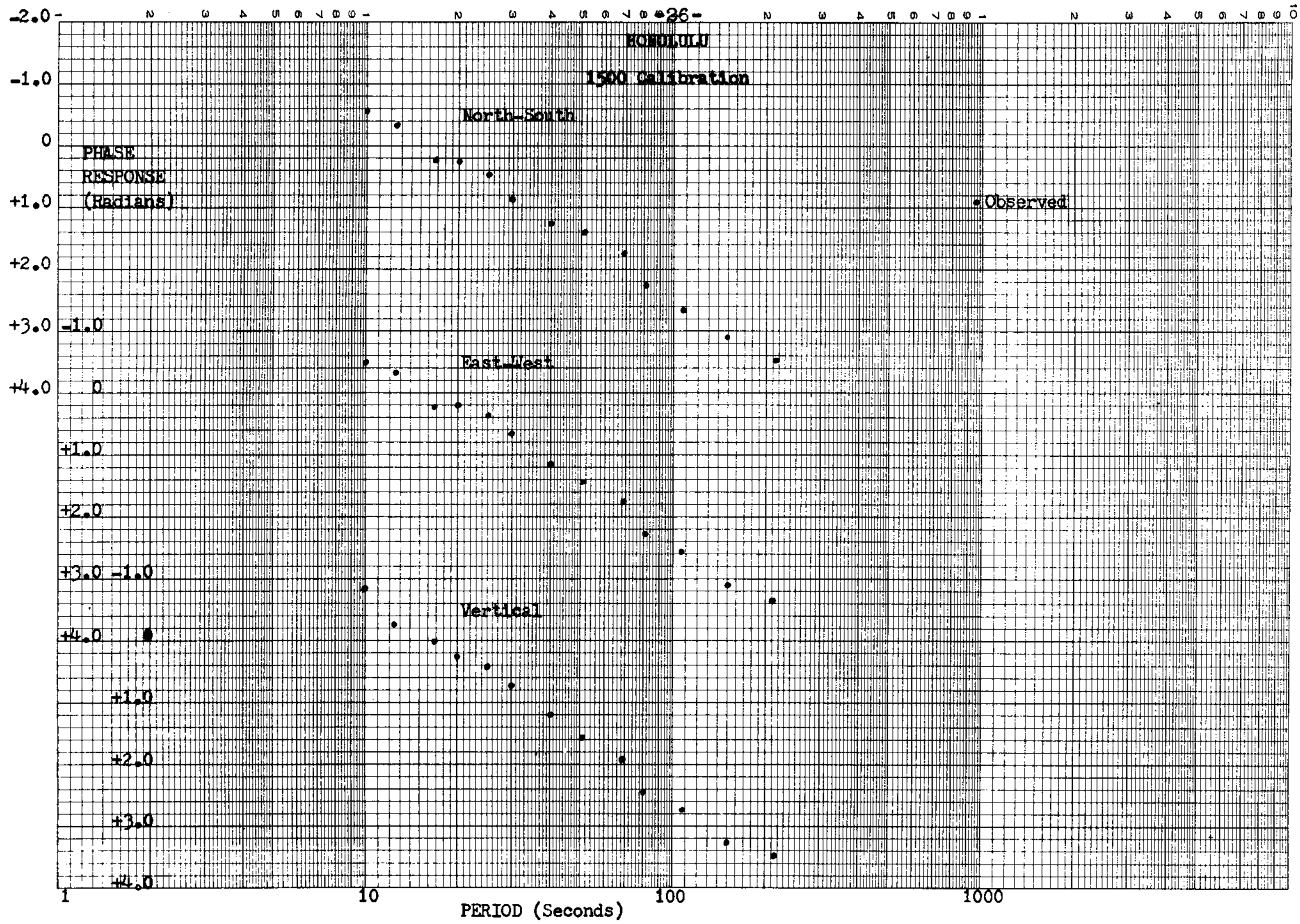

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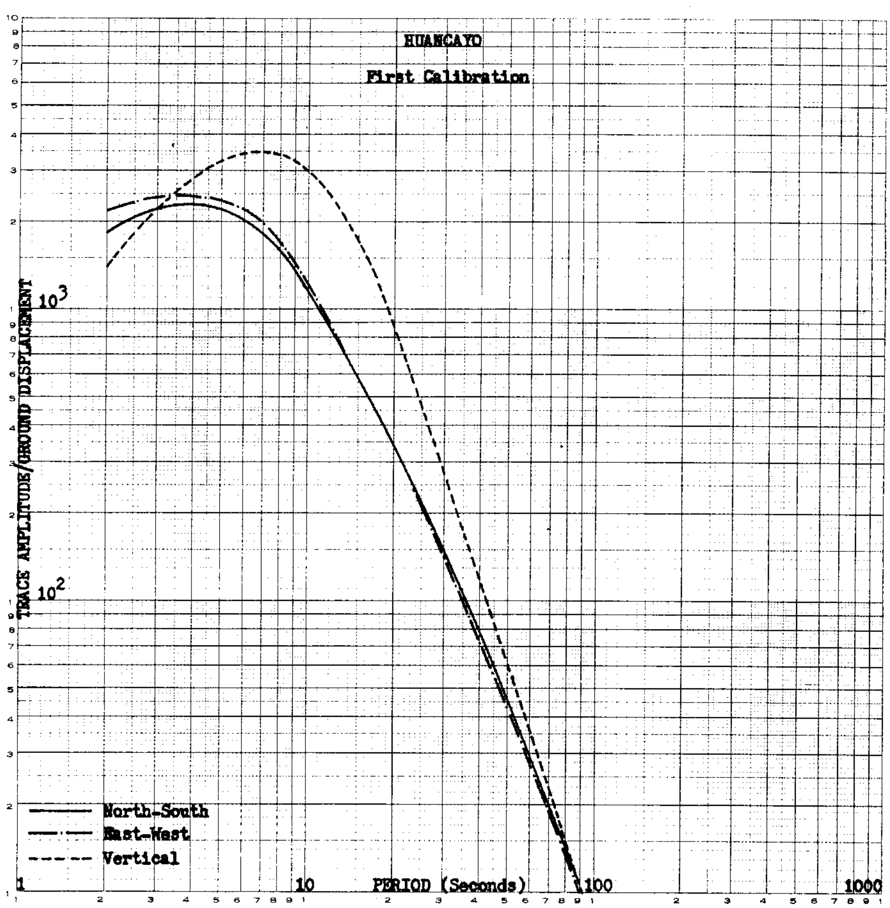

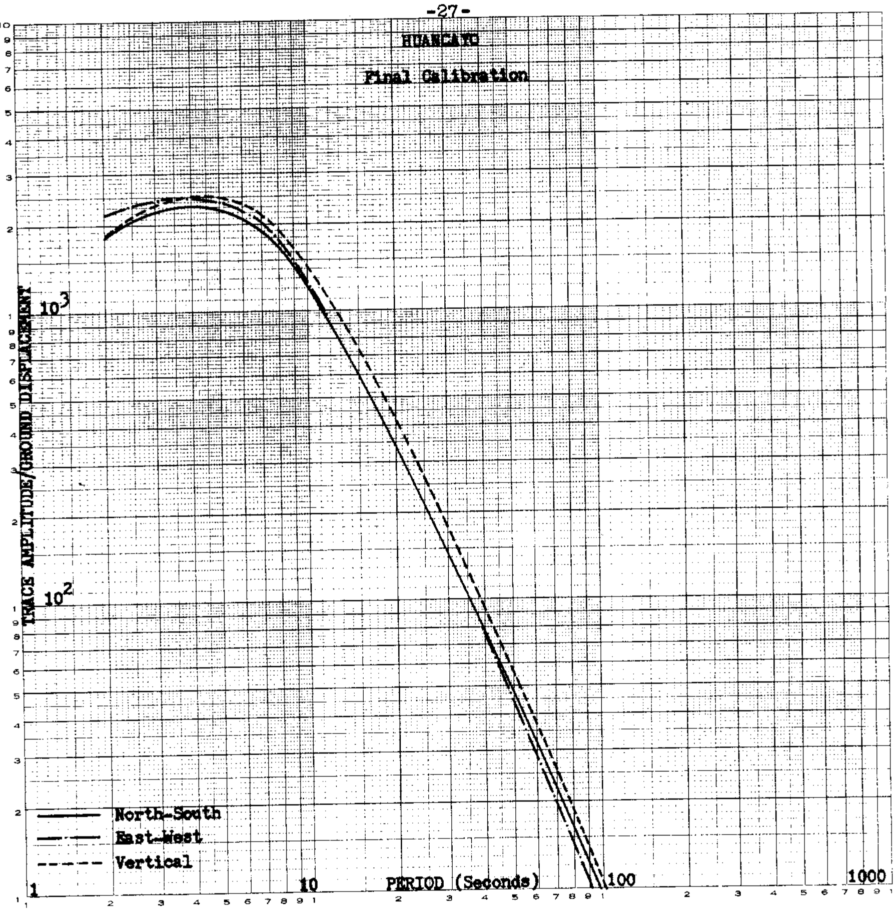

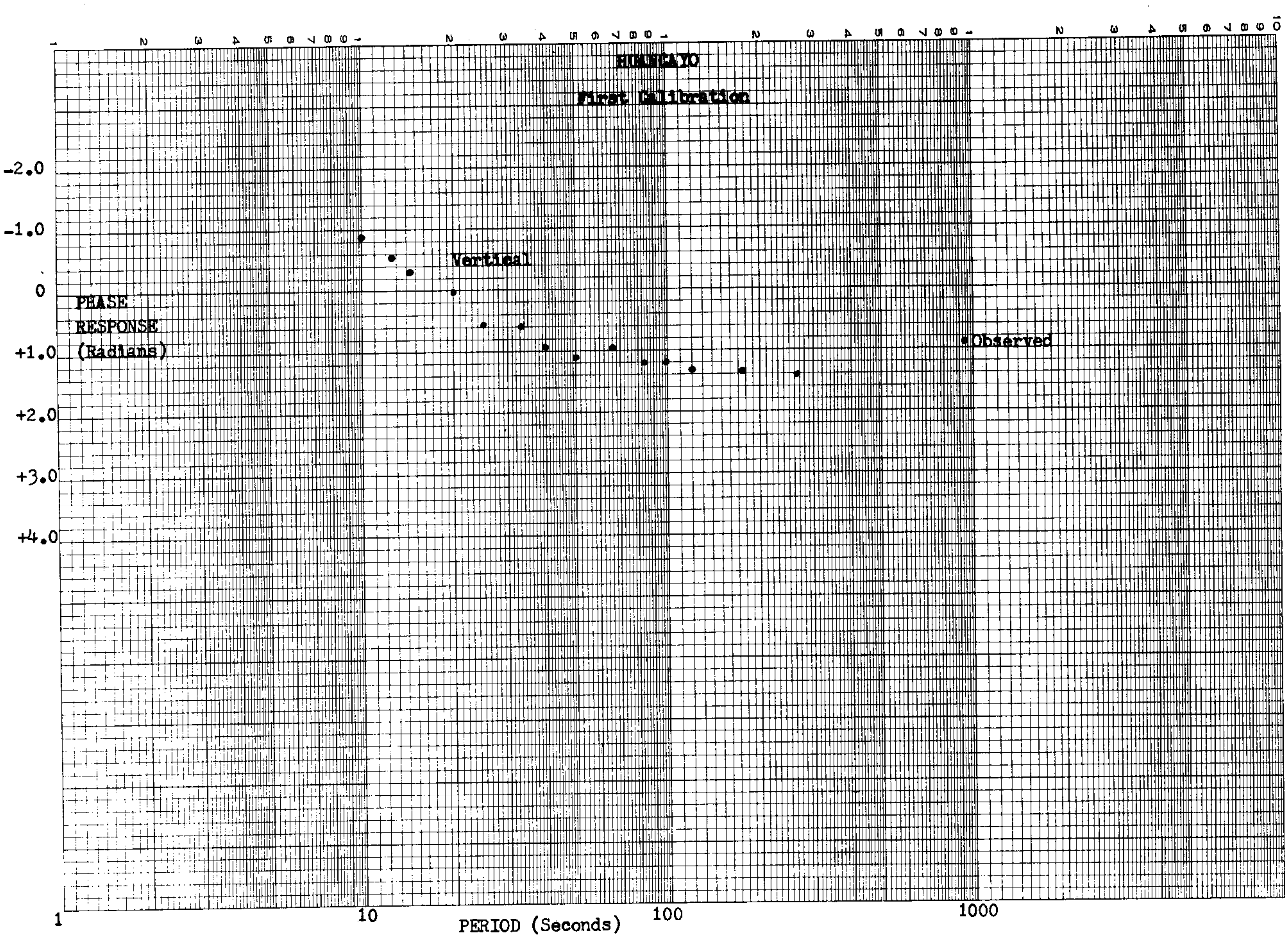

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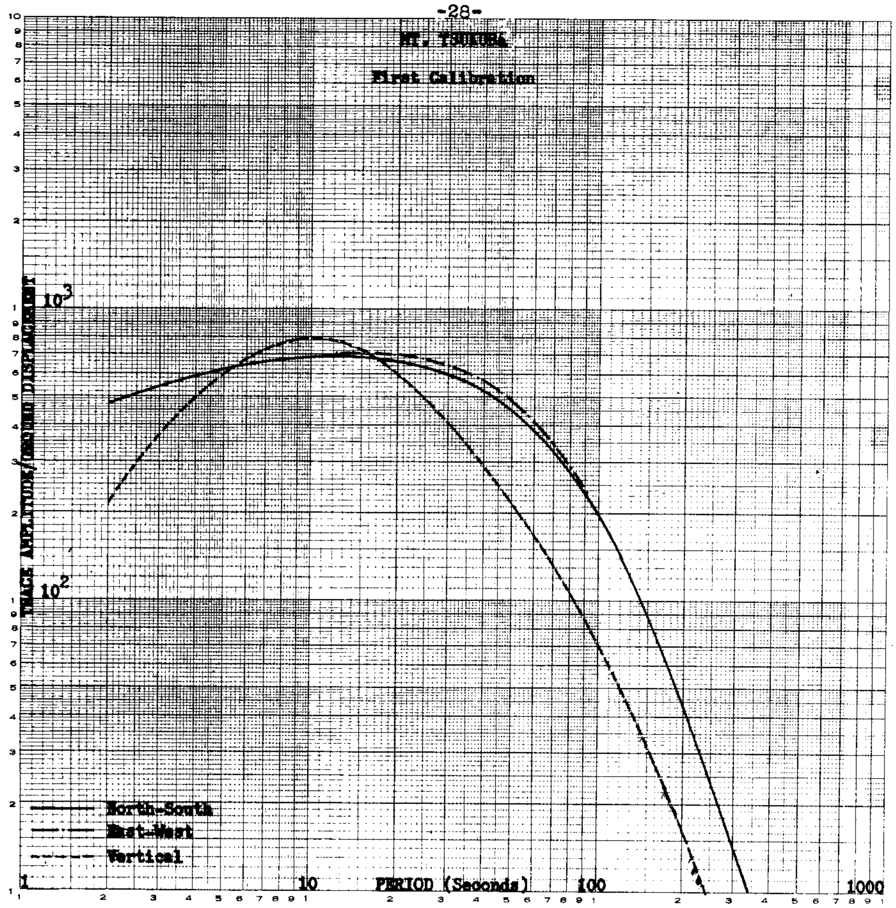
MT. TSUKUBA
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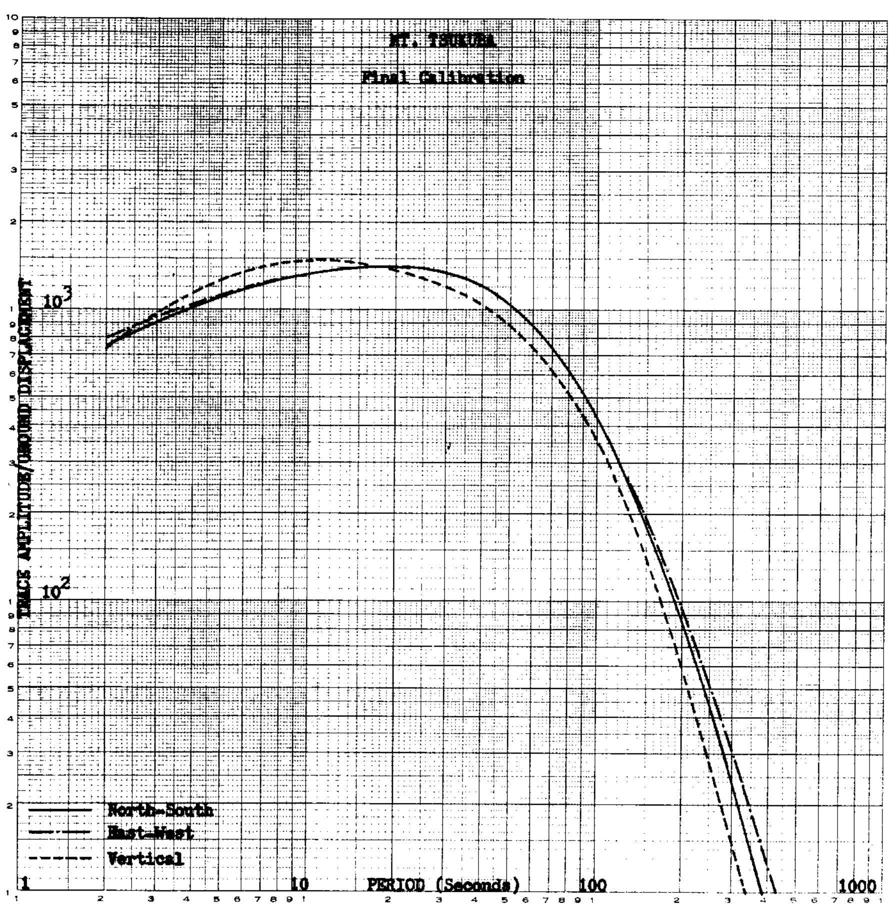
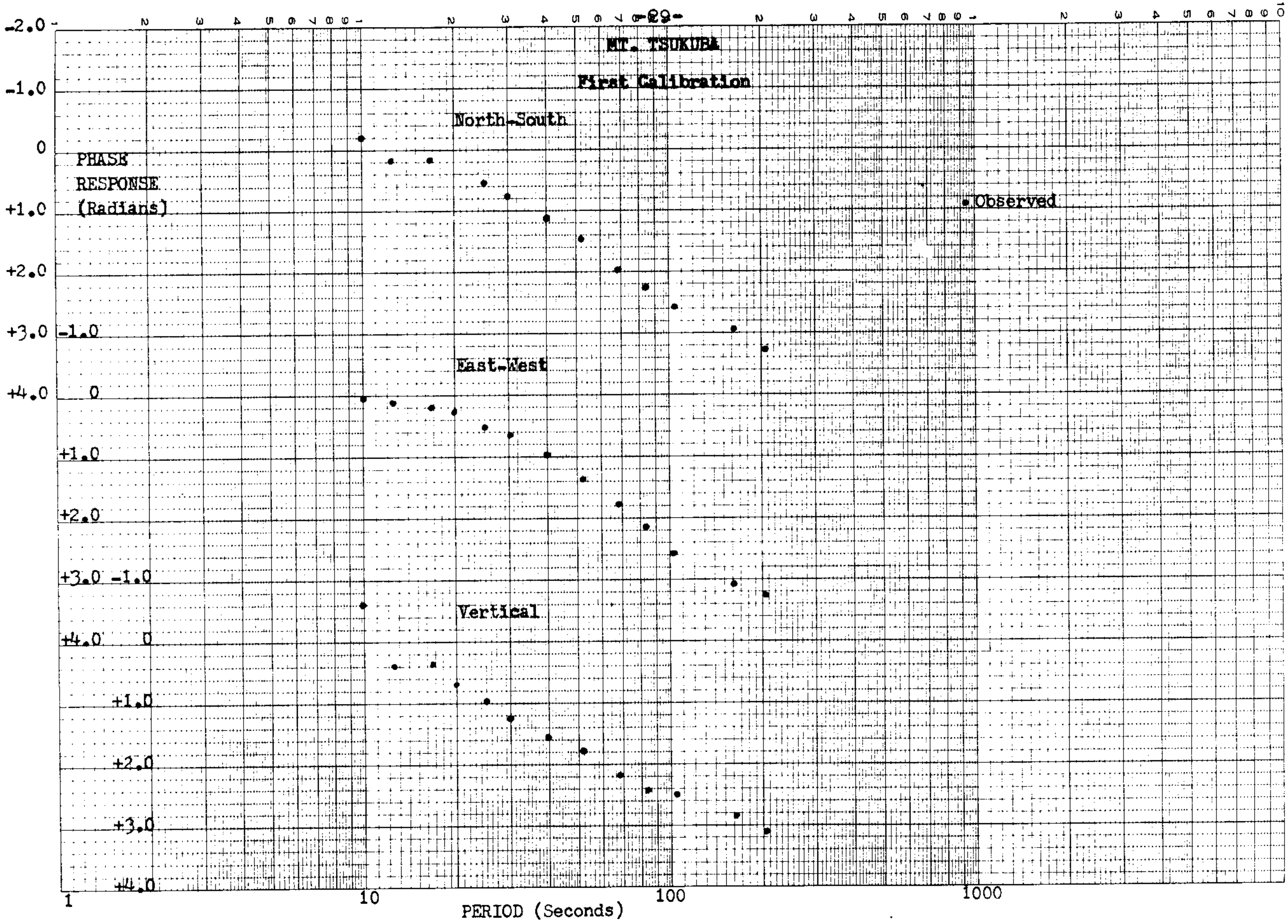
TRACE AMPLITUDE/GROUND DISPLACEMENT
10^3
10^2
North-South
East-West
Vertical
PERIOD (Seconds)
1
10
100
1000


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



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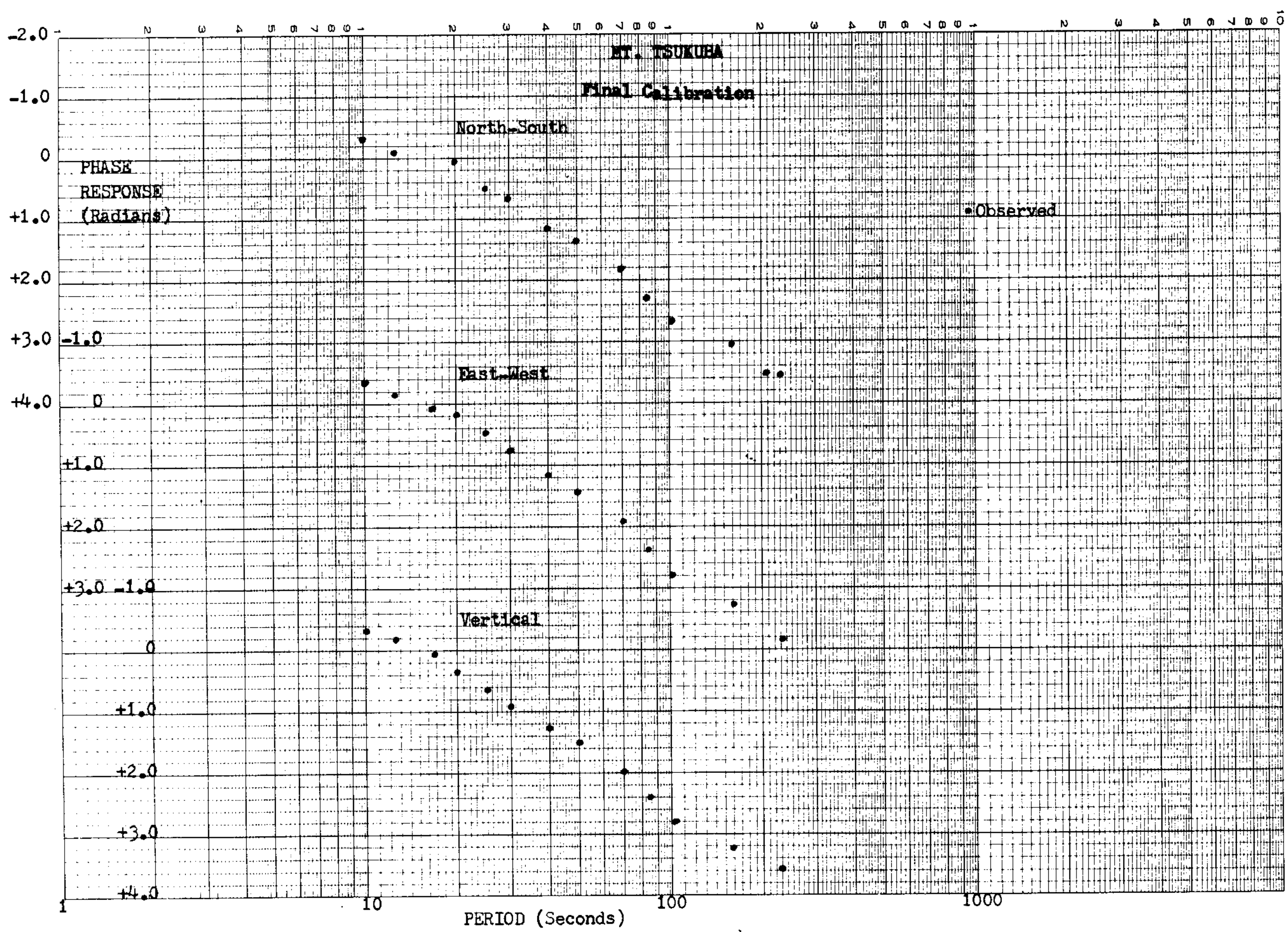
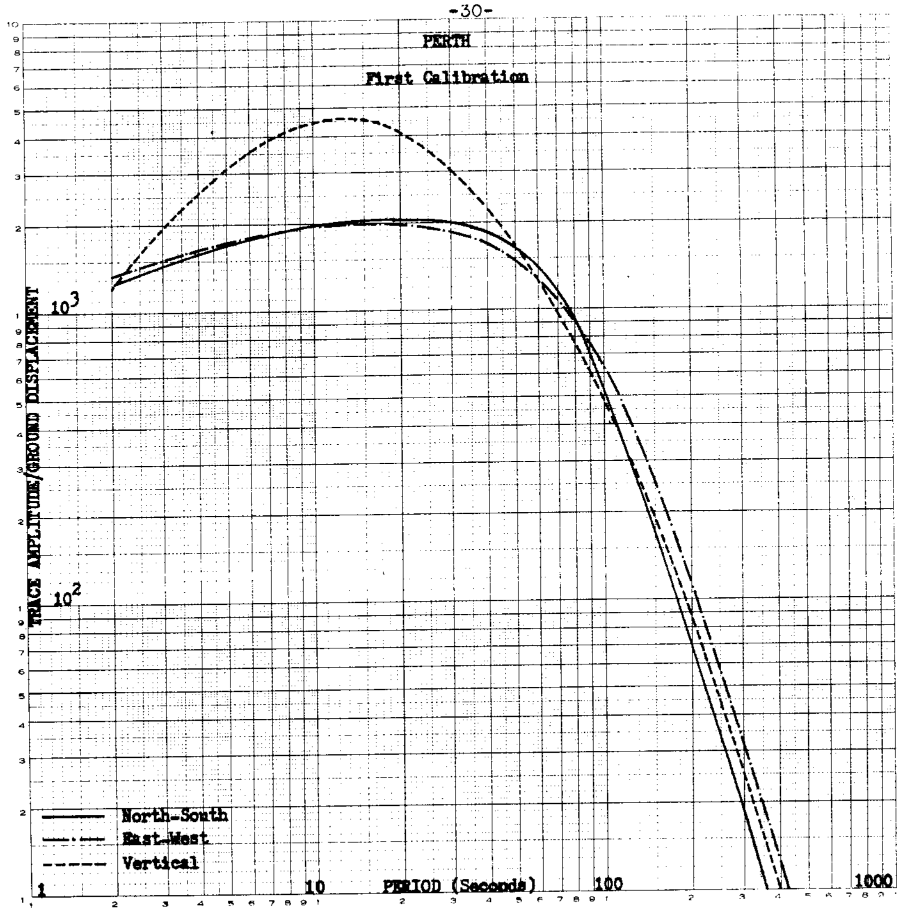
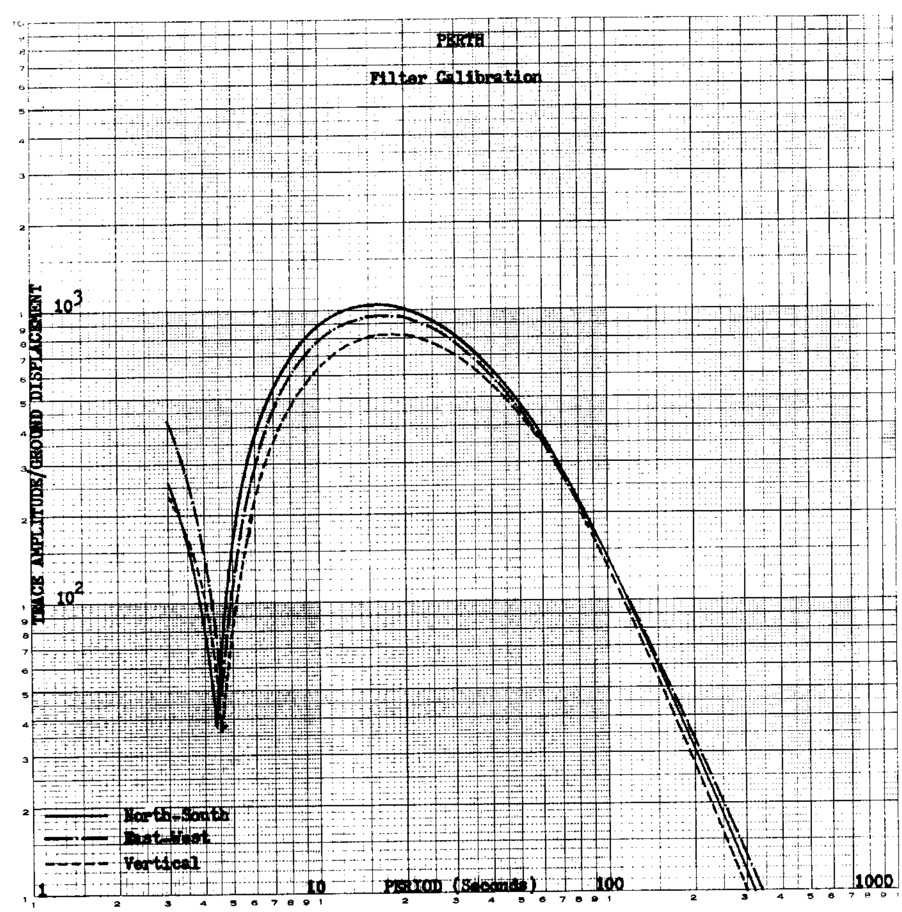
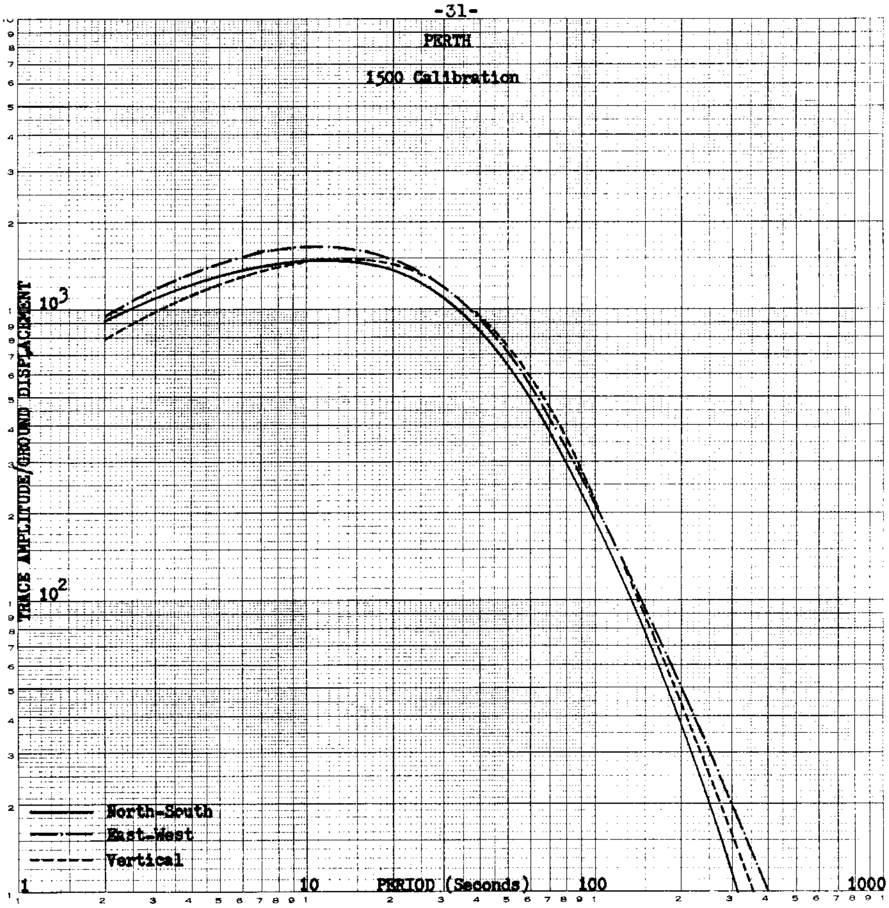
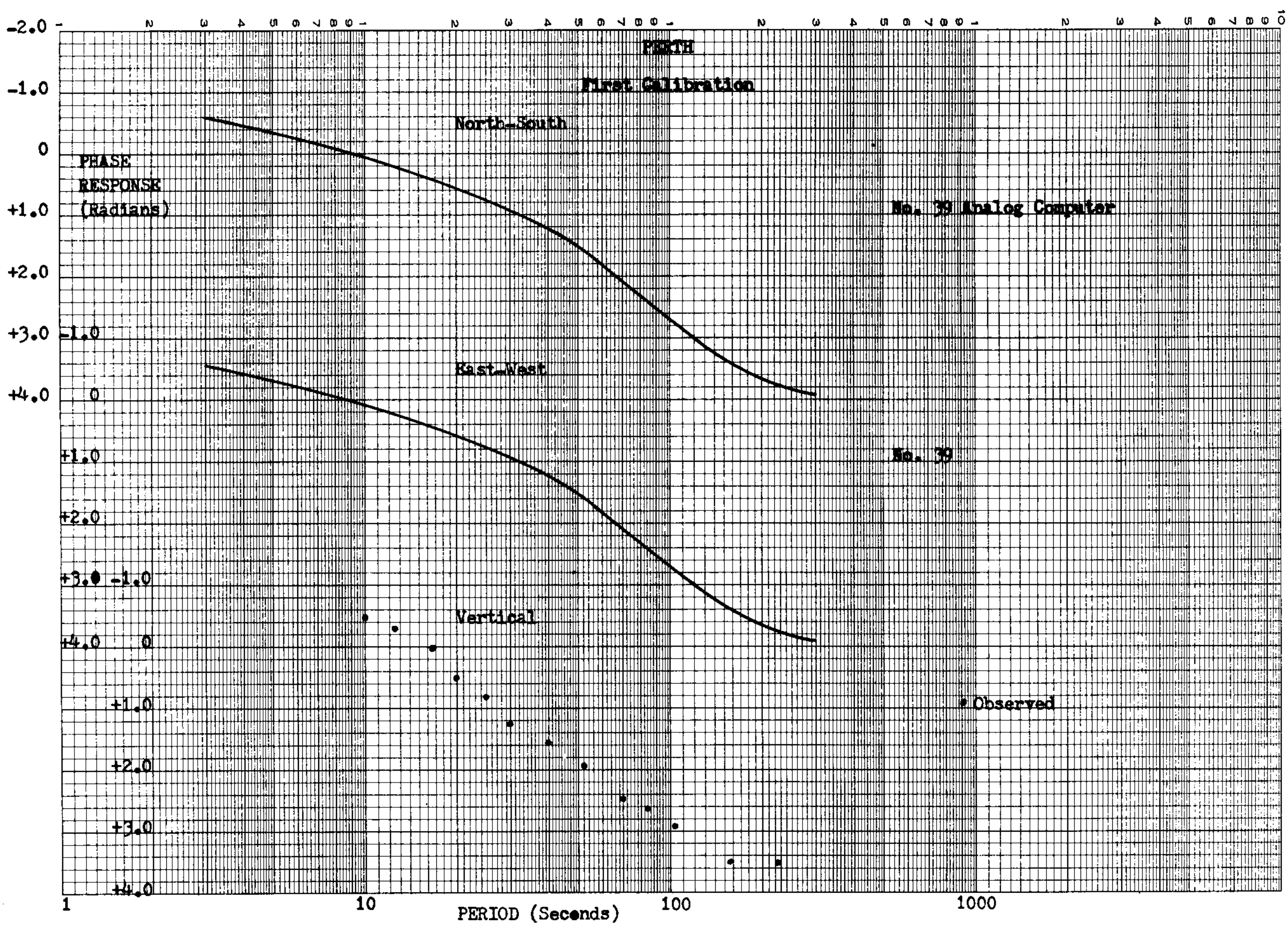


MT. TSUKUBA - Final Calibration


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





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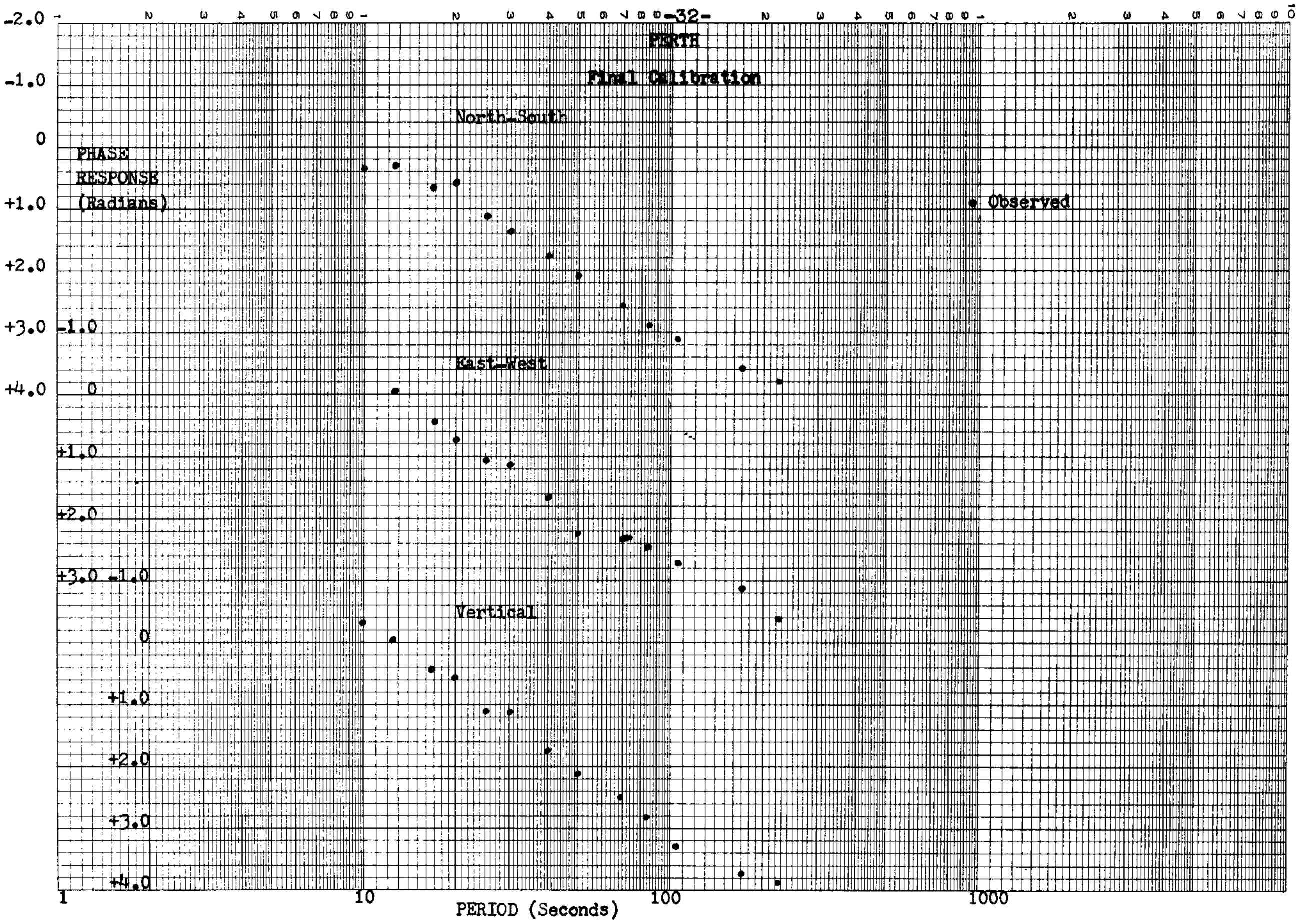

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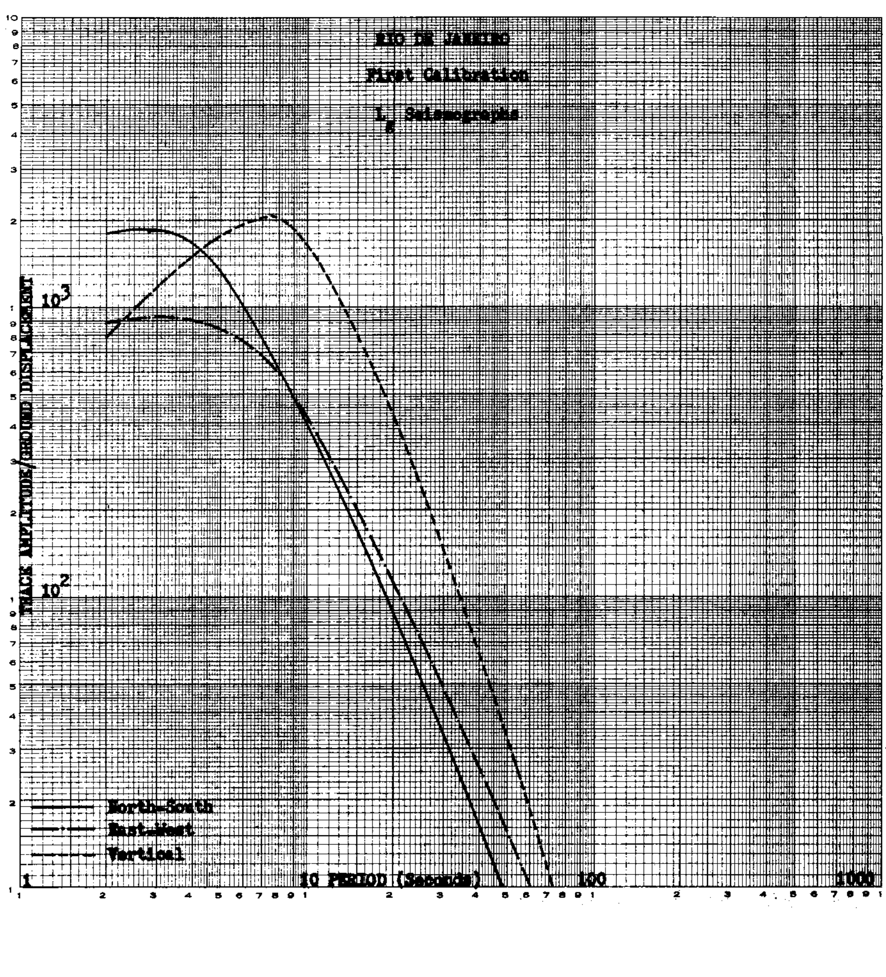
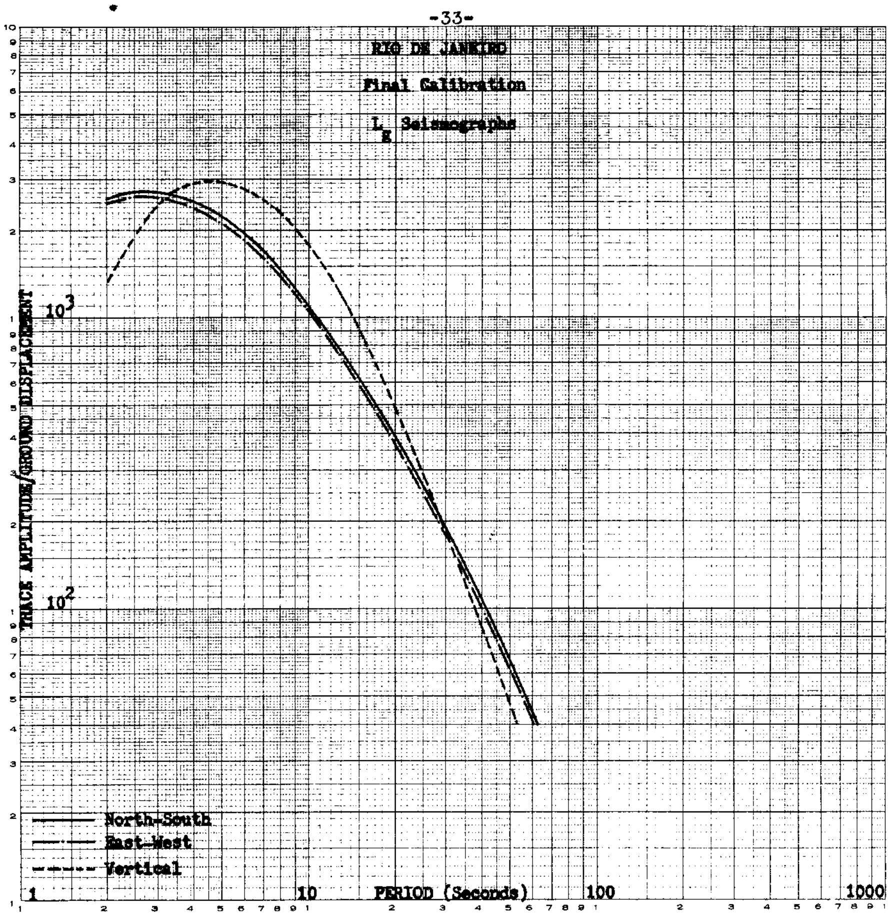
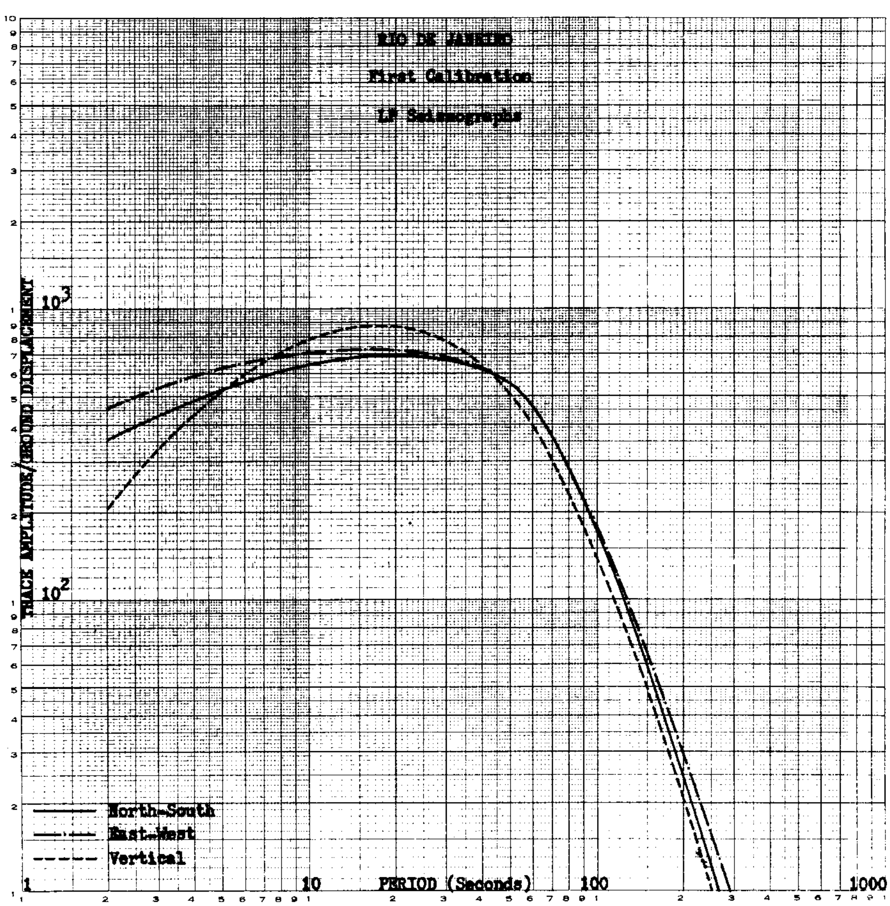



RIO DE JANEIRO
Final Calibration
L_E Seismographs
TRACE AMPLITUDE/GROUND DISPLACEMENT
10^3
10^2
North-South
East-West
Vertical
1
10
PERIOD (Seconds)
100
1000


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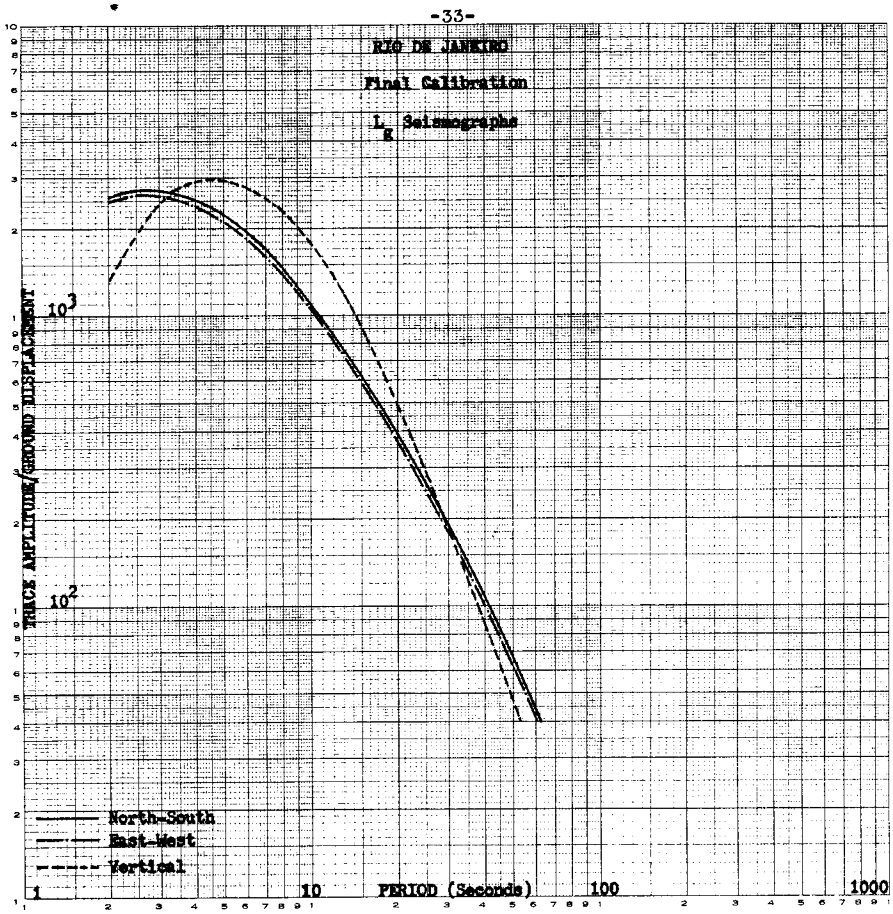
10
PERIOD (Seconds)
100
1000


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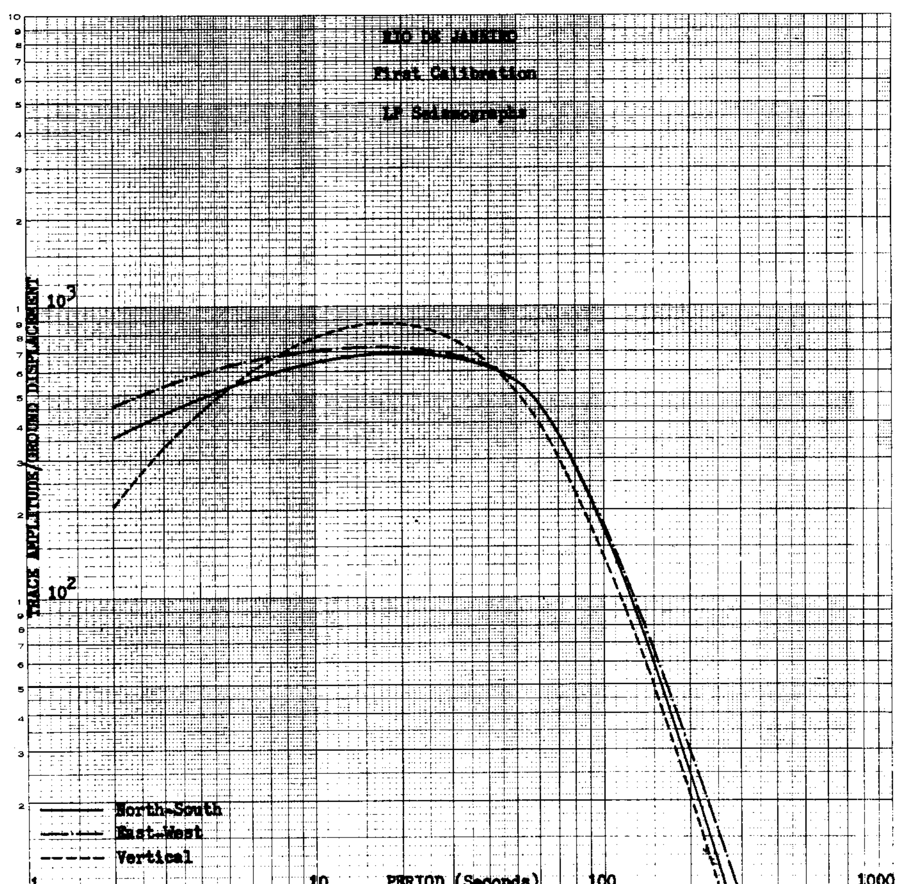
10
PERIOD (Seconds)
100
1000


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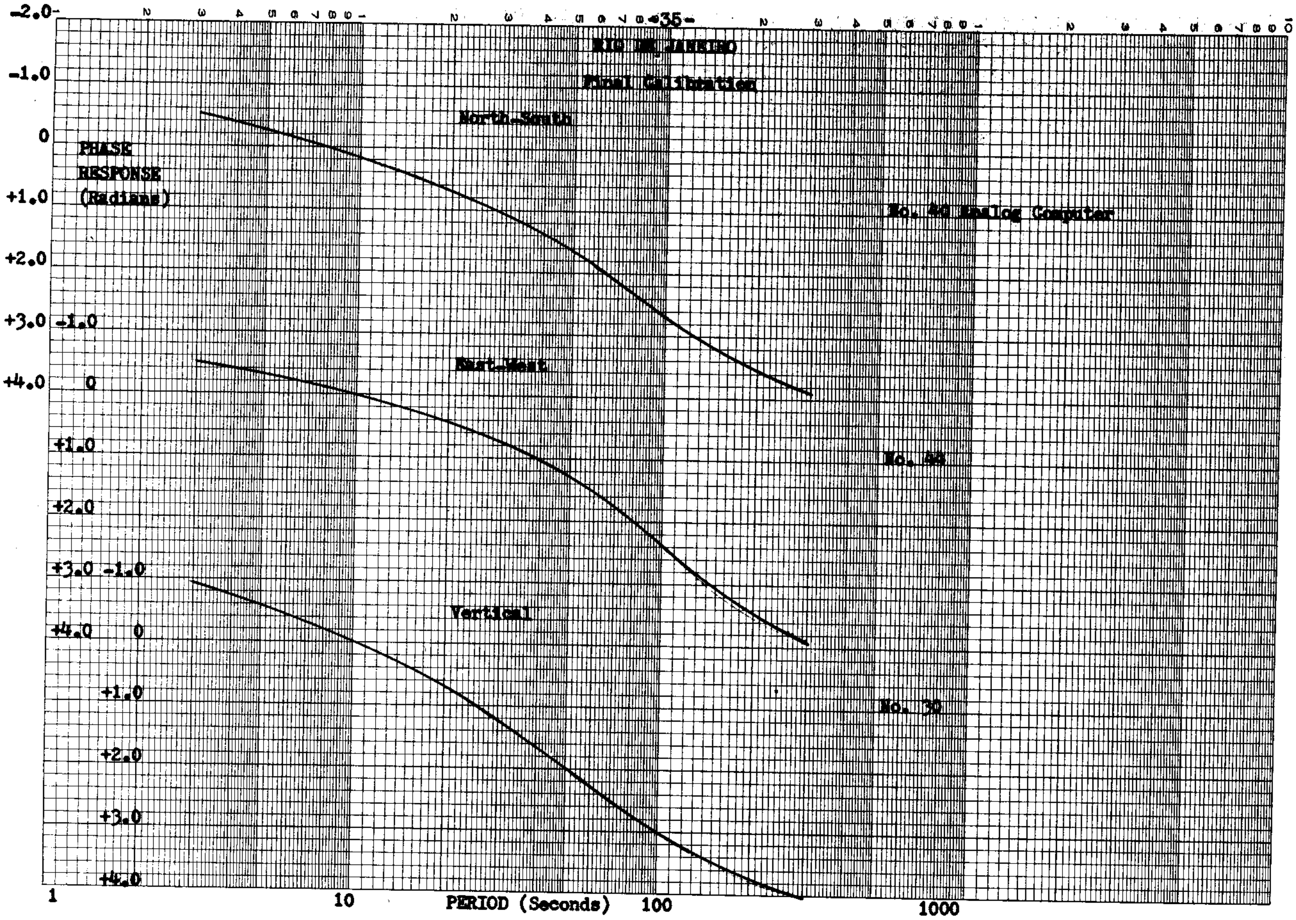
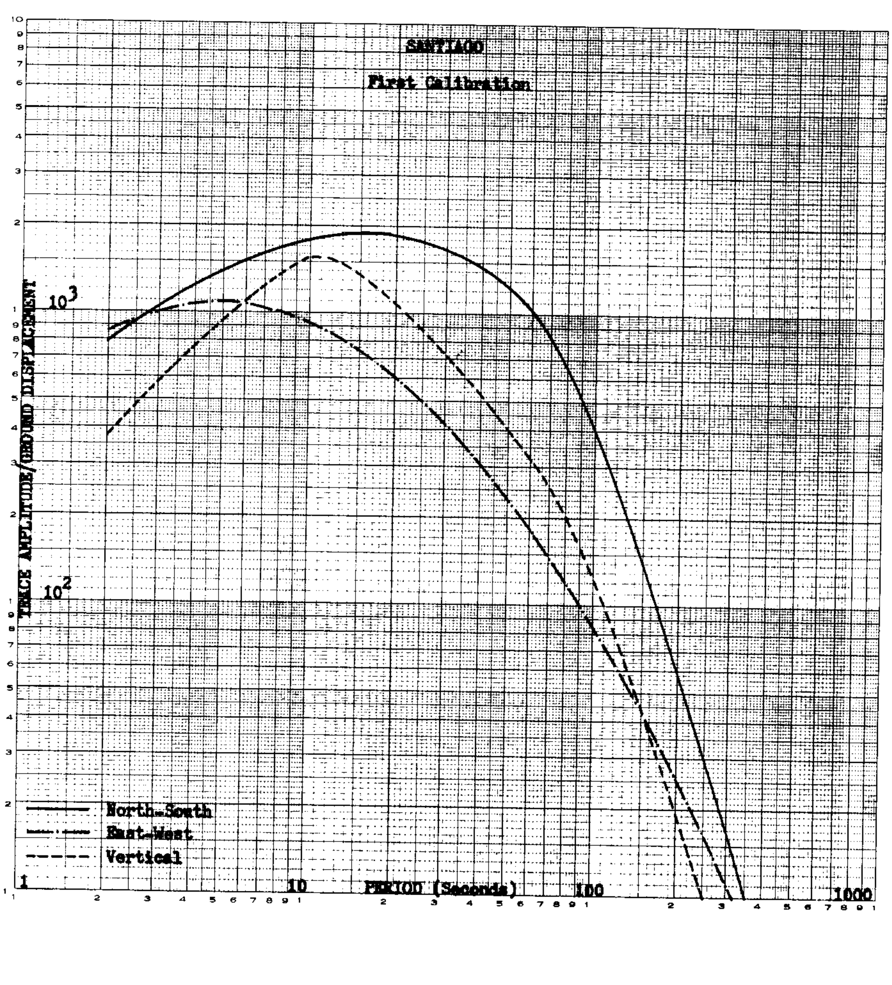
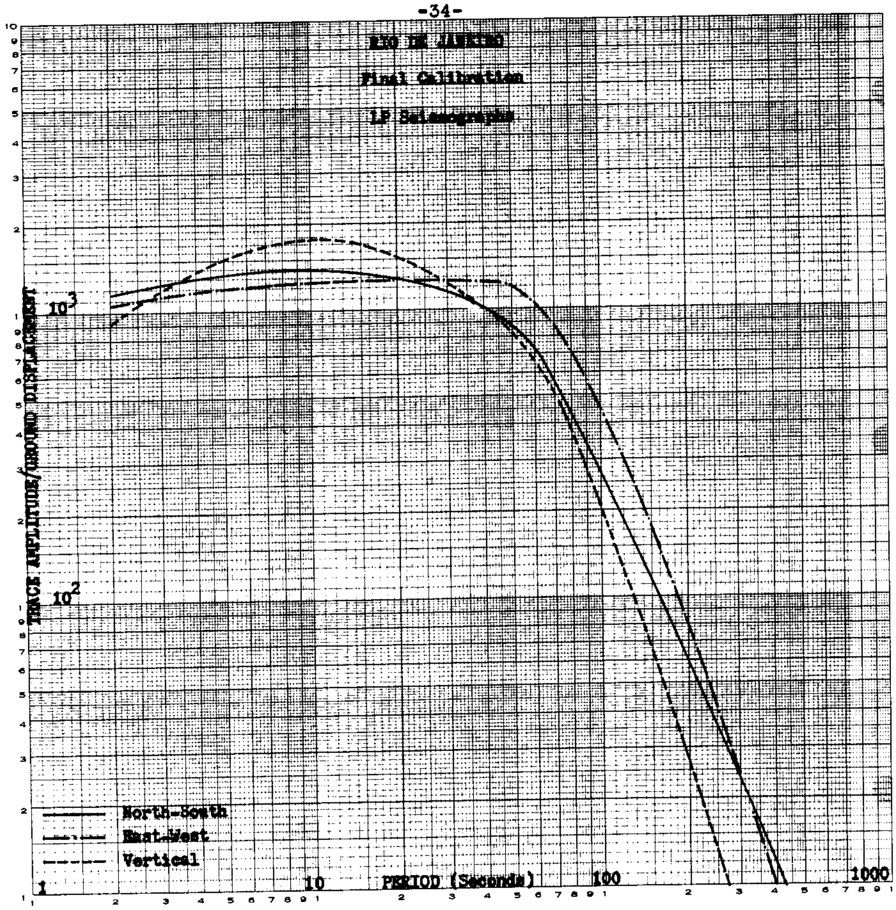
10
PERIOD (Seconds)
100
1000


RIO DE JANEIRO
Final Calibration
North-South
East-West
Vertical
PHASE RESPONSE (Radians)
No. 40 Analog Computer
No. 48
No. 30
PERIOD (Seconds)
1
10
100
1000


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


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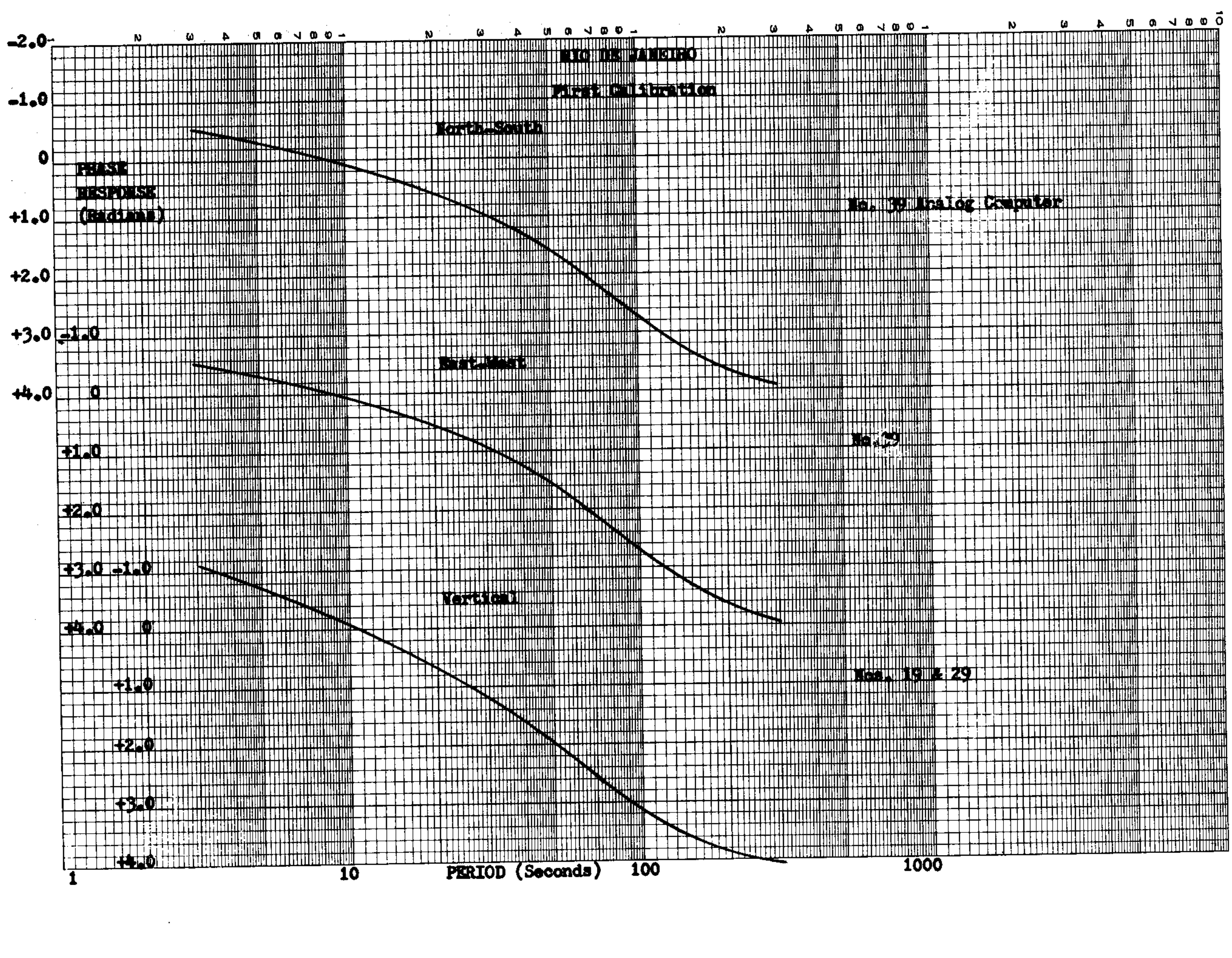
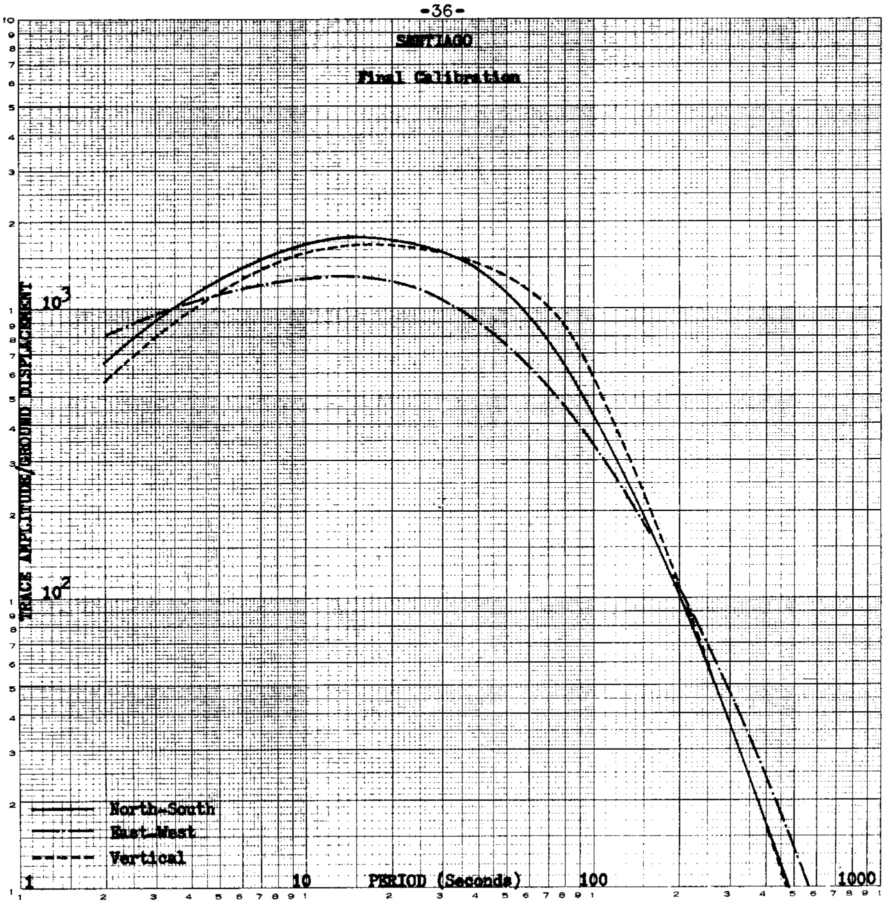
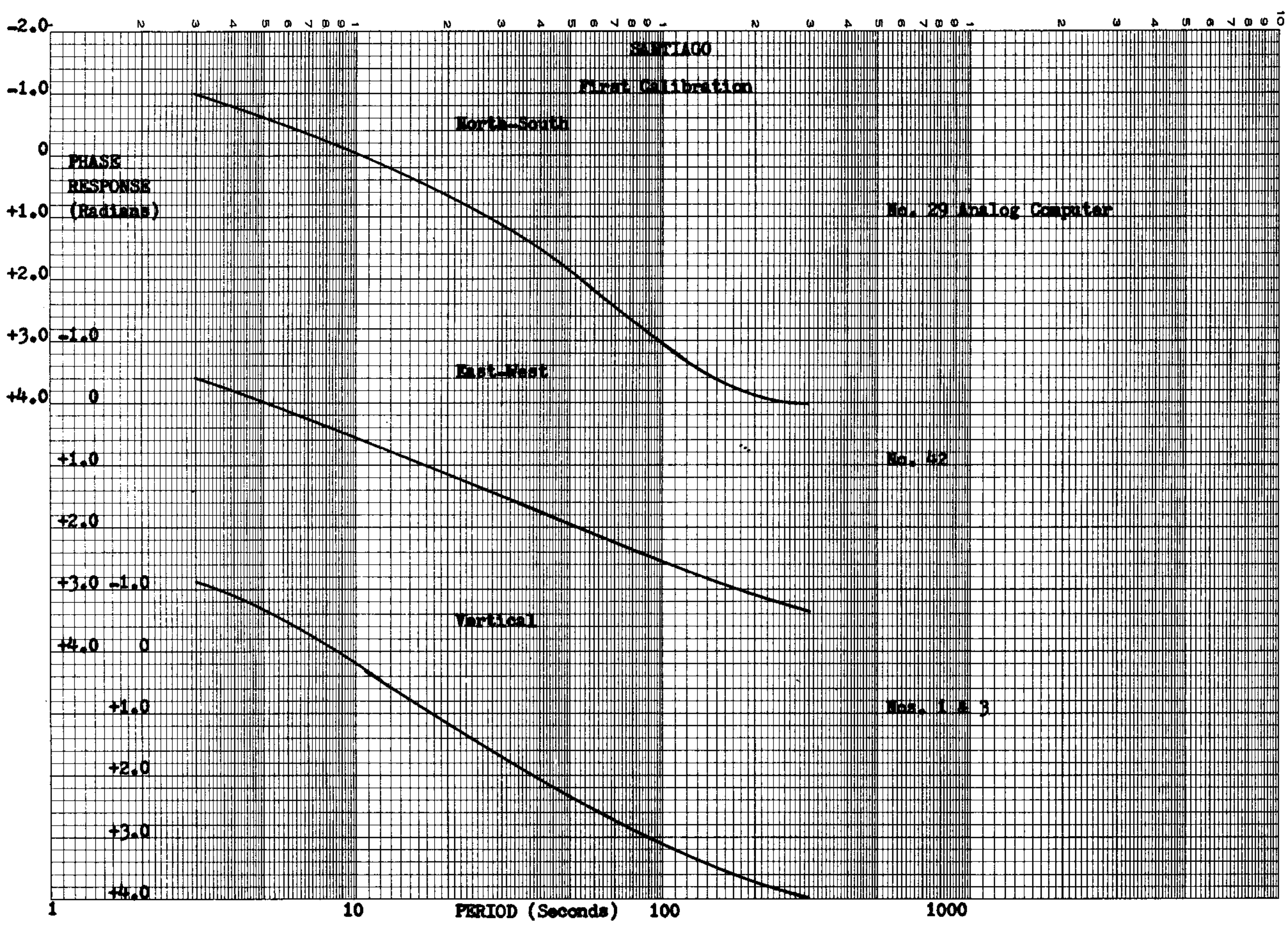
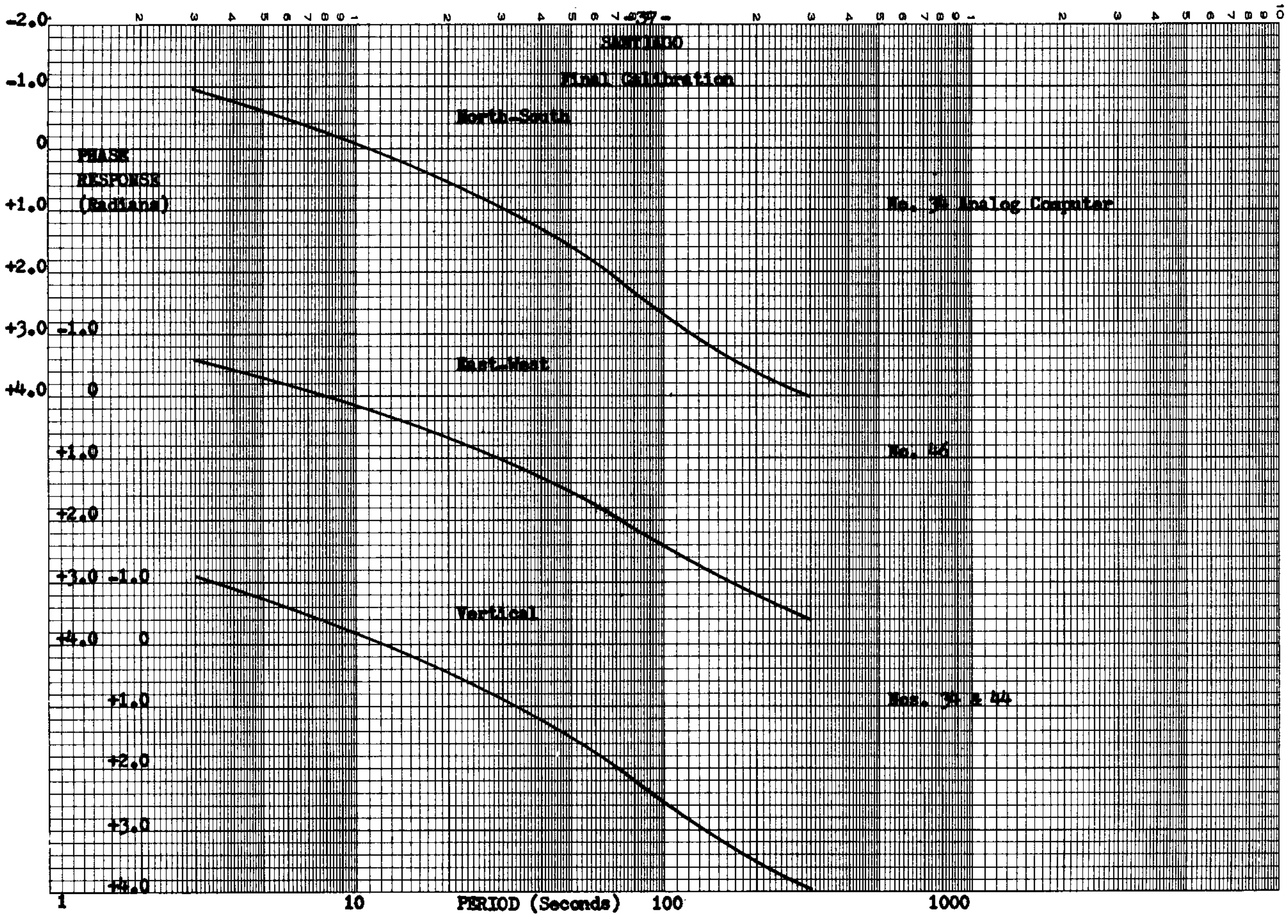
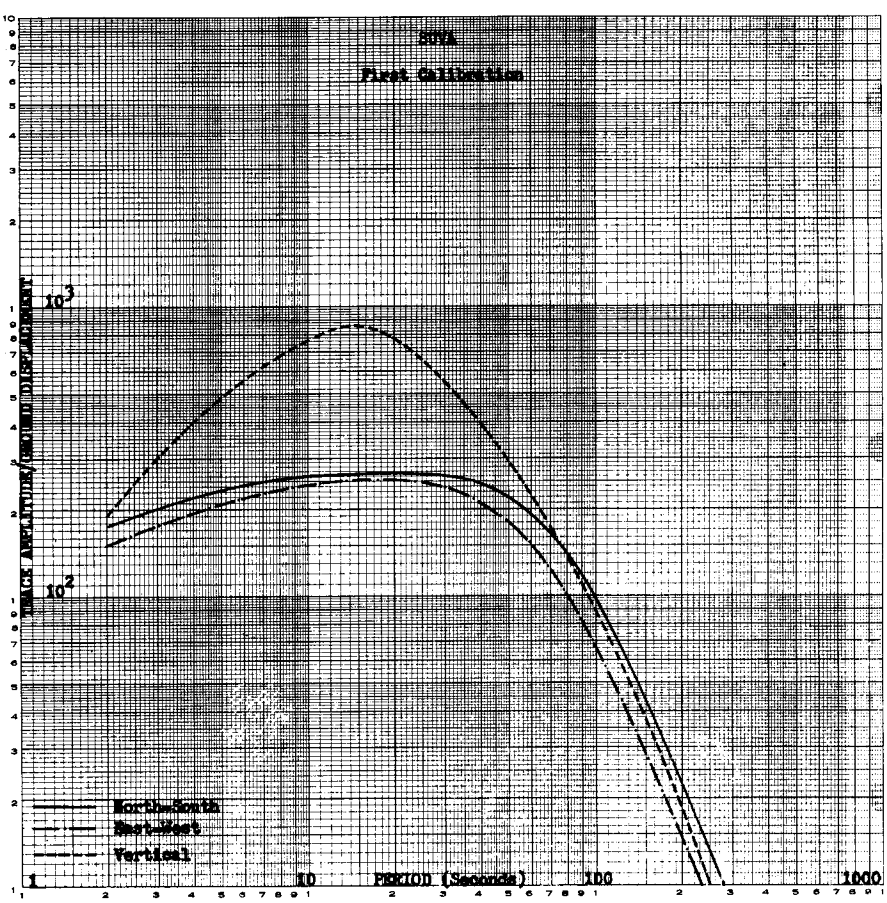
10
PERIOD (Seconds)
100
1000

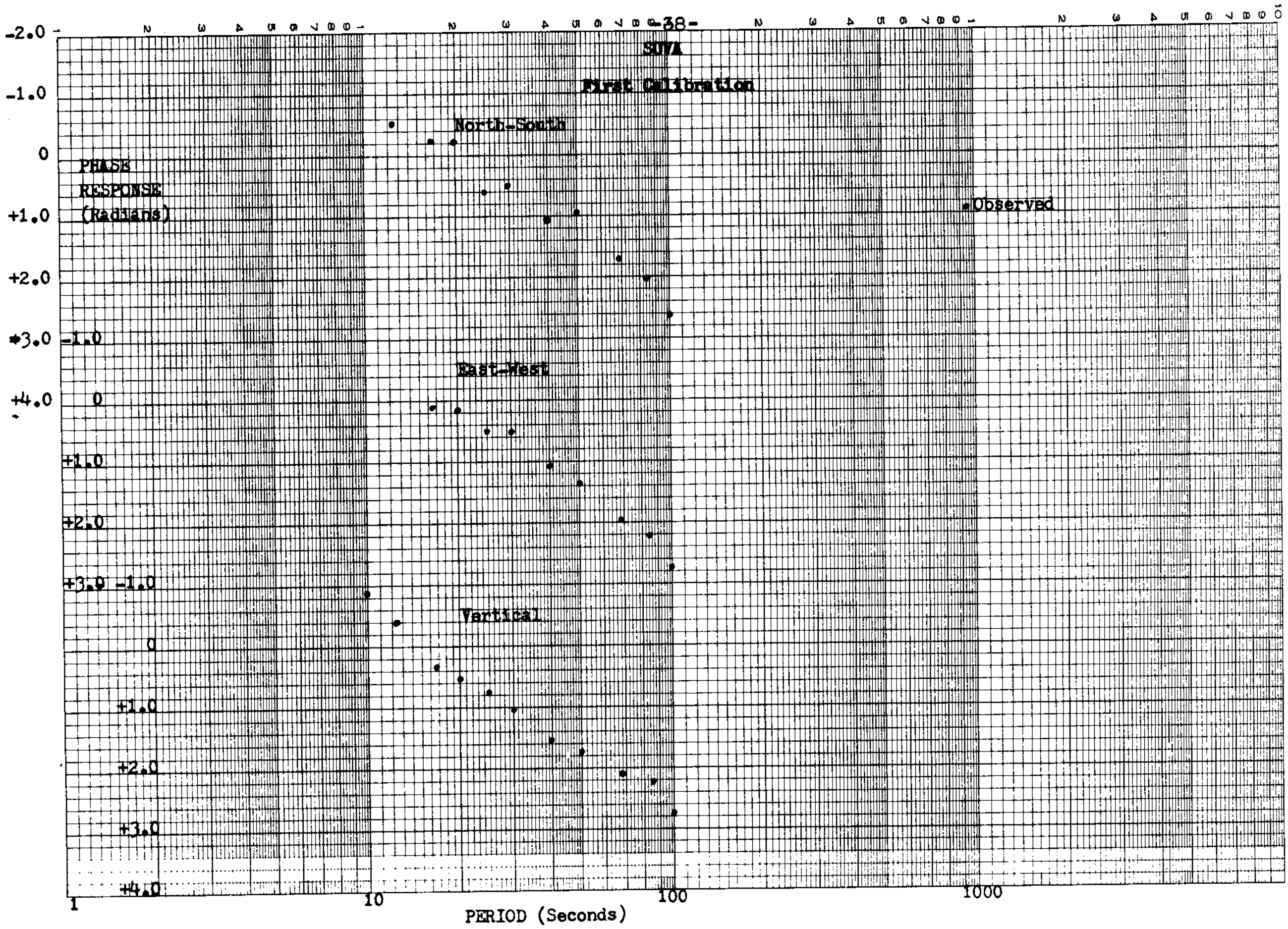

RIO DE JANEIRO
First Calibration
North-South
PHASE RESPONSE (Radians)
No. 39 Analog Computer
East-West
No. 29
Vertical
Nos. 19 & 29
1
10
PERIOD (Seconds)
100
1000


SANTIAGO
Final Calibration
TRACE AMPLITUDE/GROUND DISPLACEMENT
North-South
East-West
Vertical
PERIOD (Seconds)

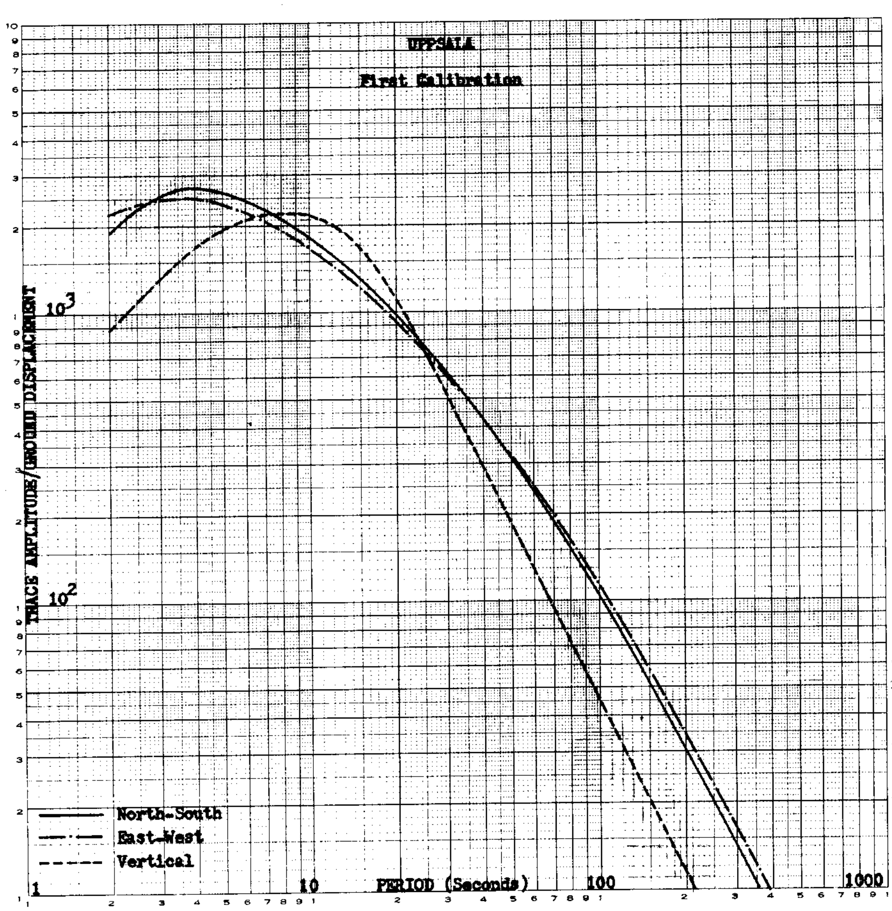

SANTIAGO
First Calibration
North-South
PHASE
RESPONSE
(Radians)
No. 29 Analog Computer
East-West
No. 42
Vertical
Nos. 1 & 3
PERIOD (Seconds)

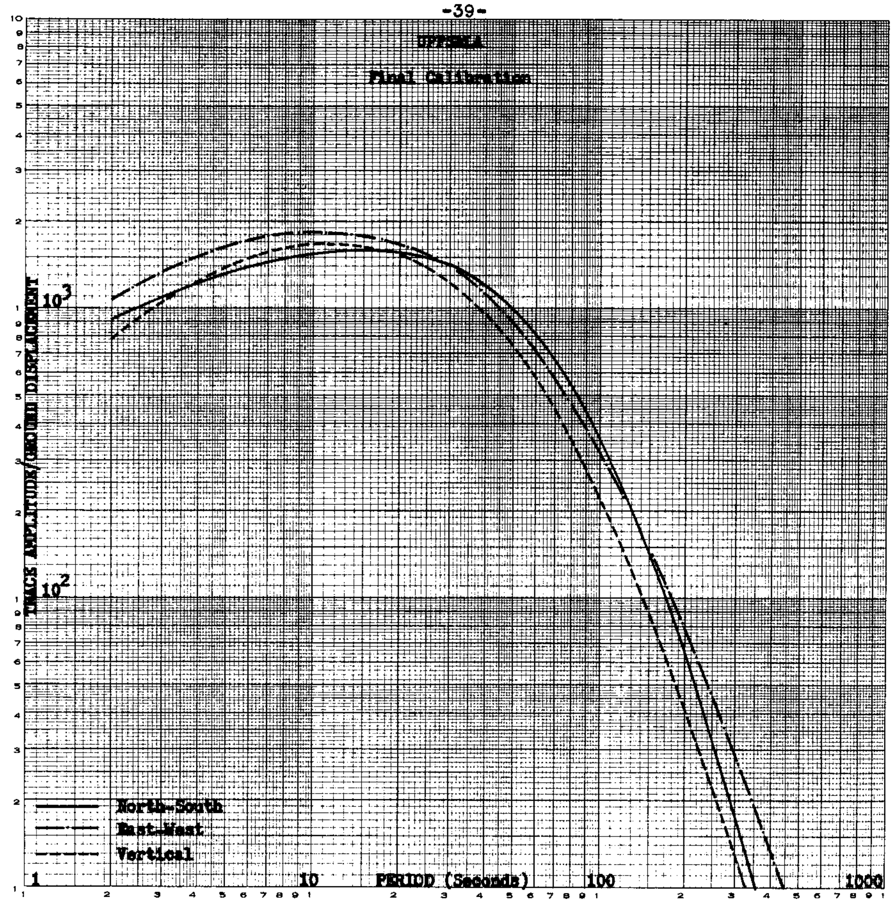

SANTIAGO
Final Calibration
North-South
PHASE
RESPONSE
(Radians)
No. 34 Analog Computer
East-West
No. 46
Vertical
Nos. 34 & 44
-2.0
-1.0
0
+1.0
+2.0
+3.0
+4.0
PERIOD (Seconds)
1
10
100
1000

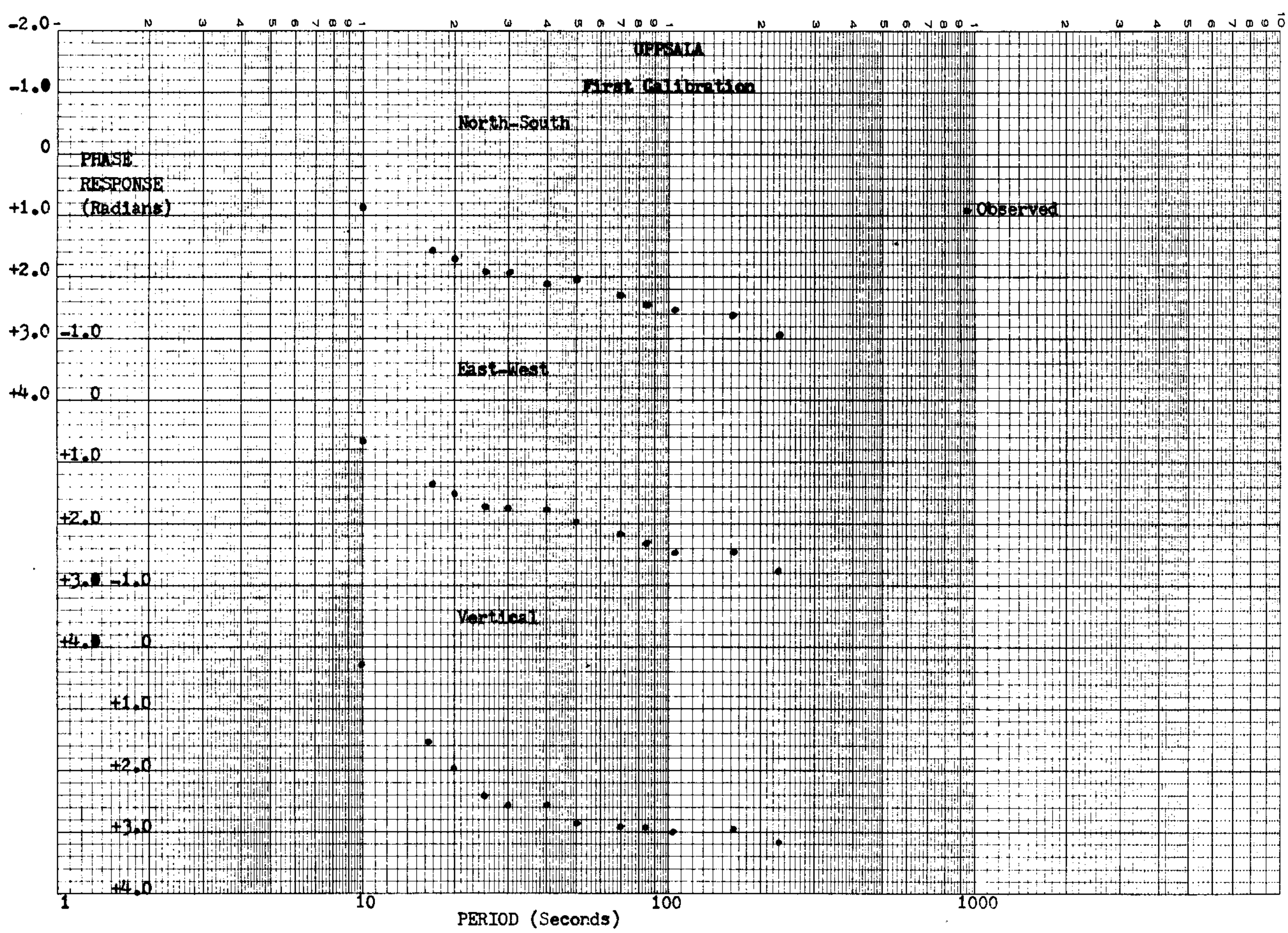

SUVA
First Calibration
TRACE AMPLITUDE/GROUND DISPLACEMENT
10^3
10^2
North-South
East-West
Vertical
PERIOD (Seconds)
1
10
100
1000



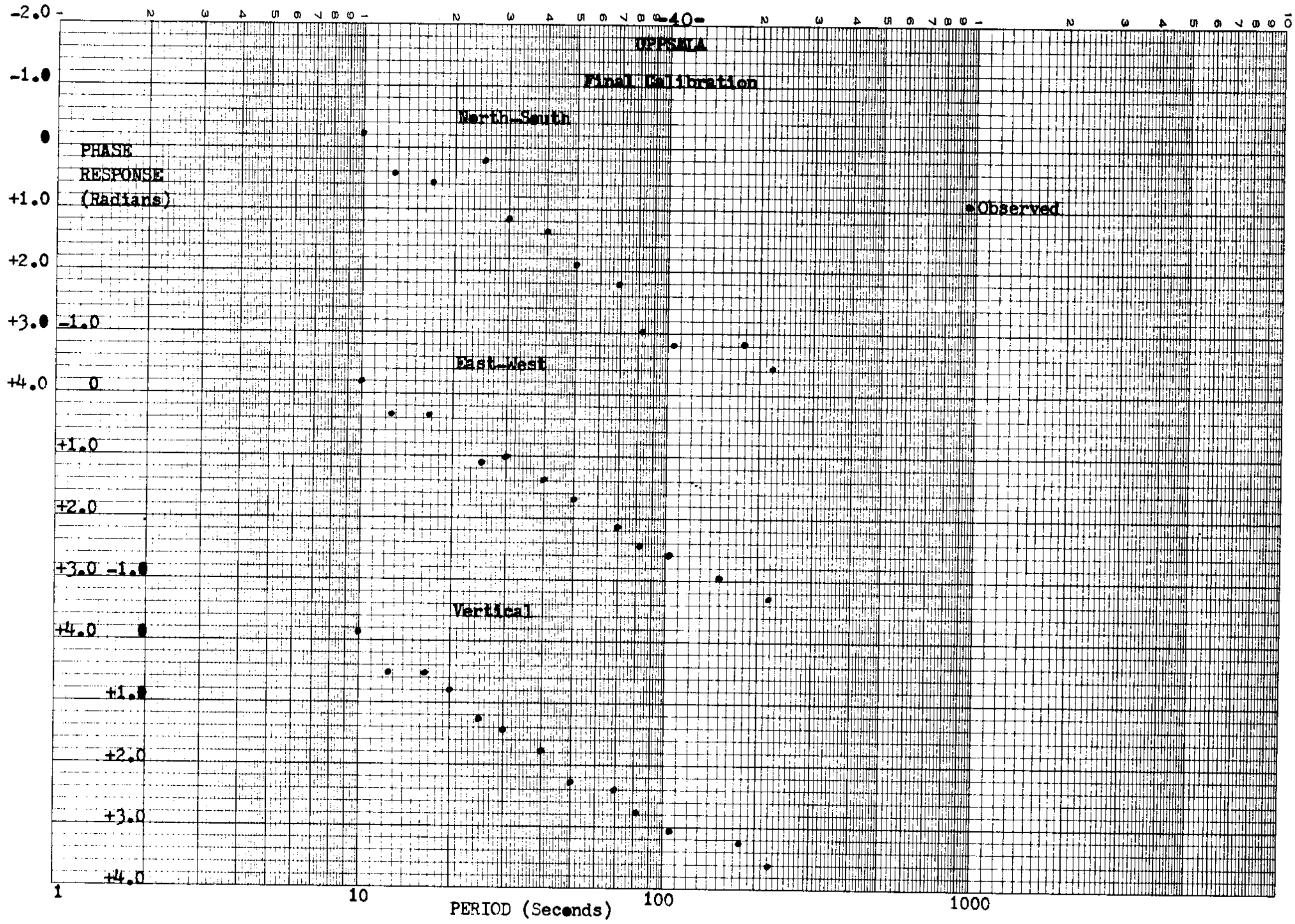
SUVA - Calibration



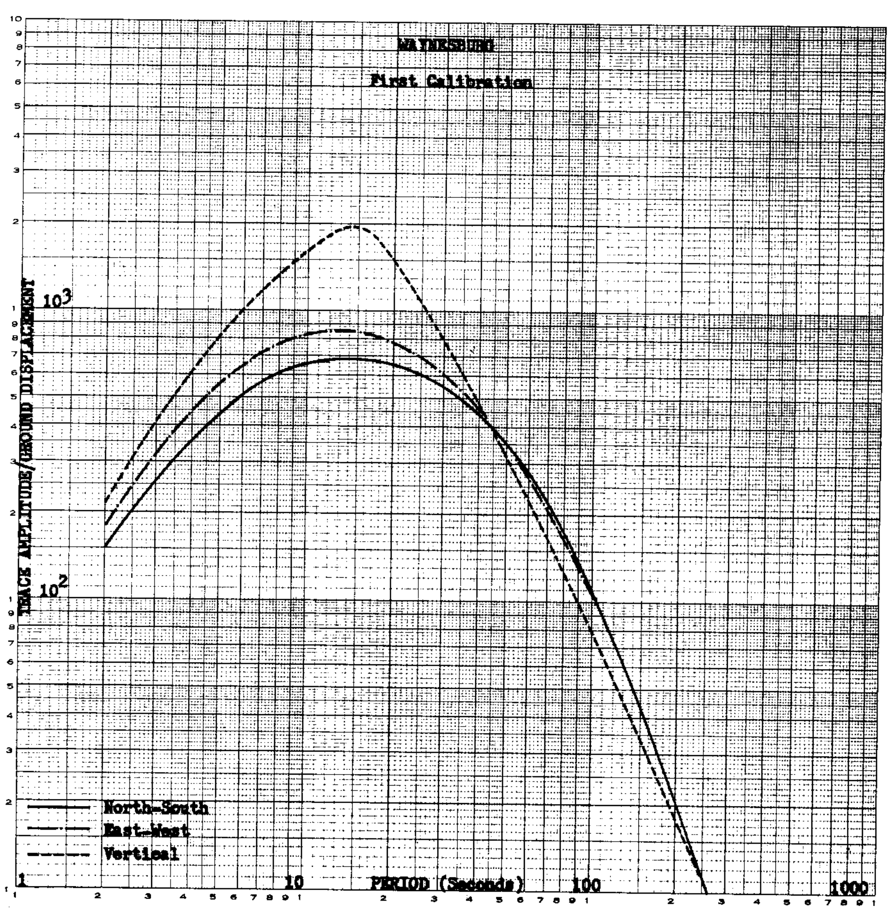


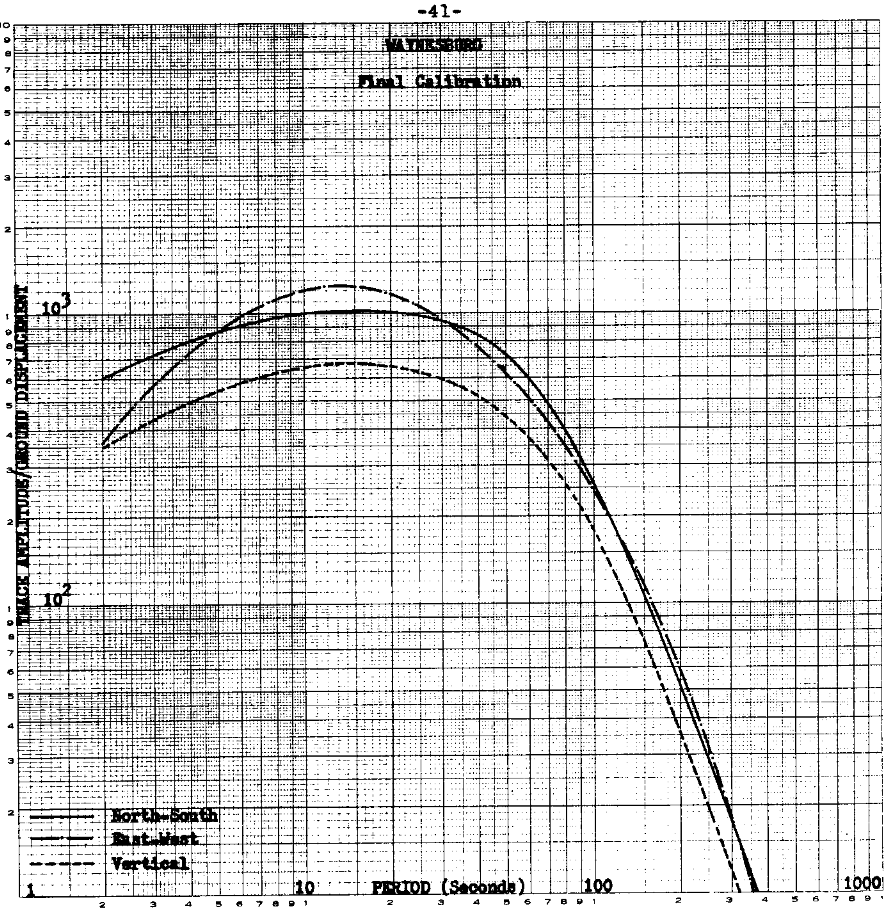


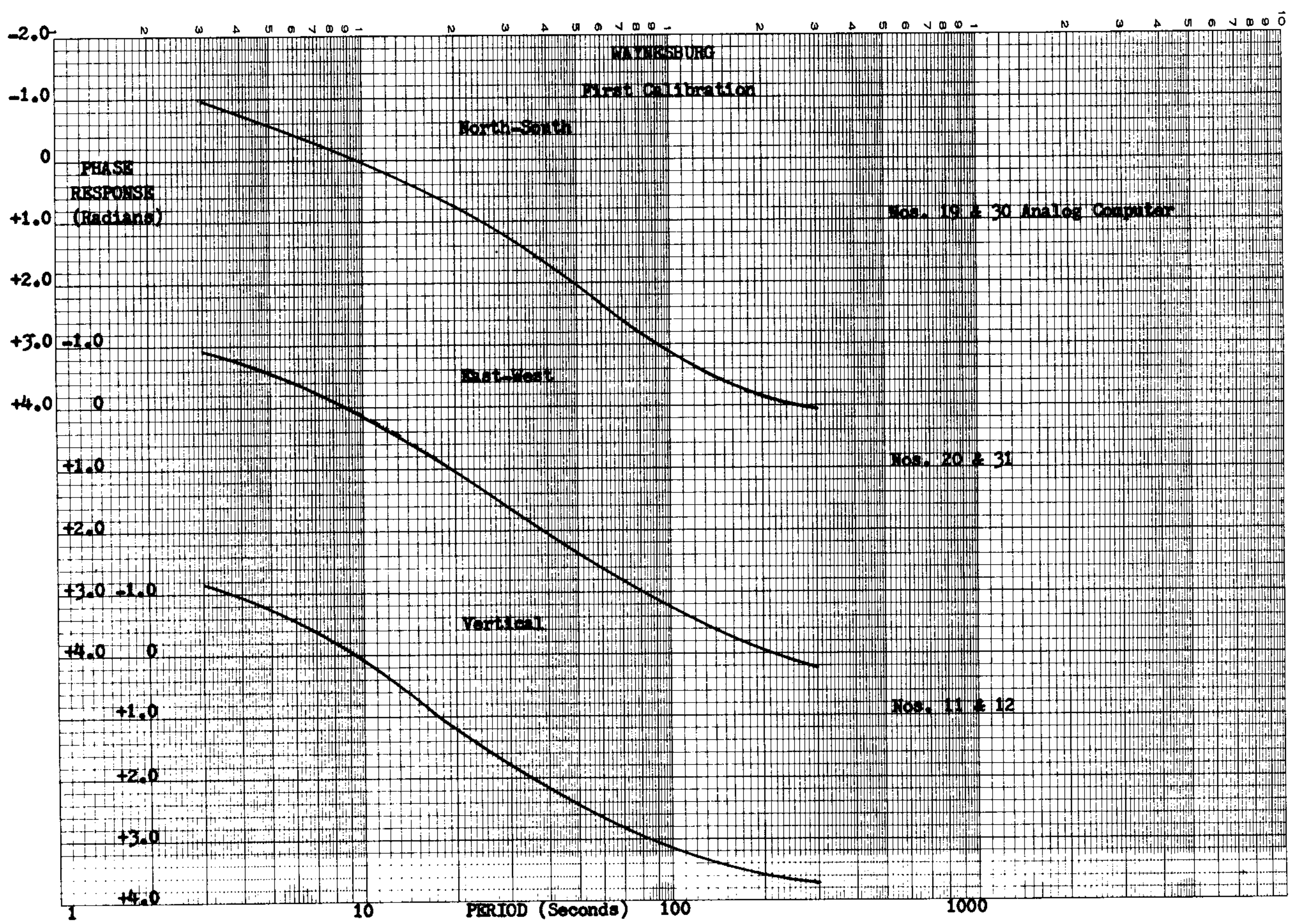
UPPSALA - First Calibration

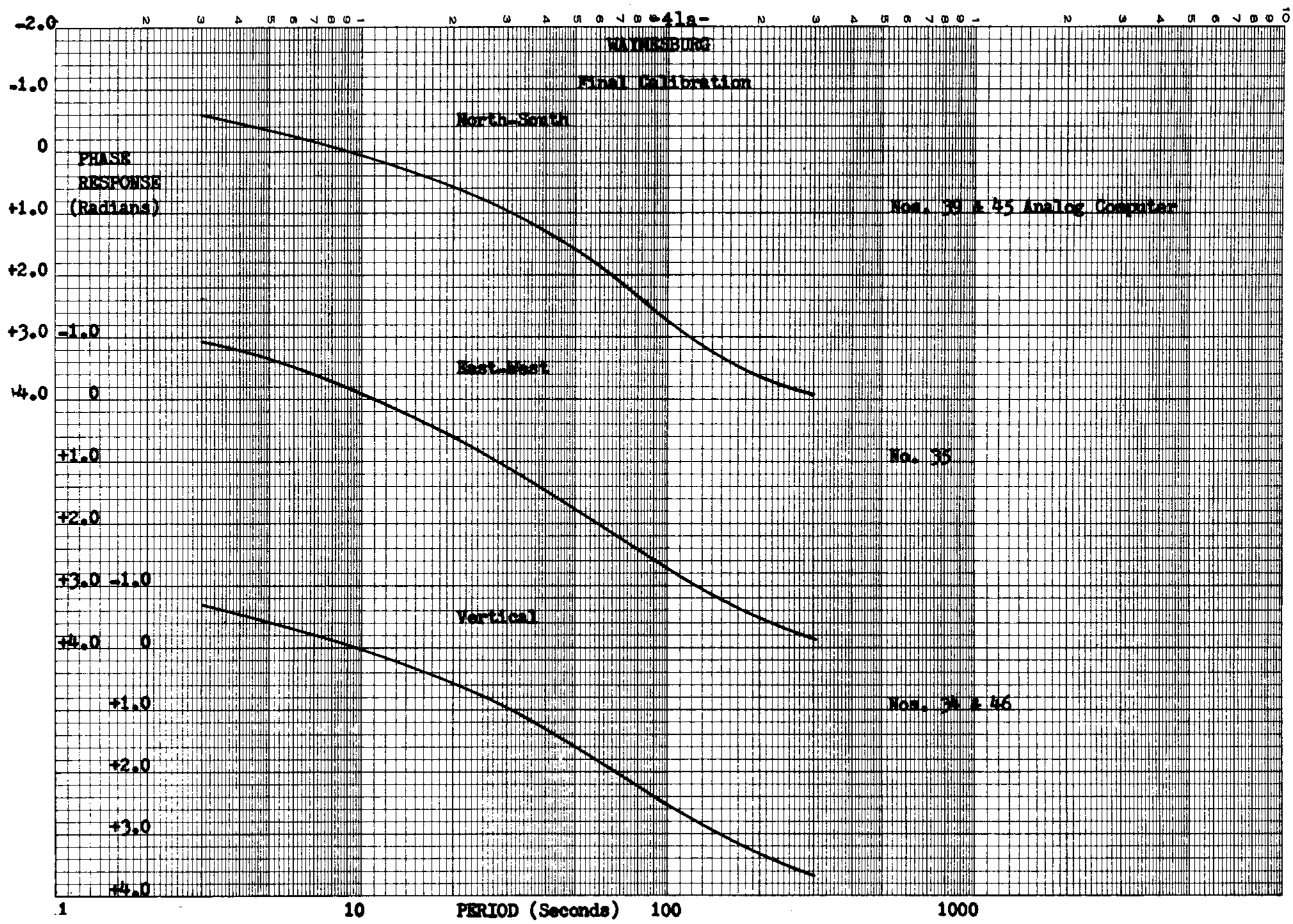


UPPSALA - Final Calibration




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


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


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

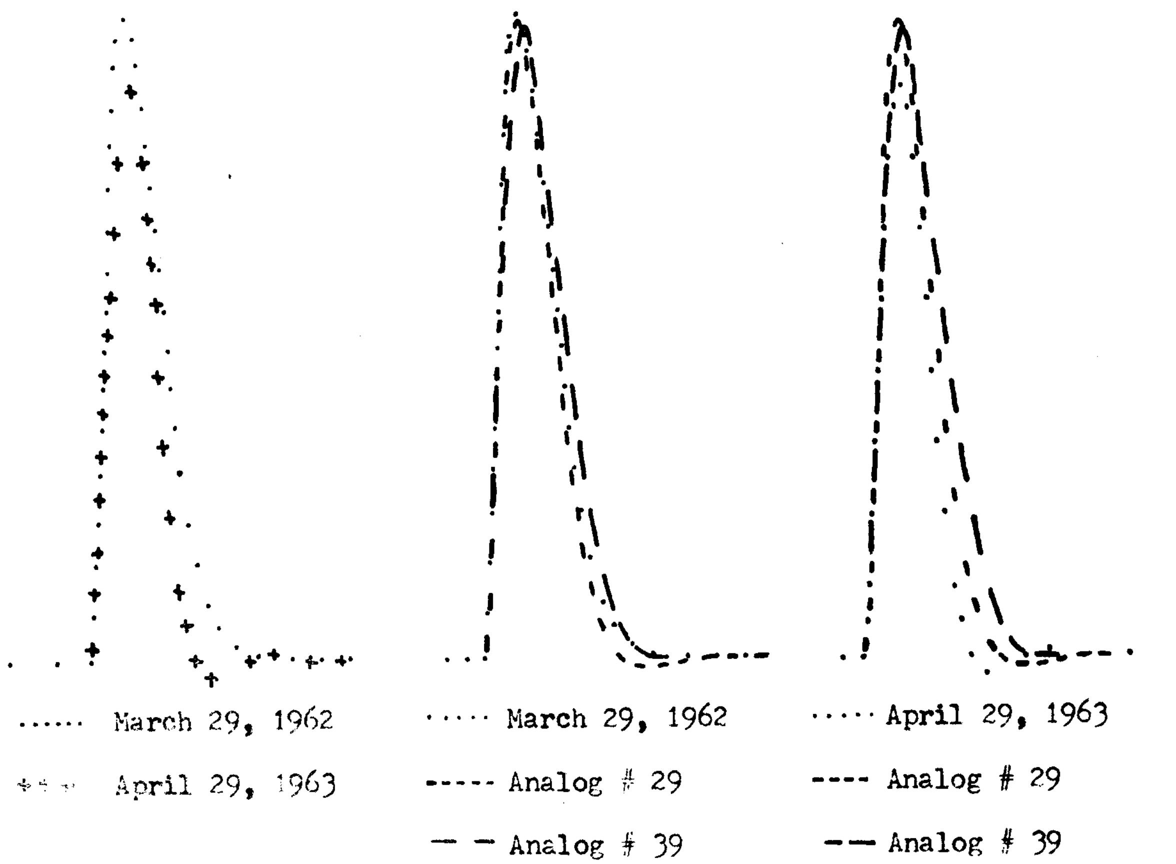


Figure 7. Comparison of pulses for the Uppsala north-south component.
a) A comparison between pulses of March 29, 1962 and April 29, 1963.
b) A comparison between pulse of March 29, 1962 and analog pulses #29 and #39.
c) A comparison between pulse of April 29, 1963 and analog pulses #29 and #39.

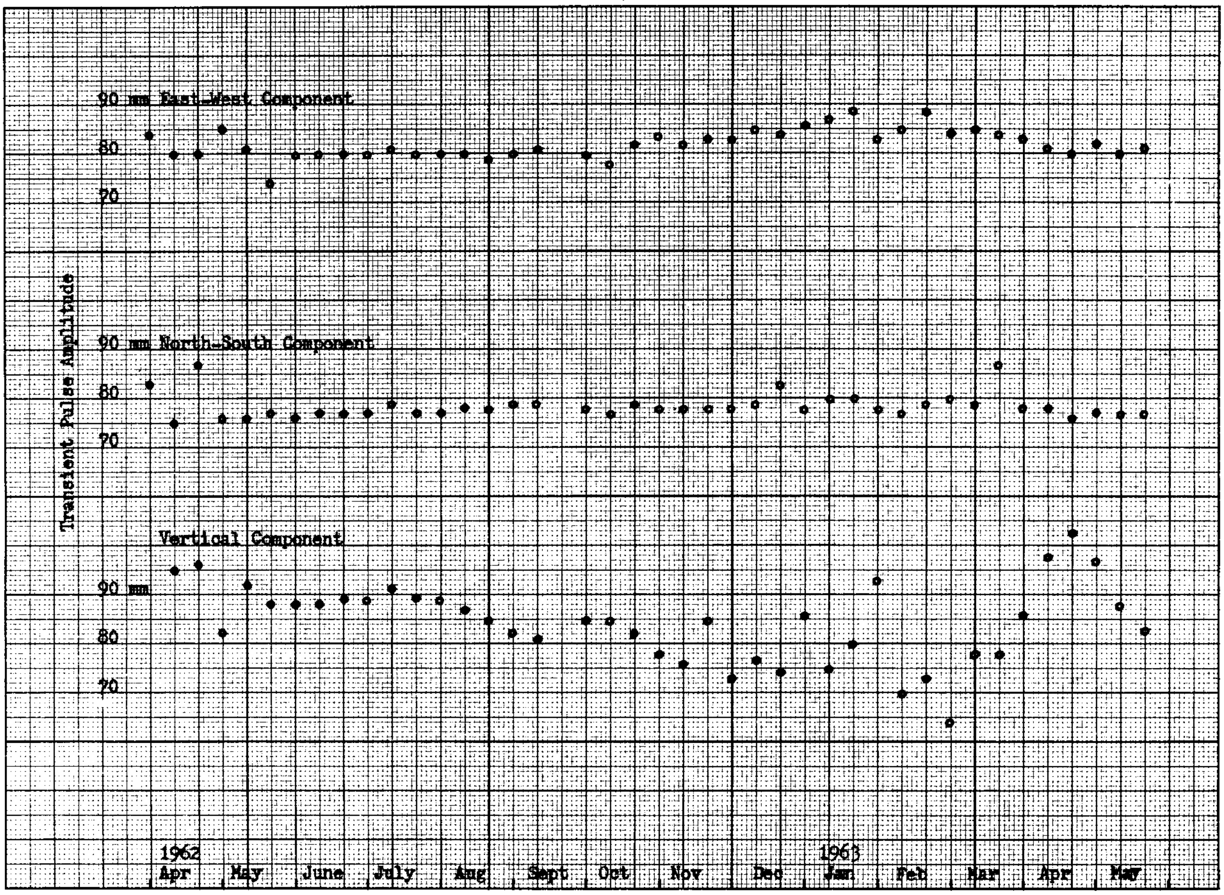


Figure 6. Variation of amplitudes of transient pulses for the Uppsala seismographs from April 1, 1962 to May 21,1963. Pulse dates are 1, 11, 21 of each month.

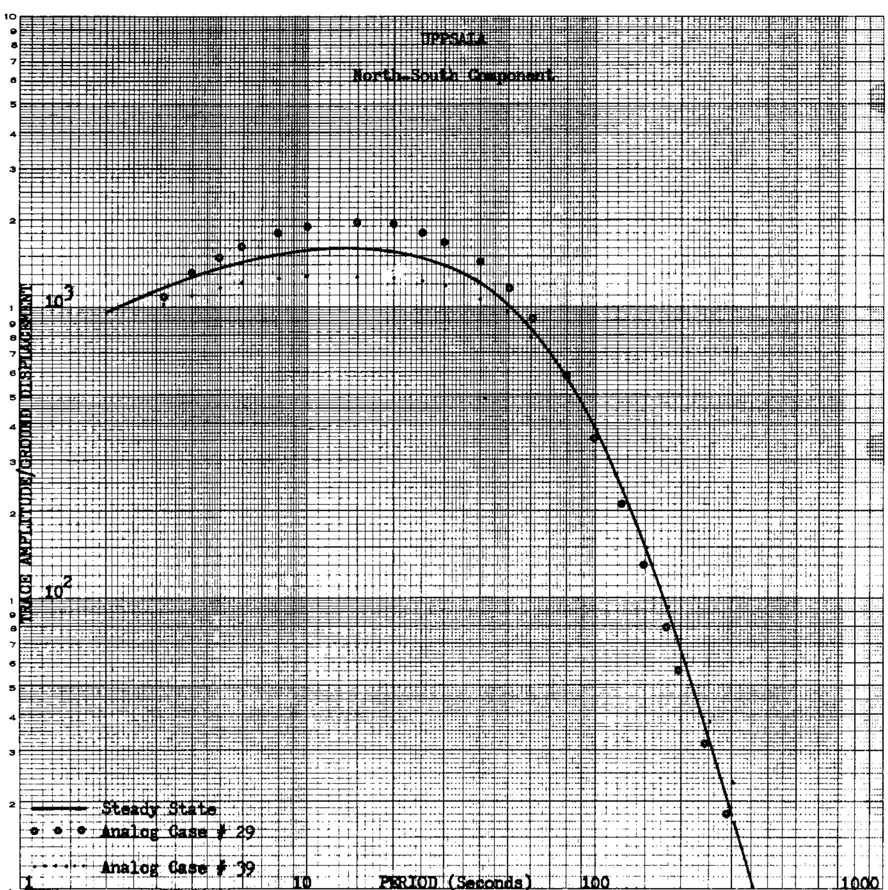


Figure 8. The north-south displacement response curve of March 29, 1962 observed by the steady-state method, is matched with displacement curves of analog cases #29 and #39. The transient pulses of these cases closely match the transient pulse of April 30, 1963.

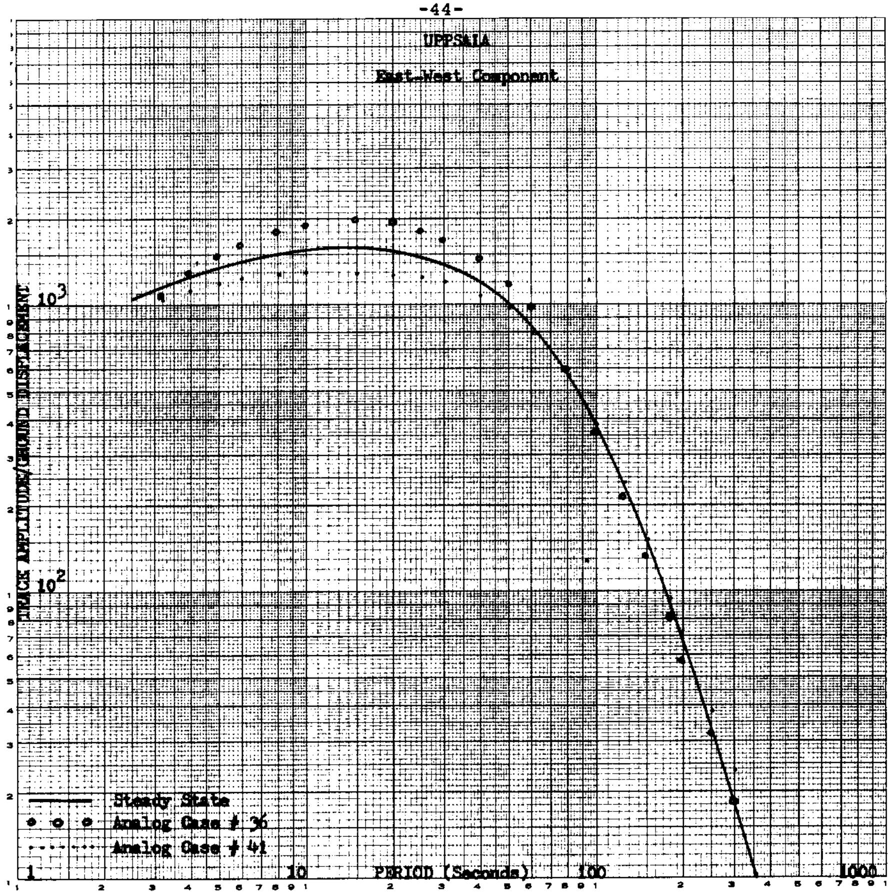


Figure 10. The east-west displacement response curve of March 29, 1962, observed by the steady-state method, is matched with displacement curves of analog cases #36 and #41. The transient pulses of these cases closely match the transient pulse of March 31, 1963.

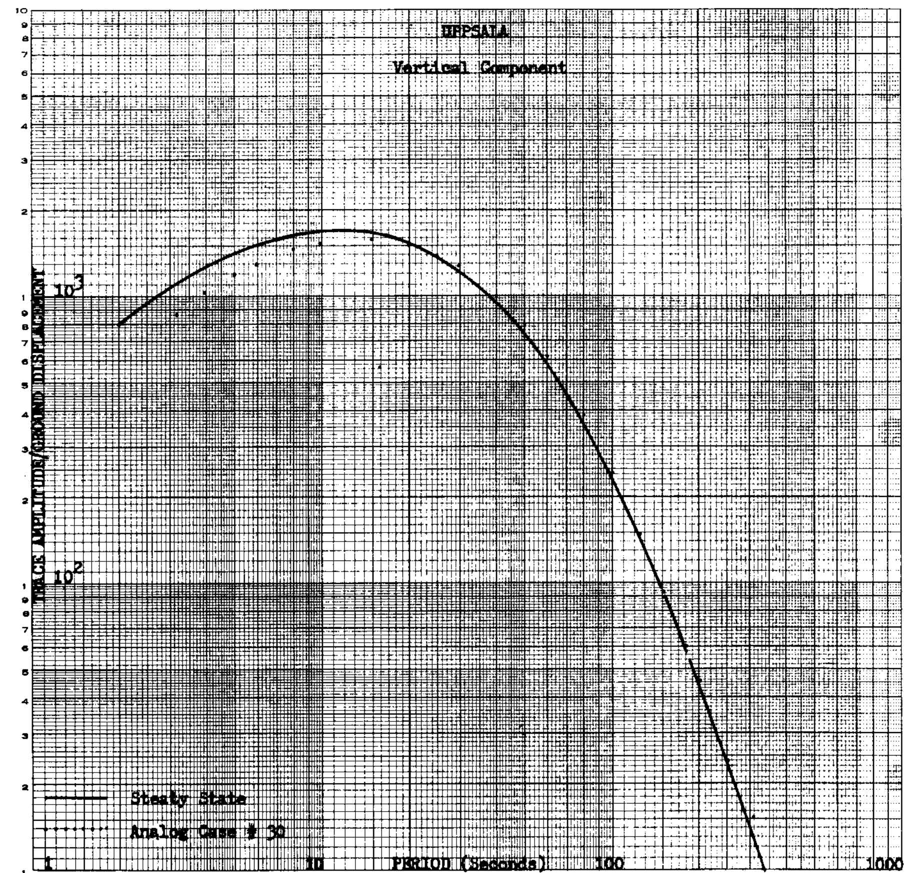


Figure 11. The vertical displacement response curve of March 29, 1962, observed by the steady-state method, is matched with displacement curve of analog case #30. The transient pulse of this case closely matches the transient pulse of April 29, 1963.

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.

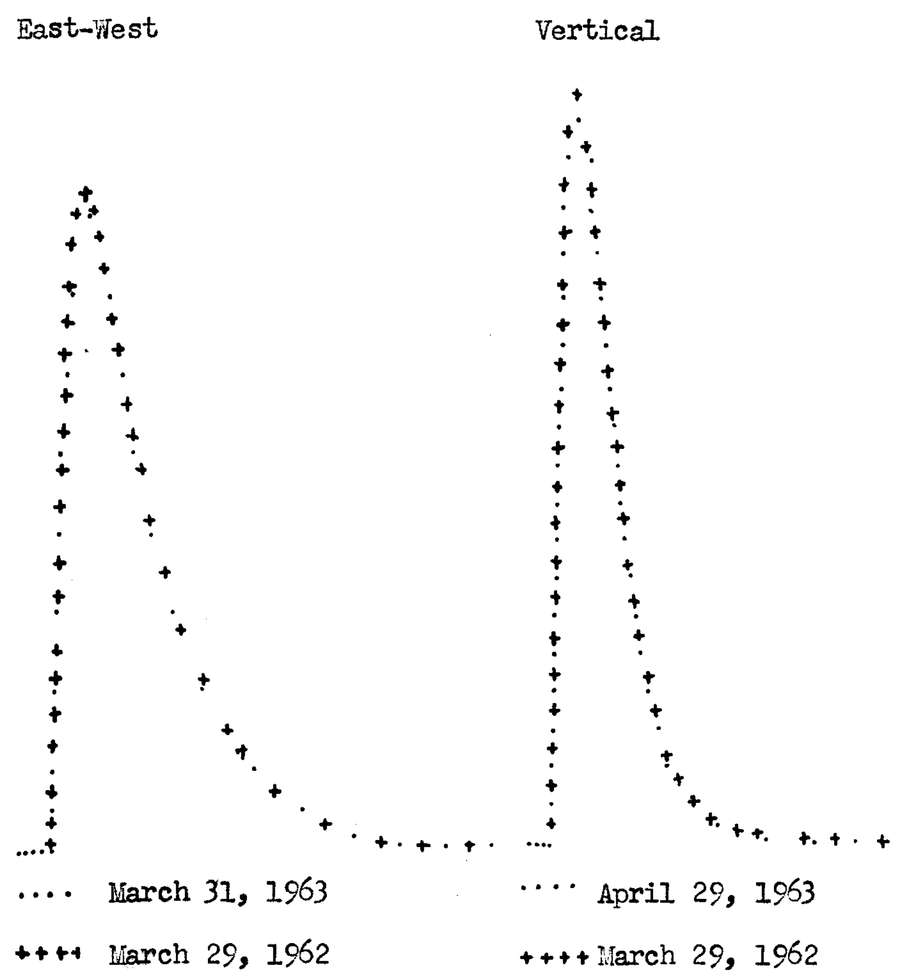


Figure 9. Transient pulses of March 29, 1962 for the East-West and Vertical components are matched against pulses made a year later on the Uppsala seismographs.

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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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.

<u>Calibration by the transient method</u>.

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).

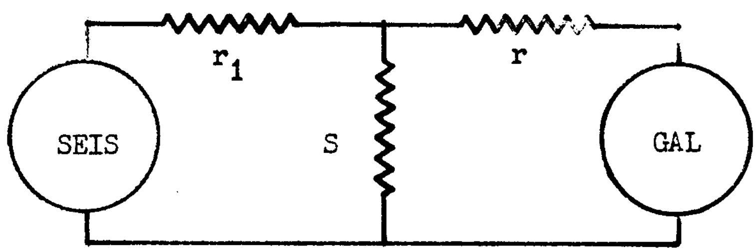

Figure 12. Coupling resistors as found on some instruments.

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 r	Prior S	Post r	Post 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 (r_1 = 330)	220	330	470
	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

Multiply scale by ... for

standard I G Y Instruments

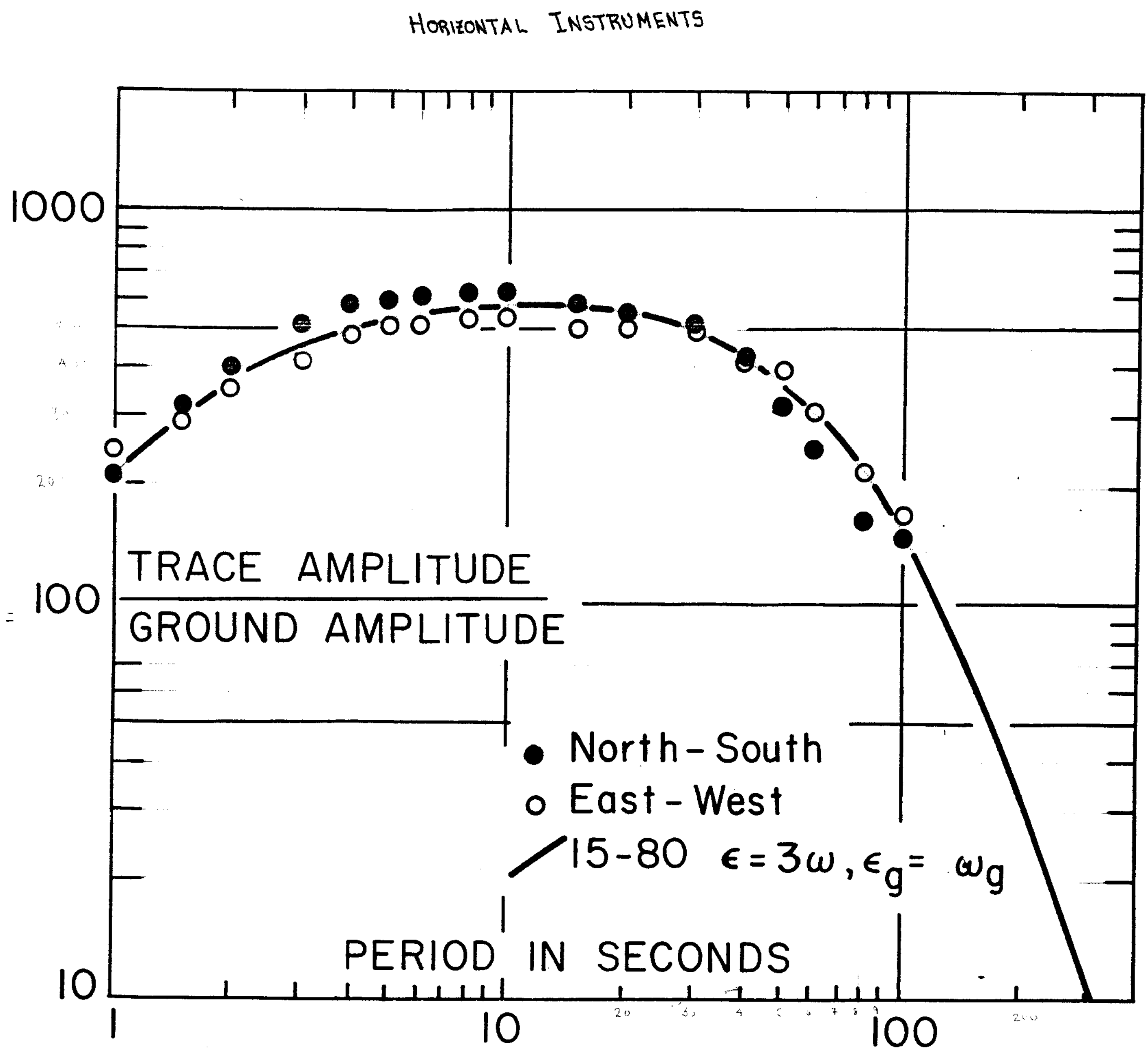

Fig. 3 of :

Sutton, G. and Oliver, J., 1959, Seismographs of high magnification at long periods, Annales de Geophysique, 15, 423-433.

Theoretical and experimental calibration for 15-80 horizontal component seismographs at Resolute Bay.