Pictures from Underground

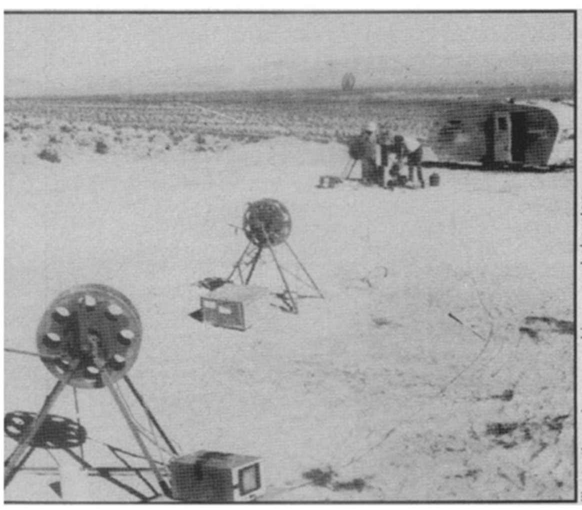
Information gained by crisscrossing radio waves can color in a view of underground structures

BY DIETRICK E. THOMSEN

Secret caves and forgotten mines have always fascinated people. Archaeologists would like to find the chambers in which the ancient mysteries were celebrated. Snow White wanted to know where the seven dwarfs went every day. Throughout the southwestern United States there are people who will tell you tales of the Lost Dutchman mine. Once these underground features get lost, they are very hard to find again, and underground features that have never been found in the first place are usually even more difficult to find.

A lot of people have spent time, money and effort looking for things underground and not finding them. Many have suffered great expense and painful damage when they found something underground that they did not expect. A sudden crash into the Lost Dutchman when you think you are excavating the One-eyed Burro can be painful. If you are digging a railroad tunnel and encounter granite where you expected gravel or vice versa, it means moving in different equipment and different workers.

From Elefsis to the Black Forest to Arizona people have thus had many reasons for wanting to know what was underground before they dug. At first the meth-



Illustrations: Lawrence Livermore Laboratory

Senders and receivers at China Lake.

ods were purely magical, seers who used second sight and witches who could see through a mountainside. More practical attempts include probes and boreholes and the use of sonar and radar to detect changes in reflectivity down below. A method now being developed at the Lawrence Livermore Laboratory and field tested by scientists there uses changes in the transmission of electromagnetic waves to produce a kind of image of what's underground. It's a color coded image, and Edwin Laine, one of the principal investigators (the other is D. Jeffrey Lytle) stresses the importance of the color: "Anybody can see a different color and say there's a difference there." The conventional geologic traces must be examined by someone experienced in reading them just to determine if something of interest is there. The two-dimensional image gives more information quicker.

What the image shows is the vertical plane between two boreholes. When excavations are planned, boreholes are usually drilled at intervals of anything up to 100 meters in advance of the digging. The core samples from the boreholes give some idea of the nature of underground structures, but the cores are 100 percent accurate only in the boreholes themselves.

The problem with boreholes is illustrated by Darrel J. Lager, another of the investigators on this project, by imagining a terrain where a soft overburden lies on a granite base that has a wavy upper boundary. If a borehole happens to hit a trough of the granite the contractor may decide that it's all sand to the depth that the excavation needs to go. Then the diggers hit a crest of the granite, and different equipment has to be called in along with different workers. Those who do sand don't do granite. Perhaps they belong to a different union. "Amalgamated granite diggers," suggests Andrew J. Poggio, another of the investigators.

The Livermore method uses the transmissions of electromagnetic waves through the earth between the boreholes to try to determine what lies between them. A transmitter is lowered into one borehole and a receiver into the other. A signal sent between them will have its strength attenuated and its phase shifted by what it may encounter.

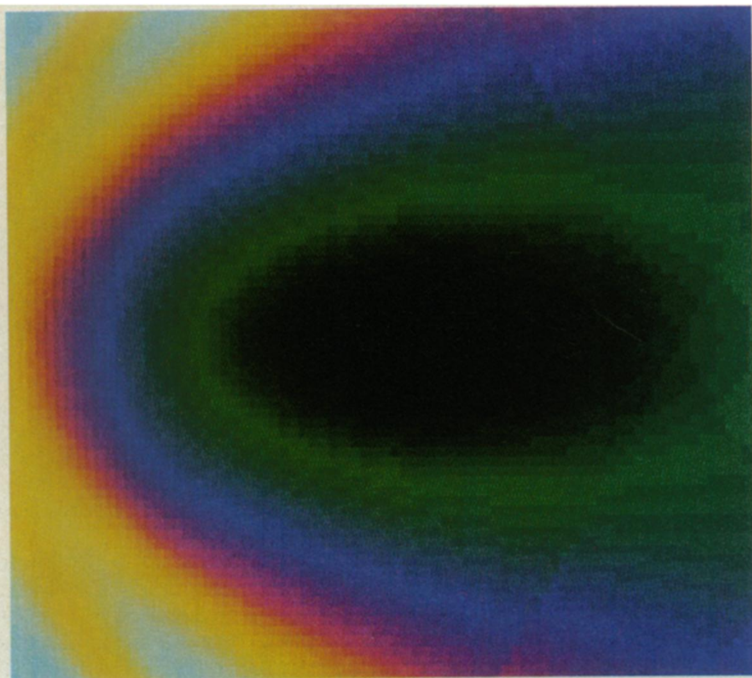
Lager makes it sound simple: "You drill the boreholes, send the signal through, and measure the received magnitude of the signal and its phase shift along the path. And then you go back and do the inverse problem; that is, take the measurements and make up an image of what exists between the boreholes."

Of course it takes more than just one transmission. Lager and Poggio stress the similarity between this technique and the computer assisted tomography (CAT) used in medicine. In CAT the patient is put on a revolving table and X-rays are shot from all angles to get information so that the computer can construct a two-dimensional picture of a slice through the patient's brain, for example. In this case the 360° scans of CAT are not possible. The angles are limited by the depth of the holes and reflections from the surface, but varying the relative positions of sender and receiver can produce a large number of paths crisscrossing the area to be investigated.

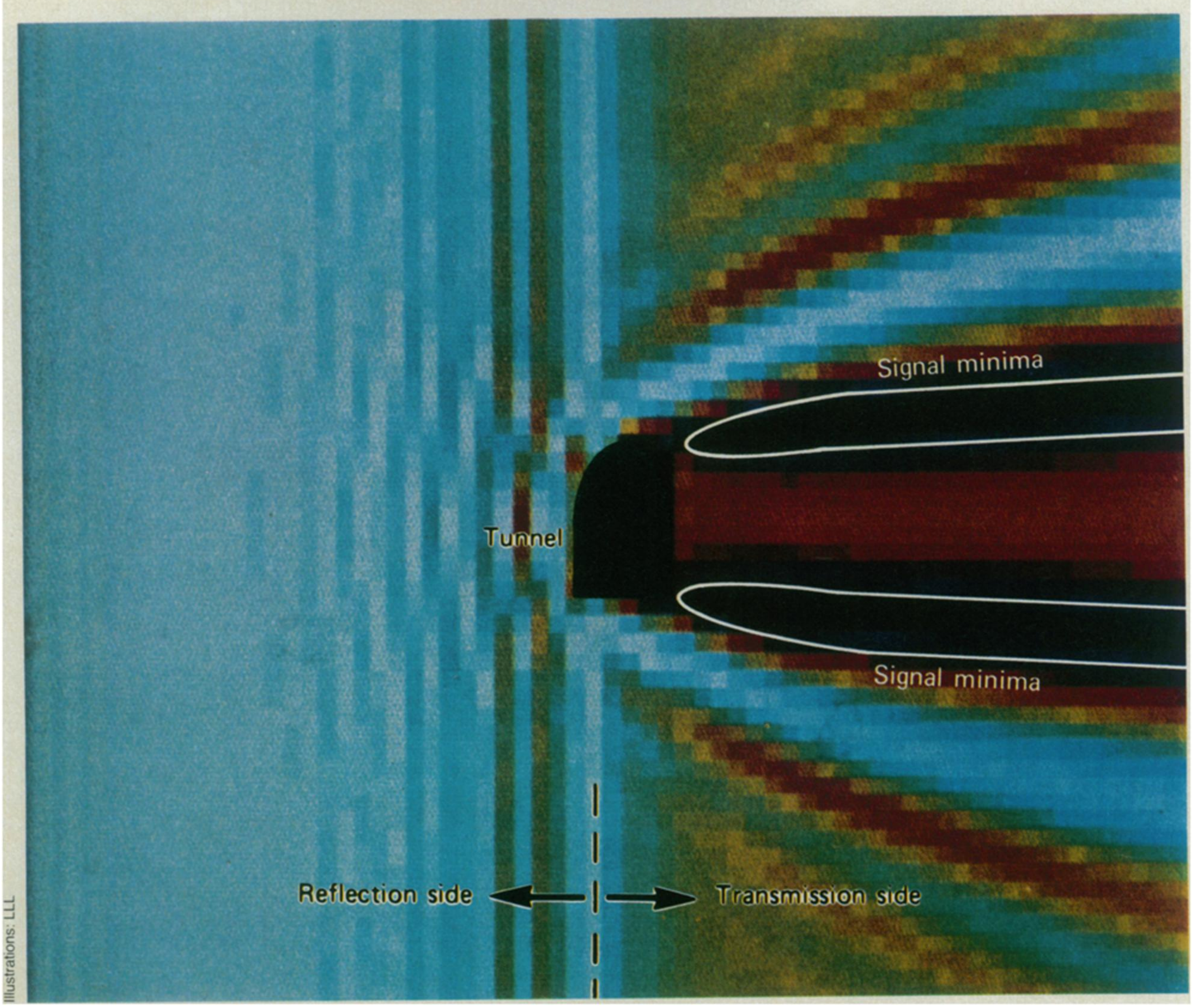
To reconstruct what is there, a beginning is made by dividing the area into a certain number of cells or pixels or picture elements. What the investigator wants to do is to assign to each cell a value of each of the two important characteristics, the electrical permitivity, or index of refraction, and the electrical conductivity. The cells can then be colored in according to the values, and people who have some knowledge of the electrical characteristics of geological formations will be able to interpret the picture. And to repeat Laine's comment, anybody looking at the picture can see something's there.

The calculation starts with data representing the changes in signal strength and phase along a series of paths between known positions of transmitter and receiver. This generates a system of equations to be solved for the index of refraction and the conductivity experienced by the signal between transmitter and receiver. Solving these to get a profile of the territory can produce four major levels of complexity depending on whether the ray paths are straight or bent and on the size of the picture, that is, the number of pixels to be covered. If the physics permits straight rays, that is, if there is low contrast in electrical properties between underground features so that there is only one path length between any given setting of transmitter and receiver, the difficulties are greatly lessened. The problem of calculating the attenuation of the signal can be separated from that of calculating the phase shift. But even under the straight-ray assumption, says Lager, a large picture with a large number of unknowns may be too big to fit in the core of the computer (a 7600). This requires iterated calculating procedures and what in current large computer traffic is a lot of time — several minutes.

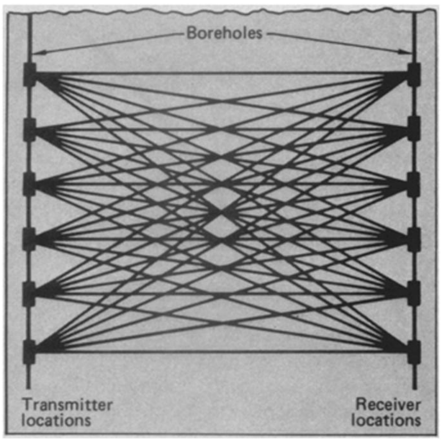
The algorithm by which the pictures are built up is known as back projection and is similar to algorithms by the same name



The classic back-projection technique of processing the data can find a tunnel, as at left, but not with very good resolution. Modified back-projection, which concentrates on anomalies in the transmitted signal, such as the sharp minima shown here, gives a better picture (below).



Illustrations: LLL



Illustrations: LLL

Multiple paths between transmitters and receivers at different positions make the crisscross ray pattern used in applying the back-projection algorithm.

used in X-ray tomography. The area to be depicted is an array of 100 or more cells or pixels. A large number of ray paths crisscross this array, and many paths traverse each individual cell. The procedure is to get a datum to assign to a particular cell, let us say the attenuation of signal that takes place in that cell, by tracing what it does to each ray.

The computation starts with the assumption that each ray has passed through a homogeneous medium and that the attenuation it has suffered can be distributed evenly over its length. Thus a given part of the ray's total attenuation can be assigned to each cell the ray traverses according to the path length through that cell. The assumption of homogeneity seems plainly wrong if there is anything between the boreholes that's worth finding out, but it is a zero-base assumption from which to begin the calculation.

This procedure with the rays leaves every cell with a list of attenuation values assigned to it, one from each ray that passes through it. To assign an attenuation value that best represents the cell itself, the procedure takes a weighted average of all the values. Where there are few data, such as at the top or bottom of a picture, the imaging can be bad, but back-projection has the advantage that if there is noise in the data, the noise will be smeared out evenly and not concentrated so as to cause misapprehensions. Back-projection can be improved by using an algorithm called iterative back-projection, which starts with the values assigned to the cells by the ordinary back-projection procedure and then computes corrections between these and the measured data, further refining the values toward a best fit to what has actually happened to the rays.

An example of a field test is the foundation for a bridge pier in the Columbia River. Concrete slurry had been poured into the area while the water was still there. When the caisson had been pumped out and the foundation was about to be set up, the builders wanted to know whether there were pockets of alien material such as sand inclusions in the concrete. The Livermore group surveyed it and found evidence for such inclusions. Subsequent drilling in one place uncovered sand about where the survey said it should be. "This was very heartening to us," Lager says, "because we had done two or three other experiments and nobody had drilled to find out whether we were right."

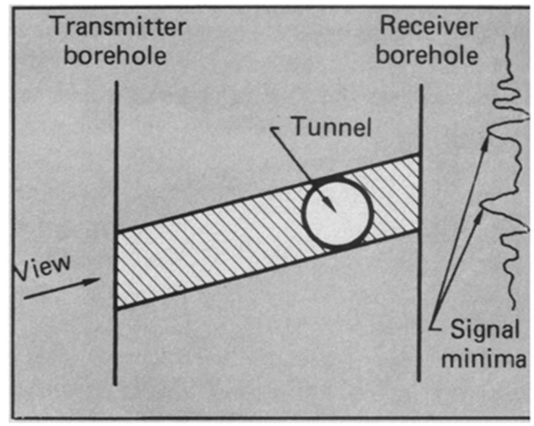
One of those places was the Forest Glen station of the Washington, D.C. subway system in Montgomery County, Md. The system had run into such serious trouble finding unexpected obstacles in the way of its tunnels that it decided to survey the Forest Glen site and invited the Livermore people to do it. But nobody has dug or drilled at Forest Glen because there is a dispute over whether that line should be built.

One that will be checked, according to Laine, is a survey of a test bed for grouting highway embankments set up in Baltimore by the Maryland Department of Transportation. When a highway cut is dug through soft material, such as sand, it is often necessary to stiffen the embankments by injecting sodium silicate. The sodium silicate is expected to form an interlocking pattern of small balls that tends to hold the sand back. Here the Livermore method was in competition with others, which used radar and other probing techniques. Laine is eager to know how the comparison went.

If the ray paths are curved — and they will be in the case of medium or high contrast — in the index of refraction for radio to another — the computation problem gets much worse. Ray tracing and the back-reflection algorithms can produce fairly reasonable pictures (in laboratory simulations, anyway), but the ray tracing is very sensitive to noise, and noise of 10 percent or more tends to wash out the picture.

While looking for general solutions to the curved ray problem, the group has concentrated on a special part of it: the diffraction patterns produced by high contrast anomalies in homogeneous material — for example, a tunnel in granite, a water deposit in rock, a high contrast mineral like gold. ("They don't make nuggets that big," says Lager.) If there are boreholes on two sides of a tunnel and the sender and receiver are let down the holes in tandem, when they pass the tunnel the reception will show a pattern similar to the diffraction patterns that ruled gratings and slits produce with light. From the details of the pattern a lot can be learned about the shape and size of the tunnel or other anomaly.

In China Lake, Calif., the group had a chance to study the site of a tunnel before and after it was dug. Observing while the digging was going on, they found the data permitted them to "see" an ore car going back and forth. In Kemmerer, Wyo., they found an indication of an anomaly, and



View through tunnel shows signal minima at its boundaries. Minima from several views at different angles can be used to bracket tunnel's location.

someone dug and found a cavern. "They are very interested in that," says Lager. "It's open pit mining country, and if one of their big powershovels crashes through one of those . . . ."

Using higher radio frequencies brings better resolution, and one of the future projects, Laine says, is to use 500-megahertz waves to examine caverns in granite or salt domes in which it is proposed to store nuclear wastes. The small cracks and openings through which things could escape might be found that way.

Another specialized use of the technique is to monitor coal fires underground. One of the common schemes for making use of the energy in coal is to burn the coal where it is and tap off the useful gases. Because the electrical conductivity of coal changes significantly from wet to dry to burning to ash, the radio waves can be used to follow the burn. An experiment at Hoe Creek, Wyo., showed that the progress of the fire from the bottom of the cavern to the top and then down again was well recorded. "They thought thermocouples were the way," says Poggio, "but the fire flashed to the top and burned out the thermocouples. They had no record of it on the way back down." Laine says the experiment is being extended in cooperation with the ARCO Corp. With two holes they simply get a picture of the fire's vertical movement. They are now setting up more holes so as to get something of a two-dimensional view.

The mathematical work, which is perhaps the most difficult part, is also continuing. Computation techniques are being developed and extended and computer programs modified. One of the purposes, Laine says, is to make computation possible on the mini and micro computers rather than the big 7600 so that computation can be done in the field. On the smaller computers it will take 15 or 20 minutes instead of the 5 or 6 on the 7600, but that's a small delay in excavation work. Laine foresees a day when a profile will be taken of a caisson, and the engineer will have the picture in 20 minutes. □