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Calculation of the Frequency Response of the USGS Telemetered Short-Period Seismic System

by

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1. Introduction

At the present time the USGS seismic telemetry network in central California consists of more than 250 short-period seismic stations. Instrumentation for the network has been developed and modified since installation of the first telemetry stations in late 1966. In the last several years the main amplitude response characteristics of the instrumentation for these stations have undergone relatively few changes. Changes do continue, however, and the exact components used may never be completely uniform. Several reports exist that describe various methods to calculate the amplitude response either of the complete short-period telemetry system, from seismometer to recording medium, or of individual components of the system (Eaton, 1975, 1977; Dratler, 1980; Bakun and Dratler, 1976; Healy and O'Neill, 1977). With the exception of Eaton, (1975, 1977), each author works with only a specific configuration of the short-period system, and the results are not simply and directly applicable to the various configurations (and output media) that currently are in use.

The purpose of this report is to describe and illustrate a fairly simple and direct method of calculating the amplitude response for the various components that make up a short-period seismic telemetry system. The method is described in Healy and O'Neill (1977). In this report we seek to clarify some aspects of their presentation, to introduce a simple computer program for routine calculation of amplitude-response curves, and to show how the effects of additional system components may be included.

The report by Dratler (1980) is the open-file version of an unpublished report that he completed in 1975 before he left the U.S. Geological Survey. The 1980 version was revised by Jay Dratler with help from Mary O'Neill, Sam Stewart, and Bill Daul. These revisions did not change any conclusions from the 1975 report. Herein we refer only to Dratler (1980), though it is the 1975 version that we used in preparing this report. This should explain an apparent inconsistency whenever a reference to Dratler (1980) seems chronologically out of place.

1.1. System Overview

Figure 1 (modified from Eaton, 1977) shows the major components of the seismic telemetry recording and playback systems and gives the standard operating parameters that combine to fix the absolute amplitude response. In a discussion of the response characteristics it is useful to divide this complete system into four major components: (1) the seismometer and L-pad, (2) the seismic amplifier and voltage-controlled oscillator (VCO), (3) the discriminator at the central recording site, and (4) the recording and display media.

Figure 2 shows the stylized frequency response for each of these major components, as well as combinations of some of them. If the ordinate ("Relative Response") is plotted in logarithmic units, then the relative response of a combination of system components is simply the sum of the relative responses of the individual curves. The "absolute response" must take into account the standard operating parameters summarized in Figure 1.

Essentially, this synthesis is what we do in this paper. The "relative response" curves for the major system components are determined in detail -- some by theoretical derivation, some by laboratory calibration. The individual relative response curves are then represented by analytical mathematical elements and the individual elements are multiplied together to give a relative response curve for the entire system. "Absolute response" is then determined by simple multiplication of the appropriate standard operating parameters.

1.2. Representation by Poles

The frequency response of most seismic systems (and their individual components) can be represented by an expression of the form

$$F(\omega) = \frac{i^{l-n}\omega^{l}(C_1 C_2 \cdots C_n)\cdot A}{(\omega-\alpha_1)(\omega-\alpha_2)\cdots(\omega-\alpha_n)} \quad (1)$$

where ω is frequency in radians per second, α_i are complex constants that are the poles of the function, C_i are real constants associated with each pole, l and n are integers, and 'A' is an amplification constant (Healy and O'Neill, 1977). 'A' itself may be the product of amplitude factors of individual components, e.g., for a complete system, those of the seismometer, the amplifier/VCO, the discriminator, and the recording device.

Because the physical system represented by $F(\omega)$ is real and causal, all of the poles lie in the upper half of the complex plane and either fall on the imaginary axis or occur as matched pairs, mirror images through the imaginary axis. The amplitude spectrum is the absolute value of $F(\omega)$, whereas the phase spectrum $\phi(\omega)$ is the arctangent of the imaginary part of $F(\omega)$ divided by the real part of $F(\omega)$, i.e.,

$$\phi(\omega) = \tan^{-1}\left[\mathcal{I}\{F(\omega)\}/\mathcal{R}\{F(\omega)\}\right] \quad (2)$$

For an electromagnetic seismographic system $F(\omega)$ is composed of the amplification constant 'A' times factors having the complex forms shown in Table 1. The seismometer response is represented by the last of these five complex expressions (see section 2.1), and the amplifier/VCO, the discriminator, and the recording device by combinations of the first four complex expressions (see sections 2.2 to 2.4). The shapes of the amplitude response curves for these five complex expressions (i.e. the amplitude response functions) are shown in Figures 3 through 6.

2. Amplitude-frequency Response of Individual Components

The response characteristics of each of the four main system components will be summarized in this section. The spectral response function that governs the shape of the response curve, and the amplitude factor that determines quantitatively the gain or amplification of each component will be given. These data are summarized in Table 2, and this table should be referred to frequently by the reader.

2.1. Seismometer and L-pad

The theoretical response of the seismometer can be derived from well-known principles. Healy and O'Neill (1977) use the Fourier transform method to find a solution to the equation of motion of the seismometer in the frequency domain. The complex response spectrum for the seismometer is

$$\mathfrak{Z} = \frac{G_{LE} \cdot i\omega^3}{(\omega^2 - \omega_0^2) - i\,2\beta\omega_0\omega} \qquad (3)$$

or equivalently

$$\mathfrak{Z} = \frac{G_{LE} \cdot i\omega^3}{(\omega - \alpha_j) \cdot (\omega - \alpha_K)} \qquad (4)$$

where $\mathfrak{F}$ = Fourier transform of the output voltage produced by a delta function of ground displacement into the combined seismometer and L-pad

G_{LE} = effective seismometer motor constant (volts/cm/sec)

ω_0 = natural frequency of seismometer (radians/second)

ω = ground motion frequency (radians/second)

β = seismometer damping constant, relative to critical damping

α_j, α_K = paired poles of the response function such that

$$\alpha_j = \omega_0(i\beta + (1-\beta^2)^{1/2})$$
$$\alpha_K = \omega_0(i\beta - (1-\beta^2)^{1/2}) \qquad (5)$$

The modulus of the complex expression in equation (3) gives the amplitude response function for the seismometer:

$$\frac{G_{LE}\,\omega^3}{[(\omega^2-\omega_0^2)^2 + 4\beta^2\omega_0^2\omega^2]^{1/2}} \qquad (6)$$

This function (with G_{LE} omitted) is shown in Figure 6. Note that below the free period (f_0 = 1 Hz) the amplitude falls off to the third power of frequency (f^{-3}). Also note from equation (4) that the seismometer response is represented by two poles, at complex frequencies α_j and α_K. In Table 2, the low-frequency fall-off for the seismometer is given as LN = 3, and the total number of poles in the representation of the seismometer response is given as LTYPE = 2. These particular designations are used because they are of the form required for input to the computer program RESPONSE. This program, which is explained in a later section, computes the frequency response functions for systems (or components) that can be described by a given set of poles. It should also be noted that in equation (1), η is equivalent to LTYPE, and ℓ is equivalent to LN.

The L-pad is a simple resistive network (Figure 1) whose main function is to couple the seismometer to the amplifier in such a way that the amplifier "sees" a seismometer with a known (and standard) damping constant (β), effective motor constant (G_{LE}), and natural frequency (f_0). These standard values ($\beta = 0.8$; $G_{LE} = 1.0\ V/(cm/sec)$; $f_0 = 1\ Hz$) are listed in Table 2. The resistances T and S associated with the L-pad (Figure 1) are chosen separately for each seismometer so that G_{LE} will be the standard 1.0 V/(cm/sec) (Eaton, 1975). Healy and O'Neill (1977) give the following relationship between the parameters of the seismometer and L-pad:

$$G_{LE} = \frac{G_L \cdot S \cdot RR}{(S + RR) \cdot (T + R) + RR \cdot S} \tag{7}$$

where

G_L = seismometer motor constant as determined by laboratory experiment (volts/(cm/sec))

S = T-pad shunt resistance (ohms)

T = T-pad arm resistance (ohms)

R = seismometer coil resistance (ohms)

RR = amplifier input impedance, fixed at 10,000 ohms.

2.2. Amplifier/VCO

The second major component of the seismic telemetry system is referred to collectively as the "field package". It contains several sub-units, including the L-pad (discussed in section 2.1), seismic amplifier with variable attenuation, voltage-controlled oscillator (VCO), automatic daily system calibration unit, frequency stabilizer, interface to the telemetry transmission circuit, summing amplifiers, VHF radio links (as needed), and power supplies. Only the L-pad, amplifier, and VCO sub-units have an effect on the frequency response characteristics.

Field packages have evolved through model numbers J302, J302M, and J402. Because there is no significant difference in the amplitude and frequency response characteristics of these packages, we will refer to them all as the J402 (Van Schaack, oral comm., 1979).

We determined the frequency response characteristic of the J402 amplifier unit by calibration in the laboratory, whereas Dratler (1980) determined it by circuit analysis techniques. Dratler's analysis represents the frequency response by simple poles -- two single poles (at 0.085 and 0.096 Hz) with a high-pass filter response, two single poles (at 48.4 and 49.8 Hz) with a low-pass filter response, and a zero at about 6,200 Hz with a low-pass filter response. Dratler (1980, p. 17) states "Since this frequency is well above the region of seismological interest, ... the zero ... may be ignored for most practical purposes." Table 2 lists the four simple poles determined by Dratler, but not the zero. The zero is not considered again in this report.

In August and September 1979, J. Van Schaack and S. Stewart calibrated three of the J402 units and two of the J302M units in the laboratory. The amplitude response characteristics for all five units, normalized to a peak value of 1.0, are shown as solid lines in Figure 7. For the frequency range 0.5 to 10.0 Hz the normalized response curves are nearly identical. Even from 10 to 100 Hz the normalized curves are very similar. In the low-frequency range, from 0.05 to 0.5 Hz, the observed response curves tend to diverge somewhat, but in the worst case are within 20 percent of each other. These lower frequencies are not of interest in most of the studies for which the instrumentation is intended.

By a process of visually fitting these observed curves to the theoretical response curves (described in Healy and O'Neill, 1977), we were able to estimate the locations of the poles (f_0) and the coefficients of damping (β). For the J402 seismic amplifier our curve-matching technique resulted in a double pole at 0.095 Hz with a high-pass filter response, and a double pole at 44.0 Hz with a low-pass filter response. In each case the parameter β was found to be 1.0. These results are summarized in Table 2 and Figure 7.

We used the program RESPONSE to calculate the amplitude-frequency relation from Dratler's poles, and from our poles, and then compared these calculated response curves to those observed in the laboratory. The results are shown as dashed lines in Figure 7. Considering that Dratler's poles were obtained by theoretical analysis, in which it is assumed that the resistive and capacitive components behave according to their design specifications, his fit to our observed response curves is quite good. Our fit is somewhat better, particularly at frequencies above 10 Hz. We assume this is because we obtained our poles directly from the same curves that we are now trying to match.

The J402 has two stages of fixed amplification, with a variable step-attenuator between the two. The first stage has a gain of 49.5 dB; the second stage has a gain of 42 dB (R. Jensen, written comm., 1979). Maximum gain therefore is 91.5 dB. Variation from these figures may be a few tenths of a dB. (A variation of 0.2 dB is approximately 2 percent). The step attenuator allows signal attenuation from 0 dB to a nominal 48 dB in steps of 6 dB.

The attenuation setting of 6 dB on the field package corresponds to a real attenuation of 6.7 dB below the 0 dB setting (Van Schaack, oral comm., 1979). The 12 dB setting is about 6.4 dB below the 6 dB setting, introducing a real attenuation of 13.1 dB below the 0 dB level (see Table 4). Differences in the remaining attenuation steps are very close to the nominal 6 dB interval (Van Schaack, oral comm., 1979). The gain of the J402 therefore is variable from 91.5 dB to 42.4 dB (91.5 - (48 + 1.1)). The equivalent voltage amplification is about 37,600 to 130, respectively.

Attenuation settings of 6 dB and 12 dB are commonly used in the Central California Microearthquake Network, so it is important to allow for the increased attenuation at these settings. The difference between 12 dB and 13.1 dB is about 14 percent.

Defining "attn" as the actual dB setting marked on the J402 field package, the voltage amplification is summarized in Table 3. The complete range of gain and amplitude ratios for the J402 is listed in Table 4, under the columns identified by "JVS". The standard "low-gain" station has the step attenuator set at 42 dB.

Dratler (1980) carried out a detailed circuit analysis of the J302 amplifier/attenuator to determine absolute gain at the various dB settings as well as the positions of the poles and zeros relevant to the frequency-response characteristics. His results for the gain of the J302 circuit are summarized in Table 4, under the columns identified by "JD". He determines the J302 gain as an amplitude ratio, which he then converts to the equivalent gain in dB to three significant figures (Dratler, 1980, Table 3.2). We recalculated his dB gain representation to four significant figures so that the numbers given by Dratler for gain as an amplitude ratio would be numerically more consistent with those for gain in dB. The right-hand column of Table 4 shows the ratio of the different values for gain listed under "JVS" and under "JD." The differences are 9 percent or less, with an average difference of 6 percent.

In addition to the gain and frequency response characteristics of the J402, the setting of the VCO sensitivity is a factor determining total gain for the entire telemetry system. That is, over how many Hertz will the VCO frequency change due to an input of ± 1 volt? At the present time the deviation adjustment of the VCO is set such that ± 2.7 VDC input to the VCO produces an output deviation of ± 100 Hz (Healy and O'Neill, 1977, p. 2-12; W. Hall, oral comm., 1979). For the maximum nominal deviation allowed of ± 125 Hz, this corresponds to ± 3.375 V or 37.04 Hz/V. These latter numbers are given in Table 2.

2.3. Discriminators

The third major component of the short-period telemetry system is the discriminator at the central recording site. Its main purpose is to demodulate the signal produced by the VCO, in order to reproduce the analog seismic signal that caused the VCO modulation in the first place.

Several brands and models of discriminators have been used with the seismic telemetry network. At the present time the J101A, J101B, and Develco model 6203 discriminators are used with the network stations that are recorded in real time. These include the Develocorder and Helicorder units and the real-time earthquake detection system. In addition, the Develco, J101B, and Tri-Com discriminators are used for magnetic tape playback and oscillographic recording and for off-line analog-to-digital conversion.

Normalized frequency response curves for the discriminators currently in use are shown in Figure 8. These were determined by J. Van Schaack and S. Stewart in August, 1979, by calibration in the laboratory. It is apparent that the frequency response diverges significantly at frequencies of 10 Hz and greater. Indeed, it turns out that the variability among the different kinds of discriminators is the most influential factor in determining the shape of the frequency response curves for the entire system. The J101A discriminator is an earlier version with the low-pass -3 dB point at about 20 Hz, and the J101B is a later version with the -3 dB point at about 40 Hz. The J101B is the accepted version at this time, and efforts are being made to modify all remaining J101A's to J101B's (Van Schaack, oral comm., 1979).

Poles were determined (by the curve-fitting method mentioned earlier) from the normalized response curves measured for the J101A, J101B, and Develco discriminators, and the program RESPONSE was used to calculate the frequency response for these discriminators. Comparisons between the observed and calculated normalized amplitude response curves for these discriminators are shown in Figures 9, 10, and 11, respectively. The observed and calculated curves for the J101A and J101B discriminators are so close that they are indistinguishable in Figures 9 and 10. This is not quite the case for the Develco discriminator (Figure 11), but we regard the fit as acceptable.

Pole positions for the Tri-Com discriminator, as obtained from the manufacturer, are given in Dratler (1980, p. 25, Eq. 4.3). Recently these were again verified by the manufacturer (Van Schaack, oral comm., 1979). These pole positions are in complex form, and are scaled to a cut-off frequency (f_c) of 1 Hz. The Tri-Com discriminators discussed in this report have a cut-off frequency of 30 Hz (time compressions of 4x and 16x will increase f_c accordingly). Dratler (1980, p. 37) gives the complex pole positions for $f_c = 30$ Hz. In Appendix A we summarize how to convert these pole positions into a form that is consistent with the representation by Healy and O'Neill (1977), and how to convert this representation to the parameters f_0 and β used in program RESPONSE. These poles were tried in program RESPONSE, and the fit between observed and calculated curves was so close (in Figure 12 the differences are indistinguishable) that we adopted these poles and did not estimate our own. In Table 2 the pole positions (expressed by f_0 and β) for the four types of discriminators currently in use are summarized.

Just as in the case of the VCO, the setting of the discriminator sensitivity is a factor that contributes to the total gain for the complete telemetry system. That is, how many Hertz of frequency deviation on input to the discriminator are required to produce a given analog voltage at its output? Presently, the deviation adjustment of all discriminators is set such that a deviation of $\pm$ 125 Hz around the center frequency of the discriminator produces an output of $\pm$ 2 VDC. This corresponds to a sensitivity of 62.50 Hz/V or 0.0160 V/Hz. These figures are given in Table 2.

It is important to note that the sensitivity of the discriminator is less than the sensitivity of the VCO. This results in a net reduction in the amplitude of the analog seismic signal between the input to the VCO and the output from the discriminator. The amount of reduction is (37.04 Hz/V)/(62.50Hz/V) or 0.593. This factor is not shown explicitly in Table 2.

2.4. Record/Reproduce Equipment

The fourth major component of the seismic telemetry system is the recording and reproducing equipment. Four devices are involved in online recording of the telemetered seismic signals (Figure 1): (1) analog tape recorders, (2) Develocorders, (3) Helicorders, and (4) an online computer. In addition, three devices are used routinely for playback from the analog magnetic tapes: (1) analog tape reproduce equipment, (2) a multi-channel oscillographic recorder (Oscillomink) with optional low-pass filtering, and (3) an analog-to-digital converter system--the front end of the moderately powerful Eclipse mini-computer system. There is also a computer-controlled tape dubbing procedure in which earthquakes from the tapes recorded online are dubbed onto master library tapes. Each of these devices will be discussed next, but only to the extent that their frequency-response characteristics are relevant to this report.

2.4.1. Tape Record/Reproduce/Dubbing Systems.

Presently there are four Bell and Howell Model 3700B tape units that record the multiplexed FM signals from the telephone lines. Because each tape recorder has 14 tracks on its 1-inch wide tape, and each track can record up to 8 seismic signals in the standard multiplexed format, then each analog tape can record data from as many as 112 seismometers. Other Bell and Howell Model 3700B tape units are used for tape playback and tape dubbing purposes.

The multiplexed FM signal from the telephone line is recorded and reproduced in Direct Mode. In the dubbing procedure the signals from each tape track are reproduced and re-recorded in Direct Mode. Because it is the FM tone bundle on each tape track that contains the seismic information, amplitude variations in the Direct Record signal (and therefore in the FM tone bundle) will not have an effect upon the discriminated analog seismic signal. This assumes, of course, that the complete seismic telemetry system, from the seismometer in the field to the tape record/reproduce system, is well adjusted.

2.4.2. Develocorder System

The Develocorder is a multi-channel galvanometric recording device that can record up to 18 seismic signals and 3 channels of time code on 16-mm photographic film. In order to minimize the problem of crossed traces due to low-frequency microseismic noise and electronically induced low-frequency drift, a high-pass R-C filter precedes the input to each channel of the Develocorder.

The response of the Develocorder (and its associated high-pass input filter) was determined in the laboratory by J. Kempt and S. Stewart in June, 1979. One channel of a Develocorder unit was calibrated. The normalized frequency response curve is shown as the solid line in Figure 13. Poles were found empirically by the curve matching process referred to earlier. The galvanometers used in the Develocorders have a natural frequency of 15.5 Hz (W. Hall, oral comm., 1979). We tried poles at 15.0, 15.5, and 16.0 Hz, and it was apparent that the pair of poles at 15.5 Hz gave the best fit to the observed data at frequencies above 7 to 8 Hz. The fit at low frequencies was more difficult to obtain and was never entirely satisfactory. Overall, the fit of the calculated response to the observed response (Figure 13) is acceptable.

The absolute gain of the Develocorder is set such that, at a frequency of 5 Hz, an input signal of 1 volt (peak) causes a galvanometer deflection of 2 cm (peak) on the Develocorder screen (W. Hall, oral comm., 1979). A film viewer is used to display and read the 16-mm films after they have been removed from the Develocorder. The film viewer has a magnification exactly twice that of the screen on the Develocorder. Thus the 2 cm/V calibration of the Develocorder is seen as a 4 cm/V calibration on the film viewer. Frequency and amplitude response factors for the Develocorder and film viewer are summarized in Table 2.

2.4.3. Helicorder System

The Helicorder is a low-speed helical translation drum recording system that records 1 or 2 analog seismic signals in the standard "observatory"-type format. Drum speeds of 0.5 and 1 mm/sec are used. A hot stylus pen records on special plastic-coated paper. High-pass filters precede the input to this system, to reduce the problem of drifting traces as the drum revolves. Unlike the Develocorder, the Helicorder electronics has a variable gain seismic amplifier on input, adjustable in 6 dB steps. The setting of this amplifier must be known in order to calculate the absolute system magnification.

The response of the Helicorder (including the high-pass input filter) was determined by J. Van Schaack in December, 1979. Two units were selected for calibration. The normalized frequency response for each unit (no. 5 and no. 6) is shown by solid lines in Figure 14. The differences in the observed responses may be due, at least in part, to differences in the frictional contact between the stylus and the paper, and differences in stylus construction. Poles for the observed response curves were found empirically by the curve matching procedure referred to earlier. Unit no. 6 was selected for curve matching because its behavior suggested less problems with frictional resistance of the stylus against the paper, particularly at the higher frequencies (Van Schaack, oral comm., 1979).

The pole positions found are summarized in Table 2. Several trial pole positions were necessary in order to achieve a reasonable match, particularly at the low-frequency end. We regard the match between the observed response (for unit no. 6) and the calculated response as acceptable.

At the present time the Helicorder amplifier unit is not adjusted to any particular gain that allows one to calculate its absolute magnification. As a part of the discussion during the calibration of Helicorders nos. 5 and 6, a calibration standard was established

(J. Eaton and J. Van Schaack, oral comm., 1979), as follows. The maximum gain of the seismic amplifier used on each Helicorder is about 18 dB higher than a nominal gain that might typically be used. The position of the 6 dB step attenuator when turned down 3 steps from this maximum gain position (to an 18 dB attenuation) will arbitrarily be defined as 0 dB gain setting for the Helicorder. At this setting the gain will be fine tuned such that a 1 Hz input signal to the amplifier, at 1 volt peak-to-peak, gives a stylus deflection of 4 cm peak-to-peak. This is the amplitude factor shown in Figure 1 and Table 2. Note that this sensitivity (4 cm/V) is the same as that for the Develocorder film viewer screen and for the high-level gain option on the Oscillomink. Thus a Helicorder attenuation recorded as 0 dB has the same "amplification factor" as those aforementioned media. A Helicorder attenuation of 6 dB reduces its magnification by one-half,

and an attenuation of -6 dB doubles its magnification. The reader should verify the actual method of setting Helicorder amplitude gain before doing any quantitative work with the records.

2.4.4. Siemens Oscillographic Recorder/Playback System

The frequency response of the Siemens oscillograph is flat from DC to well over 200 Hz, perhaps to 400 Hz (Figure 2E). At frequencies less than 200 Hz, and probably even higher, we consider its relative response to be unity. Its absolute gain has been adjusted so that there are two standard levels available for playback -- a high-level sensitivity of 4 cm/V and a low-level sensitivity of 1 cm/V. These values are given in Figure 1 and Table 2.

Depending upon the application, the telemetry tapes and dubbed tapes may be played out at time compression ratios of 1x, 4x, or 16x. Playback at 1x typically writes to the Siemens oscillograph and uses the Develco discriminators. Playback at 4x typically uses the Tri-Com 4x discriminators and writes to the Siemens oscillograph. Playback at 16x uses the Tri-Com 16x discriminators and the analog signal goes into the Eclipse digitizing system; there is no oscillographic recording.

A multi-channel low-pass active filter bank is available as an option for conditioning the output from the playback discriminators. Each filter has 10 step-selectable low-pass cut-off points within a decade range, and decade multipliers of 1x, 10x, 100x, and 1000x. The low-pass cut-off points are listed in Table 2 and Figure 15. Figure 15 also shows the response curve for these filters. In this figure, the ordinate (amplitude) is normalized so that the low frequency response has a maximum value of unity. The abscissa (frequency) is also normalized so that the beginning of the roll-off of 12 dB/octave occurs at 1 Hz. With this convention for normalizing, the poles of the filter were determined by the curve matching technique and are shown in Table 2 and in this figure. The true frequency response for a particular filter setting within a decade range, and for a particular factor of 10 multiplier, can be determined by rescaling and using these values for the poles, or by rescaling Figure 15 itself. For example, one of the filter settings is 6.3. To calculate the response of a 63-Hz high-pass filter, one would take as pole parameters $f_o = 63$, and $\beta = 0.5$. In choosing a particular filter frequency and including its effect in the calculation of system frequency response, the time compression factor of the analog tape playback system must also be accounted for. An example is given in section 3.2.

2.4.5. Analog-to-Digital Converters

A number of analog-to-digital converter units (adc) have been used with the discriminated analog seismic signals, and others are contempleted. In this report we have information on only three of them. Two of these adc units are no longer operating (the CDC-1700 online and offline computers).

Only one adc unit (part of the DGC Eclipse computer) is available for offline digitizing either from the telemetry tapes or the dubbed tapes. Relevant characteristics of these will be summarized below. In addition, an online earthquake detection and timing system, using its own adc equipment, has recently begun operating (R. Allen, oral comm., 1979), and adc units for the DEC 11/34 and 11/70 computers are installed but are not operating routinely. These will not be discussed in this report.

Because the frequency response of these adc units should be flat from DC to the Nyquist frequency, there should be no relevant poles associated with them. The amplitude factor, however, is a function of the maximum number of bits (B) used in the adc unit, and the maximum input (R, in volts) acceptable to the adc unit before it clips the signal. The amplitude conversion factor (F) may be written as

$$F = \frac{2^{B-1} - 1}{R/2} \quad \frac{\text{counts}}{\text{volt}} \tag{8}$$

At the present time the Eclipse digitizing system is operational. This system uses the Tri-Com 16x discriminators and a 10-bit analog-to-digital converter (B = 10) with a maximum input range of $\pm$ 2.5

volts peak (R = 5). Its amplitude factor (F) is ± 2.5 volts for ± 511 counts, or 204.4 counts/volt. This is shown in Figure 1 and Table 2.

Although the CDC-1700 digitizing system is obsolete, there may be some digital data from it that will need the following information. The maximum input to the CDC system, before signal clipping occurs, was ± 2.5 volts peak, (i.e., R = 5). The analog-to-digital converter had 14 bits resolution, initially (B = 14). All 14 bits were used in the on-line earthquake location system. Its amplitude factor (F) therefore is determined as follows: ± 2.5 volts corresponds to ± 8191 counts, or 3276 counts/volt.

For offline digitizing on the CDC-1700 , only the 12 most significant bits (B = 12) were written to the 7-track digital magnetic tape. In this case the amplitude factor (F) is determined as follows: ± 2.5 volts corresponds to ± 2047 counts, or 818.8 counts/volt. These amplitude factors are given in Table 2. It should also be noted that Develco discriminators were used to reproduce the signals from the telemetry magnetic tapes or dubbed tapes for CDC-1700 digitizing operations.

3. Determining the System Response

3.1. Method of Calculating System Response

The filter program RESPONSE computes the amplitude and phase spectra either of a complete seismic system or of components of a system. The parameters for the spectral elements that describe the frequency response of each component (Table 2) are the basic input to the program. For each component, these parameters are: the total number of poles (LTYPE), the power of the low-frequency fall-off (LN), the pole frequency in Hertz (f_o), and for elements with double poles the damping constant (β). Another input parameter to RESPONSE is the over-all amplitude factor (AMP) for the response function, which is the product of the amplitude factors for the appropriate individual components (Table 2). The program RESPONSE computes values of the spectral elements within frequency decades specified by the user, multiplies them together, and multiplies this product by the over-all amplitude factor (AMP). From these complex numbers it determines the amplitude and phase spectra (section 1.2).

Appendix B lists the program RESPONSE and shows the input and output for one example.

3.2. Results

Figures 16 through 21 are plots of frequency response curves for some commonly used combinations of equipment. Some features of these response curves will be discussed in this section.

In the past it has been common practice in the laboratory to determine the relative response of the amplifier/VCO/discriminator combined together as a single unit. Figure 16 shows the observed relative response for three such combined systems. These curves (the solid lines) were determined in 1976 and 1978. The dashed line represents the response calculated by using the program RESPONSE to combine the data in Table 2 for the J402 amplifier/VCO response as determined by laboratory calibration with that for the Develco discriminator. We regard the agreement between the observed and calculated curves as quite acceptable. Figure 16 also illustrates the versatility of program RESPONSE in that it can calculate the response of parts of the system as well as that of the complete telemetry system.

Figures 17 through 21 show the amplitude response spectra for the complete seismic telemetry system where the output media are most of those listed in Table 2. In all cases the field amplifier is set at 12 dB attenuation and the appropriate discriminators have been selected. Magnification for the Siemens oscillograph and the Develocorder and Helicorder systems is dimensionless (i.e. meters per meter), whereas that for the input to the Eclipse digitizing system (Figure 20) is in volts per meter. The frequency at which the peak magnification occurs varies significantly for the output media. It ranges from 4.8 Hz for the Helicorder system to 26 Hz for the input to the Eclipse digitizing system.

The effect of the low-pass filters used optionally with the Siemens oscillograph for playbacks, and the method of allowing for a time compression factor in computing system response when these filters are used, are both illustrated in Figure 18. In this example the Tri-Com 4x discriminator was used, and the low-pass filter was set at 6.3 and 10x. This means that the playback was filtered with a 63-Hz low-pass filter. Because of the 4x time compression factor, the effect on the seismic signal as seen on the playback is a low-pass filter with a setting of (63/4) 15.75 Hz. Thus in program RESPONSE the filter characteristic would be designated by setting f_0 to 15.75 and β to 0.5. Figure 18 also shows a small "bump" in the system response when this filter is added. Over a limited frequency range the system magnification becomes slightly greater with the filter than without it. The response of the filter alone (Figure 15) shows why this is so. The "bump" in the filter response rises to about 15 percent greater amplitude than the relative response at lower frequencies, reflecting the noticeably underdamped nature of the filters.

Although not illustrated here, we have used program RESPONSE and the data in Tables 2 and 4 to reproduce system response curves found in Bakun and Dratler (1976, Figure 7.12) and Dratler (1980, Figure 5.1, p. 44). The agreement is good.

4. Summary

To calculate the frequency response of a USGS short-period seismic telemetry system it is convenient to divide the instrumentation into four main components and consider individually the amplitude factor and frequency characteristics of each component. The four main components consist of two at the field site -- the seismometer and L-pad, and the seismic amplifier and voltage-controlled-oscillator (VCO), and two at the central recording site -- the discriminator, and the recording and display device.

The frequency response of the complete seismic system, or its individual components, may be represented by an expression of the form

$$F(\omega) = \frac{i^{\ell-n}\,\omega^{\ell}\,(C_1 C_2 \cdots C_n)\cdot A}{(\omega-\alpha_1)(\omega-\alpha_2)\cdots(\omega-\alpha_n)} \tag{9}$$

where ω is frequency in radians per second, α_i are complex constants that are the poles of the function, C_i are real constants associated with each pole, ℓ and n are integers, and 'A' is an amplitude constant. 'A' itself may be a product of amplitude factors of individual components.

Figure 1 illustrates the main components of a USGS short-period seismic telemetry system and gives the standard amplitude or sensitivity factors currently in use. These factors determine the magnitude of the system response and are represented by the factor 'A' in equation (9). The shape of the response curve is determined by the remaining factors in equation (9), particularly by the location of the poles (α_i) and the factor ω^{ℓ}. In this section we will outline briefly one way to compute the complete system response for a commonly used configuration of the short-period seismic system. This configuration consists of a vertical-component velocity transducer with 1-sec free period, the J402 seismic amplifier/VCO, the J101B discriminator, and the film viewer used for reading the 16-mm Develocorder films. The numbers and expressions necessary to determine the complete system response are extracted from Table 2 and presented in Table 5. In this example the J402 amplifier is set at an attenuation of 12 dB.

In order to maintain a uniform system response for all seismic stations, the seismometer is coupled to the input of the amplifier unit by an L-pad with resistances T and S (Figure 1). Values of T and S are computed individually for each seismometer such that the seismometer will have an effective damping factor (β) of 0.8 critical and an effective motor constant (G_{LE}) of 1.0 volt/(cm/sec). Eaton (1975) describes a method for determining these values.

The seismic amplifier has two stages of fixed amplification, with a variable step attenuator between the two. Attenuation is variable in steps of approximately 6 dB, from nominal settings of 0 dB to 48 dB. For settings of 12 dB or greater the gain of the seismic amplifier (G_{SA}) may be written as

$$G_{SA} = 10^{(90.4 - attn)/20} \qquad (10)$$

where "attn" is the dB setting for the amplifier. For a nominal attenuation setting of 12 dB, the amplifier gain is about 8318 (Table 4).

The deviation sensitivity of the VCO is set such that $\pm$ 3.375 VDC into the VCO results in the maximum allowed frequency deviation of $\pm$ 125 Hz (Figure 1). This corresponds to a deviation sensitivity of the VCO (D_{VCO}) of 37.04 Hz/V.

At the central recording site the deviation sensitivity of the discriminator is set such that the maximum frequency deviation of $\pm$ 125 Hz into the discriminator results in an output of $\pm$ 2.0 VDC (Figure 1). This corresponds to a discriminator deviation sensitivity (D_{DSC}) of 0.0160 V/Hz.

The sensitivity of the recording/display device combination will be denoted by L. In the case of the film viewer screen this is 4 cm/V. (The Develocorder is set to a sensitivity of 2 cm/V, and the film viewer screen has an optical magnification of 2x.)

The product of these individual amplitude factors (G_{LE} , G_{SA}, D_{VCO}, D_{DSC}, L) is used for the factor 'A' in equation (9).

The shape of the system response curve is determined from the product of the absolute values of the individual spectral elements shown in Table 5. The values of the poles (α_j and α_K) are determined from the equations at the bottom of Table 5, using the appropriate values of f_0 and β. For the seismometer, the numbers for f_0 and β are standard values governed by the type of seismometer and the resistive values calculated for the L-pad. For the remaining components the values of f_0 and β are determined by calibration in the laboratory, and then by matching the observed calibration curve to one of a set of theoretical curves. The theoretical curves are computed from the absolute value of each spectral element shown in Table 5. The method is described in Healy and O'Neill (1977).

The complete system response curve, shown in Figure 19 (for the J101B discriminator), is the product of the amplitude factors and the absolute values of the spectral elements given in Table 5. This response curve represents magnification of the ground displacement at the seismometer, relative to the amplitude measured on the film viewer screen. Between 2 and 6 Hz the slope of this curve, plotted in logarithmic coordinates, is approximately proportional to the frequency, f. The asymptote to the response curve in this frequency range may be derived by the following consideration.

Given a simple harmonic ground motion

$$x = X \sin \omega t$$

then the voltage from the seismometer as sensed at the input to the seismic amplifier is

$$G_{LE}\dot{x} = G_{LE}\,\omega\,X\cos\omega t \qquad (11)$$

where $\dot{x}$ is the instantaneous ground velocity. The maximum voltage into the amplifier is

$$G_{LE}\,\omega\,X.$$

The maximum voltage out of the amplifier is

$$G_{LE}\,\omega\,X\;G_{SA} = G_{LE}\,\omega\,X\;10^{(90.4-attn)/20}$$

where the last factor represents the gain of the amplifier for attenuation settings (attn) of 12 dB or greater. For this maximum voltage the product of VCO sensitivity (D_{VCO}) and discriminator sensitivity (D_{DSC}) gives the voltage change attributed to these two components. It should be noted that in the USGS instrumentation this product is 0.593.

System magnification is defined as H/X, where H is the amplitude recorded on the output device and X is the corresponding ground amplitude at the seismometer. The asymptotic portion of the system magnification may be represented as

$$H/X = G_{LE}\,\omega\,G_{SA}\cdot D_{VCO}\cdot D_{DSC}\cdot L. \qquad (12)$$

Substituting the numbers from Table 5, then

$$H/X = 1.24 \cdot 10^5 \cdot f \tag{13}$$

where f is frequency in Hz. This relation is plotted as the asymptotic line in Figure 19, as well as in Figures 17, 18, and 21. By eliminating the factor L from equation (12), and changing centimeters to meters as necessary, the asymptotic line in Figure 20 is obtained.

References

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Appendix A

Relating the complex pole positions of Healy and O'Neill (1977) to those of Dratler (1980)

Relating the complex pole positions of

Healy and O'Neill (1977) to those of Dratler (1980)

Healy and O'Neill (1977) place their poles on the upper half of the complex (x, y) plane, as mirror images with respect to the positive direction of the imaginary axis (i.e., the y-axis). The position of a single pole takes the general form

$$\alpha_j = i b \qquad \text{(A1)}$$

and the position of a pair of poles takes the general form

$$\begin{aligned} \alpha_j &= a + i b \\ \alpha_K &= -a + i b \end{aligned} \qquad \text{(A2)}$$

where α_j and α_K are the positions of the poles in the complex plane, a is the x-coordinate of the pole, and b is the y-coordinate.

For the response of seismic systems as considered in their report, the locations of single poles are purely imaginary

$$\alpha_j = i \omega_0 \qquad \text{(A3)}$$

and the locations of paired poles are complex

$$\alpha_j = \omega_o(i\beta + (1-\beta^2)^{1/2}) \qquad \text{(A4)}$$
$$\alpha_k = \omega_o(i\beta - (1-\beta^2)^{1/2})$$

where $\omega_0 = 2\pi f_0$ is frequency in radians/second, f_0 is frequency in Hz, and β is an effective damping constant, relative to critical damping. Note that single poles are described only by ω_0, and not β.

From equations (A2) and (A4) it follows that

$$\alpha_j \alpha_k = -\omega_0^2 = -(a^2 + b^2) \qquad \text{(A5)}$$
$$\alpha_j + \alpha_k = 2i\beta\omega_o = 2ib$$

and expressions for the parameters ω_o and β are

$$\omega_o = (a^2 + b^2)^{1/2} \qquad \text{(A6)}$$
$$\beta = \frac{b}{\omega_o} = \frac{b}{(a^2 + b^2)^{1/2}}$$

Dratler (1980) places his poles on the right-hand half of the complex (x, y) plane as mirror images with respect to the positive direction of the real axis (i.e., the x-axis). His position for a single pole takes the general form

$$\tilde{\alpha}_j = \tilde{a} \qquad \text{(A7)}$$

and his position for a pair of poles takes the general form

$$\tilde{\alpha}_j = \tilde{a} + i\tilde{b} \qquad \text{(A8)}$$
$$\tilde{\alpha}_k = \tilde{a} - i\tilde{b}$$

where $\tilde{\alpha}_j$ and $\tilde{\alpha}_k$ are the positions of the poles in the complex plane, $\tilde{a}$ is the x-coordinate of the pole, and $\tilde{b}$ is the y-coordinate.

If Dratler's pole positions ($\tilde{\alpha}_j$ and $\tilde{\alpha}_k$) are multiplied by the imaginary unit "i", the effect is to rotate his pole positions 90 degrees counterclockwise where they will then have the identical pole positions as used by Healy and O'Neill (1977). Therefore, we multiply the expressions in equations (A7) and (A8) by "i", and equate the resulting real and imaginary parts to the expressions in equations (A1) and (A2) to obtain

$$i\tilde{\alpha}_j = i\tilde{a} \equiv ib = \alpha_j \qquad \text{(A9)}$$

$$\begin{aligned} i\tilde{\alpha}_j &= -\tilde{b} + i\tilde{a} \equiv a + ib = \alpha_j \\ i\tilde{\alpha}_k &= \tilde{b} + i\tilde{a} \equiv -a + ib = \alpha_k \end{aligned} \qquad \text{(A10)}$$

From equations (A9) and (A10) Dratler's coordinates can be expressed in the notation of Healy and O'Neill as

$$\begin{aligned} a &= -\tilde{b} \\ b &= \tilde{a} \end{aligned} \qquad \text{(A11)}$$

and the expressions for ω_o and β in equation (A6) can be written in Dratler's notation as

$$\begin{aligned} \omega_o &= (\tilde{b}^2 + \tilde{a}^2)^{1/2} \\ \beta &= \frac{\tilde{a}}{\omega_o} = \frac{\tilde{a}}{(\tilde{b}^2 + \tilde{a}^2)^{1/2}} \end{aligned} \qquad \text{(A12)}$$

Dratler (1980, p. 37) gives the five pole positions for the Tri-Com discriminator as

pole		
1	$f_6 = 45.07$	
2,3	$f_7, f_8 = 41.42$	$\mp i\ 21.54$
4,5	$f_9, f_{10} = 28.73$	$\mp i\ 44.13$

(A13)

Pole 1 is a single pole; the rest are paired poles. Dratler's units in equation (A13) are in Hertz, rather than radians/second, so equation (A12) becomes

$$f_o = (\tilde{b}^2 + \tilde{\alpha}^2)^{1/2}$$

$$\beta = \frac{\tilde{\alpha}}{f_o} = \frac{\tilde{\alpha}}{(\tilde{b}^2 + \tilde{\alpha}^2)^{1/2}} \qquad \text{(A14)}$$

Using equations (A7), (A8), (A13) and (A14) we get

pole	f_o	β
1	45.1	*
2,3	46.7	0.887
4,5	52.7	0.546

(A15)

These figures are given in Table 2. The asterisk denotes a single pole, for which the parameter β is not a descriptor.

Appendix B

Listing of program RESPONSE

```
C PROGRAM RESPONSE
C SEPTEMBER 1979--- MARY O'NEILL ALLEN
C
C
C THIS PROGRAM COMPUTES RESPONSE SPECTRA FROM GIVEN POLES.
C
C
C EXPLANATION OF THE COMPUTATIONS
C   MANY FUNCTIONS OF INTEREST IN SEISMOLOGY CAN BE APPROXIMATED BY
C   SIMPLE, EXPLICIT ALGEBRAIC EXPRESSIONS.  IN THE FREQUENCY DOMAIN
C   THESE FUNCTIONS HAVE THE FORM
C   G = WW**NL*I**(NL-N)/((WW-AL(1)*(WW-AL(2))---(WW-AL(N))), WHERE
C   G = COMPLEX SPECTRUM.
C   WW = ANGULAR FREQUENCY IN RADIANS/SECOND.
C   I = SQRT(-1.).
C   N = INTEGER CONSTANT = NUMBER OF POLES OF THE SPECTRUM.
C   NL = INTEGER CONSTANT = POWER OF THE LOW-FREQUENCY FALLOFF OF
C     THE AMPLITUDE SPECTRUM.
C   AL(J) = COMPLEX CONSTANTS = POLES OF THE SPECTRUM.
C   TO PRODUCE REAL, CAUSAL TIME-DOMAIN FUNCTIONS, THE POLES AL(J) MUST
C   BE PURELY IMAGINARY, AL(J) = I*Y(J), OR MUST OCCUR IN PAIRS,
C   AL(J) = +X(J)+I*Y(J), AL(J+1) = -X(J)+I*Y(J), WHERE X(J) AND Y(J)
C   ARE REAL, POSITIVE NUMBERS.
C   OTHER FUNCTIONS IN THIS PROGRAM RELATED TO G ARE AS FOLLOWS--
C   GM = AMPLITUDE SPECTRUM = ABS(G).
C   GP = PHASE SPECTRUM.
C   GMN = NORMALIZED AMPLITUDE SPECTRUM.
C   WK = FREQUENCY IN HERTZ.
C
C
C INPUT DATA
C
C   CARD 1
C     COL 1-80   TITLE   FORMAT(20A4)
C
C   CARD 2
C     THIS CARD SPECIFIES THE AMPLITUDE FACTOR FOR THE RESPONSE CURVE.
C     COL 1-10   AMP   FORMAT(E10.4)
C
C   CARDS 3 TO KK+2
C     THESE CARDS GIVE THE PARAMETERS OF THE SPECTRAL ELEMENTS THAT
C       MAKE UP THE COMPLETE SYSTEM RESPONSE.
C     COL 1-5   LTYPE   FORMAT(I5)
C       LTYPE = 1 OR 2.
C         LTYPE = 1 SPECIFIES A SPECTRAL ELEMENT WITH ONE POLE;
C         LTYPE = 2 SPECIFIES A SPECTRAL ELEMENT WITH TWO POLES.
C         NOTE: THE SUM OF LTYPE = N.
C     COL 6-10   LN   FORMAT(I5)
```

```
C        LN: POWER OF THE LCW-FREQUENCY FALLCFF OF THE SPECTRAL ELEMENT.
C          NOTE: THE SUM OF LN = NL.
C      COL 11-20    F    FCRMAT(F10.4)
C        F = CORNER FREQUENCY IN HERTZ.
C          F IS EQUIVALENT TO THE NATURAL FREQUENCY OF A HARMONIC
C          CSCILLATCR.
C      COL 21-30    B    FORMAT(F10.4)
C        B = REAL, PCSITIVE CONSTANT CHARACTERIZING THE SHAPE OF THE
C          SPECTRAL ELEMENT WHEN LTYPE = 2.  B IS EQUIVALENT TO THE
C          DAMPING CONSTANT OF A HARMONIC OSCILLATOR.
C          WHEN LTYPE = 1. B CAN BE LEFT BLANK.
C      COL 36-75    LABEL    FCRMAT(8A4)
C        LABEL = CCMMENTS ASSOCIATED WITH SPECTRAL ELEMENT.
C
C    CARD KK+3
C      BLANK CARD.
C
C    CARD KK+4
C      THIS CARD SPECIFIES THE SCALING FACTORS FCR THE SPECTRUM.
C      COL 1-5    KD    FORMAT(I5)
C        KD = NUMBER OF DECADES OF FREQUENCY.
C      CCL 6-15    WL    FCRMAT(F10.3)
C        WL = LOWEST FREQUENCY IN HERTZ.  WL MUST BE SOME POWER OF TEN.
C          FOR EXAMPLE. .1. 1.. OR 10.
C      COL 16-25    WF    FORMAT(F10.3)
C        WF = INCREMENT CF FREQUENCY IN EACH DECADE EXPRESSED AS
C          A MULTIPLE OF THE LOWEST FREQUENCY IN THAT DECADE.
C          FOR EXAMPLE, IN THE DECADE 1. TO 10.. WF = 1. GIVES THE
C          FREQUENCIES 1..2..3..---10.;
C          WF = 2. GIVES THE FREQUENCIES 1..3..5..7..9.;
C          WF = 0.5 GIVES THE FREQUENCIES 1.0.1.5.2.0.2.5.---10.0.
C
C    CARD KK+5
C      THIS CARD SPECIFIES IF ANOTHER DATA SET IS TO FOLLOW.
C      CCL 1-5    IEND    FORMAT(I5)
C        IEND = AN INTEGER .NE. 0 IF ANOTHER DATA SET FOLLOWS OR A BLANK
C          IF NO DATA SET FOLLOWS.
C
C
      COMPLEX I
      COMPLEX AL(20)
      REAL C(20)
      REAL GM(200)
      REAL GMN(200)
      REAL GP(200)
      REAL WK(200)
      DIMENSION LABEL(10)
      DIMENSION TITLE(20)
```

```
C
C
      I=(0.,1.)
      PI=3.14159265
C
    1 FORMAT(//)
    2 CONTINUE
C
C READ INPUT PARAMETERS.
C
      READ(5,3) TITLE
    3 FORMAT(20A4)
      WRITE(6,4) TITLE
    4 FORMAT('1',20A4)
      WRITF(6,1)
      READ(5,5) ANF
    5 FORMAT(E10.4)
      WRITE(6,6) AMP
    6 FCRMAT(//'    AMP =',E10.4,'         AMPLITUDE FACTOR')
      WRITE(6,1)
      WRITE(6,10)
   10 FORMAT(//,' LTYPE    LN        F              B          COMMENTS',/)
      J=0
      NL=0
   12 CONTINUE
      READ(5,13) LTYPE,LN,F,B,LABEL
   13 FORMAT(2I5,2F10.4,5X,10A4)
      IF(LTYPE.EQ.0) GO TC 20
      IF(LTYPE.EQ.2) GC TC 15
      WRITE(6,14) LTYPE,LN,F,LABEL
   14 FCRMAT(2I6,F12.4,17X,1CA4)
      NL=NL+LN
      J=J+1
      AL(J)=I*2.*PI*F
      C(J)=1.
      IF(LN.EQ.0) C(J)=2.*PI*F
      GC TO 12
   15 WRITE(6,16) LTYPE,LA,F,B,LABEL
   16 FORMAT(2I6,2F12.4,5X,1CA4)
      NL=NL+LN
      IF(B.GT.1.) GO TO 18
      J=J+1
      AL(J)=2.*PI*F*(I*E+SQRT((1.-B)*(1.+B)))
      C(J)=1.
      IF(LA.EQ.0) C(J)=2*PI*F
      J=J+1
      AL(J)=2.*PI*F*(I*E-SQRT((1.-B)*(1.+B)))
      C(J)=1.
```

```
      IF(LN.EQ.0) C(J)=2*PI*F
      GO TO 12
   18 CCNTINUE
      J=J+1
      AL(J)=2.*PI*F*I*(B+SQRT((B-1.)*(B+1.)))
      C(J)=1.
      IF(LN.EQ.0) C(J)=2*PI*F
      J=J+1
      AL(J)=2.*PI*F*I*(B-SQRT((B-1.)*(B+1.)))
      C(J)=1.
      IF(LN.EQ.0) C(J)=2*PI*F
      GC TO 12
   20 CONTINUE
      N=J
      C(1)=C(1)*AMP
      WRITE(6,1)
      WRITE(6,21) N
   21 FORMAT(/,'   N =',I3,'      NUMBER OF PCLES')
      WRITE(6,22) NL
   22 FORMAT(/,'   NL =',I3,'      POWER CF LCW-FREQUENCY FALLOFF',/)
      WRITE(6,1)
      WRITE(6,1000)
 1000 FORMAT(/,'    J                 AL                            C',/)
      DC 1002 J=1,N
      WRITE(6,1C01) J,AL(J),C(J)
 1001 FORMAT(I5,2F12.4,5X,F13.3)
 1002 CONTINUE
      WRITE(6,1)
      WRITE(6,1100)
      WRITE(6,1101)
      WRITE(6,1106)
 1100 FORMAT('        J = NUMBER OF POLE.')
 1101 FORMAT('        AL = COMPLEX NUMBER GIVING POLE POSITION IN RADIANS
     C/SECOND.')
 1106 FCRMAT('        C = AMPLITUDE CONSTANT ASSOCIATED WITH AL.')
C
C READ SCALING FACTORS.
C
      WRITE(6,32)
   32 FORMAT(/,'   SCALING FACTORS FOR SPECTRUM',//)
      READ(5,35) KD,WL,WF
   35 FORMAT(I5,2F10.3)
      WRITE(6,36) KD
   36 FORMAT('        KD = ',I3,'            KD = NUMBER OF DECADES OF FR
     1EQUENCY.')
      WRITE(6,37) WL
   37 FORMAT('        WL =',F10.3,'       WL = LOWEST FREQUENCY IN HERTZ.'
     1)
```

```
0094           WRITE(6,38) WF
0095        38 FORMAT('         WF =',F10.3,'      WF = INCREMENT OF FREQUENCY IN E
              1ACH DECADE.')
0096           WRITE(6,1)
         C
         C COMPUTE THE RESPONSE SPECTRUM.
         C
0097           CALL SP(N,NL,AL,C,GM,GP,WK,KD,WL,WF,KS)
0098           CALL NORM(GM,GMN,GMMAX,KS,KMAX)
0099           CALL PTSP(GM,GMN,GP,WK,KS)
0100       200 CONTINUE
         C
         C CHECK IF MORE DATA FOLLOWS.
         C
0101           WRITE(6,1)
0102           READ(5,205) IEND
0103       205 FORMAT(I5)
0104           WRITE(6,210) IEND
0105       210 FORMAT('    IEND =',I5)
0106           IF (IEND.EQ.0) GO TO 300
0107           GO TO 2
0108       300 CONTINUE
0109           RETURN
0110           END
```

```
0001          SUBROUTINE SP(N,NL,AL,C,GM,GP,WK,KD,WL,WF,KS)
        C
        C THIS SUBROUTINE COMPUTES AN AMPLITUDE SPECTRUM AND A PHASE SPECTRUM
        C   FROM GIVEN PCLES.
        C
        C   N--NUMBER OF PCLES OF THE SPECTRUM.
        C   NL--LOW-FREQUENCY FALLOFF OF THE SPECTRUM.
        C   AL(J)--PCLES CF THE SPECTRUM.
        C   C(J)--CONSTANT ASSOCIATED WITH AL(J).
        C   GM(K)--AMPLITUDE SPECTRUM.
        C   GP(K)--PHASE SPECTRUM.
        C   WK(K)--FREQLENCY IN HERTZ.
        C   KD--NUMBER OF DECADES CF FREQUENCY.
        C   WL--LOWEST FREQUENCY IN HERTZ.  WL MUST BE SOME POWER OF TEN.
        C   WF--INCREMENT CF FREQUENCY IN EACH DECADE EXPRESSED AS FRACTION
        C     CF LOWEST FREQUENCY IN THAT DECADE.
        C   KS--NUMBER OF SPECTRAL POINTS.  THIS NUMBER IS COMPUTED IN THE
        C     SUBROUTINE.
        C
0002          COMPLEX I
0003          COMPLEX AL(20)
0004          COMPLEX G
0005          REAL C(20)
0006          REAL GM(200)
0007          REAL GP(200)
0008          REAL WK(200)
        C
0009          I=(0.,1.)
0010          PI=3.14159265
        C
        C COMPUTE FREQUENCY VALUES WK(K).
        C
0011          K=0
0012          WB=WL
0013          WM=WL*10.
0014          WQ=WB
0015          DO 20 M=1,KD
0016          K=K+1
0017          WK(K)=WQ
0018       10 CONTINUE
0019          WQ=WQ+WF*WB
0020          IF (WM.LE.WQ) GO TO 15
0021          K=K+1
0022          WK(K)=WQ
0023          GO TO 10
0024       15 WB=WB*10.
0025          WM=WM*10.
0026          WQ=WM
```

```
0027          20 CCNTINUE
C028             KS=K
            C
            C COMPUTE AMPLITUDE SPECTRUM GM(K) AND PHASE SPECTRUM GP(K).
            C
0029             DC 40 K=1,KS
C030             WW=2.*PI*WK(K)
0031             G=WW**NL*I**(NL-N)
0032             DC 30 J=1,N
C033             G=G*C(J)/(WW-AL(J))
0034          30 CONTINUE
0035             GM(K)=CABS(G)
C036             GR=REAL(G)
0037             GI=AIMAG(G)
0038             GP(K)=ATAN(GI/GR)
CC39             IF(GR.LT.0.) GF(K)=GP(K)+PI
C040             IF(GP(K).LT.0.) GP(K)=GP(K)+2.*PI
C041          40 CONTINUE
C042             RETURN
C043             END
```

```
001           SUBROUTINE NORM(A,AN,AMAX,MM,MMAX)
          C
          C THIS SUBROUTINE COMPUTES NORMALIZED VALUES OF A FUNCTION.
          C
          C    A(M)--VALUES OF FUNCTION.
          C    AN(M)--NORMALIZED VALUES OF FUNCTION.
          C    AMAX--MAXIMUM ABSOLUTE VALUE OF A(M).
          C    MM--NUMBER OF POINTS.
          C    MMAX--POINT NUMBER CORRESPONDING TO AMAX.
          C
002           REAL A(500)
003           REAL AN(500)
          C
004           AMAX=0.
005           MMAX=0
006           DO 10 M=1,MM
007           AA=ABS(A(M))
008           IF(AA.LE.AMAX) GO TO 10
009           AMAX=AA
0010          MMAX=M
0011       10 CONTINUE
0012          DO 20 M=1,MM
0013          AN(M)=A(M)/AMAX
0014       20 CONTINUE
0015          RETURN
0016          END
```

```
)001            SUBROUTINE PTSP(GM,GMN,GP,WK,KS)
          C
          C THIS SUBROUTINE PRINTS THE COMPUTED VALUES OF THE AMPLITUDE SPECTRUM
          C   AND THE PHASE SPECTRUM PLUS THE NORMALIZED VALUES OF THE AMPLITUDE
          C   SPECTRUM.
          C
          C   GM(K)--AMPLITUDE SPECTRUM.
          C   GMN(K)--NORMALIZED AMPLITUDE SPECTRUM.
          C   GP(K)--PHASE SPECTRUM.
          C   WK(K)--FREQUENCY IN HERTZ.
          C   KS--NUMBER OF SPECTRAL POINTS.
          C
0002            REAL GM(200)
C0J3            REAL GMN(200)
C004            REAL GP(200)
C005            REAL WK(200)
          C
C006            WRITE(6,2)
0007          2 FORMAT('1   AMPLITUDE SPECTRUM')
C008            WRITE(6,5)
0009          5 FORMAT(//,'    WK (HZ)          GM              GMN              GP',/)
C010            DO 20 K=1,KS
0011            WRITE(6,10) WK(K),GM(K),GMN(K),GP(K)
0012         10 FORMAT(4E13.3)
0013         20 CONTINUE
C014            WRITE(6,25)
C015         25 FORMAT(//)
0016            RETURN
0017            END
```

Input to program RESPONSE:

```
USGS SEISMOGRAPHIC SYSTEM RESPONSE: ECLIPSE OUTPUT (VOLTS)
 .498E+6
  2    3     1.0        .8       SEISMOMETER
  2    2      .095     1.0       AMPLIFIER
  2    0    44.        1.0       AMPLIFIER
  1    0    45.069     1.0       TRI-COM DISCRIMINATOR
  2    0    46.688      .887     TRI-COM DISCRIMINATOR
  2    0    52.660      .546     TRI-COM DISCRIMINATOR

  3       .1         .2
```

(last record is blank)

USGS SEISMOGRAPHIC SYSTEM RESPONSE: ECLIPSE OUTPUT (VOLTS)

AMP =0.4980E+06 AMPLITUDE FACTOR

LTYPE	LN	F	B	COMMENTS
2	3	1.0000	0.8000	SEISMOMETER
2	2	0.0950	1.0000	AMPLIFIER
2	0	44.0000	1.0000	AMPLIFIER
1	0	45.0650		TRI-COM DISCRIMINATOR
2	0	46.6860	0.8870	TRI-COM DISCRIMINATOR
2	0	52.6600	0.5460	TRI-COM DISCRIMINATOR

N = 11 NUMBER OF POLES

NL = 5 POWER OF LOW-FREQUENCY FALLOFF

J	AL		C
1	3.7699	5.0265	498000.000
2	-3.7699	5.0265	1.000
3	0.0	0.5969	1.000
4	0.0	0.5969	1.000
5	0.0	276.4600	276.460
6	0.0	276.4600	276.460
7	0.0	283.1768	283.177
8	135.4596	260.2004	293.349
9	-135.4596	260.2004	293.349
10	277.1997	180.6563	330.872
11	-277.1997	180.6563	330.872

J = NUMBER OF POLE.
AL = COMPLEX NUMBER GIVING POLE POSITION IN RADIANS/SECOND.
C = AMPLITUDE CONSTANT ASSOCIATED WITH AL.

SCALING FACTORS FOR SPECTRUM

KD = 3 KD = NUMBER OF DECADES OF FREQUENCY.
WL = 0.100 WL = LOWEST FREQUENCY IN HERTZ.
WF = 0.200 WF = INCREMENT OF FREQUENCY IN EACH DECADE.

AMPLITUDE SPECTRUM

WK (HZ)	GN	GMN	GP
0.100E+00	0.164E+04	0.352E-04	0.606E+01
0.120E+00	0.331E+04	0.710E-04	0.584E+01
0.140E+00	0.585E+04	0.125E-03	0.566E+01
0.160E+00	0.941E+04	0.202E-03	0.551E+01
0.180E+00	0.141E+05	0.303E-03	0.537E+01
0.200E+00	0.202E+05	0.433E-03	0.525E+01
0.220E+00	0.277E+05	0.593E-03	0.515E+01
0.240E+00	0.367E+05	0.788E-03	0.505E+01
0.260E+00	0.475E+05	0.102E-02	0.496E+01
0.280E+00	0.601E+05	0.129E-02	0.488E+01
0.300E+00	0.746E+05	0.160E-02	0.480E+01
0.320E+00	0.912E+05	0.195E-02	0.473E+01
0.340E+00	0.110E+06	0.235E-02	0.466E+01
0.360E+00	0.131E+06	0.280E-02	0.460E+01
0.380E+00	0.154E+06	0.330E-02	0.454E+01
0.400E+00	0.179E+06	0.385E-02	0.448E+01
0.420E+00	0.207E+06	0.445E-02	0.442E+01
0.440E+00	0.238E+06	0.510E-02	0.436E+01
0.460E+00	0.271E+06	0.580E-02	0.431E+01
0.480E+00	0.306E+06	0.656E-02	0.426E+01
0.500E+00	0.344E+06	0.738E-02	0.421E+01
0.520E+00	0.385E+06	0.825E-02	0.416E+01
0.540E+00	0.428E+06	0.917E-02	0.411E+01
0.560E+00	0.473E+06	0.101E-01	0.406E+01
0.580E+00	0.521E+06	0.112E-01	0.401E+01
0.600E+00	0.571E+06	0.122E-01	0.397E+01
0.620E+00	0.624E+06	0.134E-01	0.392E+01
0.640E+00	0.679E+06	0.145E-01	0.388E+01
0.660E+00	0.736E+06	0.158E-01	0.383E+01
0.680E+00	0.795E+06	0.170E-01	0.379E+01
0.700E+00	0.856E+06	0.183E-01	0.375E+01
0.720E+00	0.919E+06	0.197E-01	0.371E+01
0.740E+00	0.984E+06	0.211E-01	0.367E+01
0.760E+00	0.105E+07	0.225E-01	0.363E+01
0.780E+00	0.112E+07	0.240E-01	0.359E+01
0.800E+00	0.119E+07	0.255E-01	0.355E+01
0.820E+00	0.126E+07	0.270E-01	0.351E+01
0.840E+00	0.133E+07	0.285E-01	0.348E+01
0.860E+00	0.140E+07	0.301E-01	0.344E+01
0.880E+00	0.148E+07	0.317E-01	0.340E+01
0.900E+00	0.155E+07	0.333E-01	0.337E+01
0.920E+00	0.163E+07	0.349E-01	0.334E+01
0.940E+00	0.170E+07	0.365E-01	0.330E+01
0.960E+00	0.178E+07	0.382E-01	0.327E+01
0.990E+00	0.186E+07	0.398E-01	0.324E+01
0.100E+01	0.194E+07	0.415E-01	0.320E+01
0.100E+01	0.194E+07	0.415E-01	0.320E+01
0.120E+01	0.272E+07	0.584E-01	0.292E+01
0.140E+01	0.350E+07	0.750E-01	0.270E+01
0.160E+01	0.425E+07	0.911E-01	0.251E+01
0.180E+01	0.497E+07	0.107E+00	0.236E+01
0.200E+01	0.567E+07	0.122E+00	0.223E+01
0.220E+01	0.636E+07	0.136E+00	0.212E+01
0.240E+01	0.703E+07	0.151E+00	0.203E+01
0.260E+01	0.768E+07	0.165E+00	0.194E+01

0.280E+01	0.813E+07	0.179E+00	0.186E+01
0.300E+01	0.898E+07	0.192E+00	0.180E+01
0.320E+01	0.961E+07	0.206E+00	0.173E+01
0.340E+01	0.102E+08	0.220E+00	0.167E+01
0.360E+01	0.109E+08	0.233E+00	0.162E+01
0.380E+01	0.115E+08	0.246E+00	0.157E+01
0.400E+01	0.121E+08	0.259E+00	0.152E+01
0.420E+01	0.127E+08	0.273E+00	0.147E+01
0.440E+01	0.133E+08	0.286E+00	0.142E+01
0.460E+01	0.139E+08	0.298E+00	0.138E+01
0.480E+01	0.145E+08	0.311E+00	0.134E+01
0.500E+01	0.151E+08	0.324E+00	0.130E+01
0.520E+01	0.157E+08	0.337E+00	0.126E+01
0.540E+01	0.163E+08	0.349E+00	0.122E+01
0.560E+01	0.169E+08	0.362E+00	0.119E+01
0.580E+01	0.175E+08	0.374E+00	0.115E+01
0.600E+01	0.180E+08	0.387E+00	0.111E+01
0.620E+01	0.186E+08	0.399E+00	0.108E+01
0.640E+01	0.192E+08	0.411E+00	0.104E+01
0.660E+01	0.197E+08	0.423E+00	0.101E+01
0.680E+01	0.203E+08	0.435E+00	0.978E+00
0.700E+01	0.209E+08	0.447E+00	0.945E+00
0.720E+01	0.214E+08	0.459E+00	0.913E+00
0.740E+01	0.220E+08	0.471E+00	0.881E+00
0.760E+01	0.225E+08	0.482E+00	0.850E+00
0.780E+01	0.230E+08	0.494E+00	0.819E+00
0.800E+01	0.236E+08	0.505E+00	0.788E+00
0.820E+01	0.241E+08	0.516E+00	0.757E+00
0.840E+01	0.246E+08	0.528E+00	0.727E+00
0.860E+01	0.251E+08	0.539E+00	0.697E+00
0.880E+01	0.256E+08	0.550E+00	0.668E+00
0.900E+01	0.261E+08	0.560E+00	0.638E+00
0.920E+01	0.266E+08	0.571E+00	0.609E+00
0.940E+01	0.271E+08	0.582E+00	0.580E+00
0.960E+01	0.276E+08	0.592E+00	0.551E+00
0.980E+01	0.281E+08	0.603E+00	0.522E+00
0.100E+02	0.286E+08	0.613E+00	0.494E+00
0.100E+02	0.286E+08	0.613E+00	0.494E+00
0.120E+02	0.331E+08	0.709E+00	0.217E+00
0.140E+02	0.370E+08	0.792E+00	0.623E+01
0.160E+02	0.402E+08	0.861E+00	0.597E+01
0.180E+02	0.428E+08	0.916E+00	0.572E+01
0.200E+02	0.447E+08	0.957E+00	0.547E+01
0.220E+02	0.459E+08	0.984E+00	0.523E+01
0.240E+02	0.466E+08	0.998E+00	0.499E+01
0.260E+02	0.467E+08	0.100E+01	0.475E+01
0.280E+02	0.462E+08	0.990E+00	0.452E+01
0.300E+02	0.453E+08	0.971E+00	0.429E+01
0.320E+02	0.440E+08	0.942E+00	0.406E+01
0.340E+02	0.423E+08	0.906E+00	0.384E+01
0.360E+02	0.403E+08	0.864E+00	0.362E+01
0.380E+02	0.381E+08	0.816E+00	0.341E+01
0.400E+02	0.357E+08	0.765E+00	0.320E+01
0.420E+02	0.332E+08	0.711E+00	0.300E+01
0.440E+02	0.306E+08	0.656E+00	0.280E+01
0.460E+02	0.280E+08	0.600E+00	0.260E+01
0.480E+02	0.255E+08	0.546E+00	0.241E+01
0.500E+02	0.230E+08	0.494E+00	0.223E+01
0.520E+02	0.207E+08	0.444E+00	0.206E+01
0.540E+02	0.185E+08	0.397E+00	0.189E+01

0.560E+02	0.165E+08	0.354E+00	0.173E+01
0.580E+02	0.147E+08	0.314E+00	0.157E+01
0.600E+02	0.130E+08	0.279E+00	0.143E+01
0.620E+02	0.115E+08	0.246E+00	0.129E+01
0.640E+02	0.101E+08	0.214E+00	0.115E+01
0.660E+02	0.895E+07	0.192E+00	0.103E+01
0.680E+02	0.789E+07	0.169E+00	0.909E+00
0.700E+02	0.656E+07	0.149E+00	0.795E+00
0.720E+02	0.614E+07	0.132E+00	0.687E+00
0.740E+02	0.542E+07	0.116E+00	0.585E+00
0.760E+02	0.479E+07	0.103E+00	0.487E+00
0.780E+02	0.423E+07	0.908E-01	0.395E+00
0.800E+02	0.375E+07	0.803E-01	0.306E+00
0.820E+02	0.332E+07	0.712E-01	0.222E+00
0.840E+02	0.295E+07	0.632E-01	0.142E+00
0.860E+02	0.262E+07	0.562E-01	0.656E-01
0.880E+02	0.233E+07	0.500E-01	0.628E+01
0.900E+02	0.208E+07	0.436E-01	0.621E+01
0.920E+02	0.186E+07	0.398E-01	0.614E+01
0.940E+02	0.166E+07	0.356E-01	0.607E+01
0.960E+02	0.149E+07	0.319E-01	0.601E+01
0.980E+02	0.133E+07	0.286E-01	0.595E+01
0.100E+03	0.120E+07	0.257E-01	0.590E+01

IEND = 0

Captions for Figures

Figure

1. Block diagram of USGS short-period telemetered seismic system, showing standard amplitude factors and sensitivity settings. (Modified from Eaton, 1977).

2. Stylized amplitude response of individual components and combinations of components used in USGS short-period telemetered seismic network in central California. (Modified from Eaton, 1977).

3. Normalized amplitude response curves for spectral elements with a single pole. Note that the parameter β is not a factor in the response. (From Healy and O'Neill, 1977).

4. Normalized amplitude response curves for spectral elements with paired poles and low-pass filter characteristic. Note the effect of β on the family of curves. (From Healy and O'Neill, 1977).

5. Normalized amplitude response curves for spectral elements with paired poles and high-pass filter characteristic. Note the effect of β on the family of curves. (From Healy and O'Neill, 1977).

6. Theoretical displace-ment, / velocity and acceleration response curves for an electromagnetic seismometer with 1 Hz natural frequency and damping coefficient (β) of 0.8 critical. (From Healy and O'Neill, 1977).

7. Observed and calculated normalized response curves for the J302M and J402 seismic amplifiers. Solid lines represent the observed responses. Dashed lines represent the response calculated from data in Dratler (1980) and in this report. The asterisks (*) denote single poles, for which the parameter β does not apply.

8. Observed normalized response curves for the Develco, Tri-Com, J101A and J101B seismic discriminators. The dips between 1 and 10 Hz represent inaccurate measurements in calibrating the Develco discriminator caused by excessive 60 Hz noise superposed on the output signal.

9. Observed and calculated normalized response curves for the J101A seismic discriminator. The two curves are so close that they cannot be distinguished from one another at this scale. The asterisk (*) denotes a single pole, for which the parameter β does not apply.

10. Observed and calculated normalized response curves for the J101B seismic discriminator. The two curves are so close that they cannot be distinguished from one another at this scale.

11. Observed and calculated normalized response curves for the Develco seismic discriminator.

12. Observed and calculated normalized response curves for the Tri-Com (4x) seismic discriminator. The two curves are so close that they

cannot be distinguished from one another at this scale. The asterisk (*) denotes a single pole, for which the parameter β does not apply.

13. Observed and calculated normalized response curves for the Develocorder 16-mm film recording system. The effect of the high-pass microseism rejection filter is included. The asterisk (*) denotes a single pole, for which the parameter β does not apply.

14. Observed and calculated normalized response curves for the Helicorder drum recording system. The effect of the high-pass filter is included. The asterisks (*) denote single poles, for which the parameter β does not apply.

15. Observed and calculated normalized response curves for the 12 dB/octave low-pass filters. These filters are used optionally with playbacks to the Siemens oscillograph. The abscissa (frequency) is normalized to 1 Hz such that the response of the filter at a selected filter setting (FS) and filter multiplier (FM) can be obtained by rescaling the abscissa by the product of the two (FS x FM).

16. Normalized response curves, for three sets each, of the combination of a J402 amplifier/VCO unit and a Develco discriminator. The solid lines are the three observed responses. The dashed line is the response calculated from the individual response characteristics given in Table 2 and then combined using the computer program RESPONSE.

17. The curved line is the complete system magnification response calculated by program RESPONSE for the system components as shown. The straight line is the product of the appropriate amplitude factors in Table 2 (see Section 4), taking into account the displacement response characteristic of the electromagnetic seismometer. This configuration of components is most commonly used for playbacks to the Siemens oscillograph at a time compression of 1x.

18. The two curved lines are the complete system magnification responses calculated by program RESPONSE for the system components and low-pass filter setting as shown. The straight line is the product of the appropriate amplitude factors in Table 2 (see Section 4), taking into account the displacement response characteristic of the electromagnetic seismometer. This configuration of components is commonly used for playbacks to the Siemens oscillograph at a time compression of 4x. Use of the low-pass filter is optional.

19. The three curved lines are the complete system magnification responses calculated by program RESPONSE for the system components as shown. The straight line is the product of the appropriate amplitude factors in Table 2 (see Section 4), taking into account the diplacement response characteristic of the electromagnetic seismometer. This configuration of components is the standard used in the USGS Central California Microearthquake Network for scanning and timing the 16-mm films.

20. The curved line is the complete system magnification response calculated by program RESPONSE for the system components as shown. The straight line is the product of the appropriate amplitude factors in Table 2 (see Section 4), taking into account the displacement response characteristic of the electromagnetic seismometer. This configuration of components represents the voltage output from the Tri-Com discriminator at time compression factors of 1x, 4x, or 16x. Its most common use is for input to the analog-to-digital converter of the Eclipse digitizing system. Note that the ordinate is in units of volts output per meter of ground displacement.

21. The curved line is the complete system magnification response calculated by program RESPONSE for the system components as shown. The straight line is the product of the appropriate amplitude factors in Table 2 (see Section 4), taking into account the displacement characteristic of the electromagnetic seismometer. This configuration of components is the standard used in the USGS Central California Microearthquake Network for the Helicorder drum recorder.

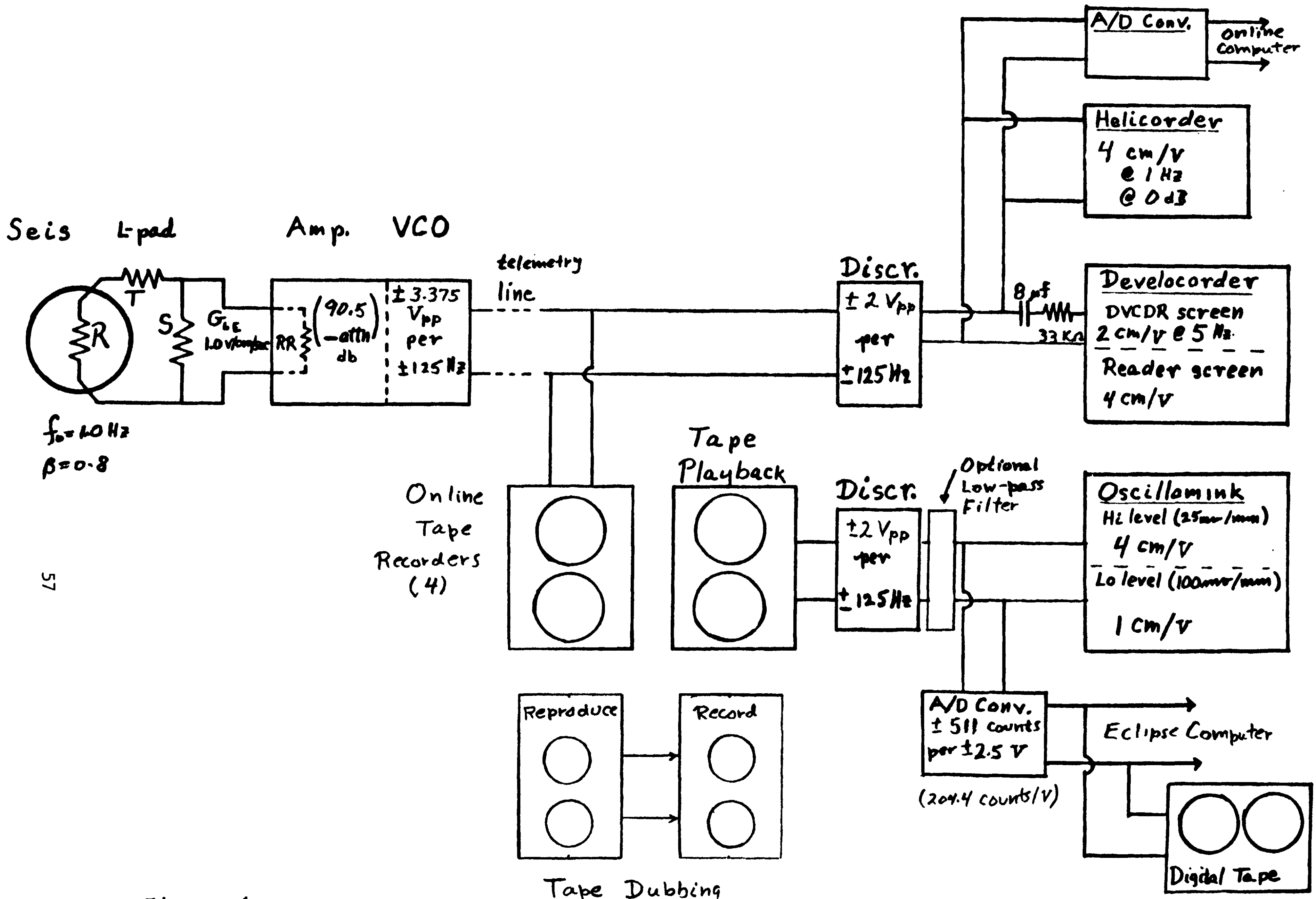

Seis
L-pad
Amp.
VCO
R
T
S
G_{LE}
RR
(90.5 —attn) db
± 3.375 V_{pp} per ±125 Hz
f_0 = 1.0 Hz
β = 0.8
telemetry line
Discr.
± 2 V_{pp} per ±125 Hz
A/D Conv.
online Computer
Helicorder
4 cm/V @ 1 Hz @ 0 dB
8 μf
33 KΩ
Develocorder
DVCDR screen 2 cm/V @ 5 Hz
Reader screen 4 cm/V
Online Tape Recorders (4)
Tape Playback
Discr.
±2 V_{pp} per ±125 Hz
Optional Low-pass Filter
Oscillomink
Hi level (25mv/mm) 4 cm/V
Lo level (100mv/mm) 1 cm/V
A/D Conv. ± 511 counts per ±2.5 V
(204.4 counts/V)
Eclipse Computer
Digital Tape
Reproduce
Record
Tape Dubbing

Figure 1

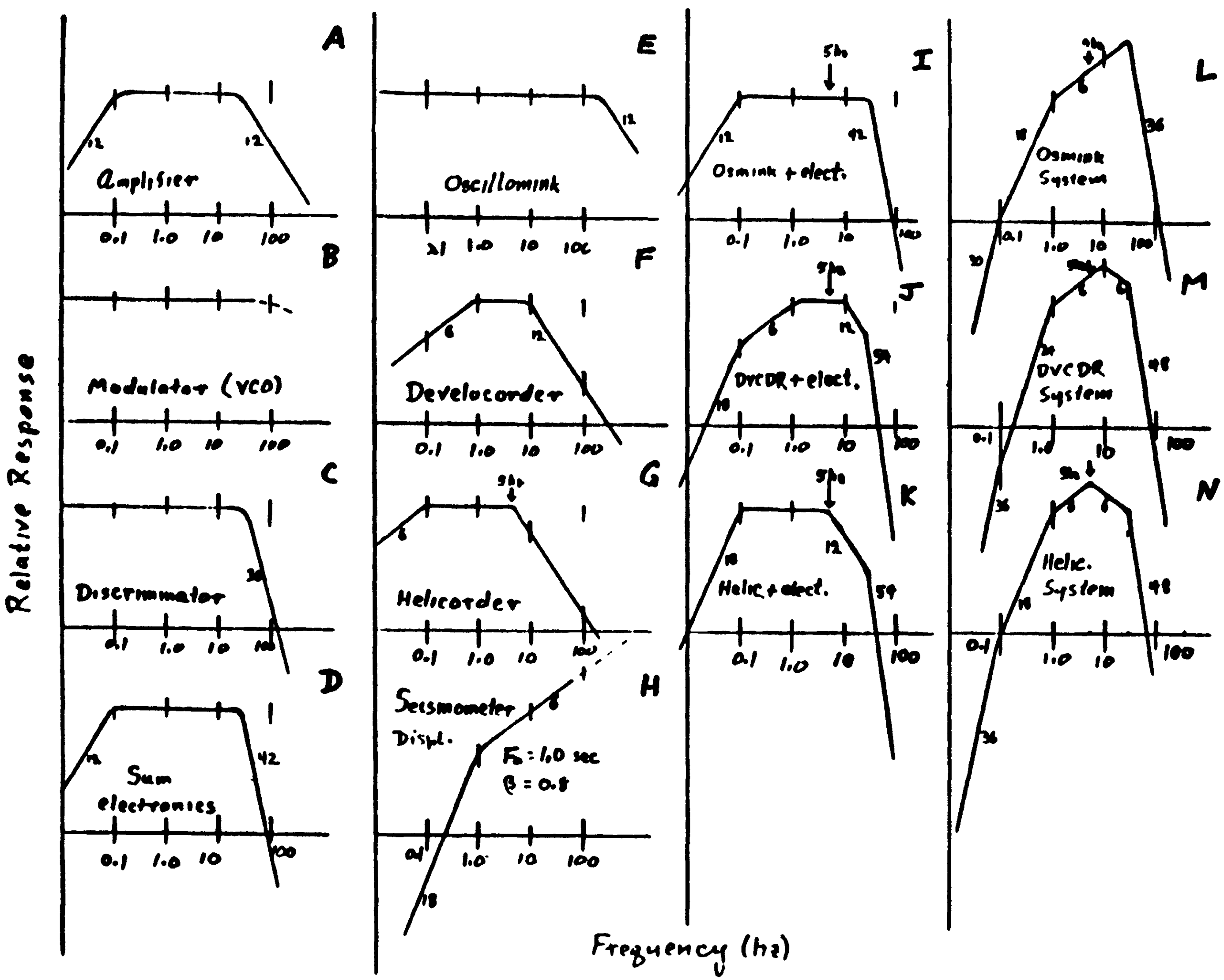

Relative Response
Frequency (hz)
A
Amplifier
B
Modulator (VCO)
C
Discriminator
D
Sum electronics
E
Oscillomink
F
Develocorder
G
Helicorder
H
Seismometer Displ.
F_0 = 1.0 sec
β = 0.8
I
Osmink + elect.
J
DVCDR + elect.
K
Helic. + elect.
L
Osmink System
M
DVCDR System
N
Helic. System
0.1
1.0
10
100

Figure 2

Elementary response functions, L = 0 and L = 1.

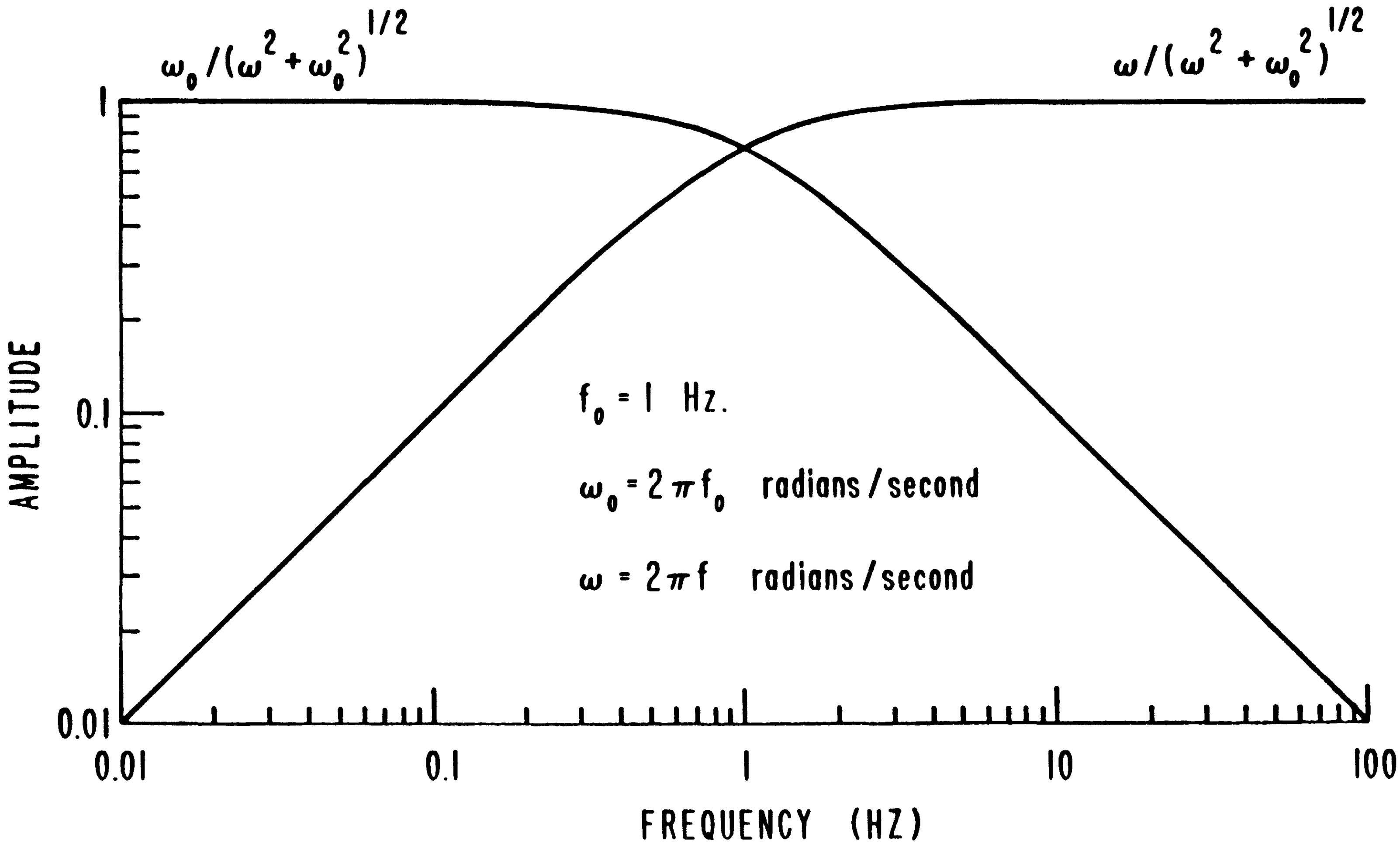
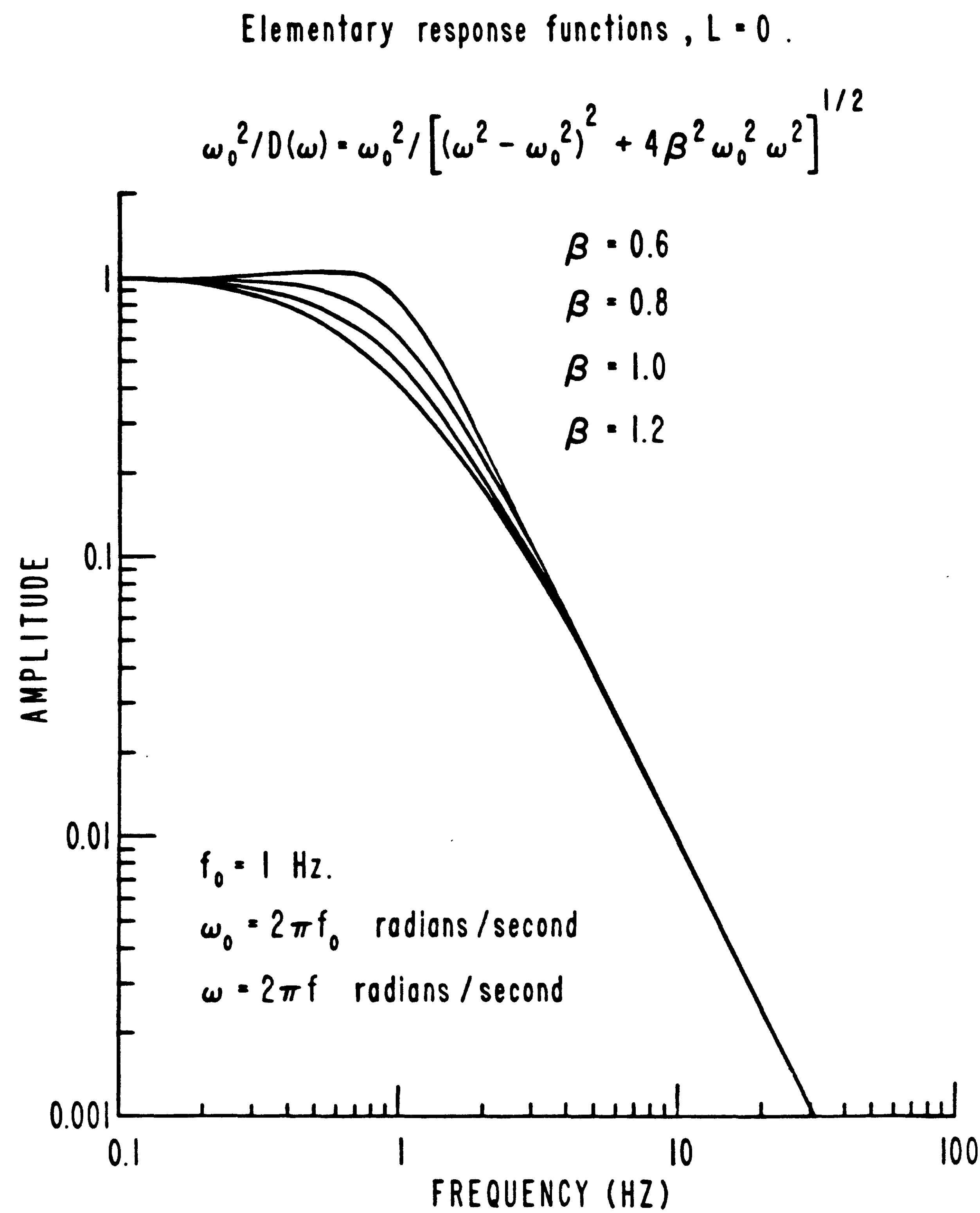
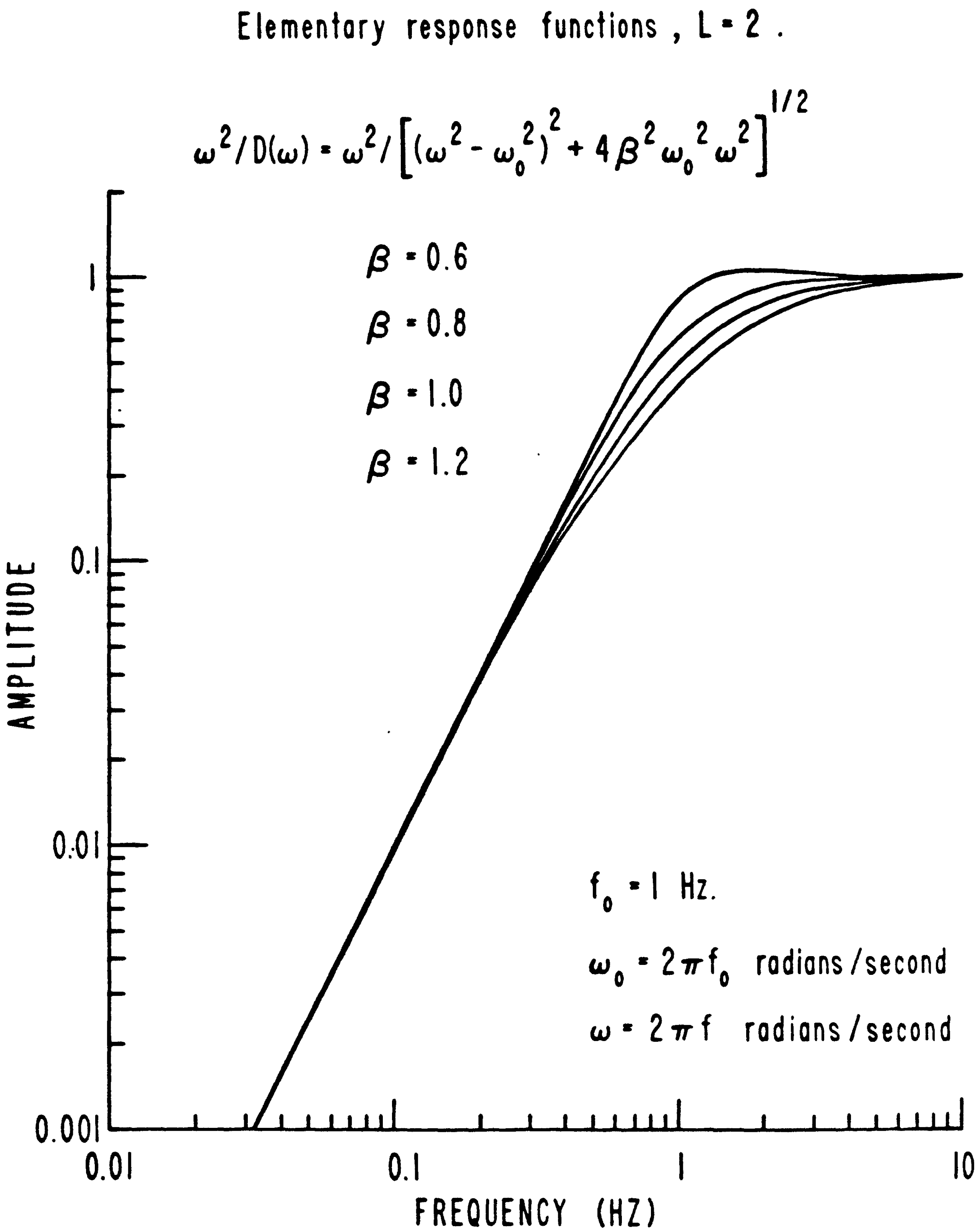


Figure 3



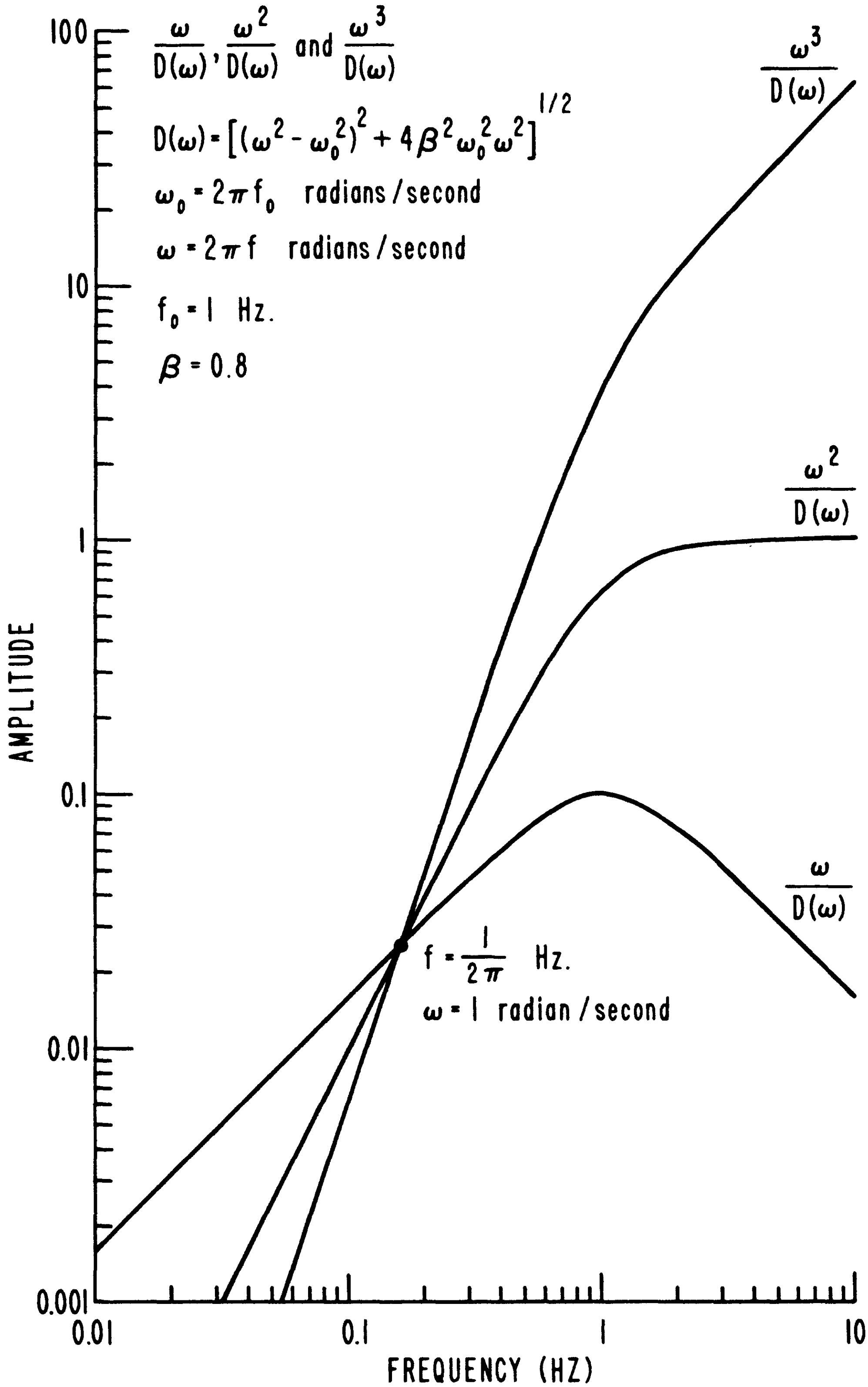
Elementary response functions, L = 0.
$\omega_0^2/D(\omega) = \omega_0^2/\left[(\omega^2 - \omega_0^2)^2 + 4\beta^2\omega_0^2\omega^2\right]^{1/2}$
β = 0.6
β = 0.8
β = 1.0
β = 1.2
1
0.1
0.01
0.001
AMPLITUDE
f_0 = 1 Hz.
$\omega_0 = 2\pi f_0$ radians / second
$\omega = 2\pi f$ radians / second
0.1
1
10
100
FREQUENCY (HZ)

Figure 4



Elementary response functions, L = 2.
$\omega^2/D(\omega) = \omega^2/\left[(\omega^2 - \omega_0^2)^2 + 4\beta^2\omega_0^2\omega^2\right]^{1/2}$
$\beta = 0.6$
$\beta = 0.8$
$\beta = 1.0$
$\beta = 1.2$
$f_0 = 1$ Hz.
$\omega_0 = 2\pi f_0$ radians/second
$\omega = 2\pi f$ radians/second
AMPLITUDE
1
0.1
0.01
0.001
0.01
0.1
1
10
FREQUENCY (HZ)

Figure 5



$\frac{\omega}{D(\omega)}$, $\frac{\omega^2}{D(\omega)}$ and $\frac{\omega^3}{D(\omega)}$
$D(\omega) = \left[(\omega^2 - \omega_0^2)^2 + 4\beta^2\omega_0^2\omega^2\right]^{1/2}$
$\omega_0 = 2\pi f_0$ radians/second
$\omega = 2\pi f$ radians/second
$f_0 = 1$ Hz.
$\beta = 0.8$
$\frac{\omega^3}{D(\omega)}$
$\frac{\omega^2}{D(\omega)}$
$\frac{\omega}{D(\omega)}$
$f = \frac{1}{2\pi}$ Hz.
$\omega = 1$ radian/second
AMPLITUDE
FREQUENCY (HZ)
100
10
1
0.1
0.01
0.001
0.01
0.1
1
10

Figure 6

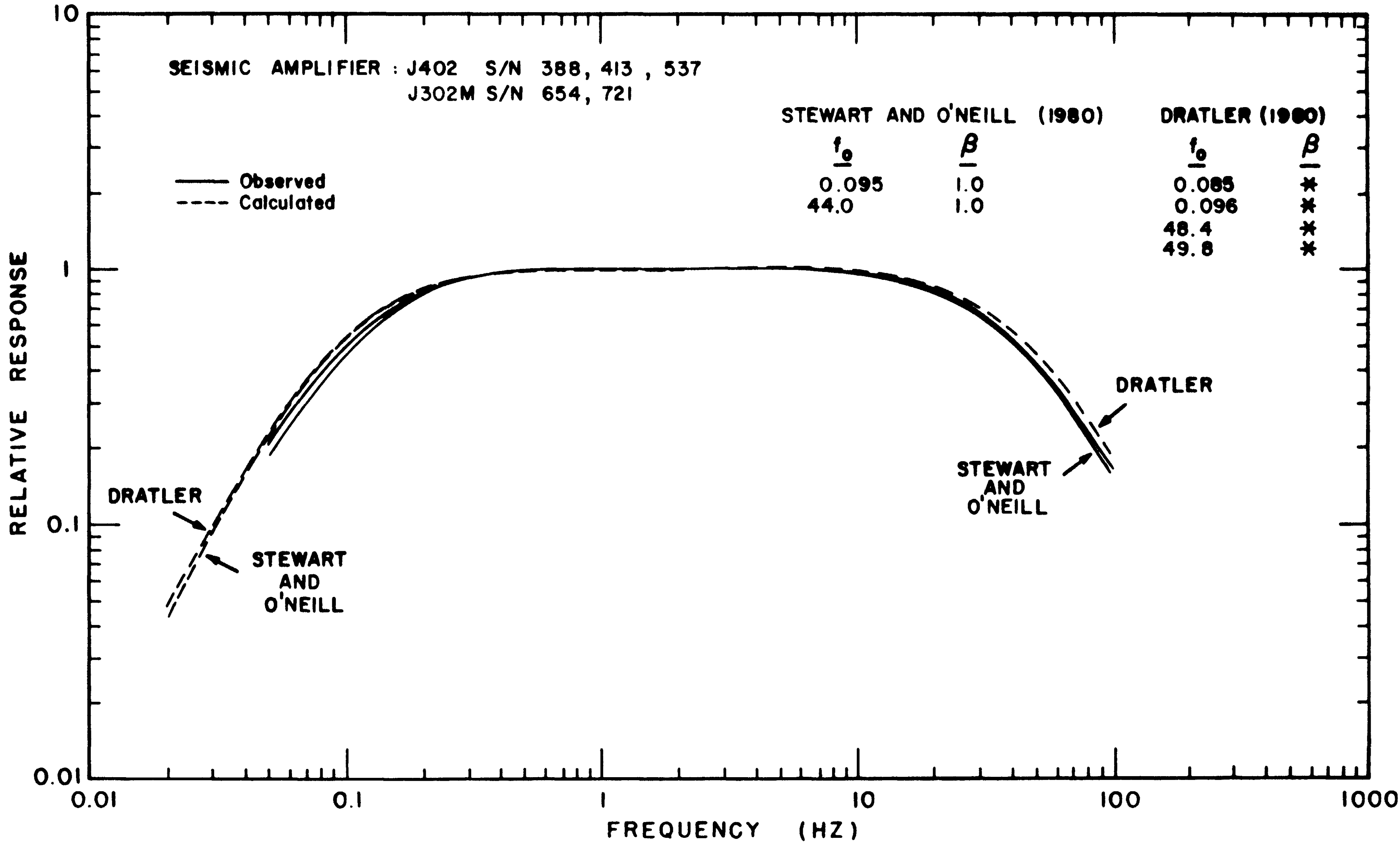

SEISMIC AMPLIFIER : J402 S/N 388, 413 , 537
J302M S/N 654, 721
Observed
Calculated
STEWART AND O'NEILL (1980)
f_o β
0.095 1.0
44.0 1.0
DRATLER (1980)
f_o β
0.085 *
0.096 *
48.4 *
49.8 *
DRATLER
STEWART AND O'NEILL
DRATLER
STEWART AND O'NEILL
RELATIVE RESPONSE
10
1
0.1
0.01
0.01
0.1
1
10
100
1000
FREQUENCY (HZ)

Figure 7

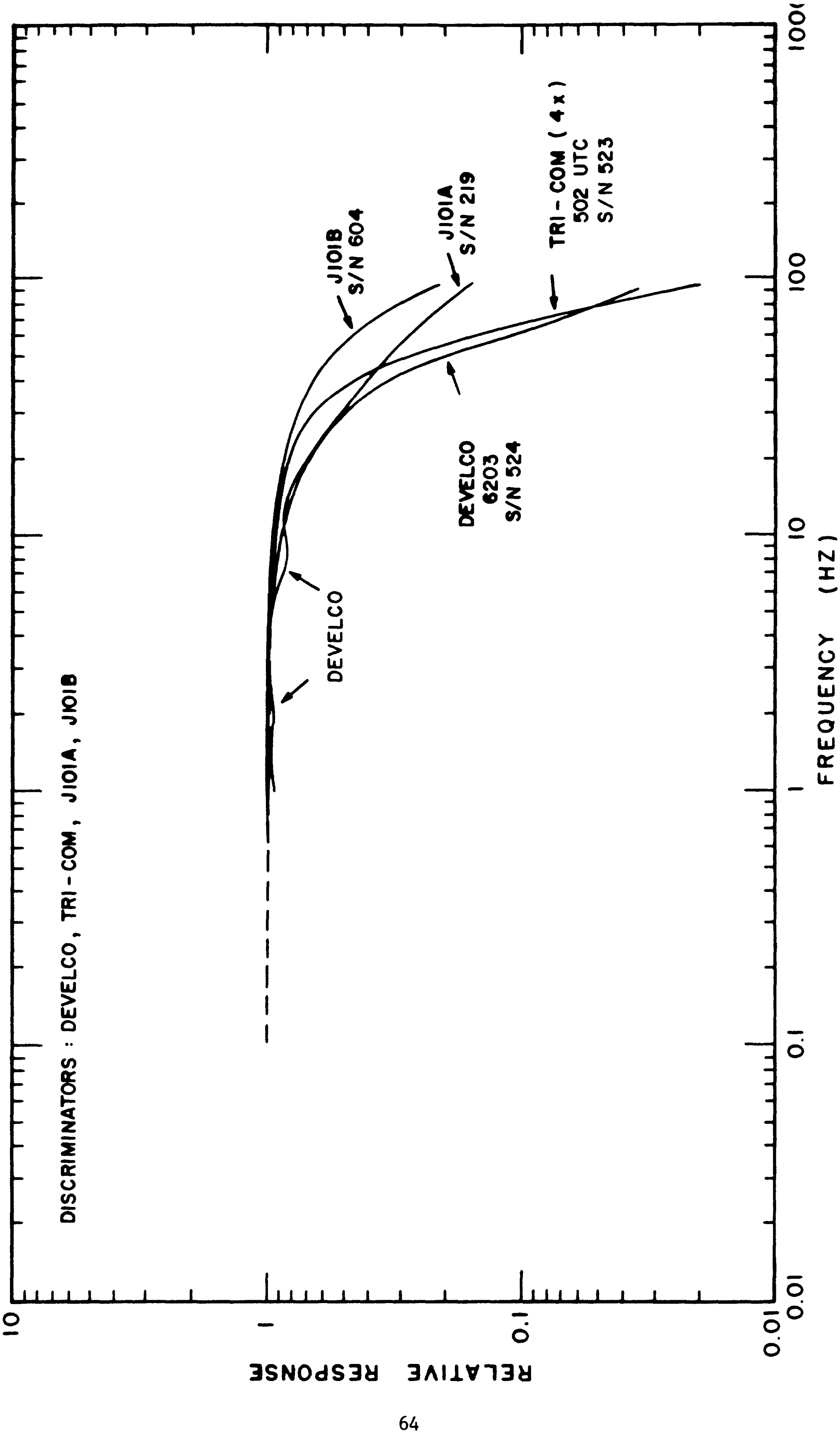

DISCRIMINATORS : DEVELCO, TRI-COM, J101A, J101B
J101B
S/N 604
J101A
S/N 219
TRI-COM (4x)
502 UTC
S/N 523
DEVELCO
6203
S/N 524
DEVELCO
10
1
0.1
0.01
RELATIVE RESPONSE
0.01
0.1
1
10
100
1000
FREQUENCY (HZ)

Figure 8

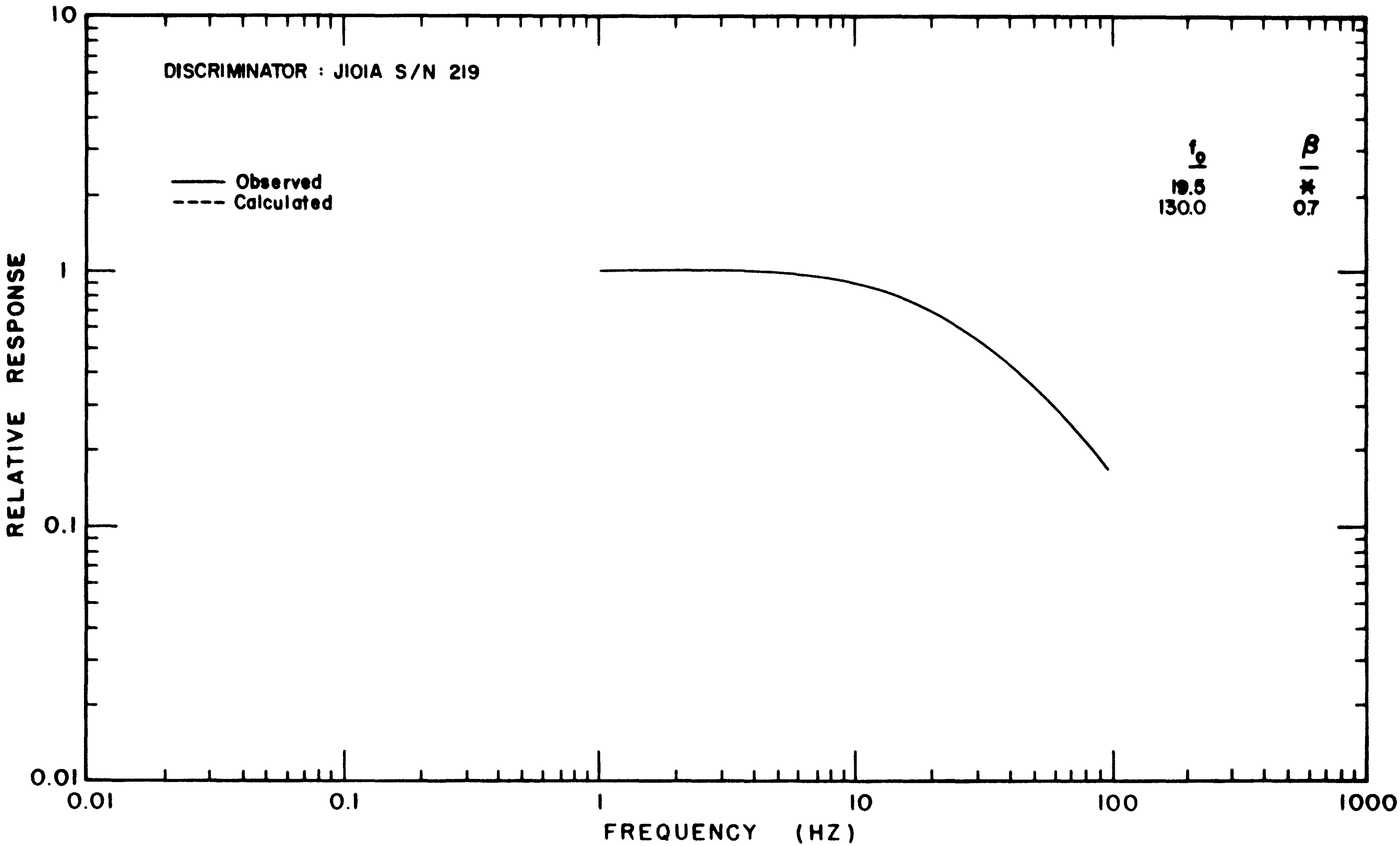

DISCRIMINATOR : JIOIA S/N 219
Observed
Calculated
f_o
19.5
130.0
β
*
0.7
RELATIVE RESPONSE
10
1
0.1
0.01
0.01
0.1
1
10
100
1000
FREQUENCY (HZ)

Figure 9

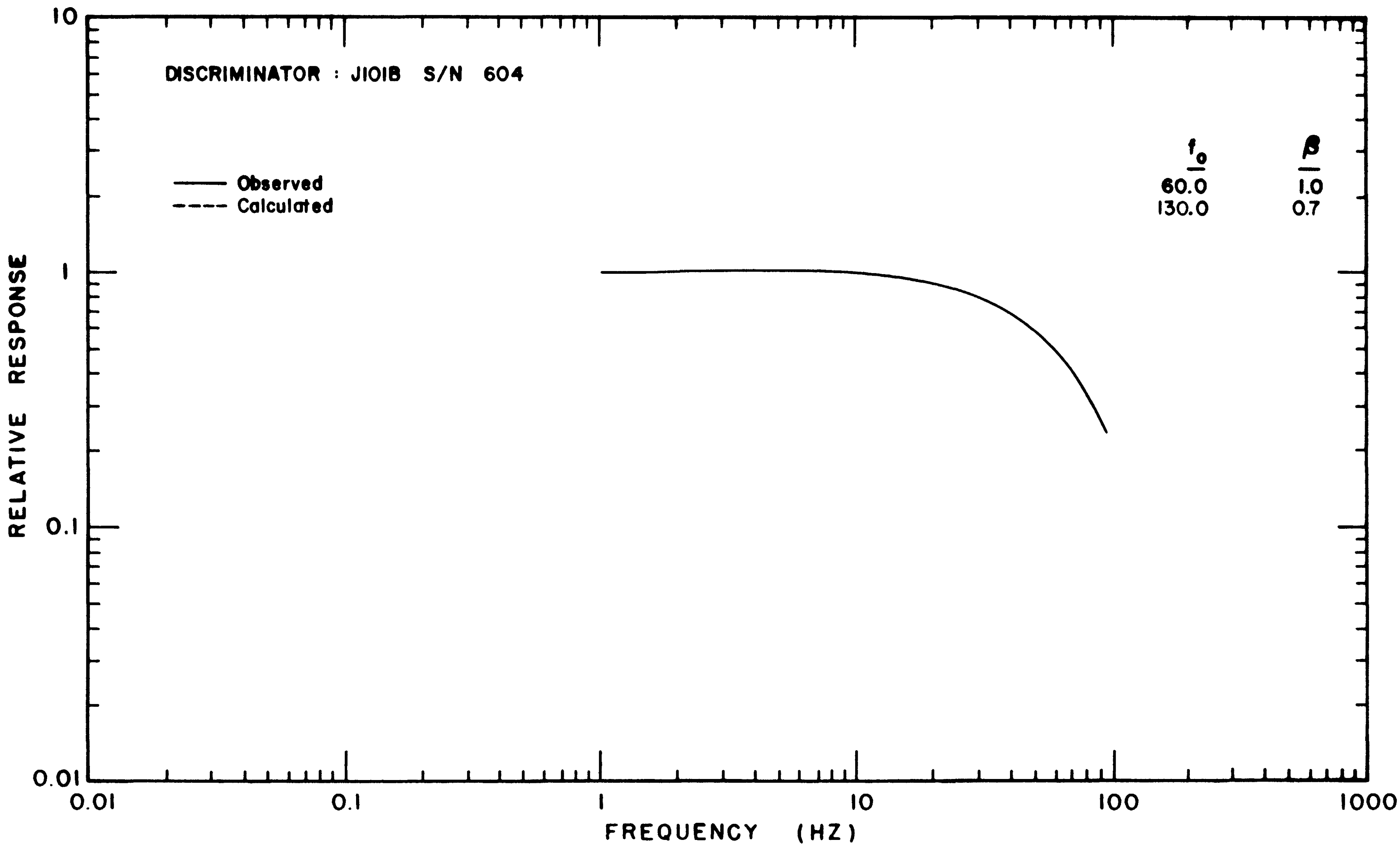

DISCRIMINATOR : J101B S/N 604
Observed
Calculated
f_o
60.0
130.0
β
1.0
0.7
RELATIVE RESPONSE
10
1
0.1
0.01
0.01
0.1
1
10
100
1000
FREQUENCY (HZ)

Figure 10

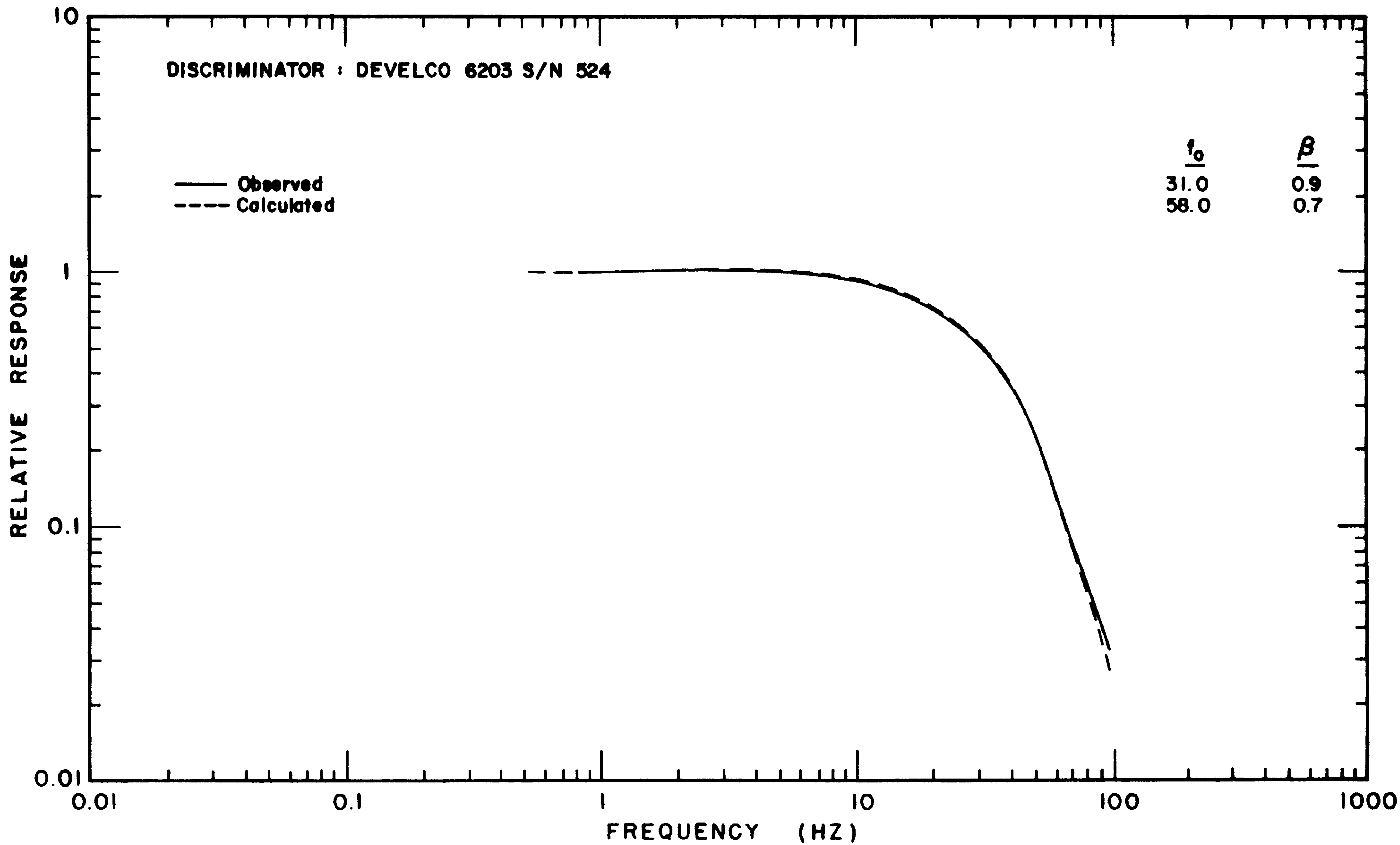

DISCRIMINATOR : DEVELCO 6203 S/N 524
Observed
Calculated
f_o
31.0
58.0
β
0.9
0.7
RELATIVE RESPONSE
10
1
0.1
0.01
0.01
0.1
1
10
100
1000
FREQUENCY (HZ)

Figure 11

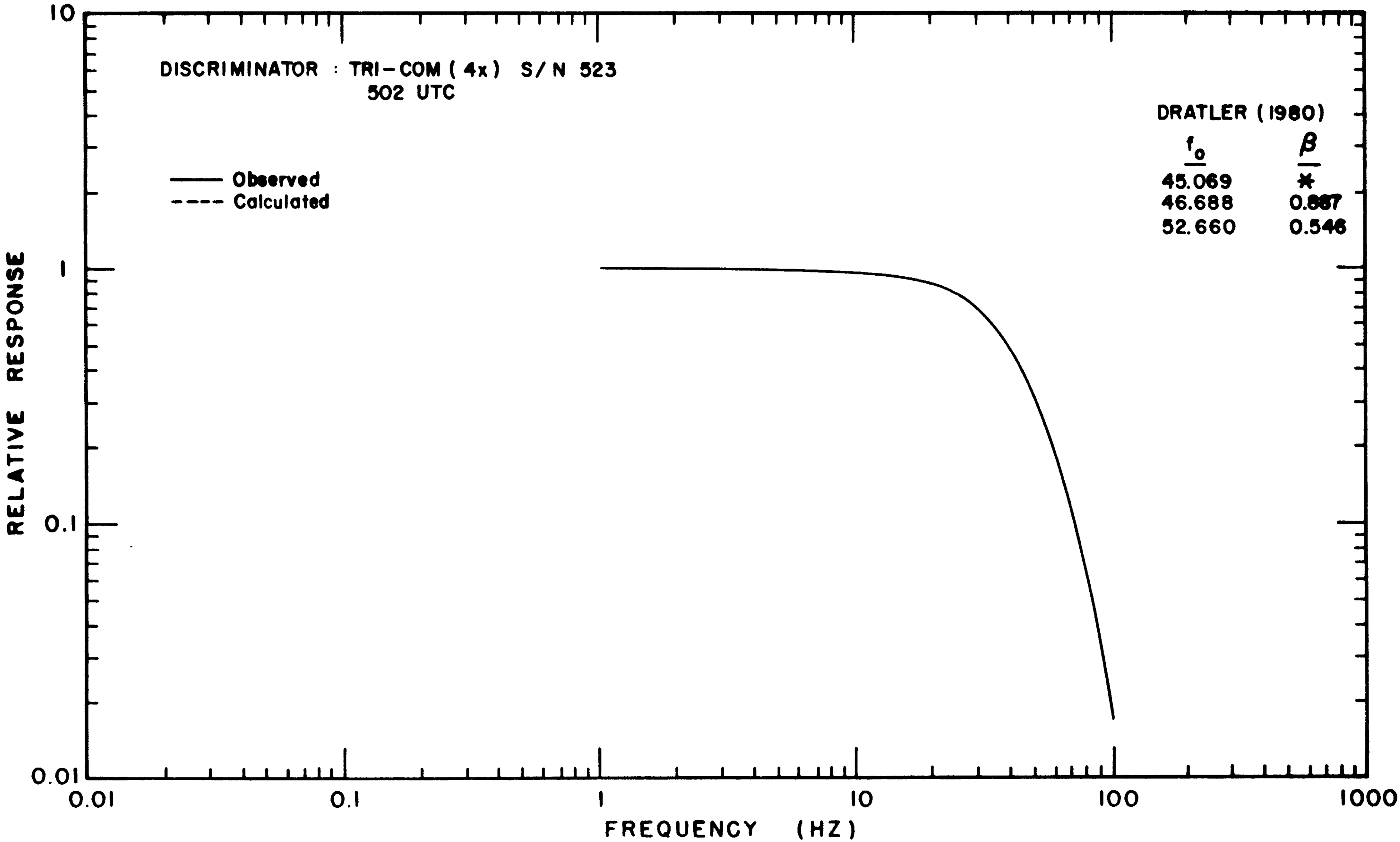

DISCRIMINATOR : TRI-COM (4x) S/N 523
502 UTC
Observed
Calculated
DRATLER (1980)
f_o
β
45.069
*
46.688
0.887
52.660
0.546
RELATIVE RESPONSE
10
1
0.1
0.01
0.01
0.1
1
10
100
1000
FREQUENCY (HZ)

Figure 12

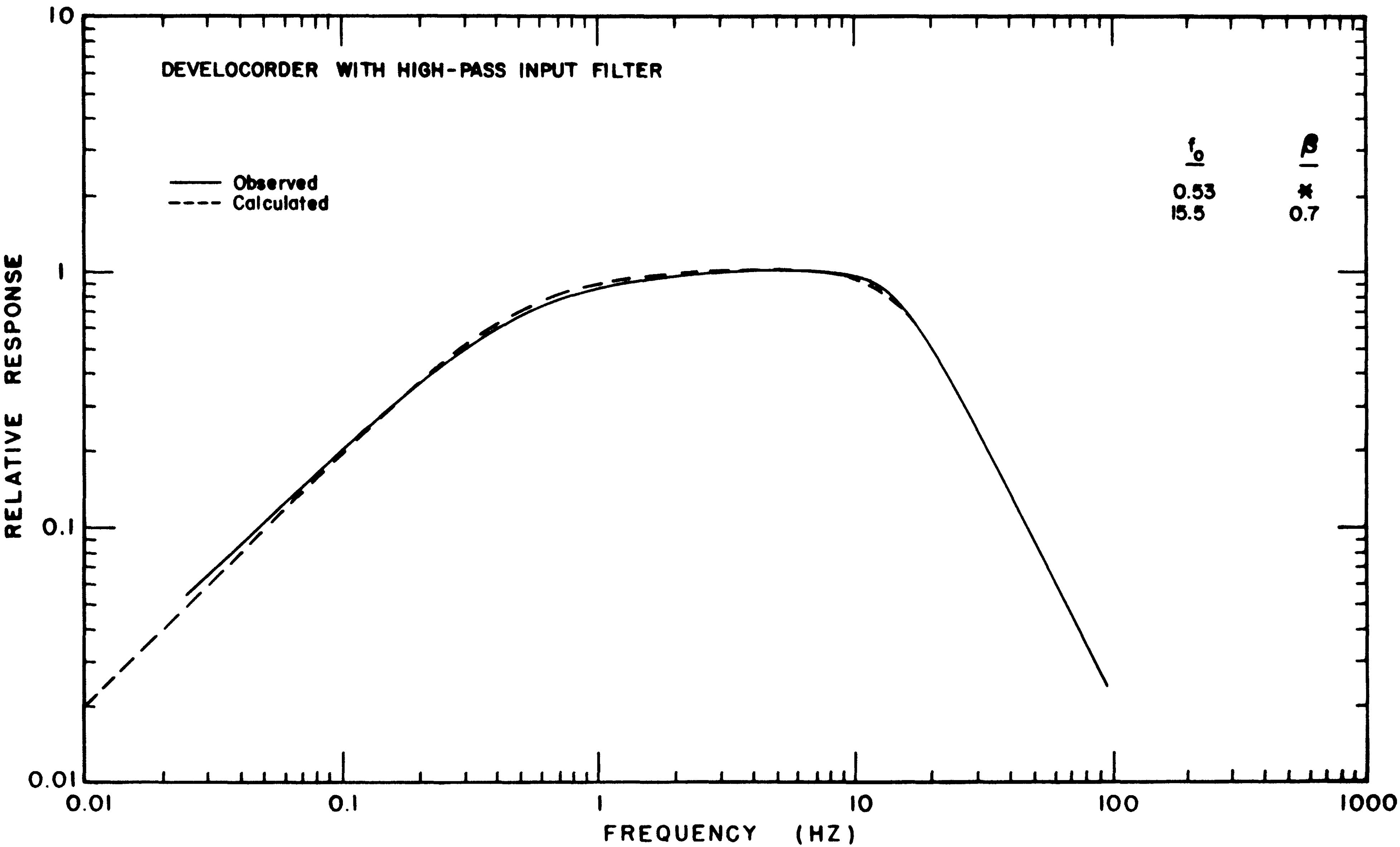

DEVELOCORDER WITH HIGH-PASS INPUT FILTER
Observed
Calculated
f0
β
0.53
*
15.5
0.7
RELATIVE RESPONSE
10
1
0.1
0.01
0.01
0.1
1
10
100
1000
FREQUENCY (HZ)

Figure 13

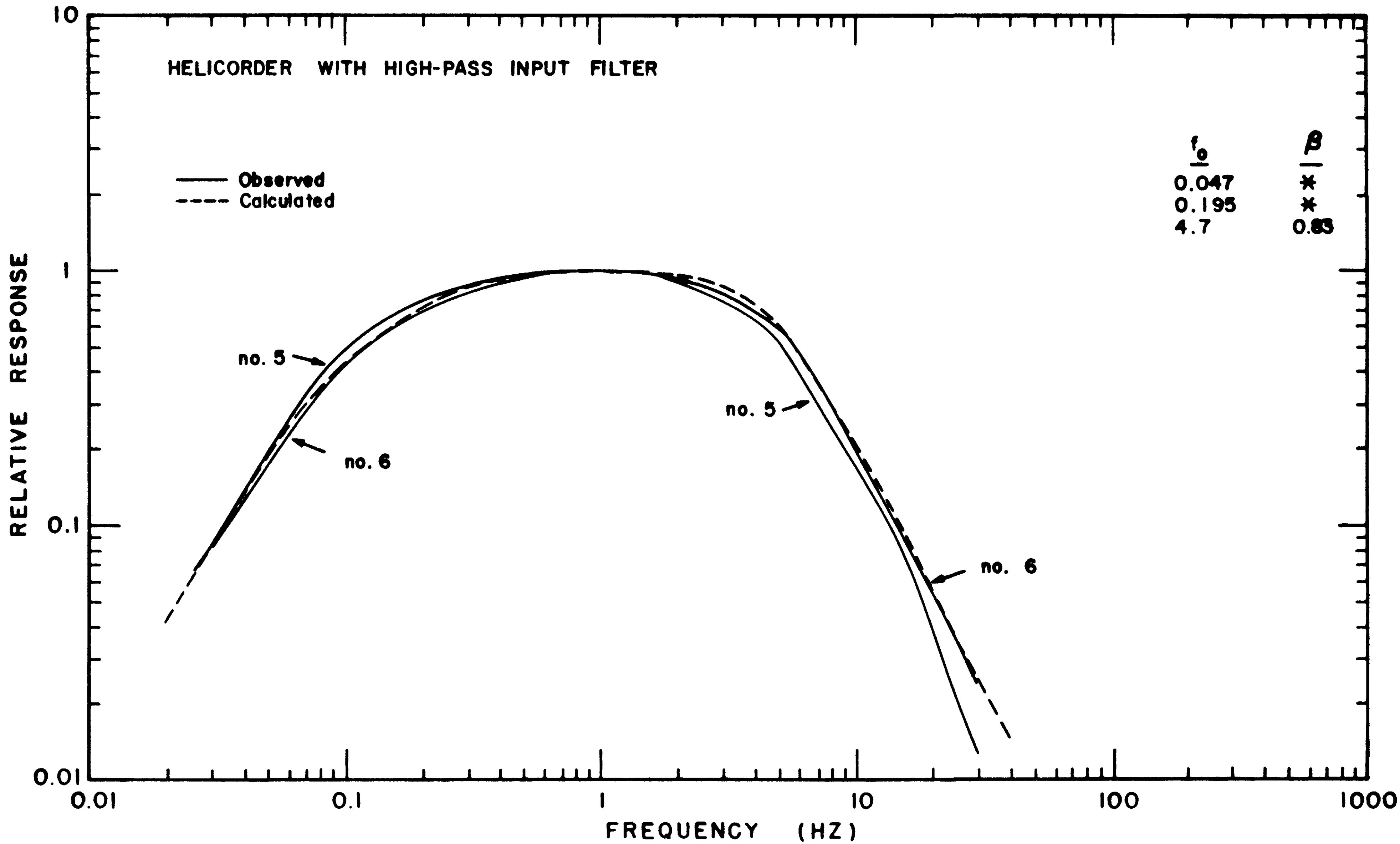

HELICORDER WITH HIGH-PASS INPUT FILTER
Observed
Calculated
f_o β
0.047 *
0.195 *
4.7 0.83
no. 5
no. 6
no. 5
no. 6
RELATIVE RESPONSE
FREQUENCY (HZ)
10
1
0.1
0.01
0.01
0.1
1
10
100
1000

Figure 14

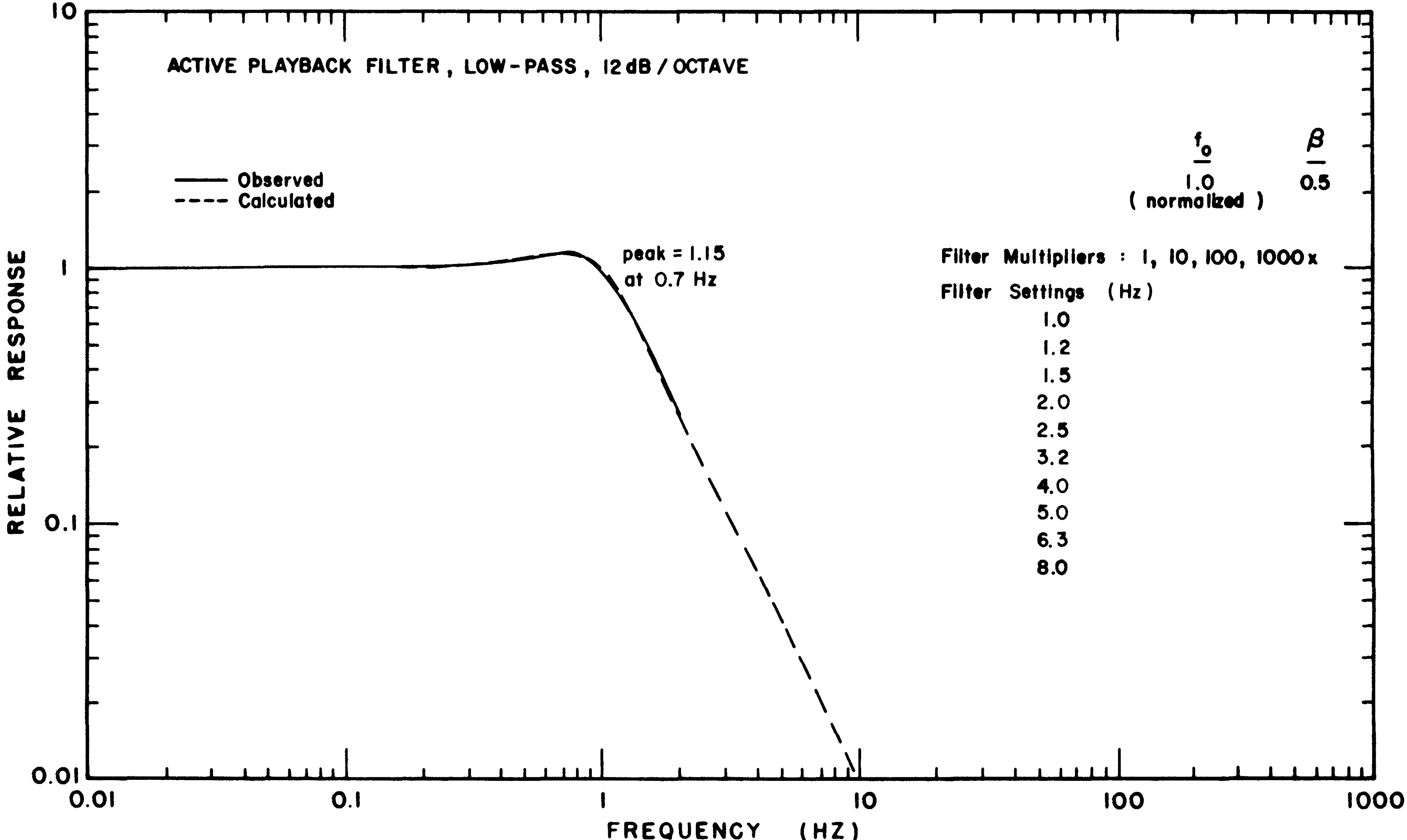
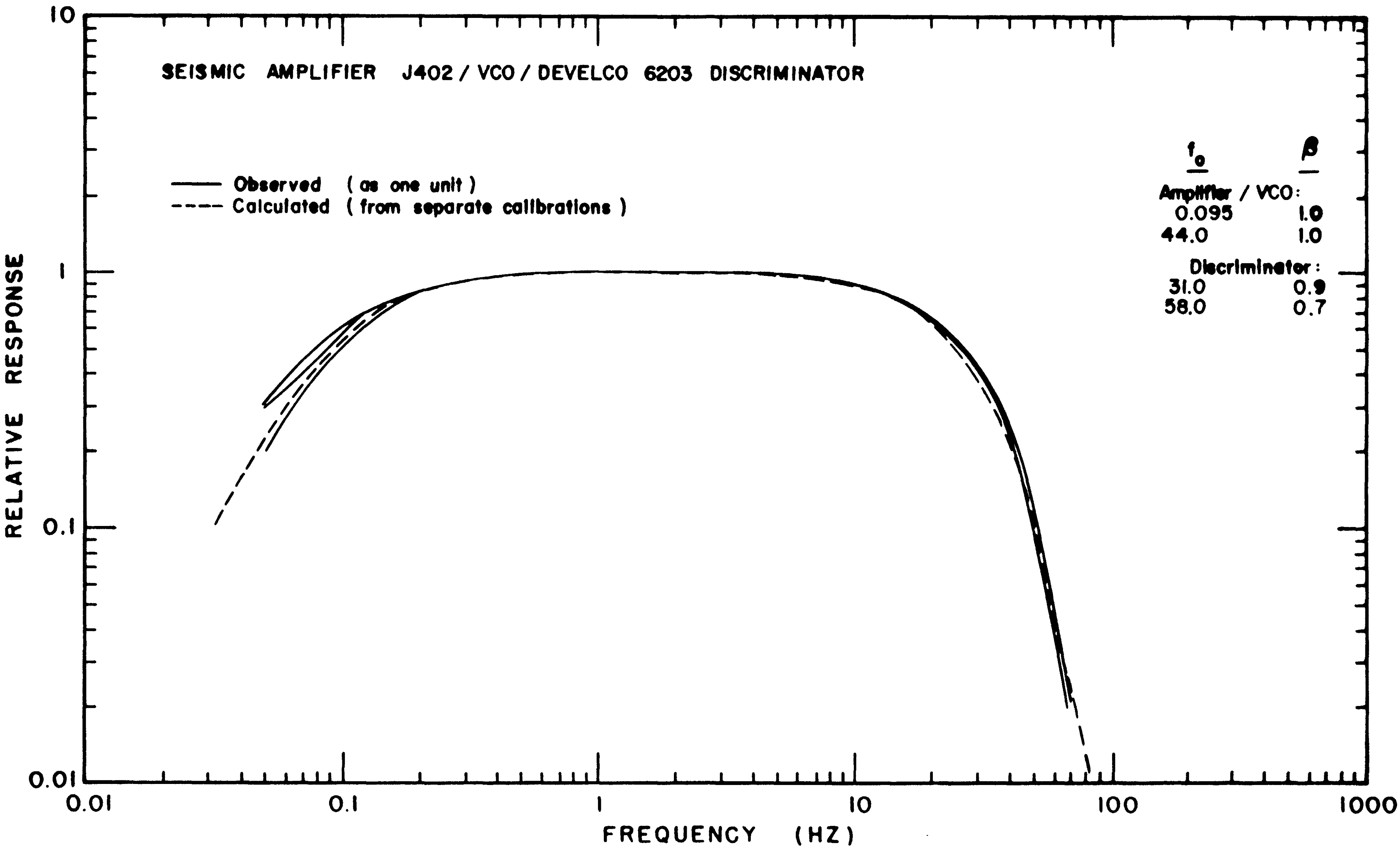

ACTIVE PLAYBACK FILTER, LOW-PASS, 12 dB / OCTAVE
Observed
Calculated
peak = 1.15
at 0.7 Hz
f_o
1.0
(normalized)
β
0.5
Filter Multipliers : 1, 10, 100, 1000 x
Filter Settings (Hz)
1.0
1.2
1.5
2.0
2.5
3.2
4.0
5.0
6.3
8.0
RELATIVE RESPONSE
10
1
0.1
0.01
0.01
0.1
1
10
100
1000
FREQUENCY (HZ)

Figure 15



SEISMIC AMPLIFIER J402 / VCO / DEVELCO 6203 DISCRIMINATOR
Observed (as one unit)
Calculated (from separate calibrations)
f_o
β
Amplifier / VCO:
0.095 1.0
44.0 1.0
Discriminator:
31.0 0.9
58.0 0.7
RELATIVE RESPONSE
10
1
0.1
0.01
0.01
0.1
1
10
100
1000
FREQUENCY (HZ)

Figure 16

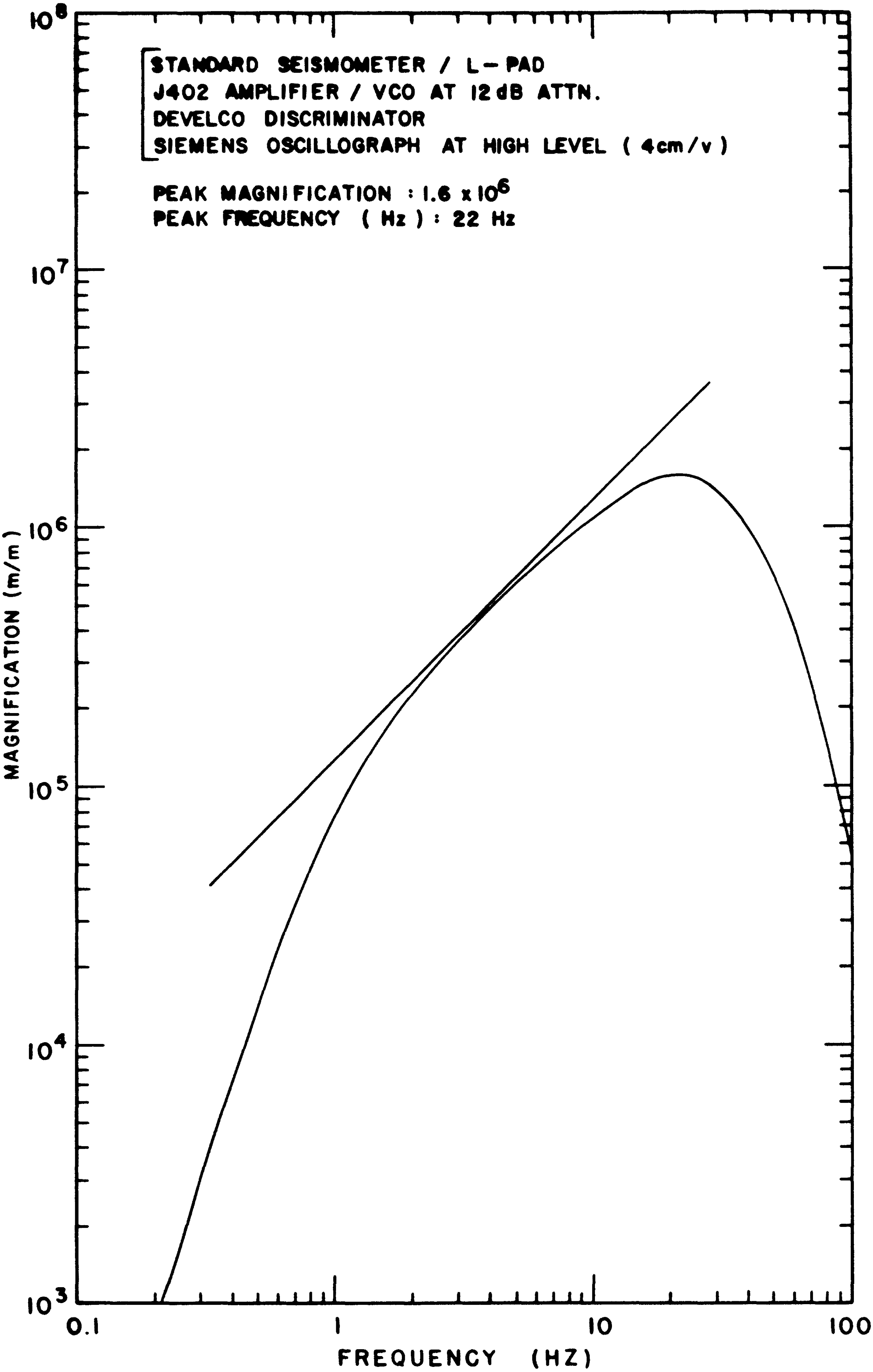

STANDARD SEISMOMETER / L-PAD
J402 AMPLIFIER / VCO AT 12 dB ATTN.
DEVELCO DISCRIMINATOR
SIEMENS OSCILLOGRAPH AT HIGH LEVEL (4cm/v)
PEAK MAGNIFICATION : 1.6 x 10^6
PEAK FREQUENCY (Hz) : 22 Hz
MAGNIFICATION (m/m)
FREQUENCY (HZ)
10^8
10^7
10^6
10^5
10^4
10^3
0.1
1
10
100

Figure 17

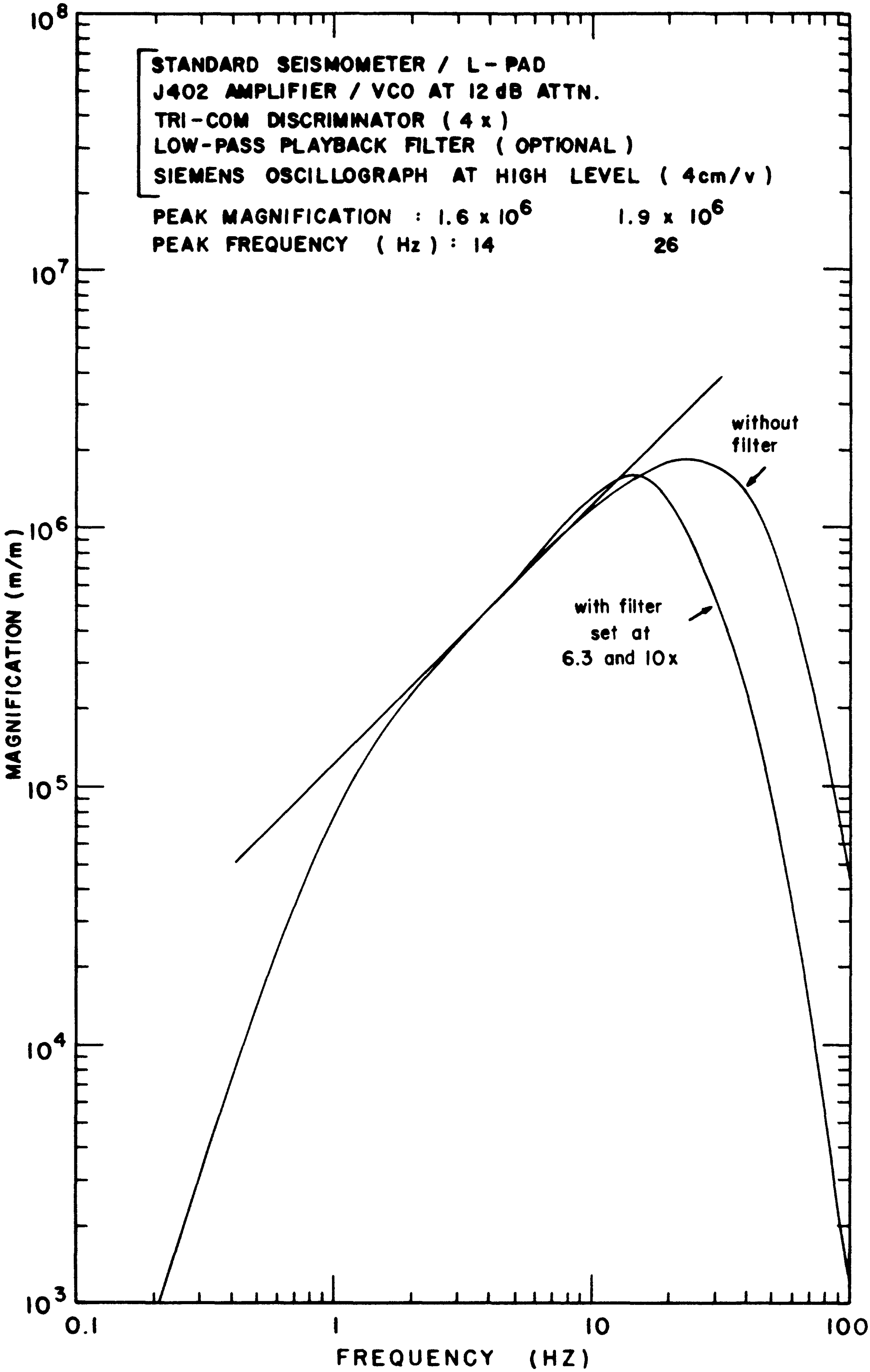

STANDARD SEISMOMETER / L-PAD
J402 AMPLIFIER / VCO AT 12 dB ATTN.
TRI-COM DISCRIMINATOR (4 x)
LOW-PASS PLAYBACK FILTER (OPTIONAL)
SIEMENS OSCILLOGRAPH AT HIGH LEVEL (4cm/v)
PEAK MAGNIFICATION : 1.6 x 10^6 1.9 x 10^6
PEAK FREQUENCY (Hz) : 14 26
without filter
with filter set at 6.3 and 10x
MAGNIFICATION (m/m)
FREQUENCY (HZ)
0.1
1
10
100

Figure 18

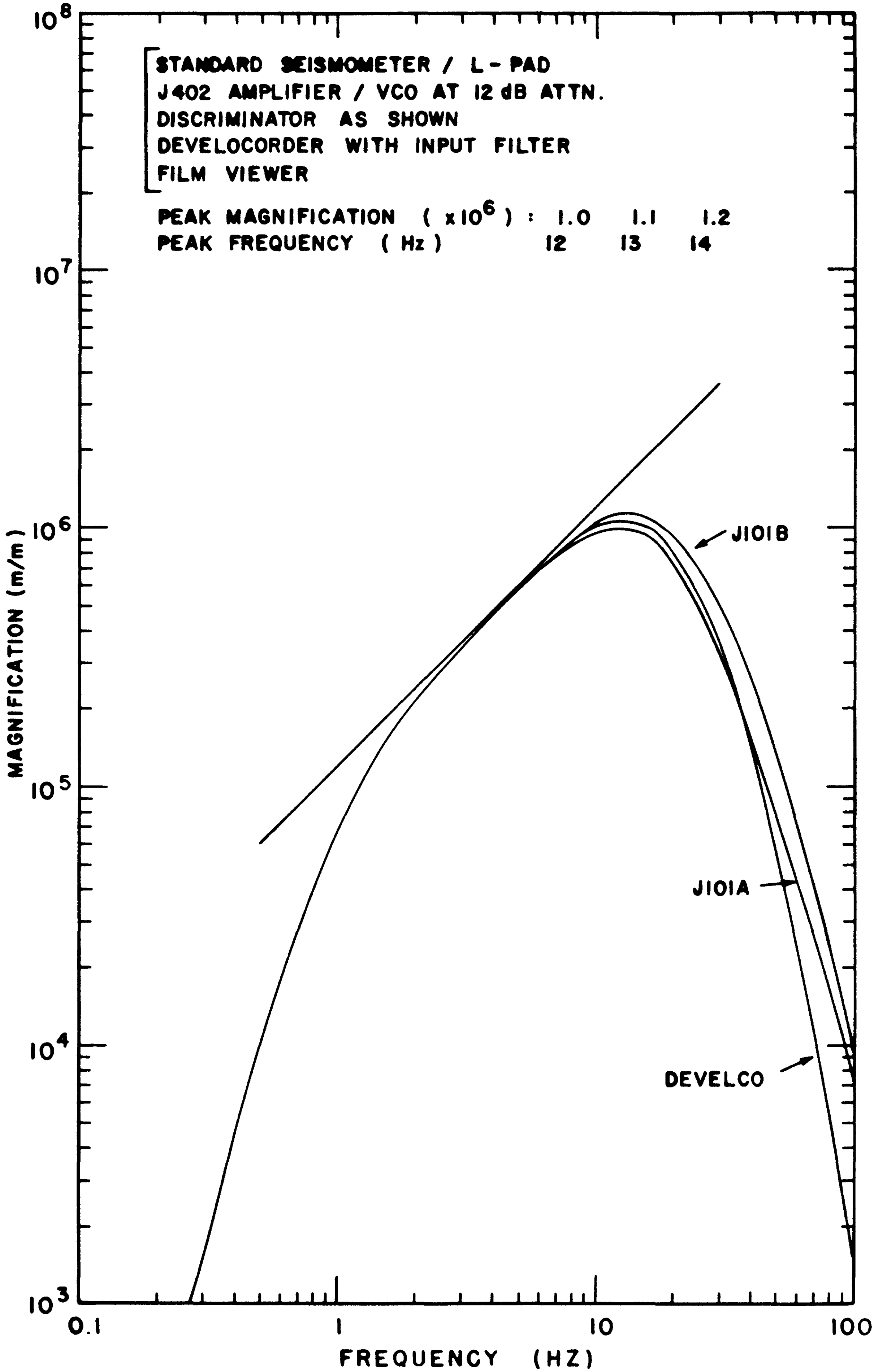
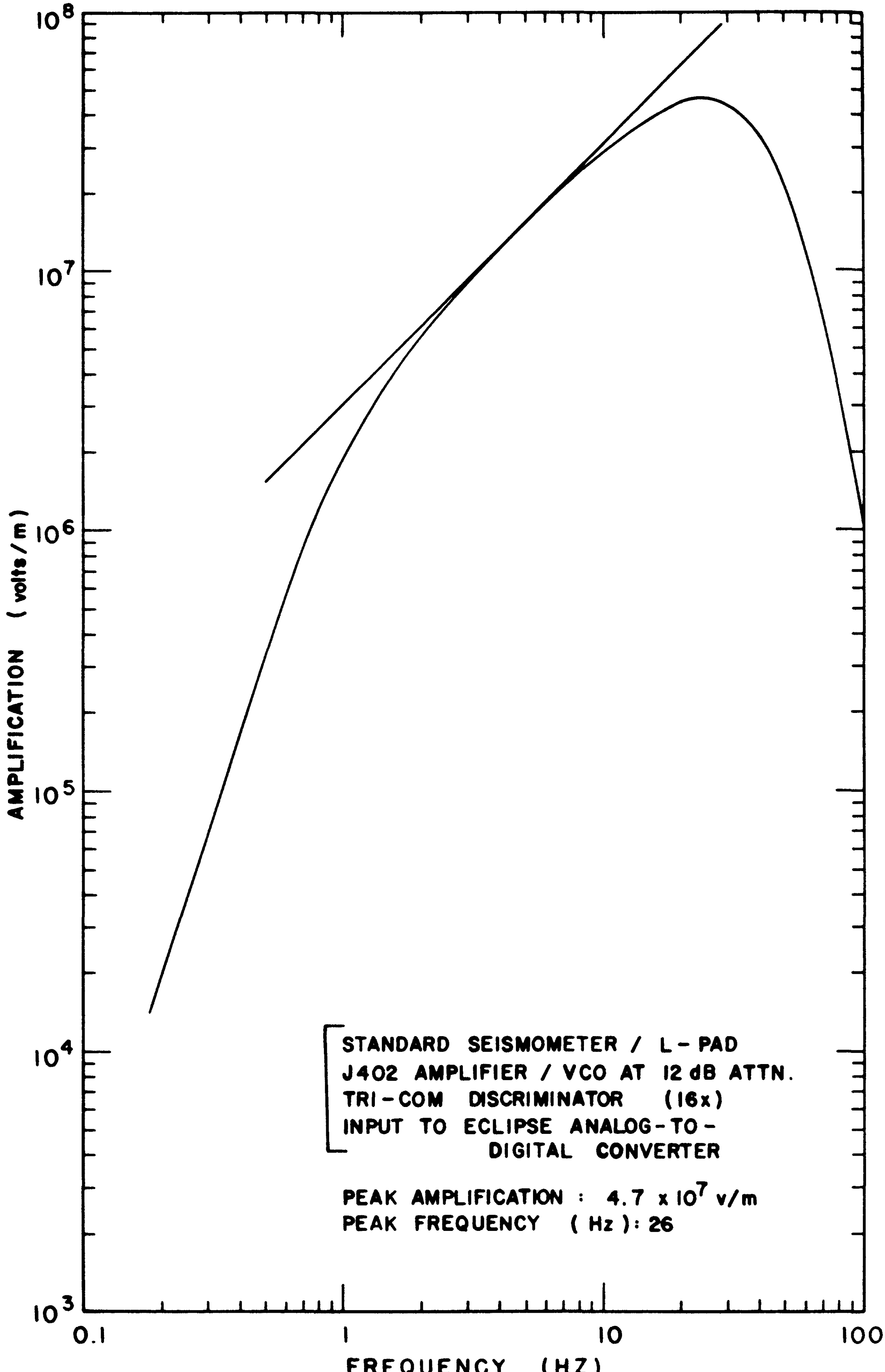

STANDARD SEISMOMETER / L-PAD
J402 AMPLIFIER / VCO AT 12 dB ATTN.
DISCRIMINATOR AS SHOWN
DEVELOCORDER WITH INPUT FILTER
FILM VIEWER
PEAK MAGNIFICATION (x10^6) : 1.0 1.1 1.2
PEAK FREQUENCY (Hz) 12 13 14
J101B
J101A
DEVELCO
MAGNIFICATION (m/m)
FREQUENCY (HZ)
10^8
10^7
10^6
10^5
10^4
10^3
0.1
1
10
100

Figure 19



10^8
10^7
10^6
10^5
10^4
10^3
AMPLIFICATION (volts/m)
STANDARD SEISMOMETER / L-PAD
J402 AMPLIFIER / VCO AT 12 dB ATTN.
TRI-COM DISCRIMINATOR (16x)
INPUT TO ECLIPSE ANALOG-TO-DIGITAL CONVERTER
PEAK AMPLIFICATION : 4.7 x 10^7 v/m
PEAK FREQUENCY (Hz): 26
0.1
1
10
100
FREQUENCY (HZ)

Figure 20

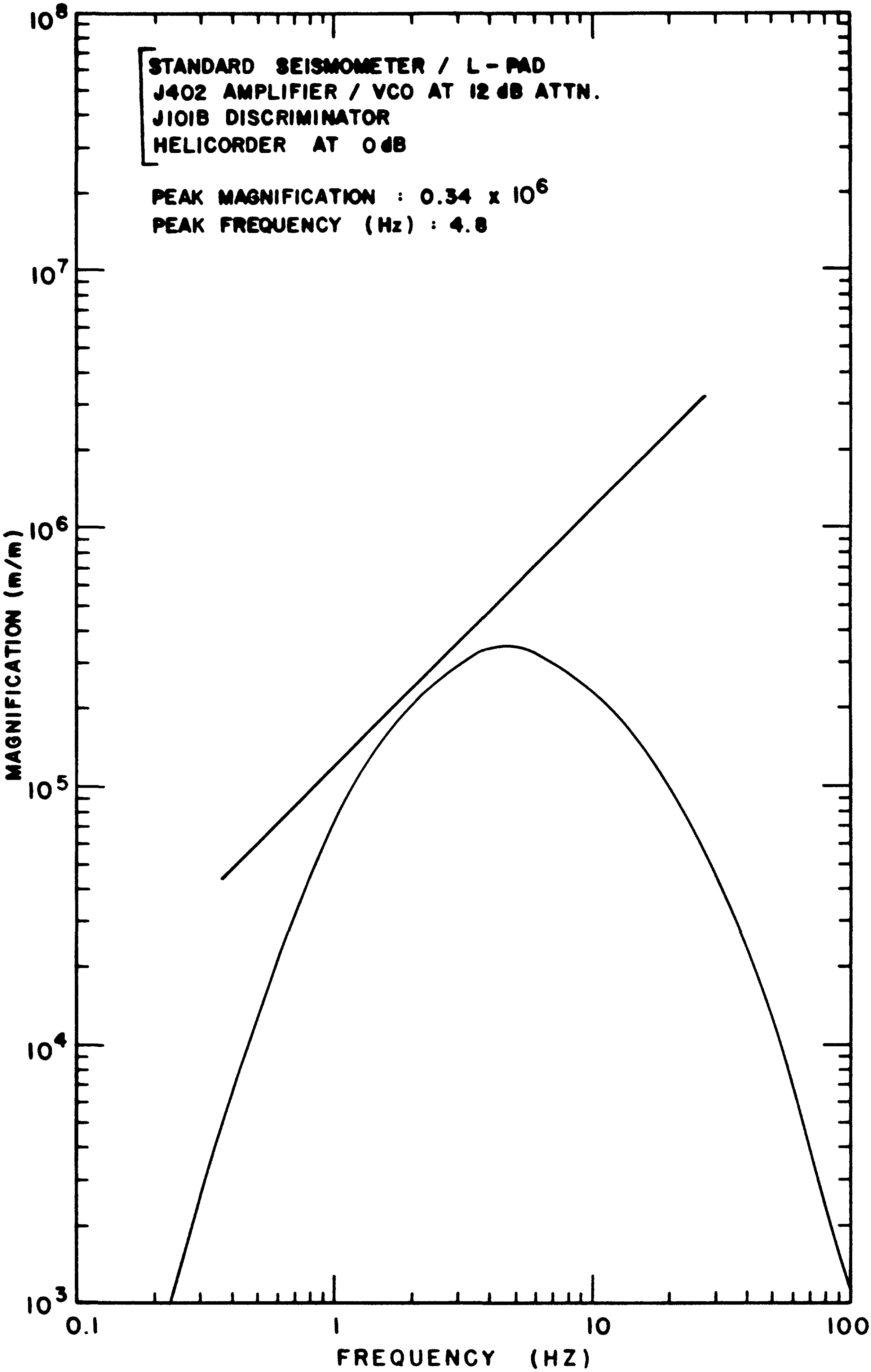

STANDARD SEISMOMETER / L-PAD
J402 AMPLIFIER / VCO AT 12 dB ATTN.
J101B DISCRIMINATOR
HELICORDER AT 0 dB
PEAK MAGNIFICATION : 0.34 x 10^6
PEAK FREQUENCY (Hz) : 4.8
MAGNIFICATION (m/m)
10^8
10^7
10^6
10^5
10^4
10^3
0.1
1
10
100
FREQUENCY (HZ)

Figure 21

Captions for Tables

Table

1. Spectral elements for an electromagnetic seismographic system. LTYPE and LN are input parameters to the program RESPONSE.

2. Amplitude and frequency response factors for the standard instrument components that comprise the USGS short-period seismic telemetry network. The asterisks denote a single-pole spectral element, for which the parameter β has no meaning.

3. Absolute gain of the J402 seismic amplifier as a function of the attenuation setting (attn).

4. Attenuation and gain factors for the J402 seismic amplifier. Columns with the heading "JD" give the figures from Dratler (1980). Columns with the heading "JVS" give the figures from Van Schaack (written comm., 1979).

5. Specific amplitude factors and spectral elements used to calculate the complete system response of a standard USGS short-period seismic telemetry station, using the J101B discriminator. Figure 16 shows the system response. The asterisk denotes a single-pole spectral element, for which the parameter β has no meaning.

TABLE 1.

SPECTRAL ELEMENTS WITH A SINGLE POLE ON THE IMAGINARY AXIS:

$$\alpha_j = i\omega_0$$

Number of poles (LTYPE)	Low-frequency fall-off (LN)	Complex Expression	Amplitude Response
1	0	$\dfrac{-\alpha_j}{\omega-\alpha_j} = \dfrac{-i\omega_0}{\omega - i\omega_0}$	$\dfrac{\omega_0}{(\omega^2+\omega_0^2)^{1/2}}$
1	1	$\dfrac{\omega}{\omega-\alpha_j} = \dfrac{\omega}{\omega - i\omega_0}$	$\dfrac{\omega}{(\omega^2+\omega_0^2)^{1/2}}$

SPECTRAL ELEMENTS WITH PAIRED POLES:

$$\alpha_j = \omega_0 (i\beta + (1-\beta^2)^{1/2})$$

$$\alpha_K = \omega_0 (i\beta - (1-\beta^2)^{1/2})$$

$$\alpha_j \cdot \alpha_K = -\omega_0^2$$

Number of poles	Low-frequency fall-off	Complex Expression	Amplitude Response
2	0	$\dfrac{\alpha_j \cdot \alpha_K}{(\omega-\alpha_j)(\omega-\alpha_K)} = \dfrac{-\omega_0^2}{(\omega^2-\omega_0^2) - i2\beta\omega_0\omega}$	$\dfrac{\omega_0^2}{\{(\omega^2-\omega_0^2)^2 + 4\beta^2\omega_0^2\omega^2\}^{1/2}}$
2	2	$\dfrac{\omega^2}{(\omega-\alpha_j)(\omega-\alpha_K)} = \dfrac{\omega^2}{(\omega^2-\omega_0^2) - i2\beta\omega_0\omega}$	$\dfrac{\omega^2}{\{(\omega^2-\omega_0^2)^2 + 4\beta^2\omega_0^2\omega^2\}^{1/2}}$
2	3	$\dfrac{i\omega^3}{(\omega-\alpha_j)(\omega-\alpha_K)} = \dfrac{i\omega^3}{(\omega^2-\omega_0^2) - i2\beta\omega_0\omega}$	$\dfrac{\omega^3}{\{(\omega^2-\omega_0^2)^2 + 4\beta^2\omega_0^2\omega^2\}^{1/2}}$

where:

ω_0 is frequency of the pole in radians/sec; it characterizes the position along the abscissa of the amplitude response function.

β is a ~~dimensionless~~ constant that characterizes the shape of the amplitude response function.

Note: f_0 $(= \omega_0/2\pi)$, in Hertz, is used in program RESPONSE.

Table 2.

COMPONENT	f_0 (Hz)	β	TOTAL NO. OF POLES: (LTYPE; n)	LOW-FREQ. FALL-OFF (LN; ℓ)	C-FACTOR FOR: α_j	C-FACTOR FOR: α_k	SPECTRAL ELEMENT	AMPLITUDE OR SENSITIVITY FACTOR
1. Seismometer with L-pad	1.0	0.8	2	3	1	1	$i\omega^3/(\omega-\alpha_j)(\omega-\alpha_k)$	G_{LE} = 1.0 V/(cm/sec)
2. J402 Amplifier/VCO								
Laboratory Calibration	0.095	1.0	2	2	1	1	$\omega^2/(\omega-\alpha_j)(\omega-\alpha_k)$	Amplifier gain: see Table 3 or 4.
	44.0	1.0	2	0	ω_0	ω_0	$-1/(\omega-\alpha_j)(\omega-\alpha_k)$	
Dratler (1980)	0.085	*	1	1	1	*	$\omega/(\omega-\alpha_j)$	VCO: ±125Hz/±3.375V
	0.096	*	1	1	1	*	$\omega/(\omega-\alpha_j)$	= 37.04 Hz/V
	48.4	*	1	0	ω_0	*	$-i/(\omega-\alpha_j)$	
	49.8	*	1	0	ω_0	*	$-i/(\omega-\alpha_j)$	
3. Discriminator								
Develco Mod. 6203	31.0	0.9	2	0	ω_0	ω_0	$-1/(\omega-\alpha_j)(\omega-\alpha_k)$	±2.0 V/±125 Hz
	58.0	0.7	2	0	ω_0	ω_0	$-1/(\omega-\alpha_j)(\omega-\alpha_k)$	= 0.0160 V/Hz
J101A	19.5	*	1	0	ω_0	*	$-i/(\omega-\alpha_j)$	
	130.0	0.7	2	0	ω_0	ω_0	$-1/(\omega-\alpha_j)(\omega-\alpha_k)$	
J101B	60.0	1.0	2	0	ω_0	ω_0	$-1/(\omega-\alpha_j)(\omega-\alpha_k)$	
	130.0	0.7	2	0	ω_0	ω_0	$-1/(\omega-\alpha_j)(\omega-\alpha_k)$	
Tri-Com Dratler (1980)	45.1	*	1	0	ω_0	*	$-i/(\omega-\alpha_j)$	
	46.7	0.887	2	0	ω_0	ω_0	$-1/(\omega-\alpha_j)(\omega-\alpha_k)$	
	52.7	0.546	2	0	ω_0	ω_0	$-1/(\omega-\alpha_j)(\omega-\alpha_k)$	
4. Output Media								
Develocorder (w/ h-p. filter)	0.53	*	1	1	1	*	$\omega/(\omega-\alpha_j)$	Recorder: 2 cm/V
	15.5	0.7	2	0	ω_0	ω_0	$-1/(\omega-\alpha_j)(\omega-\alpha_k)$	Viewer: 4 cm/V (i.e. 2X the recorder screen)
Siemens oscillograph	—	—	—	—	—	—	1	Hi-level: 4 cm/V; Lo-level: 1 cm/V
Low-pass active filters	1.0 (scaled)	0.5	2	0	ω_0	ω_0	$-1/(\omega-\alpha_j)(\omega-\alpha_k)$	Filter Settings: 1.0, 1.2, 1.5, 2.0, 2.5, 3.2, 4.0, 5.0, 6.3, 8.0, × 1; 10; 100; 1000.
CDC 1700: ADC online	—	—	—	—	—	—	1	8191/2.5 = 3276 counts/V
offline	—	—	—	—	—	—	1	2047/2.5 = 818.8 counts/V
ECLIPSE: ADC	—	—	—	—	—	—	1	511/2.5 = 204.4 counts/V
Helicorder	0.047	*	1	1	1	*	$\omega/(\omega-\alpha_j)$	4 cm/V @ 1 Hz and 0 dB.
	0.195	*	1	1	1	*	$\omega/(\omega-\alpha_j)$	
	4.7	0.83	2	0	ω_0	ω_0	$-1/(\omega-\alpha_j)(\omega-\alpha_k)$	

TABLE 3.

ATTN (dB)	GAIN	AMPLIFICATION
0	$10^{91.5/20}$	37,584
6	$10^{(91.5-6.7)/20}$ $= 10^{84.8/20}$	17,378
$\geq$12	$10^{(91.5-attn-1.1)/20}$ $= 10^{(90.4-attn)/20}$	8,318 at 12 dB attn

Table 4.

Station Attenuation Setting (dB)	Actual Attenuation (dB) JVS	JD	Actual Gain (dB) JVS	JD	Gain as an Amplitude Ratio JVS	JD	JD/JVS
0	0	0	91.5	91.43	37,584.	37,292.	0.99
6	6.7	7.05	84.8	84.38	17,378.	16,565.	0.95
12	13.1	12.85	78.4	78.58	8,318.	8,492.	1.02
18	19.1	18.59	72.4	72.84	4,169.	4,386.	1.05
24	25.1	24.41	66.4	67.02	2,089.	2,243.	1.07
30	31.1	30.34	60.4	61.09	1,047.	1,134.	1.08
36	37.1	36.31	54.4	55.12	525.	570.0	1.09
42	43.1	42.32	48.4	49.11	263.	285.5	1.09
48	49.1	48.32	42.4	43.11	132.	143.0	1.08

TABLE 5.

COMPONENT	f_o (Hz)	β	SPECTRAL ELEMENT	AMPLITUDE FACTOR (ABBREV.)	AMPLITUDE FACTOR (VALUE)
1. Seismometer with L-pad	1.0	0.8	$\frac{i\omega^3}{(\omega-\alpha_j)(\omega-\alpha_K)}$	G_{LE}	1.0 V/(cm/sec)
2. Amplifier/VCO (J402)	0.095	1.0	$\frac{\omega^2}{(\omega-\alpha_j)(\omega-\alpha_K)}$	G_{SA} @12 dB	8318
	44.0	1.0	$\frac{-\omega_o^2}{(\omega-\alpha_j)(\omega-\alpha_K)}$	D_{VCO}	37.04 Hz/V
3. Discriminator (J101B)	60.0	1.0	$\frac{-\omega_o^2}{(\omega-\alpha_j)(\omega-\alpha_K)}$	D_{DSC}	0.0160 V/Hz
	130.0	0.7	$\frac{-\omega_o^2}{(\omega-\alpha_j)(\omega-\alpha_K)}$		
4. Output Medium: film-viewer for Develocorder film	15.5	0.7	$\frac{-\omega_o^2}{(\omega-\alpha_j)(\omega-\alpha_K)}$	L	4 cm/V
	0.53	*	$\frac{\omega}{(\omega-\alpha_j)}$		

where:

for a single pole, noted by a '*' : $\alpha_j = i\omega_o$

for paired poles:

$$\alpha_j = \omega_o(i\beta + (1-\beta^2)^{1/2})$$
$$\alpha_K = \omega_o(i\beta - (1-\beta^2)^{1/2})$$
$$\alpha_j \cdot \alpha_K = -\omega_o^2$$

and

$f_o = (\omega_o/2\pi)$ in Hertz.