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CALIBRATION OF LONG-PERIOD SEISMOGRAPHS AT THIRTEEN STATIONS THROUGHOUT THE WORLD

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ABSTRACT

During mid-1962 accurate calibrations were made of 42 special seismographs located at 13 stations throughout the world. The stations are Bermuda, Buenos Aires, Delhi, Hong Kong, Honolulu, Huancayo, Mt. Tsukuba, Perth, Rio de Janeiro, Santiago, Suva, Uppsala, and Waynesburg. Two methods of calibration were used, one based on a steady-state input signal, the other on a transient pulse-like input signal. The signals were applied through a Willmore-type bridge. Analysis of the steady-state output was conventional; analysis of the pulse was made by a comparison with a family of theoretical pulses obtained by means of an analog computer. Both methods provide displacement sensitivity and phase response curves.

The instruments were calibrated according to the existing conditions. They were then adjusted for standardization and recalibrated. The bridge and the pulse generating circuit were installed permanently for frequent calibration in the future. The results of the calibrations are given here in graphical form.

INTRODUCTION

This paper is a report of accurate calibrations of certain special seismographs installed during the interval 1954-1958. Prior to the calibrations described here, an approximate response, sufficient for many studies, was known for these instruments, but as other more exacting studies called for an improved knowledge of this response, this additional effort became necessary. Curves for amplitude and phase response for 42 seismographs at 13 stations are given here, together with a discussion of the methods used for calibration and certain of the problems encountered.

To study the propagation of long-period waves, Columbia University has installed some 17 seismograph systems, 13 of which are discussed here, at various stations throughout the world. Many of the instruments were installed during the International Geophysical Year as part of the LP-Lg Seismology Program. The seismometers are of the same general type, but they appear in several versions. The oldest version was originally designed and fabricated at Lamont Observatory. The remaining seismometers are of either the Press-Ewing design made by Lehner-Griffith, or the Columbia design made by Sprengnether. Both of the latter are patterned after the original Lamont design but they differ in certain details.

The seismometers are coupled to galvanometers through a resistor network as shown in Figure 1. There are two basic arrangements. One, commonly called the long-period (or LP) seismograph, consists of a 15-second seismometer coupled to a Lehner-Griffith galvanometer with an operating period of approximately 75 seconds. The other, designed for the study of Lg surface waves and hence sometimes called the Lg seismograph, has the same type and period of seismometer, but is coupled to a Leeds-Northrup galvanometer with an operating period of 7 seconds. All the stations listed in Table 1, with the exception of Huancayo, have a 15-75 arrangement. Two stations, Huancayo and Rio de Janeiro, have the 15-7 combination.

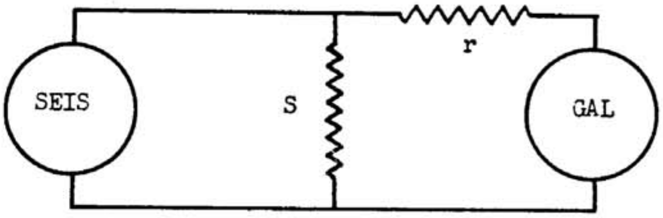


Figure 1

Network arrangement of seismometer coil, galvanometer coil, and coupling resistors, r and S.

In the original operating condition of the seismographs, the seismometer was overdamped by a factor of 1.5 while the galvanometer was overdamped by a factor of 6.0. Later, in order to improve the relative long-period response, the damping factors of the seismometer and galvanometer were changed to approximately 3.0 and 1.0, respectively. This arrangement provides a fairly flat response over a period range bounded approximately by the periods of the seismometer and galvanometer. Because of these changes which affect the response of the instrument, the first calibrations described here apply to the instruments only from the time of the last major change prior to calibration, i.e., when the damping factors were nominally 3.0 and 1.0. Since the time of final calibrations the seismographs have been operating with damping factors of approximately 2.5 to 2.8 for the seismometer and 1.0 for the galvanometer.

The purpose of these long-period seismographs is to encourage and facilitate the study of long-period seismic waves. Many valuable studies resulted from the data recorded from these seismographs, and a large number of papers have been published (see Publications List, Lamont Geological Observatory). The instruments continue to provide valuable data.

In the following there is given a discussion of the steady-state and transient calibration methods, response curves for the calibrated instruments and various associated problems.

STEADY-STATE CALIBRATION SYSTEM

Relative magnification. The steady-state calibration method consists of driving the seismometer with a known steady-state sinusoidal motion, and recording the output from the galvanometer system. When such calibrations are made for short-period instruments, the driving force is frequently a shaking table. The long-period seismometers, however, are heavy and highly tilt sensitive, and would require an elaborately engineered shaking table to provide controlled sinusoidal motions with periods up to 250 seconds. Furthermore, the shaking table method has the disadvantage that the seismograph must be moved from its operating position to the shaking table with consequent and inevitable instrumental changes. Such a system for calibrating instruments, especially long-period instruments at many stations would be impractical due to its importability.

Fortunately the electrical sine wave oscillator can be substituted for the shaking table. The portable oscillator provides an electrical sinusoidal wave which can drive the seismometer boom. The boom motion may then be detected by the galvanometer, magnified, and recorded as sinusoidal waves on photographic paper.

The sine wave current is applied to the seismometer through a Willmore calibration bridge. The purpose of this calibration bridge is to permit the application of a forcing signal to the seismometer coil without disturbing the recording element, but in such a way that this element is left free to respond to the motion of the seismometer boom resulting from the applied signal (Willmore, 1959). The steady-state sine wave current is directly proportional to simulated ground acceleration. The constant of proportionality relating the sine wave current to ground acceleration must be determined in order to compute the absolute magnification.

The bridge system of calibration has previously appeared in seismological writings by Duclaux, 1960; Sohon, 1932, and by Willmore, 1959. In his paper, Willmore describes in some detail the method of applying the Maxwell bridge to the seismometer-galvanometer network, and the steady-state calibration of the same by an electrical sine wave. The Maxwell bridge, as used in seismograph calibration, is also referred to here as the Willmore calibration bridge.

In Figure 2, a diagram of such a bridge, the components, R_1, R_2, R_3 have known values. The element, Z_s, is the component whose value is to be determined, and is assumed to have both resistance, R, and inductance, L. The resistance of the unknown component is balanced by a combination of the other three resistor components, as noted in Figure 2, while its inductance is balanced by a capacitor connected in parallel with the resistor element, R_3. Willmore placed the seismometer coil in the position of the unknown element of the Maxwell bridge. It was found by experimentation that the coils of the long-period seismometers had negligible reactive inductance in the operating frequency range of the seismometer. Consequently, the capacitor, used to balance out the inductance of the coil, is unnecessary. Since the inductance and capacitance of the long-period seismometer-bridge network are negligible, the Maxwell bridge reduces to a Wheatstone bridge. Thus though the calibration bridge is

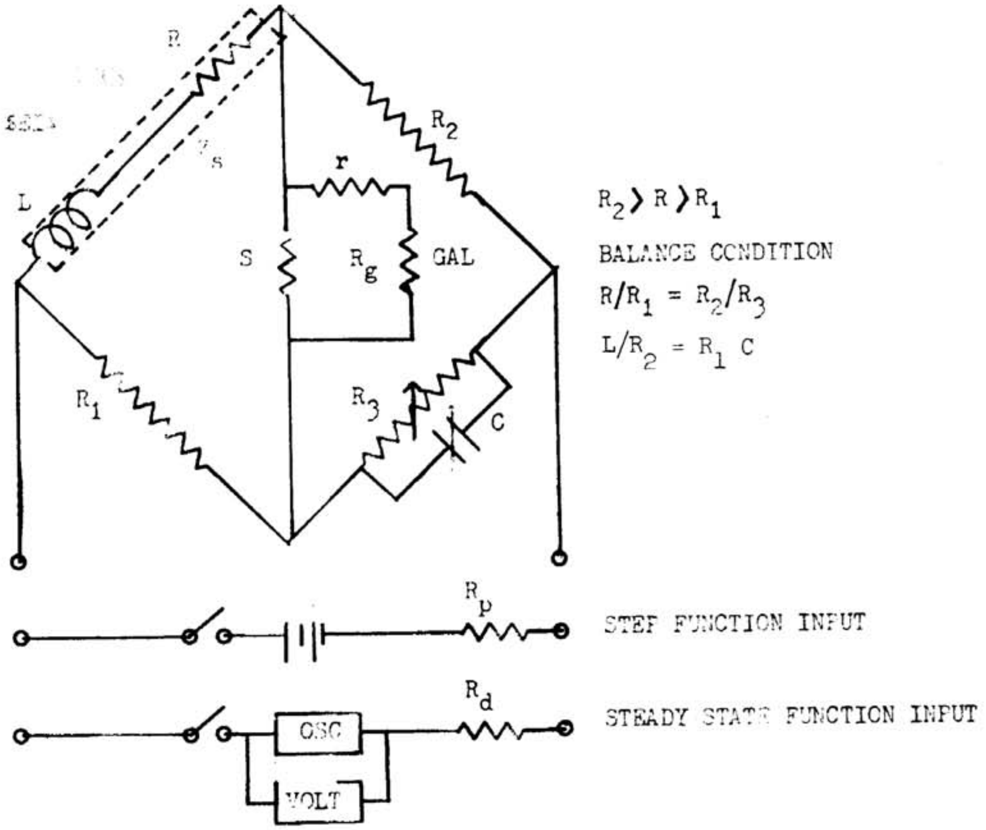


Figure 2. Circuit diagram of seismograph calibration bridge and calibration function generators. Resistors, R_p and R_d, are fixed resistors, preferably a precision type.

essentially a Maxwell bridge, when used for calibrating long-period seismographs it is a simple Wheatstone bridge.

The galvanometer and coupling resistors of the seismographs are placed in the conventional position for a bridge galvanometer. The seismograph galvanometer is therefore independent of the driving force of the sine wave current, but is sensitive to unbalance of the bridge caused by motion of the seismometer boom. The bridge is balanced by clamping the seismometer boom and adjusting the bridge's variable resistor, R_3, until no current flows through the galvanometer from the oscillator. When the bridge is balanced the galvanometer responds only to the motion of the seismometer coil and not to the driving force of the oscillator. Hence the fundamental features of the steady-state calibration system are attained, namely, that 1) the sine wave signal, which is proportional to a ground acceleration, is applied to the seismometer coil, and 2) the galvanometer responds only to the current generated in the coil, and records it as an amplified sine wave. The same result can be obtained using an auxiliary coil and magnet rather than the calibrating bridge. In this case the g of the calibrating coil must be used to determine the absolute magnification.

The sine wave current, applied to the seismometer-bridge system, is kept at constant amplitude, and if it is changed, a correction must be applied to the amplitude of the output. The sine wave used for calibration of the long-period systems has a range of periods from 2 seconds to approximately 250 seconds. The current at each period is applied to the seismometer system long enough to outlast the transient motion that results from switching from one frequency to another, and to record a sufficient number of oscillations to provide a good estimate of the average amplitude for each period.

When the output (or trace amplitude) for each frequency corresponding to the input driving force and the input voltage are recorded on the seismograph, sufficient data is available to graph the instrumental response of the seismograph. The amplitude of the input current at each frequency is tabulated, and any variation from a constant input current is normalized to an arbitrary constant value. Likewise the trace amplitude at each frequency on the output record is tabulated and normalized to correspond to the input current of constant value. The corrected trace amplitude of each frequency is plotted against the corresponding frequency (or period) giving a relative acceleration response curve. Each point of the acceleration response curve can be multiplied by ω and ω^2 to convert to velocity and displacement sensitivity curves, respectively.

Phase response. The phase response curve can be plotted from the records of the input current and trace amplitude. In Figure 3 the time difference between the same phase of the input and output of a given sine wave is represented by Δt, and this time interval corresponds to a phase angle, ϕ. The phase change is expressed in radians by the proportion, $\phi/\Delta t = 2\pi/\tau$ where τ is the value of each period in seconds, and Δt is the time difference between input and output peaks or zero crossings. The phase response, ϕ, in radians, is plotted against period, τ, in seconds.

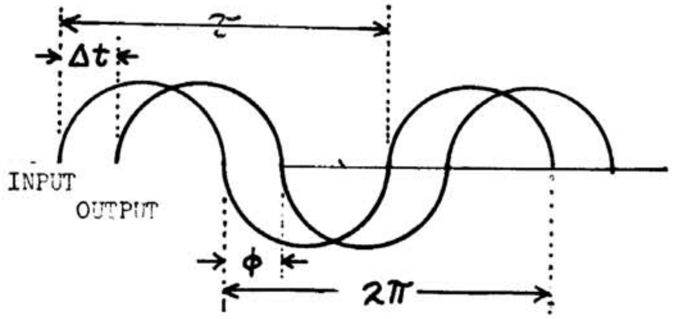


Figure 3. Input and output waves show the phase difference given by the expression, $\phi = 2\pi\,\Delta t/\tau$.

Absolute magnification. Absolute magnification may be obtained by fixing one point of the relative magnification curve. The relationship between input current and ground acceleration is expressed as

$$mY = Gi_c \qquad (1)$$

where m is the mass of the seismometer, G is the electrodynamic constant, and i_c is the current through the seismometer coil. The mass of the seismometer can be determined by weighing the boom. The constant, G, is computed from

$$G^2 = 2\ (h - h_m)\ mR_t\omega_0 \qquad (2)$$

where $h = \varepsilon_0/\omega_0$ is the seismometer damping factor when the seismometer coil sees a total resistance, R_t, including the internal coil resistance, h_m is the open circuit (or mechanical) damping, and ω is the natural period of the instrument. In the computation of G the MKS system is used to avoid transformation constants. The damping factors, h and h_m, are computed from the equation,

$$h^2 = 1/\left[1 + 4\pi^2\ \ n^2/\ln(X_m/X_{m+n})\right] \qquad (3)$$

where X_m, X_{m+n} are amplitudes of a decay curve, n being the number of extrema between X_m and X_{m+n}. The open circuit damping factor, h_m, is obtained from a decay curve for an open coil, in which case the term, R_t, in equation (2), is infinite, while the damping factor, h, involves a damping resistance in series with the coil in which case the term, R_t, is the sum of the coil resistance and the terminal resistance of the external circuit.

Having determined the values of equations (2) and (1), the absolute magnification can be computed in terms of acceleration, velocity, or displacement sensitivity by the following expressions, respectively,

$$M_a = X\ (\mathrm{cm})\ /\ddot{Y}\ (\mathrm{cm/sec^2})$$
$$M_v = X\ (\mathrm{cm})\ \omega\,(\mathrm{rad/sec})/\ddot{Y}(\mathrm{cm/sec^2})$$
$$M_d = X\ (\mathrm{cm})\ \omega^2\ (\mathrm{rad^2/sec^2})\ /\ddot{Y}(\mathrm{cm/sec^2})$$

Standardization. In addition to calibrating all the seismographs according to the conditions at which they were operating at that time, it was necessary to standardize them and then to recalibrate them. The damping constants, h_s and h_g, required by the original design of the LP seismographs were $\varepsilon_0 = 3.0\ \omega_0$ for the seismometer and $\varepsilon_g = 1.0\ \ \omega_g$ for the galvanometer. The norm for standardization was arbitrarily established to consist of a maximum displacement magnification near 1500 at 15 seconds and a rather flat response over the period range of 3 to 60 seconds. The damping constants for this case would correspond to approximately $h_s = 2.5$ and $h_g = 1.0$. The three main elements of the seismograph, namely, the seismometer, the galvanometer, and the coupling resistors, all influence the response of the seismograph. Certain specifications of the seismograph are difficult to change under the present design, e.g., the internal resistance of both the seismometer and galvanometer coils, the natural period of the galvanometer, and the strength of the galvanometer magnet.

Some features of the seismometer which affect the response curve are its natural period and the strength of its magnet. The value chosen for the operating period is 15 seconds. A change of a few seconds from this value produces only slight changes in the response curve. The period adjustment, therefore, is not a critical factor, but for the sake of uniformity the period of all the seismometers was adjusted close to 15 seconds.

The strength of the seismometer magnet has a pronounced effect on the response curve. Magnets, which become weak with age, produce low magnification and also limit the amount of overdamping which controls the flatness of the magnification response. With negligible mechanical damping the damping factor, h, of the seismometer, or galvanometer, is the ratio of the total resistance required for critical damping of the seismometer, or galvanometer, to the total resistance in the circuit. A seismometer which has a weak magnet, as found in several LP seismographs with standard circuit, has a damping factor of approximately $h = 1.0$. By replacing a weak magnet with a stronger one it is possible to get a damping factor of 2.5 to 2.8. This larger value provides a rather flat displacement response over the period range of 3 to 60 seconds.

The three features of the Lehner-Griffith galvanometer which influence the magnification response are its period, magnet strength and position of the magnet (damping) shunt. Of these the latter is the most important in terms of controlling the shape of the response curve. Depending on the position of the damping shunt the critical damping resistance varies from about 450 ohms, when the shunt touches the poles of the magnet, to 3500 ohms, when the shunt is fully separated from the poles. With the circuit used, if the shunt touches the poles the damping is approximately critical ($h= 1$). The result is that the magnification response is fairly flat over the 3 to 60 seconds period range, provided the seismometer damping constant is also of the order of 2.5 to 2.8. If the shunt is separated from the poles the galvanometer is overdamped and the magnification in the 30 to 60 seconds period range is greatly reduced.

The galvanometer period has the effect on the response curve of extending the displacement magnification over a wider range of periods as the galvanometer period is increased. The range of galvanometer periods is between 70 and 100 seconds. Experiments were performed with test galvanometers in an effort to change the period of the galvanometer without replacing the suspensions already in the instrument. Loosening the lower suspension, for example, increases the period by a few seconds. This experiment proved to be very tedious and time consuming, and had, at best, unpredictable results. Hence the galvanometer periods were not standardized.

The design of the coupling network consists of a series resistor, r, between the seismometer and galvanometer coils, and a shunt resistor, S, across the seismometer coil terminals, as shown in Figure 1. The value of r had been originally set at 330 ohms while S was 220 ohms for the horizontal components and 100 ohms for the vertical component. The selection of these resistors was made to give the damping constants of 3.0 and 1.0 for the seismometer and galvanometer, respectively. Experimentation showed that an increase in the shunt resistor, S, would increase the overall magnification without changing the shape of the response curve appreciably. The slight change that did result from an increase of S made the flat part of the displacement response only slightly more rounded, since the damping constant, h = 3.0, was thereby decreased to about 2.8 to 2.5. The adjustment of S made it possible to control the overall magnification.

TRANSIENT TECHNIQUE SYSTEM

The calibration project also included the development and application of the transient technique system of calibration. An article published in the Bulletin of the Seismological Society of America, entitled "A Transient Technique for Seismograph Calibration," by A. F. Espinosa, G. H. Sutton, and H. J. Miller, S.J., describes this technique in detail. For the sake of completeness in this report the essential ideas are briefly summarized.

The purpose of the transient technique is to provide a simple calibration which may be done routinely and frequently without disturbing the record for an extended period of time. The technique consists in applying an electrical pulse to the seismometer through a Willmore calibration bridge, or through an independent coil, and recording the transient output. The output pulse, when analyzed as the ratio of its Fourier transform to that of the input pulse, yields the relative amplitude and phase responses. The absolute calibration can be computed by experimentally determining two constants, G, the electrodynamic constant of the seismometer coil, and m, the mass of the seismometer, as described above.

Verification of the transient technique has been made with the conventional steady-state calibration method and with theoretical response curves made on both digital and analog computers. The pulse circuit used for applying a transient signal to the seismometer consists of 1.45 volt mercury cell, a resistor in series, and an on-off switch across the terminals of the bridge (see Figure 2). A step or spike may be used. The pulse is manually applied to the seismometer system so as to preclude pulses on the records when the station operator knows an earthquake is being recorded. In the process of calibrating the network of instruments a permanent Willmore bridge and pulse generating circuit were installed for each instrument. The size of the pulse resistor was experimentally determined to produce a pulse about 8 cm in amplitude.

Analog computer curves. The purpose of the analog computer curves is to have a ready method of determining the calibration of a seismograph by matching the transient pulses recorded on the seismographs with the transients made by the analog computer. To each transient there corresponds a displacement response curve and a phase response curve. Transient pulses and response curves for 94 combinations of seismometer-galvanometer parameters to cover the possible cases of long-period instruments were made with the analog computer.

To obtain the output curves, the equations of motion of the seismometer and galvanometer are first programmed into the analog computer. An electrical input is then applied to the computer in the form of 1) a steady-state sine wave of known magnitude, and 2) a transient step pulse or impulse of acceleration. The output from the step pulse input is a transient pulse whose amplitude is calibrated in volts. The time scale of the simulated seismograph is the same as that of the actual instrument. The output from the steady-state input is in the form of Lissajous figures whose horizontal component represents the input and whose vertical component represents the output. Lissajous' figures are obtained for selected periods. The amplitudes of these figures supply the displacement response. The phase response may be obtained from these Lissajous figures in a conventional way.

The absolute displacement sensitivity is computed from the following equation:

$$M = D_f/Y_f = -(m/G)\ (D_f'/D_t')\ (v_t'/v_f')\ (D_t/i_t)$$

where,

m/G = ratio of mass to electrodynamic constant of seismometer being calibrated

D_f'/D_t' = ratio of steady-state trace amplitude to maximum trace amplitude of the transient for the standard

v_t'/v_f' = ratio of amplitude of transient input to amplitude of steady-state input for the standard

D_t = maximum trace amplitude of the calibration-transient of seismograph

i_t = amplitude of calibration-transient driving current applied to coil of seismometer

D_f = steady-state trace amplitude of seismograph

Y_f = steady-state ground motion

The electrodynamic constant can be obtained from the equation,

$$G^2 = 2\ (h - h_m)\ \omega_o m R_t$$

above.

RESPONSE CURVES

Response curves were obtained for the LP and Lg seismographs for each station. These are the magnification curves in terms of absolute displacement sensitivity and phase response. The displacement sensitivity response curves were made by applying a steady-state signal to the seismometer and recording the input and output signals. Phase response curves were made from the observed data for some of the instruments. In other cases where there was insufficient data of high resolution because of a lack of time marks on the input record, the phase curves were obtained by matching observed steady-state displacement curves

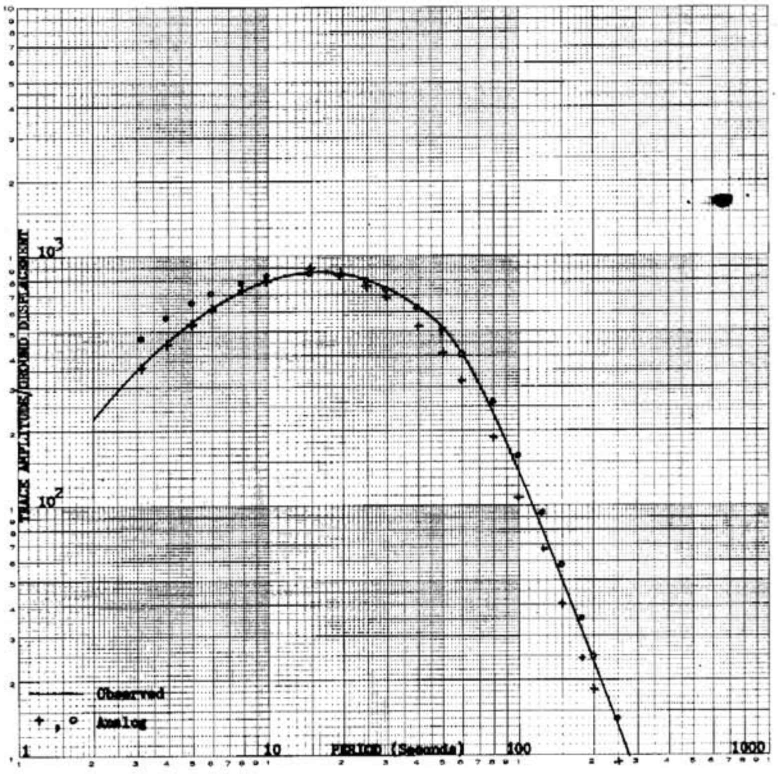


Figure 4. The displacement response, observed by the steady state method, is matched with two analog displacement curves.

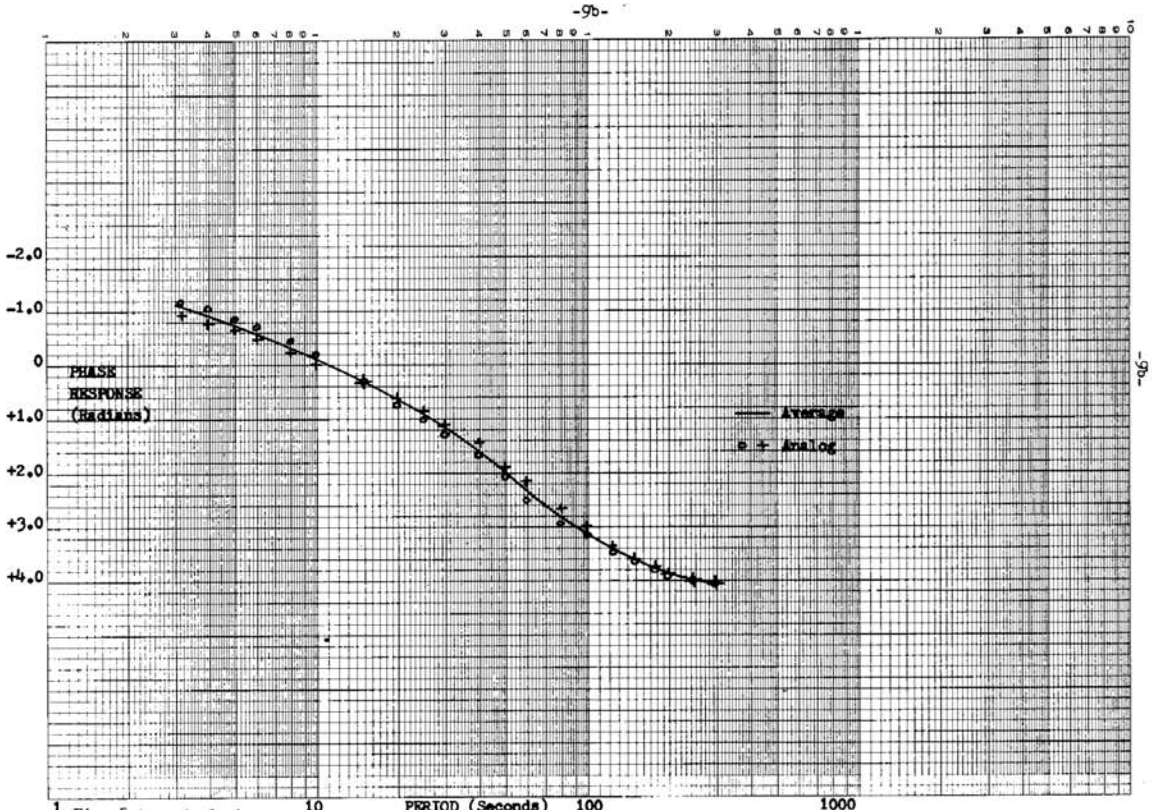


Fig. 5. A typical phase response curve (solid line) is derived from two analog phase curves (+) and (o) whose corresponding displacement curves most closely match the observed displacement response curves.

with those made by the analog computer. If only one analog curve closely matched the observed curve the analog phase curve which corresponds to the matched analog displacement curve was adopted for the calibrated seismograph. If two analog curves bracketed the observed curve, an approximate average of the corresponding analog phase curves was drawn and adopted as the phase response curve of the calibrated seismograph. Figure 4 shows the observed displacement curve and the analog curves which most closely match the observed data. Figure 5 shows a typical phase curve derived from the two analog phase curves corresponding to the analog displacement curves which most closely match the observed data. Such a typical phase response curve is adopted for the seismograph.

The calibration curves apply to the instruments over certain periods of time dating from the time of the last major instrument change. The changes which have the most noticeable effects on the response of the instrument are new seismometer magnets, coupling resistors, and position of the galvanometer damping shunt. Other changes such as seismometer and galvanometer periods have relatively little effect on the response of the instruments. In a few cases the dates of the last major instrument change are uncertain. Caution should be used when applying response curves for instruments which required some major adjustment in order to get them operating properly before calibrating them. Calibration curves are supplied for the stations listed in Table 1.

Table 1
List of stations for which there are calibration curves

Bermuda
Buenos Aires
Delhi
Hong Kong
Honolulu
Huancayo
Mt. Tsukuba
Perth
Rio de Janeiro
Santiago
Suva
Uppsala
Waynesburg

Bermuda

Instruments. Two Columbia horizontals, one Sprengnether vertical.

Response curves. The first calibration applies from January 15, 1959 to December 19, 1960. The final calibration applies from December 23, 1960 to the present day. Phase response curves were obtained by comparison with analog computer curves.

Buenos Aires

Instruments. Two Columbia horizontals, one Lehner-Griffith vertical.

Response curves. The first calibration applies from December 8, 1958 to February 23, 1962. The final calibration applies from February 26, 1962 to the present. Phase response curves were obtained by comparison with analog computer curves.

Delhi

Instruments. Two Lehner-Griffith horizontals, one Sprengnether vertical.

Response curves. The first calibration dates from November 4, 1960, when the Delhi station began operating, to April 14, 1962. No recordings were made during the change-over period of August 1, 1960 to November 4, 1960 from Agra to Delhi. Prior to this time from January 14, 1959 to August 1, 1960 the instruments underwent no major change. The final calibration applies from April 15, 1962 to the present day. The phase response curves were obtained from input and output records.

Hong Kong

Instruments. Two Lehner-Griffith horizontals, one Sprengnether vertical.

Response curves. The first calibration applies from September 24, 1958 to April 28, 1962. The final calibration applies from May 4, 1962 to the present day. The phase response curves were obtained from input and output records.

Honolulu

Instruments. Two Lehner-Griffith horizontals, one Sprengnether vertical.

Response curves and dates of application

Component	From	To	Use Calibration	Remarks
Horizontals	June 3, 1958	June 7, 1962	First	
	June 7, 1962	June 11, 1962	None	
	June 11, 1962	Present	Filter	If filters used
			1500	If filters not used
Vertical	June 3, 1958	May 29, 1961	First Vertical A	
	May 30, 1961	Oct. 16, 1961	First Vertical B	
	Oct. 17,1961	June 7, 1962	First Vertical C	
	June 7, 1961	June 11, 1962	None	
	June 11, 1962	Present	Filter	If filters used
			1500	If filters not used

The first calibration for the horizontal instruments applies from June 3, 1958 to June 7, 1962. Caution, however, should be used. On the date of the first calibration it was found that the horizontal galvanometers were acting peculiarly. Their periods were measured at 17 seconds for the NS galvanometer and 22 seconds for the EW galvanometer. It was impossible to calibrate the seismographs with the galvanometers in this condition since they responded erratically. The galvanometers were opened and adjusted to their normal long-period values before the calibration was performed. There is no record as to how long the erratic condition of the galvanometers existed.

In the case of the vertical seismograph because of strong microseisms an additional 100 ohm resistor was added to the 100 ohm shunt resistor in parallel in order to decrease the amplitudes of the microseism recordings. This practice was begun in October 1961. The instrumental response for this condition is curve C on the First Calibration sheet. During periods of small microseism activity the single 100 ohm resistor was used, and curve B applies for this condition and period of operation.

At the time of the June 1962 calibrations short-period galvanometers were installed in the seismometer-galvanometer circuits to reduce the microseisms and the system was calibrated and called the Filter Calibration. The filter galvanometers replace the series resistors between the seismometer and the long-period galvanometer. The calibrations labeled, 1500 Calibration, are the same as the ones called, Final Calibration.

On May 29, 1961 a new strong magnet was installed on the Sprengnether vertical. On June 11, 1962 another magnet slightly stronger than the former was installed on the Sprengnether vertical.

Phase response curves were obtained from the input and output records.

Huancayo

Instruments. Two Lehner-Griffith horizontal seismometers, one Sprengnether vertical seismometer, three Leeds-Northrup, #22856, 7-seconds galvanometers.

Response curves. The first calibration applies from February 21, 1958 to January 26, 1962. The final calibration applies from January 31, 1962 to the present day. Phase response curves were obtained from input and output records only for the first calibration of the short-period vertical seismograph.

Mt. Tsukuba

Instruments. Two Lehner-Griffith horizontals, one Sprengnether vertical.

Response curves. The first calibration applies from March 24, 1959 to May 9, 1962. The final calibration applies from May 12, 1962 to the present day. Phase response curves were obtained from the input and output records.

Perth

Instruments. Two Sprengnether horizontals, one Press-Ewing vertical (original design).

Response curves. The first calibration applies from August 30, 1961 to May 18, 1962.

From May 28, 1962 use

a) Filter Calibration if the filter galvanometers are in use in the circuit.

b) 1500 Calibration if the filter galvanometers are not in the circuit.

Phase response curves were obtained from input and output records.

A calibration was made with the filter galvanometer periods of 6.7 seconds. Because the microseism period appeared to be closer to 4.5 to 5.0 seconds, the suspensions of the filter galvanometers were shortened to provide a period of 4.6 seconds. This condition was calibrated and is the present filter galvanometer operating condition. No phase response for the filter system was made since the steady-state calibration was made only from 2 to 20 seconds.

Rio de Janeiro

Instruments. Two Lehner-Griffith horizontal seismometers each with two coils, one connected to a long-period galvanometer, the other to a short-period galvanometer.

Two Sprengnether vertical seismometers, one connected to a short-period galvanometer, the other to a long-period galvanometer.

Response curves. The first calibration of the short-period seismographs applies from June 1, 1958 to February 28, 1962. At the time of the first calibration it was found that the short-period galvanometers were sticking and therefore it was impossible to perform the calibration until the galvanometers were freed. There is no record as to how long the sticking condition existed. Hence the calibration curves should be applied with caution. The first calibration of the long-period instruments applies from June 1, 1958 to March 1, 1962. The final short-period calibration applies from March 1, 1962 to the present day. The final long-period calibration applies from March 6, 1962 to the present day. The phase response curves for the long-period instruments were obtained by comparison with the analog computer curves. There are no phase response curves for the short-period instruments.

Santiago

Instruments. Two Lehner-Griffith horizontals, one Sprengnether vertical.

Response curves. The first calibration applies from December 13, 1958 to February 17, 1962. The final calibration applies from February 17, 1962 to the present day. The phase response curves were obtained by matching analog computer curves.

Suva

Instruments. Two Lehner-Griffith horizontals, one Sprengnether vertical.

Response curves. The first and only calibration applies from July 8, 1958 to the present day. During the period from March 28, 1958 to July 8, 1958 the seismometer period was operating at 30 seconds. Phase response curves were obtained from input and output records.

The instruments have been operating with shunt resistors of 100 ohms on each of the three components from March 28, 1958 to the present day. At the time of calibration the station was tentatively planned to be discontinued. Hence no instrumental changes were made. In the event, however, that a magnification increase should be desired, test calibrations were made with the following results:

NS 813 Displacement Magnification at T = 20 seconds for a 470 ohm shunt
EW 1160 " " " T 20 " " " 470 " "
Z 1270 " " " T 20 " " " 220 " "

Phase response curves were obtained from the input and output records.

Uppsala

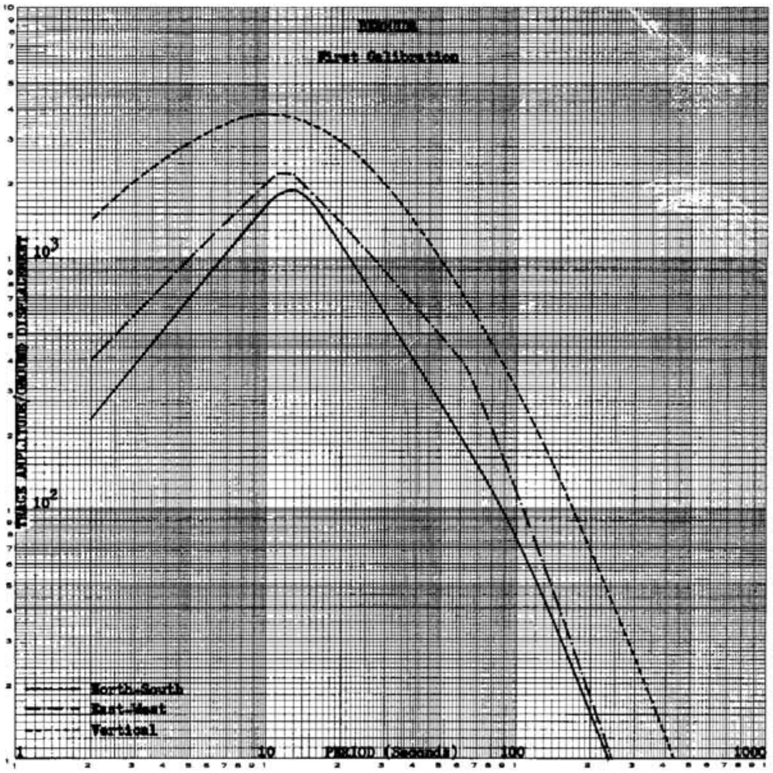
Instruments. Two Lehner-Griffith horizontals, one Sprengnether vertical.

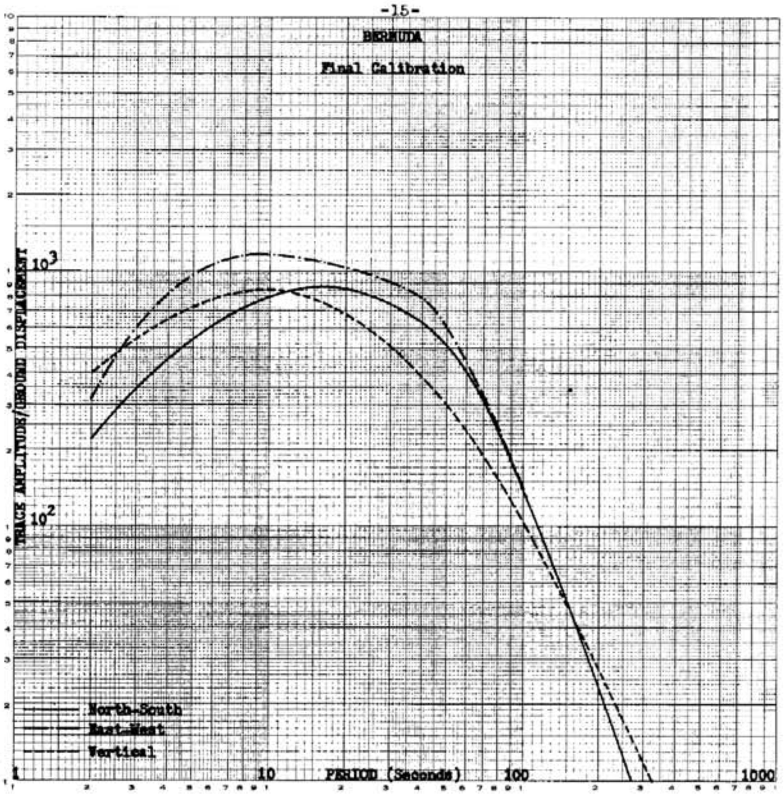
Response curves. The first calibration applies from March 21, 1959 to March 26, 1962. At the time of calibration the damping shunts of the galvanometers were all the way up. This condition decreases the magnification in the long-period range of 30 to 60 seconds. The final calibration applies from March 29, 1962 to the present day. Phase response curves were obtained from the input and output records.

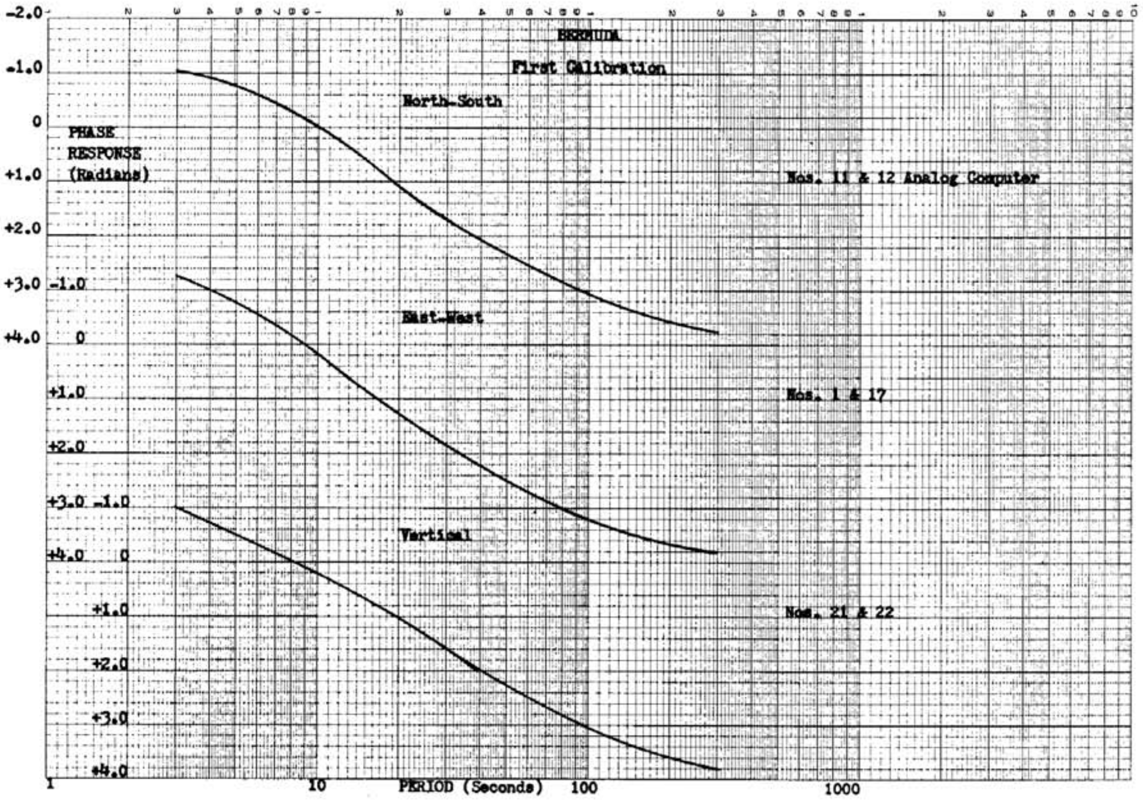
Waynesburg

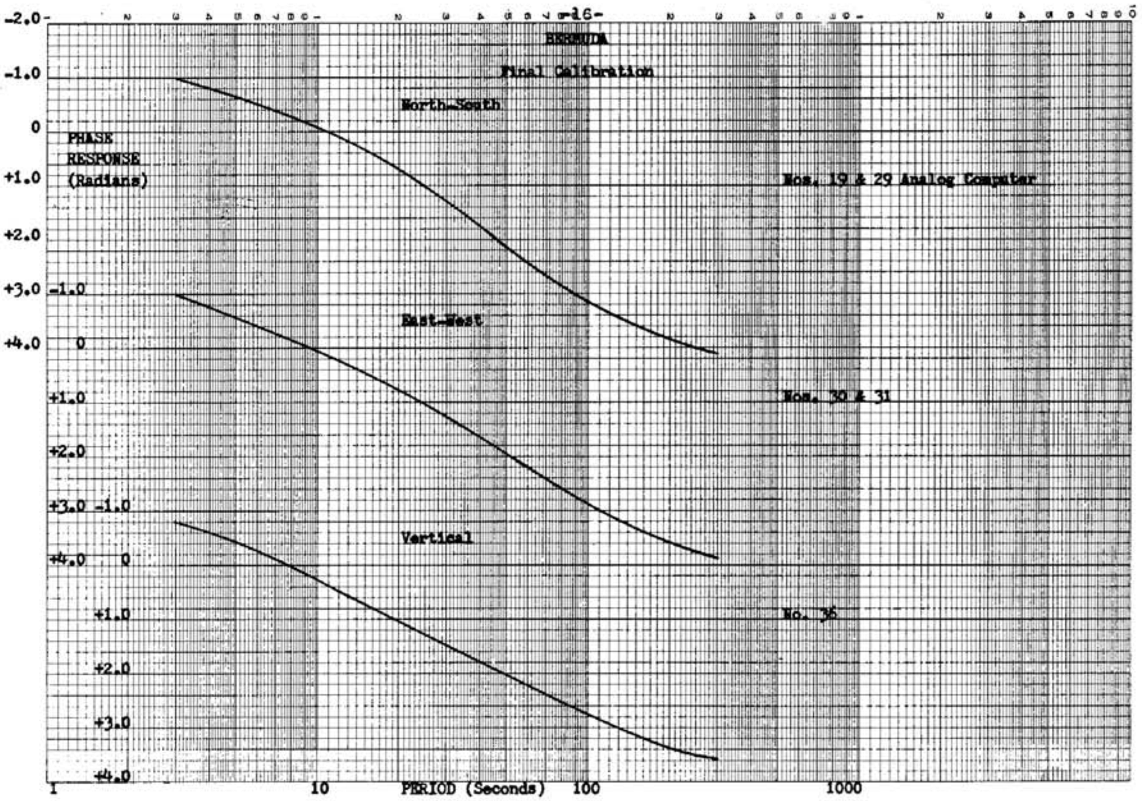
Instruments. Two original Lamont horizontals, one Sprengnether vertical.

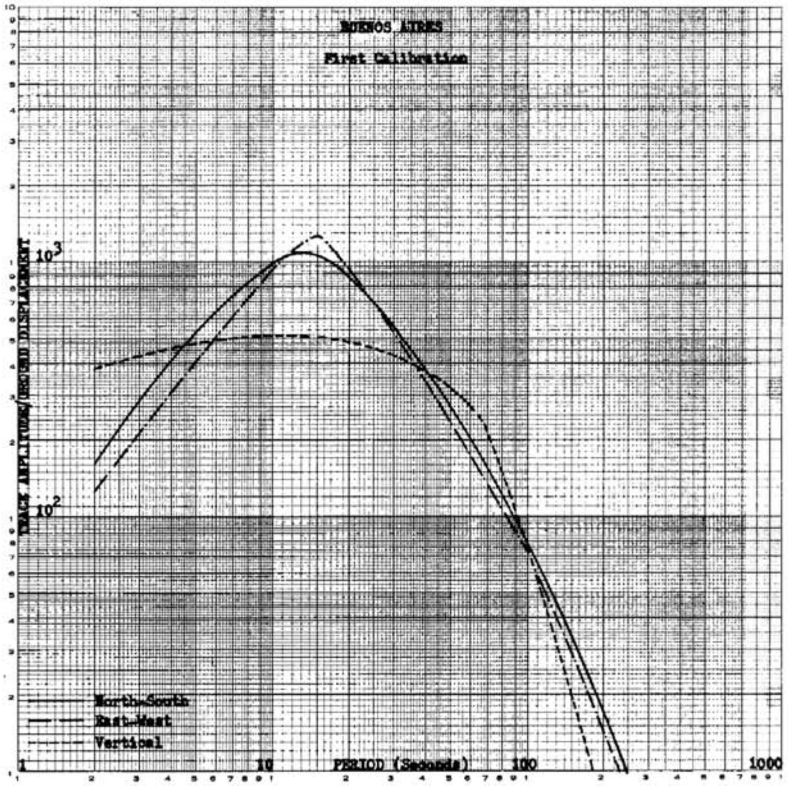
Response curves. The first calibration applies from October 17, 1960 to January 24, 1961. The final calibration applies from February 2, 1961 to the present day. Phase response curves were obtained by comparison with analog computer curves.

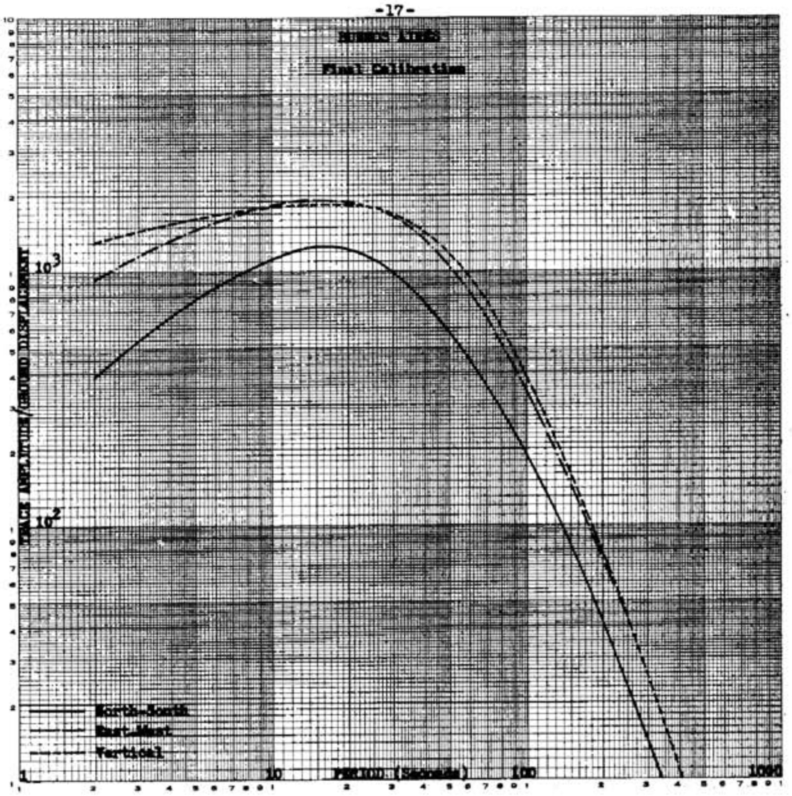


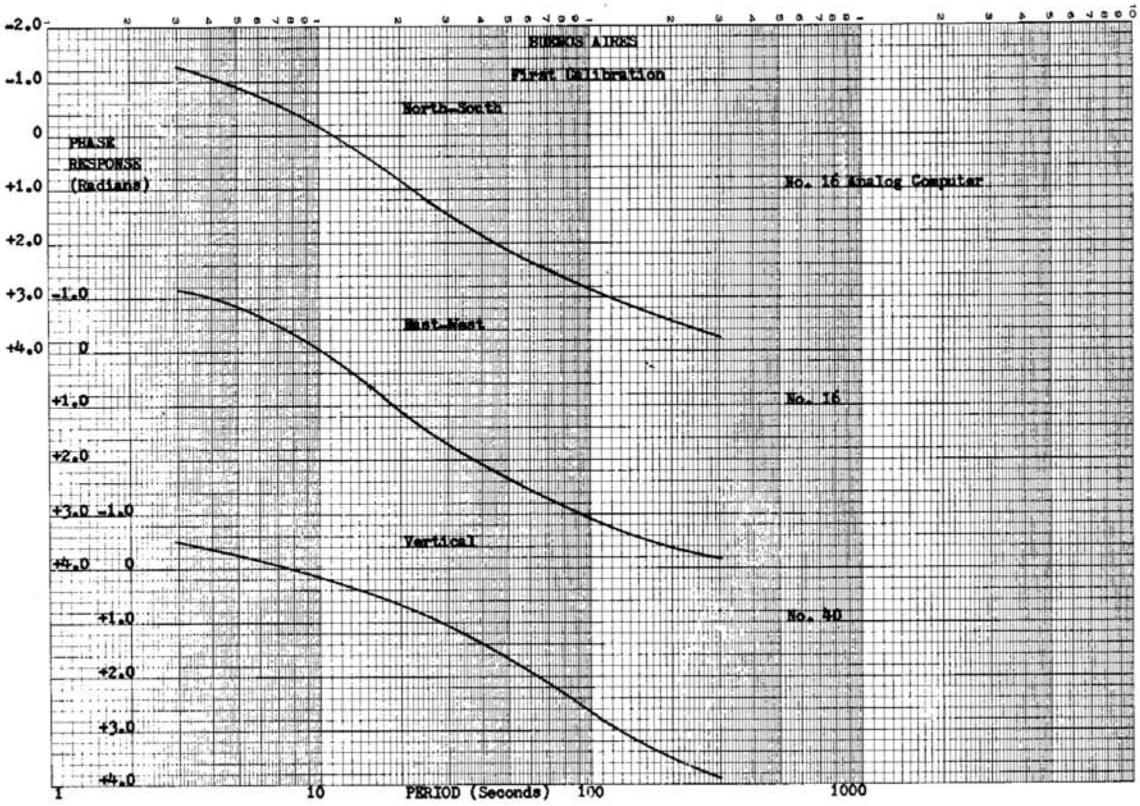

BERMUDA
Final Calibration
TRACE AMPLITUDE/GROUND DISPLACEMENT
10^3
10^2
1
10
100
1000
PERIOD (Seconds)
North-South
East-West
Vertical

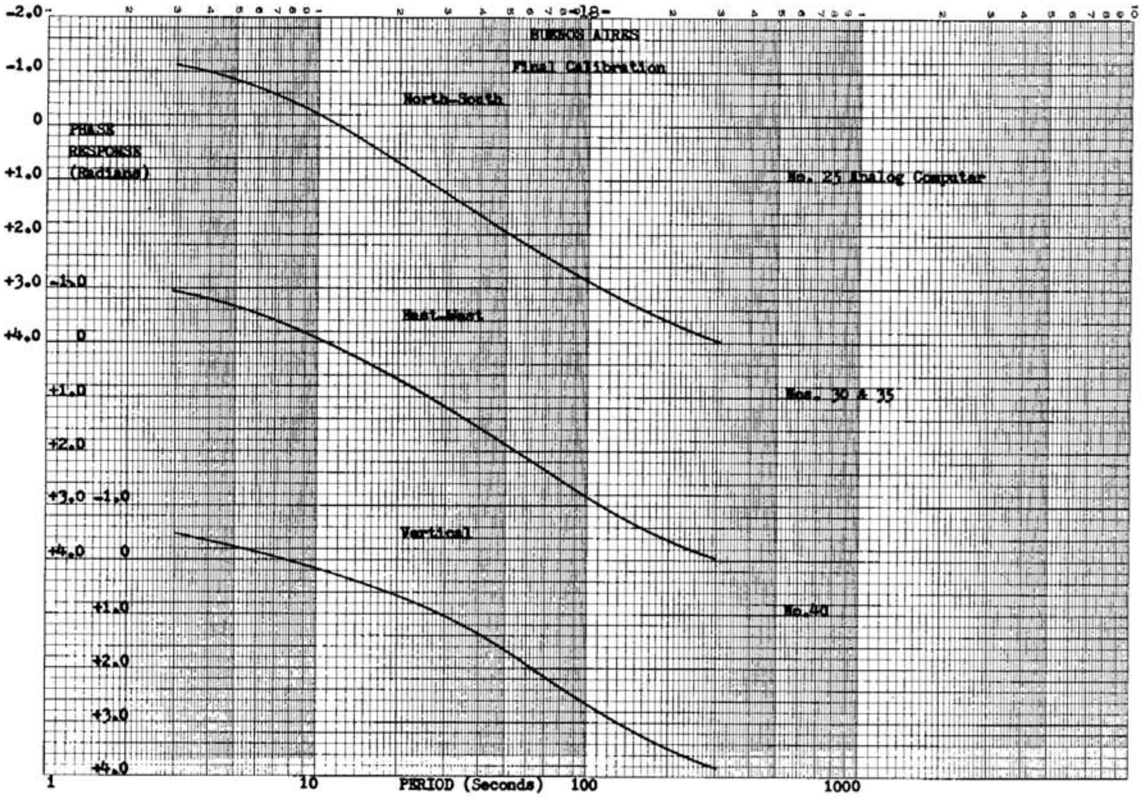

BERMUDA
First Calibration
PHASE RESPONSE (Radians)
-2.0
-1.0
0
+1.0
+2.0
+3.0
+4.0
North-South
East-West
Vertical
Nos. 11 & 12 Analog Computer
Nos. 1 & 17
Nos. 21 & 22
1
10
100
1000
PERIOD (Seconds)

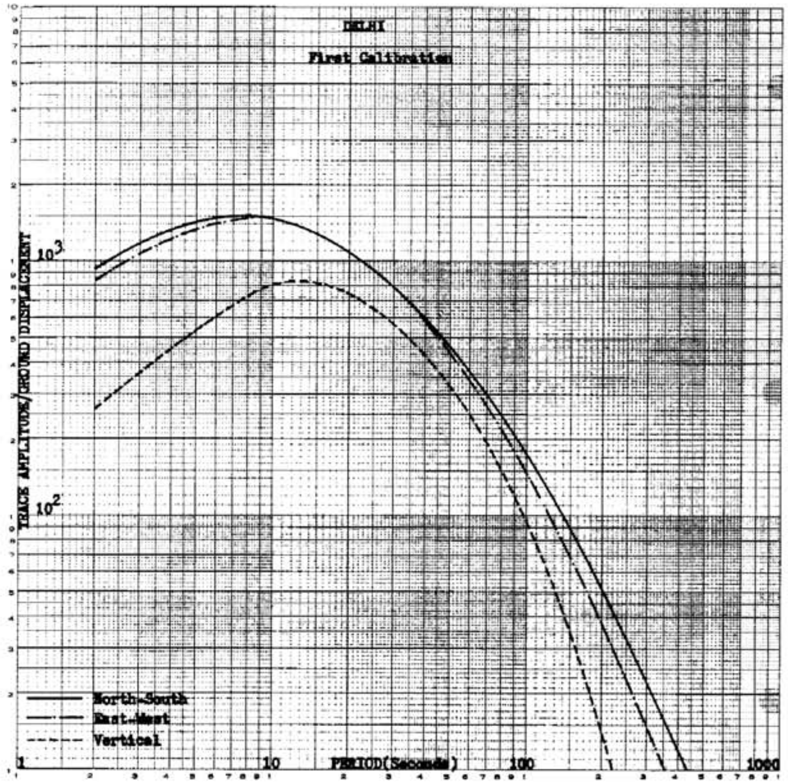

BERMUDA
Final Calibration
North-South
East-West
Vertical
PHASE
RESPONSE
(Radians)
Nos. 19 & 29 Analog Computer
Nos. 30 & 31
No. 36
-2.0
-1.0
0
+1.0
+2.0
+3.0
+4.0
1
10
PERIOD (Seconds)
100
1000

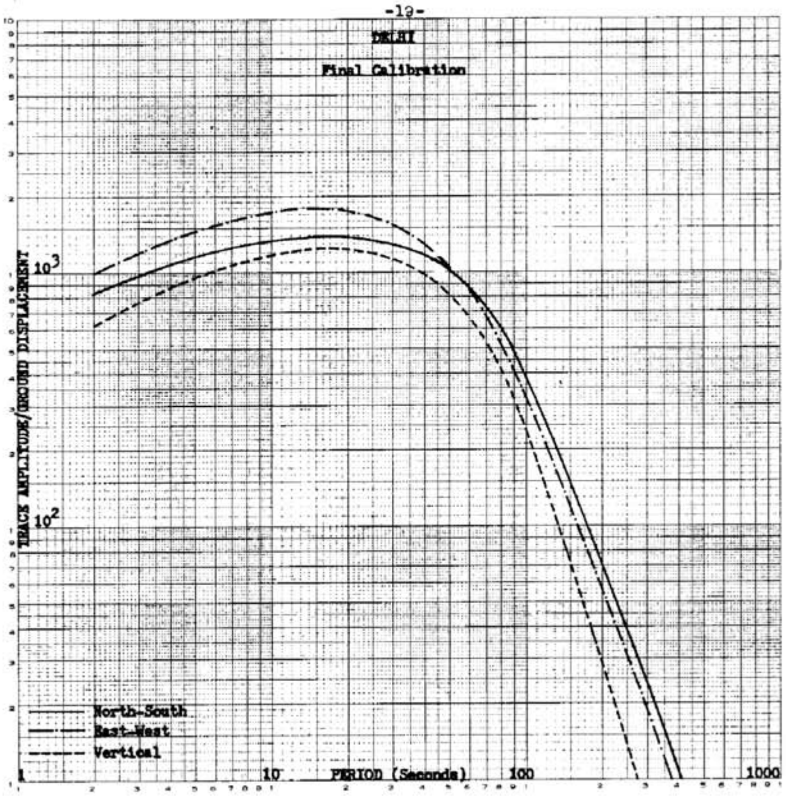

BUENOS AIRES
First Calibration
TRACE AMPLITUDE/GROUND DISPLACEMENT
10^3
10^2
North-South
East-West
Vertical
1
10
PERIOD (Seconds)
100
1000

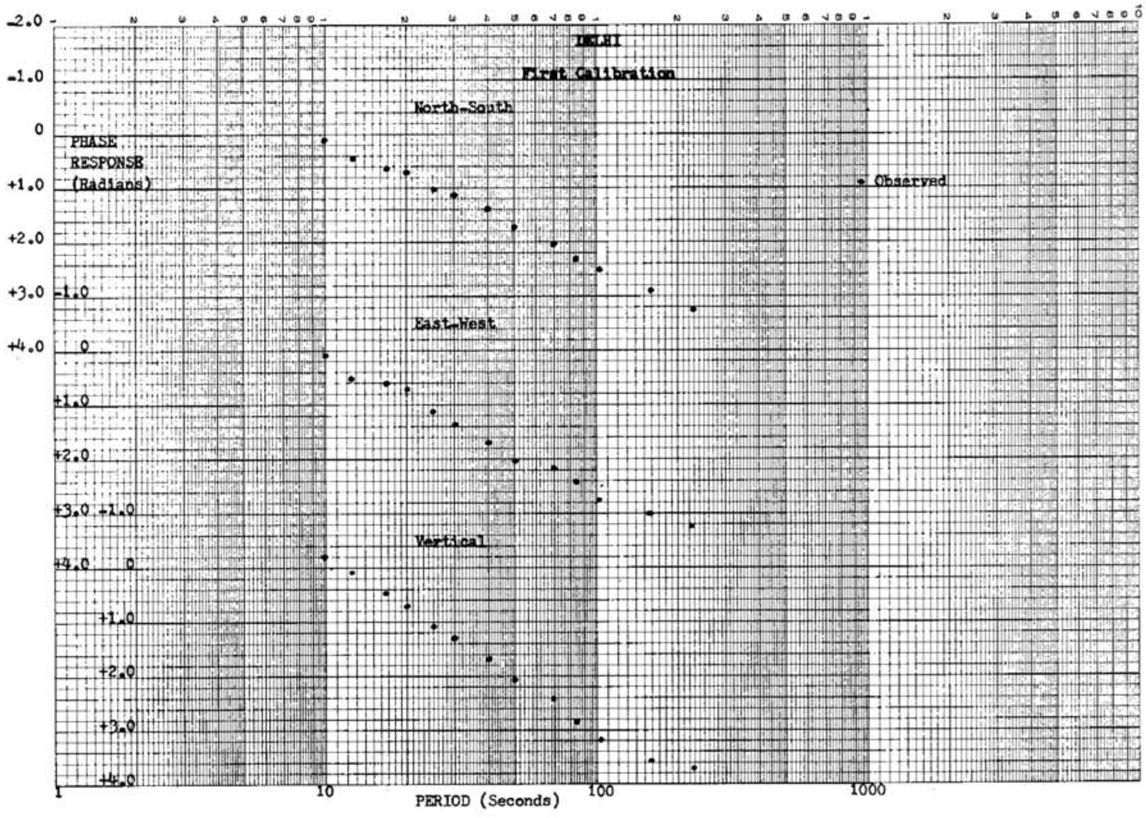

BUENOS AIRES
Final Calibration
TRACE AMPLITUDE/GROUND DISPLACEMENT
10³
10²
North-South
East-West
Vertical
1
10
PERIOD (Seconds)
100
1000

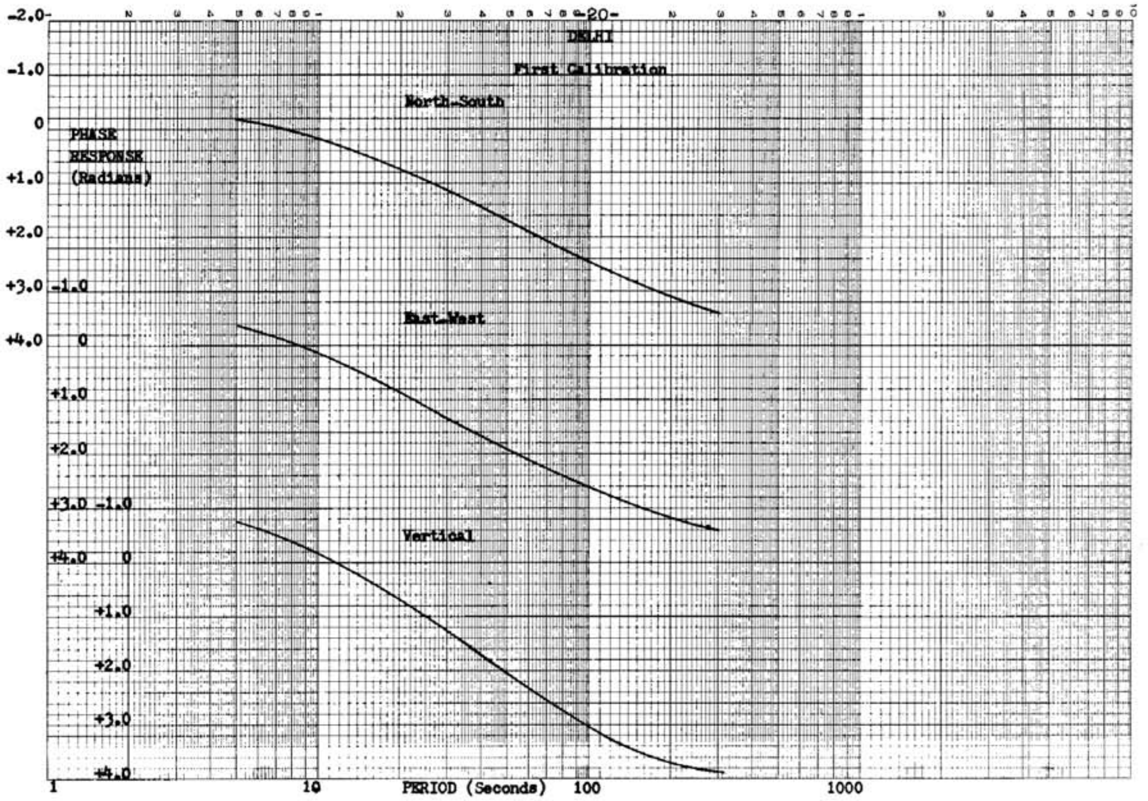

BUENOS AIRES
First Calibration
PHASE
RESPONSE
(Radians)
-2.0
-1.0
0
+1.0
+2.0
+3.0
+4.0
North-South
No. 16 Analog Computer
East-West
No. 16
Vertical
No. 40
1
10
PERIOD (Seconds)
100
1000

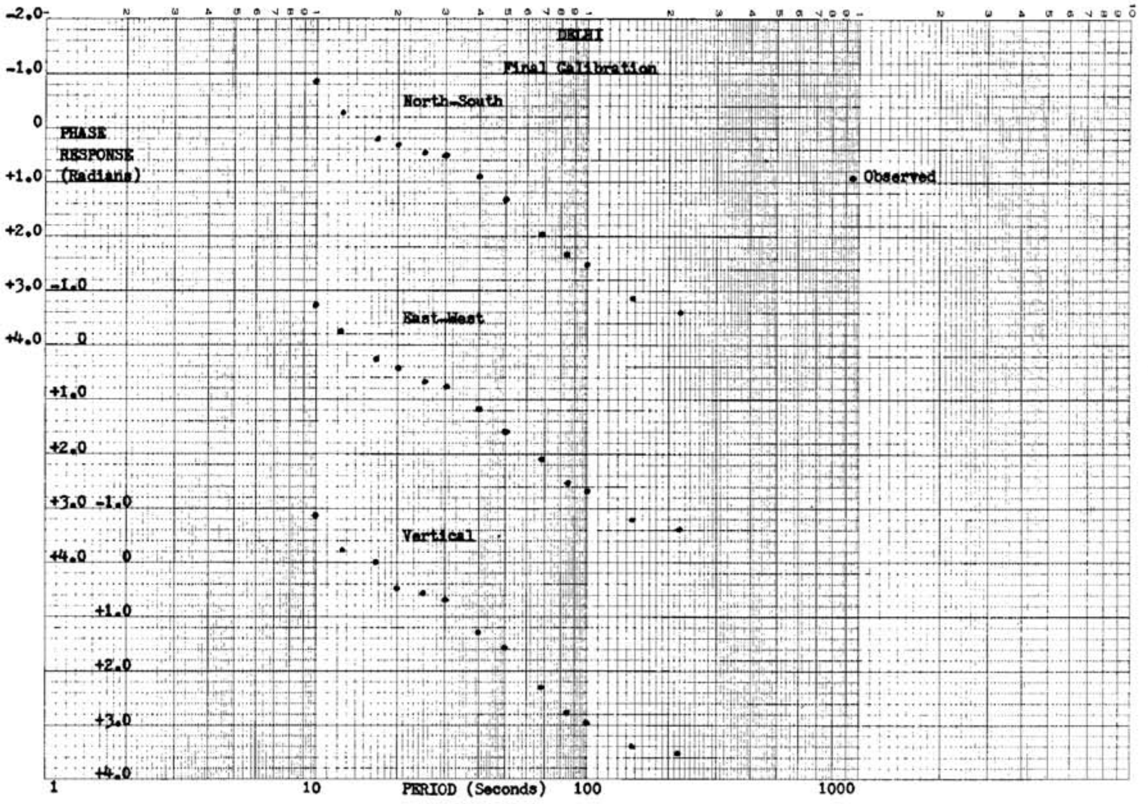

BUENOS AIRES
Final Calibration
PHASE RESPONSE (Radians)
North-South
No. 25 Analog Computer
East-West
Nos. 30 & 35
Vertical
No. 40
-2.0
-1.0
0
+1.0
+2.0
+3.0 -1.0
+4.0 0
+1.0
+2.0
+3.0 -1.0
+4.0 0
+1.0
+2.0
+3.0
+4.0
1
10
PERIOD (Seconds)
100
1000

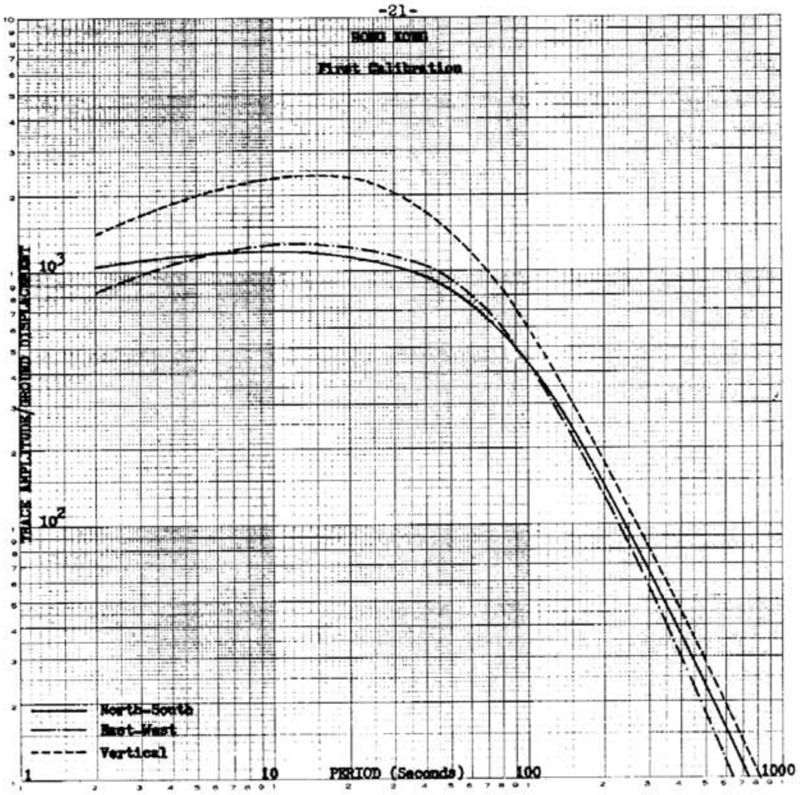

DELHI
First Calibration
TRACE AMPLITUDE/GROUND DISPLACEMENT
10^3
10^2
North-South
East-West
Vertical
1
10
PERIOD(Seconds)
100
1000

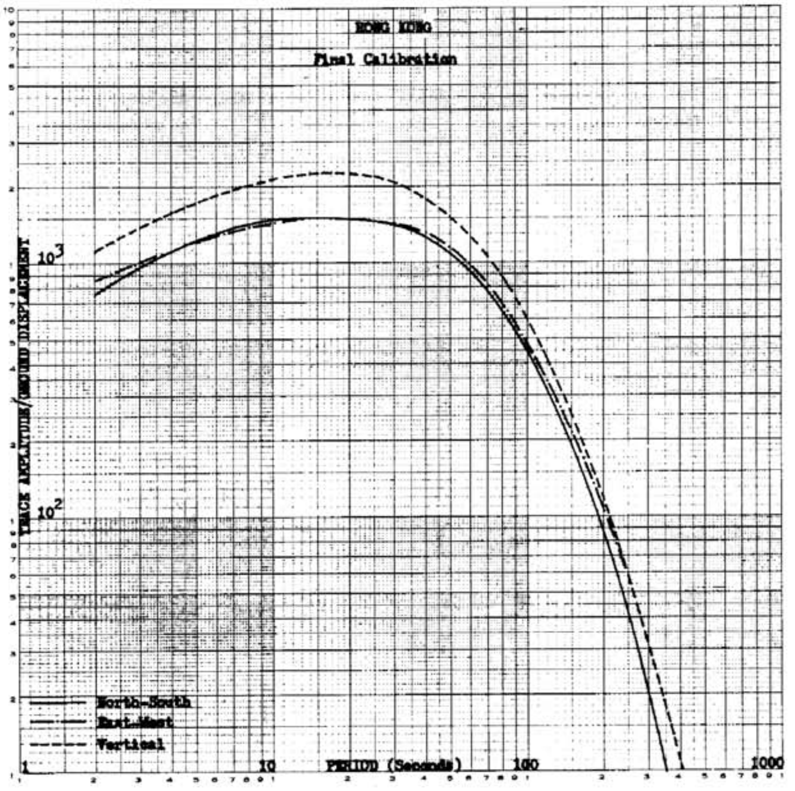

DELHI
Final Calibration
TRACE AMPLITUDE/GROUND DISPLACEMENT
10^3
10^2
North-South
East-West
Vertical
1
10
PERIOD (Seconds)
100
1000

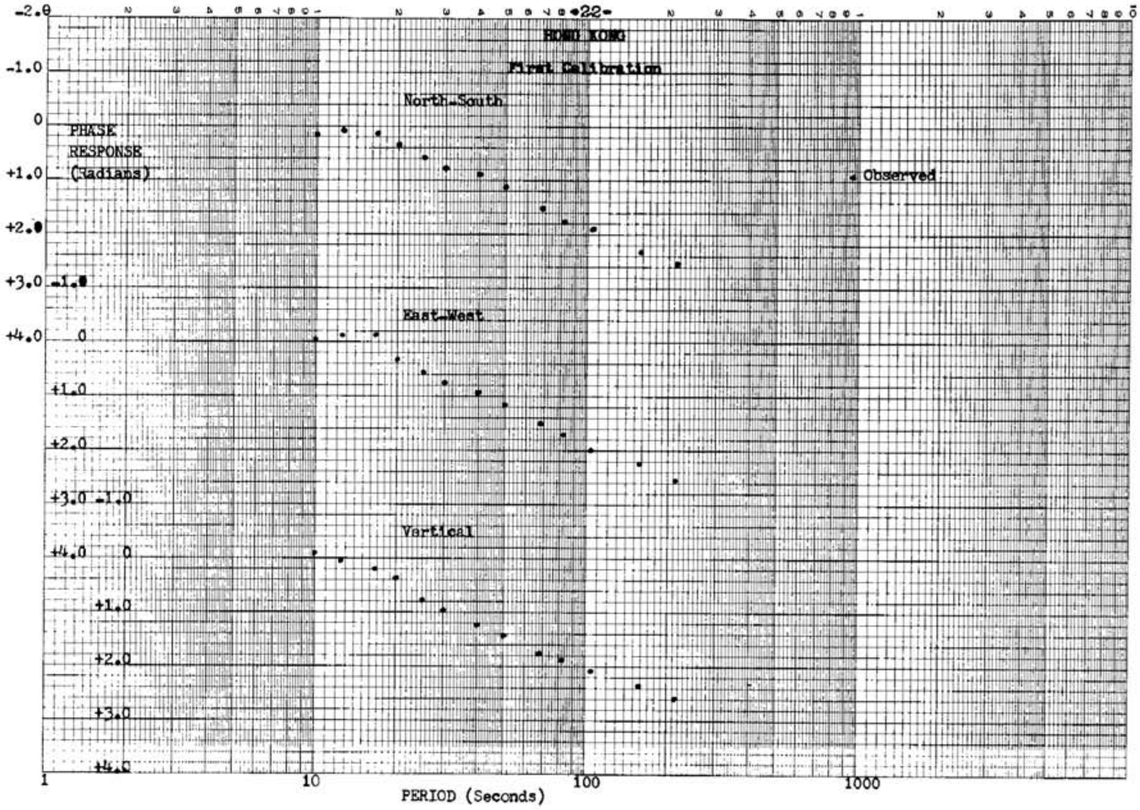

DELHI
First Calibration
North-South
East-West
Vertical
PHASE
RESPONSE
(Radians)
• Observed
-2.0
-1.0
0
+1.0
+2.0
+3.0
+4.0
-1.0
0
+1.0
+2.0
+3.0
+1.0
+4.0
0
+1.0
+2.0
+3.0
+4.0
1
10
100
1000
PERIOD (Seconds)


DELHI
First Calibration
North-South
East-West
Vertical
PHASE RESPONSE (Radians)
-2.0
-1.0
0
+1.0
+2.0
+3.0 -1.0
+4.0 0
+1.0
+2.0
+3.0 -1.0
+4.0 0
+1.0
+2.0
+3.0
+4.0
1
10
PERIOD (Seconds)
100
1000

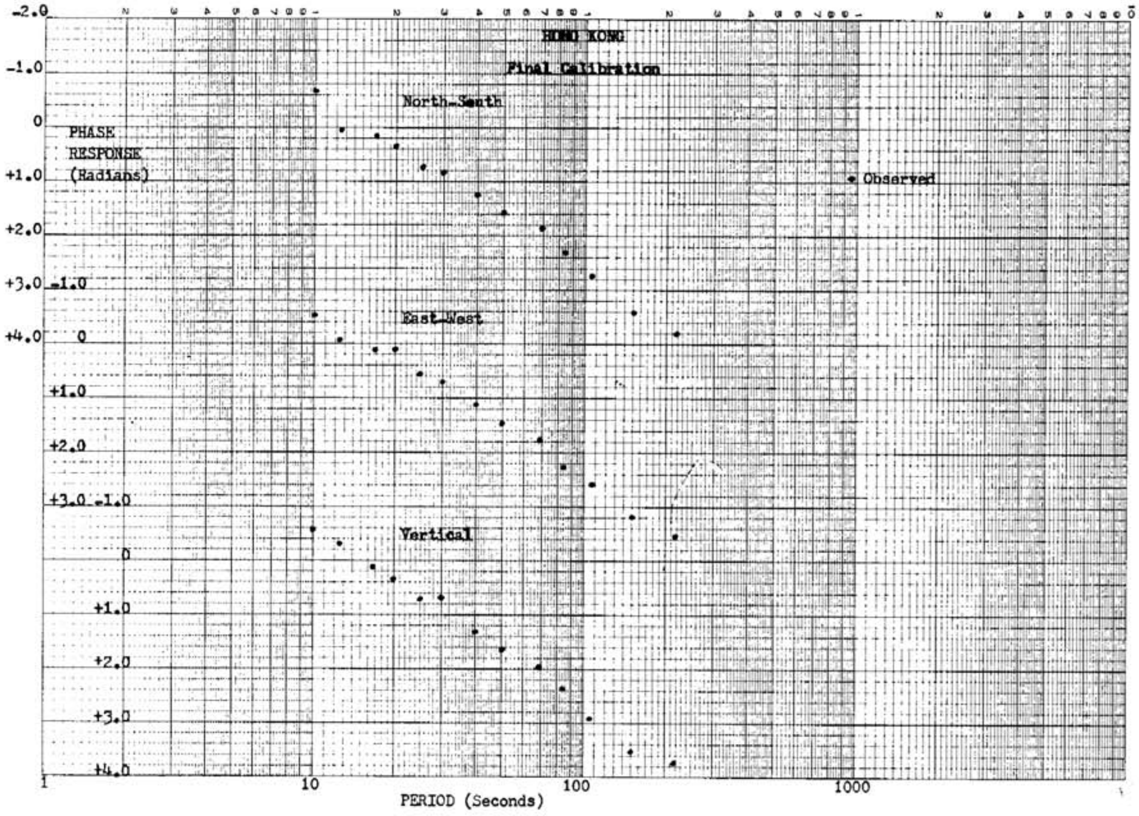

DELHI
Final Calibration
North-South
East-West
Vertical
• Observed
PHASE RESPONSE (Radians)
-2.0
-1.0
0
+1.0
+2.0
+3.0 -1.0
+4.0 0
+1.0
+2.0
+3.0 -1.0
+4.0 0
+1.0
+2.0
+3.0
+4.0
1
10
PERIOD (Seconds)
100
1000


HONG KONG
First Calibration
TRACE AMPLITUDE/GROUND DISPLACEMENT
10^3
10^2
North-South
East-West
Vertical
1
10
PERIOD (Seconds)
100
1000

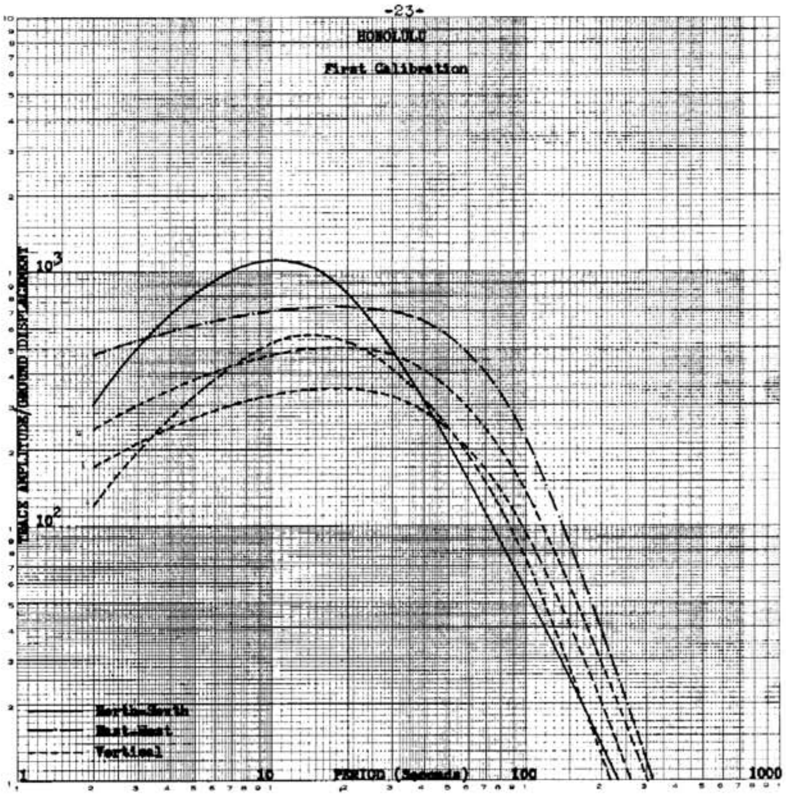

HONG KONG
Final Calibration
TRACE AMPLITUDE/GROUND DISPLACEMENT
10^3
10^2
North-South
East-West
Vertical
1
10
PERIOD (Seconds)
100
1000

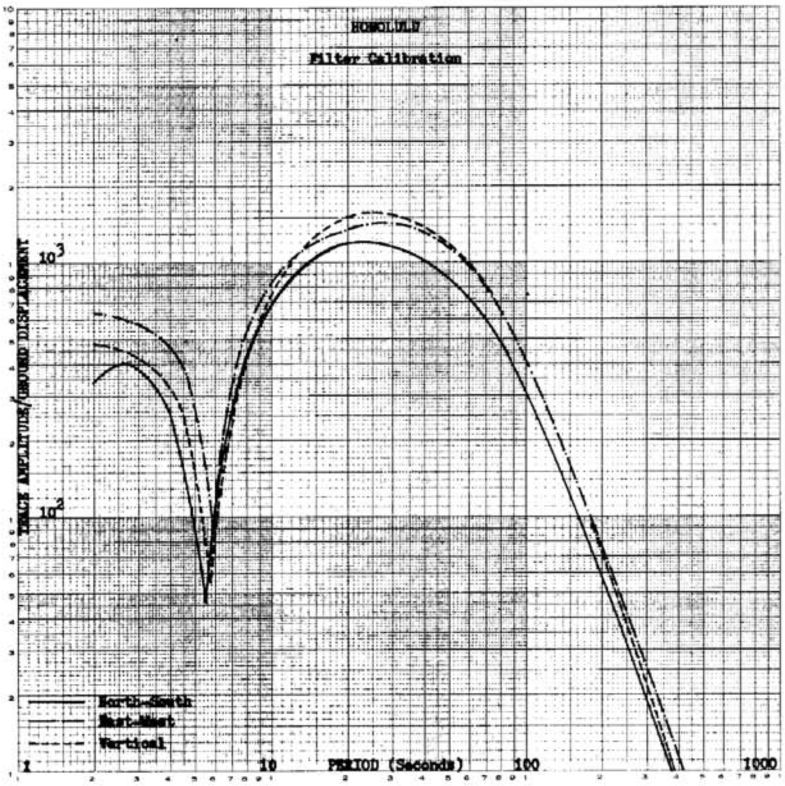


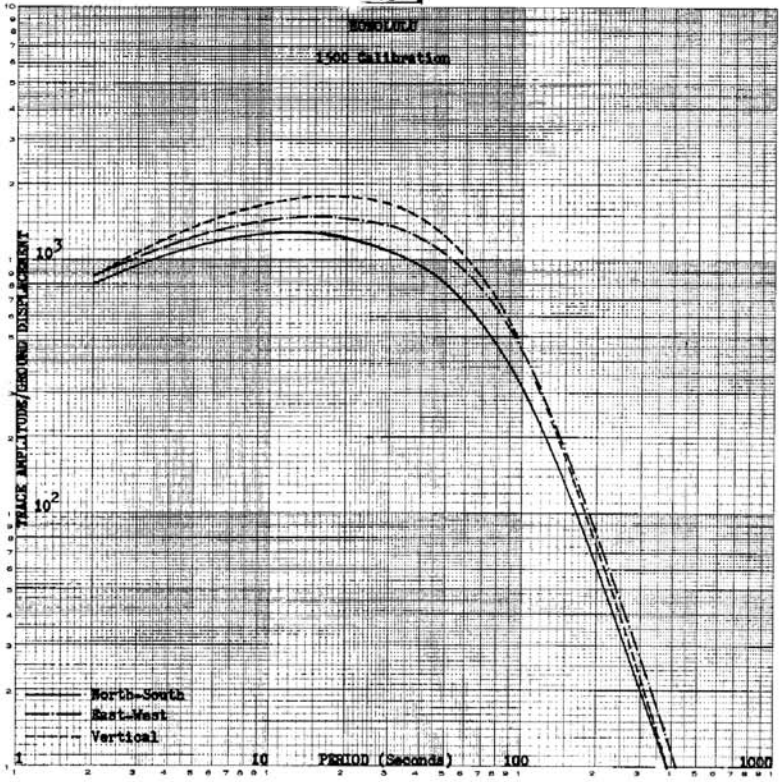
HONG KONG - First Calibration

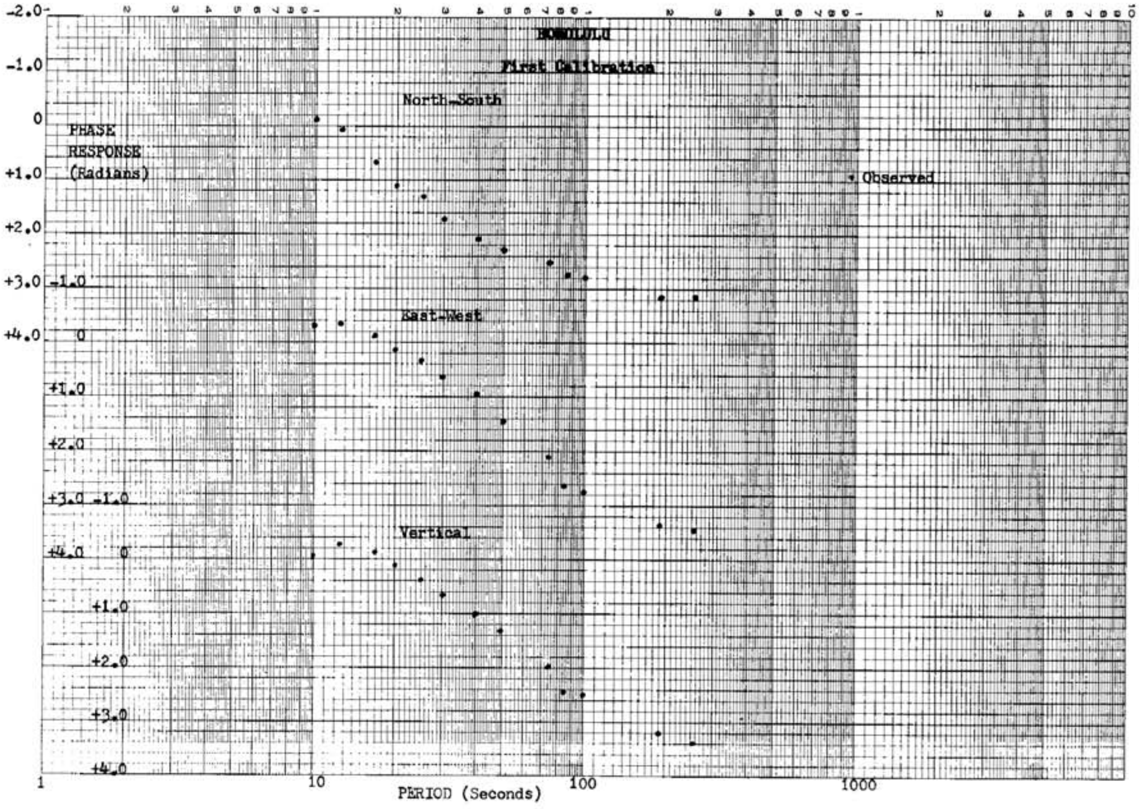


HONG KONG - Final Calibration

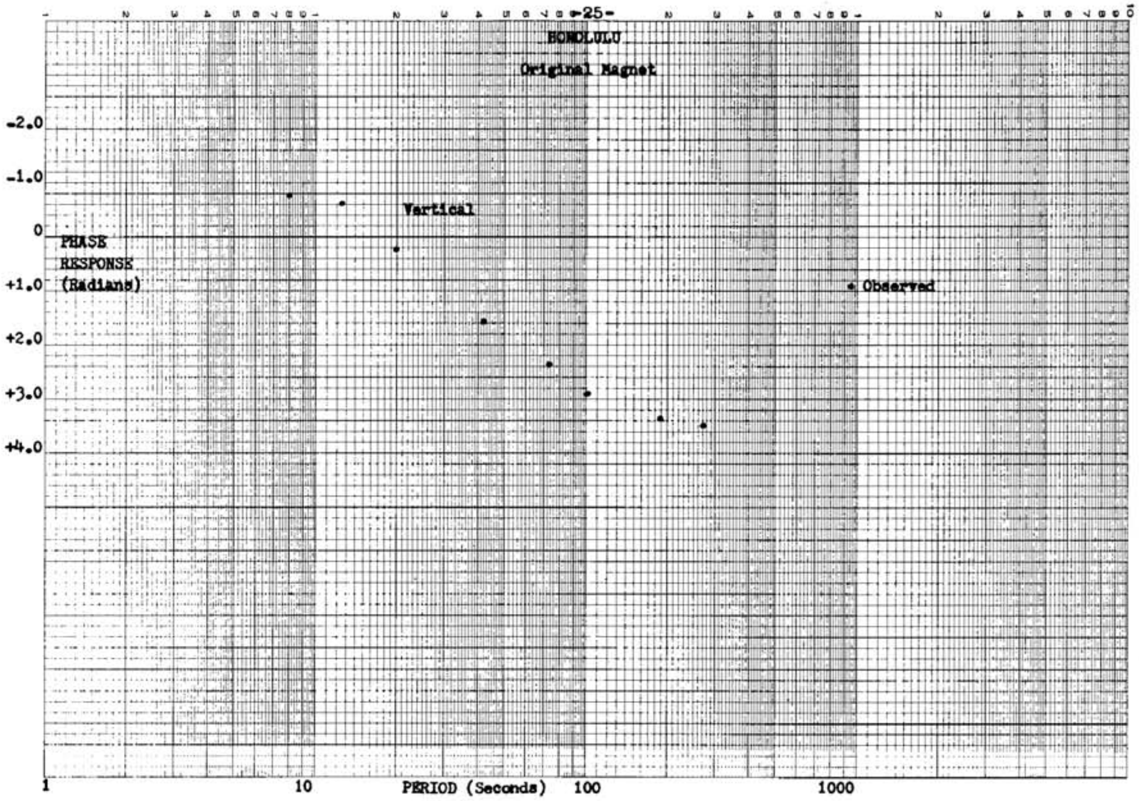

HONOLULU
First Calibration
TRACE AMPLITUDE/GROUND DISPLACEMENT
10³
10²
North-South
East-West
Vertical
1
10
PERIOD (Seconds)
100
1000

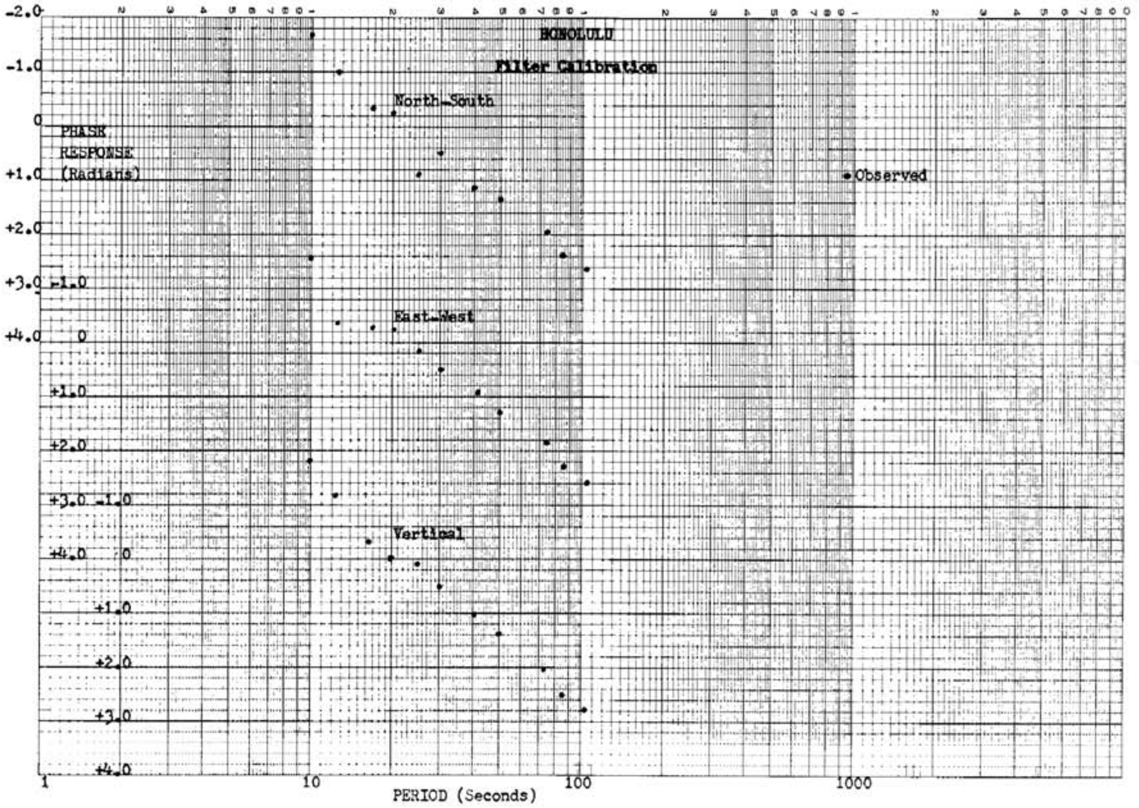

HONOLULU
Filter Calibration
TRACE AMPLITUDE/GROUND DISPLACEMENT
10³
10²
North-South
East-West
Vertical
1
10
PERIOD (Seconds)
100
1000



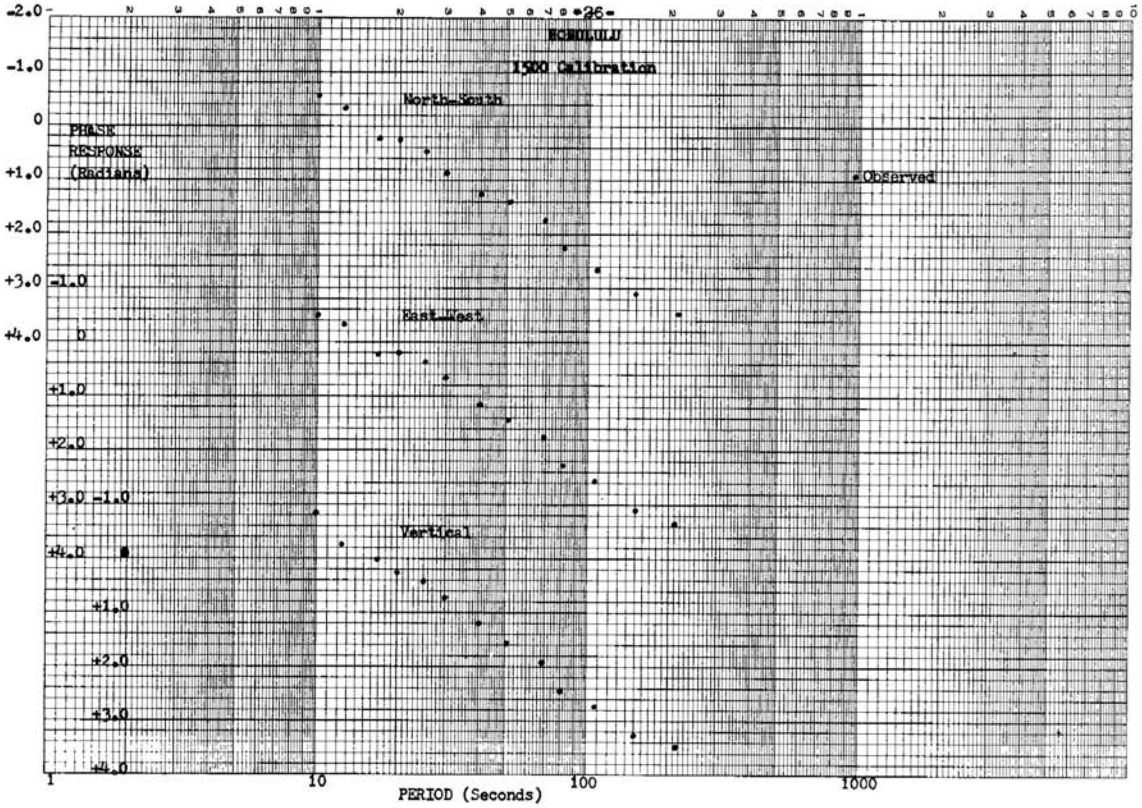


HONOLULU - First Calibration

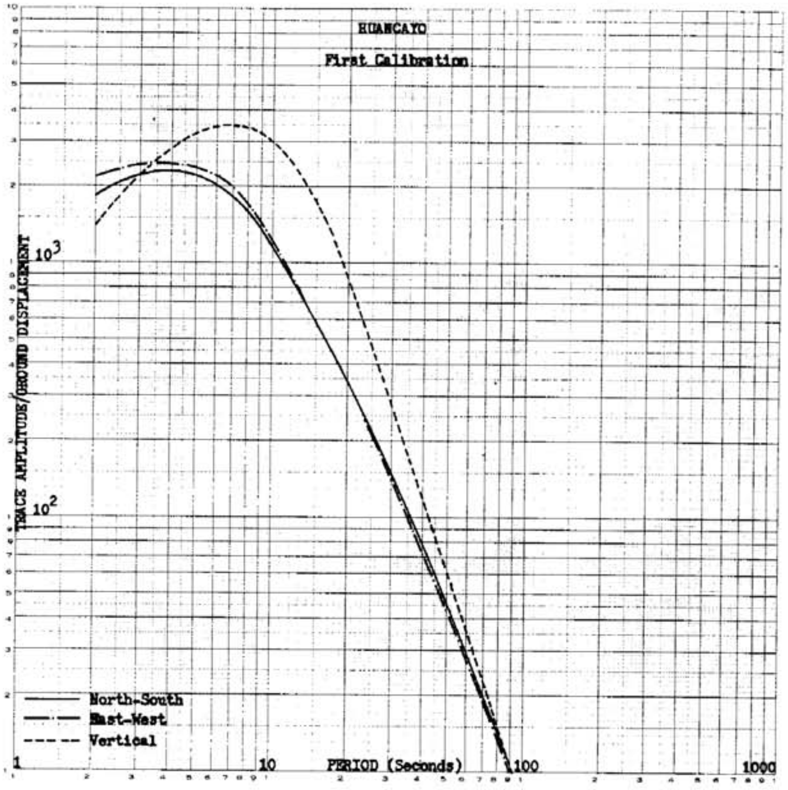


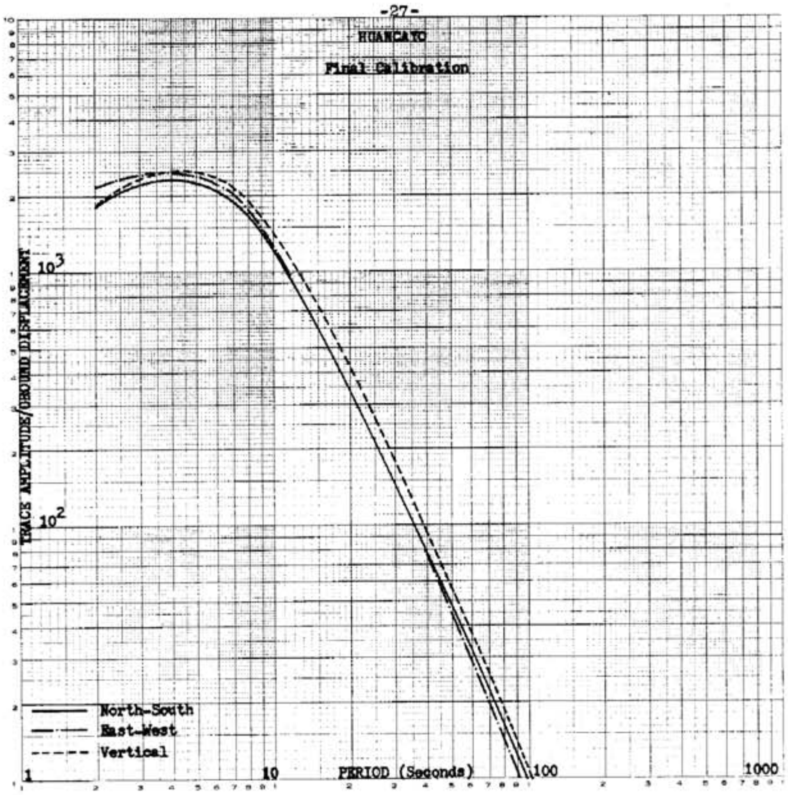


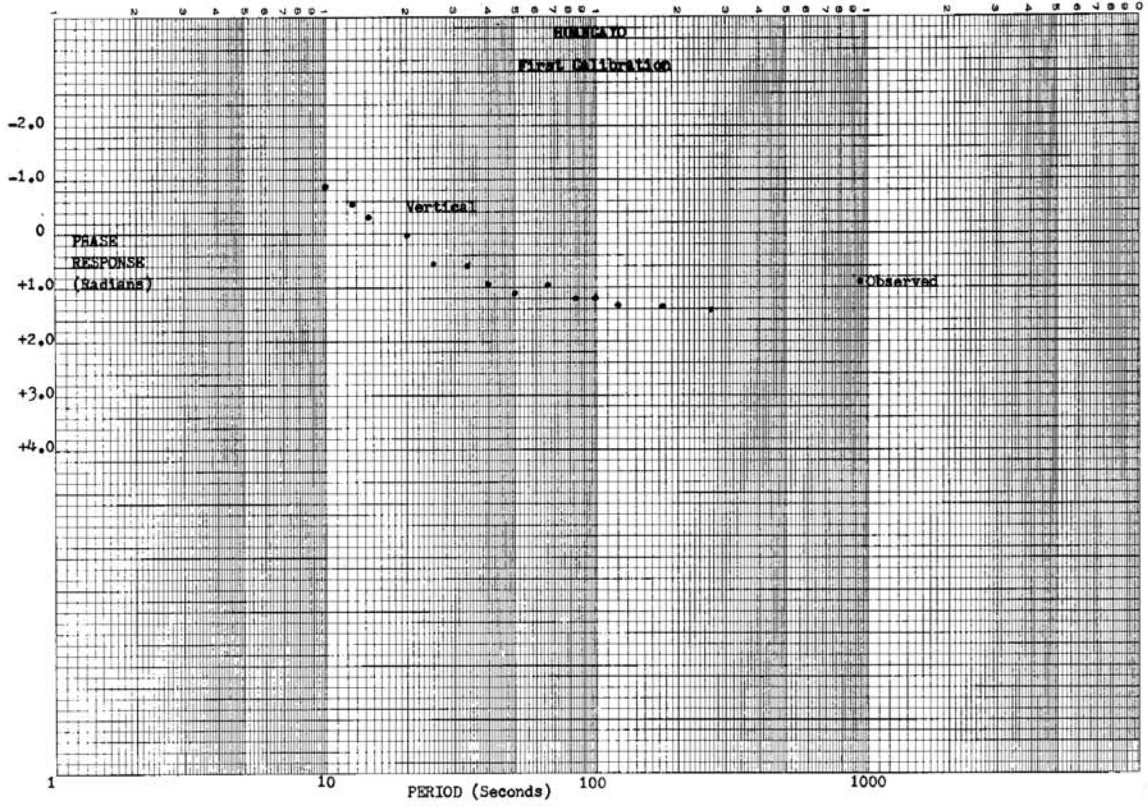
HONOLULU - Filter Calibration



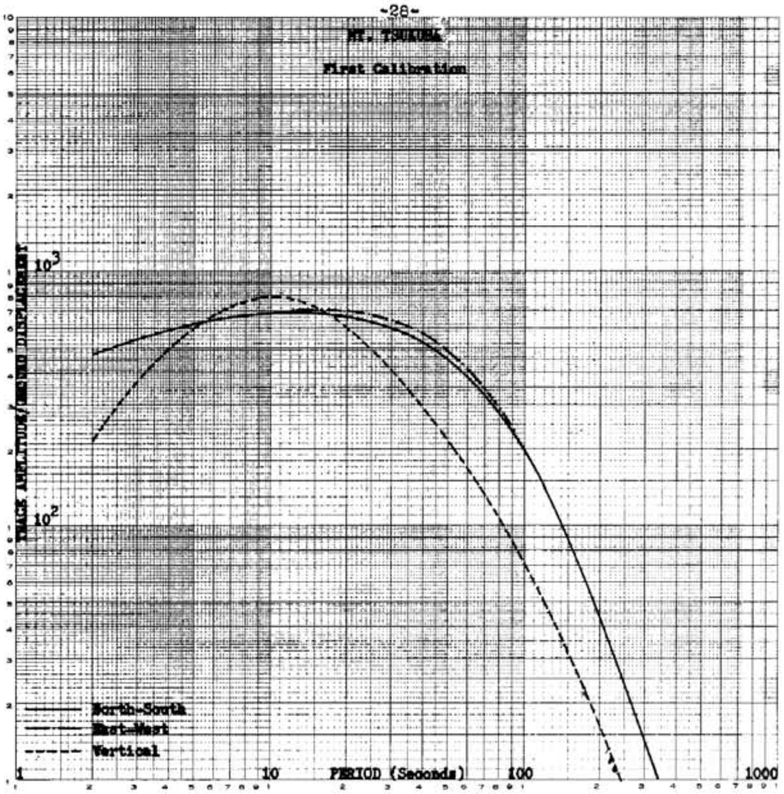
HONOLULU - 1500 Calibration

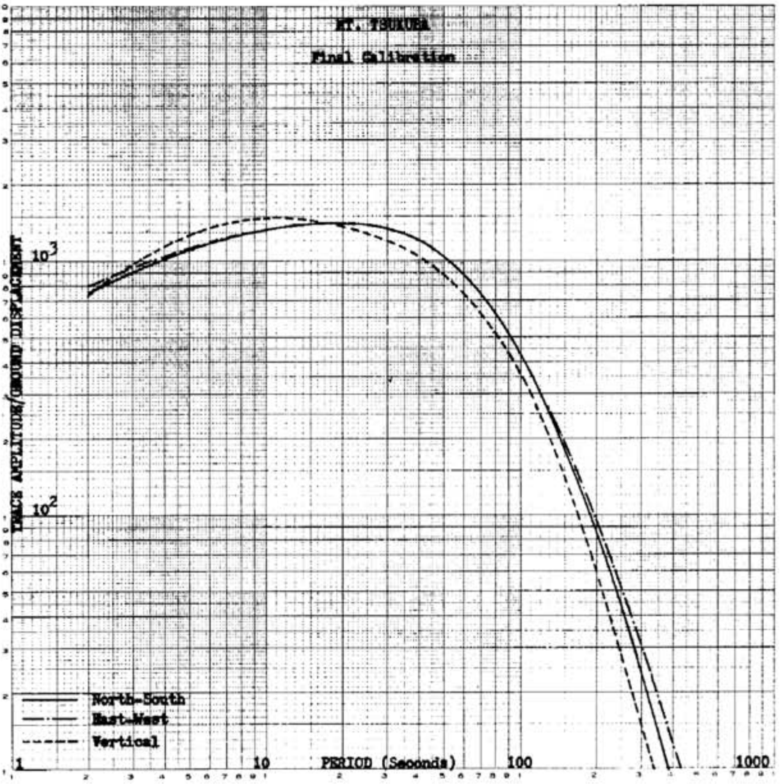


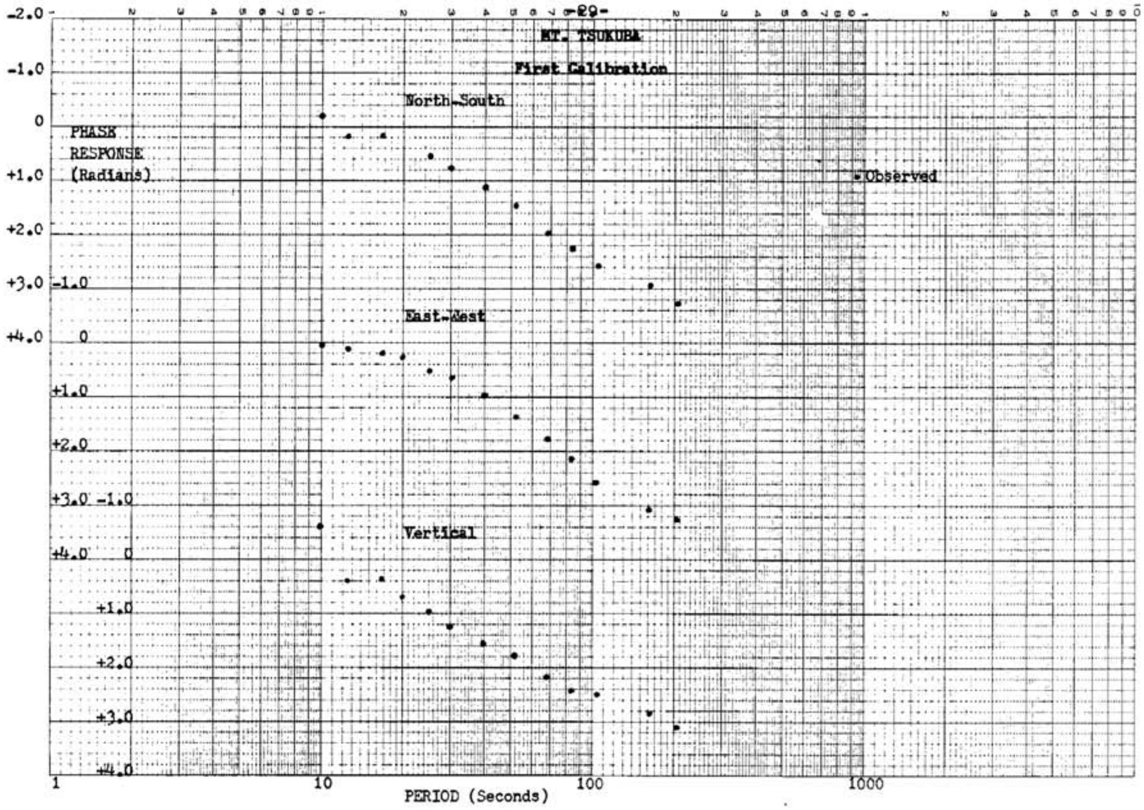




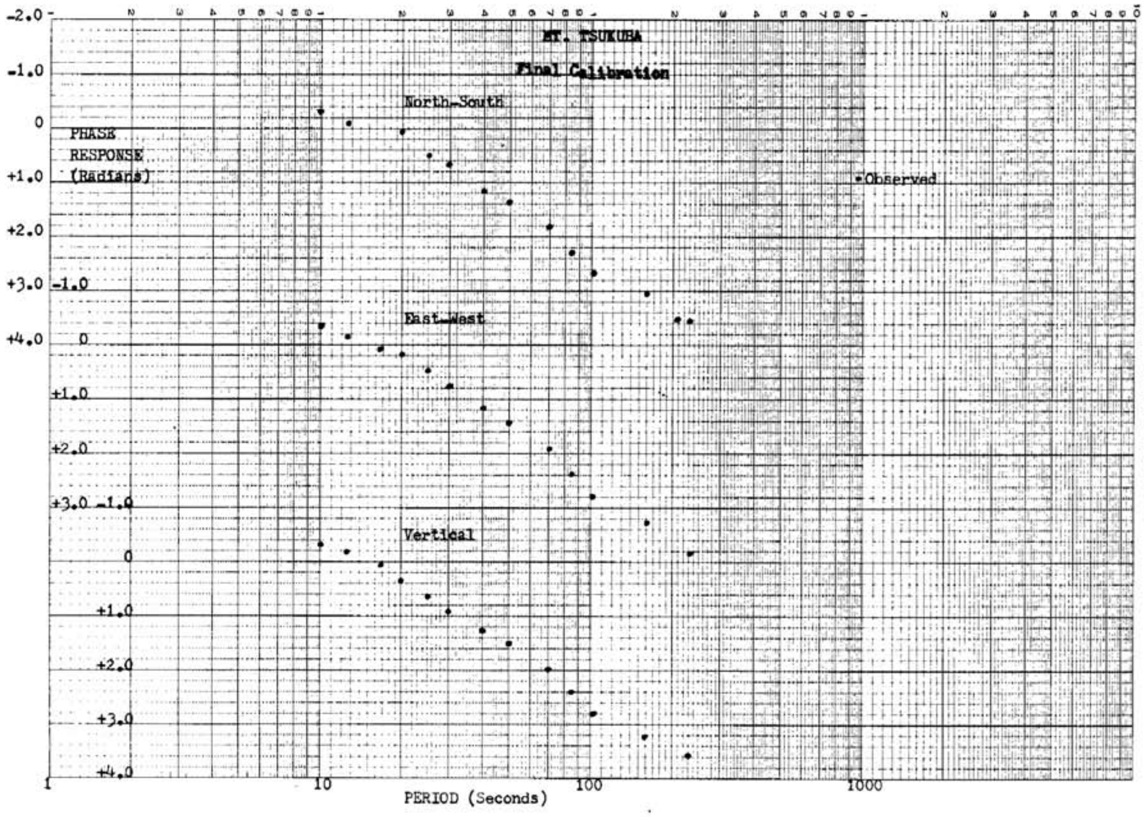
HUANCAYO - First Calibration


MT. TSUKUBA
First Calibration
TRACE AMPLITUDE/GROUND DISPLACEMENT
10^3
10^2
1
10
100
1000
PERIOD (Seconds)
North-South
East-West
Vertical

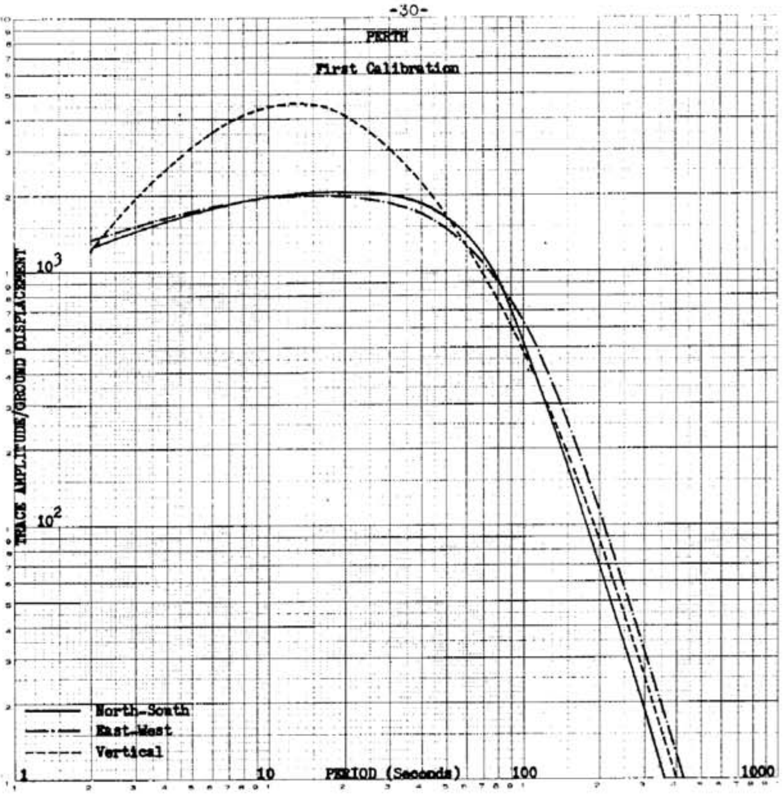

MT. TSUKUBA
Final Calibration
TRACE AMPLITUDE/GROUND DISPLACEMENT
10^3
10^2
1
10
100
1000
PERIOD (Seconds)
North-South
East-West
Vertical

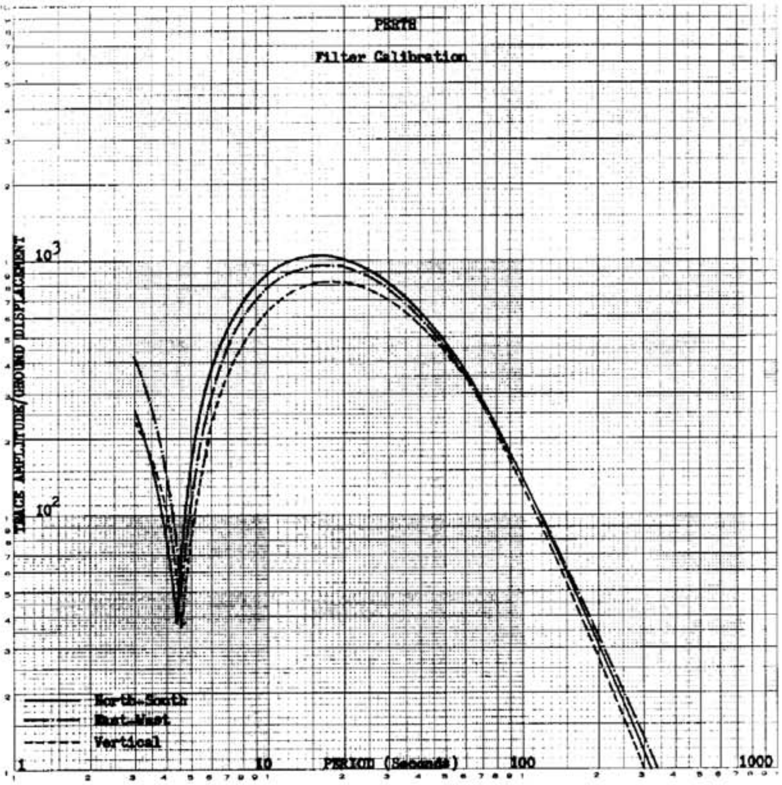


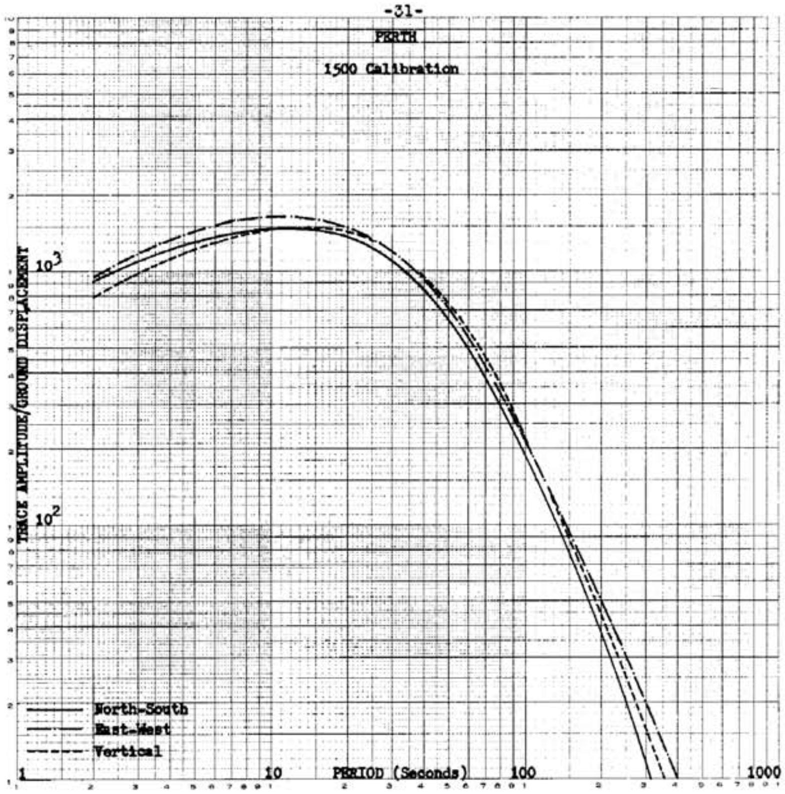
MT. TSUKUBA - First Calibration

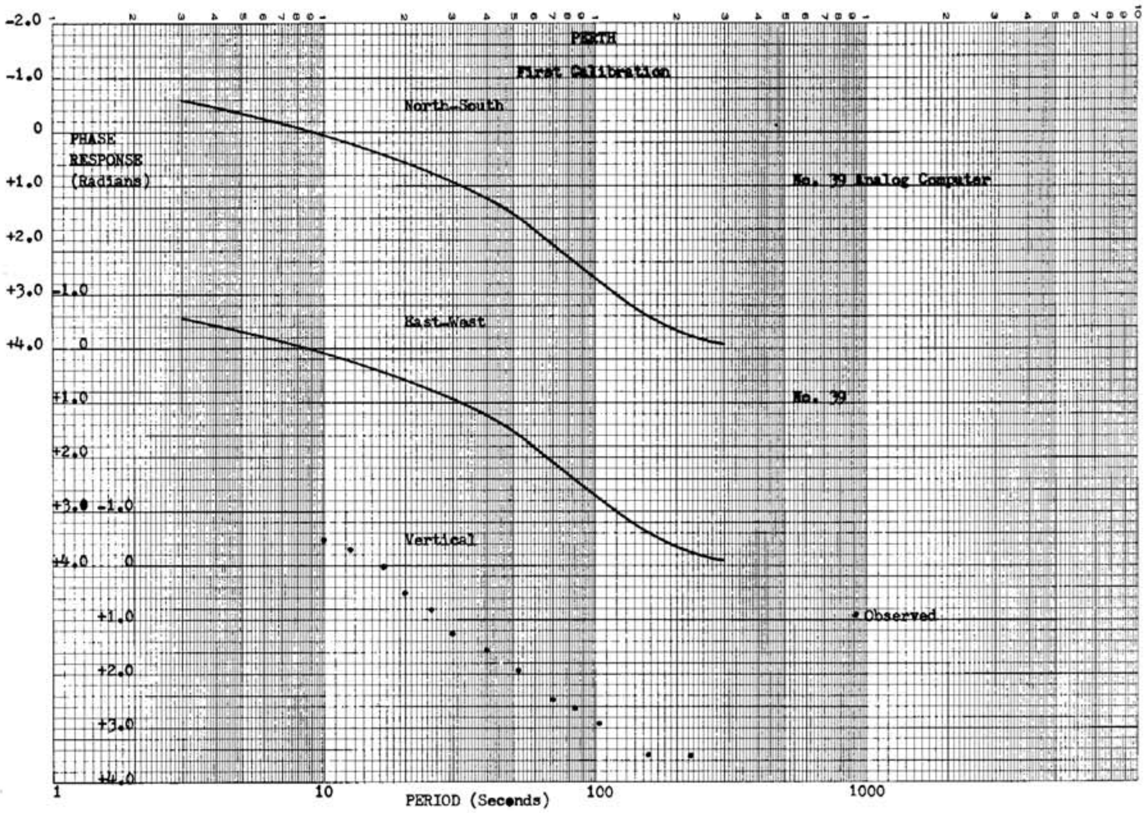


MT. TSUKUBA - Final Calibration

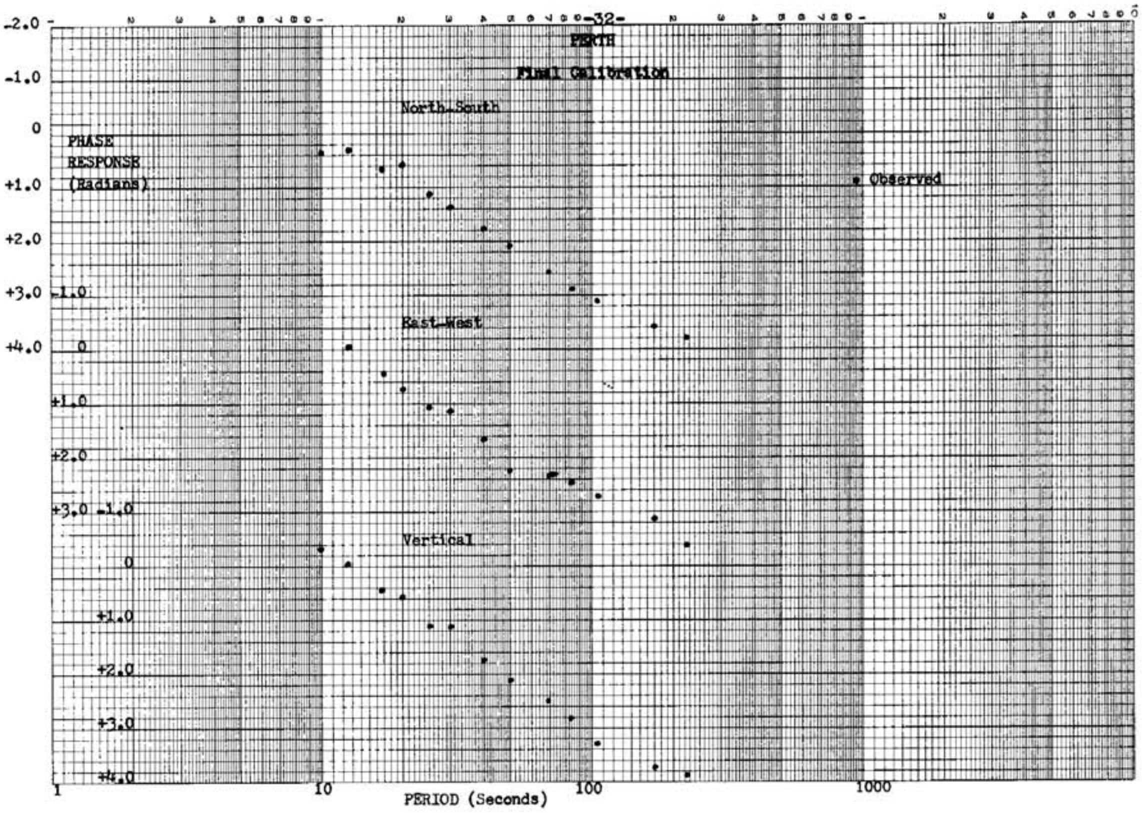

PERTH
First Calibration
TRACE AMPLITUDE/GROUND DISPLACEMENT
10^3
10^2
North-South
East-West
Vertical
1
10
PERIOD (Seconds)
100
1000


PERTH
Filter Calibration
TRACE AMPLITUDE/GROUND DISPLACEMENT
10^3
10^2
North-South
East-West
Vertical
1
10
PERIOD (Seconds)
100
1000

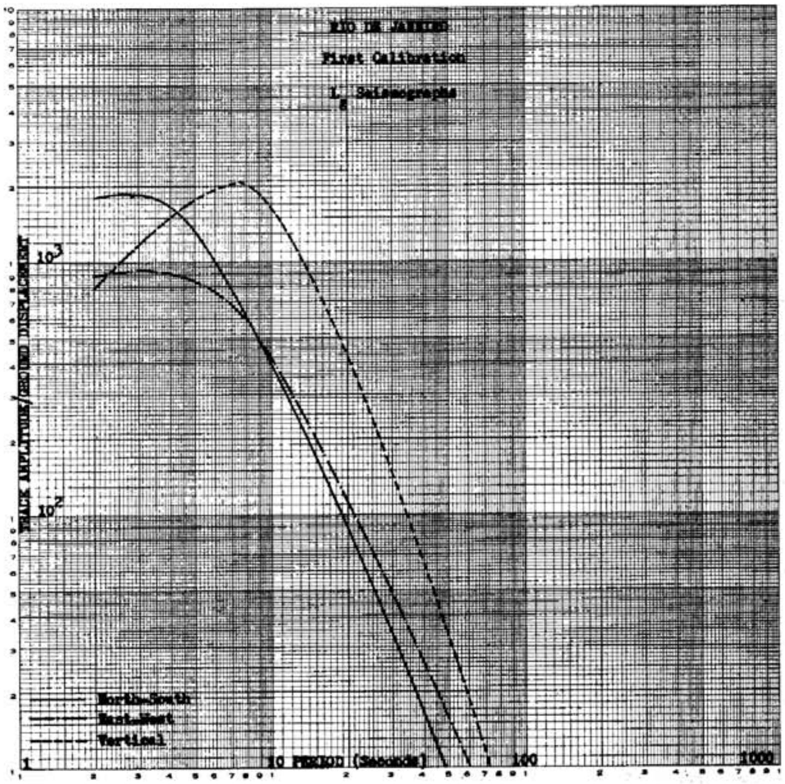


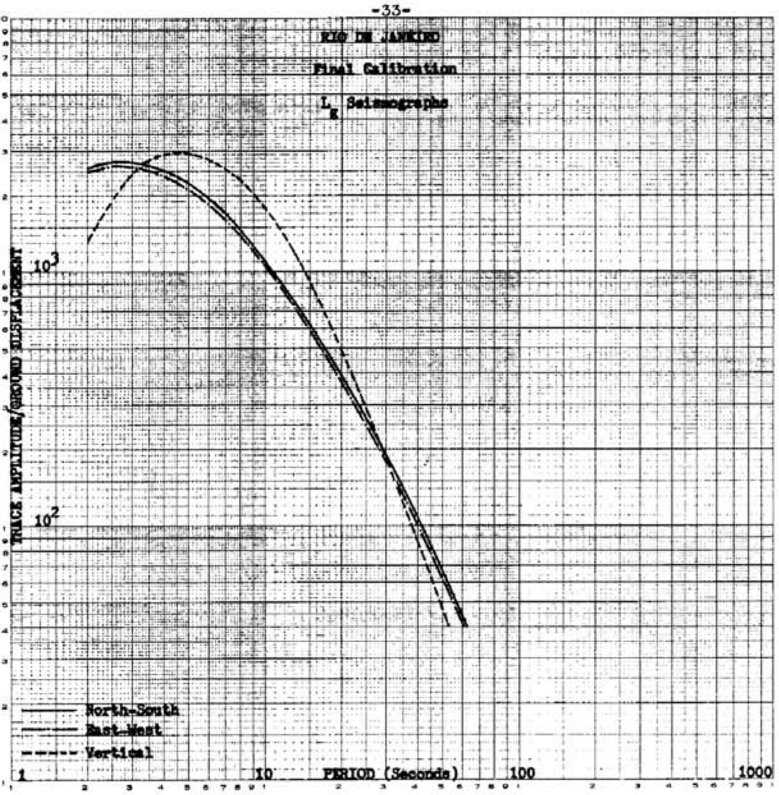


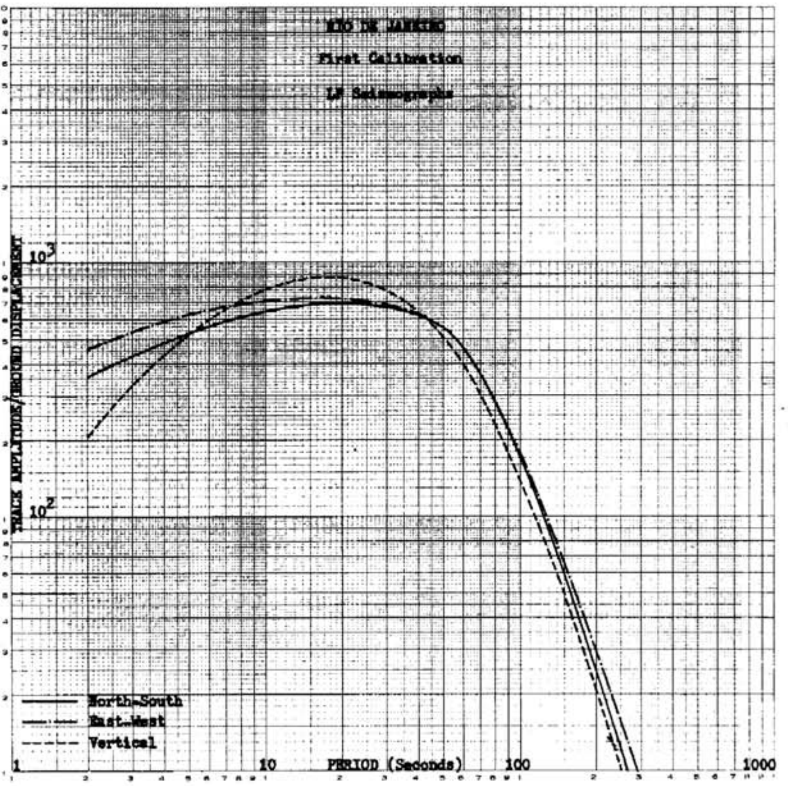
PERTH - First Calibration

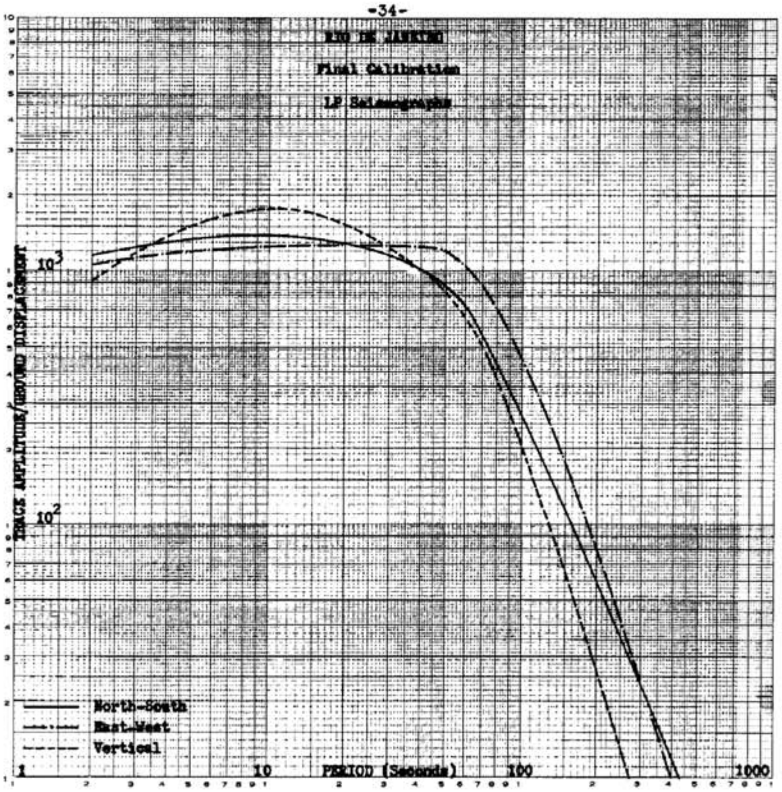


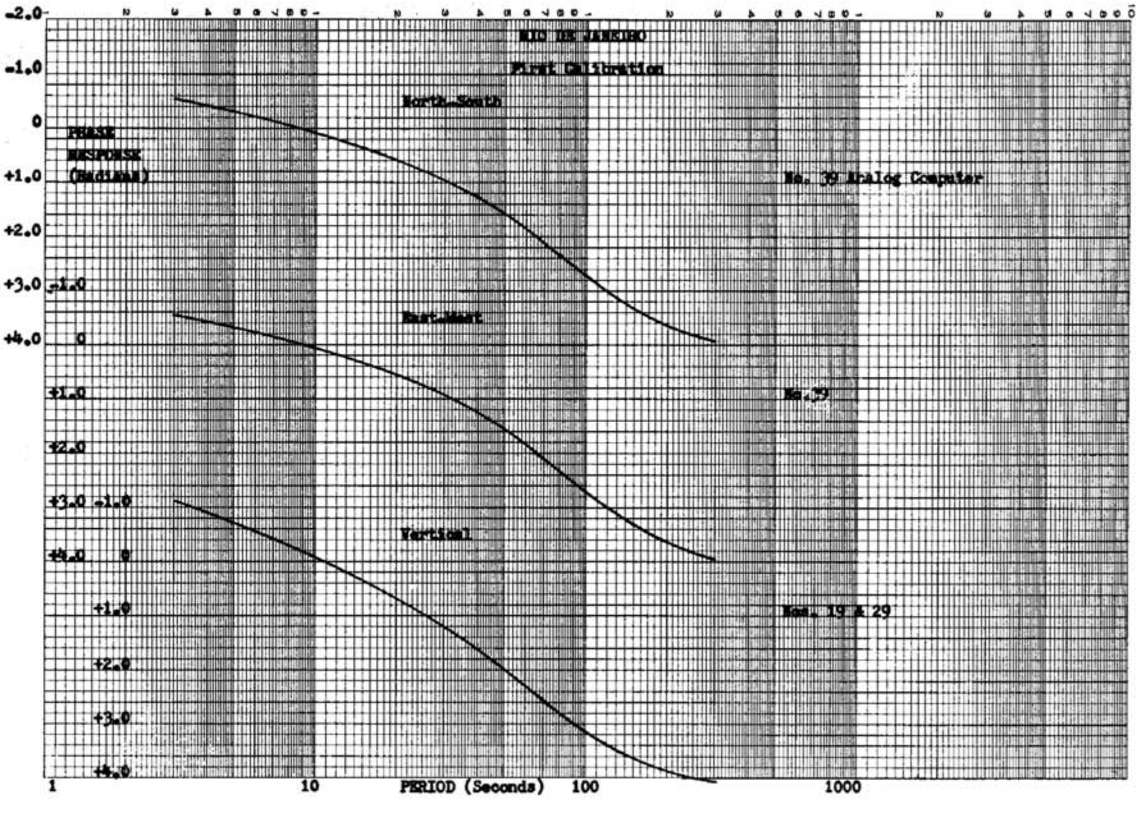
PERTH - Final Calibration

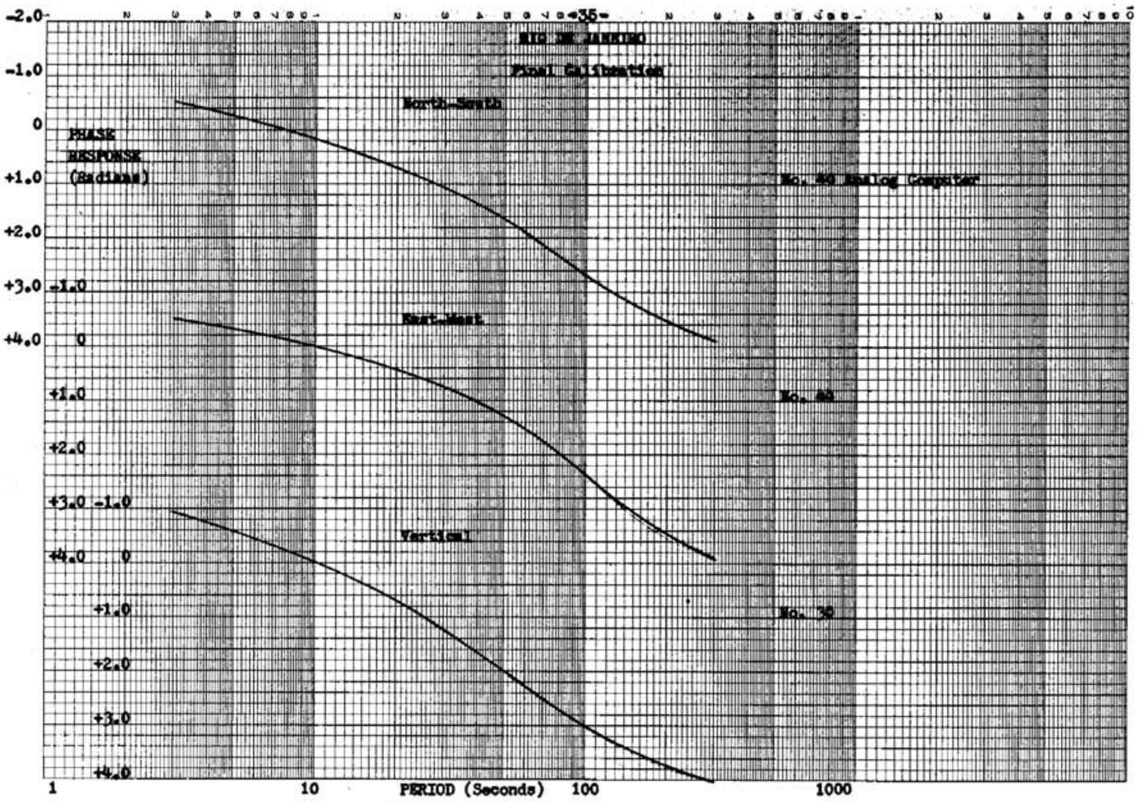


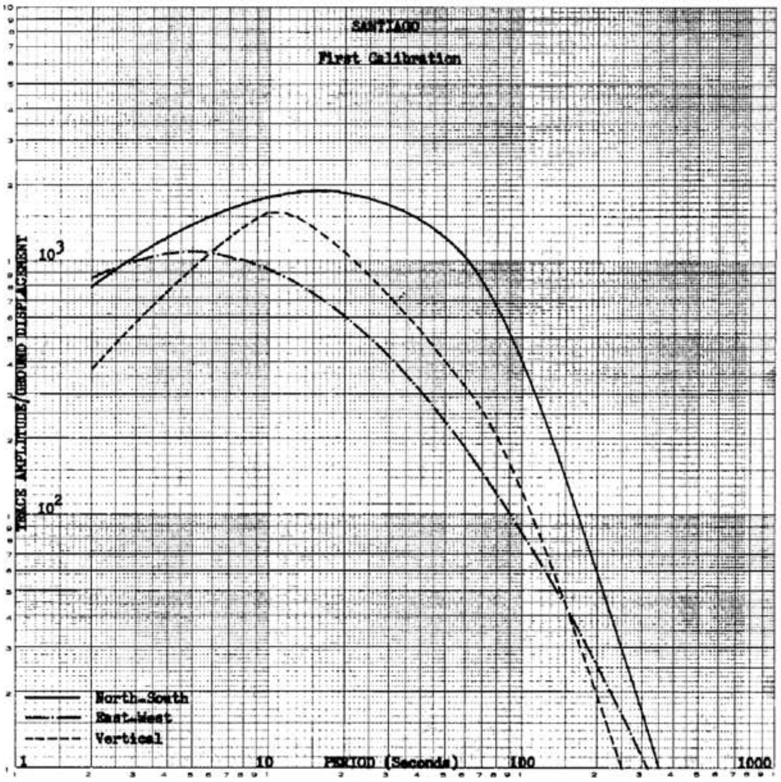

RIO DE JANEIRO
Final Calibration
L_E Seismographs
TRACE AMPLITUDE/GROUND DISPLACEMENT
10^3
10^2
North-South
East-West
Vertical
1
10
PERIOD (Seconds)
100
1000

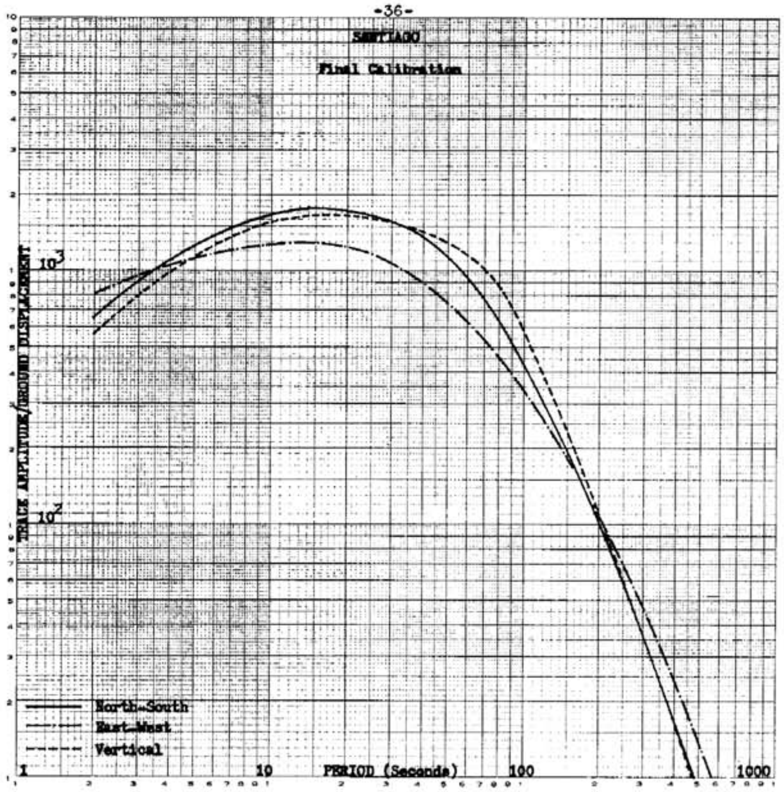

RIO DE JANEIRO
First Calibration
LP Seismographs
TRACE AMPLITUDE/GROUND DISPLACEMENT
10^3
10^2
North-South
East-West
Vertical
1
10
PERIOD (Seconds)
100
1000

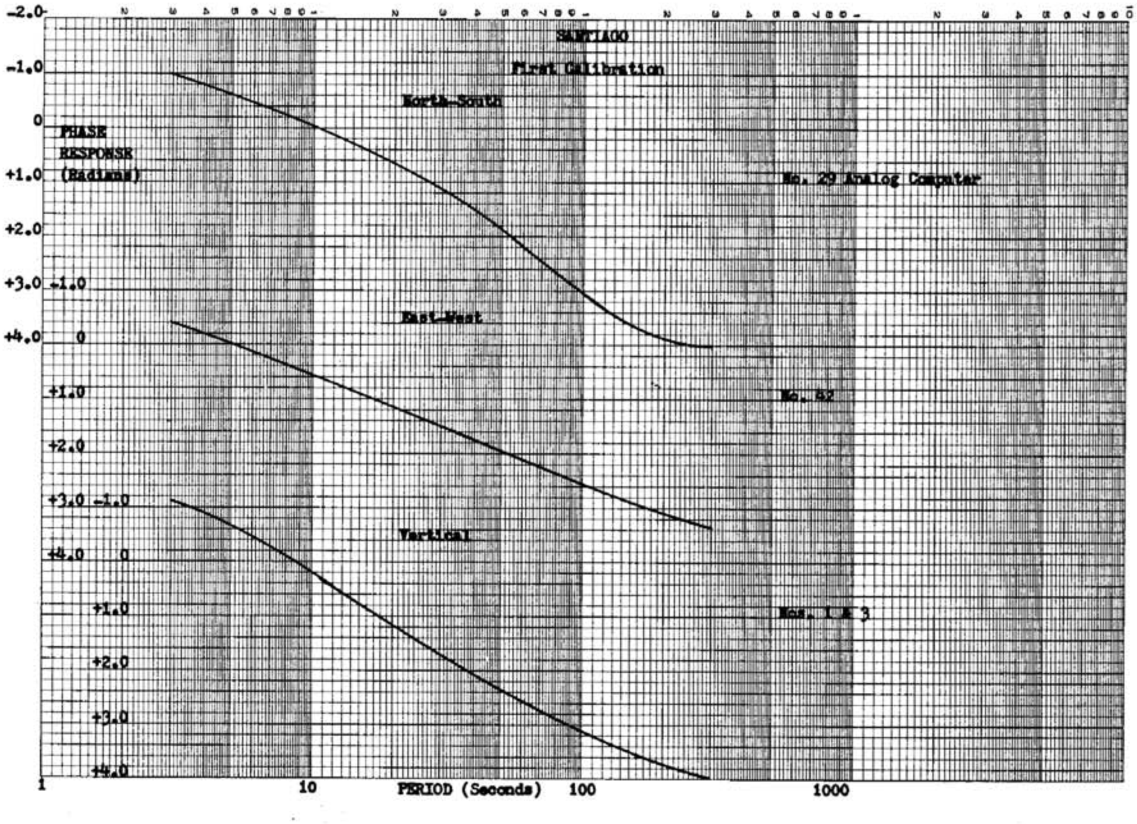

RIO DE JANEIRO
Final Calibration
LP Seismographs
TRACE AMPLITUDE/GROUND DISPLACEMENT
10³
10²
North-South
East-West
Vertical
PERIOD (Seconds)
1
10
100
1000

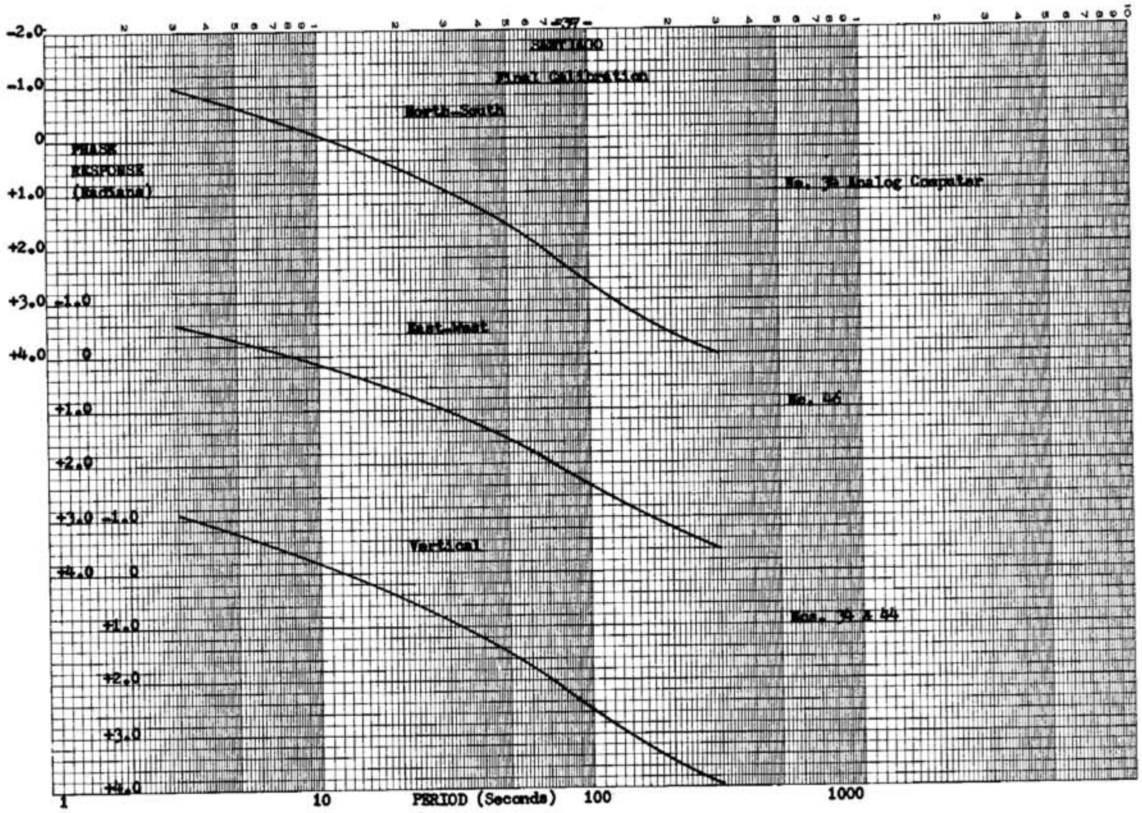

RIO DE JANEIRO
Final Calibration
PHASE
RESPONSE
(Radians)
-2.0
-1.0
0
+1.0
+2.0
+3.0
+4.0
North-South
No. 39 Analog Computer
East-West
No. 39
Vertical
Nos. 19 & 29
PERIOD (Seconds)
1
10
100
1000

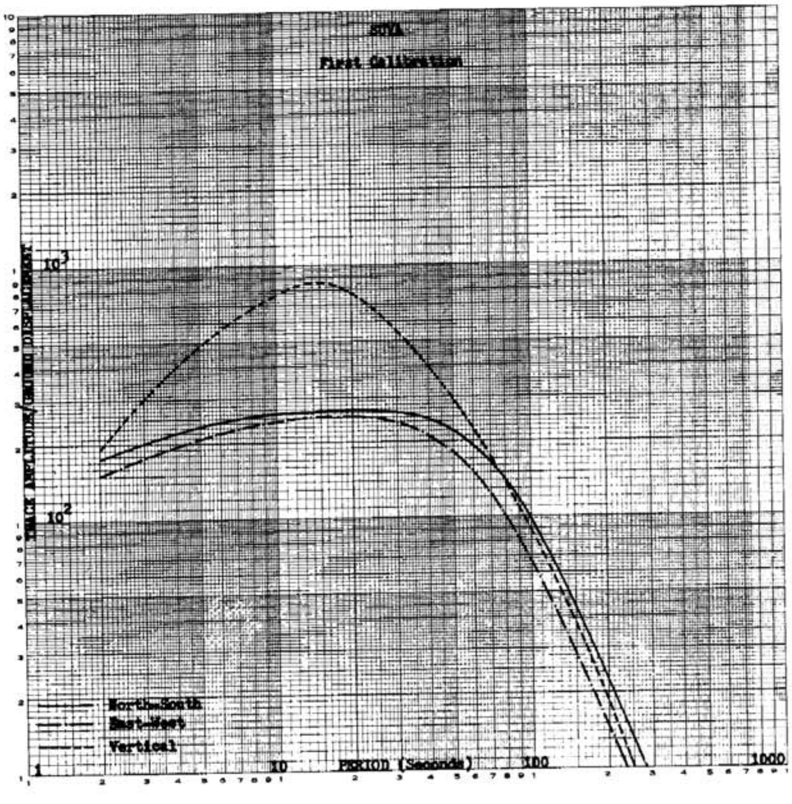

RIO DE JANEIRO
Final Calibration
North-South
East-West
Vertical
No. 40 Analog Computer
No. 40
No. 30
PHASE RESPONSE (Radians)
-2.0
-1.0
0
+1.0
+2.0
+3.0
+4.0
-1.0
0
+1.0
+2.0
+3.0
+4.0
-1.0
0
+1.0
+2.0
+3.0
+4.0
1
10
PERIOD (Seconds)
100
1000

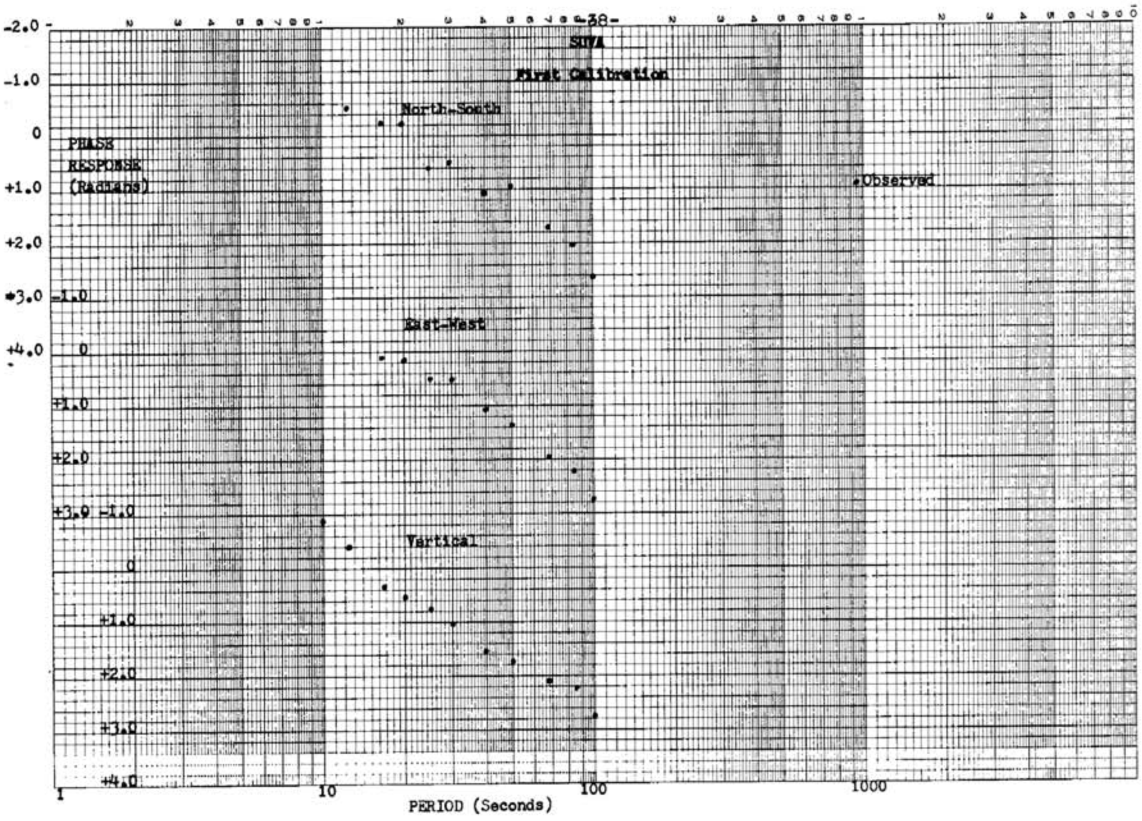

SANTIAGO
First Calibration
TRACE AMPLITUDE/GROUND DISPLACEMENT
10^3
10^2
North-South
East-West
Vertical
1
10
PERIOD (Seconds)
100
1000


SANTIAGO
Final Calibration
TRACE AMPLITUDE/GROUND DISPLACEMENT
10^3
10^2
North-South
East-West
Vertical
1
10
PERIOD (Seconds)
100
1000

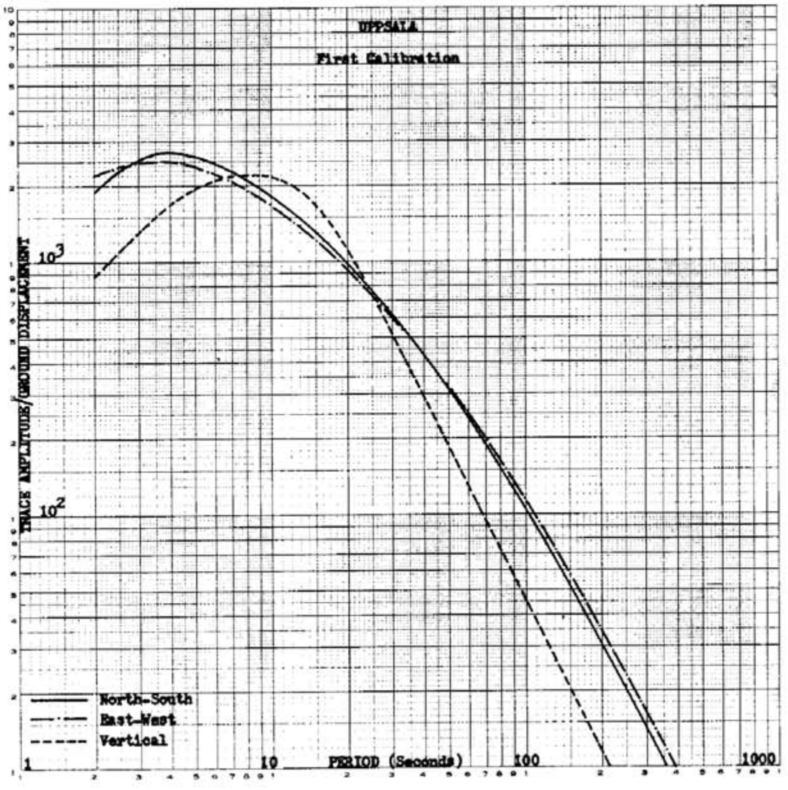

SANTIAGO
First Calibration
PHASE RESPONSE (Radians)
North-South
No. 29 Analog Computer
East-West
No. 42
Vertical
Nos. 1 & 3
-2.0
-1.0
0
+1.0
+2.0
+3.0
+4.0
1
10
PERIOD (Seconds)
100
1000

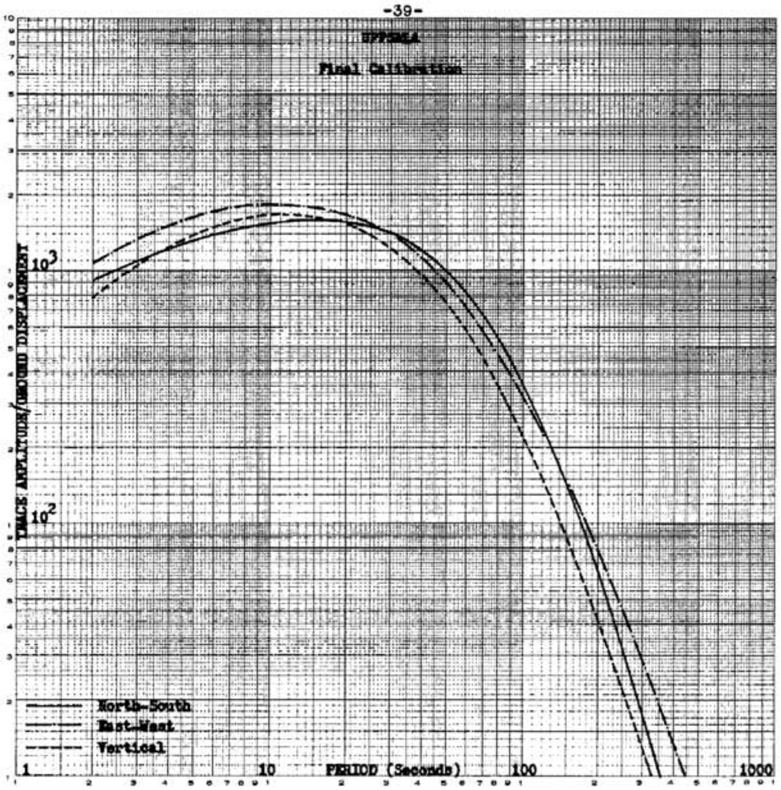

SANTIAGO
Final Calibration
North-South
No. 38 Analog Computer
East-West
No. 46
Vertical
Nos. 39 & 44
PHASE RESPONSE (Radians)
-2.0
-1.0
0
+1.0
+2.0
+3.0
+4.0
-1.0
0
+1.0
+2.0
+3.0
+4.0
-1.0
0
+1.0
+2.0
+3.0
+4.0
1
10
PERIOD (Seconds)
100
1000

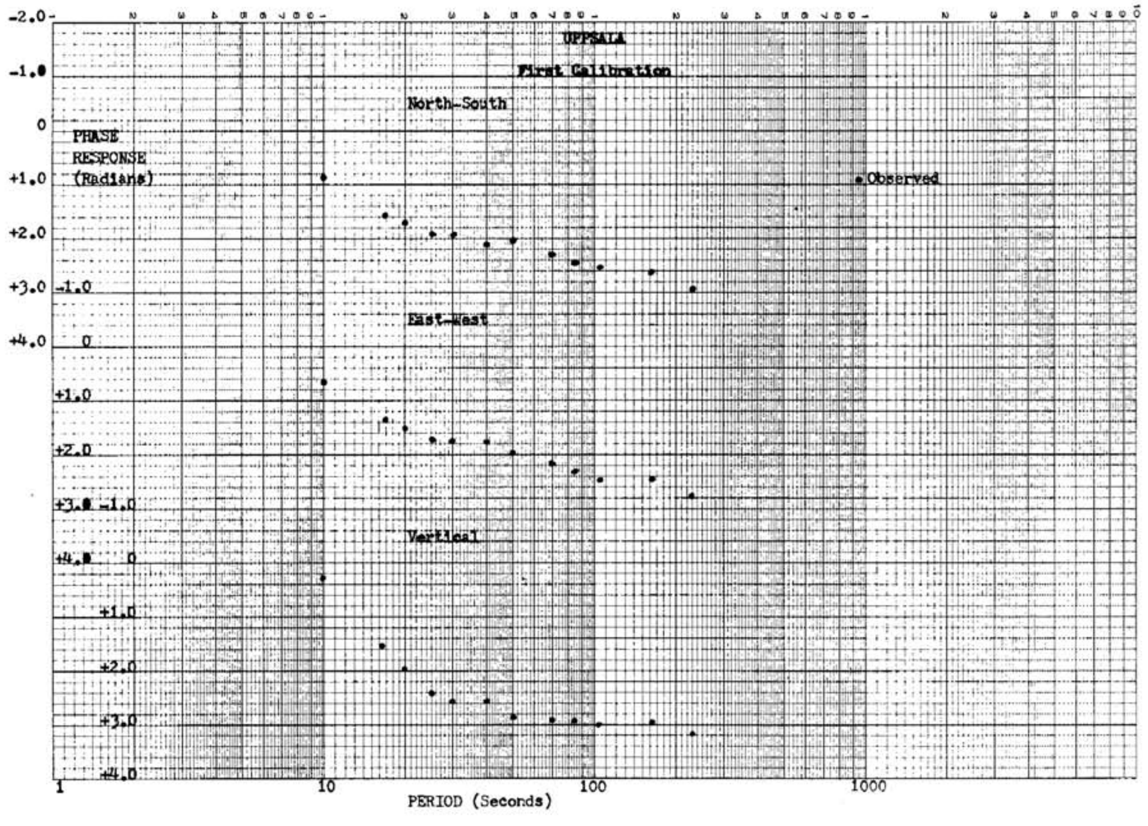

SUVA
First Calibration
TRACE AMPLITUDE/GROUND DISPLACEMENT
10^3
10^2
North-South
East-West
Vertical
1
10
PERIOD (Seconds)
100
1000



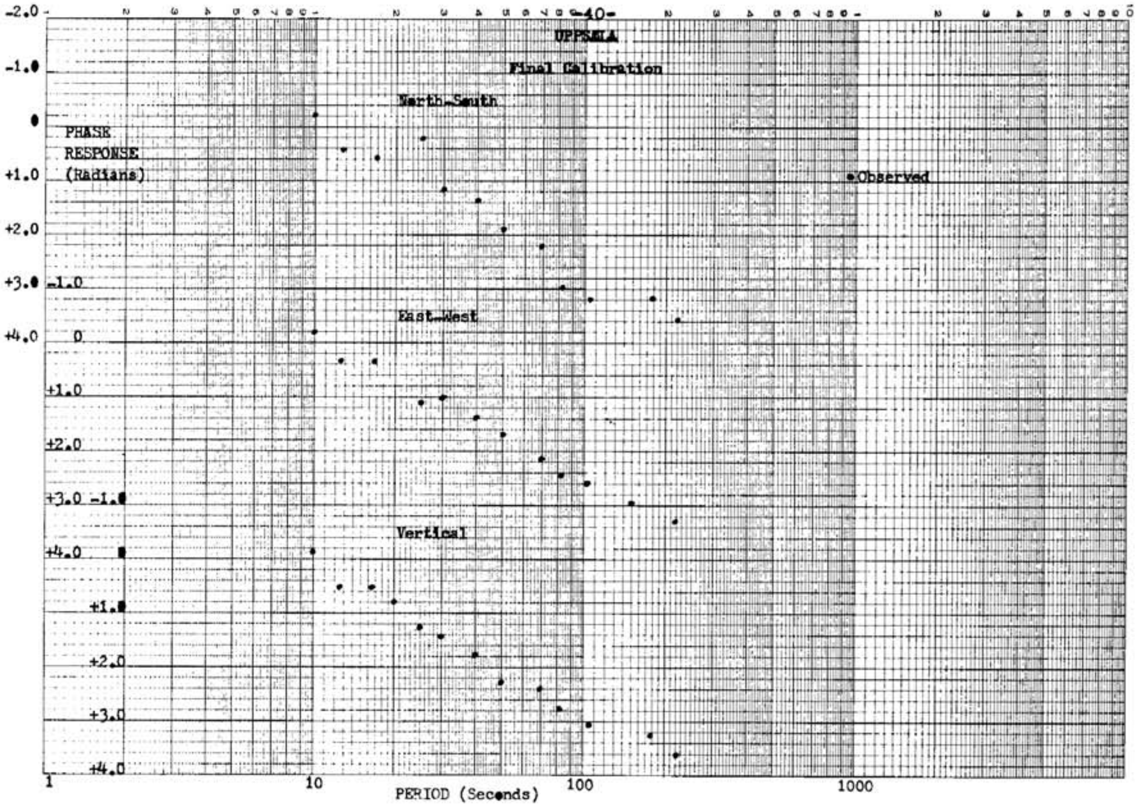
SUVA - Calibration



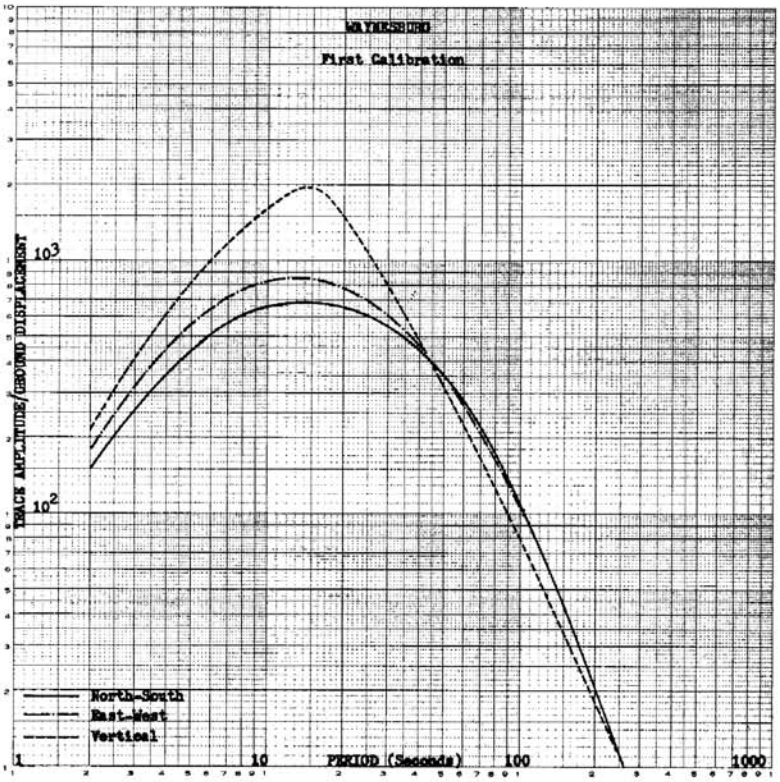


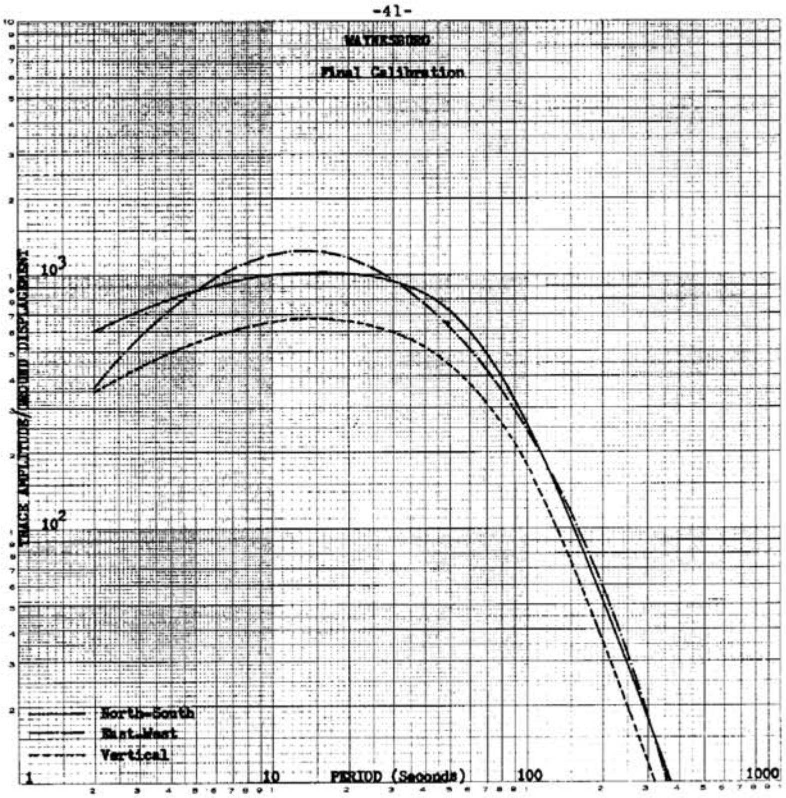


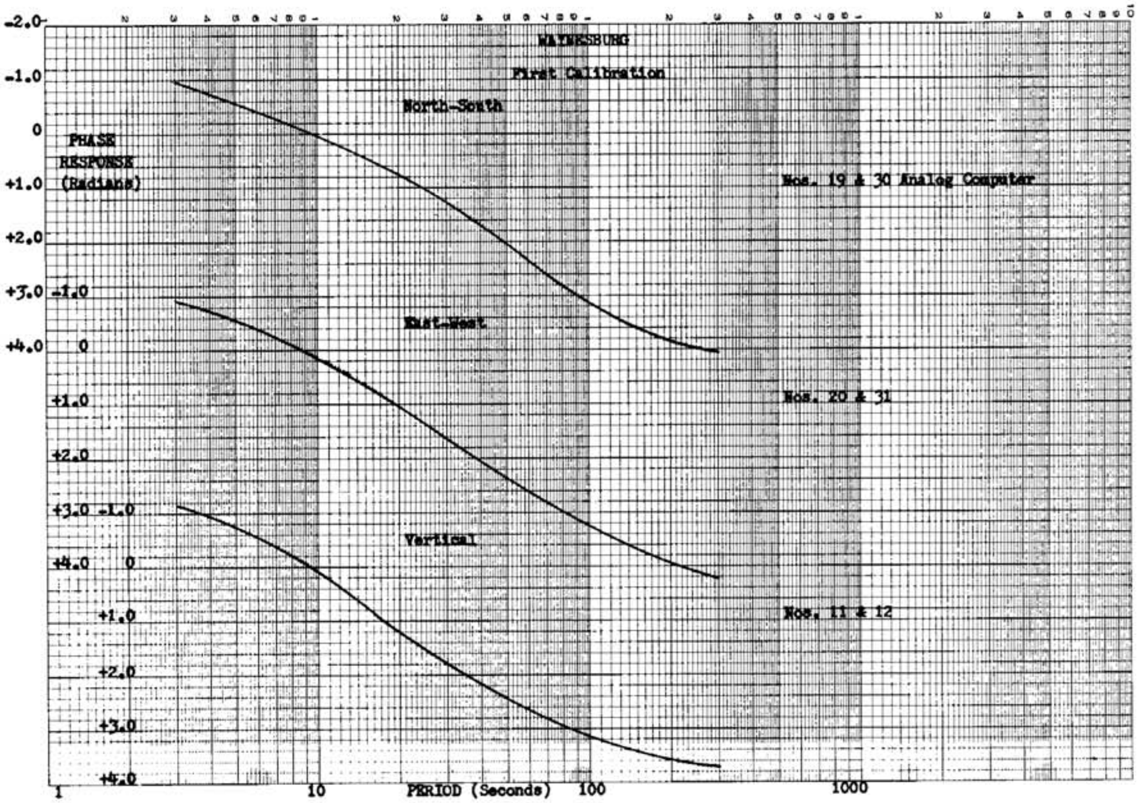
UPPSALA - First Calibration

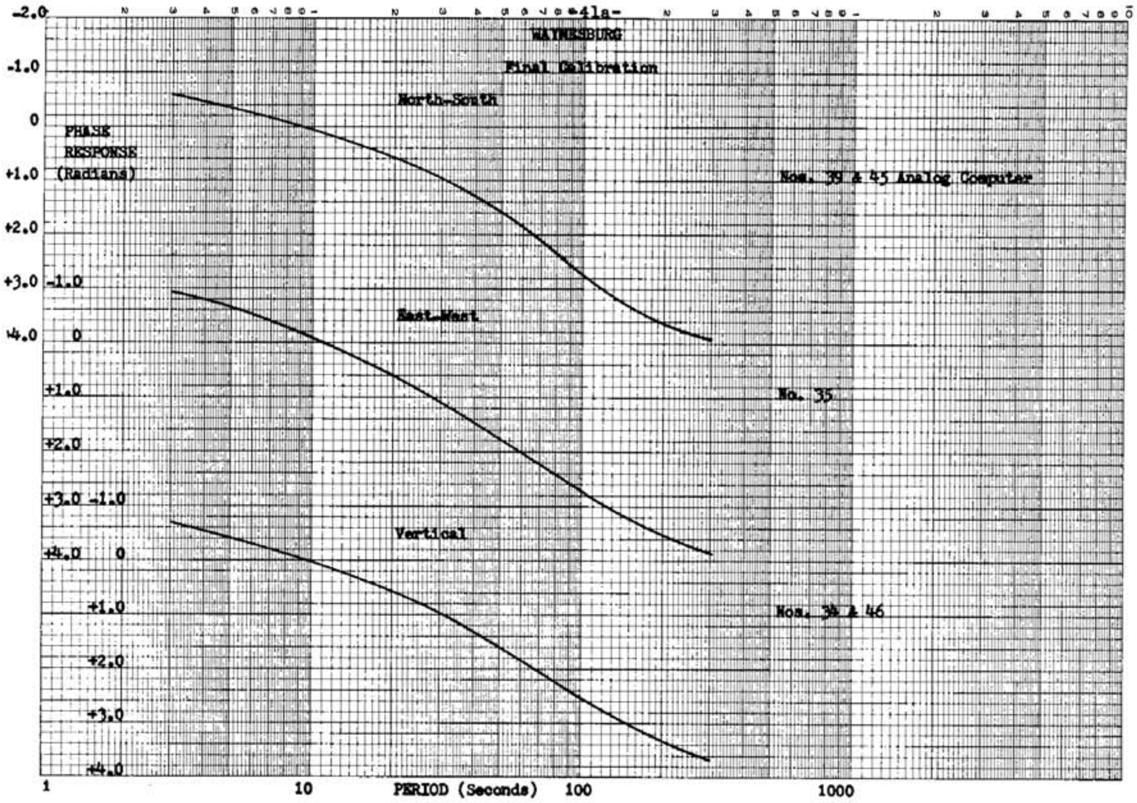


UPPSALA - Final Calibration




WAYNESBURG
Final Calibration
TRACK AMPLITUDE/GROUND DISPLACEMENT
10^3
10^2
North-South
East-West
Vertical
1
10
PERIOD (Seconds)
100
1000


WAYNESBURG
First Calibration
North-South
East-West
Vertical
PHASE RESPONSE (Radians)
-2.0
-1.0
0
+1.0
+2.0
+3.0
+4.0
Nos. 19 & 30 Analog Computer
Nos. 20 & 31
Nos. 11 & 12
1
10
PERIOD (Seconds)
100
1000


WAYNESBURG
Final Calibration
North-South
East-West
Vertical
PHASE
RESPONSE
(Radians)
Nos. 39 & 45 Analog Computer
No. 35
Nos. 34 & 46
-2.0
-1.0
0
+1.0
+2.0
+3.0
+4.0
-1.0
0
+1.0
+2.0
+3.0
-1.0
+4.0
0
+1.0
+2.0
+3.0
+4.0
1
10
PERIOD (Seconds)
100
1000

TRANSIENT PULSE STUDY

At Uppsala transient pulses made over a 14-month period from the date of the original steady-state calibration of March 29, 1962 to May 21, 1963 provide data for a study of changes in magnification response. The amplitudes of 41 pulses taken at set intervals of time are plotted against calendar time. Figure 6 shows the variation of transient pulse amplitudes. The point of interest is whether or not the seismographs change in magnification over a period of time and how much change occurs. To resolve this question the transient pulses of March 29, 1962 and those of 13 months later are used to compute the absolute displacement magnification by the transient pulse calibration method. The transient pulses, made at the time of station calibration of March 29, 1962 are compared in amplitude and shape with the pulses made during the subsequent months.

North-south component. The shape of the transient pulses made 13 months after the original calibration of March 29, 1962 differs somewhat from the original pulse in that the recent pulses overshoot the zero line and then return gradually to zero, as shown in Figure 7. This overshooting of the transient pulse suggests that the galvanometer has become underdamped. The amplitudes of the NS pulses range from 75mm to 87mm with an average of 78.4 mm.

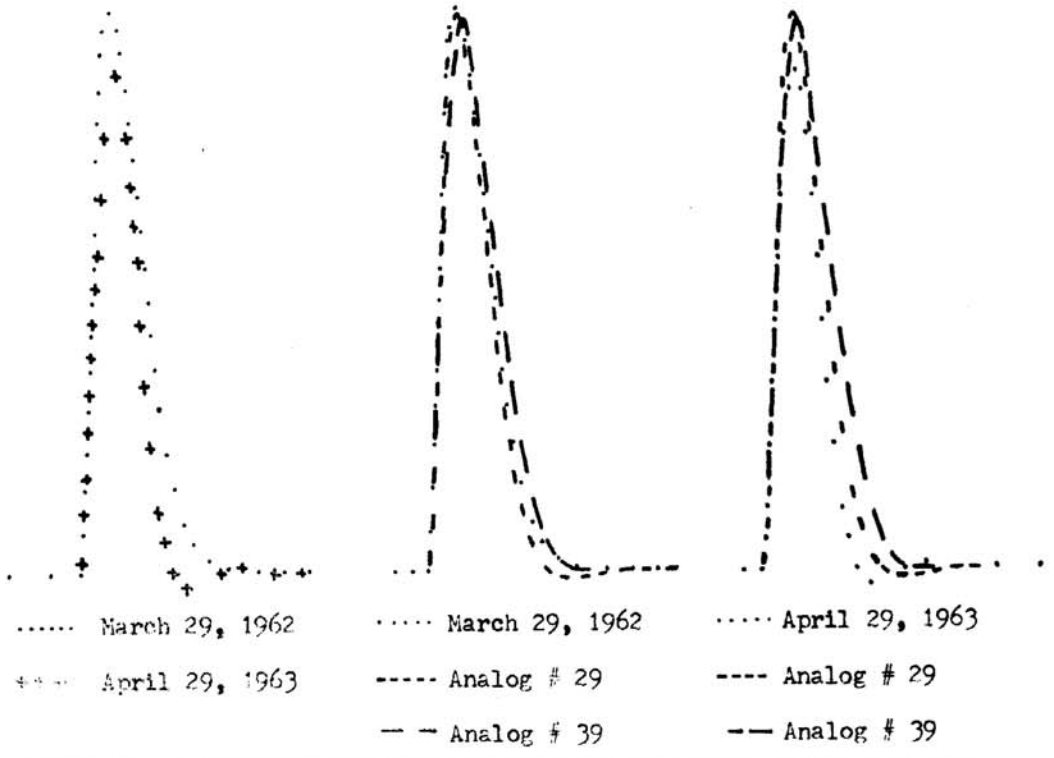


Figure 7. Comparison of pulses for the Uppsala north-south component.

a) A comparison between pulses of March 29, 1962 and April 29, 1963.

b) A comparison between pulse of March 29, 1962 and analog pulses #29 and #39.

c) A comparison between pulse of April 29, 1963 and analog pulses #29 and #39.

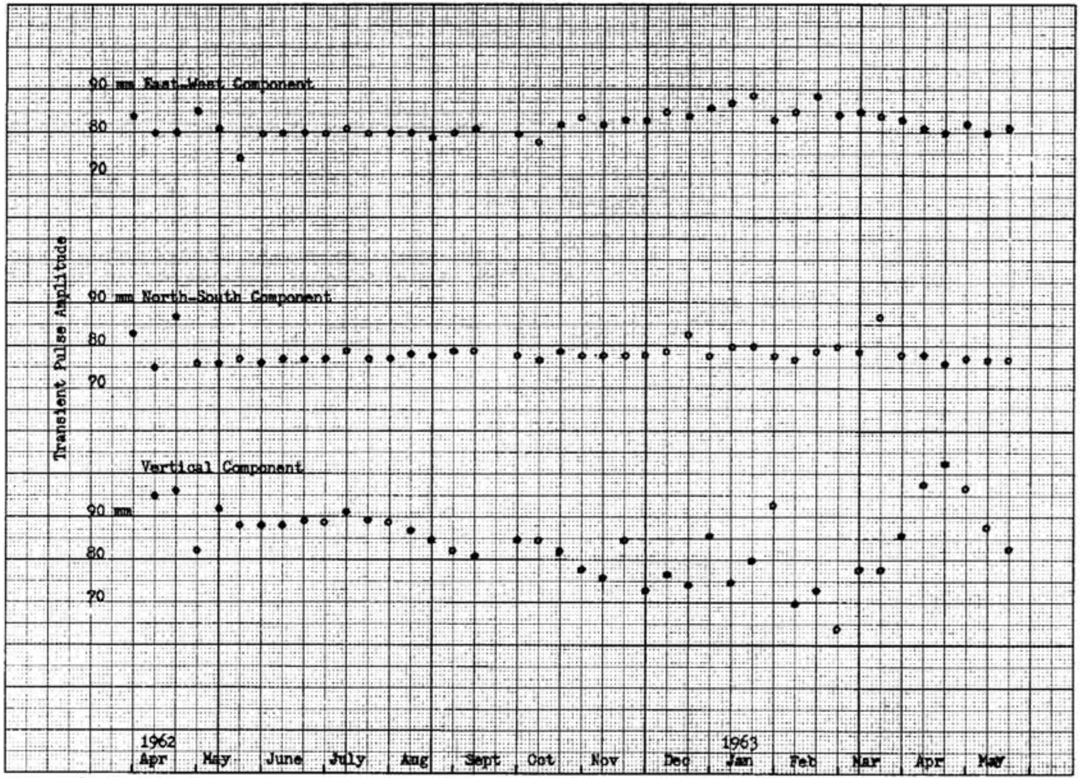


Figure 6. Variation of amplitudes of transient pulses for the Uppsala seismographs from April 1, 1962 to May 21,1963. Pulse dates are 1, 11, 21 of each month.

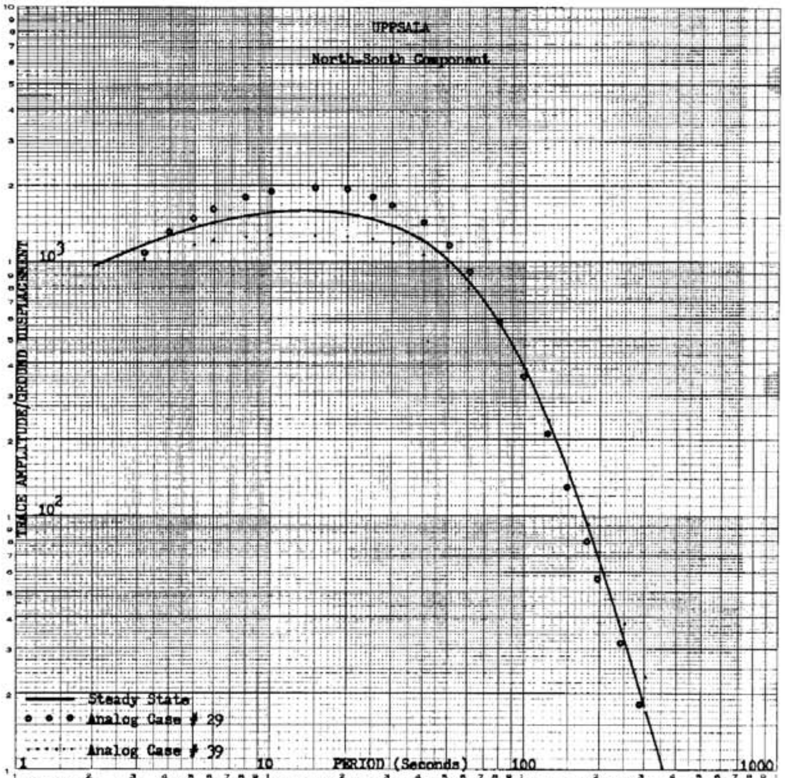


Figure 8. The north-south displacement response curve of March 29, 1962 observed by the steady-state method, is matched with displacement curves of analog cases #29 and #39. The transient pulses of these cases closely match the transient pulse of April 30, 1963.

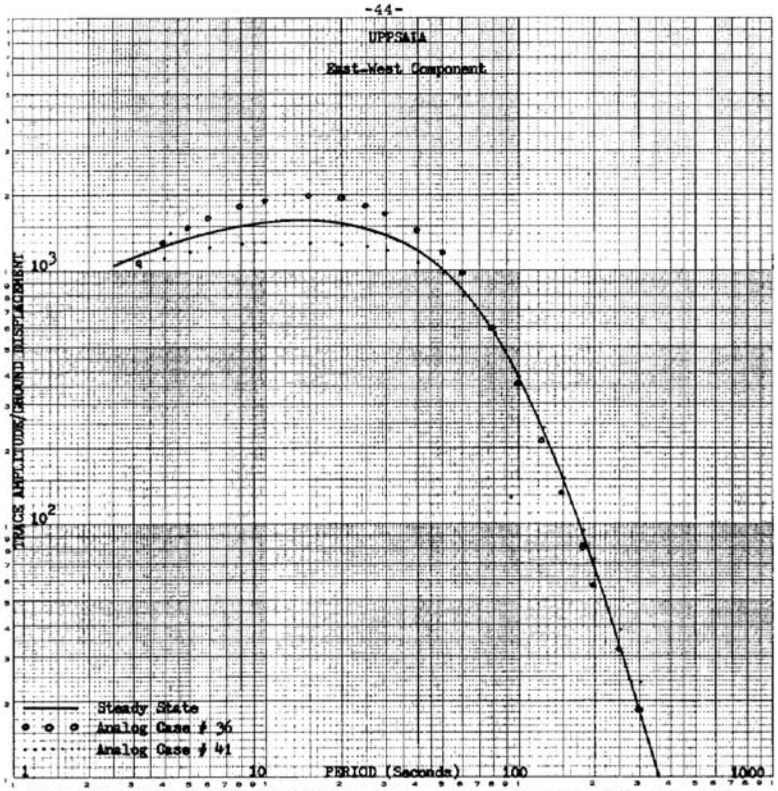


Figure 10. The east-west displacement response curve of March 29, 1962, observed by the steady-state method, is matched with displacement curves of analog cases #36 and #41. The transient pulses of these cases closely match the transient pulse of March 31, 1963.

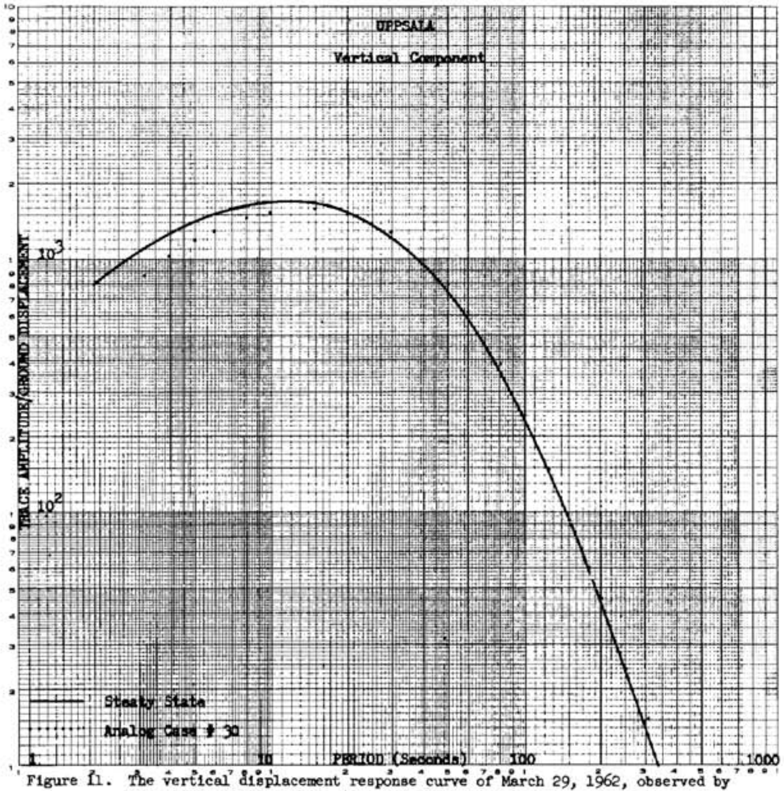


Figure 11. The vertical displacement response curve of March 29, 1962, observed by the steady-state method, is matched with displacement curve of analog case #30. The transient pulse of this case closely matches the transient pulse of April 29, 1963.

Since the instrumental constants of the NS seismograph do not have their exact equivalent among the family of analog pulses, two closely matched analog pulses bracket the NS recorded transient. These are analog cases #29 and #39 with the following parameters:

#29: $T_o = 15$, $T_g = 75$, $h_o = 1.5$, $h_g = 0.8$
#39: $T_o = 15$, $T_g = 75$, $h_o = 3.0$, $h_g = 0.8$

The pulses of these two cases most closely match both the pulse of March 29, 1962 and the pulses made a year later. Figure 7 shows a comparison of pulses of March 29, 1962 and April 29, 1963 with each other, and each with analog pulses #29 and #39. The pulse of April 29, 1963 is typical of the pulses made a year after the steady-state calibration. Figure 8 shows the NS absolute magnification response curve of March 29, 1962 obtained by steady-state calibration together with the response curves corresponding to the two closely-matched transients.

The NS absolute magnification of March 29, 1962 is compared with the magnification values obtained from the later pulses. The following results were computed for magnification at a period of 20 seconds:

M (March 29, 1962) by steady-state = 1560
M (March 29, 1962) by analog case #29 = 1950
M (March 29, 1962) by analog case #39 = 1264
M (Average of year) by analog case #29 = 1850
M (Average of year) by analog case #39 = 1200

The results represent a percentage difference of magnification by the transient pulse method between the March 29, 1962 and the year's average value of

-5.1% by case #29
-5.0% by case #39

The standard deviation of amplitudes of the year's pulses with respect to the year's average pulse amplitude is 5.6 mm and in terms of percentage is 7.1%.

East-west component. The shape of the pulse of March 31, 1963 calibration is very close to the pulse of March 29, 1962, as shown in Figure 9. The amplitudes of the year's pulses range between 75mm and 85 mm with an average of 82mm. Two analog cases, as shown in Figure 10, which most closely match both the original and the later pulses, are:

#36: $T_o = 15$, $T_g = 100$, $h_o = 1.5$, $h_g = 1.5$
#41: $T_o = 15$, $T_g = 75$, $h_o = 3.0$, $h_g = 1.5$

The EW absolute magnification of March 29, 1962 is compared with the magnification values obtained from the later pulses. The following results were computed for magnification at a period of 20 seconds:

M (March 29, 1962) by steady-state = 1680
M (March 29, 1962) by analog case #36 = 2465
M (March 29, 1962) by analog case #41 = 2000
M (Average of year) by analog case #36 = 2450
M (Average of year) by analog case #41 = 2020

The percentage difference of magnification by the transient pulse method between the March 29, 1962 calibration and that of the year's average is:

-0.6% for case #36
+1.0% for case #41

The standard deviation of amplitudes of the year's pulses with respect to the year's average pulse amplitude is 2.9mm, and in terms of percentage is 3.6%.

Vertical component. The amplitudes of the pulses range from 64mm to 103mm with an average of 84.8mm. The shape of the year's pulses show no significant change from the original pulse of March 29, 1962, as shown in Figure 9. One analog case, as shown in Figure 11, which closely matches the observed pulses, is #30 with the following parameters:

$$T_o = 15,\ T_g = 75,\ h_o = 1.5,\ h_g = 1.0$$

The following magnifications were computed:

M (March 29, 1962) by steady-state = 1530
M (March 29, 1962) by analog case #30 = 1479
M (Average of year) by analog case #30 = 1300

The percentage difference of magnification by the transient pulse method between the March 29, 1962 calibration and that of the year's average is -12.1%. The standard deviation of amplitudes of the year's pulses is 7.98mm and in terms of percentage with respect to the year's average pulse amplitude is 9.5%.

Conclusions. The absolute displacement magnification of March 29, 1962 computed by the two methods of steady-state and transient pulse calibrations are in close agreement for the NS and Z components. The EW component does not have this same close agreement. At the time of this transient pulse study the apparent discrepancy has not been resolved because of lack of data. The discrepancy, nevertheless, in no way detracts from the study of magnification response changes as determined by the transient pulse calibrations.

During the period of 14 months following the steady-state calibration of the Uppsala seismographs, the transient pulses show that the shapes of the pulses compare very closely with the pulses made at the time of calibration. The changes in pulse amplitude represent a real but slight change in sensitivity. The vertical component shows the greatest change, but this is to be expected since temperature changes affect the spring constant which in turn alters the zero position of the seismometer coil between the poles of the magnet, and thus changes the electrodynamic constant, G, of the seismometer. The relationship of pulse amplitudes to the original pulse size is made on the assumption that the pulse-generating voltage does not change. Mercury batteries were used.

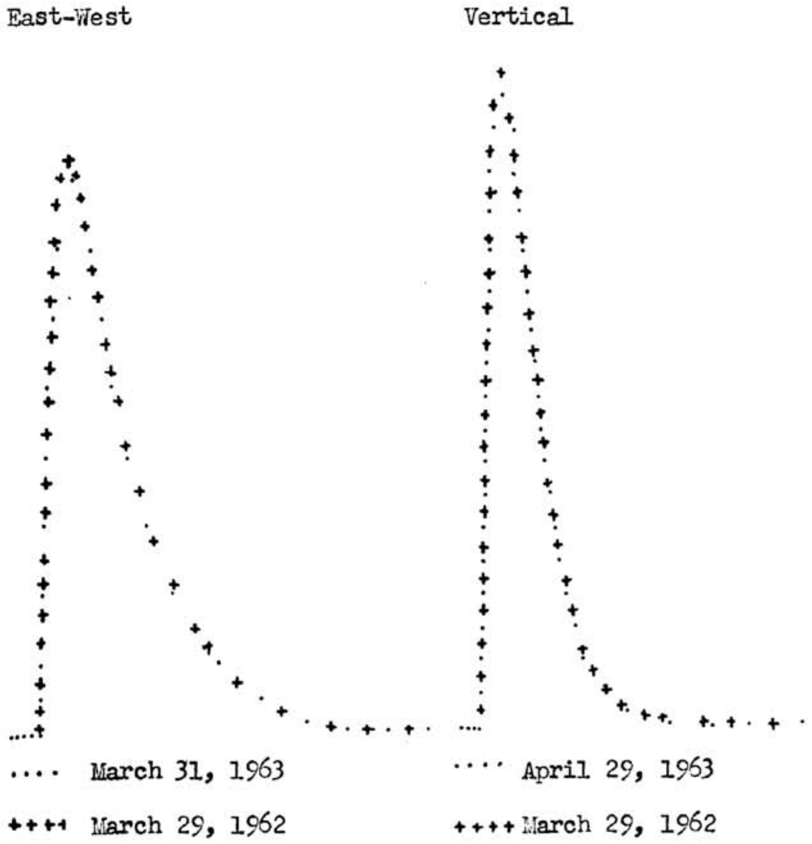


Figure 9. Transient pulses of March 29, 1962 for the East-West and Vertical components are matched against pulses made a year later on the Uppsala seismographs.

ACKNOWLEDGMENTS

Various people worked on this calibration project in one form or another for varying lengths of time. Many personnel, who operate and maintain these instruments at stations around the world, also assisted generously in the calibration work at their respective observatories. Dr. J. Oliver and Dr. G. Sutton are responsible for inaugurating the project and for the original plan of procedure and development. To Dr. Sutton belongs the credit of working out the fundamental aspects. Mr. Alvaro Espinosa did the digital computer work analyzing the experimental pulses, and obtaining theoretical response curves to match the experimental results. He is also the author of the article entitled, "A Transient Technique for Seismograph Calibration." Dr. M. Båth of the Uppsala Observatory instigated the study of the Uppsala instrument stability and compiled the data used therein.

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REFERENCES

Chakrabarty, S. K. (1949) Response characteristics of electromagnetic seismographs and their dependence on the instrumental constants; Bull. Seism. Soc. Am., 39, 205-218.

Duclaux, Mme. F. (1960) Seismometrie theorique; Memorial des Sciences Physiques, Fasc. LXIV, Gauthier-Villars, Paris, France, 38-44, 98-110.

Espinosa, A. F., G. H. Sutton, and H. J. Miller, S.J. (1962) A transient technique for seismograph calibration; Bull. Seism. Soc. Am., 52, 767-779.

Lamont Geological Observatory, Palisades, New York. 1959 Publications List.

Pomeroy, P. W. and G. H. Sutton (1960) The use of galvanometers as band-rejection filters in electromagnetic seismographs; Bull. Seism. Soc. Am., 50, 135-151.

Sohon, F. W. (1932) Seismometry. Introduction to Theoretical Seismology, Part II; John Wiley & Sons, New York.

Sutton, G. H. and J. Oliver (1959) Seismographs of high magnification at long periods; Annales de Geophysique, 15, 423-432.

Willmore, P. L. (1959) The application of the Maxwell impedance bridge to the calibration of electromagnetic seismographs; Bull. Seism. Soc. Am., 49, 99-114.

APPENDIX 1

SUMMARY OF CALIBRATION PROCEDURE

This summary contains a detailed account of the actual calibration procedure.

Calibration by the steady-state method.

1. Assemble the Willmore calibration bridge as shown in Figure 2. One bridge design adapted and found suitable is the following: R_1 = 10 ohms + two Bourne's trimpots of ratings, 0 - 50 and 0 - 10 ohms in series, R_2 = 20,000 ohms, R_3 = 2000 ohms. R_2 and R_3 are Dalohm precision resistors.

2. Assemble the pulse circuit: $R_p \simeq$ 100,000 ohms, battery 1.35 volts, and an on-off switch in series. The pulse resistor, R_p, which may be a pot or a fixed resistor, must be varied on each instrument to produce a pulse of workable size, e.g., about 6 to 10 cm.

3. Install the bridge and the pulse circuit in the seismometer-galvanometer network according to the diagram in Figure 2.

4. Balance the bridge. Three methods are practical.

(a) By a steady-state oscillator drive: clamp the seismometer; drive the seismometer with the oscillator at approximately f = 0.5 cps. In the unbalanced condition of the bridge the galvanometer will oscillate. Adjust resistor, R_1, until minimum oscillation occurs. Increase the driving voltage to 5 or 7 volts and adjust R_1 with the coarse and fine trimpots until either a null or minimum is obtained. This is the quickest but not the most refined method.

(b) By a step pulse with seismometer clamped: apply a step pulse, in place of the oscillator, to the seismometer system. In the unbalanced condition the galvanometer light spot will be displaced. As the bridge is balanced, a point will be reached where the galvanometer zero position is not displaced in response to a step pulse. This has the advantage of obtaining the best balance for a wide range of frequencies.

(c) By a step pulse with seismometer unclamped. This method requires no handling of the seismometer, but is more time-consuming. Apply the step pulse to the seismometer. In the unbalanced condition (pulse switch on) the light spot will be displaced from its zero position after tracing out the transient pulse. As the second pulse is applied (pulse switch off) the light spot will return to its original zero position after the transient pulse is completed. This method of balancing can be used in the daily calibration without disturbing the instruments. This, of course, is a D.C. balance. (If inductance is negligible, a, b, and c should be exactly equivalent).

5. For the steady-state calibration connect the oscillator, recording voltmeter and seismograph-bridge network according to the diagram in Figure 2. A recording voltmeter is placed across the oscillator terminals to measure the input signal to the bridges (three components can be calibrated at once). The time marks should be placed simultaneously on the seismograph recorders and the recording voltmeter in order to provide data for the phase response curve. These time marks can be put on by hand. The precision resistor, R_d, is a dropping resistor for each bridge because of the fact that the recording voltmeter used was too insensitive to record the small signal required to drive the bridge. The dropping resistors can be chosen so that the trace amplitudes of the oscillations at 20 seconds or thereabouts are roughly the same on the three components. R_d also serves to reduce any coupling between the seismometer circuits during calibration.

6. Make photographic records of the oscillations on the three components from the steady-state sine wave oscillator over a range of periods from 2 to 250 seconds. Allow a sufficient number of oscillations to provide a good estimate of the amplitude value for each period. The amplitude increases rapidly to a maximum around 100 seconds, and then decreases slightly. The driving voltage may need to be decreased for the larger amplitudes and increased for the smaller amplitudes. Corrections must be made to provide for a constant effective input voltage. Since the oscillator's voltage output is not exactly the same over the entire range of periods, the voltage value is noted for each period.

7. Identify the records; block off the oscillations according to each period; measure the average amplitude for each period. Correct each amplitude to a constant input voltage.

8. Plot the corrected trace amplitude output for each period against its corresponding period. This plot is a graph of the relative acceleration sensitivity. Adjust each point by multiplying the amplitude by ω to get the velocity sensitivity, and by ω^2 to get the displacement sensitivity. This can be done arithmetically but it is time-consuming and tedious. An approximate integration differing only by a factor of 2π (since $\omega = 2\pi/\tau$) can be done graphically by dividing any point on the relative acceleration sensitivity graph by the value of τ corresponding to that point. To do this graphically on a standard log-log plot inscribe about a selected point, A, a circle of radius equal to the horizontal distance from that point to the line, $\tau = 1$ second. A point on the circle vertically below the selected point, A, is a point on the velocity sensitivity curve. A point vertically below A at a distance twice the given radius is a point on the displacement curve.

9. To determine the damping factor, h, connect the seismometer coil leads to a high impedance recording voltmeter (Sanborn or Varian); apply a pulse to deflect the boom; record the decay curve noting the time scale. From this graph read the free period of the seismometer, τ_0, each amplitude, and compute h_m from the equation,

$$h^2 = 1/\left[1 + 4\pi^2 n^2/\ln(X_m/X_{m+n})\right].$$

This gives the open circuit or mechanical damping, h_m.

10. Place a 20,000 ohm resistor across the coil; deflect the boom and record the oscillations. Repeat with a 10,000 ohm resistor as a check. Comput h for the total resistance used where $R = 20{,}000$ ohms (or 10,000 ohms) + R_c (coil).

11. Compute G from the equation, $G^2 = 2\,(h - h_m)\,\omega_o\, mR_t$.

12. Measure m by weighing the boom and mass.

13. Compute the current in the seismometer coil, i_c, by applying Ohm's law in the form of the expression,

$$i_c = V_s\, Z/R_{cp}\,(R_d + Z)$$

where V_s = constant voltage input to the bridges from the oscillator,
R_d = dropping resistor,
Z = resistance of the bridge,
R_{cp} = resistance of the seismometer coil, R_c, plus R_2.

14. Compute $\ddot{Y} = Gi_c/m$ for acceleration, or $Y = Gi_c/m\,\omega^2$ for displacement.

15. Compute displacement sensitivity from the relation,

$$M = X_f/Y_f = X_f\,\omega^2/Gi_c/m$$

where X_f = trace amplitude at a specific frequency
Y_f = displacement amplitude at that frequency.

One point is sufficient to give the locus of the relative displacement sensitivity response curve on the absolute scale.

16. Plot the phase response curve, ϕ versus τ, from the equation,

$$\phi = 2\,\pi\Delta t/\tau,$$

where Δ t is the time difference between the recorded time of an input peak and the recorded time of the corresponding output peak at each period, τ.

Calibration by the transient method.

1. Apply a step pulse to the seismometer through the bridge and record the transient response.

2. Match the transient response with a similar one from the analog computer.

3. Measure the amplitude of the transient response in meters.

4. Measure the coil current, i_c, which produced the recorded pulse from the equation,

$$i_c = V_s \, Z/R_{cp} \, (R_p + Z)$$

where V_s = battery voltage in the pulse circuit, and R_p = pulse resistor.

5. Apply the equation, $M = D_f/Y_f = -\,(m/G)\,(D_f'/D_t')(v_t'/v_f')(D_t/i_t)$ where $i_t = i_c$.

APPENDIX 2

A list of values of the coupling resistors used with the seismographs prior to the first calibrations and from the final calibrations to the present (Figure 12).

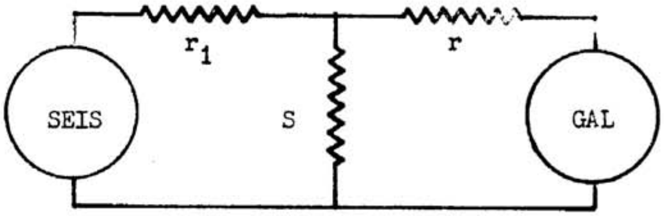

Figure 12. Coupling resistors as found on some instruments.

Long-Period Instruments

Station	Comp.	Prior r	Prior S	Post r	Post S
Bermuda	N	0	150	330	220
	E	0	250	330	220
	Z	0	430	330	100
Buenos Aires	N	-	-	330	300
	E	-	-	330	250
	Z	-	-	330	330
Delhi	N	-	-	330	560
	E	-	-	330	680
	Z	-	-	330	330

Long-Period Instruments
(continued)

Station	Comp.	Prior		Post	
		r	S	r	S
Hong Kong	N	300	220	330	850
	E	300	220	330	690
	Z	300	100	330	330
Honolulu	N	330	100	330	560
	E	330	220	330	560
	Z	330	100 or 50	330	330
				Filter Calibration	
	N				560
	E				560
	Z				330
Mt. Tsukuba	N	330	220	330	680
	E	330	220	330	560
	Z	330	100	330	330
Perth	N	470	330	330	165
	E	470	330	330	200
	Z	330	100	330	390
				Filter Calibration	
	N				100
	E				100
	Z				150
Rio de Janeiro	N	330	220	330	510
	E	330	220	330	560
	Z	330	100	330	250
Santiago	N	0	220	330	470
		(r_1 = 330)			
	E	390	85	330	450
	Z	160	100	330	430
Suva	N	390	100	390	470
	E	380	100	380	470
	Z	330	100	330	220
Uppsala	N	330	220	330	470
	E	330	220	330	470
	Z	330	100	330	220
Waynesburg	N	330	100	330	220
	E	330	100	330	220
	Z	330	100	330	100

Short-Period Instruments

		r_1	r	S	r_1	r	S
Huancayo	N	0	10k	220	0	10k	220
	E	0	10k	220	0	10k	220
	Z	0	10k	220	0	10k	110
Rio de Janeiro	N	2200	9400	1000	2200	9400	1000
	E	2200	9400	1000	2200	9400	1000
	Z	110	10k	110	110	10k	110