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FINAL REPORT

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SONAR PROBING AS A MINING AND TUNNELING TOOL

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CHAPTER I
SUMMARY OF PROJECT ACCOMPLISHMENTS

The original two year proposal for research on using sonar as a mining and tunneling tool (Unterberger 1977) envisioned the use of a 24 kHz sonar probing system and a 6.3 kHz sonar probing system (both of which were on hand) plus the acquisition of a high frequency, high resolution sonar system to probe into rock. Various techniques of coupling sonar energy into rock and methods of optimizing energy transfer by using different fluids and the use of quarter-wave matching plates were to be investigated. The problem of reverberation of sound in the transducer mount was also to be investigated. The theory of acoustic scattering from a hole drilled into salt was to be researched. All these research tasks were accomplished on schedule either at Texas A&M or at our experimental test site in the Morton salt mine at Grand Saline, Texas.

When we were about halfway through the research program, experimental and theoretical sonar probing results in salt showed the urgent need for a narrow sound beam in salt. The only classical solution was a bigger transducer which implied experimental difficulties. Fortunately, however, a new possible solution to our problem of obtaining a narrow sound beam in rock came to our attention. This was the possible use of nonlinear sonar to produce a narrow beam of sound in rock <u>without</u> the corresponding disadvantage of (1) having to use a large transducer, and (2) having side lobes in the sound pattern of the transducer that made signal interpretation very difficult. During the first year of research with fluids, we discovered that the sound beam in rock salt was very broad because of the sound wave refraction caused by the coupling fluid-rock salt interface. Theoretical calculations of the sound beam for various fluids showed that the beam in salt could be modified slightly by using different fluids (e.g., castor oil and glycerin). This theoretical result was verified by experimental sonar research in the salt mine. The fluid coupling was deemed necessary in order to eliminate shear waves from any consideration in the signal interpretation process. These shear waves are generated in the rock salt by nonnormal incidence of the sound wave.

Thus, in the summer of 1978, we discussed, at Texas A&M University with Dr. R. I. Schoen of NSF, our desire to reorient the research program in an effort to obtain a narrow beam in salt using nonlinear sonar techniques. These nonlinear sonar techniques have been much used in water, i.e., water has been driven nonlinearly and hence gives rise to a narrow sound beam, enabling greater simplification in sonar data interpretation. The U.S. Navy uses nonlinear sonar operationally in the sea, but the equipment is classified. The idea of generating a narrow beam of sound in salt was intriguing, but we did not know whether we could drive salt nonlinearly or not. No one had ever done it before.

The reorientation of the sonar probing research program was approved by NSF and using nonclassified experimental equipment of the University of Texas, Applied Research Laboratory (under subcontract with UT:ARL), we proceeded with experiments in the salt mine. Simultaneously, we investigated theoretically whether salt should be able to produce nonlinear beams of sound. Initial nonlinear sonar experimental work proved unsuccessful at two different sites in the salt mine despite the fact that our linear (ordinary) sonar worked well at both locations. Later experiments on the salt mine floor with a large salt-air interface located 12.80 meters directly below proved that salt could be driven nonlinearly, thus generating a narrow beam of sound at a low frequency using a reasonably-sized (30 cm) transducer.

This breakthrough we consider to be the most important accomplishment of this project. We need to do more work, of course, but this accomplishment opens up new vistas. It should allow us to probe salt in a fashion similar to what we accomplished with radar where a narrow beam of electromagnetic waves is produced by an antenna array in air, and this beam is sent into the salt where it can be scanned in azimuth and elevation by simply moving the antenna array in air. In addition, this advance in sonar probing technique might be used to "see into" other rocks, such as potash, trona, limestone and sandstone, if the minerals composing these rocks allow nonlinear action. So we believe we have opened up a new vista in sonar probing of rocks and are eager to move ahead on this breakthrough.

Inasmuch as the UT:ARL equipment used to probe into salt was (1) not available most of the time (it being used by Dr. Thomas Muir for U.S. Navy sponsored research programs), and (2) had primary frequencies in the 200 kHz region that was rather high for use in salt, and (3) because nonlinear sonar equipment is not available on the market, the U.S. Navy having classified the commercial equipment, we have been forced to design and build our own nonlinear sonar system to use to probe into rock salt or other rock types where applicable. At the present time, we have just received a specially-built cone transducer which is being laboratory tested. It operates at 90 kHz and 114 kHz for the primary frequencies, the difference frequency being 24 kHz which is the frequency of the (linear) sonar we originally used to probe salt with sound. When we complete our laboratory check out, we will take the system to the UT:ARL water tank and try it there. If successful, we will then be ready to go to the salt mine to try to reproduce our previous nonlinear probing results, and hopefully with a large improvement in the signal to noise ratio.

The research accomplished under this project is listed below with the location of the reported results.

1. Selection of Standard Test Site - Task I

   This was completed and reported in Unterberger, 1978a.

2. Sound Wave Coupling and Reverberation Studies - Task II

   This research was completed and was reported in Unterberger, 1978a, Chapter III.

3. Theoretical Work on the Beamwidth in Salt - Task IV

   This research was completed and was reported in Unterberger, 1978a, Chapter IV.

4. Research Program Changes

   After NSF approval early in the fall of 1978, the approved changes were reported in Unterberger, 1978b, Chapter II. Research into the theory of nonlinear acoustics and particularly into the mechanical and thermodynamic properties of salt was done to determine whether it would be theoretically possible to drive salt into a nonlinear region and thereby generate a narrow sound beam in salt. The theoretically promising results were reported in Chapter III of Unterberger, 1978b.

5. Theoretical Study of the Acoustical Scattering from Various Cylinders - Task V

   This was accomplished and reported in Chapter IV of Unterberger, 1978b.

6. Experimental Tests on the Nonlinearity of Salt - New Task

   Chapter II of Unterberger, 1979, describes the unsuccessful tests of nonlinear probing of salt. This chapter also describes the <u>successful</u> tests accomplished to make salt itself generate a difference frequency of 15 kHz when excited by both 225 kHz and 210 kHz high-intensity colinear sound beams. The nonlinear interaction between the two beams generates a narrow 15 kHz beam. This is the highlight and major accomplishment of this research project. It has never been done before and holds exciting possibilities for sonar probing of salt and possibly other types of rocks.

7. Noise in Salt - New Task

   A wide-band receiver was used to determine whether there was any minimum in the noise level at a particular frequency so that this frequency could be used for probing the salt acoustically. No such minimum was found nor did we find any particular band that was very noisy except at a very low frequency (near the power frequency of 60 Hz which we had not planned to use as a probing frequency anyway). These results are reported in Unterberger, 1979, Chapter V.

8. Construction of Texas A&M Nonlinear Sonar System - New Task

   NSF agreed that if we were successful in probing salt using the nonlinear sonar system of Dr. Muir of UT:ARL, we should build our own equipment to pursue the breakthrough made in driving salt nonlinearly. The status of this work, and a description of the nonlinear sonar system is given in this report.

9. Sound Attenuation in Rock Salt - New Task

   According to the theory of nonlinear acoustics, the beamwidth of the difference frequency generated in salt will be proportional to the square root of the attenuation of sound in the salt. Therefore, it was desirable to determine what the sound attenuation, α, was for salt at 200 kHz, 100 kHz and 24 kHz. Previous research by Unterberger (1974) into the sonar literature to determine the attenuation of sound in salt showed no data for rock salt were available except at megahertz frequencies where the attenuation was obviously much too high to permit probing into salt for a few hundred meters. So, we undertook to try to measure the attenuation in salt. Our first efforts, using acoustic probes in holes drilled into the salt floor in the salt mine, are described in Unterberger, 1979, Chapter III. This was unsuccessful and further work on this problem will be described in this report.

10. It was agreed that the planned Task III, e.g., the use of a large transducer and its associated sonar system to probe into salt at 6.4 kHz, would be eliminated in favor of nonlinear sonar research because (1) we had already obtained 300 meters of probing range with 24 kHz in dry salt and the wavelength associated with 6.3 kHz would only be expected to <u>increase</u> the range and thereby also increase the number of signals observed, and (2) the narrow beam expected from the nonlinear sonar could be tuned to 6.3 kHz using the proper primary frequencies, and thus eliminate the necessity of using such a large (½ meter diameter) and heavy (77 kg) transducer.