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

$$m\ddot{Y} = Gi_c \qquad (1)$$

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

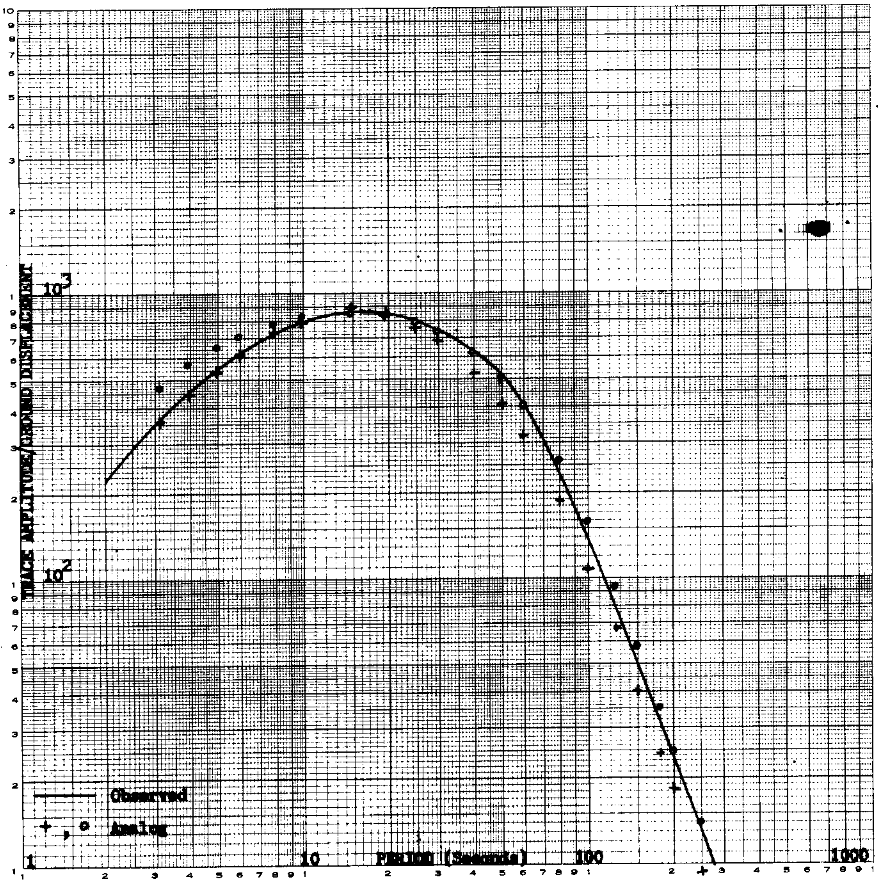


Figure 4. The displacement response, observed by the steady state method, is matched with two analog displacement curves.

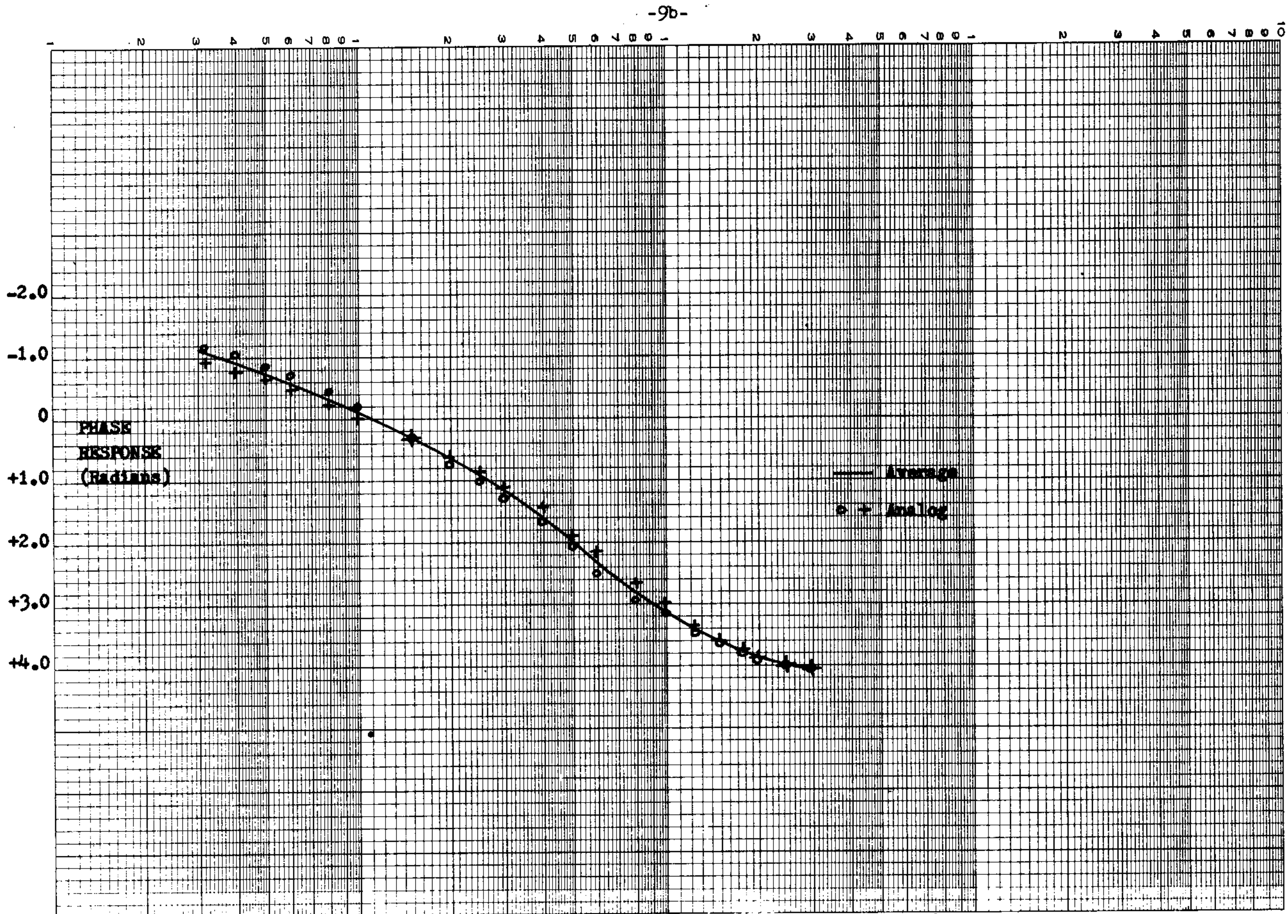


Fig. 5·A typical phase response curve (solid line) is derived from two analog phase curves (+) and (o) whose corresponding displacement curves most closely match the observed displacement response curves.

-9b-

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

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, 1 to August 1, 1960 the instruments underwent no major change. The calibration applies from April 15, 1962 to the present day. The p response curves were obtained from input and output records.

Hong Kong

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

Response curves. The first calibration applies from Septembe 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 micro-seism 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 $\mathcal{T}$ =	20	seconds	for a	470	ohm	shunt
EW	1160	"	"	" $\mathcal{T}$	20	"	" "	470	"	"
Z	1270	"	"	" $\mathcal{T}$	20	"	" "	220	"	"

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

<u>Uppsala</u>

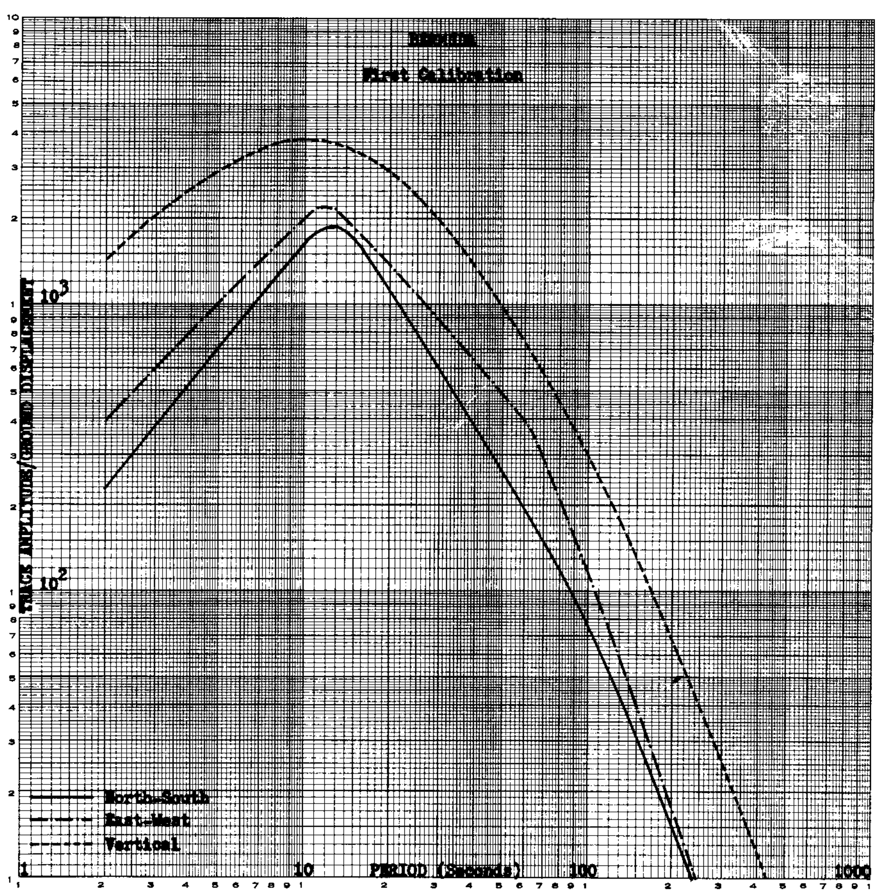
<u>Instruments</u>. Two Lehner-Griffith horizontals, one Sprengnether vertical.

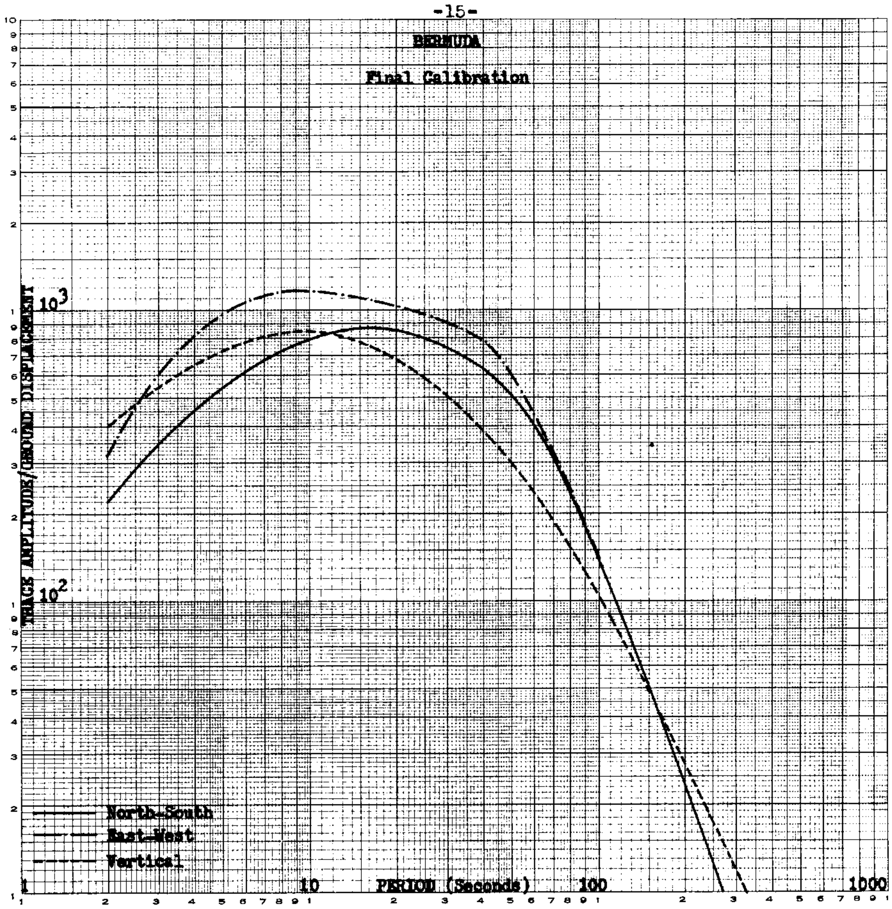
<u>Response curves.</u> The first calibration applies from March 21, 1959 to March 26, 1962. At the time of calibration the damping shunts of the galvanometers were all the way up. This condition decreases the magnification in the long-period range of 30 to 60 seconds. The final calibration applies from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

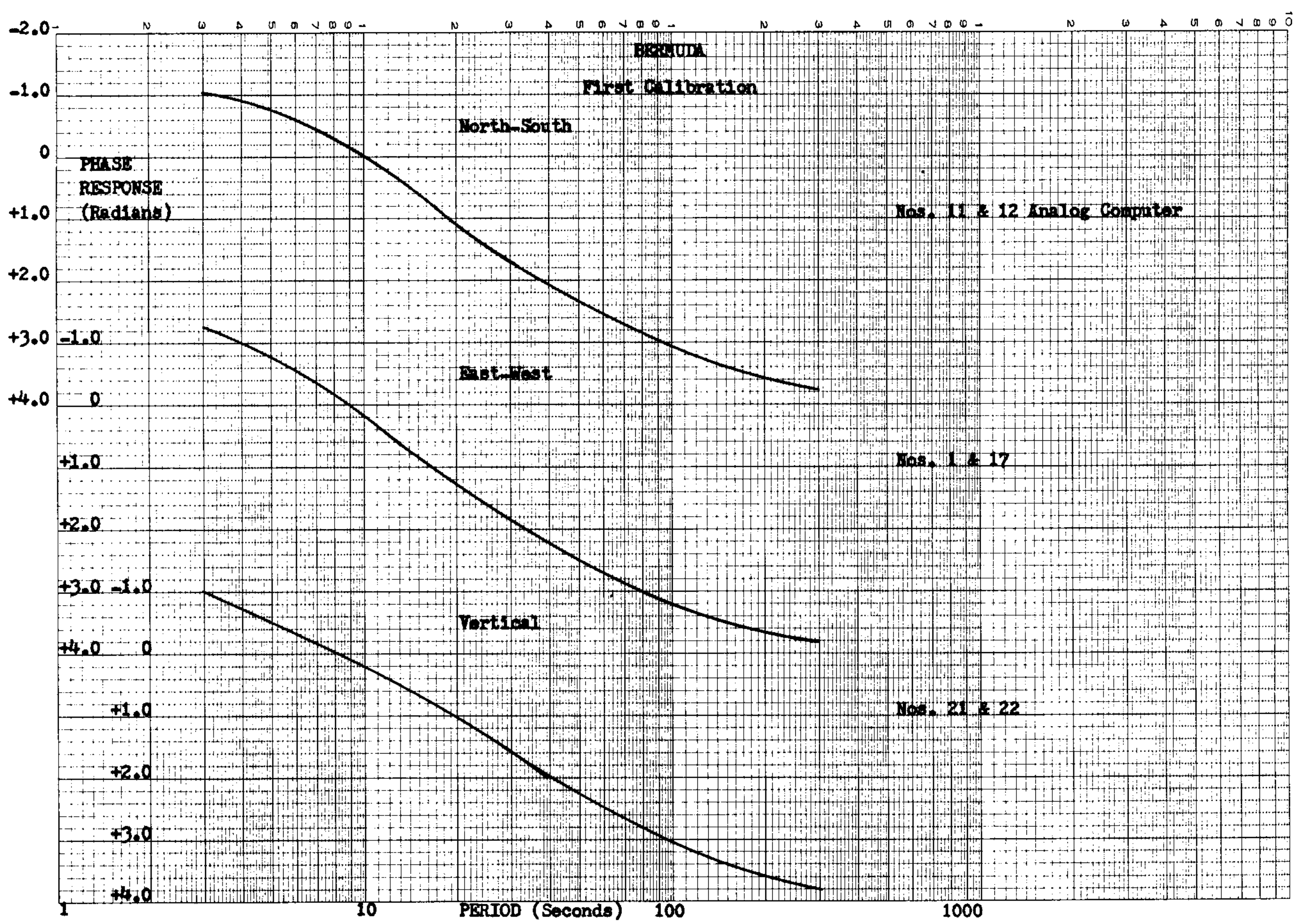
<u>Waynesburg</u>

<u>Instruments</u>. Two original Lamont horizontals, one Sprengnether vertical.

<u>Response curves.</u> 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
North-South
East-West
Vertical
1
10
PERIOD (Seconds)
100
1000


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