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MAGNIFICATION OF WWSS LONG-PERIOD SEISMOGRAPHS

by

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Abstract

To adjust the magnification M of long-period seismographs to the prescribed value at 15 seconds, the standard calibration constant $K = 0.449$ N/m is used in the World-Wide Seismograph System Network for both horizontal and vertical seismographs and for the whole range of magnification from 375 to 6,000. This calibration constant agrees well with the constant of the vertical seismograph calculated using the following standard instrumental constants: seismometer period 15 seconds and damping constant 0.9, galvanometer period 98.1 seconds and damping constant 1.0, coupling coefficient up to 0.05 (*i.e.* $M \leqslant 1{,}500$ approximately). With increasing coupling the calibration constant decreases steadily and reaches only 89 per cent of the above-mentioned standard value for a theoretical maximum coupling coefficient of the seismograph which is equal to 0.8. The calibration constant of the horizontal seismograph is systematically about 4.5 per cent smaller due to the smaller effective mass of horizontal seismometers.

For actual seismographs with certain deviations between instrumental constants and standard values, the true calibration constant can easily be calculated. The correction terms were approximated by polynomials, the coefficients of which were derived for maximum deviations of particular constants up to ±10 per cent. The transient (with corrected calibration constant) and steady-state calibration of seismographs at Nurmijärvi (NUR) were compared. The deviations of magnification from the mean value obtained by both methods did not exceed 2 per cent.

1. *Introduction*

In order to solve certain dynamical problems of seismic wave propagation the course of ground movement should be known. The recorded trace of the seismograph is distorted by the transient and the frequency-dependent amplitude and phase response of the measuring system. The general transfer function for the seismogram correction is determined exactly using certain constants of the seismograph. The minimum cardinal constants of the electromagnetic seismograph are given by the periods of the seismometer T_s, and galvanometer T_g, and the corresponding damping constants D_s and D_g, the coupling coefficient σ^2 and some amplitude scaling factor. The checking and regulation of all these basic constants should be made in order to obtain the prescribed transfer function. The same applies to the usual magnification curve and phase delay of the seismograph which are sufficient for the correction of steady-state harmonic oscillations of the seismogram.

The complete basic constants of long-period seismographs of the World-Wide Seismograph System were not published in the Operation and Maintenance Manual [1]. Only the two periods T_s = 15 s and T_g = 100 s and the galvanometer damping constant D_g = 1.0 have been prescribed and checked in the calibration procedure [2]. In this case the magnification curves and phase shift given in Appendix B [1] are used when correcting the seismogram amplitudes. The absolute magnification at period T = 15 s is checked using step-function excitation of the seismometer mass using the so-called calibration constant K = 0.449 N/m.

The complete set of constants available in [3] and another specially requested from the USCGS [4] are given in Table 1 (II, III). There are some differences in seismometer and galvanometer damping constants and also coupling coefficients. On the basis of measurements at the Nurmijärvi seismic station [12] and data supplied by USCGS [4] another constant set of long-period seismographs was decided upon. The galvanometer period T_g = 98.1 s is the true free period according to the calibration convention (the measured period of the galvanometer equals 100 seconds) taking into account the open-circuit damping constant of the galvanometer which is about 0.2. The damping constant of the seismometer (D_s = 0.9) was chosen as the average value of different measurements. The rough estimate of the coupling coefficient for maximum magnification 6,000 at 15 seconds is 0.4 – 0.6 for the Nurmijärvi horizontal and vertical seismographs. To include the values given in [3] the maximum coupling coefficient must be increased to 0.8. This is the maximum attainable coupling coefficient of the long-period seismograph if the seismometer signal coil is directly connected to the galvanometer coil without shunting the galvanometer. As there is no additional seismometer damping apart from the electromagnetic damping in the signal circuit, and the open-circuit mechanical

Table 1. Long-period seismograph constants.

References	[1, 2]	[3]	[4]	[12]
Constant	I-Calibration convention	II-USCGS	III-USCGS	IV-Standard
T_s(s)	15.0±1 %	15.0	15.0	15.0
T_g(s)	100.0±1 %	100.0	100.0	98.1
D_s		0.93	0.87	0.9
D_g	1.0	1.0	0.9	1.0
σ^2 for magnification				
375		0.003	0.0022	0.003
750		0.013	0.0094	0.012
1,500		0.047	0.035	0.05
3,000		0.204	0.130	0.2
6,000		0.805	0.46	0.8

damping of the seismometer is negligible, and that of the galvanometer equals approximately 0.2, the coupling coefficient cannot exceed 0.8 [12]. Neglecting the changes in amplitude response, the maximum magnification is only dependent on $\sqrt{\sigma^2}$. The rough estimates of the coupling coefficients for the other magnification levels at 15 seconds 375, 750, 1,500 and 3,000 are then σ^2 = 0.003, 0.012, 0.05 and 0.2, respectively. The constants with these coupling coefficients listed in case IV in Table 1 will be further denoted as standard constants of long-period seismographs in the WWSS.

The deviations of constants given necessarily mean that the seismograph response and calibration constants differ from those published in [1] and [2]. The phase and amplitude responses are very easy to calculate for the actual seismograph constants. For the calculation of absolute magnification, some seismometer constructional parameters are missing. It is too complicated to measure them with sufficient accuracy without dismantling the pendulum system. For this reason the most suitable method is to calculate new calibration constants. The necessary mechanical parameter of the seismometer, *i.e.* the mass of the pendulum, is given by the manufacturer of the seismograph.

In this paper the calibration constants of vertical and horizontal seismographs for the standard seismograph constants are determined. Further, corrections are obtained for these calibration constants for the actual seismograph constants with deviations from corresponding standard ones of up to 10 per cent. The basic assumption for the application of the calibration constant, *i.e.* its independence of the attenuation setting in the operational range of seismograph magnification, is tested. The theoretical results are used for checking the absolute magnification and the accuracy of the seismographs at the Nurmijärvi station.

2. *Seismograph response with standard constants*

If the maximum magnification of the electromagnetic seismograph is increased, the coupling coefficient must also be increased. In long-period seismographs with maximum operational magnification 6,000 at 15 seconds, the maximum value of the coupling coefficient is 0.4–0.8. The tight coupling between seismometer and galvanometer without the transformation of basic partial seismometer and galvanometer constants T_s, D_s, T_g, D_g, may change the dynamic properties of the seismograph. On the other hand, the application of the calibration constant requires that the response characteristics be kept constant. The amplitude and phase response for steady-state movement and the transient response to step-function excitation must not change their shape with magnification. How well these conditions are fulfilled can be tested for standard constants.

2.1 Equivalent constants

As a measure of the influence of coupling on seismograph response, the so-called equivalent constants can be used [9]. These constants, *i.e.* periods T_1 and T_2 and damping constants D_1 and D_2 belong to a hypothetical electromagnetic seismograph with a theoretical zero coupling coefficient which has the same transient and steady-state response as the real seismograph with the partial constants T_s, T_g, D_s, D_g and $\sigma^2 > 0$. Only for negligibly small coupling ($\sigma^2 \cong 0$) are the partial constants identical to the corresponding equivalent constants. In general 3 different sets of equivalent constants are possible for one value of the coupling coefficient. For the long-period seismograph only one set takes place at $\sigma^2 \to 0$. For this reason we denote T_1 and D_1 as equivalent constants of the seismometer and T_2 and D_2 as equivalent constants of the galvanometer if $T_1 \to T_s$, $D_1 \to D_s$, $T_2 \to T_g$, $D_2 \to D_g$ for $\sigma^2 \to 0$. This coordination of equivalent constants to the seismometer and/or galvanometer has only formal significance but is useful for further discussion. The response of the electromagnetic seismograph is then given by the responses of two linear systems defined by constants T_1 and D_1, and T_2 and D_2. As usual for independent systems we get the amplitude response of the seismograph by the multiplication of the amplitude responses, and the phase response by the addition of the phase responses of equivalent systems.

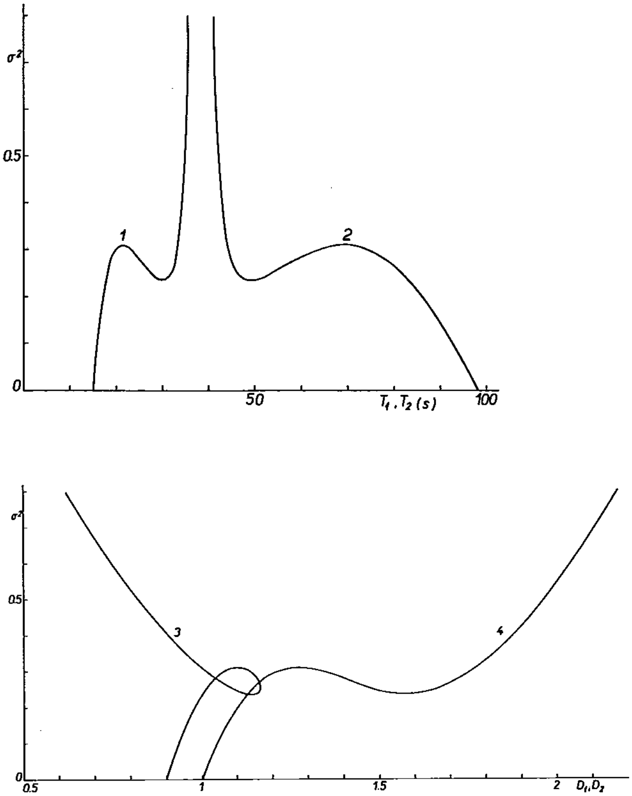

Fig. 1. Equivalent constants T_1, T_2 (1, 2), D_1, D_2 (3, 4) of a long-period seismograph with standard constants $T_s = 15$ s, $T_g = 98.1$ s, $D_s = 0.9$, $D_g = 1.0$.

The equivalent constants calculated according to the method described in [9] are given in Fig. 1. Apart from the interval of coupling constants from 0.24 to 0.31, where more than one solution exists, the general course of periods is quite normal: $T_1 < T_2$ and the smaller equivalent period increases with increasing coupling coefficient ($T_1 \geqslant T_s$); the greater equivalent period T_2 decreases monotonously ($T_2 \leqslant T_g$). The maximum changes in periods take place for coupling coefficients up to 0.31. For high seismograph magnification ($\sigma^2 > 0.3$) instead of system periods of 15 s – 100 s, which is right for small magnification ($\sigma^2 \ll 1$), we get system periods from 33.9 s – 43.4 s ($\sigma^2 = 0.35$) to 35.6 s – 41.3 s at $\sigma^2 = 0.8$.

The equivalent seismometer damping constants have an irregular course for $\sigma^2 \leqslant 0.31$, when $D_1 \geqslant D_s$. Only for $\sigma^2 > 0.31$ is there a branch with monotonous decrease as usual for systems with a smaller partial damping constant. The equivalent galvanometer damping constant has one monotonously increasing solution within the whole range of the coupling coefficient.

The matching of equivalent periods with increasing coupling coefficient tends to the peak amplitude characteristic of the seismograph. The overdamping of the galvanometer with maximum value $D_2 = 2.2$ compensates for this to some extent. Seismometer damping has the same effect for $\sigma^2 < 0.31$. For greater coupling, however, $D_1 < D_s$, and at maximum, the coupling coefficient ($\sigma^2 = 0.8$) reaches a value of only 0.62. Large differences between equivalent constants and the corresponding partial ones lead to changes in transient response, where the free movement of the seismograph is also defined by equivalent constants.

The deviations of equivalent constants go up to 0.5 % for $\sigma^2 \leqslant 0.01$. The coupling coefficient $\sigma^2 = 0.01$ is taken as negligibly small for changes in seismograph response, and for this reason this value will be used as the basic standard when comparing the seismograph response.

2.2 Deviation of seismograph response

The magnification M of the electromagnetic seismograph with pendulum seismometer is given by the general formula [6]

$$M = \frac{2A}{l}\sqrt{\frac{K_s}{K_g}}\sqrt{\frac{4D_sD_g\sigma^2}{T_sT_g}}\ U,\ U = \frac{1}{\sqrt{T^{-2} + a + bT^2 + cT^4 + dT^6}} \qquad (1a, b)$$

where A = recording distance of the galvanometer, l = reduced length of seismometer pendulum, K_s = the moment of inertia of the seismometer and K_g = the moment of inertia of the galvanometer. The amplitude response function U depends on the period of movement T, the basic constants of the seismograph and the coupling coefficient:

$$a = m^2 - 2p,\ b = p^2 - 2mq + 2s,\ \ c = q^2 - 2ps,\ \ d = s^2$$
$$m = 2(D_sT_s^{-1} + D_gT_g^{-1}),\ \ p = T_s^{-2} + T_g^{-2} + 4D_sD_gT_s^{-1}T_g^{-1}(1 - \sigma^2),$$
$$q = 2(D_sT_s^{-1}T_g^{-2} + D_gT_g^{-1}T_s^{-2}),\ \ s = T_s^{-2}T_g^{-2}$$

The phase shift in seconds is then

$$\varphi = \frac{T}{2\pi}\tan^{-1}\frac{sT^4 - pT^2 + 1}{qT^3 - mT} \qquad (2)$$

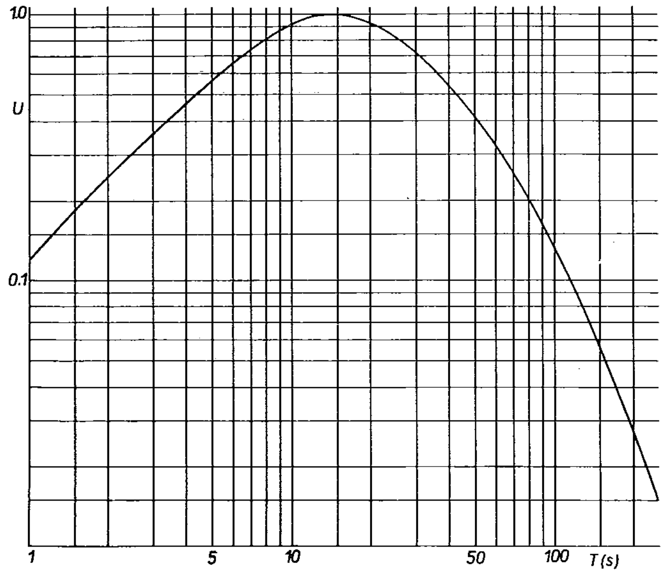

Fig. 2. Normalised amplitude response U for standard constants with $\sigma^2 = 0.01$.

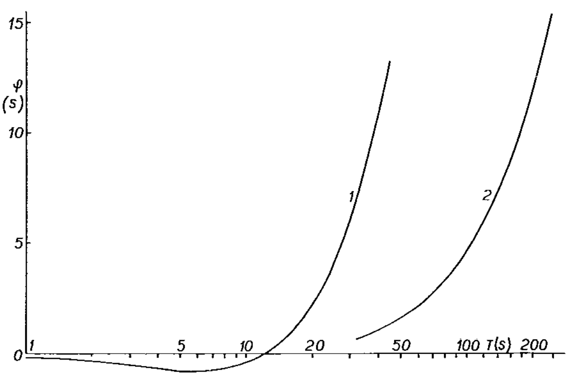

Fig. 3. Phase response $\varphi(s)$ for standard constants and $\sigma^2 = 0.01$ (1) and $\varphi(s)/10$ (2).

The normalised course of the magnification curve with a maximum equal to unity at period 15 seconds is given for $\sigma^2 = 0.01$ in Fig. 2. The phase shift is given in Fig. 3. The values of basic responses for particular periods are given in Table 2.

Table 2. Normalised magnification and phase shift for standard constants with $\sigma^2 = 0.01$ and the deviations for $\sigma^2 = 0.05$, 0.2 and 0.8.

T(s)	Magnification	δU(%) for σ^2			Phase shift (s)	$\Delta\varphi$(s) for σ^2		
		0.05	0.2	0.8		0.05	0.2	0.8
5	0.573	0.5	2.4	7.8	−0.697	0.001	0.005	0.022
10	0.921	0.5	2.4	8.6	−0.370	0.011	0.053	0.215
15	1.000	0.0	0.0	0.0	0.718	0.027	0.132	0.568
20	0.938	−0.6	−3.1	−14.9	2.27	0.036	0.179	0.858
25	0.831	−1.1	−5.6	−30.8	4.11	0.034	0.172	0.910
30	0.724	−1.3	−6.9	−42.7	6.15	0.023	0.119	0.673
40	0.546	−1.4	−7.4	−46.9	10.7	−0.012	−0.062	−0.360
50	0.417	−1.2	−6.2	−35.9	15.8	−0.053	−0.268	−1.46
60	0.324	−0.9	−4.5	−23.7	21.2	−0.091	−0.452	−2.28
70	0.255	−0.6	−2.9	−14.0	27.1	−0.121	−0.595	−2.84
80	0.203	−0.3	−1.5	−7.0	33.2	−0.143	−0.695	−3.16
90	0.165	−0.1	−0.4	−2.1	39.5	−0.157	−0.758	−3.32
100	0.134	0.1	0.4	1.4	46.1	−0.165	−0.790	−3.37
150	0.055	0.5	2.3	8.1	80.6	−0.152	−0.717	−2.90
200	0.027	0.6	2.6	8.7	117	−0.117	−0.551	−2.22
250	0.015	0.5	2.5	8.2	153	−0.088	−0.414	−1.67

The influence of coupling between seismometer and galvanometer on the shape of the magnification curve and the phase response are measured by the differences

$$\delta U = [U(\sigma^2 = 0.01) - U(\sigma^2)]/U(\sigma^2 = 0.01), \quad \Delta\varphi = \varphi(\sigma^2 = 0.01) - \varphi(\sigma^2), \tag{3a, b}$$

where both amplitude responses are normalised to the same value at period $T = 15$ seconds.

Relative differences δU and absolute differences $\Delta\varphi$ in phase shift are shown in Figs. 4 and 5 and in Table 2 for the coupling coefficients 0.05, 0.2 and 0.8, which correspond approximately to maximum magnifications of 1,500, 3,000 and 6,000 respectively at 15 seconds. For $M_{max} \leqslant 1{,}500$ the differences between magnification curves are within the limits ±1.5 per cent; for $M_{max} = 3{,}000$ and $M_{max} = 6{,}000$ the discrepancy becomes greater and has maxima of about 7.5 per cent and 47 per cent, respectively. In the limit where periods $T \to 0$ and $T \to \infty$ the differences lead to constants which correspond to a shift of response at 15 seconds by normalisation, *i.e.* −0.35 per cent, −1.6 per cent and −4.5 per cent respectively, for the given magnifications.

The differences in phase shifts have two extremes and outside the passband for $T \to 0$ and $T \to \infty$ the limit differences are zero. This follows from the fact that

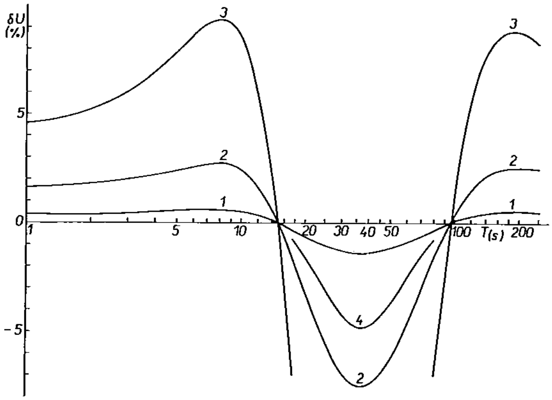

Fig. 4. Relative deviations $\delta U\%$ for $\sigma^2 = 0.05$ (1), $\sigma^2 = 0.2$ (2), $\sigma^2 = 0.8$ (3) and $\delta U/10$ for $\sigma^2 = 0.8$ (4).

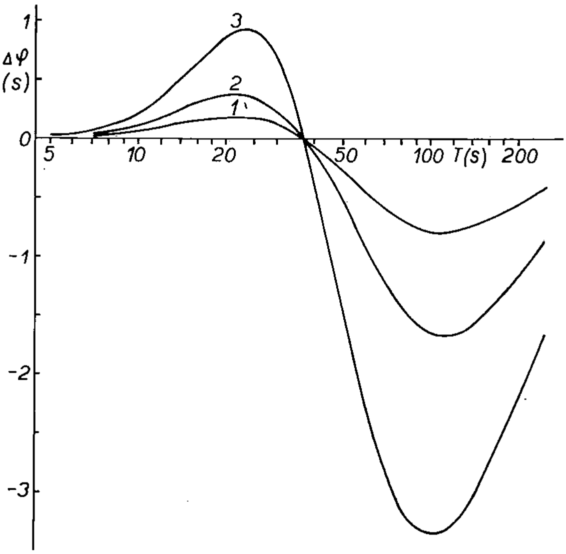

Fig. 5. Phase differences $\Delta\varphi$ in seconds for $\sigma^2 = 0.05$ (1), $\sigma^2 = 0.2$ (2), $\sigma^2 = 0.8$ (3).

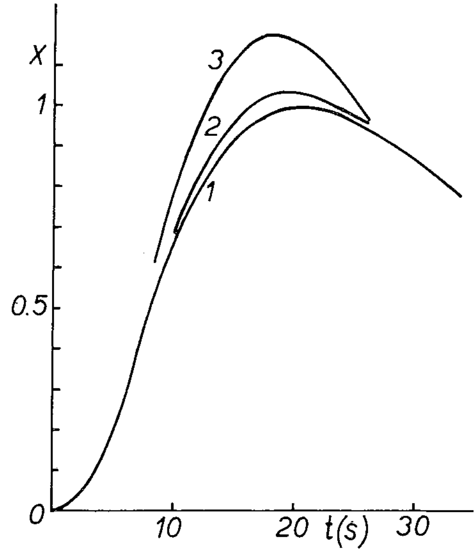

Fig. 6. Normalised transient response X for standard constants and $\sigma^2 = 0.01$ (1), $\sigma^2 = 0.2$ (2), $\sigma^2 = 0.8$ (3).

$\varphi(s) \rightarrow -T/4$ and $\varphi(s) \rightarrow 3T/4$ at these limits irrespective of the value of the constants of the seismograph.

The transient response caused by frame acceleration step can be written as follows [11]

$$X(t) = \frac{2A}{l} \sqrt{\frac{K_s}{K_g}} \sqrt{\frac{4D_s D_g \sigma^2}{T_s T_g}} F(T_s, T_g, D_s, D_g, \sigma^2, t) \frac{G_c^{\star} i_c}{M_s} \tag{4}$$

The first three terms are the same as in (1a) for magnification; the function F depends on basic seismograph constants and time t, the last term contains the adjusted excitation force (see 3.1) and the mass of the seismometer pendulum M_s. The changes in response shape are due to the non-linear dependence of function F on the coupling coefficient. This function, normalised at the first maximum to a value of 1, for $\sigma^2 = 0.01$, is given in Fig. 6. For $\sigma^2 = 0.05$ the first maximum is only about 0.07 per cent greater but for $\sigma^2 = 0.2$ it will be about 3.4 per cent, and for $\sigma^2 = 0.8$ about 17.9 per cent greater. When the coupling coefficient increases the first maximum of response occurs sooner.

From the comparison of results from (1a) and (4) it follows that the attenuation setting for $\sigma^2 = 0.2$ causes nearly the same relative change in magnification at

15 seconds and the first maximum of the transient response. The discrepancy is given only by the value of U at 15 seconds (U_{15}) and F at maximum (F_1). The increase in U_{15} is 1.6 per cent and that in F_1 3.4 per cent at $\sigma^2 = 0.2$ in relation to $\sigma^2 = 0.01$. For $\sigma^2 > 0.2$ this discrepancy further increases and at the maximum attainable coupling coefficient, $\sigma^2 = 0.8$, the changes reach +4.5 per cent in U_{15} and 17.9 per cent in F_1. Then the maximum absolute magnification determined with the aid of transient response has a reasonable systematic constant error.

3. *Calibration constant*

Appreciable discrepancies in transient and steady-state response which appear at higher coupling coefficients of long-period seismographs, *i.e.* at higher maximum magnification, bring about changes in the calibration constant. A quantitative estimate of this can be made for given standard constants and set of coupling coefficients by calculating the theoretical transient and the steady-state response. As the real seismograph constants may differ from the standard ones in some respects, the simple correction of the standard calibration constant for such cases is of great use. The calibration constant derived in this way can then be compared with calibration constants derived from recorded transient and steady-state sine-wave responses of individual seismographs.

3.1 Derivation of calibration constant

Checking the absolute seismograph magnification accroding to WWSS calibration convention is based on measuring the response to current step flowing through the calibration coil. Forcing the pendulum in this way corresponds to an acceleration step of the seismometer frame. The magnification (displacement sensitivity) M for steady-state harmonic motion at period T is, [1]

$$M = KX_p/(G_c^\star i_p) , \tag{5}$$

where K = the calibration constant for period T, in newtons per meter, X_p = the first largest zero-to-peak trace amplitude, in meters, $G_c^\star$ = an adjusted value of the electromechanical constant of the calibration coil, in newtons per ampere, i_p = direct current step zero-to-peak, in amperes.

The empirical value of the calibration constant for long-period seismographs at period 15 seconds is 0.449 N/m [2]. (In some manuals K is erroneously given as

0.499 N/m.) This value is applied to the whole range of seismograph magnification and for both vertical and horizontal instruments.

If the basic constants of the seismograph are known, the calibration constant can be calculated. For a unit excitation force we get from (1a) and (4)

$$K = M_s U_T / F_1 \tag{6}$$

where M_s = effective mass of the seismometer pendulum, in kilograms, (11.2 kg for the vertical component and 10.7 kg for the horizontal component), U_T = steady-state amplitude response at period T, in seconds, F_1 = the first maximum of the transient response function to acceleration step, in seconds^3. Both steady-state and transient response are determined exactly by the basic constants of the seismograph (T_s, T_g, D_s, D_g) and the coupling coefficient σ^2 alone.

The magnification M at period T as measured by steady-state harmonic excitation of the seismometer is

$$M = M_s X_s \frac{4\pi^2}{T^2} \frac{1}{G_c^\star i_s} \tag{7}$$

where X_s = peak-to-peak recorded trace amplitude, in meters, and i_s = peak-to-peak amplitude of the sinusoidal current flowing through the calibration coil.

From (5) and (7) we get for the calibration constant, using recorded trace amplitudes,

$$K = M_s \frac{4\pi^2}{T^2} \frac{X_s i_p}{X_p i_s} \tag{8}$$

The theoretical calculation of K from (6) and experimental determination according to (8) give the same dependence of the calibration constant on the effective mass of the seismometer. Using the same value of the calibration constant with different masses of pendulums we introduce a systematic error of absolute magnification. The difference between the masses of the horizontal and vertical components leads to a difference in K of about 4.5 per cent. The discrepancy of K determined from (6) and (8) not caused by the errors due to the measurement of seismograph parameters can mainly be explained by the non-ideal behaviour of the actual oscillating seismometer and galvanometer systems.

The influence of the coupling coefficient on the calibration constant was tested for the constants listed under II and III in Table 1. For the vertical component, using seismograph constants from [3] and [4] the calibration constants are in the range 0.429–0.379 N/m and 0.429–0.406 N/m respectively (Table 3). In the range of maximum magnification at 15 seconds from 750 to 6,000 the calculated calibration constant changes by up to 10 per cent.

For certain seismograph constants with negligibly small coupling coefficients, the calibration constants can easily be determined from the set of transient responses and steady-state response curves derived using an analog computer [5]. In this case we use (8), where instead of term $4\pi^2/T^2(X_s/X_p)$, the ratio D'_f/D'_t must be used, *i.e.* the ratio of steady-state trace amplitude for period T to maximum trace amplitude caused by acceleration step. Instead of the current ratio i_p/i_s, the ratio of voltage amplitude of the step input to voltage amplitude of steady-state input, v'_t/v'_f, may be inserted. For example, for the constants T_s = 15 seconds, T_g = 100 seconds, $D_s = D_g$ = 1.0, $\sigma^2 \cong 0$ (case 25 in [5]) we find for T = 15 seconds D'_f = 29 mm, v'_f = 0.96 V and for step input D'_t = 160 mm, v'_t = 0.192 V. This yields the calibration constant for the vertical component K = 0.406 N/m. The calibration constant calculated by digital computer for the given constants is 0.403 N/m.

3.2 Approximation of calibration constant by polynomials

The calibration constants calculated for the standard seismograph constants are in Table 3 (case IV). The recommended value K = 0.449 N/m given in Appendix B [1] and in [2] agrees for lower maximum magnification with the calibration constant of the vertical seismograph. The calibration constant of the horizontal seismograph is, according to (6), about 4.5 per cent smaller for equal magnification (more correctly for the same coupling coefficient).

The calibration constants for the standard seismograph constants are given in detail in Table 4 for $0.01 \leqslant \sigma^2 \leqslant 0.8$. With increasing coupling coefficient the

Table 3. Calibration constants K(N/m) at 15 seconds of vertical (Z) and horizontal (H) long-period seismographs.

Maximum magnification	I	II		III		IV	
	Z,H	Z	H	Z	H	Z	H
375	0.449	0.429	0.410	0.429	0.410	0.450	0.430
750	0.449	0.429	0.410	0.429	0.410	0.450	0.430
1,500	0.449	0.428	0.409	0.428	0.409	0.449	0.429
3,000	0.449	0.421	0.402	0.424	0.405	0.442	0.422
6,000	0.449	0.379	0.362	0.406	0.388	0.399	0.381

Table 4. Calibration constants for vertical and horizontal seismographs with standard constants and time t_{st} of the first maximum; percentage deviation of calibration constant δK for 1 per cent deviation in seismograph constants.

σ^2	K_{stZ}(N/m)	K_{stH}(N/m)	t_{st}(s)	$\delta K/\delta T_s$	$\delta K/\delta T_g$	$\delta K/\delta D_s$	$\delta K/\delta D_g$	$\delta K/\delta \sigma^2$
0.01	0.450	0.430	20.4	−0.97	−0.99	−0.89	0.58	−0.0007
0.05	0.449	0.429	20.3	−0.99	−0.99	−0.89	0.58	−0.004
0.10	0.447	0.427	20.1	−1.01	−0.99	−0.90	0.58	−0.010
0.15	0.445	0.425	19.9	−1.04	−0.99	−0.90	0.59	−0.015
0.20	0.442	0.422	19.7	−1.07	−0.98	−0.91	0.59	−0.022
0.25	0.439	0.420	19.6	−1.09	−0.98	−0.91	0.59	−0.031
0.30	0.437	0.417	19.4	−1.12	−0.98	−0.91	0.59	−0.039
0.35	0.434	0.414	19.3	−1.15	−0.97	−0.92	0.59	−0.050
0.40	0.431	0.411	19.1	−1.18	−0.97	−0.92	0.59	−0.060
0.45	0.427	0.408	19.0	−1.21	−0.97	−0.93	0.59	−0.070
0.50	0.424	0.405	18.9	−1.23	−0.96	−0.94	0.58	−0.086
0.55	0.420	0.401	18.8	−1.26	−0.95	−0.94	0.58	−0.10
0.60	0.416	0.397	18.7	−1.29	−0.95	−0.95	0.57	−0.11
0.65	0.412	0.394	18.6	−1.32	−0.94	−0.95	0.57	−0.13
0.70	0.408	0.389	18.5	−1.35	−0.93	−0.96	0.56	−0.15
0.75	0.403	0.385	18.4	−1.38	−0.92	−0.97	0.55	−0.17
0.80	0.399	0.381	18.3	−1.40	−0.91	−0.97	0.54	−0.18

calibration constant decreases about 10 per cent at maximum. The time t_{st}, measured from the beginning of the current step to the first maximum of transient response, becomes shorter. The average percentage values of calibration constant deviations δK for positive 1 per cent deviations in seismograph constants are also given in Table 4. The deviation of the seismometer period from the standard value has the greatest effect. The effects of deviations in galvanometer period and seismometer damping constant are very similar. The effect of galvanometer damping is about one half of that for the two previous constants. The smallest deviations in K cause deviations in the coupling coefficient. The wide range in values of δK is, in this case, partly due to large absolute deviations in the coupling coefficient, while the absolute deviations in the other constants are invariable. Taking only small tolerances for the constants, $T_s = T_g = 1$ per cent, $D_s = D_g = 2$ per cent, we get the maximum deviation in calibration constant from its standard value at corresponding σ^2 to be about 5 per cent for $\delta\sigma^2 = 0$, and approximately 5–7 per cent for $\delta\sigma^2 = 10$ per cent (Fig. 7).

To fix the calibration constant for the actual constants of long-period seismographs without repeating all the calculations of the theoretical transient course, the approximation by single polynomials was preferred. In the first step the

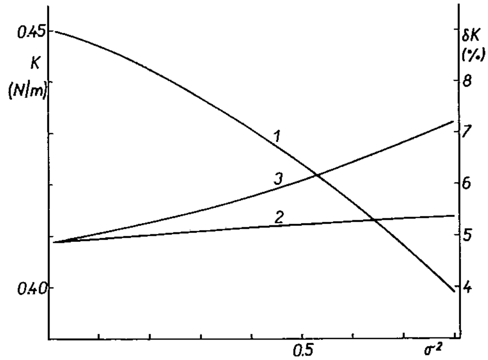

Fig. 7. Standard calibration constant K of a vertical seismograph (1) and maximum deviations δK (%) for $\delta T_s = \delta T_g = 1$ %, $\delta D_s = \delta D_g = 2$ %, $\delta\sigma^2 = 0$ (2) and $\delta\sigma^2 = 10$ % (3).

calibration constant was derived for the standard seismograph constants T_s, T_g, D_s, D_g and given coupling coefficient range. In the second step, corrections of this value due to deviations in individual constants (including σ^2) in the 10 per cent range were applied.

The time of the first maximum t_{st} and the calibration constants of vertical and horizontal seismographs K_{st} are approximated by second degree polynomials $\sum_{i=0}^{2} A_i \sigma^{2i}$ in σ^2. The coefficients A_i, derived by the least squares method and listed in Table 5, give a maximum error of approximation smaller than 0.05 per cent.

The correction terms δK_i ($i = 1, 2, \ldots, 5$) due to deviation δx_i in seismograph constant X_i from the corresponding standard value X_{ist}, $\delta x_i(\%) = 100(X_i - X_{ist})/X_{ist}$, are approximated by the polynomial [10]

$$\delta K_i(\%) = A_{i0}\delta x_i + A_{i1}\delta x_i^2 + A_{i2}\delta x_i^3 \tag{9}$$

and the dependence of coefficient A_{ik} on the coupling coefficient by the polynomial

$$A_{ik} = \sum_{j=0}^{2} K_{ijk}\sigma^{2j} \tag{10}$$

The corrected calibration constant K is then

$$K = K_{st}(1 + \sum_{i=1}^{5} \delta K_i/100) \tag{11}$$

Table 5. Coefficients for the approximation of standard values $C = \sum_{i=0}^{2} A_i \sigma^{2i}$.

C	A_0	A_1	A_2
t_{st}	20.44	–3.89	1.56
K_{stZ}(N/m)	0.4506	–0.0350	–0.0371
K_{stH}(N/m)	0.4305	–0.0334	–0.0354

Table 6. Coefficients K_{ijk} at 15 seconds.

i	j	k		
		0	1	2
1	0	–0.964	0.0043	0
	1	–0.508	0.0063	0
	2	–0.057	0.0059	0
2	0	–0.989	0.0146	–0.00020
	1	0.002	0.0032	–0.00010
	2	0.113	–0.0029	0.00006
3	0	–0.891	0.0102	–0.00011
	1	–0.069	0.0012	–0.00002
	2	–0.045	0.0005	0
4	0	0.579	–0.0003	0
	1	0.083	0.0028	0
	2	–0.156	–0.0014	0
5	0	0	0.0001	0
	1	–0.070	–0.0003	0
	2	–0.202	–0.0004	0

The coefficients K_{ijk}, determined by the least squares method, are shown in Table 6. The constants deviate by ±10 per cent. Here $i = 1$ corresponds to the seismometer period, $i = 2$ to galvanometer period, $i = 3$ to the seismometer damping constant, $i = 4$ to the galvanometer damping constant and $i = 5$ to the coupling coefficient. The number of significant figures in K_{ijk} values is chosen so as to give, for maximum deviations of ±10 per cent, absolute errors of coefficients in hundredths of a per cent, and to get the maximum absolute error δK_j by rounding off figures smaller than 0.1 per cent. The tests which have been made demonstrate that this accuracy is achieved. The error of the whole correction term cannot then exceed 0.5 per cent if all deviations in constants are non-zero.

The coefficients K_{ijk} were calculated at the time of the first maximum of standard response t_{st} for a given coupling coefficient. For this reason, when applying this method the measurement of amplitude X_p at this time must be done as accurately as possible. When there are great deviations in constants the maximum of the transient response should not occur at the time t_{st}.

As an example of the calculation of correction terms we can use the constants from [3]: T_s = 15.0 s, T_g = 100 s, D_s = 0.93, D_g = 1.0, σ^2 = 0.204 with maximum magnification 3,000 at period 15 seconds. For the standard constant and the given coupling coefficient we get, using the coefficients in Table 5, K_Z = 0.442 N/m and t_{st} = 19.7 s. The non-zero deviations are only at T_g and D_s:δx_2 = 1.9 per cent and δx_3 = 3.3 per cent. The coefficients A_{ik} at σ^2 = 0.204 will be A_{20} = -0.984, A_{21} = 0.0151, A_{22} = -0.00022, A_{30} = -0.907, A_{31} = 0.0104, A_{32} = -0.00011 and δK_2 = -1.85 per cent, δK_3 = -2.91 per cent so that K = 0.952 K_{st} = 0.421 N/m. For horizontal seismographs it will be 4.5 per cent smaller, of course. From analytical formulae we get the same values for K. The calculated time of the first maximum (20.2 s) is very close to the standard value (19.7 s).

Table 6 also gives the values of K_{ijk} for coupling coefficients. This correction is not needed since the standard calibration constant can be calculated for the actual coupling coefficient of the seismograph and then δx_5 can be equated to zero. These values are added to provide consistent formulae for testing the errors δK_5 due to the coupling coefficient deviations in the same way as for the other constants.

The spontaneous changes in seismometer and/or galvanometer periods during seismograph operation cause simultaneous percentage changes in the corresponding damping constants. Then the correction terms are defined by $K_{1jk} + K_{3jk}$ for the seismometer constants and $K_{2jk} + K_{4jk}$ for the galvanometer constants, respectively. The roughly estimated linear terms in Table 6 show that a seismometer with the same signs for both coefficients has a greater total correction than a galvanometer where the opposite signs of coefficients partly reduce the resulting term. The coupling coefficient is not at all affected by the deviations in periods.

4. *Magnification measurements at Nurmijärvi* (NUR)

A comparison of the maximum magnification of Nurmijärvi long-period seismographs using transient and steady-state methods is given as an example of the application of the above method of determining the calibration constant. The

Table 7. Constants of long-period seismographs at NUR in April, 1974.

Constant	Component		
	N–S	E–W	Z
T_s(s)	15.00	15.0	15.0
T_g(s)	98.4	97.7	98.2
D_s	0.85	0.93	0.84
D_g	1.03	1.05	1.05
σ^2	0.025	0.025	0.035
$G_c^\star$(N/A)	0.0969	0.0972	0.1009

cardinal constants listed in Table 7 were obtained using the standard WWSS procedure completed by several measurements in April 1974 [12].

The adjusted values of the electromechanical constants of the calibration coils $G_c^\star$ which are necessary for both calibration methods were newly determined by the method of lifting small weights [1]. The mass was weighed together with the acting part of the lifting wire, with a maximum error of 0.5 per cent; the accurate value of acceleration due to gravity at Nurmijärvi, g = 9.819 m/s^2, was used. The maximum error of the distance from the hinge to the centre of gravity d_{cg} and/or to the point of weight-lift d_m, given in the Manual, was estimated to be ±0.5 mm. The DC current step amplitude (about 10 mA) was measured with a high class ammeter with a maximum error of 0.2 per cent. As both amplitudes X_{lp} and X_{lm} are almost equal the shrinkage of the recording photographic paper and the arc error can be neglected. The maximum relative error of both amplitude measurements during low level microseismic noise and with high accuracy scale, was estimated to be 0.2 per cent. Under these circumstances the total maximum error of $G_c^\star$ was estimated to be 1.5 per cent.

The determination of $G_c^\star$ for horizontal seismometers is more troublesome because special jigs are needed for lifting the weights. The inaccuracy of angles and distances in the geometry of this *jig* may cause some additional error compared with the vertical seismometer. The maximum deviations of $G_c^\star$ during ten years of operation were ±3 per cent.

4.1 Absolute magnification at 15 seconds

4.1.1 Transient method

The calibration constant was calculated for the given coupling coefficients of the horizontal and vertical seismograph for the standard constants, and then the

Table 8. Standard calibration constants and corrections for deviations of constants X_i from standard.

Component	K_{st}	t_{st}	X_1		X_2		X_3		X_4		$\Sigma\delta K_i$	K
	(N/m)	(s)	δx_1 (%)	δK_1 (%)	δx_2 (%)	δK_2 (%)	δx_3 (%)	δK_3 (%)	δx_4 (%)	δK_4 (%)	(%)	(N/m)
N–S	0.430	20.3	0	0	0.3	−0.3	−5.5	5.3	3.0	1.7	6.7	0.459
E–W	0.430	20.3	0	0	−4.1	4.3	3.3	−2.9	5.0	2.9	4.3	0.449
Z	0.449	20.3	0	0	0.1	−0.1	−5.5	5.3	5.0	2.9	8.1	0.485

Table 9. Transient calibration; parameters and magnification at 15 seconds.

Parameter	Component		
	N–S	E–W	Z
i_p(mA)	0.2	0.2	0.2
X_p(mm)	63.5	70.0	68.4
M at 15 s	1,500	1,610	1,650
ΔM_{md}	±120	±125	±130
ΔM_{sd}	± 45	± 50	± 50

correction terms were derived for the deviations in individual constants from the standard. All necessary data are listed in Table 8. Although the individual corrections are in some cases substantial, the resulting correction term gives a calibration constant of the horizontal components which is close to the recommended value of 0.449 N/m. Only for the vertical component does the calibration constant differ much more.

Basic calibration parameters for all 3 components are shown in Table 9. A rough estimate of the maximum deviation in calibration constant for maximum deviations of 1 per cent in the seismograph period and 2 per cent in the damping constants, taking only linear terms of K_{ijk}, yields a value for δK_{md} of about 6 per cent. The maximum error of the method (0.4 per cent) and the maximum deviation in effective mass (0.5 per cent) were considered here. With the maximum deviation of the adjusted electromechanical constant of 1.5 per cent, current step 0.2 per cent and amplitude, X_p, 0.5 per cent, the maximum deviation of magnification can be estimated to be 8 per cent. If we take the maximum estimated errors of the above-mentioned parameters as their standard deviations, we get the estimate of standard deviation in magnification as 3.1 per cent. The rounded values of maximum deviations of magnification are then ΔM_{md} = 120–130 and standard deviations ΔM_{sd} = 45–50.

4.1.2 Steady-state calibration at period 15 seconds

The calibration coils were connected in series as in the preceding calibration; a low-frequency generator, Racal-Airmec 422, and a precision ammeter were also used. The values of the trace and current amplitudes are given in Table 10. The period error of the generator can be neglected due to its extreme accuracy (the reading is given in 6 figures). The arc error for 100 mm amplitude is 0.3 per cent, the shrinkage of the seismogram was estimated to be 0.5 per cent and the uncertainty in amplitude measurement to be 0.3 per cent. The maximum deviation in amplitude is then 1.1 per cent. The peak current value was measured for longer periods (50 seconds) and the ammeter reading at 15 seconds was corrected by checking the current level on the short-period recorder. If the upper limit of the ammeter scale is used, the absolute current error is 0.2 per cent. If we take the same estimates for the maximum deviations of M_s and $G_c^\star$ as in the preceding case, the maximum deviation of magnification is estimated to be 3.3 per cent. The maximum error values used as standard deviations in measurements give a standard deviation in magnification of 2 per cent. The corresponding absolute maximum and standard deviations are in this case 50–55 and 30, respectively.

Table 10. Steady-state calibration; parameters and magnification at 15 seconds.

Parameter	Component		
	N–S	E–W	Z
i_s(m A)	1.311	1.311	1.311
X_s(mm)	99.9	106.6	107.7
M at 15 s	1,480	1,570	1,600
ΔM_{md}	± 50	± 50	± 55
ΔM_{sd}	± 30	± 30	± 30

4.1.3 Steady-state calibration at 32.2 seconds

To be sure that the seismograph is regular when it works for longer periods, too, a calibration at about double the period of maximum magnification (T = 32.2 seconds) was performed. This period is in the area of minimum seismic noise and sufficiently removed from the most disturbing microseisms which occur at 6 seconds. The magnification derived for this period according to (7) can using actual seismograph constants be transformed to the level of that at 15 seconds.

In this case the portable Hewlett-Packard signal generator model 3311A was used to drive the seismometer. Instead of direct measurement of current amplitude in the calibration circuit, the total resistance of the circuit and the voltage input were determined using a DC-AC digital volt and ohmeter model 34740A with a reading accuracy of ±0.03 per cent and 0.1 per cent range accuracy. For the amplitude of the generator's square voltage output the value of the sinusoidal voltage amplitude was read from the film 12 shots per second of digital readings (8 times per second). At a given period of 32.2 seconds, which is the maximum period of the generator, the ratio of sinusoidal amplitude to square voltage amplitude was 0.9583 ±0.1 per cent. The maximum error in the period was 0.2 per cent and the square voltage amplitude had the same error. For the same estimates of the other errors as in 4.1.1 and 4.1.2, the maximum error of magnification is 3.8 per cent. The standard deviation of 2 per cent is close to the estimate of the preceding steady-state calibration at 15 seconds.

The parameters of calibration and calculated magnification at 32.2 seconds are shown in Table 11. To get the magnification at 15 seconds, this magnification must be multiplied by the ratio of amplitude responses at both periods. This ratio was calculated for the constants given in Table 7. For the estimation of maximum

Table 11. Steady-state calibration; parameters and magnification at 32.2 seconds and 15 seconds.

Parameter	Component		
	N–S	E–W	Z
i_s(mA)	0.3883	0.3883	0.3883
X_s(mm)	93.0	99.5	98.9
M at 32.2s	1,000	1,070	1,070
$U_{15}/U_{32.2}$	1.521	1.466	1.533
M at 15s	1,530	1,570	1,640
ΔM_{md}	±90	±90	±95
ΔM_{sd}	±35	±35	±40

and standard deviations in magnification at 15 seconds, the different influences of deviations in constants at each period were taken into account. The rough estimate for 1 per cent period tolerances and 2 per cent damping constant tolerances gives an additional maximum deviation of 2–3 per cent for the coupling coefficient in the interval 0.01–0.8 and an additional standard deviation of 1.1–1.5 per cent. The maximum deviation of magnification at 15 seconds is therefore 5.8–6.8 per cent and the standard deviation 2.3–2.5 per cent for this method. The absolute values of the maximum and standard deviations are 90–95 and 35–40, respectively.

4.2 Errors in magnification

The estimates of maximum and standard deviations for the three methods are greatest for the transient method and least for the sinusoidal direct driving of the seismometer. This is caused due to the smaller number of parameters in the last case compared with all the measurements of constants which are needed for the calibration constant corrections. The deviations of all the parameters mentioned are small. The estimated standard deviations need carefully performed calibrations and their further reduction is very difficult. The application of the calibration constant at other periods gives no independent magnification value as the basic seismograph constants used are the same, and from the transient response we take only one amplitude value. The discrepancies in magnification from the average are in the range of ±2 per cent for the 3 methods and for all components.

The seismograph magnification was determined with an accuracy better than ±7 per cent, which is advisable if measurements of the displacement of the earth's motion are to be improved [15].

Great random errors in calibration are easy to eliminate by repeating the whole procedure. To find systematic errors, different methods and measuring instruments are recommended. Only the electromechanical constant of the calibration coil $G_c^\star$ and errors in seismometer mass M_s cannot be obtained from transient and steady-state calibration. This is evident if (6) and (7) are compared.

In [5] the electromechanical constant (= motor constant) G, adjusted to the centre of gravity, is defined by the following formula

$$G^2 = 2(h - h_m)\frac{2\pi}{T_s}M_sR \qquad (12)$$

where h = seismometer damping constant when the coil has a total output resistance R, including the internal resistance of the coil, h_m = open circuit damping constant of the seismometer. The meanings of the other symbols are the same throughout this paper. It must be remembered that this formula is valid only when in the moment of inertia of the pendulum $K_s = M_s d_{cg}^2 + K_{00}$ with respect to the axis of seismometer rotation, the second term K_{00}, the moment of inertia about an axis passing through the centre of pendulum mass and parallel to the seismometer axis, can be neglected. The general formula for the electromechanical constant of the pendulum seismometer is given by

$$G^2 = 2(h - h_m) \frac{2\pi}{T_s} \frac{K_s}{d_{cg}^2} R \tag{13}$$

The calibration circuit should not change the damping of the seismometer. The additional electromagnetic damping constant D_{sc} due to the calibration circuit

$$D_{sc} = \frac{(G_c^\star d_{cg})^2 T_s}{4\pi K_s R} \tag{14}$$

where R is the total resistance of the calibration coil as in (12).

In the transient method, when the calibration current is turned off, $R = \infty$ and $D_{sc} = 0$ and the condition is fulfilled independent of the circuit resistors. When the current is turned on and for sinusoidal calibration where the calibration circuits are closed in the course of the tests, the value of D_{sc} can be estimated as follows: instead of K_s we take $M_s d_{cg}^2 \leqslant K_s$ and from (14) we get

$$D_{sc} \leqslant \frac{G_c^{\star 2} T_s}{4\pi M_s R} \tag{15}$$

If we now put the average electromechanical constant of the calibration coil $G_c^\star$ = 0.1 N/A, the mass of the horizontal seismometer 10.7 kg and T_s equal to 15 seconds, then $D_{sc} < 0.001/R$. As the seismometer damping constant is about 0.9, for $R > 1\ \Omega$ the electromagnetic damping of the calibration circuit is smaller than 0.1 per cent. This condition is satisfied for transient calibration with $R > 1{,}000\ \Omega$ in WWSS calibration procedure, as it is for steady-state calibration at 15 seconds and at 32.2 seconds ($R \cong 1{,}000\ \Omega$) which were used in the above-mentioned measurements. Using a signal detection coil and a Maxwell bridge for calibration, sufficiently large resistors must be added because the motor constant of the signal coil is usually several orders greater than $G_c^\star$.

For the measurement of $G_c^\star$ when transient response caused by weight lift is compared with transient response to a known current step, the total resistance of the circuit is 1,057 Ω and D_{sc} is again much smaller than 0.1 per cent of the seismometer damping constant D_s. The scaled differences between current on and current off are not, therefore, caused by calibration circuit damping.

On principle all calibration procedures should be made at operation magnification attenuator setting, especially when the accuracy of different calibration methods is being studied. (To decrease the scatter of the trace amplitude due to microseismic noise the attenuation is sometimes increased during the calibration.) The accuracy of the step attenuator gives only the accuracy of the ratio of the currents (1–2 per cent) flowing through the galvanometer coil. The magnification attenuation depends on coupling coefficient changes, too. Up to $\sigma^2 = 0.05$ (maximum magnification about 1,500) this discrepancy is up to 2 per cent. For greater coupling coefficients it may reach 10–20 per cent or higher at periods of 30–40 seconds, as follows from Table 2 in the case of standard seismograph constants.

5. *Conclusions*

The previous study [12] of the WWSS calibration procedure for long-period seismographs makes it possible to fix certain standard constants of the seismometer and the galvanometer and the range of coupling coefficient values for the applied levels of maximum magnification. The basic property of the standard calibration constant – its dependence on maximum magnification and seismometer mass – has now been determined. The polynomials give a very accurate approximation of standard calibration constant corrections due to deviations of particular seismograph constants in the range of ±10 per cent from the corresponding standard values $T_s = 15.0$ s, $T_g = 98.1$ s, $D_s = 0.9$, $D_g = 1.0$.

As a rule not all constants are checked and values for D_s, D_g and σ^2 are not available [2, 13]. The direct determination of constants is too tedious to be performed frequently. For routine daily calibration another convenient procedure may be chosen from those derived specially for long-period seismographs.

The method of matching an experimental transient response to a precalculated set of transient responses by eye fitting as described in [5] is too rough for our purposes. A more objective method is the best fitting of time between six points on the observed transient and at the same six points measured on standard transient response. The points Q_i are at the maximum height of pulse D, at $D/3$ and $2D/3$ on both the rising and falling side, and at $D/10$ in the decay part of transient [5]. Both these methods are restricted to negligible coupling and the accuracy depends on the extent and completeness of the transient set and/or the computer library with standard Q_i measurements. The constants for the selected case with closest fit may not correspond to the actual constants. For a negligibly small coupling coefficient these methods are applicable only for lower magnification gain.

A more general method is the least-square inversion method [7] which gives the periods and damping constants of the seismometer and galvanometer if the coupling coefficient is known in advance. In this method a digitized transient response at one sample per second was used. For every coupling coefficient in the admissible interval 0–0.8 the calculated constants give true phase delay, group delay and relative magnification curves although the constants different from the actual ones. The standard value for each maximum magnification can be chosen as the initial approximation of the coupling coefficient. To get the actual constants the method is easily modified. The actual coupling coefficient can be obtained if one more seismograph constant is known. The period of the seismometer is most convenient for this purpose because it is measured with greatest accuracy by conventional calibration [2, 12]. The best fitting of σ^2 will give minimum deviation between calculated and measured periods. In this case the deviations of all calculated constants from the corresponding standard values will be used to derive the correction of the calibration constant and, further, the absolute magnification. This procedure is admissible for the whole range of seismograph magnification, including the highest magnification levels of 3,000 and 6,000 used at some seismic stations [8]. The modified long-period seismograph calibration adapted in the Canadian Seismograph Network, where a rectangular pulse of 7 seconds duration is applied [14], can be completed in the same way.

The constants and the absolute magnification at one period computed from the transient response are sufficient for the derivation of the seismograph transfer function if computer methods of seismogram analysis are being used. For routine seismogram evaluation only the magnification curve [15] is necessary and this can be determined simply and more accurately by the steady-state harmonic-drive method.

Acknowledgement: The author, VLADIMÍR TOBYÁŠ, wishes to express his gratitude to the Rector of the University of Helsinki, for the opportunity to visit the Institute of Seismology, which made this joint paper possible.

REFERENCES

1. ANONYMOUS, 1962: *Operation and maintenance manual World-Wide Seismograph System, Model 10700. Calibration of the World-Wide Seismograph System. Appendices A and B.* Geotechnical Corporation, Garland.
2. ANONYMOUS, 1970: *Calibration of the WWSSN and ESN seismograph systems.* U.S. Coast and Geodetic Survey, Washington, D.C.
3. CHANDRA, U., 1970: Analysis of body-wave spectra for earthquake energy determination. *Bull. Seism. Soc. Am.,* 60, 539–563.

4. DATA suppiied by U.S. Coast and Geodetic Survey, Albuquerque Seismological Center, to the Institute of Seismology, University of Helsinki: a) March 20, 1970 (Locke), b) April 13, 1970 (Locke), c) July 15, 1970 (Peterson).

5. ESPINOSA, A.F., G.H. SUTTON and H.J. MILLER, 1965: A transient technique for seismograph calibration – Manual and standard set of theoretical transient responses. *Vesiac Special Report no. 4410–106–X. Inst. of Sci. and Technology, University of Michigan,* Michigan.

6. KIRNOS, D.P. (ed.), 1962: *Apparatura i metodika nablyudeniy na seismicheskikh stantsiakh SSSR.* Izd. Akad. Nauk SSSR, Moskva.

7. MITCHELL, B.J. and M. LANDISMAN, 1969: Electromagnetic seismograph constants by least-square inversion. *Bull. Seism. Soc. Am.,* 59, 1335–1348.

8. POWELL, T. and D. FRIES, 1964: *Handbook, World-Wide Standard Seismograph Network.* Inst. of Sci. and Technology, University of Michigan, Michigan. Revised July 1964, August 1965, July 1966.

9. TOBYÁŠ, V. and Z. HÜBNEROVÁ, 1972: Equivalent and partial constants of electromagnetic seismographs. *Travaux Inst. Géophys. Acad. Tchécosl. Sci.* No. 305, Geofysikální sborník 1969. Academia, Praha.

10. TOBYÁŠ, V., 1974: The approximation of partial and calibration constants of electromagnetic seismographs with standard A – type characteristics by polynomials. *Studia Geoph. et Geod.* 18, 140–147.

11. –»– , 1975: Partial and calibrations constants of electromagnetic seismographs with standard type A characteristics. *Travaux Inst. Géophys. Acad. Tchécosl. Sci.* No.405, Geofysikální sborník 1973. Academia, Praha.

12. –»– , P. TEIKARI and E. VESANEN, 1976: Constants of long-period seismographs at Nurmijärvi (Finland). *Geophysica,* 14, 99–109.

13. WAN-KYU, Eu, 1975: Calibration and treatment of World-Wide Standard Seismograph. *Individual Studies, International Institute of Seismology and Earthquake Engineering,* 11, 19–36.

14. WICKENS, A.J., H.S. HASEGAWA and M.N. BONE, 1974: Pulse calibration and its application to the daily calibration of the Canadian Standard Seismograph Network long-period seismometers. *Can. J. Earth Sci.,* 11, 691–697.

15. WILLMORE, P.L. (ed.), 1970: *Manual of seismological observatory practice.* International Seismological Centre, Edinburgh.