RADAR PROPAGATION IN ROCK SALT *

BY

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ABSTRACT

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Four radar systems at three different frequencies are described which are useful in probing into salt for finding information of interest to miners. Ranges in salt to (a) the edge of a salt dome, (b) the top of the salt dome, (c) boreholes in salt, or (d) faults or hazards ahead of mining can be determined using one or more of these radar systems. Radar wave velocities in salt are determined by radar probing through pillars of known length, and then used to determine ranges in salt to timed radar reflections. Radar probing results are shown obtained in different salt mines probing upwards and downwards. Enclosed areas in the mine are the best radar station locations to probe into salt as air reverberation of radar energy is shortened.

RADAR PROPAGATION IN ROCK SALT

Many investigators have considered radiowave propagation through rocks (Pritchett 1952, Minaw 1958, Dokoupil, Karpinski, and Kaspar 1962, McGehee 1954, Ryazantsev and Shabel'nikov 1965, Ames, Frazier, and Orange 1963, Fritsch 1942, Haycock, Madsen, and Hurst 1949, Wheeler 1961, Wait 1960, Silverman and Sheffet 1942, Fritsch 1963, Cooper 1948, Bhattacharyya 1957, Horton 1946, Stetson 1934, King 1968, Wait 1965, Carolan and de Bettencourt 1963, Viggh 1963, Wait 1966, and Gabillard and Desbrandes 1967), through glacier ice and permafrost (Evans and de Q. Robin 1966, Bogorodskii and Trepov 1969, Weber and Andrieux 1970, Christensen 1970, Christensen, Gundestrup, Nilsson, and Gudmandsen 1970, Christoffersen and Gudmandsen 1970, and Petrovskii 1947), to find groundwater (Jiracek 1967), for communications (de Bettencourt 1967, Williams 1951, Wundt 1964, Colburn, Bouton, and Freeman 1922, Ilsley, Freeman, and Zellers 1928, Jakosky and Zellers 1924, Jakosky 1924, Burrows 1963, Tsao and de Bettencourt 1967, and Jakosky and Zellers 1925), or mining (Nickel 1968, Barret 1952, Fritsch 1948, Shu, Miao-Li, Hsiao-Ch'ang, and Tsao 1964, Gröbner 1964, Petrovskiy

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1961, Cook 1971, and Dolphin 1974). One paper (Löwy and Leimbach 1910) dates back to 1910.

We have concentrated on radiowave propagation through salt for many years, first as a logging tool for outlining salt domes (Holser, Brown, Roberts, Fredriksson, and Unterberger 1972) and subsequently as a safety feature in salt mining (Unterberger 1974, Hluchanek and Unterberger 1973, Stewart and Unterberger 1974, Unterberger 1975, Tarantolo and Unterberger 1978), to "see" ahead of mining to look for faults, edge of salt domes, cased holes, or upward to map the top of the salt. We have made dielectric measurements on rock salt and found loss tangents of salt in the VHF region to vary from 10^{-3} to 2×10^{-5} depending on the sample measured. Thus there is excellent salt ($\tan \delta = 2 \times 10^{-5}$) for transmitting VHF radar waves and there is some lossy salt (10^{-3}) that is difficult to probe. One example of the latter is the Weeks Island salt mine salt in Louisiana. Measurements by others (Aufricht and Howard 1961) show that this salt has porosity and permeability. Generally, however, most salt mines have rock with little or no porosity and thus are good transmitters of electromagnetic waves in the VHF region. By experience we have learned that if a salt mine is dusty, e.g., there are clouds of salt in places where rocks are being crushed to smaller sizes, then we can expect radar transmission to be good. If there is slight moisture content to the rock, the dust will be a minimum and radar transmission will be less good.

The types of radar ranges in salt we are discussing here range from a few meter to 8 or 9 kilometer. The range of detection depends on the type of target we are trying to find. A large target (such as a salt dome flank) can be detected at long ranges—typically 300 m for our low power radar system to 1500 m for our high power radar system. Small targets reduce the range of detectability.

Types of Discontinuities Detected

A radar system probing into salt (or any other rock) will detect discontinuities in the rock material if a facies change is represented by a change in the electric permittivity (dielectric constant) of the rock or if the rock remains the same but is filled with water. Thus we list the type of discontinuities (or radar targets) that we can detect.

1. Salt dome flanks—This is the salt-wet sediment contact. It is important to know where this flank is, if one is mining salt inside a salt dome.
2. Top of salt—The three dimensional shape of the top of salt is important to know if leaks develop in a mine, because ground water flow can be understood and a drilling and cementing program can then be based on topological information.

3. Faults ahead of mining—Sometimes a layer of bedded salt will be faulted and an anhydrite or shale section will appear. Probing ahead with radar will reveal this as the discontinuity in electric permittivity (dielectric constant) causing a radar reflection. An accurate range to this fault based on the velocity of radar waves in salt can be useful to mine management.
4. Boreholes penetrating the mine—These can be a hazard to an underground mine if encountered and filled with water. Radar detection of these in advance of mining is theoretically possible (Tarantolo and Unterberger 1978) and practical; we have detected a number of known cased holes in salt.
5. Fractures in rock—Fractures in salt have been detected by radar and confirmed by drilling.

Radar Systems Used

Presently we have four radar systems which can be used to probe into rock, depending on the type of target that it is desired to detect. These operate on three different frequencies. The lowest is 230 MHz, the intermediate 440 MHz, and the highest is 4300 MHz. These frequencies represent wavelength in salt of 54 cm, 28 cm, and 2.8 cm, respectively. The radar systems are called (after the phonetic alphabet) Bravo, Charlie, Echo, and Foxtrot. Two radars operate at the highest frequency (4300 MHz), one (Echo) being a CW-FW radar for very short range (less than 30 m) high resolution detection work, the other (Foxtrot) is a pulsed radar like Bravo and Charlie but with a narrow pulse so as to reduce the radar minimum range. Some characteristic parameters are given for these radars in table I.

Table I

	BRAVO	CHARLIE	ECHO	FOXTROT
Frequency in MHz	230	440	4300	4300
Wavelength in Salt in cm	54	28	2.8	2.8
Peak Power Output	20 kW	10 W	1 W	100 W
P.R.F.	981 Hz	9.83 kHz	CW	10 kHz
Pulse Width	600 ns	300 ns	CW	35 ns
Beamwidth in Salt	$\pm 11.6^0$ (*H*) by $\pm 16.5^0$ (*E*)	$\pm 7.6^0$ (*E* and *H*)	$\pm 3.3^0$ (*E* and *H*)	$\pm 8.0^0$ (E^0) $\pm 5.5^0$ (*H*)
Antenna Gain	14.3 dB	17 dB	18 dB	14 dB
Power Required	115 V 400 Hz	24 V dc	24 V dc	24 V dc
Antenna Array	two bay stacked in *H* plane	four bay stacked in *E* and *H* plane	two horns	two horns

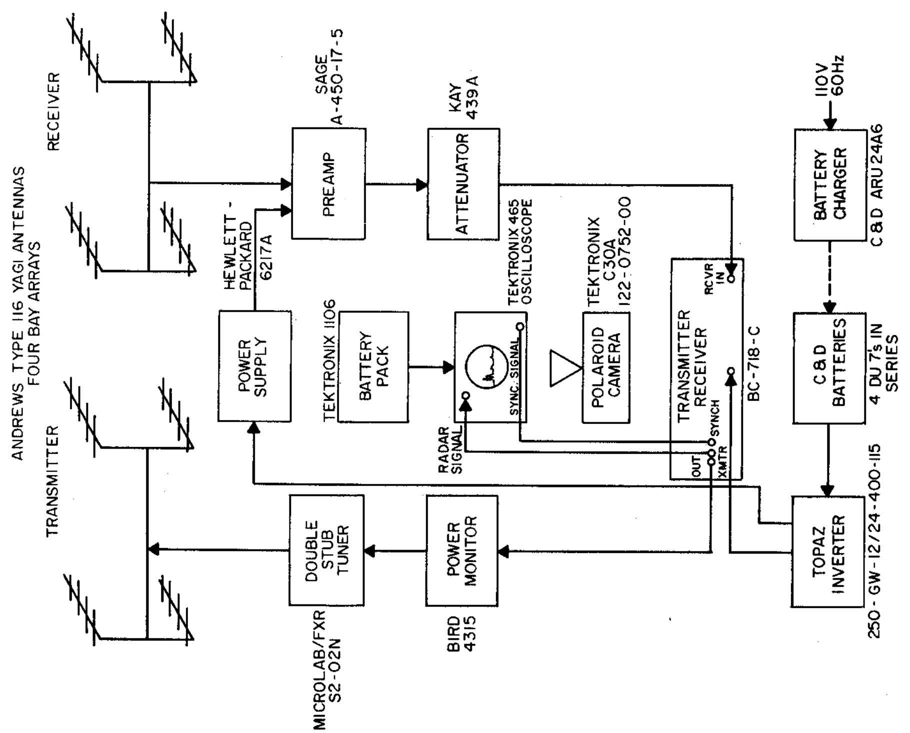


Fig. 1. Block diagram of Charlie radar system

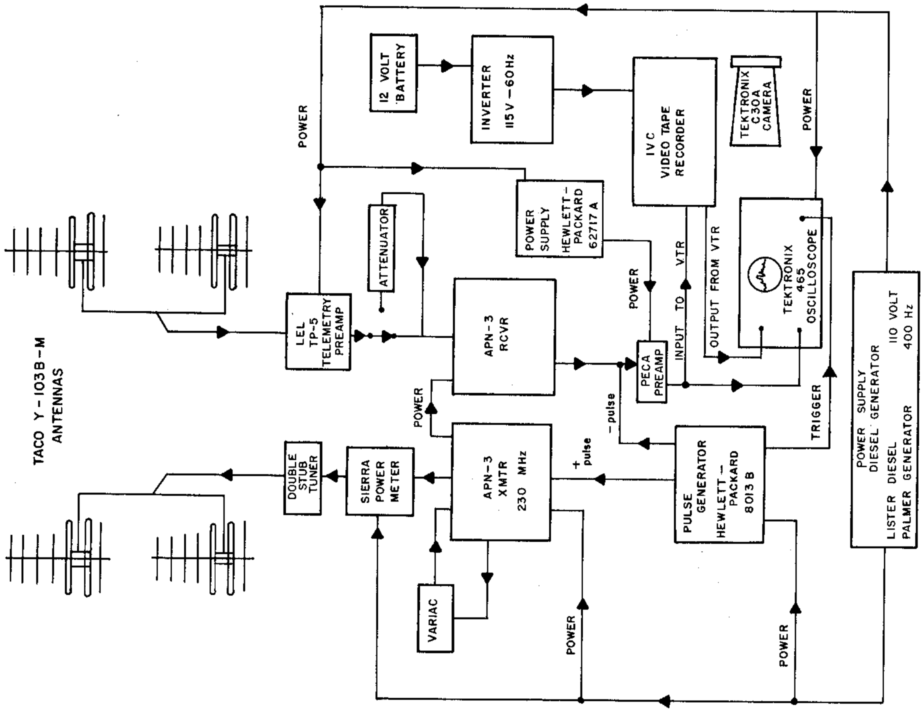


Fig. 2. Block diagram of Bravo radar system

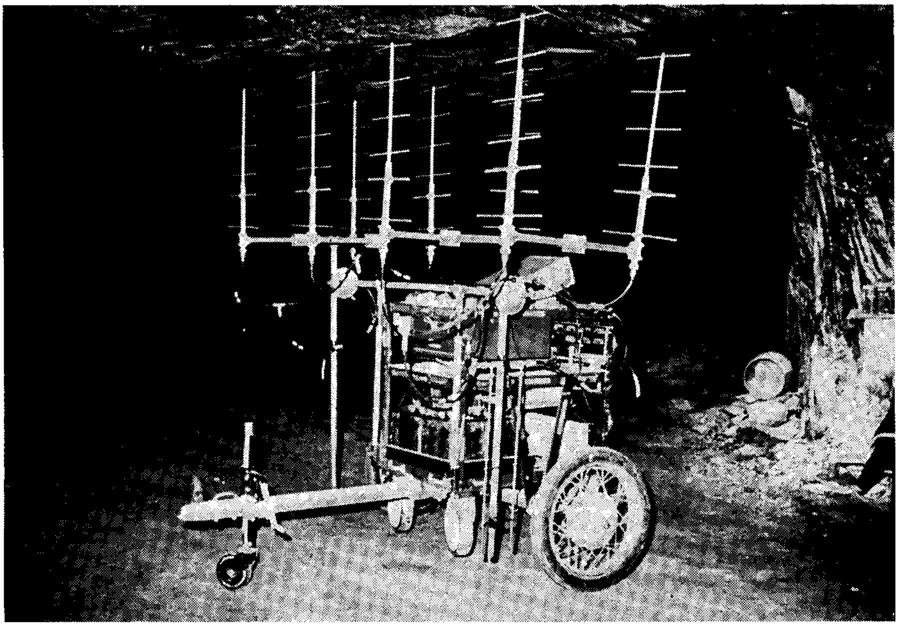


Fig. 3. Photograph of Charlie radar system

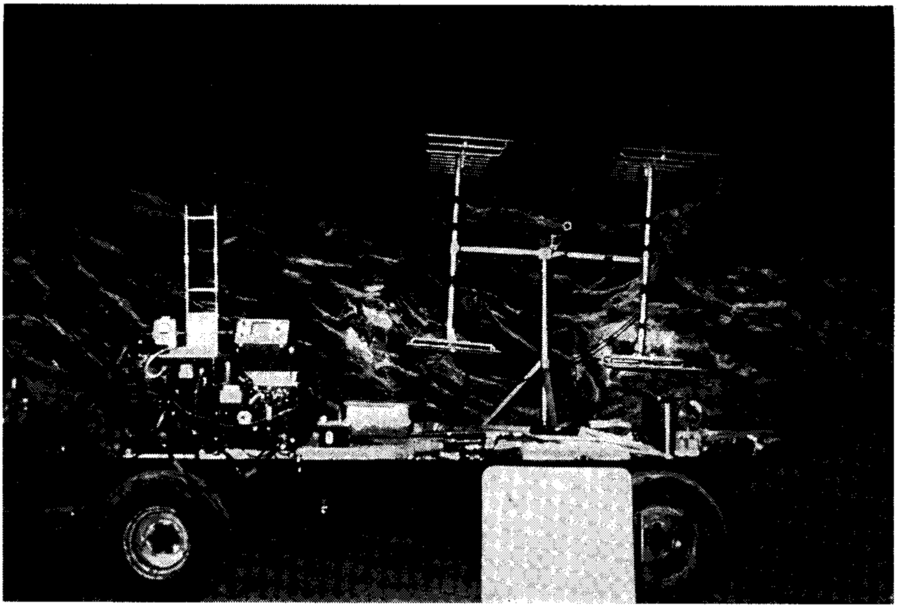


Fig. 4. Photograph of Bravo radar system

A block diagram of the Charlie radar system is shown in fig. 1. Fig. 2 shows a block diagram of the Bravo radar system. The former runs on batteries, the latter from a diesel generator. The Charlie system is mounted on a two wheeled cart which is attached to any mine vehicle by a standard trailer hitch. A photograph of the system in a mine is shown in fig. 3. The Bravo radar system needs a four wheeled trailer to transport it. A photograph of the radar system on a trailer is shown in fig. 4.

Note that in using radar to probe rock, a continuous recording of the radar

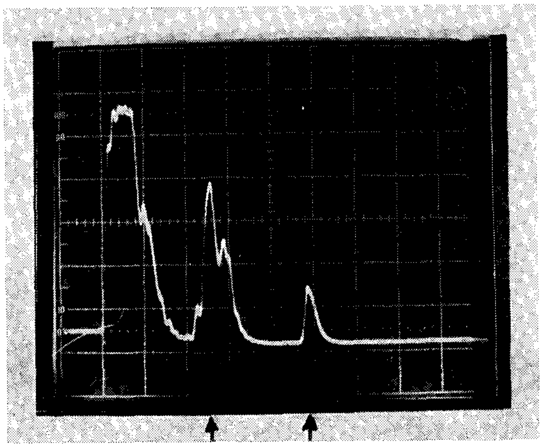
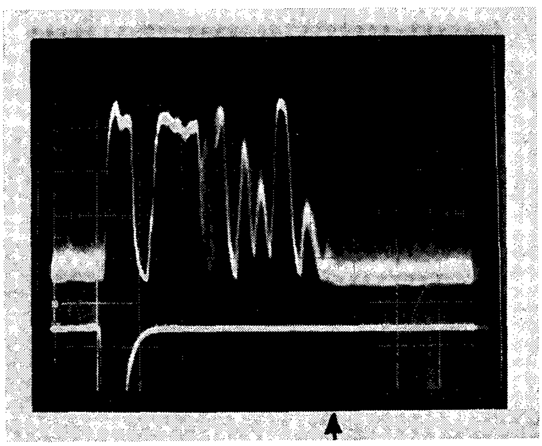


Fig. 5. Radar Data Photographs. Horizontal deflection 1 μs/major division.

a) Charlie system—Oscilloscope photograph shows (arrows) signals at 2.6 μs and at 4.9 μs corresponding to reflections from discontinuities 114 m and 262 m in salt, respectively.



b) Bravo system—Oscilloscope photograph (top trace) shows many reflected signals out to 5.4 μs (arrow) corresponding to a distance of 288 m. The bottom trace shows transmitted energy and serves as a zero time mark.

data can be accomplished by using a video tape recorder to record the "A" scope (amplitude of reflected radar signals versus time) data while the radar is moving. Two photographs of oscilloscope radar data are shown in fig. 5 with explanation. Thus if we wish to know the shape of the edge of a salt dome as determined from a long straight mine corridor we can probe the salt while moving along the corridor of the mine. The audio channel of the video tape recorder (VTR) is used to record comments about the time location of the radar for later interpretation of the radar data. Using the "stop-action" feature of the VTR, familiar to all TV watchers of football games, we can then record interesting radar data on *film* by photographing the oscilloscope display from the tape played back. In practice, after each VTR run in the mine, we immediately play back the video tape and observe the data on the oscilloscope. This is to be sure we *have* the radar data. If we don't we can rerun the profile immediately. This check-out system was a big advantage for magnetically recording the radar data as opposed to taking motion pictures of the radar data on the oscilloscope screen which we first considered.

A feature of the Charlie radar system is the four bay array of Yagi antennas stacked, two each in the *E* and *H* plane. This is simple to do because of the rather small size of the antennas. The larger (almost double) size of the Yagi antennas of the low frequency Bravo system makes a four bay antenna array for the transmitter and the receiver rather cumbersome. Thus we use only a two bay array stacked in the *H* plane. Low noise preamplifiers are used in both Charlie and Bravo radar systems to decrease the input noise level to the high gain receivers.

Velocity of Radar Waves in Salt

In order to know the range in salt to the discontinuity in the salt giving rise to a radar reflection we must know the velocity of radar waves in salt. This is the first thing we determine when in a salt mine. A number of large salt pillars are chosen and radar probed. From the size of the pillar and the time of travel for the reflection to come back to the radar from the opposite end of the pillar it is simple to determine the radar speed in salt. The speed will depend on the type and amount of impurity in the salt but generally runs from 60.98 m/μs (for very pure salt) to 51.22 m/μs for relatively impure salt. This range covers salt between 99 % and perhaps 95 % purity. In most mines we repeatedly obtain the same radar speed when probing eight to ten different pillars of salt located in various sections of the mine. In South Louisiana we have found the same radar speeds independent of the depth of the mine (91 m or 412 m). The radar speed is half the actual speed of the wave in the salt. Thus we simply multiply the radar speed by the (two way) travel time of the radar reflection as measured by the oscilloscope to determine its range in salt. A small amount ($< 1\ \mu s$) of radar cable and receiver delay is also taken into account when calculating the distance to a reflection. Sometimes, in radar probing of a salt pillar, we find that the radar energy goes through not only the pillar we are probing but also the pillar behind it and a third pillar also. This has happened in the Cote Blanche salt mine (Stewart and Unterberger 1974) as well as the Avery Island salt mine in Louisiana.

Radar Results Obtained in Mines

We have used radar probing techniques in thirteen different salt mines in the U.S. and Canada. We give here only a few examples of results obtained. In general, the results can be categorized under the following types of problems.

1. Radar probing for a salt dome flank.
2. Radar probing for the top of the salt.
3. Radar probing for directly ahead of mining for any discontinuity.
4. Radar probing for boreholes in salt.
5. Radar probing down to determine the shape of a tunnel below.

The first two apply to salt domes. Mine management wishes to keep their mine a certain safe distance from the edge of the salt dome. Usually the salt dome contour lines are obtained by seismic surveys, and the accuracy of these contours are sometimes in doubt considering the long wavelength used to determine the contour lines. Radar probing of the salt-sediment contact is used to obtain independent data. We have sometimes found dome flanks at the range indicated by the seismic contour lines, and at other times the dome flank is a few tens of meters further away. It is the latter case that helps miners as they can then extend their mine out further before having to mine (more expensively) at a lower level in the salt dome.

Radar probing for the top of the salt also helps in determining the contour lines of the top of the salt dome. This information can be vital to mines that are shallow in the salt and domes that have no anhydrite cap. Circulating ground waters are in contact with the salt and sometimes fractures in the top of the dome give rise to water leaks into the salt mine. A knowledge of the configuration of the top of the salt can lead to expeditiously cementing off leaks.

Radar probing ahead of mining is quite useful in mines in both domes and bedded salt. By radar probing ahead, we can detect discontinuities in the salt by their radar reflections in advance of mining. Discontinuities are anything that is not salt, such as anhydrite, carbonate rock, lenses of sand, fractures, faults, etc. In one mine in upstate New York we have detected a possible fault 400 m in advance of mining. In other mines we have detected anhydrite masses ahead, or, the best answer, nothing but salt ahead. In the *only* salt mine in Great Britain, mining ahead without radar probing led to undercutting into a borehole (unknown) which intersected a high pressure water zone above the level of the mine. This mine was almost lost before the water was shut off.

Because of the presence of oil around salt domes in Louisiana and Texas, many salt domes (and hence salt mines) have been penetrated by wells drilled originally for oil. Sometimes these "dry holes" are abandoned without cementing them from the bottom to the top. Thus these holes represent hazards to the integrity of the salt mine. Usually large pillars of salt are left around them for safety purposes.

Some examples of radar probing of salt will be considered next. In a south Louisiana salt dome in which there is a salt mine at three different levels (see fig. 6) we radar probed from the lowest level pointing the antennas of

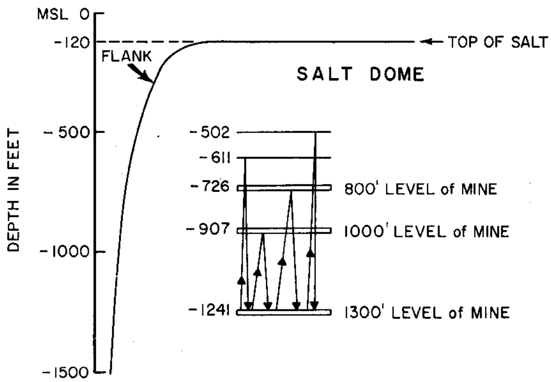


Fig. 6. Interpreted radar paths, station G″ data

our low power Charlie radar system straight up, but positioned in the mine such that we were directly beneath salt pillars on the 300 m (1000 ft) level and on the 240 m (800 ft) level of the mine. From this radar probing we detected signals reflected from the floor of the 300 m level, the floor of the 240 m level, and two other discontinuities shown in fig. 6 between the 240 m level of the mine and the top of the salt. Because of the low power used in this radar system we did not penetrate completely to the top of the salt. We have done this, however, even with this low power radar system at other parts of the lowest mine level where there is no 240 m and 300 m mining level directly above. Thus with one radar probing direction we obtained four different radar reflections from four separate targets. With the high power radar (Bravo) we could have bounced radar signals off the top of the salt.

A simple problem is finding the top of the salt using the low power Charlie radar system. This salt mine was in Texas and the known top of the salt (salt-anhydrite contact as measured in the air shaft) was 156 m (519 ft) above the mine level as shown on the left of fig. 7. Radar probing detected this rock interface 518 ft above the salt mine level but also found two other signals which were interpreted as anhydrite stringers in the salt. Accuracy of .3 m (1 foot) in 150 m radar probing is not to be expected routinely, as the usual accuracy of this radar equipment is $\pm$ 3 m in range to a discontinuity.

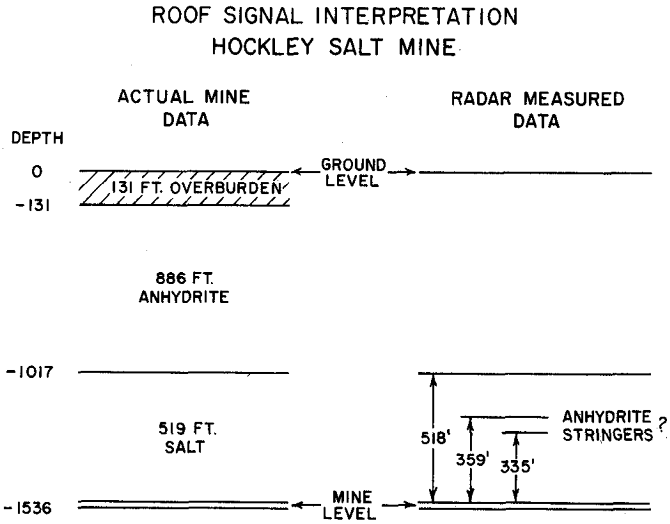


Fig. 7. Roof signal interpretation, Hockley Salt Mine

Both Charlie and Bravo radar systems have been used to locate salt dome flanks. In general, the lower frequency Bravo system is better for this task as the target is usually large and the range far. Signals have been received as late as 23 μs after the transmitted pulse was emitted which means reflections are received by the radar from 1400 m. This is not the longest reflection range in salt as W. T. Holser (personal communication) has measured a reflection from a dome flank over 3000 m away using a 16 MHz radar in the Grand Saline salt mine of Texas.

The CW-FM radar system shown in the block diagram of fig. 8 has been used for short-range, high-resolution detail probing of salt. In this case we outlined a tunnel beneath a salt floor in the Grand Saline salt mine of Texas. Fig. 9 shows the results of a radar profile made on (2 ft) 0.61 m stations on a line perpendicular to the axis of the tunnel below. Note the (13′-8″) 4.17 m hole in salt to check our actual measurement of the thickness of salt at that point. Further, at the extremes of the profile, radar detected and ranged to

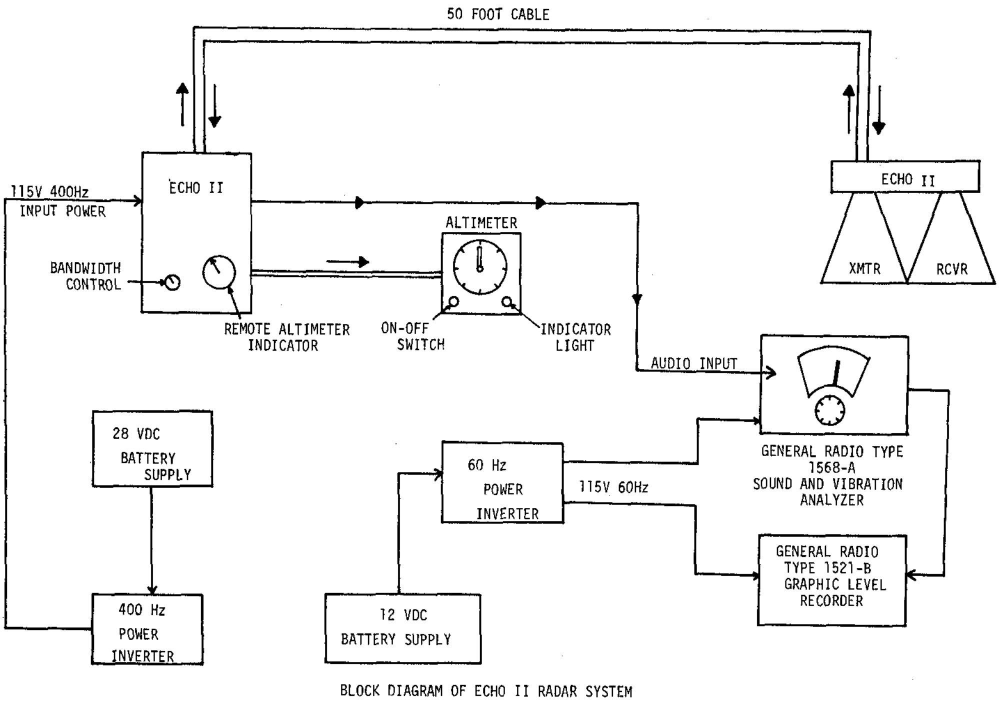


Fig. 8. Block diagram of Echo system

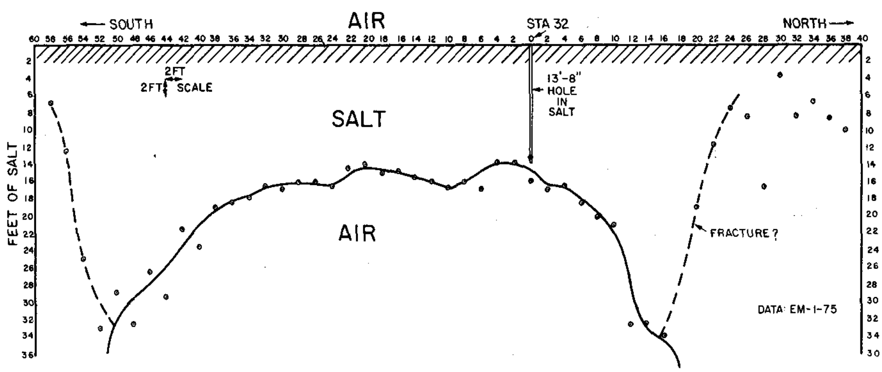


Fig. 9. Radar profiling of tunnel beneath a salt floor N-S

what are probably fractures in the salt at the corners of the tunnel below. With a wavelength in salt of 2.87 cm it seems plausible that this is what the radar detected.

A better example of this high resolution radar probing in salt is shown by a radar profile taken along the axis of the tunnel and extending beyond the end of the tunnel, i.e. at right angles to the profile of fig. 9. This is shown in fig. 10. It is a good representation of the fracture shown on the left of this figure.

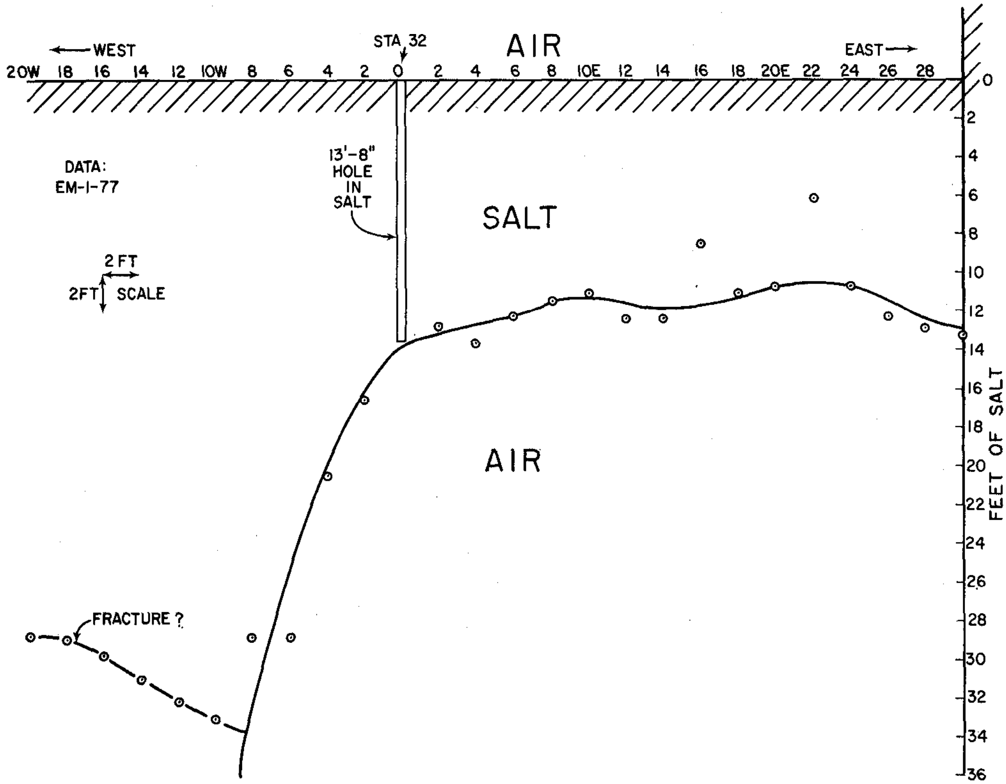


Fig. 10. Radar profiling of tunnel beneath a salt floor E-W

Other examples of radar probing in the Hockley salt dome, particularly for the top of the salt can be found in Hluchanek (1973) and Unterberger and Hluchanek (1973). A very good transmitter of 440 MHz waves is the Cote Blanche salt dome in Louisiana. Work done here has been described by Stewart (1974) and Stewart and Unterberger (1974).

Another example of radar detection in advance of mining occurred in a salt mine in upstate New York. Here we detected a possible fault in the mining layer 400 m in advance. When the mining face advances closer, we will probe again from a closer range for better definition of this target.

Examples of the detection of boreholes in salt by radar probing can be found in Unterberger (1971) and Steward and Unterberger (1974).

A more recent example of the use of radar probing ahead of mining concerns the sinking of a new shaft into an existing mine. In this case we were asked to probe upward from the mine level at 396 m (1300 ft) directly beneath the location of the shaft. Radar probing found a water layer at —51 m (167 ft), and actual drilling found it at —53 m (173 ft), meaning this water zone was detected within 2 m (6 ft) over a range of over 335 m (1100 ft), a radar probing accuracy of better than 1 %. Three other signals (reflections from discontinuities in the salt) were also detected and will be checked as to their nature by drilling as the shaft proceeds downward.

Countinuous Recording of Radar Probing Data

In the past seven years of radar probing in salt we simply established fixed radar stations in salt mines to detect salt dome flanks, or the top of the salt, or merely to "look ahead" of mining so that management could be aware of any future hazard. However, there are times when it is desirable to obtain continuous data on ranges to the flank, for example. Since radar waves in salt travel fast, the reflection from even a dome flank a kilometer or two away comes back to the radar and is presented on the oscilloscope screen almost instantaneously (33 μs). Therefore moving the whole radar system slowly along a mine corridor while radar probing continuously is feasible. The problem is recording the radar data displayed on the oscilloscope. We considered both film and magnetic tape and finally decided on a video tape recorder (VTR). So now we can record our data, say the range to a dome flank, continuously while moving along a mine corridor. The use of a VTR has two distinct advantages: one is an audio channel which is very convenient for recording position locations in the mine, the other the ability to play back the whole recording to see if the data are satisfactory. The "stop-action" feature of the VTR allows us to photograph the oscilloscope displayed radar data for a report or other reasons.

Signal Interpretation

Like seismic data, the radar display is not simple to interpret. Under very good conditions, such as shooting upward to detect the top of the salt dome in a dome consisting of very clean salt, there is no problem. Usually, however, one has to worry about reverberation and multiples. The mine geometry at the radar station determines how long energy will "ring" in the area. Although for normal incidence of an electromagnetic wave on salt, only 17 % of the energy is reflected, it takes a few microseconds before all this energy is dissipated by repeated reflections when the receiver sensitivity is of the order of 10^{-13} W. The power output of the radar also has an effect on the length of time of reverberation. The higher the power, the longer the energy will bounce around in the air before finally being absorbed in the salt.

Multiples are a problem particularly when strong reflections are present in the salt. However, straightforward calculations can show where they are expected and relative amplitudes of original reflection and its first multiple can sometimes allow a signal to be detected despite the fact that it comes in at a time appropriate for a multiple.

Conclusions

Salt is a good transmitter of VHF electromagnetic waves with radar probing ranges to discontinuities in salt of up to 10 km obtainable. Since radar reflections are measured in time, a number of salt pillars in the mine are radar probed initially to determine the velocity of radar waves for that mine. This velocity is then used for converting times to ranges in other mine areas. Mining companies find radar ranging to salt dome flanks useful in planning future mining. The configuration of the top of a salt dome can be mapped by radar and is useful in determining ground water flow in order to cement off leaks into salt mines. Radar probing ahead of mining is very useful in alerting management of possible troubles ahead. A CW-FM radar is useful for high resolution short range radar probing because it solves the minimum range problem of pulse radars. Radar probing ranges to discontinuities in salt have been confirmed by drilling in a few cases and accuracies of better than 3 m ($\pm$ 10 ft) in probing over 300 m have been obtained.

References

Ames, L. A., Frazier, J. W., and Orange, A. S., 1963, Geological and geophysical considerations in radio propagation through the earth's crust, IEEE Transactions on Antennas and Propagation AP-11, 369-371.

Anonymous, 1963, Bibliography of Soviet-Bloc Literature for the period 1960-1962, AID Report B-63-99, July.

Aufricht, W. R., and Howard, K. C., 1961, Salt characteristics as they affect storage of hydrocarbons, Journal of Petroleum Technology, 733-738, August.

Barret, William N., 1952, Note on the radio transmission demonstration at Grand Saline, Texas, Geophysics 17, 544-549.

de Bettencourt, Joseph T., 1967, Review of radio propagation below the earth's surface, Raytheon Company, Norwood, Massachusetts, 697-767.

Bhattacharyya, Bimal Krishna, 1957, Propagation of an electric pulse through a homogeneous and isotropic medium, Geophysics 22, 905-921.

Bogorodskii, V. V., and Trepov, G. V., 1969, Radar measurements of the thickness of mountain glaciers, Soviet Physics — Technical Physics 13 (8), 1135-1136.

Burrows, C. R., 1963, Radio communication within the earth's crust, IEEE Transactions on Antennas and Propagation AP-11 (3), 311-317.

Carolan, J. and de Bettencourt, J. T., 1963, Radio waves in rock near overburden-rock interface, IEEE Transactions on Antennas and Propagation AP-11, 336-337.

Christensen, E. L., Gundestrup, N., Nilsson, E., and Gudmandsen, P., 1970, Radioglaciology 60 MHz radar, Laboratory of Electromagnetic Theory, R77, January.

CHRISTENSEN, E. L., 1970, Radioglaciology 300 MHz radar, Laboratory of Electromagnetic Theory, R93, August.
CHRISTOFFERSEN, P. D., and GUDMANDSEN, P., 1970, Experiments with electromagnetic probing of sea ice, Laboratory of Electromagnetic Theory, R83, October.
COLBURN, C. L., BOUTON, C. M., and FREEMAN, H. B., 1922, Experiments in underground signalling with radio sets, Reports of Investigations, Bureau of Mines, Department of the Interior, Serial No. 2407, October.
COOK, JOHN C., 1971, A study of radar exploration of coalbeds, Technical Report No. 71-8, BuMines OFR 5-72, PB 207 362, NTIS, June.
COOPER, R. I. B., 1948, The attenuation of ultra-high frequency electromagnetic radiation by rocks, Proceedings of the Physical Society of London, 40-47.
DOKOUPIL, S., KARPINSKY, J., and KASPAR, M., 1962, The attenuation of electromagnetic waves in rocks, Ceskoslovenska Akademie Ved. Studia Geophysica et Geodaetica 6, 176-192.
DOLPHIN, L. T. JR., BOLLEN, R. L., and OETZEL, G. N., 1974, An underground electromagnetic sounder experiment, Geophysics 39 (1), 49-55.
EVANS, S. and de Q. ROBIN, G., 1966, Glacier depth-sounding from the air, Nature 210, 883-885.
FRITSCH, V., 1942, The range of transmission of Hertzian waves through geological conductors, Geofisica pura e applicata 4, 15-37.
FRITSCH, V., 1948, Die Ausbreitung hochfrequenter Hertzscher Felder in Kalilagerstätten, Geofisica pura e applicata 12, 1/2.
FRITSCH, V., 1963, Propagation of radiofrequency electromagnetic fields in geological conductors, Journal of Research of the National Bureau of Standards—D. Radio Propagation, 67D (2), 161-178.
GABILLARD, J. M., and DESBRANDES, R., 1967, Experimental and theoretical study of the propagation of electromagnetic pulses of short duration through the earth, Institution of Electrical Engineers, London-Conference Publications 36, 326-330.
GREENBERG, J., 1962, Methods used to study the absorption, reflection and emission of inorganic salts above and below the melting point, Lewis Research Center, National Aeronautics and Space Administration, Cleveland, Ohio, Prepared for Symposium on Measurement of Thermal Radiation, Dayton, Ohio, September.
GRÖBNER, O., 1964, VLF measurements in the mine of Bleiberg, Scientific Report 11, Defense Documentation Center AD610024.
HAYCOCK, O. C., MADSEN, E. C., and HURST, S. R., 1949, Propagation of electromagnetic waves in earth, Geophysics 14, 162-171.
HLUCHANEK, J. A., 1973, Radar investigation of the Hockley Salt Dome, M.S. Thesis, Texas A&M University.
HLUCHANEK, J. A., and UNTERBERGER, R. R., 1973, Mapping a salt dome top by electromagnetic waves from inside the salt, Talk given at 43rd Annual International Meeting of the Society of Exploration Geophysicists, Mexico City, Mexico, October.
HOLSER, W. T., BROWN, R. J. S., ROBERTS, F. A., FREDRIKSSON, O. A., and UNTERBERGER, R. R., 1972, Radar logging of a salt dome, Geophysics 37, 889-906.
HORTON, C. W., 1946, On the use of electromagnetic waves in geophysical prospecting, Geophysics 11, 505-517.
ILSLEY, L. C., FREEMAN, H. B., and ZELLERS, D. H., 1928, Experiments in underground communication through earth strata, Technical Paper 433, Department of Commerce, Bureau of Mines.
JAKOSKY, J. J., 1924, Radio as a method for underground communication in mines, Reports of Investigations, Department of the Interior, Bureau of Mines, Serial No. 2599, April.
JAKOSKY, J. J., and ZELLERS, D. H., 1924, Factors retarding transmission of radio signals underground, and some further experiments and conclusions, Reports of Investigations, Department of the Interior, Bureau of Mines, Serial No. 2651, November.

JAKOSKY, J. J., and ZELLERS, D. H., 1925, Transmission of radio signals underground, Arizona Mining Journal 8 (19), February.

JIRACEK, G. R., 1967, Feasibility of radio sounding to the groundwater table in Hawaii, Technical Report 10, Water Resources Research Center, University of Hawaii, Honolulu, Hawaii, August.

JOYCE, J. W., 1931, Electromagnetic absorption by rocks, Technical Paper 497, U.S. Department of Commerce, Bureau of Mines, June.

KING, R. W., and HARRISON, C. W. JR., 1968, The transmission of electromagnetic waves and pulses into the earth, Journal of Applied Physics 39 (9), 444-452.

LÖWY, H., and LEIMBACH, G., 1910, An electrodynamic method for the investigation of the interior of the earth, Part 1, Physikalische Zeitschrift 11 (16), 697-705.

MINAW, F., 1958, Penetration of electric waves into desert rocks, Pure and Applied Geophysics 39, 55-64.

MUIR, W. G., 1967, Salt mining at Goderich, Can. Min. & Met. Bul. 60, 457-463.

MCGEHEE, F. M., 1954, Propagation of radio frequency energy through the earth, Geophysics 19, 459-476.

NICKEL, H., 1968, Experiments to determine the radius of action of radio waves in level-bedded hydrogenetic rocks, Kali und Steinsalz 3, 95-99.

ORSINGER, A., and VAN NOSTRAND, R., 1954, A field evaluation of the electromagnetic reflection method, Geophysics 19, 478-489.

PETROVSKII, A. A., 1947, The first experiment in the transmission ot radio waves through the permanently frozen rocks, Trudy Institut Merzlotovedeniya im V.A. Obruchev 5, 122-159.

PETROVSKIY, A. D., 1961, Prospecting by the use of radio waves transmitted from boreholes to the surface of the ground in one of the ore deposits beyond the Artic Circle, Translated from Prikladnaya Geofizika 29, 187-201.

PLIUSNIN, M. I., and PETROVSKII, A. D., 1959, Radiowave penetration from exploratory boreholes to the surface, Moskoriskii Geologorzavedocganyi Institut Trudy 36, 70-77.

PRITCHETT, W. C., 1952, Attenuation of radio frequency waves through the earth, Geophysics 17, 193-217.

RYAZANTSEV, A. M., and SHABEL'NIKOV, A. V., 1965, Propagation of radio waves through the earth's crust (A Review), Radio Engineering and Electronic Physics 11, 1643-1657.

SHU, S.-KUANG; MIAO-LI, HSU; HSIAO-CH'ANG, MA; and T'AO, CH'EN; 1964, Experiments on penetration of radio waves in mine tunnels, in the Chinese-language periodical Ti-ch'iu Wu-li Hsueh-pao (Acta Geophysica Sinica), Vol. XIII, No. 3, Peiping, 234-242.

SILVERMAN, D., and SHEFFET, D., 1942, Note on the transmission of radio waves through the earth, Geophysics 7 (4), 406-413.

STETSON, H. T., 1934, Further studies of radio transmission in geophysical investigations, Transactions, American Geophysical Union 15, 158-160.

STEWART, R. D., 1974, Radar investigation of the Cote Blanche Salt Dome, M.S. Thesis, Texas A&M University.

STEWART, R. D., and UNTERBERGER, R. R., 1974, Seeing through rock salt with radar, Talk given at 44th Annual International Meeting of the Society of Exploration Geophysicists, Dallas, Texas, November, to be published in February 1976 issue of Geophysics.

TARANTOLO, PAUL J. JR., and UNTERBERGER, ROBERT, R., 1978, Radar detection of boreholes in advance of mining, Geophysical Prospecting 26, 000-000.

TSAO, C. K. H., 1964, Investigations of electrical characteristics of the subsurface rock medium in Essex County, New York, Scientific Report No. 5, Raytheon Company, Contract AF19(628)-2362, August.

TSAO, C. K. H., and DE BETTENCOURT, J. T., 1967, Measurement of the phase constant for rock propagated radio signals, IEEE Transactions on Communication Technology, COm-15 (4), 592-597.

UNTERBERGER, R. R., 1971, Fourth Biannual Report, Project 682, Texas A&M University, May.

UNTERBERGER, R. R., 1974, Electromagnetic wave propagation in salt—probing into salt with radar, Fourth International Salt Symposium, Vol. 2.

UNTERBERGER, R. R., 1975, Radar probing ahead of mining, Presented at the 37th Meeting of the European Association of Exploration Geophysicists, Bergen, Norway, June.

VIGGH, M. E., 1963, Modes in lossy stratified media with application to underground propagation of radio waves, IEEE Transactions on Antennas and Propagation AP-11 (3), 318-323.

WAIT, J. R., 1960, Propagation of electromagnetic pulses in a homogeneous conducting earth, Applied Scientific Research, Sec. B, 8, 213-253.

WAIT, J. R., 1965, Propagation of electromagnetic pulses in terrestrial waveguides, IEEE Transactions on Antennas and Propagation AP-13 (6), 904-918.

WAIT, J. R., 1966, Some highlights of a symposium on subsurface propagation of electromagnetic waves, Paris, April, Radio Science, 1 (New Series), (9), 1115-1118.

WEBER, J. R., and ANDRIEUX, P., 1970, Radar soundings on the Penny Ice Cap, Baffin Island, Journal of Glaciology 9 (55), 49-54.

WHEELER, H. A., 1961, Radio-wave propagation in the earth's crust, Journal of Research of the National Bureau of Standards—D. Radio Propagation 65D (2), 189-191.

WILLIAMS, P. H., 1951, Subterranean communication by electric waves, Journal of the British Institution of Radio Engineers 11, 101-111.

WUNDT, R. M., 1964, Underground communications, IEEE 52.

WYNN, L. E., 1965, Movement within the Jefferson Island, Louisiana Salt Dome, Rock Mechanics Symposium Proceedings, 19-34.