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GPR – TRENDS, HISTORY, AND FUTURE DEVELOPMENTS

A. P. Annan

Sensors & Software Inc., 1040 Stacey Court, Mississauga, ON L4W 2X8, Canada
apa@sensoft.ca

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A. P. Annan
Sensors & Software Inc.
apa@sensoft.ca

Introduction

Ground penetrating radar (GPR) is a relatively new geophysical technique. The last decade has seen major advances and there is an overall sense of the technology reaching a level of maturity.

The history of GPR is intertwined with the diverse applications of the technique. GPR has the most extensive set of applications of any geophysical technique. As a result, the spatial scales of applications and the diversity of instrument configurations are extensive.

Both the value and the limitations of the method are better understood in the global user community. The goal of this paper is to provide a brief history of the method, a discussion of current trends and give a sense of future developments.

What is GPR?

Before delving into the history, GPR needs definition. GPR uses electromagnetic fields to probe lossy dielectric materials to detect structures and changes in material properties within the materials. Reflection and transmission measurements, as depicted in Figure 1, are employed. Most applications to date have been in natural geologic materials, but widespread use in man-made composites such as concrete, asphalt and other construction materials also occurs. In such lossy dielectric materials, electromagnetic fields will penetrate to some depth before being absorbed.

With GPR, the electromagnetic fields propagate as essentially non-dispersive waves. The signal emitted travels through the material, is scattered and/or reflected by changes in impedance giving rise to events similar to the emitted signal. In other words, signal recognition is simple because the return signal looks like the emitted signal. Figure 2 depicts the general character of EM field phase velocity and attenuation in a lossy dielectric material versus frequency illustrating the "GPR plateau".

One has to contrast GPR measurements with electromagnetic induction sounding methods where the fields are diffusive and dispersive in character (Annan (1996)). GPR field behavior occurs over a finite frequency range generally referred to as the GPR plateau where velocity and attenuation are frequency independent. The GPR plateau usually occurs in the 1 MHz to 1000 MHz frequency range. At lower frequencies the fields become diffusive in character and pulses are dispersed. At higher frequencies several factors increase signal absorption such that penetration is extremely limited.

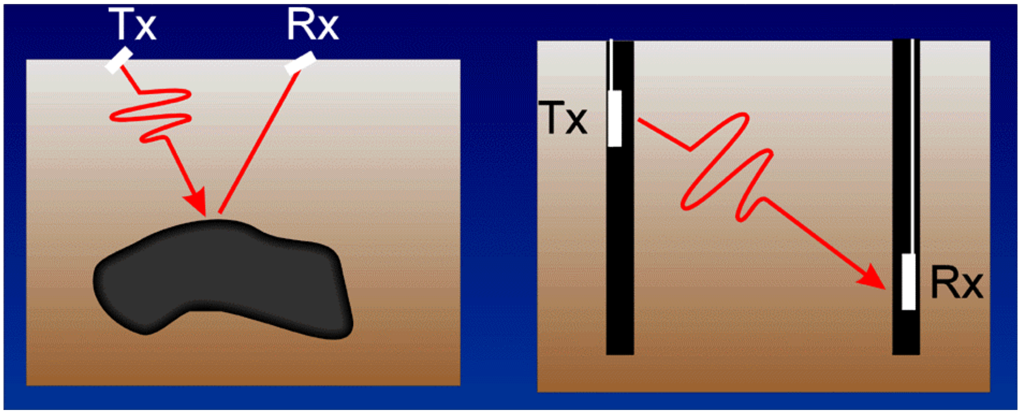
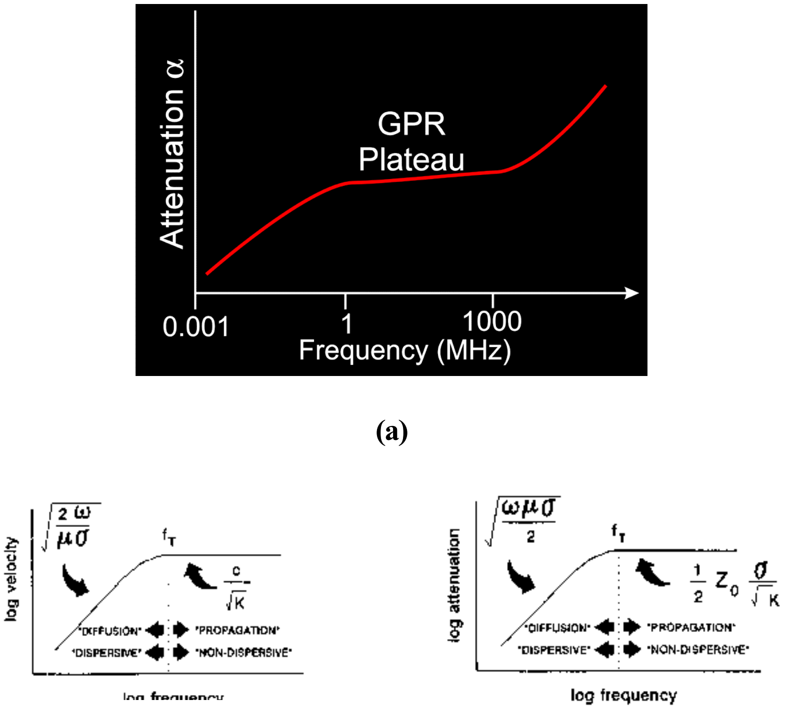


Figure 1: *Ground penetrating radar uses radio waves to probe the subsurface of lossy dielectric materials. Two modes of measurement are common. In the first, detection of reflected or scattered energy is used. In the second, variation after transmission through the material is used to probe a structure.*



(a)

(b) **(c)**

Figure 2: *General character of an EM field phase velocity and attenuation with frequency illustrating the "GPR plateau". (a) Shows the ground character whereas (b) and (c) show the detailed behavior for a simple material and the relationship to relative permittivity* K *and electrical conductivity* s.

History

The following is necessarily brief and intended to give high lights. References lead to other perspectives for those interested in a more extensive understanding of GPR. It is interesting to note that accounts of some activities are published many years later and sometimes not all.

1900 – 1950

During this time a great deal of research on radio wave propagation above and along the surface of the earth occurred. Although several hints at the possibility of using radio waves to probe the subsurface are mentioned, there are no reports of successfully making this type of measurement. Vast number of papers appeared on the subject of communications, direction finding and radar.

1950 – 1955

In this time frame, the first reported attempt at measuring subsurface features with radio wave signals was reported. El Said (1956) attempted to use the interference between direct air transmitted signals and signals reflected from the water table to image the water table depth.

1955 – 1960

The next reported observation of radio frequency sounding of geological materials came about when the USAF reported altimeter errors when attempting to land aircraft on the Greenland ice sheet (Waite and Schmidt (1961)). This was the first time that repeatable indications of penetration into the subsurface through a naturally occurring material were reported. This spawned the era of researchers focused on developing radio echo sounding in ice.

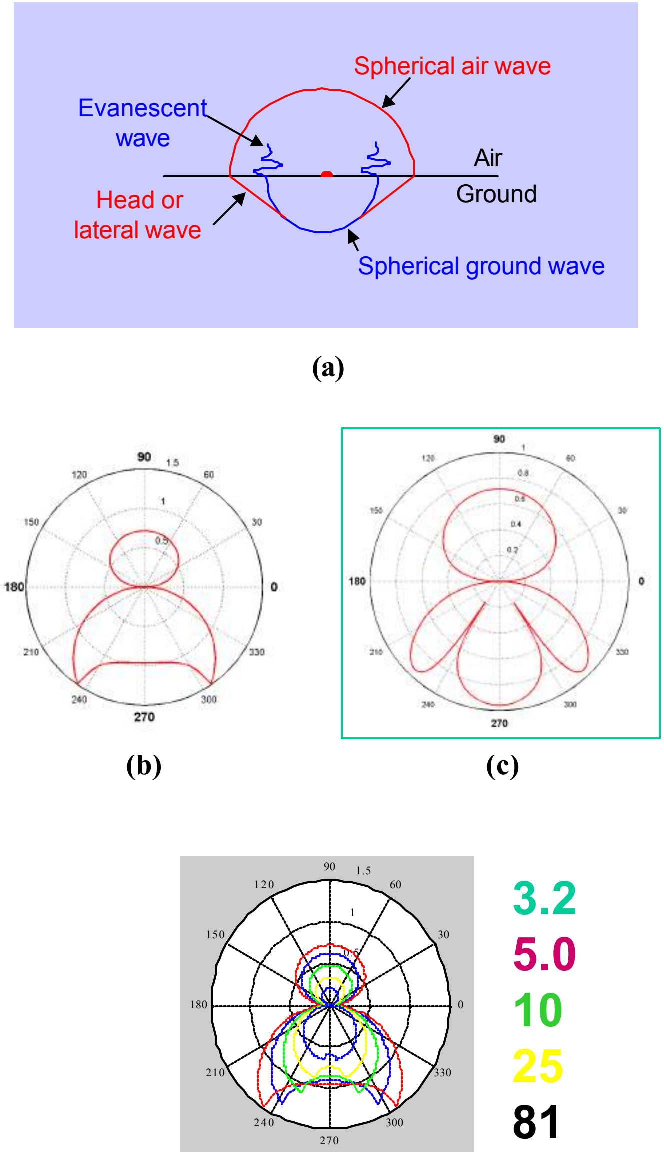
1960 – 1965

The majority of activity during this interval involved the radio echo sounding in ice. Groups, such as the Scott Polar Research Institute at Cambridge, Bailey et al (1964) and the Geophysical and Polar Research Center at the University of Wisconsin, Bentley (1964), Walford (1964) were active in polar regions and also on glaciers.

1965 – 1970

During this time the ice radio echo sounding activity continued. In addition, applications in other favorable geologic materials started to be explored. Cook (1973) explored the use in coal mines since coal can be a low loss dielectric material in some instances. Similarly, Holser et al (1972), Unterberger (1978) and Thierbach (1973) initiated evaluations in underground salt deposits for similar reasons.

This period was the start of lunar science mission planning for the Apollo program. Several experiments were devised to examine the lunar subsurface which was believed to have electrical character similar to that of ice. The work of Annan (1973) reports on some of these developments. Key discoveries were the understanding of wave fields about antennas on the ground surface and modified antenna directivity as indicated in Figure 3.



(a)

(b) (c)

(d)

***Figure 3**:* *(a) Wave fronts and antenna directivity for a small electric dipole on the surface of a dielectric. (b) & (c) Show the TE and TM antenna directivity when the source is placed on the surface of a dielectric. (d) Shows the variation of the TE pattern as relative permittivity is changed.*

1970 – 1975

This period saw numerous advances. The Apollo 17 lunar exploration program involved the surface electrical properties experiment (Figure 4) which used interferometry concepts similar to the work carried out by El Said (1956) while the work lunar orbitor carried a pulsed radar sounder similar to the ice sounders which made measurements from orbit over the lunar surface (Simmons et al (1973) and Ward et al (1973)).

***Figure 4**: The surface electrical properties experiment carried out on Apollo 17 used a 3 component vector receiver mounted on the lunar rover and a dual axis multi-frequency dipolar antenna laid out on the surface to sound the subsurface.*

During the same period Morey and others formed Geophysical Survey Systems Inc. which has been manufacturing and selling ground penetrating radar since that time (Morey (1974)).

In addition a better understanding of electrical properties of geologic materials at radio frequencies started to become available. Work such as that by Olhoeft (1975) led to a much better understanding of the electrical character of natural occurring geological materials and the relationship between electrical conductivity and dielectric polarization of these materials.

1975 – 1980

During this period, applications started to grow because of the availability of technology and a better understanding of geology. The Geological Survey of Canada explored a number of applications, the primary one being a better understanding of permafrost terrain in the Canadian Arctic. A GPR system in operation is shown in Figure 5. Proposals for pipelines out of the Arctic to carry oil and gas to southern markets drove a great deal of interest in engineering in frozen soil and environments. GPR was a tool which offered great promise and some of the initial results are reported by Annan and Davis (1976).

During this period the effect of scattering on radio echo sounding in temperate glaciers became better understood. The impact of scattering and the need for lower frequency radars was reported by Watts and England (1976).

Experiments with GPR were reported by the Stanford Research Institute where measurements were made by Dolphin et al (1978) for archeological applications.

Other work carried out in this period which paralleled the Geological Survey of Canada permafrost efforts was lead by Olhoeft at the United States Geological Survey who worked on the Alaska pipeline routes.

Figure 5: *GPR system being used to survey potential pipeline routes in the Canadian Arctic (1975).*

Extensive work was carried out in potash mines in western Canada. This led to a whole series of ever improving GPR measurements and work in this geological setting by the Geological Survey of Canada. These results were reported by Annan et al (1988). Further coal mine developments were reported by Coon et al (1981).

In addition, the potential for use of borehole radar to investigate rock quality in potential hard rock nuclear waste disposal sites became a topic of interest. The Geological Survey of Canada and Atomic Energy of Canada supported this work (Davis and Annan (1986)).

Commercial units were used for most of this work and the number of activities spawned commercial interest. Geophysical Survey Systems Inc. remained the dominant supplier at this time but Ensco/Xadar was spawned in an attempt to create an alternate commercial product.

One of the major issues that was noted by the Geological Survey of Canada work was the great difficulty in using existing equipment in remote areas. Equipment was heavy, bulky and consumed too much power. In addition there was a need to get data into a digital form to exploit the digital seismic processing advances which were rapidly evolving in the petroleum seismic field at the time.

1980 – 1985

During this period, interest in GPR waned to a degree. The initial optimism for the technology gave way to the reality that many environments weren't favorable for GPR. There was considerable confusion over whether failures were equipment related or due to natural material responses. In addition, very little money for technology development was available.

During this time OYO Corporation of Japan developed a radar product called "Georadar" spawned by association with Xadar developments. This instrument met some initial commercial success in Europe.

A-Cubed Inc. was formed in 1981 and started development of ground penetrating radars. The low frequency digital GPR developments were reported by Davis et al (1985). This technology development led to the pulseEKKO series of GPR's.

The nuclear waste disposal problem was continually studied and a number of countries funded the Swedish Geological Survey in the development of borehole radar. This work is reported by Olsson et al (1987).

Other applications for GPR such as road investigations and utility mapping met with mixed success. In general, the technology was quite new and not optimized for these applications. Work by Ulriksen (1982) provided a good foundation for some of these applications.

Many non-commercial developments occurred with prototypes that embodied the ideas for portability, digital recording and the use of fiber optics cables.

Other little reported work was conducted by Southwest Research and the U.S. Army on borehole GPR to detect tunneling in sensitive military areas (Owen (1981)).

1985 – 1990

GPR finally started to come into its own during this period. The strengths and weaknesses were becoming better understood and real problems in the near surface created a demand for high resolution mapping. The U.S. Environmental Protection Agency instituted many initiatives to investigate and clean up contaminated land (Benson et al (1984)). GPR was a natural tool to address high-resolution subsurface mapping and as a result a strong commercial driver started to appear.

In addition, many of the previous applications were continually explored and movement to lower frequency GPR's with full digital recording appeared in commercial products. Other applications such as soil classification for agricultural needs appeared (Doolittle & Asmussen (1992)). Adaption of one dimensional seismic modelling occurred in this period (Annan & Chua (1992)).

In 1988, Sensors & Software Inc. was spawned from A-Cubed Inc and commenced commercialization of the pulseEKKO technology.

1990-1995

The real explosion in the advancement of GPR occurred during this period. Many groups worldwide became interested in the technology.

On the commercial side, Geophysical Survey Systems Inc. exhibited strong commercial success and was bought by OYO Corporation. During this period, Mala Geosciences was spawned from the Swedish Geological Survey roots. ERA in the UK also became more active using its research into unexploded ordinance and landmine detection to create commercial products. Sensors & Software Inc. grew rapidly broadening its pulseEKKO product line.

On the research side, much attention started to be paid by both the geophysical and electrical engineering community. Developments such as multi-fold data acquisition (Fisher et al (1992)), digital data processing (Maijala (1992), Gerlitz et al (1993)), and 2D numerical simulation (Zeng et al (1995), Cai and McMechan (1995)) occurred. Advances in applications in archeology (Goodman (1994)), environmental (Brewster and Annan (1994)), geological stratigraphy using radar facies (Jol (1996)) and many other areas expanded. Environmental borehole GPR development was reported by Redman et al (1996).

Ground penetrating radar user meetings became more formalized and were held every 2 years at various locations around the world. This meeting provided a forum for the leading players in this field to meet, present results and discuss problems. These meetings led to series of proceeding publications which are listed as references. These proceedings provide a great deal of information for new users to the GPR field.

1995 – 2000

In this period, the evolution of the computers drove all of GPR advances. Numerical modelling of full 3D problems became possible albeit still with large computers (Holliger & Bergmann (2000), Lampe & Holliger (2000)). The ability to manage the large volumes of information in digital form and manipulate them quickly became routine. As a result, acquisition of data on grids to make maps and grids and 3D visualization became practical (Grasmueck (1996), Annan et al (1997)). The commercial market and demand resulted in a variety of different and simpler systems such as the Noggin from Sensors & Software Inc. (Figure 6).

***Figure 6**: Sensors & Software Inc.'s Noggin Smart Cart.*

Strong research groups appeared at a number of universities. ETH led by Alan Green, the University of Texas at Dallas led by George McMechan and the group at TU-Delft led by Jakob Fokema are some examples of groups pushing development of expertise and advancement of GPR frontiers.

The fundamental vector nature of GPR started to become critical. Understanding this full vector nature of the fields became of more interest (Roberts and Daniels (1996)). In addition, there was much more pressure on acquiring accurate positioning of information than historically needed because the need to do data manipulation requires very accurately controlled positioning information (Greaves et al (1996)).

Current Activities & Future Developments

GPR is now on very solid footing. Research groups with good understanding of the basic physics are developing modelling tools and analysis capabilities. More work is still required on measurement of electrical properties of materials. Electrical properties of mixtures are understood in general but the complexities and interactions in specific instances are still subjects for research.

Digital processing power now exceeds our current capability to make use of it. As a result, development of software and processing algorithms to exploit the computer power available will cause an ever more rapid advance in the manipulation of data to address application needs.

Instrumentation is now stable and reliable. In the early days of GPR, instrumentation was always of marginal capability because of the extremely critical demands placed on the instruments. Designing ultra wideband antennas and electronics to work in close proximity to a variable lossy dielectric media is not a trivial engineering exercise and only now are products becoming stable, reliable and reproducible.

Even now, the amplitude of GPR data is not well controlled. As instruments evolve and designs get better, the amplitude information of the data is becoming more reliable. Historically, the travel time was the most useful part of the GPR record. Relative amplitudes were good indicators but absolute amplitude information was unattainable.

As GPR becomes more sophisticated and stable, reliable quantitative amplitude information will spawn another generation of data analysis and interpretation tools based on inversion to image material properties. Already inversion in various forms to extract electrical properties is being attempted with success at the research level (van der Kruk (2001)).

A major trend already visible is the extraction of "user" information. In the early days of GPR, just acquiring the GPR cross section image in some form was the end goal of GPR measurement. With full digital data and analysis capability, display information in many forms is mundane and extraction of specific user information much more critical.

Much of the GPR practitioner community is still locked into looking at GPR cross sections as the fundamental piece of information. Some applications no longer look at GPR sections but treat them as a given and only display derived data. This is a sign of increasing maturity and eventually one will seldom see raw GPR sections used for presentation or interpretation. More and more derived products of various attributes (reflectivity impedance) and quantitative numbers (depth, target size, etc.) will be extracted which are specific to a particular application.

A good example is the SnowScan snow thickness application (see Figure 7). In the initial measurement process, the data were displayed as radar sections. Within months the application had auto picking and tracking capability which displayed a snow depth profile and could output the information as a single depth number versus position using GPS (global positioning system) location. In its current embodiment the system no longer needs to display radar data (or any data for that matter) but logs snow thickness along with the GPS coordinates. These data are transformed into a map (see Figure 8) without anyone ever looking at the raw GPR cross section.

Figure 7: *Photos of a compact, lightweight SnowScan GPR designed specifically to measure snow depth and combine with GPS positioning.*

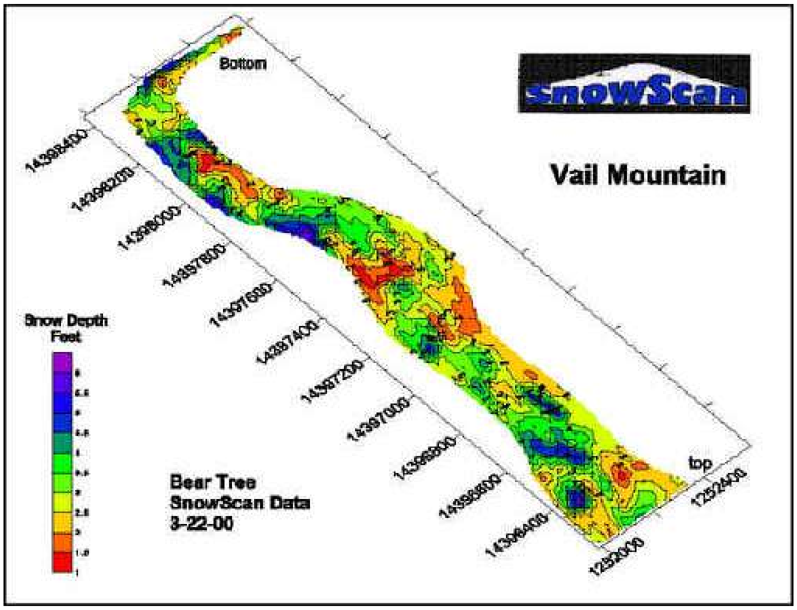


Figure 8: *Example of a snow depth map created using a SnowScan GPR system.*

A similar transition is occurring with concrete inspection as demonstrated by the Sensors & Software Inc.'s Conquest (see Figure 9). Users measure data following a prescribed menu to image an area. The data are immediately turned into depth slice maps on site in minutes as shown in

Figure 10. In this system the vector nature of the measurement is critical. Imaging makes use of vector information to generate pseudoscalar maps.

Figure 9: *Photo of Conquest GPR system designed specifically for imaging concrete. Data are acquired on a predefined survey grid.*

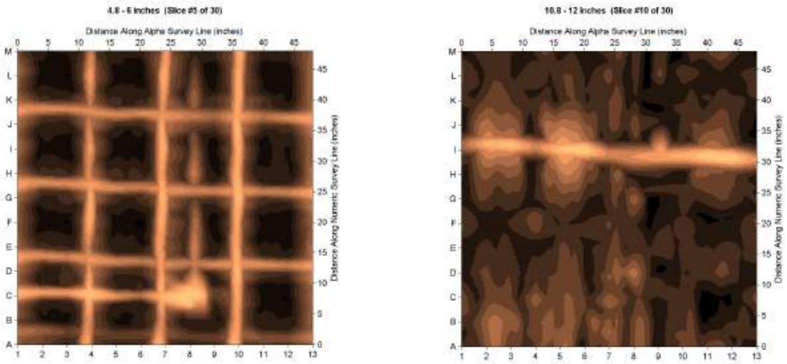


Figure 10: *Example of depth slice output of a Conquest system showing rebar and an electrical conduit. Conquest generates depth slice maps of a concrete structure enabling the location of embedded objects such as rebar, post tension cables and utility conduits. The slices show two depth images from the same location. The left sees a rebar grid and an electrical conduit meeting at a junction box. The right shows another conduit at a greater depth.*

These two examples indicate the way GPR technology will evolve in the next few years.

Summary

The future of GPR is bright. The opportunities are still vast and new developments will occur at an every increasing pace. Major points to note at present are as follows.

1. GPR is becoming a mature method.
2. Instrumentation is attaining a high level of quality and dependability.
3. Data processing and advanced presentation of imaging information is easy and is advancing daily.
4. Instrumentation focused on specific applications and user needs are starting to appear and will be the way of the future.

If the next ten years brings as many changes as the last ten years, we will see very wide spread use of GPR.

References

Alumbaugh, D.L. and Newman, G.A., 1994, **Fast Frequency-Domain Electromagnetic Modeling of a 3-D Earth Using Finite Differences**: Extended Abstracts from the Society of Exploration Geophysicists 1994 Annual Meeting, Los Angeles, California, pp. 369-373.

Annan, A. P. and Davis, J.L., 1976, **Impulse Radar Soundings in Permafrost**: Radio Science, Vol. 11, pp. 383-394.

Annan, A. P. and Chua, L.T., 1992, **Ground Penetrating Radar Performance Predictions**: The Geological Survey of Canada, Paper 90-4, pp. 5-13.

Annan, A. P. and Davis, J.L., 1978, **Methodology for Radar Transillumination Experiments**: Report of Activities, Geological Survey of Canada, Paper, 78-1B, pp. 107-110.

Annan, A. P., Davis, J.L., and Gendzwill, D., 1988, **Radar Sounding in Potash Mines: Saskatchewan, Canada.** Geophysics, Vol. 53, pp. 1556-1564.

Annan, A. P., 1993, **Practical Processing of GPR Data**: Proceedings of the Second Government Workshop on Ground Penetrating Radar, October, 1993, Columbus, Ohio.

Annan, A. P., Davis, J.L. and Johnston, G. B., 1997, **Maximizing 3D GPR Image Resolution: A Simple Approach:** Proceedings of the High Resolution Geophysics Workshop, University of Arizona, Tucson, AZ, January 6-9, 1997.

Annan, A. P., 1973. **Radio Interferometry Depth Sounding: Part I - Theoretical Discussion**: Geophysics, vol. 38, p. 557-580.

Annan, A. P., 1996, **Transmission Dispersion and GPR**, JEG, v.0, no. 2, January 1996, pp. 125-136.

Bailey, J.T., Evans, S., and Robin, G. de Q., 1964, **Radio echo sounding of polar ice sheets**, Nature, Vol. 204, No. 4957, pp. 420-421.

Benson, R.C., Glaccum, R.A. and Noel, M.R., 1984. **Geophysical Techniques for Sensing Buried Wastes and Waste Migration**. US EPA Contract No. 68-03-3053. Environmental Monitoring Systems Laboratory. Office of R&D. US EPA, Las Vegas, Nevada 89114. 236p.

Bentley, C.R., 1964, **The structure of Antarctica and its ice cover**, Research in Geophysics, Vol. 2: Solid Earth and Interface Phenomena, Cambridge Mass., Technology Press of Massachusetts Institute of Technology, pp. 335-389.

Brewster, M.L. and Annan, A.P., 1994: **Ground-penetrating radar monitoring of a controlled DNAPL release: 200 MHz radar**, Geophysics, Vol. 59, pp. 1211-1221.

Cai, J. and McMechan, G.A., 1995, **Ray-based Synthesis of Bistatic Ground-Penetrating Radar Profiles**. Geophysics, Vol. 60, pp. 87-96.

Cook, J.C., 1973, **Radar Exploration Through Rock in Advance of Mining**. Trans. Society Mining Engineers, AIME, V. 254, pp. 140-146.

Coon, J.B., Fowler, J.C. and Schafers, C. J., 1981, **Experimental Uses of Short Pulse Radar in Coal Seams**. Geophysics, Vol. 46, No. 8, pp. 1163-1168.

Davis, J.L., and Annan, A. P., 1989. **Ground Penetrating Radar for High-Resolution Mapping of Soil and Rock Stratigraphy**, Geophysical Prospecting, 37 p. 531-551.

Davis, J.L., and Annan, A. P., 1986, **Borehole Radar Sounding in CR-6, CR-7 and CR-8 at Chalk River, Ontario**. Technical Record TR-401, Atomic Energy of Canada Ltd.

Davis, J.L., Annan, A.P, Black, G., and Leggatt, C.D., 1985: **Geological sounding with low frequency radar**; in Extended abstracts, 55th Annual International Meeting of the Society of Exploration Geophysics, Washington, D.C.

Dolphin, L.T., et al; 1978, **Radar Probing of Victorio Peak, New Mexico**, Geophysics, Dec., Vol. 43, No. 7, pp. 1441-1448.

Doolittle, J.A., and Asmussen, L.E., 1992, **Ten years of applications of Ground Penetrating Radar by United States Department of Agriculture**, Proceedings of the Fourth International Conference on Ground Penetrating Radar, Geological Survey of Finland, Special Paper 16, p. 139-147.

El Said, M.A.H. 1956, **Geophysical prospection of underground water in the desert by means of electromagnetic interference fringes**, Pro. I.R.E., v. 44, p. 24-30 and 940.

Fisher, E., McMechan, G.A., and Annan, A. P., 1992 **Acquisition and processing of wide-aperture ground penetrating radar data**: Geophysics, 57, p. 495.

Fisher, E., McMechan, G. A., Annan, A. P., and Cosway, S. W., 1992, **Examples of reverse-time migration of single-channel, ground-penetrating radar profiles**, Geophysics, 57, pp. 577-586.

Gerlitz, K., Knoll, M.D., Cross, G.M., Luzitano, R.D., and Knight, R., 1993, **Processing ground penetrating radar data to improve resolution of near-surface targets**, Proceeding of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, San Diego, California.

Goodman, D., 1994, **Ground-Penetrating Radar Simulation in Engineering and Archaeology**. Geophysics, Vol. 59, pp. 224-232.

Grasmueck, M., 1996, **3-D Ground-Penetrating Radar Applied to Fracture Imaging in Gneiss**. Geophysics, Vol. 61, pp. 1050-1064.

Greaves, R.J, and Lesmes, D.P, Lee, J.M, and Toksoz, M.N 1996, **Velocity Variation and Water Content Estimated from Multi-Offset, Ground Penetrating Radar**, Geophysics, Vol. 61, No. 3, May-June 1996, pp. 683-695.

Holliger, K. and Bergmann, T., 2000, **Finite-difference modelling of borehole georadar data**, akzeptiert, Geophysics.

Holser, W.T., Brown, R.J., Roberts, F.A., Fredrikkson, O.A., and Unterberger, R.R., 1972, **Radar logging of a salt dome** : Geophysics, 37, pp. 889-906.

Jol, H., 1996, **Digital Ground Penetrating Radar (GPR): A New Geophysical Tool for Coastal Barrier Research (Examples from the Atlantic, Gulf and Pacific Coasts U.S.A.)**. Journal of Coastal Research, Fall 1996.

Lampe B. and Holliger K., 2000, **Finite-difference modelling of ground-penetrating radar antenna radiation**, 556 bis 560, Proceedings of the 8th International Conference on Ground Penetrating Radar, Gold Coast, Australia.

Maijala, P., 1992, **Application of Some Seismic Data Processing Methods to Ground Penetrating Radar Data**. Fourth International Conference on Ground Penetrating Radar June 8-13, 1992, Rovaniemi, Finland.

Morey, R.M., 1974. **Continuous Subsurface Profiling by Impulse Radar. Proceedings of Engineering Foundations Conference on Subsurface Exploration for Underground Excavations and Heavy Construction.** Henniker, N. H.. p. 213-232.

Olhoeft, G.R., 1975, **The Electrical Properties of Permafrost**, Pers. Com., 172 pages.

Olhoeft, G.R., 1981, **Electrical Properties of Rock and Minerals Short Course Notes**, Pers. Com., 196 pages.

Olhoeft, G.R., 1987, **Electrical Properties from 10^{-3} to 10^{+9} Hz - Physics and Chemistry**. Proceedings of the 2nd International Symposium on the Physics and Chemistry of Porous Media, American Institute of Physics Conference Proceedings, Vol. 154, pp. 281-298.

Olsson, O., Falk, L., Forslund, O., and Sandberg, E., 1987. **Crosshole Investigations - Results from Borehole Radar Investigations**. Stripa Project TR 87-11. SKB, Stockholm, Sweden.

Owen, T.R., 1981, **Cavity Detection Using VHF Hole to Hole Electromagnetic Techniques**. Proceedings of the Second Tunnel Detection Symposium, Colorado School of Mines, Golden CO, July 21-23, 1981, U.S. Army MERADOM, Ft. Belvoir, VA, pp. 126-141.

Redman, J.D., Kunert, Gilson, E.W., M., Pilon, J. A., Annan, A. P., 1996, **Borehole Radar for Environmental Applications: Selected Case Studies**. Proceedings of the Sixth International Conference on Ground Penetrating Radar (GPR'96), September 30-October 3,1996, Sendai, Japan.

Rees, H. V., and Glover, J. M., 1992: **Digital enhancement of ground probing radar data ground penetrating radar**, ed. J. Pilon; Geophysical Survey of Canada, Paper 90-4, p. 187-192.

Roberts, R. L. and Daniels, J. J, 1996, **Analysis of GPR Polarization Phenomena**, JEEG, vol. 1, no. 2, p. 139-157.

Sigurdsson, T. and Overgaard, T., 1996, **Application of GPR for 3D Visualization of Geological and Structural Variation in a Limestone Formation**. Proceedings of the Sixth International Conference on Ground Penetrating Radar (GPR'96), September 30-October 3,1996, Sendai, Japan.

Simmons, G., Strangway, D., Annan, A.P., Baker, R., Bannister, L., Brown, R., Cooper, W., Cubley, D., deBettencourt, J., England, A.W., Groener, J., Kong, J.A., LaTorraca, G., Meyer, J., Nanda, V., Redman, J.D., Rossiter, J., Tsang, L., Urner, J., Watts, R., 1973, **Surface Electrical Properties Experiment**, in Apollo 17: Preliminary Science Report, Scientific and Technical Office, NASA, Washington D.C., pp. 15-1 – 15-14.

Thierbach, R., 1973, **Electromagnetic Reflections in Salt Deposits**: J. Geophys. (1974) Vol. 40, pp. 633-637.

Tillard, R. and Dubois, J-C., 1992, **Influence and lithology on radar echoes: analysis with respect to electromagnetic parameters and rock anisotropy**, Fourth International Conference on Ground Penetrating Radar June 8-13, 1992

Ulriksen, C.P.F., 1982, **Application of Impulse Radar to Civil Engineering**, Unpublished Ph.D. Thesis, Dept. of Engr, Geol., U. of Technology, Lund, Sweden, p. 175.

Unterberger, R.R., 1978, **Radar propagation in rock salt**: Geophys. Prosp., Vol. 26, pp. 312-328.

van der Kruk, J, 2001, **Three dimensional imaging of multi-component ground penetrating radar**, Ph.D. Thesis, Delft University of Technology, pp. 242.

Waite, A. H. and Schmidt, S. J., 1961, **Gross errors in height indication from pulsed radar altimeters operating over thick ice or snow**. IRE International Convention Record, Part 5, pp. 38-54.

Ward, S.H., Phillips, R.J., Adams, G.F., Brown, Jr., W.E., Eggleton, R.E., Jackson, P., Jordan, R., Linlor, W.I., Peeples, W.J., Porcello, L.J., Ryu, J., Schaber, G., Sill, W.R., Thompson, S.H. and Zelenka, J.S., 1973, **Apollo Lunar Sounder Experiment**, in Apollo 17 Preliminary Science Report, scientific and Technical Office, NASA, Washington, D.C., p. 22-1 – 22-26.

Walford, M.E.R., 1964, **Radio echo sounding through an ice shelf**, Nature, Vol. 204, No. 4956, pp. 317-319.

Watts, R. D., and England, A.W., 1976, **Radio-echo Sounding of Temperate Glaciers: Ice Properties and Sounder Design Criteria**. Journal of Glaciology, Vol. 21, No. 85, pp. 39-48.

Zeng, X., McMechan, G.A., Cai, J., and Chen, H.W., 1995, **Comparison of Ray and Fourier Methods for Modeling Monostatic Ground-Penetrating Radar Profiles**. Geophysics Vol. 60, pp. 1727-1734.

GPR Conference References

Proceedings of the International Workshop on the Remote Estimation of Sea Ice Thickness Centre for Cold Ocean Resources Engineering (C-CORE), St. John's Newfoundland, Sept. 25-26, 1979.

Proceedings of the Ground Penetrating Radar Workshop, Geological Survey of Canada, Ottawa, Ontario, Canada, May 24-26, 1988, Special Paper 90-4.

Abstracts of the Third International Conference on Ground Penetrating Radar, United States Geological Survey, Lakewood, Colorado, USA May 24-26, 1990.

Proceedings of the Fourth International Conference on Ground Penetrating Radar, Geological Survey of Finland Special Paper file, Rovaniemi, Finland, June 8-13, 1992.

Proceedings of the Fifth International Conference on Ground Penetrating Radar (GPR'94), Kitchener, Ontario, Canada, June 12-16, 1994.

Proceedings of the Sixth International Conference on Ground Penetrating Radar (GPR ' 96), Sendai, Japan, Sept. 30- Oct. 3, 1996.

Proceedings of the Seventh International Conference on Ground Penetrating Radar (GPR '98), Lawrence, Kansas, USA, May 27-30, 1998.

Proceedings of the Eighth International Conference on Ground Penetrating Radar (GPR 2001), Goldcoast, Australia, May 23-26, 2000, SPIE vol. 4084.