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A performance review of digital solid state accelerographs vs analog film recording accelerographs

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ABSTRACT: The factors which determine the incremental operating costs for both analog film and digital solid state accelerograph networks are identified. A relationship between the factors is developed with consideration given to earthquake data analysis costs. A method for estimating the data analysis costs for a given network is shown; using well known formulas by Esteva and Dalal. As a gauge against which to measure assumptions made in the authors' analytical cost analysis, the results from a survey of accelerograph network operators familiar with both types of instruments is presented. The most important results from the survey are discussed; including any impact on the network operation and maintenance costs.

1 INTRODUCTION

Little data is available on the maintenance requirements and performance of digital solid state accelerographs vs. analog film recording accelerographs- based upon data gathered from operating networks. This information is of great value to earthquake engineers involved in the design of large strong motion networks or the instrumentation of complex civil structures. Furthermore, the commercial availability of PC compatible flatbed scanners blurs what used to be a clear distinction between these types of accelerographs.

The objective of this paper is to provide earthquake engineers with the real costs and real factors associated with the maintenance and performance of networks employing both types of accelerographs. Although Kinemetrics instruments are discussed in this paper (for obvious reasons), it is expected that the findings are applicable to other manufacturers' instruments with similar specifications.

In addition to data available to the authors, operators of other strong motion networks were given the opportunity to respond to a questionaire, including questions on the following subjects: consumables, maintenance labor time per accelerograph, maintenance interval, test equipment requirements, training, factors affecting data quality and, earthquake data processing time.

1.1 Analog film recorders

The Kinemetrics Model SMA-1 Strong Motion Acclerograph is a film recording instrument. With nearly 8,000 units in service around the world, this instrument has become the standard by which all other accelerographs are compared.

The primary features which characterize the SMA-1 are: triaxial recording, vertical threshold trigger, 55 dB dynamic range (based on 300 dpi scanner digitization), 0.1 to 25 Hz bandwidth, 2494 RAR film media, 70 mm, 25 minute recording capacity (non-expandable), low current drain and proven reliability.

1.2 Digital solid state recorders

The Kinemetrics Model SSA-1 and SSA-2 Strong Motion Acclerographs are solid state recording instruments.

The primary features which characterize the solid state units are: triaxial recording, standard digital threshold trigger voting among the vertical and horizontal channels, 72 dB dynamic range, DC to 50 Hz band-width, solid state static RAM memory, 18 minutes of standard recording capacity expandable to 140+ minutes, pre-event memory and remote interrogation capability.

1.3 Installation and data retrieval hardware

To firmly couple the accelerograph to the structure to be monitored, an anchoring tool or other device is usually required. The anchoring requirement is true for analog and digital instruments. Other considerations for accelerograph installation are the vault or enclosure with pad and pedestal, power source (110/220 Vac, solar, etc.), interconnect cabling for common timing/ triggering for multiple instrument arrays, UTC reference timing source for alignment of data from different sites and, antenna/solar panel mast, as applicable.

The civil work necessary to prepare a site can vary widely. Budget time for the following activities: site selection, site preparation, concrete work, erection of the mast (if any), vault construction or accelerograph hut installation and laying/pulling any interconnect cabling.

Once the civil work is complete, the installation and commissioning should take about 3 hours per accelerograph, including any connector wiring, anchoring of the accelerograph, functional testing and commissioning report with sensor orientation information. The equipment normally used for installation work includes anchor driver, voltmeter, miscellaneous hand-tools and any accelerograph specific special tools (i.e. SMA-1 ground glass alignment screen or FC-1 Field Calibrator).

For the film recorders, a spare take-up magazine and scissors are the only tools required in the field for data retrieval. However, to perform any analysis beyond peak acceleration and strong motion duration the film record must be digitized- preferably with a flatbed scanning device with at least 300 dpi (dots per inch) resolution. The HP Scanjet + with PC Paintbrush IV Plus is such a system. For solid state instruments an IBM PC or 100% IBM compatible lap-top pc is required for data retrieval. Minimum specifications for this instrument are 640 Kbyte RAM memory, 286 processor, 8 MHz, dual 3-1/2" diskette drives.

1.4 Data processing facilities

For film records the data processing facility requires a dark room and sufficient stock of film chemicals. A small area is needed to permit film records to be hung for drying. A film copy should be made of all important earthquake film records. A film archival area and system for film retrieval is necessary.

Whether processing large amounts of data (i.e. digitizing and analyzing film records) or performing extensive calculations (i.e. integrating for velocity and displacement) a fast IBM PC or 100% compatible machine is recommended, such as: 386 processor, 387 coprocessor, 4 Mbytes RAM, 33 MHz, and, an 80 Mbyte hard-disk drive with a fast access time.

2 ACCELEROGRAPH NETWORK COSTS

The purpose of this study is to examine the network operating costs for analog vs. digital solid state accelerographs to see if we could determine the economics of each, and the effect of processing (number of events over the service period) on the total cost. The conclusion is that the processing costs governed by the earthquake recurrence interval in a network does control the total costs, and that a return period of about X# events per year is the crossover point. Above this level (i.e. X + 1 or more events per year) the SSA is more cost effective than the SMA-1 due to processing costs.

The analysis recognized three major cost areas:

$$\textit{Fixed Cost} = NC + H + P + F, \qquad (1)$$

$$\textit{Maintenance Cost} = NY \times (M+S) + T, \qquad (2)$$

$$\textit{Analysis Cost} = NRA = NYA/I_m, \qquad (3)$$

where

N = no. of instruments
Im = recurrence interval, years for magnitude Ml
C = initial instrument cost
H = transcription hardware cost
P = spare parts
F = field retrieval unit initial cost
M = cost of maintenance, per year
S = cost of supplies, per year
A = analysis cost, per record
$ = total cost

Y = years of service
T = Training
R = number of records analyzed

Then

$$\$ = NC + H + P + F + NY(M + S) + NRA, \quad (4)$$

Now

$$I_m^{-1} = (\text{number of events at } M_l)/\text{years}, \quad = (\text{number of records} \bullet M_l)/\text{years}, \quad = R/Y, \quad (5)$$

Then

$$\$ = NC + H + P + F + NY(M + S) + (NYA/I_m), \quad (6)$$

Annualized,

$$\$/Y = (NC + H + P + F)/Y + N(M + S) + (NA)/I_m, \quad (7)$$

Per Instrument

$$\$/(NY) = (NC + H + P + F)/(NY) + M + S + A/I_m, \quad (8)$$

Now from Esteva, 1969,

$$a = (1230e^{0.8M})/(R_h + 25)^2 \quad (9)$$

Where

a = *ground acceleration, cm/sec²*
R_h = *hypocentral distance, km*
M = *Richter magnitude,* M_L

Rearrange and

$$M = \frac{[\ln(a) + 2\ln(R + 25) - \ln(1230)]}{0.8}, \quad (10)$$

for

$$a = 9.8 \text{ cm/sec}^2 \quad (i.e.\ 0.01g)$$

and

$$R_h = 0 \text{ to } 100 \text{ km}$$

then

$$M = 2 \text{ to } 6$$

Assume a return period relationship for this 100 km radius area. For example, for Northern California this relationship is roughly:

Example: from Dalal, $\log_n = 6 - 1 \times M_L$ (11)

Since an ML = 2 event would have to occur

Then for $M_L = 2;\ n = 10{,}000$
and, for $M_L = 6,\ n = 1$
where $n = I^{-1}$

directly beneath the instrument for it to trigger, use ML = 6, or n = 1, or I = 1. This is a realistic value for I for Northern California.

Table 1 presents the data used in these analyses. It should be emphasized that these costs are estimated only, and can vary to a great degree from country to country. In general, the hardware prices are Kinematrics' EXPORT prices and the maintenance costs are based on the authors' Western United States and Mexico experience and information supplied by the respondents to the maintenance survey.

Table 1. Data for network cost calculations

	SMA-1	SSA-1	SSA-2
(C) Instrument Cost	4380(4)	7800	4620
(T) Trnscrptn Hrdwre	8000	0	0
(P) Spare Parts(1)	2190	4560	3890
(F) Field Rtrvl Unit	0	2000	2000
(M) Maint., per year(3)	457	428	419
(S) Consum., per year	67	38	29
(A) Analysis(2)	460	0	0

1. Minimum recommended spare parts.
2. Analysis required to produce digital, equally spaced, uncorrected record.
3. One visit per year. This is incremental cost (see text)
4. Cost includes a spare magazine and case.

The maintenance costs in particular can vary tremendously from network to network. The costs shown are the average incremental costs to add one instrument assuming the infrastructure and service organization already exist to service one more instrument. The reader should keep in mind that there is a minimum organization necessary to operate even a one-instrument network. For example, it would be a mistake to multiply \$457 times 10 for a 10-instrument network and assume that this network can be operated for one year for \$4570; considering the annual cost to employ a qualified technician is US\$25000 per year in addition to overhead expenses (tools, floor space, fringes, etc.). It is true that many organizations already have technicians who could take on the maintenance of one instrument in addition to their other duties without much difficulty. This concept can be extended indefinitely. Network costs can also vary depending on how dense the network is. A technician who can service 400 instruments per year in high-rise buildings in L.A., may only be able to service 75 in a network spread out over a mountainous region. The equipment necessary for such a network would also be more expensive (4-wheel drive, etc.). Finally, costs depend tremendously on the labor costs in each respective country. Therefore, the costs presented should only be used for the purposes of comparison.

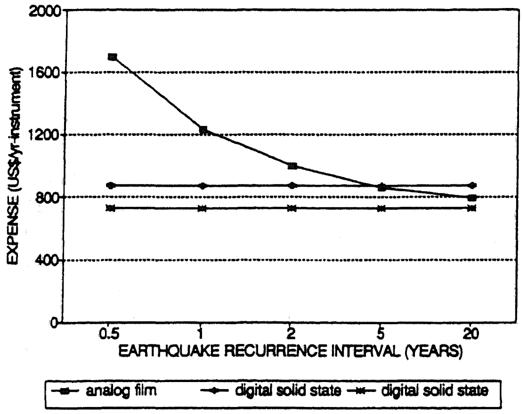

Fig. 1 Incremental accelerograph expense for a 30 instrument network calculated at 5 discrete intervals.

Figure 1 shows the incremental expense per accelerograph for a 30 instrument network at varying earthquake intervals. Figure 2 assumes a 1 year earthquake recurrence interval and presents the economies of scale for various size networks. Each figure illustrates the cost savings in digital instruments for seismically active areas. In comparison with the high end solid state accelerographs, the lower cost of operation advantage shifts to the film recorder at recurrence intervals in the range of 3 to 5 years. However, in comparison with the low cost solid state accelerographs, the lower cost of operation advantage remains with the solid state unit beyond 20 years.

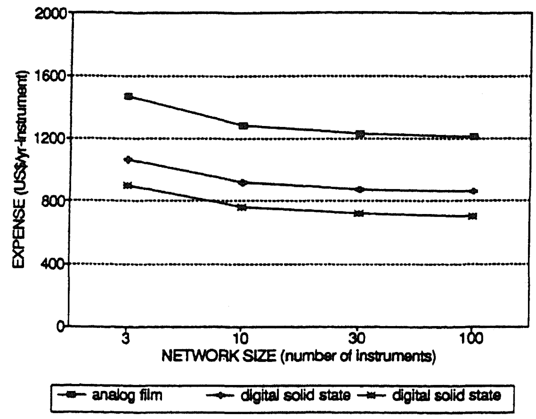

Fig. 2 Incremental accelerograph expense for various network sizes assuming a 1 year earthquake recurrence interval

3 NETWORK OPERATOR SURVEY

In early 1992, a survey was sent to a number of Kinemetrics customers; known by the authors to be operating strong motion accelerograph networks with both analog film and solid state recording type instruments. The intent of the survey was to either confirm or reject the general premises upon which the preceding cost analysis was based.

The requested information included: the type and approximate quantity of instruments operated and maintained, the maintenance activities and intervals, the human and material resources utilized by these operators to sustain the network, and their comparison of the data quality from the film recording and solid state instruments.

The survey responses were compiled to obtain the following "user consensus" information. Where appropriate, the high, low and average values are given. Consensus for subjective information (i.e. "important", "above average", etc.) is based on a simple majority.

Accelerograph Network Types and Sizes Reporting:

Large Networks, (30+ instruments), 5 respondents total. 4 with film and solid state recording instruments. 1 with film recording and non-Kinemetrics digital cassette recording instruments. Medium Sized Networks, (11 - 30 instruments), 1 respondent with solid state and FM cassette recording instruments. Small Networks, (1 - 10 instruments), 0 respondents.

Table 2. Network labor (expressed as a unit of time) for operation, maintenance and, data analysis activities

Survey Parameter	Analog	Digital
Planned site visits per year.	Low: 1	0
	High: 4	4
	Avg: 2.7	2.3
Actual site visits per year.	Low: 1	0.75
	High: 4	4.5
	Avg: 2.5	2.4
Field maintenance time per accelerograph in minutes.	Low: 15	15
	High: 45	150
	Avg: 33	62
Office time recovering and reporting data per accelerograph in minutes	Low: 30	10
	High: 2 days+ 240++	60
	Avg: 170	41

\+ Using X - Y digitizer, not used in determining the avg.
++ Using flatbed scanner

Table 3. The importance of factors affecting data quality.

Analog Film / Digital Solid State
(Very Important, Important, Less Important)

Analog Film High	Low	Consensus	Factor	Digital Solid State High	Low	Consensus
V	V	V	Instrument/sensor specs	V	V	V
V	I	I	Film age			
			Type of storage media	V	V	V
			Storage media condition	V	V	V
V	L	V	Technicians' skills	V	L	I
V	L	L	Instrument Age	I	L	L
I	L	I	General Site Conditions	V	L	I
I	L	I	Maintenance Interval	I	L	I
V	L	I	Spare Parts	V	L	L

Regarding Table 2, the average field maintenance time for digital accelerographs is skewed by the single 150 minute reported time. Setting that response aside, the average time for digital accelerograph maintenance is 41 minutes. The reported 2 days for x-y digitization of film records was not used in obtaining the average time for recovering and reporting analog film data. The reported high/low variance for planned and actual digital accelerograph visits is reflective of the wider range of applications for which the instrument lends itself. One customer, with telephone modem communication, does not appear to plan visits but, rather, visits the site when it is necessary. It is presumed that these instruments are located in highly stable environments. This information is supportive of the authors' cost analysis with respect to the labor costs for processing analog film records.

Individuals who service analog film recording accelerographs are often looked at as "craftsman" for these instruments. Table 3 suggests that solid state accelerographs are less dependent on the skills of the technician for continued operation.

Table 4. Minimum test equipment considered necessary for proper network operation, maintenance and calibration.

Analog	Test Equipment	Digital
(100%)	Digital Voltmeter	(100%)
(50%)	Function Generator	(50%)
(83%)	Oscilloscope	(100%)
(33%)	Counter	(33%)
(50%)	Microscope	
	Laptop PC	(100%)
	EPROM Programmer	(50%)
	Logic Analyzer	(33%)
(83%)	Starter Flexure Kit	
(83%)	FC-1 Field Calibrator	
(50%)	Shake table apparatus	(33%)
(67%)	Tilt table	(67%)
(83%)	Trace alignment kit	
(50%)	Power supply	(67%)
(33%)	Spectrum analyzer	(50%)
(50%)	Voltage calibrator	(50%)
(20%)	UTC receiver and clock	(20%)
	RS232C Breakout Box	(50%)

The authors' are generally in agreement with the user consensus (identified here as items with 50% or above); the exception being the EPROM Programmer. The EPROM Programmer and the Logic Analyzer were intended to act as controls for the survey. The assumption being that anyone identifying these items as necessary for the proper operation, maintenance and calibration of their network either misunderstood the question, the accelerographs or the function of the listed test equipment.

Table 5. Consummable Replacement Interval

	High	Low	Consensus
Analog Film:			
Film	24	12	12 (months)
Batteries	24	12	24
Desiccant	24	6	6
Developer	12	12	12
Digital Solid State:			
Batteries	24	24	24
Desiccant	36	6	6
Diskettes	12	12	12

Table 7. Comparison of General Accelerograph Characteristics

	Consensus
Easier to install	Equal
Higher data quality	Digital
Easier to operate	Digital
Easier to maintain	Digital
More reliable	Digital
Less expensive to operate (labor and consumables)	Digital
Less training required	Analog
Easier to repair	Digital
Easier data analysis	Digital
Easier archivability of data	Digital
Higher integrity archival media	Digital

Based upon Table 5, batteries in analog and digital instruments are being changed every two years. This would have the effect of slightly (i.e. less than 1%) increasing the incremental operational cost estimate for both types of instruments. However, the consensus on film replacement is once every year which further, slightly increases this cost for the analog film instrument. Table 7 is interesting because, up until this point, the comparison between analog film recorders and digital solid state instruments has been primarily focused on cost. Although the consensus was digital solid state instruments for the "More reliable" and "Easier to repair" categories, two respondents (three if the completed survey just received was counted) answered analog; indicating that the survey is not conclusive for these issues.

Respondents were asked to grade (A = excellent...F = fail) the quality of data recovered from their digital solid state units with the following consensus results: Sufficient pre-event and post-event recording to determine noise levels; grade = A. Unsaturated amplitudes throughout the record; grade = A. Proper absolute time to allow correlation of records from different instrument locations; grade = A. Record clean of electronic "glitches" from the A/D converter and/or the data acquisition system; grade = B. Satisfactory retention of the first three features above; grade = B+ (two "A" votes, two "B" votes and two non-votes).

4 CONCLUSION

Digital instruments become cost effective when the earthquake recurrence interval is between 3 to 5 years. As indicated in Figure 2, this is not dependent on network size.

There is no user consenus on the issues of reliability or ease of repair. The digital accelerograph instruments are relatively new to the world. As such, there is inevitably a learning curve which must be overcome before a conclusion can be reached one way or another.

Given the calculated incremental network accelerograph expenses and the issue of reliability, it seems that analog film recording accelerographs still have a niche at low seismicity sites were power supply autonomy and accelerograph robustness are an issue.

The digital accelerographs, as demonstrated by one responding organization, have the potential for increasing the period between on-site maintenance intervals through remote monitoring. More importantly, digital accelerographs are providing higher accuracy data of a consistent quality.

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