Radar and Sonar Probing of Salt

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ABSTRACT

Four radar systems have been designed to probe into salt ahead of mining for the detection of impurities in the salt such as anhydrite, sandstone or shale or even fractures with water. A microwave high resolution CW–FM radar system at 4300 MHz gives excellent resolution and can detect small (≈ 1 cm) fractures at ranges from 1 to 30 meters in salt. A 440 MHz radar system has a longer detection range—out to 300 meters in dry salt—but has less resolving power. A 230 MHz radar system obtains greater ranges (over 400 m) and is useful in detecting and mapping salt dome flanks and tops of salt domes. Both of the above two radar systems can detect boreholes (cased or uncased) in salt and supply data on direction and range. A low frequency radar system at 30 MHz has also been found useful to probe extremely long ranges (up to 2000 m) for large discontinuities in the salt such as brine cavities or salt dome flanks. This radar system is also useful in probing salt with small moisture content and can be used in probing potash as well. All radar systems operate under their own diesel-generated or battery-supplied power.

In salt (or other rock) that contains some moisture, radar waves are attenuated and the range of probing is reduced drastically. To overcome this, a sonar system has been developed using 24 kHz sound pulses. Probing ranges of 400 meters in dry salt have been obtained and ranges of 215 meters in wet salt have been recorded. Dome flanks have been detected with sonar, as well as sandstone stringers in salt 15 meters ahead of mining.

Both sonar and radar have been used to predict water zones encountered in sinking a new shaft into an existing salt mine. Drilling verified the prediction.

INTRODUCTION

This paper is divided into two sections. The first section deals with *radar* (or radiowave) probing of salt and the second section deals with *sonar* (or sound wave) probing of salt. The theory of each is discussed briefly but most of the emphasis will be on the accomplishments of the actual probing of radar and sonar in salt mines.

RADAR PROBING OF SALT

Theory. The theory of radar probing of salt is identical to the standard radar theory for detecting airplanes in the sky with one difference. The medium through which the radar is transmitted is not air but *salt*. Ordinarily, radar sends energy through the air without loss at VHF frequencies. When probing into salt, we are concerned about the attenuation or loss of the energy of the electromagnetic wave as it travels *through* the salt. Further, we must consider what frequency to use in our probing of salt as the attenuation of the wave by the salt will be frequency dependent. Figure 1 shows the electrical properties of salt with the top part a graph of the variation of ϵ' [the real part of ϵ^*, the complex electric permittivity (dielectric constant)] with frequency, and the bottom is a graph of the loss tangent $\left(\tan\,\delta = \frac{\epsilon''}{\epsilon'}\right)$ as a function of frequency. The loss tangent of the material through which an electromagnetic wave must travel (salt in our case) is associated with the power attenuation in Np/m of the electromagnetic wave by the equation

$$\alpha = \frac{2\pi\ \tan\delta}{\lambda}\sqrt{(\epsilon'/\epsilon_o)(\mu'/\mu_o)}\ \text{Np/m}$$

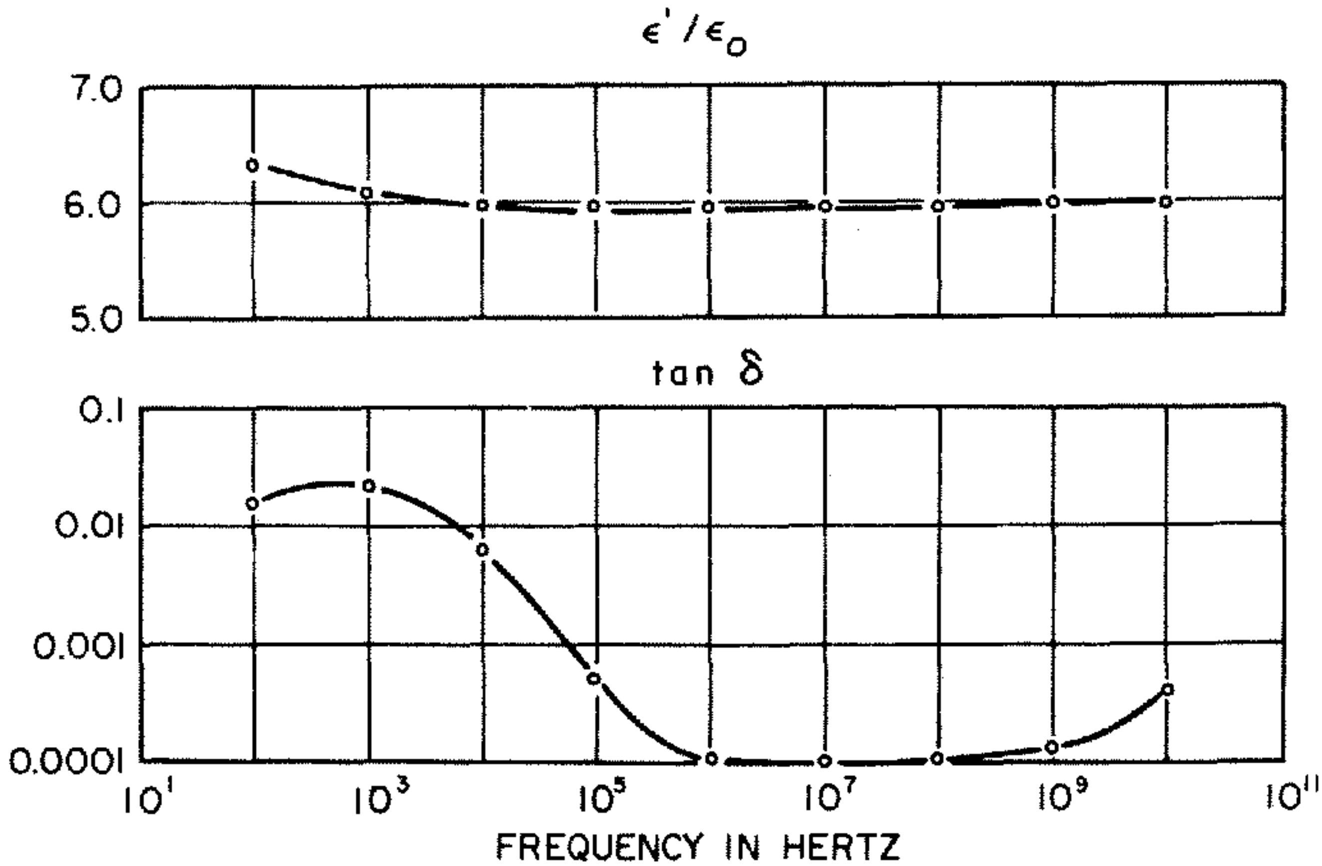

Figure 1. Dielectric Properties of NaCl Crystal.

where the first quantity under the square root sign is the relative electric permittivity of salt (≈ 6.0) and the second quantity its relative magnetic permeability ($= 1$). λ is the wavelength of the radar in air. We can see from Figure 1 that the attenuation of a wave will be higher at either microwave frequencies (10^{10}–10^{11} hertz) and at lower frequencies ($< 10^5$ Hz) than in the VHF region in the middle. It is for this reason that we have chosen most of the frequencies of our radar systems to operate in the 10^6–10^9 hertz region, except where we purposely needed the short wavelength radar for high resolution.

For further discussion of the theory, see Unterberger (1974).

Description of radar systems. We now discuss briefly the four radar systems we have developed for probing salt. Just as a single frequency radar system will not suffice for all the many things we use radar in air for, such as early warning radar, anti-collision ship radar, harbor surveillance, airport taxi-control, missile guidance, etc., so in our radar probing of salt no *one* system will cover all requirements. If we wish to see large targets (such as a salt dome flank) at long distances, we will need a high power, low frequency radar. In order to see detail of the target (airplanes in a cluster or a small fracture in salt) we need short wavelength and then get high resolution. This is bought at the price of range, however. With this in mind we discuss briefly the four radar systems, which are named after the phonetic alphabet letters, Echo, Charlie, Bravo and Alpha.

ECHO II. We start with the highest frequency (microwave) system called the ECHO II radar system. This is a modified microwave CW–FM radar system operating at 4300 MHz, whose block diagram is shown in Figure 2. It was originally used as an aircraft radio altimeter (Skolnik, 1962). The basic operation of the CW–FM radar system is shown in Figure 3. A photograph of the ECHO II horns are shown in Figure 4. The parameters of this radar are given in Table 1.

An FM–CW radar has three distinct advantages over the three other radars discussed in this paper. They are:

1. A short wavelength (2.85 cm) thus giving high resolution
2. A narrow beamwidth because of use of horns
3. An essentially zero minimum range.

These are all desirable advantages for very short range probing into salt (say to 20 meters). The three other radars are pulse radars and thus have a minimum range which is at least 20 meters. The short wavelength allows us to detect small fractures in salt and small impurities. The narrow

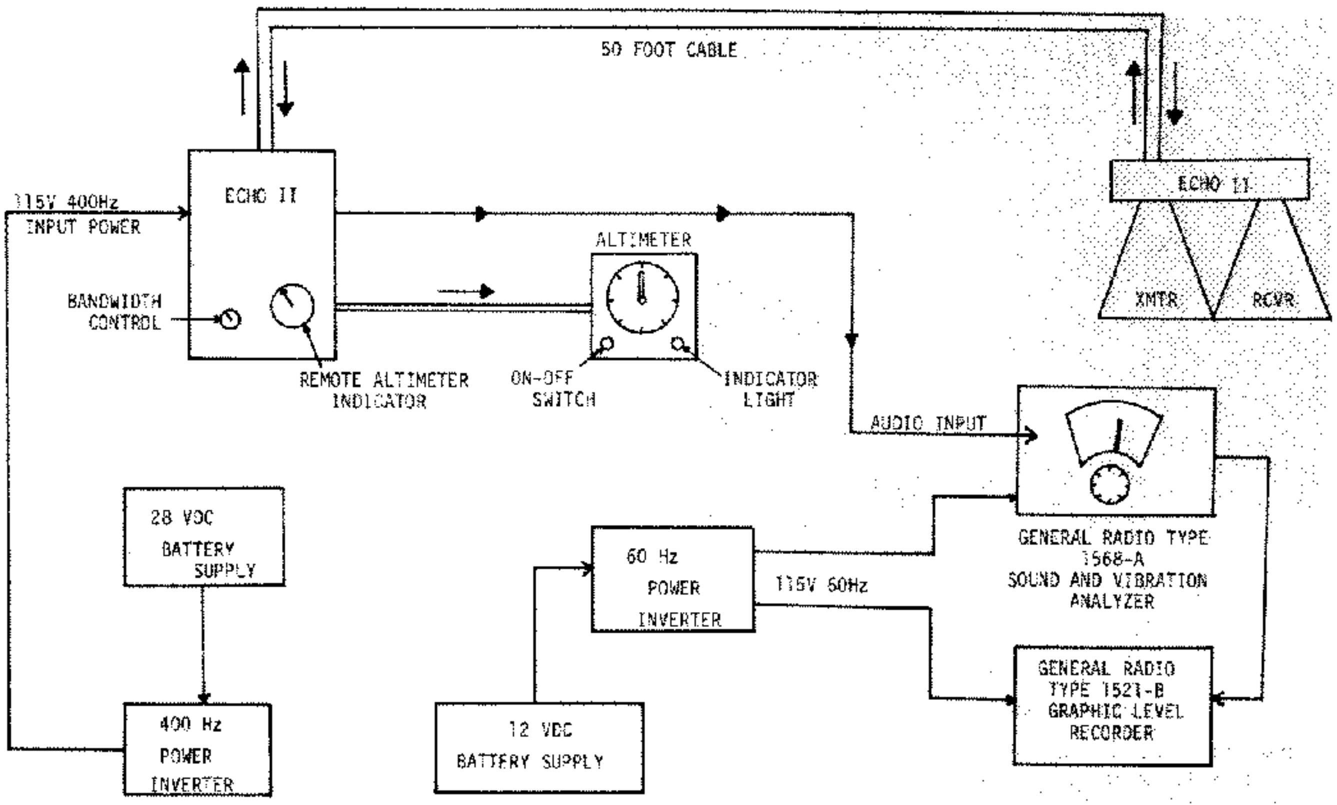

Figure 2. Block Diagram of ECHO II Radar System.

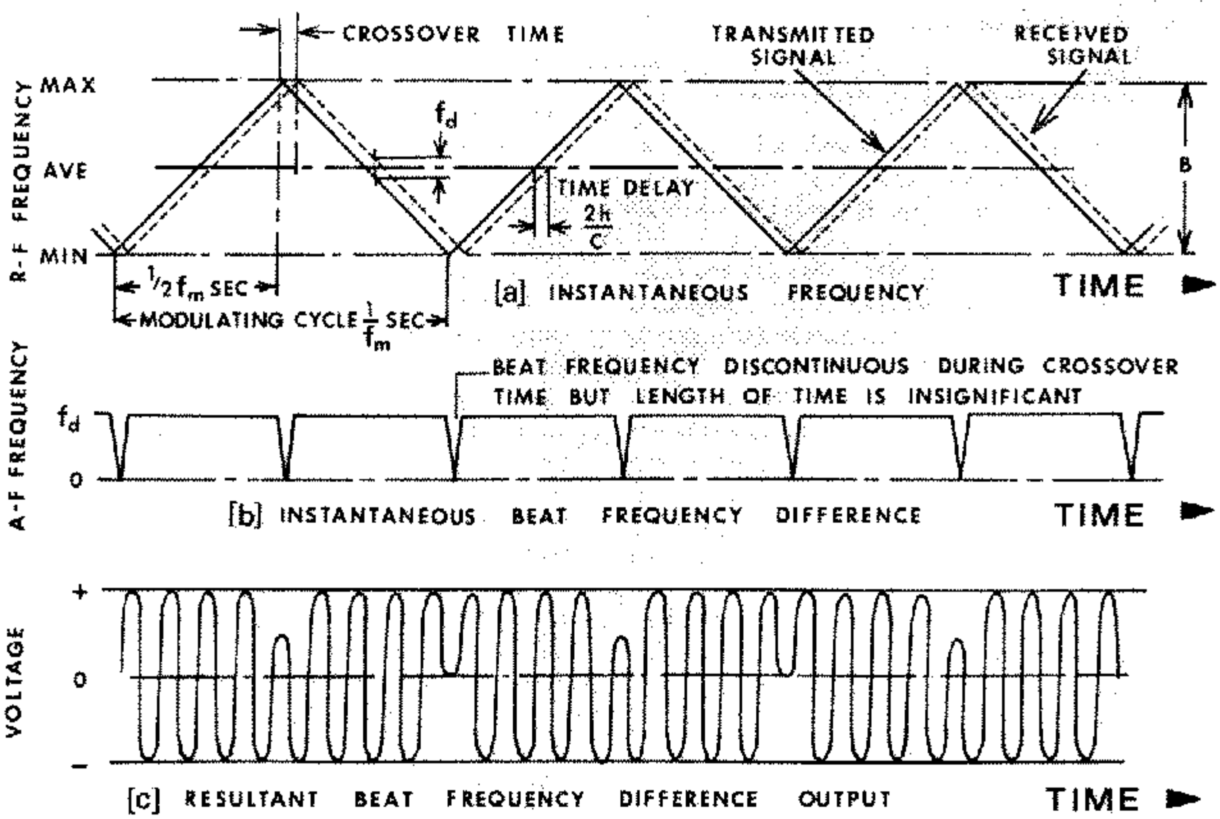

Figure 3. Operation of the CW–FM Radar.

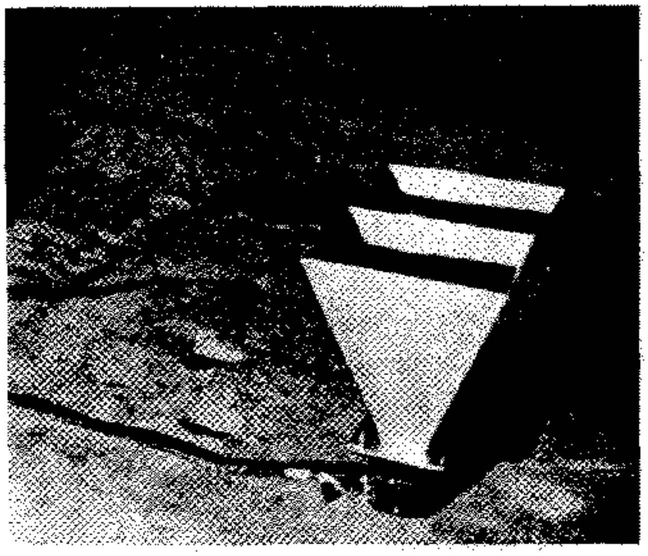

Figure 4. Photo of ECHO II Horns (pointing up).

TABLE 1

Echo II Radar Parameters

Basic frequency of operation	4300 MHz
Range of FM sweep Δf	70 MHz
Modulation frequency f_m	120 Hz
Wavelength in air	6.98 cm
Wavelength in salt	2.85 cm
Power output	1.5 W
Antenna beamwidth in salt	
transmitter horn	± 3°
receiver horn	± 3°

beamwidth helps us locate the discontinuities in salt accurately. We pay for all this at the expense of range. Because of the high attenuation, the range is limited to about 20 meters.

CHARLIE II. This is a 440 MHz pulse airborne radar altimeter modified for probing into salt. A block diagram is shown in Figure 5. The radar parameters are given in Table 2.

A photograph of the CHARLIE II radar system is shown in Figure 6. This radar system is mounted on a two (motorcycle) wheeled cart which has its own battery power and can operate anywhere in the salt mine by pulling it with a vehicle. Ranges of targets in salt (such as the dome flank or top of salt) to 300 meters have been observed using this radar system.

BRAVO III. For a really *long* range probing system CHARLIE II is inadequate. We need to go to lower frequency and higher power. This is the BRAVO III system shown in Figure 8. The important radar parameters are given in Table 3 (Unterberger, 1978). Because of the high power of this radar system we needed more energy than batteries could give so we went to the smallest diesel generator we could find. A photograph of BRAVO III is shown in Figure 11. This radar is mounted on a four wheeled cart in the salt mine and moved around to locations for probing. Figures 9 and 10 show the 22.5° angle into salt that refraction allows us to look into salt. At angles greater than ± 22.5° we cannot "see" into salt because this is the critical angle for the salt-air interface. Figure 8 shows a video tape recorder that can be used to record the data when profiling the top of salt or a salt dome flank as the radar system is moving. In the laboratory the magnetic tape data are played back to analyze the range to the salt target as a function of place in the mine and thus map the contour of the interface.

TABLE 2

Charlie II Radar Parameters

Frequency	440 MHz	
Power output	10 W	
Pulse width	0.3 μs	
Pulse repetition rate	1095 pps	
4 bay antenna array		
transmitting beamwidth	7.6° in salt	see Figure 7
receiving beamwidth	7.6° in salt	see Figure 7
Receiver sensitivity	2 dB above noise	
Power source	24 volt battery system	

TABLE 3

Bravo III Radar Parameters

Frequency	230 MHz
Wavelength in air	1.3 m
Wavelength in salt	53 cm
Power output	20 kW
Pulse width	0.6 μs
Pulse repetition frequency	980 pps
Antenna beamwidth in salt	
E-plane	see Figure 9
H-plane	see Figure 10
Power supply	diesel generator

ALPHA. A recently developed radar system for long range probing has been designed specifically for "seeing" into wet salt or probing other rocks with small amounts of water. This is the ALPHA radar system shown in Figure 12. This radar was designed to operate at 30 MHz, the frequency at which the loss tangent for water is a minimum (Bogoroditskii and Pasynkov, 1967). Because some salt has 0.1 to 1% water in it, the dipole moment of water increases the attenuation of radar waves probing the salt, thus minimizing the radar range capability. To probe long distances (almost 2000 meters) in dry salt, and to probe reasonable ranges (500 meters) in wet salt, we have developed this radar at 30 MHz. Figure 13 shows a photo of the components on a bench in a Texas salt mine. On the left is the radar transmitter, next to it is the video tape recorder. Top center is one of the two (large) Yagi antennas. To the right is the receiver, receiver power supply oscilloscope, and

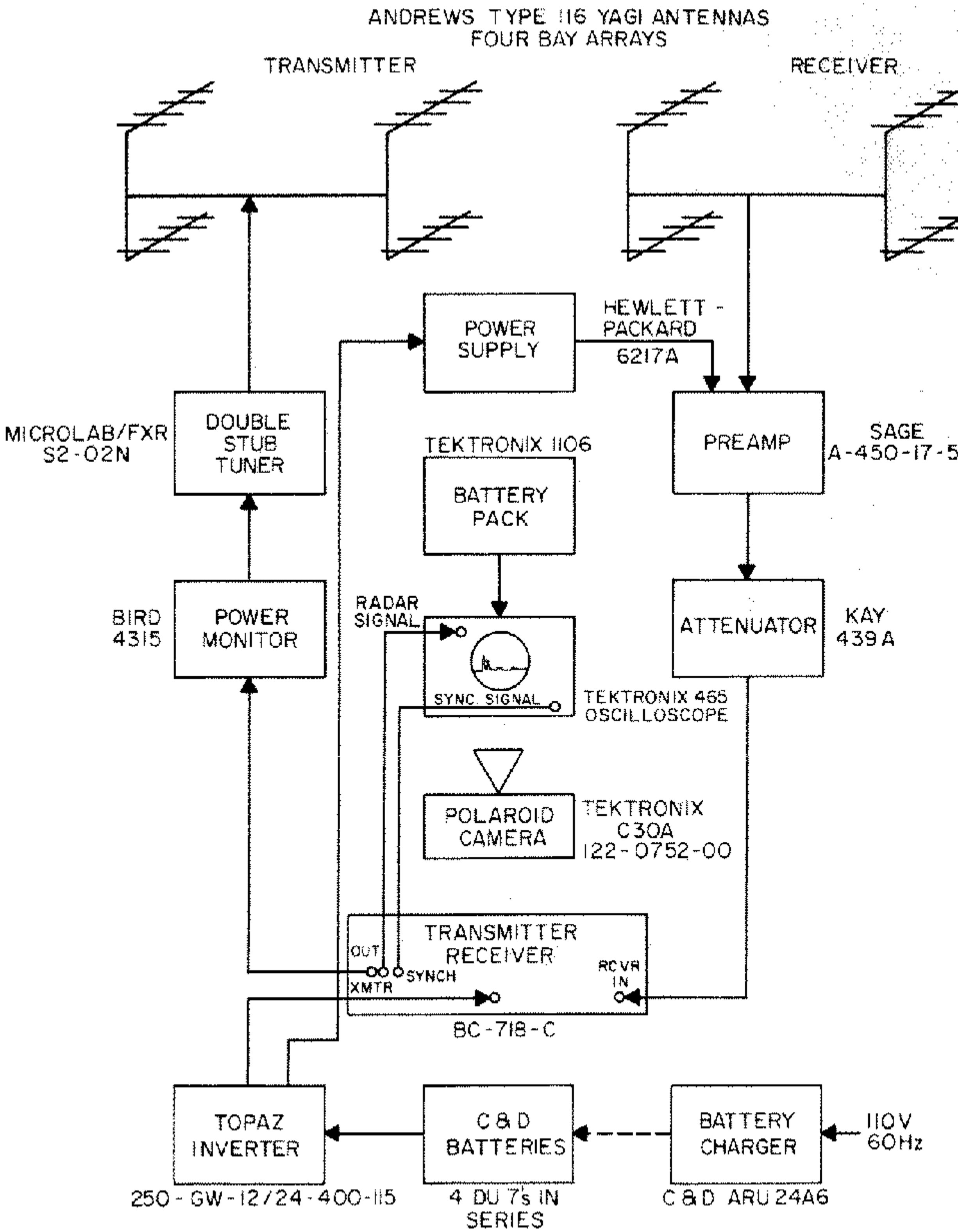

Figure 5. CHARLIE II Block Diagram.

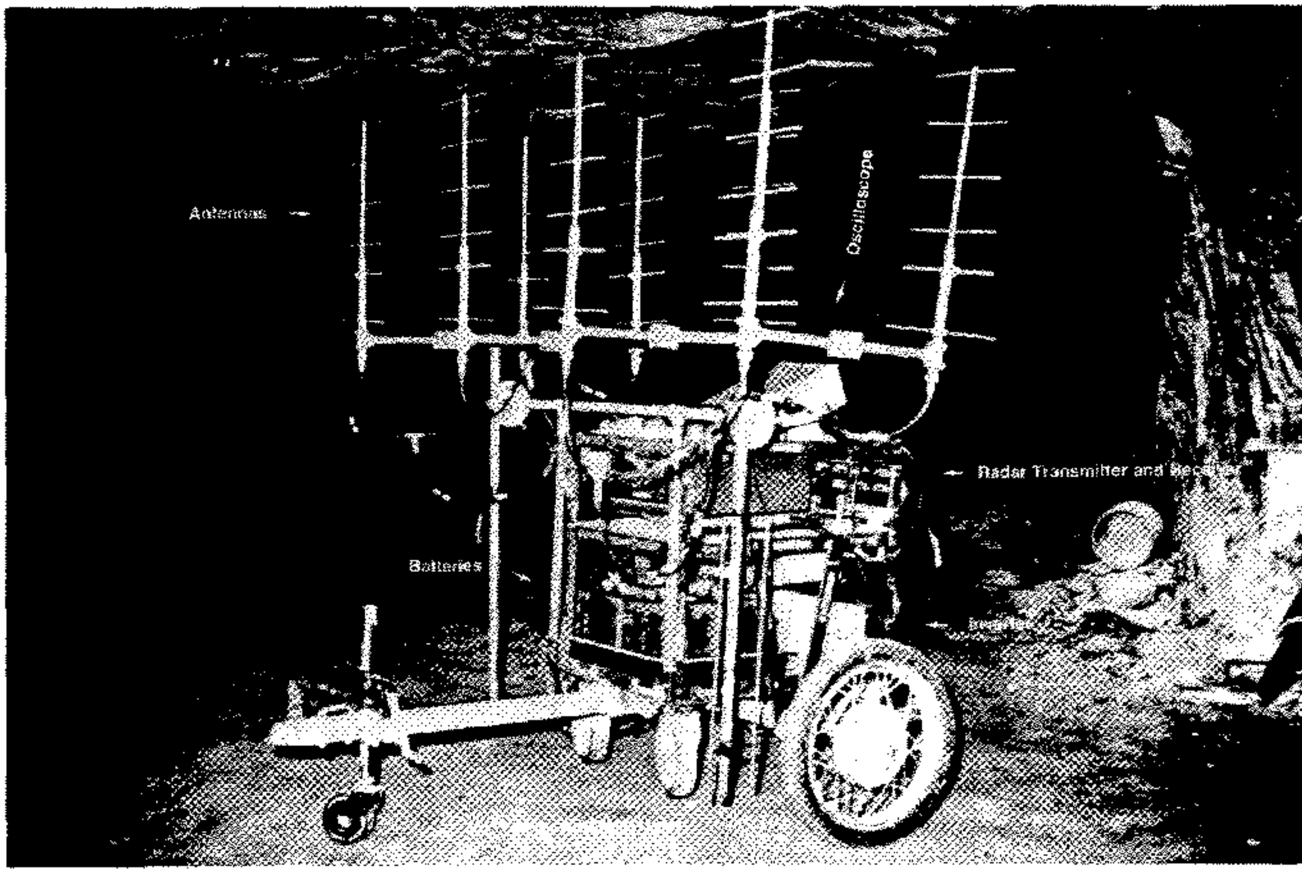

Figure 6. CHARLIE II Radar System.

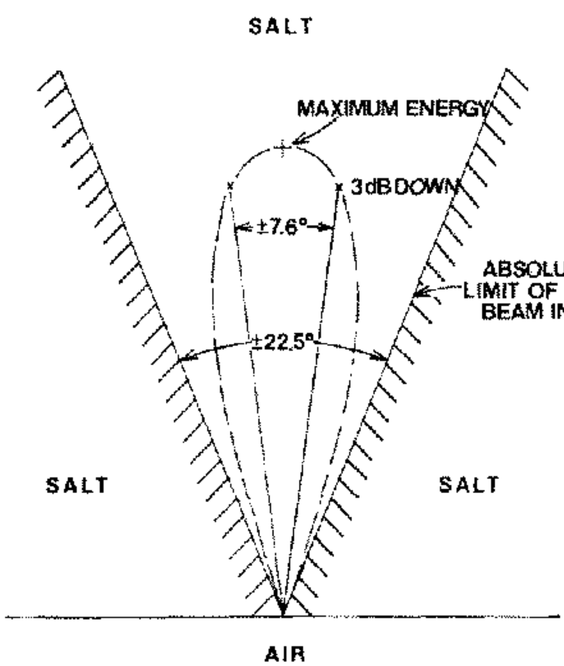

Figure 7. CHARLIE Radar Beamwidth in Salt.

transmitting antenna matching network. Table 4 gives the radar parameters of the ALPHA radar system (Tarantolo, 1978).

Radar probing results. Radar measures *time* and we wish to know *distance* in salt to the discontinuity or target. Thus we need to know, or measure, the radar velocity in the salt.

TABLE 4

Alpha Radar Parameters

Frequency	30 MHz
Peak power output	10 kW
Average power output	10 W
Pulse width	1 μs
Wavelength in salt	4.08 m
Receiver bandwidth	1.5 MHz
Maximum receiver gain	108 dB
Receiver delay	0.2 μs
Output impedance	93 Ω
Antenna gain	8.0 dB
Impedance	50 Ω
Beamwidth in salt	
E-plane	23.8°
H-plane	36.8°

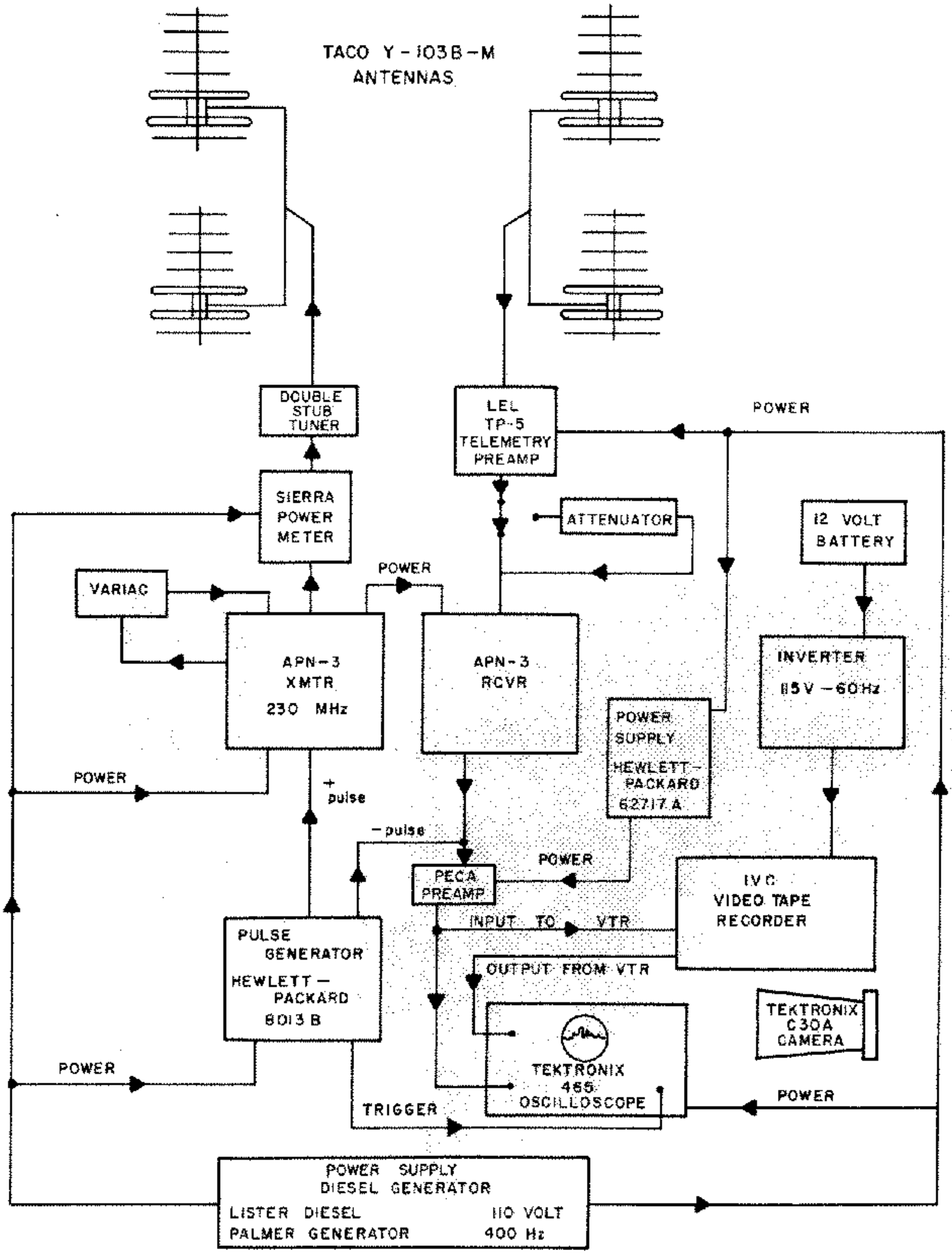

Figure 8. BRAVO III Radar System for Probing Salt.

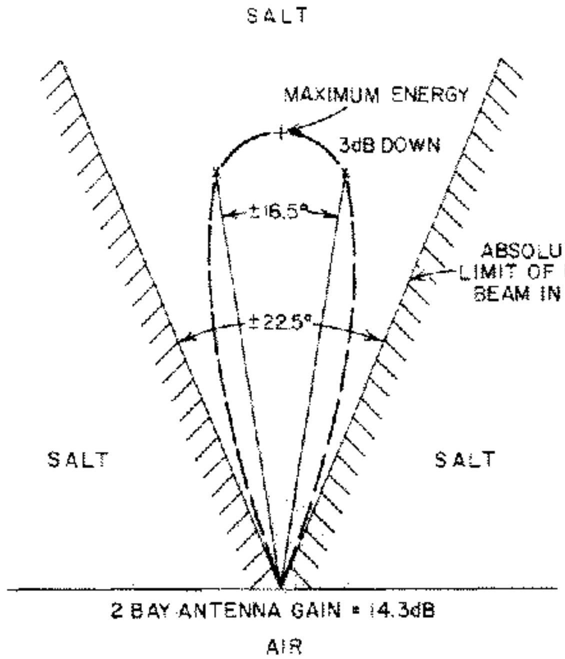

Figure 9. BRAVO II Beamwidth in Salt E-plane.

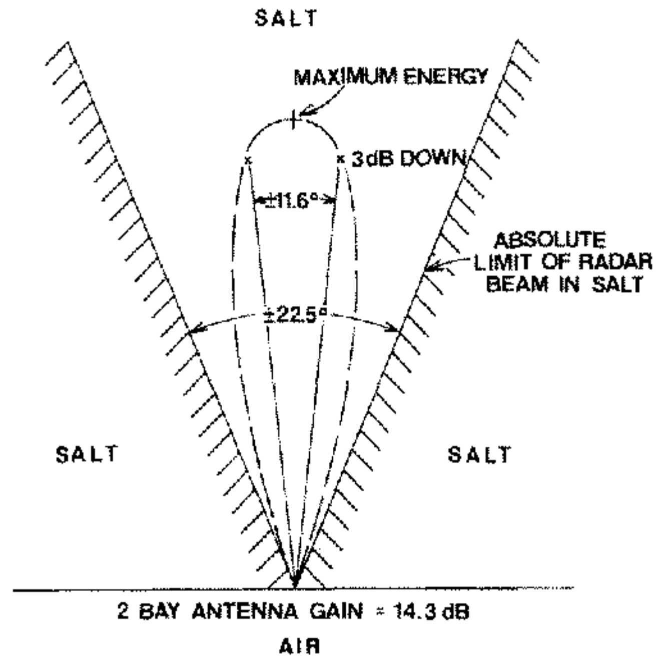

Figure 10. BRAVO II Beamwidth in Salt H-plane.

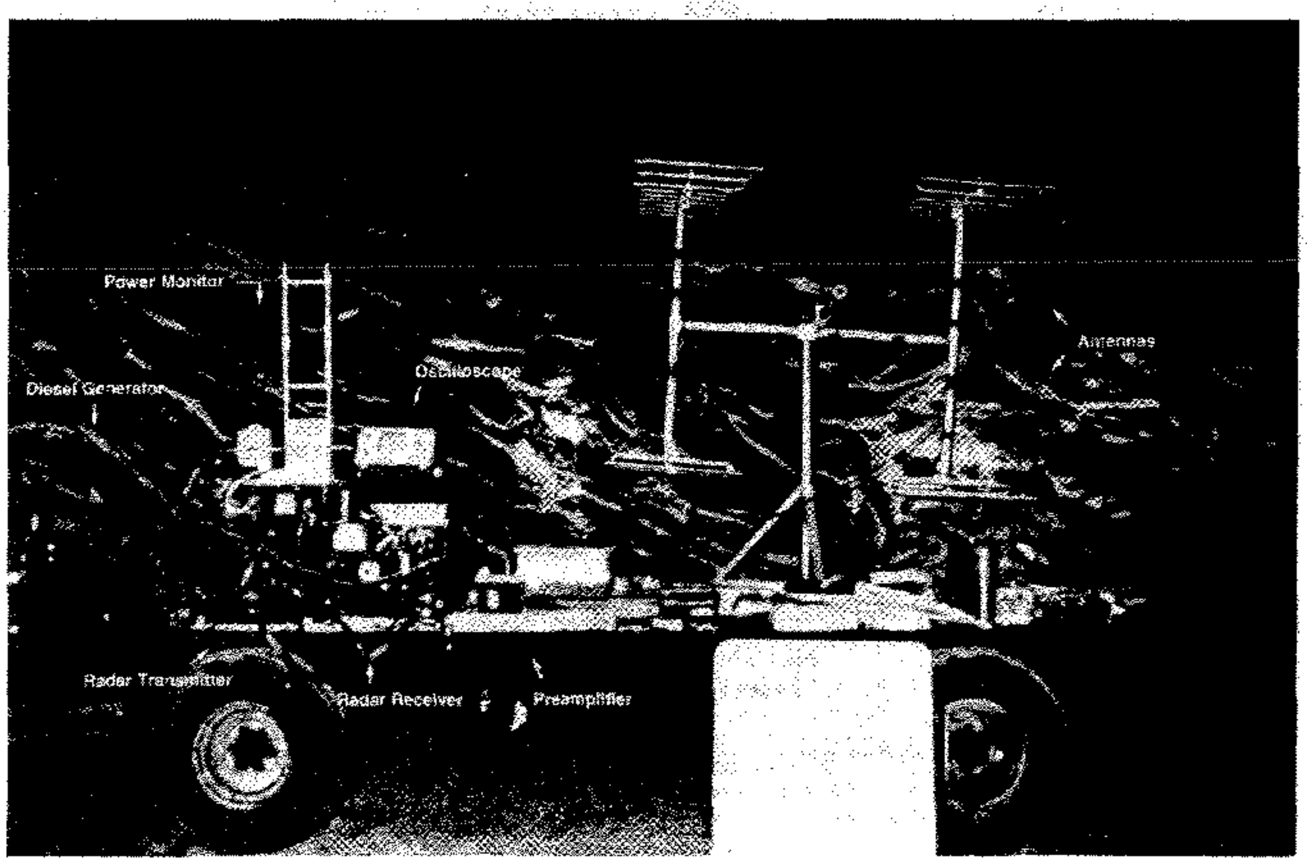

Figure 11. BRAVO III Radar System.

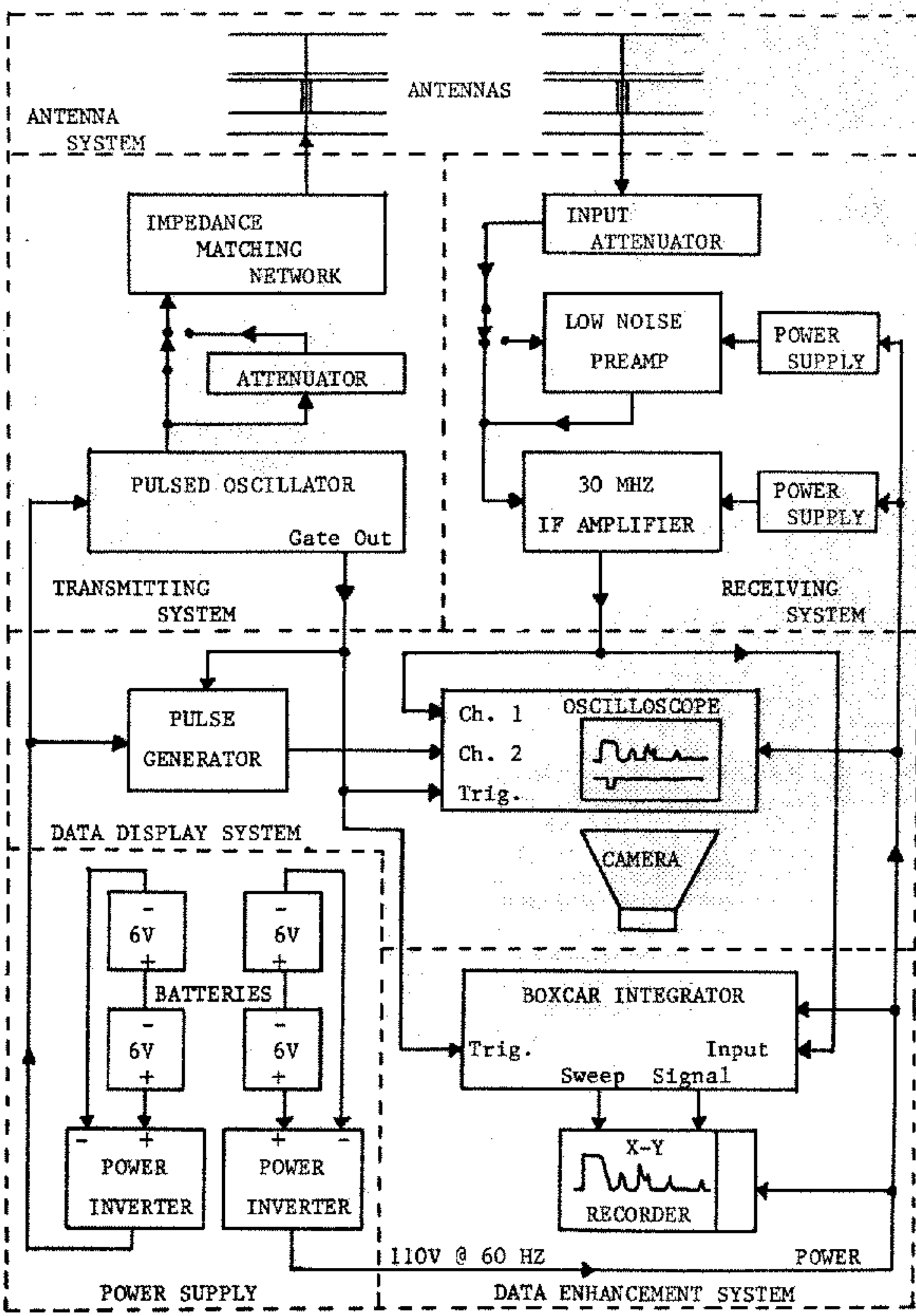

Figure 12. Schematic Diagram of the ALPHA II Radar System.

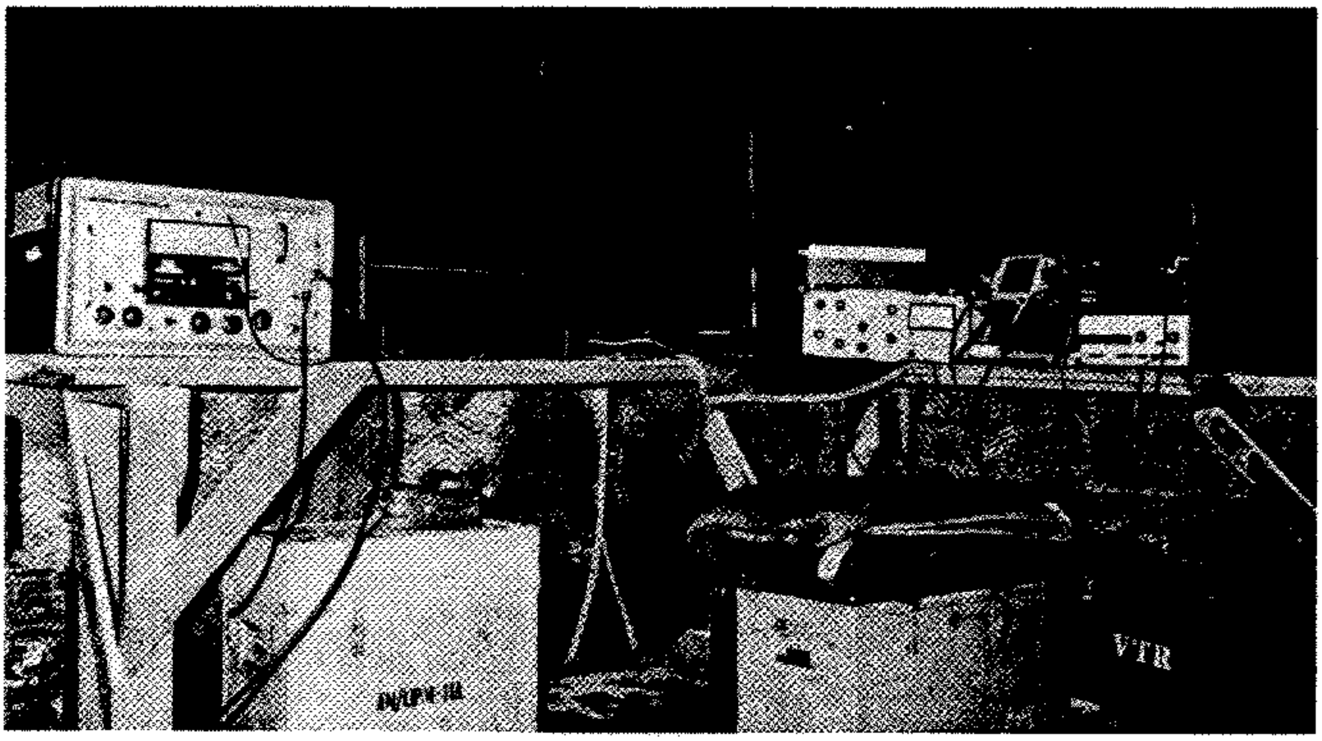

Figure 13. ALPHA Radar System Photograph.

Velocity determination. All radar data (and sonar data) are taken as a function of time. That is, a pulse is sent out and a discontinuity in salt (such as sandstone, shale, anhydrite, sylvite, water, fracture, etc.) gives rise to a reflected pulse whose two way travel time we measure. To correct these data in time to data in distance, we need to know the actual speed in the salt of the radar waves. We measure this by sending a radar pulse through a large pillar, the salt-air interface at the other end serving as a good reflecting target. We then measure the time of arrival of this reflection and knowing the length of the salt pillar we obtain the measured velocity of the radar waves in the salt. Doing this for a few pillars, we average the velocity values and use that value thereafter to interpret ranges from time measurements.

The measured velocities in various salt mines we have been privileged to probe with radar are given in Table 5.

TABLE 5

Measured Radar Velocities* in Salt Mines

Location	Velocity in Salt
Cote Blanche, Louisiana	57.3 m/s
Avery Island, Louisiana	57.0 m/s
Jefferson Island, Louisiana	60.0 m/s
Hockley, Texas	61.0 m/s
Grand Saline, Texas	61.0 m/s
Seneca Lake, New York	51.2 m/s
Cayuga Lake, New York	59.1 m/s
Pugwash, Nova Scotia, Canada	54.0 m/s

*Radar velocities are traditionally given as *half* the true velocity in salt so that the measured (two-way) travel time to the target can simply be multiplied by this radar velocity to give the correct range to the target.

The *direction* to a radar target is not so well known as the *range* to the target (discontinuity in salt) and this uncertainty in direction will be a function of the beam angle of the antenna system. The narrower the beam angle the less the uncertainty in the location of the radar target. So most targets are located at a particular range, azimuth and elevation with the uncertainty being represented by an arc as shown in Figure 14 (Stewart and Unterberger, 1975).

Latest radar probing results. Some radar probing results not previously given at the last Salt Symposium (Unterberger, 1974) are given here.

At Seneca Lake in New York state a possible fault was located by the BRAVO III radar system 396 m in advance of mining. Mine management did not mine in this direction but continued mining ahead in another direction where our probing indicated no discontinuities. The mine proceeded 400 m with good salt production.

The top of the salt in a Louisiana salt mine was probed with radar to determine the topography of the salt-sediment interface so that low spots in the salt might be located as possible hazardous areas where ground water leaks might occur into the salt mine. Many traverses were made with the upward probing BRAVO III radar system using the video tape recorder to profile the top of salt. Such profiles did *not agree* with the contour map of the salt obtained from an oil company exploration department at one particular area. Subsequent drilling by the salt company in this area where radar differed drastically from the seismic data revealed the

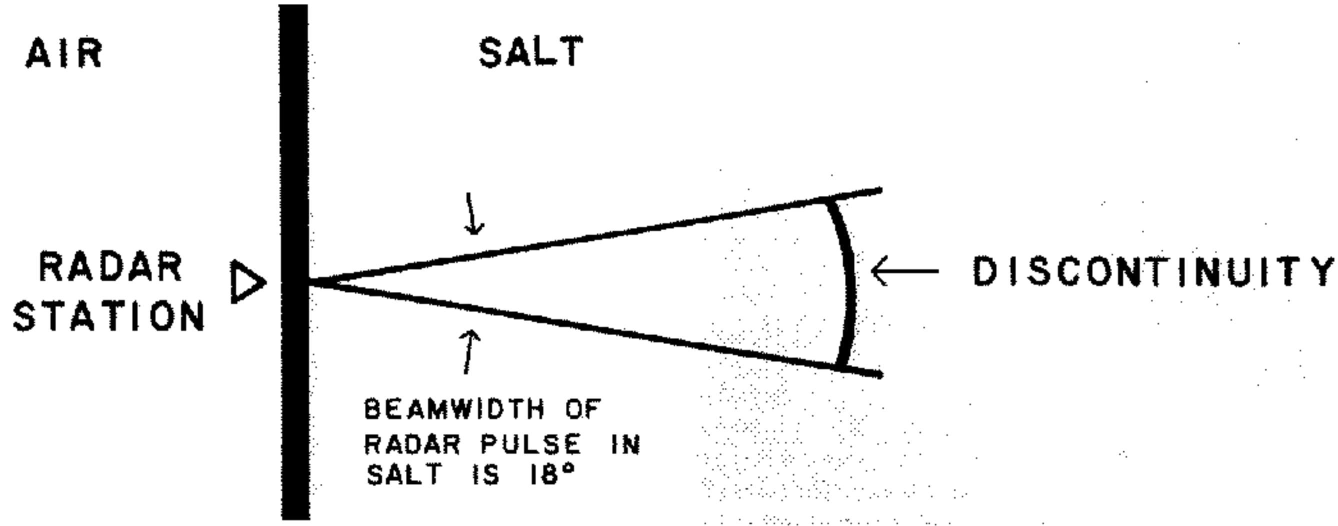

Figure 14. The Arc Gives the Location of the Discontinuity in Salt.

radar data was correct. This is not surprising when we think of the wavelength of the seismic wave (92 m) compared to the wavelength of the radar wave (0.53 m), more than 100 times shorter.

In another salt mine in South Louisiana the salt dome contours for the edge of the salt at a particular location in the mine were not very well known. After radar probing horizontally it was determined that there was at least 300 meters of salt horizontally. Management was interested in moving their mine closer to the dome flank if there were salt out there. To check the radar, a core test was horizontally drilled to 300 meters and stopped. It was still in salt. This verified our radar probing.

In a salt mine in East Texas, ECHO II was used successfully to measure the extent of a tunnel beneath a floor of salt as well as the thickness of salt below. The probing was downward, taking advantage of the smooth saw-cut floor to give good radar probing results. In this case, we used a CW–FM radar system and the data are not measured in *time* but in *frequency*. The beat frequency (between the received signal and that being transmitted at the instant of receiving that signal) is a direct measure of the *range* to the target. Thus the salt-air interface of the tunnel below gave a good signal return and it was easily measured through 12.5 meters of salt.

Another salt company was sinking a new shaft into salt and asked us to use our radar to determine the direction and distance from the mine up to the bottom of the shaft in salt and predict its ultimate location in the mine. We used our CHARLIE II radar to probe upward and obtained a range, an elevation, and an azimuth to the target by maximizing the signal strength while orienting the antennas in azimuth and elevation. The reflected signal from the bottom of the 1.15 meter diameter hole (filled with salt water) is shown in Figure 15. The large peak on the left is the *transmitted*

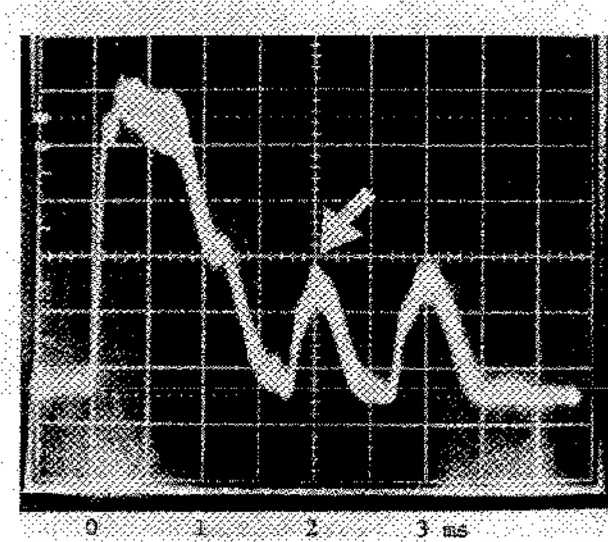

Figure 15. Radar Probing Upward for Shaft and Top of Salt.

radar pulse signal (plus some air reverberation; the room was 12 meters high). The peak in the middle (arrow) is the radar reflection from the bottom of the shaft. The last peak at the right is the reflection from the top of the salt. There is anhydrite above this. The range in salt to the bottom of the shaft is 95 meters whereas the range to the top of the salt is 150 meters.

SONAR PROBING OF SALT

We now come to the second section of this paper. This section treats a different method of probing of salt—sonar. Instead of electromagnetic waves (radar) to probe salt we use *sound*. If radar is so successful, why do we need sound?

To answer this we must discuss the types of salt we have in the United States and Canada. We have *dry* salt most often (but not always) associated with salt domes in the Gulf Coast region, Texas and Louisiana. In these we can radar probe a kilometer or two. Although some salt mines in bedded salt are susceptible to radar probing, a few such mines as the Detroit mine in the Michigan Basin contain small amounts of water in the salt. This contained water has a dipole moment which causes an increase in the attenuation of the radar wave as it travels through the salt. With sufficient water in the salt, the radar probing ranges become too small to be useful.

In an effort to solve this problem we went to *sound wave* probing or sonar. We searched the literature for a value of sound wave attenuation in salt as a function of frequency and found much data in the megahertz region of ultrasonics that showed that these high frequencies could *not* be used for probing salt to any considerable distance. The literature gave no clue as to the attenuation of sound in salt in the kilohertz region. So we decided to try it. We chose a high-power pulsed sonar that was built by EDO-Western, a large Navy contractor in the field of sonar equipment. After two years of testing in salt mines and after making many equipment modifications we now believe we have a useful sonar to probe into salt. Not only will it probe into *dry* salt but also into *wet* salt. It should also be able to probe into rocks other than salt, such as potash, trona, limestone, etc. but we just have not had the opportunity to prove its capability in that direction.

Sonar probing system. The important parameters of this sonar are given in Table 6. The most important modification we made to the sonar system was to use an oscilloscope data display rather than a chart recorder. This eliminated many mechanical "instabilities" in timing that could be tolerated in its original use offshore but *not* in probing salt.

TABLE 6

Sonar System Parameters

Frequency	24 kHz
Pulse length	variable, but 0.3 ms used most
Pulse repetition rate	variable, but 5–10 pps used most
Power required	24 V. d.c.
Transducer:	23 cm diam. array of lead titanate zirconate, mass-loaded ceramics
Transmitting sensitivity	+73 dB
Receiving sensitivity	−75 dB

Sonar coupling to salt. In *radar* probing we simply launch the radiowaves from an antenna and point the antenna at the wall of salt we want to probe. No wall preparation is necessary. Less than 20% of the total radar energy is reflected at the salt-air interface with the remainder (83%) being transmitted into the salt.

The sonar is different. The transducer is mounted in an aluminum box that is bolted to a saw-cut face of a salt wall. The smooth salt need only be a meter square. A caulking compound is placed between the salt and the aluminum box to prevent leaking of the fluid (glycerin) used to transmit the sound energy into the salt. The acoustic impedance mismatch at the liquid-salt interface gives rise to reflections which are absorbed in the box by filter material.

SONAR VELOCITY MEASUREMENTS

As with radar we need to know the distance in salt to the discontinuity or target (borehole, anhydrite, sand lenses, water, fracture, sylvite streaks) in salt. Thus we need to measure the velocity in salt as we did with radar. Since most floors are made by an undercutter, the floor is well suited to mount the sonar. All we need is a known target (such as a tunnel below for a conveyor belt) at a known distance. Sometimes another level of the salt mine suffices. If neither are available we then sonar probe through a pillar of known (or measured) length. In all cases the salt-air interface is a good reflector of sonar energy.

We have also used a one-way transmission method to measure the speed of sound in salt. We then put a transducer on each side of the pillar and measure the time of travel through the known length of salt. A value well substantiated for 24 kHz sound in dry salt velocity is 2240 m/s (Butler, 1977). Remember, this sonar speed is *half* the *true* sound speed in salt.

SONAR PROBING RESULTS

This sonar has proven its capability of probing through *dry* as well as *wet* salt. Two salt mines in Louisiana, that our radar completely failed to penetrate, are Weeks Island and Belle Isle. They are both porous and wet. The sonar probed through both of these wet salt mines as well as the Windsor mine in Canada. The maximum ranges obtained in these salt mines, plus Grand Saline—a dry salt mine—are given in Table 7.

A sonar probing through the floor of one salt mine level to the top of the next level gave a big reflected signal. This signal was recorded on a strip chart recorder (shown in Figure 16) and the salt-air interface 51.8 m below is clearly shown as the dark horizontal strip on the recorder. The interface was measured in a drill hole through the floor 8 meters away. Note that the signal came in at 57 feet on the

TABLE 7

Maximum Sonar Probing Ranges in Some Salt Mines

Mine	Probing Range	Type of Salt
Grand Saline, Texas	374 m	dry
Weeks Island, Louisiana	215 m	wet
Belle Isle, Louisiana	100 m	wet
Windsor, Ontario, Canada	192 m	wet

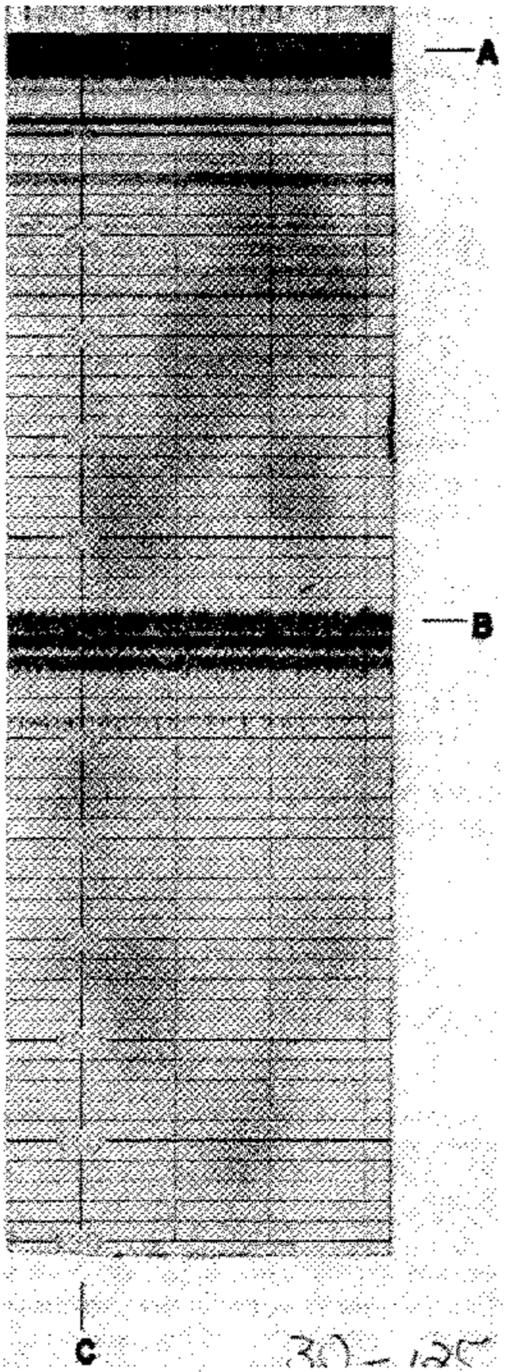

Figure 16. Sonar Probing Through Salt Floor 51.8 m Thick. A) Salt floor of upper mine level. B) Salt roof of lower mine level. C) Water scale in feet.

chart (the chart was intended for sound in water). To convert this equivalent water depth to depth in salt we multiply by three and convert to meters and get 52.1 m. Thus we measured the thickness of the salt to less than 1 m.

A known 10 cm sandstone band at a range of 14.6 m was detected in Weeks Island salt mine. The reflected signal energy is shown in Figure 17.

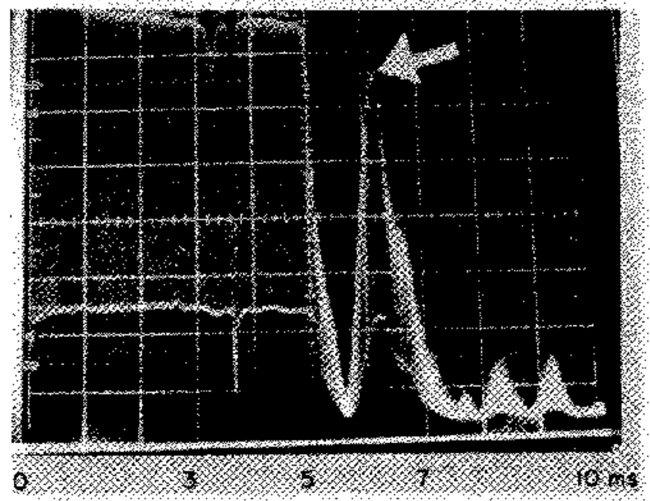

Figure 17. Reflection from Sandstone Band in Salt.

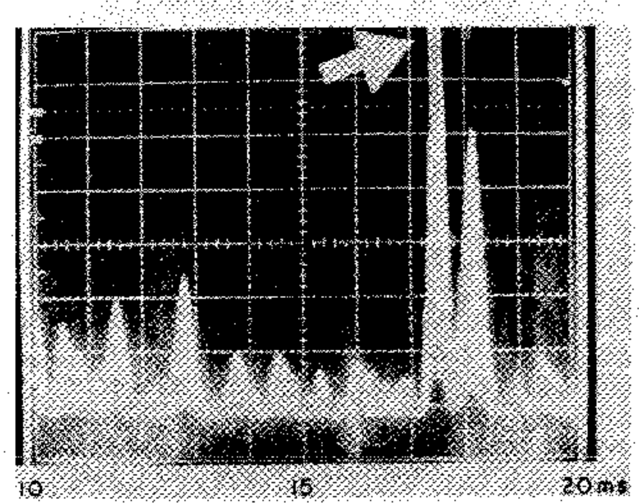

Figure 18. Sonar Probing Through a Salt Pillar at Grand Saline. The arc gives the location of a discontinuity detected in the salt.

Probing through a 41.5 m pillar in Grand Saline we obtained the large sonar signal reflected from the other side of the pillar as shown in Figure 18 by the arrow. This oscilloscope data display does *not* start at 0 ms as all the others do, but is a *delayed* sweep showing only the signals received between 10 and 20 ms. The signal from the other side of the pillar comes in at 17.4 ms (arrow). The signal on its right is from the corner of the pillar, slightly further away.

Salt dome flank echos have also been obtained using sonar probing. Interpretation is difficult here because of the many impurities (discontinuities) associated with the outer edges of the salt.

Four bands of sylvite were also ranged to and detected in salt. They were known to be present as they cut across certain exposed areas of the mine. They were found by probing through 8 m of salt and additionally by probing through 42 m of salt (Butler, 1977). Data from the former are shown in Figure 19.

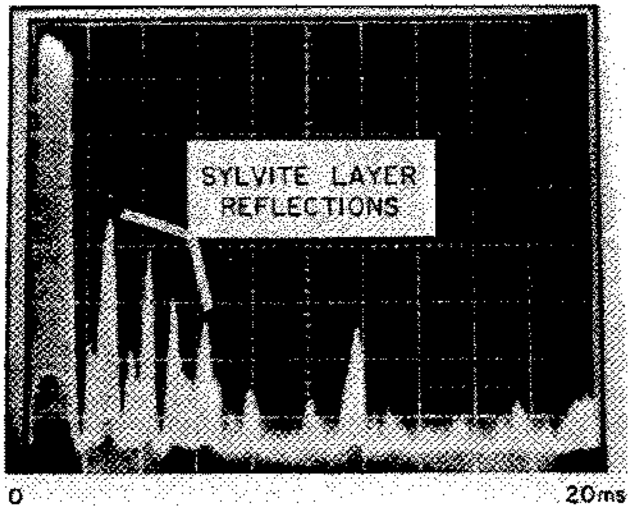

Figure 19. Sylvite Layer Reflections.

COMBINED RADAR AND SONAR PROBING

Sometimes we can use both types of probing to advantage. For example, a salt company in Louisiana was sinking a new shaft to the lowest level of their mine. We were asked to use radar to probe upwards to find any discontinuities in the salt that they should know about. We did this and found *four* signals looking upward as shown in Figure 20, (1), (2), (3), and (4). We also obtained radar reflections from the two mining levels above. The important depths are the signals indicated by arcs as −167, −226, −403 and −522 ft. The signals could come from anywhere in this beamwidth of the BRAVO radar system and not necessarily in the path of the downcoming shaft. What was encountered at these depths? A small test hole was drilled ahead and water was encountered at −173 ft, whereas we said it was −167 ft. After that was cemented, another test hole was drilled and water was found at −226 ft just where we got a reflected signal. After that was cemented, the large shaft was brought down to −202 ft and a small drill hole tested the other two elevations, i.e. −403 and −522 ft. Nothing but salt was found.

At this time we brought in our sonar and probed *downwards* from the bottom of the air shaft which was, of course, in salt. From our previous work we already knew the velocity of sound in salt. So we probed downward with sonar trying to discover what it was we "saw" with radar probing upwards from the lowest mine level but which was *not* directly below the axis of the air shaft. We obtained two sonar signals that were at a range of −435 ft and −533 ft. Figure 21 shows the intersection of the sonar and radar range arcs is *off* the axis of the new shaft and hence the drill should not (and did not) intersect these two discontinuities. This shows clearly that the discontinuities are *off to the side of the shaft*. This is a good example of one probing system

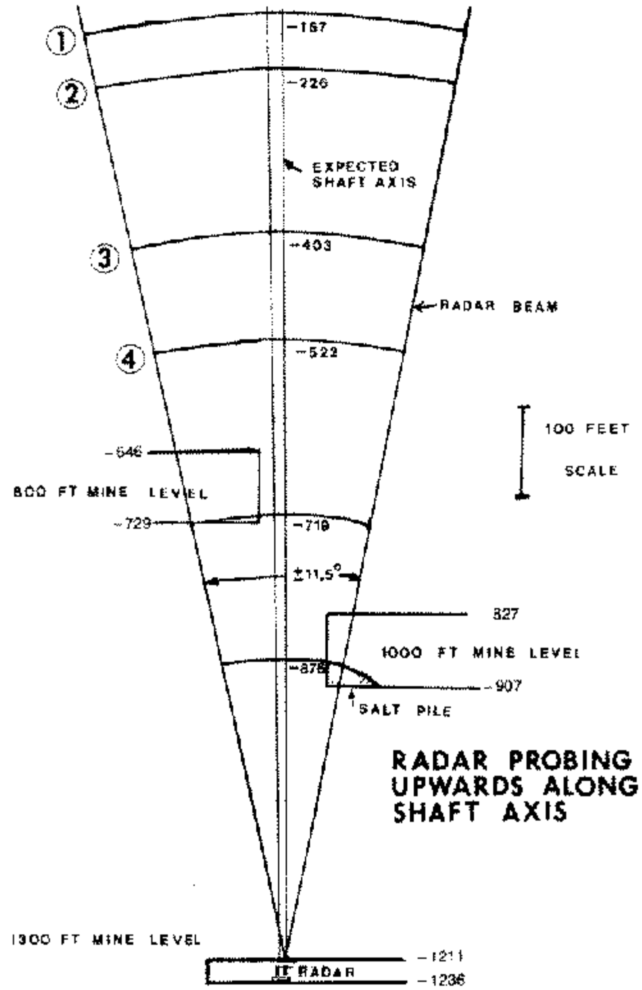

Figure 20. Radar Probing Upwards Along Shaft Axis.

being used to verify another—and both working together to get answers valuable to miners.

CONCLUSIONS

Four radar probing systems for salt (4300 MHz to 30 MHz) have been developed to locate discontinuities in salt, such as impurities of anhydrite, sandstone, sylvite, carbonate, fractures, boreholes, water, etc. One or more of these systems have been used in fourteen salt mines in the United States and Canada. These systems have probing ranges from one half meter to 2000 meters, with the highest resolution for the shortest range system and lowest resolution for the long range system. These radars operate well in *dry* salt but have limited use (or none) in *wet* salt.

A sonar probing system (wavelength = 19 cm) has been developed that can probe from 2 meters to 400 meters depending upon the size of the discontinuity in salt. Some of

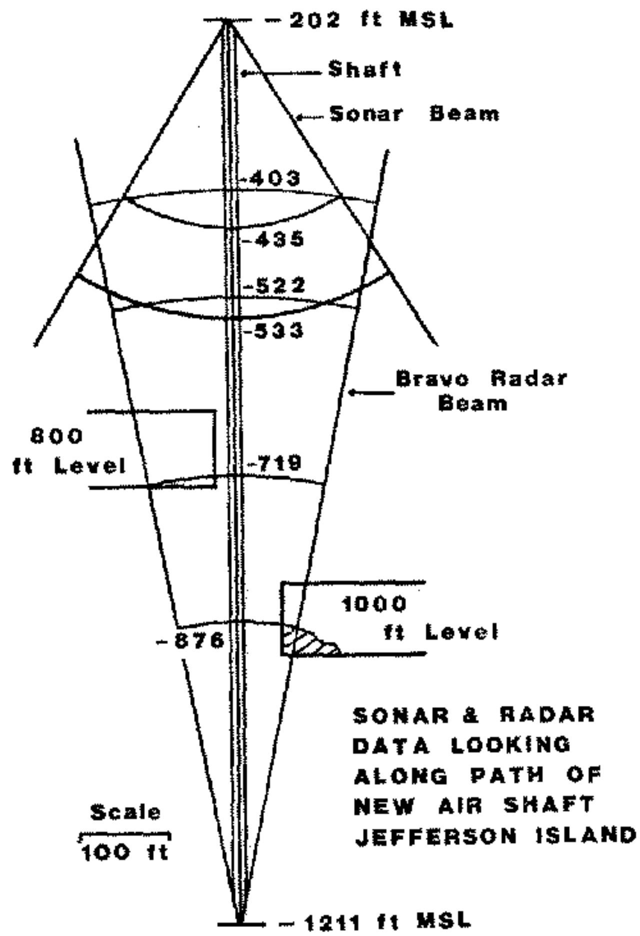

Figure 21. Sonar and Radar Probing.

the accomplishments of these systems include the determination of the range and direction to

1. a borehole in salt,
2. a fault ahead of mining,
3. a wet zone in salt ahead of shaft sinking,
4. a sandstone stringer in salt, and
5. a fracture in salt.

In addition we have mapped the top of the salt and the dome flank of a salt dome. Applications of these systems to probing rocks other than salt are possible.

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