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Amplitude response of a telemetered seismic system from seismometers to digital acquisition systems

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Abstract

Automated amplitude response of the complete seismometer, telemetry and recording system is obtained from sinusoidal inputs to the calibration coil. Custom-built software was designed to perform fully automatic calibration analyses of the digital signals. In this paper we describe the signals used for calibration and interactive and batch procedures designed to obtain calibration functions in automatic mode. By using a steady-state method we reach a high degree of accuracy in the determination of both the frequency and amplitude of the signal. The only parameters required by this procedure are the seismometer mass, the calibration-coil constant and the intensity of the current injected into the calibration coil. This procedure is applicable to telemetered seismic systems and represents an optimization of the processing time. The software was designed to require no modifications if the device used to generate the sinusoidal current should change. In particular, it is possible to change the number of monofrequency packages transmitted to the calibration coil with the only restriction that the difference between the frequency of two consecutive packages be greater than 5%; for these reasons the procedure is expected to be useful for the seismological community. The paper includes a general description of the designing criteria, and of the hardware and software architecture, as well as an account of the system's performance during a two year period of operation.

Key words *transfer function – seismic network – calibration method*

1. Introduction

Progress in computing resources often results in an improvement of the application performances of seismic instrumentation. The main purpose of this automatic procedure is the real time monitoring of proper functioning and the setting up of seismic stations. The «Istituto Nazionale di Geofisica» (hereinafter referred to as «ING») technicians periodically perform tests and calibration operations on the Italian Telemetered Seismic Network (ITSN) stations.

A computer code for the automatic analysis of the transfer functions of Telemetered Seismic Networks and digitally acquired data has been designed and has been operating at the ING since 1991.

With this procedure it is possible to obtain the amplitude response of the complete system from ground motion to final recording.

Thanks to this procedure, the transfer function is promptly and automatically determined in the ING data acquisition center located in Rome. The data resulting from the analysis are used to test the correct functioning of the stations.

An automatic calibration procedure has many advantages. In particular, it performs the acquisition and automatic calibration of the transfer functions, and it allows high precision in the connections with reduced working times.

Furthermore, the software procedure was specially designed to require no modifications when the characteristics of the applied signal change.

The parameters required to determine the transfer function are the mass, the calibration coil constant, and the current injected into the calibration coil. It should be stressed that this method can be directly applied to find the transfer function of any system equipped with a calibration coil.

The results obtained at the ITSN over a period of two years show that using a standard transfer function to compute the ground displacement may result in large errors.

2. Calibration method

The overall architecture of the Italian Telemetered Seismic Network has been described in detail by De Simoni and Di Giovambattista (1988). What follows is only an overview of the main features of the network design for a better understanding of the problems involved in calibration operations.

The hardware of the network can be schematically represented by several distinct modules. The centralized seismic network includes three main parts:

- remote stations;
- transmission system;
- data acquisition and recording systems.

Each station is equipped with an *S13 Teledyne Geotech* short period vertical seismometer with a natural period of 1 s and damping of 70% of the critical, and a *Kinemetrics* frequency modulator voltage controlled oscillator which amplifies band filters and modulates the signals. The signals are then transmitted over telephone lines or radio relay systems to the ING data acquisition center where they are finally demodulated and recorded both on analog recordings (thermosensitive paper Helicorder drums) and on digital devices with a sampling rate of 50 Hz (Mele, 1993).

The S-13 seismometers include a calibration circuit designed to receive special signals. This operation is equivalent to pushing the mobile mass of the sensor (Chapman *et al.*, 1988).

On the basis of the technical characteristics provided by the manufacturer we can determine the equivalent displacement of the ground due to the signal injected into the calibration coil. The output voltage produced by the seismometers during the calibration is telemetered similarly to the actual seismic signals and recorded in analogue mode on the drum recorders and on the digital acquisition systems. Digital voltage values are expressed in counts (1 count $\simeq$ 0.61 mV).

The steady-state calibration method allows the modulus of the transfer function to be determined, that is, the magnification for each value of the frequency used to excite the sensor. A current $i(t)$ circulating in a calibration coil with a G calibration constant produces a force (on the seismometer mass) equal to

$$F(t) = G \cdot i(t). \qquad (2.1)$$

For sinusoidal currents, $i(t)$ can be expressed as follows:

$$i(t) = i_0 \sin \omega t \qquad (2.2)$$

knowing the seismometer mass, the equivalent ground acceleration is:

$$a(t) = \frac{G \cdot i_0 \cdot \sin\omega t}{M}. \qquad (2.3)$$

Once the acceleration is known, we can determine the equivalent ground displacement by means of a double integration:

$$S(t) = S_0 \cdot \sin\omega t \qquad (2.4)$$

$$S(t) = -\frac{1}{M \cdot \omega^2} \cdot G \cdot i_0 \sin \omega t. \qquad (2.5)$$

A system transfer function is given by the spectral ratio between the output and the input signals. Therefore, the transfer function of the complete system (including the detection, transmission and acquisition of ITSN digital data), can be determined for any value of the angular frequency ω:

$$A(\omega) = \frac{y_0}{S_0} = \frac{y_0}{i_0 \cdot G} \cdot \omega^2 M \qquad (2.6)$$

where y_0 is the amplitude in counts.

In the steady-state calibration of the ITSN sensors, the signal transmitted to the secondary circuit consists of sinusoidal waves generated by a device designed by the ING laboratories (Romeo *et al.*, 1985) with frequency in the range 0.1 Hz and 4 Hz and current in the range 2 mA - 1 mA. These values are set according to the ITSN characteristics.

While the seismometer is being subjected to the excitation produced by the calibration signals, its output voltage is acquired and processed by means of the designed algorithm to determine the amplitude in counts for each value of the angular frequency ω. The previous formula does not involve approximations and the error associated with the computed amplification value depends on the accuracy of some characteristic values of the sensors and on the value of the current injected into the calibration coil.

Teledyne Geotech (Teledyne Geotech, 1976) supplies the value of the transducer mobile mass with a maximum tolerance of 1% and the value of the generator constant with a maximum tolerance of 2%.

The accuracy in the determination of both the amplitude values (counts) and the frequency of the acquired calibration signals is another fundamental factor in estimating the error associated with the complete amplification value. These values, which are determined from the parameters assumed in the algorithm, will be discussed later.

Table I contains the values of the parameters used in eq. (2.6) with the associated tolerance, while table II contains the errors associated with the values estimated by the procedure.

Table I. Values of the parameters used in eq. (2.6) with associated tolerance.

	Symbol	Value	Tolerance
Inertial mobile mass	M	* 5 kg	1%
Calibration coil-motor constant	G	* 0.1975 N/A	0.002 N/A
Calibration current	i_0	** 2 mA	5%
	$\frac{i_0}{2}$	** 1 mA	5%

* S-13 Operation manual (Teledyne Geotech, 1976); ** Romeo *et al.* (1985).

Table II. Errors associated with variables of eq. (2.6). The relative error depends on the maximum variation accepted around the mean value, computed on $2N$ half periods contained in the window T_{rec}, where $N = T_{rec} \cdot \omega$ and $T_{rec} = 27$ s; the error on the mean value depends on the burst frequency, and is referred to $\omega = (0.1 \div 4.0)$ Hz.

	Symbol	Relative error	Error on the mean value
Amplitude (counts)	y_0	$\Delta Y_0 = 4.5\%$	$\Delta y_0 = \frac{\Delta Y_0}{2N} = 0.02\% \div 0.83\%$
Frequency (Hz)	ω	$\Delta\Omega = 4.5\%$	$\Delta\omega = \frac{\Delta\Omega}{2N} = 0.02\% \div 0.83\%$

3. Polarity test

The S13 seismometers are supplied by the manufacturer complete with connectors that are used to transmit the output signal to the transmission system. A mistake made in the link of these connectors or other components of the amplification, transmission and registration system may cause an inversion of polarity *i.e.* a wrong representation of the direction of ground motion. The polarity of a station can be tested by adding weight to the seismometer mass and thus forcing it to move towards the ground. According to seismologic convention, this procedure, which is equivalent to a ground lift, must always be followed by a positive onset of the first pulse in the registered waveform.

The automatic procedure can perform the acquisition and the analysis of the polarity test.

4. Algorithm for the calibration analysis

We used the steady-state method to identify transfer functions of the seismograph system. Our goal was to develop a computer algorithm for revising theoretical ITSN transfer functions. This method consists in measuring amplitude values for discrete harmonic frequencies across the system passband (Mitronovas and Wielandt, 1975). This is a long procedure to follow but it is less affected by nonlinearities and by noise (Plesinger, 1993). The algorithm used in the automatic procedure was designed to compute the amplitudes in counts and the period in seconds for each set of monochromatic signals injected into the calibration coil. The procedure is based on a window moving on the digitally acquired data: the mean amplitude and period are computed for each monochromatic set of signals. The length of the window is set accordingly. A monochromatic set of signals is identified by performing a test based on the permanence of the frequency and amplitude within an assigned tolerance from the mean value. The tolerance is determined taking into account the fluctuations due to the telemetry system. The mean of the extreme values of the sinusoidal signals inside each moving window is computed in connection with the mean of the associated periods. The quality of the acquisition is evaluated by means of a simple pre-analysis based on the following conditions: the data are accepted if the maximum values differ from the mean values by less than 4.5%; the same tolerance is assumed for the periods. The length of the window (approximately 27 s) was set on the basis of the duration of the monofrequency burst (about 31 s) and of the attenuation time of the exponential factor (1.5 s maximum). The shift of the starting value of the window is assumed to be approximately equal to $\frac{2}{3}$ of the difference between the duration of the monofrequencies and the window length. These values represent a compromise between the running time and the number of recognized monochromatic packages transmitted to the calibration coil (usually 13 over 15). The error associated with the estimate of the amplitudes and periods was considerably reduced by assuming the mean value for each mobile window. Within the examined frequencies we used from 4-8 to 100-200 available values depending upon the analyzed frequency. The algorithm includes a filter used to reduce the high frequency noise when dealing with low frequencies. This filter consists of a running average of 1 s on a window with a shift of 1 sample. It does not introduce significant signal distortions for frequencies lower than 1 Hz.

5. Computer program

The system software was entirely written in FORTRAN language and runs on a VAX computer. The flowchart is shown in fig. 1. As we mentioned before, this procedure is used for the calibration of the complete system, including the seismometer, the transmission and the acquisition system.

The procedure was designed according to the following requirements:

– applicability to the routine calibration of an arbitrary seismograph system equipped with a calibration coil;

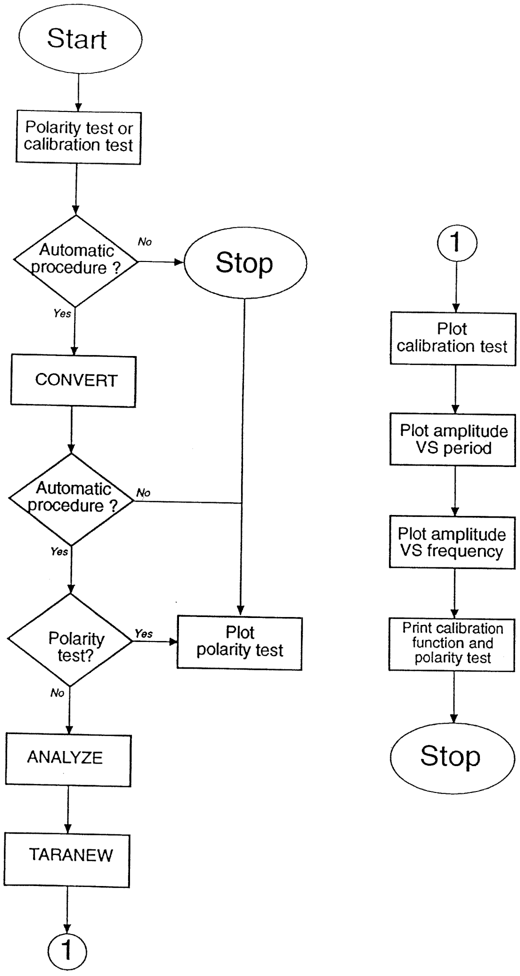

Fig. 1. Flowchart of the proposed calibration procedure.

– use of all the previous information on the transfer properties of the investigated system (zeroes, poles, scale factor of the theoretical transfer function and assumed accuracy of the individual parameters) (Di Maro, 1993);

– automatic quality check.

The procedure is divided into two main parts: the first concerns the acquisition and the analysis of the polarity test, and the second deals with the acquisition and analysis of the calibration function. It can be activated by a command procedure that defines the true logical names and the necessary privileges to perform the calibration acquisition. Furthermore, it can run in automatic or interactive mode and can be activated in all the acquisition systems running at the ING. The polarity test only requires typing a command that allows the acquisition and display of the corresponding output signal.

The procedure for the acquisition and analysis of the calibration signal is more complex. The calibration function is automatically plotted on a laser printer. Figures 2 through 4 show examples of the automatic output. A simple comparison between the theoretical and the experimental calibration functions allows us to verify that the station functions properly.

As we mentioned before, the automatic procedure may stop working depending on the results of the check performed on the acquired data. In case of high seismic or electronic noise the automatic procedure will stop and an error message will be displayed. This error usually occurs when electronic disturbances are recorded, in which case the portion of recording can be removed by means of a routine. Other special modules are available to analyze the acquired data when the automatic procedure does not run. For instance it is possible to cut out parts of the analyzed data if noise or any kind of interference are recorded.

Furthermore, the signal can be converted to SAC, Seismic Analysis Code of the Lawrence Livermore National Laboratory input standard format, and amplitudes and periods can be obtained using the picking utility. This utility is very useful in case the automatic procedure cannot run because of a high noise level. Indeed, in some cases the operator can interactively recognize the noise superimposed on the calibration signal.

6. Results

The calibration function of the ITSN is given using either *poles* and *zeroes* or *frequency-amplitude* formulations.

The standard format for GSE (Group of Sci-

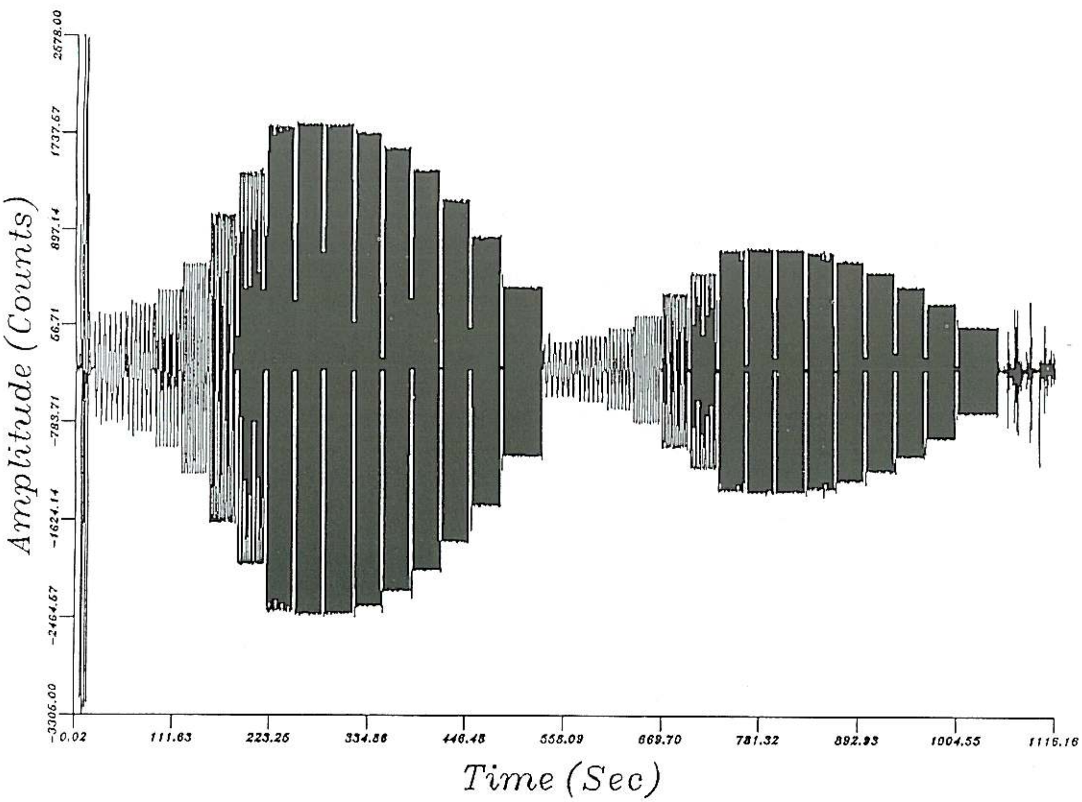

Fig. 2. Example of the calibration signal injected into the calibration coil of a sensor and digitally recorded at the ING data acquisition center.

entific Experts) waveform data exchange was followed (GSE, 1989) for both the representations. Poles and zeroes are defined so that the complex instrumental transfer function $T(\omega)$ relating ground displacement $G(\omega)$ to the recorded digital seismogram $S(\omega)$ is

$$S(\omega) = T(\omega)\, G(\omega) \tag{6.1}$$

where

$$T(\omega) = \frac{C\,\Pi_{i=1}^{n\,\mathrm{zero}}(s - \mathrm{zero}_i)}{\Pi_{i=1}^{n\,\mathrm{pole}}(s - \mathrm{pole}_i)} \tag{6.2}$$

ω is angular frequency ($\omega = 2\pi f$ where f is frequency in Hertz) and $s = j\omega$.

The modulus of $T(\omega)$ gives the number of units of ground motion in nanometers (nm) corresponding to one digital count at frequency ω.

The polynomials are specified by their roots. The roots of the numerator polynomial are the instrument zeroes, and the roots of the denominator polynomial are the instrument poles. Because the polynomials have real coefficients, complex poles and zeroes will occur in complex conjugate pairs.

The scale factor C was computed from the period-amplitude data determined by the automatic procedure. In this application we have N samples of the preprocessed and non-equally spaced experimental response h_i. Poles and zeroes are taken as fixed, *i.e.* the inversion proce-

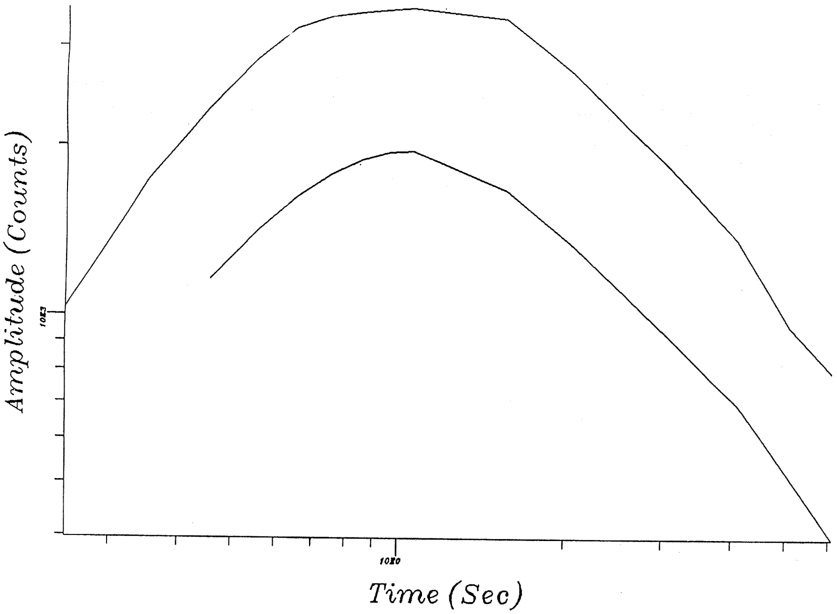

Fig. 3. Plot of amplitude versus period for the two calibration signals transmitted to the sensors with current i_0 and $i_0/2$ and acquired at the ING data acquisition center.

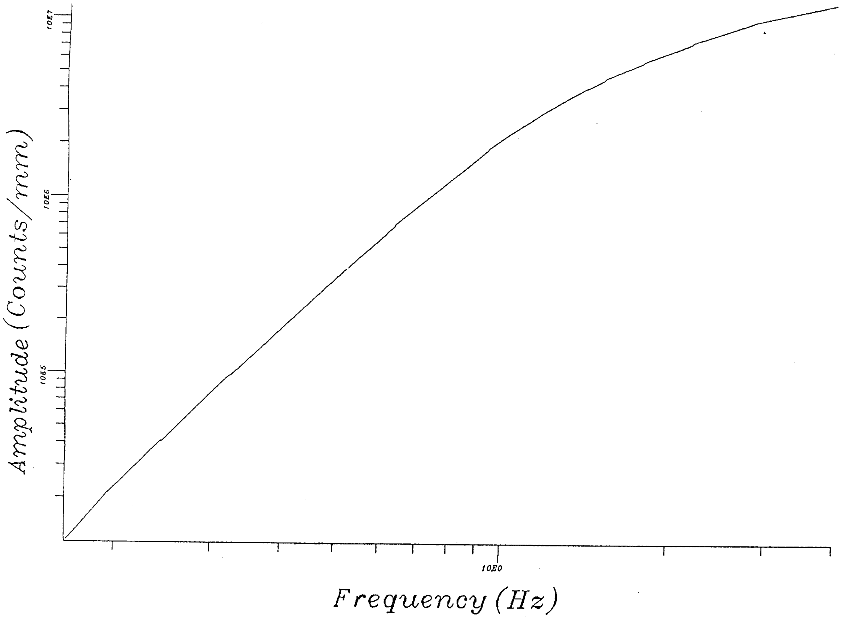

Fig. 4. Amplitude response versus frequency of a ITSN station.

dure does not alter them. To obtain the scale factor that gives the best fit of the experimental data, we compute for each value of the frequency the C_i value obtained from the ratio between the experimental and the theoretical value computed in (6.2) assuming that $C = 1$. The C_i values associated with frequencies that are less affected by noise are weighted more than the others. The minimum and maximum of the computed values are then determined, and starting from an interval ranging from $C_{\max} + \delta C$ and $C_{\min} - \delta C$ we compute the least-square fit with an $\in$ increment of 1 count/nm. The C value for which we obtain the best fit of the experimental data is then assumed as scale factor to determine equally-spaced values of the calibration function.

The limitations of the automatic calibration procedure are represented by the ratio of calibration signal amplitude to seismic background noise. Indeed, if the ground noise is too high the maximum value of amplitudes and periods of each monochromatic signal may differ from the mean value by more than 4.5%, thus preventing the automatic procedure from working.

Figure 5 shows some calibration functions of stations working at the same nominal amplification, together with the theoretical transfer function. Comparing the theoretical transfer functions to those obtained for several stations having the same amplification shows significant differences between the experimental and theoretical amplifications. Using a standard

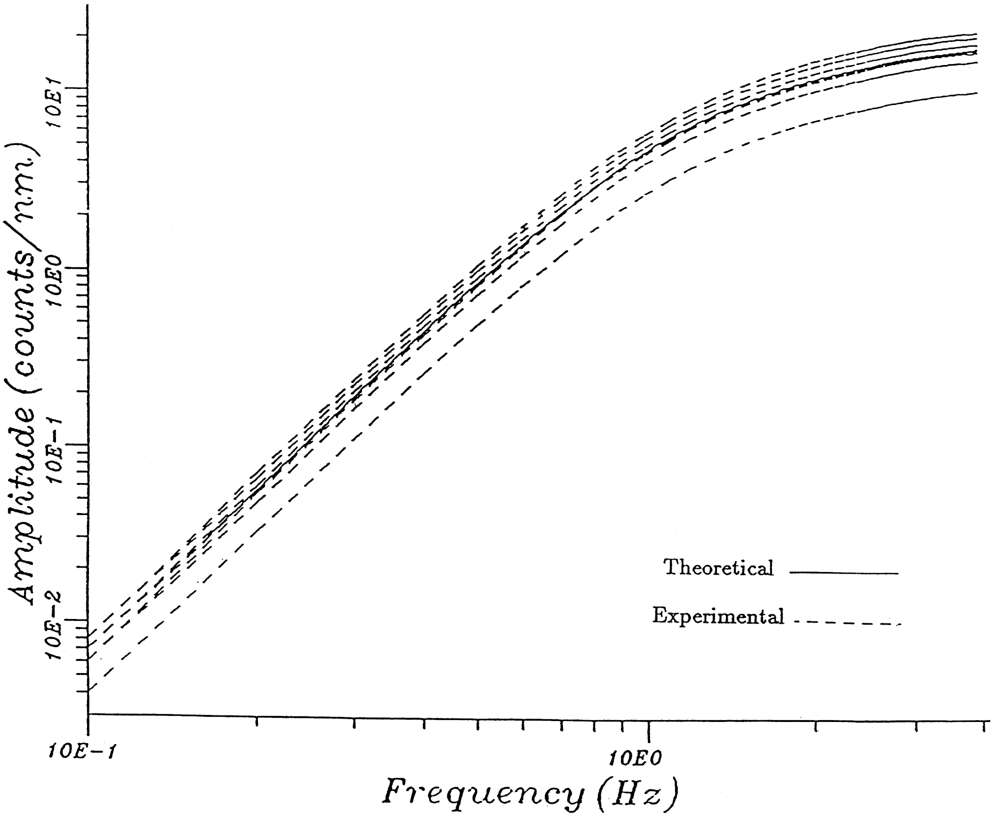

Fig. 5. Calibration functions of stations working at the same nominal amplification.

transfer function to compute the ground displacement may result in large errors. The differences demonstrate that some seismometers and, more likely, other components of the transmission system are not ideal instruments and therefore cannot be represented by nominal parameters.

7. Discussion

Many approaches to identify seismograph system transfer functions are described in literature.

In our procedure we make use of a steady state calibration method; this method is time consuming, but insensitive to nonlinearities and less affected by noise (Plesinger, 1993).

Other approaches, like the transient method, are faster to apply, but need correlation filtering to reduce noise (Berg and Chesley, 1976). The *random binary signal* method (Berger, *et al.*, 1979; Steck and Prothero, 1989) offers more advantages than the steady-state method or the transient one, but we cannot apply this procedure because of the increasing difficulties of generation and acquisition of particular calibration signals.

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