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TECHNICAL REPORT NO. 71-8

A STUDY OF RADAR EXPLORATION OF COALBEDS

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A STUDY OF
RADAR EXPLORATION OF COALBEDS

by

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Final Report on Contract No. H0101620

U. S. Department of the Interior
Bureau of Mines
Pittsburgh Mining Research Center

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A STUDY OF RADAR EXPLORATION OF COALBEDS

1. SUMMARY

A 1-year program of exploratory research, to determine the feasibility of radar exploration in advance of coal mining, has been completed. Advance detection of obstructions including faults, clay veins, abandoned wells, and pyritic concretions would improve the safety and efficiency of mining. Initial calculations based on laboratory tests of the RF electrical properties of bituminous coals indicated feasibility; radar waves at frequencies below 100 MHz should be detectable through tens to hundreds of meters of coal and be well-reflected by clay, pyrite and metal obstructions. Using a proprietary, experimental, VHF short-pulse "mining radar" system, two cycles of field testing and equipment improvement were completed. Measurements were made in three bituminous coal mines, a quarry, and a salt mine. Comparisons were made with ground-penetrating radar equipment developed by others for salt dome exploration and for military tunnel detection.

The proprietary mining radar equipment and techniques used were found to be the most effective known for coal exploration, but further improvements are needed; one major problem in all systems is interfering clutter signals arising in the equipment and from mine room reverberations through leakage coupling of the antennas to the air. Nevertheless, several practical goals have been achieved: excellent radar reflections were received and identified through up to 30 feet of coal; reflections from a wet, abandoned drill hole were identified by their polarization property and detected at distances up to 272 feet, and mine-wall reflections were detected at distances up to 735 feet (both through salt); propagation through and reflections from large vertical clay veins in coal were demonstrated; experimental results agree reasonably well with theory. The results and experience gained during the project affirm the feasibility of the method. They also provide a firm basis for the development of a practical radar technology for exploration in advance of mining.

No Subject Inventions, as defined in the contract, were made in the course of this work.

2. BACKGROUND

The objective of this study was to make a preliminary determination of the usefulness of V.H.F. (P-band), short-pulse ("monocycle") radar in detecting dislocations and obstructions in advance of coal mining.

Of particular interest were "clay veins," nearly vertical fracture fillings of indurated clay minerals, commonly 1/2 to 2 feet thick, which occur sporadically in the extensive Pittsburgh coalbed. "Clay veins" tend to obstruct the free drainage of native methane through the normal joint pattern of the coal into the mine workings where it can be continuously diluted and removed by forced ventilation. Breaching of an unexpected clay vein can result in unsafe methane concentrations near the working face. On the other hand, prior detection and location of the clay vein would permit excessive methane to be removed via drill holes before the continuation of mining, with a consequent improvement in mine safety.

Other possible hazards which it would be desirable to locate include pyrite concentrations ("sulfur balls") and lost or unknown well casings, which can dull the cutters of a continuous mining machine, cause the striking of dangerous sparks at the working face, and drain water and oil into the mine workings.

Preliminary calculations indicated that bituminous coal should be reasonably transparent to radar waves in the 50 to 300 MHz (V.H.F.) range, and that both clay veins and metallic objects should be good reflectors. Coal and clay specimens provided by Mr. Maurice Deul and others of the Pittsburgh Mining Research Center were tested by Geotech and their electrical properties were found to be such as to further support these conclusions. See Appendix 1.

Consequently, this program of computations, laboratory and field studies was undertaken under contract to test the applicability of radar to the exploration of coal in advance of mining. For this purpose, a portable V.H.F. "monocycle" radar system belonging to the Teledyne Micronetics Co. was made available. This radar is capable of detecting objects at distances as short as 1 meter in front of the antennas, and it can resolve reflectors as little as 1 meter apart in range. Although this equipment was experimental in character and was, therefore, rather bulky, heavy and delicate, it was highly flexible and otherwise ideal for a practical feasibility study in the field.

Late in the program, a VHF short-pulse, ground-penetrating radar known as the "advanced prototype VHF tunnel detector" was made available by the U.S. Army Mobility Equipment R & D Laboratories. Extensive tests were made with this equipment also, which is much more portable but less flexible.

The remainder of this report will summarize the work of the contract in accordance with the arrangement of items in the Scope of Work.

3. SECTION 1.1 - "CONDUCT TESTS OF ELECTRICAL PROPERTIES OF COALS AND OTHER ROCKS IN THE LABORATORY"

Since this work was completed on all the appropriate samples that were available, prior to receipt of the contract there was no need to repeat it. The results have been published and are summarized in Appendix 1.

4. SECTION 1.2 - "CALCULATIONS OF EXPECTED SYSTEM PERFORMANCE"

Initial computer calculations were made, on the basis of the data in Appendix 1 (extrapolated somewhat for higher frequencies) of attenuation coefficients, wave velocities and complex intrinsic impedances vs. frequency, for four hypothetical average substances:

"Coal-PR" (with polarization parallel to bedding), "Coal-N" (with polarization normal to bedding), "pyritic" coal and "clay." Figures 1, 2, 3, 4, 5, 6, and 7 summarize these results. From the complex impedances, complex reflection coefficients R vs. frequency were calculated for coal-PR vs. clay, coal-N vs. clay, and coal-N vs. pyritic. These are plotted in figures 8, 9, 10, and 11. The formulae used, taken from standard textbooks,* were as follows:

Attenuation coefficient α:

$$\alpha = (60\,\pi\,/\rho\sqrt{\kappa}\,)\ \text{meters}^{-1}$$

where ρ = equivalent resistivity, ohm meters
κ = relative dielectric constant
f = frequency, Hz.

Wave velocity v:

$$v = \left[\frac{\kappa}{18 \times 10^{16}}\left[1 + \sqrt{1 + (18 \times 10^{9}/\kappa\rho f)^{2}}\right]\right]^{-1/2}\ \text{m/sec}$$

Intrinsic impedance Z:

$$Z = 120\pi/\ [1-j(1.8 \times 10^{10})/\kappa\rho f]^{1/2}\ \text{ohms}$$

Reflection coefficient R of an interface (normal incidence):

$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

*For example, A. von Hippel, "Dielectrics," chapter 7, p. 4-110 in the Handbook of Physics, ed. by E. A. Condon & H. Odishaw, McGraw-Hill, N.Y., 1958.

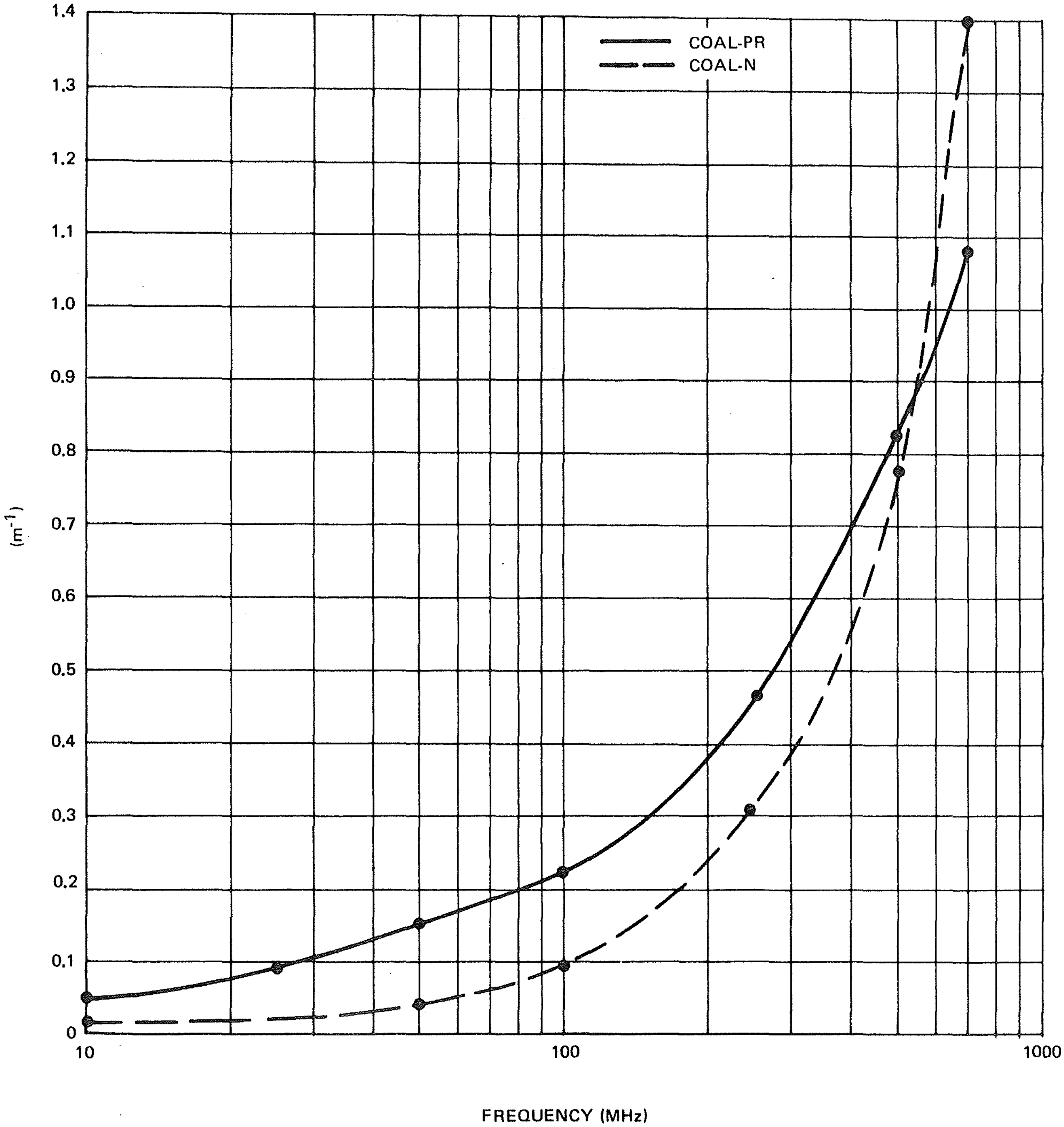


Figure 1. Attenuation coefficients α vs frequency

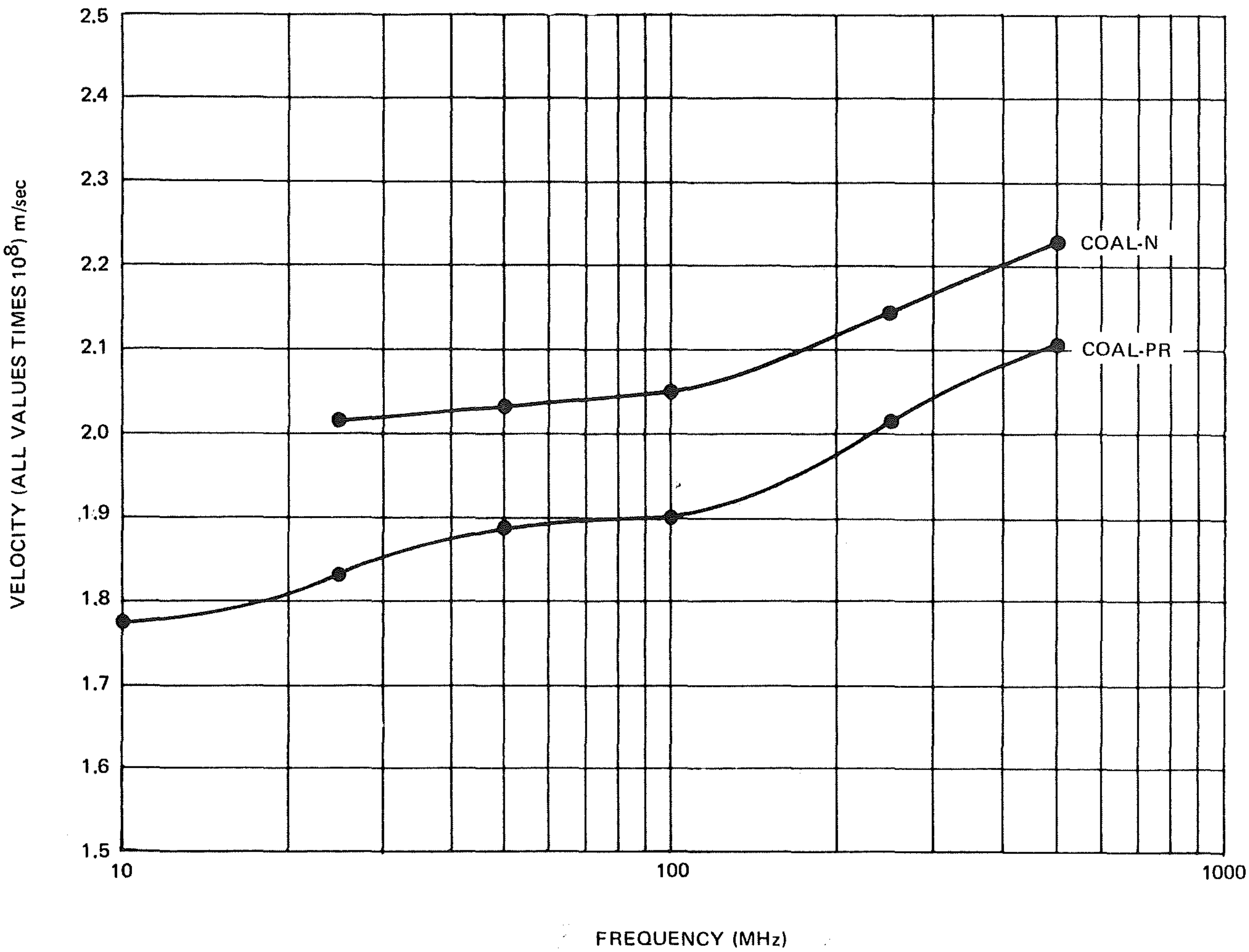
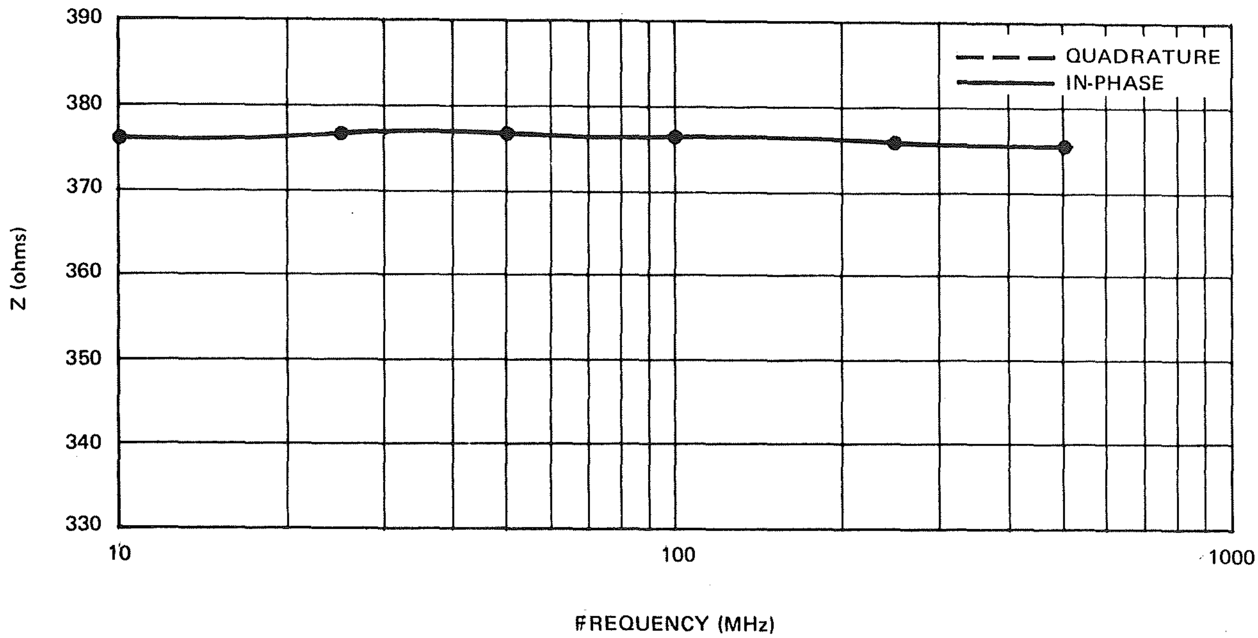


Figure 2. Wave velocities vs frequency for "clean" coals



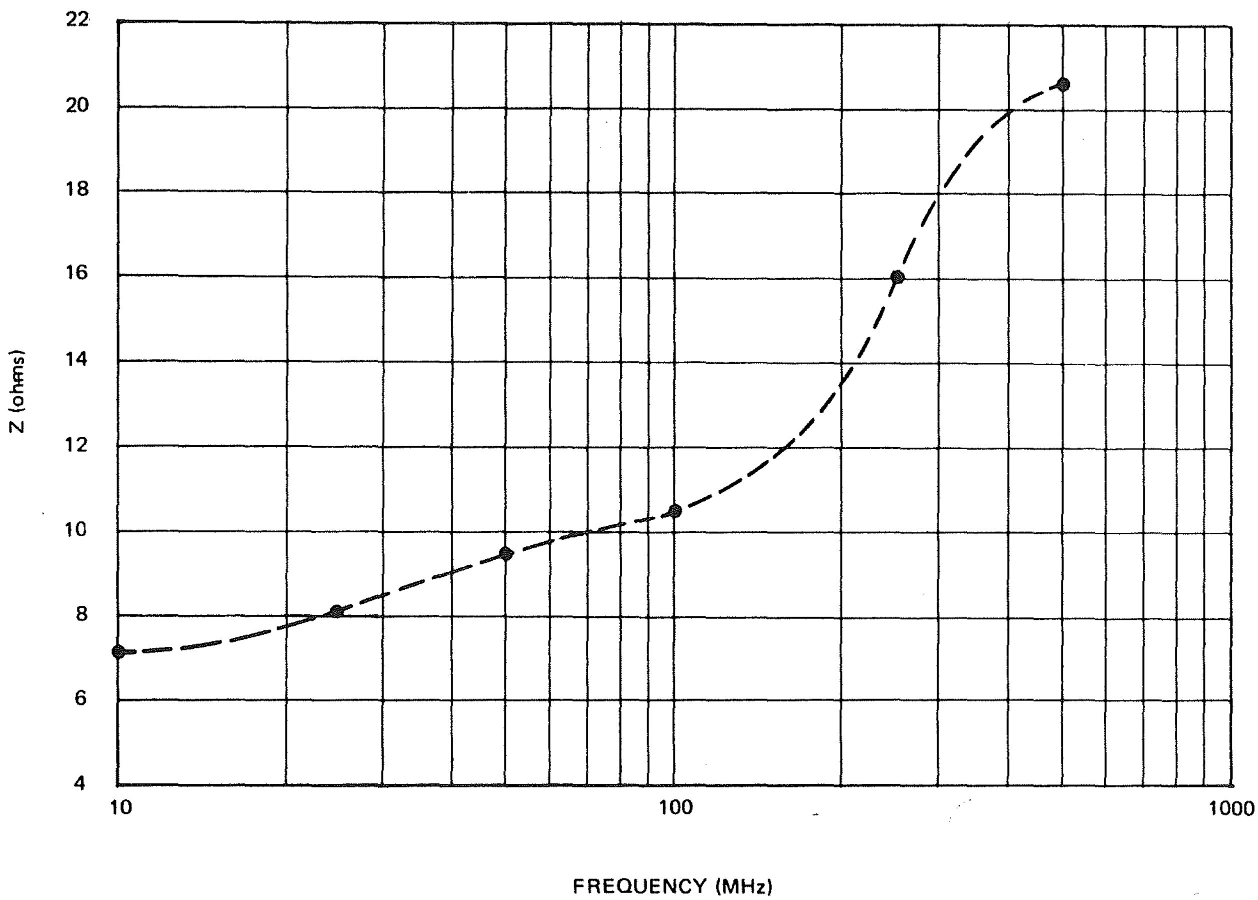


Figure 3. Intrinsic impedance vs frequency, for coal-N

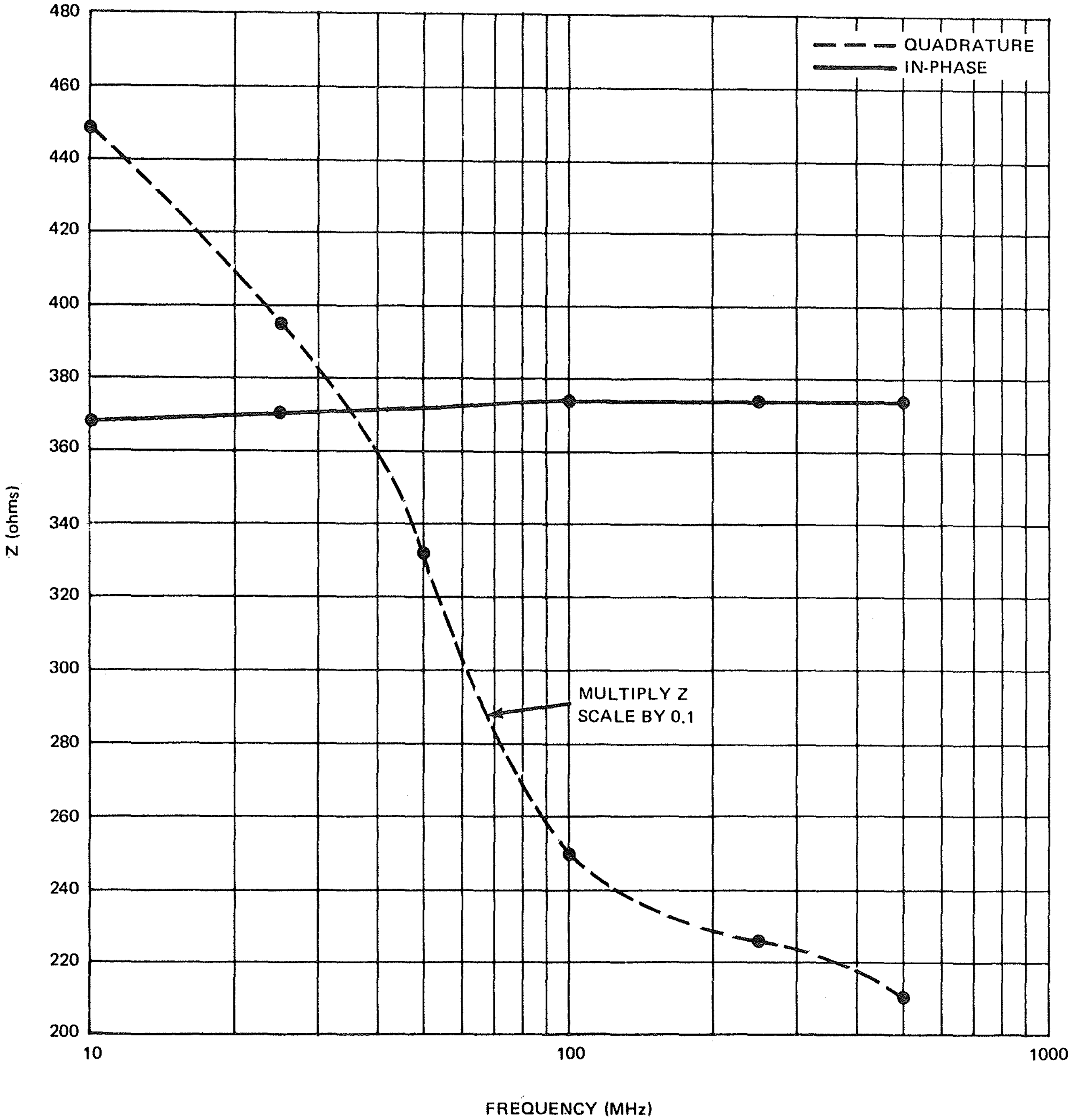


Figure 4. Intrinsic impedance vs frequency for Coal-PR

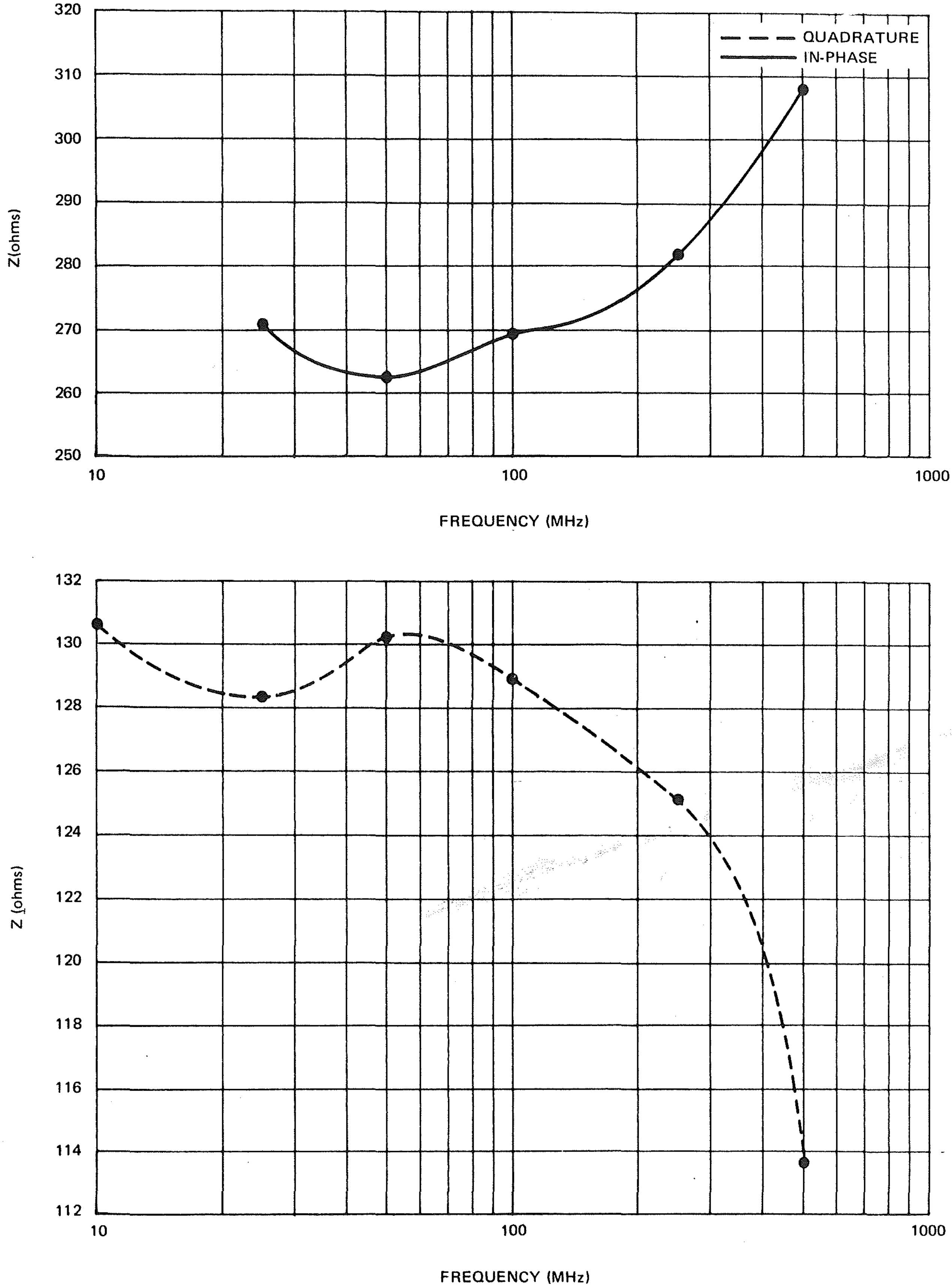


Figure 5. Intrinsic impedance vs frequency for clay-N

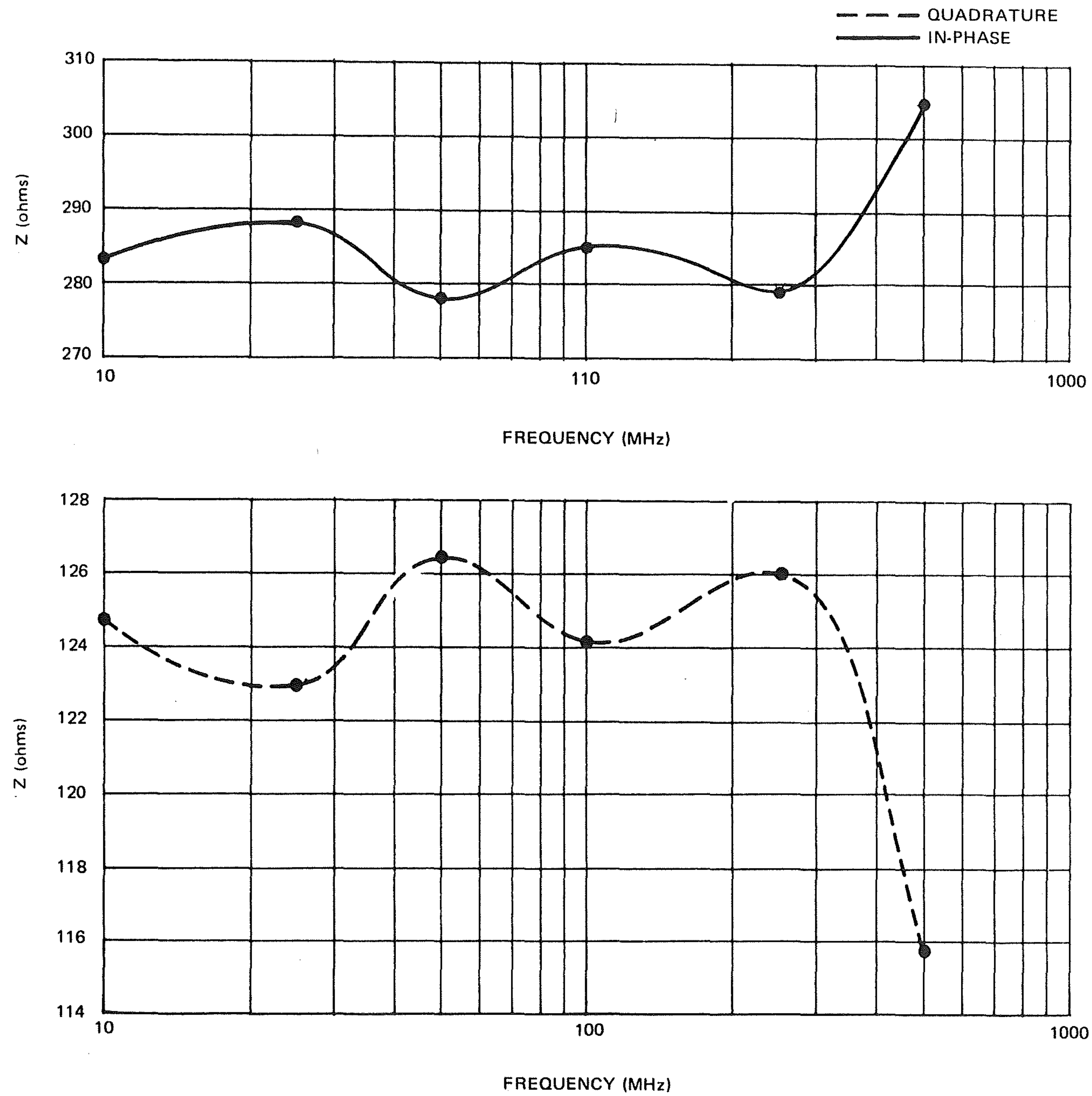


Figure 6. Intrinsic impedance vs frequency for clay-PR

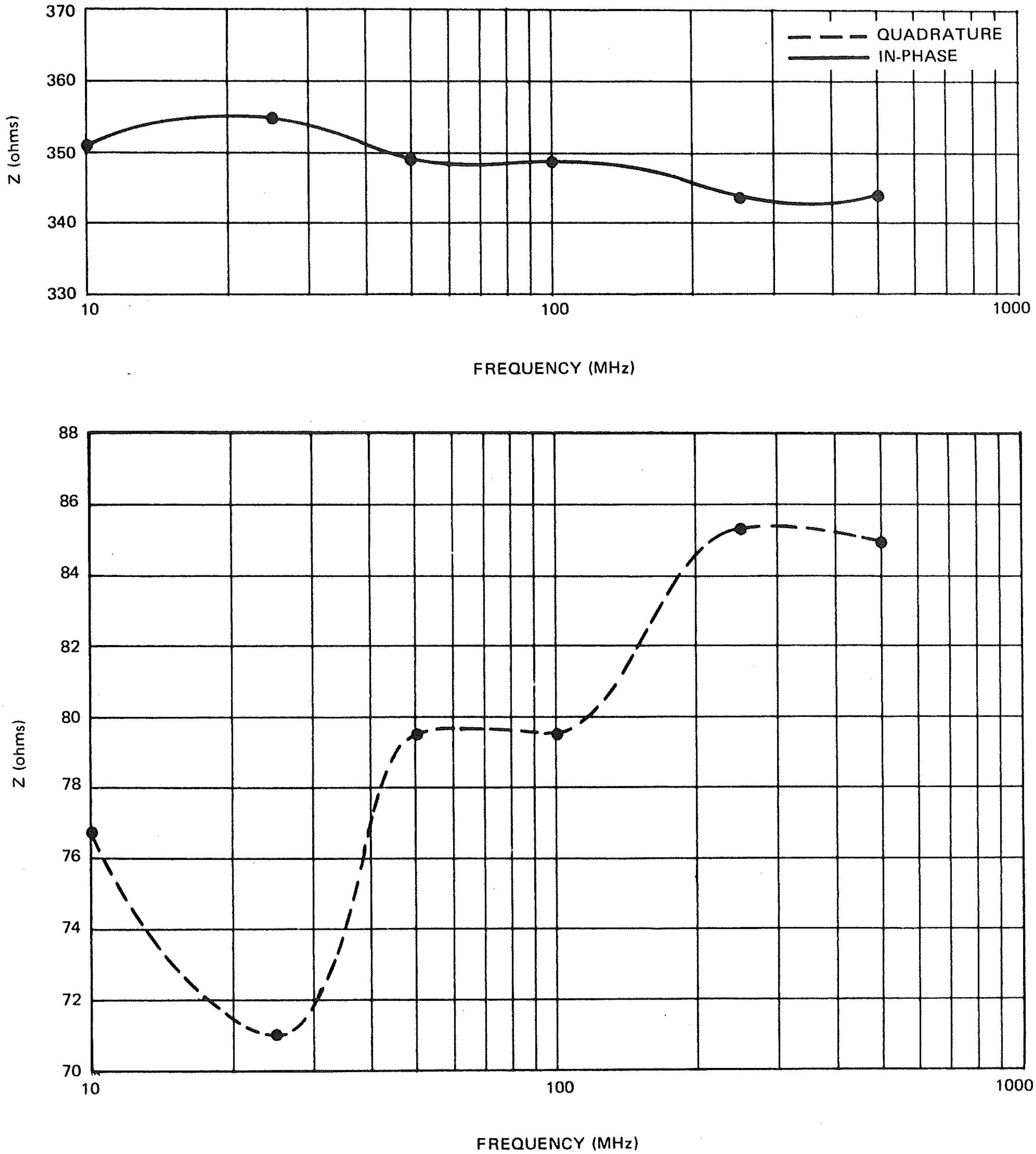


Figure 7. Intrinsic impedance vs frequency for pyritic coal

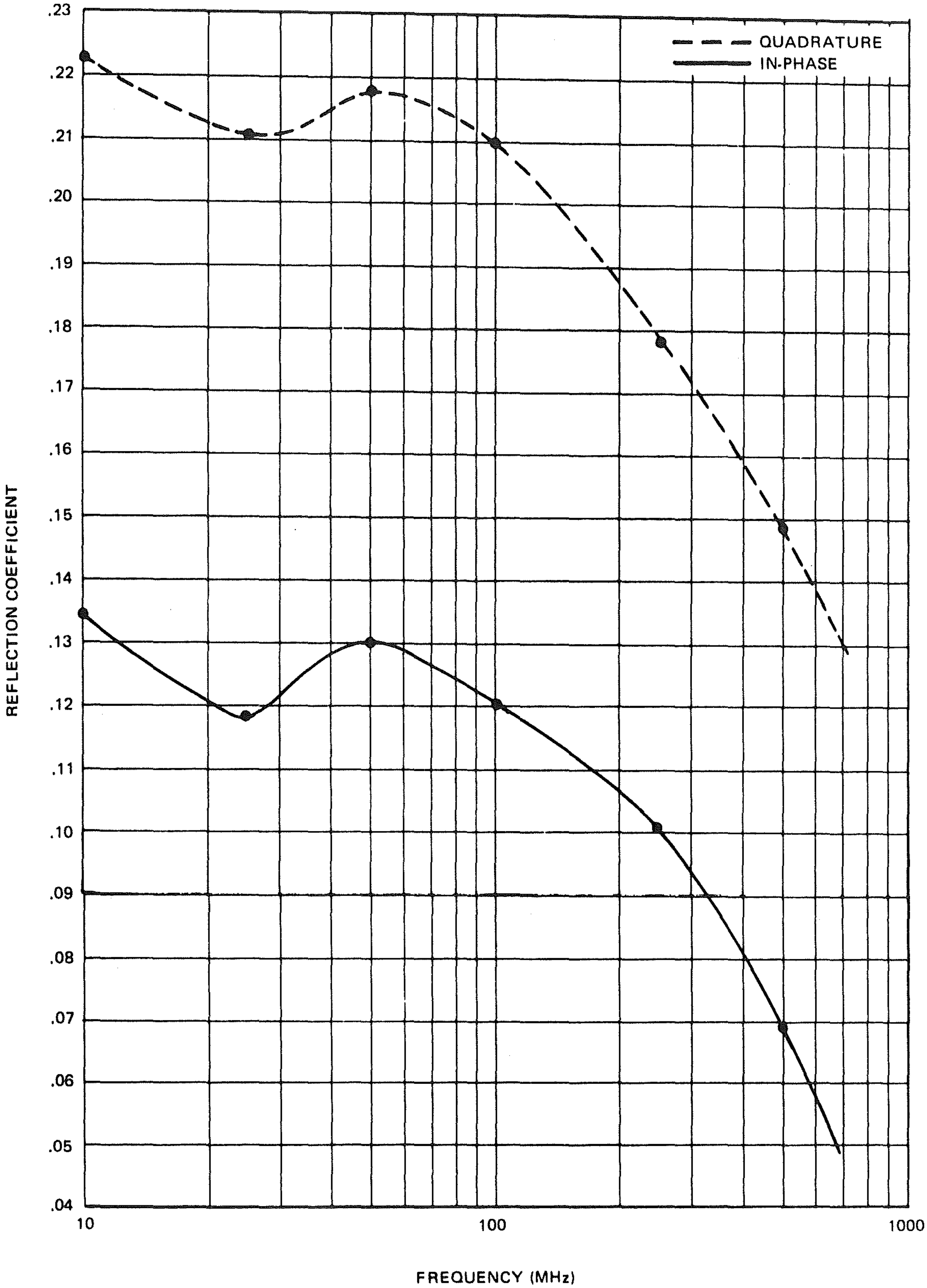


Figure 8. Reflection coefficient, coal-N vs clay-N

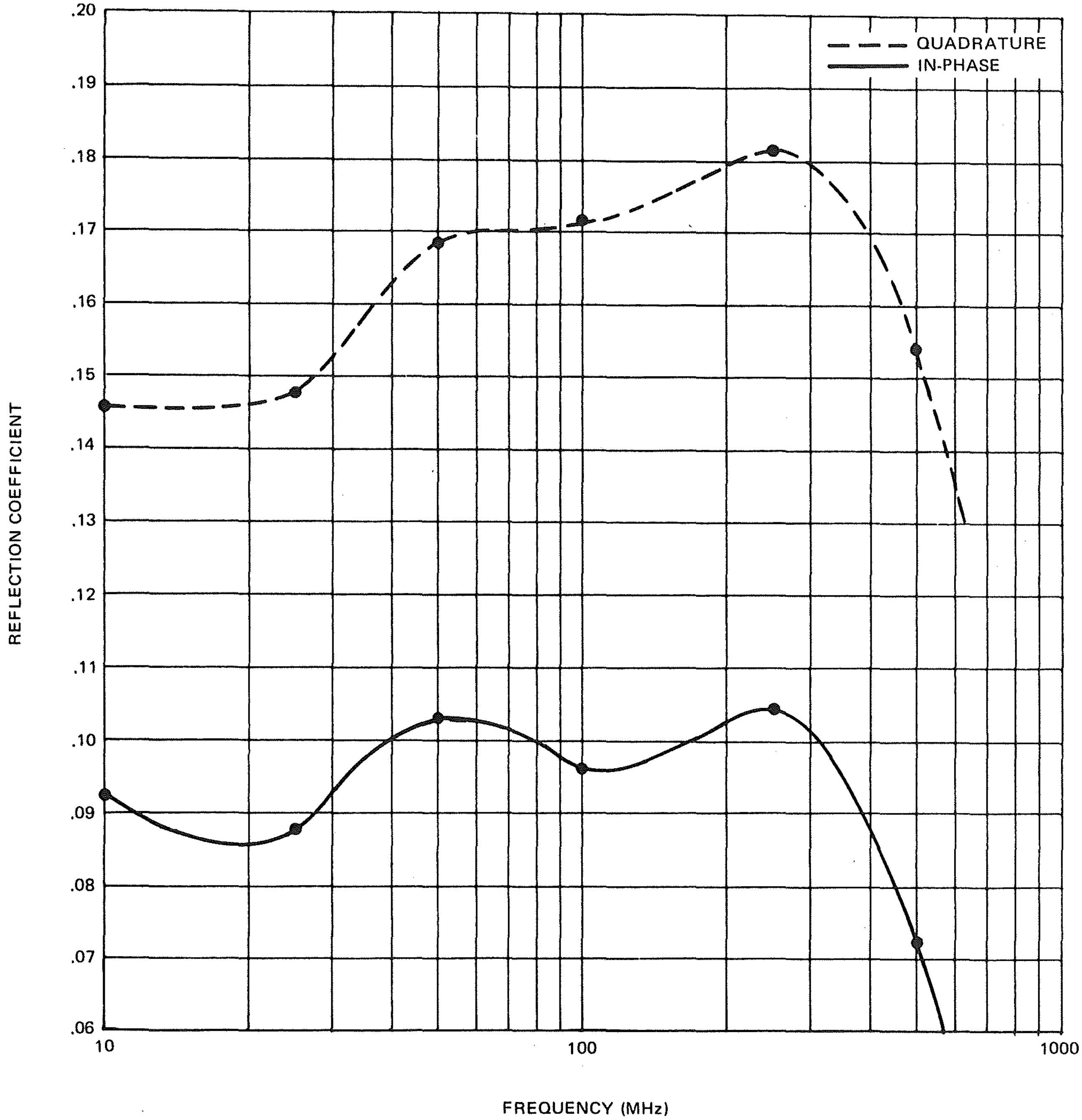


Figure 9. Reflection coefficient, coal-PR vs clay-PR

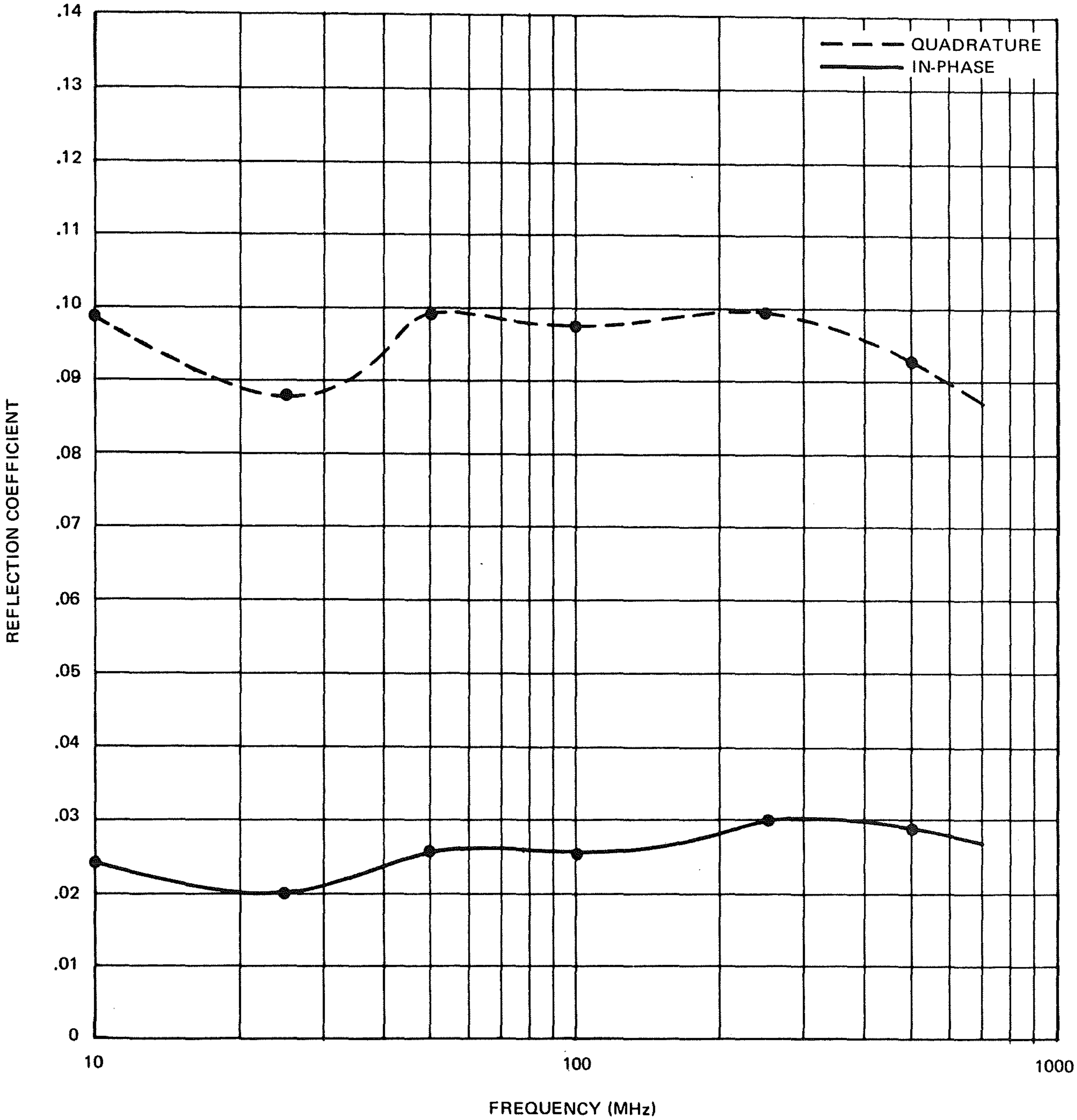


Figure 10. Reflection coefficient, coal - N vs pyritic

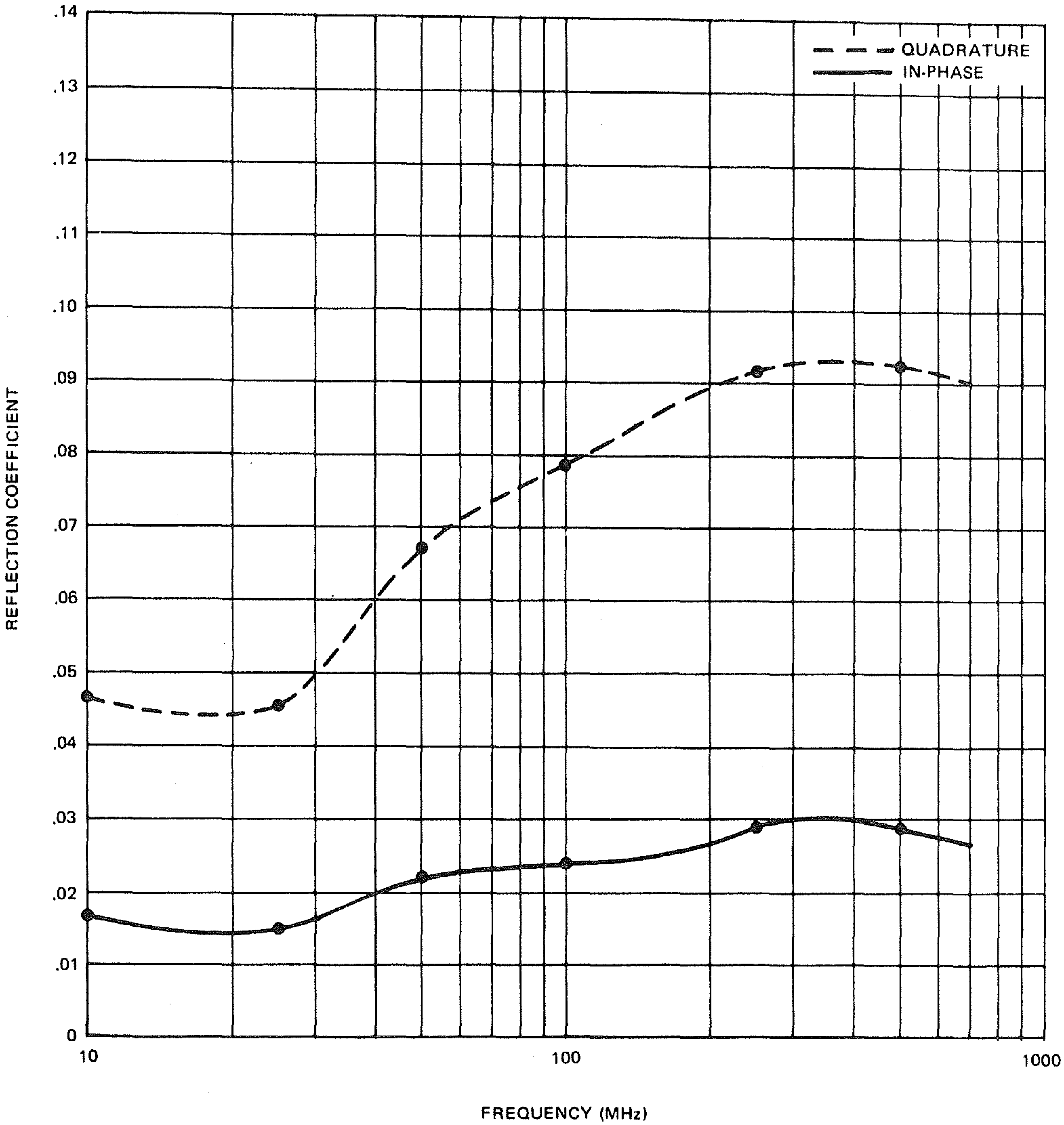


Figure 11. Reflection coefficient vs frequency, coal-PR vs pyritic

All these quantities are functions of frequency. The curves show approximate values and general trends, but should not be considered accurate in detail, because of both the extrapolation above 100 MHz and the fact that the involved computer calculations were not checked by manual computations, since the values and trends are all physically reasonable.

These results were to be used in predicting the effect of propagation through coal and reflection from various obstructions upon the waveform and amplitude of a VHF monocycle radar signal.

Figure 12 shows two digital computer waveform plots: (a) the waveform radiated by the Teledyne Micronetics radar as digitized from an oscilloscope photograph, and (b) the expected waveform after propagation through 6 meters of "coal-PR," that is, a representative coal, with the waves polarized parallel to the bedding. The latter plot was computed by convolution of the attenuation filter function: exp. $[-\alpha(f)x]$ with the radiated waveform (a), using the values of α vs. frequency given by the solid curve of figure 1. Figure 13 shows similar plots for normal polarization (using the dashed curve of figure 1) for (a) propagation through 6 meters (b) through 20 meters of coal. The relative amplitudes are noted on each plot. Note that in each of the three computed plots, there has been marked smoothing (that is, filtering-out of higher frequencies) and reduction in the size of the wave, as would be expected.

Attempts were made to apply the attenuation function exp. $[-\alpha(f)\ x]$ to the original waveform shown in figure 12(a), for longer paths x than those shown in figures 12(b) and 13. This effort was unsuccessful because of mathematical limitations in the "single-sided" filter computer program available; plots were obtained which were physically unreasonable. Data-processing experts suggest that a "two-sided" filter program will be needed. However, the effort of preparing such a program was not warranted for determining general feasibility of the radar method, so this refinement was not attempted.

The waveform shown in figure 13(a) was convolved with a time-domain filter corresponding to the scattering operator* for a small sphere of radius a:

$$S = \frac{\sigma}{4\pi x^2} = \frac{44{,}500\ a^2}{4\ \pi x^2} \left(\frac{a\kappa f}{3\mathrm{x}10^8}\right)^4$$

A sphere 0.1 meter in radius (8 inches in diameter) was assumed. The backscatter distance x from the sphere to the receiving antenna was taken to be 6 meters. The medium in which the sphere is embedded was assumed to have the dielectric constant κ of coal-N. The result is shown in figure 14(a). (Note that the time scale in figures 12, 13, and 14 is denoted by tick marks 2×10^{-9} sec or 2 nanoseconds apart on the baseline.)

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*From the ITT Handbook, "Reference Data for Radio Engineers," 1956, p. 804.

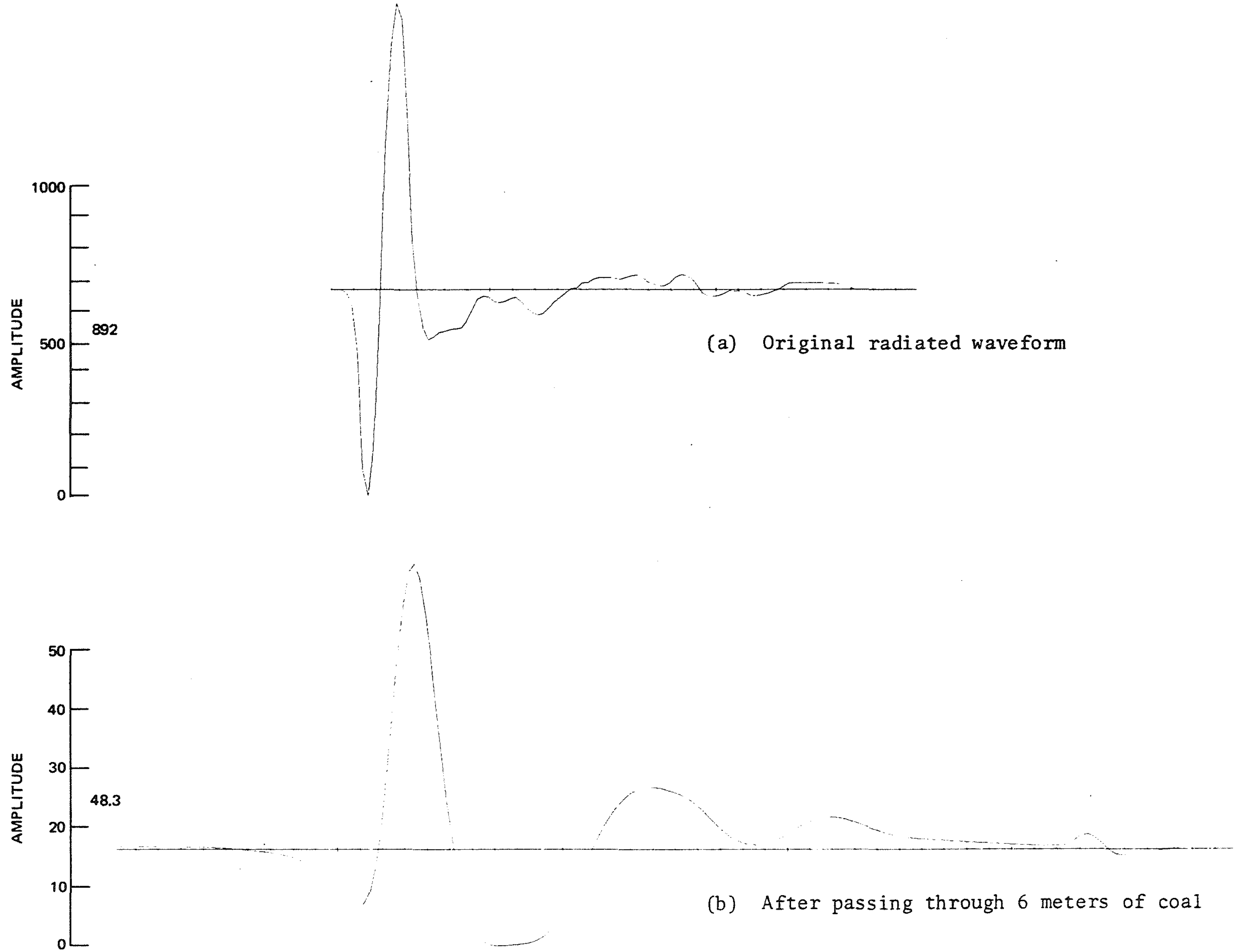

Figure 12. Computer waveform plots for coal - PR

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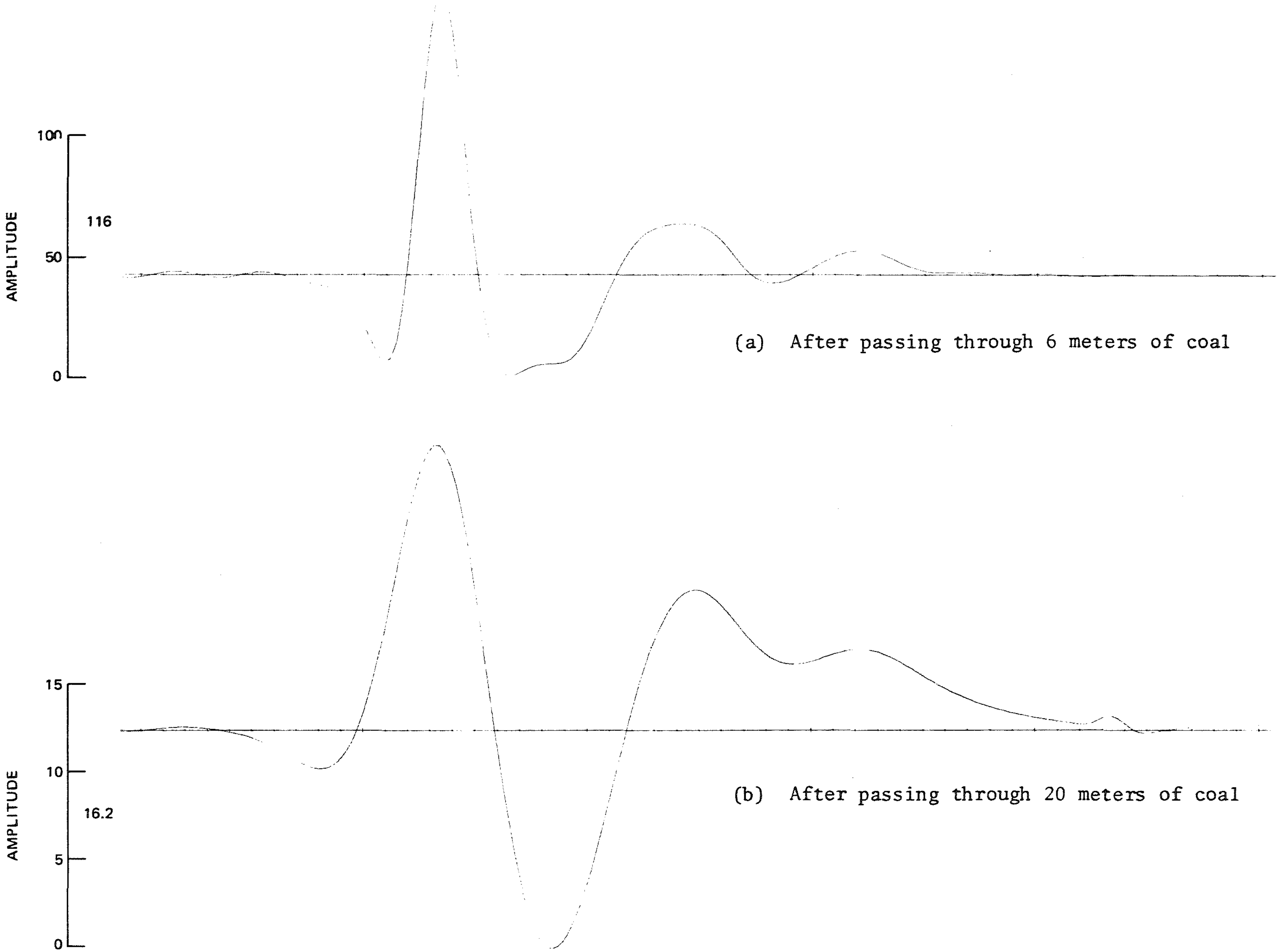

Figure 13. Computer waveform plots for coal - N

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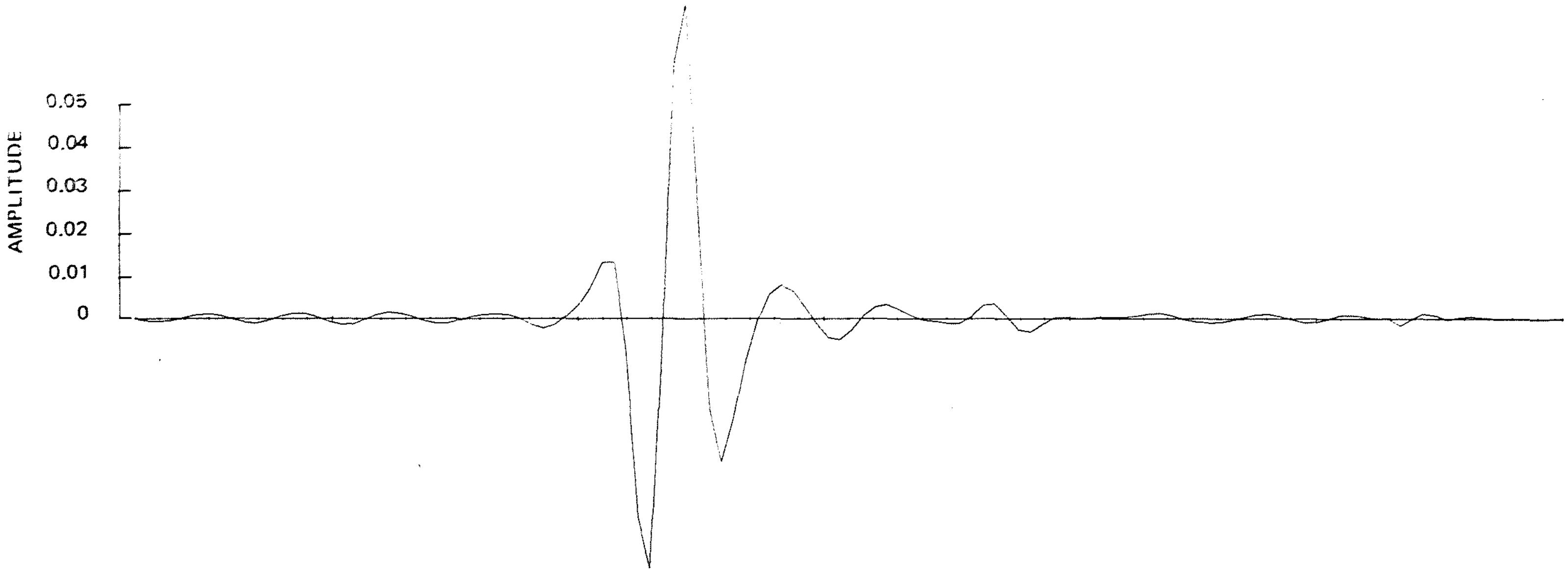
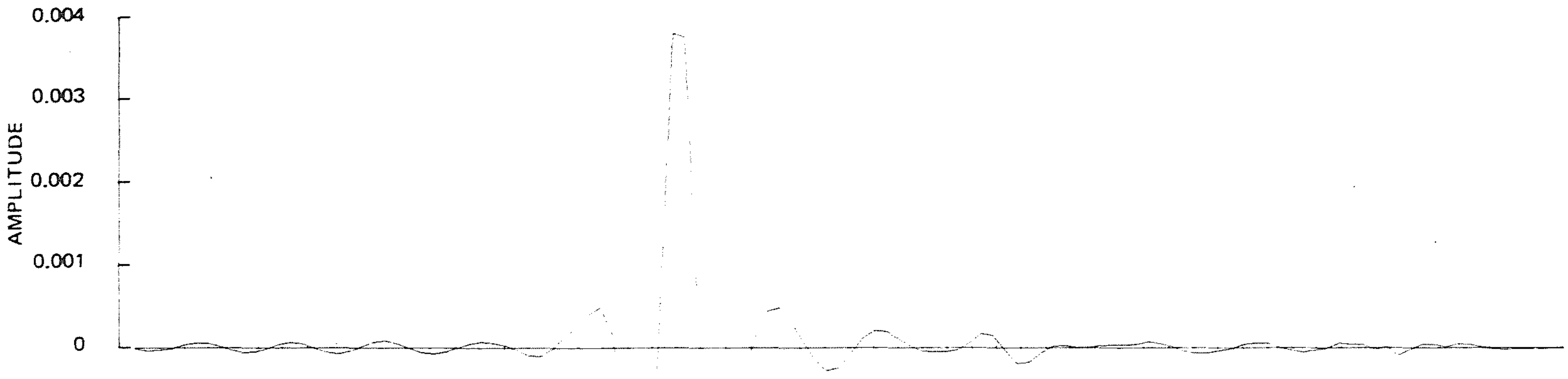


(a) After attenuation by 6 M of coal-N and scattering to 6 M by an 8-inch sphere



(b) After attenuation by 6 M of coal-N, scattering 6 M from an 8-inch pyritic sphere, and dispersion by 6 M of coal-N

Figure 14. Computed radar waveforms

Comparing this waveform with that of figure 13(a) shows that reflection from a small sphere would favor the high frequencies. This filtering effect, plus the rapid spreading of energy in the return path, would result in a signal 60 dB weaker than that impinging upon the sphere (figure 13(a)). Hence, small pyrite concretions will be relatively difficult to detect; but if detected, they can perhaps be identified by their strong tendency to reflect the higher frequencies, for which the wavelengths in coal are comparable to the sizes of the concretions.

Attempts were made to convolve the waveform scattered 6 meters from an 8-inch sphere in coal-N, figure 1(a), with the dispersive delay operator, which is already in the time domain:

$$D = \frac{x}{v} = x \left\{ \frac{\kappa}{18\times10^{16}} \left[1 + \sqrt{1 + \left[\frac{18\times10^{9}}{\kappa\rho f}\right]^{2}} \right] \right\}^{1/2}$$

This should introduce slightly greater delays for the lower frequencies, since the change in ρ does not quite offset that in f for coal-N (see figure 2, Appendix 1). Attempts were also made to introduce the effect of the reflection coefficient R of pyritic coal embedded in coal-N, to take account of the fact that a pyritic-coal sphere is not a perfect reflector. For this purpose, a time-domain filter corresponding to the complex operator plotted in figure 10 was programmed and applied to the waveform.

The result of these two additional operations is shown in figure 14(b). The high frequencies remain dominant, though the expected waveform has changed. Additional attenuation by about 26 dB has also occurred. There is some doubt that these last two computer operations were done correctly, because the plot after dispersion showed no change of waveform. However, we did not recheck, de-bug and repeat this series of computations, because the general trends of the results are physically reasonable, and are useful qualitative guides for interpreting actual radar signals as they stand. It is probably not important to refine these calculations, since it appears that if the additional filtering by the attenuation function in the return 6-meter path were added, as would be necessary, the signal from an 8-inch pyrite sphere at 6 meters' distance in coal-N would become essentially undetectable.

Attempts were made to apply the appropriate filter functions to the radiated waveform (figure 12(a)) for two additional cases:

(a) A flat, vertical, thick "half-space" of clay in contact with coal-N at a distance of 6 meters. The filters needed are: attenuation, dispersion, hemispherical spreading and reflection coefficient. The first two are applied twice.

(b) A vertical metal pipe embedded in coal-N at a distance of 6 meters. The filters needed are: attenuation, dispersion, hemispherical spreading, and scattering function. The first <u>three</u> filters must be applied twice.

These attempts were abandoned in favor of approximate manual calculations at a single frequency, because of the slowness and high cost of programming, checking and de-bugging detailed calculations on the computer. It was concluded that sufficient initial insight into the effect upon waveform of propagation through coal had been attained through the calculations summarized in figures 12, 13, and 14.

During the predictive computer work, initial performance figures on the Teledyne Micronetics radar became available through direct laboratory tests. The radar receiver output noise is approximately 4 millivolts (mv) peak-to-peak, which is close to the theoretically expected thermal noise for a bandwidth of 50 to 750 MHz, at the 50-ohm impedance level used. Underground, the RF ambient noise received through the antenna appears to approach this level, as was hoped. On the other hand, in the labs at Geotech, the ambient RF noise is 60 to 100 mv peak-to-peak, probably coming mostly from TV and radio stations.

The radar power available at the transmitting antenna gave 320 mv at the receiver output, with 60 dB of attenuation in the line (equivalent receiver output = 320 volts) and the two antennas coupled together, with their solid apertures touching. This means that the radar performance figure (signal-to-noise ratio) is about 73 dB in the lab, and is 98 dB in a quiet underground environment.

This capability was compared with the estimated absorption losses, spreading losses, scattering and reflection losses to be expected underground. Over a 20-meter path (2D) (round-trip) in coal, with vertical polarization, these are:

(1) Absorption loss at 100 mHz: 20 log exp. $(-\alpha 2D)$ = 17 dB.

(2) Spreading loss: $10 \log \left(\frac{4\pi D^2}{GA}\right) = 35$ dB

(where the effective transmitting antenna gain G and receiving antenna aperture A are given by: $G = 10 \text{ (horn area)}/\lambda^2 = 3.35$, $A = G\lambda^2/4\pi = 0.12 \text{ meter}^2$)

(3) Reflection loss at 100 mHz: $-10 \log |R|$

= 13.6 dB for coal-N vs. clay (figure 8).
= 3.8 dB for coal-N vs. air ($R \simeq 0.4$).

(4) Scattering loss: $10 \log \left(\frac{4\pi D^2}{\sigma}\right)$

= 6 dB for a flat wall (spreading distance doubled).
= 14.6 dB for an 8-inch vertical pipe (for which the scattering cross-section σ of the first Fresnel zone* is given by $\sigma = \frac{2\pi(\text{radius})}{\lambda} \times (0.68D)^2 = 43 \text{ meter}^2$).

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*The effective length L of a cylindrical scatterer is that of the first Fresnel zone, over which a curved wavefront impinges with a maximum delay of /2. At a distance D from the source this is: $L = 2D\sqrt{1-4D^2/(\lambda+2D)^2}$. The scattering cross-section formula for a cylinder, from the ITT Handbook, is somewhat in doubt because it does not include a polarization effect.

$= 37.2$ dB for an 8-inch sphere (for which the scattering cross-section $\sigma = 9\pi a^2 \left(\frac{2\pi a}{\lambda}\right)^4 = 0.22 \text{ meter}^2$).

These estimates give the following totals and signal-to-noise ratios with the 98-dB radar performance:

Flat coal-air interface through 10 m of coal: total losses 62 dB, S/N = 36 dB.

Flat coal-clay interface through 10 m of coal: total losses 72 dB, S/N = 26 dB.

8-inch metal well casing through 10 m of coal: total losses 67 dB, S/N = 31 dB.

8-inch metallic (pyrite) nodule through 10m of coal: total losses 89 dB, S/N = 10 dB.

In general, the echo time delay expected in coal is $\sqrt{\kappa} \approx \sqrt{2.2}$ times that expected in air; that is, 3.02 nanoseconds per foot of range.

These results all appeared favorable, and justified proceeding with field experiments.

5. SECTION 1.3 - "DIRECT TRANSMISSION EXPERIMENTS," and SECTION 1.4 - "REFLECTION EXPERIMENTS."

Since these two kinds of experiments were both performed at each test location and over several months of time, they will be discussed together.

After initial familiarization and calibration, the radar was set up in a small wooden building surrounded by open ground near Geotech, to measure reflections from various objects. The antennas are designed to operate into solid material, and when operating into the air there is an additional mismatch loss of 4.3 dB. The following reflected peak-to-peak signal equivalents were measured:

6 ft. chain-link fence at 16.5 meters: 1.0 volt
small truck at 10 meters: 0.54 volt
2-inch pipe (in E-direction) at 6 meters: 0.63 volt
2-inch pipe (in E-direction) at 3 meters: 3.5 volt
5-gallon can at 4.5 meters: 0.47 volt
5-gallon can at 2 meters: 1.9 volts
1-gallon can at 2 meters: 0.63 volt
man standing at 2 meters: 1.9 volts

It is noteworthy that these reflectors could clearly be detected at such close ranges with this radar. Polarization effects were as expected theoretically; that is, a pipe oriented in the direction of the electric vector gave a good reflection, but gave very little at right angles to the E-vector. All the signals listed were much larger than the receiver noise, but were obscured by large fixed "clutter" echoes in the equipment, cables, and from surroundings and by low-frequency reverberations in the system. Identification was generally possible only by removing the test reflector, as shown in figure 15. Sheets of RF absorber material placed over the antenna apertures did cause a specific decrease in test reflector echoes, and would permit their identification, except that the clutter patterns were also changed somewhat. Underground, working into a solid medium, this problem is less serious because of reduced leakage into the air, and better antenna matching.

The back-scattered signal intensities did not obey the expected fourth-power law of decrease with distance, apparently because of antenna-aperture and ground-reflection effects at such close ranges.

The absolute signal amplitude measured with the pipe reflector at 6 meters, 630 millivolts, is in reasonable agreement with a predicted signal of 330 millivolts calculated from the antennas-touching experiment, the mismatch-to-air loss, and the formulas given in (2), (4), and the footnote at the end of foregoing Section 3. But the signal measured from the 5-gallon can at 4.5 meters, 470 millivolts, is 30 dB larger than the 14 millivolts predicted by calculation, considering the can to be a sphere 0.17 meter in radius. This indicates that the cross-section formula may not apply in this size/wavelength range, and the possibilities of detecting a pyrite nodule may be much better than was predicted by figure 14.

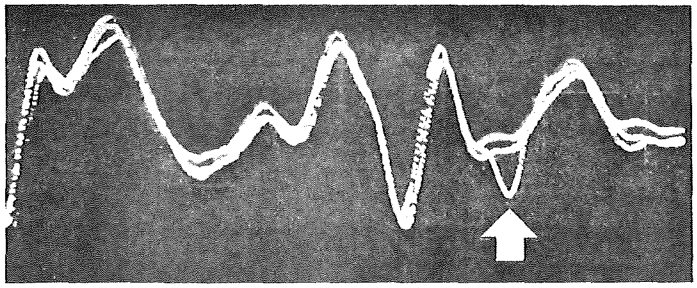
5.1 FIRST COAL MINE TESTS, AUGUST, 1970

Following the lab checkouts of the radar system, it was packed and shipped to Pittsburgh. By arrangement with the Bureau of Mines, the equipment was placed in passage No. 7 of the experimental coal mine near Bruceton, Pennsylvania (figure 16) by a diesel mine locomotive, where careful and exhaustive tests were begun. Because of excessive condensation and dripping in No. 7, the equipment was later moved to No. 6, since all tests were made on the 24 ft. by 56 ft. "thin" pillar between these passages. Oscillograms and magnetic tapes were recorded from the following tests:

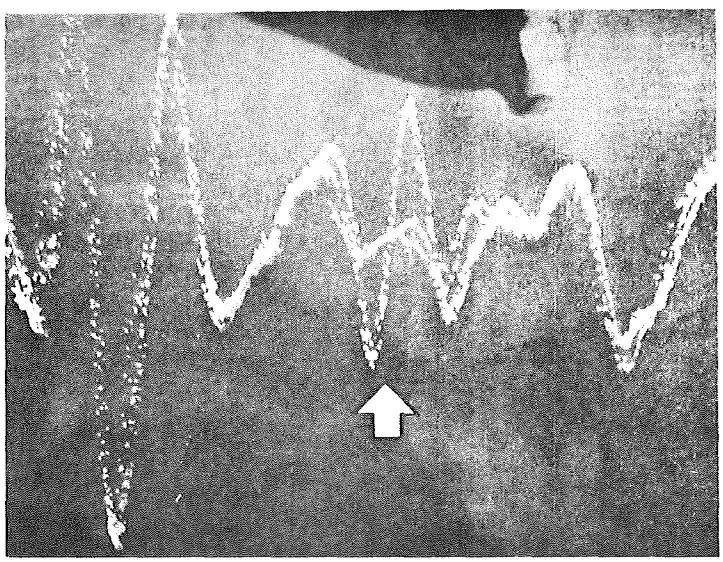
1. Direct propagation one way through the coal;
2. Propagation over an equal air path, for comparison;
3. Propagation through coal containing a clay vein "barrier;"
4. Reflections from the far side of the pillar;
5. Reflections from the clay vein.

Great difficulty was experienced in making a clear interpretation of the recordings in the field. A signal was apparently received one-way through 24 feet of coal, and it apparently traveled at about half its speed in air. However, no reflections were identified at this time.

After 4 days at this mine, the equipment was packed for a trip to the Putnam coal mine of the Union Carbide Company in western West Virginia. The company gave a thorough guided tour of this new modern mine, which utilizes conveyor-belt transport, with explanations of the economics,



(a) Truck at 5 meters (1 trace); no truck (2 traces)



(b) Ten ft., 2" pipe at 3 meters (1 trace); no pipe (2 traces)

Figure 15. Radar oscillograms with and without test reflectors

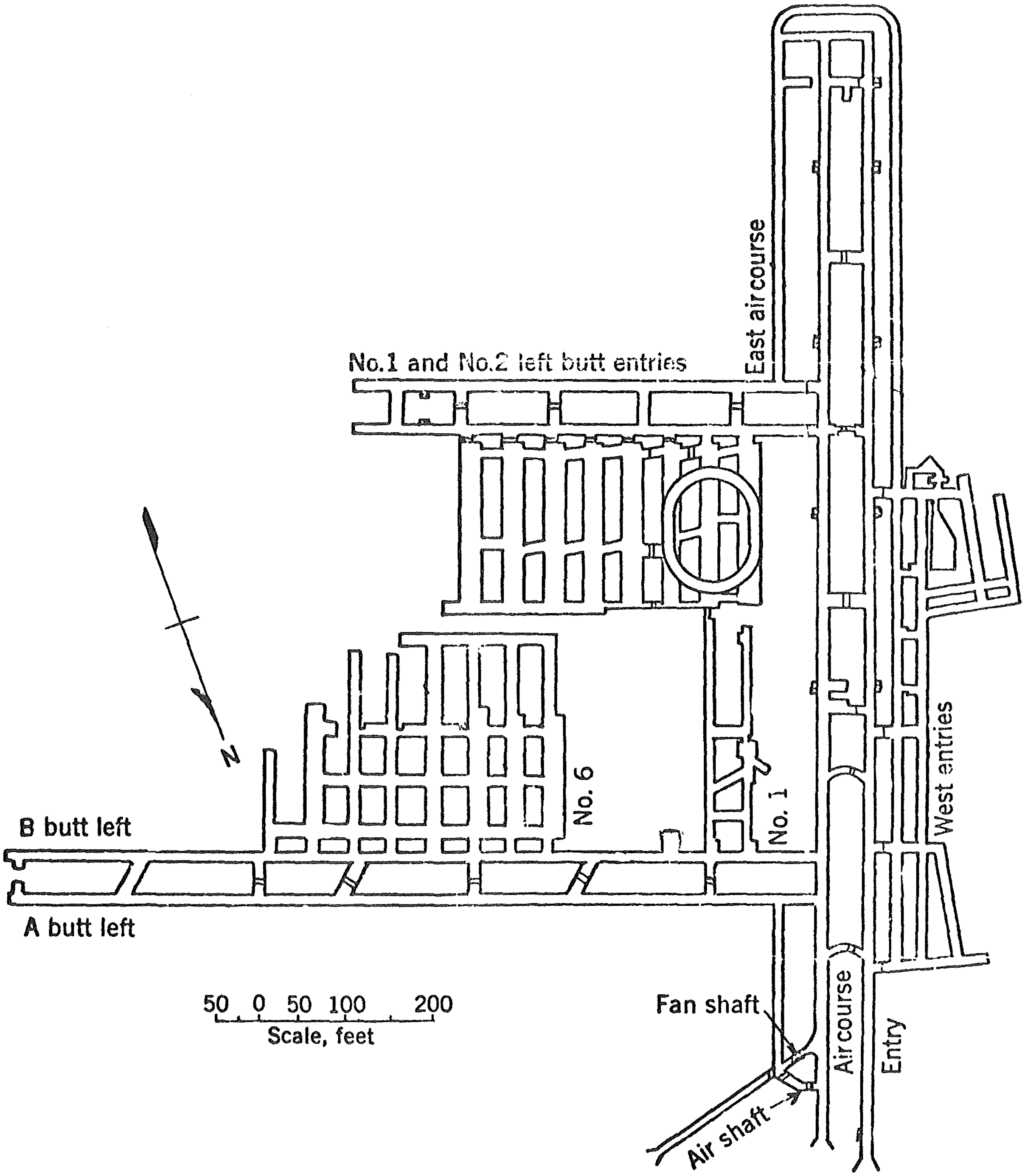


Figure 16. Plan of experimental coal mine

operation problems and equipment by two mining engineers. The same five tests listed above were completed at acute-angled corners of two different trapezoidal pillars; all the pillars were at least 40 feet thick except near the corners. Clay veins were erratic and discontinuous, and it was uncertain whether any of the radar paths were through clay-free coal. The results were again quite complex, and interpretation in the field was not attempted.

Arrangements were then made with the Marianna mine of the Bethlehem Mines Corporation, near Washington, Pennsylvania, by USBM personnel to perform radar tests. This old, large mine is served by permanent, high-speed, electric-trolley trains running in the fresh-air intake passages. The thinnest accessible pillar in the mine was selected, adjacent to No. 1 entry of 3 Butt C face N, and the 500 pounds of equipment was carried in, the last 200 feet on foot. The selected pillar proved to have a prominent clay vein running lengthwise along its axis, with 70° dip and blocking all possible radiation paths through the coal. Nevertheless, direct-propagation and reflection recordings were made. As at the previous sites, RF absorber sheets were inserted in the main beams of the antennas for alternate recordings, to assist in interpreting and identifying "true" signals passing through the coal. All other pillars in the vicinity were about 90 feet thick, which were at that time considered beyond the capabilities of the radar. The tests were completed and the equipment was repacked for reshipment to Texas in a single working day.

Figure 17 illustrates a typical radar setup and the equipment used in these experiments. The enclosed, dielectric-filled horn antennas were always placed in close contact with the coal face, which had been trimmed flat to within an inch, using a miner's pick. All the equipment had been provided with stout protective enclosures for rough handling in a dirty environment. It was powered either by existing 110 V mine power lines (at Bruceton) or by two 350-watt solid-state inverters operating from 12-volt automobile batteries. The antennas and cables had been examined and the transmitter pulses had been tested by allowing them to spark inside an explosion test jig containing an explosive air-methane mixture at the Bureau of Mines' testing laboratories, and so had been certified as permissible for use at a coal mine face. The other experimental equipment was used only in fresh-air passages with Bureau of Mines' permission or supervision.

5.2 INITIAL DATA REDUCTION AND INTERPRETATION, BRUCETON MINE.

The 1970 data from the Bruceton mine were studied first. These data consisted of the following:

August 18 - Three sets of 'scope photos - "reflection from clay vein;"
August 19 - Two 'scope photos - "reflection from pillar end;"
Nine 'scope photo pairs - "one-way propagation;"
August 20 - Three 'scope photo sets - "reflection from pillar end;"
Two 'scope photo pairs - "one-way propagation;"
Four 'scope photo sets - "reflection from pillar wall;"

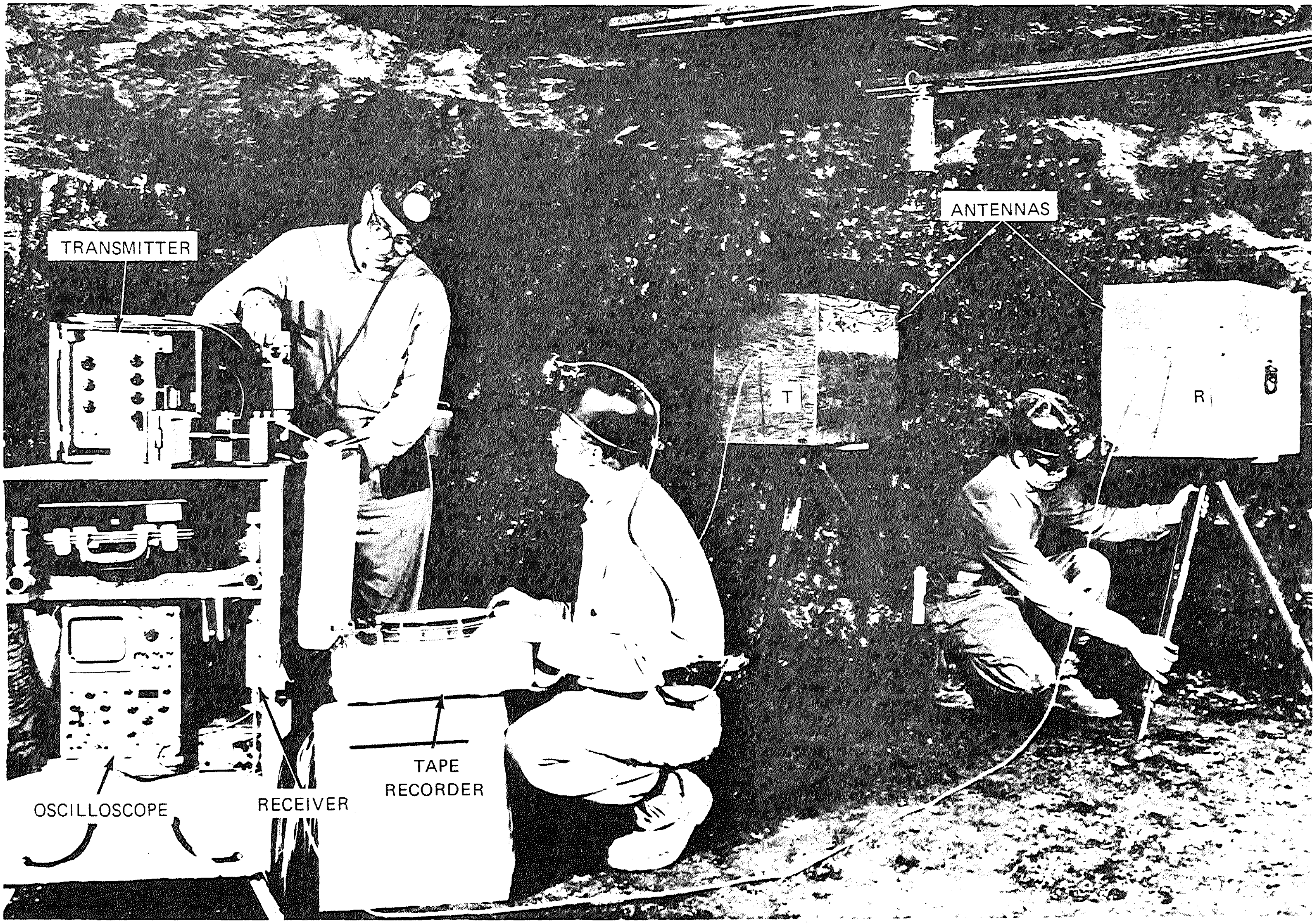


Figure 17. Radar test in Bruceton Mine (USBM photo)

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August 21 - Magnetic tape and pen-recorder records from 15 experiments on pillar-wall reflection, clay-vein reflection, and one-way propagation.
Two 'scope photos from the last-named.

The 'scope photos were all studied carefully at least twice. Fifteen segments of the magnetic tape were played through corrective filters, then recorded on paper, to remove noise and objectionable low-frequency reverberation to bring out the desired radar signals. These recordings appeared to be far superior to the 'scope photos in clarity and detail. Initial observations made and conclusions drawn from the above-listed materials were as follows:

(1) As shown in figure 18(a), a strong signal was received in the direct propagation of vertically-polarized waves through a 24-foot thick pillar of coal. By comparison with figure 18(b), this signal is seen to be 15 dB weaker than a corresponding signal through air, and of lower frequency: 100 MHz vs. 250 MHz, as would be expected.

(2) The air signal (figure 18(b) appears to contain a 100 MHz component about equal in magnitude to the coal signal. This means that the absorptive attenuation in 24 feet of coal is comparable to the mismatch loss suffered when the antennas operate into an air medium, which was estimated at 5 dB. This in turn implies an attenuation constant for vertically-polarized waves in this coal of approximately $\alpha = 0.08$ meter^{-1} at 100 MHz, in good agreement with figure 1.

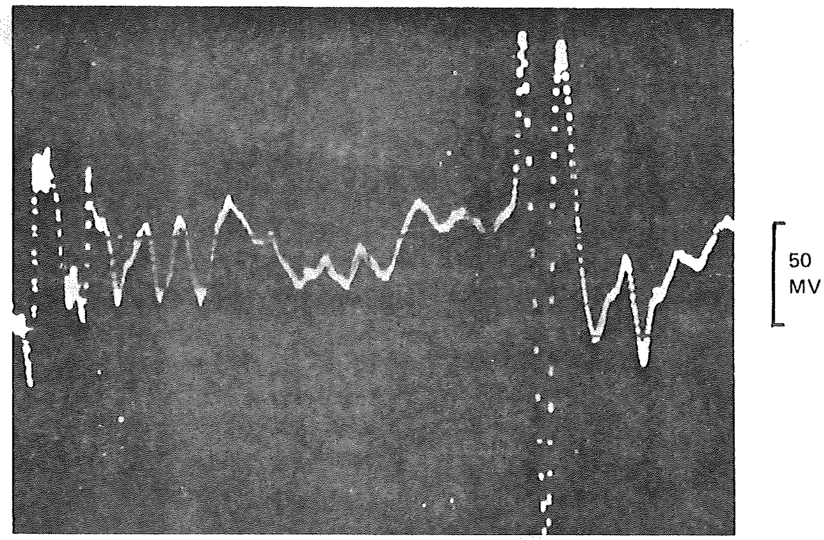
(3) The additional propagation delay in the coal is 26 nanoseconds. This gives an average refractive index of 2.11 or a dielectric constant of $\kappa = 4.5$ at 100 MHz, somewhat higher than was expected from the hand-sample tests (figure 3, Appendix 1). However, this result means that these antennas, which are matched to a dielectric constant of 5, should operate very well in coal.

(4) Horizontally-polarized waves (figure 18(c), top) were not received, so must suffer at least 33 dB of attenuation in 24 feet of this coal, implying an attenuation constant of at least $\alpha = 0.51$ meter^{-1}, much more severe than would be expected from figure 1.

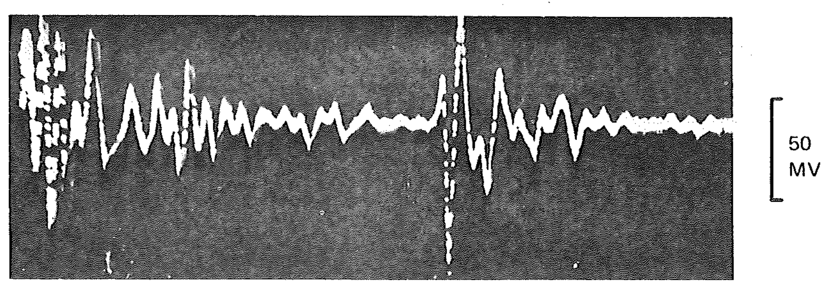
(5) Cross-polarization of the receiving antenna causes decoupling by 18 dB, as can be seen in comparing figure 18(c), bottom, with figure 18(a).

(6) Diagonal propagation paths through the coal result in amplitude decreases which imply a half-power beam width in coal for each antenna of approximately 80° in the horizontal plane, using vertical polarization.

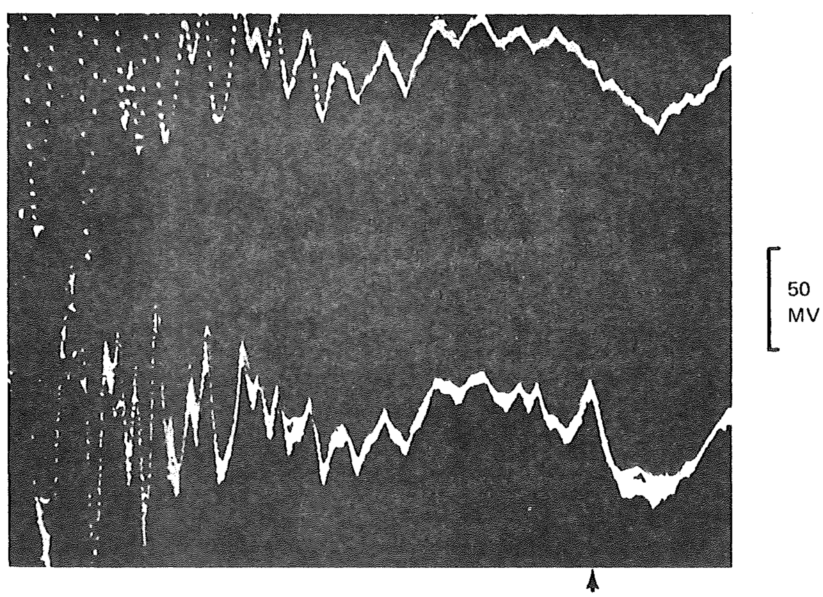
(7) One-way propagation lengthwise through a coal pillar 56 feet long was apparently unsuccessful. Since the distance was 2.33 times as great as through the narrow dimension of the pillar, additional losses of 7 dB from beam-spreading and 7 dB from absorptive attenuation at 100 MHz were expected, which should have provided a signal 1/5 as large in amplitude as that shown in figure 18(a). A 100 MHz signal half this size was obtained,



(a) Vertical polarization; 10 dB attenuation



(b) 24 ft. air path; 30 dB attenuation



(c) Horizontal polarization (top); trans. V, Rec. H (bottom); 10 dB attenuation

Figure 18. Direct transmission through 24 ft. of coal. All sweep lengths = 140 nsec. All vertical scales equal

as shown in figure 19(a), but it arrived at too early a time. This signal could be interpreted as a leakage signal propagating around the pillar through the air, except for its low frequency. The two 20 MHz "signals" later in time on figure 19(a) are spurious effects and may be ignored. A number of other mysteries remain, such as the difference in 20 MHz spurious signal amplitude relative to noise between figures 19(a) and 19(b), bottom, and the cause of the second, larger air-propagated signal in figure 19(b), top.

(8) Reflections were apparently identified from a clay vein known to be approximately 10 feet within the coal, using the Geotech method of inserting RF absorbing sheets in the main antenna beams (figure 19(c).

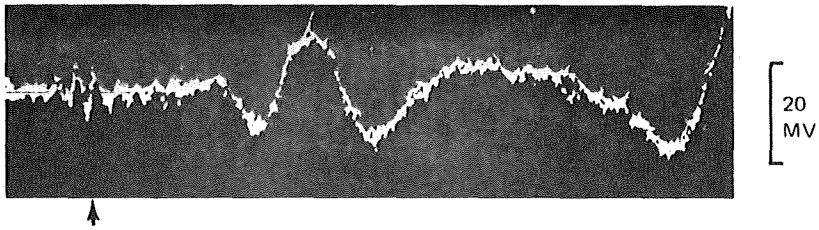
In the 15 radar experiments performed in the Bruceton mine on August 21, which were all recorded on magnetic tape, all recordings were repeated three times, so that the three identical records could be composited (added) to improve the signal-to-noise ratio by a factor of $\sqrt{3}$ or 4.8 dB. Preliminary analog filtering and re-recording of the field records in visible form by an oscillograph showed that they were all of good quality. Compositing them by means of a "mirragraph" magnetic-drum record/reproduce system was considered, but was not attempted because of the high noise level and limited dynamic range of this machine, (as little as 20 dB) and the extensive labor for reconditioning thought to be required to restore it to an operative condition.

Instead, all the recordings were filtered and converted into digital form, for processing by the CDC 3100 digital computer at Geotech. An example of the processing done is as follows:

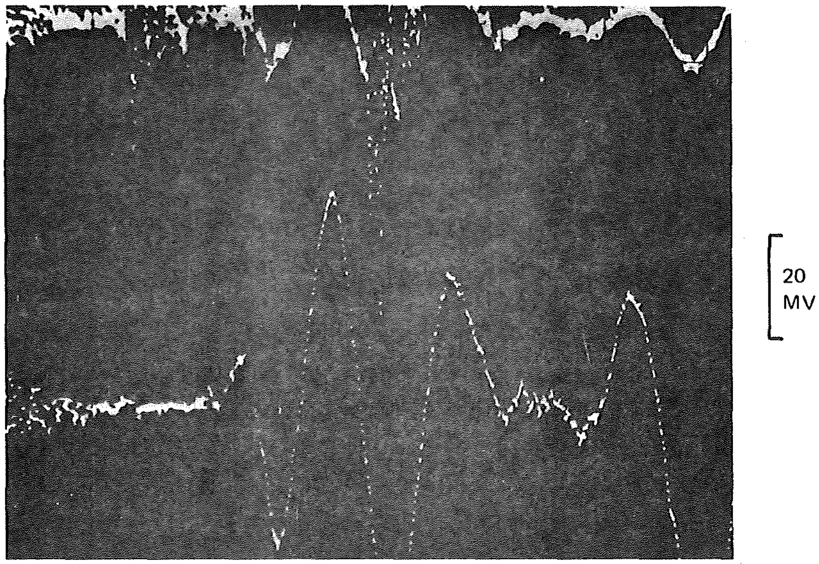
Print-out records A_1, A_2, and A_3, and plot
Print-out records B_1, B_2, and B_3, and plot
Add $A_1 + A_2 + A_3$, phased for max. effect; plot x1/3
Add $B_1 + B_2 + B_3$, phased for max. effect; plot x1/3
Subtract $\Sigma A - \Sigma B$, phased for min. effect; plot

An example of the nine resulting plots is shown in figure 20. Note that the signal-to-noise ratio is noticeably better in the two summation plots. In the difference plot, made to the same vertical scale as the six single records, the noise should be, and is, $\sqrt{6}$ times larger, since the noise power levels add from all six records. The difference record clearly brings out the signal "R", which is considered to be the reflection sought, from the far side of a coal pillar 24 feet thick. In retrospect, however, R can also be seen on the individual records.

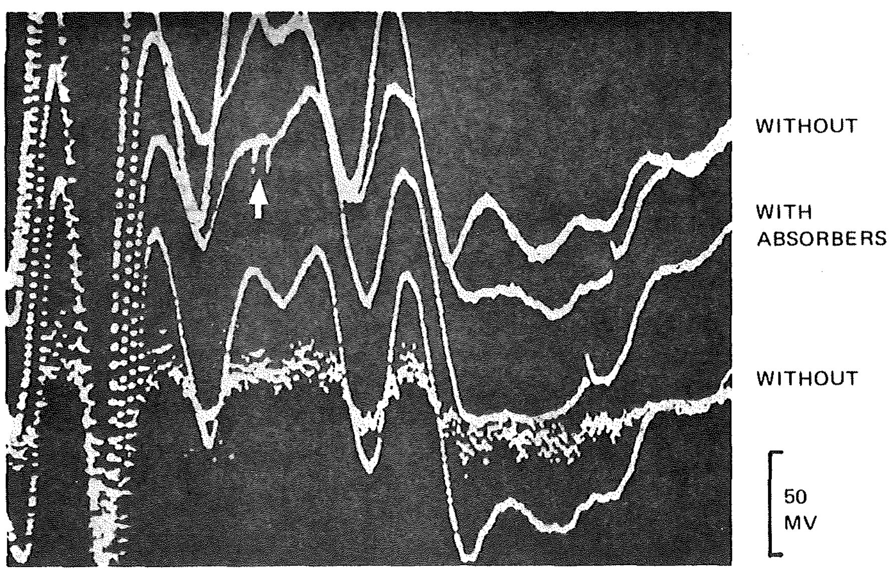
Phasing for the additions and subtractions was accomplished by locating the largest signal peak value on the printout of each individual trace, and instructing the computer to skip the right number of digital samples in each trace to bring them all into coincidence. This process was sometimes not too successful, because waveforms were not the same, for example, between records A and records B, made under slightly different conditions. However, the digital process is generally satisfactory; it is certain,



(a) One-way 56 ft. through coal. 10 dB attenuation, 350 nsec sweep



(b) Upper: One-way in air 56 ft., 20 dB attenuation. Lower: One-way 56 ft. through coal. 10 dB attenuation, 350 nsec sweep



(c) Reflection (?) from clay vein 10 ft. inside coal. 10 dB attenuation, 70 nsec sweep

Figure 19. Radar oscillograms, Bruceton Mine

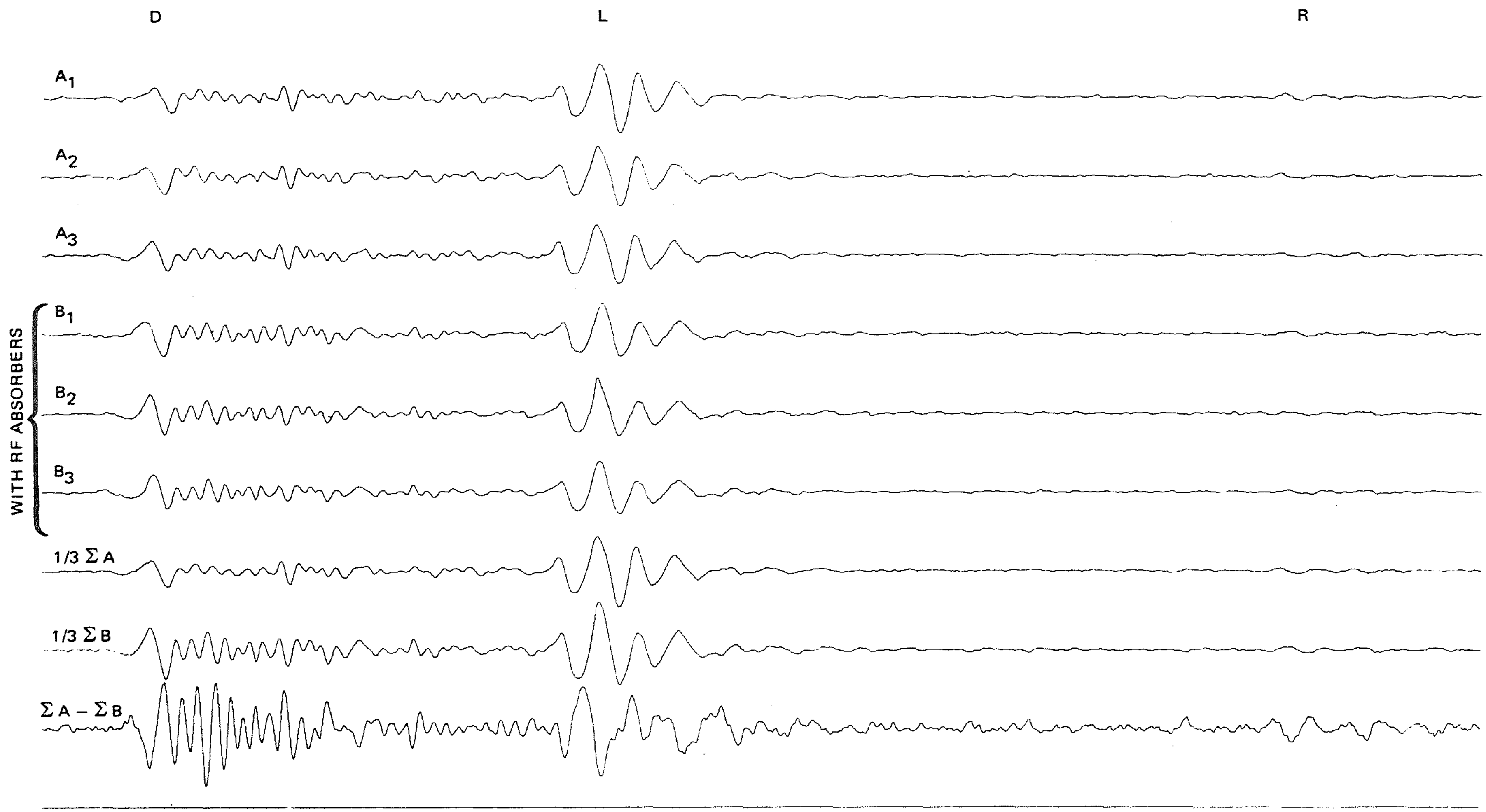


Figure 20. Computer plot of direct, leakage and reflection (?) signals

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inexpensive, and does not increase the noise appreciably above that inherent in the data.

A very powerful signal-enhancement technique which might be used in future work is that of "matched filtering": an idealized signal waveform, obtained either from predictive computations or from a strong field signal of appropriate frequency, such as the 100 MHz direct-leakage signal "L" in figure 20, would be cross-correlated with the noisy signal trace by means of the digital computer. In favorable cases this should improve the signal-to-noise ratio by 10 to 20 dB.

If the signal "R" in figure 1 was indeed the radar echo from the far surface of the 24-foot-thick coal pillar, its occurrence at an estimated 157 nanoseconds after the direct crosstalk leakage "L" would mean that the wave velocity in the coal is 1/3.5 that in air, giving a dielectric constant of $(3.5)^2 = 12$. This disagrees with the direct-propagation value of 4.5, so the identification of "R" is in doubt. It is unfortunate that the time scales of all the magnetic recordings are in doubt by $\pm$ 15 percent, because of large battery-voltage variations in the improvised horizontal-sweeping arrangement used in these first tape recording experiments.

Nevertheless, signal "R" was of about the right amplitude to be the reflection: 10 mv vs. 5 mv calculated from attenuations, etc. It was also reduced in size by the insertion of RF absorbers, so it is interpreted as a two-way reflection through 24 feet of coal. In figure 20, the first, high-frequency wavetrains marked "D" are believed to be direct leakage from the transmitter into the receiving antenna, since they are absent in experiments where the receiving antenna is on the opposite side of a mass of coal. The estimated 67 nsec between the starts of "D" and "L" is consistent with this interpretation. The low frequency of "L" is mysterious, but explains the low frequency of the signal surmised to be leaking lengthwise around the pillar in figure 19(b). Three explanations for this low frequency have occurred to us:

1. Retuning of the transmitting system to a lower frequency (100 MHz vs. 330 MHz) when tightly coupled to a medium of high dielectric constant (coal).

2. Propagation of the leakage signal partially through the coal or along its surface, rather than through air.

3. A cavity resonance effect, caused by re-enforcement of successive arrivals after various numbers of reflections from the conductive shale ceiling and floor: 0, 1, 2, 3, 4, etc. as shown in figure 21 by ray paths a, b, c, etc.

Hypothesis No. 3 was investigated by calculating the complex Fresnel reflection coefficients and delay times for the various reflection angles shown in figure 21, to predict the "resonant" frequency and wavetrain length to be expected. This work is shown in Appendix 2. It resulted in a largely satisfactory explanation for "L", except that subsequent experiments in an open quarry indicated that hypotheses (1) and (2) may also be necessary.

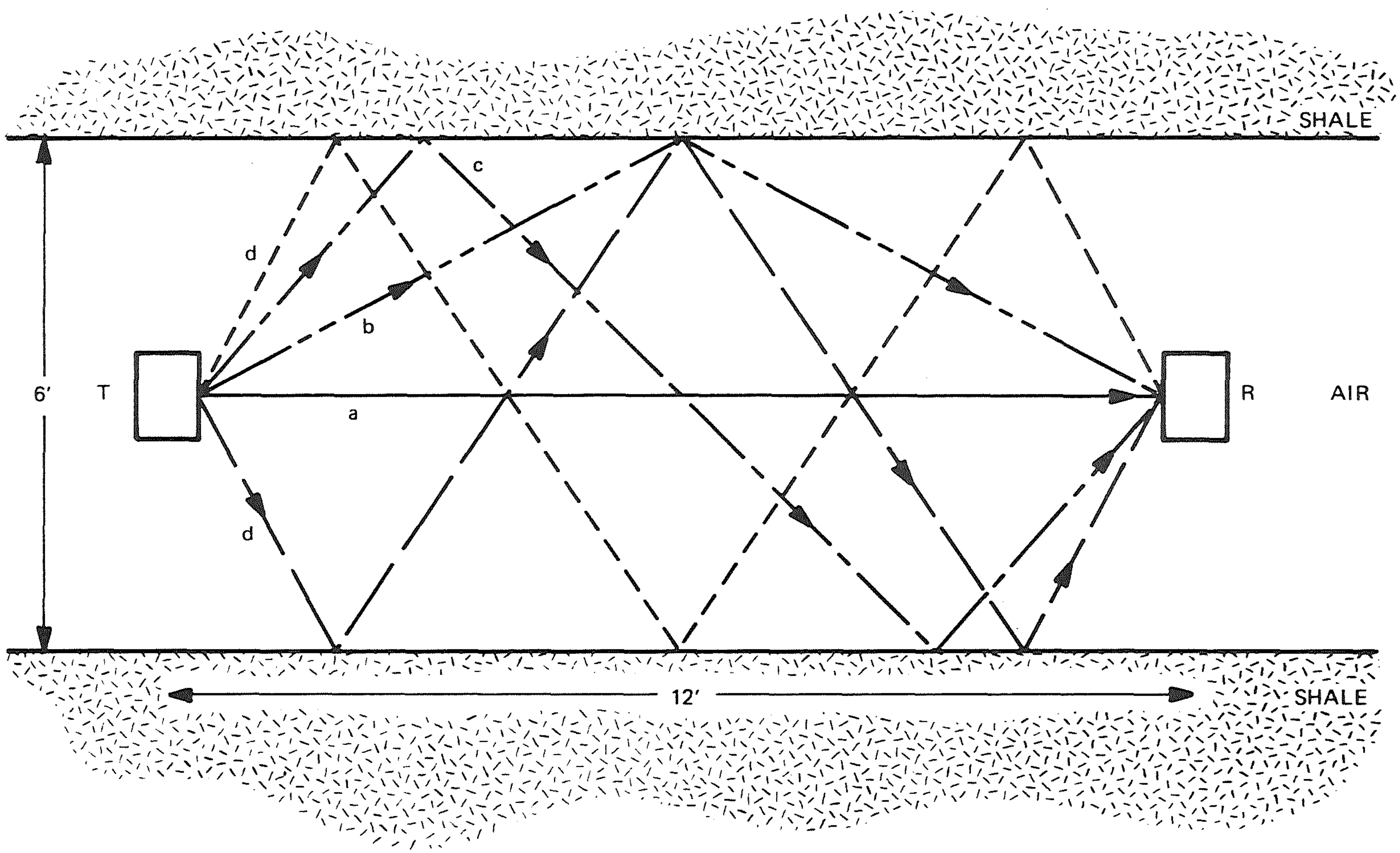

Figure 21. Possible reverberation ray paths.

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The fact that "L" (as well as "R") is reduced about 2 dB by the insertion of two RF absorber sheets in the main antenna beam tends to re-enforce hypothesis No. 2.

Attempts were made at the Bruceton mine to enhance the reflection from the far side of the 24-foot thick pillar by pegging a 6-foot x 20-foot area of (chicken wire) radar reflecting mesh to the reflecting surface. This would permit positive identification of the signal. Unfortunately, none of the computer-plot records had sufficient phase accuracy for the detection of this effect. The filtered analog recordings show that the mesh did make small changes near "R", but these were not considered positive enough and the reflection was not verified thereby.

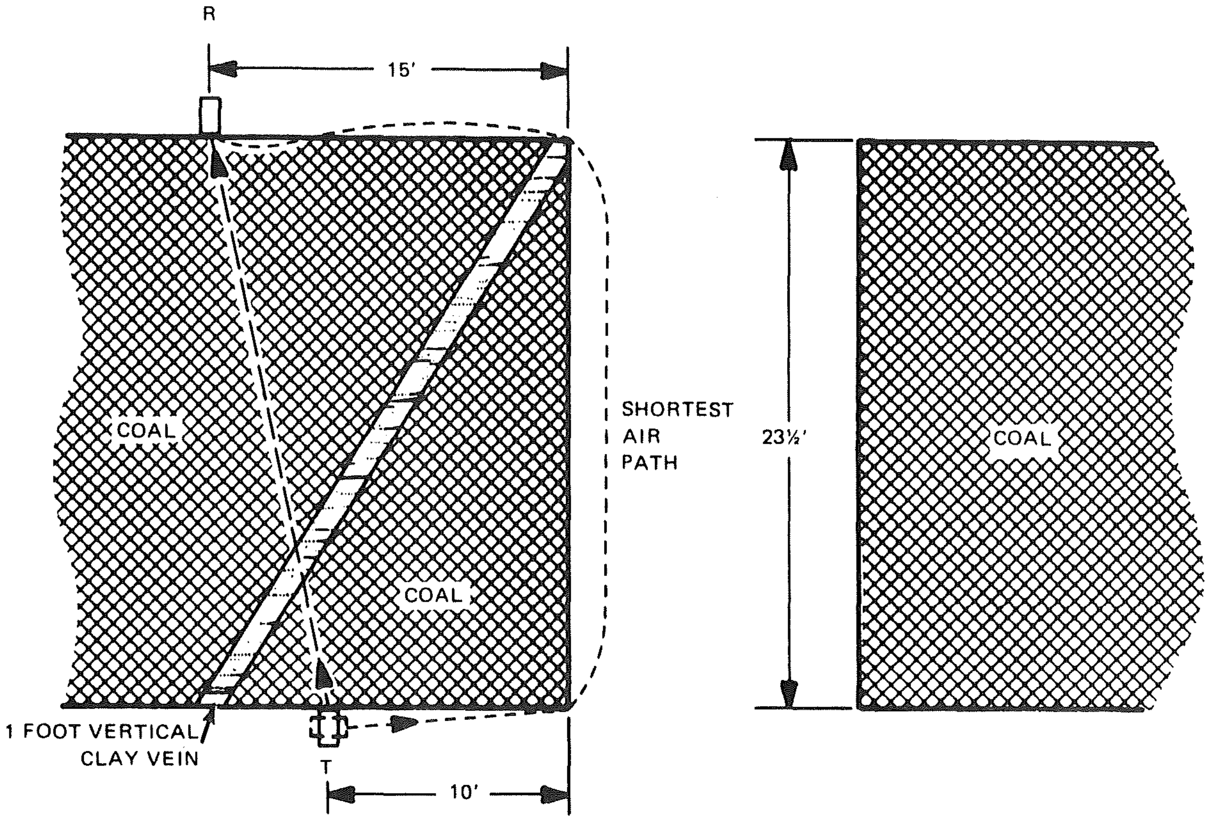
Propagation one-way through 24 feet of coal and through a diagonal 1-foot clay vein (figure 22(a)) was apparently successful. A strong 100 MHz signal occurred at about the right time, which was reduced about 2 dB by RF absorbers in the main beam. There was a problem of proving this signal had propagated through the coal and clay, because the delay times through the coal and around the pillar via the air would have been about the same: the clay vein happened to be near the end of the pillar. However, a test with one antenna turned away from the coal toward the air path (dotted in figure 22(a)) reduced the signal 3.5 dB and did not change the frequency, indicating that it went through the coal and clay.

Efforts were made to obtain a radar reflection from the clay vein, as shown in figure 22(b). Figure 23 shows one example each of the three analog records "M_2", taken with the antennas as shown in figure 22(b), and the records "O", taken with both antennas turned toward the shortest air diffraction path, but not moved, as shown dotted in figure 22(b). Each record is displayed in three forms: as taken from the magnetic tape, after band-pass filtering to remove DC offsets and cable reverberation, and the latter at 18 dB greater gain.

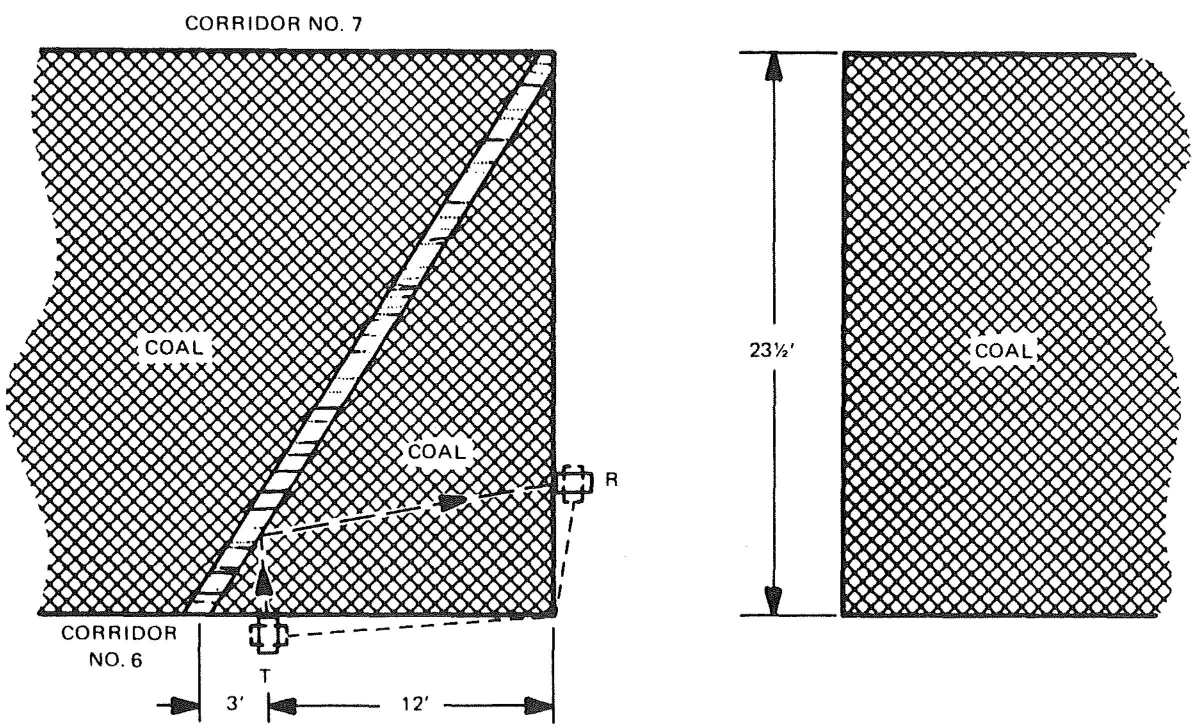
It can be seen that there are 4 or 5 distinct events in figure 23. On the basis of approximate time positions, of amplitudes, of frequencies, of the effect of absorbers in the main antenna beam, and of rotation of the antennas from the path in coal to the air path (including diffraction at the corner of the coal pillar), the following tentative identifications have been made:

- D - A direct signal radiated from the transmitter box through the air to the receiving antenna.
- L - Leakage signal directly between antennas via the shortest air path (dotted in figure 22(b)).
- R - Signal reflected from the clay vein inside the coal (dashed in figure 22(b)).
- r - Possible first multiple of R.

Figure 23 is considered deserving of further study, assisted by a variety of computer-processed plots. The five criteria named at the beginning of this paragraph, together with further experimental study of equipment delay times and leakage paths, should permit positive identifications to be made.



(a) Setup for propagation through clay.



(b) Setup for reflection from clay.

Figure 22. Plan view of clay vein experiments at Bruceton

G 6084

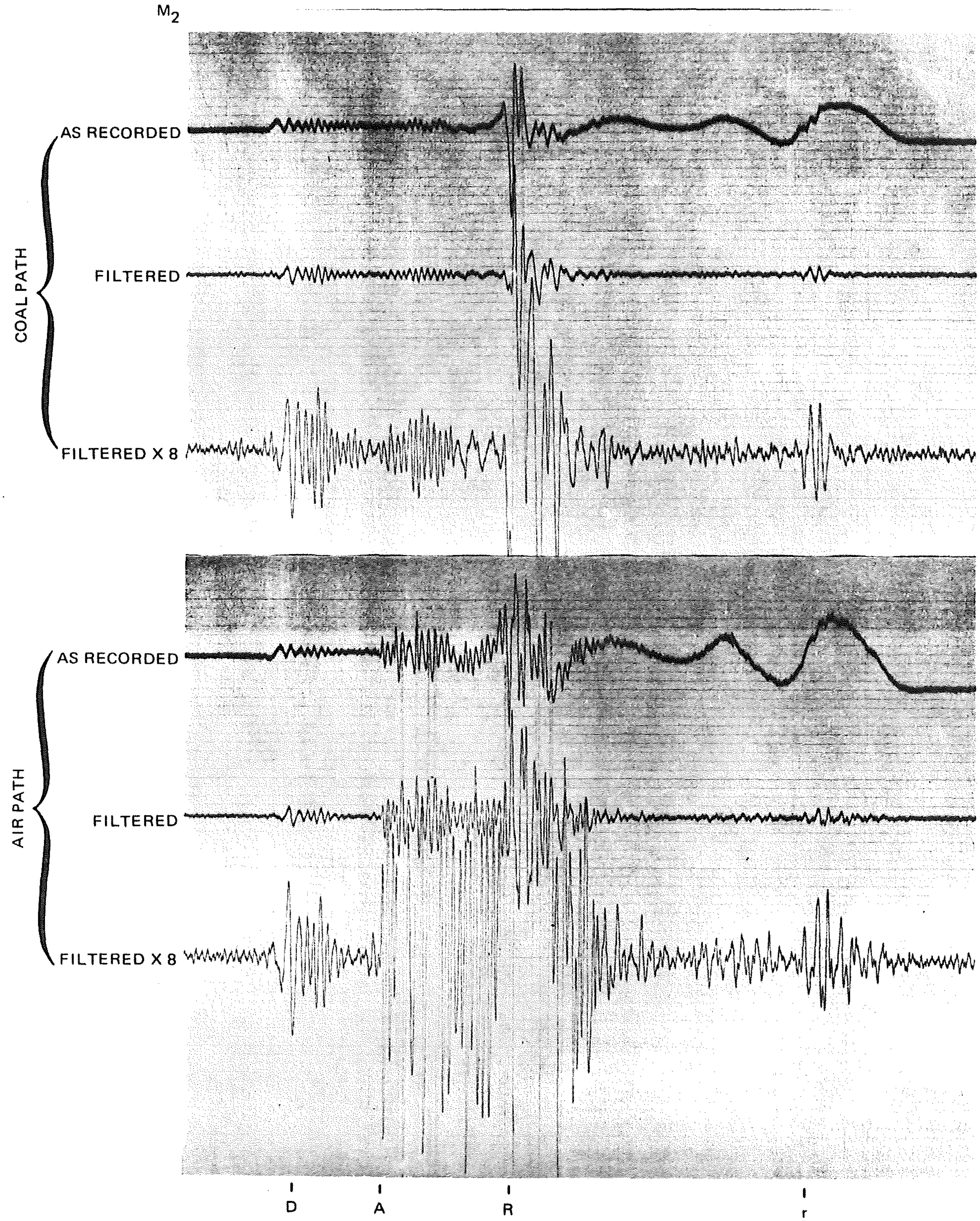


Figure 23. Analog signal displays, clay - vein reflection test

As in any new art, interpretation can be done with relative ease, once the necessary techniques have been learned through a slow process of testing various hypotheses.

5.3 FIELD DATA STUDY, PUTNAM MINE

The extensive data taken at the Putnam mine were processed into computer plots similar to figure 20. Two additional difficulties were encountered for the first time:

A. At the Putnam mine there are no pillars of narrow rectangular shape. Hence, all one-way propagation tests were done on wedge-shaped pillars having a 60° corner. The propagation path through the coal across the 60° corner was just half the air-path around the corner. Therefore, with a wave speed in coal approximately half that in air, the two signals could arrive simultaneously and identification would be difficult, particularly since the air-leakage signals seem to have frequencies as low as those propagated through coal all the way. In any future tests at the Putnam mine, one of the several 45° corners might be used to improve the situation, if these are in the intake-air areas and are otherwise accessible.

B. In an effort to reduce amplifier noise, several sets of records were made with a "zero dB" attenuator setting. All such records contain many strong reverberation wavetrains of various frequencies, because of the lack of a proper resistive cable termination. Because of their complex appearance, these interfering signals did not arouse suspicion in the field. However, they do not change in response to the usual checks with absorbers, etc., so are known to be spurious. It is doubtful that very much information could be salvaged from these records.

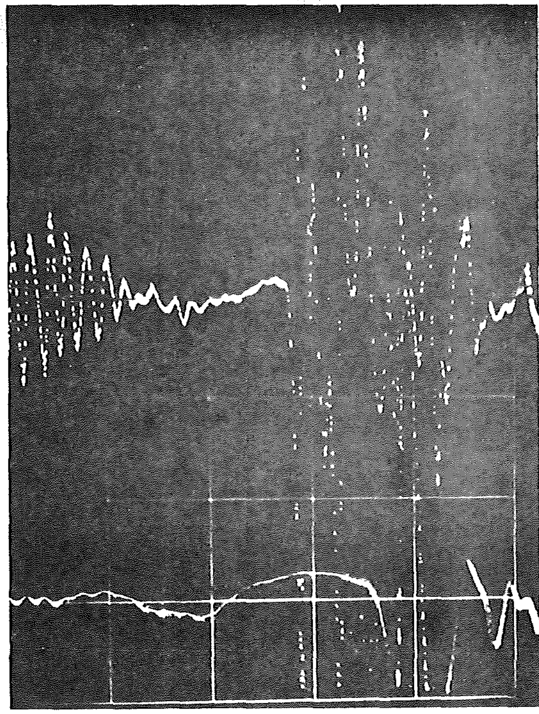
Nevertheless, some successful one-way propagation tests were made. These are shown in figures 24(a),(b). Attenuator and gain settings were unchanged between the coal-path and air-path recordings. The frequencies of the first-arriving signals are about 200 to 250 MHz for the air signals and 28 to 100 MHz for the coal signals, as is appropriate.

The propagation time differences and their meanings are as follows:

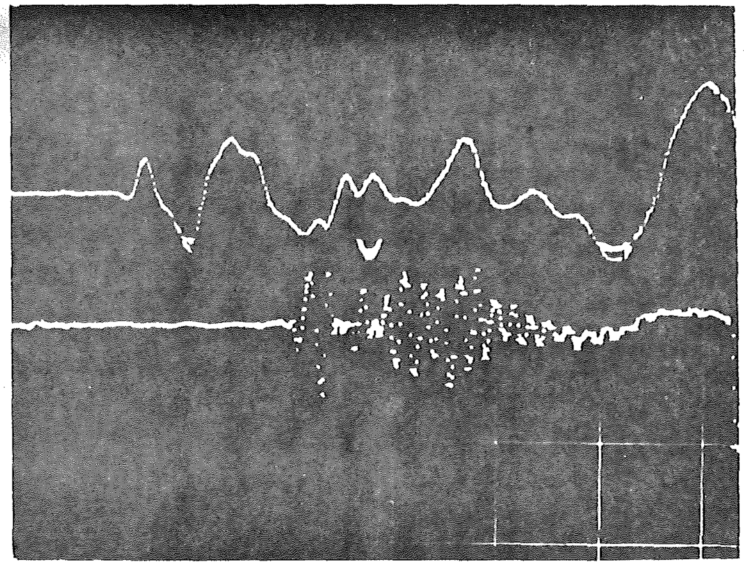
	Time diff.	distance	wavespeed	κ
Figure 24(a)	16 nsec	16.5 ft.	c/2	4
Figure 24(b)	28 nsec	27.3 ft.	c/2	4

These results agree very well with earlier sample test results and the Bruceton field results for 24 feet of coal. It appears that one-way propagation through 27 feet of the Pittsburgh coal bed, including a 1-foot clay vein dipping at 45°, can be done, with a signal-to-noise amplitude ratio of at least 10.

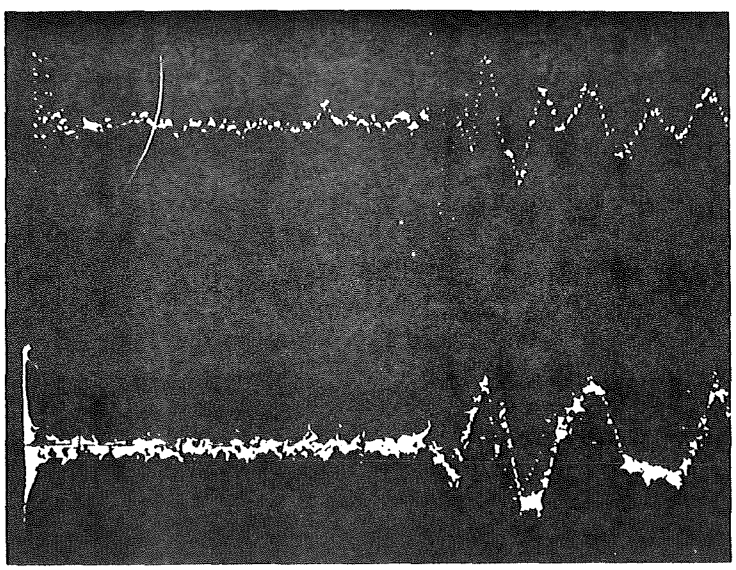
The complex waveform to the right of the first arriving signal in figure 24(b) (top) is mostly receiver cable reverberation set off by the first-arriving



a. (top) over 16-1/2 ft air path
(bottom) over 16-1/2 ft coal path.
Horiz scale 20 nsec/div.



b. (top) over 27.3 ft path in coal w/clay vein, scale 50 nsec/div.
(bottom) over 27.3 ft path in air, scale 20 nsec/div.
(Time origin is 4.5 div left of hatched line)



c. Unsuccessful tests over 63 ft-paths.
(top) air path. (bottom) coal path.
Horiz scale 100 nsec/div.
Attenuator = 0 dB.

Figure 24. One-way propagation tests at Putnam Mine.

signal (the attenuator was set at zero). It is this phenomenon which so greatly interfered with the reception of reflected radar signals.

Figure 24(c) illustrates the failure of an attempt to obtain one-way propagation lengthwise through a 63-foot-long pillar of coal. The frequencies of the sharp first-arriving air signal (top) and "coal signal" (bottom) are logical, as is the high sensitivity (and noise level) needed to display these signals, and also their relative amplitudes according to figures 24(a)(b) and the reasoning outlined earlier. However, no time difference over 30 nsec in the two signals is apparent. It must be concluded that the bottom signal is also an air-propagated one (plus reverberations), which may have started in the coal (hence the low frequency) but took the 98-foot short-cut through the air along the surface of the pillar. This experiment failed to prove one-way propagation through 63 feet of coal.

It was evident that interpretation of mine radar signals would continue to involve a difficult learning process, and there remain several mysteries. However, the following additional things were learned:

1. Because of the low-frequency air-propagated leakage signal (whose mode of propagation is not yet understood) successful one-way coal propagation tests can only be made across the width of mine pillars of long, thin shape.

2. Both antenna cables should be resistively terminated to suppress complex reverberations, even though this degrades the system performance by 6 to 20 dB.

3. Magnetic-tape time bases should be accurately calibrated by noting or photographing the actual sweep length on the oscilloscope, for every experiment.

4. The several direct leakage paths from transmitter to receiver needed to be explored, understood and suppressed if possible.

5. In reflection tests, all the indirect signal-identifying techniques known, including time, frequency, amplitude, absorbers and turning the antennas from coal to air paths, should be employed.

5.4 FIELD DATA STUDY, MARIANNA MINE

Figure 25 shows the arrangement of the tests at the Marianna Mine of the Bethlehem Mines Corporation near Washington, Pennsylvania. Figure 25 shows the interesting computer plots obtained in the direct-transmission experiment. The signal "L" has the characteristics of an air-cavity multipath reverberation, as described in Appendix 2, but it occurs too early to have gone through the 100-foot transmitting cable and around the pillar; one can only conclude that it leaked directly out of the transmitter, perhaps at a dirty cable connection. The causes of "clutter" C are unknown. Signal "D" is of the right waveform, and occurs near the right time, to be the direct radar signal transmitted through 34 feet of coal. Its absolute amplitude (for zero attenuator

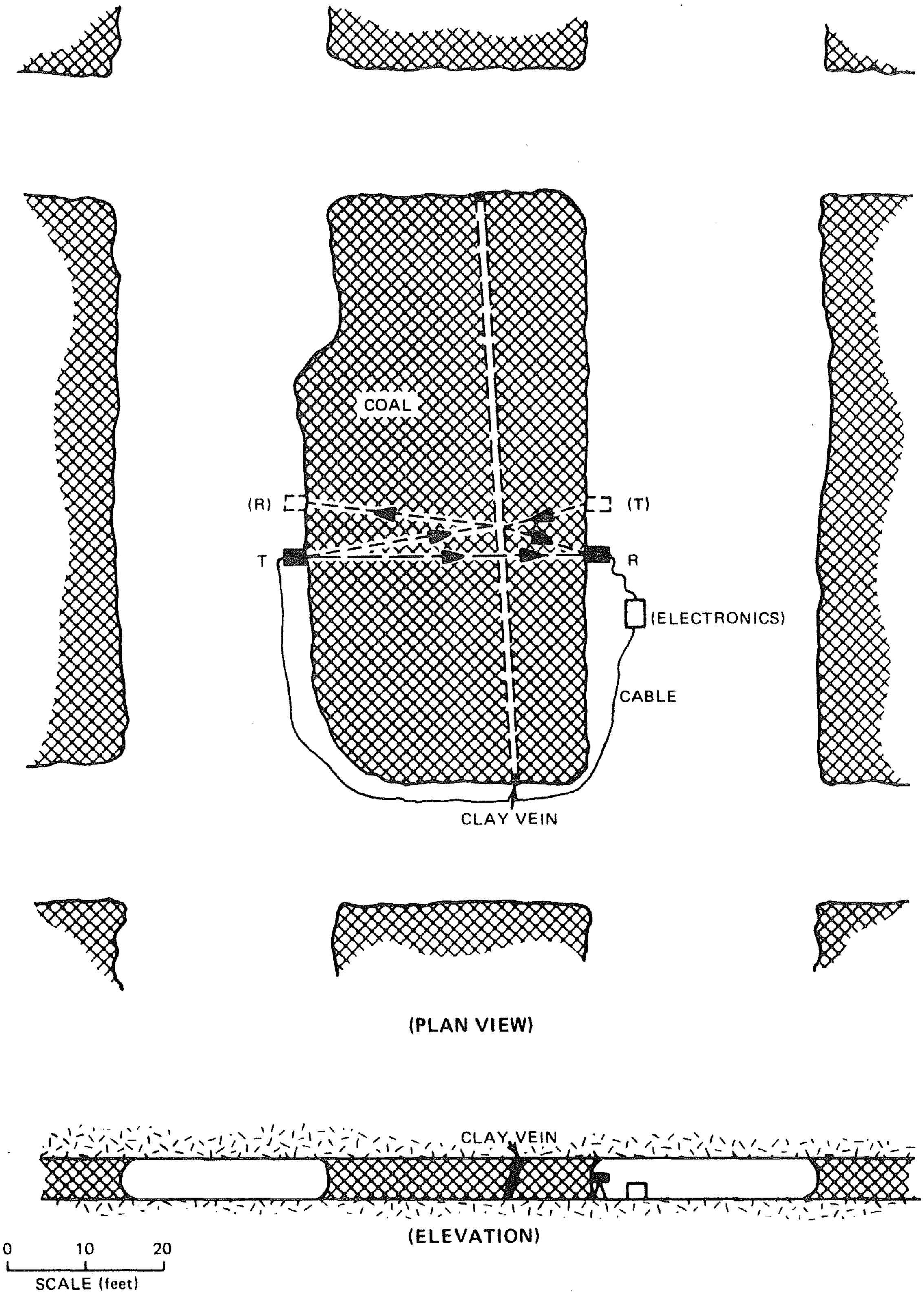


Figure 25. Test arrangement at the Marianna Mine

G 6150

setting) is 100 mv. at the receiver output. On the basis of the Bruceton data, 435 mv would be expected. However, extra propagation losses through, and reflection losses from the 1-foot clay vein in the Marianna pillar account nicely for this discrepancy; the variable thickness and properties of the clay vein could produce extra loss factors over a range from 2 to 6 (6 to 14 db). Signal "D" is about 23 db above the amplifier noise. This implies that it should be possible to detect a similar direct signal through a pillar ten times as thick (340 feet). It should also be possible to obtain a reflected signal from the far side of this 34 foot pillar (10 db spreading and reflection loss) if the one-way loss in the clay is less than 10 db.

Incidentally, both "L" and "D" in figure 26 exhibited a decrease by about 1.6 dB when the absorbers were used, showing that they entered through the receiving antenna. The lowest (difference) trace shows that the digital additions and subtractions are generally too inexact to be useful. This was thought to be a result of phase wobble from the tape recorder. It can be largely overcome in future work by accurate tape speed control (by using a special power inverter) and by recording a tape-speed monitoring trace from which phase corrections can be made during the digitizing process.

Figure 27 shows computer plots from a reflection experiment (see figure 25). The wave "R", which responds markedly to insertion of the absorber sheets in the antenna beams, occurs at about the right time to be a reflection from the clay vein at a slant distance of about 9 feet inside the pillar. Its absolute amplitude is about 130 mv, which is also reasonable. It is unfortunate that it occurs too near the leakage and clutter for clarity.

Figure 28 shows a plot, at higher gain, of a reflection experiment on the opposite side of the pillar, as shown dotted in figure 25. Here the clay vein is about 22 feet away, and reflections would be sought at about 80 nsec after leakage "L" for the clay and about 130 nsec for the air interface. There is indeed a signal "R" near 80 nsec which changes markedly with the insertion of absorbers, and it is attributed to the clay vein 22 feet away. If there is a reflection near 130 nsec, some 10 dB above noise, it cannot be seen clearly through the clutter. Once again it can be seen that the subtraction process was not successful and accurate tape speed control and correction will be necessary in future to employ this technique.

5.5 INTERIM SUMMARY AND ACTIVITIES

After thorough study of all the field data taken in August 1970, and compilation of many pages of study notes, the following preliminary conclusions were drawn:

1. Radar exploration through coalbeds was feasible, but improvements in equipment and techniques were needed to make it practical.

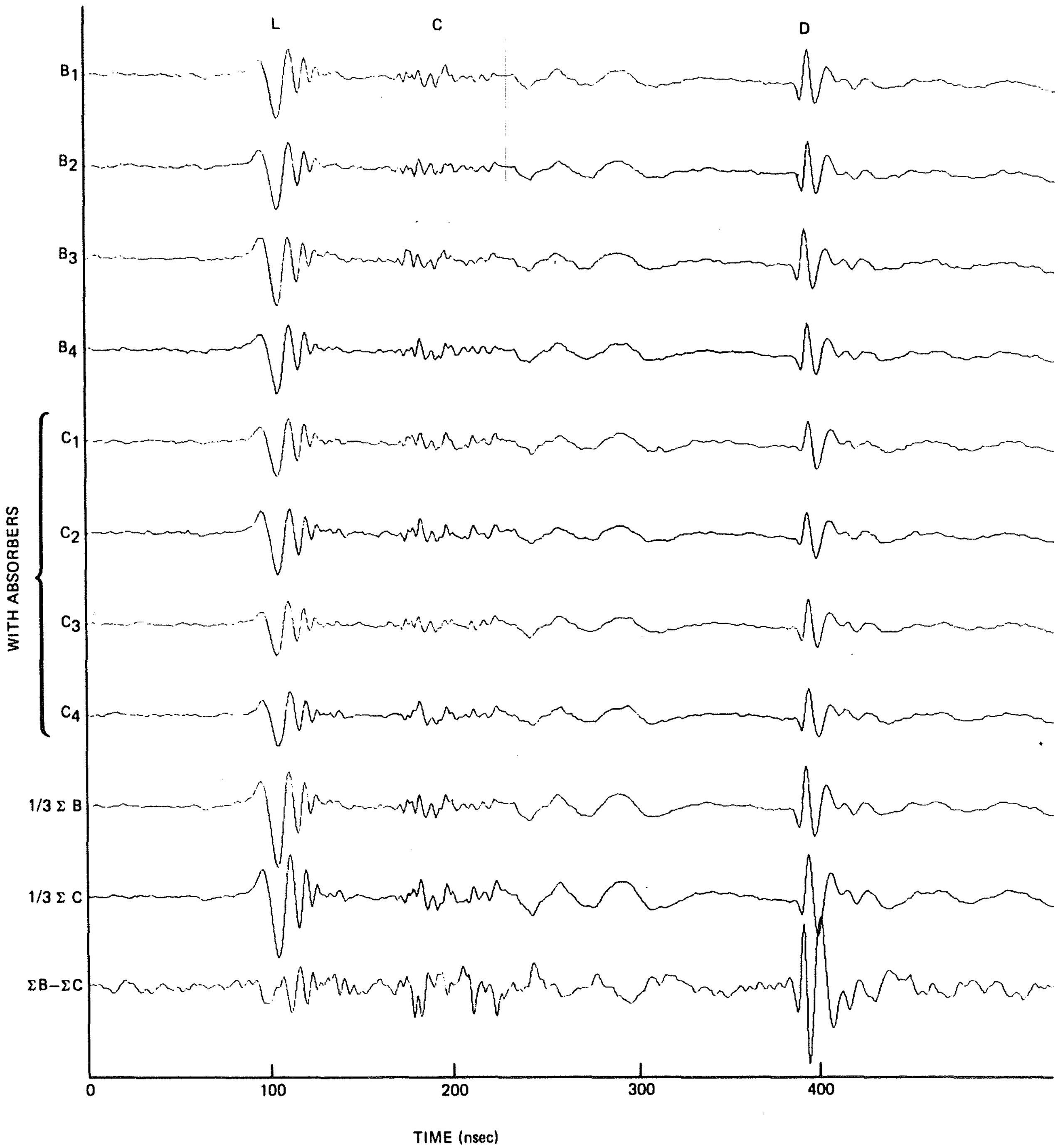


Figure 26. One-way propagation through 34 ft of coal, Marianna mine G 6151

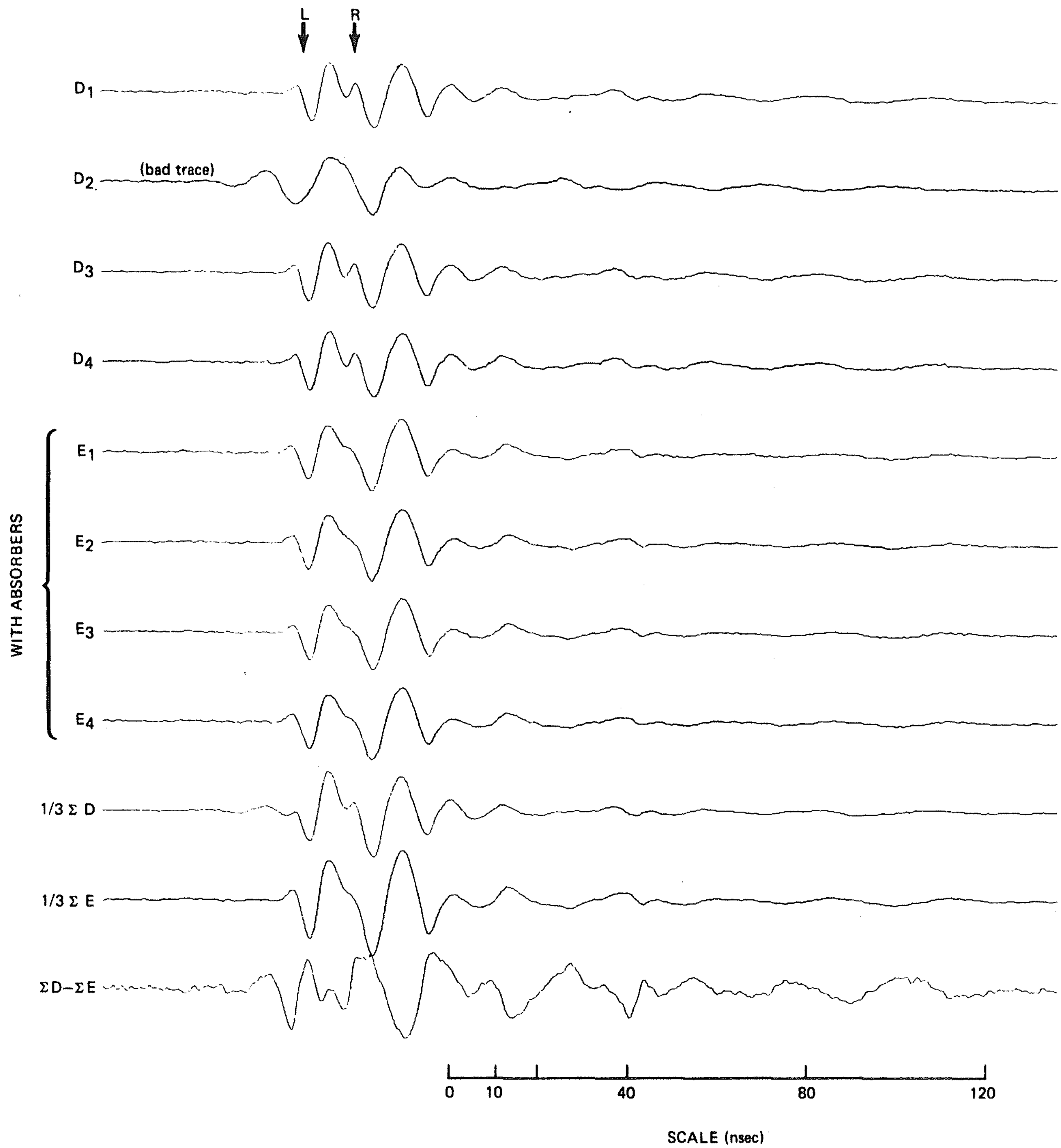


Figure 27. Reflection (?) from clay vein 9 ft inside coal

G 6152

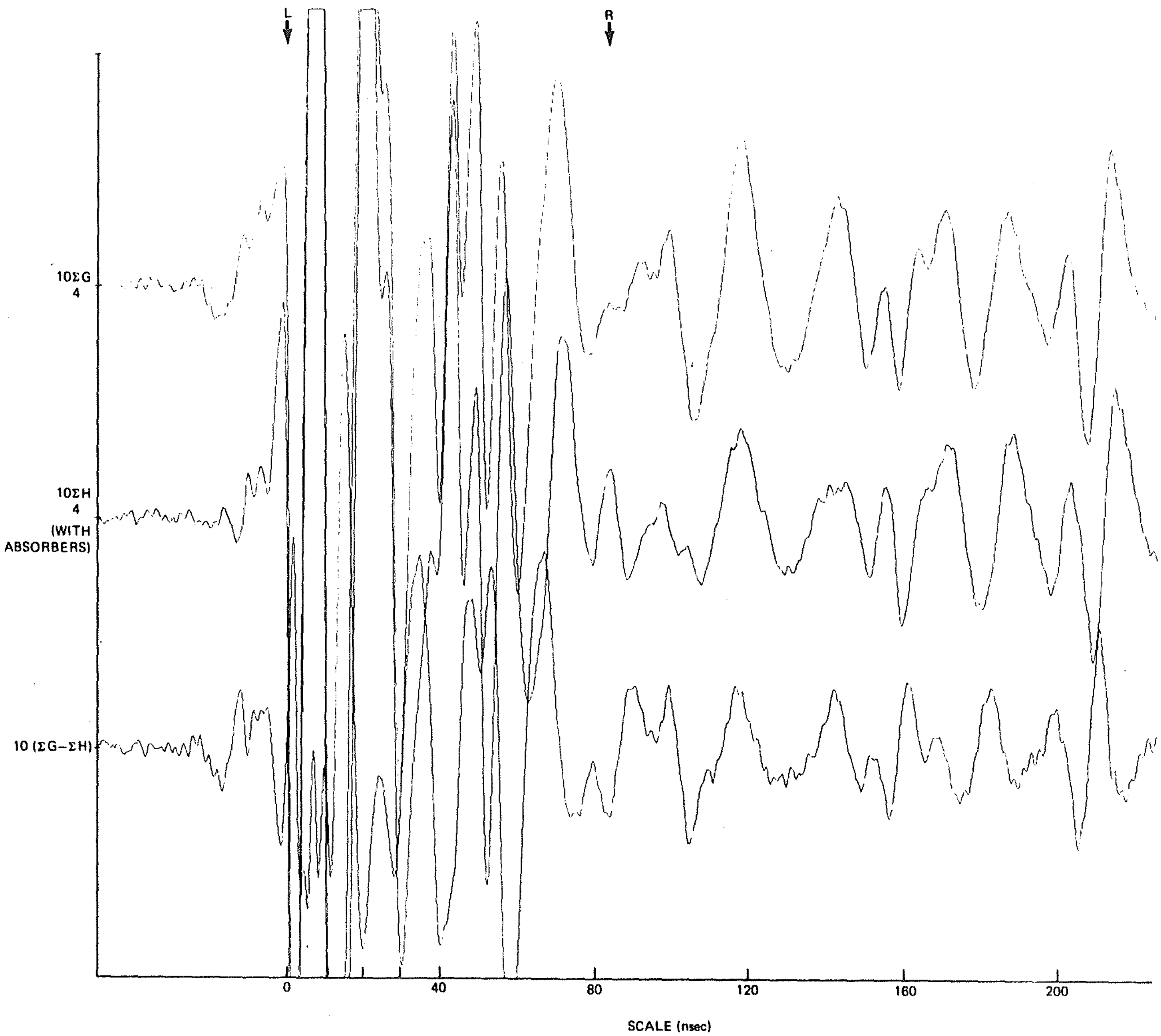


Figure 28. Reflection record, Marianna Mine

G 6153

2. One-way propagation of vertically-polarized radar waves through 34 feet of the Pittsburgh coal bed, and reflections from an air interface at 24 feet and a clay vein at 22 feet had been demonstrated.

3. Some of the many interfering effects had been satisfactorily explained. Several improvements in equipment and technique could be suggested.

5.5.1 Discussion of Related Work by Chevron

In November 1970, at the annual meeting of the Society of Exploration Geophysicists in New Orleans, two papers were presented by Chevron Research Company staff members. These papers revealed several years' research by Chevron on electromagnetic propagation in dome-salt masses. This work had been applied to delineating the shape of the dome flank by means of a radar borehole logging tool with some success. The R and D effort appears to have cost $200,000 to $500,000 and was said to have been amply paid for by the oil discovered as a result of its application.

The frequencies used were 15 to 1000 MHz, with the emphasis at 200 MHz, near the center of our own operating spectrum. However, the salt is a much more radar-transparent medium than coal: absorptive attenuation at 100 MHz varied from 1 dB to 20 dB per 100 feet (one way) in various mines, averaging 10 dB/100 feet as compared to a minimum of 26 dB/100 feet for "Coal-N" according to the sample tests (Appendix 1). Dielectric constants in salt were similar to those of coal: 4.5 to 5.9.

The radar logging tool operated at 15 kw peak power and a bandwidth of 1.6 MHz, a power/bandwidth ratio of 9 kw/MHz. This is much more favorable than the ratio of 0.017 in the present Teledyne radar. Their sharpest antenna pattern had a gain of 20 dB, comparable to that of our antennas, about 22 dB. They received echoes from ranges as great as 1,700 feet through salt, where an exceptionally reflective and well-oriented wall was encountered. A more usual range was 1,000 feet. Because of the long pulse duration associated with their narrow bandwidth, detection was not possible at ranges less than 300 feet.

Many unidentified reflectors within the salt dome were detected, and there appeared to be problems of interpretation which were not discussed. This appeared to be true particularly of the propagation experiments from inside the Morton Salt Company Kleer mine at Grand Saline, Texas, where experimental equipment somewhat comparable to ours was used. This equipment, operating at 15 to 20 MHz with pulses about 500 nanoseconds long, employed a large directional antenna which could be rotated to explore in various directions. A figure in the Chevron presentation showed purported locations of a number of reflectors within the salt mass. The direction lines shown for these reflectors must really be ambiguous by a good fraction of the antenna beamwidth, estimated to have been 90°. With this limitation in mind, the "flank" reflections shown were reasonable, and were received from apparent distances as great as 5800 feet!

Apparently no attempt was made to plot reflections from less than 1,750 feet away, perhaps to avoid reflections from within the mine which was 3,000 feet across, equivalent in time to 1300 feet through salt. Nevertheless, second and third reverberations may have occurred in the air-filled passages, which could well have produced many of the "in-salt" reflections indicated. They are therefore doubtful.

Apparently only the large, isolated signals were interpreted as reflections; the "clutter" no doubt was largely caused by reverberation within the mine. No indirect methods of verifying reflectors, other than rotating the antenna, were mentioned. There is nothing here applicable to our problem; the dimensions of the salt dome are much larger than those of the mine, so that the desired signals are well removed in time from the clutter. In our problem, these distances are of the same order, and signals are mixed with clutter. The methods of verification we have developed appear to be the most advanced known.

The Chevron papers were not at all helpful in resolving our problems of spurious signals, leakage and reverberation artifacts. These may be related to our shorter working ranges. However, they encouraged us to anticipate working ranges of 100 to 200 feet in dry bituminous coal. Although the Chevron logging tool was 360 times (50 dB) more "effective" than our radar in terms of the power/bandwidth ratio, ours should perform equally well at ranges (in salt) up to (1,700 feet/ $\sqrt[4]{360}$) = 390 feet as an extreme. It was also seen that to overcome the additional attenuation expected in a 230-foot round trip in coal, our present radar design could be improved by as much as 30 dB, and better adapted to coal problems, by making the following design compromises:

1. Reduce the system bandwidth to 20 MHz centered at 100 MHz, by rebuilding the antennas and using a 5-cycle pulse generator. The resulting transmitted waveform would contain about five carrier cycles. The minimum usable range and the distance resolution would be degraded thereby from its present 2 or 3 feet to about 12 feet in coal, but with a "performance" gain of 12 db.

2. Increase the transmitter operating voltage from the present 500 volts to 4,000 volts (18 db) for a peak power of 1/3 megawatt. This would require a new type of transmitter switch such as a thyratron, and a new power supply.

3. Reduce the pulse repetition rate from the present 720/sec to 30/sec, to keep the average antenna power level well within the "intrinsically safe" range for gassy coal mines. This would lengthen the time required to make a radar record from the present 4 seconds to 1-1/2 minutes, which is still quite satisfactory.

The need for these radar system improvements had been borne out by study of our own field results up to that time. Other changes, to reduce spurious effects, were also needed.

5.5.2 Local Quarry Tests, and Further Test Arrangements

The most serious impediment to interpretation of the early radar field results was "clutter." This effect, rather than thermal noise, had limited the practical radar dynamic range about 57 dB. In preparing reports and recommendations, it became clear that certain simple modifications of the radar system might reduce this RF leakage. We therefore tested these modifications and found them quite effective.

The radar was set up in a nearby limestone quarry, so that the antennas would be matched into a semi-transparent, absorbing medium. Figure 29(a) shows the "direct" signal of type "D" from the pulse generator box to the receiving antenna, with the box placed 45 and 18 feet, respectively, from the antenna. A further doubling of the amplitude of this leakage occurred at 10 feet. Evidently, this type of interference can be greatly reduced merely by keeping the pulse generator (Xmtr) box far enough away from the receiving antenna. A further reduction by x2 was obtained by adding an outer shield of aluminum foil to the receiving antenna, and another reduction of x4 was obtained by wrapping the pulse Xmtr box with a grounded foil shield. Hence, clutter from "D" was reduced by a total of 18 to 30 dB by equipment shielding and careful layout.

Figure 29(b) shows the strong "leakage" signal of type "L" traveling through the air from the transmitting antenna to the receiving antenna, first with foil on the receiver antenna only, and second with foil on both antennas. There was a reduction of this interference by x5.3 when shielding is added to one antenna, and thus presumably by $x(5.3)^2$ or x28 when both were shielded. The <u>least</u> improvement inferred from actual observation in the shielding experiments is x10.6. Hence, shielding reduces the clutter from "L" and its reverberations, which often fill those parts of the trace where reflection signals are sought, by 20 to 29 dB. The waveform produced by the transmitting antenna did not appear to be adversely affected by the addition of the external shielding.

On the basis of these results, and for an opportunity to obtain and employ an RF band-pass filter and improved tape-recording techniques in the field, a contract extension was requested in December 1970. It was received in March 1971. A 50-ohm, RF filter passing 50 to 150 MHz was immediately ordered from a supplier. Permanent shielding of aluminum screening was applied to the antenna and transmitter boxes at this time also. When the filter was received, laboratory and quarry tests were made which showed that the improved Teledyne Micronetics radar system was indeed much less disturbed by spurious clutter interference: with the antennas against a quarry face 3 ft. apart, leakage "L" was 50 mv peak-to-peak and the useful dynamic range was 77 dB. With a 15 ft. antenna separation, "L" was 3 mv and useful dynamic range was 102 dB! The improvement over the earlier 98 dB signal-to-noise ratio was made possible by the narrowed bandwidth when the filter was used. The equipment was therefore considered ready for the field.

In the interim period, we had also learned that an apparatus known as the Advanced Prototype VHF Tunnel Detector (hereafter abbreviated to "VHF-T.D.") might be available for comparative testing. This apparatus is a short-pulse, monocycle radar specifically designed to operate into a solid medium, and had reached a fairly sophisticated state of development after nearly 3 years of Army-supported development and testing by three successive contracting companies, all of them very competent in electronics. Therefore, an interagency loan was arranged. The equipment and its confidential instruction

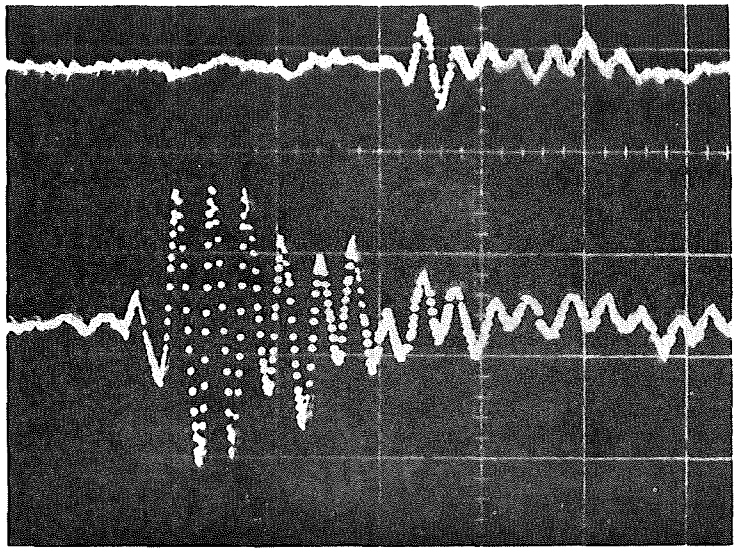


Figure 29(a). Clutter "D"; top: Xmtr. to R antenna = 45 ft
bottom: Xmtr. to R antenna = 18 ft

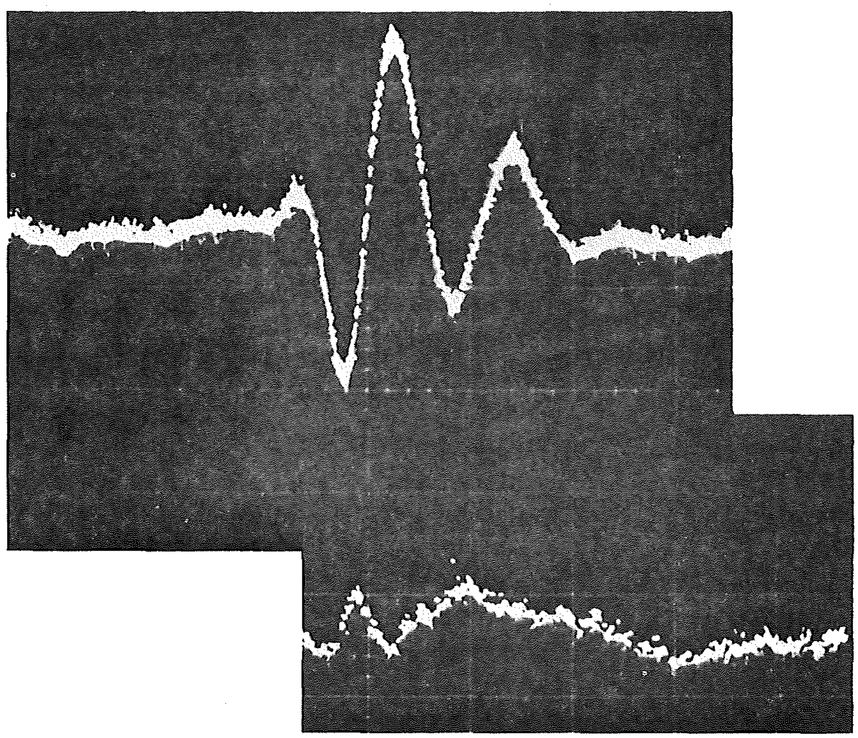


Figure 29(b). Clutter "L"; top: Foil shield on R antenna only
bottom: Foil shield on R and T antennas

manual were obtained from the U.S. Army Mobility Equipment R & D Labs and were delivered to the Bureau of Mines' Bruceton facility during the subsequent field tests in April 1971.

5.6 Second Test Series at Bruceton, Pa., Coal Mine.

The Bruceton mine was again made available together with minor personal equipment and part-time assisting personnel. In mid-April, two Geotech men performed three full days of experiments, taking 53 oscillogram photos and 13 sets of precision magnetic tape recordings.

As was hoped, the VHF filter and the new shielding greatly clarified the radar signal, and a clear reflection, 7 times as strong as the equipment noise and 3 times the nearby clutter, was received through a pillar of coal 30 ft. thick. In figure 30, this signal is identified by an arrow.

This figure also shows how the reflection was positively identified. First, it began about 80 nanoseconds after the direct leakage signal from transmitter to receiver, which traveled 15 ft. through air; thus, the travel time over a 60 ft. path in coal, in which the velocity has been found to be 0.64 ft/nanosecond, was exactly what it should be. Finally, the signal polarity was approximately reversed when a 6 ft. x 6 ft. metallic reflector (chicken wire) was added to the reflecting coal-air interface on the far side of the pillar. This was unexpected (we expected a signal increase) but appears to be in accord with theory, since a coal/metal interface should reflect approximately out of phase, but a coal-air interface approximately in phase. The most important conclusion is that the signal shown in figure 30 was markedly changed by adding the screen, so is firmly identified as the reflection from the far side of the 30 ft. pillar.

Numerous repeats of this experiment were made, on two different pillars, with generally consistent and repeatable results. The improvement in radar system performance appears to be at least 26 dB above that found in August 1970, with respect to clutter suppression.

Unfortunately, there are no pillars in the Bruceton mine thicker than about 30 ft., despite mine maps showing 50 ft. pillars. Hence, the experiment could not be extended to greater thicknesses of coal under the first contract extension. Indications are that this radar in its present form could obtain reflections through 40 to 80 ft. of coal.

The U.S.Army VHF Tunnel Detector is shown in use in figure 31 in the mine; the large square loop antenna is against the pillar rib, and the operator is carrying the electronics unit on his chest and the battery on his back, as designed. The rib at this point had been whitened with rock dust.

This equipment is relatively light and compact. Its electronics portion can perhaps serve as a model for the design of a future permissible mining radar. The facsimile paper display, however, is designed for a continuously searching system, and is quite unsuitable for a mining radar; a miniature wiggle-trace chart recorder and cassette magnetic-tape recorder would be more suitable. The square loop antenna appeared to be electrically inferior

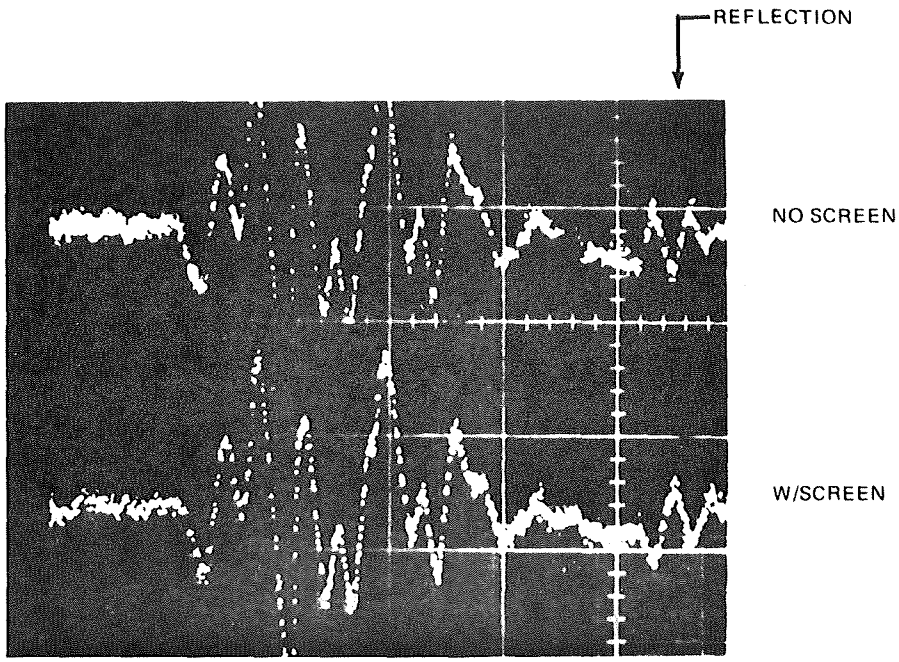


Figure 30. Radar reflection through 30-foot pillar (20 nanoseconds = 1 large horizontal division)

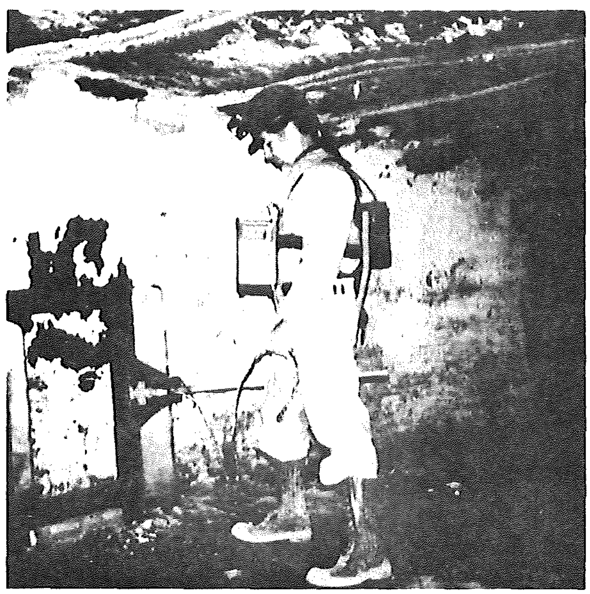


Figure 31. Man-portable VHF radar in mine

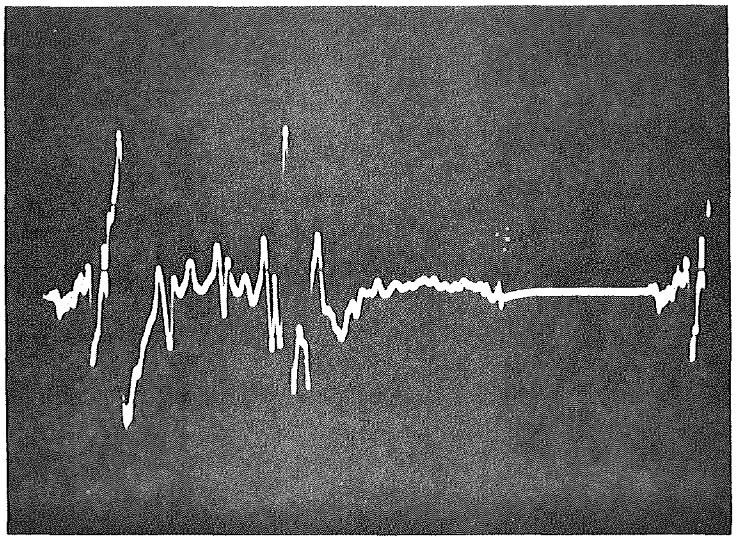
to the horn antennas used in the Teledyne radar. The loop is lighter, but both types of antennas are somewhat clumsy to handle.

To conserve waning battery power (a special mercury battery was furnished), and to improve over the facsimile paper chart results, which showed no evidence of reflections through a 23 ft. pillar of coal, subsequent tests were displayed on an auxiliary portable oscilloscope and were photographed. Twelve such oscillograms were produced with various appropriate settings of receiver gain and gain time-dependence, with and without the chicken-wire reflection modifier. No evidence of a radar reflection through the coal was seen through the clutter-filled trace. It appeared that the clutter was many times as severe, compared to signals, than it is in the improved Teledyne Micronetics radar.

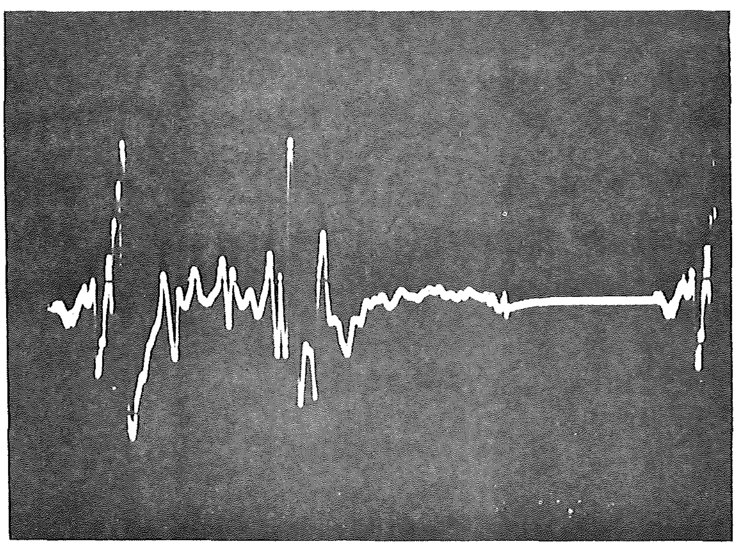
After we had returned to Texas, the VHF tunnel-detector radar was refurbished (bad cables repaired), then received considerable study on the bench, and all the oscillograms produced with it at the Bruceton mine were carefully analyzed. Some of these oscillograms spanned an entire pulse repetition period of 320 nanoseconds (figure 32), so that there would be no doubt about their horizontal scale. Approximately 240 nanoseconds of this is available for the display of echoes; during the remainder, the receiver is blanked for circuit resetting and transmitter firing. As used at Bruceton, the equipment was adjusted so that echoes from reflectors right against the antenna appeared at the beginning of the trace, for most settings of the delay switches. This "zero setting" was uncertain at Bruceton, but was later verified. The available display length should permit the detection of reflectors up to about 60 feet away through coal. Unfortunately, there was no clear indication of the reflection from the far side of the 23-foot-thick coal pillar, which should have showed up as a difference in oscillograms made with and without the reflecting chicken wire against the opposite pillar face. Five such pairs of oscillograms were photographed, with various polarizations, delays, and gain-versus-time settings. Figures 32 and 33 are examples. These figures illustrate the excellent repeatability obtained on successive tests. The clutter echoes were surprisingly irregular. Nevertheless, they appear to be due to electrical impedance mismatches at the antenna-rock interface, in the antenna, in the coaxial cable and in its connectors, on the basis of experiments under simplified laboratory conditions. For example, figure 34 compares the clutter obtained with two different antennas placed against the ground in the center of an open field. Such clutter could be greatly reduced in a future system by careful design, adjustment and maintenance of the antenna and its cable.

5.6.1 Study of the new Bruceton Mine Data

Some of the initial tests made at Bruceton were intended to determine whether the system modification made to suppress clutter were as successful with a coal medium and in closed mine galleries as they were with a limestone medium and in an open quarry. Direct leakage "L" responded as follows to antenna coupling into the coal, using the VHF filter and a 15 ft. antenna separation:

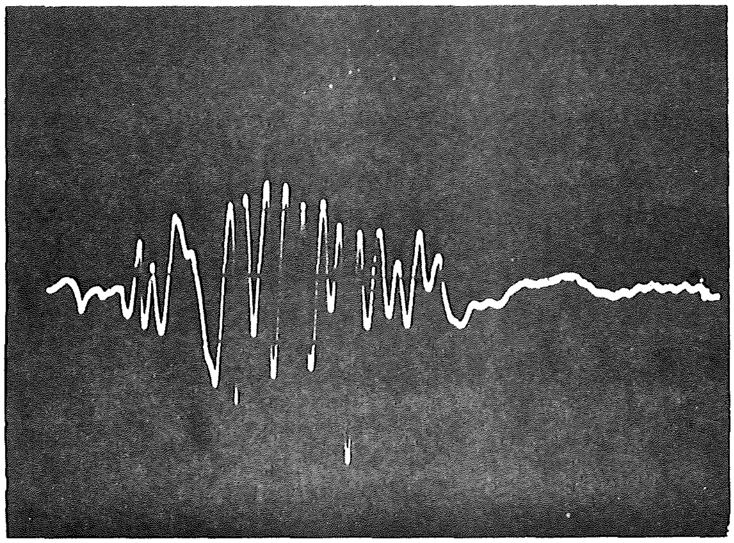


(a) Without screen reflector

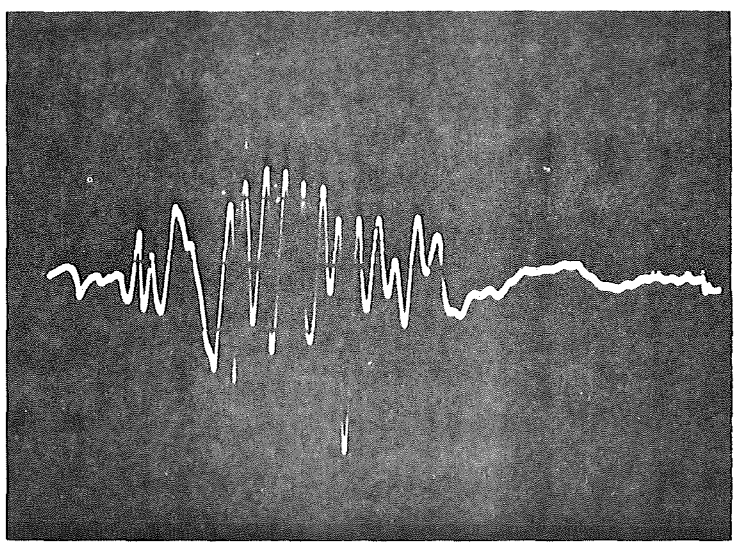


(b) With screen reflector

Figure 32. VHF-T.D. Oscillograms from 23-ft. coal pillar. Vertical polarization. 320 nsec. between repeated onsets (350 nsec. sweep). Begins 15 nsec. early. Gain 24 dB plus 0.3 dB/nsec. (no delay), 1 volt/div.

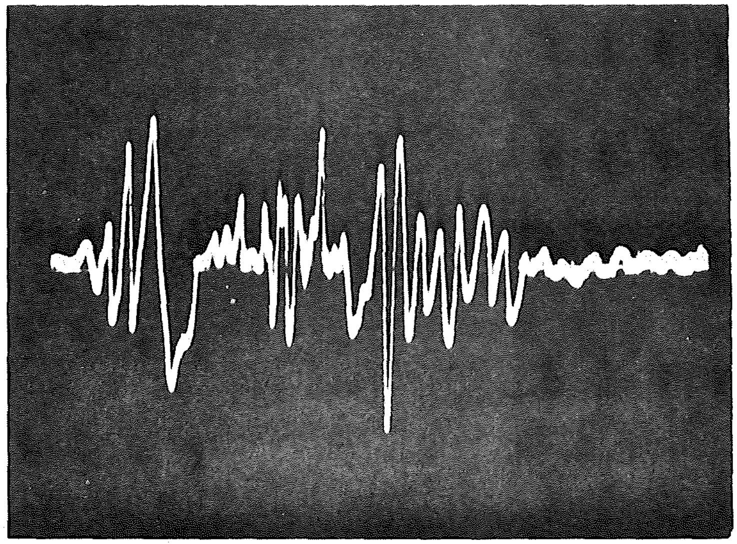


(a) Without screen reflector

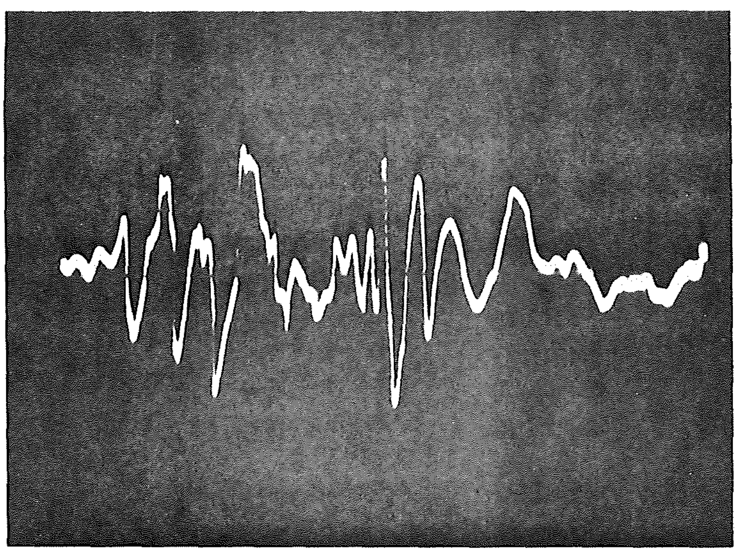


(b) With screen reflector

Figure 33. Magnified VHF-T.D. Oscillograms from 23-ft. coal pillar. Vertical polarization. 240 nsec. sweep length, gain 20 dB plus 0.7 dB/nsec. (no delay), 1 volt/div.



(a) Using Army loop antenna



(b) Using Teledyne horn antenna

Figure 34. Clutter patterns obtained with antennas on flat, "semi-infinite half space." 240 nsec. sweep length, begins 8 nsec. early. Gain 20 dB plus 0.5 dB/nsec. slope, no delay, 1 volt/div.

Condition	"L" Amplitude
Both antennas against coal	40 mv
T against, R facing away	250 mv
T facing R through air	2,500 mv

These signal strengths were measured at the receiver output. They indicate about 37 dB of clutter suppression by proper antenna coupling in a coal mine environment. These tests also showed clearly that the leakage occurring with the antennas closely coupled to the coal consists largely of lower-frequency components between 120 and 160 MHz, compared to the 200 to 250 MHz frequencies which are dominant when the antennas are coupled into the air.

Direct leakage "D" from the transmitter box was suppressed 12 dB by closing the shielded lid, and an additional 12 dB by coupling the receiving antenna into coal rather than air.

These figures for clutter suppression are not as good as were expected on the basis of the quarry experiments. Furthermore, clutter is still a potentially serious problem since, as can be seen by comparing the reflection in figure 30 with the larger clutter to the left, this reflection would be very hard to identify if it had occurred earlier in time. The earliest part of this clutter was shown to be leakage "L" between the antennas. Subsequent, larger portions of this clutter were tentatively identified as echoes from mine walls and steel support posts, by their times of occurrence and their re-enforcement by the echo from a man moving from place to place. A steel mine car 52 ft. away gave a small, isolated, identifiable signal of 0.22 volt (equivalent at the receiver output) when the antennas were aimed toward it, but this echo shrank to 6 mv, much smaller than the desired reflection (35 mv) when the antennas were coupled into the coal. Other clutter was identified as mismatch echoes in the antennas and cables, by its disproportionate attenuation when a 50-ohm resistive termination with 3 dB loss was inserted. Again, careful design and matching of the antennas should remove much of this effect in a future mining radar.

The transmitter pulse length was tailored in the field to a 5 nanosecond length, for maximum signal through the RF filter. Remeasurement showed a direct signal from the transmitting antenna equivalent to 600 volts peak-to-peak at the output of the receiver. This was an improvement of 5.5 dB in transmitter performance, for an effective radiated peak power of about 72 milliwatts. Since the transmitting antenna is driven with 72-volt pulses (100 watts available) from a 500-volt supply, it would appear that there is much room for further transmitter and antenna improvement.

The magnetic-tape recordings made at Bruceton were transcribed into visible form later in the laboratory for checking. It was found by careful study that the time scale was too variable to permit successful addition and subtraction in the computer. The time scale employed in the April field tests originated in the horizontal scan speed of the oscilloscope. When the scan period was adjusted to 20 seconds or so to permit good tape recording, it apparently became prone to drift by as much as ± 10% between scans, although this was not noticed in the field. Hence, the magnetic records could not be used at all.

Fortunately, an X-Y plotter and the oscilloscope camera were also used in conjunction with the tape recordings. Although computer plots of the difference between the radar traces with and without the reflecting wire mesh cannot be made, the difference can readily be seen in overlays such as figures 35 and 36. Figure 35 presents the same data as figure 30, free of the recording defects inherent in a storage oscilloscope operating near 120°F. The left end of the trace begins just before leakage "L". The low-frequency interference at the right is now normally removed by the RF filter. Figure 36 presents the time region immediately around the reflection, at higher magnification. System noise and drift were made evident by making three recordings of each type; the signal-to-noise ratio is about 22 dB. The retrace lines of the X-Y recorder should be ignored. The time and amplitude scales must be obtained from figure 30.

Figure 37 presents an overlay from a similar experiment through a different pillar of coal 23 ft. thick, using the RF filter. Some drift is apparent in the amplitude of the largest clutter, between "L" and "R", during the time required for the wire mesh to be removed from the pillar wall. The source of this clutter was not identified. The amplitude of the 23-foot reflection was about 60 mv equivalent at the receiver output, compared to 35 mv for the 30-foot reflection. This indicates an inverse-square law of decrease with distance, and essentially specular reflection from the mine pillar wall or the screen mesh. On this basis, useful reflections 6 dB above system noise would be expected to be obtainable with the present radar from large flat reflectors up to 75 feet distant through the Pittsburgh coalbed.

It is to be noted that these reflections can only be obtained with vertical polarization.

The final test at Bruceton was an attempt to bounce a signal from a nearly-vertical clay vein which passed through a pillar between rooms #7 and #8 at about 45°. Figure 38 shows the experimental arrangements. Figure 39 shows the two major wave groups received. The second group (figure 39 (c)) was believed to be of less interest than the first, so was not studied. The first group should contain the corner-diffracted or surface propagated signal indicated by (a) on figure 38, as well as the first in-coal direct signal (b) and the clay-vein reflection (c). Attempts at identification were made by inserting absorbers, by turning the antennas from the coal to the air path (a), and by moving the receiving antenna R to position R' as shown in figure 38. The results were contradictory and inconclusive.

Figure 39(b) indicates that the 80 MHz first-arriving signal A_1 in figure 40(a) is received only when both antennas are well-coupled to coal; this should mean that it corresponds to path (b). Signal A_2 is equally strong when

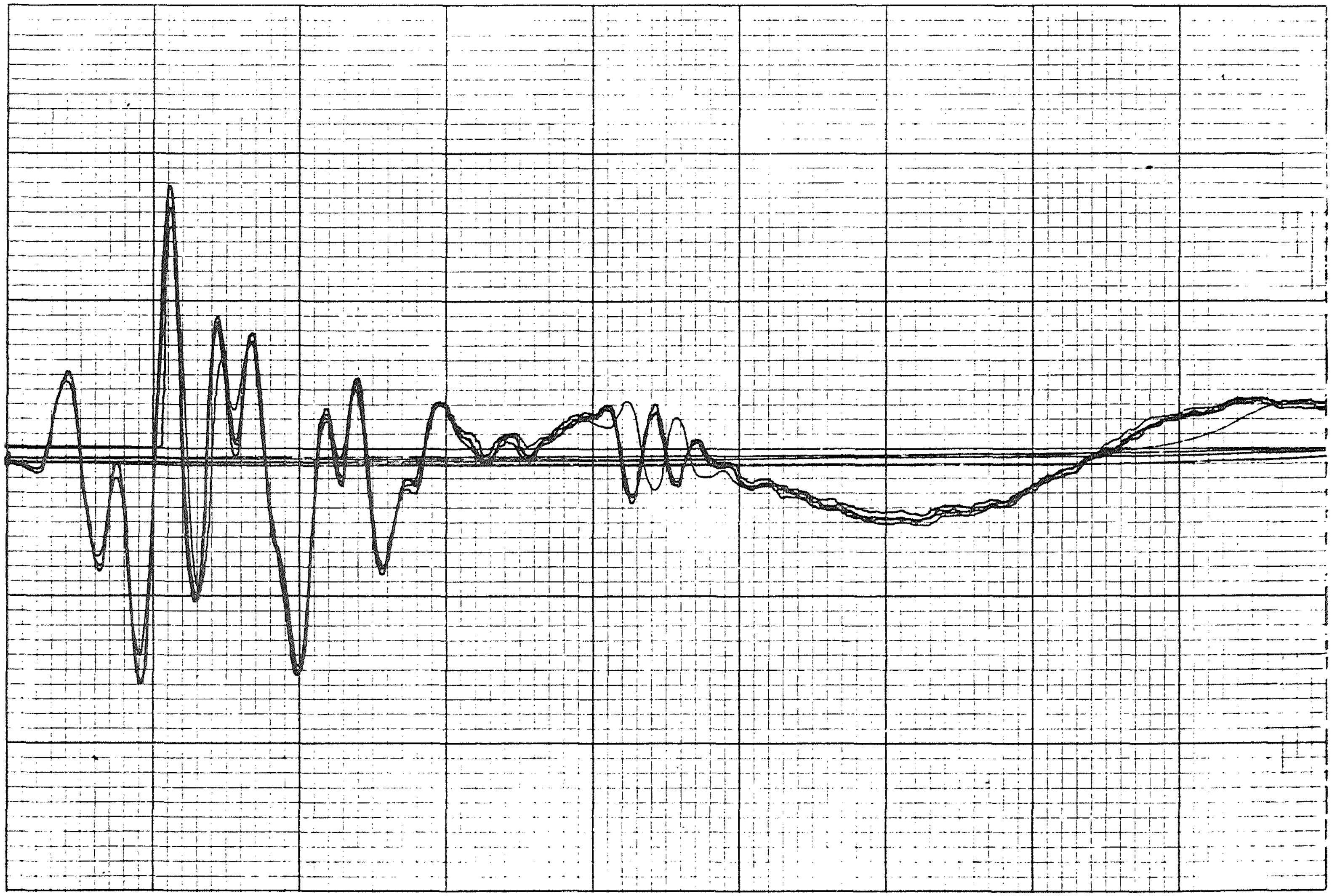


Figure 35. X-Y plots of 30 ft coal reflection without wire mesh (double line) and with wire mesh (single line), no filter

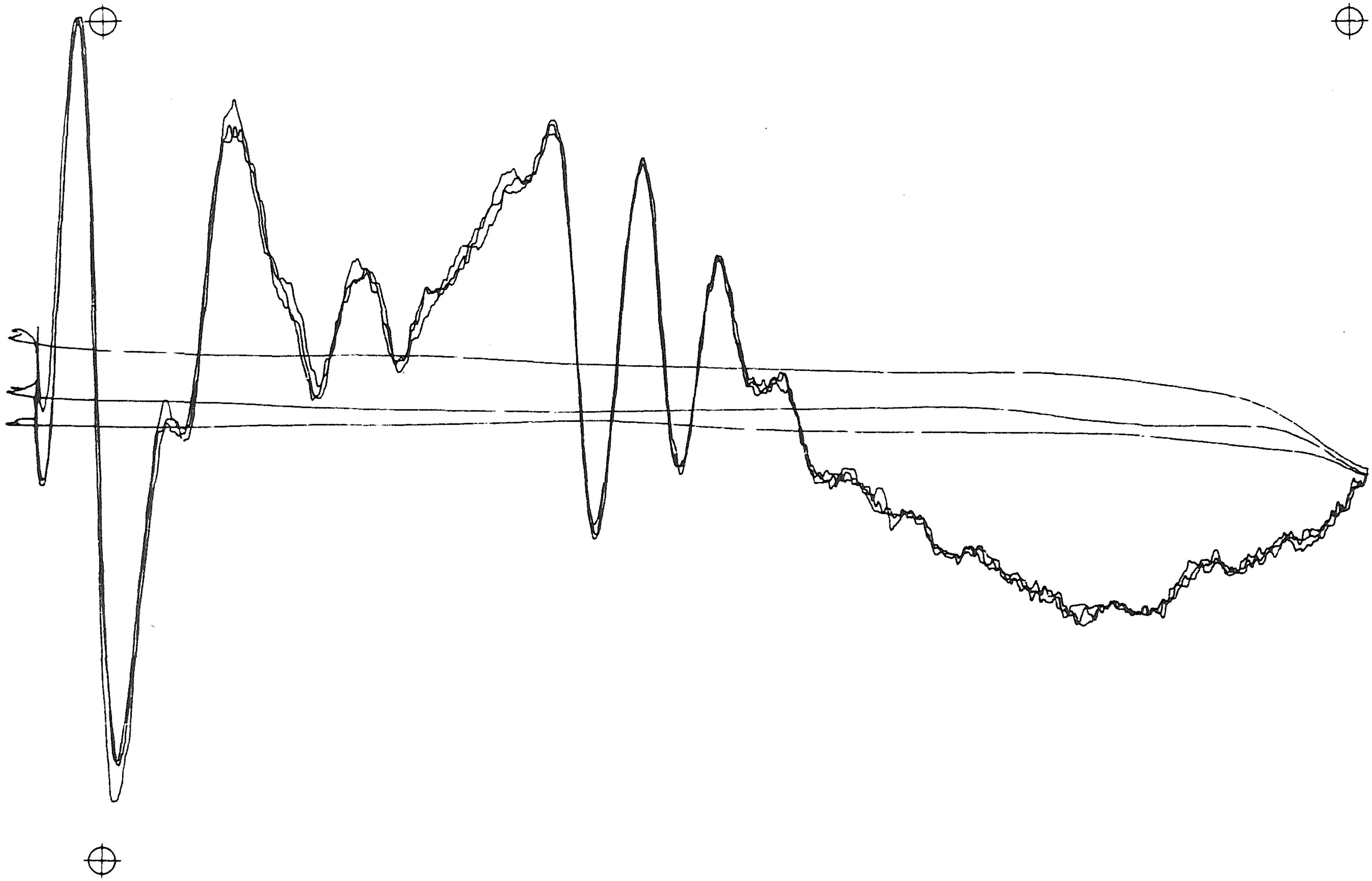


Figure 36(a). Magnified X-Y plots of radar reflection from coal-air interface, taken through 30 ft of coal

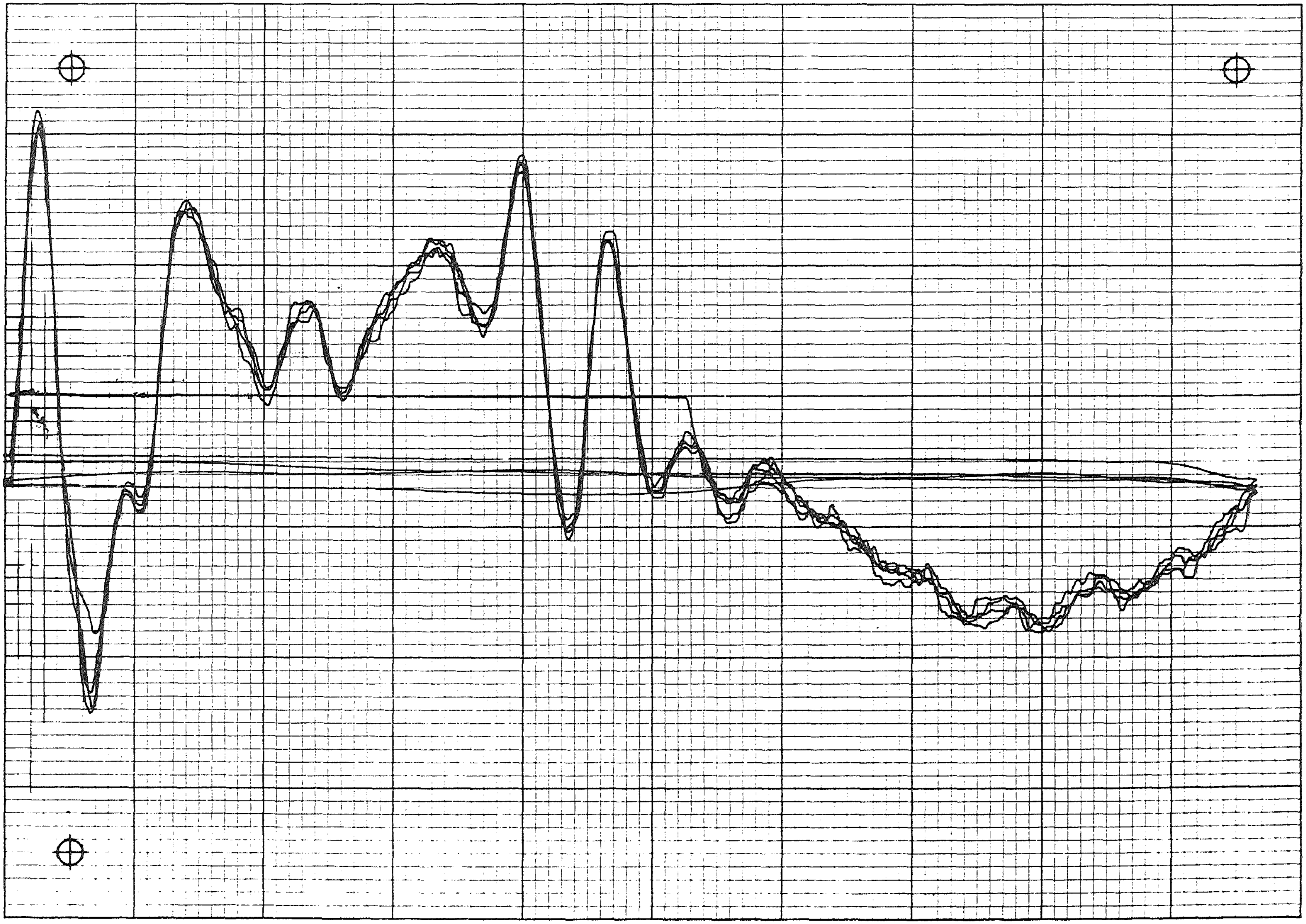


Figure 36(b). Magnified X-Y plots of radar reflection from wire mesh reflector, taken through 30 ft of coal

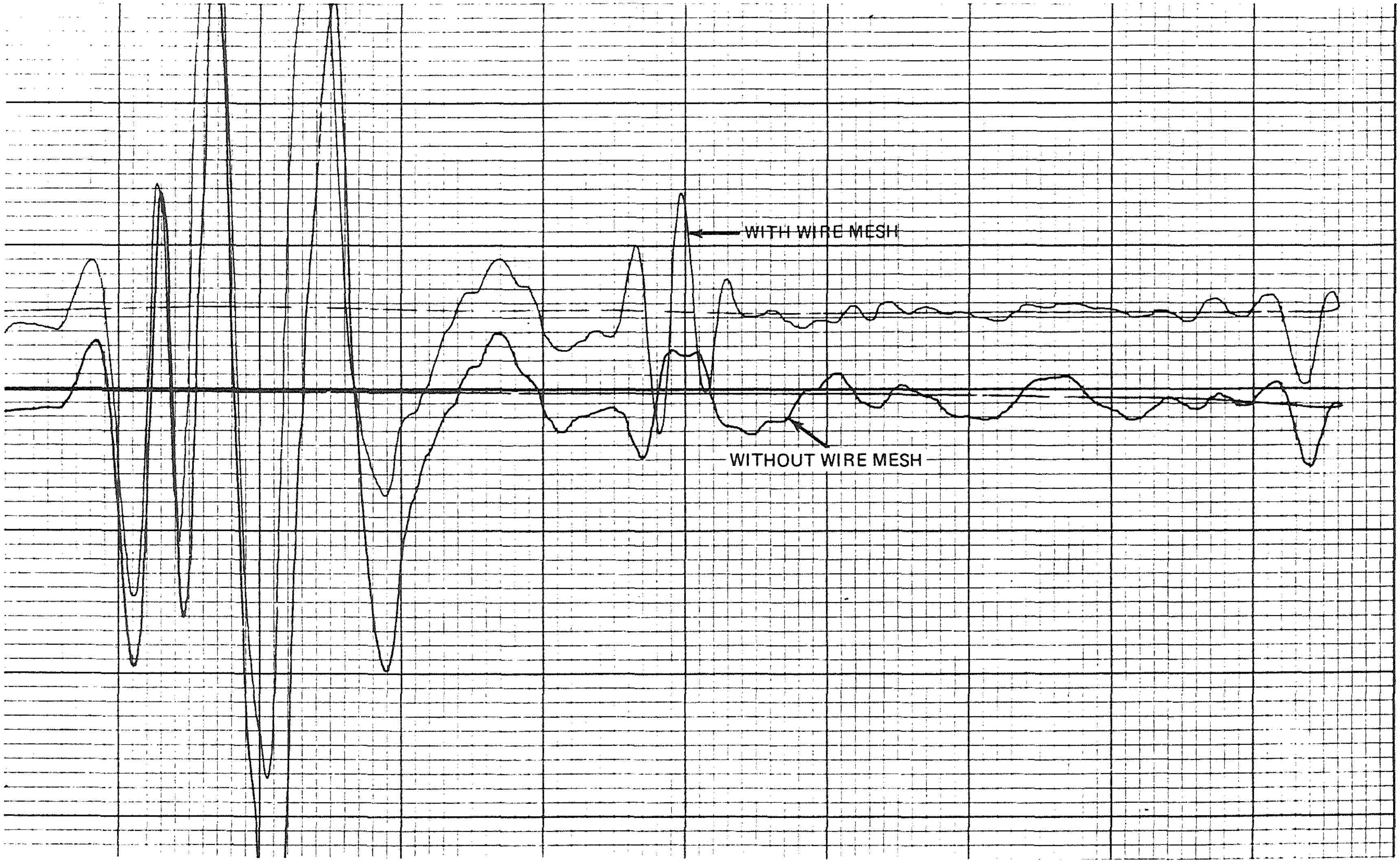


Figure 37. Overlay of X-Y plots of leakage "L" and reflection through 23 ft pillar of coal

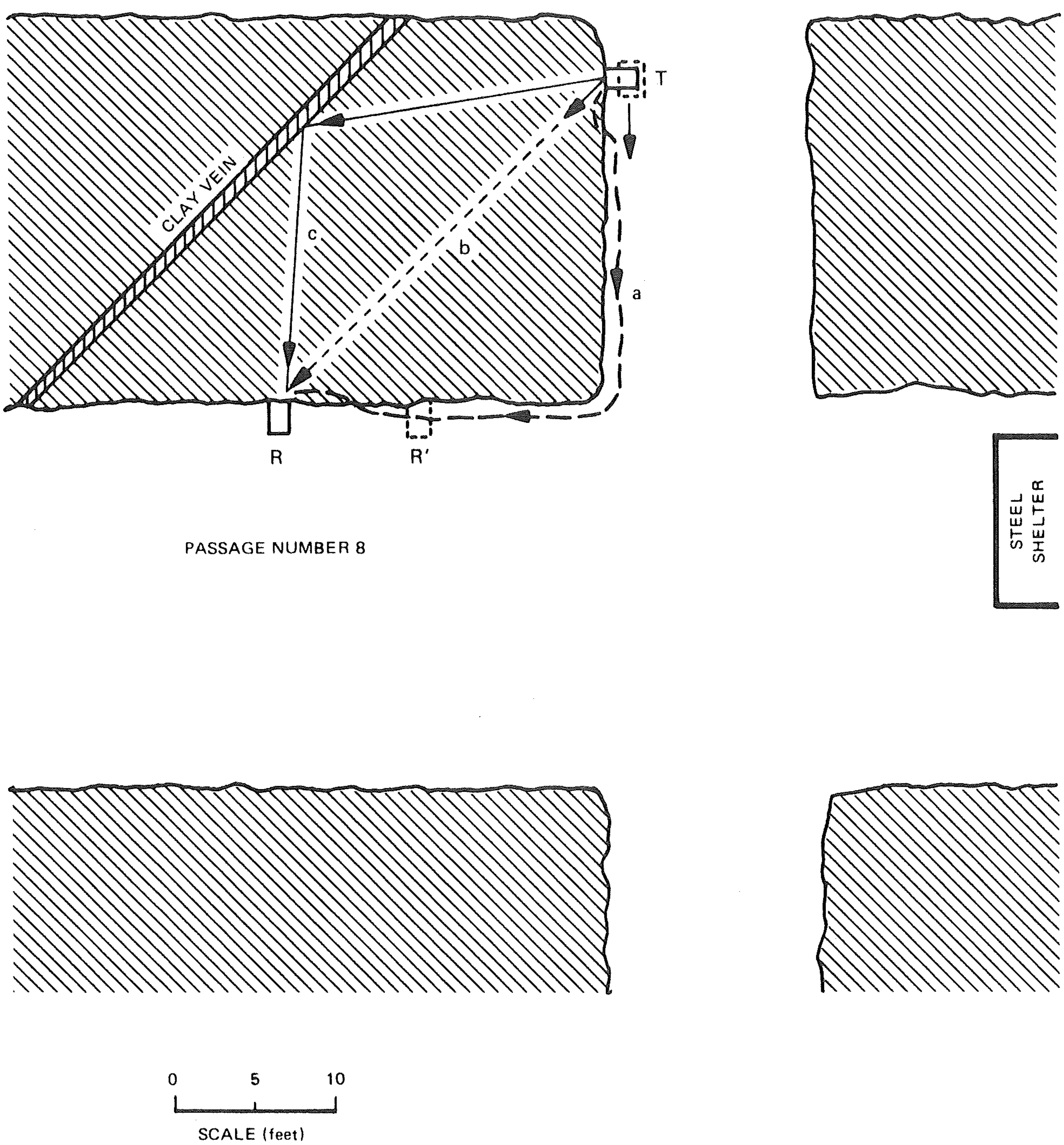
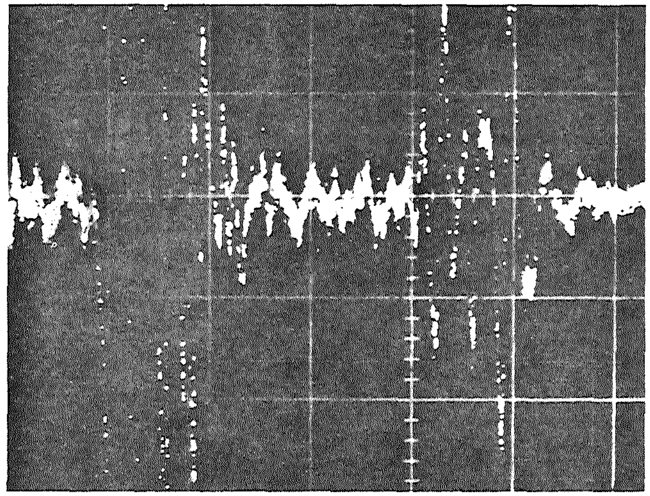
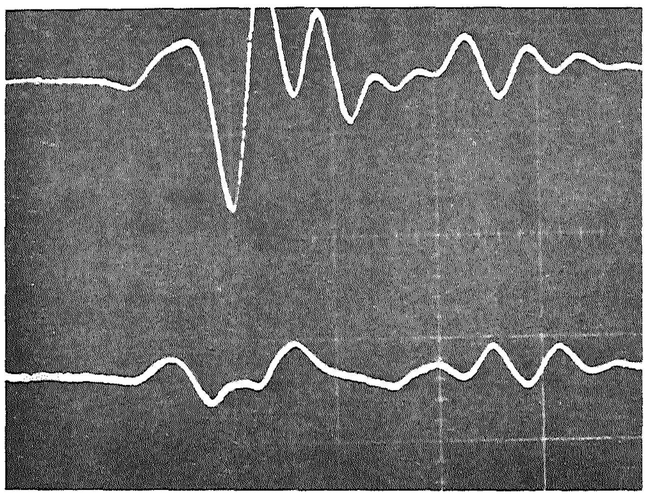


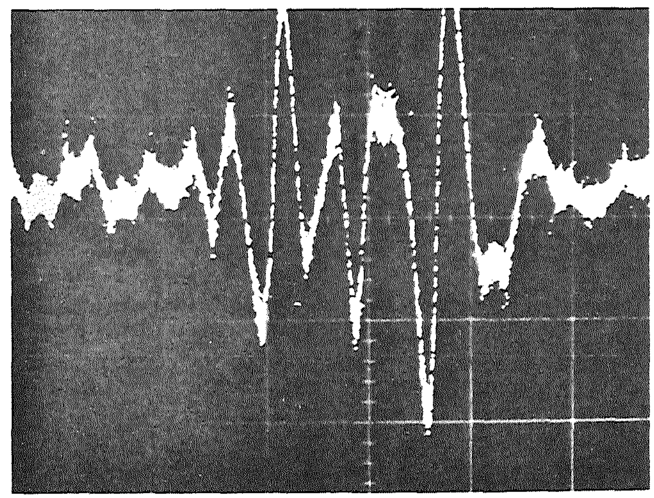
Figure 38. Corner test arrangement



(a) Groups A (left) and B (right), 50 nsec, 10 mV/div.

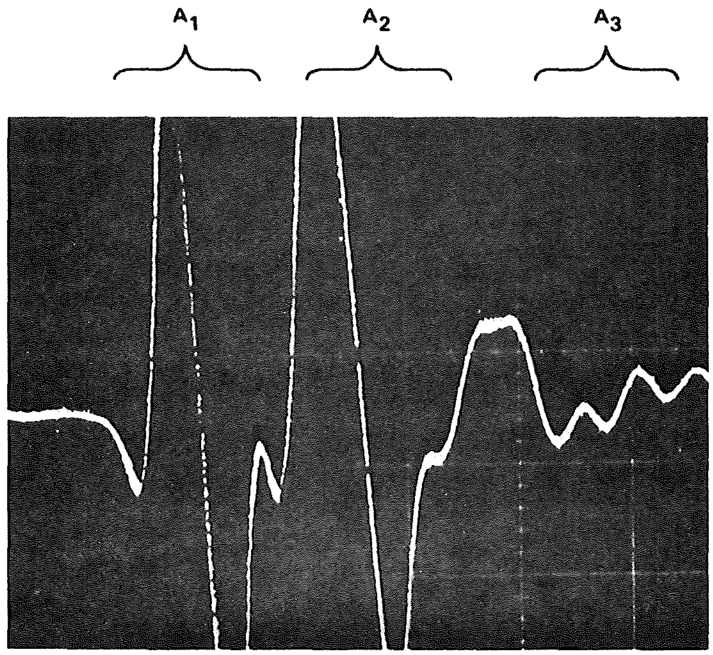


(b) Group A, 10 nsec, 100 mV/div.
Upper: T ant. facing corner
Lower: Same, 2 ft from coal.

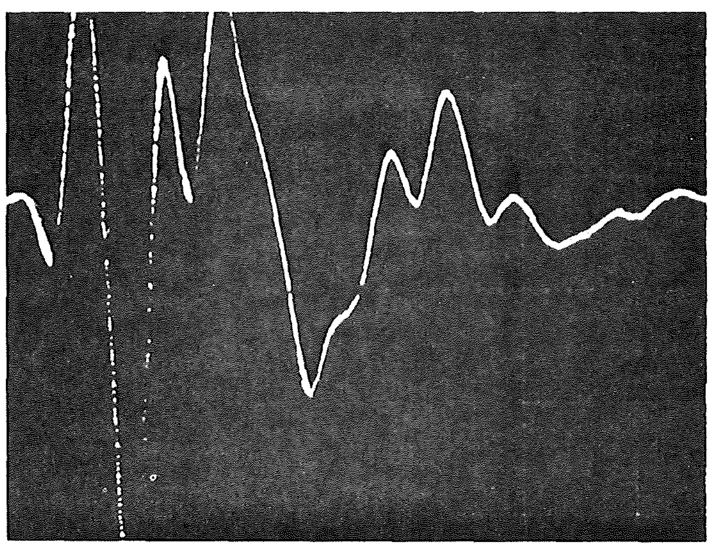


(c) Group B, 20 nsec, 10 mV/div.

Figure 39. Signal groups recorded in corner test



(a) R antenna 20 ft from corner.



(b) R antenna 12 ft from corner.

Figure 40. Corner test; effect of moving R antenna upon initial signals.
10 nsec, 50 mV/div.

launched into or along the coal surface, which should mean that it corresponds to path (a). Figure 40 shows that both signals are shifted by 5 to 8 nanoseconds when R is moved to R', which is consistent with this interpretation. However, if (a) is air-propagated, it should arrive 16 nanoseconds before (b), instead of after it. There are insufficient data to clarify the contradiction. Signal A_3, which is not affected by decoupling the transmitting antenna from the coal (figure 39(b)) but which is shifted by moving R to R', may be an in-air reflection from the Westinghouse experimental shelter nearby. The clay-vein reflection (c) could not be disentangled from interfering signals, and the test was therefore unsuccessful, although productive of additional mysteries.

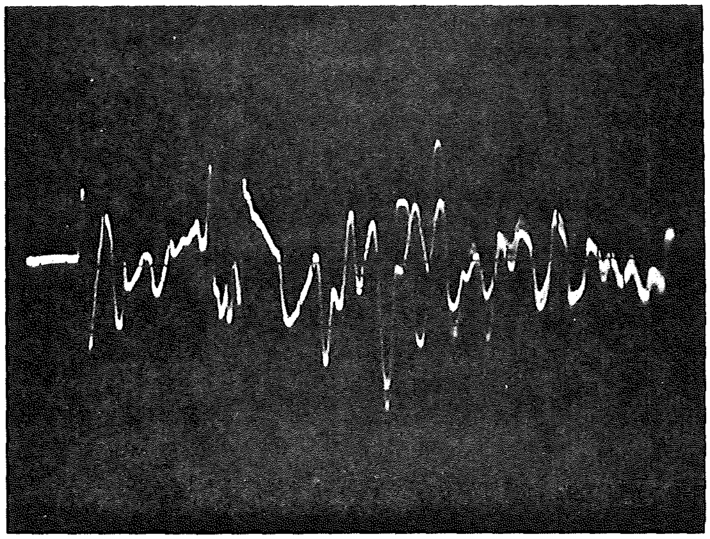
5.7 COMPARISON OF THE TWO RADAR SYSTEMS

Following the second Bruceton test series, a variety of field and laboratory tests of the equipment were made in Texas. After reconditioning the cable connectors and providing new batteries for the V.H.F. tunnel detector system, attempts were made to see and study a strong, bona fide reflection received by this equipment through a solid medium. It was taken to the Kleer salt mine near Dallas, where the antenna was placed against a mine pillar of solid salt about 30 ft. thick and 90 ft. long. The speed of propagation in salt is known to be about 0.43 ft./nanosecond. The reflection should have been at 140 nanoseconds. Since the reflecting wall was inaccessible, attempts were made to identify the reflection by moving the antenna away from the near wall; this should have caused a reflection to decrease in size, but clutter should increase. All signals near the expected time increased, so no identifiable reflection was seen through the salt. The reflection of a man walking away from the antenna could be followed to a distance of 50 feet, which corresponded to about "215 nanoseconds," which is double the expected range. This would explain the lack of a clear reflection in both the salt mine and coal mine tests with this equipment. The actual repetition frequency is evidently 6.72 MHz rather than the 3.12 MHz stated in the manual, and it has a working range of only 150 nsec (75 nsec with the "delay" knob on X2), insufficient for most mine experiments.

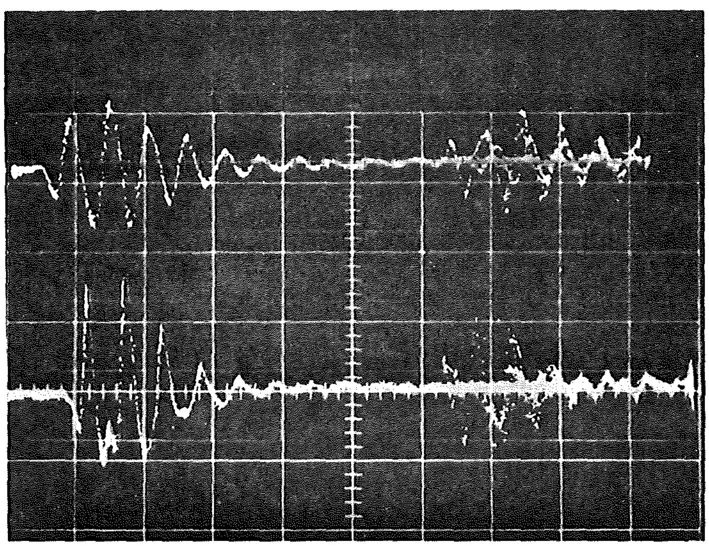
Both sets of equipment were set up coupled into the air beside a truck road, and signals from identical tractor trailer truck reflectors at 40 $\pm$ 3 feet were photographed numerous times. Vertical polarization was used. Figure 41 illustrates the approximate arrangement of the VHF-T.D. (except that the antenna and operator faced the road). Figure 42 shows typical results. In figure 42(a) the entire 150 nsec working range, plus some of the initial dead time, is shown. The gain and gain rate were adjusted for uniform clutter amplitude throughout. Traces with and without the truck are superimposed. The truck signal begins near the center, at 78 nanoseconds, where it should be by the new calibration. Its maximum amplitude is about 1 volt, and the clutter amplitude is also 1 volt, peak-to-peak, or about 50 times system noise.

Figure 42(b) is the best of several photographs of the storage 'scope signal recordings made using the bistatic (two-antenna) Teledyne Micronetics radar. High ambient temperature caused trace smearing and lining-through of the

Figure 41. Arrangement of VHF-T.D. for reflectors in air



(a) VHF-T.D. clutter and truck signals
16.7 nsec 0.5 volt/div.
gain = 17 dB + 0.5 dB/nsec



(b) Teledyne radar leakage "L" and truck signals
10 nsec, 10 mV/div., antennas 27' apart
Upper - with VHF filter, Bottom - without

Figure 42. Comparison of radar systems

truck signal by 'scope noise. The maximum amplitudes seen were 1-1/2 to 2 times as large as shown in figure 42(b). The trace is entirely free of clutter beyond 30 nanoseconds past "L" with this equipment, and the truck signal is 30 to 40 mV, some 15 times system noise.

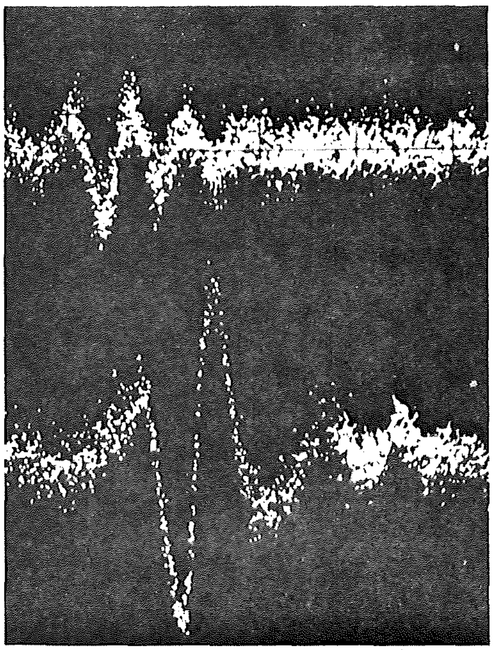
In planning a future mining radar, it is necessary to choose between the bistatic and monostatic systems. This experiment demonstrates that the bistatic system is at least seven times better with respect to clutter, even when due allowance is made for the reduction of clutter amplitudes to about half those shown when the VHF-T.D. loop antenna is placed against an appropriate solid medium. To what extent the clutter produced within the RF portion of the VHF-T.D. could be reduced by careful design and adjustment is not known, but the bistatic system is expected to have an inherent, permanent initial advantage and to require far less critical adjustments for low standing-wave-ratio. Figure 42 also makes clear, however, that the present VHF-T.D. is some four times as efficient as the present Teledyne Micronetics radar with regard to signal-to-noise ratio, despite the much higher transmitter input power of the latter.

Numerous experiments were performed in the Kleer salt mine to compare the performance of the loop antenna of the VHF-T.D. with the shielded, dielectric-filled horn antennas of the Teledyne Micronetics radar. The latter radar system was used in this work. In one-way transmission through 115 ft. of salt, the loop antenna used for reception gave twice as great a signal amplitude as the horn. The same ratio was found in receiving reflections from distances of 115 ft. and 170 ft. within the salt (see figure 43(a)). Leakage into the loop antenna (against the salt) from a transmitting antenna in air 27 ft. away was 720 mV, comparable to the 1700 mV picked up by a horn receiving antenna in air. However, when the horn receiving antenna was coupled to salt, it received only 40 mV of leakage, so it is 18 times better than the loop for suppressing clutter from transmitter leakage and mine-chamber echoes.

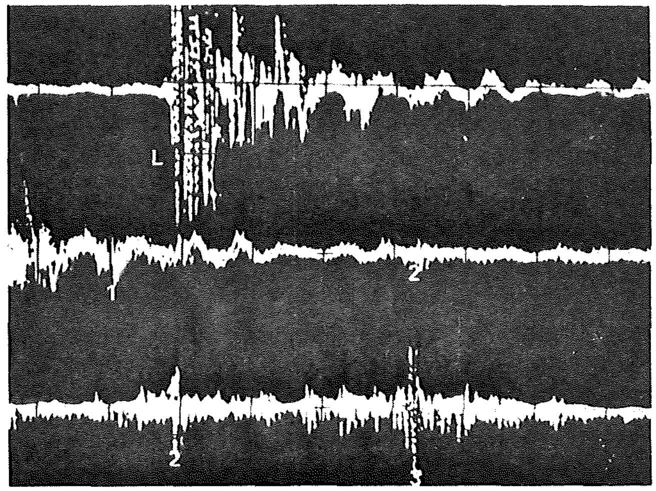
5.8 LONG-RANGE AND ABANDONED-WELL DETECTION

In the course of other salt-mine tests, a distinct, isolated echo was detected at a distance of about 170 ft. inside a large mine pillar some 450 ft. square. An abandoned drill hole, made long ago in a search for oil, was known to be somewhere inside this pillar; in fact, brine leakage presumably coming from this hole had been encountered on two sides of the pillar. The radar echo is clearly displayed in figure 43(a). Unlike other salt-mine echoes known to come from flat pillar faces, this echo could only be obtained with vertically-polarized antennas; this is an expected property of long, thin vertical reflectors such as a brine-filled drill hole.

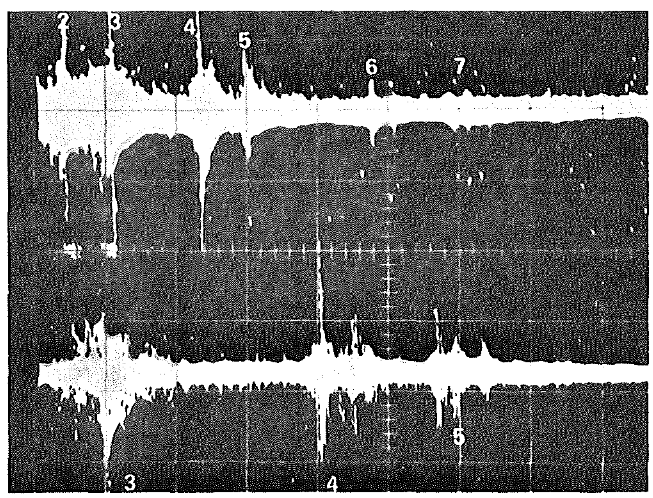
The calculated distance of the reflector was consistent with the probable location of the known drill hole, but its direction was unknown because of the broad antenna beams necessarily used. Hence, reflection experiments were performed at four other stations around the pillar. At all stations, one or two isolated, vertically polarized reflectors were detected at plausible distances. These are plotted in figure 44; the less clear reflections are shown



(a) Echo from wet drill hole 170 ft away. 10 nsec, 5 mV/div.
Upper: with horn R antenna.
Lower: with loop R antenna.
(at station 0)



(b) Station 3 echoes, time-shifted. 100 nsec, 50 mV/div.



(c) Most distant Station-3 echoes, 20 mV/div.
Upper: 500 nsec/div,
Lower: 200 nsec/div.

Figure 43. Salt mine performance achieved by Teledyne radar

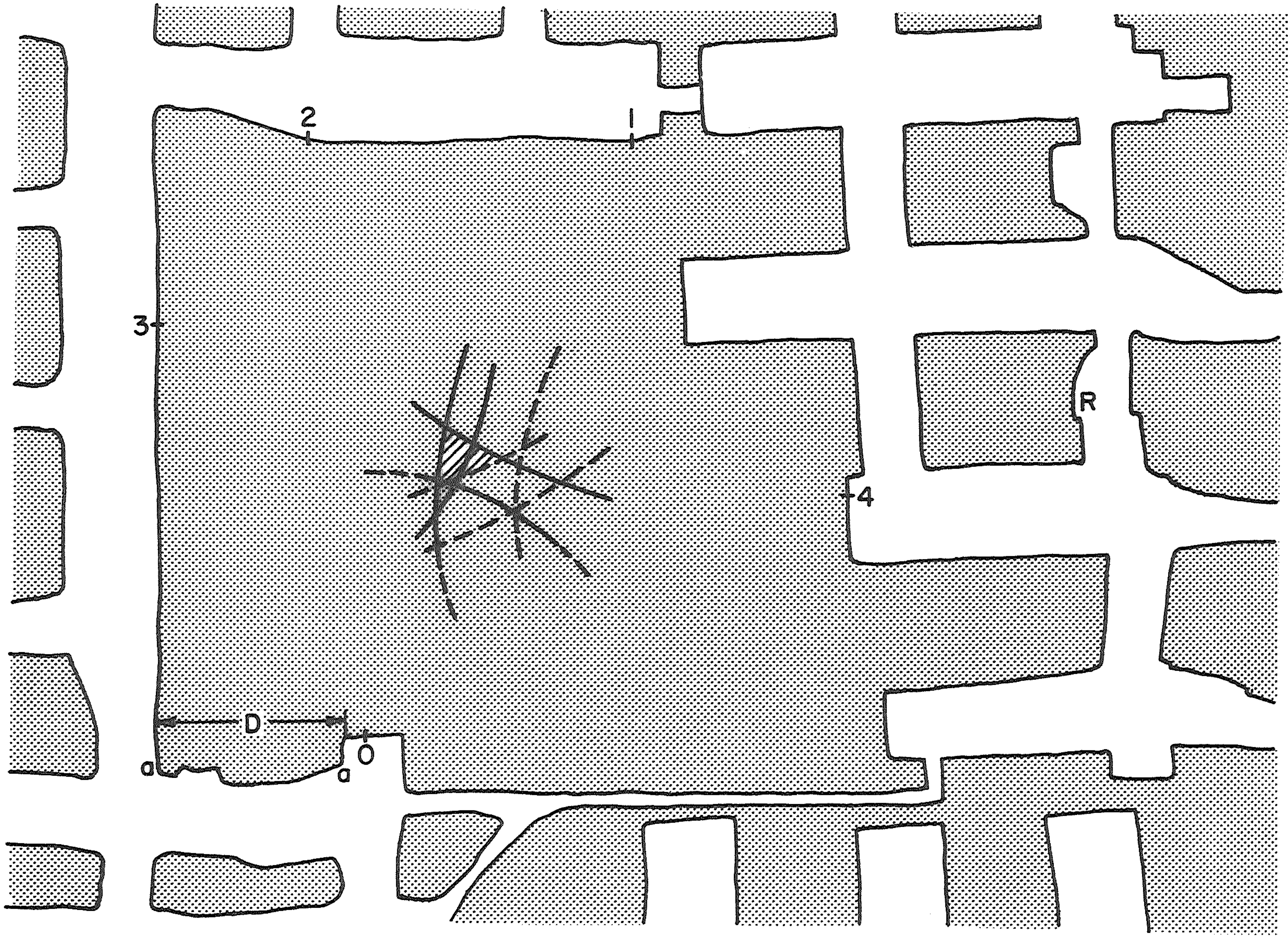


Figure 44.- Map of salt mine pillar and drill hole location.

dashed. The well is believed to have been located within the shaded triangle by means of these tests. The lack of accurate agreement may be a result of (a) uncertainty and variations in the velocity of radar waves in this particular mass of salt; (b) small changes of 'scope calibration with increasing temperature (at station 4, the equipment was operated on batteries and the cooling fan could not be used). The greatest detection distance of the well through salt in these experiments was 272 ± 10 ft.

In these tests, echo times were measured from the direct-leakage "L", which was known to arrive at the receiving antenna 25 to 27 nanoseconds after the emission of the radar pulse. Fortunately, there were always a number of reflectors at intermediate distances within the antenna beam, which were used as markers No. 1, No. 2, etc. to measure accumulated time as the trace was moved to successive positions with the delay knob and the gain was raised to see the weaker signals at greater range, as illustrated in figure 43(b). This oscillogram and figure 43(c) were made at station 3 (figure 44). The most distant reflector seen was "7" on figure 43(c), which unfortunately did not record well, although it was clearly seen. It occurred 3510 nanoseconds after emission of the radar pulse, so was from a reflector 735 ± 25 ft. distant through the salt. This agrees well with the distance to the wall of the second cross-cut room (marked "R") in figure 44. This room is 100 ft. high, extending high into the salt above the first cross-cut, so was clearly in view from radar station 3. Many of the distant reflectors were verified as being within the salt by the fact that they decreased in size when one of the antennas was decoupled from the salt surface.

These striking successes in salt encourage the hope that much greater working ranges than have yet been demonstrated can soon be achieved in coal as well, and that water-filled, abandoned drill holes (and metal casings) can readily be located by radar in advance of coal mining.

6. CONCLUSIONS FROM THE STUDY

(1) Present VHF short-pulse radar equipment has obtained proven reflections through up to 30 feet of coal in the Pittsburgh coalbed. It is estimated to be capable of detections through 75 feet of this coal.

(2) Various calculations and experiments predict that the following reflectors are detectable by radar at successively decreasing distances through coal: air-filled passages, water-filled passages, clay veins, cased or water-filled vertical drill holes, and large pyritic nodules.

(3) Success in obtaining and interpreting radar echoes through coal depends at present almost entirely upon prevention of the "clutter" of spurious echoes arising in the equipment and in the air-filled mine passages. Clutter suppression is now the most important consideration in equipment design; bistatic systems seem superior to monostatic systems. Clutter suppression in the present equipment was improved by a factor of at least 50 during the 1-year R & D program reported here. Further substantial improvements are believed possible.

(4) The VHF spectrum most useful for coal exploration extends from about 150 MHz downward. Short pulses employing a spectrum between 50 and 125 MHz give good distance resolution.

(5) The speed of radar waves in the Pittsburgh coalbed is typically about half that in air.

(6) Vertical polarization must be used.

(7) Radar waves can successfully penetrate through a foot or so of shaley "clay vein" material, but are also reflected well from it.

(8) The beam width of a mining exploration radar cannot easily be made narrow enough to locate reflectors laterally. However, this can be done by calculation if the antennas are placed at different stations separated at least several meters apart.

(9) We have developed several indirect techniques to aid in radar echo identification, including polarization, decoupling, and the use of wave absorbers. Additional techniques are needed and are possible. For this reason alone, radar exploration in advance of mining may require trained specialists for some time to come.

(10) Magnetic tape recording and computer reduction of data are much less effective than electrical system improvements in up-grading radar performance. However, these will ultimately be desirable for making three-dimensional interpretations of multi-station radar data.

(11) Exploration of coal at ranges beyond 75 ft. will require higher transmitter power and/or greater electrical efficiency than is available in the present radar. Portability and "permissibility" for coal mines are also practical requirements of mining radar equipment.

7. RECOMMENDATIONS

(1) An experimental mining radar system should be designed and built, incorporating the best features of the two radars tested under this program, but designed specifically for mining. Such equipment is required, to further advance the embryo art of radar exploration in advance of coal mining.

(2) The new equipment should be used in a stepwise program of testing and improvement to develop and demonstrate a practical capability to detect and locate typical hazards ahead of mining. Such a proving-out program should extend over a minimum period of 1 year.

APPENDIX 1 to TECHNICAL REPORT 71-8

REPRINT OF PAPER PUBLISHED IN GEOPHYSICS, DEC. 1970
"RF ELECTRICAL PROPERTIES OF BITUMINOUS COAL SAMPLES"

Not Included Here

This Report is Published as Referenced Above

APPENDIX 2 to TECHNICAL REPORT 71-8

THE MULTIPLE AIR-PATH EFFECT

THE MULTIPLE AIR-PATH EFFECT

Calculations have been completed, which give the waveform expected as a result of multipath direct leakage of a monocycle wavelet from the transmitter to the receiver antenna, as illustrated in figure 21. This work is outlined in the following.

The two antennas are considered to be small vertical electric dipoles, 12 feet apart on the centerline of an air-filled passage 6 feet high, bounded at top and bottom by shale (figure 21). The shale is assumed to have electrical properties similar to those of clay vein material (figures 2 and 3 of Appendix 1) as follows: resistivity ρ = 25 ohm meters, relative dielectric constant $(\varepsilon'/\varepsilon_0) = 6$. The relative amplitudes E of wavelets reaching the receiving dipole via paths a, b, c, etc., can be calculated by taking account of spreading, reflection and antenna-pattern losses:

$$E_n = 2(12'/D)(|A_2/A_1|)^n \cos^2 \overline{(90°-\theta)} \text{ for } n>o.$$

Here D is the distance along a particular path in feet, n is the number of reflections involved, θ is the angle of incidence (from the normal to the shale surface) at each reflection, and (A_2/A_1) is the complex reflection coefficient for each reflection. The factor of 2 takes account of the two possible paths of each type (see figure 21).

To calculate the delay times **t** via these paths, the propagation distance D and reflection phase shifts ψ are used:

$$t = D + n\left(\frac{180° \pm \psi}{360°}\right)T \qquad \text{where } \psi = \arctan y/x, \quad A_2/A_1 = x + jy,$$

and T = wavelet period, = 3 to 10 nanoseconds.

While either sign of the reflection phase shift ψ may probably be used, the + sign, representing a phase delay corresponding to partial penetration into the shale before reflection, is physically the more reasonable.

The complex reflection coefficient is given by Fresnel's formula[1] for a wave polarized in the plane of incidence:

$$(A_2/A_1) = \frac{(\tan\phi - \tan\theta)(1-\tan\theta\tan\phi)}{(\tan\phi + \tan\theta)(1+\tan\theta\tan\phi)}$$

Table 1. Multiple air-path delays and amplitudes

Path No.	Distance D, ft.	Refl. No. n	Incid. Angle θ	Refl. Coeff. A_2/A_1	Abs. Value $\lvert A_2/A_1 \rvert$	Phase ψ	Delay t, nsec	Amplitude E
a	12	0	-	-	-	-	12	1.0
b	13.4	1	63.5°	-0.17+j(0.19)	0.26	48.5°	19.7	0.38
c	17	2	45°	-0.38+j(0.17)	0.43	24.7°	28.4	0.13
d	21.6	3	33.6°	-0.50+j(0.15)	0.52	17.3°	38	0.048
e	26.9	4	26.5°	-0.50+j(0.17)	0.53	19°	49	0.014
f	32.3	5	21.8°	-0.50+j(0.17)	0.53	19.3°	54.5	0.002

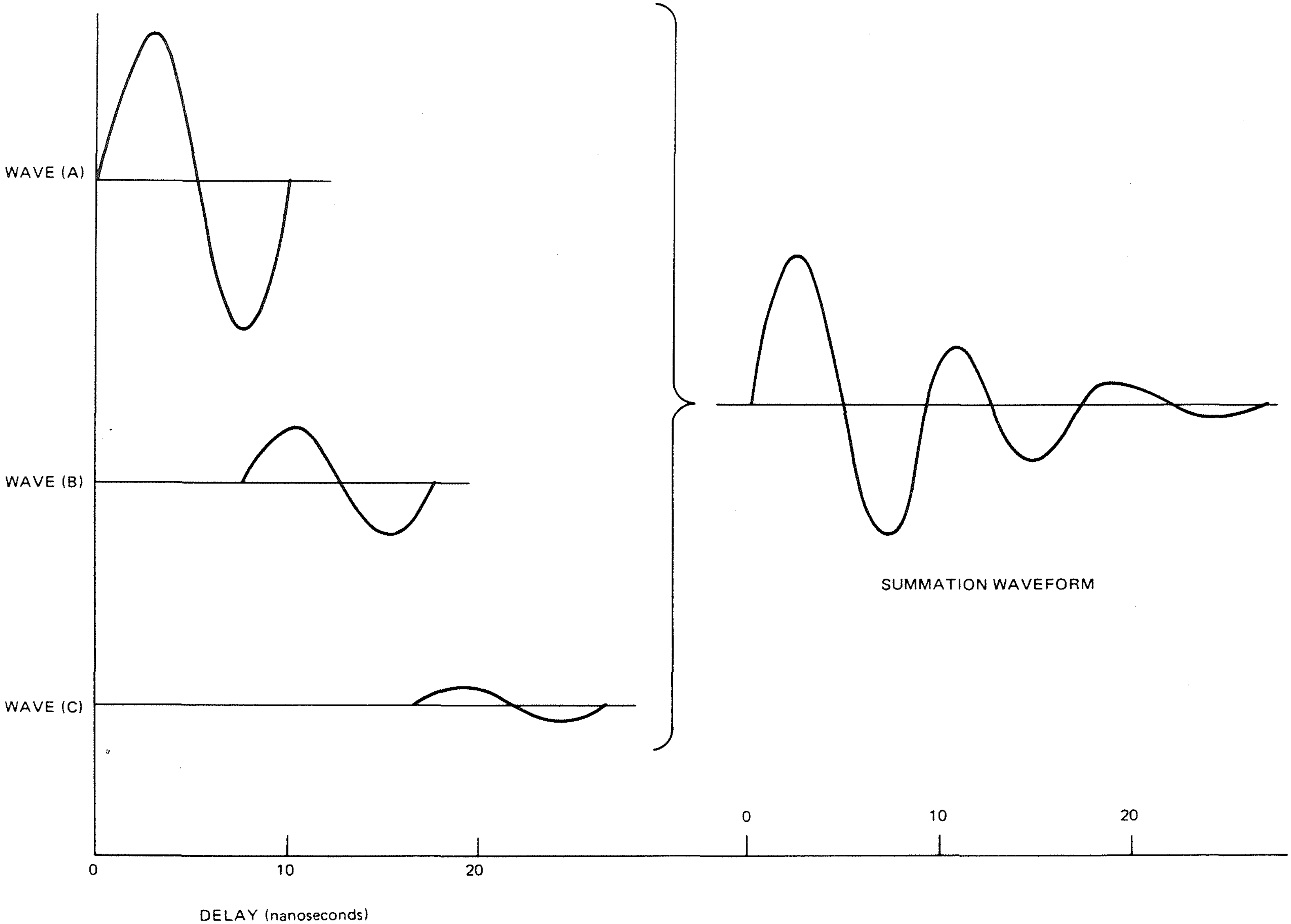


Figure 1. Calculated multiple-air-path leakage waveform

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