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,

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

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.

<u>Analog computer curves.</u> 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