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Nevada Test Site Seismic- Telemetry Measurements

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NEVADA TEST SITE SEISMIC-TELEMETRY MEASUREMENTS

by

James N. Albright, Larry E. Parker, and Everett H. Horton

ABSTRACT

The feasibility and limitations of surface-to-tunnel seismic telemetry at the Nevada Test Site were explored through field measurements using current technology. Range functions for signaling were determined through analysis of monofrequency seismic signals injected into the earth at various sites as far as 70 km (43 mi) from installations of seismometers in the G-Tunnel complex of Rainier Mesa.

Transmitted signal power at 16, 24, and 32 Hz was measured at two locations in G-Tunnel separated by 670 m (2200 ft). Transmissions from 58 surface sites distributed primarily along three azimuths from G-Tunnel were studied. Transmitted signal power was highly variable from site to site at comparable ranges, with the signal power of the detected transmissions varying by as much as 20 dB. The maximum range for detection of transmissions was only exceeded for 24 and 32 Hz. A statistically significant range function for signal power was measured for the 16-Hz transmissions.

The G-Tunnel noise environment was monitored over the 20-day duration of the field tests. Noise-power probability functions were calculated for 20-s and 280-s seismic-record populations. The probability function for the 20-s record population showed a contribution to G-Tunnel noise from vehicular traffic on the roads surrounding Rainier Mesa within 1.6 km (1 mi) of the seismometer installations. Noise at the two G-Tunnel seismometer locations was comparable even though the signal power of detected transmissions was often greatly different.

Signaling rates were calculated for signals transmitted from superior transmitter sites to G-Tunnel. A detection threshold of 13 dB re 1 nm^2 displacement power at 95% reliability was demanded. The dependence of signaling rate R (bits/s) on range D (km) at each transmission frequency is closely approximated by a function of the form $\log R = A - 3.37 \log D$ where A is a constant, which is different for each transmission frequency. Evaluation of B at 10 km for each frequency shows that signaling rate rapidly increases with decreasing frequency. The signaling rate at 10 km is 0.3, 0.2, and 0.05 bits/s at 16, 24, and 32 Hz, respectively. Extrapolation of the signaling rate at 10 km to lower frequency indicates that a rate potentially greater than 1 bits/s is possible for lower transmission frequencies still within the range of current servo-hydraulic vibrator technology.

Consideration of field results suggests that even for the frequency range used in this study, substantially higher signaling rates are likely to be obtained in future work in view of the present lack of information relevant to hardware-siting criteria and the seismic propagation paths at the Nevada Test Site.

I. INTRODUCTION

During a study of the ICBM deep basing option, the USAF Ballistic Missile Office directed attention towards determining the feasibility of alternate means for through-the-earth communications. Feasibility of the modes of communication under consideration was to be established only to the extent permitted by existing technology and current engineering practice. Because of time constraints for the decision making in progress, neither research nor development activities could be undertaken. Los Alamos was selected to explore the potential for use of mechanically generated seismic waves in surface-to-tunnel communications through a case study of the feasibility of seismic telemetry at the Nevada Test Site (NTS). In pursuit of this goal, Los Alamos undertook a program of field measurements using commercially available hardware to measure the range dependence of signal power and signaling rate for constant-frequency (CF) signals transmitted from surface sites to tunnel-based receivers. A precondition to the calculation of signaling rate, a derived parameter, was the statistical characterization of the seismic-noise environment seen at the sensors. In addition, under subcontract, the University of Texas at Dallas (UTD) made conventional seismic-refraction measurements for the purposes of (i) determining the propagation path for the transmissions, and (ii) acquiring broadband seismic data (Ward 1983). Only the latter objective of the UTD work was realized.

For both operational and technical reasons, the NTS and bordering Nellis AFB afforded an attractive location for seismic-telemetry measurements. The existence of tunnel complexes, of sufficient land under federal jurisdiction, of Los Alamos and Sandia National Laboratories' field-support offices, and of mobile radio communications facilitated operations relative to alternative sites. Rainier Mesa, the location of the tunnel complex selected for the installation of seismic receivers, was the generic equivalent in geology (Danilchik 1967; Ege and Lee 1971) of one class of the several deep-base sites under consideration. The nature and complexity of the local and regional

geologic structure (Cornwall 1954) represented a potential worst case environment for seismic telemetry: the exposed rock and soil cover at the NTS is highly variable; the rocks comprising Rainier Mesa (Ege and Lee 1971) strongly attenuate seismic waves; and the noise environment in an active tunnel is less than the optimum obtainable.

To carry out the measurements, hardware currently in widespread use for oil and gas exploration and in earthquake monitoring was secured under contract. Data were acquired with the signal source driven in both CF and swept-frequency (SF) modes at frequencies from 8 to 32 Hz. Nighttime measurements were conducted over a 20-day period during July and August, 1982. This report is restricted to the analysis and discussion of CF data.

II. INSTRUMENTATION

Instrumentation for detection of seismic signals was placed in the U12g Tunnel complex (or simply G-Tunnel) of Rainier Mesa at the NTS. This instrumentation consisted of two triaxial seismic stations and six geophone strings installed at three different locations (EV-5 and HF-47 drifts, and incline to U12g.08) within the tunnel complex. A schematic of the G-Tunnel installation is shown in Fig. 1. The instrumentation installed in the tunnel was connected via an existing cableway through U12g.08 to data acquisition and recording equipment installed directly above G-Tunnel on Rainier Mesa. A six-pair shielded cable was routed from each instrument location to the cableway and spliced into existing conductors that went to the surface.

Each seismic station consisted of three Teledyne Geotech Model 18300 seismometers and three Teledyne Geotech seismic amplifiers. The seismometer mounting area was cleared of muck and loose debris and rough leveled with a chipping hammer. The seismometers were then placed on the tunnel floor in a triaxial configuration, leveled, and oriented with one axis along true north.

The seismic amplifiers and batteries were mounted in 50-gal drums placed approximately 6.1 m (20 ft) from the seismometers. Bags of desiccant were placed in the drum and the drum sealed to reduce the effects of high humidity and dust on the system reliability. The outputs of the seismic amplifiers were connected to B&F instrument signal conditioners, Ectron, Inc. Model 750 instrumentation amplifiers, and low-pass filters on the surface through a six-pair shielded cable. A block diagram of a typical seismometer channel is shown in Fig. 2.

Fig. 1.
Location of instrumentation installed in G-Tunnel.

Fig. 2.
Block diagrams of typical geophone and seismometer channels.

Six geophone strings, supplied by the UTD, were installed in the G-Tunnel complex for the measurements. Each string contained six series-connected geophones spaced approximately 6.1 m (20 ft) apart on a two-conductor cable. Two strings were used at each of the three locations previously mentioned. Pairs of strings were placed along perpendicular lines within the constraints of the tunnel. A hole was chipped into the base material of the tunnel for each geophone, and the geophones were cemented in place to provide good coupling to the earth.

Each geophone string was connected to a battery-operated instrumentation amplifier used to drive the signals up the cable to the surface. The geophone amplifiers used were Burr-Brown 3660 instrumentation amplifiers in Los Alamos-fabricated assemblies to obtain a usable signal-to-noise ratio at the surface. The surface equipment for the geophone channels is similar to the seismometer channels. Both are shown in Fig. 2.

The signal conditioner provided a DC bucking voltage to compensate for the output-offset voltage in the tunnel-mounted amplifiers. Although the amplifier offsets were set to zero periodically, they did drift during operating periods when access to the tunnel was limited. Signal conditioners were required to compensate for the offset drift. The Ectron instrumentation amplifiers were used for several reasons including differential to single-ended signal conversion, common-mode rejection, additional voltage gain, surface-controllable gain, and 100-Hz low-pass filtering of the seismic signals.

The output of the Ectron amplifier was connected to a 4-pole, 35-Hz low-pass filter to band-limit the seismic signal and reject the 60-Hz noise induced on the instrumentation cable from the tunnel AC power system. The filters used were Kronhite Model 3550 active filters or active filters designed and fabricated by Los Alamos National Laboratory. The filter type used on a specific channel was at the operator's discretion.

All geophone and seismometer channels were recorded on an Ampex PR 2230 data recorder using 13 FM channels for data and one direct-record channel for IRIG time codes. Additional equipment used as required included a Nicolet 660A Dual Channel FFT Analyzer interfaced to a Hewlett Packard Model 85 desk-top computer, a Tektronix Model 468 digital oscilloscope, and several miscellaneous frequency counters, digital voltmeters, and power supplies.

The data acquisition and recording equipment used at the surface was mounted in one of the Los Alamos National Laboratory, Earth and Space Science

Division's, wellside service units (WSSU). Although the WSSU is designed and equipped for data acquisition in geothermal wells, it is ideally suited as a data acquisition center in remote locations as required by this experiment.

III. TRANSMITTERS

Two Model Y1100-A truck-mounted, servo-hydraulic vibrators, manufactured by the George E. Failing Company, were used to provide a source of seismic signals (Failing Co. 1982). A photograph of the unit is shown in Fig. 3. Truck-mounted vibrators of this kind are referred to as "Vibroseis" units, although in strict usage the vibrator is only a part of a complete system of seismic exploration known by the Continental Oil Company trademark Vibroseis. Vibroseis forms the basis of a domestic exploration industry with earnings of several hundred million dollars a year. Seismic signals generated by Vibroseis sources have been observed at distances up to 66.4 km (40 mi) under special circumstances (Fowler and Waters 1975).

The "Vibroseis" used for the telemetry measurements was owned and operated by Petty Ray Corp., a U.S. leader in the seismic-exploration industry. Vibration sequences are controlled by pilot signals generated by a microprocessor referred to as a radio controller. The microprocessor operates from the cab of the Vibroseis unit. The controller was activated by a tone burst radioed from the Rainier Mesa recording facility. The controller in use was a

Fig. 3.

A model Y1100-A truck-mounted servo-hydraulic vibrator manufactured by George E. Failing Company.

Model SHV-310A, designed and manufactured by Petty Ray Corp. The controller enables two or more Vibroseis units to be driven simultaneously in phase.

A servo-hydraulic system on the Petty Ray Corp. Y-1100 truck drives a 1.98 m^2 (3068 in.²) base plate centrally located beneath the truck with a peak force of 121,160 N (27,240 lbs). The combined weight of the plate and truck, 155,000 N (34,500 lbs), provides ground loading. The weight of Vibroseis units is limited by statutory laws that prescribe road weight limits on state and federal highways. However, there are no apparent design limits for Vibroseis hardware should it find use in special applications where over-the-road use is not necessary.

The Vibroseis units were operated at less than peak force. A peak force of 90% was used for 24- and 32-Hz CF transmissions, while only 60% peak force was possible at 16 Hz. Use of greater force at these frequencies initiated violent motion of the truck, which could not be sustained without damage to the unit. Therefore, to increase energy coupled into the earth below 16 Hz, additional Vibroseis units must be used. Signals of 16, 24, and 32 Hz were transmitted serially during 5-min intervals at all CF sites within 48 km (30 mi) of G-Tunnel. Between transmissions at each frequency, the Vibroseis units were powered down, radio controllers were coded, and output power levels adjusted during short signal bursts. Generally less than 3 min separated transmissions in the sequence.

During the field effort, as measurements were made at successively greater distances, the 32-Hz signals became extremely weak or were not seen. In general, no 32-Hz signals were seen beyond 40 km (25 mi). With this information known, the transmission sequence for sites farther than 48 km (30 mi) was then modified to 16-20-24 Hz.

One Vibroseis unit was used at sites where sufficient transmitted power for a range-power measurement could be anticipated. Generally those sites were closer than 32 km (20 mi) from G-Tunnel. At distances greater than 32 km (20 mi), increased use of two units was made, barring poor radio reception at a transmitter site, which effectively prohibited simultaneity with two Vibroseis. Judicious use of one unit in place of two reduced project costs.

IV. TRANSMITTER SITE SELECTION

Transmissions were attempted from each of the sites shown in Fig. 4 in addition to four sites to the northwest. The 58 sites were sequentially

Fig. 4.
Location of CF transmitter sites in NTS.

occupied according to increasing site number. Site-selection criteria evolved and were modified as the inventory of evaluated sites increased and the signaling range lengthened. Signaling from outside of the NTS was attempted

at only a few sites because of the lack of desirable sites accessible by road for which radio communications could be maintained. Only unsurfaced roads and ground disrupted by construction or vehicular movement were considered as candidate sites either within or outside the NTS. The sites selected were concentrated along lines to the east, south, and northwest of G-Tunnel to ensure evaluation of sites for which signal-transmission paths would necessarily either parallel or intersect the major geologic structural trends in the region.

At the commencement of the telemetry measurement series, sites were selected sufficiently close to G-Tunnel so that the detection system could be tuned and operational procedures wrung out. Later sites were chosen either to extend range, to increase the number of sites at ranges less than the established maximum, or to randomize effects in range/rate measurements arising from extremes in soil conditions and local geology. An inspection of a geologic map of the NTS shows that the lithologies and structures exposed at the NTS are numerous; the local geology is highly variable from site to site.

No concerted effort was made to quantify site parameters that significantly affected the coupling of Vibroseis energy into the earth; however, certain differences between good and poorly coupled sites are suggested by the analysis we will report. Good coupling appeared to be achieved if the ground at the site was compacted, soil cover was gravel or a comparable natural equivalent, and bedrock was close to the surface -- as usually indicated by the presence of nearby outcrops. These sites were generally found on sloping terrain or on topographic saddle points. After use, indentations caused by the Vibroseis base plates would generally be of the order of a few centimeters. Transmissions were detected only from sites that apparently satisfied these conditions; however, the apparent fulfillment of these criteria did not assure the detection of transmissions from that site. Poorest coupling arose where sites were situated on fine, powdery soil covering the alluvial terrain common at topographic lows. In these cases a significant volume of soil would be displaced through base plate action during transmission.

V. DATA PROCESSING

Analogue recordings taken in the field were replayed for processing with the same hardware used in recording the original data. Recorder output was

filtered to pass frequencies less than 50 Hz to avoid aliasing in spectral-power estimates.

Digitization of signal and noise records was identical. Sequential 20-s analogue records of West Seismometers (WS) and East Seismometers (ES) were simultaneously digitized in 4096-channel data blocks without data loss. Digitizing was triggered automatically by the onset of the recorded tone burst, which synchronized and initiated each Vibroseis transmission. Exceptions were those instances when single Vibroseis units were manually started due to poor radio communications between transmitter and receiver sites. Replay tape speed differed from speed during recording by a constant amount within each playback. The difference, which was as great as 0.2%, is significant in analysis because spectral estimates of signal power were degraded when this occurred. Signal power could be measured properly by coherent signal analysis if the replay tape speed was known; consequently, a measurement of tape speed during digitizing was necessary. Tape-playback speed was measured by a single 400-s count of IRIG E time-code cycles encompassing each digitized 5-min transmission. Combined IRIG signal stability and counter accuracy was better than one part in 4×10^6 at 16 Hz, so that tape-speed measurements were accurate to 0.0025% -- assuming that no degradation of IRIG signal occurred during recording or playback.

Digitized records were automatically searched to identify instances when the dynamic response of the seismometers was exceeded. Signal amplitudes, expressed in nanometers (nm) displacement, were calculated from digital records of seismometer voltage output. The frequency response of the seismometers is shown in Fig. 5 (Teledyne Geotech 1975). The log of seismometer terminal voltage is linear with the log of frequency over the frequency range studied. Transmitted signal and noise power were calculated in terms of dB re 1 nm^2 at the appropriate transmission frequency. The bandwidth of the calculations is 50 Hz. Power density in all cases is obtained by adding 13.06 dB to power values.

VI. CALCULATIONS

Two approaches, which we shall refer to as the Fourier-spectrum and coherent-detection methods, were used to calculate the displacement power of either signal or noise. In the first approach, power at transmission frequencies was calculated using standard algorithms for the Fourier transform

Fig. 5.
Terminal voltage of the Teledyne Model 18300 seismometer.

and complex multiplication of digitized time series. This method was of limited use in our calculations of power because often either the actual transmission frequency or error in replay of the analogue record of that transmission was not precisely at a frequency sampled by the Fourier-spectrum calculation. The spectral power of the true signal in either case appears distributed among sampled frequencies close to the real frequency through a phenomenon called spectrum leakage. Spectrum leakage occurs when $N_i \cdot \Delta f < 2 f_{\text{meas.}} < N_{i+1} \cdot \Delta f$, where Δf is the frequency resolution of the spectrum calculation and N_i is the number of amplitude samples in the time series under study. In our calculations $\Delta f = 0.05$ Hz and $N_i \leq 4096$, respectively. An example of spectrum leakage is given in Fig. 6. Signals having unit power lying between the sampled frequencies 16.00 and 16.05 Hz distribute to each

Fig. 6.

Spectrum leakage vs frequency within the sampling bandwidth.

sampled frequency the indicated spectral power. A 0.0-dB signal transmitted at 16.025 Hz would be measured as -6 dB at either of the closest sampled frequencies.

Because of leakage, spectral-power calculations were used only as a qualitative check to corroborate calculations based on the coherent-detection method. Leakage, however, provided a means of calculating the exact frequency of Vibroseis output, because strong signals transmitted within a fraction of the frequency resolution of the spectrum calculations could be observed as an apparent constant phase drift of the signal at the closest sampled frequency from record to record over the transmission-time interval. An example is given in Fig. 7 for a typical 16-24-32-Hz transmission sequence. Figure 7 shows signal power calculated using the coherent-detection method discussed below and signal phase calculated at the closest frequency sampled in the Fourier spectrum. The apparent phase of the transmitted signal changes at a

Fig. 7.

Representative power vs time and phase vs time for the 16-24-32-Hz transmission sequence.

constant rate at each study frequency. The playback-corrected transmitted frequency in this case is approximately 6×10^{-4} Hz less than expected at each study frequency. Using the time-rate of phase change calculated using linear regression, an exact frequency that would give rise to the apparent drift in phase was calculated.

Often a strong coherency in phase, which was not present in prior or subsequent transmissions in the sequence, was associated with the initiation of a transmission even though power levels would not change perceptibly. If two criteria were fulfilled, phase coherency was cited as supporting although inconclusive evidence for detection of a transmitted signal. Those criteria were (i) that the calculated frequency was less than half a bandwidth from the closest Fourier-sampled frequency because a greater difference would make detection by this method improbable; and (ii) that the regression coefficient of determination (Ostle 1963) for the phase change with time exceeded 0.85.

The coherent-detection method enabled power to be calculated at the exact study frequencies. Let the received signal plus noise during a transmission be $S(t)$, then the displacement power is

$$P = 20 \text{ Log } \frac{1}{T} \left[\left(\int_0^T S(t) \sin(\omega' t) dt \right)^2 + \left(\int_0^T S(t) \cos(\omega' t) dt \right)^2 \right]^{\frac{1}{2}}, \quad (1)$$

where $\sin(\omega' t)$ and $\cos(\omega' t)$ are in-phase and quadrature reference signals corrected for replay speed and T is the integration period.

VII. G-TUNNEL NOISE CHARACTERIZATION

Noise-power cumulative distribution functions (CDF) were calculated to characterize the G-Tunnel noise environment during the period of the field test and to provide the statistical measures of noise-power probabilities necessary to determine signaling rate. In determining the noise-power CDF at a given frequency, we plot noise power P vs the cumulative occurrence of noise power greater than P in units of dB re nm^2 and cumulative percentage, respectively. For the abscissa we use as cumulative percentage Q , the cumulative probability for a standard normal distribution, where

$$Q = \int_t^{\infty} \frac{1}{\sqrt{2\pi}} e^{-\frac{t^2}{2}} dt \quad (2)$$

and t is expressed in standard deviations about the mean of the distribution. In plotting noise power vs cumulative percent occurrence in this way, a log-normal noise-power distribution will plot as a straight line. For further discussion of the significance and use of this type of plot the reader is referred to Sinclair (1978).

In preparing CDF plots, data were grouped into 15 interval classes, each corresponding to $1/3$ a standard deviation in P , and cumulative percentage was calculated at the median of the class intervals. In plotting, the class values were connected with straight line segments by computer.

The time intervals selected for digitizing were those during which either no SF transmissions were underway or CF transmissions were at a frequency other than that at which noise power was calculated. The latter accounts for roughly half of the noise records used for analysis and results in a high percentage of records taken within 10 min before or after a CF transmission. However, since SF and CF transmissions were randomly distributed in time over the course of field tests, the noise records studied can be effectively considered as randomly chosen.

Samples were rejected from statistical analysis of noise if records in a computer search showed that signals on records had been clipped during recording; that is, the amplified seismometer output exceeded the voltage range selected as optimum for analogue recording of Vibroseis signals. Approximately 8% of samples were so rejected. The cause for the high noise in these instances was vehicular traffic and road maintenance work close to G-Tunnel. Figure 8 shows the situation. Traffic occurring within 1.6 km (1 mi) of the G-Tunnel installation on Rainier Mesa, Stockade Wash, and Holmes Roads could be detected by ES and WS. In addition, resurfacing of these roads with oil and gravel throughout late July was also observed. A high percentage

Fig. 8.
Roads within 1.6 km (1 mi) of the G-Tunnel WS and ES.

of the late night traffic involved vehicles used in support of Los Alamos field operations.

From radio communications with personnel in those vehicles the following can be concluded: In general, a 3/4-ton pickup truck could be seen to some degree anywhere on the road network. Signals became clipped when a vehicle was east or west of the installation at the elevation of the tunnel. Light-auto-generated noise exceeded seismometer dynamic range only when the vehicle was traveling on the top of Rainier Mesa on a pot-holed dirt road almost directly over a seismometer. In discussion of the results of noise measurements, the above will be referred to simply as road noise. When road noise was not present, conditions closely approached those required for the measurement of actual geophysical noise.

No measurements could be made during normal G-Tunnel working hours. Personnel movement near the seismometers, train traffic, and mechanized mining produced ground motion that kept amplifiers optimally set for the nighttime measurements continuously in saturation. In general, by the nominal start-up time for Los Alamos operations, all G-Tunnel personnel had left the portal and nearby vehicular traffic was infrequent.

Noise generated in G-Tunnel after work hours, we believe, was restricted to that arising from air and water movement. Air ducts and drain lines were located within 12 m (40 ft) of the seismometer installations. During off-hours the tunnel air-conditioning system operated at 50% normal capacity. Noise from the flow of air in the duct work was ubiquitous on seismometer output, but not of sufficient amplitude to degrade records. Water flowing in nearby drain lines was continuous irrespective of the hour, but generally only of the order of a few tens of liters per minute. Although surely present, no basis for the identification of the effect of flowing water on seismic records could be established. Similarly, noise originating from mechanized mining occurring throughout the night elsewhere in Rainier Mesa, although probably present, was not visually distinguishable on seismic records.

The shortest temporal unit of analysis was a single 20-s digital record. Noise statistics were derived for two populations. One population consisted of individual 20-s record, noise-power averages. A second consisted of average noise power for 280-s periods obtained from 14 consecutive 20-s records. The latter population provided the basis for calculations of signal-to-noise ratios during signal transmission.

Noise power was calculated for each record using Eq. (1). Since the noise was expected to be log normally distributed and noise power was expressed in decibels, normal distribution statistics were calculated. The process is summarized for the 280-s record population by

$$\bar{P}_s = \frac{1}{n_s} \sum_{r=1}^{n_s} P_r \quad (3)$$

and

$$\sigma_s = \sqrt{\frac{\sum P_r^2 - n_s \bar{P}_s^2}{n_s - 1}} \quad (4)$$

where $\bar{P}_r$ is the mean displacement power of a single 20-s record. Population statistics $\bar{P}_s$ and σ_s for the 280-s record populations were calculated using $n_s = 14$ samples of $\bar{P}_r$. For the 20-s record populations, $\bar{P}_s = \bar{P}_r$.

VIII. TRANSMITTED SIGNAL POWER

Tables I, II and III give the CF site number, start time of the transmission, transmitter frequency, the mean and standard deviation ground-motion power at the transmission frequency during transmissions, the mean and standard deviation of noise power within 10 min before or subsequent to the transmission, the basis for positive identification of a transmission on seismic records, the distance of the transmitter site from G-Tunnel and the number of Vibroseis units in use. Statistics are reported for both ES and WS locations so that differences in the capability of detecting signals at different receiver sites may be investigated.

Statistical measures derived from samples containing records in which amplified seismic signal output exceeded the permissible voltage range for recording are so indicated. The effect of using these samples is that both signal and noise-power levels are underestimated. The result is an acceptable bias for signal, but not for noise calculations. Since saturation needs to be present for only approximately 5×10^{-3} s for a 14-record ensemble to be identified as saturated and suspect in calculations, the criterion for identification is severe. Studies of the time stability of noise power have not been undertaken so the noise statistics are cited only to provide an indication of the noise conditions that may have been present during transmissions.

TABLE I
16-HZ TRANSMISSIONS

West Seismometer							East Seismometer					Range		No.
Site	Time	Signal		Noise		IC ^d	Signal		Noise		IC			
		$\bar{p}^{a,b,c}$	σ	$\bar{p}$	σ		$\bar{p}$	σ						
1	2344	-41.4	0.6	-52.5 ¹	5.8	0,2	-36.6	0.6	-49.8 ¹	7.5	0,2	9.3	(5.8)	1
2	0126	-15.9	0.3	-41.2	3.8	0,2	-47.4	0.9	-68.6	4.3	0,2	13.0	(8.1)	1
3	2028	-45.8 ²	2.9	-50.7	4.7	1,2	-39.8 ¹	0.7	-55.6	4.2	0,2	10.8	(6.7)	1
4	2322	-38.0	0.7	-60.1	5.1	0,2	-50.0	3.5	-42.6	8.6	1	20.4	(12.7)	1
5	0500	-45.4	1.0	-67.7	7.7	0,2	-36.9	1.8	-59.9	10.8	0,2	13.8	(8.6)	1
6	1839	-43.7	0.6	-52.3	8.2	0,2	-49.3	4.4	-45.9	5.5	1,2	27.2	(16.9)	1
7	0016	-54.6	2.7	-62.5	4.7	1,2	-47.4	1.6	-62.1	7.4	0,2	30.9	(19.2)	1
8	2240	-50.7	4.9	-69.7	3.3	0,2	-43.1	2.6	-60.3	4.3	0,2	33.5	(20.8)	1
9	2331	-43.4	0.7	-69.6	7.0	0,2	-47.7	2.7	-61.6	2.7	0,2	35.2	(21.9)	1
10	0055	-47.7 ³	5.5	-65.5 ¹	6.2	0	-43.3 ³	1.4	-58.0	4.3	0,2	37.0	(23.0)	1
11	0224	-54.6	4.8	-55.8	5.5	4	-55.6	5.7	-53.5	5.2	4	41.4	(25.7)	1
12	0315	-44.8	2.6	-57.1	5.8	0,2	-53.3	10.4	-56.9	4.2	5	47.6	(29.6)	2
13	1906	-54.9	5.7	-43.3 ^{1,4}	5.4	5	-54.1	3.5	-44.4	5.1	4	54.1	(33.6)	2
14	1953	-50.7 ²	7.2	-49.3	5.2	5	-54.6 ³	7.8	-52.7	6.1	5	55.7	(34.5)	2
15	0051	-50.1	4.3	-55.6	5.9	5	-55.5	4.5	-53.4	4.6	5	58.7	(36.5)	2
16	0228	-52.3	3.5	-59.1	5.8	3	-57.5 ³	4.9	-56.6 ⁴	6.4	5	50.7	(31.5)	1
17	0300	-56.5	5.2	-59.6	6.2	5	-56.2 ⁴	4.0	-57.8 ^{1,4}	6.4	5	56.5	(35.1)	1
18	2332	-35.3 ³	0.5	-59.9	7.2	0	-39.1	0.4	-60.8	3.0	0	23.0	(14.3)	1
19	0044	-39.4	1.2	-57.9	6.4	0,2	-59.0	4.7	-56.6	5.9	4	23.5	(14.6)	1
20	0200	-43.1 ²	1.0	-59.7	6.4	0,3	-59.4 ²	5.8	-60.9	4.9	3	28.3	(17.6)	1
21	0305	-45.3	1.4	-57.4	5.9	0,2	-45.3	1.2	-61.2	5.6	0,2	23.5	(14.6)	1
22	2340	-54.1	8.2	-50.2	3.8	5	-57.3	6.7	-54.6	5.4	5	43.0	(26.7)	1
23	0048	-51.0	5.9	-51.2	3.5	5	-52.5 ¹	3.6	-54.7	8.3	3	41.0	(25.5)	1
24	0134	-47.9 ³	2.5	-51.7 ²	3.5	3	-45.3 ³	2.3	-57.1 ²	5.8	3	27.4	(17.0)	1
25	0221	-39.4	2.3	-51.8	3.9	0,2	-49.1	2.7	-59.4	7.4	3	25.4	(15.8)	1
26	1829	-32.3	1.7	-58.7	5.6	0,3	-41.6	5.9	-59.0	5.4	0,3	20.8	(12.9)	2
27	2248	-58.0	5.2	-53.7	5.1	5	-58.9	5.8	-63.0	6.9	5	18.5	(11.5)	2
28	1833	-38.0	0.7	-55.6	5.6	0,2	-52.0	3.4	-68.1	5.2	1,3	45.1	(28.0)	2
29	1821	-34.2	1.2	-50.9	7.9	0,2	-42.8	9.6	-57.9	6.4	5	10.1	(6.3)	2
30	1944	-32.0	0.3	-60.4 ¹	5.0	0,2	-46.4	1.9	-62.0	6.3	0,2	16.4	(10.2)	2
31	2059	-34.1	0.4	-63.7	5.3	0,2	-38.8	0.3	-68.1	5.0	0,2	21.6	(13.4)	2
32	2233	-21.9	0.9	-54.1 ¹	7.3	0,2	-43.9	0.6	-62.6	5.7	0,2	21.9	(13.6)	2
33	2359	-36.2	1.5	-60.7	4.9	0,3	-53.4 ²	2.1	-67.3	7.3	0,3	25.7	(16.0)	2
34	0250	-40.4	0.6	-60.4	5.5	0,2	-51.5	1.2	-65.4	4.1	0,3	23.5	(14.6)	2
35	0133	-41.0 ²	0.8	-59.6 ¹	6.3	0,3	-51.6	1.1	-66.8	5.5	0,3	29.3	(18.2)	1
36	1957	-73.8	9.1	-61.5	8.9	5	-60.1	5.9	-58.3	5.2	5	26.1	(16.2)	1
37	2058	-47.8	5.3	-56.3	3.7	5	-47.0	5.1	-58.5	3.7	5	33.6	(20.9)	1
38	2155	-51.7 ¹	6.9	-50.7	6.2	5	-56.1 ¹	6.8	-52.3	7.7	5	35.4	(22.0)	1
39	2233	-50.5 ²	5.1	-51.8 ³	6.2	3	-53.0	6.7	-55.1	6.2	5	38.6	(24.0)	1
40	2315	-60.6	10.1	-50.5	7.6	5	-55.2 ²	5.1 ¹	-50.2 ²	2.7	5	45.1	(28.0)	1
41	0006	-50.3	4.8	-52.4 ¹	5.4	5	-53.5	5.6	-55.1	4.2	5	51.5	(32.0)	2
42	0100	-54.0 ²	5.4	-55.0	4.9	5	-54.3	5.3	-55.4	7.6	5	58.4	(36.3)	2

TABLE I (cont)

West Seismometer							East Seismometer					Range		No. Vibrators
Site	Time	Signal		Noise		IC ^d	Signal		Noise		IC			
		$\bar{p}^{a,b,c}$	σ	$\bar{p}$	σ		$\bar{p}$	σ						
43	2308	-43.8	2.0	-57.9	5.5	0,2	-54.6	3.7	-60.2	7.9	5	42.6	(26.5)	2
44	0024	-44.6 ^a	7.6	-56.8 ²	5.1	1,3	-46.5	4.4	-56.2	3.7	0,2	49.6	(30.8)	2
45	0113	-49.2	3.1	-58.9	9.4	5	-41.7	2.2	-60.6	4.3	0,2	47.6	(29.6)	2
46	0213	-53.2	4.4	-60.1	6.2	5	-55.8	4.0	-61.1	5.7	5	46.7	(29.0)	2
47	0316	-56.2	4.9	-56.1	3.0	5	-60.4	8.0	-59.3	4.5	5	51.3	(31.9)	2
48	0108	-45.1	6.5	-53.5 ³	7.8	5	-44.5 ²	4.3	-58.1 ¹	10.5	5	42.2	(26.2)	2
49	0205	-40.5	1.2	-59.0	5.1	0,2	-40.7	0.8	-62.4	6.4	0,2	35.9	(22.3)	2
50	0302	-43.4	2.2	-58.0	4.1	0,2	-54.5	3.0	-60.9	6.5	1,2	40.2	(25.0)	2
51	0414	-43.9	1.5	-60.3	5.7	0,2	-54.4	3.6	-58.9	4.0	5	44.6	(27.7)	2
52	1846	-43.5	6.5	-57.9	5.2	1,4	-47.2	6.0	-60.2	4.4	1,4	60.5	(37.6)	2
53	1947	-62.1	8.0	-60.1	5.6	4	-53.3	2.3	-65.7	5.8	1,4	58.9	(36.6)	2
54	2054	-55.7	2.4	-64.2	6.4	1,4	-57.8	2.6	-64.5	4.3	4	64.4	(40.0)	2
55	2241	-49.6	7.6	-54.5 ¹	4.0	5	-47.0 ²	7.0	-61.8	6.4	5	62.4	(38.8)	2
56	2324	-49.6	1.8	-61.4	6.2	1,4	-59.9	3.4	-64.8	5.1	4	63.4	(39.4)	2
57	0138	-59.9	7.5	-84.2	5.3	1,4	-53.0	2.5	-83.9	5.0	0,3	66.5	(41.3)	2
58	0219	-60.5	3.4	-66.2	7.2	5	-60.6	7.2	-66.8	4.1	5	69.7	(43.3)	1

^a All measurements are reported in dB re 1 dB nm² in a bandwidth of 0.05 Hz.

^b The numeric value of the superscript is equivalent to the number of saturated records; in these cases the estimate is low.

^c $\bar{p}$ and σ are calculated using equations (3) and (4) respectively, where $n_s = 14$.

^d Identification Code (IC)

0 - Visual inspection of pwr vs time plot; good s/n (6).

1 - Visual inspection of pwr vs time plot; poor s/n (6).

2 - $r^2 > 0.95$; coherent phase on ϕ vs time plot.

3 - $0.85 > r^2 > 0.95$; coherent phase on ϕ vs time.

4 - Not observed on pwr vs time plot; weak coherent phase on ϕ vs time plot.

5 - Not observed.

TABLE II
24-HZ TRANSMISSIONS

West Seismometer							East Seismometer					Range		No.
Site	Time	Signal		Noise		IC ^d	Signal		Noise		IC			
		$\bar{p}^{a,b,c}$	σ	$\bar{p}$	σ		$\bar{p}$	σ						
1	235	-63.4 ¹	3.8	-69.6	4.3	0,2	-41.5 ^{1,2}	3.1	-66.6 ⁵	4.5	0,2	9.3	(5.8)	1
2	0134	-21.1	2.9	-47.0 ¹	3.9	0,2	-56.2	1.0	-72.1 ²	2.2	0,2	13.0	(8.1)	1
3	2046	-38.5	-0.5	-61.8 ¹	4.3	0,2	-39.6	0.2	-69.6 ¹	5.0	0,2	10.8	(6.7)	1
4	2331	-58.5	3.9	-69.1	2.6	0,4	-56.3 ¹	4.8	-65.0	4.3	1,2	20.4	(12.7)	1
5	0452	-53.4	-5.5	-74.2	8.4	0,2	-48.7	7.2	-67.0	10.3	0,2	13.8	(8.6)	1
6	1858	-55.6	0.8	-75.2	6.6	0,2	-59.1	3.5	-63.8	4.6	1,4	27.2	(16.9)	1
7	0034	-50.5	0.5	-78.9	6.3	0,2	-61.4	3.4	-67.8	6.2	1,2	30.9	(19.2)	1
8	2305	-53.4 ¹	2.1	-75.6	6.3	0,2	-50.5	2.4	-67.3	4.5	0,2	33.5	(20.8)	1
9	2350	-45.5	0.4	-77.3	6.6	0,2	-53.8	0.8	-59.9	4.9	0,2	35.2	(21.9)	1
10	0114	-58.1 ^{1,2}	2.1	-76.0 ¹	7.3	0,2	-62.0	4.4	-76.0	7.3	3	37.0	(23.0)	1
11	0242	-58.1	4.5	-60.3	6.2	1,3	-55.6	5.7	-53.5	4.4	4	41.4	(25.7)	1
12	0332	-56.1	3.9	-60.6	7.8	2	-60.5	3.0	-64.4	3.5	3	47.6	(29.6)	2
13	1924	-55.2 ^{1,2}	6.3	-66.9	7.5	5	-61.8 ^{1,2}	7.0	-74.8	7.9	5	54.1	(33.6)	2
14	2009	-64.5	6.0	-66.5	7.4	5	-67.8	7.4	-67.9	5.4	5	55.7	(34.5)	2
15	2125	-61.9	4.4	-65.2	6.0	5	-68.1	4.9	-66.3	5.8	4	58.7	(36.5)	2
16	0244	-64.7 ¹	9.8	-68.2	3.2	5	-69.8	4.2	-74.3 ¹	7.3	5	50.7	(31.5)	1
17	0317	-67.4	5.1	-69.5	9.2	5	-69.4 ^{1,2}	5.7	-67.6 ¹	4.1	5	56.5	(35.1)	1
18	2354	-51.6	1.2	-62.4	6.9	0,3	-56.4	1.1	-72.4	4.2	0,2	23.0	(14.3)	1
19	0105	-49.6 ¹	1.6	-66.9	4.6	0,2	-70.6	5.2	-73.8	4.7	5	23.5	(14.6)	1
20	0217	-49.0	1.1	-69.5	5.6	0,2	-61.8 ¹	2.0	-73.5	6.0	1,3	28.3	(17.6)	1
21	0328	-47.1	4.7	-70.7	9.2	0,2	-50.4	5.0	-72.7	5.2	0,2	23.5	(14.6)	1
22	0013	-59.3	4.5	-61.6	6.0	3	-70.0	4.9	-69.7	4.0	3	43.0	(26.7)	1
23	0117	-59.4	6.2	-60.3	5.1	5	-63.8	4.0	-66.3	4.5	5	41.0	(25.5)	1
24	0152	-57.8 ¹	4.6	-61.5 ¹	5.2	5	-65.3 ¹	7.2	-67.0	6.0	5	27.4	(17.0)	1
25	0246	-46.3	1.8	-61.5	4.8	0,2	-54.0	1.3	-69.3	5.8	0,2	25.4	(15.8)	1
26	1846	-38.5	6.7	-60.6	6.4	0,2	-63.7	3.9	-65.7	4.3	3	20.8	(12.9)	2
27	2312	-45.2	2.4	-61.7	3.7	1,4	-65.4	5.4	-65.4	5.9	5	18.5	(11.5)	2
28	1949	-51.9	2.4	-62.9	10.1	1,4	-62.0	4.6	-64.0	5.4	4	45.1	(28.0)	2
29	1838	-38.5	2.5	-58.9	7.3	0,2	-65.8	3.9	-58.5	3.1	5	10.1	(6.3)	2
30	2006	-52.7	1.2	-69.0	4.4	0,2	-63.5	3.4	-71.8	5.2	0,2	16.4	(10.2)	2
31	2116	-34.4	1.1	-69.5	4.6	0,2	-55.5	1.0	-81.0	4.3	0,2	21.6	(13.4)	2
32	2253	-32.0	0.6	-66.3	4.9	0,2	-51.9	0.9	-77.5	5.1	0,2	21.9	(13.6)	2
33	2354	-50.7	0.5	-67.9	6.4	0,2	-64.7	1.7	-77.6	3.4	1,2	25.7	(16.0)	2
34	0306	-56.8	1.7	-68.2	2.5	0,3	-73.2	3.1	-76.8	4.5	1,3	23.5	(14.6)	2
35	0150	-55.5 ¹	1.7	-69.9 ²	8.2	0,3	-65.7	1.8	-78.2	12.0	0,3	29.3	(18.2)	1
36	2013	-60.8	5.3	-75.1	6.0	5	-65.5	3.1	-65.5	5.6	3	26.1	(16.2)	1
37	2115	-55.1	4.1	-57.1	5.2	5	-63.9	4.5	-64.8	5.4	3	33.6	(20.9)	1
38	2203	-55.3	3.6	-55.7 ¹	3.5	4	-61.7	5.3	-64.7	7.1	2	35.4	(22.0)	1
39	2250	-59.6 ¹	6.2	-58.8 ²	8.6	2	-63.6	6.3	-65.3	4.5	5	38.6	(24.0)	1
40	2332	-57.5 ¹	6.0	-68.6	11.5	4	-62.5 ¹	6.5	-65.5 ¹	5.3	2	45.1	(28.0)	1
41	0023	-57.3 ¹	7.2	-56.8	5.2	5	-62.8	4.9	-85.5	6.0	5	51.5	(32.0)	2
42	0116	-56.2	6.9	-62.1	9.7	5	-63.0	5.4	-63.2	6.1	3	58.4	(36.3)	2

TABLE II (cont)

Site	Time	West Seismometer					East Seismometer					Range		No. Vibrators
		Signal		Noise		IC ^d	Signal		Noise		IC			
		$\bar{p}^{a,b,c}$	σ	$\bar{p}$	σ		$\bar{p}$	σ	$\bar{p}$	σ		km	(mi)	
43	2342	-51.1	6.9	-61.3	6.5	5	-66.1	5.4	-67.4	7.8	2	42.6	(26.5)	2
44	0040	-54.6*	7.3	-69.1 ²	5.0	3	-64.2	5.0	-65.2	3.8	3	49.6	(30.8)	2
45	0132	-44.3	1.6	-59.9	7.0	0,2	-60.0	3.8	-62.7	4.6	1,3	47.6	(29.6)	2
46	0230	-53.2	3.2	-57.2	2.5	4	-64.0	3.7	-64.7	3.4	3	46.7	(29.0)	2
47	0333	-56.9	4.6	-58.6	4.6	2	-63.7	5.1	-65.1	7.0	5	51.3	(31.9)	2
48	0124	-52.2 ¹	5.7	-50.5	5.5	5	-61.4	4.3	-64.4	7.6	5	42.2	(26.2)	2
49	0221	-53.5	5.2	-49.5	3.4	5	-65.9	5.2	-67.1	4.8	5	35.9	(22.3)	2
50	0319	-48.1 ¹	4.6	-50.9	5.3	5	-65.5	5.9	-64.2	3.6	5	40.2	(25.0)	2
51	0430	-53.2	3.7	-51.9	6.4	5	-62.1	4.3	-68.4	5.2	5	44.6	(27.7)	2
52	1908	-57.4	2.4	-54.0 ¹	6.2	5	-63.3	3.1	-54.0	6.2	5	60.5	(37.6)	2
53	2015	-59.8	3.5	-66.9	3.8	1	-65.9	2.4	-66.8	3.8	1	58.9	(36.6)	2
54	2116	-60.5	3.2	-70.2	5.1	5	-70.4	5.2	-70.8	5.1	5	64.4	(40.0)	2
55	2306	-61.0	5.2	-66.8 ¹	4.4	5	-70.5	5.8	-73.3	3.6	5	62.4	(38.8)	2
56	2347	-60.4	3.9	-68.7	7.6	5	-71.0	5.5	-68.8	7.6	5	63.4	(39.4)	2
57	0138	-59.9	7.5	-84.2	5.3	1,4	-53.0	2.5	-83.9	5.0	0,3	66.5	(41.3)	2
58	0243	-65.1	4.7	-67.0	4.3	5	-56.8	3.5	-57.0	3.5	5	69.7	(43.3)	1

^a Refer to Table I for explanation of units, superscripts and IC.

TABLE III
32-HZ TRANSMISSIONS

West Seismometer							East Seismometer					Range		No. Vibrators
Site	Time	Signal		Noise		IC ^d	Signal		Noise		IC			
		p ^{a,b,c}	σ	p	σ		p	σ	p	σ		km	(mi)	
4	2339	-68.1	2.6	-75.4	3.7	4	-58.7	1.2	-69.4	3.0	1,2	20.4	(12.7)	1
5	0445	-70.8	10.2	-70.2	5.4	1,2	-66.0	10.8	-79.4	9.2	1,2	13.8	(8.6)	1
6	1908	-70.2	4.0	-77.9	5.1	3,4	-62.9	2.5	-77.9	5.1	2,4	27.2	(16.9)	1
7	0042	-69.6	3.0	-79.9	4.7	2	-58.2	1.3	-79.9	4.7	1,2	30.9	(19.2)	1
8	2313	-63.7	1.4	-77.5	5.3	0,2	-63.8	2.8	-77.9	5.3	1,2	33.5	(20.8)	1
9	0000	-60.8	1.4	-76.2	7.0	1,2	-64.4	3.2	-76.2	7.0	1,2	35.2	(21.9)	1
10	0121	-68.7 ¹	2.2	-73.8 ^{1,1}	7.1	1,2	-72.3	4.6	-73.9	5.2	5	37.0	(23.0)	1
11	0249	-64.0	5.1	-62.0	3.9	5	-74.2	3.9	-62.0	3.8	5	41.4	(25.7)	1
12	0341	-58.7	7.4	-64.0	7.2	5	-71.6	7.0	-63.9	7.2	5	47.6	(29.6)	2
13	1933	-56.4	4.4	-66.7	4.8	5	-63.3	9.4	-66.0	4.8	5	54.1	(33.6)	2
14	2016	-64.8	3.7	-67.2 ²	5.2	5	-78.9	6.9	-77.7 ³	6.1	5	55.7	(34.5)	2
15	0132	-65.1	5.8	-71.5	9.6	3	-76.5	4.7	-77.5	9.6	5	58.7	(36.5)	2
16	0252	-65.9	5.0	-68.2	5.0	3	-78.6 ⁶	4.3	-74.5 ⁵	5.0	5	50.7	(31.5)	1
17	0324	-66.9 ¹	4.4	-66.1	6.1	5	-75.5 ^{1,5}	4.2	-72.1 ⁶	6.1	5	56.5	(35.1)	1
18	0008	-62.9 ⁵	3.7	-71.8	4.7	1,4	-76.8 ²	5.5	-67.0	5.0	5	23.0	(14.3)	1
19	0111	-66.7	5.9	-69.7	3.9	2	-80.3	4.7	-76.4	1.5	5	23.5	(14.6)	1
20	0224	-70.9	5.0	-71.6 ¹	9.3	5	-80.5	6.1	-77.9	4.3	5	28.3	(17.6)	1
21	0333	-71.5	5.3	-71.4 ²	5.7	5	-66.4	2.0	-71.4	4.9	1,3	23.5	(14.6)	1
22	0341	-62.4	5.2	-62.1	4.0	5	-75.1	5.5	-62.1	4.0	5	43.0	(26.7)	1
23	1933	-62.4	4.1	-60.5	7.2	5	-68.7	5.4	-60.5 ¹	7.2	5	41.0	(25.5)	1
24	2016	-61.5 ³	4.9	-61.9 ³	5.5	5	-74.4	5.4	-61.9 ¹	5.5	5	27.4	(17.0)	1
25	0132	-58.6	5.3	-59.8	5.5	4	-68.3	3.1	-59.8	5.5	2	25.4	(15.8)	1
26	0252	-57.2 ³	5.8	-61.1	3.5	4	-69.9	3.2	-61.1	3.5	4	20.8	(12.9)	2
27	0324	-60.8	6.8	-60.9	4.0	4	-70.5	5.1	-70.8	8.9	5	18.5	(11.5)	2
28	0008	-62.3 ²	7.3	-66.1	7.2	5	-71.4	5.5	-65.4	7.2	5	45.1	(28.0)	2
29	0111	-60.1	4.3	-66.5	4.3	3	-70.3	4.1	-62.7	5.4	5	10.1	(6.3)	2
30	0224	-46.1 ¹	0.5	-57.6	1.7	0,2	-72.3	4.7	-57.6	1.7	0,2	16.4	(10.2)	2
31	2134	-57.6	4.1	-57.9	1.9	0,2	-72.0	1.7	-63.9	1.9	0,2	21.6	(13.4)	2
32	2310	-53.6 ¹	2.4	-56.8	4.6	0,2	-67.9 ¹	1.7	-62.8	4.6	0,2	21.9	(13.6)	2
33	2349	-53.6	1.0	-73.4	8.6	0,2	-78.4	4.1	-83.0	4.7	3	25.7	(16.0)	2
34	0048	-67.4	4.2	-73.2	5.9	5	-84.3	5.7	-79.2	5.9	5	23.5	(14.6)	2
35	0140	-69.5	5.8	-57.8 ¹	3.7	4	-83.5	6.6	-75.3	4.7	4	29.3	(18.2)	1
36	0237	-61.9 ⁴	7.2	-78.6	5.2	3	-76.0 ³	4.0	-76.3	4.3	5	26.1	(16.2)	1
37	0340	-59.4 ¹	5.0	-62.9	5.0	5	-75.6 ³	2.7	-76.5 ¹	4.4	5	33.6	(20.9)	1
38	0131	-62.4 ³	4.8	-59.0 ³	4.5	5	-74.0 ³	5.9	-62.1	8.4	5	35.4	(22.0)	1
39	0228	-68.0	8.6	-50.9	7.5	5	-76.2	6.2	-60.9	7.5	5	38.6	(24.0)	1
40	0326	-60.2 ³	5.8	-70.4	10.8	5	-77.7 ¹	5.2	-70.3 ¹	10.8	5	45.1	(28.0)	1
41	0436	-60.6 ¹	6.0	-60.4	4.6	5	-74.4	6.0	-60.3	4.6	5	51.5	(32.0)	2

^a Refer to Table I for explanation of units, superscripts and IC.

Clearly, because G-Tunnel noise environment had not been fully characterized until subsequent to field measurements, unavoidable instances arose when the detection of inherently weak transmissions was attempted during either abnormally noisy or abnormally quiet periods. These instances may be indicated but not substantiated by comparison of signal and noise power within 10 min of the transmission. Transmissions of at least one frequency were detected from 80% of the sites studied.

Corroborative indicators of the detection of weak transmitted signals are small standard deviations in power during transmission, coefficients of determination of phase coherency greater than 0.85, and often visual comparison of the signature of noise phase before and subsequent to the transmission.

Figure 9 gives histograms of transmitter site quality as a function of distance from G-Tunnel, coded using the identification code given in Table I. Histograms are given for the results at each frequency and for both WS and ES. The histograms are useful for summarizing the fraction of good or potentially useful sites versus distance from G-Tunnel as well as the relative performance of the WS and ES stations. Transmissions at 16 Hz from 34 of 58 possible sites were clearly detected by WS in comparison with 28 on the ES. Clear transmissions were detected from sources as distant as 69 km (43 mi). Post-field analysis of records clearly indicates that under the most favorable of noise conditions that existed at NTS, detection of transmissions from good sites as distant as 96 km (60 mi) is possible.

Detection of transmitted signals at WS was more likely than at ES with the notable exception that transmissions from the furthest sites were best detected at ES. On the basis of the UTD work, a fault with large vertical displacement is now known to separate WS and ES locations and thus may possibly account for the observed difference.

Figures 10 and 11 give detected signal power versus range for ES and WS. Signal power is highly variable from site to site with roughly a factor of 20 dB between best and only weakly observable sites. Only transmissions at 16 Hz provide evidence of a weak but significant regional trend in signal decay with distance from G-Tunnel. Regression parameters derived from Figs. 10 and 11 are given in Table IV.

Overall the best data were obtained when WS detected signals generated using two Vibroseis units. Comparable values for the rate of signal-power

Fig. 9.
Histogram of transmission site quality vs distance for ES and WS.

Fig. 10.

16-Hz transmissions observed at WS vs distance.

Fig. 11.

16-Hz transmissions observed at ES vs distance.

change with distance were also obtained using ES and WS detection of single Vibroseis transmissions.

Tables II and III and Figs. 9, 12, 13, and 14 summarize the results for 24- and 32-Hz transmissions. WS was superior for the detection of CF transmissions. From 27 of the possible 58 sites, 24-Hz transmissions were detected at WS. No signals originating from sites greater than 48 km (30 mi) were observed. From 8 of the possible 38 sites, 32-Hz signals were detected. No unambiguous confirmation of 32-Hz signals transmitted from sites greater than 40 km (25 mi) could be obtained. Phase coherency during some 32-Hz transmission periods suggests that some signals transmitted from the 48- to 64-km (30- to 40-mi) range may have been detected. Figures 12, 13, and 14 again show a great range in signal power among transmissions from sites at comparable distances from G-Tunnel. No systematic variation of signal power with site

TABLE IV
SIGNAL POWER VS RANGE REGRESSION PARAMETERS

	n^a	a_0^b	a_1^b	r^2c	s_{yx}^d	s_o^e	s_1^f
16 Hz-WS							
1 unit	22	-36	-0.47	0.4	4.9	2.7	0.1
2 units	25	-31	-0.57	0.5	5.5	2.9	0.1
16 Hz-ES							
1 unit	19	-38	-0.49	0.4	4.9	2.7	0.1
2 units	23	-42	-0.28	0.2	5.4	3.1	0.1

^aNumber of data.

^bRegression coefficients to fit a straight line $y=a_0 + a_1x$.

^cCoefficient of determination.

^dStandard error of the estimate of y on x .

^eStandard error of the regression coefficient a_0 .

^fStandard error of the coefficient a_1 .

distance can be observed, other than simply a decrease to extinction at both frequencies in the 32- to 48-km (20- to 30-mi) range.

IX. NOISE SPECTRUM

The power spectrum of noise measured at WS during high and low noise periods is shown in Figs. 15 and 16 respectively. The spectral peak at 9.4 Hz and its harmonics arose from the air-conditioning system. No effort was made to identify noise sources outside the 8- to 32-Hz frequency band. With the exception of the pronounced spectral peaks, the shape of the spectrum appears characteristic of geophysical noise.

X. NOISE POWER CDFS

Noise-power CDFs at the CF transmission frequencies of 16, 24 and 32 Hz were calculated for both ES and WS locations. Figure 17 gives the results for 280-s-record populations of n samples each, where the subscript to n indicates whether the records are taken from WS or ES. At 16 Hz the noise-power CDF for both sites are equivalent within measurement uncertainty, while higher noise levels at 24 and 32 Hz were often measured at WS. That WS was located approximately 300 m (1000 ft) closer to road traffic at its elevation than was ES

Fig. 12.
24-Hz transmissions observed at WS vs distance.

Fig. 13.
24-Hz transmissions observed at ES vs distance.

(refer to Fig. 8) probably accounts for the difference. In the absence of differences from road noise, the noise environments at both sites may be close to equivalent, a result to be expected in view of the comparable 460 m (1500 ft) burial depth beneath the mesa of the respective installations. Based on noise environment alone, one would expect that ES would be more useful than WS in the detection of transmitted signals; in fact ES was not.

That road traffic affected the noise environment at WS is substantiated by the difference in the 16-Hz noise-power CDFs obtained using only unclipped records of the 20-s and 280-s record populations; Fig. 18 shows the difference. As a vehicle passed near WS, noise levels would increase and then fade. The noise from the passage of a vehicle could be clearly observed for roughly 2 min during which time clipping often occurred. Consequently the

Fig. 14.

32-Hz transmissions observed at WS vs distance.

Fig. 15.

Power spectrum of noise at WS during relatively noisy period.

Fig. 16.

Power spectrum of noise at WS during relatively quiet period.

Fig. 17.
Noise-power CDF at 16, 24, and 32 Hz
observed at WS and ES.

Fig. 18.
Noise-power CDF derived from 20-s
and 280-s record populations.

rejection of clipped samples from the analysis of the 280-s record population was likely to purge most samples of traffic noise in that population.

The population of WS 20-s records was large enough for a search for diurnal changes in the G-Tunnel noise environment. Figure 19 gives 16-Hz noise-power CDF calculated for 2-h time intervals from 1800 to 0400 h. The contribution of road traffic noise appears small if present at all after 2200 h. The linearity of the CDFs for periods after 2200 h indicates that the noise power at WS is log normally distributed as would be the case for an environment comprised of only geophysical noise (Sax et al. 1966). During the 10-h nighttime period studied, there are no systematic changes in noise structure at WS, apart from the traffic noise contribution.

Fig. 19.
Noise-power CDF at 2-h intervals observed at WS.

XI. SIGNALING RATE PER CHANNEL

The following rationale was used in the selection of data for signaling rate calculations. The rationale comes closest to fulfilling the generalities of the primary objective of the measurements in G-Tunnel: that of determining the feasibility of surface-to-tunnel seismic telemetry using currently available technology. Further, the rationale is developed recognizing that the assessment of feasibility should relate to prospective installations in which operating conditions for seismic communications have been optimized by selection of the best available transmitter and receiver sites. The latter probably will be the quietest sites, perhaps even in deep boreholes beneath the installation -- locations removed from nongeophysical noise sources or locations at which quiet periods approaching geophysical noise levels can be realized through cessation of movement of personnel and mechanized equipment. Because of the high operating frequency of seismic telemetry, lower frequency seismic noise arising from distant sources in wartime does not need to be considered. Using this rationale, the "best" or optimum detection location in

G-Tunnel was WS. The noise-power CDF of the 280-s records at 16 Hz closely replicates geophysical noise conditions, while the 280-s records at 24 and 32 Hz approach geophysical noise. For optimum transmitter sites we chose those sites at increasing distance from G-Tunnel for which the transmitted signal power represents strong relative maxima.

We seek the signaling rate having a 95% reliability for signals transmitted between the superior transmitter sites and WS. For reliable communications, we require a signal-to-noise power ratio $(S/N)_{\text{req}}$ of 20 (13 dB). Expressing the relevant relationships for calculation of signaling rate in terms of ratios and requiring a bandwidth, B_{req} , equal to the bit rate R necessary to obtain the desired signal-to-noise ratio, we find

$$S/N_{\text{req}} = S/N \times \frac{B}{B_{\text{req}}}$$

where S is the average signal power, N is the noise power having a 95% probability at the signal-transmission frequency, and B is the bandwidth of the detection system in use. Substituting, rearranging, and simplifying

$$R = \frac{1}{400} \cdot S/N$$

S for the appropriate site and frequency is found in Table I, II, or III. N is derived graphically from the appropriate CDF in Fig. 17 by finding the mean noise power and adding two times the standard deviation of noise power, σ . The value for 2σ is obtained by taking the positive difference of the noise powers in the 16 and 84 percentiles, respectively. These data are summarized in Figs. 20, 21, and 22 and in Table V.

Table V gives the signaling rate per channel. Figure 23 gives a log-log plot of these data vs site range. The dependence of signaling rate, R (bits/s) on range D (km) at each transmission frequency is closely approximated by a function of the form $\log R = A - 3.37 \log D$ where A is some function of frequency. The 16-Hz data should be adjusted upward if they are to be equated with the 24- and 32-Hz data on the basis of force. Recall that only 60% of the total force used for the higher frequency transmissions was available at 16 Hz. Figure 24 shows the functional dependence of the constant A on frequency evaluated at 10 km (6.2 mi). For illustrative purposes, brackets have been added to show the effect of a ± 2 dB re nm^2 systematic error in the estimation of noise power at 95% probable occurrence. Also shown

Fig. 20.

16-Hz signals and noise used in signaling rate vs distance calculations.

Fig. 21.

24-Hz signals and noise used in signaling rate vs distance calculations.

is a value for 16-Hz transmissions to which a theoretical correction has been applied to account for the cited force difference. Substantially increased signaling rates, which are potentially in excess of 1 bits/s at 10 km (6.2 mi), appear to be available on reduction of the transmission frequency to 10 Hz or below.

XII. DISCUSSION

Referring to Fig. 20 one can see that with the noise conditions prevalent in G-Tunnel, the detection of 16-Hz transmissions from optimum sites as distant as 95 km (60 mi) may have been possible. It seems likely that the ultimate range at which transmissions can be detected has yet to be measured.

There are several possibilities, derived from the conduct and conclusions of this project, for increasing the signaling rate for seismic communications at the NTS or wherever seismic telemetry may serve a purpose. Additional

Fig. 22.
32-Hz signals and noise used in signaling rate vs distance calculations.

Fig. 23.
Calculated signaling rate vs distance for the 16-, 24-, and 32-Hz transmissions.

TABLE V
SIGNALING RATE AT 95% RELIABILITY

Frequency Hz	Site #	Range km (mi)	S dB re nm ²	N dB re nm ²	R bits/s
16	30	16.4 (10.2)	-32.0	-50	0.158
	33	25.7 (16.0)	-36.2		0.060
	49	35.9 (22.3)	-40.5		0.022
	51	44.6 (27.7)	-43.9		0.010
	56	63.4 (39.4)	-49.6		0.003
24	32	21.9 (13.6)	-32.0	-48	0.100
	45	47.6 (29.6)	-44.3		0.006
32	30	16.4 (10.2)	-46.1	-58	0.006
	33	24.1 (15.0)	-53.6		0.001
	9	35.2 (21.9)	-60.8		<0.001

Fig. 24.
The frequency dependence of A evaluated at 10 km.

alternatives are suggested by the accumulated experience represented by the seismological literature. Possibilities may be enumerated, but not exhausted, in terms of the components of the seismic telemetry system examined at NTS, namely: source and sensor technology, siting, and propagation-path determinations.

The standard servo-hydraulic vibrator may be modified to increase energy and decrease the frequencies available for transmission. The Vibroseis units that we used were operated at 16 Hz with 60% of the total available force. That percentage continually decreased with frequency until CF transmissions were impossible at 8 Hz, although that frequency was in the range available

for SF transmission. Having experienced these operational limitations, we contacted the George E. Failing Co. and visited their manufacturing plant to discuss our problem. Using a version of the Y-1100 vibrator with standard modifications, they demonstrated its capability for continuous 8-Hz operation at peak force. The modifications increased base-plate loading and provided greater available hydraulic power.

Extreme variability of signal power from site to site at comparable distances from G-Tunnel is shown in Figs.10-14 and Table IV. Only known in vague generalities is the relationship between energy coupled into the earth and the nature and composition of the soil cover and local bedrock. The data suggest that the selection of optimum transmission sites may be possible if suitable selection criteria are developed.

The attempt to determine the propagation path through the earth's crust of seismic transmissions (Ward 1983) proved impossible within the scope of the project, principally because of the contamination of SF data by coherent noise sources in the tunnel and because suitable processing software was unavailable. Without a determination of signal-propagation paths, it is not known how the sites used relate to the seismic-velocity structure at the NTS. That the structure is complex is indicated by the heterogeneity of the regional geology. A determination of seismic structure would enable advantage to be taken of transmission through wave guides or along highly refractive layers and in choosing transmission frequencies least attenuated by characteristic physical dimensions in the velocity structure.

The observations above regarding coupling and seismic structure apply equally well to siting criteria for tunnel-based or borehole seismometer installations. The difference in S/N of signals detected at the ES and WS locations is almost certainly related to the seismic structure of rock immediately beneath G-Tunnel. UTD showed that a major fault overlain by the younger Rainier Mesa volcanics of G-Tunnel separates ES and WS.

Noise reduction or suppression is a tractable approach for increasing the S/N for seismic transmissions. Little difference in the noise environment at ES and WS was seen. This meager evidence and the fact that each location was at comparable depth below the Rainier Mesa implies that a substantially quieter site would not be found in G-Tunnel. The installation of seismometers in boreholes dug beneath G-Tunnel might have afforded quieter conditions. Douze (1964) reported measurements of 1-Hz noise in deep wells in the U.S. At

3 km (~10,000 ft) in various wells, the improvement in noise varied from 0 to 20 dB.

That earth noise varies with physiographic environment has been shown by Franitti (1963). For example, noise at the NTS is 20 dB higher than that at Castle Cliff, Utah, at comparable times of day. The highly variable landform represented at the NTS implies improvement in noise environment based on tunnel location in relation to the NTS physiography is possible.

In summary, siting criteria based on coupling phenomena, local and regional seismic structure, and noise variability with depth and physiography, can be developed. These criteria in turn should enable definition of the ultimate limitations on an installation-by-installation basis of seismic telemetry.

XIII. CONCLUSIONS

Within the limitations explored through the field test at NTS, mono-frequency seismic telemetry using existing telemetry has been shown feasible. Those limitations, to a good first approximation, are defined by the empirical relations elucidated in this report between signaling rate, range, transmission frequency, system-component siting, and tunnel noise properties.

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