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Technical Report: NAVTRADEVCEN IH-186

SEISMIC SCORING SYSTEM FOR AIR-TO-GROUND WEAPONS TRAINING RANGES

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February 1971

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NAVAL TRAINING DEVICE CENTER
ORLANDO, FLORIDA

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ABSTRACT

This report describes a method for scoring air-to-ground missiles and bombs using seismic techniques. By using a many element detector array coupled through an elaborate interface to a small computer, the x-y coordinates of the hit may be rapidly calculated. Feeding this information via radio link to the pilot while pulling out of the dive will provide a closed loop system, allowing him to make the necessary adjustments prior to the following training run.

As is well known, seismic signals attenuate rapidly in the earth. If the detector is far from the projectile impact point, the seismic signal generated by the projectile will be masked by noise from other sources such as the aircraft, wind and microseisms. With the use of a many detector array, the maximum distance between the impact point and near detectors can be designed to provide good signal to noise ratios. The interface equipment will select the detector which receives the first seismic signal. Under computer control, the nearest neighbors will be selected and the outputs from these detectors will be stored in core memory. The primary pulse from the nearest detector will then be correlated with the neighboring signals to obtain the time difference of arrivals. This correlation technique will further enhance the signal to noise ratio of the input data.

After the time differences have been determined, the computer will calculate the x-y coordinates using seismic velocities stored in core memory. By using relatively closely spaced detectors, the tolerance required on the velocities is reduced which considerably reduces the calibration requirements.

A 16 bit, 16K memory computer such as the PDP-11/20 with a multiply time of 4.3 μs is required. The system cost installed is estimated to be $256,090.

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Air-to-Ground weapons training range						
Time correlation technique						
Pulse detection						

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FOR AIR-TO-GROUND WEAPONS TRAINING RANGES

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NOMENCLATURE

α	Attenuation (db)
f	Frequency (Hz)
λ	Wave length (feet)
r	Source to detector distance (feet)
s	Seconds
t	Time (seconds)
v	Seismic velocity (feet per second)

BACKGROUND

A report[1] "Device X3B57 Feasibility Demonstration, Report" by Melpar, Inc., August 1968, describes work on a seismic scoring technique for air-to-ground bombs and missiles. The scoring accuracy objectives for this device were:

Radial Range	± 10 feet	0 range 100 feet
	± 10%	100 range 3000 feet
Azimuth	No Spec	0 range 20 feet
	± 30°	20 range 100 feet
	± 15°	100 range 3000 feet

Melpar used three geophones (velocity detectors) spaced at 120° intervals with radii of 250, 500, 1000, 2000 and 3000 feet for the various tests. The target center corresponded to the center of the three geophone arrays for each test. The instrumentation consisted of amplifiers, level detectors and counters. The seismic signal (voltage) from the geophone was amplified and fed to the level detectors. If the signal from a first geophone exceeded a preset level, the counter was initiated. A signal from a second geophone exceeding the preset level stopped the counter. The contents of the counter then contained the time difference between seismic arrivals at the first and second geophones. In a similar manner, a second counter measured the time interval between the first and third geophone. The time differences were then used in a computation program at the home office to calculate the x-y coordinates of the hit. A Honeywell DDP 224 having a multiply time of about 300 microseconds could perform the calculation in less than one second.

The earth is an inhomogeneous anisotropic medium which causes seismic velocity variations both in azimuth and range for horizontally traveling waves. Lateral as well as vertical velocity variations are caused by density changes in the earth.

The velocity of longitudinal waves in solids[2] is given by

$$C = \frac{B + \frac{4}{3} G}{\rho_0} \qquad (1)$$

Where B and G are respectively the bulk and shear modulus of the solid and ρ_0 its density. As the depth increases, the earth usually changes from a loose unconsolidated weathered layer to more consolidated materials. In

(1) Alderson, W.S., M. Butler, Hagan, T.W. and Wavering, A.J., "Device X3B57 Feasibility Demonstration Report" Technical Report: NAVTRADEVCEN 67-C-0202-1.
(2) Kinsler, Lawrence E. and Frey, Austic R., "Fundamentals of Acoustics". John Wiley and Sons, Inc., New York (1966).

these cases, the velocity increases with depth. As illustrated in Figure 1, the velocity of a first arrival will increase as the source to detector distance increases.

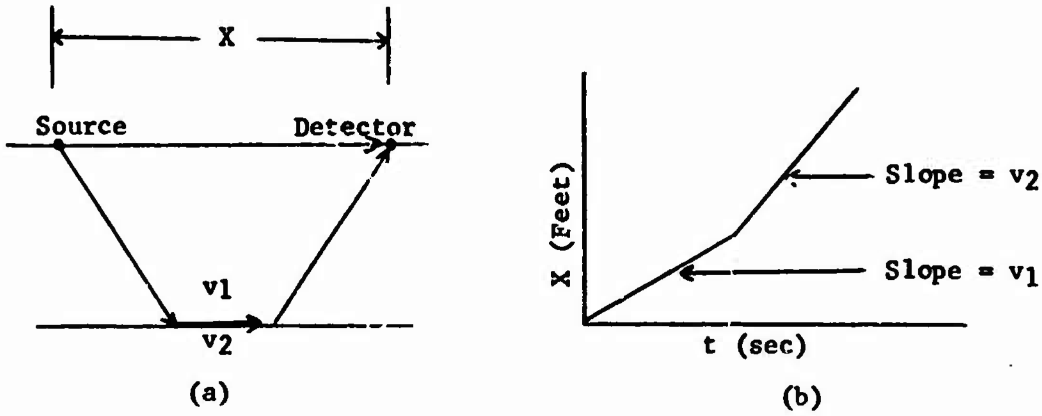

Figure 1. (a) Section of earth showing two velocity layers (b) Source to detector spacing as a function of initial pulse arrival time, $v_2 > v_1$

Usually, the density increase is gradual near the surface so the velocity is a gradual increase with distance rather than a step as illustrated in Figure 1.

Near surface vatiations such as large boulders, rock outcrops and river or stream beds will also cause lateral velocity variations. So in addition to the variations as depicted in Figure 1, we may also have variations depending on azimuth due to these lateral velocity variations. Because of these velocity variations, the range must be calibrated. Melpar used an average of 37 calibration shots for each three-geophone patterns for the calibration data. Using this data, good results were obtained using fixed dynamite charges on the surface as test shots.

Although the test shots produced good results, very poor results were obtained using bombs and rockets as the seismic sources. The reasons for failure were basically poor detection and low signal to noise ratios. No satisfactory results at all were obtained with the A-6 aircraft and many of the drops using the A-4 aircraft produced bad results. Methods of overcoming these problems will now be described.

APPROACH

Geophone Array:

Seismic signals attenuate at the rate of 0.3 to 16 db per wavelength[3] depending on the media. This attenuation is in addition to the decay due to

(3) White, J. E. "Seismic Waves: Radiation Transmission, and Attenuation". McGraw Hill, New York (1965).

spherical spreading which is inversely proportional to the radius. As an example, consider a hit 10 feet from a first detector and 500 feet from a second detector. Assuming a wavelength of 100 feet (f = 50 Hz and V = 5000 feet/sec), and an attenuation of 6 db per wavelength, the signals at the detectors have an amplitude ratio of 30 db due to attenuation alone and an additional 34 db due to spreading or a total ratio of 64 db (3,170:1). It is also apparent from the above that the attenuation goes proportional to frequency. As the distance increases, the received signal has a proportionally smaller high frequency content.

For purposes of illustration, let us assume a unit step (U (t))input to the earth and determine the response at some remote station. The earth acts like a low-pass dilter whose cut-off frequency is determined as follows. We begin with

$$\lambda f = v \qquad (2)$$

The attenuation is 6 db at $r = \lambda$

From Equation 2 we have

$$f_1 = \frac{v}{r} \qquad (3)$$

where f_1 is the frequency corresponding to 6 db attenuation. Plotting the attenuation (2) versus frequency on a log-log plot results in a graph as shown in Figure 2.

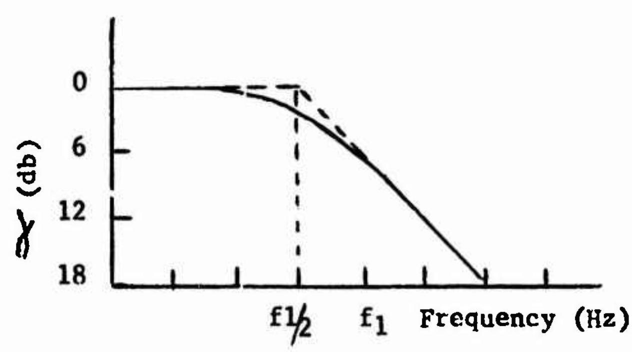

Figure 2. Attenuation vs Frequency for earth naving 6 db per wavelength attenuation

In terms of electrical engineering, the earth acts like a R-C coupling network as shown in Figure 3.

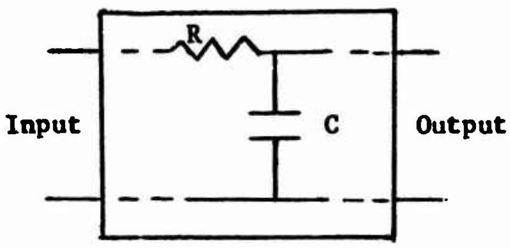

Figure 3. An electrical circuit whose transfer function is equivalent to the earth response shown in Figure 2

The cut-off frequency corresponding to $\frac{f1}{2}$ is given by

$$\frac{f1}{2} = \frac{1}{2\pi RC} \tag{4}$$

Applying a unit step to the circuit of Figure 3 results in an exponential output (f(t)) as shown in Figure 4.

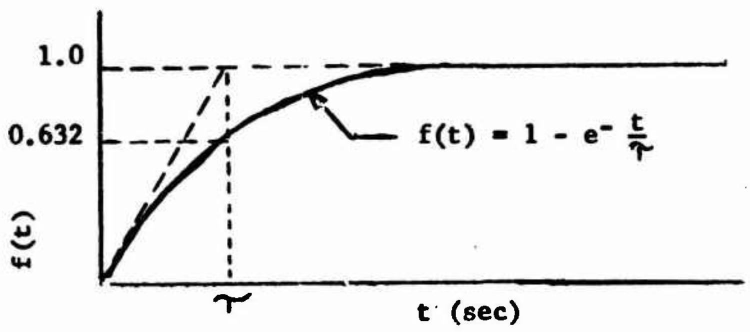

Figure 4. Response of the circuit shown in Figure 3 to a unit step input

where $\tau = RC$ (5)

Using Equations (3) and (4) in Equation (5) gives

$$\tau = \frac{r}{\pi v} \tag{6}$$

From these results, it is clear that the rise time (τ) of the detected signal is directly proportional to thr source-dectector separation. The certainty with which an on-set time of a signal can be measured is proportional to the rise time (τ). For these reasons, the detectors should be closely spaced. As an example, assume again r = 100 ft and v = 5000 f/s then

$$\tau = \frac{100}{5000\pi} = 6.7 \text{ ms}$$

At 5000 f/s, one ms corresponds to five feet. For a 10 foot error we are only allowed 2 ms error in time at this velocity.

Compensating networks can be designed into the input amplifiers which will partially compensate for this high-frequency attenuation. In practice, the amount of compensation is limited by signal to noise considerations. Amplifiers are usually not compensated for frequencies higher than 200 Hz in conventional seismic work.

We shall now consider the errors in distance (ΔX) due to errors in velocity. Consider a source placed at X where X is the distance from the center of two detectors as shown in Figure 5.

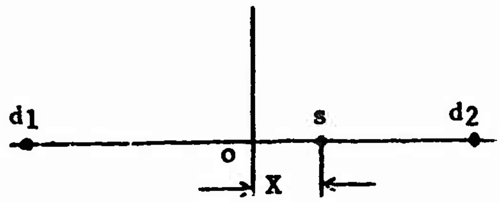

Figure 5. Seismic source placed on a line connecting two detectors

The time difference of seismic arrivals is given by

$$\Delta t = \frac{2X}{v} \tag{7}$$

If a pertubation (Δv) is placed on v, then the corresponding change in X is given by

$$2(X + \Delta X) = \Delta t \ (v + \Delta v) \tag{8}$$

substituting Equation (7) into Equation (8) and simplifying results in

$$\frac{\Delta X}{X} = \frac{\Delta v}{v} \tag{9}$$

These results are shown in Figure 6 for a $\pm$ 20% velocity error.

This further justifies a close detector spacing (for small errors, we need a small X). If the detector spacing is 100 feet (X max = 50 feet), then we will have a $\pm$ 10 feet error for a $\pm$ 20% error in velocity. As the radial distance increases, the radial range spec becomes larger (measured in feet), so the detectors can be placed further apart and less velocity calibration will be required. At a 1000 feet radial range and using a 500 feet detector spacing, the radial range spec (± 100 feet) will be met if the velocity is known to within ± 40%. It is anticipated that very little velocity calibration will be required for radial ranges greater than 1000 feet if a maximum detector spacing of 500 feet is maintained.

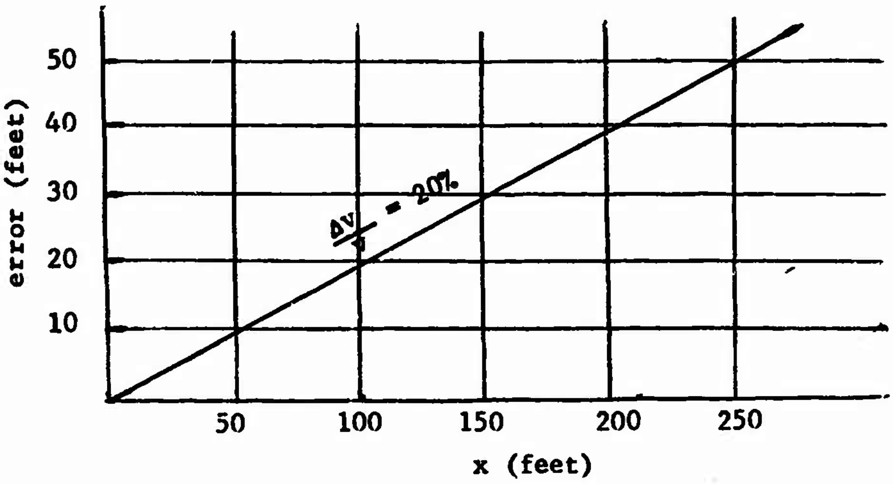

Figure 6. Error vs distance of source from midpoint between two detectors for 20% velocity error

The maximum detector spacing is limited by signal to noise considerations. As was illustrated earlier, the signal decays rapidly with source to detector spacing. The noise due to wind, microseisms, trees, rain and other acts of nature is independent of source to detector spacing. The aircraft noise (which will most likely be the largest noise encountered and is a function of the source position) attenuates(2) at the rate of 10^{-6} db/meter at 100 Hz. For an altitude of 1000 meters, the attenuation is only 10^{-3} db which is negligible. Of course, we have the spherical spreading which goes inversely with the radial distance from the aircraft to the detector. If the aircraft in 1000 feet over a first detector, and a second detector is 1000 feet from the first detector, then the difference in noise amplitude is only 3 db which is very small compared to the seismic signal decay over a 1000 feet distance. We can conclude for small detector spacings (less than 1000 feet) that the noise is essentially constant.

Based on the foregoing calculations, the signal amplitudes due to bomb and rocket drops and the aircraft noise amplitudes, the minimum detector spacing (for a 16% velocity variation) should be 125 feet. The spacing can be increased proportional to radial range until the signal-noise becomes the predominate factor at 500 feet (as indicated by the Melpar data). The maximum detector spacing should then be maintained at 500 feet for the radial range of 500-3000 feet. Figure 7 illustrates one possible array having symmetrical triangular patterns and containing 175 geophones.

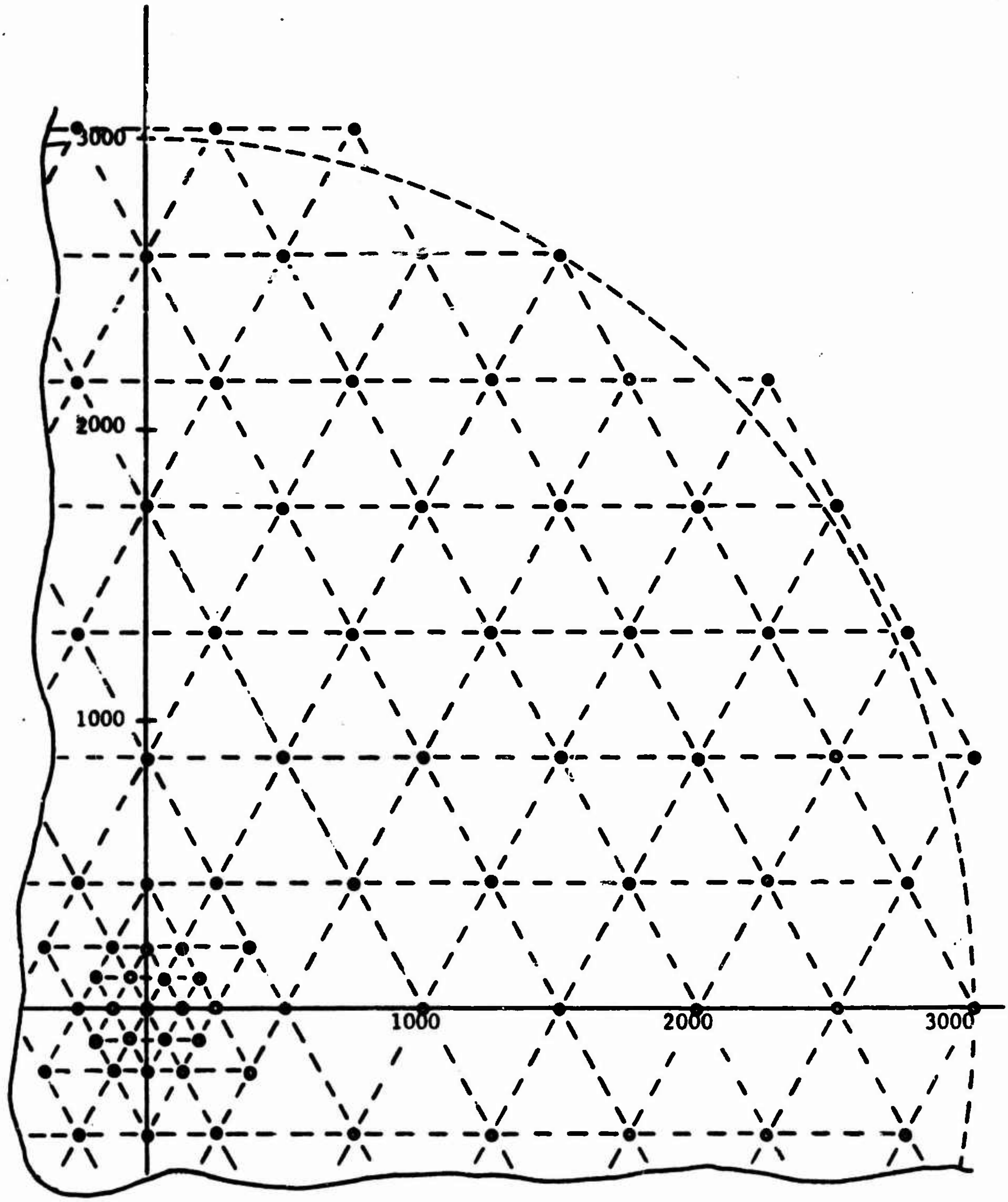

Figure 7. Geophone array pattern based on equiangular triangles and containing 175 detectors

Detectors, Amplifiers and Interface

Velocity sensitive detectors are normally used for seismic work. These devices consist of a coil of wire suspended by springs in a magnetic field. The velocity of the earth is imparted to the geophone case. At frequencies above the resonant frequency of the suspended coil-spring system, the coil remains stationary while the magnet (attached to the case) moves due to the velocity of the earth. This movement between magnet and coil induces a voltage in the coil proportional to the relative velocity. The geophone has a lower cut-off frequency depending upon the mass of the coil suspension and the spring constants. The geophone can be placed on the earth's surface or preferably buried for better coupling and greater isolation from noises associated with air movements. The coupling between the geophone case and the earth also has a cut-off frequency but this is a high frequency cut-off. This cut-off occurs in the neighborhood of 500 Hz ($\pm$ 200 Hz) depending upon the mass of the case and the type of earth. The sensitivity of conventional geophones is about 1 volt/inch/second, the size varies from about 1 cubic inch to 27 cubic inches and the cost is around $10 depending on size and quantity. The lower resonant frequency geophones have softer springs and are therefore less rugged than the higher frequency geophones. For the seismic scoring system, the geophones should be buried at a depth sufficient to prevent damage from the drops. The geophones are connected to the amplifiers with hard wiring which should also be buried. These burial depths can be readily determined by measuring the penetration depth of test drops.

A wave which only travels near the surface was first described by Lord Raleigh[4]. This is commonly called "ground roll" by geophysicists and is similar to an ocean wave. This unwanted wave has a much smaller velocity than compressional waves and is generally quite low (5-10 Hz) in frequency compared to signals of interest. The Raleigh wave can be reduced by using geophones with a resonant frequency of 18-30 Hz and additional low cut filtering in the amplifier. Melpar used 4.5 Hz geophones which caused the ground roll to be very noticeable on their test data. Geophones must also be electrically damped to reduce the resonant peak of the spring-coil suspension and thus provide a flat response of voltage vs frequency.

It would be well at this point to consider the effects of the long line (6000 feet) between the far geophones and the instruments. A number 22 AWG wire has a total resistance of 194 ohms for 12,000 feet. Usual geophone impedances are 500 ohms. Considering a matched load of 500 ohms, inserting the wire resistance would reduce the voltage at the amplifier input by only 16% which can be easily compensated. The capacitance of a two wire line with 1/32 inch insulation (22 AWG, 6000 feet long) is $0.0235 \mu f$. The inductance of this line is 0.81 mH. These values result in RC and L/R time constants of $28 \mu s$ and $0.68 \mu s$ respectively, which are negligible at the frequencies of interest (a few hundred Hz). Marine seismic cables of 9000 feet lengths are quite commonly used in oil exploration work with pressure sensitive hydrophones and instruments having 500 ohm load impedances.

(4) Raleigh, Lord, "On Waves Propagated Along the Plane Surface of an Elastic Solid", Proceedings of London Mathematical Society, 17(1885)4.

The signals from the drops recorded by Melpar were about 500μvolts at the geophone which had a sensitivity of 1.5 volts/inch/second. These were recorded with gains of 54 to 66 db which caused most of the oscillograph displays to overload at output levels above $\pm$ 0.5 volts. Since the correlation is a linear process, we need linear signals for optimum results. Therefore the maximum gain (with $\pm$5 volt maximum output) should be about 50 db. This would put the minimum expected signal 30 db below maximum. If a near geophone has an output 60 db above the far geophone, then the amplifier would overload. For this reason, a second output tap with a gain of say 20db is desirable since we will have no apriori knowledge of the signal amplitude. By burying the geophones at a depth of 5 feet (maximum ratio of radii is then 100) and using frequency compensation in the amplifiers, the maximum signal ratios for a near and far geophone should be limited to 60 db.

Input transformers should be used between the geophones and amplifiers. This helps to eliminate 60 Hz interference from the power lines, makes line leakage less of a problem in field usage and impedance matches the geophone to the amplifier.

Two outputs for each of the 175 geophones will require 358 analog multiplexer channels. A tremendous amount of analog to digital converter equipment and computer storage would be required to process all 358 channels. To overcome this obstacle, the number of channels to be processed can be reduced to 7 by incorporating some the channel selection in the interface equipment as follows:

As previously described, the initial rise on the seismic pulse contains high frequencies as compared to the noise and remainder of the input signal. By providing a high frequency filter for one of the outputs for each geophone, the initial rise of the drop signal can be sensed. The nearest detector to the drop point will receive the first and largest signal. By detecting this first arrival signal, the computer can then select the nearest neighbors. The analog signals from the nearest detector and its neighbors will then be converted to digital numbers and stored in core memory. After a sufficient time (say 200 ms) has elapsed to ensure that all signals are in core-memory, the signals will be normalized and the largest non-overloaded output from each amplifier selected. The initial pulse (which is similar to one cycle of a sine wave) from the nearest detector will then be correlated with its neighbors to achieve the time of arrivals for each neighboring channel. It should be pointed out at this time that the initial pulse will broaden as the distance from source to detector increases. The attenuation of higher frequencies discussed earlier is one contributing factor to this broadening. A second factor is due to reflections and refractions. This is depicted in Figure 8 as the primary initial pulse is added to a reflected initial pulse to give a broadened resultant pulse. This broadening will result in a greater delay in the measured time of arrival. This will be partially compensated by the usual increase in seismic velocity with source to detector distance as discussed earlier (See Figure 1). Proper velocity calibration will take these broadening and velocity variation effects into consideration to give final results within specifications.

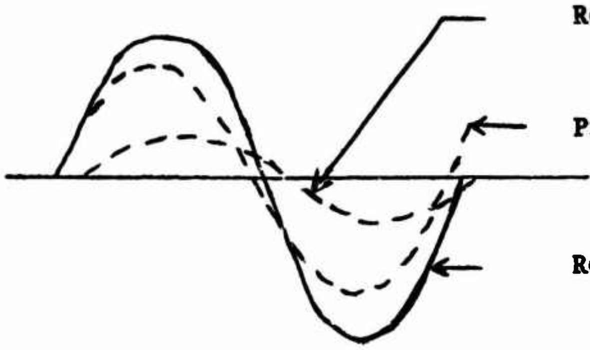

Figure 8. Addition of a primary pulse and reflected pulse to produce a resultant broadened pulse

Computer

The requirements demand a computer capable of storing the pre-determined data such as detector site coordinates, nearest neighbors and calibration velocities, performing the correlations and computing the x, y coordinates of the drop. Speed requirements demand that the entire computation be completed within one or two seconds. First, the memory requirements will be estimated. Until the programs are completed for the actual computer to be used, the exact amount of memory required cannot be determined. The major requirements are listed in Table 1.

Table 1. Memory Requirements

Store site numbers (for nearest neighbor)	1200
Store site x,y	400
Store site velocities	800
Store signal data (7 x 250)	1750
Store correlation (6 x 200)	1200
Square Root Subroutine	100
Main Program	5000
	10,450

A 16,000 word (16K) core memory will provide a 50% safety margin over the above estimate and should be made available for the prototype model. This can possibly be cut some on production models.

Second, the speed requirements will be considered. The correlation of a function f(t) with a second function g(t) is defined as follows:

$$P(t) = \int_{-\infty}^{\infty} f(\tau)\, g(t+\tau)\, d\tau \qquad (10)$$

If the functions are sampled, then the correlation is accomplished as

$$P(t_i) = \Delta t \sum_{n=-} f(n\,\Delta t)\, g(ti + \Delta t) \qquad (11)$$

where

$$\Delta t = t_{i+i} - t_i \qquad (12)$$

Let us assume a 1 ms (Δt = 1 ms) sampling rate. If f(t) is one cycle of a 20 Hz sine wave, then we will have 49 sample points (all others will be zero). With a maximum 500 feet detector spacing and a minimum 2500 feet per second velocity, it is possible to have a 200 ms time difference of arrivals. Therefore g(t) must be 250 ms (251 sample points). This requires 49 x 201 = 9849 multiplications and 48 x 200 = 9648 summations. These operations will require an average of 472 ms for each of the six correlations (2.83 seconds total) using a PDP-8/E (12 bit machine) with extended arithmetic (hardware multiply) option. This computer requires an average of 48 μs to multiply two signed numbers and add the product to a third number. One method for reducing this time is to sample at a 2 ms rate. This cuts the operator and the data points each by 1/2 and will reduce the time by 1/4 for a total correlation time of about 708ms. The correlation function should then be fitted to a parabola (near the peak) and the maximum of the parabola used for the time as 2 ms corresponds to 10 feet with a 5000 fPS velocity. This 2 ms uncertainty would result in excessive error without a smooth fit for interpolation purposes.

A PDP-11 (a 16 bit machine released early this year) can multiply two signed numbers and add the product to a third number in only 6.6 μs. This machine could perform a single correlation (9849 multiplications and 9648 additions using 1 ms sampling) in 65 ms which results in a correlation time for all six data sets of 390 ms.

Since Melpar could compute the position of the drop (given the arrival time differences for a 3 detector array) in less than one second using a computer with a 300 μs multiply time, the PDP 8/E with 48 μs multiply time should perform this portion of the computation in less than 200 ms. The PDP-11 with 4.3 μs multiply time should perform this portion of the computation in less than 100 ms.

Based on the above data, a PDP 8/E computer with extended arithmetic could produce the solution in less than four seconds from drop impact using one millisecond sampling periods or in less than two seconds using two millisecond sampling periods. The PDP-11 computer with extended arithmetic could produce the solution in less than one second using 1 ms sampling.

Third, the word size of the computer with regard to number of bits will be considered. The most common word sizes for minicomputers are 8, 12 and 16 bits. We will be working towards 10% accuracy. Since $2^8 = 256$, $2^{12} = 4096$ and $2^{16} = 65{,}536$ and we wish solutions within 10 feet for a 6000 feet range, then it is clear that an 8 bit machine could only have a precision of 6000/256 = 24 feet which is too large. The 12 bit machine could be precise to within 2 feet which falls within the minimum 10 foot accuracy spec. The 16 bit machine could be precise to within 0.1 feet which is much better than the accuracy required and would allow more margin for error in the velocity calibration and time of arrival determination.

At the present time, there are a considerable number of 16 bit minicomputers on the market and a few 12 bit machines. By far the most popular 12 bit machine is the PDP-8 family. Because of the large usage, much software is available. In addition to the large software availability, many pieces of peripheral and interface (as well as logic components for those who wish to do their own interfacing) equipment are also available. A visit was made to the Navy Underwater Sound Reference Laboratory here in Orlando which has two PDP-8 computers (a 2.5 year old PDP-8 and an 8 month old PDP-8/I). They are well pleased with these machines. The latest version, which will be on the market later this year, is the PDP-8/E which will also use the same software and peripheral equipment as other PDP-8 models but is approximately 20% faster than the PDP-8/I and 40% less expensive.

As mentioned previously, the PDP-11 was introduced earlier this year (March). It has a large instruction set (400) which simplifies programming. A priority level interrupt allows data from peripheral equipment to interrupt the program. A "Unibus" system is incorporated which simplifies connections and interfacing to peripheral equipment. All peripheral equipment are connected through the "Unibus". Data from peripheral equipment such as the analog-digital converter can be read directly into core memory (by-passing central processor registers) which further reduces the overall computation time. Because of the many advantages of the PDP-11, its added margin of safety in both speed and accuracy over the PDP-8, a system cost estimate will be made using the PDP-11 as the computer element, Table 2. For additional units, the cost would be reduced by the design and development costs with some additional reductions in other unit costs because of mass production. These figures could best be determined after the first unit is completed. It should be pointed out also that the price is for a unit installed and operating on a range.

CONCLUSION

A scoring system using seismic methods and meeting the earlier described specifications is feasible with state of the art techniques and hardware components.

RECOMMENDATIONS

Based on the foregoing analytical study and cost analysis, experimental field data should be taken using the maximum and minimum recommended detector spacings. The data should be recorded in a linear manner using a wide-band recording system. The data should then be used to verify the

Table 2. System Cost Estimate

Computer Components

Quantity			
1	-	PDP-11/20 with 4K memory and teletypewriter, rack mounted	$ 11,450
1	-	Additional 12K memory	10,500
1	-	Real time clock	950
1	-	Extended arithmetic element	2,250
1	-	High speed paper tape reader/punch	3,900
			$ 29,050

Multiplexer - Analog/Digital Converter

1	-	ADC-1 A/D Converter	$ 3,200
1	-	AM08 Multiplexer control	2,500
3	-	AM02A Multiplexer chassis (128 channels each)	6,600
96	-	A122 Multiplexer cards (4 channels each)	6,240
1	-	Rack Cabling	1,000
			$ 19,540

Miscellaneous

1	-	Interface unit	$ 10,000
200	-	Input amplifiers ($200 each)	40,000
1	-	Wire (1,000,000 feet at 3 cents/foot)	30,000
200	-	Detectors ($10 each)	2,000
1	-	Output device	5,000
1	-	Labor (wire and detector burial 46,000 feet at 33 cents/foot)	15,500
1	-	Van type truck	5,000
1	-	Engineering, Design, Development and Velocity Calibration	100,000
			$207,500
		Total	$256,090

results of the study as well as providing input data for computing miss distances on an in-house computer. Correlation methods and time domain digital filtering should be used to enhance the signal to noise ratio of the experimental data. The miss distances thus computed should be compared with the visually observed coordinates of the drop. A successful completion of this phase of the work will insure a high probability of success during the following phases.

Using the techniques and methods derived from the above study, a real-time system should be designed and fabricated. This system should then be used on a small target area to confirm the feasibility of a full scale real-time system. The system used here should use the basic components such as computer and A/D converter of a full scale system, but only sufficient detectors and amplifiers for a small target area.

Upon satisfactory completion of the feasibility study, a full scale prototype model should then be designed, manufactured and field tested.