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HARMONIC MAGNIFICATION OF THE COMPLETE TELEMETERED SEISMIC SYSTEM, FROM SEISMOMETER TO FILM VIEWER SCREEN

by

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A collection of notes on the standardization, adjustment, and calibration of the seismic systems employed in the USGS central California microearthquake network (compiled 9/15/70; revised 8/20/73)

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I. Harmonic Magnification of the Complete Telemetered Seismic System, From Seismometer to Film Viewer Screen

The harmonic magnification MF(f) of the complete system can be separated into two factors, the "seismometer response" SP(f) and the "system response" V(f), that can be determined independently. $MF(f) = SP(f) \times V(f)$, where $SP(f) = EP(f)_{p-p}/2h$ is the ratio of the peak-to-peak seismometer-generated emf across the preamp input $(EP(f)_{p-p})$ to the peak-to-peak ground motion amplitude (2h) driving the seismometer and where $V(f) = {}^{2H}/EP(f)_{p-p}$ is the ratio of the peak-to-peak signal amplitude on the viewer screen (2H) to the peak-to-peak emf across the preamp input, at frequency f.

SP(f) can be calculated from the seismometer parameters $F_o, \beta, G_L, + R$, the preamp input impedance RR, and the T-pad resistors T, S, and TT (or L-pad resistors T and S), all of which can be measured or determined by simple experiments. V(f) depends upon the "gain" and other operating characteristics of the preamp-VCO, the discriminator, the coupling filter between the discriminator and the Develocorder, and the Develocorder. V(f) can be determined directly by experiment: a set of signals at selected frequencies f across the system pass-band, all at the same voltage level VC_{p-p}, are applied in succession to the preamp input, and the resulting signals are recorded on the Develocorder and their amplitudes $A(f)_{p-p}$ are measured on the film viewer.

In order to separate V(f) into "sensitivity" and "frequency response" factors, we can write:

$$V(f) = V(5.0) \times \frac{V(f)}{V(5.0)} = \frac{C_{10}}{28.28} \times \frac{A(f)}{A(5.0)}, \quad [\text{units are } mm_{p-p}/\mu V_{p-p}]$$

where C_{10} is the peak-to-peak viewer amplitude, in mm, produced by a 5.0 hz, $10\mu V_{rms}$ (i.e. a 28.28 μV_{p-p}) calibration signal into the preamp.

From the expression for $EP(f)_{p-p}$ and from the definition of SP(f),

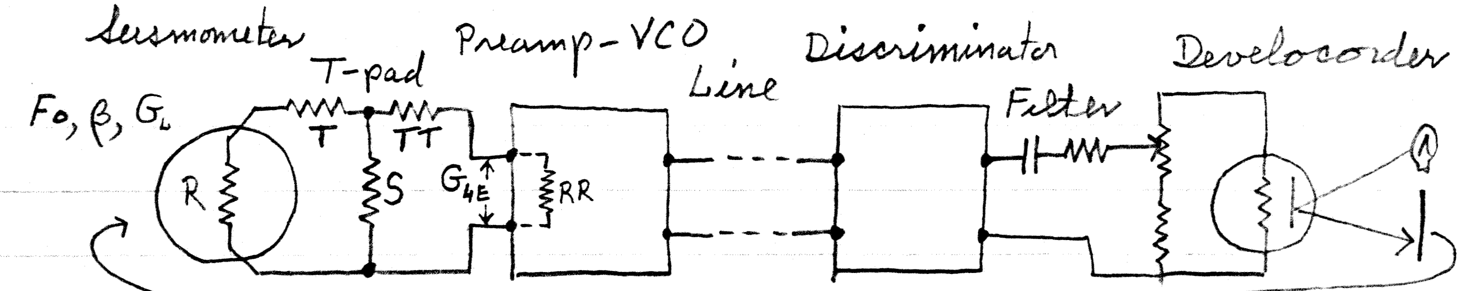
$$SP(f) = \frac{EP(f)_{p-p}}{2h} = \frac{2\pi f^3 G_{LE}}{\left[(F_o^2 - f^2)^2 + 4\beta^2 F_o^2 f^2\right]^{1/2}} \quad [\text{units are } \mu V_{p-p}/mm]$$

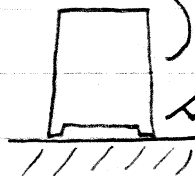
Thus,

$$MF(f) = \frac{2\pi f^3 G_{LE}}{\left[(F_o^2 - f^2)^2 + 4\beta^2 F_o^2 f^2\right]^{1/2}} \times \frac{A(f)}{A(5.0)} \times \frac{C_{10}}{28.28} \quad [\text{dimensionless}]$$

In this expression for MF(f) we can identify the first factor as the seismometer response, the second factor as the system frequency response, and the third factor as the system sensitivity.

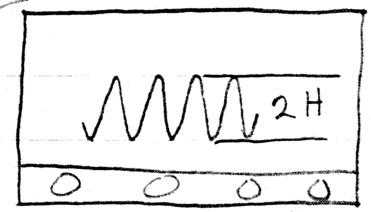
Fig 1





Seismometer

Film Viewer



Ground Motion

$$\xi = h \sin 2\pi f t$$

Seismogram

$$Z = H \sin(2\pi f t + \varphi(f))$$

$MF(f) = \frac{2H}{2h}(f)$ Magnification at frequency f

$\varphi(f)$ Phase angle at frequency f

Harmonic response of seismometer mass:

$$Z(t) = -\frac{h f^2 \sin\left[2\pi f t + \tan^{-1}\left(\frac{-2\beta f F_0}{F_0^2 - f^2}\right)\right]}{\left[(F_0^2 - f^2)^2 + 4\beta^2 F_0^2 f^2\right]^{1/2}}$$

emf produced across the preamp input:

$$EP(t) = G_{LE} \cdot \dot{Z}(t) = -\frac{2\pi h f^3 G_{LE} \cos\left[\left(2\pi f t + \tan^{-1}\left(\frac{-2\beta f F_0}{F_0^2 - f^2}\right)\right)\right]}{\left[(F_0^2 - f^2)^2 + 4\beta^2 F_0^2 f^2\right]^{1/2}}$$

Peak-to-peak emf across the preamp input:

$$EP(f)_{P-P} = \frac{4\pi h f^3 G_{LE}}{\left[(F_0^2 - f^2)^2 + 4\beta^2 F_0^2 f^2\right]^{1/2}}$$

Units: h[mm], G_{LE}[μv/mm/sec], $EP(f)_{P-P}$[μv_{P-P}]

To deal conveniently with many stations that have seismic systems that are virtually identical except for sensitivity, it is convenient to introduce the "unit calibration" harmonic response, MF1(f), which corresponds to a system sensitivity of 1 mm_{p-p} for a 10 μV_{rms} calibration signal into the preamp input. The harmonic magnification of a particular station, with calibration amplitude C_{10}, at frequency f is: $MF(f) = MF1(f) \times C_{10}$. As used here C_{10} is a dimensionless scaling factor, its "units" ($mm_{p-p}/10\ \mu V_{rms}$) having been absorbed in MF1(f). Finally,

$$MF1(f) = \frac{G_{LE}}{28.28} \frac{2\pi f^3}{\left[(F_o^2 - f^2)^2 + 4\beta^2 F_o^2 f^2\right]^{1/2}} \times \frac{A(f)}{A(5.0)} \qquad [C_{10} = 1.0]$$

Here we can identify two factors that must be treated separately because they are evaluated in different manners:

$$TGN(f) = \frac{G_{LE}}{28.28} \times \frac{2\pi f^3}{\left[(F_o^2 - f^2)^2 + 4\beta^2 F_o^2 f^2\right]^{1/2}} \qquad [C_{10} = 1.0]$$

combines the seismometer response and the system "unit calibration" sensitivity, and it can be computed from parameters that can be measured or determined explicitly.

$A(f)/A(5.0)$ is the system frequency response, which can be determined for any desired set of frequencies f but cannot be calculated for an arbitrary frequency.

By calculating TGN(f) for the frequencies at which A(f)/A(5.0) is measured, we can establish the values of MF1(f) at those same frequencies. The choice of frequencies is important because we wish to be able to obtain the value of MF1(f) at an arbitrary frequency, by interpolation between a minimum number of established values of MF1(f), with a precision that is independent of frequency. It is convenient to carry out the interpolation in terms of log(FM1(f)) vs log f and to choose the 40 frequencies corresponding to log f = -2.0 + 0.1n, n = 1, 40, as those for which MF1(f) is established directly.

To calculate magnitudes of earthquakes by the method employed in the "subroutine" MAGNTD it is necessary to convert the signal amplitude read from the viewer screen AM(f) (from the telemetered seismic system) to the amplitude B(f) that would have been read on the seismogram from a standard Wood-Anderson seismograph located at the site of the telemetered seismic station. The magnification of the Wood-Anderson is ($F_o = \frac{1}{0.8}$, $\beta = 0.8$, $\bar{V} = 2800$):

$$MWA(f) = \frac{2800 f^2}{\left[(1.25^2 - f^2)^2 + 4.0 f^2\right]^{1/2}} .$$

Then

$$B(f) = \frac{AM(f)}{MF(f)} \times MWA(f) = \frac{AM(f)}{C_{10}} \times \frac{MWA(f)}{MF1(f)} .$$

The computer program HARMAG calculates MF(f), MF1(f), and log[MF1(f)/MWA(f)] for the values of f (from log f = -2.0 + 0.1 N, N= 1,40) at which A(f)/A(5) is determined. The value of MF1(f)/MWA(f) at an arbitrary frequency can then be determined by interpolation (of log[MF1(f)/MWA(f)] vs log f). As input, HARMAG requires the natural frequency and damping constant of the seismometer F_o and β, and the effective linear motor constant of the seismometer G_{LE}. As output, it also provides the array log [MF1(f)/MFW(f)], where f = antilog (-2.0 + 0.1 N) and N = 1,40. This 40-element array is on 2 punched cards in F4.2 format (with the decimal suppressed), as required for input to the epicenter location program HYPOMAG. Such an array can be used for an entire family of seismic systems that differ only in their sensitivities; i. e., only in their calibration amplitudes, C_{10}.

The systems in use at NCER that constitute such families are the following:

Refraction trucks with HS-10 seismometers

Refraction trucks with EV-17 seismometers

Portable tape systems with EV-17 seismometers

Telemetered systems - it is necessary to distinguish 7 separate system configurations as separate families. The first of these is a new "standard" configuration to which all systems will be adjusted when they are calibrated. The other 6 represent configurations in present or past use.

II Calculation of response arrays for the NCER telemetered seismic systems

Three different seismometers, at least two different discriminator-Develocorder coupling filters, and two different preamp-VCO's have been used in various combinations in the NCER network. In general, seismometer parameters have not been measured and the frequency response of various system configurations employed have not been measured. The only efforts made to cope with the problem of calibration have been 1) the periodic introduction of a calibration signal (10 hz at levels of 1mV, 100 μV, and 10μV) into the preamp inputs, 2) attempts to provide the correct damping resistance (for β = 0.6 to 0.7) for the seismometers, and 3) the keeping of records of what seismometers and damping circuits or adjustments were employed at each station, as well as which kind of preamp-VCO was used there.

To calculate approximate response arrays for these systems, we shall proceed as follows:

1) The intrinsic parameters of the seismometers will be taken from the manufacturer's specifications.

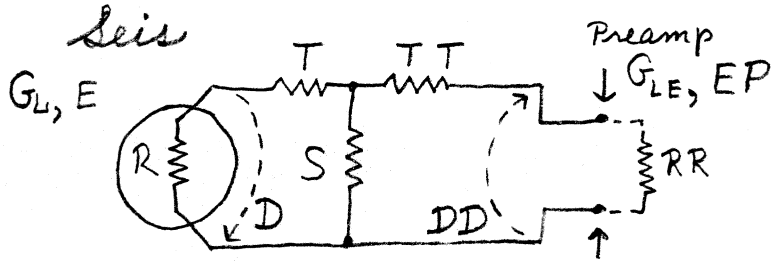
2) The seismometer damping and effective motor constant will be calculated from those intrinsic seismometer parameters and the configuration and values of resistors employed in the seismometer-preamp coupling network.

3) The system frequency response will be taken from limited tests carried out with the two types of preamp-VCO's and various discriminator-Develocorder coupling filters.

4) The response arrays will then be calculated by the methods outlined above.

A) Nominal constants of seismometers used in the NCER telemetered seismic network -- derived from the manufacturers' specifications and limited tests on a few instruments.

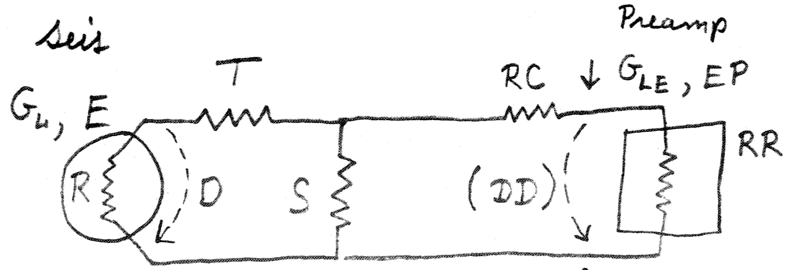
Type	EV-17	L-4C	HS-10	
F_o	1.00	1.00	2.00	hz
β_o	0.33	0.28	0.19	
Γ	7140	5940	697	ohms
G_L	4.80	2.73	1.18	V/cm/sec
R	5000	5500	390	ohms
$D_{0.8}$	10,200	5900	750	ohms



Nomenclature used with T-pad

$$G_{LE} = G_L \frac{(RR \times S)}{(R+T+S)(RR+TT+S) - S^2}$$

$$\beta_1 = \frac{\Gamma}{R+D}$$, D is resistance external to seismometer



Nomenclature used with L-pad

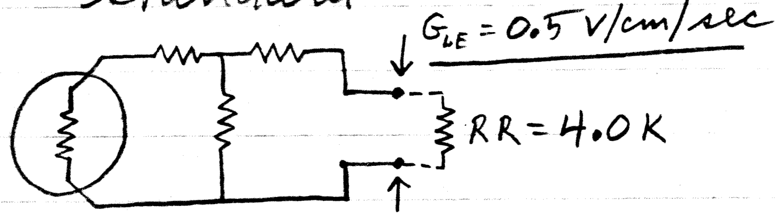
$$G_{LE} = G_L \times \frac{S \times RR / (S+RR+RC)}{R+D}$$

B) Seismometer — Preamp-VCO hook-ups

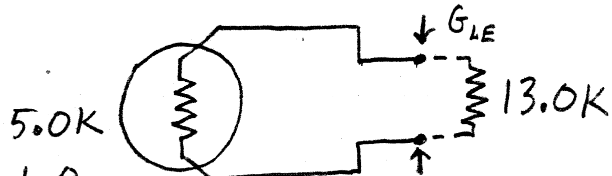
#1 Standard

$F_0 = 1.0$

$\beta = 0.8$



#2 EV-17 — Develco



$F_0 = 1.0$

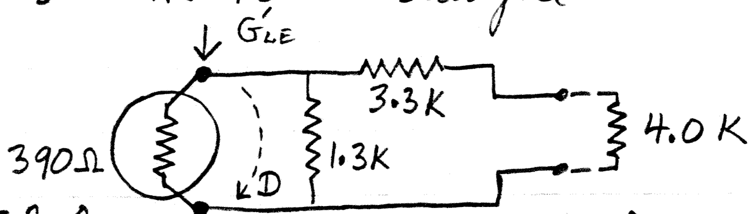
$$\frac{13.0}{5.0+13.0} \times 4.80 = 3.47 = G_{LE}$$

$$\frac{7.140K}{18.0K} = .40 = \beta_1$$

$.33 = \beta_0$

$0.73 = \beta$

#3 HS-10 — Teledyne



$F_0 = 2.0$

↑ Calibration applied here, with seis removed

$D = 1100\,\Omega$.

$$\frac{697}{390+1100} = 0.47 = \beta_1$$

$0.19 = \beta_0$

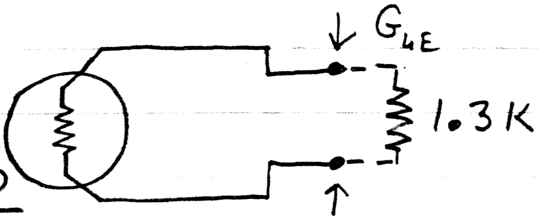
$0.66 = \beta$

$$G'_{LE} = G_L \times \frac{D}{R+D} \qquad 1.18 \times \frac{1100}{1490} = 0.872 = G'_{LE}$$

#4 HS-10 — Develco

390Ω

$F_o = 2.0$



$$\frac{697}{390+1300} = 0.41 = \beta_1$$

$0.19 = \beta_0$

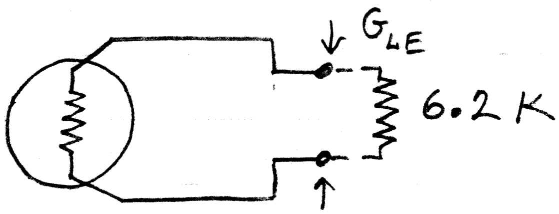
$\underline{0.60 = \beta}$

$$\frac{1300}{390+1300} \times 1.18 = \underline{0.908 = G_{LE}}$$

#5 L-4C — Develco

5.5K

$F_o = 1.0$



$$\frac{5940}{5500+6200} = 0.507 = \beta_1$$

$0.28 = \beta_0$

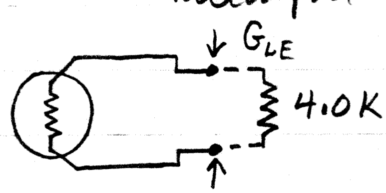
$\underline{0.79 = \beta}$

$$\frac{6200}{5500+6200} \times 2.73 = \underline{1.45 = G_{LE}}$$

#6 L-4C — Teledyne (Replacement for HS-10)

5.5 K

$F_o = 1.0$



$$\frac{5940}{5500+4000} = 0.625 = \beta_1$$

$0.28 = \beta_0$

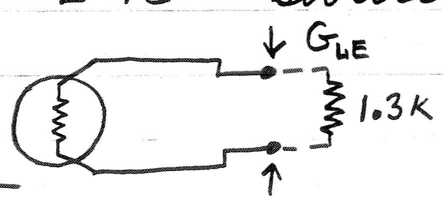
$\underline{0.91 = \beta}$

$$\frac{4000}{5500+4000} \times 2.73 = \underline{1.15 = G_{LE}}$$

#7 L-4C — Develco (Replacement for HS-10)

5.5K

$F_o = 1.0$



$$\frac{5940}{5500+1300} = 0.87 = \beta_1$$

$0.28 = \beta_0$

$\underline{1.15 = \beta}$

$$\frac{1300}{5500+1300} \times 2.73 = \underline{0.522 = G_{LE}}$$

Summary of Telemeter net Seismometer Parameters

Syst #	Seis -	Preamp	G_{LE}	GE	β	F_o
#1	XX -	Teledyne	0.50	1770	0.80	1.00
#2	EV-17 -	Develco	3.47	12,200	0.73	1.00
#3	HS-10 -	Teledyne	0.87	3080	0.66	2.00
#4	HS-10 -	Develco	0.91	3220	0.60	2.00
#5	L-4C -	Develco	1.45	5130	0.79	1.00
		L-4C Replacements for HS-10				
#6	L-4C -	Teledyne	1.15	4070	0.91	1.00
#7	L-4C -	Develco	0.52	1840	1.15	1.00

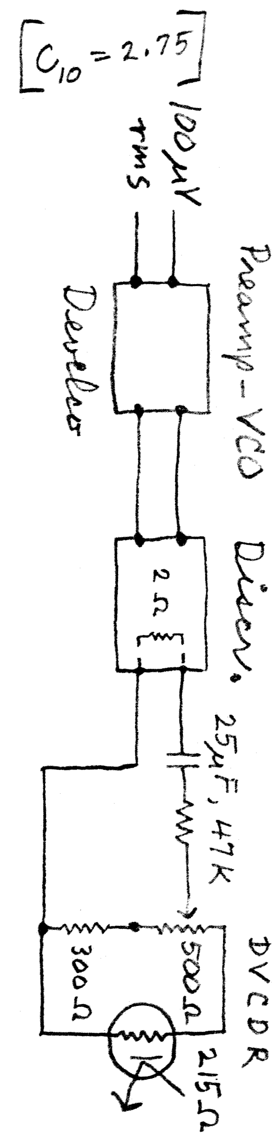
In all cases but #3, the calibration signals were applied across the preamp input, with the seismometer detached. In case #3, the calibration signal was applied, in place of the seismometer, to the "seismometer" end of the coupling network.

Cases #6 and #7 were in use during July - November, 1970, while the network was being upgraded and calibrated.

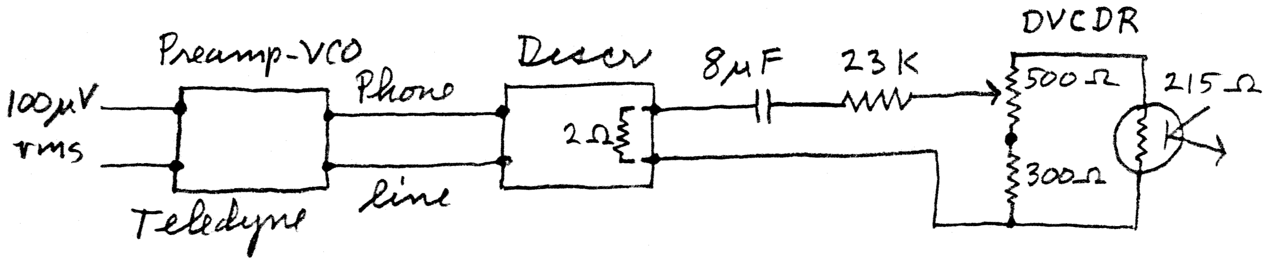
C ~~III.~~ System response tests

1) System test: Develco --DVCDR (Test set-up at NCER, 100 μV_{rms} into Develco unit with 42 db atten produced max of 27 mm_{p-p} on the DVCDR screen in the 1.0 to 10.0 hz range)

I	Freq	DVCDR Amp MM_{p-p}	$\frac{Amp}{27.5}$	$\log \frac{Amp}{27.5}$
1	.013	-	-	-
2	.016	-	-	-
3	.020	-	-	-
4	.025	0.25	.0091	-2.040
5	.032	.50	.0182	-1.740
6	.040	.94	.0342	-1.466
7	.050	1.75	.0636	-1.196
8	.063	3.15	.114	-0.943
9	.079	5.60	.202	-0.694
10	.100	9.00	.327	-0.485
11	.126	12.00	.436	-0.360
12	.158	15.00	.545	-0.264
13	.200	18.00	.655	-0.184
14	.251	20.5	.745	-0.129
15	.316	22.4	.815	-0.088
16	.398	24.0	.872	-0.059
17	.501	25.0	.909	-0.041
18	.631	25.8	.938	-0.028
19	.794	25.9	.941	-0.026
20	1.000	26.0	.949	-0.022
21	1.259	26.3	.956	-0.019
22	1.585	26.5	.963	-0.016
23	1.995	26.7	.970	-0.013
24	2.512	27.0	.981	-0.008
25	3.162	27.5	1.00	0.00
26	3.981	27.5	1.00	0.00
27	5.012	27.5	1.00	0.00
28	6.310	27.3	.992	-0.003
29	7.943	26.8	.975	-0.010
30	10.00	25.4	.924	-0.034
31	12.59	22.3	.810	-0.091
32	15.85	17.0	.618	-0.202
33	19.95	11.4	.415	-0.382
34	25.12	6.2	.226	-0.646
35	31.62	2.5	.0909	-1.041
36	39.81	1.0	.0364	-1.438
37	50.12	0.4	.0145	-1.838
38	63.10	-	-	-
39	79.43	-	-	-
40	100.00	-	-	-



The amplifier output is flat from 0.2 to 15 hz, with 3 db down points at 0.095 and 30 hz. The total system response is down 3 db at 0.25 and 14 hz.



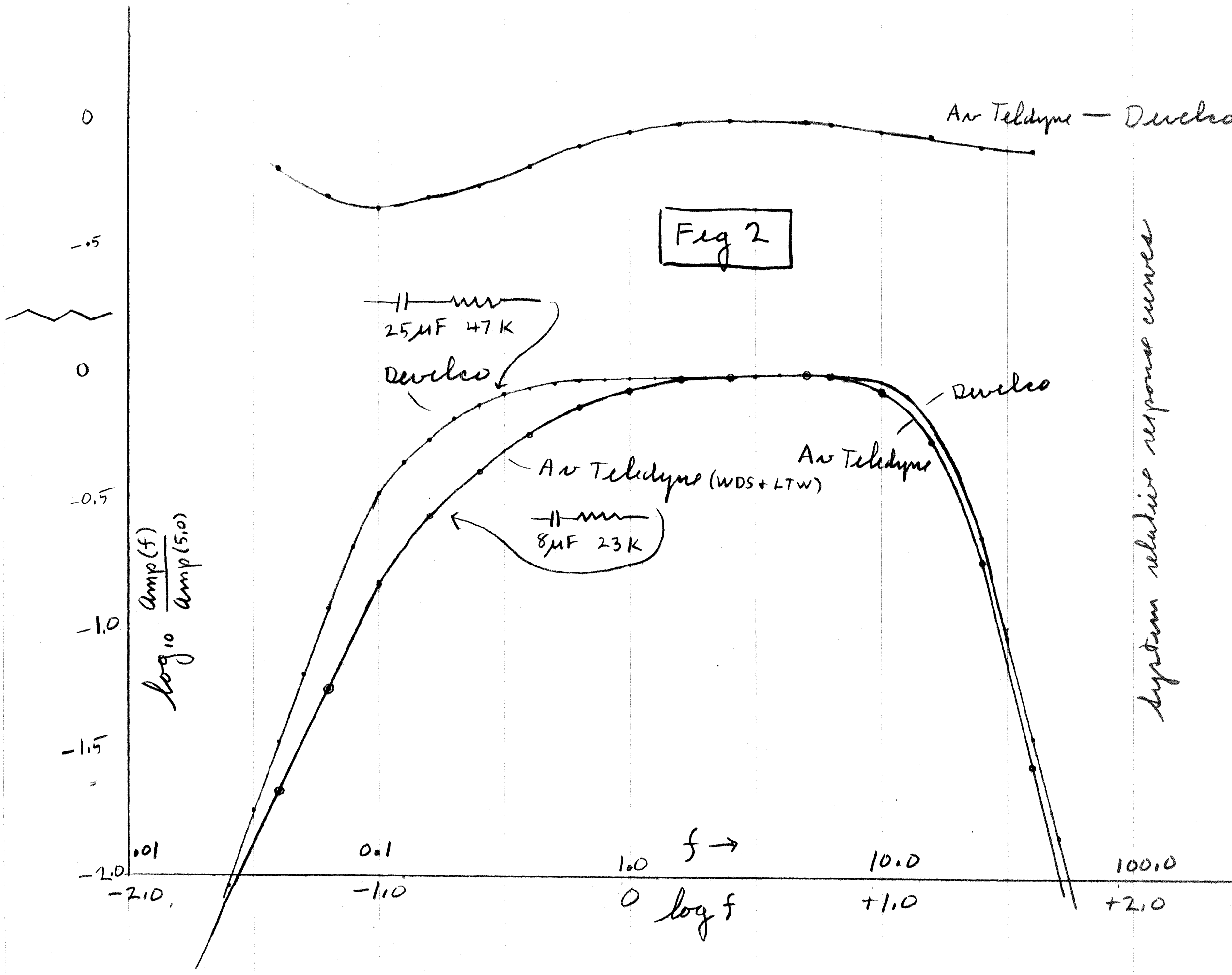
2) **Station Calibration System Tests**

I	Freq	SR(LTW)	SR(WDS)	SRav	$alog_{10}$ SRav	SR (Develco)	Av-Develco
4	.025			-2.080	.0083		
5				-1.875	.0133		
6	.040	-1.647	-1.682	-1.665	.0216	-1.466	-.199
7				-1.46	.0346		
8	.063	-1.152	-1.355	-1.254	.0558	-0.943	-.311
9				-1.04	.0912		
10	.100	-0.744	-0.932	-0.838	.1452	-0.485	-.353
11				-0.70	.1997		
12	.158	-0.478	-0.666	-0.572	.2680	-0.264	-.308
13				-0.48	.331		
14	.251	-0.309	-0.471	-0.390	.407	-0.129	-.261
15				-0.31	.490		
16	.398	-0.181	-0.307	-0.244	.570	-0.059	-.185
17				-0.18	.660		
18	.631	-0.093	-0.167	-0.130	.741	-0.028	-.102
19				-0.09	.813		
20	1.00	-0.045	-0.084	-0.065	.861	-0.022	-.043
21				-0.04	.912		
22	1.585	-0.019	-0.023	-0.021	.953	-0.016	-.005
23				-0.01	.977		
24	2.512	-0.006	-0.006	-0.006	.986	-0.008	+.002
25				0.0	1.000		
26				0.0	1.000		
27	5.00	0.0	0.0	0.0	1.000	0.0	0.0
28	6.310	-0.008	-0.011	-0.010	.977	-0.003	-.007
29				-0.03	.934		
30	10.00	-0.061	-0.082	-0.072	.847	-0.034	-.038
31				-0.14	.725		
32	15.85	-0.234	-0.295	-0.265	.544	-0.202	-.063
33				-0.47	.339		
34	25.12	-0.705	-0.786	-0.746	.1794	-0.646	-.100
35				-1.15	.0708		
36	39.81	-1.521	-1.586	-1.554	.0279	-1.438	-.116
37				-1.96	.01096		

Interpolated from plot

Much of the difference Av-Develco should be due to the difference in the filters used in the tests: 25 μF, 47K for the Develco, and 8 μF, 23K for the Teledynes.

The system response curves for the two cases treated here are plotted in figure 2 along with the difference between them. The discriminator - Develocorder coupling filter used with the Develco unit is typical of those used in the network to date. The filter used with the Teledyne units will be installed as the standard one as the network is calibrated. Consequently, the system response determined with the Develco unit will be used with all of the instrument configurations in use prior to the "standard" configuration now being established. That determined with the Teledyne units will be used with the "standard" configuration.


Av Teledyne — Develco
Fig 2
system relative response curves
25μF 47K
Develco
Av Teledyne (WDS + LTW)
8μF 23K
Develco
Av Teledyne
log10 amp(f)/amp(5.0)
0
-.5
0
-0.5
-1.0
-1.5
-2.0
.01
0.1
1.0
10.0
100.0
f →
-2.0
-1.0
0
+1.0
+2.0
log f

D. Calculation of the Response Arrays

The computer program HARMAG was used to calculate the arrays of log [MF1(f)/MWA(f)], as well as MF1(f), MF(f) for C_{10} = 10.8, and log MF(f), for the 40 values of log f = -2.0 + Nx0.1, N = 1.40. These arrays are shown in figures 3 - 9.

The arrays of log [MF1(f)/MWA(f)] vs log f that were punched on cards are summarized in figure 10 and plotted in figure 11.

Fig 3

#1 STD SYST:TELEDYNE FREQ = 1.000 PERIOD = 1.000 BETA = 0.800 GLE = 0.500 C10 =10.000 GF = 1768.03

LF	PER	FREQ	PHI	AF	AF/A5	TGN	MF1	MF	LG MF1/WA	LG MF
-1.90	79.433	0.013	-1.154	0.000	0.0001	0.2216E-01	0.2216E-05	0.2216E-04	-5.1077	-4.6544
-1.80	63.096	0.016	-1.453	0.000	0.0001	0.4422E-01	0.4422E-05	0.4422E-04	-5.0077	-4.3544
-1.70	50.119	0.020	-1.829	0.000	0.0001	0.8823E-01	0.8823E-05	0.8823E-04	-4.9077	-4.0544
-1.60	39.811	0.025	-2.303	0.080	0.0080	0.1760E 00	0.1408E-02	0.1408E-01	-2.9046	-1.8513
-1.50	31.623	0.032	-2.899	0.130	0.0130	0.3512E 00	0.4565E-02	0.4565E-01	-2.5938	-1.3405
-1.40	25.119	0.040	-3.650	0.220	0.0220	0.7006E 00	0.1541E-01	0.1541E 00	-2.2653	-0.8121
-1.30	19.953	0.050	-4.596	0.350	0.0350	0.1398E 01	0.4891E-01	0.4891E 00	-1.9637	-0.3106
-1.20	15.849	0.063	-5.788	0.560	0.0560	0.2787E 01	0.1561E 00	0.1561E 01	-1.6597	0.1934
-1.10	12.589	0.079	-7.288	0.910	0.0910	0.5558E 01	0.5057E 00	0.5057E 01	-1.3489	0.7039
-1.00	10.000	0.100	-9.180	1.450	0.1450	0.1108E 02	0.1606E 01	0.1606E 02	-1.0468	1.2058
-0.90	7.943	0.126	-11.567	2.000	0.2000	0.2206E 02	0.4413E 01	0.4413E 02	-0.8074	1.6447
-0.80	6.310	0.158	-14.580	2.680	0.2680	0.4390E 02	0.1177E 02	0.1177E 03	-0.5807	2.0706
-0.70	5.012	0.200	-18.391	3.310	0.3310	0.8720E 02	0.2886E 02	0.2886E 03	-0.3898	2.4604
-0.60	3.981	0.251	-23.218	4.070	0.4070	0.1727E 03	0.7029E 02	0.7029E 03	-0.2012	2.8469
-0.50	3.162	0.316	-29.344	4.900	0.4900	0.3402E 03	0.1667E 03	0.1667E 04	-0.0228	3.2220
-0.40	2.512	0.398	-37.123	5.700	0.5700	0.6641E 03	0.3786E 03	0.3786E 04	0.1389	3.5781
-0.30	1.995	0.501	-46.961	6.600	0.6600	0.1275E 04	0.8413E 03	0.8413E 04	0.2954	3.9249
-0.20	1.585	0.631	-59.196	7.410	0.7410	0.2374E 04	0.1759E 04	0.1759E 05	0.4329	4.2453
-0.10	1.259	0.794	-73.808	8.130	0.8130	0.4207E 04	0.3420E 04	0.3420E 05	0.5521	4.5341
0.00	1.000	1.000	90.000	8.610	0.8610	0.6943E 04	0.5978E 04	0.5978E 05	0.6470	4.7766
0.10	0.794	1.259	73.808	9.120	0.9120	0.1057E 05	0.9638E 04	0.9638E 05	0.7379	4.9840
0.20	0.631	1.585	59.196	9.530	0.9530	0.1498E 05	0.1428E 05	0.1428E 06	0.8271	5.1546
0.30	0.501	1.995	46.961	9.770	0.9770	0.2020E 05	0.1974E 05	0.1974E 06	0.9171	5.2953
0.40	0.398	2.512	37.123	9.860	0.9860	0.2644E 05	0.2607E 05	0.2607E 06	1.0086	5.4161
0.50	0.316	3.162	29.344	10.000	1.0000	0.3402E 05	0.3402E 05	0.3402E 06	1.1077	5.5318
0.60	0.251	3.981	23.218	10.000	1.0000	0.4338E 05	0.4338E 05	0.4338E 06	1.2038	5.6373
0.70	0.200	5.012	18.391	10.000	1.0000	0.5502E 05	0.5502E 05	0.5502E 06	1.3016	5.7405
0.80	0.158	6.310	14.580	9.770	0.9770	0.6958E 05	0.6798E 05	0.6798E 06	1.3903	5.8324
0.90	0.126	7.943	11.567	9.340	0.9340	0.8784E 05	0.8204E 05	0.8204E 06	1.4700	5.9140
1.00	0.100	10.000	9.180	8.470	0.8470	0.1108E 06	0.9383E 05	0.9383E 06	1.5271	5.9723
1.10	0.079	12.589	7.289	7.250	0.7250	0.1396E 06	0.1012E 06	0.1012E 07	1.5593	6.0052
1.20	0.063	15.849	5.788	5.440	0.5440	0.1759E 06	0.9567E 05	0.9567E 06	1.5344	5.9808
1.30	0.050	19.953	4.596	3.390	0.3390	0.2215E 06	0.7509E 05	0.7509E 06	1.4289	5.8756
1.40	0.040	25.119	3.650	1.790	0.1790	0.2789E 06	0.4993E 05	0.4993E 06	1.2515	5.6983
1.50	0.032	31.623	2.899	0.710	0.0710	0.3512E 06	0.2494E 05	0.2494E 06	0.9498	5.3968
1.60	0.025	39.811	2.303	0.280	0.0280	0.4422E 06	0.1238E 05	0.1238E 06	0.6457	5.0928
1.70	0.020	50.119	1.829	0.110	0.0110	0.5567E 06	0.6124E 04	0.6124E 05	0.3399	4.7870
1.80	0.016	63.096	1.453	0.000	0.0001	0.7009E 06	0.7009E 02	0.7009E 03	-1.6015	2.8456
1.90	0.013	79.433	1.154	0.000	0.0001	0.8824E 06	0.8824E 02	0.8824E 03	-1.5015	2.9457
2.00	0.010	100.001	0.917	0.000	0.0001	0.1111E 07	0.1111E 03	0.1111E 04	-1.4015	3.0457

Fig 4

#2 EV17:DEVELCO FREQ = 1.000 PERIOD = 1.000 BETA = 0.730 GLE = 3.470 C10 = 1.250 GE =12270.15

LF	PER	FREQ	PHI	AF	AF/A5	TGN	MF1	MF	LG MF1/WA	LG MF
-1.90	79.433	0.013	-1.053	0.000	0.0001	0.1538E 00	0.1538E-04	0.1923E-04	-4.2663	-4.7161
-1.80	63.096	0.016	-1.326	0.000	0.0001	0.3069E 00	0.3069E-04	0.3836E-04	-4.1663	-4.4161
-1.70	50.119	0.020	-1.669	0.000	0.0001	0.6124E 00	0.6124E-04	0.7654E-04	-4.0663	-4.1161
-1.60	39.811	0.025	-2.102	0.250	0.0091	0.1222E 01	0.1111E-01	0.1388E-01	-2.0077	-1.8575
-1.50	31.623	0.032	-2.646	0.500	0.0182	0.2438E 01	0.4432E-01	0.5540E-01	-1.6066	-1.2565
-1.40	25.119	0.040	-3.332	0.940	0.0342	0.4864E 01	0.1663E 00	0.2078E 00	-1.2324	-0.6823
-1.30	19.953	0.050	-4.196	1.750	0.0636	0.9704E 01	0.6175E 00	0.7719E 00	-0.8625	-0.1124
-1.20	15.849	0.063	-5.284	3.150	0.1145	0.1936E 02	0.2218E 01	0.2772E 01	-0.5071	0.4428
-1.10	12.589	0.079	-6.657	5.600	0.2036	0.3862E 02	0.7865E 01	0.9831E 01	-0.1572	0.9926
-1.00	10.000	0.100	-8.389	9.000	0.3273	0.7704E 02	0.2521E 02	0.3152E 02	0.1491	1.4985
-0.90	7.943	0.126	-10.579	12.000	0.4364	0.1536E 03	0.6704E 02	0.8381E 02	0.3743	1.9233
-0.80	6.310	0.158	-13.352	15.000	0.5455	0.3063E 03	0.1671E 03	0.2089E 03	0.5716	2.3198
-0.70	5.012	0.200	-16.877	18.000	0.6545	0.6103E 03	0.3995E 03	0.4993E 03	0.7514	2.6984
-0.60	3.981	0.251	-21.377	20.500	0.7455	0.1214E 04	0.9053E 03	0.1132E 04	0.9087	3.0537
-0.50	3.162	0.316	-27.157	22.400	0.8145	0.2410E 04	0.1963E 04	0.2454E 04	1.0481	3.3899
-0.40	2.512	0.398	-34.633	24.000	0.8727	0.4756E 04	0.4151E 04	0.5189E 04	1.1789	3.7151
-0.30	1.995	0.501	-44.339	25.000	0.9091	0.9270E 04	0.8428E 04	0.1053E 05	1.2962	4.0226
-0.20	1.585	0.631	-56.840	25.800	0.9382	0.1760E 05	0.1651E 05	0.2064E 05	1.4054	4.3147
-0.10	1.259	0.794	-72.348	25.900	0.9418	0.3175E 05	0.2990E 05	0.3738E 05	1.4937	4.5726
0.00	1.000	1.000	90.000	26.000	0.9455	0.5281E 05	0.4992E 05	0.6241E 05	1.5687	4.7952
0.10	0.794	1.259	72.348	26.300	0.9564	0.7975E 05	0.7627E 05	0.9534E 05	1.6362	4.9793
0.20	0.631	1.585	56.840	26.500	0.9636	0.1110E 06	0.1070E 06	0.1338E 06	1.7019	5.1263
0.30	0.501	1.995	44.339	26.700	0.9709	0.1469E 06	0.1427E 06	0.1783E 06	1.7761	5.2512
0.40	0.398	2.512	34.633	27.000	0.9818	0.1894E 06	0.1859E 06	0.2324E 06	1.8617	5.3662
0.50	0.316	3.162	27.157	27.500	1.0000	0.2410E 06	0.2410E 06	0.3013E 06	1.9579	5.4790
0.60	0.251	3.981	21.377	27.500	1.0000	0.3051E 06	0.3051E 06	0.3813E 06	2.0509	5.5813
0.70	0.200	5.012	16.877	27.500	1.0000	0.3851E 06	0.3851E 06	0.4814E 06	2.1466	5.6825
0.80	0.158	6.310	13.352	27.300	0.9927	0.4855E 06	0.4820E 06	0.6024E 06	2.2409	5.7799
0.90	0.126	7.943	10.579	26.800	0.9745	0.6117E 06	0.5961E 06	0.7451E 06	2.3313	5.8722
1.00	0.100	10.000	8.389	25.400	0.9236	0.7704E 06	0.7116E 06	0.8895E 06	2.4070	5.9491
1.10	0.079	12.589	6.657	22.300	0.8109	0.9702E 06	0.7867E 06	0.9834E 06	2.4499	5.9927
1.20	0.063	15.849	5.284	17.000	0.6182	0.1222E 07	0.7551E 06	0.9439E 06	2.4316	5.9749
1.30	0.050	19.953	4.196	11.400	0.4145	0.1538E 07	0.6376E 06	0.7970E 06	2.3579	5.9014
1.40	0.040	25.119	3.332	6.200	0.2255	0.1936E 07	0.4366E 06	0.5457E 06	2.1932	5.7370
1.50	0.032	31.623	2.646	2.500	0.0909	0.2438E 07	0.2216E 06	0.2770E 06	1.8986	5.4425
1.60	0.025	39.811	2.102	1.000	0.0364	0.3069E 07	0.1116E 06	0.1395E 06	1.6006	5.1446
1.70	0.020	50.119	1.669	0.400	0.0145	0.3864E 07	0.5620E 05	0.7025E 05	1.3027	4.8467
1.80	0.016	63.096	1.326	0.000	0.0001	0.4864E 07	0.4864E 03	0.6080E 03	-0.7601	2.7839
1.90	0.013	79.433	1.053	0.000	0.0001	0.6124E 07	0.6124E 03	0.7655E 03	-0.6601	2.8839
2.00	0.010	100.001	0.837	0.000	0.0001	0.7710E 07	0.7710E 03	0.9637E 03	-0.5601	2.9839

Fig 5

#3 HS10:DEVELCO FREQ = 2.000 PERIOD = 0.500 BETA = 0.660 GLE = 0.870 C10 = 5.000 GE = 3076.38

LF	PER	FREQ	PHI	AF	AF/A5	TGN	MF1	MF	LG MF1/WA	LG MF
-1.90	79.433	0.013	-0.476	0.000	0.0001	0.9642E-02	0.9642E-06	0.4821E-05	-5.4692	-5.3169
-1.80	63.096	0.016	-0.599	0.000	0.0001	0.1924E-01	0.1924E-05	0.9619E-05	-5.3692	-5.0169
-1.70	50.119	0.020	-0.755	0.000	0.0001	0.3838E-01	0.3838E-0[illegible]	0.1919E-04	-5.2691	-4.7169
-1.60	39.811	0.025	-0.950	0.250	0.0091	0.7659E-01	0.6963E-03	0.3481E-02	-3.2105	-2.4583
-1.50	31.623	0.032	-1.196	0.500	0.0182	0.1528E 00	0.2778E-02	0.1389E-01	-2.8095	-1.8572
-1.40	25.119	0.040	-1.506	0.940	0.0342	0.3049E 00	0.1042E-01	0.5211E-01	-2.4352	-1.2831
-1.30	19.953	0.050	-1.896	1.750	0.0636	0.6084E 00	0.3872E-01	0.1936E 00	-2.0652	-0.7131
-1.20	15.849	0.063	-2.387	3.150	0.1145	0.1214E 01	0.1391E 00	0.6953E 00	-1.7098	-0.1578
-1.10	12.589	0.079	-3.006	5.600	0.2036	0.2422E 01	0.4933E 00	0.2466E 01	-1.3597	0.3921
-1.00	10.000	0.100	-3.785	9.000	0.3273	0.4834E 01	0.1582E 01	0.7910E 01	-1.0533	0.8982
-0.90	7.943	0.126	-4.769	12.000	0.4364	0.9647E 01	0.4209E 01	0.2105E 02	-0.8279	1.3232
-0.80	6.310	0.158	-6.009	15.000	0.5455	0.1925E 02	0.1050E 02	0.5251E 02	-0.6301	1.7202
-0.70	5.012	0.200	-7.576	18.000	0.6545	0.3843E 02	0.2516E 02	0.1258E 03	-0.4495	2.0996
-0.60	3.981	0.251	-9.561	20.500	0.7455	0.7673E 02	0.5720E 02	0.2860E 03	-0.2907	2.4564
-0.50	3.162	0.316	-12.082	22.400	0.8145	0.1533E 03	0.1248E 03	0.6242E 03	-0.1485	2.7953
-0.40	2.512	0.398	-15.301	24.000	0.8727	0.3062E 03	0.2673E 03	0.1336E 04	-0.0123	3.1259
-0.30	1.995	0.501	-19.440	25.000	0.9091	0.6121E 03	0.5565E 03	0.2782E 04	0.1159	3.4444
-0.20	1.585	0.631	-24.819	25.800	0.9382	0.1223E 04	0.1148E 04	0.5739E 04	0.2475	3.7589
-0.10	1.259	0.794	-31.900	25.900	0.9418	0.2441E 04	0.2299E 04	0.1150E 05	0.3796	4.0605
0.00	1.000	1.000	-41.348	26.000	0.9455	0.4837E 04	0.4573E 04	0.2287E 05	0.5306	4.3592
0.10	0.794	1.259	-53.995	26.300	0.9564	0.9387E 04	0.8978E 04	0.4489E 05	0.7071	4.6521
0.20	0.631	1.585	-70.422	26.500	0.9636	0.1733E 05	0.1670E 05	0.8349E 05	0.8952	4.9216
0.30	0.501	1.995	-89.794	26.700	0.9709	0.2915E 05	0.2830E 05	0.1415E 06	1.0736	5.1508
0.40	0.398	2.512	70.798	27.000	0.9818	0.4363E 05	0.4283E 05	0.2142E 06	1.2242	5.3308
0.50	0.316	3.162	54.295	27.500	1.0000	0.5946E 05	0.5946E 05	0.2973E 06	1.3501	5.4732
0.60	0.251	3.981	41.573	27.500	1.0000	0.7700E 05	0.7700E 05	0.3850E 06	1.4530	5.5855
0.70	0.200	5.012	32.068	27.500	1.0000	0.9764E 05	0.9764E 05	0.4882E 06	1.5507	5.6886
0.80	0.158	6.310	24.945	27.300	0.9927	0.1229E 06	0.1220E 06	0.6102E 06	1.6444	5.7855
0.90	0.126	7.943	19.537	26.800	0.9745	0.1545E 06	0.1506E 06	0.7528E 06	1.7337	5.8767
1.00	0.100	10.000	15.376	25.400	0.9236	0.1941E 06	0.1793E 06	0.8966E 06	1.8084	5.9526
1.10	0.079	12.589	12.141	22.300	0.8109	0.2441E 06	0.1979E 06	0.9896E 06	1.8505	5.9954
1.20	0.063	15.849	9.607	17.000	0.6182	0.3069E 06	0.1897E 06	0.9487E 06	1.8318	5.9771
1.30	0.050	19.953	7.613	11.400	0.4145	0.3862E 06	0.1601E 06	0.8004E 06	1.7577	5.9033
1.40	0.040	25.119	6.038	6.200	0.2255	0.4859E 06	0.1096E 06	0.5478E 06	1.5928	5.7386
1.50	0.032	31.623	4.791	2.500	0.0909	0.6116E 06	0.5560E 05	0.2780E 06	1.2981	5.4440
1.60	0.025	39.811	3.803	1.000	0.0364	0.7698E 06	0.2799E 05	0.1400E 06	1.0000	5.1460
1.70	0.020	50.119	3.020	0.400	0.0145	0.9690E 06	0.1409E 05	0.7047E 05	0.7020	4.8480
1.80	0.016	63.096	2.398	0.000	0.0001	0.1220E 07	0.1220E 03	0.6099E 03	-1.3608	2.7852
1.90	0.013	79.433	1.905	0.000	0.0001	0.1536E 07	0.1536E 03	0.767[illegible] 03	-1.2609	2.8852
2.00	0.010	100.001	1.513	0.000	0.0001	0.1933E 07	0.1933E 03	0.9665E 03	-1.1609	2.9852

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Fig 6

#4 HS10:DEVELCO FREQ = 2.000 PERIOD = 0.500 BETA = 0.600 GLE = 0.910 C10 = 5.000 GE = 3217.82

LF	PER	FREQ	PHI	AF	AF/A5	TGN	MF1	MF	LG MF1/WA	LG MF
-1.90	79.433	0.013	-0.433	~~0.000~~	~~0.0001~~	0.1008E-01	~~0.1008E-05~~	~~0.5042E-05~~	~~-5.4496~~	~~-5.2974~~
-1.80	63.096	0.016	-0.545	~~0.000~~	~~0.0001~~	0.2012E-01	~~0.2012E-05~~	~~[illegible]~~	~~-5.3496~~	~~-4.9973~~
-1.70	50.119	0.020	-0.686	~~0.000~~	~~0.0001~~	0.4015E-01	~~0.4015E-05~~	~~0.2007E-04~~	~~-5.2496~~	~~-4.6973~~
-1.60	39.811	0.025	-0.864	0.250	0.0091	0.8011E-01	0.7283E-03	0.3641E-02	-3.1910	-2.4387
-1.50	31.623	0.032	-1.087	0.500	0.0182	0.1598E 00	0.2906E-02	0.1453E-01	-2.7899	-1.8377
-1.40	25.119	0.040	-1.369	0.940	0.0342	0.3189E 00	0.1090E-01	0.5451E-01	-2.4157	-1.2635
-1.30	19.953	0.050	-1.724	1.750	0.0636	0.6364E 00	0.4050E-01	0.2025E 00	-2.0457	-0.6936
-1.20	15.849	0.063	-2.170	3.150	0.1145	0.1270E 01	0.1455E 00	0.7273E 00	-1.6902	-0.1383
-1.10	12.589	0.079	-2.733	5.600	0.2036	0.2534E 01	0.5161E 00	0.2580E 01	-1.3401	0.4117
-1.00	10.000	0.100	-3.442	9.000	0.3273	0.5058E 01	0.1655E 01	0.8277E 01	-1.0337	0.9179
-0.90	7.943	0.126	-4.337	12.000	0.4364	0.1010E 02	0.4406E 01	0.2203E 02	-0.8081	1.3430
-0.80	6.310	0.158	-5.466	15.000	0.5455	0.2016E 02	0.1099E 02	0.5497E 02	-0.6101	1.7402
-0.70	5.012	0.200	-6.895	18.000	0.6545	0.4026E 02	0.2635E 02	0.1318E 03	-0.4293	2.1198
-0.60	3.981	0.251	-8.706	20.500	0.7455	0.8045E 02	0.5998E 02	0.2999E 03	-0.2702	2.4769
-0.50	3.162	0.316	-11.012	22.400	0.8145	0.1609E 03	0.1311E 03	0.6554E 03	-0.1273	2.8165
-0.40	2.512	0.398	-13.967	24.000	0.8727	0.3223E 03	0.2812E 03	0.1406E 04	0.0098	3.1481
-0.30	1.995	0.501	-17.789	25.000	0.9091	0.6465E 03	0.5877E 03	0.2939E 04	0.1396	3.4681
-0.20	1.585	0.631	-22.803	25.800	0.9382	0.1300E 04	0.1219E 04	0.6097E 04	0.2738	3.7851
-0.10	1.259	0.794	-29.504	25.900	0.9418	0.2618E 04	0.2465E 04	0.1233E 05	0.4099	4.0909
0.00	1.000	1.000	-38.660	26.000	0.9455	0.5263E 04	0.4976E 04	0.2488E 05	0.5672	4.3958
0.10	0.794	1.259	-51.364	26.300	0.9564	0.1043E 05	0.9974E 04	0.4987E 05	0.7528	4.6978
0.20	0.631	1.585	-68.633	26.500	0.9636	0.1971E 05	0.1899E 05	0.9495E 05	0.9510	4.9775
0.30	0.501	1.995	-89.774	26.700	0.9709	0.3354E 05	0.3256E 05	0.1628E 06	1.1345	5.2117
0.40	0.398	2.512	69.038	27.000	0.9818	0.4964E 05	0.4873E 05	0.2437E 06	1.2803	5.3868
0.50	0.316	3.162	51.671	27.500	1.0000	0.6609E 05	0.6609E 05	0.3304E 06	1.3960	5.5191
0.60	0.251	3.981	38.881	27.500	1.0000	0.8381E 05	0.8381E 05	0.4190E 06	1.4898	5.6223
0.70	0.200	5.012	29.664	27.500	1.0000	0.1047E 06	0.1047E 06	0.5236E 06	1.5811	5.7190
0.80	0.158	6.310	22.922	27.300	0.9927	0.1306E 06	0.1297E 06	0.6483E 06	1.6707	5.8118
0.90	0.126	7.943	17.879	26.800	0.9745	0.1632E 06	0.1590E 06	0.7952E 06	1.7575	5.9005
1.00	0.100	10.000	14.036	25.400	0.9236	0.2043E 06	0.1887E 06	0.9436E 06	1.8306	5.9748
1.10	0.079	12.589	11.066	22.300	0.8109	0.2563E 06	0.2078E 06	0.1039E 07	1.8717	6.0166
1.20	0.063	15.849	8.748	17.000	0.6182	0.3218E 06	0.1990E 06	0.9948E 06	1.8524	5.9977
1.30	0.050	19.953	6.928	11.400	0.4145	0.4045E 06	0.1677E 06	0.8385E 06	1.7778	5.9235
1.40	0.040	25.119	5.492	6.200	0.2255	0.5088E 06	0.1147E 06	0.5735E 06	1.6127	5.7585
1.50	0.032	31.623	4.357	2.500	0.0909	0.6401E 06	0.5819E 05	0.2909E 06	1.3179	5.4638
1.60	0.025	39.811	3.459	1.000	0.0364	0.8055E 06	0.2929E 05	0.1464E 06	1.0197	5.1657
1.70	0.020	50.119	2.746	0.400	0.0145	0.1014E 07	0.1475E 05	0.7373E 05	0.7216	4.8676
1.80	0.016	63.096	2.181	~~0.000~~	~~0.0001~~	0.1276E 07	~~0.1276E 03~~	~~0.6380E 03~~	~~-1.3412~~	~~2.8048~~
1.90	0.013	79.433	1.732	~~0.000~~	~~0.0001~~	0.1606E 07	~~0.1606E 03~~	~~0.803[illegible]~~	~~-1.2413~~	~~2.9048~~
2.00	0.010	100.001	1.375	~~0.000~~	~~0.0001~~	0.2022E 07	~~0.2022E 03~~	~~0.1011E 04~~	~~-1.1413~~	~~3.0048~~

Fig 7

#5 L4C:DEVELCO   FREQ = 1.000   PERIOD = 1.000   ETA = 0.790   GLE = 1.450   C10 = 2.500   GE = 5127.29

LF	PER	FREQ	PHI	AF	AF/A5	TGN	MF1	MF	LG MF1/WA	LG MF
-1.90	79.433	0.013	-1.140	0.000	0.0001	0.6427E-01	0.6427E-05	0.1607E-04	-4.6453	-4.7940
-1.80	63.096	0.016	-1.435	0.000	0.0001	0.1282E 00	0.1282E-04	0.3206E-04	-4.5453	-4.4940
-1.70	50.119	0.020	-1.806	0.000	0.0001	0.2559E 00	0.2559E-04	0.6397E-04	-4.4453	-4.1940
-1.60	39.811	0.025	-2.274	0.250	0.0091	0.5105E 00	0.4641E-02	0.1160E-01	-2.3867	-1.9355
-1.50	31.623	0.032	-2.863	0.500	0.0182	0.1018E 01	0.1852E-01	0.4629E-01	-1.9857	-1.3345
-1.40	25.119	0.040	-3.605	0.940	0.0342	0.2032E 01	0.6945E-01	0.1736E 00	-1.6115	-0.7604
-1.30	19.953	0.050	-4.539	1.750	0.0636	0.4053E 01	0.2579E 00	0.6448E 00	-1.2416	-0.1906
-1.20	15.849	0.063	-5.716	3.150	0.1145	0.8084E 01	0.9260E 00	0.2315E 01	-0.8864	0.3645
-1.10	12.589	0.079	-7.198	5.600	0.2036	0.1612E 02	0.3283E 01	0.8207E 01	-0.5366	0.9142
-1.00	10.000	0.100	-9.068	9.000	0.3273	0.3213E 02	0.1052E 02	0.2629E 02	-0.2307	1.4198
-0.90	7.943	0.126	-11.426	12.000	0.4364	0.6402E 02	0.2794E 02	0.6984E 02	-0.0059	1.8441
-0.80	6.310	0.158	-14.406	15.000	0.5455	0.1274E 03	0.6950E 02	0.1738E 03	0.1907	2.2399
-0.70	5.012	0.200	-18.176	18.000	0.6545	0.2532E 03	0.1657E 03	0.4143E 03	0.3693	2.6174
-0.60	3.981	0.251	-22.958	20.500	0.7455	0.5018E 03	0.3741E 03	0.9352E 03	0.5248	2.9709
-0.50	3.162	0.316	-29.037	22.400	0.8145	0.9897E 03	0.8061E 03	0.2015E 04	0.6616	3.3043
-0.40	2.512	0.398	-36.777	24.000	0.8727	0.1935E 04	0.1688E 04	0.4221E 04	0.7883	3.6254
-0.30	1.995	0.501	-46.601	25.000	0.9091	0.3721E 04	0.3383E 04	0.8458E 04	0.8998	3.9272
-0.20	1.585	0.631	-58.878	25.800	0.9382	0.6949E 04	0.6519E 04	0.1630E 05	1.0018	4.2121
-0.10	1.259	0.794	-73.614	25.900	0.9418	0.1234E 05	0.1162E 05	0.2906E 05	1.0834	4.4633
0.00	1.000	1.000	90.000	26.000	0.9455	0.2039E 05	0.1928E 05	0.4819E 05	1.1555	4.6830
0.10	0.794	1.259	73.614	26.300	0.9564	0.3100E 05	0.2965E 05	0.7413E 05	1.2259	4.8700
0.20	0.631	1.585	58.878	26.500	0.9636	0.4385E 05	0.4225E 05	0.1056E 06	1.2984	5.0238
0.30	0.501	1.995	46.601	26.700	0.9709	0.5898E 05	0.5726E 05	0.1432E 06	1.3797	5.1558
0.40	0.398	2.512	36.777	27.000	0.9818	0.7702E 05	0.7562E 05	0.1891E 06	1.4711	5.2766
0.50	0.316	3.162	29.037	27.500	1.0000	0.9897E 05	0.9897E 05	0.2474E 06	1.5714	5.3934
0.60	0.251	3.981	22.958	27.500	1.0000	0.1260E 06	0.1260E 06	0.3151E 06	1.6670	5.4985
0.70	0.200	5.012	18.176	27.500	1.0000	0.1598E 06	0.1598E 06	0.3994E 06	1.7646	5.6014
0.80	0.158	6.310	14.406	27.300	0.9927	0.2019E 06	0.2005E 06	0.5012E 06	1.8600	5.7000
0.90	0.126	7.943	11.426	26.800	0.9745	0.2549E 06	0.2484E 06	0.6209E 06	1.9511	5.7931
1.00	0.100	10.000	9.068	25.400	0.9236	0.3213E 06	0.2968E 06	0.7420E 06	2.0273	5.8704
1.10	0.079	12.589	7.198	22.300	0.8109	0.4049E 06	0.3284E 06	0.8209E 06	2.0704	5.9143
1.20	0.063	15.849	5.716	17.000	0.6182	0.5101E 06	0.3153E 06	0.7883E 06	2.0524	5.8967
1.30	0.050	19.953	4.539	11.400	0.4145	0.6424E 06	0.2663E 06	0.6657E 06	1.9787	5.8233
1.40	0.040	25.119	3.605	6.200	0.2255	0.8089E 06	0.1824E 06	0.4559E 06	1.8141	5.6589
1.50	0.032	31.623	2.863	2.500	0.0909	0.1019E 07	0.9259E 05	0.2315E 06	1.5196	5.3645
1.60	0.025	39.811	2.274	1.000	0.0364	0.1282E 07	0.4663E 05	0.1166E 06	1.2216	5.0666
1.70	0.020	50.119	1.806	0.400	0.0145	0.1614E 07	0.2348E 05	0.5871E 05	0.9237	4.7687
1.80	0.016	63.096	1.435	0.000	0.0001	0.2033E 07	0.2033E 03	0.5081E 03	-1.1391	2.7060
1.90	0.013	79.433	1.140	0.000	0.0001	0.2559E 07	0.2559E 03	0.6397E 03	-1.0391	2.8060
2.00	0.010	100.001	0.905	0.000	0.0001	0.3222E 07	0.3222E 03	0.8054E 03	-0.9391	2.9060

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Fig 8

#6 L4C:DEVELCO FREQ = 1.000 PERIOD = 1.000 BETA = 0.910 GLE = 1.150 C10 = 2.500 GE = 4066.48

LF	PER	FREQ	PHI	AF	AF/A5	TGN	MF1	MF	LG MF1/WA	LG MF
-1.90	79.433	0.013	-1.313	~~0.000~~	~~0.0001~~	0.5097E-01	0.5097E-05	~~0.1274E-04~~	~~-4.7460~~	-4.8947
-1.80	63.096	0.016	-1.653	~~0.000~~	~~0.0001~~	0.1017E 00	0.1017E-04	~~0.2542E-04~~	~~-4.6460~~	-4.5947
-1.70	50.119	0.020	-2.081	~~0.000~~	~~0.0001~~	0.2029E 00	~~0.2029E-04~~	~~0.5072E-04~~	~~-4.5460~~	-4.2948
-1.60	39.811	0.025	-2.619	0.250	0.0091	0.4048E 00	0.3680E-02	0.9199E-02	-2.4875	-2.0362
-1.50	31.623	0.032	-3.297	0.500	0.0182	0.8074E 00	0.1468E-01	0.3670E-01	-2.0865	-1.4353
-1.40	25.119	0.040	-4.151	0.940	0.0342	0.1610E 01	0.5505E-01	0.1376E 00	-1.7125	-0.8613
-1.30	19.953	0.050	-5.225	1.750	0.0636	0.3211E 01	0.2044E 00	0.5109E 00	-1.3428	-0.2917
-1.20	15.849	0.063	-6.577	3.150	0.1145	0.6401E 01	0.7332E 00	0.1833E 01	-0.9878	0.2632
-1.10	12.589	0.079	-8.278	5.600	0.2036	0.1275E 02	0.2597E 01	0.6492E 01	-0.6384	0.8124
-1.00	10.000	0.100	-10.417	9.000	0.3273	0.2538E 02	0.8307E 01	0.2077E 02	-0.3331	1.3174
-0.90	7.943	0.126	-13.106	12.000	0.4364	0.5045E 02	0.2201E 02	0.5504E 02	-0.1094	1.7407
-0.80	6.310	0.158	-16.483	15.000	0.5455	0.1001E 03	0.5457E 02	0.1364E 03	0.0856	2.1349
-0.70	5.012	0.200	-20.716	18.000	0.6545	0.1977E 03	0.1294E 03	0.3235E 03	0.2618	2.5099
-0.60	3.981	0.251	-26.010	20.500	0.7455	0.3884E 03	0.2896E 03	0.7239E 03	0.4136	2.8597
-0.50	3.162	0.316	-32.598	22.400	0.8145	0.7563E 03	0.6161E 03	0.1540E 04	0.5448	3.1876
-0.40	2.512	0.398	-40.729	24.000	0.8727	0.1452E 04	0.1267E 04	0.3167E 04	0.6635	3.5007
-0.30	1.995	0.501	-50.617	25.000	0.9091	0.2726E 04	0.2478E 04	0.6194E 04	0.7645	3.7920
-0.20	1.585	0.631	-62.339	25.800	0.9382	0.4950E 04	0.4644E 04	0.1161E 05	0.8545	4.0648
-0.10	1.259	0.794	-75.680	25.900	0.9418	0.8583E 04	0.8083E 04	0.2021E 05	0.9256	4.3055
0.00	1.000	1.000	90.000	26.000	0.9455	0.1404E 05	0.1327E 05	0.3318E 05	0.9934	4.5209
0.10	0.794	1.259	75.680	26.300	0.9564	0.2156E 05	0.2062E 05	0.5154E 05	1.0681	4.7122
0.20	0.631	1.585	62.339	26.500	0.9636	0.3123E 05	0.3010E 05	0.7524E 05	1.1511	4.8765
0.30	0.501	1.995	50.617	26.700	0.9709	0.4320E 05	0.4194E 05	0.1049E 06	1.2444	5.0206
0.40	0.398	2.512	40.729	27.000	0.9818	0.5780E 05	0.5674E 05	0.1419E 06	1.3464	5.1519
0.50	0.316	3.162	32.598	27.500	1.0000	0.7563E 05	0.7563E 05	0.1891E 06	1.4546	5.2766
0.60	0.251	3.981	26.010	27.500	1.0000	0.9757E 05	0.9757E 05	0.2439E 06	1.5558	5.3873
0.70	0.200	5.012	20.716	27.500	1.0000	0.1247E 06	0.1247E 06	0.3119E 06	1.6571	5.4940
0.80	0.158	6.310	16.483	27.300	0.9927	0.1586E 06	0.1574E 06	0.3935E 06	1.7549	5.5950
0.90	0.126	7.943	13.106	26.800	0.9745	0.2009E 06	0.1957E 06	0.4893E 06	1.8476	5.6896
1.00	0.100	10.000	10.417	25.400	0.9236	0.2538E 06	0.2344E 06	0.5861E 06	1.9248	5.7680
1.10	0.079	12.589	8.278	22.300	0.8109	0.3203E 06	0.2598E 06	0.6494E 06	1.9686	5.8125
1.20	0.063	15.849	6.577	17.000	0.6182	0.4039E 06	0.2497E 06	0.6242E 06	1.9510	5.7953
1.30	0.050	19.953	5.225	11.400	0.4145	0.5090E 06	0.2110E 06	0.5275E 06	1.8776	5.7222
1.40	0.040	25.119	4.151	6.200	0.2255	0.6411E 06	0.1445E 06	0.3614E 06	1.7132	5.5579
1.50	0.032	31.623	3.297	2.500	0.0909	0.8075E 06	0.7340E 05	0.1835E 06	1.4188	5.2637
1.60	0.025	39.811	2.619	1.000	0.0364	0.1017E 07	0.3697E 05	0.9243E 05	1.1208	4.9658
1.70	0.020	50.119	2.081	0.400	0.0145	0.1280E 07	0.1862E 05	0.4655E 05	0.8229	4.6680
1.80	0.016	63.096	1.653	~~0.000~~	~~0.0001~~	0.1612E 07	~~0.1612E 03~~	~~0.4030E 03~~	~~-1.2398~~	2.6053
1.90	0.013	79.433	1.313	~~0.000~~	~~0.0001~~	0.2029E 07	0.2029E 03	~~0.5072E 03~~	~~-1.1398~~	2.7053
2.00	0.010	100.001	1.043	~~0.000~~	~~0.0001~~	0.2555E 07	~~0.2555E 03~~	0.6387E 03	~~-1.0398~~	2.8053

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Fig 9

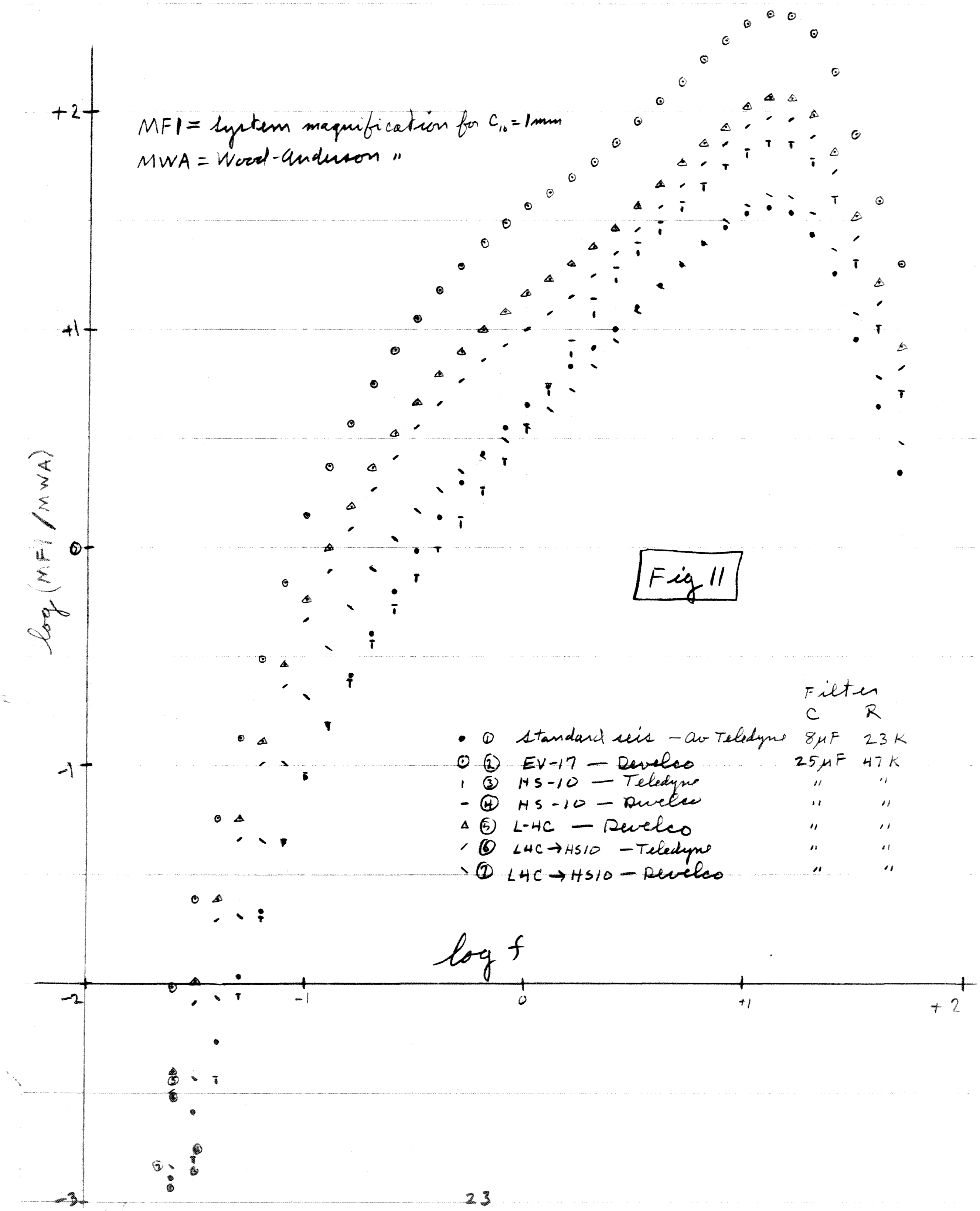
#7 L4C:DEVELCO FREQ = 1.000 PERIOD = 1.000 BETA = 1.150 GLF = 0.520 C10 =10.000 GE = 1838.76

LF	PER	FREQ	PHI	AF	AF/A5	TGN	MF1	MF	LG MF1/WA	LG MF
-1.90	79.433	0.013	-1.659	0.000	0.0001	0.2305E-01	0.2305E-05	0.2305E-04	-5.0907	-4.6374
-1.80	63.096	0.016	-2.088	0.000	0.0001	0.4597E-01	0.4597E-05	0.4597E-04	-4.9908	-4.3375
-1.70	50.119	0.020	-2.629	0.000	0.0001	0.9171E-01	0.9171E-05	0.9171E-04	-4.8909	-4.0376
-1.60	39.811	0.025	-3.309	0.250	0.0091	0.1829E 00	0.1663E-02	0.1663E-01	-2.8324	-1.7791
-1.50	31.623	0.032	-4.164	0.500	0.0182	0.3647E 00	0.6632E-02	0.6632E-01	-2.4316	-1.1784
-1.40	25.119	0.040	-5.240	0.940	0.0342	0.7271E 00	0.2485E-01	0.2485E 00	-2.0578	-0.6046
-1.30	19.953	0.050	-6.592	1.750	0.0636	0.1448E 01	0.9218E-01	0.9218E 00	-1.6885	-0.0354
-1.20	15.849	0.063	-8.290	3.150	0.1145	0.2883E 01	0.3303E 00	0.3303E 01	-1.3342	0.5188
-1.10	12.589	0.079	-10.418	5.600	0.2036	0.5731E 01	0.1167E 01	0.1167E 02	-0.9858	1.0671
-1.00	10.000	0.100	-13.079	9.000	0.3273	0.1137E 02	0.3720E 01	0.3720E 02	-0.6820	1.5706
-0.90	7.943	0.126	-16.395	12.000	0.4364	0.2247E 02	0.9805E 01	0.9805E 02	-0.4606	1.9915
-0.80	6.310	0.158	-20.502	15.000	0.5455	0.4419E 02	0.2410E 02	0.2410E 03	-0.2692	2.3821
-0.70	5.012	0.200	-25.545	18.000	0.6545	0.8623E 02	0.5644E 02	0.5644E 03	-0.0985	2.7516
-0.60	3.981	0.251	-31.660	20.500	0.7455	0.1664E 03	0.1240E 03	0.1240E 04	0.0453	3.0934
-0.50	3.162	0.316	-38.943	22.400	0.8145	0.3157E 03	0.2572E 03	0.2572E 04	0.1654	3.4102
-0.40	2.512	0.398	-47.416	24.000	0.8727	0.5862E 03	0.5116E 03	0.5116E 04	0.2697	3.7089
-0.30	1.995	0.501	-56.992	25.000	0.9091	0.1058E 04	0.9619E 03	0.9619E 04	0.3536	3.9831
-0.20	1.585	0.631	-67.473	25.800	0.9382	0.1847E 04	0.1733E 04	0.1733E 05	0.4264	4.2388
-0.10	1.259	0.794	-78.580	25.900	0.9418	0.3107E 04	0.2926E 04	0.2926E 05	0.4843	4.4663
0.00	1.000	1.000	90.000	26.000	0.9455	0.5023E 04	0.4749E 04	0.4749E 05	0.5470	4.6766
0.10	0.794	1.259	78.580	26.300	0.9564	0.7804E 04	0.7463E 04	0.7463E 05	0.6268	4.8729
0.20	0.631	1.585	67.473	26.500	0.9636	0.1165E 05	0.1123E 05	0.1123E 06	0.7229	5.0504
0.30	0.501	1.995	56.992	26.700	0.9709	0.1677E 05	0.1628E 05	0.1628E 06	0.8335	5.2117
0.40	0.398	2.512	47.416	27.000	0.9818	0.2334E 05	0.2291E 05	0.2291E 06	0.9525	5.3601
0.50	0.316	3.162	38.943	27.500	1.0000	0.3157E 05	0.3157E 05	0.3157E 06	1.0752	5.4993
0.60	0.251	3.981	31.660	27.500	1.0000	0.4179E 05	0.4179E 05	0.4179E 06	1.1875	5.6210
0.70	0.200	5.012	25.545	27.500	1.0000	0.5441E 05	0.5441E 05	0.5441E 06	1.2968	5.7357
0.80	0.158	6.310	20.502	27.300	0.9927	0.7004E 05	0.6953E 05	0.6953E 06	1.4001	5.8422
0.90	0.126	7.943	16.395	26.800	0.9745	0.8946E 05	0.8718E 05	0.8718E 06	1.4964	5.9404
1.00	0.100	10.000	13.079	25.400	0.9236	0.1137E 06	0.1050E 06	0.1050E 07	1.5759	6.0212
1.10	0.079	12.589	10.418	22.300	0.8109	0.1440E 06	0.1167E 06	0.1167E 07	1.6213	6.0672
1.20	0.063	15.849	8.290	17.000	0.6182	0.1819E 06	0.1125E 06	0.1125E 07	1.6046	6.0510
1.30	0.050	19.953	6.592	11.400	0.4145	0.2296E 06	0.9517E 05	0.9517E 06	1.5318	5.9785
1.40	0.040	25.119	5.240	6.200	0.2255	0.2895E 06	0.6526E 05	0.6526E 06	1.3678	5.8146
1.50	0.032	31.623	4.164	2.500	0.0909	0.3647E 06	0.3316E 05	0.3316E 06	1.0736	5.5206
1.60	0.025	39.811	3.309	1.000	0.0364	0.4595E 06	0.1671E 05	0.1671E 06	0.7759	5.2229
1.70	0.020	50.119	2.629	0.400	0.0145	0.5787E 06	0.8417E 04	0.8417E 05	0.4781	4.9251
1.80	0.016	63.096	2.088	0.000	0.0001	0.7287E 06	0.7287E 02	0.7287E 03	-1.5846	2.8625
1.90	0.013	79.433	1.659	0.000	0.0001	0.9175E 06	0.9175E 02	0.9175E 03	-1.4845	2.9626
2.00	0.010	100.001	1.318	0.000	0.0001	0.1155E 07	0.1155E 03	0.1155E 04	-1.3845	3.0626

Fig 10

log (MF1/MWA) vs log f relative magnification arrays. Read under F4.2 format.

I	1	2	3	4	5	6	7
4	-289	-201	-321	-319	-239	-249	-283
5	-258	-161	-281	-279	-199	-209	-243
6	-227	-124	-244	-242	-161	-171	-206
7	-197	-087	-206	-205	-124	-134	-169
8	-166	-051	-171	-169	-089	-099	-134
9	-135	-016	-136	-134	-054	-064	-099
10	-105	+015	-105	-103	-023	-033	-068
11	-081	+037	-083	-081	-001	-011	-046
12	-058	+057	-063	-061	+019	+009	-027
13	-039	+075	-045	-043	+037	+026	-010
14	-020	+091	-029	-027	+052	+041	+004
15	-002	+105	-015	-013	+066	+055	+017
16	+014	+118	-001	+001	+079	+066	+027
17	+030	+129	+012	+014	+090	+076	+035
18	+043	+140	+025	+027	+100	+086	+043
19	+055	+149	+038	+041	+108	+093	+049
20	+065	+157	+053	+057	+116	+100	+055
21	+074	+163	+071	+075	+123	+107	+063
22	+083	+170	+090	+095	+130	+115	+072
23	+092	+177	+107	+114	+138	+125	+083
24	+101	+186	+123	+128	+147	+135	+095
25	+111	+196	+135	+140	+157	+146	+108
26	+120	+205	+145	+149	+167	+156	+119
27	+130	+214	+155	+158	+177	+166	+130
28	+139	+224	+165	+167	+186	+176	+140
29	+147	+233	+174	+176	+195	+185	+150
30	+153	+241	+181	+183	+203	+193	+158
31	+156	+245	+185	+187	+207	+197	+162
32	+153	+244	+184	+186	+206	+196	+161
33	+143	+236	+176	+178	+198	+188	+153
34	+125	+218	+159	+161	+182	+172	+137
35	+095	+190	+130	+132	+152	+142	+107
36	+065	+159	+100	+102	+122	+112	+078
37	+034	+130	+070	+072	+092	+082	+048


MF1 = system magnification for C_{10} = 1mm
MWA = Wood-Anderson "
log (MF1 / MWA)
log f
+2
+1
0
-1
-2
-3
-2
-1
0
+1
+2
Fig 11
Filter
C R
• ① Standard seis — av Teledyne 8μF 23K
⊙ ② EV-17 — Develco 25μF 47K
ı ③ HS-10 — Teledyne " "
- ④ HS-10 — Develco " "
Δ ⑤ L-HC — Develco " "
/ ⑥ LHC → HS10 — Teledyne " "
\ ⑦ LHC → HS10 — Develco " "

III Seismograph Station Calibration Procedure

1) Record setting of Preamp-VCO attenuator: Atn db

2) Measure seismometer coil resistance: R

3) Determine seismometer natural frequency: f_0

4) Carry out the seismometer "damping tests" to determine β_0, Γ, + G_4.

5) Measure the Preamp-VCO gain and input impedance

   a. Develco units

      1. Set the Preamp-VCO attenuator at 60 db

      2. Verify that the Preamp gain (for 60 db atten) is 60 db. Adjust if necessary.

      3. Determine the Preamp-VCO input impedance: RR

      4. Substitute the fixed resistor (953 Ω) for the "damping" potentiometer

      5. Determine the new value of the Preamp-VCO input impedance: RR

   b. Teledyne units

      1. Set the Preamp-VCO attenuator at 42 db

      2. Determine the Preamp gain (preamp input to amplifier "high" output) for 42 db atten.

      3. Determine the Preamp-VCO input impedance: RR

6) Carry out the system frequency response, linearity, and amplitude calibration

7) Connect the seismometer to the Preamp-VCO through the appropriate (L4C, EV17, or HS10) "standard" T-pad (or L-pad).

8) Set the Preamp-VCO attenuator so that the background earth noise measured at the amplifier output is approximately 20 mV_{rms} (Develco) (or 60 mV_{rms} (Teledyne)).

Name______________________________

Station:______________________________Date______________

Preamp-VCO type:____________________; unit number:____________

Seismometer type:____________________; seis number:____________

Initial Preamp-VCO attenuator setting ______________________db

Seismometer parameters

Coil resistance, R : ______________________________ohms

Natural frequency, f_0 :______________________________hertz

Open circuit damping, β_0 :______________________________

Electrical damping factor, Γ :______________________________

Motor constant, G_L :______________________________V/cm/sec

0.8 critical damping resistance, $D_{0.8}$:____________________ohms

Preamp-VCO parameters

Amplifier gain

Develco units, with 60 db atten :____________________ratio

Teledyne units, with 42 db atten :____________________db

Input impedance: ______________________________ohms

Final "working" attenuator setting: ____________________db

Ground noise level at amplifier output: ____________________mV_{rms}

System calibration constant, C_{10} : ____________________$\frac{\text{Viewer mm p-p}}{10\ \mu V\ \text{rms}}$

Remarks:

Name ________________________________

Seismometer Calibration

Station: ______________________________ Natural Frequency Test

Date: ______________________________ Drive Level: ______________________

Seis. Type: ____________________________ Frequency, f_o : ______________________

Seis. Number: __________________________ Decoupling Resistance: ______________

Seis. Coil Resistance, R: ______________________

Damping Test

S	A_o	A_1	$A_{1,2}$	$A_{2,3}$	$A_{1,2}/A_{2,3}$	λ	β	β_1	Γ
∞							$= \beta_o$	—	—
20.0K									
15.0K									
10.0K									

Γ_{av} = __________ G_L = __________ $D_{0.8}$ = __________

$$\lambda = \ln(A_{1,2}/A_{2,3})$$

$$\beta = 1\Big/\sqrt{(\pi/\lambda)^2 + 1}$$

$$\beta_1 = \beta - \beta_o$$

$$\Gamma = \beta_1 (R + S)$$

$$D_{0.8} = \Gamma/(0.80 - \beta_o) - R$$

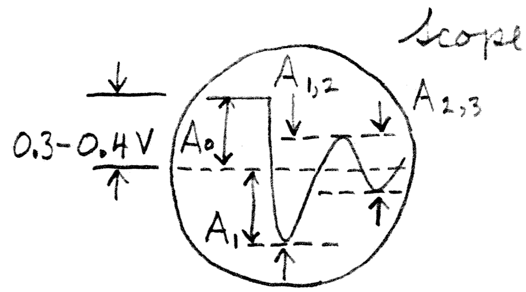
EV 17: $G_L = 0.0568\sqrt{f_o \Gamma}$

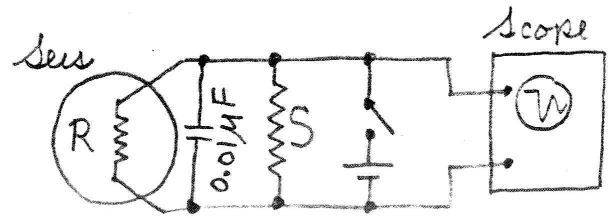
L-4C: $G_L = 0.0354\sqrt{f_o \Gamma}$

H510: $G_L = 0.0303\sqrt{f_o \Gamma}$

R, S, $D_{0.8}$ are in ohms

G_L is in volts/cm/sec; f_o is in hertz





Name__________________________

Teledyne Preamp-VCO Calibration

Station:__________________________

Date: __________________________

Teledyne unit number:____________________

1) Original attenuator setting: ________________________db

2) Preamp gain measurement

   a) Set attenuator at 42 db (__________________)

   b) Connect 1.0 mV_{rms} 2.5 ohm source to Preamp input. Verify that the Wavetek signal into the "source box" is 1.0 V_{rms} (_____________) at 3 hz (___________________)

   c) On the 'scope, measure the signal at the amplifier <u>High</u> output:

   $\overline{VH}$ = ______________V_{p-p}

   d) $VG_{42db} = \frac{1000.0}{2.828} \times \overline{VH}$ = ____________________________

   $GN_{42db} = 20.0 \times \log_{10} VG_{42}$ = __________________________

3) Preamp input impedance measurement

   a) Check that attenuator is at 42 db (__________________)

   b) Connect 0.25 μA source to Preamp input. Verify that the Wavetek signal into the source box is 1.0 V_{rms} (___________) at 3 hz (________)

   c) On the 'scope, measure the signal at the amplifier high level output*

   $\overline{VRH}$ = _______________V_{p-p}

   d) $RR = 4000.0 \times \frac{\overline{VRH}}{\overline{VH}}$ = ______________________ohms

* Sketch 'scope waveform on back of this sheet.

Name ______________________________

Develco Preamp-VCO Calibration

Station ______________________________________

Date ________________________________

Develco unit number _______________________

1) Original attenuator setting _______________ db

2) Preamp gain measurement and adjustment

   a) Set attenuator at 60 db (________________)

   b) Connect 1.0 mV_{rms} 2.5 ohm source to Preamp input. Verify that the Wavetek signal into the source box is 1.0 V_{rms} (________) at 3 hz (______________)

   c) On the 'scope, measure the signal at the amplifier output:

   $\overline{VH}$ = ______________ V_{p-p} ; $VG_{60db} = \frac{1000.0}{2.828} \times \overline{VH}$ = ___________ ;

   $GN_{60db} = 20 \times \log_{10} VG_{60db}$ = ______________.

   d) Adjust the Preamp gain trim pot. so that $\overline{VH} = 2.828\ V_{p-p}$ (____________).

   Then $VG_{60\ db} = 1000$ and $GN_{60\ db} = 60$ db

3) Preamp input impedance measurement

   a) Check that attenator is at 60 db (_____________)

   b) Connect 0.25 μA source to Preamp input. Verify that the Wavetek signal into the source box is 1.0 V_{rms} (_________) at 3 hz (__________).

   c) On the 'scope, measure the signal at the amplifier output*

   $\overline{VRH}$ = ________________ V_{p-p}

   d) $RR = 4000.0 \times \frac{\overline{VRH}}{\overline{VH}}$ = ____________________ ohms

* Sketch 'scope waveform on back of this sheet.

Name: ______________________

Station: ________________ Unit Type: ________________

Date: ________________ Unit Number: ________________

System Frequency Response
(100 μV_{rms} into preamp with atten of 48 / 30 db Develco / Teledyne)

Freq	Period	Amplfr Output V_{p-p}	DVCDR Ampltd MM_{p-p}	SR*	Freq	Period	Amplfr Output V_{p-p}	DVCDR Ampltd MM_{p-p}	SR*
.025	39.8				1.26	.794			
.032	31.6				1.59	.631			
.040	25.1				2.00	.501			
.050	20.0				2.51	.398			
.063	15.8				3.16	.316			
.079	12.6				3.98	.251			
.100	10.0				5.01	.200			
.126	7.94				6.31	.158			
.158	6.31				7.94	.126			
.200	5.01				10.0	.100			
.251	3.98				12.6	.079			
.316	3.16				15.9	.063			
.398	2.51				20.0	.050			
.501	2.00				25.1	.040			
.631	1.59				31.6	.032			
.794	1.26				39.8	.025			
1.00	1.00				50.1	.020			

Time: Begin ________________, End ________________

* SR = log (Amp(f)/Amp(5.0))

Name: ____________________

Station: ____________________ Unit Type: ____________________

Date: ____________________ Unit Number: ____________________

System Linearity Test (10 μV_{rms} into the preamp)

Atten	Amplfr Output V_{p-p}	DVCDR Ampltd MM_{p-p}	log Ampltd
66 db	______	______	______
60	______	______	______
54	______	______	______
48	______	______	______
42	______	______	______
36	______	______	______
30	______	______	______
24	______	______	______
18	______	______	______
12	______	______	______
6	______	______	______
0	______	______	______

Time: Begin ______________, End ______________

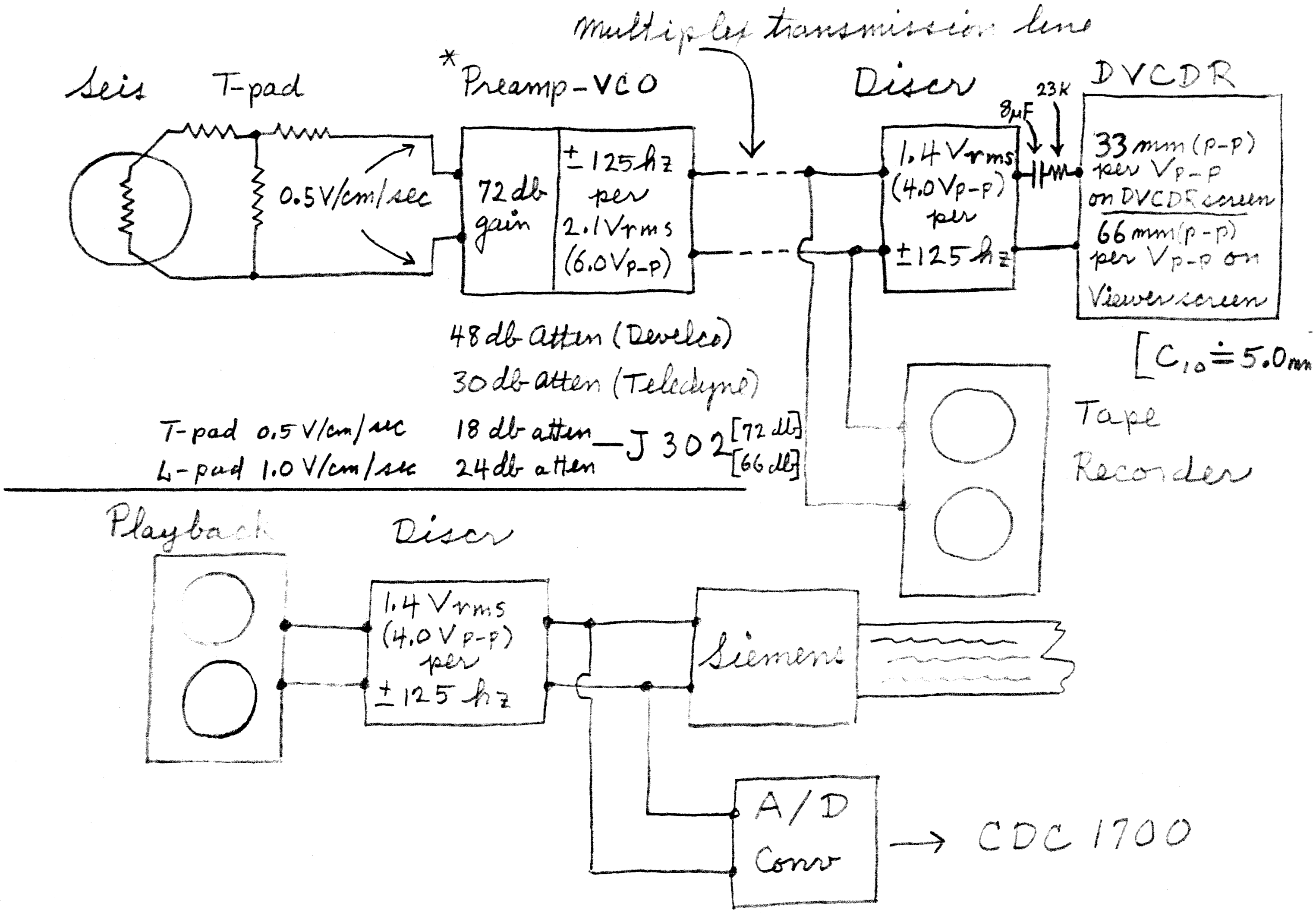
System Calibration Test (5 hz 2.5 Ω source at preamp input)

	48 / 30 db atten	Develco / Teledyne	______* db atten	
V_{rms}	Amplfr Output V_{p-p}	DVCDR Ampltd MM_{p-p}	Amplfr Output V_{p-p}	DVCDR Ampltd MM_{p-p}
1.0 mV	______	______	______	______
100 μV	______	______	______	______
10 μV	______	______	______	______
2.5 ohm short	______	______	______	______

Time: Begin ____________________ End ____________________

C_{10} = ______________ MM_{p-p} (Viewer)/10 μV_{rms}. * Working Attenuation

IV Block diagram and description of the standard system and its components and their nominal operating characteristics



Seis: L-4C with $T_o = 1.0$, $\beta = 0.8$, $G_L \doteq 2.8$ V/cm/sec

EV-17 with $T_o = 1.0$, $\beta = 0.8$, $G_L \doteq 4.9$ V/cm/sec

T-pad: Couples seis to Preamp and adjusts effective motor constant to $G_{LE} = 0.50$ V/cm/sec while providing proper damping resistance to seis and preamp.

L-pad: " $G_{LE} = 1.0$ V/cm/sec

* Parameters of the Develco unit are shown. In the Teledyne unit the amplifier gain is about 12 db greater, but this signal is attenuated 20 db before going to the VCO, which requires 2V p-p for ± 125 hz deviation.

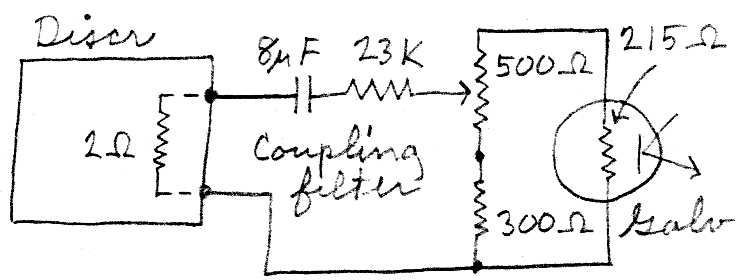
Preamp-VCO: Amplifies seis signal and uses it to modulate an audio frequency FM subcarrier for transmission via radio or phone line to recording site. Typical amplifier gain is +72 db. A 2.1 V_{rms} signal from the amplifier produces 100% modulation (±125 hz) of the audio carrier. The NCER system uses 8 carrier channels in the voice-grade phone line range of 300 to 3000 hz.

Multiplex transmission line: Up to 8 seismic signals on different audio subcarriers are transmitted over a standard telephone circuit or over an FM VHF radio channel with comparable audio signal band-width.

Discriminator: Selects audio subcarrier from transmission line and detects the seismic signal carried on it. ±125 hz modulation produces 1.4 V_{rms} (4.0 V_{p-p}) output.

Develocorder: Produces film record of up to 20 seismic and timing channels. Sensitivity and low frequency response of seismic channels is controlled by the series R-C circuit that couples the galvanometer to the discriminator. High frequency response is limited by the galvanometer, which has a natural frequency of 16 cps and is damped 0.8 critical.

The standard coupling circuit employs an 8μF capacitor in series with a 23K resistor, as drawn:



The channels tested with this coupling circuit (on 8/20/73) had a sensitivity of 33 MM (p-p) / volt (p-p) on the Develocorder screen, or 66 MM (p-p)/ volt (p-p) on the Viewer screen.

Tape Recorder: 1", 14 channel, 14 inch reel, 15/16 ips drive CEC Recorder employing direct mode recording. Each channel can record a "phone line" with its 8 undiscriminated multiplexed seismic signals.

Playback recorder: 1", 14 channel, 14-inch-reel machine capable of 15/16 ips playback of at least 2 channels through "direct reproduce" electronics.

Playback discriminators: 2 sets of 8 discriminators for "natural speed" playback of 16 seismic channels from 2 tape channels. ±125 hz deviation should produce a 1.4 V_{rms} (4 V_{p-p}) signal at the discriminator output. This sensitivity is the same as that of the "real time" discriminators that drive the Develocorder.

Siemens: 16 channel ink jet strip chart oscillographic recorder.

A/D converter: Input to the CDC 1700.

For the standard system and operating conditions indicated in the sketch on page 8 we can compute the signal level produced by a 1 mμ, 1 hz ground motion. [$C_{10} \doteq 5.0$ mm].

Peak ground displacement 1.0 mμ
Peak ground velocity 6.28 mμ/sec
Peak preamp input 6.3 x .05 = .31μV
Peak VCO input .31μV + 72 db = 1.24 mV (or .62μV + 66 db = 1.24 mV if L-pad used
Peak Discriminator output 2/3 x 1.24 = 0.82 mV
Peak Viewer screen amplitude 66 x .00082 = .054 mm

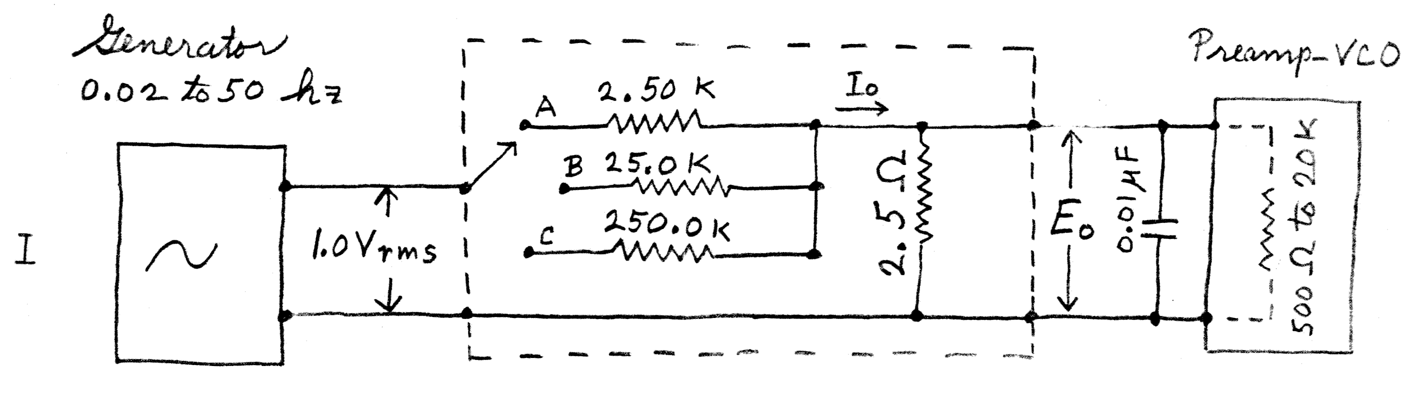
Magnification (Viewer screen amplitude/ground motion amplitude)
.054 mm/1.0 mμ = 0.54 x 10^5

In the range of earth motion frequency, f, between 1 and 10 hz we have approximately:

$M(f) = 0.54 \times 10^5 \times f$.

V Test circuits, definitions, and procedures

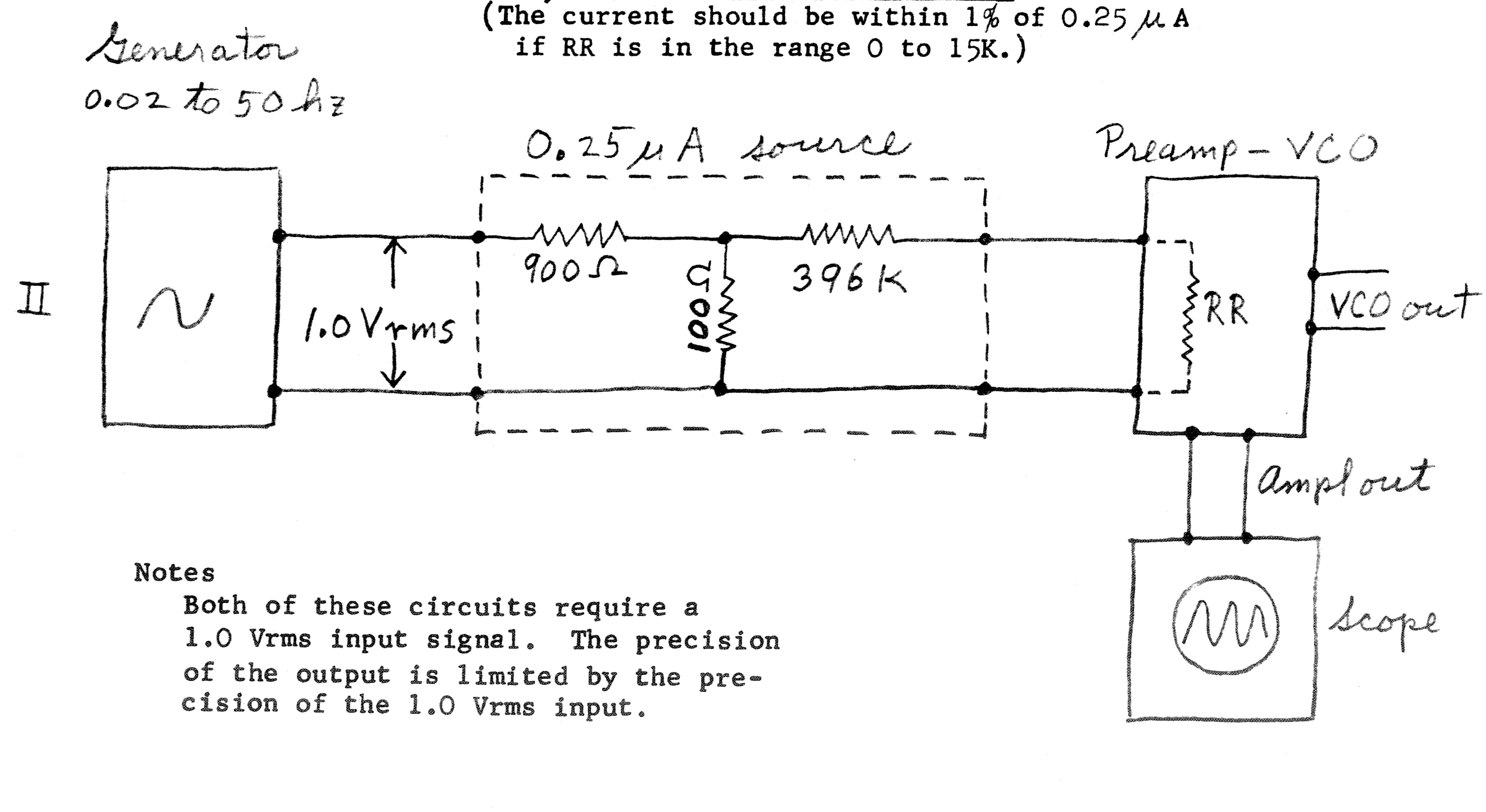
3-level 2.5 ohm "constant voltage" source



Switch	E_o	I_o
A	1.00 mV	400 μA
B	100.0 μV	40 μA
C	10.0 μV	4 μA

0.25 μA "constant current" source

(The current should be within 1% of 0.25 μA if RR is in the range 0 to 15K.)



Notes

Both of these circuits require a 1.0 Vrms input signal. The precision of the output is limited by the precision of the 1.0 Vrms input.

Definitions, equations, etc.

$\lambda = \ln(A_1/A_2)$ — logarithmic decrement

$\beta = \lambda/\sqrt{\pi^2+\lambda^2} = \lambda/\sqrt{9.87+\lambda^2}$ — damping constant

$\Gamma = \beta_1 (R+S) \qquad \left(= \frac{1}{\Omega_0}\frac{G^2}{2K}\right)$ — damping factor

$G_L = \sqrt{4\pi f_0 \frac{LM}{\ell} \times \Gamma \times 10^{-7}}$ (For a hinged seismometer)

$G_L = \sqrt{4\pi f_0 M \Gamma \times 10^{-7}}$ "linear" motor constant (For a linear seismometer)

Units: R and S in ohms, M in gm, L and ℓ in cm, f_0 in hertz

EV-17: $G_L = 0.0568 \times \sqrt{f_0 \Gamma}$

L-4C: $G_L = 0.0354 \times \sqrt{f_0 \Gamma}$

HS-10: $G_L = 0.0303 \times \sqrt{f_0 \Gamma}$

$D_{0.8} = \Gamma/(0.80-\beta_0) \quad -R$ — external resistance for 0.8 critical damping

Seismometer parameters

	M (gm)	ℓ (cm)	L (cm)	LM/ℓ (gm)
EV-17	2768	12.5	11.65	2570
L-4C	1000			
HS10	729			

Develco Preamp-VCO gain adjustment and input impedance measurement (See diagram I for the 1 mv circuit and diagram II for the 0.25 μA circuit)

1) Set the preamp attenuator at 60 db

2) Verify that the preamp gain (atten at 60 db) is 60 db:
Attach the 2.5 ohm -- 1.0m Vrms source (3 hertz) to the preamp input and adjust the preamp gain trim to get 1.0 Vrms (2.828 Vp-p) at the preamp output.

3) Attach the 0.25 μA "constant current" source (3 hertz) to the preamp input and read the preamp output, $\overline{\text{VRH}}$ rms, on the scope (DC range). 60 hertz noise may be a problem. If the 60 hertz noise is not larger than 2 or 3% of the 3 hertz signal, it should be possible to "read through" the noise and get an adequate (1%) measurement of the 3 hertz signal.

4) $RR = 4000.0 \times \overline{\text{VRH}}\ V_{rms} = 1414.0 * \overline{\text{VRH}}\ V_{p-p}$

Teledyne Preamp-VCO gain measurement and input impedance measurement (See diagram I for the 1 mv circuit and diagram II for the 0.25 μA circuit)

1) Set the Preamp-VCO attenuator at 42 db

2) Measure the voltage gain between the preamp input and the amplifier "high output":

   a) Using the 2.5 ohm "constant voltage" source introduce a 1.0 mv $_{rms}$ 3 hz signal into the preamp input

   b) With a scope, measure the signal at the amplifier high level output, $\overline{VH}$ V p-p

   c) The system voltage gain (with 42 db atten) is then:

$$VG_{42db} = \frac{1000.0}{2.828} * \overline{VH}\ V p\text{-}p; \quad DbG_{42} = 20.0 \log_{10} VG_{42db}$$

3) Measure the preamp input impedance (Atten. at 42 db):

   a) Using the high impedance "constant current" source, introduce an 0.25 μA rms 3 hz current into the preamp

   b) With a 'scope, measure the signal at the amplifier high level output, $\overline{VRH}$ V p-p

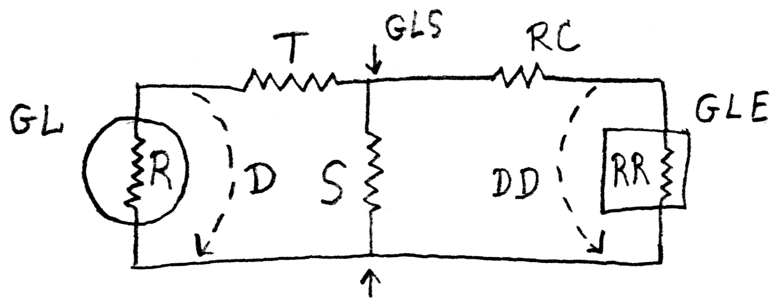
   c) The voltage drop across the preamp input is:

$$\overline{VDIV}_{rms} = \frac{\overline{VRH}\ V\ p\text{-}p}{2.828} \times \frac{1}{VG_{42}} = \frac{\overline{VRH}\ V\ p\text{-}p}{\overline{VH}\ V\ p\text{-}p} * 10^{-3}$$

   d) The preamp input impedance is:

$$RR = \frac{\overline{VDI}\ V_{rms}}{0.25 \times 10^{-6}} = 4000.0 \times \frac{\overline{VRH}\ Vp\text{-}p}{\overline{VH}\ V\ p\text{-}p}$$

L - pad attenuator to damp seismometer and to adjust its output to a desired level.



R = seismometer resistance

D = required external seis damping resistance

RR = preamp. input impedance (resistive)

RC = resistance of line between shunt and preamp.

T = seis series resistance

S = seis shunt resistance

GL = emf induced in the seis coil

GLE = resulting emf across preamp. input

GLS = resulting emf across S (in parallel with $RC+RR$)

$R' = S\,(RC+RR)/[\,S+(RC+RR)]$ resistance of S and $(RC+RR)$ in parallel

$f = GLS\,/GL$

$F = GLE\,/GE = f\,\dfrac{RR}{RR+RC}$

For given values of R, RR, RC, and GL we wish to select T and S to provide the correct external seismometer damping resistance, D, and to adjust the seismometer output (sensed across RR) to a prescribed value GLE.

Our basic relationships are:

$$D = T + \frac{S(RC+RR)}{S+(RC+RR)}$$

$$F = \frac{GLE}{GL} = \frac{S(RR+RC)/(S+RR+RC)}{R+T+S(RR+RC)/(S+RR+RC)} \times \frac{RR}{(RR+RC)}$$

The second equation reduces to

$$F = \frac{S \times RR/(S+RR+RC)}{R+D}$$

Solving for S

$$(1) \quad S = \frac{F(R+D)(RR+RC)}{RR - F(R+D)}$$

From the first equation, solving for T

$$(2) \quad T = D - \frac{S(RR+RC)}{S+(RR+RC)}$$

I. If $D \geqslant (RR+RC)$

$$T_{min} = D - (RR+RC)$$

$$F_{max} = RR/(R+D)$$

$$GEM = GL \times RR/(R+D)$$, where $GEM = GLE_{max}$

$$S = \infty$$

II. If $D < (RR + RC)$

$$S_{max} = \frac{D(RR+RC)}{(RR+RC)-D}$$

$$T_{min} = 0$$

$$F_{max} = \frac{RR}{(RR+RC)} \times \frac{D}{(R+D)}$$

$$GEM = \frac{D}{(R+D)} \times \frac{RR}{(RR+RC)} \times GL$$

To calculate S & T (for given R, RR, RC, D, and GL) to attain a desired value of GLE:

(A) Calculate $F = \frac{GLE}{GL}$

(B) Test F for admissability

i. e., $F \leq \frac{RR}{(R+D)}$ if $D \geqslant (RR + RC)$

$F \leq \frac{D}{(R+D)} \times \frac{RR}{(RR+RC)}$ if $D < (RR + RC)$

(C) Calculate S from (1)

(D) Calculate T from (2)

(E) Calculate

$$DD = RC + \frac{S(T+R)}{S+(T+R)}$$

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An Unbalanced T-Attenuation for Seismic Application

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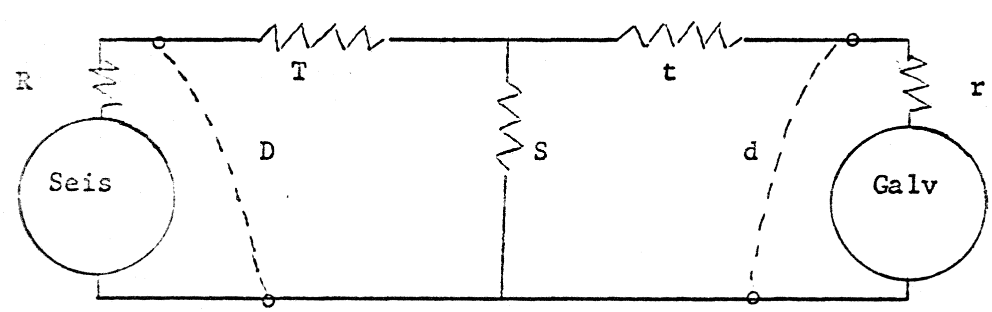
It is frequently convenient to calibrate the seismometer-galvanometer seismograph systems when they are operating at reduced sensitivity. The resistive network employed for this purpose must preserve the proper load across the seismometer and galvanometer while decreasing the fraction of the seismometer current that passes through the galvanometer. Such a network is also useful for adjusting the sensitivity of a given seismograph to the optimum level for the site where it is installed. Simple expressions relating the adjustable circuit parameters to the desired fraction of maximum sensitivity and to fixed circuit parameters are needed.



Let us modify Wenner's simple seismometer-galvanometer circuit, in which a shunt S was placed in parallel across the terminals of both the galvanometer, of internal resistance r, and the seismometer, of internal resistance R, by inserting a resistance T between the seismometer and the shunt and a resistance t between the galvanometer and the shunt (shown above). In Wenner's equations (in r, R, & S) substitute $R' = R + T$ and $r' = r + t$ for R and r, respectively. Furthermore, let us stipulate that the total external resistance across the seismometer terminals must be D, and across the galvanometer terminals, d.

$$D = T + \frac{S(t + r)}{t + r + S} \tag{1a}$$

$$d = t + \frac{S(T + R)}{T + R + S} \tag{1b}$$

Equations (1a) and(1b) can be solved for T and t in terms of d, r, D, and R with S as a variable parameter.

$$T = \frac{D - R}{2} - S + \sqrt{S^2\left(\frac{D + R}{d + r}\right) + \left(\frac{D + R}{2}\right)^2} \tag{2a}$$

$$t = \frac{d - r}{2} - S + \sqrt{S^2\left(\frac{d + r}{D + R}\right) + \left(\frac{d + r}{2}\right)^2} \tag{2b}$$

For any variation of t, T and S consistent with eq. (1a), and with the galvanometer clamped, the seismometer current I_G will depend only on the emf generated in the seismometer coil and R + D, which is constant: $I_G = \frac{G}{R + D} \frac{d\varphi}{dt}$. The fraction of this current which flows through the galvanometer, I_g, does vary with t, T, and S.

$$\frac{I_g}{I_G} = f = \frac{S}{r + t + S} \tag{3}$$

Eliminating t between (2b) and (3),

$$S = \frac{\frac{d + r}{f}}{\frac{1}{f^2} - \left(\frac{r + d}{R + D}\right)} \tag{4}$$

If D = r and d = R, S can go to ∞ and f can go to 1. For any other relationship among r, d, R and D, S must remain finite (and f must remain less than 1) in order that t and T remain positive.

By differentiating eqs. (2a) and (2b) with respect to S, setting the derivatives equal to zero, finding the values of S corresponding to the minima of T and t, and substituting these values of S in eqs. (2a) and (2b) we find:

$$T_{min} = \frac{D - R}{2} + \frac{\sqrt{(D + R)\left[(D + R) - (d + r)\right]}}{2} \qquad (5a)$$

$$t_{min} = \frac{d - r}{2} + \frac{\sqrt{(d + r)\left[(d + r) - (D + R)\right]}}{2} \qquad (5b)$$

If $D + R > d + r$, T_{min} will be real and t_{min} imaginary.

If $D + R < d + r$, t_{min} will be real and T_{min} imaginary.

Case I. $D + R > d + r$:

As $S \rightarrow 0$, $t \rightarrow d$ and $T \rightarrow D$ (from eqs. (2a) and (2b)).

As $S \rightarrow \infty$, t becomes and remains < 0 and T becomes and remains > 0.

Because t has no extremum and is negative for large S and positive for $S = 0$, it must have just one zero. T is positive for $S = 0$ and for large S; and it has a minimum which may be positive, zero or negative. Thus T will have no zeros, 1 zero, or 2 zeroes according to whether T min is positive, zero, or negative.

The value of S corresponding to $t = 0$ is:

$$S_{t\emptyset} = \frac{(d - r) + \sqrt{(d - r)^2 + 4rd\,\frac{(R + D) - (r + d)}{(R + D)}}}{2\left[\frac{(R + D) - (r + d)}{(R + D)}\right]} \qquad (6)$$

If T min is negative, the value of S corresponding to the zero of T between $S = 0$ and that for T min is:

$$S_{T\emptyset L} = \frac{(D - R) + \sqrt{(D - R)^2 + 4RD \dfrac{(r + d) - (R + D)}{(r + d)}}}{2\left[\dfrac{(r + d) - (R + D)}{(r + d)}\right]} \tag{7}$$

The value of S corresponding the the zero of T for S greater than that for T min is:

$$S_{T\emptyset U} = \frac{(D - R) - \sqrt{(D - R)^2 + 4RD \dfrac{(r + d) - (R + D)}{(R + D)}}}{2\left[\dfrac{(r + d) - (R + D)}{(r + d)}\right]} \tag{8}$$

Let S max be the smaller of $S_{t\emptyset}$ and $S_{T\emptyset L}$. For all $S \leq S$ max, both t and T will be real and positive (or zero).

If T min is negative and $S_{t\emptyset} \geq S_{T\emptyset U}$, there will be additional valid solutions (t and T real and ≥ 0) for values of S between $S_{T\emptyset U}$ and $S_{t\emptyset}$. We shall neglect this possible set of solutions in the discussion that follows.

Case II. $R + D < r + d$:

Interchange R and r, D and d, and T and t in the arguments and equations given for Case I, above.

Calculation of S, t, and T for T-pad attenuators:

This is designed to adjust the fraction of the signal originating in the seismometer that is delivered to the galvanometer (or preamplifier).

Substitute S max into equations (2a) and (2b) to determine the corresponding values of t and T (t max and T max, say). Determine f max from equation (3). Recall that $f = \frac{I_g}{I_G}$, the ratio of galvanometer current to seismometer current.

Let E be the emf generated in the seismometer coil. Then $I_G = E/(R + D)$.

Let e be the emf appearing across the galvanometer (or preamplifier) terminals.

Then,

$$e = I_g \times \cancel{R}^{\,r} = f \times I_G \times r = (f \times E \times r)/(R + D)$$

Thus,

$$\left(\frac{e}{E}\right)_{max} = f_{max} \times r \,/\, (R + D)$$

To calculate S, t, and T for reduced values of f max, e.g., 0.1 f max, etc., substitute the desired value of f into equation (4) and solve for S. Substitute this value of S into equations (2a) and (2b) to determine the corresponding values of t and T.