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MERGING OF ANALOG AND DIGITAL DATA IN THE NORTHERN CALIFORNIA SEISMIC NETWORK, AND CHARACTERISTICS OF THE PRINCIPAL SEISMIC SYSTEMS IT EMPLOYS

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I. Introduction

The Northern California Seismic Network is built upon field instrument and telemetry technologies developed more than 20 years ago. That technology provided for efficient collection of seismic data from hundreds of sensors scattered throughout central and northern California and reliable transmission of that data to the USGS recording and analysis center in Menlo Park, California. Initially, the dynamic range of the system was well matched to the data recording systems that were available: 16mm film strip recorders (Develocorders) and analog magnetic tape recorders, which had dynamic ranges of 40 to 50 db if managed carefully. With the introduction of computers (and A to D converters) for the recording and analysis of network data about 10 years ago, the dynamic range of the recording system suddenly increased remarkably: to nearly 72db (12-bit A/D), to nearly 96db (16-bit A/D), or to as much as 120+ db (24-bit A/D). The limitation on dynamic range in the current analog NCSN system is due primarily to the analog telemetry system that it employs; and the most promising way to improve the overall system dynamic range is to replace the analog telemetry with digital telemetry. This solution requires replacement of the single A/D converter that resides between the bank of network discrimiators and computer recording system in Menlo Park with separate A/D converters at each field site. These changes have important impacts on network telemetry and on collection of network data into a single stream for processing. The analog telemetry system permits data from as many as nine field sites to be combined, by simple "addition" of their modulated carrier signals, onto one channel for telemetry to the recording station. The current digital systems require a clear telemetry channel from each field site to the recording site. The discriminated analog signals from more than 600 seismometers are introduced to a single multiplexer-A/D converter, which blends them into a single multiplexed data stream for processing in the computer. The separate digital streams from different field sites are captured by digital receivers (typically PC-type computers) that handle a limited number of incoming digital streams. For systems now being evaluated, that number ranges from 8 to 64. Networks as large as NCSN will require many such receivers as well as further downstream merging of their data to produce a single network data stream for processing.

Two digital systems are now being installed and evaluated in Menlo Park. One is a 6-channel 24-bit commercial system manufactured by Nanometrics. It consists of eight 6-channel field units and one PC-based digital receiver/data logger. The other is a 3-component 16-bit field system developed at the USGS by Gray Jensen (DST) and a PC-based digital receiver/data logger developed by an IASPEI consortium led by Willie Lee. The IASPEI system can record as many as 64 3-component stations on a single PC, and the Nanometrics system can record eight 6-component stations on a single PC.

Yet another digital recording and analysis system (EARTHWORM) that is being developed to replace the aging RTP and the ad hoc alarm/paging system in Menlo Park is expected to play an important role in recording and analyzing a hybrid analog/digital NCSN in the future. It has an "open" architecture that promises to facilitate collection and merging of data from several digital and/or analog sources in near-real-time.

In addition to the real time digital systems noted above, several field-recorded digital seismic system are now in use. These include the RefTek system employed in the portable PASSCAL stations and the portable GEOS recorders employed in the USGS strong ground motion program.

To facilitate evaluation and use of data from the Nanometric system (in the East Bay digital net) and the DST/IASPEI digital system we plan to merge digital data from those systems with the analog network data recorded by CUSP so that records from all three sources can be examined simultaneously by TIMIT and processed by CUSP. Programs have been written to translate the Nanometrics and IASPEI formats to CUSP; and the resulting CUSP files are handled correctly by TIMIT (Alan Walter, personal communication).

The Nanometrics PC and the VAX-station EUREKA have been linked by Ethernet, and a routine that identifies, extracts, moves, and merges the Nanometrics records corresponding to events recorded by the CUSP system has benn written and tested (Alan Walter, personal communication). It appears that a similar procedure can be written to capture data from the IASPEI system, although it may be necessary to run the IASPEI software under a non-DOS, multitasking operating system, such as the OS/2 system employed on the Nanometrics system. This procedure should be satisfactory for a hybrid network with only a few digital stations. We anticipate that the EARTHWORM system will eventually have the ability to merge the analog (Tustin) and digital (IASPEI and Nanometrics) data streams in near-real-time so that event detection can be carried out on the complete data set, not just on the analog data set.

Combining stations of the analog and digital nets, which employ several different sensors and A/D converters of different sample rate and dynamic range, raises a number of issues that require solutions. This short paper attemts to identify and clarify some of those issues and suggests what we might do to resolve them.

II. Plan for entering DST and East Bay Net stations into NCSN station location and maintenance history files

As we prepare to incorporate the 16-bit digital USGS (DST) and the 24-bit digital Nanometrics stations into NCSN for processing on CUSP, we must decide how to designate the new sites and instrument components as well as how to specify their operating characteristics. To facilitate the maintenance and use of these data it is desirable to incorporate them into the existing lochst (site location and history) and mnthst (maintenance history) files currently used for the analog network. In addition to digital telemetry, the new stations will introduce several new field systems (DST and Nanometrics), seismometers (L22, HS-1, Wilcoxon, Kinemetrics FBA), Sacks-Evertson dilatometer, sensor-to-preamp coupling networks, and a new "location" parameter - instrument depth below ground surface at the site.

Specification of gain for the digital systems is somewhat simpler than for the analog systems that employ VCO's and discriminators. Our practice with the analog systems has been to specify gain in terms of attenuation below maximum amplifier gain [literally, the "attn" setting on the VCO unit: gain(db)=(92-attn)db]. To get the total system gain (preamp input to discriminator output) allowance also has to be made for the difference in VCO and discriminator modulation indices (approx. 5 to 3). Because of the limited dynamic range of the analog system, attenuation is adjustable in 6db steps to match system gain to site background noise. Frequency dependent elements in the analog system are distributed among the seismometer, amplifier/VCO and discriminator.

In the digital system the frequency response is determined by the seismometer and amplifier (which incorporates an anti-aliasing filter); and the system gain is determined by choice of a "gain" resistor in the amplifier, not by an adjustable attenuator.

Although we shall continue the practice of specifying the gain of the analog systems (which all have the same maximum gain) by attenuation setting, we shall specify the gain of the digital systems simply as the amplifier magnification expressed in decibells. The manner in which the "attenuation/gain" parameter in the mnthst file is to be interpreted will be determined by the type of system to which it applies.

Conventions that will be applied to specify site, component, and instrument attributes are described below.

Site: Normal 3-letter mnemonic suggesting the site name, with the first letter designating network subregion.

Component:

USGS code	Caltech code	Description
U	VDZ	USGS digital short period vertical (veloc)
W	VDN	USGS digital short period N-S (veloc)
X	VDE	USGS digital short period E-W (veloc)
Z	VDZ	Namometrics digital short period vertical (veloc)
N	VDN	Nanometrics digital short period N-S (veloc)
E	VDE	Nanometrics digital short period E-W (veloc)
I	ASZ	Nanometrics vertical accelerometer (VLG)
J	ASN	Nanometrics N-S accelerometer (VLG)
K	ASE	Nanometrics E-W accelerometer (VLG)
S		Dilatometer - high gain analog telemtry
Q		Dilatometer - low gain analog telemetry
D		Dilatometer - digital telemetry

Field systems

J..	USGS analog VCO's of various types
G..	USGS digital system (Jensen)
N..	Nanometrics digital system
R..	RefTek digital system
Q..	Quanterra digital system

Seismometers

L4C	Mark Products 1 hz, moving coil seis (1 component)
L22	Mark Products 2 hz, moving coil seis (3-component)
HS1	Oyo Geospace HS-1 4.5 hz moving coil seis (3-comp)
K23	Kinemetrics model FBA23 accelerometer (3-comp)
X73	Wilcoxon model 731 accelerometer (3-comp)
S-E	Sacks-Evertson dilatometer

Pads

T	T-pad, adjusts L4C to 0.5v/cm/sec output
L	L-pad, adjusts L4C to 1.0v/cm/sec output
A	L-pad, adjusts L22 to 0.5v/cm/sec output
B	L-pad, adjusts HS-1 to 0.2v/cm/sec output

MNTHST file content and format

col	fmt	content
1-3	a3	site code
4	a1	component
5	1x	

6-10	i5	julian day of visit
11	1x	
12-15	i4	hr, min of visit
16	1x	
17-19	a3	field unit type
20-23	i4	field unit ser. #
24-27	i4	calib code
28	1x	
29	i1	channel
30	1x	
31-33	i2,1x	attn / f3.1 gain; for J-, or D- and N-series, resp.
34-38	i5	date field unit installed
39	1x	
40-43	i4	yr,mo VCO batt installed
44	ix	
45-48	i4	yr,mo calib batt installed
49	1x	
50-52	a3	seis type
53-54	2x	
55-58	i4	seis ser. #
59	a1	seis comp (V or H)
60	1x	
61	a1	pad type
62	1x	
63-66	i4	yr,mo seis installed
67-68	2x	
69-70	i2	A/D bits
71	1x	
72-74	f3.1	A/D total range (eg 9.0 volts)
75	1x	
76-78	i3	seis depth (meters)
79	1x	
80-89	a10	repair codes
90-92	3x	
93-95	a3	operating agency

The new parameters Gain(db), A/D bits, A/D total range, and seis depth below ground surface refer to individual components at a given site. The designation of "field unit type" will determine the correct format for reading the new parameters.

II. Calculation of system magnification and C_{10} factor

Magnification (Amplifier input to A/D input)

J series: M=0.594*10**[(90.3-attn)/20]

G, N series M=1.0*10**[G/20]

attn is the attenuation setting on the J-series amp/vco in db.

G is the gain of the G- or N-series amplifier in db.

C_{10} factor

This factor was defined, for the analog system employing J series amp/VCO's and recorded on Develocorders, as "the p-p amplitude in millimeters on the Develocorder Viewer (40 mm per volt) produced by a 10 microvolt rms signal at the amplifier input". For the digital systems, this definition is equivalent to "40 times the p-p amplitude in volts at the A/D input produced by a 10 microvolt rms signal at the amplifier input".

J series: C_{10}=21.99/[10**(attn/20)]

G,N series C_{10}=0.001312*10**[G/20]

This factor scales a "unit response curve" to the actual gain of stations used in the computation of amplitude magnitude by HYPOINVERSE and several other programs.

III. Characteristics of seismometers and accelerometers used in NCSN

For more than 20 years the seismometer used almost exclusively in NCSN has been the Mark Products L4C seismometer, and we have become well acquainted with its characteristics and quirks. We now wish to incorporate several other seismometers, as well as accelerometers, into the network, and we need to know what to expect from them. Along with the new seismometers we shall also introduce new modes of telemetry and recording - digital telemetry and both 16-bit (IASPEI) and 24-bit (Nanometrics) PC-based recording systems. The present analog telemtery system and 12-bit A/D converter associated with the CUSP system seriously limit the performance of sensors in NCSN.

We shall first review the characteristics of 3 moving-coil seismometers, the L4C, L22, and HS1: free period, coil resistance, moving system mass, open circuit damping, and motor constant. The detection threshholds of these three instruments can be estimated in terms of the ground motion required to produce an output of 1μV(p-p),approximately the input noise level of the amplifier that follows the sensor in the system. We shall then review the characteristics of the Wilcoxon model 731 accelerometer and the Kinemetrics model FBA23 accelerometer: range of acceleration recorded, output voltage range, sensitivity, and internal noise. Then, we shall examine the dilatometer and relate its output to the amplitude of a plane, incident P wave. The accelerometers, velocity seismometers, and dilatometer will then be compared in terms of: 1) output voltage as a function of ground motion frequency for a constant amplitude sinusoidal ground motion, and 2) output voltage as a function of ground motion amplitude for sine waves of frequencies 1.0hz, 5.0hz, and 10.0hz.

From these relationships we can then examine the detection threshholds of the various devices as well as the ranges of ground motion amplitudes and frequencies that each serves best.

Finally, we shall examine how the potential performance of these sensors is limited by the telemetry and recording modes employed in NCSN.

1. Mark Products L4C moving coil seismometer (V and H)

f_0 = 1.0	natural frequency
R = 5500 ohms	coil resistance
M = 980 gm	mass of moving system
$ß_0$ = 0.27	open circuit damping
G_L = 2.7 v/cm/sec	motor constant
RR = 10,000 ohms	amplifier input impedance
G_E = 1.0 v/cm/sec	working motor constant
ß = 0.8	working seismometer damping

The L4C is connected to the amplifier by an L-pad coupling network that adjusts its output to 1.0 v/cm/sec and its damping to 0.8 critical. It is the "standard" NCSN seismometer and is used in both its vertical- and horizontal-component versions.

2. Mark Products L22-D moving coil seismometer (3-component)

f_0 = 2.0 hz	natural frequency
R = 5700 ohms	coil resistance
M = 72.8 gm	mass of moving system
$ß_0$ = 0.45	open circuit damping
G_L = 1.2 v/cm/sec	motor constant
RR = 100K, 1M	amplifier input impedance
G_E = 0.5 to 0.8 v/cm/sec	working motor constant
ß = 0.8	working seismometer damping

The L22-D is used with the GEOS system and with the G-series (USGS digital) seismic system.

3. Oyo Geospace HS-1 4.5 hz geophone (V and H)

f_0 = 4.5 hz	natural frequency
R = 2500 ohms	coil resistance
M = 23 gm	mass of moving system*
$ß_0$ = 0.27	open circuit damping
RR = 100K, 1M	amplifier input impedance
G_L = 0.2 to 0.4 v/cm/sec	working motor constant
ß = 0.6 to 0.8	working seismometer damping
Γ = 2960	seismometer damping constant*

* = calculated from other constants

Three-component HS1-LT's have been assembled by UC Berkeley for downhole installation along with 3-component Wilcoxon accelerometers and Sacks-Evertson dilatometers in the East Bay network. These packages have been recorded on GEOS, pending installation of Nanometrics digital telemetry and recorders.

4. Wilcoxon model 731 accelerometers (V and H)

recording range	± 0.5 g
output voltage range	± 5.0 V
sensitivity	10.0 V/g
internal noise	±0.5 μg
dynamic range	120 db
output impedance	100 ohms
(sensitivity	1μV/0.1μg or 1μV/0.98μm/sec^2)
(acceleration detection threshhold	0.5μg or 5μm/sec^2)

The Wilcoxon accelerometers are in the downhole "packages" in the East Bay network. They will be telemetered and recorded by the 24-bit Nanometrics systems.

5. Kinemetrics FBA23 accelerometer (3 component)

recording range	± 2.0 g
output voltage range	± 10.0 V
sensitivity	5.0V/g
internal noise	1 mV(p-p) (LT1013 chip)
"	3-4 mV(p-p) (LT062 chip)
dynamic range	86 db (LT1013 chip)
"	74 db (LT062 chip)

(sensitivity 1μV/0.2μg or 1μV/1.96μm/sec^2)
(acceleration detection threshhold
LT1013: 1mV(p-p) 0.1 mg or 1mm/sec^2)
LT062: 4mV(p-p) 0.4 mg or 4mm/sec^2)

note: The acceleration detection threshhold of the "quiet" FBA23 is 200 times larger than that of the Wilcoxon.

6. Sacks-Evertson dilatometer

This instrument measures dilatation in rocks of the earth's crust with astonishing sensitivity (Sacks, 1979). Hydraulically, it consists of a fluid-filled chamber and a communicating small fluid-filled tube and attached bellows. It is grouted into a borehole, typically at a depth of about 200 meters. Dilatation of the crust and imbedded dilatometer drives fluid into or withdraws it from the tube and bellows. The large volume of the detector assembly compared to the small diameter of the tube and bellows provides a hydro-mechanical magnification of 250,000 times. The motion of the bellows is detected by an LVDT (linear voltage differential transformer) which is powered from and returns its signal to a module at the well-head, which outputs the LVDT signal with amplifications of x1, x10, and x50. These output signals can be passed through high-pass filters (cutoff in the range 400 to 4000 seconds) to block secular and tidal strains so that transient dilatation produced by earthquakes can be recorded.

The primary record of secular strain and tides is taken from an unfiltered x1 output, which is sampled once every 10 minutes and recorded via satellite in Menlo Park. The primary seismic output is normally from a filtered (400 sec high-pass) x10 output and is recorded locally on a 16-bit GEOS recorder or transmitted to Menlo Park for recording. The six stations of the East Bay net will be telemetered and recorded by the 24-bit (nominal) Nanometrics system.

To compare the dilatometer with the moving coil (velocity) seismometers and the accelerometers, the outputs of all three types of sensor can be expressed in terms of the amplitude, frequency, and velocity of an incident plane P wave. The displacement amplitude of such a wave is:

$$Z(x,t)=A\sin[2\pi f(x/V-t)]$$

where Z(x,t) is displacement at point x and time t, and A, f, and V are amplitude, frequency, and velocity of the incident wave.

Taking the appropriate partial derivatives of this expression with regard to x and t, we obtain the peak ground motion acceleration, velocity, and dilatation as:

$a_{max}=(2\pi f)^2A$, $v_{max}=2\pi fA$, and $D_{max}=2\pi fA/V=v_{max}/V$.

In principle, the dilatometer sensitivity can be deduced from its hydro-mechanical amplification and the sensitivity of the LVDT. In practice, however, it is calculated with reference to the amplitude of the earth tide, which is well recorded by the instrument. The empirical calibration is thought to be more appropriate than the theoretical sensitivity because the latter would not include possible effects of the coupling between the dilatometer and the enclosing rock. Although the empirical calibration factors vary from site to site, they are in the range 0.006 μstrain/mv (or 170 mv/μstrain) for the unfiltered x1 output.

For a plane wave with amplitude A(μ) travelling in a medium with P-velocity V_p=3 km/sec, $D_{max}=2.09fA(\mu)10^{-3}$ μstrain, and for a sensitivity of 170 mv/μstrain, $L_{max}=0.355fA(\mu)$mv, where L_{max} is the output of the LVDT. The line labelled "Sacks-Evertson" on figure 1 is based on these relationships. It compares the x1 output of the Sacks-Evertson to those of the three seismometers and two accelerometers for a plane P wave with an amplitude of 1μ and frequency f.

The dilatometer system noise appears to be so small that it can be neglected for the purpose of estimating detection threshholds for systems with only modest amplification of the LVDT output. To raise LVDT signal levels above the telemetry noise in the analog system, however, requires significant amplification, between x200 (46db) and x10,000 (80db). With x10,000 amplification a base-level noise of 1μV in the LVDT circuit or a 1μV input noise level in the LVDT output amplifier is raised to 10 mv, which is comparable to the telemetry noise in our analog system. Examination of the ambient earth strain noise versus frequency curve for a quiet dilatometer site in the Mojave Desert (Borcherdt, Johnston and Glassmoyer, 1989, figure 2) suggests that the Sacks-

Evertson instrumental noise is smaller than earth strain noise for frequencies lower than about 20 hz.

IV. Seismic systems

The principal recording systems that we shall consider include 1) the NCSN analog telemetry system and 12-bit Tustin A/D, 2) the 16-bit GEOS digital recorder, 3) the 16-bit DST (USGS) digital seismic system, and 4) the 24-bit (20-bit?) Nanometrics digital system.

1. FM analog telemetry and 12-bit (Tustin) A/D converter

The 8 (or 9) channel FM constant bandwidth telemetry system employed by NCSN seriously limits the dynamic range of signals transmitted over it. The dynamic range actually attained is between 40 db and 50 db, with most stations closer to 40 than 50 db. We shall adopt 46 db as the nominal (optimistic) dynamic range of the system. The dynamic range is limited by electronic noise introduced in the modulator, multiplexed transmission path, and discriminator. It is very broad band noise, and when passed through the discriminator output filter (0 to 20 hz) it is indistinguishable from background earth noise. The 12-bit A/D converter accepts a full range signal of ±2.5V: 4096 counts/5.0 V; 1.22 mV/c. For an A/D noise level of 3 counts, the A/D dynamic range is 62.7db. The signal presented to the A/D converter is limited (nominally) to ±2.0 V by clipping in the amplifier preceding the modulator and by the modulator and discriminator modulation indices.

An analysis of pre-event noise at the normal high-gain NCSN L4C stations shows a median value of 61mV p-p at the discriminator output (about 14 µV p-p at the amplifier input). A 61 mV p-p signal is only 38 db below the 5000 mV p-p full range of the A/D converter. 14 µV is about 14 times the nominal "input"noise (about 1 µV) of the seismic amplifier.

The median noise on the lo-gain vertical components (48 db attenuation) was 18 mV p-p at the discriminator output. This figure is judged to represent electronic noise introduced by the system, because the median noise on the high-gain verticals (judged to be dominated by ground noise), scaled down from the "average" 18 db station to the 48 db low-gain vertical components, should have been only about 2 mV p-p. Thus, the system noise (18 mV p-p) is about 49 db below the A/D input range; and the "ground noise" on the high gain verticals is only about 3.4 times (10.6 db) larger than system noise. These figures suggest that the 63 db dynamic range of the 12-bit A/D exceeds that of the analog telemetry systen (49 db) by 14 db, or a factor of 5.

2. USGS DST digital seismic station

This system multiplexes and digitizes three seismic channels in a field site at a rate of 100 sps and transmits the digital signal, by means of a modem, over a radio or telephone link to an IASPEI PC-based recorder at the recording site. Each sample sweep is transmitted as it occurs in the field unit, and timing is introduced in the PC receiver unit when the sample sweep arrives. The DST employs a 16-bit A/D converter with an input range of ±4.5V. It employs an amplifier, with gain set by choice of a resistor, and a 7-pole 25 hz anti-aliasing filter.

The A/D sensitivity is 0.137mV/count. For an A/D noise level of 3 counts, the dynamic range of the A/D is 86.8db. If the system is operated with a gain of x100 (40 db), its preamp noise (nominally 1µV p-p) is amplified to about 0.100 mV p-p at the A/D input, which is somewhat smaller than 1 count in the A/D converter. In the previous section we reported that background earth noise at an average NCSN site produced an output of about 14 µV p-p from an L4C seismometer (1V/cm/sec). After x100 amplification in the DST, such a signal would produce about 10 counts in the A/D converter. Assuming an A/D "noise" level of 3 counts, the backgrond earth noise would be about 3.3 times (10 db above) the system noise. This is essentially the same earth noise to system noise ratio as we found (at the A/D output) for the analog system operating at 18 db attenuation (approximately 72 db = x4000 gain). In the 16-bit system, background earth noise of 10 counts is 76 db below the largest signal the system can record. The corresponding figure for the analog system is only 38 db! With amplifier gains set to achieve the same ground noise to system noise ratio, the DST will clip at a signal level nearly 80 times larger than the one that clips the analog system.

3. Nanometrics HRD24

This unit is used with the East Bay digital network to record "downhole" accelerometers, velocity seismometers, and dilatometers.

The field unit produces a multiplexed, 6-channel, 24-bit, 200 sps/channel (selectable) digital stream that is telmetered via radio or high-grade phone line to a PC-based recorder in Menlo Park that can accomodate as many as eight 6-channel field units. The actual sampling rate is much higher than 200 sps, which permits an enhancement of the precision of the 200 sps output stream. Anti-aliasing filtering is accomplished digitally in the high-sample-rate stream. The field unit is supplmented by a GPS clock and radio, which provide accurate time that is "stamped" in the headers of the 1 sec, multiplexed blocks of data that are transmitted to the recording station.

Calculation of the sensitivity of the HRD24 is less straightforeward than for the DST, presumably because of the technique employed to maximize the dynamic range of its A/D converter. One must first specify the maximum input voltage range to be recorded. The system gain is then set so that the required input voltage range is adjusted to ±7.50V by the selection of the appropriate "gain resistor" for the system. With this information one can then calculate the system sensitivity and the total number of counts corresponding to the input voltage range specified. This number is approximately $2^{23.6}$ (12,714,572 counts), not the 2^{24} (16,777,216 counts) corresponding to the full range of a 24-bit A/D.

The sensitivity of the system, referred to the input of the A/D engine, can be calculated as $15.0V/2^{23.6}$counts = 1.180 µV/c or as $(15.0 \times 2^{24}/2^{23.6})/2^{24} = 19.79/2^{24}$. To specify the characteristics of this A/D in the maintenance history file, we shall use the "adjusted" input voltage (19.79) and the full 24-bit count (2^{24}). Preliminary tests indicate an internal noise of "several bits". Let us stipulate an internal noise level of 4 bits: 16 counts or 18.88µV(p-p). The dynamic range of the system would then be 118db. This figure is very sensitive to the A/D internal (input) noise level, which is critically dependent on electronic noise picked up between the sensor and the A/D input.

The input impedance and gain for each channel should be set in accordance with the type of sensor it records. The Wilcoxon accelerometer has on output range of ±5.0 V and an output impedance of 100 Ω (nominal). To be specific , we suggest for the accelerometer that the Nanometrics be set up with an input impedance of 100K and a gain of x1.50 (+3.5 db).

The HS-1 has about 1/3 the output of the L4C in the range 5 to 20 hz. The L4C output for background earth noise at an average NCSN site was found to be about 14 µV p-p; so we expect that the corresponding figure for the HS-1 will be about 5 µV p-p. The downhole noise level should be almost an order of magnitude smaller than the surface noise level, let us say only 1/5 that level, or about 1µV(p-p) for the HS1. This level is approximately the same as the input noise level of the amplifier following the sensor. The Nanometrics 4-bit noise level corresponds to about 18.9µV(p-p). Thus the HS1 channel should have a gain of about x20 (26 db) to bring the HS1 downhole background earth noise signal up to the system noise level. We suggest that the Nanometrics HS1 channels be set up with 100K input impedance and a gain of x20 (26 db).

4. RefTek digital systems

16-bit system

The RefTek system used in the original PASSCAL stations employed a 16-bit A/D with an input range of ±3.75 V. The sensitivity of the A/D is 0.114 mv/count. It is configured for 3 channels and permits a variety of sampling rates, including 100 sps. The field unit is supplemented by a GPS clock and radio; so accurate timing is available at each site. Recording is on an internal hard disc; and the data are "harvested" at appropriate intervals by a roving PC unit that can copy data from the station disc.

This system most commonly employs L4C or L22 seismometers. It can be set up to record "events", to record during pre-set time intervals, or to record continuously.

24-bit system

The 6-channel 24-bit RefTek system is the functional equivalent of the Nanometrics HRD24.

5. GEOS

GEOS was one of the earliest portable digital field recorders and has been used extensively by the USGS for about 10 years (Borcherdt, et. al., 1985). The system employs a 16-bit A/D converter and records on a digital cassette tape recorder. The input range of the A/D converter is ±10 V, which yields a sensitivity of 0.305 mv/c. For a noise level of 3 counts, the dynamic range of the A/D converter would be 86.8db. GEOS is set up to record data from 6 channels at a variety of sample rates, including 100 sps. It can be set to operate in a self-triggered "event" mode, in a "timed interval" mode, or (for a very short interval) continuously. It employs a precision local clock with radio synchronization.

This system has been used for many recording purposes; but in its most common configuration it records three "velocity" channels (3-component L22) and three "accelerometer" channels (Kinemetrics FBA23).

VI. Comparison of sensor response, and recording range of various system configurations

Figure 1 shows the output voltages of three moving coil seismometers, two accelerometers, and the Sacks-Evertson dilatometer as a function of frequency, for sinusoidal ground motion with an amplitude of 1μ (10^{-6} m). The response curves for the moving coil seismometers are the straight line asymptotes to the actual response curves. The detection threshhold for the seismometers, 1μV(p-p), is the approximate internal noise, referred to the input, of the amplifiers driven by the seismometers. The threshholds for the accelerometers are the base noise levels at the output of the accelerometer electronics.

We can define the recording range of a seismic system in terms of two limits: the detection threshhold and the clipping level. The detection threshhold is the ground motion amplitude that produces a signal level at the A/D output that is equal to the system noise at the A/D output. The clipping level is the ground motion amplitude that produces a signal level that equals the maximum permissable level in some electromic component of the system; and larger amplitudes would result in truncated waveforms at the A/D output.

In a digital system, clipping normally occurs when the amplified sensor signal reaches the maximum output level of the amplifier driving the A/D converter. The maximum output level is selected to avoid exceeding the input range of the A/D converter. In the analog system, clipping normally occurs when the amplified sensor signal reaches the maximum output level of the amplifier driving the VCO. The maximum output level is selected to avoid overmodulating the FM carrier.

The detection threshhold depends on a variety of possible noise sources: intrinsic noise in the sensor, noise in the amplifier, noise in the transmission path (for analog systems), and A/D input noise levels.

Amplifier gain levels are critically important for obtaining optimal performance from both analog and digital seismic systems. Amplification is employed to assure that the desired seismic signals are presented to the A/D converter at a level that exceeds the A/D input noise level. Excessive amplification, however, needlessly diminishes the overall dynamic range of the system. In analog systems, amplification is also employed to assure that the desired seismic signals are not lost in telemetry noise. The amplifier input noise, however, is amplified along with the sensor signal and limits the system's ability to recover very weak sensor signals in both analog and digital systems.

Moving coil seismometers have very low intrinsic noise because they are passive devices (no internal electronics), and the smallest earth motion that can be detected is normally limited by the input noise of the amplifier that follows the sensor. The accelerometers (Wilcoxon and Kinemetrics) as well as the Sacks-Evertson dilatometer are active devices, and their intrinsic noise levels depend on their internal electronics. The operating characteristics of the accelerometers are specified by recording range, sensitivity, and base noise levels in their electronic output. The dilatometer appears to have a high output-signal to internal-noise signal ratio. When recorded with low magnification on a high-dynamic-range digital recorder, system noise appears to be well below the background earth noise level. When recorded by the telemetered analog system, however, high magnification (up to 10,000) is required to overcome telemetry noise. Under these conditions, amplified electronic noise may be a problem.

To compare the recording range of the sensors described above, in combination with different telemetry and recording systems, we shall calculate detection threshholds as well as clipping ground motion amplitudes for 1 hz, 5 hz, and 10 hz ground motion. To calculate the detection threshhold we must know the A/D input noise levels, the transmission path noise level, the amplifier noise level (which depends on amplifier gain), and the signal levels output by each sensor for the prescribed ground motion. For the 12-bit and 16-bit A/D converters we shall assume an internal noise level of 3 counts(p-p), but for the 24-bit A/D we shall assume a noise level of 4 bits (16 counts p-p).

A properly operating digital telemetry system should introduce no noise: the recorder reads the exact digital representation of the signal as encoded by the A/D. The analog telemetry system (when adequately managed) has a base noise level of about 18mv(pp). Moreover, the discriminator output is only 3/5 the level of the modulator input (4.4db loss).

Finally, we must know the output of the various sensors at the prescribed ground motion frequencies as a function of ground motion amplitude. The expressions for a_{max}, v_{max}, and D_{max} show that all three are linear functions of ground motion amplitude, A. Figure 1 shows the output of the various sensors as a function of frequency for a ground motion amplitude of 1µm. Thus, we can read the output signal levels of the various sensors, in response to a ground motion amplitude of 1µm, from figure 1 and scale those output levels to the actual ground motion amplitude.

Table I. Sensor output levels in µV/µm(0-p) at 1hz, 5hz, and 10hz

sensor	input noise	1hz	5hz	10hz
L4C	1µV	628 (393)*	3140	6280
L22	"	83	1570	3140
S-E	"	310	1550	3100
HS1	"	6.6	623 (389)*	1260
W731	5µV	40.3	1008	4032
K23	1mV	20.2	504	2016

* divided by 1.6 to account for departure of response curve from asymptotic curve near the natural frequency of the sensor.

Telemetry and recorder base noise levels: telem ±9000μV, Tustin 12-bit A/D ±1830μV, GEOS 16-bit A/D ±458μV, DST 16-bit A/D ±206μV, Nanometrics 24-bit A/D ±9.44μV. Note ±1μV=2μV(p-p).

Table II. Summary of system parameters

System	Magnif	Amplifier	Telem	A/D	Threshhold	A/D range mV(p-p) Clipping
		|-------Noise levels (p-p)			--------|	
18db L4C	4121	4.1mV	18mV	3.66mV	18mV(Telem)	4000mV
48db L4C	130	0.13mV	"	"	"	"
72db L4C	8.2	0.008mV	"	"	"	"
Dx100L4C	100	0.1mV	-	0.42mV	0.42mV(A/D)	9000mV
Dx100L22	100	"	-	"	"	"
Dx.45K23	0.45	0.45mV	-	"	0.45mV(int)	"
Tx1K23	.594	0.59mV	18mV	3.66mV	18mV(Telem)	4000mV
Nx20HS1	20.0	0.020mV	-	.0189mV	0.02mV(int)	15000mV
Nx5L4C	5.0	0.005mv	-	"	.0189mV(A/D)	"
Nx1.5W731	1.5	0.0075mV	-	"	"	"
Nx.75K23	0.75	0.75mv	-	.0189mV	0.75mV(int)	"
Nx1S-E	1.0	0.001mV	-	"	"	"
Gx50S-E	50	0.05mV	-	0.916mV	0.916mV(A/D)	20000mV
Tx2000SE	1188	1.19mV	18mV	3.66mV	18mV(Telem)	4000mV
Tx60S-E	35.6	.036mV	"	"	"	"

Table II footnote: The 18dbL4C, 48dbL4C, and 72dbL4C indicate telemetered analog NCSN stations with the attenuation setting indicated. The TK23 indicates the Kinemetrics FBA23 telemeterd over the analog system. Dx0.45 and Dx100 indicate the USGS DST system (16-bit) with magnifications of 0.45 and 100, respectively. Nx0.75, Nx1, Nx1.5, Nx5, and Nx20 indicate the Nanometrics HRD24 (24-bit) systems with magnifications of 0.75, 1, 1.5, 5 and 20 , respectively. Gx50 indicates the GEOS system with x50 magnification. Tx2000 and Tx60 indicate the USGS telemetered analog system with magnifications of x2000 and x60, respectively. The effecive magnification of the Txxx systems is diminished by the different modulation indices of the modulator and discriminator used in the telemetry system.

Table III. Threshhold and clipping ground motion amplitudes

System	Thhld | Clip 1hz		Thhld | Clip 5hz		Thhld | Clip 10hz		DynRng
18dbL4C	5.6mµ	1.23µ	.695mµ	.155µ	.348mµ	.077µ	47db
48dbL4C	176mµ	39.1µ	22.0mµ	4.90µ	11.0mµ	2.45µ	47db
72dbL4C	2.8µ	621µ	350mµ	77.7µ	175mµ	38.8µ	47db
Dx100L4C	5.34mµ	115µ	.669mµ	14.3µ	.334mµ	7.17µ	87db
Dx100L22	25.3mµ	542µ	1.34mµ	28.7µ	.669mµ	14.3µ	87db
Dx.45K23	24.7µ	495mm	0.992µ	19.8mm	.248µ	4.96mm	86db
Tx1K23	750µ	167mm	30.1µ	6.68mm	7.52µ	1.67mm	47db
Nx20HS1	75.8mµ	56.8mm	1.29mµ	.964mm	.397mµ	.298mm	118db
Nx5L4C	4.81mµ	3.82mm	0.61mµ	.448mm	.301mµ	.239mm	118db
Nx1.5W731	156mµ	124mm	6.25mµ	4.96mm	1.56mµ	1.24mm	118db
Nx.75K23	24.7µ	495mm	.992µ	19.8mm	.248µ	4.96mm	86db
Nx1S-E	30.5mµ	24.2mm	6.10mµ	4.84mm	3.05mµ	2.42mm	118db
Gx50SE	29.5mµ	.645mm	5.91mµ	129µ	2.95mµ	64.5µ	87db
Tx2000SE	24.4mµ	5.43µ	4.89mµ	1.09µ	2.44mµ	.543µ	47db
Tx60S-E	816mµ	181µ	163mµ	36.2µ	81.6mµ	18.1µ	47db

Figures 2a, 2b, and 2c show the recording range of various system configurations, expressed in terms of ground motion amplitude and acceleration, for 1 hz, 5 hz, and 10 hz sinusoidal ground motion, respectivly. The lower end of the vertical bar indicating recording range corresponds to the detection threshhold (seismometer signal equals system noise) and the upper end corresponds to the clipping level. Traces are identified as in Table II.

In addition to showing the recording ranges of the various system configurations described above, figures 2a, 2b, and 2c illustrate the dramatic improvement in recording range from the telemetered analog 12-bit system, to the 16-bit DST and GEOS systems, and to the nominal 24-bit (practically, 20-bit) Nanometrics system.

Assuming a base-level noise of 3 counts in the 12- and 16-bit A/D's and 16 counts in the 24-bit A/D, we find their effective dynamic ranges to be 63db, 87db, and 118db, respectively. If signals are transmitted over the USGS analog telemetry system, with a dynamic range of only about 47 db, it is clear that the 12-bit Tustin A/D can record them without further loss of dynamic range.

For digital telemetry, however, the dynamic range of the A/D sets an upper limit on the dynamic range of any signal it records. Whether that limit is attained, however, depends on the sensor and associated electronics. The K23 accelerometer, for example, has an output that ranges from its 1mV(p-p) base noise level to ±10V maximum output level, for a total dynamic range of 86db. Thus, a 16-bit A/D, with 87db dynamic range, is adequate to record the K23. Because larger dynamic range requires more telemetry capacity (bandwidth), it is wasteful to devote a 24-bit digital system to recording the K23. On the other hand, the W731 accelerometer has an output range of ±0.5μg (±5μV) base level noise to ±0.5g (±5V) maximum output level, for a total dynamic range of 120db. Thus, the 24-bit Nanometrics system, with a dynamic range of 118db, is appropriate for recording the W731.

It appears that the Sacks-Evertson dilatometer also has a dynamic range of 120db or more and is appropriately recorded on the Namometrics system.

The relatively low output signal from moving coil seismometers usually requires amplification to raise background earth noise to a level above the A/D or other electronic system noise. The amplifiers used for this purpose in NCSN have an internal input noise level of about 1μV(p-p), which establishes the minimum ground signal level that can be detected by the system. Once the amplification required to raise the background earth signal above the system noise is determined, we can calculate the output signal level corresponding to the maximum frame-to-coil displacement of the seismometer at a given frequency. That signal level may be less tham the input range of the A/D; and in such a case the effective dynamic range of the system will be less than that of the A/D.

To record the entire working range of the L4C - about ±1mμ quiet site background noise to about ±1mm relative coil-to-frame motion - requires a 120db recording system. Thus, the Nanometrics system can exploit the L4C, but the 16-bit DST or telemetry system (12-bit) cannot.

The performance of four sensors, L4C, K23, W731, and S-E, are shown as a function of telemetry and recording system (from Fig 2 and Table III) for 5 hz ground motion in Table IV.

Table IV. Sensor performance as a function of recording system, for 5 hz ground motion

Sensor	Recorder	Ground Motion Amplitude	Dynamic Range
L4C	T18db	0.7mμ to 0.16μ	47db
"	T48db	22mμ to 4.9μ	47db
"	T72db	350mμ to 78μ	47db
"	Dx100	0.7mμ to 14μ	87db
"	Nx5	0.61mμ to .45mm	118db
K23	Tx1	30μ(3mg) to 6.7mm(.67g)	47db
"	DSTx.45	1.0μ(0.1mg) to 2.0cm(2g)	86db
"	Nx.75	1.0μ(0.1mg) to 2.0cm(2g)	86db
W731	Nx1.5	6.258mμ(0.6μg) to 5.0mm(0.5g)	118db
S-E	Nx1	6.1mμ to 4.8mm	118db
"	Gx50	5.9mμ to 129μ	87db
"	Tx2000	4.8mμ to 1.1μ	47db
"	Tx60	163mμ to 36μ	47db

To attain the dynamic range indicated in Tables III and IV and Figure 2 requires very careful management of the analog circuitry between the sensor and the A/D converter. Noise pickup from a variety of sources, power supplies, inadvertant "ground loops", nearby radio transmitters, etc., can have a disastrous impact on the overall performance of these systems. It is good practice to test these systems in the field with "shorted" input to establish the system noise level before putting them in service.

VII. Telemetry requirement for the analog, DST, and Nanometrics systems

The analog telemtery system is most conservative in its use of telemetry capacity. Eight standard channels (680, 1020, ...3060hz±113hz) plus one slightly degraded channel (400hz±75hz) can be carried over one voice grade telephone, radio, or microwave channel. Combination of signals from several sites is accomplished by simple summation wherever the signals can be brought together. The telemetry system used by NCSN, which was developed to support the analog telemetry, consists primarily of radio or phone line links from the individual sites to the NCSN microwave system (towers) that serves the function originally performed by "long distance" phone lines and brings the signals back to Menlo Park.

The DST system was designed to use the current NCSN telemetry system, i.e., to utilize standard voice grade communications channels for its telemetry. One voice grade (9600 baud) circuit serves one site, which generates a multiplexed data stream from three seismic components sampled 100 times per second by a 16-bit multiplixer-A/D. Each multiplexed sample is transmitted without delay, and timing is added at the receiving station. Only one-way communication is required, as with the analog systems. Use of the NCSN communications network to carry DST data is compatible with its continued use to support the analog net. This approach will permit incremental upgrading of NCSN to establish a digital sub-net to increase the dynamic range of the network and provide high-quality digital data throughout the network. Because of its simplicity, the DST unit is much less expensive than the more elaborate commercial units. Moreover, prospects for upgrading the DST to 20-bit performance without significant change in cost or telemetry requirements are encouraging.

The 24-bit commercial systems, such as Nanometrics, RefTek, and Quanterra, are much more sophisticated than the DST. They offer more channels, higher sample rates, local time stamping, etc., but at a great increase in cost and telemetry requirements.

To implement an eight-station Nanometrics network in the South Bay region, it has been necessary to set up an independent radio telemetry network to accomodate the 38.4 kilobaud data rate of that system. The radios required for this net are not available from standard suppliers. They appear to "press the envelope" of standard practice, at least as regards receiver selectivity, and the number of units required is too small to interest the larger manufacturers. Much of the delay in getting the East Bay net into operation has been caused by the "radio problem".

In principal, digital phone circuits might be a solution to this problem. It appears, however, that the ultimate cost (tariff) may be excessive, and such service does not yet appear to extend to much of the area covered by the net. The present situation with digital telephone service is not unlike that with standard service when the network was first installed. Very favorable local rates, combined with the Federal "Telpac" long-line lease service, made phone lines the obvious choice for network telemetry. We were forced to develop the use of VHF radio links to extend the net into crucial regions beyond the reach of phone service,however; and we soon were using "borrowed" microwave ciruits, in combination with radio links, to extend the net northward to Cape Mendocino. Subsequent deregulation of the phone system and loss of Telpac service led to a precipitous (unbearable) increase in the cost of telephone service. Fortunately, we had sufficient experience with radio links and microwave systems by the time these changes occurred that we were able to save the network by converting to the communication system that we now use. We should be cautious about adopting a telemetry system that we cannot afford in the long term because it might be offered "free" as an initial inducement to choose it. Telemetry is at the core of the network, and if it is not managed wisely we could lose the network.

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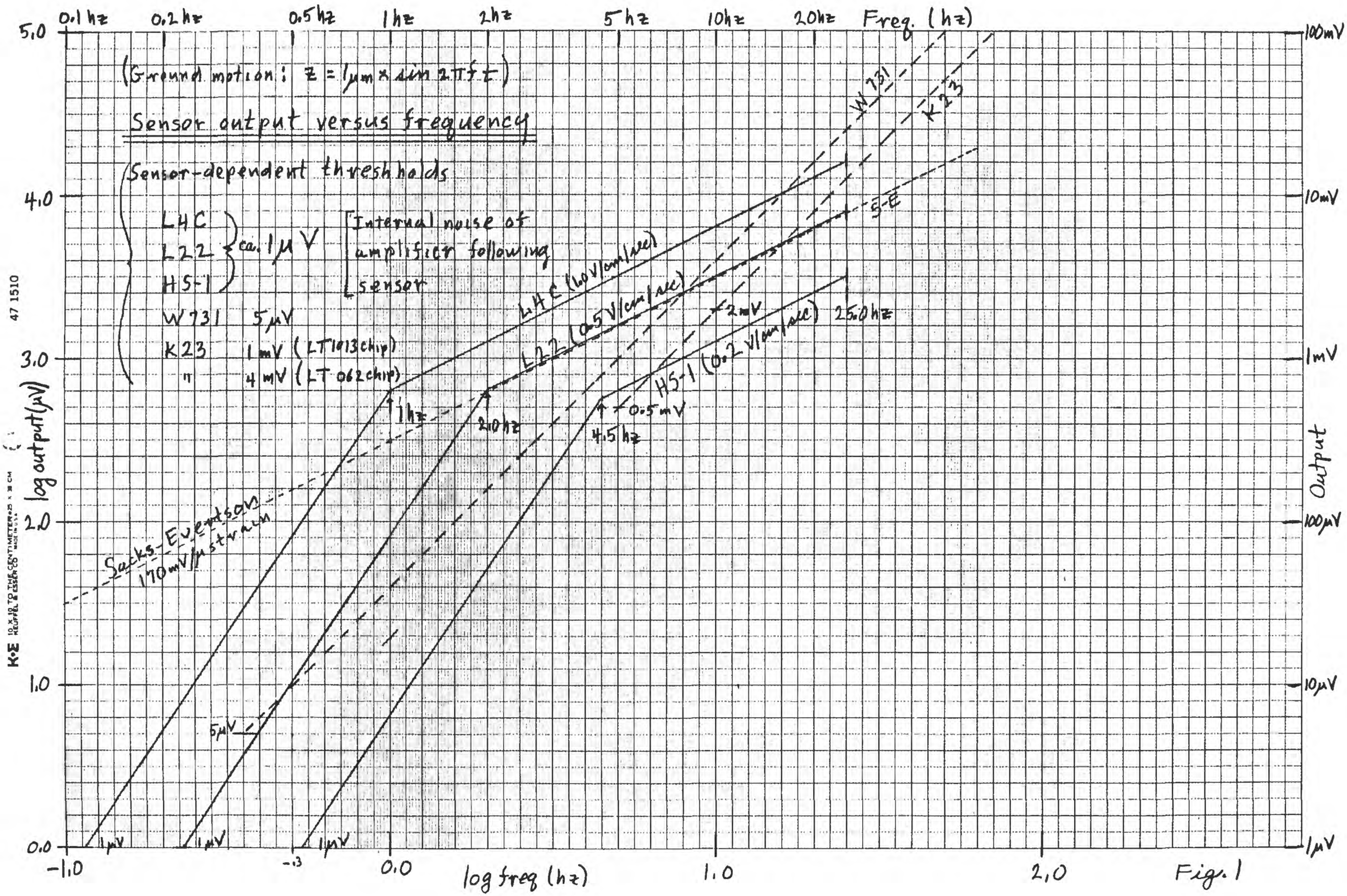
(Ground motion: z = 1μm × sin 2πft)
Sensor output versus frequency
Sensor-dependent threshholds
L4C
L22
HS-1
ca. 1μV
Internal noise of amplifier following sensor
W731 5μV
K23 1mV (LT1013chip)
" 4mV (LT062chip)
L4C (6.0V/cm/sec)
L22 (0.5V/cm/sec)
HS-1 (0.2 V/cm/sec)
1hz
2.0hz
4.5hz
0.5mV
2mV
25.0hz
W731
K23
S-E
Sacks-Evertson 170mV/μstrain
5μV
1μV
1μV
1μV
-.3
log output(μV)
5.0
4.0
3.0
2.0
1.0
0.0
-1.0
0.0
1.0
2.0
log freq (hz)
0.1hz
0.2hz
0.5hz
1hz
2hz
5hz
10hz
20hz
Freq. (hz)
100mV
10mV
1mV
100μV
10μV
1μV
Output
K•E 10 X 10 TO THE CENTIMETER 47 1510

Fig. 1

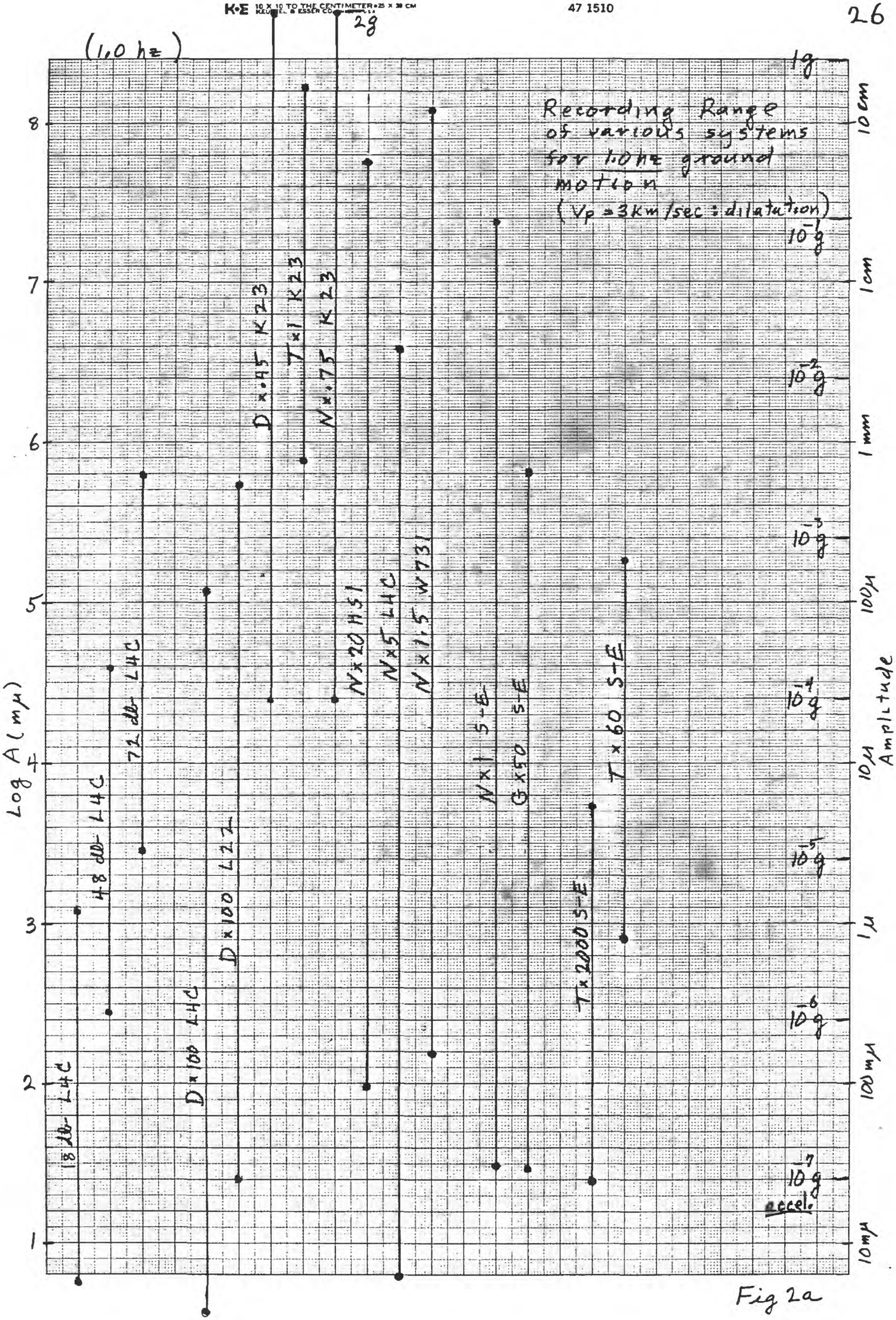
K·E 10 X 10 TO THE CENTIMETER 25 X 38 CM KEUFFEL & ESSER CO.
47 1510
(1,0 hz)
2g
Recording Range of various systems for 1.0hz ground motion (Vp = 3Km/sec : dilatation)
Log A (mμ)
1
2
3
4
5
6
7
8
Amplitude
1g
10 cm
10^{-1}g
1 cm
10^{-2}g
1 mm
10^{-3}g
100μ
10^{-4}g
10μ
10^{-5}g
1μ
10^{-6}g
100 mμ
10^{-7}g
accel.
10 mμ
18 db L4C
48 db L4C
72 db L4C
D×100 L4C
D×100 L22
D×.45 K23
T×1 K23
N×.75 K23
N×20 HS1
N×5 L4C
N×1.5 W731
N×1 S-E
G×50 S-E
T×2000 S-E
T×60 S-E

Fig 2a

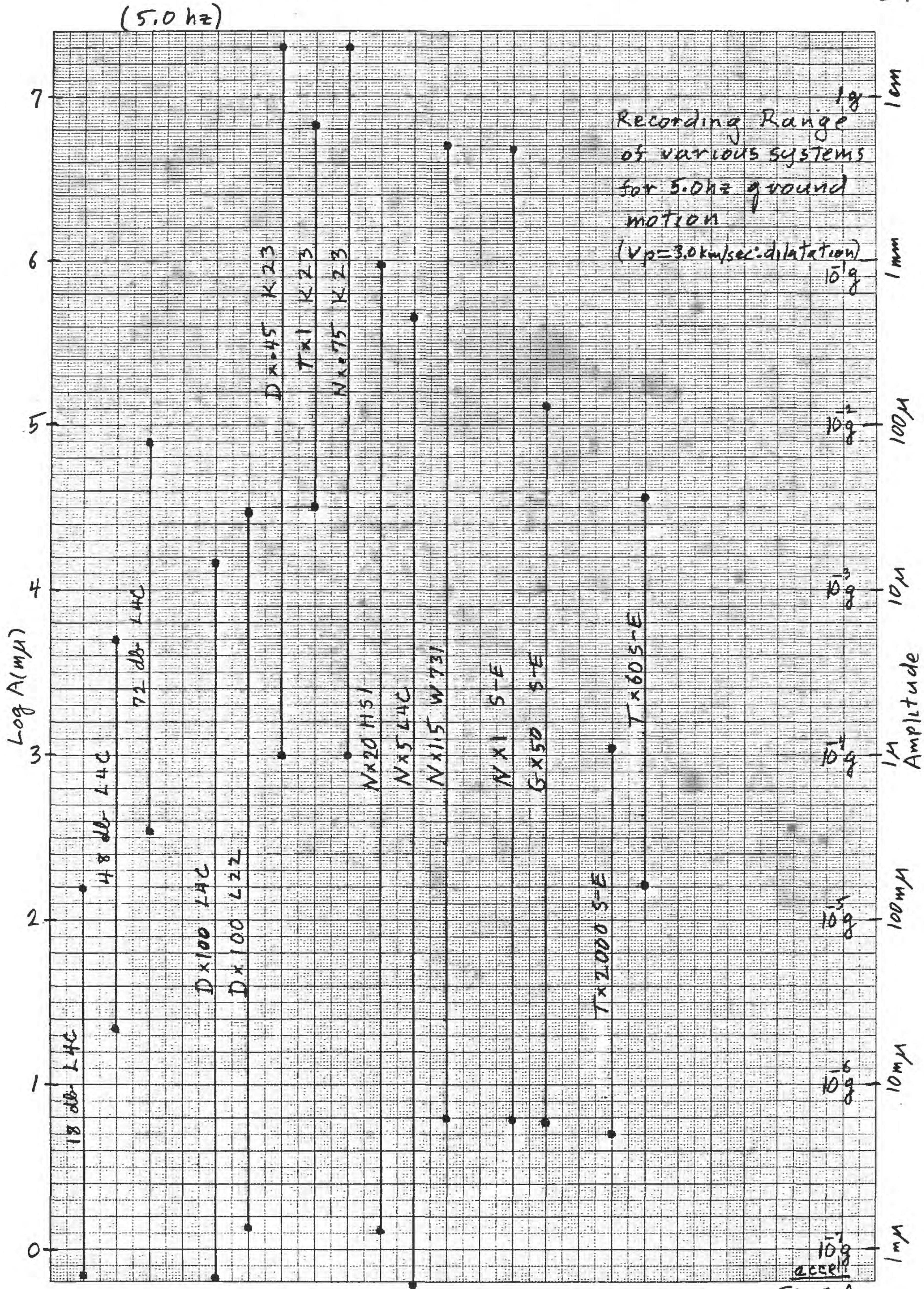
(5.0 hz)
Recording Range of various systems for 5.0hz ground motion (Vp=3.0km/sec: dilatation)
Log A(mμ)
Amplitude
accel.
1g
10^{-1}g
10^{-2}g
10^{-3}g
10^{-4}g
10^{-5}g
10^{-6}g
10^{-7}g
1cm
1mm
100μ
10μ
1μ
100mμ
10mμ
1mμ
18 db L4C
48 db L4C
72 db L4C
D×100 L4C
D×100 L22
D×.45 K23
T×1 K23
N×.75 K23
N×20 HS1
N×5 L4C
N×1.5 W731
N×1 S-E
G×50 S-E
T×2000 S-E
T×60 S-E

Fig 2b

K+E 10 X 10 TO THE CENTIMETER 25 X 38 CM KEUFFEL & ESSER CO. MADE IN U.S.A. 47 1510

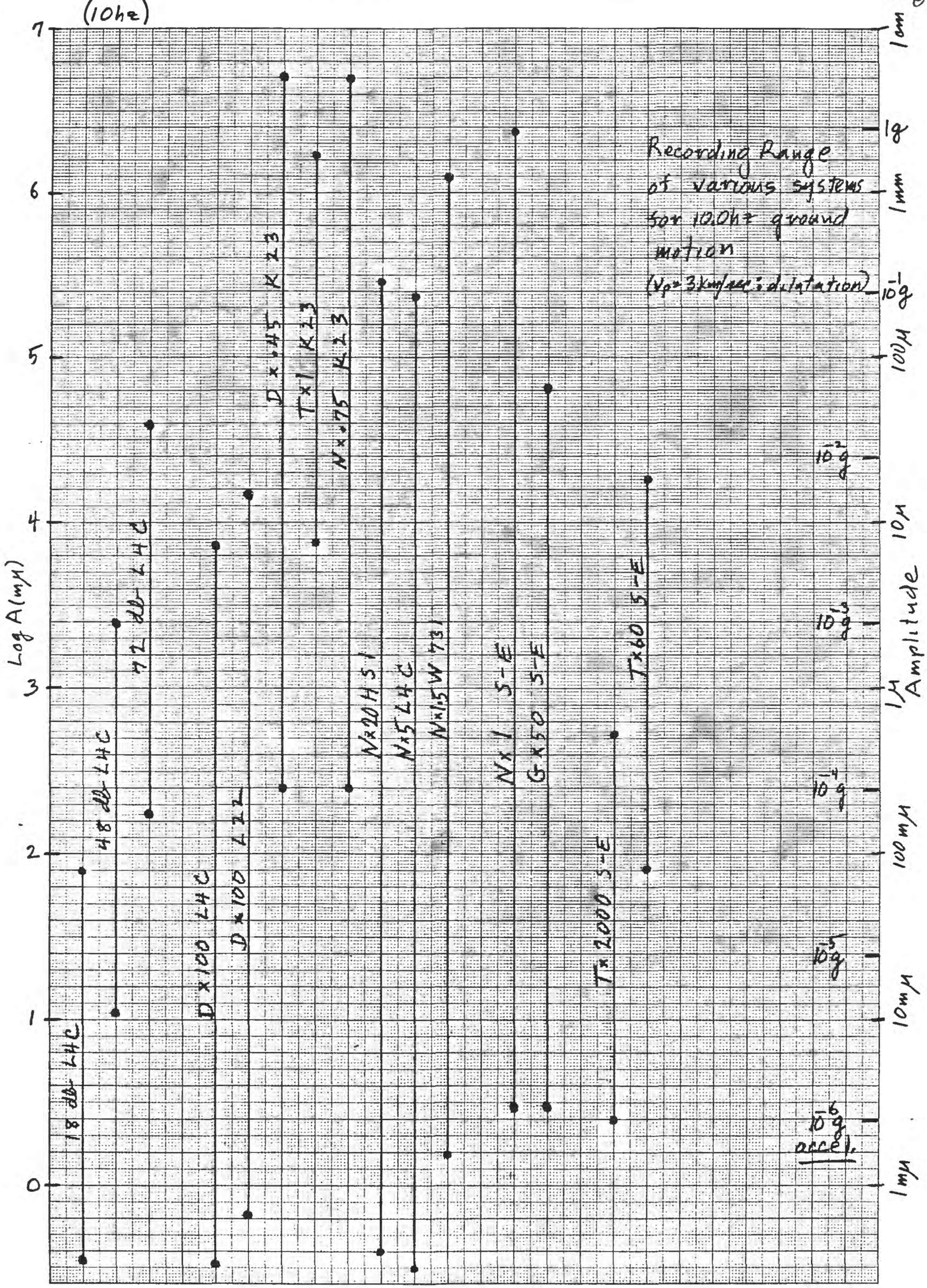

Fig 2C