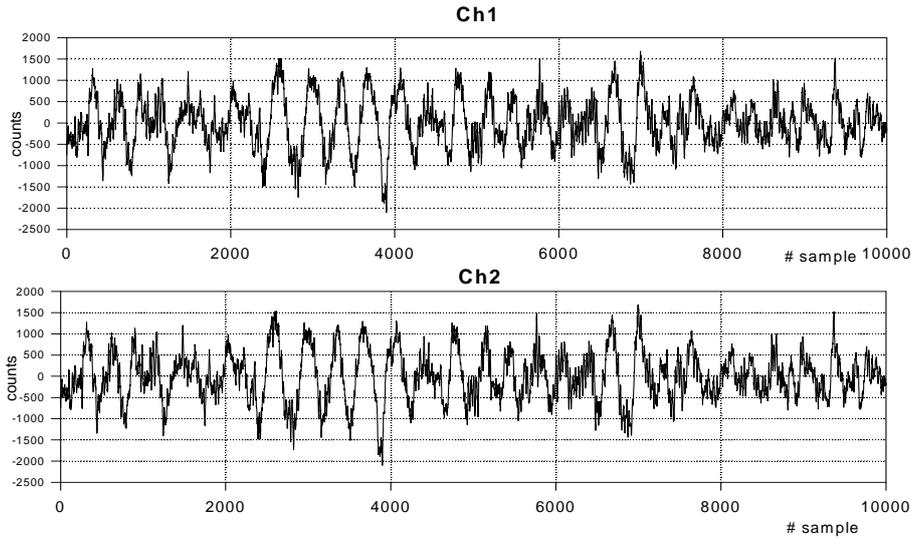

Figure 6. An example of records of two short-period seismic sensors installed on the same pillar

V. Conclusions

Power spectral densities of recording channel self-noise are plotted together with the power spectral densities of the local seismic background noise and with the Peterson new low noise model (NLNM) [5], as seen on the example on Figure 7.
As it is seen from the graph, the requirement for self-noise to be at least 10 dB below the minimum seismic background is met only for frequencies below 6 Hz.
Performing similar tests for all models of seismometers and digitizers used or planned for deployment in the IMS network and preparing noise plots as on Figure 7 allows not only for selection of the most suited equipment for the IMS stations, but provides comprehensive general-purpose information about the quality and performance of seismic measuring equipment available today.
Testing and checking compliance of digitizer and seismometer equipment from different providers with the IMS technical requirements not only allow to ensure that all seismic stations in the IMS network are set for the mission of explosion monitoring but also provide invaluable feedback to equipment manufacturers on improvement of the equipment qualities and capabilities.
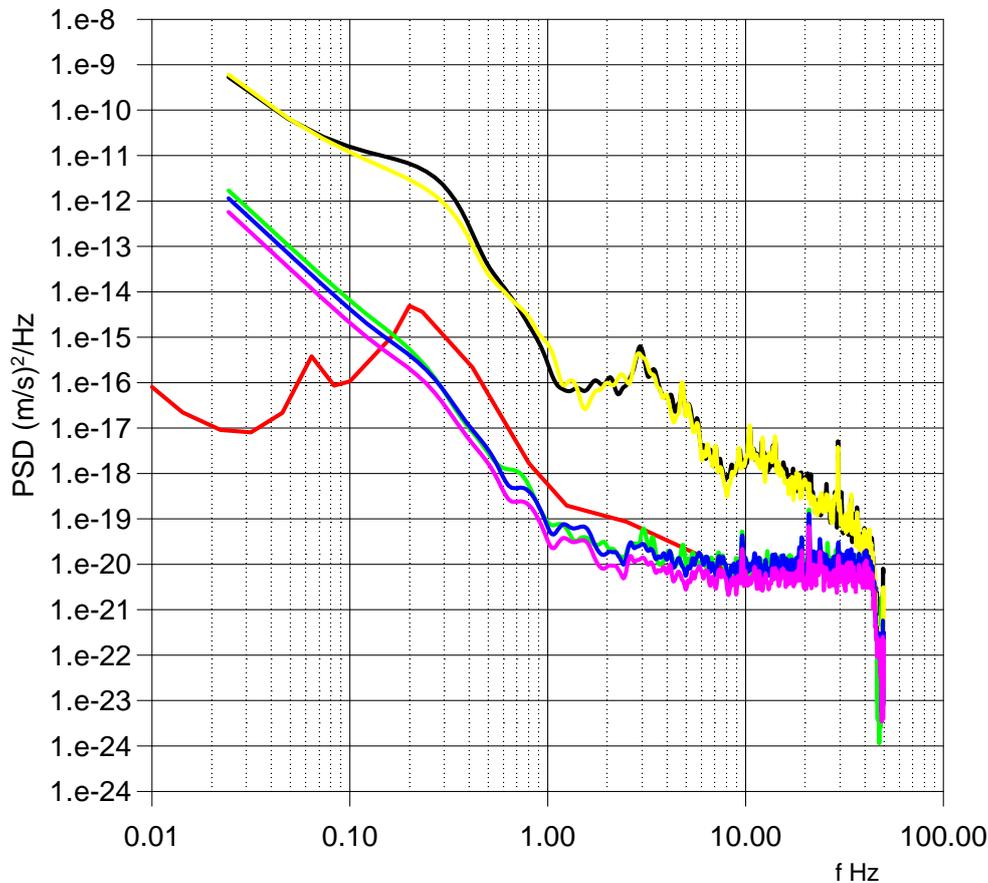
Side-by-side JEP-225 (PS22, Japan)

Figure 7. Estimation of the JEP-225 seismometer plus preamplifier self-noise for PS22 station, Matsushiro Japan. Self-noise (three channels: blue line, yellow line, red line) has been calculated for several data fragments using side-by-side method of channel noise estimation. Self-noise curves are compared against minimum background seismic noise for PS22 (green line) obtained during station site survey. Data were collected using the same Europa-T 24-bit digitizer for both channels. The NLNM is depicted with a red line.

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