Applications and Frustrations in Using Ground Penetrating Radar

Gary R. Olhoeft
Colorado School of Mines

The spectrum of electromagnetic energy used in exploration geophysics extends from the lowest frequency equivalent to the period of magnetic observatory recordings (about 150 years) up through microwaves into gamma rays. The lower frequency portion of this spectrum is shown in Figure 1. At this Ultra Wideband Conference, nearly all of the other presentations would be considered by geophysicists to be very narrow band. Roughly shown in the figure are the various frequency ranges used for the many applications of electromagnetic geophysics. At the low end of the frequency range, the EM transmitters are the natural sources of EM energy such as fluctuations in the Earth's magnetic field, solar wind interactions with the Earth's magnetic field, and thunderstorm lightning. At these very low frequencies, EM exploration geophysics looks down to 400 km deep into the mantle, with decreasing depth of investigation as frequency increases. Depth of investigation is related to the skin depth which is approximately $^1/_2\ \pi$ of a wavelength in the low frequency inductive limit. For general background reading about this range of electromagnetic geophysical exploration, see Nabighian [9]. Somewhere in the tens of kilohertz to few megahertz, depending upon material properties, the physics of low frequency electromagnetic induction (diffusion) slowly transitions to higher frequency wave propagation behavior [1]. When this happens, the depth of investigation becomes determined by the attenuation length, which may be several wavelengths long. Depth of investigation for ground penetrating radar in the 1 to 1,000 MHz range varies from 5,400 m through polar ice in Antarctica to 10's of m in freshwater saturated clean sand to less than 1 m in sea water or montmorillonite clay [11, 14]. For the rest of this paper, I will concentrate just on the narrow portion of the electromagnetic spectrum from a few MHz to a few GHz where geophysicists used ground penetrating radar and overlap with the discussion in the rest of the conference.

Author's Current Address:
Colorado School of Mines, Department of Geophysics, 12500 Illinois Street, Golden, CO 80401-1887, USA.

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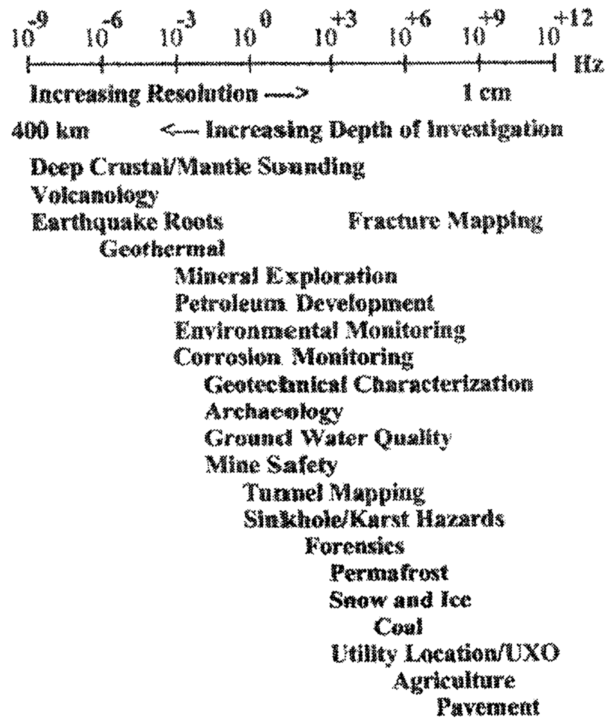
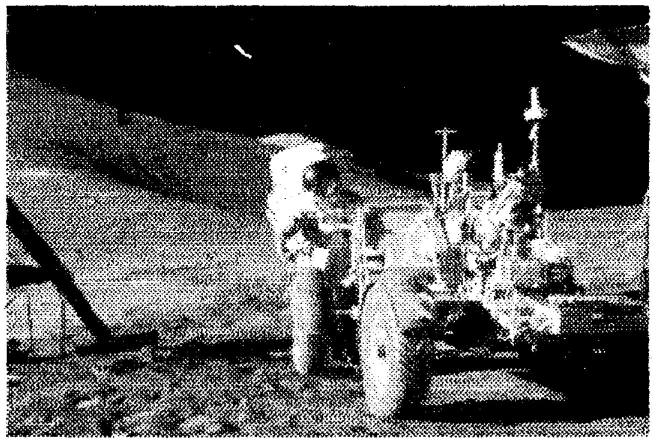
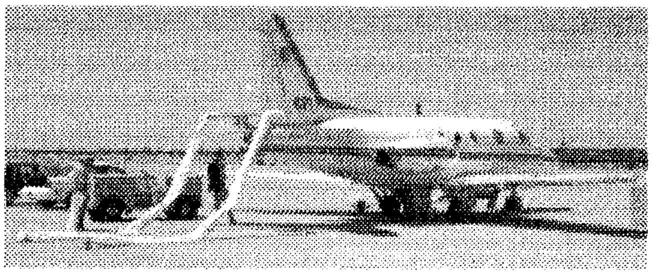
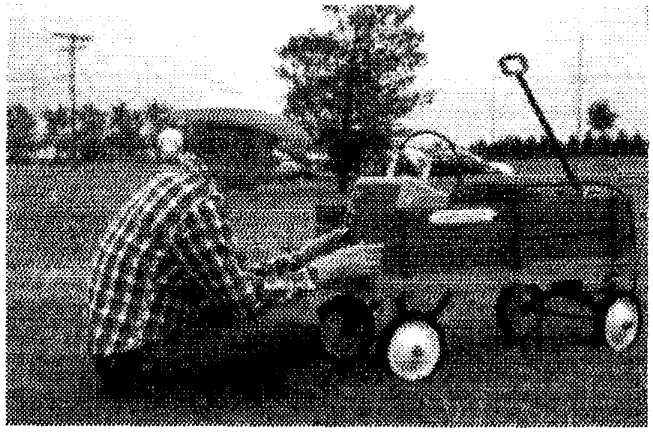


Fig. 1. Geophysics spectrum

RADAR is an acronym coined in 1934 for RAdio Detection And Ranging [3]. The first ground penetrating radar survey was performed in Austria in 1929 to sound the depth of a glacier [28, 29]. The technology was largely forgotten (despite more than 36 patents filed between 1936 and 1971 that might loosely be called subsurface radar) until the late 1950s when US Air Force radars were seeing through ice as planes tried to land in Greenland, but misread the altitude and crashed into the ice. This started investigations into the ability of radar to see into the subsurface not only for ice sounding but also mapping subsoil properties and the water table (see history in [19]). In 1967, a system much like Stern's original glacier sounder was proposed, and eventually built and flown as the Surface Electrical Properties Experiment on Apollo 17 to the moon. (See Figure 2, on next page.) Before the early 1970s, if you wanted to do GPR, you had to build your own; but in 1972, Rex







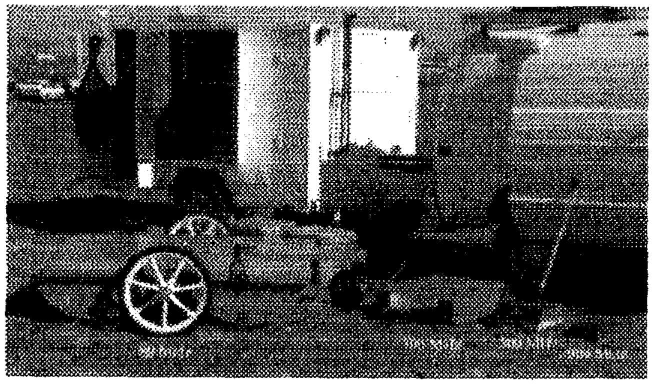


Fig. 3.

Fig. 5.

Morey and Art Drake began Geophysical Survey Systems, Inc. to sell commercial ground penetrating radar systems [7].Thus began an explosion of applications, publications, and research, fostered in part by research contracts from the Geological Survey of Canada, the US Army Cold Regions Research and Engineering Laboratory (CRREL), and others. There are now over 300 patents that might loosely be related to ground penetrating radar around the world, several companies making commercial equipment, many companies offering it as a service, and many institutions performing research. Ground penetrating radar is sometimes called georadar, ground probing radar, or subsurface radar.

Ground penetrating radar is deployed today from the space shuttle [26], aircraft (such as the Swedish CARABAS system shown in Figure 3), on the surface of the ground mud [5], in boreholes [31], and between boreholes ([15, 17]; sometimes from within or between mine shafts). Figure 4 shows a commercially available Geophysical Surveys Systems, Inc.

SIR-2 system being used at Dover Air Force Base in an environmental study using an unconventional but convenient form of transportation. Ground penetrating radar systems come in several types [5]; of which most of the commercially available systems are short-pulse, time domain systems. They operate over a wide range of frequencies because the Earth is a frequency-dependent filter with unpredictable properties, and because the wide variety of applications in problem solving require a wide range in depth of investigation and resolution, which vary with frequency. Figure 5 illustrates a typical set of several pairs of bistatic antennas (separate transmitter and receiver antennas) with center frequencies in air from 80 to 900 MHz. These are GSSI ground loaded antennas whose specified center frequencies in air become lower when coupled to the ground (depending upon the properties of the ground). Antenna size is proportional to wavelength and inversely proportional to frequency.

Because ground penetrating radar systems are used in many applications, the antennas are transported in a variety of ways, from the space shuttle, and aircraft, to people on foot, and a variety of surface vehicles. Figure 6, on next page, shows an application of a GSSI 500 MHz antenna on foot in a wilderness area where wheeled vehicles are banned, Great Sand Dunes National Monument [27]. Studies there were of the internal structure of the dunes as well as of the water table that stabilizes the movement of the dunes. Hand-held deployment may be required by regulatory or logistical constraints, such as access, rugged terrain, or soft soils.

However deployed, one of the largest sources of error in geophysical surveys is knowing the location and orientation of the sensor (in this case, the antennas). This is especially true when floating antennas across water such as shown in Figure 7, on next page. Here, a GSSI 80-MHz monostatic antenna is

Fig. 6.

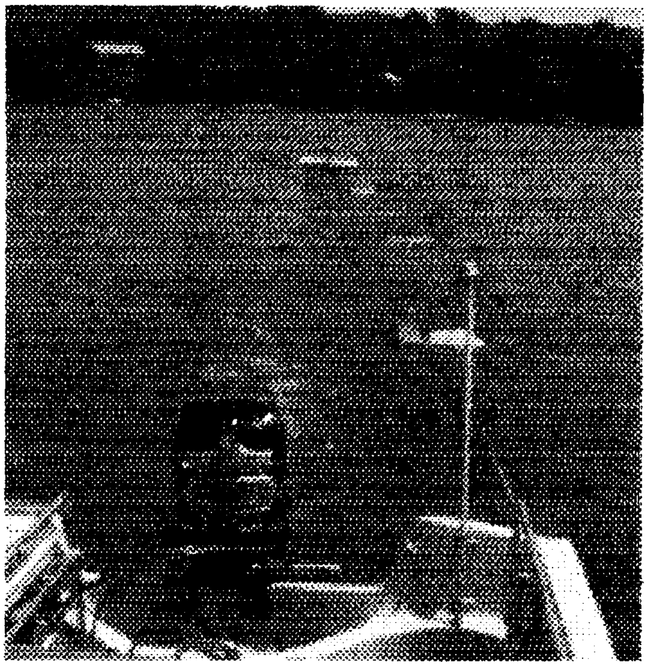


Fig. 7.

being floated across Ashumet Pond to study the impact of a sewage plume on ground water quality [30].

The data from this survey are shown in Figure 8. This is exactly what the operator sees on the boat in real-time, without

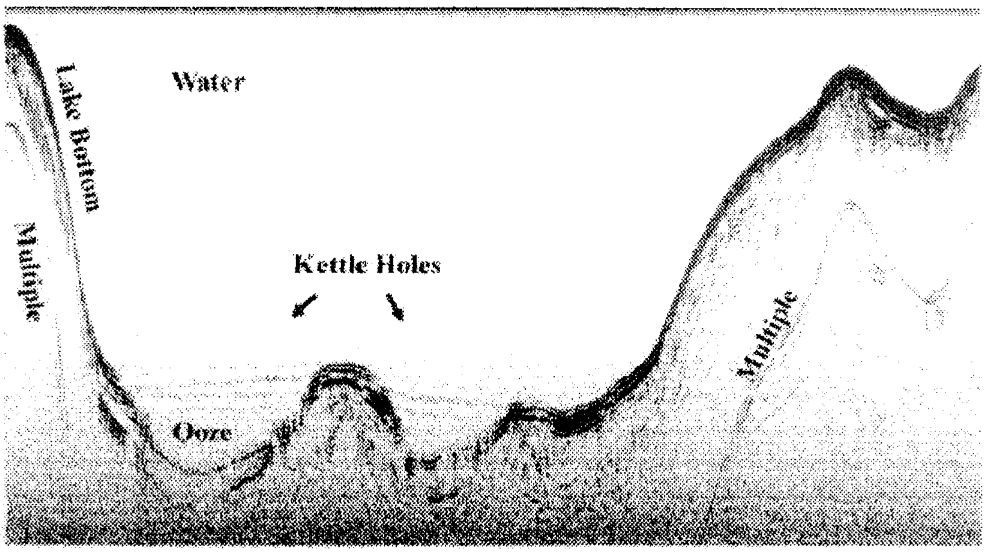


Fig. 8.

any data processing. The vertical scale is two way travel time and the horizontal scale is traverse distance. To scale horizontal distance, the location of the antenna needs to be known. To scale the vertical distance, the velocity of electromagnetic propagation needs to be known. In this case, the lake is about 20 m deep. Note that this is a fresh water lake and radar cannot see through electrically conductive materials like sea water.

Figure 9, on next page, shows the use of a tracking laser total station (on tripod) to measure the location of the mirrors which are mounted on the GSSI 80-MHz antennas. These are about to be towed by the boat in the background down a sand beach and out into Lake Michigan in a coastal erosion investigation. Figure 10, on next page, shows an antenna being towed. The bicycle wheel marks the radar record so the traverse distance is known. Some wheel systems put a mark in the data, and others actually trigger the data acquisition process at fixed distance intervals. This antenna being towed is shielded so it only looks down and can be placed close to the truck. Lower frequency (longer wavelength) antennas can only be shielded with great

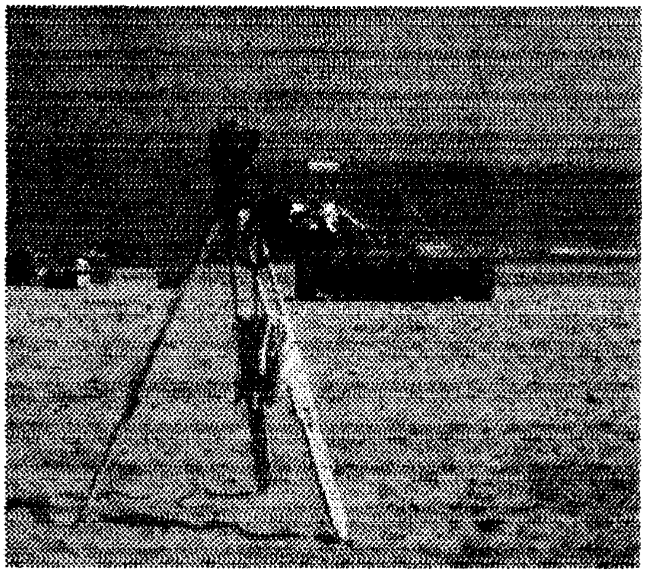


Fig. 9,

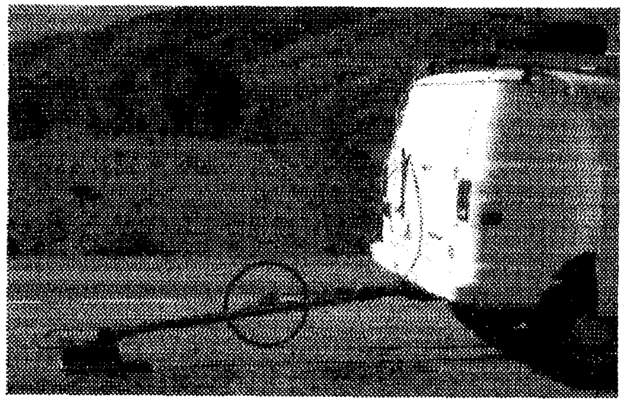


Fig. 10.

difficulty, if at all. In this case, the antenna is towed behind the truck to look at pavement and roadbed problems, especially the compaction of bridge approaches, sub-base voids, and intermittent water springs under roads [8]. GPR is commonly used at airports to determine runway and taxiway integrity, and detect subpavement voids.

In some applications, antenna position is determined by the global positioning system as in Figure 11. In this photo, a Sensors & Software system is being used to study agricultural soil compaction, which has a strong influence on crop yields. The farmer uses a GPS system to keep track of his plowing, seeding, spreading of agricultural chemicals, and harvesting, so it was also used to position the radar system. GPR is also used to study nonpoint source agrochemical pollution [6]. Some differential GPS systems that communicate by radio between a roving station and a fixed base station can interfere with GPR systems, but I have never heard of a GPR system interfering with GPS.

Figure 12 shows a GSSI 80-MHz monostatic antenna mounted on the back of a 4-wheel drive vehicle. This is a logistical compromise as the vehicle is a big metallic object. However, the vehicle is at constant range and may be removed in processing of the data.

The arched object in the background is a lava tube, formed as certain types of lavas flow from erupting volcanos. As the eruption ends, the hot lava runs out of the tube, leave a hollow cave behind that may be up to tens of meters across and kilometers long.

In Hawaii, these lava tubes are the principle drains of the volcano, causing flooding at lower elevations and are a distinct hazard when constructing roads.

Figure 13, on next page, is of a 500 MHz GSSI antenna being used to image an active lava tube from the August 1999 eruption in Hawaii. It is flowing a few feet below the surface, eventually reaching the sea and producing the billowing steam

Fig. 11.

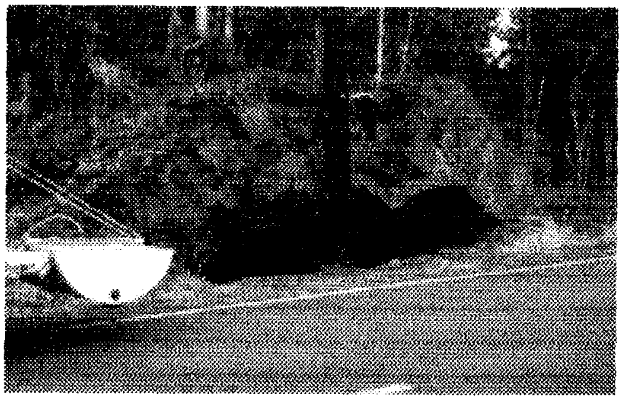


Fig. 12.

plumes in the background. Such studies are of volcanological scientific interest as well as useful in hazard determination and forecasting.

Figure 14, on next page, is a GPR data record taken along Crater Rim Road in Hawaii Volcanos National Park in 1978.

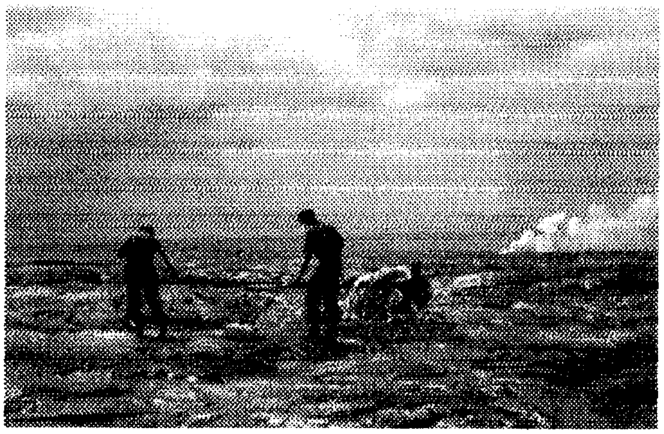


Fig. 13.

These codes are used to predict the behavior of the contaminants as the natural ground water flow system changes or is manipulated during the remediation of the site.

Ground penetrating radar has been applied to problems in many areas, including agriculture, archaeology, land mine and unexploded ordnance detection, environmental site characterization and monitoring, forensics, geological mapping, ground water quality, lunar and planetary exploration, minerals exploration and development, earthquake, landslides, and subsidence hazards assessment, void detection, and pavement evaluation. There are many more applications of ground penetrating radar than can be discussed here (see references in [14, 15], or: http://www.g-p-r.com). These can be found in the *Proceedings* of the many international conferences on ground penetrating radar,

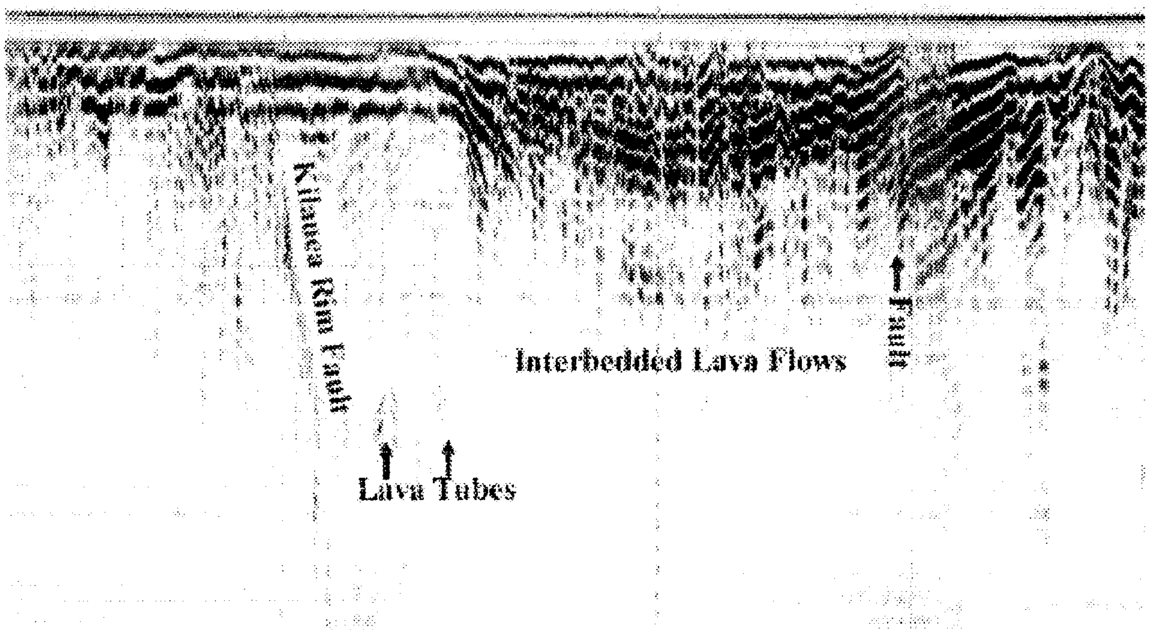


Fig. 14.

Using GSSI 80-MHz radar antennas towed behind a vehicle, the raw radar record (unprocessed) clearly shows the caldera rim fault, interbedded lava flows, and, at depth, two lava tubes as hyperbola shaped features. On the first pass down the road with the radar, the rim fault and the lava tubes did not show up in the radar data. In the second pass (shown) right after a rain, the rim fault and the lava tubes (now filled with water) are clearly visible.

Figure 15 shows surface radar at 200, 300, 500, and 900-MHz, and borehole and hole-to-hole radar tomography being performed at Canadian Forces Base Borden in 1991 to understand the flow of the most common industrial contaminants, Dense NonAqueous Phase Liquids in a natural sand aquifer. The high resolution of the radar images, taken repeatedly in time, allowed the first detailed description of the multiphase DNAPL fluid flow. This data set is a benchmark against which multiphase fluid flow model codes are tested.

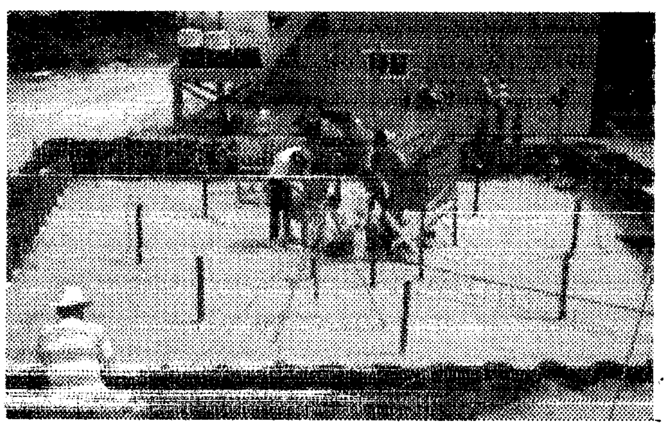


Fig. 15.

Fig. 16.

Fig. 17.

professional society conferences such as the ***Symposium on the Application of Geophysics to Engineering and Environmental Problems*** (SAGEEP) or ***SPIE*** [20], and books [5, 4].

Figure 16 shows a Sensors & Software 900-MHz radar system being used to track a 100-million-year-old dinosaur in 1998. Unlike the normal dinosaur fossil footprints left behind as impressions recorded in sand, at this location the dinosaur walked through soft mud which was then filled in by an advancing sand sheet. This left the footprints as sandstone casts on the underside of a sheet of sandstone. The sandstone was nominally 15 cm thick, doubling to 30 cm at the footprint casts, so they were readily found with 900-MHz ground penetrating radar. This is a protected site with large signs admonishing people that it is illegal to climb on the rocks. Although we had permission to climb in order to do the radar survey as shown, passing motorists would regularly stop and call the sheriff, turning us in. The only problem was their use of 900 MHz analog cell phones interfered with the acquisition of 900 MHz GPR data, requiring us to repeat the data acquisition.

This kind of interface with ground penetrating radar surveys is becoming more commonplace. Figure 17 shows a difficult survey site in Hawaii near a rare world class deposits of xenolith beds and numerous transmission towers. The radar system was positioned, as much as possible, to minimize coupling and interference from the other radio sources, but signal averaging stacking had to be increased, slowing the speed of the radar surveying.

Figure 18, on next page, illustrates the effect of a 900-MHz analog cell phone on a GSSI 500-MHz antenna sitting on a concrete floor in the basement of a building. The horizontal black line across the record near the bottom of the image shows

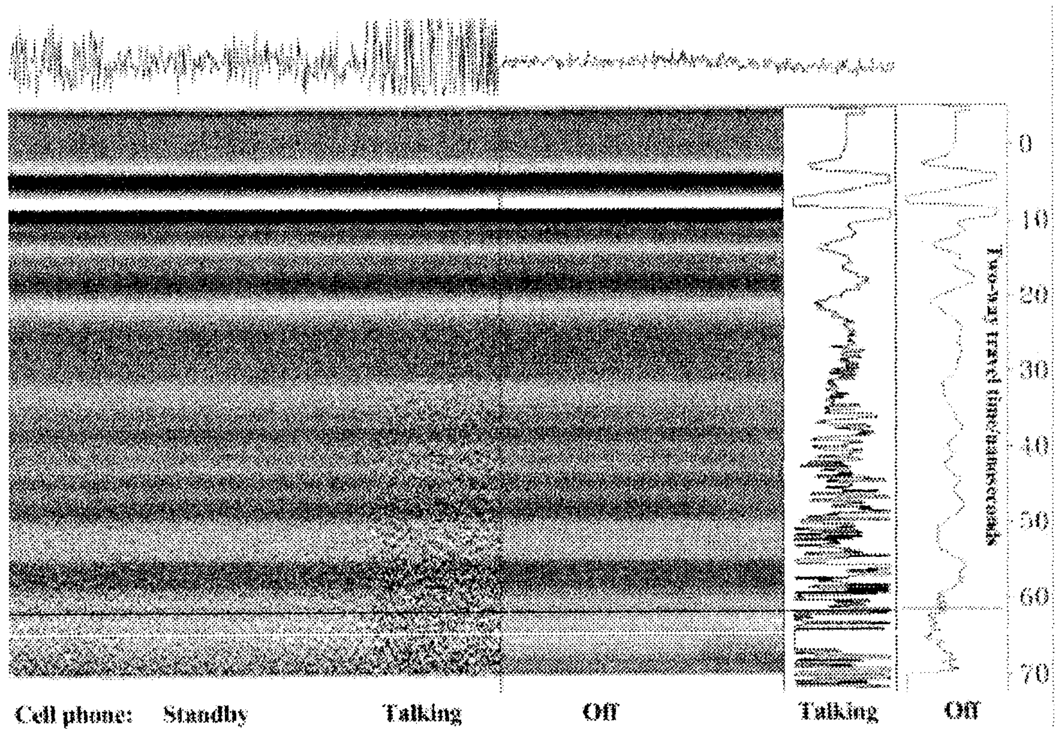


Fig. 18.

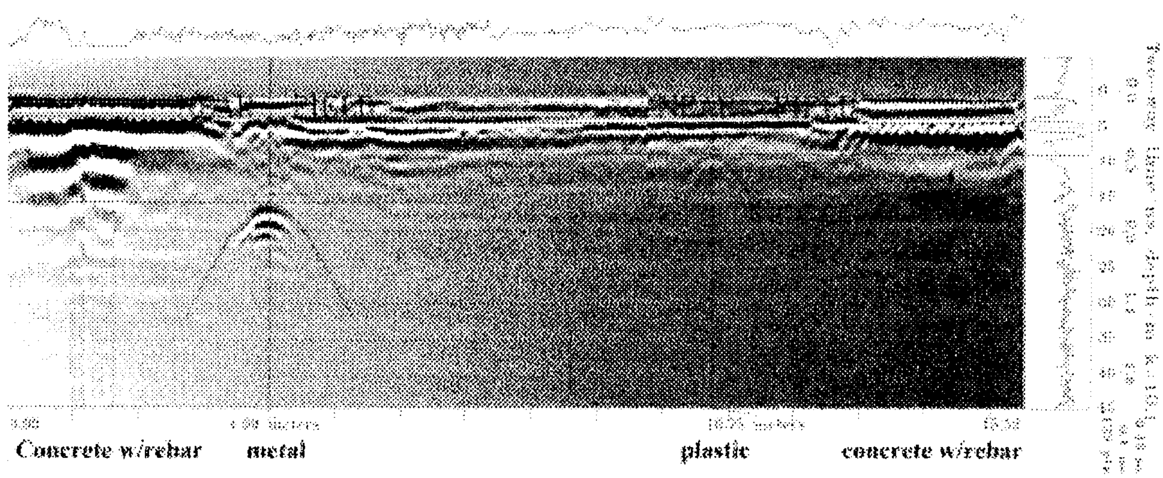


Fig. 19.

the location of the wiggle trace plotted horizontally across the top of the record. The vertical black line shows the location of the two wiggle traces plotted to the right.

The right side of the image and the right vertical wiggle trace are plotted with the cell phone turned off. The left vertical wiggle trace is one scan to the left where the phone is on and being used for talking. The left half of the image shows the phone on but in standby. At no point did the radar system transmission interfere with the operation of the cell phone. However, the radar is a wideband receiver with time varying gain. The gain is increasing with increasing time to compensate for geometric spreading and exponential material losses as the electromagnetic wave propagates out and back. In this location with the antenna sitting on the concrete floor and the cell phone off, the radar system can map the thickness of the concrete, the presence and location of rebar in the concrete, and of a sewer pipe below the concrete floor. With the cell phone in standby, the cell phone interference makes it impossible to see the presence or map the position of the sewer pipe. With the cell phone on and talking, the radar system can still see the rebar presence but can no longer detect and measure the thickness of the concrete. This has impacts on the use of ground penetrating

radar to map pavement problems on interstate highways, where the data becomes unusable near cell phone towers as well as when people in nearby vehicles are talking.

The advent of HDTV broadcasting digital television in the 500-MHz region will have a severe impact on the ability to use ground penetrating radar to map plastic utility pipes, such as gas lines. Excavation breakage of plastic gas lines is recognized as a major hazard by the National Transportation Safety Board [10], 500-MHz GPR is one of the few technologies available to locate them. Figure 19, on previous page, is a traverse across an asphalt city street, starting in a concrete drain pan with rebar on the left and ending in a similar concrete pan on the right using a 450 MHz Sensors & Software Pulse Ekko 1000. The ripple patterns at far left and right are the rebars. Labeled on the left is a buried metal telecom cable and on the right is a buried plastic gas pipe. The hyperbola shapes are fit to calibrate the velocity and turn two-way travel time into depth.

Horizontal position was determined with a wheel that triggered the radar system to take data every 1 cm of traverse. Using a lower frequency antenna (such as 225-MHz) allowed location of water and sewer pipes. Note the higher contrast of the metal good reflector versus the plastic poor reflector. In a higher noise environment, the plastic pipe would not be visible at all, even though it is more shallow.

The bad news is the proliferation of radio transmitters for internet access, HDTV, cell phones, and so forth, by the billions is only going to make worse the problems of using ground penetrating radar near people and their gadgets. The good news is eventually all the radio noise will be a source to be used, like geophysicists currently use lower frequency natural sources such as lightning in magnetotellurics. Thus, eventually noise radars will be possible, requiring no transmitter, but only two or more receivers. In the interim, things will be difficult. Unfortunately, the allocation of frequencies just for ground penetrating radar is not an effective solution as the frequency dependent filtering properties of the Earth are variable with location and with time (such as *wet season vs. dry season* or *winter frozen vs. summer thaw*).

REFERENCES

[1] Balanis, C.A., 1989,
Advanced engineering electromagnetics:
Wiley, NY, p. 981.

[2] Brewster, M.L., Annan, A.P., Greenhouse, J.P., Kueper, B.H., Olhoeft, G.R., Redman, J.D. and Sander, K.A., 1995,
Observed migration of a controlled DNAPL release by geophysical methods: Ground Water,
Vol. 33, pp. 977-987.

[3] Buderi, R., 1996,
The Invention That Changed the World:
Simon & Schuster, p. 544.

[4] Conyers, L.B. and Goodman, D., 1997,
Ground-penetrating radar: an introduction for archaeologists:
Altimira, p. 232.

[5] Daniels, D., 1996,
Surface penetrating radar:
IEE, London, p. 320.

[6] Lucius, J.E., and Olhoeft, G.R., 1993,
Statistical analysis of field-scale subsurface heterogeneity at the Princeton, Minn., Management Systems Evaluation Area using ground penetrating radar,
in Agricultural research to protect water quality conference proceedings,
Feb. 21-24, 1993, Minneapolis, MN: Soil and Water Conservation Society, Ankeny, IA, pp. 355-358.

[7] Morey, R.M., 1974,
Geophysical surveying system employing electromagnetic impulses:
US Patent # 3,806,795, p. 11.

[8] Morey, R.M., Armaghnai, J.M., Bernstein, R., Bertrand, C., Clemena, G.G., Jayaprakash, G.P., Kopac, P.A., Olhoeft, G.R., Rix, G.J., Robson, G., and Springer, J., 1998,
Ground Penetrating Radar for Evaluating Subsurface Conditions for Transportation Facilities:
National Cooperative Highway Research Program Synthesis of Highway Practice 255, NRC Transportation Research Board, Washington, DC.

[9] Nabighian, M.N., 1988/1991,
Electromagnetic methods in applied geophysics, 2 vols.,
Tulsa, OK, Soc. Explor. Geophys.,
p. 1520.

[10] NTSB (National Transportation Safety Board), 1997,
Protecting public safety through excavation damage prevention:
Safety Study NTSB/SS-97/01, Washington DC,
p. 106.

[11] Olhoeft, G.R., 1984,
Applications and limitations of ground penetrating radar:
Society of Exploration Geophysicists, 54th Annual International Meeting and Exposition, Atlanta, GA,
pp. 147-148.

[12] Olhoeft, G.R., 1986,
Direct detection of hydrocarbon and organic chemicals with ground penetrating radar and complex resistivity,
in Proc. of the NWWA/API Conference on Petroleum Hydrocarbons and organic chemicals in ground water — prevention, detection and restoration, Nov., 12-14, 1986, Houston: Dublin, OH, NWWA,
pp. 284-305.

[13] Olhoeft, G.R., 1987,
Electrical properties from 10^{-3} to 10^{+9} Hz — physics and chemistry,
in Physics and Chemistry of Porous Media II, American Institute of Physics Conf. Proc. 154, Ridgefield, CT, 1986, J.R. Banavar, J. Koplik, and K.W. Winkler, eds., NY, AIP,
pp. 281-298.

[14] Olhoeft, G.R., 1988a,
Selected bibliography on ground penetrating radar,
in Proceedings of the Symposium on the Applications of Geophysics to Engineering and Environmental Problems, March 28-31, 1988, Golden, CO,
pp. 462-520.

[15] Olhoeft, G.R., 1988b,
Interpretation of hole-to-hole radar measurements,
in Proceedings of the Third Technical Symposium on Tunnel Detection, January 12-15, 1988, Golden, CO,
pp. 616-629.

[16] Olhoeft, G.R., 1991,
Quantitative statistical description of subsurface heterogeneities with ground penetrating radar at Bemidji, Minnesota:
in U.S. Geological Survey Toxic Substance Hydrology Program, Proceedings of the technical meeting, Monterey, California, March 11-15, 1991,
USGS WRI 91-4034, pp. 650-653.

[17] Olhoeft, G.R., 1993,
Velocity, attenuation, dispersion and diffraction hole-to-hole radar processing,
in Proceedings of the Fourth Tunnel Detection Symposium on Subsurface Exploration Technology, Colorado School of Mines, Golden, CO, 2629 April 1993, Miller, R., ed.:
US Army Belvoir Research, Development and Engineering Center, pp. 309-322.

[18] Olhoeft, G.R., 1994,
Modeling out-of-plane scattering effects:
in Proc. of the Fifth Int'l. Con£ on Ground Penetrating Radar, Kitchener, Ontario, 12-16 June 1994,
pp. 133-144.

[19] Olhoeft, G.R., 1996,
Application of Ground Penetrating Radar:
in Proceedings of the 6th Int'l. Conf. on Ground Penetrating Radar, GPR'96, Sept 30- Oct 3, 1996, Sendai, Japan, p. 1-4. (invited keynote).

[20] Olhoeft, G.R., 1999,
Ground penetrating radar: use and misuse:
SPIE Subsurface Sensors and Applications Conference 3752 Proceedings, C. Nguyen, ed., 19-21 July 1999, Denver, CO,
pp. 166-173.

[21] Olhoeft, G.R., Lucius, J.E. and Phillips, S.J., 1994,
Geophysical tracking of the injection of trench stabilization material at US DoE Hanford Site, Richland, Washington:
USGS Open File Report 94-146,
p. 77.

[22] Olhoeft, G.R., Powers, M.H. and Capron, D.E., 1994,
Buried object detection with ground penetrating radar:
in Proc. of Unexploded Ordnance (UXO) detection and range remediation conference, Golden, CO, May 17-19, 1994,
pp. 207-233.

[23] Powers, M.H. and Olhoeft, G.R., 1996,
Computer Modeling to Transfer GPR UXO Detectability Knowledge Between Sites:
in Proc. UXO Forum 1996 Conference Proceedings, Williamsburg, VA, March 26-29, 1996, Dept of Defense Explosives Safety Board, Alexandria, VA,
pp. 347-356.

[24] Powers, M.H. and Olhoeft, G.R., 1996,
Modeling the GPR response of leaking, buried pipes:
in Proc. of SAGEEP'96, R.S. Bell and M.H. Cramer, eds., Keystone, Colorado, EEGS, Wheat Ridge, CO, pp. 525-534.

[25] Sander, K.A. and Olhoeft, G.R., 1994,
500-MHz ground penetrating radar data collected during an intentional spill of tetrachloroethylene at Canadian Forces Base Borden in 1991:
US Geological Survey Digital Data Series DDS-25, CD-ROM.

[26] Schaber, G.G., McCauley, J.F., Breed, C.S. and Olhoeft, G.R., 1986,
Shuttle imaging radar: physical controls on signal penetration and subsurface scattering in the eastern Sahara:
Institute of Electrical and Electronic Engineers Trans. Geoscience and Remote Sensing, v. GE-24,
pp. 603-623.

[27] Schenk, C.J., Gautier, D.L., Olhoeft, G.R. and Lucius, J.E., 1993,
Internal structure of an eolian dune using ground penetrating radar, Lancaster, N., and Rye, K., eds.,
Ancient and Modern Eolian Sediments: Spec. Publ. Int. Assoc. Sediment, Vol. 16,
pp. 61-69.

[28] Stern, W., 1929,
Versuch einer elektrodynamischen Dickemnessung von Gletschereis:
Ger. Beitr. zur Geophysik, Vol.23,
pp. 292-333.

[29] Stern, W., 1930,
Uber Grundlagen,Methodik and bisherige Ergebnisse elektrodynamischer Dickenmessung von Gletschereis:
Z. Gletscherkunde, Vol.15,
pp. 24-42.

[30] Wright, D.L., Olhoeft, G.R. and Watts, R.D., 1984,
Ground-penetrating radar studies on Cape Cod,
in Conference on Surface and Borehole Geophysical Methods in Ground Water Investigations, Proceedings:
U.S. Environmental Protection Agency and National Water Well Association, San Antonio, TX, Feb. 7-9,
pp. 666-680.

[31] Wright, D.L., Olhoeft, G.R., Hsieh, P.A., Majer, E.L., Paillet, F.L. and Lane, J.W. Jr., 1996,
Electromagnetic and seismic tomography compared to borehole acoustic televiewer and flowmeter logs for subsurface fracture in mapping at the Mirror Lake Site, New Hampshire:
US Geological Survey Toxic Substances Hydrology Program Review, Proc. of the technical meeting, Colorado Springs, CO, September 20-23, 1993,
D.W. Morganwalp and D.A. Aronson, eds.,
USGS WRI Report 944015,
pp. 119-126. ■