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REVIEW OF PROCEDURES FOR CALCULATING USGS SHORT-PERIOD SEISMOGRAPH SYSTEM RESPONSE

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HISTORICAL REVIEW

Efforts to calculate ground motion amplitudes from USGS short period electronic seismic systems date back to the 1966 Parkfield earthquake (Eaton, et. al., 1970). An equation for the harmonic response of the 10-day-tape portable seismic system was obtained by combining the theoretical seismometer response with the experimentally measured harmonic response of the amplifier/recorder/playback system. The equation was applied only to the flat portion of the electronic passband of the latter (0.5 to 15 hz) to avoid having to deal with its frequency response. The sensitivity of the electronics at each station was determined experimentally by means of a calibration signal that was recorded when the tapes were changed.

During the early stages of the northern California telemetered network (1966 - 1970), several different seismometers, amplifier/VCO's, and discriminators were employed. These systems used the same fm telemetry system, employed the same discriminator sensitivities, and were all recorded on Develocorders. Beyond these common features, however, the different systems were not constructed and adjusted to common standards. Eaton (1975a) reviewed a variety of system configurations employed prior to 1970 and proposed a set of standards for the adjustment and operation of network equipment after that date (i.e. mid-1970).

The standard seismometer employed a velocity transducer, had a free period of 1.0 sec, and was damped at 0.8 critical and adjusted to an output level of 0.5 v/cm/sec by means of a T-pad connecting it to the preamp/VCO. The standard sensitivity was later increased to 1.0 v/cm/sec to increase the seismometer-to-preamp signal-to-noise ratio by replacing the T-pad with an L-pad. Electronic and recording sensitivity standards were: 72 db preamp (reference) gain, 125hz/3.0v modulator deviation, 2.0v/125hz discriminator sensitivity, and 33mm/v Develocorder sensitivity (66mm/v on the film viewer screen). The standard Develocorder sensitivity was later reduced to 20mm/v (40mm/v on the film viewer screen) to decrease the level of background noise and to increase the effective dynamic range of the Develocorder.

The frequency characteristics of the preamp/VCO's and discriminators were not specified, but those used had passbands of at least 0.2 sec to 20 hz and dc to 20 hz, respectively. The most stringent limit on overall system response was imposed by the Develocorder: its recording galvanometers set the upper passband edge at about 15 hz, and the R-C coupling between the discriminator and the Develocorder used to reduce microseism levels and to suppress zero-line drift set the lower passband edge at about 0.5 hz.

The frequency response of the combined electronics and recording system was measured experimentally. That response was then combined with the theoretical response of the standard seismometer to get the overall system harmonic response curve for the preamp gain at a prescribed "unit" value. The resulting unit response curve was then multiplied by a factor based on the preamp gain at the attenuator setting actually used.

It was initially planned to calibrate each station by applying a standard signal (5 hz sine wave at a level of 10 μv rms) to the preamp input. The "unit" gain described above was that for which the Develocorder amplitude was 1 mm p-p in response to the standard calibration signal (effective amplifier gain of about 63 db). This approach proved to be impractical when station visits became infrequent as network equipment was improved. It was also unnecessary for a system operated under the standard conditions adopted for the network.

Because of the limited dynamic range and timing resolution, as well as the inflexibility, of film records, attempts to record the incoming electronic signals from the network on magnetic tape were begun in the early 1970's. By 1975 suitable equipment and procedures for recording and playing back network signals were available. Some of the issues and solutions encountered in this effort were described in open-file reports: Eaton (1975a, 1975b, 1976a, 1976b, 1976c), Eaton and Vanschaack (1977), Criley and Eaton (1978), and Eaton (1978).

The principal advantages of tape over film records were 1) the dynamic range of the recovered signals was increased from about 30 db (film) to as much as 40 to 46 db (tape), 2) the time base could be expanded to utilize the entire electronic passband, and 3) the signals could be digitized electronically for analysis in computers. Expanded use of network records permitted by these improvements increased the need for a more flexible and accurate means of determining and characterizing the seismic system response.

The overall response of the seismic system and how that response depends on the characteristics of its constituent components was described in general terms by Eaton (1977), who also showed how the overall system response is adapted to background earth noise and complements the signals from M1 to M4+ earthquakes in northern and central California.

Until 1975, at least, the response of the electronic and recording system had been judged to be intractable analytically. That problem was overcome by Healy and O'Neill (1977). They observed that the responses of the individual components could be modelled by a small set of "elementary response functions" and that those responses could be combined to determine the response of the system as a whole. They went on to show which elementary response functions were required to model each component as well as how to determine the parameters required to fit the measured response curves. Finally, they wrote a computer program that computes the response of the components, individually or in combination, as well as that of the entire system in terms of the elementary response functions and the parameters for the individual components.

The elementary response functions employed by Healy and O'Neill are, in fact, those describing first and second order mechanical or electronic filters. They are solutions of first and second order ordinary differential equations that describe the movement of a damped mass-and-spring system (i.e., a seismometer) and the currents and voltages in an L-R-C electrical circuit. Filters of order greater than two are obtained by "cascading" the required number of suitably isolated first or second order filters.

Stewart and O'Neill (1980) applied the method of Healy and O'Neill to determine the responses of the individual components used in the USGS short-period seismic networks and to calculate the overall responses of the various configurations of those components employed in the networks. Their work has been adopted widely as the most convenient method of calculating network response.

SPECTRAL ELEMENTS

Although the nature of the spectral elements is conveniently evaluated in terms of the amplitude functions (moduli) and the limits approached by the amplitude functions for very high and very low ground motion frequencies, the actual calculation of the response of spectral elements, the seismic components they represent, or the seismic system as a whole is carried out in terms of the complex poles and zeroes of the spectral elements. This dichotomy poses no problem for the Healy and O'Neill program because it calculates the required poles and zeroes from the input values that characterize the components of the seismic system. The required inputs include: 1) a single sensitivity factor obtained as the product of the sensitivity factors of the individual components, and 2) for each spectral element: single or double pole? (LP=1,2); low frequency fall-off? (LN=0,1,2,3); natural frequency of the pole (ω_0); and damping of the pole (ß). The program computes the complex poles (α_j, α_k) and the corresponding C-factors (C_j, C_k) for each spectral element. Except for the separate ω factor representing the seismometer velocity transducer, the spectral elements are all normalized by their C-factors (their values approach 1.0 inside their passbands); so all information on system sensitivity is carried by the overall system sensitivity (input #1, above) and the term due to the velocity transducer. The asymptote to the system response curves shown in figures 17 to 21 of Stewart and O'Neill (1980) represents that sensitivity. The departure of the calculated curves from that asymptote shows the combined effect of all the high- and low-pass filters in the system.

Expressions for the different types of spectral element in complex form, as well as their amplitude functions (moduli) and the limits the moduli approach at very high and very low ground motion frequencies, are shown in table 1. Spectral element type is determined by LP and LN, and the complex roots, or poles, (α_j, α_k) of the spectral elements are given in term of the corresponding component parameters (ω_0, ß). In these expressions ω is the circular frequency of the driving motion and ω_0 and ß are the natural circular frequency and damping, respectively, of the spectral element. For the elements with a single pole (LP=1), the case LN=0 represents a 6 db/octave low-pass filter and the case LN=1 represents a 6 db/octave high-pass filter.

Note that the expressions for LN=0 and LN=1 are the same except for the interchange of ω and ω_0. For elements with double poles (LP=2), the case LN=0 represents a 12 db/octave low-pass filter and the case LN=2 represents a 12 db/octave high-pass filter. For LP=2, the expressions for LN=0 and LN=2 are the same except for the interchange of ω and ω_0. The case LP=3, LN=2 can be resolved into two factors: $\omega \times \omega^2/[(\omega^2-\omega_0^2)^2+4\beta^2\omega_0^2\omega^2]^{1/2}$. The second factor represents a 12 db/octave high-pass filter (seismometer coil motion relative to the seismometer frame), and the first term, ω, represents the velocity transducer.

In spite of the symmetry of the high- and low-pass filters of a given order in ω and ω_0, the ω's or ω_0's in the numerators are treated very differently in the complex analysis of the spectral elements: the ω's in the numerators of the high-pass filters are zeroes of those elements, while the ω_0's in the numerators of the low-pass filters are not zeroes, but normalizing factors.

Some potential users of network data (SAS, SEED) require that the system response be characterized by the poles, zeroes, C-factors, and the sensitivity factors of its components. Moreover, the complex poles and zeroes they require must be specified according to standard circuit analysis conventions, not those employed by Healy and O'Neill (and Stewart and O'Neill). The Healy and O'Neill poles and zeroes must be multiplied by "i", or rotated 90 degrees counterclockwise in the complex plane, to convert them to the required form.

We shall analyze each component of the seismic system (seismometer and L-pad, preamp/VCO, discriminator, and recorder) in terms of: 1) its design objectives, 2) the amplitude functions of its spectral elements, 3) its spectral elements in complex form and their characterization by the Healy and O'Neill input parameters, 4) the poles, zeroes, and C-factors of its spectral elements and its sensitivity factor in the notation of Healy and O'Neill. The poles and zeroes will also be given in the form required by SAS and SEED.

Finally, for specific combinations of the system (seismometer, preamp/VCO, discriminator, various recording devices such as Develocorder, Siemens Oscillograph, CUSP A/D converter, etc.) we shall summarize the overall system specifications in terms of 1) the Healy and O'Neill input parameters, 2) the Healy and O'Neill poles, zeroes, C-factors, and sensitivity factor, and 3) the SAS/SEED poles, zeroes etc.

The most common use of the system response is in the hypocentral program HYPOINVERSE, where maximum record amplitudes and associated periods are reduced to the equivalent Wood-Anderson amplitudes for the calculation of amplitude magnitudes (Eaton, 1980, 1992). For this program, arrays of W-A amplitude / USGS system amplitude (unit sensitivity) for various system configurations are included in the program, along with sensitivity factors for various preamp attenuator settings, as data statements. Values of this amplitude ratio at specific frequencies are obtained by interpolation between array values. The arrays are log-log representations of the amplitude ratios versus frequency.

RESPONSE OF INDIVIDUAL COMPONENTS

Seismometer with L-pad

The seismometers used in CALNET (Mark Products L4-C's, principally) were chosen for their small size, rugged moisture-proof construction, high output, relatively long period (for a compact seismometer), and low cost. The L-pad is used simultaneously to damp the seismometer at 0.8 critical and to adjust its output level to 1.0 v/cm/sec. The harmonic response of the seismometer is the product of two factors. The first represents its velocity transducer (moving coil) and the second relates the motion of the seismometer coil to the driving ground motion. The second factor characterizes a high-pass filter with 12 db/octave roll-off below the natural frequency of the seismometer and the first factor represents a 6 db/octave increase in signal with increasing frequency.

Seismometer parameters

Element	LP	LN	F_0(hz)	ß	Spectral element
Seis.	2	3	1.00	0.80	$i\omega \times \omega^2/[(\omega-\alpha_j)(\omega-\alpha_k)]$

Seis	Zeroes: 3 zeroes at 0.0 + 0.0i		(0.0i - 0.0) SEED
Seis	C-factors	Poles (H & O)	Poles (SEED)
"	C_j=1.000	α_j=5.0265i+3.7699	(-5.0265+3.7699i)
"	C_k=1.000	α_k=5.0265i-3.7699	(-5.0265-3.7699i)
	Sensitivity $A_s=G_{LE}$=1.00 v/cm/sec (L-pad)		

Preamp/VCO's

The J512 is one of a series of preamp/VCO's with operating characteristics based broadly on those of the DEVELCO preamp/VCO used in the network in the early 1970's. The J202, J302, J402, and J502 are different implementations of a general design based on low-power integrated circuits with approximate characteristics: 90± db peak gain, 12 db/octave roll-off below 0.1 hz, 12 db/octave roll-off above 30 hz, and modulator frequency deviation to voltage ratio of about 125hz/3.0v. The overall gain can be reduced by as much as 48 db in 6 db steps by means of a step-adjustable voltage divider at the input of the second stage amplifier. The successive implementations strove to 1) decrease the preamp input noise level, 2) improve the shape and stability of the fm carrier waveform, and 3) improve the stability of the modulator center frequency. Models from the J302 onward have also incorporated an automatic calibrator that induces a voltage step test and a seismometer current release test once per day.

The 12 db/octave low-frequency roll-off is accomplished by capacity coupling between the first and second stage amplifiers and between the second stage amplifier and the modulator. The 12 db/octave high-frequency roll-off is obtained by 6 db/octave active filters associated with each of the two amplifier stages. The high-pass filter sections are approximately matched, as are the low-pass filter sections. Healy and O'Neill chose to model both the high-pass and the low-pass filters as double poles with ß=1.00 rather than as pairs of single poles.

J512 Preamp/VCO

Parameters

Element	LP	LN	f_0(hz)	ß	Spectral element
Hi-pass	2	2	0.095	1.00	$\omega^2/[(\omega-\alpha_j)(\omega-\alpha_k)]$
Lo-pass	2	0	44.00	1.00	$-1/[(\omega-\alpha_l)(\omega-\alpha_m)]$

Zeroes

Hi-pass	2 zeroes at 0.0 + 0.0i		(0.0i - 0.0) (SEED)
Lo-pass	none		
	C-factors	Poles (H & O)	Poles (SEED)
Hi-pass	C_j=1.00	α_j=0.5969i+0.0	(-0.5969+0.0i)
"	C_k=1.00	α_k=0.5969i-0.0	(-0.5969-0.0i)

Lo-pass C_l=276.460 α_l=276.460i+0.0 (-276.460+0.0i)
" C_m=276.460 α_m=276.460i-0.0 (-276.460-0.0i)

Sensitivity

$A_A=10^{(92.6-attn)/20}$

A_M=105/4.05=25.926 hz/v

$A_{VCO}=25.926 \times 10^{(92.6-attn)/20}$

The preamp, step attenuator, and amplifier sections have remained virtually unchanged in the J302, J402, and J502. In the early units the "18db" gain was 72.3db and the deviation was set at 100hz/2.70v. In later units the deviation was decreased to 115hz/4.05v, and the "18db" gain was increased by 2.3db, to 74.6db, to compensate for the change in deviation. The transduction factor (for 18db attenuation) was virtually unaffected by these changes (0.1528 hz/μv for the J302, 0.1528 hz/μv for the J402, and 0.1529 hz/μv for the J502).

When the deviation was decreased from 115hz/4.05v to 105hz/4.05v to decrease the maximum deviation, the "18db" gain was kept at 74.6db. To compensate for the diminished preamp/VCO deviation the discriminator sensitivity was increased from 2.0v/125hz to 2.2v/125hz. Throughout these changes, the total electronic gain of the system (preamp input to discriminator output) remained virtually unchanged: "18db" gain 2440 for the J302 and J402 and 2450 for the J502. For the J312, J412, and J512 , used with the J121 discriminator, the corresponding figures are 0.04 db (0.4%) larger.

The foregoing discussion is based on design values. The degree to which a "built" device corresponds to its design depends on the precision of the components used in its construction. The components determining the gain in operational amplifier circuits are the resistors. In the preamp/VCO's discussed above, the gain-determining resistors have 1% tolerances. The preamp, step attenuator, and amplifier stages in series determine the gain of the amplifier from preamp input to amplifier output; so we should expect an uncertainty of about 3% (0.26db) in the gain computed from component values.

We have a set of gain measurements for the principal types and modifications of the preamp/VCO's used in CALNET. With the attenuator set at 18db, 5hz sine waves at levels of 10 and 100 μv rms were introduced at the preamp input. The output from the amplifier was measured with a digital rms voltmeter. The gains measured for the 10μv rms input averaged 4.6% larger than those for the 100μv rms input. This difference can be explained by the preamp input noise (1+ μv p-p), which is 4 to 5 % of the 10μv rms input but only 0.5 % of the 100μv rms input. We have adopted the results from the 100μv rms tests for comparisons of the various preamp/VCO's.

Table 2 summarizes data on the principal preamp/VCO's used in CALNET. The content of the different columns is as follows:

1. The different types and modifications of the preamp/VCO's tested
2. Time interval in which the unit was used
3. Power supply: Hg = mercury battery, Li = Lithium battery, Solar = solar panel with lead-acid battery and regulator
4. VCO deviation (hz/v)
5. Gain of basic units calculated from circuit values with attenuator at 18db: ratio / db
6. Gain measured with 100μv rms input signal
7. Overall unit sensitivity, deviation(hz)/preamp input (μv), at 18db attenuation. These values are calculated from the unit gains (calculated and measured) and from the indicated deviations
8. Sensitivity of discriminators used with the different preamp/VCO types
9. Overall system gain [discriminator output (μv)/ preamp input (μv)]. The overall system gains are calculated from the unit gains (calculated and measured) and from the modulator deviations and discriminator sensitivities indicated
10. Comparison of the overall system gains with that of the "calculated" J302. The comparison is reported both in terms of gain ratios and their differences in db.

Comparison of the calculated overall system gains, at 18db attenuation, of the J302, J402, and J502 shows that the design objectives were fulfilled to within about 1%.

Comparison of the measured overall system gains, at 18db attenuation, of all 9 measured units with that calculated for the J302 shows that the measured values average 2.3% low and range from 7% low to 4% high. About half of that range can be attributed to the variations in the 1% resistors used to construct the preamp/VCO's. About an equal amount can be attributed to errors in the measured values of amplifier gain:

reading and calibration errors limit the precision of the VTVM rms voltage measurements to 2 or 3 %.

The total system gains, relative to that calculated for the J302, for units that have been used in CALNET since 1989 are: J312, 3% low; J412, 4% low: J512, 1% high.

We believe that the calculated preamp/VCO gains are better estimates of the gains of average units than are those measured for the individual units reported above. Accordingly, we shall adopt the following values for the gains at the 18db attenuator setting.

Gain(18db)		Deviation	Units
4126	(72.31db)	100hz/2.7v	J302, J402L, J402
5383	(74.62db)	115hz/4.05v	J302M, J402H, J502
5383	(74.62db)	105hz/4.05v	J312, J412, J512

Discriminators

Interest in the design and performance of discriminators has increased steadily as the network has grown and analysis of its data has become more sophisticated. The principal functions of the discriminator are 1) to recover the seismic analog signal from the audio fm carrier, and 2) to provide low-pass filtering of the recovered signal to limit telemetry noise and to prepare the signal for recording. Until 1989, all discriminators used with CALNET were adjusted to the same sensitivity (2v/125hz), and they all had passbands of dc to at least 20 hz. The differences among them were limited primarily to the position of the upper edge of the passband and the rate of roll-off at higher frequencies and to the internal noise of the discriminators.

In 1989 the maximum deviation of the preamp/VCO's was reduced by 10% (units J312, J412, and J512) and the sensitivity of the discriminators was increased by 10% from 2.0v/125hz to 2.2v/125hz (unit J121).

Prior to 1975, when recording was primarily on Develocorders, which had an effective dynamic range of only about 30 db and a passband of 0.5 to 15 hz, the performance of the discriminators was not a critical factor. Introduction of tape recording and playback with effective compensation substantially improved recording. The full range of frequencies passed by the telemetry system (up to 30 hz) could be recorded with a dynamic range of 40 to 46 db. The bank of J101A and J101B discriminators driving the Develocorders had rather poor low-pass filters, but their output was further filtered by the Develocorders. For tape playback and digitization, a small number of high quality TRICOM discriminators with a passband of dc to 30 hz and a high-frequency roll-off of 30 db/octave were purchased.

The problem of discriminator response arose again, and even more severely, when the CUSP system went on-line in early 1984. With its 12-bit A/D convertor it could record a dynamic range of 72 db, which brought up system noise that was not a serious problem previously. Moreover, with its sampling rate of 100 sps, it required anti-aliasing filtering that was not provided by the J101's. A new discriminator (J110) with lower internal noise and a 24 db/octave 30 hz low-pass filter was built and tested. Further analysis of system noise, Eaton (1984), and consideration of the CUSP aliasing problem prompted redesign of the new discriminator and a further reduction of the low-pass filter passband to dc to 20 hz. It retained the 24 db/octave high-frequency roll-off. At that time the deviation of the preamp/VCO's was decreased by 10% and the sensitivity of the discriminators was increased by 10% (J121).

DEVELCO Model 6203

The response of this discriminator was modelled by Healy and O'Neill with two double-pole low-pass filters with different natural frequencies and damping. The response was down to 0.707 peak at about 23 hz and 0.50 peak at about 32 hz. Its high frequency fall-off was about 24 db/octave.

Parameters

Element	LP	LN	f_0(hz)	ß	Spectral element
Lo-pass #1	2	0	31.00	0.90	$-1/[(\omega-\alpha_j)(\omega-\alpha_k)]$
Lo-pass #2	2	0	58.00	0.70	$-1/[(\omega-\alpha_l)(\omega-\alpha_m)]$

Zeroes

L.P.#1	none
L.P.#2	none

	C-factors	Poles (H & O)	Poles (SEED)
L.P.#1	C_j=194.779	α_j=84.9021+175.3009i	(84.9021i-175.3009)
"	C_k=194.779	α_k=-84.9021+175.3009i	(-84.9021i-175.3009)

L.P.#2 C_l=364.425 α_l=260.2513+255.0973i (260.2513i-255.0973)
" C_m=364.425 α_m=-260.2513+255.0973i (-260.2513i-255.0973)

Sensitivity

A_D=2.0v/125/hz = 0.0160v/hz

J101A and J101B discriminators

These discriminators were developed as low cost substitutes for the DEVELCO discriminator when the network was recorded on Develocorders. Their limitations were not apparent until recording was improved by the introduction of magnetic tape and A/D converters. The J101A response is down to 0.707 peak at 19hz and falls off at 18 db/octave at higher frequencies. The J101B response is down to 0.707 peak at about 38 hz and falls off at 24 db/octave at higher frequencies.

J101A

Parameters

Element	LP	LN	f_0(hz)	ß	Spectral element
Lo-pass #1	1	0	19.50	*	$-i/(\omega-\alpha_j)$
Lo-pass #2	2	0	130.00	0.70	$-1/[(\omega-\alpha_k)(\omega-\alpha_l)]$

Zeroes

L.P.#1 none
L.P.#2 none

	C-factors	Poles (H & O)	Poles (SEED)
L.P.#1	C_j=122.522	α_j=0.0+122.5221i	(0.0i-122.5221)
L.P.#2	C_k=816.814	α_k=583.3220+571.7698i	(583.3220i-571.7698)
"	C_l=816.814	α_l=-583.3220+571.7698i	(-583.3220i-571.7698)

Sensitivity

A_D=2.0v/125hz = 0.0160 v/hz

J101B

Parameters

Element	LP	LN	f_0(hz)	ß	Spectral element
Lo-pass #1	2	0	60.00	1.00	$-1/[(\omega-\alpha_j)(\omega-\alpha_k)]$
Lo-pass #2	2	0	130.00	0.70	$-1/[(\omega-\alpha_l)(\omega-\alpha_m)]$

Zeroes

L.P.#1 none
L.P.#2 none

	C-factors	Poles (H & O)	Poles (SEED)
L.P.#1	C_j=376.991	α_j=0.0+376.9911i	(0.0i-376.9911)
"	C_k=376.991	α_k=-0.0+376.9911i	(-0.0i-376.9911)
L.P.#2	C_l=816.814	α_l=583.3220+571.7698i	(583.3220i-571.7698)
"	C_m=816.814	α_m=-583.3220+571.7698i	(-583.3220i-571.7698)

Sensitivity

A_D=2.0v/125hz = 0.0160 v/hz

TRI-COM discriminator

In order to play back tape recordings of multiplexed signals from the network, several sets of high quality TRI-COM discriminators were purchased. One set (of 9 data channels plus two timing channels and one compensation channel) provided for playback of one track at a time, at x4 recording speed, for playouts on the Siemens Oscillomink. Four additional sets provided for playing back four tracks at a time, at x16 recording speed, for digitization. Center frequencies and filter frequencies were scaled up so that the recorded signals would match those played back at x1 recording speed with the filters described below.

The spectral elements of the TRI-COM discriminators were calculated by Jay Dratler (1980) by means of circuit theory. The calculated curve based on those elements was then shown to match an experimental response curve. The TRI-COM response is down to 0.707 peak at 30 hz and falls off at 30 db/octave at higher frequencies.

Parameters

Element	LP	LN	f_0(hz)	ß	Spectral element
Lo-pass #1	1	0	45.10	*	$-i/(\omega-\alpha_j)$
Lo-pass #2	2	0	46.70	0.890	$-1/[(\omega-\alpha_k)(\omega-\alpha_l)]$
Lo-pass #3	2	0	52.70	0.550	$-1/[(\omega-\alpha_m)(\omega-\alpha_n)($]

Zeroes

L.P.#1	none
L.P #2	none
L.P.#3	none

	C-factors	Poles (H & O)	Poles (SEED)
L.P.#1	C_j=283.372	α_j=0.0+283.3716i	(0.0i-283.3716)
L.P.#2	C_k=293.425	α_k=133.7901+261.1480i	(133.7901i-261.1480)
"	C_l=293.425	α_l=-133.7901+261.1480i	(-133.7901i-261.1480)
L.P.#3	C_m=331.124	α_m=276.5429+182.1181i	(276.5429i-182.1181)
"	C_n=331.124	α_n=-276.5429+182.1181i	(-276.5429i-182.1181)

Sensitivity

A_D=2.0v/125hz = 0.0160 v/hz

J110 discriminator

The J110 has a response similar to that of the TRI-COM. Its response is down to 0.707 peak at 30 hz and falls off at 24 db/octave at higher frequencies. It employs two low-pass active filter elements with the same natural frequency (30 hz) but different damping. It was designed from an active filter handbook to have specified poles. The calculated response for a filter with those poles matches the measured response of the actual discriminators very closely.

J110 (J110-30)

Parameters

Element	LP	LN	f_0(hz)	ß	Spectral element
Lo-pass #1	2	0	30.00	0.3827	$-1/[(\omega-\alpha_j)(\omega-\alpha_k)]$
Lo-pass #2	2	0	30.00	0.9239	$-1/[(\omega-\alpha_l)(\omega-\alpha_m)]$

Zeroes

L.P.#1 none

L.P.#2 none

	C-factors	Poles (H & O)	Poles (SEED)
L.P.#1	C_j=188.496	α_j=174.1459+72.1372i	(174.1459i-72.1373)
"	C_k=188.496	α_k=-174.1459+72.1373i	(-174.1459i-72.1373)
L.P.#2	C_l=188.496	α_l=72.1248+174.1510i	(72.1248i-174.1510)
"	C_m=188.496	α_m=-72.1248+174.1510i	(-72.1248i-174.1510)

Sensitivity

A_D=2.0v/125/hz = 0.0160 v/hz

In a later version (J110-20) the low-pass filter natural frequency was reduced to 20 hz, as in the J120.

J120 discriminator

Network noise tests undertaken when the J110 was first installed showed that further reduction of the upper edge of the passband would further reduce system noise as well as insure more adequate sampling of transient seismic data. The lo-pass filters were modified to drop the upper passband edge to 20 hz, and a new, sharper input bandpass filter was adopted to get better separation of adjacent telemetry channels. The J120 response is down to 0.707 peak at 20 hz and falls off at 24 db/octave at higher frequencies.

When the preamp/VCO deviation was decrease by 10% in 1989, the J120 output sensitivity was increased by 10%, to 2.2v/125hz. The more sensitive unit is called the J121.

Parameters

Element	LP	LN	f_0(hz)	ß	Spectral element
Lo-pass #1	2	0	20.00	0.3827	$-1/[(\omega-\alpha_j)(\omega-\alpha_k)]$
Lo-pass #2	2	0	20.00	0.9239	$-1/[(\omega-\alpha_l)(\omega-\alpha_m)]$

Zeroes

L.P.#1 none

L.P.#2 none

	C-factor	Poles (H & O)	Poles (SEED)
L.P.#1	C_j=125.664	α_j=116.0973+48.0915i	(116.0973i-48.0915)
"	C_k=125.664	α_k=-116.0973+48.0915i	(-116.0973i-48.0915)
L.P.#2	C_l=125.664	α_l=48.0832+116.1007i	(48.0832i-116.1007)
"	C_m=125.664	α_m=-48.0832+116.1007i	(-48.0832i-116.1007)

Sensitivity

J120: A_D=2.0v/125hz = 0.0160 v/hz

J121: A_D=2.2v/125hz = 0.0176 v/hz

A summary of the characteristics of discriminators used in CALNET is given in Table 3.

Recording devices

Develocorder

The Develocorder is a multichannel oscillograph that records up to 18 seismic and 3 time channels on 16 mm photographic film. The 15.5 hz recording galvanometers constitute mechanical low-pass filters with 0.707 peak response at 15.5 hz and 12 db/octave fall-off at higher frequencies. Each galvanometer is preceded by an R-C filter to suppress line drift from unbalanced discriminators and to reduce coastal microseisms in the 1 to 3 second period range. The Develocorder sensitivity is set at 20 mm/v (40 mm/volt on the film reader). The poles of the response functions were determined by matching the experimental response curve by the methods of Healy and O'Neill.

Parameters

Element	LP	LN	f_o(hz)	ß	Spectral element
Hi-pass	1	1	0.53	*	$\omega/(\omega-\alpha_j)$
Lo-pass(Galv)	2	0	15.50	0.70	$-1/[(\omega-\alpha_k)(\omega-\alpha_1)]$

Zeroes

Hi-pass	1 at 0.0+0.0i	(0.0i-0.0) (SEED)	
Lo-pass	none		
	C-factors	Poles (H & O)	Poles (SEED)
Hi-pass	C_j=1.00	α_j=0.0+3.3301i	(0.0i-3.3301)
Lo-pass	C_k=97.389	α_k=69.5499+68.1726i	(69.5499i-68.1726)
"	C_1=97.389	α_1=-69.5499+68.1726i	(-69.5499i-68.1726)

Sensitivity

A_R=20 mm/v (40 mm/v on the viewer screen)

Siemens Oscillomink

The Siemens Oscillomink is a 16-channel high-speed ink-writing oscillograph used to play back seismic data from magnetic tape. It is coupled to the discriminators by dc-blocking R-C filters and records by means of very high frequency galvanometers; so its response function is characterized by both a high-pass filter and a low-pass filter. The passband of this system encompasses the whole range of seismic frequencies emerging from the discriminators, so it is treated like a dc device.

The Siemens is adjusted to a standard gain level on the basis of a calibration signal. It is usually operated at either of two sensitivity levels: 40 mm/v or 10 mm/v.

The Siemens is also operated in conjunction with a set of frequency-switchable active filters. Although both band-pass filtering with 24 db/octave fall-off and low-pass filtering with 12 db/octave fall-off are available, standard playback procedures employ only the low-pass filters.

Parameters

Element	LP	LN	f_0(hz)	ß	Spectral element
S. Osc.	*	*	*	*	1.0
L.P. Fil.	2	0	f_0	.50	$-1/[(\omega-\alpha_j)(\omega-\alpha_k)]$

Zeroes

Siemens	none
Lo-pass filt.	none

	C-factors	Poles (H & O)	Poles (SEED)
Siemens	*	*	*
Lo-pass	$C_j=\omega_0$	$\alpha_j=\omega_0(0.500i+0.8660)$	$[\omega_0(-0.500+0.8660i)]$
"	$C_k=\omega_0$	$\alpha_k=\omega_0(0.500i-0.8660)$	$[\omega_0(-0.500-0.8660i)]$

where $\omega_0=2\pi f_0$

Sensitivity

Siemens: A_R=40mm/v (Hi); =10mm/v (Lo)

Lo-pass: A_F=1.0 (normalized by its C-factors)

CUSP

As a recorder, the response of the CUSP system depends on its A/D converter. Within the seismic passband the A/D converter is a dc device: so we are interested only in its sensitivity expressed as counts/volt.

CUSP/TUSTIN

Parameters

Element	LP	LN	f_0(hz)	ß	Spectral element
Tustin	*	*	*	*	1.0

Sensitivity

Tustin: A_R=2047 counts/2.5v = 818.8 counts/v.

RESPONSE OF THE ENTIRE SYSTEM

The response of the system as a whole is obtained by combining the spectral elements and sensitivity factors of its constituent parts. The systems that we shall use to illustrate the process consist of: 1) the L4-C seismometer with L-pad, the

J512 preamp/VCO, the J121 discriminator, and CUSP recording system (12-bit Tustin A/D converter), and 2) the L4-C seismometer, the J302 preamp/VCO, the J101B discriminator, and the Develocorder.

Both methods of characterizing the system (parameters versus poles and zeroes) require the overall system sensitivity, which is the product of the sensitivities of the individual components:

$A=A_S x A_{VCO} x A_D x A_R$

$A_S=1.0$ v/cm/sec	L4-C with L-pad
$A_{VCO}=25.926x10^{(92.6-attn)/20}$ hz/v	J512
$A_{VCO}=37.037x10^{(90.3-attn)/20}$ hz/v	J302
$A_D=0.0176$ v/hz	J121
$A_D=0.0160$ v/hz	J101B
$A_R=818.8$ counts/v	CUSP
$A_R=40$ mm/v	Develocorder film viewer

Let $A_E=A_{VCO}xA_D$. Then $A=A_SxA_ExA_R$.

For the J302 and J101B combination,

$A_E=37.037x0.0160x10^{(90.3-attn)/20}=0.5926x10^{(90.3-attn)/20}$.

For the J512 and J121 combination,

$A_E=25.926x0.0176x10^{2.3/20}x10^{(90.3-attn)/20}=0.5946x10^{(90.3-attn)/20}$.

Thus, within 1% tolerance, the A_E's for the J512/J121 and J302/J101B combinations are the same:

$A_E=0.594x10^{(90.3-attn)/20}$ J512/J121 and J302/J101B.

This result is by design. When changes were made in the preamp/VCO, compensating changes were made so that the product $A_AxA_MxA_D$ remained constant. A_A is the gain of the amplifier, A_M is the gain of the modulator, and A_D is the gain of the discriminator.

The system sensitivities of the two system configurations we are examining are:

$A_1=1.0x0.594x10^{(90.3-attn)/20}x818.8 = 486.4x10^{(90.3-attn)/20}$ c/cm/sec.

$A_2=1.0x0.596x10^{(90.3-attn)/20}x4.0 = 2.376x10^{(90.3-attn)/20}$ cm/cm/sec.

At 18db attenuation: $A_1=2.004x10^6$ c/cm/sec

$A_2=9.791x10^3$ cm/cm/sec

Characterization of system #1 in terms of its parameters

Sensitivity: $486.4x10^{(90.3.attn)/20}$c/cm/sec

LP	LN	f_0(hz)	ß	Element
2	3	1.00	0.80	Seismometer with L-pad
2	2	0.095	1.00	J512 hi-pass filter
2	0	44.00	1.00	J512 lo-pass filter
2	0	20.00	0.3827	J121 lo-pass filter #1
2	0	20.00	0.9239	J121 lo-pass filter #2

Characterization of system #1 in terms of its poles and zeroes

Sensitivity: $486.4x10^{(90.3-attn/20)}$c/cm/sec

Zeroes	Healy and O'Neill	SEED	Element
1	0.0+0.0i	0.0i-0.0	Seismometer and L-pad
2	0.0+0.0i	0.0i-0.0	"
3	0.0+0.0i	0.0i-0.0	"
4	0.0+0.0i	0.0i-0.0	J512 hi-pass filter
5	0.0+0.0i	0.0i-0.0	"

C-factors	Poles (H & O)	Poles (SEED)	Element
1.00	5.0265i+3.7699	-5.0265+3.7699i	Seismometer/L-pad
1.00	5.0265i-3.7699	-5.0265-3.7699i	"
1.00	0.5969i+0.0	-0.5969+0.0i	J512 hi-pass filt.
1.00	0.5969i-0.0	-0.5969-0.0i	"
276.460	276.4602i+0.0	-276.460+0.0i	J512 lo-pass filt.
276.460	276.4602i-0.0	-276.460-0.0i	"
125.664	48.0915i+116.0973	-48.0915+116.0973i	J121 lo-pass #1
125.665	48.0915i-116.0973	-48.0915-116.0973i	"
125.665	116.1007i+48.0832	-116.1007+48.0832i	J121 lo-pass #2
125.664	116.1007i-48.0832	-116.1007-48.0832i	"

Characterization of system #2 in terms of its parameters

Sensitivity: $2.376\text{x}10^{(90.3\text{-attn})/20}$cm/cm/sec

LP	LN	f_0(hz)	ß	Element
2	3	1.00	0.80	Seismometer with L-pad
2	2	0.0950	1.00	J302 hi-pass filter
2	0	44.00	1.00	J302 lo-pass filter
2	0	60.00	1.00	J101B lo-pass #1
2	0	130.00	0.70	J101B lo-pass #2
1	1	0.53	*	Develocorder hi-pass filter
2	0	15.50	0.70	Develocorder lo-pass filter

Characterization of system #2 in terms of its poles and zeroes

Sensitivity: $2.376\text{x}10^{(90.3\text{-attn})/20}$cm/cm/sec

Zeroes	Healy and O'Neill	SEED	Element
1	0.0+0.01	0.0i-0.0	Seismometer/L-pad
2	0.0+0.0i	0.0i-0.0	"
3	0.0+0.0i	0.0i-0.0	"
4	0.0+0.0i	0.0i-0.0	J302 hi-pass filt.
5	0.0+0.0i	0.0i-0.0	"
6	0.0+0.0i	0.0i-0.0	Develocordr hi-pass filt.

C-factors	Poles (H & O)	Poles (SEED)	Element
1.00	5.0265i+3.7699	-5.0265+3.7699i	Seismometer/L-pad
1.00	5.0265i-3.7699	-5.0265-3.7699i	"
1.00	0.5969i+0.0	-0.5969+0.0i	J302 hi-pass filt.
1.00	0.5969i-0.0	-0.5969-0.0i	"
276.460	276.4602i+0.0	-276.4602+0.0i	J302 lo-pass filt.
276.460	276.4602i-0.0	-276.4602-0.0i	"
376.991	376.9911i+0.0	-376.9911+0.0i	J101B lo-pass #1
376.991	376.9911i-0.0	-376.9911-0.0i	"
816.814	571.7698i+583.3220	-571.7698+583.3220i	J101B lo-pass #2
816.814	571.7698i-583.3220	-571.7698-583.3220i	"
97.389	68.1726i+69.5499	-68.1726+69.5499i	Devcrdr lo-pass
97.389	68.1726i-69.5499	-68.1726-69.5499i	"
1.00	3.3301i+0.0	-3.3301+0.0i	Devcrdr hi-pass

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References

Criley, Ed, and Eaton, J. P.,(1978) Five-day recorder seismic system (with a section on the TIME CODE GENERATOR, by Jim Ellis):USGS Open-File Report 78-266.

Dratler, J., Jr.,(1980) Theoretical transfer functions for stations in the central California seismographic network: USGS Open-File Report 80-376.

Eaton, J. P., (1975a) Harmonic magnification of the complete telemetered seismic system from seismometer to film viewing screen: USGS Open-File Report 75-95.

Eaton, J. P.,(1975b) Notes on some experiments on the application of subtractive compensation to USGS seismic magnetic tape recording and playback systems: USGS Open-File Report 75-663.

Eaton, J. P.,(1976a) Notes on a broad-band variant of the NCER seismic data multiplex system for use with field tape recorders: USGS Open-File Report 76-87.

Eaton, J. P.,(1976b) 15/16 ips operation of the P. I. 5100 tape recorder to record the standard (30 hz) NCER seismic data multiplex system: USGS Open-File Report 76-252.

Eaton, J. P.,(1976c) Tests of the standard (30 hz) NCER FM multiplex telemetry system, augmented by two timing channels and a compensation reference signal, used to record multiplexed seismic network data on magnetic tape: USGS Open-File Report 76-374.

Eaton, J. P.,(1977) Frequency response of the USGS short-period telemetered seismic system and its suitability for network studies of local earthquakes: Open-File Report 77-844.

Eaton, J. P.,(1978) Playback station #2 for CALNET and 5-day-recorder tapes: USGS Open-File Report 78-542.

Eaton, J. P.,(1980) Response arrays and sensitivity coefficients for standard configurations of the USGS short-period telemetered seismic system: USGS Open-File Report 80-316.

Eaton, J. P.,(1984) Noise analysis of the seismic system employed in the northern and southern California seismic nets: USGS Open-File Report 84-657.

Eaton, J. P.,(1992) Determination of amplitude and duration magnitude and site residuals from short-period seismographs in northern California: Bull. Seism. Soc. Amer., v. 82, no. 2, p 533-579.

Eaton, J. P., O'Neill, M. E., and Murdock, J. N.,(1970) Aftershocks of the 1966 Parkfield-Cholame, California, earthquake: a detailed study: Bull. Seism. Soc. Amer., v. 60, p 1151-1197.

Eaton, J. P., and VanShaack, J. R.,(1977) Factors limiting the sensitivity and dynamic range of a seismic system employing magnetic tape recording and a seismic amplifier with adjustable gain settings and several output levels: USGS Open-File Report 77-224.

Healy, J. H., and O'Neill, M. E.,(1977) Calibration of seismographic systems, USGS stations in the central California network: USGS Open-File Report 77-736.

Stewart, S. W., and O'Neill, M. E.,(1980) Calculation of the frequency response of the USGS telemetered short-period seismic system: USGS Open-File Report 80-143.

Table 1

Spectral element with single pole on imaginary axis

$\alpha_j = i\,\omega_0$

LP	LN	Complex expression	Amplitudes	Limits: $\omega \to 0$	Limits: $\omega \to \infty$
1	0	$\dfrac{-\alpha_j}{\omega-\alpha_j} = \dfrac{-i\omega_0}{\omega - i\omega_0}$	$\dfrac{\omega_0}{(\omega^2+\omega_0^2)^{1/2}}$	$\dfrac{\omega_0}{\omega_0} \to 1$	$\dfrac{\omega_0}{\omega} \to 0$
1	1	$\dfrac{\omega}{\omega-\alpha_j} = \dfrac{\omega}{\omega - i\omega_0}$	$\dfrac{\omega}{(\omega^2+\omega_0^2)^{1/2}}$	$\dfrac{\omega}{\omega_0} \to 0$	$\dfrac{\omega}{\omega} \to 1$

$C_j = 1.0$ if $LN=1$; $C_j = \omega_0$ if $LN=0$

Spectral element with paired poles

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

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

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

LP	LN	Complex expression	Amplitudes	Limits: $\omega \to 0$	Limits: $\omega \to \infty$
2	0	$\dfrac{\alpha_j\alpha_K}{(\omega-\alpha_j)(\omega-\alpha_K)} = \dfrac{-\omega_0^2}{(\omega^2-\omega_0^2) - i2\beta\omega_0\omega}$;	$\dfrac{\omega_0^2}{\left[(\omega^2-\omega_0^2)^2 + 4\beta^2\omega_0^2\omega^2\right]^{1/2}}$;	$\dfrac{\omega_0^2}{\omega_0^2} \to 1$	$\dfrac{\omega_0^2}{\omega^2} \to 0$
2	2	$\dfrac{\omega^2}{(\omega-\alpha_j)(\omega-\alpha_K)} = \dfrac{\omega^2}{(\omega^2-\omega_0^2) - i2\beta\omega_0\omega}$;	$\dfrac{\omega^2}{\left[(\omega^2-\omega_0^2)^2 + 4\beta^2\omega_0^2\omega^2\right]^{1/2}}$;	$\dfrac{\omega^2}{\omega_0^2} \to 0$	$\dfrac{\omega^2}{\omega^2} \to 1$
2	3	$\dfrac{i\omega^3}{(\omega-\alpha_j)(\omega-\alpha_K)} = \dfrac{i\omega^3}{(\omega^2-\omega_0^2) - i2\beta\omega_0\omega}$;	$\dfrac{\omega^3}{\left[(\omega^2-\omega_0^2) + 4\beta^2\omega_0^2\omega^2\right]^{1/2}}$;	$\dfrac{\omega^3}{\omega_0^2} \to 0$	$\dfrac{\omega^3}{\omega^2} \to \omega$

$C_j = 1$ if $LN = 2$ or 3; $C_j = \omega_0$ if $LN = 0$

$C_K = 1$ if $LN = 2$ or 3; $C_K = \omega_0$ if $LN = 0$

Table 2 Preamp/VCO Types, Parameters, and Dates of Operation

Unit	In use	Power	Deviation Hz/V	Gain at 18 db atten. (calculated) ratio/db	Gain at 18db atten. (measured) ratio/db	Sensitivity at 18db atten. hz(out)/µV(in) Calc.	Meas.	Discrim. Sensit. V/hz	Syst. Gain at 18 db atten Disc(µV)/Preamp(µV) Calc.	Meas.	Relative Syst. gain at 18db atten XXX/J302 Calc.	Meas.
J302	Pre-'81	4.05 V Hg	100/2.7	4126 (72.31)	4135 (72.3)	.1528	.1531	2.0/125	2440	2450	1.0 (0)	1.004 (+.04)
J302L	80-86	3.65 V Li	100/2.7		3876 (71.8)		.1436	2.0/125		2300		.9426 (-.51)
J302M	86-89	3.65 V Li w/5V reg.	115/4.05		5184 (74.3)		.1524	2.0/125		2440		1.004 (+.04)
J312	89-	"	105/4.05		5185 (74.3)		.1344	2.2/125		2370		.9713 (-.25)
J402	78-86	3.65 V Li	100/2.7	4126 (72.31)	3838 (71.7)	.1528	.1421	2.0/125	2440	2270	1.000 (0)	.9302 (-.63)
J402H	86-89	Solar 5V reg	115/4.05		5400 (74.6)		.1587	2.0/125		2540		1.041 (+.35)
J412H	89-	"	105/4.05		5130 (74.2)		.1330	2.2/125		2340		.9590 (-.36)
J502	—	"	115/4.05	5383 (74.62)	5230 (74.3)	.1529	.1485	2.0/125	2450	2380	1.004 (+.04)	.9754 (-.22)
J512	89-	"	105/4.05	" "	5410 (74.7)	.1396	.1403	2.2/125	2460	2470	1.008 (+.07)	1.012 (+.11)
1	2	3	4	5	6	7		8	9		10	

Table 3

Discriminator types and parameters

Name	Code	Sens(v/hz)	0.707 Resp	Slope	Sept'88
Develco	D	2.0/125	23 (hz)	24 (db/oct)	--
J101A	-	"	19 "	18 "	--
J101B	01	"	38 "	24 "	221
JJ		"	38 "	24 "	22
J110-30	10-30	"	30 "	24 "	85
J110-20	10-20	"	20 "	24 "	105
J120	20	"	20 "	24 "	43
J121	21,21/1,21/2	.2/125	20 "	24 "	--
TRI-COM	-	2.0/125	30 "	30 "	--

The JJ discriminator was a transitional type. It employed the same sensitivity and low-pass filter as the J101B. The codes 21/1 and 21/2 denote different constructional details of the J121. Functionally, the 21, 21/1, and 21/2 are identical.