SEISMOMETER CALIBRATION: REMOTE NUMERICAL PROCEDURE APPROACH

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Abstract

A typical seismic station of the Slovenian National Seismic Network is equipped with a Quanterra Q730 data- logger and a broadband Güralp CMG 40T seismometer. While the producer of the seismometer guarantees long term stability of the sensor transfer properties a question regarding this guarantee arises. That is the reason why the calibrations of sensors need to be performed periodically. Typical parameters for broadband seismometers are damping and its natural period. For CMG 40T seismometer the natural period is 30s and the damping factor is 0.707. In order to control the stability of the seismometer it is sufficient to evaluate these two parameters only. A computer software tool has been developed which starts calibration on request and automatically analyzes the seismometer`s output signal. This task is performed telemetrically using the step calibration signal built in Quanterra 730 data-logger. A reconstruction filter used to set up a smooth analogue signal from the output of a DAC causes that step-type excitation function rises to its maximum value in a finite length of time τ, having a value around half of a second. The rise time affect the result. Another disadvantage using the built-in calibration signal is that start time of the calibration signal is unknown.

The algorithm for the precise determination of the corner period and damping for seismometer using step calibration pulse is developed which does not require the exact data regarding the start time and amplitude of the calibration pulse and also allows non-ideal step calibration signal with unknown rise time, e.g. much lover than sampling time. The algorithm is not very sensitive in the high-frequency range of the seismic noise and in the presence of the long-period portion of seismic noise the error can be estimated as well. The above procedure is useful in modern digital seismological system and allows fast and simple regular verification of the stability of seismometer`s transfer properties.

Keywords: seismometer, step calibration.

Presenting Author's biography

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1 Introduction

The earthquake on 12 April 1998 in the Upper Soča Valley, Slovenia, which caused major damage in the wider earthquake area, showed that the Slovenian seismological service was not adequately equipped. For this reason, the Government of the Republic of Slovenia secured the funds and appointed the Seismology and Geology Office (USG) of the Environmental Agency of the Republic of Slovenia (EARS), at that time organized as Geophysical Survey of Slovenia, to upgrade and improve national seismic network, which at those time consist of 6 digital seismic stations. At the end of the project of the modernization of the SNRS (Seismic Network of the Republic of Slovenia), the network will consist of 26 modern broadband stations (Fig.1).

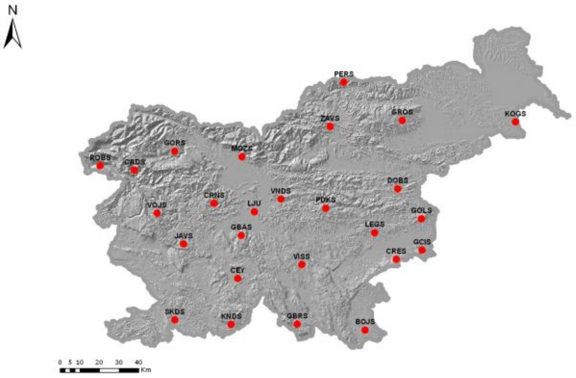

Fig. 1 Seismic network of the Republic of Slovenia

After comprehensive site selection studies and an international bid for the instrumentation, the network has been gradually built with the first new stations put into permanent operation at the beginning of 2002. At present (June 2007) 23 new permanent seismological stations are operating, while three more are already built but not yet connected. All are broadband stations and are sending data in real time to the SNRS (Seismic Network of the Republic of Slovenia) data centre at the USG in Ljubljana. The standard equipment is a Quanterra Q730 data-logger equipped with precise GPS timing system and a Guralp CMG-40T seismometer. Sampling rates are 200sps, 20sps and 1sps. There are a lot of Quanterra seismic digital acquisition units used all around the world, as is known as the observatory seismology technology leader for more than 20 years. For the financial reasons, medium quality and narrower band Guralp CMG-40T seismometers were purchased. This is a three-component seismometer, completely waterproof and self-contained apart from the external dc power supply and recording device, with a response which is flat to velocity from 50 Hz to 0.033 Hz (30 s) and with the dynamic range (or signal to noise ratio) more than 136 dB. The damping coefficient for sensor transfer function is β=0.707. The standard specification corner frequencies is 0.033Hz (period is To=30s) [1]. While the producer of the seismometers guarantees long term stability of their transfer properties a question remains if this is really the case. Also for this reason, verification of seismometer's transfer properties needs to be periodically performed. Manufacturer's suggestion is ones per year.

The verification can be done in absolute terms by evaluating the transfer function of the system, also known as the calibration of seismometers, or just partially, where some characteristic parameters of the seismometer are evaluated. Which approach to use depends on the nature of the calibration procedure, the technical feasibility, the cost and time availability. The most direct way to obtain an absolute calibration is by using a shake table, but precision is usually poor outside a frequency band roughly between 0.5 to 5 Hz [2]. Additional disadvantage of this approach is that the sensor has to be moved from its location (a seismic shaft) to the laboratory, where it should be in a stable environment requiring temperature stabile chamber not only in the time of doing verification but also hours before the verification begin [3]. During all this procedure, seismic station is not operational. In-situ measurement of the seismograph system transfer function is also possible with the help of a standard impulse and harmonic calibration signals [4], but recorded calibration and response signal of the system are necessary. For this reason visiting the seismic station is needed for temporary redesign of acquisition system. Opening the shaft and connecting the seismometer to some special calibration unit cause some disorder and the whole system should be stabilized again, while the procedure is time consuming.

All mentioned procedures request additional equipment and staff and are time consuming…

System performance may be specified in terms of some characteristic parameters instead of the complete bandwidth. Typical characteristics of broadband seismometers are the damping factor and its natural period which can be easily evaluated using the step calibration signal built in the modern seismic acquisition units, where amplitude of the step signal and exact time of start of calibration signal is known. Knowing the step response gives us the information regarding the stability of such a system. The calibration signal, which is built in the seismic acquisition units, can be initialized telemetrically and immediately after calibration measurements the seismometer can be automatically set into normal operation mode.

The step response is the time behavior of the outputs of a seismological system when its inputs change from 0 to some value in a very short time and is of considerable importance in seismological context [5]. The quality of step calibration signal is of great importance in the precise definition of seismometer characteristics and is expected, that producer of acquisition units takes care about quality of test calibration signal. But during first measurements we found that in the case of the Quanterra Q730 acquisition unit, the step-type excitation function rises to its maximum value actually in a finite length of time τ, called the rise time, which is around half of the second. Using all known algorithms, this rise time affects the result. Also start time of the calibration signal is incorrectly entered into local “log” file. Regards to this, information about amplitude of input signal is questionable. Relatively long rise time is caused by reconstruction filter [6]. The sampling theorem describes why the input of an ADC requires a low-pass analog electronic filter, called the anti-aliasing filter. For the same reason, the output of a digital to analogue converters (DAC) requires a low-pass analog filter, called a reconstruction filter. A reconstruction filter is used to construct a smooth analogue signal from the output of a DAC [7].

Considering the above mentioned problems, we have developed a precise algorithm to analyze the response signal, caused by Q730 built-in calibration signal, in time domain. The algorithm is not very sensitive to the rise time τ of the step excitation signal and does not need information about the start time and the amplitude of a calibration signal. The algorithm is also not very sensitive in the high-frequency range of the seismic noise.

2 Fundamentals

A seismometer can be represented as a second order single degree-of-freedom linear system with damping, where damping force is proportional to velocity. This approach is valid for the long period spectrum of a broadband seismometer [3]. For an inertial seismometer ground acceleration is equivalent to the calibration current forced into the calibration coil. The system response $y(t)$ can be written in the simple form

$$y(t) = \omega_0 \xi \left[\frac{e^{(-\omega_0 \beta\, t)}}{\sqrt{1-\beta^2}} \sin(\omega_0 \sqrt{1-\beta^2}\, t) \right] \tag{1}$$

Using relation $T_0 = 2\pi / \omega_0$, the response of the system $y(t)$ to the step input as function of time t is defined by the following parameters: the damping β, the natural period T_0, the time t and the amplitude ξ of a step calibration signal:

$$y(t) = \begin{cases} f(\beta, T_0, t, \xi) & t \geq 0 \\ 0 & t < 0 \end{cases} \tag{2}$$

where t=0 is start time of the calibration signal. Theoretically, β and T_0, can be evaluated analytically by observing the response of the system to a step input. For damping β the ratio of amplitudes of two neighbors extremes can be used [5], or the time difference of first extreme and zero crossing can be used

$$\beta = \sqrt{\frac{1}{\left[\left(\tan\left(\frac{\pi t_{ext}}{t_{zero}} \right) \right)^2 + 1 \right]}} \tag{3}$$

The natural period T_0 can also be evaluated using first extreme

$$T_0 = \frac{\left(\sqrt{1-\beta^2} \right) 2\pi t_{ext}}{\left(\arctan \frac{(\sqrt{1-\beta^2})}{\beta} \right)} \tag{4}$$

In practice, the evaluation of these two parameters from real data is not a simple task. In practice information contained in digitized transient response is distorted due to the background noise of different origin. The equilibrium position and peak values are affected by the seismic noise and also by the sampling rate of acquisition units. For this reason numerical approach is more appropriate.

3 Numerical evaluation of T_0 AND β

Let the vector Y, $Y = [y_i, y_{i+1}, y_{i+2}, ..., y_{i+n}]$, represent the observed digitalized output signal from the seismometer. The index 'i' represents the start of calibration signal. If start time t_i and the amplitude of a step calibration signal ξ is known, β and T_0 can be evaluated in the time domain with the help of synthetic trace, where the synthetic trace is an analytical (theoretical) response of the system. Suppose that our synthetic trace $S_{k,l}$, $S_{k,l} = \lfloor s_{i(k,l)}, s_{i+1(k,l)}, s_{i+2(k,l)}, ..., s_{i+n(k,l)} \rfloor$, is modeled by a function that depends on parameters β_k, T_l, ξ and t

$$s_{k,l}(t) = f(\beta_k, T_l, t, \xi)\,. \tag{5}$$

We try to find the values for β and T_0 that fit the synthetic trace as close to the original one as possible. For β_k and T_l, the Euclidian distance D_E between synthetic trace S and actual output Y is calculated

$$z_{k,l} = D_E(Y, S_{k,l})\,. \tag{6}$$

For all β_k and T_l, such parameters β and T_0 are chosen as a solution of f_D, where the Euclidian distance is smallest of all

$$f_D(\mathbf{Z}\ ) = \beta_K, T_L \ni: z_{K,L} \leq z_{k,l} \text{ for } \forall k,l \tag{7}$$

This can be done in many different ways. E.g. an iterative method attempts to solve a problem by finding successive approximations to the solution starting from an initial guess. In our procedure values

β and T_o are estimated using nonlinear least-squares data fitting, where the Gauss-Newton method is used. The Gauss-Newton algorithm is used to solve nonlinear least squares problems. Initial guess for the parameter vector p, $p^0=[\beta_{\text{factory}}, T_{o\_\text{factory}}]$ is provided by user and are values defined in a factory calibration sheet. Given an approximate solution, a new approximate solution is computed based on local linearization about the current point using the Jacobian matrix of the residual function (residual between the actual output of the system Y and synthetic trace $S(\beta^n, T_o^{\ n})$), which results in a linear least squares problem to be solved for the step to the new approximate solution. This process is repeated until convergence [8].

4 If amplitude and the start time of step signal is unknown

When the amplitude ξ of step function is not known, we have to transform a function $f(\beta,T,t,\xi)$ in into function $\Phi(\beta,T,t)$ that does not need information about the amplitude of the step. For the synthetic trace it can be done in two steps. With the first step the amplitude of the step calibration signal is normalized, $\xi = 1$. In the second step, the synthetic trace is normalized

$$\hat{S}(t) = \frac{S(t) - \min(S)}{\max(S)} = \Phi(\beta,T,t) \tag{8}$$

The synthetic trace $\hat{S}(t)$ is a normalized trace of S. The equation can be rewritten as nonlinear function that depends only on parameters β, T_0 and t. The trace is normalized between the values 0 and 1. In the same way, the actual output of the system Y has to be transformed

$$\hat{Y}(t) = \Phi_Y(Y(t)) = \frac{Y(t) - \min(Y)}{\max(Y)} \tag{9}$$

Values β and T_o are estimated using previous description of the nonlinear least-squares data fitting. For numerical procedure, output data Y should contain enough information to be used in iterative procedures. The signal must be of sufficient length that the processing yields an optimal result. For T_o=30s and β =0.7071 the Y data should have information of at least three zero crossings, coming to more than 63.4s. In our numerical experiments, using a sensor with $T_0 \sim$ 30s, a 70s time interval is used.

If the start time of calibration signal is not precisely known the output of the system Y can be erroneously defined. In our procedure the unknown start time of step calibration signal does not cause any problems only the computing time increases. Let the vector O, $O = [o_0, o_1, o_2, ..., o_i, ..., o_k, ..., o_m]$, represents the observed output signal from the seismometer. The index '$_0$' represents the start of recording, and the index 'i' the start of the calibration signal which is not known. The vector Y_l is a sub vector of vector O,

$$Y_l \subset O\,;\; Y_l = [o_l, o_{l+1}, o_{l+2}, ..., o_{l+n}];\;\; n < m, \tag{10}$$

and $\hat{Y}_l = \Phi_Y(Y_l)$ is its transform. Let the values β_l, T_l represent the best estimation for $\hat{Y}_l$ (values β_l, T_l are solution for nonlinear least squares problem), $\hat{S}_l$ is synthetic trace $\hat{S}_l(t) = \Phi(\beta_l, T_l, t)$ and z_l is Euclidian distance D_E between vectors $\hat{Y}_l$ and $\hat{S}_l$:

$$z_l = D_E(Y_l, S_l); Z = [z_0, z_1, ..., z_l, ..., z_n] \tag{11}$$

The start time $t_{\hat{i}}$ of a step calibration signal (and best β and T_0) is chosen as the solution of f_D, where Euclidian distance is smallest at all:

$$f_D(\mathbf{Z}) = t_{\hat{i}}, \ni: z_{\hat{i}} \le z_l \text{ for } \forall l = 0,1,2,3,...n. \tag{12}$$

Numerical experiment: a response of 10000 different cases with damping β=0.7071+dβ and T_0=30s +dT in time interval length of 70s was designed, where dβ is randomly chosen on an interval [-0.0177, 0.0177] and dT is randomly chosen on an interval [-1s,1s]. The sampling frequency is 200 sps. Initial values were set to T=30s and β=0.7071 respectively. Results: the start time was correctly defined at 100%, without an error and the relative error for β and T_0 was less than 10^{-11}.

5 Influence of seismic noise - quasi normalized signal

Seismic noise affects the estimated values. If we just normalize the output signal between the values 0 and 1 we get an unpredictable error, which strongly affects the result. The higher is amplitude of seismic noise, the greater is the error of estimated parameters. For this reason we need to take the seismic noise into the account while normalizing the signal. So we define a quasi-normalized signal. Equation (9) is corrected to

$$\hat{Y}(t) = \frac{Y(t) - \min(Y) - noisedown}{\max(Y(t) - \min(Y) - noisedown) - abs(noiseup)}\,. \tag{13}$$

The values *noiseup* and *noisedown* depend on the local seismic noise around maximum and minimum values of the output signal. Because of the seismic noise, the maximum value of the quasi-normalized signal could be a little higher than 1, and its minimum value could be a little lower than 0. For the value *noiseup* we have to first define the vector $Y_{\max} = [y_{\max-k1}, ..., y_{\max}, y_{\max+1}, ..., y_{\max+k1}]$ where $\hat{y}_{\max}$ is the maximum value of the response signal Y. The vector $Y_{\max}$ is a sub vector of vector Y. Because of the seismic noise the value $\hat{y}_{\max}$ does not represent theoretical maximum value of the response signal. Then the coefficients of a polynomial of degree 3, $p(t_i) = p_1 t_i^3 + p_2 t_i^2 + p_3 t_i^1 + p_4$ that fits $Y_{\max} = [y_{\max-k1},..., y_{\max}, y_{\max+1},..., y_{\max+k1}]$, are evaluated in a least squares sense. Value *noiseup* is defined as the difference *noiseup* =*max*(Y_{max})-max(*P*) where *P* is $P = [p(t_{\max-k1}),..., p(t_{\max}), p(t_{\max+1}),..., p(t_{\max+k1})]$.

The procedure for value *noisedown* is similar as the procedure for a value *noiseup*, only that we are now looking for coefficients of a polynomial that fit data with $Y_{\min}$; $Y_{\min} = [y_{\min-k2},..., y_{\min}, y_{\min+1},..., y_{\min+k2}]$. The value *noisedown* is defined as difference *noisedown* = *min*(*P*)-*min*(Y_{min}). The values of index k1 and k2 (time interval) can also differ from each other. For system with β ~ 0.7 and T_0 ~ 30s the following values of parameters are experimentally evaluated: k1=0.15s and k2=0.3s.

Numerical experiment: We have taken some real seismic noise data from the seismic station LJU at the middle of the day. Since this seismic station is located close to city Ljubljana these data represent a real noise situation. The noise data multiplied by a constant is added to the signal, which represents the response of sensor to an ideal step. 10000 different systems of second order were created. In these systems we use as parameters uniform and randomly defined natural periods in the interval [29.0s and 31.0s] and uniform and randomly defined damping values in the interval [0.6900 and 0.7240]. For these system parameters β and T_0 were evaluated using the previously described procedure. Systems where inputs are quasi-normalized signals, give significantly better results (Figure 2) compared to systems where normalized signals are used (Figure 3).

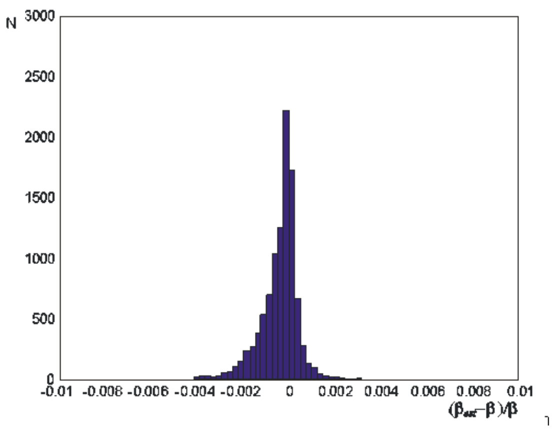

Fig. 2 Evaluated damping, where inputs are quasi-normalized signals

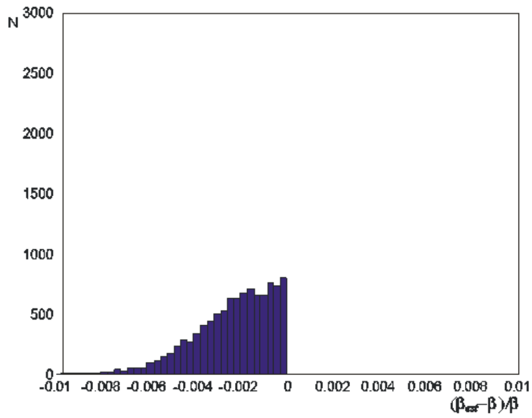

Fig. 3 Evaluated damping, where inputs are normalized signals

6 Real data estimation

Algorithm was developed in the end of the year 2003 and after that seismometers were (after installation at the seismic station) regularly checked at least once a year. Whole system consists of three different units: the seismic monitoring station (equipped with a Quanterra 730 data-logger and a seismometer CMG 40T), the SUN work station equipped with Solaris OS and Antelope acquisition software) where waveform data is collected, a PC unit (with Windows OS and our own software which automatically analyzes response signals). Both the SUN and PCs are located at the data centre at the USG in Ljubljana. The PC sends a calibration request to Quanterra 730 and after that extracts data from the Sun working station and analyzes waveform data automatically. Units communicate via TCPIP protocol.

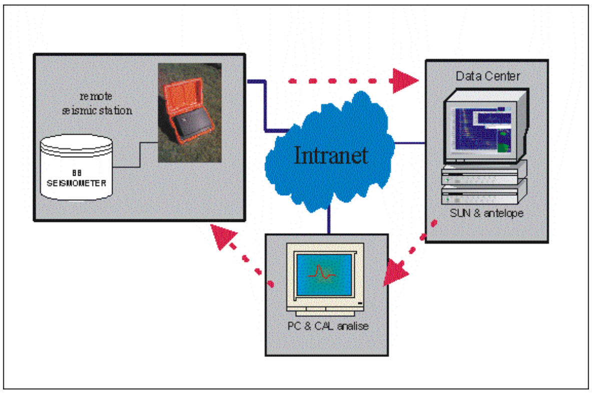

Fig. 4 System description: a PC triggers a calibration signal in Q730, Q730 starts to send the current to the sensor calibration circuit and also starts sending digitized data from the sensor to the Sun work station in real time. After calibration procedure, the PC extracts data from the SUN work station, stores them in its local memory unit, automatically estimates necessary parameters from response signal and releases a report.

Algorithm which automatically estimates necessary parameters from response signal goes on as follows:
- a response signal of 900s duration is extracted form buffer,
- the start point of the searching interval is automatically defines,
- a signal of 70s is select at the beginning of searching interval,
- the range of seismic noise is estimated, quasi-normalized response signal is formed with respect to seismic noise, and the damping and corner period are evaluated,
- procedure is repeated to the end of the searching interval,
- the best fit is defined as best estimates of the damping and corner period, report is automatically print.

The factory specification corner period for all sensors CMG 40T is *To*=30s, the damping coefficient is β =0.707. According to our tests, the results for some sensors differ from the factory specification almost 5 %, but parameters are relatively stable and with this procedure we did not observe any significant changes during the four year period. Example for seismometer CMG 40T (s/n = T4B28), located at seismic station PDKS, is in Table 1.

Tab. 1 Evaluated parameters for three-component seismometer CMG-40T s/n T4B28. Result of every year testing.

YEAR	To			β		
	E-W	N-S	Z	E-W	N-S	Z
2004	30.5	30.3	30.1	0.698	0.700	0.698
2005	30.6	30.4	30.2	0.698	0.700	0.698
2006	30.6	30.4	30.2	0.698	0.700	0.698
2007	30.6	30.4	30.2	0.698	0.700	0.698

7 Improvements of algorithm

Our goal is to analytically describe the recorded response of the system but the system response, as is in equation (1) do not take into account, that step calibration function is not ideal but rise to its maximum value in a finite length of time. For this reason precise definition of seismometer characteristics is limited. It is only enough to simply control the stability of seismometer. Accuracy can be improved, if instead of equation (1) a step-type excitation functions having finite rise time can be used. The response of two such functions can be analytically obtained, the step calibration function with constant slope front is:

$$f_{slope}(t) = \begin{cases} \xi \dfrac{t}{\tau_o} & 0 \le t \le \tau_o \\ \xi & \tau_o \le t \end{cases} \qquad (14)$$

and step function with exponential asymptotic rise is:

$$f_{epx}(t) = \xi(1 - e^{(-at)})\,;\ 0 \le t. \qquad (15)$$

The response of the system for step calibration function with constant slope front is

$$y_{slope}(t) = \frac{\xi}{\tau}\left[1 - e^{(-\omega_0\beta\, t)}\left(\cos(\omega_d t) + \frac{\beta}{\sqrt{1-\beta^2}}\sin(\omega_d t)\right)\right]$$

for $0 \le t \le \tau$ and

$$y_{slope}(t) = \frac{\xi}{\tau_o}\left(e^{(-\omega_0\beta\, t)}\left(\left(e^{(\omega_0\beta\, \tau_o)}\cos(\omega_d(t-\tau_o)) - \cos(\omega_d t)\right)\right)\right) + \qquad (16)$$
$$+ \frac{\xi}{\tau_o}\left(e^{(-\omega_0\beta\, t)}\left(\frac{\beta}{\sqrt{1-\beta^2}}\left(e^{(\omega_0\beta\, \tau_o)}\sin(\omega_d(t-\tau_o)) - \sin(\omega_d t)\right)\right)\right)$$

for $\tau_o \le t$, with $\omega_d = \omega_0\sqrt{1-\beta^2}$. The response of the system for step excitation function with an exponential asymptotic rise is

$$y_{\exp}(t) = \frac{\omega_0^2 \xi a \exp(-at)}{(\omega_0^{\,2} - 2a\omega_0\beta + a^2)} + \frac{\omega_0^2 \xi a \exp(-\omega_0\beta\, t)}{(\omega_0^{\,2} - 2a\omega_0\beta + a^2)} \times$$
$$\times\left(\frac{(a-\omega_0\beta)}{\omega_0\sqrt{1-\beta^2}}\sin((\omega_0\sqrt{1-\beta^2})t) - \cos((\omega_0\sqrt{1-\beta^2})t)\right) \qquad .(17)$$

Following previous mentioned procedure, the synthetic trace $\hat{S}(t)$ in eq. (8) in now transformed in function with additional parameter, regards to the excitation signal

$$\hat{S}_{slope}(t) = \Phi_{slope}(\beta, T, \tau_o, t),\ \hat{S}_{\exp}(t) = \Phi_{\exp}(\beta, T, a, t) \qquad .(18)$$

Example of using these two functions in the procedure of evaluating seismometer parameters are in Table 2 and Table 3. Relative error between procedures is less than 0.4‰. With the help of both procedures we can precisely define seismometer parameters. Differences between solutions can be as result of more complex transfer function of seismometer Guralp CMG-40T. It consists of three poles and three zeros [1].

From the Table 2 and Table 3 it is also evident that the transfer function is slowly changing. This can be also established if data about magnitude and phase at frequencies 0.033Hz, which is in calibration data sheet (the specification from the year 2001), is compared with evaluated one (Table 4).

Tab. 2 Evaluated parameters for seismometer CMG-40T s/n T4B28, where the function with constant slope front is used.

YEAR	*To*			β		
	E-W	N-S	Z	E-W	N-S	Z
2004	30.49	30.30	30.11	0.6980	0.6998	0.6979
2005	30.54	30.35	30.15	0.6982	0.6999	0.6981
2006	30.59	30.39	30.19	0.6983	0.7000	0.6981
2007	30.63	30.42	30.23	0.6988	0.7002	0.6981

Tab. 3 Evaluated parameters for the three- component seismometer CMG-40T s/n T4B28, where the function with exponential asymptotic rise is used.

Year	To			β		
	E-W	N-S	Z	E-W	N-S	Z
2004	30.48	30.29	30.10	0.6981	0.6999	0.6980
2005	30.53	30.34	30.14	0.6983	0.6999	0.6981
2006	30.58	30.38	30.19	0.6983	0.7000	0.6981
2007	30.62	30.41	30.22	0.6989	0.7003	0.6982

Tab 4. Changes of specification through time. Data from the calibration sheet (year 2001) and evaluated data.

Year	Magnitude (@0.033Hz)			Phase [deg] (@0.033Hz)		
	E-W	N-S	Z	E-W	N-S	Z
2001	*-2.8*	*-2.9*	*-2.9*	*-89*	*-90*	*-90*
2004	-2.8	-2.8	-2.9	-89	-89	-90
2005	-2.8	-2.8	-2.9	-89	-89	-90
2006	-2.7	-2.8	-2.8	-88	-89	-89
2007	-2.7	-2.8	-2.8	-88	-89	-89

8 Conclusion

The algorithm for precise determination of corner period and damping for seismometers is presented. Algorithm was developed for systems, where step calibration signal, built in seismological acquisition system Quanterra Q730 is used. On these systems, step excitation signals raise to its maximum value in a finite length of time τ, having a value around half of a second. Whole task is performed automatically and telemetrically and is regularly used at Environmental Agency of the Republic of Slovenia, Office of Seismology and Geology from the year 2004, to check the stability of seismometers of Seismic Network of the Republic of Slovenia. According to our tests the results for some Guralp sensors differ from the factory specification by almost 5%. This error is not significant for the local earthquakes, but it should be taken into account for teleseismic data, where period exceed 10s. From our result is also evident, that specifications of seismometers slowly change but so far these changes are negligible.

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