U.S. DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

THIRD INTERNATIONAL CONFERENCE ON GROUND PENETRATING RADAR

Abstracts of the technical meeting

Lakewood, Colorado, USA

May 14-18, 1990

Jeffrey E. Lucius, Gary R. Olhoeft, and Steven K. Duke, editors

U.S. Geological Survey

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May 1990

THIRD INTERNATIONAL CONFERENCE
ON
GROUND PENETRATING RADAR

CONFERENCE PROGRAM

May 14-18, 1990

Organizing Committee
Gary R. Olhoeft
Jeffrey E. Lucius
David L. Wright

U.S. Geological Survey
P.O. Box 25046, DFC, MS 964
Denver, CO 80225-0046 USA

Arrangements: Bob and Sharon Seeley

Sheraton Hotel and Conference Center
360 Union Boulevard
Lakewood, Colorado 80228 USA

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MONDAY 14 May 1990 Grand Ballroom

Session Chair: Gary R. Olhoeft, U.S. Geological Survey

8:30a **High Frequency Electrical Properties.** (tutorial)
Gary R. Olhoeft, U.S. Geological Survey, Denver, CO, USA

9:30a **Extending Time Average dielectric mixing laws to lower frequencies: The Dispersion Time Average mixing law.**
Paul Baker, Monash University, Clayton, Victoria, Australia

9:55a coffee, Assembly Area

Session Chair: Steven A. Arcone, U.S. Army Cold Regions Research and Engineering Laboratory

10:20a **The effect of saturation history on electrical properties of the unsaturated zone.**
Rosemary Knight and Michael Knoll, University of British Columbia, Vancouver, British Columbia, Canada

10:45a **Dielectric permittivity depth profiles using laboratory measurements of core from a sandy aquifer.**
J. David Redman[1], Paul Bauman[2] and A. Peter Annan[1]
[1] University of Waterloo, Waterloo, Ontario, Canada
[2] Piteau Engineering Ltd, Calgary, Alberta, Canada

11:10a **Attenuation of L-band microwaves by permafrost.**
Stephen Wall[1], T.G. Farr[1], K.G. Dean[2] and L.R. Sweet[2]
[1] Jet Propulsion Laboratory, Pasadena, CA, USA
[2] University of Alaska at Fairbanks, Fairbanks, AK, USA

11:35a **Velocity estimation from fixed-offset ground penetrating radar data.**
Michael Knoll and Guy Cross
University of British Columbia, Vancouver, British Columbia, Canada

12:00 lunch, City Lights Room

Session Chair: Loris Asmussen, Agricultural Research Service

1:30p **Soil surveys: A guide for ground penetrating radar applications.**
Delbert Mokma[1] and James Doolittle[2]
[1]Michigan State University, East Lansing, MI, USA
[2]U.S. Department of Agriculture, Chester, PA, USA

1:55p **Calibration of water table location in a sandy soil using ground penetrating radar.**
Matt Smith[1], George Vellidis[1], D.L. Thomas[1] and Loris E. Asmussen[2]
[1] University of Georgia, Tifton, GA, USA
[2] U.S. Department of Agriculture, Tifton, GA, USA

2:20p **Detecting soil water movement in a sandy soil with ground penetrating radar.**
George Vellidis[1], Matt Smith[1], D.L. Thomas[1] and L.E. Asmussen[2]
[1] University of Georgia, Tifton, GA, USA.
[2] U.S. Department of Agriculture, Tifton, GA, USA

2:45p **Mapping vadose zones in groundwater recharge areas with ground penetrating radar.**
Wim van Dalfsen, TNO Institute of Applied Geoscience, Delft, The Netherlands

3:10p coffee, Assembly Area

Session Chair: Richard C. Benson, Technos Inc.

3:35p **Detailed geophysical investigation of a shallow sandy aquifer.**
Paul Bauman, John Greenhouse and J. David Redman
University of Waterloo, Waterloo, Ontario, Canada

4:00p **Improving solute sampling protocol in sandy soils by using ground penetrating radar.**
S.V. Donohue, X-X. Cheng and K-J. Samuel Kung
University of Wisconsin-Madison, Madison, WI, USA
4:25p **Assessing the ability of ground penetrating radar to delineate different fluvial sediments.**
Brian Moorman[1], Derald Smith[1], Alan Judge[2] and Harry Jol[1]
[1] University of Calgary, Calgary, Alberta, Canada
[2] Geological Survey of Canada, Ottawa, Ontario, Canada
4:50p **Evaluation of fractures in silts and clays using ground penetrating radar.**
Richard Benson and Lynn Yuhr, Technos, Inc., Miami, FL, USA
5:15p adjourn

TUESDAY 15 May 1990 Grand Ballroom

Session Chair: Gary R. Olhoeft, U.S. Geological Survey
8:30a **Modification of radar scattering signatures by antenna parameters.** (tutorial)
Rexford Morey, Morey Research, Hollis, NH, USA
9:30a **Impact of antenna pattern on survey design and data interpretation.**
A. Peter Annan and Steve W. Cosway
Sensors and Software, Mississauga, Ontario, Canada
9:55a coffee, Assembly Area

Session Chair: David L. Wright, U.S. Geological Survey
10:20a **Influence of wavelength, antenna height, and soil roughness in nearfield microwave detection of buried dielectric objects.**
W. Davis, E.L. Rope, J.T. Nilles and Gus Tricoles
General Dynamics, Electronics Division, San Diego, CA, USA
10:45a **Microwave antenna arrays for nearfield detection of buried objects.**
W. Davis, E.L. Rope, J.T. Nilles and Gus Tricoles
General Dynamics, Electronics Division, San Diego, CA, USA
11:10a **Directional antenna for borehole radar measurements.**
Lars Falk[1], Olle Ollson[2], Eric Sandberg[1], Olof Forslund[3] and Lars Lundmark[3]
[1] ABEM AB, Uppsala, Sweden
[2] ABEM AB, Stockholm, Sweden
[3] ABEM AB, Mala, Sweden
11:35a **Directive antenna array for a borehole radar.**
Motoyuki Sato, Tohoku University, Sendai, Japan
12:00 lunch, City Lights Room

Session Chair: James Doolittle, U.S. Department of Agriculture
1:30p **Burial detection using ground penetrating radar.**
Steve Persons, RED-R Services, Inc., Atlanta, GA, USA
1:55p **GPR survey of an African-American cemetery in Little Ferry, NJ.**
James S. Mellett and Joan H. Geismar, New York University, New York, NY, USA
2:20p **Ground penetrating radar applications for the purpose of archaeological investigation in Japan.**
Mohsen Badiey[1], Dean Goodman[2] and T. Yamamoto[3]
[1] University of Delaware, Newark, DE, USA
[2] University of Miami, Geo-Acustics Laboratory, Nakajima, Ishikawa, Japan
[3] University of Miami, Key Biscayne, FL, USA

2:45p **Investigation of Mayan structures at Caracol, Belize, using ground penetrating radar.**
William L. Wilson and Diane C. Wilson
Subsurface Evaluations, Inc., Winter Springs, FL, USA
3:10p coffee, Assembly Area

Session Chair: Jeffrey J. Daniels, The Ohio State University
3:35p **Poster sessions.**
4:00p **Ground penetrating radar surveys for archaeological purposes.**
Mauro Piccolo, Progera s.r.l., Venice, Italy
4:25p **The "radar rivers" of the Eastern Sahara: Signal penetration and surface scattering observed by the shuttle imaging radar.**
Gerald G. Schaber[1], Gary R. Olhoeft[2], John S. McCauley[1], Carol S. Breed[1] and Philip Davis[1]
[1] U.S. Geological Survey, Flagstaff, AZ, USA
[2] U.S. Geological Survey, Denver, CO, USA
4:50p **Ground penetrating radar imaging of sequence boundaries and lithofacies variations in a mixed siliciclastic carbonate depositional sequence.**
James M. Forgotson[1], John D. Pigott[1] and Jay D. Skinner[2]
[1] The University of Oklahoma, Norman, OK, USA
[2] ORYX Energy Company, Dallas, TX, USA
5:15p adjourn

WEDNESDAY 16 May 1990 Grand Ballroom

Session Chair: Gary R. Olhoeft, U.S. Geological Survey
8:30a **Ground penetrating radar system hardware design.** (tutorial)
David L. Wright, U.S. Geological Survey, Denver, CO, USA
9:30a **Ground penetrating radar for shallow exploration: Acquisition rate limitations of a modular GPR.**
Paul L. Baker and J.P. Cull, Monash University, Clayton, Victoria, Australia
9:55a coffee, Assembly Area

Session Chair: Rexford Morey, Morey Research
10:20a **Estimating fracture orientation in granite using ground penetrating radar reflection profiles.**
Arthur L. Holloway, Atomic Energy of Canada Limited, Pinawa, Manitoba, Canada
10:45a **Experience with ground penetrating radar in geotechnical applications.**
Anthony F. Siggins, Commonwealth Scientific and Industrial Research Organization, Mt. Waverly, Victoria, Australia
11:10a **A synthetic pulse GPR based on a network analyzer.**
Georges Pottecher, Bureau de Recherches Geologiques et Minieres, Orleans, France
11:35a **Inspection of concrete embankments and measurement of lake bottom sediment thicknesses - Case histories in GPR**
Richard J. Yelf
Georadar Research Pty Ltd., Armidale, New South Wales, Australia
12:00 lunch, City Lights Room

Session Chair: Robert W. Jacobel, St. Olaf College

1:30p **Some field, laboratory, and theoretical investigations of fresh water, ice and soil layers using short pulse radar.**
Kevin O'Neill[1], Steven A. Arcone[1] and Lance Riek[2]
[1] U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH, USA
[2] Lockheed Sanders, Nashua, NH, USA

1:55p **Some GPR results in salt and potash mines.**
Robert R. Unterberger, Texas A&M University, College Station, TX, USA

2:20p **Radar ice thickness measurements in the Lincoln Sea.**
John P. Todoeschuck[1] and R.I. Verrall[2]
[1] Jasco Research Ltd., Sidney, British Columbia, Canada
[2] Defense Research Establishment Pacific, Victoria, British Columbia, Canada

2:45p **Multiyear landfast sea ice: Observations and models.**
R.I. Verrall[1] and John P. Todoeschuck[2]
[1] Defense Research Establishment Pacific, Victoria, British Columbia, Canada
[2] Jasco Research Ltd., Sidney, British Columbia, Canada

3:10p coffee, Assembly Area

Session Chair: Rexford Morey, Morey Research

3:35p **Radar studies of internal layers and bedrock topography on ice streams B and C, West Antarctica.**
Robert W. Jacobel[1], Steven M. Hodge[2] and David L. Wright[3]
[1] St. Olaf College, Northfield, MN, USA
[2] U.S. Geological Survey, Tacoma, WA, USA
[3] U.S. Geological Survey, Denver, CO, USA

4:00p **Use of an impulse radar in peat research.**
Pauli Hanninen, Geological Survey of Finland, Kuopio, Finland

4:25p **The development of geophysical subsurface radar in the USSR and its practical use.**
Moisey I. Finkelstein, Riga's Institute of Civil Aviation Engineers, Riga, USSR

5:15p adjourn

THURSDAY 17 May 1990 Grand Ballroom

Session Chair: Gary R. Olhoeft, U.S. Geological Survey

8:30a **Ground penetrating radar data processing and modeling.** (tutorial)
Gary R. Olhoeft, U.S. Geological Survey, Denver, CO, USA

9:30a **Emulation of a phased array by application of F-K filtering to single fold GPR data.**
A. Peter Annan and Steve W. Cosway
Sensors and Software, Mississauga, Ontario, Canada

9:55a coffee, Assembly Area

Session Chair: J. Les Davis, CanPolar Inc.

10:20a **Reverse time migration applied to ground penetrating radar.**
Elizabeth Fisher[1], George A. McMechan[1] and A. Peter Annan[2]
[1] University of Texas at Dallas, Richardson, TX, USA
[2] Sensors and Software, Mississauga, Ontario, Canada

10:45a **Calibration and forward modeling of ground penetrating radar data.**
Steve K. Duke and Gary R. Olhoeft, U.S. Geological Survey, Denver, CO, USA

11:10a **Time domain radar signature of a cylinder for ray paths at an arbitrary angle to the axis.**
Mark L. Moran[1] and Roy J. Greenfield[2]
[1] U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH, USA
[2] Pennsylvania State University, University Park, PA, USA

11:35a **Modeling and tomographic inversion of cross borehole radar in layered media.**
Roy J. Greenfield[1], Robert S. Polzer[2] and Steven M. Shope[2]
[1] Pennsylvania State University, University Park, PA, USA
[2] Sandia National Laboratory, Albuquerque, NM, USA

12:00 lunch, City Lights Room

Session Chair: Roy Greenfield, Pennsylvania State University

1:30p **Measurements and modeling of ground penetrating radar field strengths in a large laboratory set up.**
Gert Greeuw, W.A. Wensink, J. Hoffman and J.K. van Deen
Delft Geotechnics, Delft, The Netherlands

1:55p **Numerical simulation of subsurface radar for detection of buried pipes.**
Ce Liu and Liang C. Shen, University of Houston, Houston, TX, USA

2:20p **Case History: GPR evaluation for detection of buried pipes and barrels at the Columbia Test Site, Waterloo, Ontario, Canada.**
J.E. Scaife, P. Giamou and A. Peter Annan
multiVIEW Geoservices, Mississauga, Ontario, Canada

2:45p **Software enhanced ground penetrating radar (GPR) detecting underground voids.**
Robert C. Kemerait and Jeffrey L. Meade, ENSCO, Inc., Melbourne, FL, USA

3:10p coffee, Assembly Area

Session Chair: A. Peter Annan, Sensors and Software

3:35p **UHF model experiments of airborne short-pulse radar void detection in the HF band.**
Steven A. Arcone, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH, USA

4:00p **Application of GPR to gap detection and floor subsidence.**
Gerald R. Rupert[1], Richard Stephenson[1] and Douglas Whitman[2]
[1] University of Missouri-Rolla, Rolla, MO, USA
[2] Amoco International, Houston, TX, USA

4:25p **Examples of sinkhole subsurface structure, in Florida, as revealed by ground penetrating radar.**
William L. Wilson, Subsurface Evaluations, Inc., Winter Springs, FL, USA

4:50p **Detection of abandoned coal mine workings with radio waves.**
Larry G. Stolarczyk, Stolar, Inc., Raton, NM, USA

5:15p adjourn

FRIDAY 18 May 1990 Grand Ballroom

Session Chair: Gary R. Olhoeft, U.S. Geological Survey

8:30a **Velocity, attenuation, dispersion and diffraction tomography.** (tutorial)
Gary R. Olhoeft, U.S. Geological Survey, Denver, CO, USA

9:30a **Radar crosshole tomography at the Grimsel Test Site with application to migration of saline tracer through fracture zones.**
Borje Niva[1], Olle Olsson[1] and Peter Blumling[2]
[1] ABEM AB, Uppsala, Sweden
[2] NAGRA, Baden, Switzerland

9:55a coffee, Assembly Area

Session Chair: Robert Unterberger, Texas A&M University

10:20a **Investigation of flow distribution in a fracture zone using differential radar measurements.**
Per M. Andersson[1], K. Peter Andersson[1], Erik Gustafsson[1] and Olle Olsson[2]
[1] Swedish Geological Company, Uppsala, Sweden
[2] ABEM AB, Uppsala, Sweden

10:45a **Electromagnetic tomography of grout penetration in fractures.**
William Daily and Abelardo Ramirez
Lawrence Livermore National Laboratory, Livermore, CA, USA

11:10a **Fracture characterization in granite using borehole radar.**
Arthur L. Holloway and Kevin M. Stevens
Atomic Energy of Canada Limited, Pinawa, Manitoba, Canada

11:35a **Case studies of radar tomography using borehole radar.**
Tetsuma Toshioka, OYO Corporation, Saitama, Japan

12:00 lunch, City Lights Room

Session Chair: Clark Davenport, EBASCO Environmental Division

1:30p **Condition assessment of reinforced concrete using radar.**
Udaya B. Halabe[1], Kenneth R. Maser[2] and Arash Sotoodehnia[2]
[1] Massachusetts Institute of Technology, Cambridge, MA, USA
[2] Infrasense Inc., Cambridge, MA, USA

1:55p **Electromagnetic sounding in the successful search for buried World War II aircraft on the Greenland ice cap.**
Austin Kovacs, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH, USA

2:20p **The role of ground penetrating radar in dam safety investigations.**
Andrew R. Blystra, Purdue University Calumet, Hammond, IN, USA

2:45p **Determination of erosion channels beneath a dike revetment by ground probing radar.**
J.W. de Feijter[1], Gert Greeuw[1] and J. Eikelboom[2]
[1] Delft Geotechnics, Delft, The Netherlands
[2] Dutch Water Authority, Delft, The Netherlands

3:10p coffee, Assembly Area

Session Chair: Mel Lepper, U.S. Bureau of Mines

3:35p **GPR applications for bridges and highways in Massachusetts.**
Doria Kutrubes[1] and Laurinda Bedingfield[2]
[1] Weston Geophysical Corporation, Westboro, MA, USA
[2] Massachusetts Department of Public Works, Boston, MA, USA

4:00p **Applications of ground radar to coal mining.**
Richard Yelf[1] and Greg Turner[2]
[1] Georadar Research, Armidale, New South Wales, Australia
[2] Australian Coal Industry Research Laboratories, Sydney, New South Wales, Australia

4:25p **Detection of seam anomalies with a synthetic pulse radar system.**
Robert S. Dennen and William P. Stroud, U.S. Bureau of Mines, Denver, CO, USA

4:50p **Case histories of GPR in mining and archaeological applications.**
Richard Yelf, Georadar Research, Armidale, New South Wales, Australia

5:15p adjourn

POSTER PRESENTATIONS

Airborne radar survey of late winter ice conditions on the White River at Hartford, Vermont.
Steven A. Arcone, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH, USA

Ground penetrating radar for detecting near-surface fluids.
Jeffrey J. Daniels[1] and Mark A. Vendl[2]
[1] The Ohio State University, Columbus, OH, USA
[2] U.S. Environmental Protection Agency, Chicago, IL, USA

Surface radar survey of unfrozen water beneath ice mounds in the Sagavanirktok River.
Allan Delaney, Steven A. Arcone, Ed Chacho and Charlie Collins
U.S. Army Cold Regions Research & Engineering Laboratory, Hanover, NH, USA

Numerical simulation of subsurface radar for detecting buried pipes.
Richard C. Liu, University of Houston, Houston, TX, USA

GPR research at the University of Arizona.
James W. McGill, Ben K. Sternberg, Charles E. Glass, and Mary M. Poulton
University of Arizona, Tuscon, AZ, USA

GPR cracks homicide case.
James S. Mellett, New York University, New York, NY, USA

Deriving length scales, correlations and statistics of soil structure from ground penetrating radar data.
Gary R. Olhoeft and Jeffrey E. Lucius, U.S. Geological Survey, Denver, CO, USA

Sedimentology of eolian sand by multifrequency ground penetrating radar.
Gary R. Olhoeft, Jeffrey E. Lucius, Don L. Gautier and Chris J. Schenk
U.S. Geological Survey, Denver, CO, USA

Anatomy of a waste burial trench, southeastern United States.
Steven Persons, RED-R Services, Inc., Atlanta, GA, USA

Borehole radar measurements.
Motoyuki Sato, Tohoku University, Sendai, Japan

Radio imaging method (RIM) tomography imaging.
Larry Stolarczyk, Stolar, Inc., Raton, NM, USA

Application of ground probing radar to archaeological investigation.
Tetsuma Toshioka, M. Osada and T. Sakayama, OYO Corporation, Saitama, Japan

Amplitude, velocity, and dispersion tomography at the Idaho Springs Test Facility using a fiber-optic borehole radar and radio-frequency digital data acquisition system.
David L. Wright and Gary R. Olhoeft, U.S. Geological Survey, Denver, CO, USA

Georadar research.
Richard Yelf, Georadar Research, Armidale, New South Wales, Australia

Underground Electromagnetic Wave Method.
Wu Yiren, Beijing Computer Centre, Beijing, People's Republic of China

GROUND PENETRATING RADAR MEETINGS

October, 1986 (no proceedings)
First International Symposium on Geotechnical Applications of Ground Penetrating Radar
Agricultural Research Service
Tifton, Georgia, USA

February, 1988 (abstracts and proceedings, contact Mary Collins, USDA/SCS)
Second International Symposium on Geotechnical Applications of Ground Penetrating Radar
Soil Conservation Service
Gainesville, Florida, USA

May, 1988 (proceedings published by Geological Survey of Canada)
Workshop on Ground Penetrating Radar
Geological Survey of Canada
Ottawa, Ontario, Canada

November, 1989 (no abstracts or proceedings)
Research Workshop -
Ground Penetrating Radar: Antenna Design, Geoelectric Properties and Propagation Characteristics
Society of Exploration Geophysicists
Dallas, Texas, USA

May 1990 (abstracts published by U.S. Geological Survey)
Third International Conference on Ground Penetrating Radar
U.S. Geological Survey
Lakewood, Colorado, USA

NOTICE

This collection of abstracts of the technical oral and poster presentations was initially made available to the conference attendees. The abstracts are presented in alphabetical order, based on the first author's last name. Jeff Lucius, Gary Olhoeft and Steve Duke edited the abstracts from materials submitted by the contributors. A list of conference attendees and exhibitors appears at the end.

INVESTIGATION OF FLOW DISTRIBUTION IN A FRACTURE ZONE USING DIFFERENTIAL RADAR MEASUREMENTS

Per M. Andersson[1], K. Peter Andersson[1], Erik Gustafsson[1], and Olle Olsson[2]

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Box 1424
S-751 44 Uppsala, Sweden

[2]ABEM AB
Box 20086
S-161 02 Bromma, Sweden

The development of the RAMAC® borehole radar system has provided unique possibilities for mapping groundwater flow in a rock volume. The objective of the presented project was to map the steady state flow distribution in a fracture zone when water was injected into the zone from a borehole. The basic idea was to map the flow paths by taking the difference between radar results obtained prior to and after injection of a saline tracer into the fracture zone. The radar experiments were combined with a more conventional migration experiment to provide validation and calibration of the radar results.

The Crosshole Site in the Stripa mine was selected as the experimental site as the geological and the hydrological conditions were well known. The site is located at the 360 m level where seven boreholes were used for this experiment. Radar measurements were performed with a center frequency of 60 MHz. Potassium bromide (KBr) with a concentration of 0.5% was chosen as the active saline tracer.

Tomographic inversions were made on the difference between the radar data collected prior to and after injection, to show the location of the saline tracer. The data presented were of good quality and sufficiently consistent throughout the investigated rock volume. The interpreted results verified previous findings in the surveyed granite volume and contributed to new and unique information about the transport properties of the rock at the site.

From the differential attenuation tomograms the migration of the injected tracer was mapped and presented both in the injected zone and in the entire investigated granite volume. From the radar tomographic model, the major tracer migration was found to be concentrated to a few major flow paths. Two additional fracture zones originally detected within this project, were found to transport portions of the injected tracer.

The amount of tracer flow path or "preferential flow fraction" was defined as the area with tracer transport divided by the investigated area. The "preferential flow fraction" within the injected zone, expressed as percent of surveyed area, in the three studied sections, was in the range 19% to 37%.

The integration of the radar method and the conventional tracer migration experiment made it possible to compare the radar interpretation of the groundwater flow paths with the actual breakthrough locations of the tracer. Analysis of tracer break-through data has confirmed the radar interpretations both with respect to the flow path distribution within the injected zone and with respect to the spreading of tracer to other zones within the surveyed rock volume.

The radar results combined with the tracer breakthrough data were used to estimate the area with tracer transport as well as flow porosity and the wetted surface.

EXPERIMENTAL RESULTS OF REMOTE RADAR SENSING OF FROZEN SOILS
(Not presented)

Vladimir A. Andrianov, V.N. Marchuk, S.D. Nazarenko, and D.Ya. Shtern

USSR Academy of Sciences
Institute of Radioengineering and Electronics
K. Marx Av. 18
103907 Moscow GSP-3, USSR

Experimental results and an algorithm for processing data obtained in remote radar sensing of soils in the region of permafrost are discussed.

Vertical sensing was carried out from a helicopter in the 100 MHz and 240 MHz frequency ranges with pulses on the order of nanoseconds width. The objectives of the investigations were a) measuring the reflectivity of soils of different types and analysis of its variations along the route of chosen flight lines and b) solution of the statistical problem of detecting subsurface signals reflected from the upper boundary of permafrost and a gas pipeline running in the soil.

The soil reflectivity estimated value was found from processing the ensemble of the realizations obtained. Mathematical average and variance of the peak and mean power values were calculated. Statistical evaluations of the power parameters were corrected for the radiowave geometrical divergence in vertical sensing and flight altitude variations. The accuracy characteristics of the valuation are given.

The reflected signal parameter variation versus the bedrock type has been analyzed. The data obtained are compared with the geological data and physical parameters of the soils being sensed. It is noted that signals reflected from sandy and sand loam soils have a lower power as compared to those reflected from peat soils. The power variation range reaches 10 db.

An algorithm for detecting subsurface signals was developed which is based on the statistical evaluation of the autocorrelation function envelope of the reference signal reflected by a water surface and the signal reflected by the soil being investigated. For the envelope of the autocorrelation function $R(\tau)$ of the reference signal its mean value $\langle R(\tau) \rangle$ was evaluated and the evaluation variance $\sigma^2(\tau)$ was calculated. It is shown that $\sigma^2(\tau)$ in a time delay range of $\tau<20$ ns is defined by fluctuations of the signal reflected by the practical surface and is 3 to 10 times as high as the evaluation variance at long time delays τ. The estimates of $\langle R(\tau) \rangle$ and $\sigma^2(\tau)$ were used in formation of the detection threshold. Increase in the signal-to-noise ratio was obtained as a result of accumulation of signals and interference selection in the time and frequency regions of processing. The autocorrelation function envelope for reflected signals on the order of nanoseconds was calculated based on the Hilbert transform.

The report presents results of detection problem solution for chosen radar sensing routes. It is noted that the time delay between signals reflected from the frozen layer boundary falls within a range of 10 to 20 ns which corresponds (for the soil permittivity $\epsilon=9$) to depths of 0.5 to 1 m. Accuracy parameters for measurement of the time delay of reflected signals and probability characteristics of the detection problem are given.

IMPACT OF ANTENNA PATTERN ON SURVEY DESIGN AND DATA INTERPRETATION

A. Peter Annan and Steve W. Cosway

Sensors and Software Inc.
5566 Tomken Road
Mississauga, Ontario, L4W 1P4 Canada

In most reflection profiling applications, the antennas of a ground penetrating radar (GPR) system are held in close proximity to the ground. The antennas interact with the ground resulting in an antenna radiation pattern which is substantially modified from the pattern which would be anticipated in a free space environment. The modification of the antenna pattern has implications both for maximizing coupling with targets during data acquisition as well as in the interpretation of amplitude information from survey data.

For most systems in current use, the antennas employed are dipolar in nature. The far field radiation patterns of dipolar sources placed on the ground surface are readily analyzed. The majority of the energy directed into the ground is contained in a cone defined by the critical angle for the air ground interface. The beam width is approximately 70° for very dry sandy soils whereas the beam width is only 15° when antennas are placed over water.

Example data acquired over a strong reflector are used to illustrate that the theoretical predications are as anticipated. Maximum coupling of energy with targets is a function of target depth and average relative permittivity in the material overlying the target. As a simple rule of thumb, the antenna separation should be 20 percent of the depth of the target being mapped.

EMULATION OF A PHASED ARRAY BY APPLICATION OF F-K FILTERING TO SINGLE FOLD GPR DATA

A. Peter Annan and Steve W. Cosway

Sensors and Software Inc.
5566 Tomken Road
Mississauga, Ontario, L4W 1P4 Canada

In many common geological environments, a GPR antenna placed on the ground surface illuminates a broad region of the subsurface. The result is that signals from scatterers off to the side as well as directly beneath the measurement system are detected. The variation of reflections in space and time for a reflection section provide diagnostic keys as to the position of the scattering source with respect to the radar system.

With single fold coverage GPR data, the radar antennas are moved as a fixed unit along a line over the ground surface with data being acquired at fixed spatial intervals. Each measurement position can be treated as an individual radiating element. By appropriately phase shifting (or time delaying) data as a function of antenna position one can effectively narrow the beam width of the system along the profiling direction.

The concept of treating the data in this manner is identical to the concept of F-K filtering commonly applied in seismic reflection data processing. In this presentation, examples of data which have been processed by F-K filtering to enhance reflections from directly beneath the radar system at the expense of reflections off to the side or above the radar system demonstrate the utility of this technique. This approach can have significant advantages over the creation of a multiple element antenna when attempting to move the radar system through rugged terrain.

UHF MODEL EXPERIMENTS OF AIRBORNE SHORT-PULSE RADAR VOID DETECTION IN THE HF BAND

Steven A. Arcone

U.S. Army
Cold Regions Research and Engineering Laboratory
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A model study of the interaction between airborne-launched short-pulse radar signals and rectangular voids in bedrock is presented. Frequencies in the UHF band radiating into a small sand box containing Styrofoam strips were used to model the interaction of HF radiation with voids having widths on the order of 2 m. The sand box was about 1 m deep, 4.5 m long, 2.5 m wide and contained three square Styrofoam strips 5, 10, and 20 cm on a side. The dielectric constant of the sand was measured at 4.1 by timing reflections from the concrete substrate. The antenna transducer was situated 30-60 cm above the sand surface, and data were recorded continuously and compiled at a rate of 25.6 scans/sec as the transducer moved over the Styrofoam strips. The spectrum of the radar wavelet was centered near 900 MHz which corresponds to 22.5, 45 and 90 MHz when the three voids are scaled to 2 m. The results showed all the voids to produce hyperbolic spatial responses for polarization both parallel and perpendicular to the long axis of the strips. Both polarizations produced reflections in which the shape of the incident wavelet was retained, and also reflections where resonant responses occurred, the latter case especially for the two larger voids that had side lengths equal to 0.3 and 0.6 free space wavelengths. Although real HF signal attenuation was not simulated in this model, the results suggest that under nearly ideal conditions, meter-sized voids at over 10 meters depth can be detected easily with a moderately powered transmitter on an airborne platform using polarization either parallel or perpendicular to the void axis. The use of pulses with spectra centered near 20 MHz is recommended.

POSTER: AIRBORNE RADAR SURVEY OF LATE WINTER ICE CONDITIONS ON THE WHITE RIVER AT HARTFORD, VERMONT

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An airborne radar survey was carried out along a 4 km stretch of the White River near Hartford, VT on March 13, 1989. The purpose was to determine ice thickness and therefore, estimate ice volume to assess the possibility of severe jamming on the Connecticut River into which the White River feeds. A "500 MHz" short pulse radar antenna was mounted off the skids of a Bell 206B helicopter, and the survey was performed at about 3-5 m altitude and a speed of about 5 m/s. The ice conditions included floating and grounded smooth sheets with and without surface rubble, broken plates, upended slabs in small jams, and grounded rubble. The ice was thoroughly frozen and no surface melt was present. Ice thickness was generally interpretable over most of the record; i.e., the average smooth sheet ice thickness was 43.4 cm and the average thickness interpreted for the rough sections was 49.9 cm.

GROUND PENETRATING RADAR APPLICATIONS FOR THE PURPOSE OF ARCHAEOLOGICAL INVESTIGATION IN JAPAN

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The application of the ground penetrating radar for archaeological studies in Japan is considered. Limitations as well as the advantages of this method over the existing methods for clayey soil beds are discussed in detail. To assist in the process of excavation which is presently the primary method for archaeological investigations in Japan and to reduce the time and cost of blind surveys, this method was used to estimate the distribution of possible cultural relics before digging at a site located in Nakajima City, Ishikawa Ken, Japan. In a series of experiments, first the bedrock was located by using a 500 MHz antenna to be about 2 meters from the surface of the ground. Then the anomalies within the 1.5 m depth from the ground surface were located by using a 900 MHz antenna. The method was found to be applicable for archaeological investigations with certain limitations when applied in wet clayey soils.

EXTENDING TIME AVERAGE DIELECTRIC MIXING LAWS TO LOWER FREQUENCIES: THE DISPERSION TIME AVERAGE MIXING LAW

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Time average mixing laws have been extensively used for high-frequency dielectric logging and soil moisture sensing. Derived from the Complex Refractive Index equation, specific algorithms are expressed in terms of the real and imaginary parts of the dielectric permittivity, and also in propagation time and attenuation. In high-frequency dielectric logging, these algorithms are used to estimate the water and hydrocarbon volume fractions from the propagation time and the porosity, lithology, water salinity and temperature. However in soil moisture sensing, statistically derived soil moisture equations are often used. These time average laws can also model the soil laboratory data and reveal some limitations of the statistical approach. These algorithms lead to a procedure for the direct readout of soil moisture content from a digital portable time domain reflectometer.

At the lower frequencies typical of ground penetrating radar, there is no satisfactory model to account for an increase in the dielectric permittivity of water saturated rocks at lower frequencies. Several models have been suggested to physically explain dielectric dispersion for different media but none have gained widespread acceptance. As the very low frequency radar system performance in conductive formations improves there will be an increasing need to account for dispersion.

Given the relative utility of the time average approach, an extension to lower frequencies is proposed. Recognizing that the refractive index square root law implicitly gives an Archie type conductive relationship with a cementation exponent of two, a number of generalizations and approximations can be made. The Dispersion Time Average mixing law has the familiar time average form with an additional resistivity power law term due to dispersion. From this mixing law, we develop algorithms suitable for ground penetrating radar and assess their applicability.

GROUND PENETRATING RADAR FOR SHALLOW EXPLORATION: ACQUISITION RATE LIMITATIONS OF A MODULAR GPR

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Ground penetrating radar can be used for mineral exploration at shallow depths subject to a range of geological conditions. However, for commercial application the production rate must be made cost effective compared to competing methods such as drilling and magnetics. An Australian Mineral Industries Research Association Project (AMIRA) has been funded to assess the method. Recent field work with a modular ground penetrating radar unit indicate different configurations are required for mine sites with difficult or easy terrain conditions.

The rate at which the ground can be traversed depends on three factors: the recording time per station, the spacing between stations required to satisfactorily image the target, and the ease at which the equipment can be moved from station to station. The recording time for one station is controlled by the waveform length, sampling rate and the number of waveform stacks, which are a function of target depth, propagation velocity, signal attenuation and frequency. The minimum recording time is approximately one stacked waveform per second due to data transfer limitations.

In difficult terrain, equipment modifications and improved operational procedures allow backpacking the computer and control unit to record data from the hand-carried radar antennas. Production rates are comparable to ground magnetic surveys. Several kilometer long traverses at 1 meter stations along narrow forest paths can be recorded in a day with this configuration. However due to coherent noise interference, two people are required to perform the survey.

In easy terrain where vehicles can be driven along the traverse line, lightweight plastic components are used to configure the radar as a towed sled. Under optimum conditions, speeds up to several kilometers per hour are possible. However the profile quality becomes degraded if the stack number is significantly reduced. Digital signal processing is used to remove the consistent vehicle reflection and the direct signal arrival from the radar section.

DETAILED GEOPHYSICAL INVESTIGATION OF A SHALLOW SANDY AQUIFER

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As part of a field study of the behavior of chlorinated solvents in the subsurface, the physical properties of two 15 x 15 x 12 m cells in a sandy aquifer have been established by detailed seismic refraction, streaming potential, complex resistivity, terrain conductivity and borehole logging measurements. Recovered cores have been profiled for changes in electrical conductivity on a scale of 2 cm, and by time domain reflectometry on a scale of 5 cm. Most importantly, detailed ground penetrating radar (GPR) data have been obtained on a fine grid. Correlations of outstanding radar reflectors with significant hydrogeological features have been made.

A detailed GPR survey has also been done over a proposed solvent spill cell. The observed distribution of liquid phase solvent introduced into the test cell is to be compared with data collected from this baseline survey. This will reveal whether subsurface radar reflectors correspond to subsurface features that control solvent migration.

These detailed geophysical surveys on such a small scale must be unique; for this reason alone the data are important. The immediate relevance of this work is a better understanding and description of heterogeneities which may influence the path of chlorinated solvents in a slow release spill.

EVALUATION OF FRACTURES IN SILTS AND CLAY USING GROUND PENETRATING RADAR

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Site specific soil conditions often limit the use of ground penetrating radar (GPR) in many investigations. Dielectric and conductivity losses associated with fine grain silts and clay soils can limit radar penetration to a few feet or less. As a result, we are often discouraged by the poor radar penetration associated with these soil conditions and avoid using GPR at such sites. However, in certain cases, radar response may be sufficient to allow mapping of shallow features which in turn provide clues to deeper seated problems. An example of such an application is where shallow fractures in soils are caused by a deeper seated phenomena.

Radar response over fractures in silts and clay soils which occur in response to deeper seated causes are often significant. However, we suspect that the radar response is dominated by changes in antenna loading (impedance mismatch) and that reflections, if they exist at all, are a small part of the response.

Three examples illustrate the use of GPR in such applications:

- Mapping of fractures in the lakebed runways at Edwards Air Force Base, California, where ground water withdrawal has caused subsidence leading to surface fracturing and fissures within the lakebed,

- Cracks in earthen dams located in new Mexico and Arizona which are probably caused by settlement and desiccation, and

- Small fractures within loess soils which are caused by paleo-fractures in an underlaying limestone and shale sequence in Kansas.

THE ROLE OF GROUND PENETRATING RADAR IN DAM SAFETY INVESTIGATIONS

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Ground penetrating radar can be a very effective tool in helping to assess the structural integrity of earth and concrete dams. The purpose of this paper is to present five case histories where GPR was used to help evaluate existing conditions.

The Prairie du Sac Hydropower Project is located on the Wisconsin River. During the installation of piezometers, voids were found beneath the spillway slab. A GPR survey was made of the area beneath the spillway slab and inside one of the powerhouse draft tubes. The radar data contained several anomalies which were believed to be voids. Cores were made through the concrete to verify the presence and depth of the voids. The radar data also was used to estimate the quantity of grout that would be required to fill the voids. Several hundred cubic yards of grout were pumped beneath the spillway to stabilize the structure.

Voids also were suspected to be present beneath the spillway at Lake Bloomington in Illinois. There were several areas where sections of concrete floor slab were partially missing and voids could be observed beneath the remaining slab. Since the extent of the voids was unknown, a GPR survey of the entire spillway was made. The results of the survey indicated that the visible voids were local and there was not a major problem of loss of foundation material.

Several earth dams in Michigan were constructed by hydraulic fill methods. Typical construction consisted of transporting sand to the site by means of railroad cars. Usually timber trestles were built across the valley to accommodate the railroad, and these trestles remained in the embankment after construction was completed. At several projects these timber trestles have rotted causing voids to be present in the embankments. GPR surveys have been used to initially locate these voids and also to monitor the development of any new voids. The Hardy Project on the Muskegon River and the Alcona Project on the Au Sable River are presented as examples. The problem of the limited depth of the GPR survey is discussed.

The upper reservoir at the Ludington Pumped Storage Project has a liner which consists of two layers of asphalt separated by a layer of stone. Fluctuation of the reservoir results in flexing this liner. Leakage through the liner was suspected at two locations. Instrumentation data and acoustic testing was used to better define the suspected seepage areas. Then the reservoir was drawn down and a GPR survey was conducted. Cracks in the lower asphalt liner, which was not visible, were found using GPR.

The above listed case histories deal primarily with investigating the structural integrity of earth embankments and hydraulic structures. In addition, a side benefit of the GPR survey is the additional information that can be obtained about a structure. For example, GPR surveys have been used to locate reinforcing steel, to map changes in the types of foundation materials, and to determine the depth to the phreatic surface in embankments.

USING GROUND PENETRATING RADAR TO EVALUATE AN AIRPORT RUNWAY

(Not presented)

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The available design information and the records on file at the Federal Aviation Administration (FAA) showed that the main runway at the Gary Airport in Gary, Indiana consisted of 6 inches of asphalt underlain by 8-1/2 inches of stone base course. A coring program conducted in 1982 revealed that the asphalt thickness averaged over 6 inches and the base course thickness was approximately 12 inches.

It was desired to allow 727 aircraft to land at the airport; however, the pavement strength, based on design information on file at the FAA, was marginal. To verify that the actual pavement thickness was greater than the data on file at the FAA, a ground penetrating radar survey of the runway and taxiways was conducted. Six continuous survey lines were made of the main runway and two continuous survey lines were made of the taxiways. Six lines were made of the main runway because the runway had been widened and lengthened. The six lines were necessary to provide coverage of all the variations in the pavement cross section. The survey was conducted using a 500 MHz antenna. A survey base line along each taxiway and along the runway was set so that the radar chart data could be located in the field.

The previous pavement cores were used to correlate the radar survey data. Pavement and base course thicknesses were scaled from the chart data. After all the chart data was studied, average pavement and base course thicknesses were determined for the runway and the taxiways. Since a very limited number of cores had been obtained previously, additional cores of the pavement were obtained. At the time of the coring, the thickness of the base course was measured and the strength of the subgrade was determined using a pressuremeter. The thickness of the asphalt pavement and the thickness of the stone base course correlated well with the radar data. In general, the scaled values from the chart did not vary by more than one-quarter of an inch from the cores and field measurements.

One of the main advantages in using ground penetrating radar for this project was the continuous record of pavement thickness that was obtained for the various cross sections. Even an extensive coring program could not have provided a continuous record. Furthermore, the cost of the ground penetrating radar survey was considerably less than an extensive coring program.

The results of the ground penetrating radar survey, correlated with the coring data, formed the basis of a request by the Gary Airport that the FAA records be modified to show that the actual pavement thicknesses were greater than design information on file.

ELECTROMAGNETIC TOMOGRAPHY OF GROUT PENETRATION IN FRACTURES

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As part of a grouting test at the Atomic Energy of Canada Limited Underground Research Laboratory, Lawrence Livermore National Laboratory conducted an electromagnetic cross borehole tomography experiment to evaluate the potential of the technique to delineate grout invasions. Tomographs of the electromagnetic attenuation rate at 385 MHz were made along 256 ray paths in two regions each about 6 meters high and 3 meters wide. The spatial resolution of these images was 20-30 cm. Changes of the electromagnetic attenuation rate of the rock were detected within the highly permeable altered region of a fracture zone after both jet washing and grouting of the zone. However, the electromagnetic skin depth was observed to decrease where grout was injected in one part of the fracture zone and increase where grout was injected in another part of the formation. The quantity of material removed from the fracture zone by jet washing, as well as the quantity of grout accepted by these two regions was different. It is suggested that the observed difference in electromagnetic response at the two locations depends on both grout invasion and the amount of infilling material removed by the jet washing process. From the tomographs we infer the depth of penetration of grout into the fracture zone in both regions where grout is injected. These inferences agree very well with the other information about the location of grout penetration: the location of the highly permeable region of the fracture zone and the locations where jet washing removed fracture infilling material.

POSTER: GROUND PENETRATING RADAR FOR DETECTING NEAR-SURFACE FLUIDS

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Ground penetrating radar (GPR) is an electromagnetic technique that produces a distance-versus-time image that can be interpreted as a distance- versus-depth cross section of the near-surface. GPR can detect and define the extent of near-surface spills when there is an electrical properties contrast between the host material and the spilled fluid, and the fluid has not migrated deeper than the detection range of the GPR signal. The detection range of the GPR technique depends primarily upon the complexity of the electrical properties of the host material, the volume of fluid, and the fluid's depth with respect to the water table.

The significance of ground penetrating radar as a tool to detect near-surface fluids is illustrated at sites in the Midwest representing petroleum product above the water table, lead-based paint near the surface, and salt brine spread on the surface. In each case GPR is shown to exhibit a change in amplitude, phase, and character in response to the presence of the fluids. The conductive brine and the lead-based paint at the surface simply increased the amplitude and decreased the two-way travel time of the radar signal, while the petroleum product gave a complicated response that was dependent upon the depth of burial and the thickness of the petroleum product above the water table. Petroleum product in the vadose zone accumulates in small localized concentrations that can be detected by GPR measurements. Petroleum product on the water table changes the propagation characteristics of the radar wave that in some cases can be identified on a GPR record.

MICROWAVE ANTENNA ARRAYS FOR NEARFIELD DETECTION OF BURIED OBJECTS

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A common microwave technique for detecting buried objects is to scan an antenna over an area. This procedure is relatively simple and reliable, but it is slow because data are acquired sequentially. Data acquisition can be accelerated by an array of antennas.

This paper describes experiments with two distinct arrays of micro-stripline antennas. One array had 24 elementary antennas, arranged in subarrays of three collinear antennas. In each subarray the central antenna transmitted. The outer two were connected out of phase and received. The second array had 21 elements, in two staggered rows; each element radiated and received. A switching matrix connected the 21 elements to the transmitter and receiver. Mutual coupling was measured and used to correct measured reflectance.

Reflectance data are presented. The reflectance values were processed by forming gradients and applying a Sobel operator. Contour plots are images in the sense that the contours resemble object configuration.

INFLUENCE OF WAVELENGTH, ANTENNA HEIGHT, AND SOIL ROUGHNESS IN NEARFIELD MICROWAVE DETECTION OF BURIED DIELECTRIC OBJECTS

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Many factors influence the design and operation of microwave systems for detecting buried objects. The paper describes experiments that show the influence of three factors, wavelengths, antenna height, and surface roughness. Measurements were made with continuous waves at four frequencies in the range 300 to 900 MHz with a monostatic system that used a sequence of antennas, each appropriate to a frequency. Each antenna was mechanically scanned over an area to measure reflectance. For smooth soil, with no object present, measured peak values of reflectance depended on height to wavelength ratio h/λ. The data followed a nearly common locus for the four frequencies when plotted as a function of h/λ. With an object present, reflectance varied as the antenna passed over the object, but the height dependence was similar to that without object. Measurements were made for soil with periodic grooves, with and without a buried object. At a small value of h/λ (0.06) the reflectance varied with period of the grooves; however, at the larger h/λ (0.18), reflectance was smooth. At the small height, the periodic reflectance variations obscured the object; at the larger height, the object contrast was clearly observed. Reflectance data for dielectric objects through a broad frequency range plotted as spirals in the complex plane. Properties of the curves were interpreted in terms of an approximate inverse scattering model to determine object depth, thickness, and dielectric constant.

DETERMINATION OF EROSION CHANNELS BENEATH A DIKE REVETMENT BY GROUND PROBING RADAR

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The coastline of the Netherlands consists of dunes and dikes which protect the lowlands against the sea. At many places, the clay dikes are provided with a revetment of rocks, concrete blocks or asphalt to protect the clay against wave attack and erosion. Beneath these blocks cavities may develop through erosion of the clay by water entering through the seams and flowing behind the blocks. Due to clamping of the blocks the channels are generally not visible from the outside but may nevertheless develop into dangerous proportions. Under large load conditions, the revetment can collapse, leaving the subsoil unprotected to wave attack.

In order to determine the presence and extent of erosion channels, a 900 MHz ground probing radar system (GSSI) was applied, coupled to the specifically designed digital data acquisition and processing equipment, GRAS. The measurements were performed along traverses in a square grid at distances equal to the block dimensions (50 by 50 cm). After performing the ground radar measurements, and after a first analysis of the data, some of the 20 cm thick blocks were removed from the revetment, and an accurate record was made of the features showing up. The ground radar results predict the lateral extension of the erosion channels, which have typical widths of 10 to 60 cm, within 5 cm. The depth determination was done in a semi-quantitative scale 'no cavity', 'shallow' (<10 cm) and 'deep' (>10 cm) channels, and this discrimination appeared to be adequate.

The successful pilot experiments have led to the formulation of a program to develop the radar system into a routine instrument for regular block revetment inspection.

DETECTION OF IN SEAM ANOMALIES WITH A SYNTHETIC PULSE RADAR SYSTEM

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A synthetic pulse ground penetrating radar system[1] has been used to probe a small coal pillar. The data derived from this system subjected to temporal tomographic analysis indicated the presence of a low velocity anomaly interior to the pillar. Later core sample data showed this anomaly to be an interior clay vein. A direct tomographic reconstruction of the temporal data was used in the analysis. The synthetic pulse radar scanning system offers potential advantages in depth penetration over a more standard short pulse system but requires additional data preparation and analysis prior to the presentation of a tomogram display. Details of this radar/tomographic technique will be discussed as well as some proposed future applications of the system.

[1]This system was built under contract to the Bureau of Mines by Xadar Corp., Springfield, VA.

IMPROVING SOLUTE SAMPLING PROTOCOL IN SANDY SOILS BY USING GROUND PENETRATING RADAR

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Experimental results showed that preferential flow such as macropore flow in finer-textured soil or fingering flow in coarser-textured soil could be the dominant transport mechanism of water-soluble contaminants in the vadose zone. More recently, a field experiment conducted in Plainfield sand in the central sand areas of Wisconsin demonstrated that water and solute applied uniformly to soil surfaces were funnelled by interbedded and inclined soil layers into concentrated flow paths that occupied only a small portion of the soil matrix in the vadose zone and bypassed the bulk of the soil, yet, accounted for most of the transport. The preferential flow paths have a significant impact on groundwater contamination. The contamination potential of a water-borne chemical carried by preferential flow increases significantly because the flow is more concentrated and therefore faster, hence the time available for degradation is greatly reduced. Because the preferential flow carries a chemical through a very small portion of the soil matrix, total adsorption will be also greatly reduced.

All current soil solute sampling protocols are based on the assumption that water, and hence water-borne chemicals, will flow through the entire soil matrix in the unsaturated zone, while the spatial distribution of the vertical flow velocity is log-normally distributed. Therefore, soil solute samples taken from a vadose zone by current monitoring techniques (i.e., soil cores and suction-cup samplings) are randomly obtained because the representativeness of the samples is implicitly assumed to depend only on the total number of samples instead of the locations of samples. Samples are assumed to become more representative as more samples are taken. However, when preferential flow is the dominant flow pattern in a soil system, this assumption is violated because water flow through more scattered regions as it moves deeper. Hence, the current solute sampling protocols become invalidated because the locations of the samplers will determine the representative of the samples.

In order to accurately predict and monitor the fate of a contaminant in sandy vadose zone with funnel flow and hence to unmistakably determine the susceptibility of the groundwater contamination under a given land use strategy, it is essential to develop a technique to non-destructively ascertain the three-dimensional physical properties (especially bedding structures with textural discontinuity) so that the existence of preferential paths can be predicted. The objective of this presentation is to demonstrate that ground penetrating radar (GPR) has a great potential for non-destructively mapping the soil structure in the vadose zone.

In our field experiments conducted in the central sand areas of Wisconsin, we found that a 500 MHz GPR can detect the location, dimension, and inclination of the cross-bedding structure in a sandy vadose zone up to 2.5 m. Based on the detected soil layers with textural discontinuity, four suction cup solute samplers were installed at locations where preferential flow triggered by the funnel phenomena would occur at 1.85 m depth. Another four samplers were randomly installed at 1.5 m depth. With these eight suction samplers, bromide breakthrough patterns were collected. The results showed that the averaged bromide breakthrough pattern, as well as the averaged volumes of solution samples from the samplers installed with aid of the ground penetrating radar images, were much higher than those from the randomly installed suction samplers. This clearly demonstrated that the current solute sampling protocol needs to be modified because the concentration of water- soluble contaminant could be grossly underestimated when the samplers were randomly installed.

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CALIBRATION AND FORWARD MODELING OF GROUND PENETRATING RADAR DATA

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A calibrated ground penetrating radar (GPR) transmitted wavelet signature is traced through a layered medium of known electrical properties to compute a synthetic radar scan (forward model). The wavelet is convolved in time (or distance) with a variety of frequency-dependent filters which define the attenuation, dispersion, transmission, and reflection properties of the layered medium. The calculated forward model is fitted to field data to estimate subsurface electrical properties (ie. material attenuation and complex dielectric permittivity) as a function of depth. The calculation of attenuation and dielectric permittivity versus depth provides information indicative of changes in fluid content and bulk density in the material.

Calibration experiments were performed with 300, 500, and 900 MHz antennas to measure transmitted wavelet signatures normal to the antenna. Forward modeling algorithms were developed to trace calibrated wavelet paths through four-layer mediums. 300, 500, and 900 MHz scans collected at the same location at the Great Sand Dunes National Monument area were modeled. The results indicate that GPR forward modeling is a viable processing technique for quantitatively evaluating subsurface material properties to 10-20 percent accuracy. At the accuracy which the data was modeled, the frequency dependence of layer parameters was not observed, since one model fit the three different frequency scans. Subsurface fluid content and bulk density of layers were estimated using the Bruggeman-Hanai-Sen formula.

DIRECTIONAL ANTENNA FOR BOREHOLE RADAR MEASUREMENTS

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During the last five years, the RAMAC® borehole radar system has been successfully applied to mapping fracture zones, tunnels and other reflectors. The instrument was originally developed by ABEM within the International Stripa Project on nuclear waste storage, and many tests have shown that reflectors can be discovered more than a 100 meters from a borehole in crystalline rock. In order to determine the orientation of fracture zones, different measurement techniques have been developed: single hole reflection, crosshole reflection and crosshole tomography. By combining data from different measurements one can build detailed models of the fracture systems. These methods have been tested extensively at many sites with excellent results.

If only a single borehole is available, the previously mentioned methods are inapplicable and the cylindrical symmetry of the dipole antennas will leave the direction to a reflector undetermined. In order to solve this problem, a directional antenna has been developed, which can determine the position of a reflector from measurements in a single borehole. Tests performed in Stripa mine in central Sweden demonstrate that the resolution of the antenna is better than 5° for well defined fracture zones.

The function of the directional antenna has been analyzed theoretically and in practice to study the effects of asymmetries in the system. A directional antenna is by necessity rather inefficient and special care must be taken to avoid contamination by other signals. Tests are even performed during measurements to check that the system is functioning well at all times.

The directional antenna has been applied in real site investigations, and the techniques used to analyze the measured data will be described. A detailed comparison with logging data shows that the directional antenna is an efficient and exact tool for analyzing the fracture geometry.

THE DEVELOPMENT OF GEOPHYSICAL SUBSURFACE RADAR IN THE USSR AND ITS PRACTICAL USE

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In 1967, Riga's Institute of Civil Aviation Engineers began to investigate high-frequency electrical properties of sea ice "in situ". The method of synthesized video pulses for sea ice thickness worked out by the author in 1969 is based on inverse filtering by means of amplitude and phase correction of radio pulses having multiple frequencies. This radar was tested in many field experiments, was used during the trip of the atomic powered icebreaker "Arctica" to the North Pole, and was used in a number of other aerial ice surveys. The second generation of sea ice thickness measuring radars uses a multichannel analyzer without stroboscopic processing. There are also some freshwater ice thickness radars for winter track laying, for ice runway monitoring and so on.

Our investigations of geological radars began in 1967, and there are ten years of practical use in engineering geology and adjacent fields. It has been designed to obtain continuous cuts of subsurface structures in sand and sandy loam sediments, frozen soil, peat and sapropel deposits for freshwater basin bed profiling, detecting and mapping of karst voids in limestone and dolomite, and in archaeology. Another georadar is designed for subsurface prospecting both from air plane or helicopter and from land vehicles. The sounding by radio pulses of nanosecond duration from airplane or helicopter was also used for snow and vegetative cover height measurements. In all mentioned devices, we use computer data processing with the help of a special software package.

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REVERSE TIME MIGRATION APPLIED TO GROUND PENETRATING RADAR

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There are theoretical similarities between the kinematic properties of elastic and electromagnetic wave propagation (Ursin, 1983). Thus, migration techniques originally developed for the processing of scattered seismic waves may be applied to radar soundings in ice (Harrison, 1970, Jezek et al., 1985, Fisher et al., 1989), to ground penetrating radar (GPR) data (Hogan, 1988), and satellite based radar data (Rocca et al., 1989). In reverse time migration, the data are treated as time-dependent boundary conditions for numerical solution of the wave equation, which propagates the energy backward in time, into the medium. This extrapolation continues until time=0, when all the reflected and diffracted energy is at the spatial position where they originated. During this process, the time axis is converted to depth, and diffractions are collapsed, thereby producing a focused image of the scatters. Several GPR data sets are successfully processed.

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GROUND PENETRATING RADAR IMAGING OF SEQUENCE BOUNDARIES AND LITHOFACIES VARIATIONS IN A MIXED SILICICLASTIC CARBONATE DEPOSITIONAL SEQUENCE

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A subsurface interface radar system with a 120 MHz transducer providing zero source-receiver offset and a 0.2 m SP interval was used to collect 18 km of data within a 10 km^2 area of the Martha Brae delta-reef complex at Falmouth, Jamaica. Subsurface penetration exceeded 25 m. The minimum bed thickness resolved was approximately 0.2 m. The digitally recorded data were redisplayed in conventional wiggle trace format using RADAN® software. Predictive deconvolution, automatic gain control and several low pass and high pass filters were applied prior to interpretation of the records. Eighteen shallow (12 m) boreholes and 9 radiocarbon dates within the survey area provided ground truth for comparison with the radar images.

The use of conventional seismic stratigraphic interpretation techniques revealed five sequences based on differences in reflection configurations and interval velocities, each corresponding to genetically discrete geological sequences. From oldest to youngest they are interpreted as 1) subparallel karsted, 2) coral-algal biolithite, 3) quartzose and detrital carbonate alluvium, 4) lagoonal-subtidal carbonates, 5) interdistributary bay muds, peats, point bar accretion deposits, and storm wash-over fans. Units 3, 4 and 5 correspond to the sequences identified in the boreholes and are consistent with the radiometric dates. Units 1 and 2 are below the deepest borehole penetration. Resolution and definition of the radar images is sufficient to identify geological process including channels, lateral accretion of beach sand units and spits, point bar accretion represented by Epsilon cross-bedding, delta plain progradation, karst development, and groundwater dissolution of limestone.

MODELING AND TOMOGRAPHIC INVERSION OF CROSS BOREHOLE RADAR IN LAYERED MEDIA

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Cross borehole radar is widely used to determine subsurface characteristics and to look for natural caverns and tunnels. Forward models of time domain wave forms are computed to aid in interpretation of such data. The forward modeling for multi-layered media, is done in the frequency domain at a sufficient set of frequencies; results are then transformed to give time domain records. The frequency domain results are obtained by numerical integration. Appropriate measures are used to obtain accurate results for source positions near layer interfaces.

Models containing thin layers with both high and low velocities are studied. The ability to resolve such layers is delineated. Also studied are earth models with many layers. Results will be compared to various actual record sections for cross hole radar with a 20 to 40 MHz signal band. Waveform distortions, arrival time and amplitude anomalies are of interest. Time and attenuation ray tomographic inversion are applied to synthetic record sections to show how well tomography can resolve various types of layered earth structure.

MEASUREMENTS AND MODELING OF GROUND PENETRATING RADAR FIELD STRENGTHS IN A LARGE LABORATORY SET UP

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In 1987, Delft Geotechnics started a fundamental research program on the properties of ground penetrating radar. The aim is to develop a system with much better performance than presently available. The major research objects have been:

- measuring and modeling of the electric field strength in the medium as a function of depth, radiation angle and antenna height;
- measuring and modeling the amplitude of pulses reflected by steel and PVC pipes with various diameters.

For the experimental research, a large test facility was constructed. The main part is a 4 m high, 3 m diameter steel cylindrical vessel, filled with tap water. In the vessel a receiving probe can be positioned in a vertical plane. Until now, a 300 MHz GSSI dipole antenna has been used as a transmitter above the vessel. The distance between the antenna and the water surface has been varied from 0 to 20 cm. For the reflection measurements, a second receiving probe has been mounted above the vessel. The following results will be presented:

- measured vertical plane field patterns as a function of radial distance;
- calculated field patterns with the transmitter approximated by a point dipole;
- reflection cross-sections of steel pipes and PVC pipes, the latter massive, water-filled and air-filled; the range of diameters was 0.4 to 7.5 cm;
- calculated reflection cross-sections, using the approximation of plane wave incidence for field polarization parallel with the pipes.

In both cases we found a fairly good agreement between the experiments and the calculated amplitudes. Steel pipes give much stronger reflections than PVC pipes, in spite of the high dielectric contrast between PVC and water. The diameter dependence of the reflected amplitude is much smaller for steel pipes than for PVC pipes.

CONDITION ASSESSMENT OF REINFORCED CONCRETE USING RADAR

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A model has been developed to predict the velocity and attenuation of electromagnetic waves in concrete as a function of frequency, temperature, moisture content, chloride content and concrete mix constituents. The electromagnetic properties of concrete are predicted by aggregating the individual properties of its constituents, water, salt, air, cement paste, and aggregate solids. Results predicted by this mixture model have been found to compare favorably with those obtained from laboratory experiments.

This model, in conjunction with a rebar model developed to account for the reflection produced from reinforcing bars embedded within the concrete, has been utilized to synthesize waveforms for representative reinforced concrete bridge deck geometries. Parameter studies have been carried out to observe the influence of various conditions on the output waveform.

A least squares inversion procedure has been applied to the computer generated synthetic waveforms. Results from this inversion have shown that spatial variations in volumetric water content, salt content, and rebar cover can be accurately predicted.

USE OF AN IMPULSE RADAR IN PEAT RESEARCH

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The Geological Survey of Finland bought an impulse radar in 1985: the Subsurface Interface Radar (SIR) manufactured by Geophysical Survey Systems Incorporated.

Measurements carried out in the summer give better radar profiles than those carried out in the winter when frost and snow cause disturbances, particularly in the surface layer. District border surfaces and also watery flark places can clearly be distinguished inside the peat layer. The impulse radar gives a most accurate picture of the topography of the bottom of the mire. When the peat is Sphagnum-type (moss peat), it is easy to distinguish different kinds of peat layers inside the profiles. This is because in Sphagnum peat there are rapid changes in moisture content. Carex peat (sedge peat) profiles are quite homogeneous.

For practical reasons, radar is mainly used in winter. On the basis of the results from radar, very accurate maps of the thickness of peat layers and bottom soil can be drawn. In the deep areas, driving lanes are situated at 100 meter intervals. The quality and stratigraphy of the peat is studied in the summer at sampling sites which have been staked out during the radar surveys. In winter, the thickness of peat and sapropel is checked in some places by drilling. These drilling sites are also used as reference points when interpreting the radar profile. 80 MHz, 100 MHz, 120 MHz and 500 MHz antennas have been tested in peat research.

ESTIMATING FRACTURE ORIENTATION IN GRANITE USING GROUND PENETRATING RADAR REFLECTION PROFILES

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Last minute substitute presentation. No abstract.

FRACTURE CHARACTERIZATION IN GRANITE USING BOREHOLE RADAR

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Atomic Energy of Canada Limited (AECL) is studying granite of the Canadian Shield as a potential disposal medium for nuclear fuel waste. As part of this research, a number of areas (called Permit Areas) are being investigated near AECL's Whiteshell Nuclear Research Establishment, on the Lac du Bonnet batholith, in southeastern Manitoba. Borehole radar surveying is one of the techniques being used for identifying fracture zones in the granitic rock.

Two cored boreholes have been completed on Permit Area B to assist in geological mapping of the area, and in locating major fracture zones. These holes are collared approximately 120 m apart and plunge to the north at approximately 60°. Radar energy can propagate through granite for distances suitable for geological mapping applications because of the high resistivity of the granitic rock mass. Reflections from within the rock mass are received from changes in the dielectric constant and resistivity of the granite. Fracture zones are more electrically conductive than the rock and are thus suitable targets for the radar method.

Single-hole radar reflection and crosshole tomography surveys at 22 MHz have assisted in mapping the fracture regime surrounding the boreholes. Reflections interpreted as fractures within the rock mass were identified from as far as 120 m away from the boreholes in the single-hole reflection surveys. The positions of the major fracture zones between the boreholes were mapped by the tomography survey.

In this presentation, details of the survey, processing and interpretation techniques are discussed, and the fracture data determined by the radar method are compared with fracture data collected by more conventional methods such as core logging.

RADAR STUDIES OF INTERNAL LAYERS AND BEDROCK TOPOGRAPHY ON ICE STREAMS B AND C, WEST ANTARCTICA

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Surface-based radar studies of Ice Streams B and C, West Antarctica were carried out by a collaboration from St. Olaf College and the U.S. Geological Survey during the 1987-88 and 1988-89 field seasons. The primary purpose of these experiments was to examine in detail conditions at the bed of the ice streams, and echo returns from structures within the ice which might give information about ice stream dynamics and ultimately help in determining the response of the West Antarctic Ice Sheet to climate change. Two high density 100 km transverse profiles were made across ice stream C, and a 5 x 20 km region was studied in detail in a closely spaced grid. Longitudinal profiles 36 km in length were made on ice stream B at 5 transmitter frequencies from 1 to 12 MHz to enable spectral studies of the echo energy content. In the two seasons over 750 km of high-density profiling was completed, resulting in approximately 2 gigabytes of digital data which are currently being processed and studied. Strong returns from the ice-bed interface were obtained in all profiles, and in many places features such as basal crevasses and decimeter-scale bed roughness can be resolved.

The most striking feature of the data however, is the complex pattern of folding and deformation of the internal layering which occurs at a range of spatial scales on both ice streams, and is present in longitudinal as well as transverse profiles. In most cases the folding does not correspond to surface or bed topography and presents a difficult problem of interpretation glaciologically. One hypothesis is that the folding results from non-steady state behavior of the ice streams due to changes in the mass balance at various times in the past. Measured velocities on ice stream C today show it to be nearly at rest, with the shut-down estimated to have begun about 200 years ago. In contrast, the other ice streams have velocities of 1 to 2 meters per day. Radar results from the internal layering may be depicting the consequences of ice stream instability on time scales as short as a few hundred years.

SOFTWARE ENHANCED GROUND PENETRATING RADAR (GPR) DETECTING UNDERGROUND VOIDS

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Several situations exist where detection and localization of long cylindrical air-filled voids are of interest. Examples are the abandoned uncased gas wells in coalfields (vertical), utility pipes (can be PVC or metal and in any orientation), and the much-researched infiltration-tunnel situation.

We have developed a HP workstation-based system which processes and analyzes the GPR output and then optimizing the characteristics common to the above-mentioned situations. These characteristics include aberrations in velocity, amplitude, and frequency content. Signal-to-noise ratios, variability in velocity, frequency content, etc., are also included. The results obtained from our software depend on the number of observations that are made (number of offsets if transmitter and receiver boreholes are utilized). The decision-maker is a "score" that is a weighted combination of the individual characteristics. We have included in the system statistical tests so that probabilities of detection, identification, and misidentifications are proceeded by the addition of representative data sets to the database.

THE EFFECT OF SATURATION HISTORY ON ELECTRICAL PROPERTIES OF THE UNSATURATED ZONE

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In the unsaturated zone, there are two factors related to water content that can significantly affect the electrical properties, and thus the radar response, of the zone. The first factor is the level of water saturation. The second factor is the saturation history within the zone which can be extremely complex due to repeated cycles of wetting and drying. While the dependence of the electrical properties of geologic materials on the level of water saturation has been extensively studied, the effect of saturation history has to date been largely neglected. The laboratory data obtained in this study suggest that saturation history can have a significant effect on electrical properties, and illustrate the importance of considering saturation history in the interpretation of GPR data from the unsaturated zone.

In Knight and Nur (1987), pronounced saturation hysteresis was observed in the dependence of the dielectric constant (K′) on water saturation (Sw) during an inbibition/drainage experiment. In the present study, data were collected during multiple imbibition/drainage cycles in order to more fully characterize the dependence of K′ and conductivity on changes in microscopic fluid distribution. In all cases saturation hysteresis exists, with K′ and conductivity measured during imbibition consistently greater than measured during drainage. The presence of the saturation hysteresis, and thus the non-unique dependence of K′ and conductivity on Sw, can be related to changes in the geometrical arrangement of water and air in the pore space. Specifically, imbibition favors the development of thin, central air pockets and enhanced connectivity of the water phase causing an increased K′ and conductivity.

Knight, R. J., and A. Nur, 1987, Geometrical effects in the dielectric response of partially saturated sandstones: The Log Analyst, v. 28, p. 513-519.

VELOCITY ESTIMATION FROM FIXED-OFFSET GROUND PENETRATING RADAR DATA

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Determination of electromagnetic propagation velocities is important for depth conversion of travel times, post-acquisition signal processing, and inversion of radar data for material properties. We have found several graphical methods, easily applied in the field, for estimating the average velocity to a reflector/scatterer and the interval velocity between two reflectors/scatterers given radar data collected in zero- or fixed-offset mode. If point scatterers are present, they will result in hyperbolic events on zero- or fixed-offset records. The average velocity (v) to the scatterer may be computed from measurements of the slope (dt/dx) of the tangent to the hyperbola at a point (x,t) using the simple relation $v^2=(4xt)(dx/dt)$. Interval velocities may also be estimated graphically given two or more diffraction hyperbolas or reflection events. The same principles may be applied to estimating the depth of scatterers located out of the vertical plane of a radar profile, given two or more parallel profiles. Accuracy of these techniques depends upon how well the positions of the antennas are known, hence data should be collected on regular grids with antennas towed at constant speed.

GROUND PENETRATING RADAR USING A FREQUENCY SWEEPING SIGNAL

(Not Presented)

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In 1989, Norwegian Geotechnical Institute started a new project of applying Georadar technique to the area of environment and engineering geology, to meet the increasing demands from the area. The radar used for performing the project was developed at Environmental Surveillance Technology Programme in Norway. The device consists of an HP-8753A Network Analyzer, antennas, hardware such as amplifiers etc., and an AT computer to perform data acquisition and signal processing.

The radar signal is synthesized by 201 frequency samples to cover any frequency band within 0.3 MHz - 3000 MHz. Hence it is easy to generate radar signals optimal to our existing antennas which are listed below:

- Horn Antenna, working band 1.4-1.9 GHz
- Yagi Antenna, working band 320-380 MHz
- Dipole Antenna 1, working band 5-20 MHz
- Dipole Antenna 2, working band 20-80 MHz

The software is written in the ASYST programming language. This provides the system with a powerful real-time (or field-site) signal processing ability such as 2-D FFT, 2-D matched filtering, color display, etc. The details concerning this frequency sweeping radar, as well as a comparison with conventional impulse radar systems, are discussed in the paper. The radar was successfully used in the previous year to perform the following field tests:

- Detection of the dam core in two large dams where the core is located 5 m deep in rockfill.
- Detection of cavities located 5-10 m deep in rock.
- Detection of tanks and ground water level 2-3 m deep in sandy soil.
- Location of buried tubes, 3-5 m deep, under a traffic street below ground water level.
- Geological investigation of a waste disposal area.

The case studies, together with discussing the difficulties we have met and future improvement directions, are presented in the paper.

Kong, F.N., 1983, Impulse Radar: Ph.D. Thesis, Cambridge University.

ELECTROMAGNETIC SOUNDING IN THE SUCCESSFUL SEARCH FOR BURIED WORLD WAR II AIRCRAFT ON THE GREENLAND ICE CAP

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On July 15, 1942 a squadron of six P-38 fighters and two B-17 bomber aircraft were on a ferry flight between Greenland and Iceland when they encountered bad weather. They turned back to Greenland where they were forced to land on the east coast when their fuel ran out. All aircraft landed without serious injury to the 25 crew members. Six of the aircraft were clustered within about a 400 m diameter area. The other two aircraft were less than about 2000 meters away.

Serious interest in retrieving the aircraft appears to have developed in 1974 with the first on-site visit in 1981. In 1982 an impulse radar and magnetometer search were made. In 1983, radio echo sounding was also used and with this device the aircraft were apparently located. However, because the aircraft were not visually seen or contacted by drilling, the radio echo findings were considered suspect. In addition, the estimated depth of the aircraft was revised several times to increasingly deeper depths. This led some to disbelieve that the aircraft were found.

This paper presents an overview of the expeditions which went in search of the aircraft, and the successful 1988 expedition which verified the location of the aircraft using both radio echo and impulse radar sounding and drilling. Examples of the radio echo and impulse radar sounding records of the buried aircraft are shown. Reasons why the aircraft were not found during earlier impulse radar sounding surveys are also given.

GPR APPLICATIONS FOR BRIDGES AND HIGHWAYS IN MASSACHUSETTS

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GPR (ground penetrating radar) was used in several Massachusetts projects to evaluate bridge abutments and bridge decks, and to detect and delineate subpavement voids.

The abutments, consisting of granite blocks and cobble stones, are over 100 years old and of unknown dimensions. The bridge decks are 8 inch thick concrete sections with two levels of rebar and overlain by 1 to 2 inches of asphalt; deterioration and delamination is suspect due to spalling and pothole occurrences. The subpavement voids are suspect due to surface settlement and coincide with the alignments of jacked pipelines.

The GPR systems include 900 and 500 MHz antennas to provide adequate penetration and resolution. All objectives were accomplished, but record quality was variable due to a variety of field conditions.

Although such targets as rebar with varying spacings and bi-level occurrences are readily observed, the detection of a delamination depended on moisture or "weathering" of materials that occur within the delamination. Abutment blocks are readily penetrated, but interfering reflectors are noted for all "faces", including the incident face of the block-fill boundary. Void detection was readily achieved, but lateral and vertical delineation required a gridded program of intense coverage.

NUMERICAL SIMULATION OF SUBSURFACE RADAR FOR DETECTING BURIED PIPES

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A subsurface radar for the detection of dielectric or metal pipes buried in the ground is investigated numerically. The two-dimensional transmission line matrix (TLM) method is used to obtain images of buried pipes illuminated by electromagnetic pulses generated by a ground-penetrating radar. The efficiency of the TLM method is greatly increased when non-uniform grids and absorbing boundary conditions are used. The returned signal from the pipe is plotted with 20 different color codes. In the case of a single buried pipe, the false-color image looks like a hyperbola which becomes flatter when the diameter of the pipe becomes greater. The results also show that metal pipes produce single images while air-filled plastic pipes produce double images. Images of two parallel pipes buried at different depths are also obtained.

POSTER: GPR RESEARCH AT THE UNIVERSITY OF ARIZONA

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The Laboratory for Advanced Subsurface Imaging (LASI) conducts geophysical research using signal and image processing with several EM techniques. One part of this research utilizes a Geophysical Survey Systems, Inc. (GSSI) ground penetrating radar (GPR) system with 300 and 500 MHz antennas to investigate four topics:

1. Southwestern U.S. Surveys -- study the effectiveness of GPR in the conductive soils of the Southwestern US in archaeological, geotechnical, and criminal investigation surveys.

2. Test Site -- observe changes in target responses as functions of changes in dielectric constant and conductivity at a test site where moisture content and conductivity can be controlled, as well as monitored using Time Domain Reflectometry (TDR), resistivity, borehole neutron surveys, and temperature surveys.

3. Data Processing -- digitize the radar returns and apply commercial PC and mainframe seismic data processing software for target enhancement.

4. Neural Networks -- use known target locations and observed velocities to train neural networks to recognize target patterns and predict target location.

Through these investigations, we have found that GPR can be useful in conductive soils, if its limitations are recognized. Research at the test site defined these limitations. Signal processing and neural network image training extend the usefulness of GPR to areas where automated target location is needed.

GPR SURVEY OF AN AFRICAN-AMERICAN CEMETERY IN LITTLE FERRY, NJ

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A ground penetrating radar (GPR) reconnaissance survey was carried out on 17 August 1989 at Gethsemane Cemetery, an African-American burial ground in Little Ferry, NJ, in order to assess and locate unmarked burial sites. Scans were run on 1.5 m (5 ft) parallels with a GSSI model 3102 500 MHz transducer, which provided excellent target resolution in the sandy soil. Radar penetration was obtained in excess of 50 ns, corresponding to a depth of about 3 m (10 ft), at an assumed dielectric constant of 6.25 for the sand. A total of 44 radar echoes that could be interpreted as individual burial sites were located and mapped in a 420 m^2 (4500 ft^2) area. All radar targets lay at a consistent depth between 1 and 2 m (3-6 ft) below the surface. Stacked or multiple echoes could be seen on some returns, with a shallow one at 0.1-1.2 m (3-4 ft), and a deeper one at 1.5-1.8 m (5-6 ft), consistent with an interpretation of multiple burials in one plot. In addition, targets were seen side by side, at the same depth, suggesting penecontemporaneous burial. The appearance and depth of the targets at the unmarked sites were consistent with radar returns obtained around known gravestones and markers in this cemetery. Based on this GPR survey we estimate a total cemetery population of 367. This estimate is consistent with various records indicating that a minimum of 331 burials were made in Gethsemane from 1861 to 1924.

SOIL SURVEYS: A GUIDE FOR GROUND-PENETRATING RADAR APPLICATIONS

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Knowledge of the dielectric properties of earthen materials can be used to assess the feasibility and potential profile depths of GPR applications. The dielectric properties of earthen materials varies with changes in moisture content, particle-size, clay mineralogy, salt content, organic matter content, and temperature. General information concerning the nature and distribution of these parameters can be obtained from the classification of soil taxa and maps found in published soil survey reports. In addition, the criteria used to define soil taxa can be used to aid interpretations of signatures appearing on radar profiles. Once signatures have been properly identified, detailed soil maps can be prepared from parallel radar profiles. GPR techniques were used to prepare a detailed soil survey of a portion of the Southwest Michigan Research and Extension Center near Benton Harbor.

ASSESSING THE ABILITY OF GROUND PENETRATING RADAR TO DELINEATE DIFFERENT FLUVIAL SEDIMENTS

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The distinctive dielectric properties of gravels, sands and muds enable ground penetrating radar (GPR) to be useful for examining the various depositional textural units in fluvial sediments. A field study was carried out to determine the ability of GPR to delineate the extent and internal structure of fluvial sediment bodies in the Columbia River Valley near Golden, British Columbia, Canada. GPR surveys were carried out over abandoned channels, levees, crevasse splays and wetlands. Both 50 MHz and 100 MHz antennas were used to profile ancient deltaic deposits to compare depth of penetration and resolution attainable with the different antennas. In all the surveys, traces were recorded every meter along the profile. Vertical resolution was determined to be in the order of 50 cm from theoretical calculations and borehole information.

By surveying across a makeshift bridge and from a wood floored zodiac boat, the GPR unit was used as a sub-bottom profiler of sediments in active river channels. The surveys provided channel bottom profiles and displayed the sub-bottom sediment structures. The considerable difference in propagation velocity between saturated sediment and the water in the channel, created lateral variations in the signal travel time relationships from reflectors from beneath the river. This problem was corrected by differentially windowing portions of the profile when processing the digital data.

The profiles demonstrate how GPR is able to map the interfaces between various fluvial lithofacies as well as the internal structure of each unit. The deepest penetration, 32 m, was achieved in the dry gravelly delta deposits, using 50 MHz antennas. At the same location, 100 MHz antennas detected dielectric variations to a maximum depth of 24 m. In the channel and floodplain deposits the increased dielectric constant and conductivity limited depth of penetration to an average of 7.4 m. The greatest attenuation occurred in lacustrine muds, where reflections were observed to a depth of only 3 m. While there was less penetration in the floodplain deposits, the decrease in velocity produced a much needed increase in the resolution.

TIME DOMAIN RADAR SIGNATURE OF A CYLINDER FOR RAY PATHS AT AN ARBITRARY ANGLE TO THE AXIS

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Exact expressions were found for the cross borehole radar signature of a cylindrical anomaly. The source and receivers are point electric dipole antennas. The frequency domain solutions are valid for both near and far field. Let α be the angle between the perpendicular to the tunnel axis and the ray path. Computer evaluations are used to construct waveforms for arbitrary α. Previous results have given good fit to PEMSS (Pulsed Electromagnetic Sensing System, center frequency 30 MHz) field data using a two dimensional model for paths with $\alpha = 0°$ (perpendicular to the axis). In the present work, an excellent fit is obtained to field data with $\alpha = 28°$ for a 2 m diameter air filled tunnel. The waveforms are considerably different than for an $\alpha = 0°$ raypath.

Further modeling of the air filled tunnel shows how the waveform changes with α. The early arrival that is present for $\alpha = 0°$ gradually changes and disappears around $\alpha = 30°$. The disappearance is consistent with simple ray theory arguments. For $\alpha > 40°$ the waveform is shown to be due to energy that refracts around the cylinder; the wave shape is not affected by the presence of the tunnel, but the amplitude is decreased.

Results are also presented for different tunnel sizes, for dipping tunnels, for water filled tunnels, and for tunnels lined with conducting material.

TUTORIAL: MODIFICATIONS OF RADAR SCATTERING SIGNATURES BY ANTENNA PARAMETERS

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Antennas and scattering determine the subsurface radar profile used for data processing and interpretation. The subsurface radar image is a rough approximation of the real geological structure. In data interpretation, radar time-of-flight converts to a depth scale with knowledge of the complex dielectric constant of the medium. Propagation and scattering of electromagnetic (EM) pulses in earth materials is frequency dependent. Antenna design is a critical element in the optimization and operation of ground penetrating radar (GPR). Antenna design influences radar system output, and therefore data processing techniques.

Antenna radiation patterns determine the scattering image of subsurface targets, while the dielectric properties of the ground shape the radiation pattern within the ground. The air/ground interface is usually within the radiating near-field (Fresnel zone) of GPR antennas; therefore, antenna parameters change as a function of ground coupling and EM ground properties. Generally scatterers are in the far-field (Fraunhofer zone) and their scattering cross section is determined by their dielectric contrast, size, shape and orientation.

From an electromagnetic perspective, geological materials are heterogeneous mixtures consisting of two or more substances. Propagation and scattering are related to the complex dielectric constant of the individual substances, their volume fraction, their spatial distribution, and their orientation relative to the direction of the incidence electric field vector. The resultant average complex dielectric constant of the mixture is frequency dependent and influences the attenuation, diffraction, diffusion, dispersion, reflection and refraction of the wideband GPR signal.

RADAR CROSSHOLE TOMOGRAPHY AT THE GRIMSEL TEST SITE WITH APPLICATION TO MIGRATION OF SALINE TRACER THROUGH FRACTURE ZONES

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A comprehensive radar crosshole tomography survey has been carried out at the Grimsel Rock Laboratory in order to test the radar method with respect to its capability to describe geological features and to map migration of saline tracer through difference tomography. The radar survey has provided a map of the attenuation and slowness distribution of radar waves in a planar section with the dimensions 150 x 225 m. The program has included measurement points along parallel boreholes and a tunnel connecting these boreholes.

The slowness and attenuation tomograms give similar images of the structures at the investigated site. The largest anomalies are caused by lamprophyric dikes which are almost parallel to the boreholes while fracture zones give rise to anomalies of smaller magnitude. The attenuation tomograms have poorer resolution and contain more artifacts than the slowness tomograms. This is caused by systematic errors in the amplitude data caused by inadequate knowledge of the antenna radiation pattern for source points located in the tunnel.

The transport of saline tracer was investigated by making a tomographic inversion of the difference between data collected prior to injection of saline tracer and during injection. Two such experiments were performed with different injection points. The largest concentrations of tracer were observed close to the injection points. The tracer followed fracture zones extending from the injection points. The results clearly show the unique capabilities of the radar method to map tracer transport through fractured rock.

TUTORIAL: HIGH FREQUENCY ELECTRICAL PROPERTIES

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At frequencies above a few megahertz, the magnetic permeability of most geological materials is indistinguishable from free space. Thus, the electrical properties of the material dominantly describe the propagation of electromagnetic energy through the material. Electrical properties are parameterized to describe the low frequency charge transport process (DC conductivity) and the high frequency charge separation process (dielectric permittivity). Above a few hundred megahertz, the electrical properties of geological materials are describable by simple physical mixing of their different component parts, and fall within the predictions of the Hashin-Shtrickman bounds for the Bruggeman-Hanai-Sen (BHS) formula. Frequency dependence in high frequency electrical properties arises from the properties of water, geometric scattering, and chemistry. The BHS formula also works using the frequency dependent, complex permittivity of the components as long as the materials are non-interacting. At frequencies below 100 MHz, chemical interactions occur between water and clay minerals that violate the assumptions of the BHS formula, invalidating its predictions when wet clay minerals are present. At higher frequencies (dependent upon scale of heterogeneity), geometric scattering may cause interaction between the propagating electromagnetic wave and inhomogeneities of comparable size to a wavelength in the material, again invalidating the formula predictions. In general, the effects of gravel sized scales are observable near 1000 MHz, with boulders important at 100 MHz.

The loss mechanisms that control the depth to which ground penetrating radar may penetrate include the losses in the system (particularly antenna efficiency), geometric spreading losses, and four types of material loss. These include electrical conduction loss which turns electromagnetic energy into thermal energy (heat); dielectric relaxation of the rotational orientation of the water molecule in a viscous medium in response to an electrical polarizing field; diffusion-limited ion transport in the cation exchange at the surface of wet clay minerals (clay-sized surface reactive minerals are required -- engineering clay fraction materials like silica rock flour do not qualify); and geometric scattering that sends energy in unwanted directions. Different losses are important in various geological materials or at various frequencies. At the highest frequencies of ground penetrating radar usage (1,000 MHz), water relaxation and scattering losses are more important than conductivity and clay losses. At the lower frequencies (below 100 MHz), the reverse is true. From one to several hundred MHz, the type of material and its state are most important in determining which loss is dominant. In ice, the temperature determines whether the ice is fully frozen (polar ice) or contains pockets of water (temperate glacier). The difference is a degree of scattering loss and the frequency of deepest penetration. In granite, the dominant loss is scattering from fractures. In soil the dominant loss is water relaxation or mineralogical clay content.

TUTORIAL: GROUND PENETRATING RADAR DATA PROCESSING AND MODELING

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Electromagnetic propagation in the earth is deceptively similar to elastic (seismic) propagation in the earth. Both involve wave propagation, but the differences in detail create problems when directly applying unmodified seismic processing and modeling methods to ground penetrating radar data. The electromagnetic wave equation contains a conduction term that is not present in the elastic wave equation. The electric and magnetic fields are tightly coupled in electromagnetics, but the compressional and shear components are only loosely coupled in seismics. Mode conversions are common in seismics but uncommon in electromagnetics. Seismic wavelets may be minimum phase, but electromagnetic wavelets are mixed phase, never minimum phase. Electromagnetic wavelets routinely exhibit considerable pulse broadening (distortion) due to frequency dependent velocity and attenuation (dispersion), but dispersion is often safely ignored in seismics. Nonetheless, ground penetrating radar data may be deconvolved and migrated, ray-traced, and full waveform synthesized much like seismic data.

Most often, no processing of ground penetrating radar data is required to solve the problem posed. The image produced by the radar system has sufficient detail to directly solve the problem (such as locating a lost metallic pipe) with little interpretation uncertainty or ambiguity. Other times, it is necessary to determine whether the reflections observed on the radar record are below or above ground, to correct the record for data acquisition distortions (produce a true geometric cross section), to eliminate pitfalls (similar to seismic pitfalls), or to pull subtle details from the data (tracking a rainfall wetting front). In such cases, computer processing is required.

The first step in computer processing of ground penetrating radar data is to combine the radar data with surveying data to correct for distortions of the data acquisition process. Using timing marks on the radar record with surveyed locations of the places where the antenna was when the mark was put on the record, the radar record can be rubber-sheeted to correct for location (vertically due to topography and horizontally due to variations in antenna movement speed). Next, differences in contrast on the radar record may be enhanced by adaptive deconvolution -- where the deconvolution filter changes to accommodate dispersion in the wavelet. Next, the results of a radar calibration using a walk-away reflection test to acquire velocity and dielectric permittivity may be combined with the radar record to migrate the section from a time section into a depth section. Last, the radar reflectivity and wavelet dispersion may be corrected for spreading and full waveform modeled using antenna system calibrations to derive dielectric permittivity and attenuation versus depth. These may then be used to estimate changes in density and water content versus depth. Without doing the deconvolution and full-waveform modeling, ray tracing may be used to enhance the location accuracy of specific features in the record.

TUTORIAL: VELOCITY, ATTENUATION, DISPERSION AND DIFFRACTION TOMOGRAPHY

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Tomography is a mathematical process that exploits geometry to reconstruct the properties of a material that has been observed from several different viewpoints. Velocity and attenuation transmission tomography utilize the first arrival information in wavelets propagated through the material between boreholes. Dispersion tomography utilizes information in the full wavelet. Diffraction tomography utilizes the information in the full received wavetrain (not just the first arriving wavelet). Velocity tomography principally represents the physical properties (density, porosity, etc.) and state (liquid content, saturation, etc.) of the media along the raypath which the wavelet transits. Attenuation tomography represents the physical properties and state plus the scattering effects of geological heterogeneities and interferences from combinations of multiple propagation paths. Dispersion tomography is a full waveform view of attenuation effects, approximately proportional to frequency dependence of velocity and attenuation. Velocity transmission tomography must precede diffraction tomography to provide the estimate of velocities required in the diffraction migration or inversion. Diffraction tomography can produce nearly an order of magnitude higher resolution imaging of heterogeneities.

In practice, the construction of velocity, attenuation and dispersion tomographs is always possible, but diffraction tomographs are not always possible due to noise, insufficient diffraction events, and complexity of geological heterogeneity. Velocity, attenuation and dispersion tomographs may be misleading if the data is not properly acquired and processed. Errors in borehole location, hole deviation surveys, offset between probes, probe depth locations, distorted waveforms, and digitization or trigger timing errors all contribute to distorted tomographs. Common tomographic reconstruction methods assume normal statistics, allowing a least square fit of the calculated model tomograph to the measured data; however, geology commonly exhibits log-normal, multimodal or other variant statistical descriptions, invalidating the least square fit.

The similarities between electromagnetic and elastic wave propagation are great (both propagate according to nearly identical equations), and most of this discussion applies equally to both. However, their differences are also great, and the details are important when implementation occurs. For example, the electric and magnetic vectors in electromagnetic wave propagation are always tightly coupled, but the compression and shear components of elastic wave propagation are only loosely coupled. Elastic wave sources create tube waves that re-radiate from the borehole almost creating a line source, while EM waves do not. EM has less transducer-media coupling problems than elastic waves. Intrinsic attenuation mechanisms are very different, but scattering losses are very similar. In general, one tomographic processing algorithm cannot process both electromagnetic and elastic wave data without considering the differences.

POSTER: SEDIMENTOLOGY OF EOLIAN SAND DUNES BY MULTIFREQUENCY GROUND PENETRATING RADAR

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In November, 1988, a multifrequency (80, 150, 300, 500, and 900 MHz) ground penetrating radar survey was performed at the Great Sand Dunes National Monument in Colorado. The separate frequency radar data sets were geometrically corrected for topography and variations in antenna movement. The corrected datasets were merged and presented as 'radar trench' cross-sections in directions parallel and perpendicular to the prevailing winds. The 900 Mhz antenna data exhibited centimeter resolution to depths of four meters; with decreasing frequency, the other antennas penetrated deeper but with less resolution (the 80 MHz antenna penetrated about 40 meters with decimeter resolution).

Collectively, the multifrequency data set clearly shows the major sedimentological structures in the eolian dunes, avalanche foresets, blowbacks, interbedding, and their abrupt change when the dunes are crossed by a river. The 'radar trench' shows the dramatic changes in sedimentary history that occur as the eolian and fluvial processes compete, with one over-riding the other periodically. The process boundaries and the transition from sand to alluvial fan are very clearly mapped to a depth of 40 meters over traverses of 300 meters. The 'radar trenches' also show the river feeding the water table under the dunes and the detailed structure at the water table as the water level recedes in annual cycle (the river is fed by snow melt -- high in late spring, low in late fall).

Detailed sedimentological analysis of the structures, processes, and their relationships in this modern eolian environment can lead to insights of use to petroleum reservoir modelling of similar ancient eolian sedimentary rocks. The length scales, interbed correlations and statistical descriptions are directly useful in stochastic fluid flow models. Within the same environment and only tens of meters of distance, dramatic changes occur with the process of sedimentation (eolian versus fluvial) as well as change in material (sand versus alluvium).

POSTER: DERIVING LENGTH SCALES, CORRELATIONS AND STATISTICS OF SOIL STRUCTURE FROM GROUND PENETRATING RADAR DATA

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In 1984 through 1988, several gigabytes of 80 and 300 MHz ground penetrating radar data were acquired over a three-dimensional grid at the U.S.G.S. Water Resources Division research site near Bemidji, Minnesota (Hult, 1988). The original purpose in acquiring the data was to map the location of a petroleum plume floating on the water table. The plume resulted from a petroleum pipeline break. This was accomplished from the raw radar field records without processing of the data (Olhoeft, 1986).

The radar data also exhibited detailed soil structure and depth to the water table. To enhance interpretations of the hydrogeology, the data were processed to remove acquisition distortions (topography and variations in antenna movement), and normalized to cancel geometric spreading losses. The resultant data were smoothed with a 5-scan running average, and then contoured at the wavelet zero-crossings. The contours were color coded by length of horizontal connected structure. These color-coded contours indicated the scale of heterogeneity in existence at the site as well as the structural relationships. The length-scales, structure correlations, and statistics were derived using methods of describing soil variability comparable to Jury (1985). However, the radar data alone could not indicate whether the mapped radar structures were conduits for hydrologic flow or barriers to hydrologic flow. Comparison of the radar cross-sections to cores acquired on the radar lines indicated the radar structures were thin, finer-grained and slightly higher moisture content tills than the average background glacial outwash materials.

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SOME FIELD, LABORATORY, AND THEORETICAL INVESTIGATIONS OF FRESH WATER, ICE, AND SOIL LAYERS USING SHORT PULSE RADAR

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An overview is presented of recent activities and results in the use of commercially available short pulse UHF radar for surveying various environmental conditions. Elevated antennas are used to produce relatively well-defined transmitted wavelets and thus allow more revealing signal processing. Newer radar systems cannot do away with the need for lower frequency systems with diminished resolution which achieve greater penetration in wet or otherwise lossy media. Fresh water ice is considered as a first example hydrological system. Beyond deconvolution methods for recognizing isolated interfaces with a noisy, non-minimum delay wavelet, we show results for thin ice layers which cannot ordinarily be distinguished in unprocessed returns. The two methods applied are designed to recognize the interference patterns from parallel interfaces close to one another. In the frequency domain, a phase signature algorithm has been successfully applied over a wide range of thicknesses; a time domain method performs similarly well on new data from pond ice. Both methods distinguish an ice-free surface from an ice layer a few centimeters thick when the wavelet length in ice is much greater than that.

The general effects and constraints imposed by wet and inundated surfaces are discussed, when one wishes to detect features below the surface. The implications of sloping bottoms for surveying the depth of surface water bodies are also analyzed, particularly in relation to critical angle effects. In both cases, theoretical guidelines are born out in limited field data. Work in progress is reviewed on the characterization of a thin thawed (wet) surface soil layer over a frozen (dry) depth. The goal is to infer the product of surface layer thickness times layer-average moisture content. Preliminary tests are encouraging. An approach to characterization of smoothly changing moisture content profiles in unsaturated soil is also suggested.

BURIAL DETECTION USING GROUND-PENETRATING RADAR

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In November of 1989, two ground penetrating radar (GPR) surveys were performed in conjunction with archaeological investigations of suspected cemeteries in the southeastern United States. The first survey was conducted over a site situated in the proposed corridor of a natural gas pipeline in Caroline County, Virginia, being studied by Espey, Huston, & Associates for the Virginia Natural Gas and Virginia Power Companies. The second site, identified as a probable cemetery by the Phase I archaeological investigation of the I-85 alternative corridor in Spartanburg County, South Carolina, was surveyed in conjunction with the Phase II investigation conducted by New South Associates for the South Carolina Department of Highways and Public Transportation. In both surveys, GPR was successful in detecting anomalous features that were confirmed by "ground-truth" excavations to be historic burials. Some of the anomalous reflections resulted from natural stratigraphic variations. The GPR interpretation of probable burial locations is compared to existing conditions uncovered by archaeological excavation. GPR data profiles are presented with trench excavation profiles to compare actual features to the resulting reflections, and explain data interpretation. The right-of-way alignment was altered to bypass the first site, based on the GPR survey findings. Burial removal is scheduled to begin May 1990 on the second site, using the GPR anomaly map as guide for locating burial pits.

GROUND PENETRATING RADAR SURVEYS FOR ARCHAEOLOGICAL PURPOSES

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During 1989 Progera s.r.l. carried out several GPR (ground penetrating radar) surveys for archaeological purposes. Three case histories are here presented to confirm the capability of radar in detecting not only archaeological remnants but also to verify the status of old pavements and mosaics.

1) An archaeological site situated between Venice and Trieste (Italy) was investigated by a 300 MHz antenna. It was characterized by Roman buildings, walls, and a paved road. Geology was alluvial deposits. The depth of objectives varied from about 2 meters to about 6 meters below ground level.

2) A survey was carried out inside St. Peter's Basilica, Vatican City - Rome by a SIR 8 System with a 500 MHz antenna. Radar was able to distinguish all the strata below the marble pavement. The whole survey was performed without any disturbance to the normal pilgrim activity.

3) The last survey tried to distinguish voids and/or delamination beneath mosaics, by means of a 900 MHz antenna. The site was S. Apollinare Nuovo Basilica near Ravenna (Italy).

A SYNTHETIC PULSE GPR BASED ON A NETWORK ANALYSER

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An experimental system has been constructed to carry out GPR measurements in the frequency domain and then convert them into the time domain (the synthetic pulse technique). The system is built around a Hewlett Packard network Analyzer and the help of F. Caspers from C.E.R.N. (Geneva, Switzerland) is acknowledged in that respect. In operation, the Analyzer measures the characteristics of the two antennas plus the ground underneath, as it would do with an electronic component.

The aim of this project is to produce high penetration measurements with a well known wavelet.

Measuring with a network Analyzer provides several interesting features:
- a relatively high dynamic range can be obtained thanks to the narrow receiver bandwidth. Calibration functions enable antenna response correction;
- If necessary, the hardware can be tuned at each frequency;
- the combined use of time and frequency domains brings a good understanding of physical phenomena;
- it is possible to measure in the bistatic and/or monostatic mode and to determine in situ the antennas RF characteristics;
- antennas can be designed interactively and matched to the ground with the network Analyzer.

Achievements today include antennas, software programs and methodology. Three antenna sets have been designed, loaded dipoles and pseudo-dipoles (15 MHz - 150 MHz and more) and zigzag spirals (500 MHz - 3 GHz). Processing has been focused on the combined use of histogram equalization and signal envelope, together with conventional data enhancement. Extensive methodology and penetration tests have been performed in various French limestone facies.

Ongoing research deals with deconvolution and wavelet calibration, measurement in the low frequency dispersive domain, modeling, tomographic analysis, and methodology.

DIELECTRIC PERMITTIVITY DEPTH PROFILES USING LABORATORY MEASUREMENTS OF CORE FROM A SANDY AQUIFER

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Ground penetrating radar (GPR) surveys on surficial deposits are capable of detecting subtle stratigraphic boundaries. In some cases, it is difficult to attribute the reflectors observed in a radargram to specific stratigraphic horizons. Previous attempts at correlating laboratory measurements of the dielectric permittivity in core, with radar reflectors observed in the field, have not been very successful. We have developed an improved measurement technique that can be applied to undisturbed core collected in aluminum tubes using a piston coring system. As well, the technique causes minimal disturbance to the core during the measurement process. TDR (time domain reflectometry) is used to measure the dielectric permittivity in the coaxial transmission line that is formed by the core tube and an inserted inner conductor. Using this technique, depth profiles of dielectric permittivity have been obtained on 5 ft core segments from the Canadian Forces Base Borden hydrogeological test site. The cores were collected below the water table in a relatively uniform sandy aquifer. These measurements clearly show a thin peat zone of high dielectric permittivity that is a known radar reflector at this site. The measured dielectric permittivity depth profiles are used to generate synthetic radargrams and these are compared to the GPR field data.

APPLICATION OF GPR TO GAP DETECTION AND FLOOR SUBSIDENCE

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Two ground penetrating radar surveys were conducted over the floor of an industrial plant. The objectives were twofold, 1) to determine the areal extent and type of gaps or cavities causing partial floor subsidence and 2) to detect cavities having the potential to cause subsidence and/or damage to heretofore undisturbed portions of the factory. Analyses consisted of displaying both migrated and unmigrated data in color, examining amplitude anomalies, and noting polarity changes. Data were integrated with visual observations, utility maps and exploratory drilling. Interpretation of the radar data revealed several anomalies. One was subsequently drilled and found to be associated with a previously unknown 8 centimeter gap. Other amplitude anomalies could be correlated with the grouting program, suggesting GPR color displays can be used to determine the direction of grout flow and the program's efficiency.

DIRECTIVE ANTENNA ARRAY FOR A BOREHOLE RADAR

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Some attempts have been tried to obtain a directional antenna for a borehole radar. A corner reflector antenna, and an eccentric antenna have possibility with one antenna element, and a few types of an array antenna have also been investigated.

A set of cross-loop antennas and an Adcock array have almost a common principal for achieving the directivity. Both of them measure the phase difference of the arriving electromagnetic field. When they are used as an antenna for a borehole radar, both of them have relatively long straight wire elements and the only difference between them is mutual connections of these element at antenna tips. Consequently, the general configuration of these types of array is loaded elements at their tips, and its characteristics can be controlled with the loading impedance. Because of the small diameter of a borehole, the antenna elements must set quite closely together. Consequently, the mutual coupling between them is large, and the antennas should be treated as a quasi transmission-line.

We have theoretically analyzed the receiving mechanisms of this type of antenna and present a method to achieve optimum design of an antenna array. The basic idea used for the design is understanding of an impulse response of the antenna, and synthesis of the desired signal form in the time domain. A faster damping of the receiving signal was achieved compared to the conventional cross-loop antennas or an Adcock array without the loss of sensitivity or directivity.

This design methodology was examined by laboratory experiments. The experiments were carried out in a borehole drilled in a block of granite. Measurements support the validity of the theory.

CASE HISTORY: GPR EVALUATION FOR DETECTION OF BURIED PIPES AND BARRELS AT THE COLUMBIA TEST SITE, WATERLOO, ONTARIO, CANADA

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The Department of Earth Sciences at the University of Waterloo has established the Columbia test site for evaluating the effectiveness of various geophysical techniques for detecting buried pipes and barrels. At this site which is a clay silty soil, single barrels are buried at varying depths from 0.5 meters to 2 meters. In addition, groups of four and nine barrels are buried in clusters. Metallic and plastic (air and water filled) pipes are buried at depths varying from 0.5 to 2 meters.

Test surveys at this site with a pulseEKKO IV radar system have been carried out to evaluate the lateral detection limit achievable with radar methods. In addition, the radar data method was used with magnetic gradiometer and EM techniques.

The lateral detection limit for single 45 gallon barrels was found to be about 1.5 meter with a system operating at 100 MHz center frequency and a 1 meter antenna separation. This very localized response is consistent with a high resolution of the radar method. Very accurate depth to target determinations are also achieved.

When compared with the EM and magnetic methods, which have larger detection foot points, much higher spatial data density is required with radar to assure no targets are missed in a reconnaissance survey. The optimal search, detection and discrimination survey normally requires a blending of these techniques to be cost effective.

THE "RADAR RIVERS" OF THE EASTERN SAHARA: SIGNAL PENETRATION AND SUBSURFACE SCATTERING OBSERVED BY THE SHUTTLE IMAGING RADAR

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Using images from the Shuttle Imaging Radar (SIR-A/B) Experiments, McCauley et al (1982, 1986) showed that fluvial processes have played an important part in shaping the extremely flat, featureless landscape of the Eastern Sahara over the past 10,000 to 30,000,000 years. In the extremely dry core of the Eastern Sahara, the SIR A/B 23.5-cm-wavelength signals penetrated the modern eolian sand mantle (centimeters to several meters thick) and were locally scattered, attenuated, or reflected from dielectric discontinuities within the unconsolidated alluvium or bedrock below. As a result, a vast network of broad alluvial valleys ("radar rivers") and smaller channels was revealed. Subsequent field expeditions to the Eastern Sahara have provided important new data on subsurface radar responses (Schaber et al, 1986), groundwater potential (McCauley et al, 1986), and the relation of early Stone Age man (McHugh et al, 1988a, 1988b, 1989) to the previously unrecognized late Quaternary fluvial environments. The dominant factors related to efficient microwave signal penetration into the sedimentary blankets in the Eastern Sahara were shown to be extremely low moisture content, scarcity of clay minerals, and minimum attenuation and geometric scattering at the SIR-A/B frequency (1.3 GHz). Given the tradeoffs between frequency and depth of penetration due to scattering, the SIR frequency lies at the transition between DC conduction and scattering losses, and thus in a frequency region of minimum signal attenuation. For SIR-A, the "radar-mapping depth" (1.5 to 3 m) in hyperarid, sandy alluvium of the Eastern Sahara was found to be about 0.25 times the measured electrical skin depth.

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EXPERIENCE WITH GROUND PENETRATING RADAR IN GEOTECHNICAL APPLICATIONS

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The Geomechanics Division of CSIRO has been carrying out field investigations with ground penetrating radar (GPR) since suitable equipment was obtained in 1986. The Division's experience with GPR in a wide variety of sites and geological conditions has clearly shown that the radar method is capable of generating valuable information concerning shallow sub-surface structure. Radar data obtained from a variety of field investigations is presented including images obtained from tunnel walls in an hydroelectric scheme in Southern China, buried pipe-lines, foundation studies in Australia and New Guinea and radar profiling over water.

In addition to the collection of field data, a program of equipment development has been carried out by the Division. Developments include:

° High speed data acquisition of radar waveforms using an IBM-PC/AT with a 130 kHz, 12 bit A/D and supporting software developed within the Division.

° Software (IBM-PC compatible) to produce a "real time" color image display with a choice of color palettes and to carry out simple on-line signal processing tasks such as waveform stacking. Additional software has been developed to perform deconvolution, classical migration and a variety of image analysis routines such as high-pass and low-pass filtering and edge detection/enhancement.

° The measurement of radio-frequency electrical properties of rock samples up to 100 MHz using an impedance bridge and dielectric sample holder. The impedance measurements can be used to calculate dielectric properties, resistivity and loss tangent values using PC based software. These values are then used to estimate radar pulse velocity and attenuation.

Technical details of the software will be discussed together with the theoretical background to the attenuation measurements and radar image processing.

CALIBRATION OF WATER TABLE LOCATION IN A SANDY SOIL USING GROUND PENETRATING RADAR

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A study was conducted to assess the implications of GPR calibration of the depth to a water table using different procedures. A Geophysical Survey Systems, Inc., SIR-8 impulse radar with a 120 MHz antenna operating at a scanning rate of 100 ns was used to produce GPR images along seven 130 m transects of a field site. The study site is located near Tifton, Georgia, in the Coastal Plain physiographic region of the southeastern U.S. The soil on the study site is classified as a Lakeland sand with profile depths from 1.9 to 4.4 m. Underlying the sand is a restricting layer consisting of tight clays. Thirty shallow monitoring wells were located adjacent to the transects on a 12 by 12 m grid. Sections of 2.5 cm diameter galvanized iron pipe, 1 m in length, were buried at three depths beneath two of the transects as depth standards. The GPR was used to map the position of the water table daily during a ten day interval. Four different methods were used to develop a calibration between the observed depth to the water table and the distance recorded on the GPR chart.

Calibration based on observed depths to the water table is the best method. For cases where the water table is present over the entire site, only a few monitoring wells are needed in order to develop a reliable calibration. Calibration of GPR to predict depths to the water table based upon known depths to objects within the unsaturated zone did not produce accurate results. Additional work will be required in order to determine what interface is being shown by the GPR and identified as the water table.

DETECTION OF ABANDONED COAL MINE WORKINGS WITH RADIO WAVES

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Coal and metal/non-metal mines worked in past years are often times poorly documented. Passageways in these mines may be air (methane or carbon dioxide) or water filled. The collapse of passageways has created subsidence problems in built up areas. The threat of intersecting old workings in mining creates ventilation and water flood problems in open pit and underground mines. This paper describes the use of electromagnetic (EM) seam waves in the low and medium frequency band to delineate the boundaries of an abandoned coal mine.

RADAR ICE THICKNESS MEASUREMENTS IN THE LINCOLN SEA

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In April and May of 1989 we measured ice thickness in the Lincoln Sea, which is north of Greenland and Ellesmere Island, with a pulsed radar operating at a center frequency of 200 MHz. We examined both pack ice on the open ocean and multiyear landfast sea ice (MLSI) in several bays along the northern coast of Ellesmere Island.

A 512-m long line was surveyed at 1-m intervals on a large pan of pack ice 150 km from shore. There were few surface features but the thickness varied by factors of two over short intervals, which means that care must be taken when comparing radar and borehole measurements.

The bay west of Stuckberry Point on Ellesmere Island is filled with MLSI. We surveyed a 3.8-km line down the bay and a 1.9-km line across its mouth, both at 10-m intervals. Several holes drilled through the ice allowed calibration and yielded a radar speed of about 16.7 cm/ns. The MLSI is about 10 m thick at the mouth of the bay thinning to 2.5 m near its head, which is typical of the thicknesses we found in other bays. Superimposed on this are undulations in thickness less than 1 m in amplitude and 40 to 80 m in wavelength. These undulations or rolls appear to be on the surface, and we have some indication that the bottom of the ice is relatively flat. The line across the mouth shows evidence of cracks perpendicular to these rolls which may be related to their formation.

We intend to obtain both top and bottom profiles by simultaneous measurement of thickness and surface elevation in April of 1990. If circumstances permit we will report on these measurements as well as on any changes observed after one year.

CASE STUDIES OF RADAR TOMOGRAPHY USING BOREHOLE RADAR

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The propagation velocity of electromagnetic (EM) waves in the ground is mainly determined by the water content of the ground. This relationship makes it possible to estimate ground structures with reference to water content through identifying the distribution of EM wave velocity in the ground by the radar tomography technique.

We conducted radar tomography using borehole radar in the following two types of ground:

(1) Granite rock site

The granite in this site has very high resistivity, higher than 1000 ohm-m. Cross-hole measurement was conducted using two boreholes spaced 40 meters apart, and a maximum propagation distance of 56 meters was obtained. Tomographic analysis identified low velocity zones which represent alteration zones.

(2) Soil ground site

The resistivity of the soil in this site is relatively low, about 80 ohm-m or below. The distance between boreholes was 10 meters and the length of each borehole was 20 meters. Clay layers and silt layers showed up as low EM wave velocity zones, and sand layers as high velocity zones. Furthermore, we estimated how far each layer continued horizontally.

POSTER: APPLICATION OF GROUND PROBING RADAR TO ARCHAEOLOGICAL INVESTIGATION

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Archaeological investigations using geophysical methods have been conducted in Japan with increasing frequency since the early 1980s. Among various geophysical methods, ground probing radar is widely used because of its high resolution. It has high efficiency for investigating the structural remains covered by high resistivity soil.

In this poster, we show a field example of this type of application. The site is covered by volcanic pumice which was ejected from a nearby active volcano about 1500 years ago. Pumice accumulated just below the ground surface down to about 2 meters, and its resistivity is about 500 ohm-m. The boundary between this pumice layer and the underlying black soil, that had been the top soil before pumice fell, generated large electromagnetic wave reflections. We were able to trace this interface beneath whole observation lines using ground probing radar. An isodepth contour map was prepared, in which the ancient micro-terrains could be estimated. This map revealed a group of ancient tumuli. Each tumulus consisted of a mounded tomb and a peripheral ditch. The tumulus was approximately 10 meters square in plane and 2 meters high, and the ditch was 1 to 2 meters deep.

This interpretation was almost confirmed through archaeological excavation.

SOME GPR RESULTS IN SALT AND POTASH MINES

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The radar velocity, half the true velocity, in a salt mine such as that owned by the Morton Salt Company in Grand Saline, Texas, has been measured as 61.7 meters per microsecond. This corresponds to a relative dielectric permittivity of 5.9 as given for pure Harshaw Chemical salt by von Hippel. The extremely low loss tangent of Grand Saline salt, measured at the U.S. Bureau of Standards as $2x10^{-5}$, means it is an excellent transmitter of 230 MHz radar waves, and hence one gets excellent transmission results for GPRs operating in this VHF region. Signals to beyond ranges of 61 meters are available in this salt. GPR results will be shown, showing the mapping of mine entries below, as well as above, and ranging to potash streaks in a salt mine.

In the Zechstein salt of Germany's Borth mine, we have had similar good results, although the salt is not as pure. Ranges to a maximum of 600 meters of salt penetration have been obtained with a high power radar at 230 MHz. GPR mapping of massive anhydrite below the salt, and watching its rise can be important to the method of mining for engineers. Mining into anhydrite with a continuous miner is not what mine engineers like to see. Some examples of GPR scans in Borth and in a British potash mine will be shown that include a known fault, known impurities, and some hazards to good GPR results. For example, some radar polarization problems can arise when the mine has power cables along the walls. When it does not, more subsurface information can be obtained by scanning with a different polarization.

MAPPING VADOSE ZONES IN GROUNDWATER RECHARGE AREAS WITH GROUND PENETRATING RADAR

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TNO Institute of Applied Geoscience, The Netherlands, has recently started a program to develop GPR applications in the field of groundwater hydrology. Efforts have been focused first on vadose zones of sand and gravel in groundwater recharge areas. The main targets to be mapped are sedimentary architecture, moisture content, perched groundwater and the permanent water table to a depth of 30 m.

Accurate depth imaging of GPR data requires detailed information on propagation velocities of radar pulses in the vadose zone. A simple dielectric model of this zone indicates that wave velocities vary by a factor of nearly two, depending on whether the wave propagates in coarse sand or in fine sand with water percolating in it.

Radar echograms have been obtained with a commercially available GPR system at selected sites in geologically various terrains. Processing and interpretation of these radar echograms are constrained by groundwater level data, and by detailed records of borehole lithologic sequences.

DETECTING SOIL WATER MOVEMENT IN A SANDY SOIL WITH GROUND PENETRATING RADAR

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A study was conducted to evaluate ground-penetrating radar as a tool for detecting soil water movement in a sandy soil. A Geophysical Survey Systems, Inc., Subsurface Interface Radar (SIR) System 8 impulse radar with a 120 MHz antenna operating at a scanning period of 100 ns was used to produce GPR images at 6 transects of a field site. The site is located in the coastal plain physiographic region of the southeastern U.S. near Tifton, Georgia, and has a permanent bahia grass cover. The soil on the site is classified as a Lakeland sand with soil profile depths from 1.9 to 4.4 m. A restricting layer consisting of tight clays underlies the sand.

A 125 mm irrigation was applied to instigate discernable soil water movement in the soil profile. Application uniformity was carefully monitored and application uniformity curves were created for each of the transects. GPR images of the field site were produced at the 6 transects before irrigation, immediately following irrigation, and 3, 6, 9 and 24 hr after irrigation. Soil samples were collected to a depth of 1.80 m in 150 mm increments at 4 locations immediately following each of the 3 GPR runs. Gravimetric water contents were determined from the soil samples.

The radar images clearly detected the wetting fronts in the soil profile at all transects. The GPR images also reliably discerned the downward movement of the wetting front through the soil profile with time. The wetting front movement was verified by the water content data. The wetting front shapes depicted on the GPR charts markedly resembled the application uniformity curves despite poor application uniformity.

MULTIYEAR LANDFAST SEA ICE: OBSERVATIONS AND MODELS

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Multiyear landfast sea ice is characteristic of the northern coast of Ellesmere Island. This ice is about 10 m thick and is more or less permanent. Much thicker ice, 40 to 70 m thick, forms ice shelves as at Ward Hunt Island. The surface of both types is marked by the presence of parallel ridges and troughs known as rolls. Ice penetrating radar observations at Stuckberry Point and previous measurements elsewhere reveal that the wavelength of the rolls varies as the two-thirds power of the thickness, with 100 m rolls corresponding to about 10 m thick ice. Furthermore the amplitude of the rolls is about 0.01 of the wavelength. Complete isostatic compensation of the rolls would require bottom relief nine times that on the surface. Observations are limited but any bottom relief seems likely to be less than that. We have some evidence from estimates of surface topography and freeboard measurements in boreholes that the bottom of the ice at Stuckberry Point is relatively flat. This means that there are elastic stresses in the ice. A model in which the ice deforms at a critical beam stress governed by the size of the rolls and the thickness of the ice predicts the two-thirds law.

ATTENUATION OF L-BAND MICROWAVES BY PERMAFROST

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This paper will describe the results of an experiment to measure the in situ penetration of L-band microwaves into permafrost. The experiment was carried out as a part of a research program associated with the ERS-1 satellite, currently scheduled for launch in 1991, which will map large parts of the world using C-band Synthetic Aperture Radar (SAR). The objective of the program is to better understand the physics of microwave interaction with natural volumes and to support the interpretation of ERS-1 SAR image data. Penetration and attenuation must be accounted for in quantitative models of microwave interaction with dry, disperse, or frozen volumes, since significant parts of returns may have their source in the subsurface volume. Even qualitative SAR image analysis must consider the possibility of subsurface imaging, as has been demonstrated by recent SIR-A and SEASAT SAR images of arid regions.

Penetration of permafrost by lower-frequency microwaves has been used for many years for the purpose of detecting subsurface structure. Lower wavelengths can penetrate frozen silt for tens of meters, and instruments operated in the 100 - 400 MHz range have practical use in civil engineering fields. Less attention has been paid to higher frequencies. However, remote sensing uses of microwaves, including SAR, have concentrated on X, L and C bands (frequencies from 1 - 5 GHz, wavelengths from 1 to 20 cm) and, for the reasons cited above, attenuation at these bands now becomes more important to measure.

Attenuation in materials is usually measured in a laboratory apparatus such as a waveguide or resonant cavity. This means that natural materials must be disturbed in order to make the measurements. It is well known, however, that packing and moisture content play critical roles in determining the attenuation at SAR wavelengths, so it is essential to make the desired measurements on undisturbed material. In addition, the small sample sizes used in laboratories usually preclude the evaluation of scattering losses caused by wavelength-scale inhomogeneities in the volume. Natural inhomogeneities in permafrost, including vegetation, rocks and ice lenses, can occur at depth. Under suitable conditions, subsurface inhomogeneities will appear in SAR images and, if unknown to the analyst, can confuse interpretation. Quantitative analysis of microwave remote-sensed data must consider the possibility of such features when attempting to model the volume under scrutiny. The present experiment was devised (1) to obtain preliminary measurements of the one-way penetration of natural permafrost by microwaves and (2) to evaluate the method employed using existing equipment prior to designing and deploying similar C-band equipment for the ERS-1 experiment.

Details and results of the experiment will be described. The current state of modeling efforts in work at JPL to predict volume scattering will be reported, and future experiments in support of the ERS-1 project will be summarized. The research described in this work was performed in part by the Jet Propulsion Laboratory, California Institute of Technology, under a grant from the National Aeronautics and Space Administration.

EXAMPLES OF SINKHOLE SUBSURFACE STRUCTURE, IN FLORIDA, AS REVEALED BY GROUND PENETRATING RADAR

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The presence of sandy soil, over much of Florida, makes ground penetrating radar (GPR) a very satisfactory technique for investigating the subsurface structure of sinkholes. Surveys are commonly performed with an SIR-3 control unit and 120 megahertz transducer. Ancient sinkholes (those that have had topographic expression since prehistoric times) commonly have reflective interfaces that dip steeply toward the center of the depression. These reflections usually represent sand or peat that has in-filled the sinkhole subsequent to subsidence, which usually occurs episodically. Older soil/sediment layers are commonly truncated near the center of the depression and thus give evidence of the throat, or aven, of the sinkhole. Surficial material passes down through the throat, which has truncated soil/sediment layers overlying the cavernous opening in the carbonate bedrock. Hyperbolic reflections from soil voids or bedrock caverns may be present, but usually are absent. New sinkholes commonly have few, or no, radar reflections beneath them. The soil/sediment layers are disaggregated during sinkhole collapse and this, presumably, homogenizes the siliciclastic material, thus producing a non-reflective area on GPR profiles. Many new sinkholes have no downwarped soil/sediment layers or other indicators that sinkholes either had formerly occurred at the site or that the site was susceptible to new sinkhole activity. A new sinkhole in Highlands County developed at a site where a hardpan layer was found to occur 6 meters beneath the surface. On radar profiles of the sinkhole, displacements on the upper surface of the hardpan were interpreted as representing reverse faulting that developed along lines of tension that formed when the sinkhole collapsed. GPR profiles from this site (the Valerie Boulevard Sinkhole) are the first to show subsurface evidence of the lines of force associated with sinkhole collapse. GPR surveys are an effective method of locating buried sinkholes (former sinkholes with no topographic expression as a result of in-filling), which are objective sites at which renewed sinkhole activity will most likely occur. Also, many buried sinkholes are in-filled with soft or loose sediment that requires stabilization before a site is suitable for development.

INVESTIGATION OF MAYAN STRUCTURES AT CARACOL, BELIZE, USING GROUND PENETRATING RADAR

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Caracol is the modern name given to a Mayan urban ruin that was occupied from Early to Middle Postclassic Periods (300 BC to 1250 AD). Major structures were built during the Classic Period (250 AD to 900 AD). Caracol is located in west-central Belize, on the Vaca Plateau of the Cayo District, in the Mountain Pine Forest Reserve, 5 km east of Guatemala. Ground penetrating radar (GPR) surveys were conducted principally on three major structures, A3, B5, and Caana, and on the floor of B Court. The survey was conducted with an SIR-3 control unit/profiling recorder, 500 MHz transceiver, and 120 MHz transceiver, manufactured by Geophysical Survey Systems, Inc. The survey was conducted during April, 1989 (the dry season). Approximately 2,800 m of transects were scanned, in a two-week period, by hand-towing the antennas. Mayan construction materials consisted of 1) dry-core fill (loosely piled limestone cobbles and boulders), 2) crude layers of limestone blocks in which the interstices were filled with brown loamy soil, and 3) stone masonry; typically covered originally with stucco. Much of the exterior stucco has dissolved. Debris consist of chaotic limestone blocks mixed with light brown, marly soil. Abundant semi-layered to chaotic reflections were received from depths of 3 to 4.5 m in the dry-core fill with both antennas. These reflections served to indicate the absence of buried architecture, to the depth from which reflections were received. Radar wave velocity (based on two-way travel time) in the dry-core fill was typically 7.6 cm/ns, based on the known depths to stone floors, documented by archaeological excavation. No reflections were received from buried masonry surfaces where they were covered with marly soil. This was attributed to the soil's high calcium carbonate content, which may have been derived, in part, from dissolved stucco. The lack of reflections between limestone masonry and marly soil was a great hindrance in mapping buried masonry and distinguishing between marly soil and buried, air-filled rooms. Extensive shallow scanning (17 ns two-way travel time) was conducted on the floor of B Court (between B5 and Caana) to test for the presence of buried, slab-like, carved monuments. Prominent reflections were obtained in some areas, but excavation revealed the source to be plaster floors. GPR was most effective where scanning was conducted on masonry surfaces that had been exposed by archaeological excavation. In this situation, the radar could reveal the presence of dry-core fill beneath the masonry and thus show that further excavation would encounter little of interest. Due to the similar conductivity of masonry and marly soil, at this site, GPR could not positively identify buried masonry structures.

TUTORIAL: GROUND PENETRATING RADAR SYSTEM HARDWARE DESIGN

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Although electromagnetic interferometry experiments were done on glaciers as early as the late 1920s, ground penetrating radar (GPR) did not become a practical reality until the 1960s, well after the military radar developments of World War II. GPR system hardware design has evolved and been shaped by technical and economic possibilities and by anticipated applications. Design and applications of GPR should be governed by knowledge of the electromagnetic properties of the media to be probed, the required and achievable resolution and maximum depth of penetration, any requirement for continuous profiling, and other operational and environmental factors. When system and media parameters are known, it is possible to estimate maximum range using the radar equation. Unfortunately, the methods and vocabulary used to describe GPR systems and performance are not consistent in the literature, and detailed knowledge of the media is often unavailable, making comparisons difficult at best. An important advantage of some GPR systems is generation of real-time video or hard-copy displays while profiling, giving immediate data visualization. Good system design leads to cleaner data and avoids unnecessary and time-consuming cosmetic digital processing.

So much emphasis has been placed in recent years on digital circuits that analog receivers have become very sensitive about it. Digital circuits are by nature noise-producing and the higher the clock rate, the greater the potential for electromagnetic interference. If you are a designer, your mission, should you choose to accept it, is to use shielding, filtering, and isolation to ensure that your sensitive analog receiver remains unaware that you have used a single digital circuit in the entire system. Remember that there are always two classes of antennas in any GPR: deliberate and accidental. Be careful with metallic cables, power supplies, and DC-to-DC converters. Should you fail in your mission, your receiver will disavow any knowledge of your data, and your data record will self-destruct. Conceptual elegance is no substitute for clean execution. Details matter.

Both frequency and time domain GPRs have been built. Some preserve phase information and some do not. Particular examples are frequency modulated continuous wave (FMCW) radars, "gated carrier" and "chirped" systems, and the more recent "stepped frequency" or "synthetic pulse" systems. Synthetic pulse systems use the Fast Fourier Transform to produce a synthesized pulse from a sequence of discrete frequencies. Each type has strong and weak points. By far the most common GPR, however, is the "monocycle-pulse", "impulse", or "short-pulse" radar that ideally radiates only one cycle of a sine wave for each transmission at a "center frequency" selected mainly by the antennas, thus providing relatively good resolution at relatively low frequencies. Additional advantages are the ease of generating very high instantaneous power levels, high repetition rates, phase preservation, simple compact electronics, light weight, and modest power requirements. Wide bandwidth imposes some penalties including degraded receiver noise figure, increased susceptibility to electromagnetic interference, and compromises in antenna gain and efficiency. Key elements for short-pulse radars include avalanche transistor pulsers, fast sampling circuits, Schottky or "hot-carrier" diode transmit/receive switches, and the non-reflecting loaded antenna. Most short-pulse radar systems use analog sampling to create an audio frequency replica of the radio frequency waveform. Sampling requires repetitive and essentially identical waveforms over the duration of sampling, typically 250 to 1000 times the repetition period. Formerly, the sampled analog data were recorded. More recently, digital recording has become customary, but the digitization is usually done after analog sampling.

The recent tremendous increase in the speed of digitizers has made it possible to capture an entire waveform on a single-shot basis. This capability can lead to significant improvements in signal-to-noise ratio by using summation averaging (stacking) at a rate two or three orders of magnitude faster than can be done with a sampling system. Unfortunately, digital oscilloscopes do not add or transfer data nearly as fast as they acquire data, so they do not achieve this potential speed advantage. Recently, a data acquisition system (DAS) has been built that overcomes many limitations of digital oscilloscopes (Wright et al, 1989). An ice radar system incorporating the DAS, real-time color graphics display, fiber-optic cable, and digitally-based sensitivity time control in the receiver to compensate for the limited dynamic range of the digitizer and analog fiber-optic link has also been built and used in Antarctica (Wright et al, 199_). The DAS has also been successfully used to acquire hole-to-hole tomography data.

The latest advances in digitizers, static random access memory (SRAM) chips, Gallium-Arsenide devices, and data storage devices and media such as helical scan tape drives and erasable magneto-optical disc drives make this a good time to consider a next-generation system.

Wright, D.L., Bradley, J.A. and Hodge, S.M., 1989, Use of a new high-speed digital data acquisition system in airborne ice-sounding: IEEE Transactions on Geoscience and Remote Sensing, v. GE-27, p. 561- 567.

Wright, D.L., Hodge, S.M., Bradley, J.A., Grover, T.P. and Jacobel, R.W., 199_, A digital low-frequency, surface-profiling ice radar system: Journal of Glaciology [in press].

POSTER: AMPLITUDE, VELOCITY, AND DISPERSION TOMOGRAPHY AT THE IDAHO SPRINGS TEST FACILITY USING A FIBER-OPTIC BOREHOLE RADAR AND RADIO-FREQUENCY DIGITAL DATA ACQUISITION SYSTEM

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During 1989, a radar tomography experiment was run at the test facility operated by the Colorado School of Mines (CSM) near Idaho Springs, Colorado. Data were acquired in boreholes 10 m, 20 m, and 30 m apart in pairs that straddled a drift of the CSM experimental mine. The host rock is crystalline, but rather highly fractured and mineralized, so the air-filled drift signature is partially obscured by the geologic effects. Attenuation, scattering, and dispersion are higher than in many crystalline rocks. Despite the difficult local geology, the drift can be clearly identified in the 10 m separation case. The drift signature is not as clear at greater spacings.

Individual logs were run without stopping at a speed of about 1.5 meters per minute and relative transmitter offsets of 0, +/-5 m, and +/-10 m. The transmitter center frequency is approximately 30 MHz, but dispersion shifted the received waveforms to lower frequencies. The data acquisition system (DAS) has a 100 Megasample/second digitizer, but trigger delays in 1 ns steps were used to "interleave" data to achieve 1 Gigasample/second data density in the records. Each record written to tape was an average of 512 waveforms to enhance signal-to-noise ratio by about 27 db for incoherent noise. The spatial interval over which data were added while continuously logging was 0.2 m. Some obvious digital errors appeared in the raw data which were removed in processing.

The electronics of the downhole tool are similar to those described in Wright et al (199_) and the DAS is described in Wright et al (1989). Tomographic processing is discussed in Olhoeft (1988).

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Wright, D.L., Hodge, S.M., Bradley, J.A., Grover, T.P. and Jacobel, R.W., 199_, A digital low-frequency, surface-profiling ice radar system: Journal of Glaciology [in press].

INSPECTION OF CONCRETE EMBANKMENTS AND MEASUREMENT OF LAKE BOTTOM SEDIMENT THICKNESSES - CASE HISTORIES IN GPR

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Two Australian case histories are described. The first project involved the examination of a 1.5 km section of a major storm water channel near Sydney which passed through a meandering water course area. The banks of the reinforced concrete channel are underlain by dispersive clays. Collapse by rotational failure of some of the 14 m long concrete slabs had occurred where seepage and voids had developed under the concrete. Radar scans were conducted from base to crest while the channel was in a minimum flow state. Enhanced color data was processed in the field. Conventional 600 MHz antenna produced strong multiple reverberations from the steel reinforcing mesh acting as a diffraction grating. Another antenna (with a nominal mid-frequency of 350 MHz) was used successfully to image thickness variations and structural defects (such as honeycombing) in the concrete, as well as wet areas of clay sub-base and associated voids. Defects identified were proven by coring and penetration testing with a success rate of 100%.

The objective of the second project was to measure the thickness of accumulated silts on the bottom of Lake Burley Griffin, which surrounds Parliament House in Canberra. This is an artificial lake and sedimentation rates appear to be higher than expected in the inlet basin; potentially requiring drainage of the lake and removal of sediment. A GPR survey was conducted by placing antennas in the floor of a rubber inflatable dinghy and towing it slowly along fixed transects. Distance run was measured with a precision impellor. The course was maintained by sighting with a theodolite between two fixed markers 1 km apart on opposite banks and passing instructions to the helmsman by radio. A 250 MHz antenna system proved too sensitive, since the radargrams were dominated by hyperbolae from numerous cans and bottles within the sediments. A 120 MHz antenna gave less resolution and was more suitable for this purpose. The sediment thickness was calibrated by bottom sampling and the results presented as sediment isopach maps.

CASE HISTORIES OF GPR IN MINING AND ARCHAEOLOGICAL APPLICATIONS

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Argyle Diamond Mine in the Kimberly area of Western Australia produces some 25 M carats/yr of industrial diamonds and gem stones. The diamond source is a Lamorite pipe, the upper part of which has been eroded and redeposited as alluvial gravels over a 10 x 50 km flood plain. Three GPR surveys have been conducted on these alluvial areas to determine the depth and types of gravels/silts and the bedrock profile. Control was provided by extensive test pits and long trenches. Data quality has improved very significantly since the initial survey in 1985, which utilized 120 MHz antennas and an OYO YLR2 system. Subsequent surveys utilized 60 MHz antennas and produced good resolution to typically 8 m depth, which is sufficient in most areas at this site. In the latest survey conducted in October 1989, continuous recording onto DAT tape and fixed station recording at discrete points (e.g., 1 m stations) was compared. Due to rapid lateral facies variations, we found it easier to interpret the continuous data. The GPR sections enable the mine planning engineers to estimate alluvial reserves and should enable selective mining, thus minimizing the volume of unnecessary material processed through the plant.

The second project involved the archaeological site investigation of the Tower Mill site in Brisbane. This is Queensland's oldest surviving building, being originally constructed in the 1820s as a lighthouse and then converted to a dutch style windmill to grind grain. Vagaries in wind strength and direction necessitated that a convict powered treadmill was then installed. The site was recently proposed for re-development as a restaurant complex. This prompted local outcry for its preservation, necessitating a detailed archaeological investigation. A high resolution Cesium vapor magnetometer survey was first conducted at 0.25 m stations over the whole site to delineate potential target areas. These targets were investigated with 250 MHz GPR on a 1 m grid. Subsurface depressions identified what appear to be the excavations and foundation areas of the treadmill and associated buried structures. The geophysical data has contributed to convincing the authorities to reconsider the development of the site. Excavation at the site commenced in April 1990.

APPLICATIONS OF GROUND RADAR TO COAL MINING

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Results of trials in open cut coal mines show that ground radar with a center frequency of 250 MHz can accurately map the base of coal seams between 20 cm and 2 meters deep and can detect faults with displacements as small as 5 cm. Accurate fore-knowledge of these small structures is important for the optimum performance of mining machinery. Using lower frequency antennas, reflections from coal/shale interfaces have been mapped at depths of up to 16 meters, and old underground workings have been detected several meters below the surface. Along a section of a major highway, ground radar has been used to delineate areas of collapse resulting from underground mining. In underground mines, reflection survey results show that ground radar can be used to map fractures in the mine roof and up to 7 meters into a coal pillar using 250 MHz antennas. The results of roof inspection surveys are complicated by the presence of rock bolts and steel straps; however extensive tests have indicated the types of features attributable to interference from these structures. Transmission tests have been conducted to investigate propagation and anisotropic characteristics in coal pillars, and tomographic methods are currently being applied for the internal inspection of pillars. Data obtained from the field can be substantially enhanced by computer processing. Techniques such as frequency filtering, gain application, velocity filtering, migration and color display have been used to improve the resolution and interpretability of the data.

POSTER: UNDERGROUND ELECTROMAGNETIC WAVE METHOD

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The underground electromagnetic wave method (UEWM) has been widely used in geological exploration in China for thirty years. As in any geological exploration, the main purpose of UEWM is to detect the existence, location and shape of geological objects (such as ore bodies, caves, underground water channels and others) in two-dimensional or three-dimensional space using electromagnetic field data recorded from the site. UEWM includes conventional EM logging, single-borehole, cross-borehole, borehole-surface, cross tunnel, tunnel-surface, and other EM geometries. Most UEWM are based in the frequency domain between 10^5 and $5x10^7$ Hz, though a few are in the time domain. Research investigations encompass the development of data acquisition systems, processing (including ray-tracing, tomography and holography), forward modelling and interpretation methods, including software packages for on-site processing and interpretation using portable 80386 workstations. Research has been performed in cooperation with the Geophysical and Geological Research Institute of the Ministry of Geology and Mineral Resources, and with the Hebei Coal Mines Geological Research Institute of the Ministry of Coal Industries.

Some of the applications of UEWM in China include cooperative efforts with over 14 institutes of the Ministry of Geology and Mineral Resources, Ministry of Coal Mine Industry, Ministry of Railway Management, and Ministry of Hydroelectricity and Electricity in areas of metallic and nonmetallic mineral exploration, coal exploration and development, oil and gas exploration, hydrology, engineering geology, and environmental geology.

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