Overview of Environmental Geophysics
Thomas Brackman, Geology Professor
Northern Kentucky University

Friday, October 12, 2012

Program:

7:30 a.m.	***Registration—Coffee and rolls (provided as part of fee)***
8:00 a.m.	***Opening Session, Introductions and Purpose of Session***
8:15 a.m.	***Session 1—Introduction to Geophysics, Grids, and GPS***
9:30 a.m.	***Break***
9:45 a.m.	***Session 2—Magnetics***
10:45 a.m.	***Break***
11:00 a.m.	***Session 3—Electromagnetics***
11:50 a.m.	***Lunch Break—Billy's BBQ (provided as part of fee)***
12:50 p.m.	***Session 4—Seismic Overview***
1:15 p.m.	***Break***
1:30 p.m.	***Session 5—Ground Penetrating Radar***
3:00 p.m.	***Break***
3:15 p.m.	***Session 6—Demonstration of Equipment—Magnetics, EM, and GPR***
4:30 p.m.	***Question and Answer Session***
5:00 p.m.	***Adjournment***

American Institute of Professional Geologists
(Kentucky Section)
Professional Development Conference

An Overview of Environmental Geophysics

Conference Moderators:

Charles Mason, President, American Institute of Professional Geologists, Kentucky Section (AIPG-KY)

Thomas Brackman, Geology Professor, Northern Kentucky University

Schedule: Friday, October 12, 2012, 7:45 a.m. to 5:00 p.m.

Location: **Kentucky Geological Survey,**
Well Sample and Core Library
2500 Research Park Drive
Lexington, Kentucky 40511

Course Description

This 1-day course provides persons who have little or no geophysical exploration experience with practical information on the strengths and limitations of the five most used geophysical techniques. It is intended to introduce the participants to the electrical resistivity, seismic, magnetics, electromagnetics, and ground penetrating radar methods for site characterization and waste location. It is intended for personnel responsible for inspections, site characterization, site investigations, and removal and remedial actions at Superfund sites. The course focuses on simple plan design, types of equipment suitable for characterization of hazardous waste sites, and operation of equipment for the three methods and characteristic data displays.

The course is designed to be consistent with the EPA protocol and guidance documents, *Compendium of ERT Soil Sampling and Surface Geophysics Procedures, A Compendium of Superfund Field Operations Methods, and Data Quality Objectives Process for Superfund*.
Instructional methods include lectures, group discussions, and outdoor field exercises that give the participants a chance for some hands-on use of the more common geophysical instruments.

Eight professional development hours will be awarded upon completion of the course.

After completing the course, participants will be able to:

- Describe the various geophysical methods available for shallow environmental characterization
- Describe the advantages and limitations of the magnetic, electromagnetic, and ground-penetrating radar methods in environmental applications
- Operate geophysical instrumentation under field conditions.

United States
Environmental Protection
Agency

Off ce of Emergency and
Remedial Response
Washington, DC 20460

February 2010
www.epa.gov/superfund

Superfund

Overview of Environmental Geophysics

Student Manual

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
ENVIRONMENTAL RESPONSE TEAM
LAS VEGAS, NV 89119

It is the policy of the U.S. Environmental Protection Agency's Environmental Response Training Program to provide and maintain a learning environment that is mutually respectful.

Please refrain from any actions or comments, including jokes, which might make another class participant feel uncomfortable.

The Course Director is prepared to take appropriate action to ensure your full participation and benefit from our training. Please present your concerns to the Course Director, or to the U.S. EPA Project Officer, JoAnn Eskelsen, at (702)784-8006.

OVERVIEW OF GEOPHYSICAL METHODS

Geophysical Surveys

- Characterize geology
- Characterize hydrogeology
- Locate metal targets and voids

Physical Properties Measured

- Velocity
  - Seismic
  - Radar
- Electrical Impedance
  - Electromagnetics
  - Resistivity
- Magnetic
  - Magnetics
- Density
  - Gravity

Magnetics

- Measures natural magnetic field
- Map anomalies in magnetic field
- Detects iron and steel

Electromagnetics (EM)

- Generates electrical and magnetic fields
- Measures the conductivity of target
- Locates metal targets

Resistivity

- Injects current into ground
- Measures resultant voltage
- Determines apparent resistivity of layers
- Maps geologic beds and water table

Seismic Methods

- Uses acoustic energy
- Refraction - Determines velocity and thickness of geologic beds
- Reflection - Maps geologic layers and bed topography

Seistronix Seismograph

Gravity

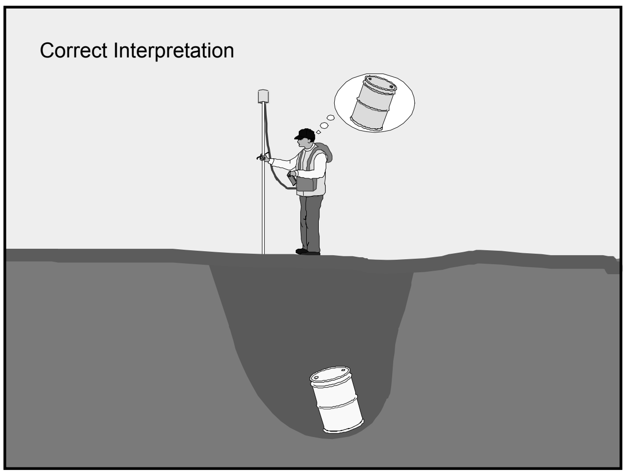
- Measures gravitational field
- Used to determine density of materials under instrument
- Maps voids and intrusions

Ground Penetrating Radar

- Transmits and receives electromagnetic energy
- Maps geology
- Locates cultural targets
- Has very high resolution

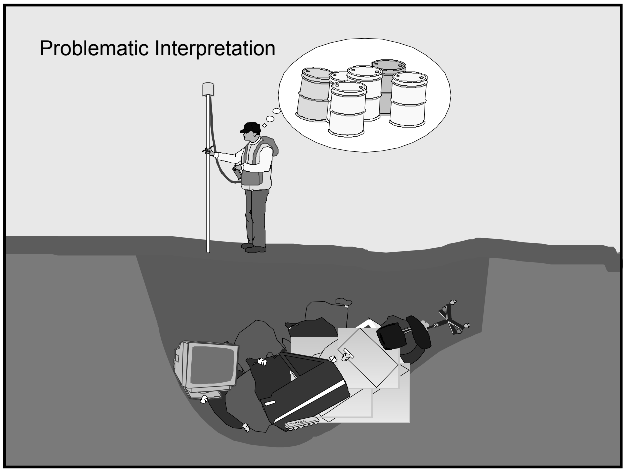
Geophysical Methods
Advantages

- Non-intrusive
- Rapid data collection
- Detects a variety of targets
- Screens large areas
- Fills in data gaps



Geophysical Methods
Limitations

- Methods require a specialist
- Interpretations are non-unique
- May be expensive
- Physical contrasts must exist
- Resolution varies by method and depth of target


Problematic Interpretation

GEOPHYSICAL SURVEY DESIGN

December 3, 2009 Northern Kentucky University

Jim Ursic – Region 5, U.S. Environmental Protection Agency
Ursic.James@epa.gov - 312.353.1526

A Good Survey Results In…

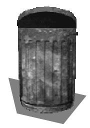
- A record of useful information
  - Background data to support survey
  - Rationale for methods used
  - Survey data - maps
  - Conclusions in lay terms
- Efficient use time - money
- A document that maintains its value

Survey Design Rationale

- Establishes a plan
- Find potential pitfalls
- Maximize benefit
- Minimize surprises
  - Property line issues
  - Archeological sites
  - Utility lines
- Customize requests

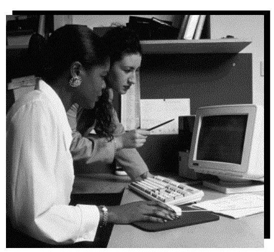
Pre-survey Planning: Garbage IN – Garbage OUT

- Inadequate background information & planning dooms a survey before it starts:
  - Requires more time in the field
  - Increases costs
  - Missed targets
  - Questionable data



Define Problem

- List issues of concern
- Can geophysics help?
- Data confirmable?
- How will results benefit your plan?



Background Paperwork Review

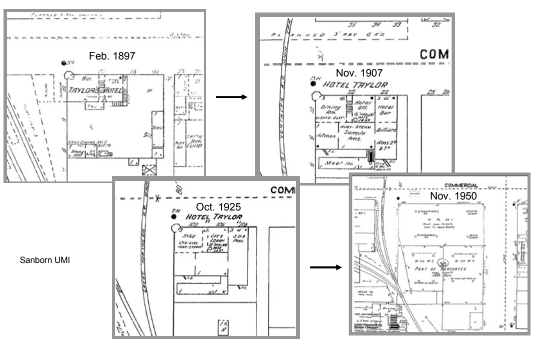
- Site history
- Previous studies
- Geology
- Geohydrology
- Geographic issues
- Health, safety & QAPP issues

Background Map Review

- Sanborn or other Public Maps
  - Historical site records & buildings

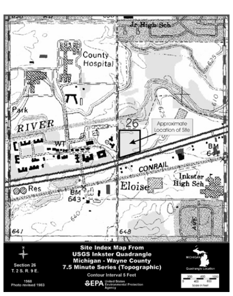
- Topographic Maps
  - Terrain conditions
- Geologic Maps
  - Indirect conditions

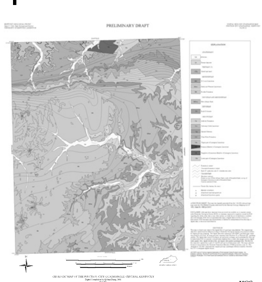
Sanborn Maps: Anacortes, Washington State



Sanborn UMI

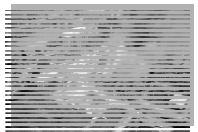
Topographic & Geologic Maps

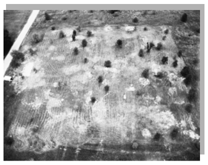




Background Photo Review


Recent Site Photo


Historical Site Photo

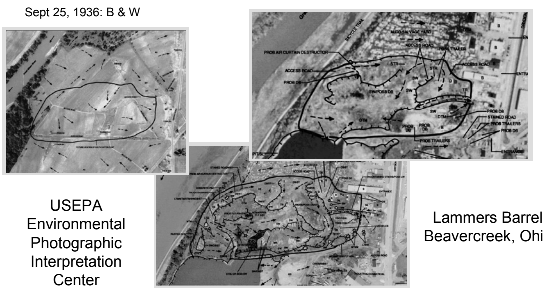

Recent Aerial Photo


Historical Aerial Photo

Photo Interpretation

Sept 25, 1936: B & W

May 7, 1981: Color Infrared



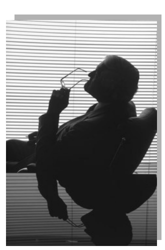
April 5, 1988: Color

USEPA Environmental Photographic Interpretation Center

Lammers Barrel
Beavercreek, Ohio

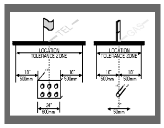
Other Issues To Consider

- Property boundaries
- Consent for access
- Traffic & pedestrians
- Vegetation status
- “Noise” issues
- Utility location
- Archeological sites



Utility Locating

- Utility services require several days notice
- Service provides "dig" number for site area
- Not all utilities are members of service
- Have service remark area if necessary
- Know tolerances of service provider

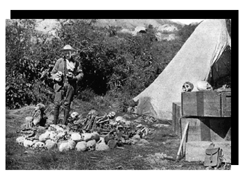


Courtesy: Ohio State University

Dial 811
on your phone
for local utility
location service

National Historic Preservation Act

- Why should we care?
  – It's the law
  – Regulations require it
  – It's EPA's policy
  – It's a good idea



Public Law 89-665; 16 U.S.C 470 & Subsequent Amendments

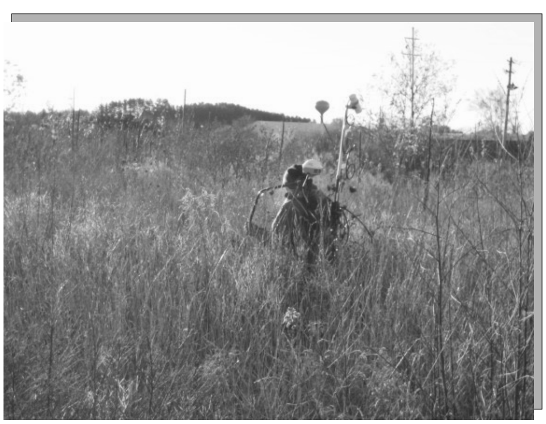
EPA Contact: Loichinger.Jamie@epa.gov - State Contacts: www.ncshpo.org

Code of Federal Regulations (CFR) Handling Drums & Containers

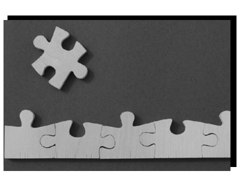
- 1910.120 (j) (1) (x)
  – " A ground-penetrating system or other type of detection system or device shall be used to estimate the location and depth of buried drums or containers"

Analyze Background Information to Determine..

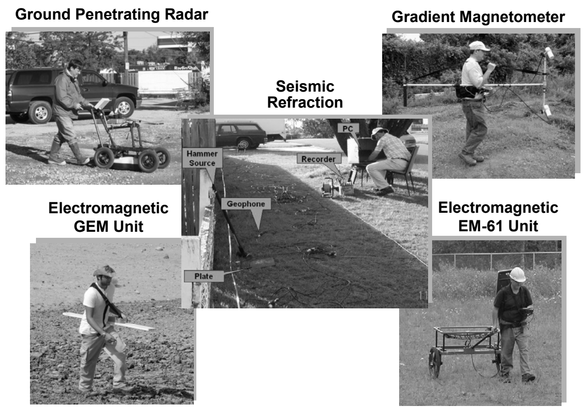
- Area to be surveyed
- Size - number of suspect targets
- Potential problems
- Site reconnaissance needed?



Match Most Favorable Geophysical Techniques to Problem



- What method(s) contrast most from background?
- Note depth confines
- “Noise” issues

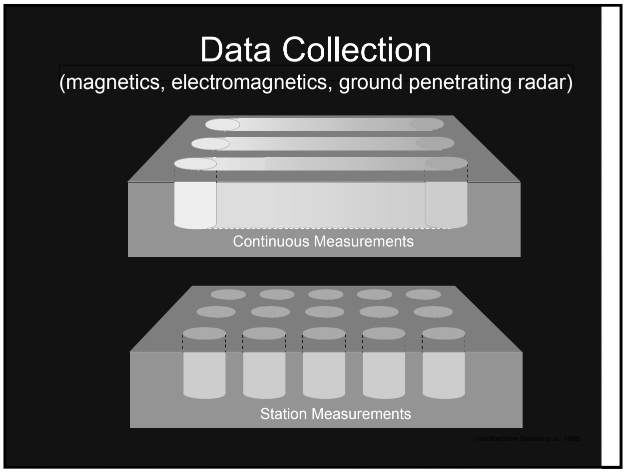


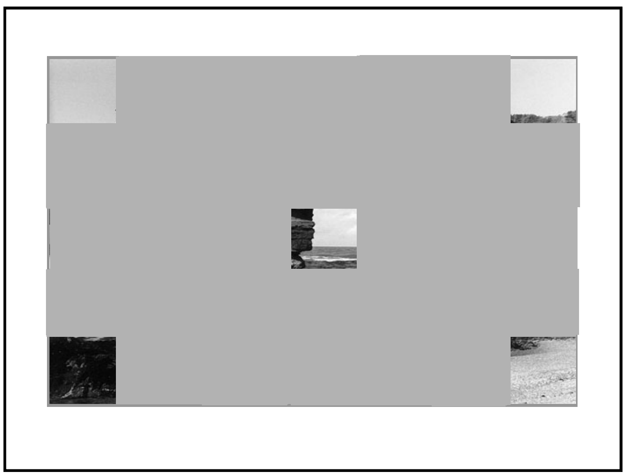
Optimize Data Collection

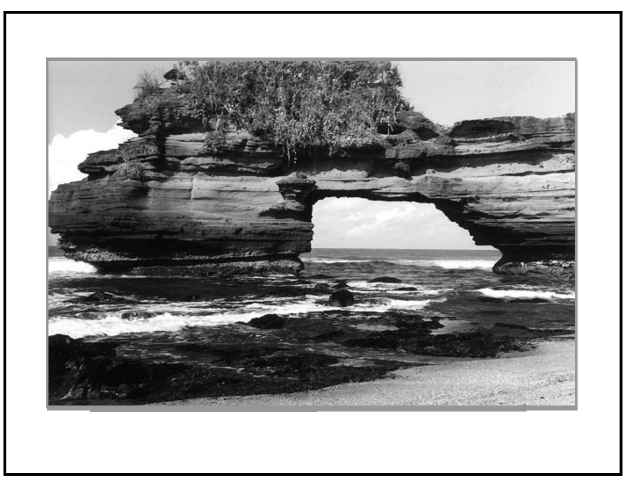
- Establish how data will be collected
  - Traverse pattern
  - Grid spacing
  - Axis labeling
  - Data Location ID

Key Issues For Collecting Data

- Systematic collection (grid or lines)
- Spacing dependent on target size
- Accurate grid or line establishment
- Method to ensure location accuracy
- Label grids or lines reasonably
- Maintain good field notes


Data Collection
(magnetics, electromagnetics, ground penetrating radar)
Continuous Measurements
Station Measurements





Detection Probability

(Using Individual Station Measurements)

At = Area of Target 4,356	At = Area of Target 435	At = Area of Target 43
As = Area of Site 43,560	As = Area of Site 43,560	As = Area of Site 43,560

Probability of Detection	As/At = 10	As/At = 100	As/At = 1000
100	16	160	1600
98	13	130	1300
90	10	100	1000
75	8	80	800
50	5	50	500

Number of data points required

(modified from Benson et al., 1988)

Determining Grid Spacing

$$\frac{\text{Area of Site in ft}^2}{\text{Area of Target in ft}^2} = a \text{ in ft}^2$$

a x Probability Factor = Sampling Points (Approx.)

$$\frac{\text{Area of Site in ft}^2}{\text{Sampling Points}} = b$$

$$\sqrt{b} = \text{Grid Spacing in Feet}$$

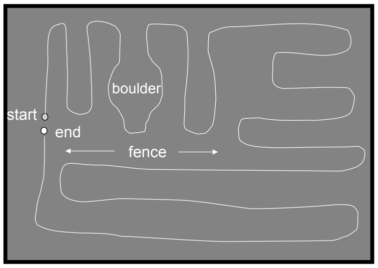
Probability Factors

100% = 1.625
98% = 1.3
90% = 1.0
75% = 0.8
50% = 0.5

Typical Acquisition Traverses

- Alternating mode
  - Most often used
- Random mode
  - Used for small or large areas
- Parallel mode
  - Irregular shaped sites
- Areas broken into rectangular shapes
- Irregular boundaries
  - Use multiple rectangles
- Positioning methods
  - Station
  - Timed – collection
  - Wheel encoder
  - GPS

Random Survey Pattern
(Small Area)

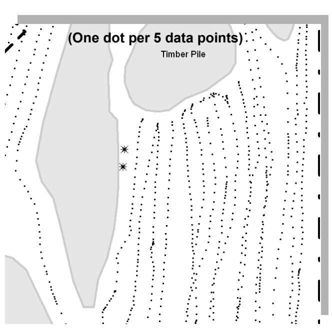


Random Survey Using GPS
(Large Area)

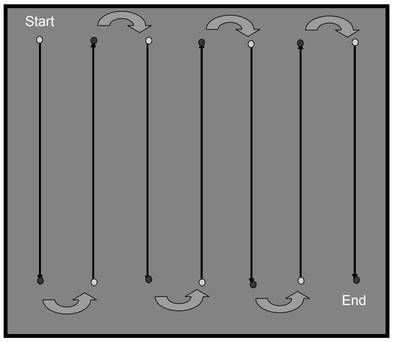
- Maximize productivity
- Data linked to GPS
- Best in obstructed areas
- Areas must be free of:
  - Vegetative canopies
  - Tall buildings
  - Major power lines

Random Survey GPS Issues

- Data locations from Mag on ATV
- Dots show data points
- Note N-S dot spacing due to speed changes
- Note data gaps

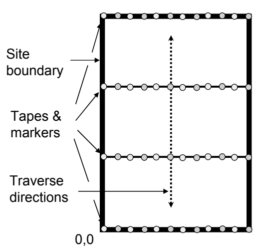


Alternating Traverse
No GPS

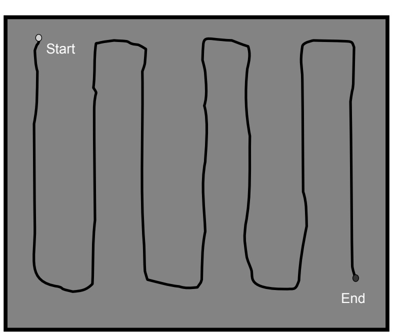


Alternating Traverse Grid Setup
No GPS

- Layout grid markers at desired spacing
  - Flagging (plastic)
  - Spray chalk or paint
  - Ropes
  - Alignment placards
  - Wooden stakes
- Large sites require multiple marker lines



Alternating Traverse
Parallel Swath GPS



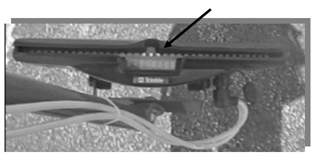
Parallel Swathing GPS

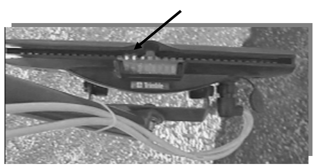
- Initialize start & end points of line
- GPS maintains parallel lines
- Operator follows cursor on lightbar
- Lat. - Long. output to sensor data

Photo: Geometrics

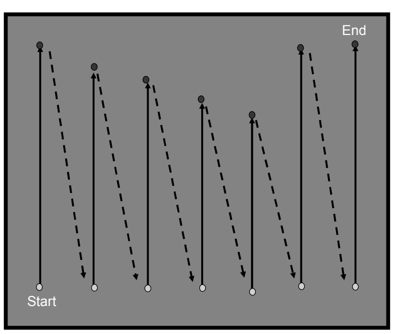
Lightbar Guidance

- Center: on line
- Left: move left
- Right: move right
- Outer edges yellow: nearing line end
- Outer edges red: at line end
- Advances to next spacing





Parallel Traverse – No GPS



Linking Data to a Location

- Define X and Y
- X, line or longitude
- Y, position or latitude
- Several data collection options for tagging X, Y
  - Data logger sets method

Data Recorder Methods

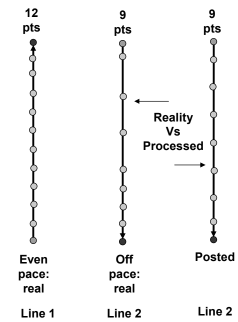
- Station position
- Time – distance
- Encoder wheel
- GPS

Correcting for Position (Y)

- Time-distance issue
  - Must correct for pace
- GPS
  - Correct for errors
  - Use proper datum
- Wheel Encoder
  - Resolve distance errors

Continuous Data Acquisition Issues for Y Axis

- Operator inputs start & end points per line
- Unit auto "fits" data to input distance
  - Assumes same pace
- Obstacles usually slows pace



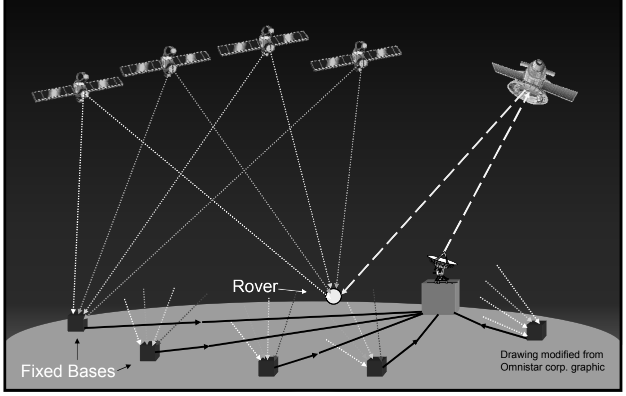
Global Positioning Systems

- Accuracies vary by method & equip. used
- Some on a scale to locate an airport
- Others on a scale to find center of runway

Several GPS Methods

- Stand alone GPS receiver
- Differential correction (DGPS)
  - Real time using beacons, base stations
  - Post processing
- 3 Grades of GPS accuracy
  - Recreational, mapping, survey

How a Differential GPS Service Works



Ground Based Local Positioning & Data Collection System

System Overview

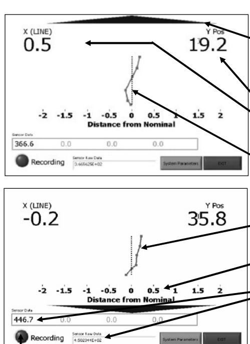
- Laser beam tracking
- Line-of-site system
- Merges & stores
  - Total station data
    +
  - Geophysical data
    or
  - Radiological data
- Positioning options
  - guidance or tracking
- Real-time displays

Auto Tracking & Guidance

How It Works

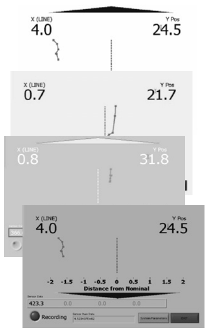
- Laser tracks optical target
- Collects data
  - Position x, y, z data
  - Sensor data
- Computes coordinates
- Merges data into one file
- Transmits to rover
- Displays data/position on HUD

2 Screen Views of HUD



- Blue Arrow shows direction related to X-axis baseline
- Coordinates
- Target path line
- Current path
- Distance L/R line
- Data readouts
- Recording indicator

Screen Color On Rover's HUD Has Meaning

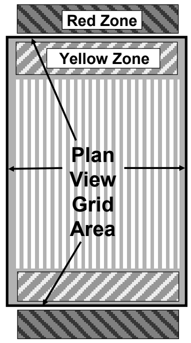


White:
Normal

Yellow:
Near End

Red:
Passed End

Blue:
Lost Tracking
Link



Pre-Planning for Seismic Survey

- Length of line required
- Number of lines & orientations
- Ambient "noise" issues
- Topography-elevation changes
- Good consistent ground coupling
- Line protection (traffic, etc.)

Which Method is Applied First?

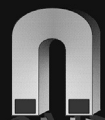
- Dependent on site goals
- Generally........First
  - Methods having larger sensing areas
  - Rapid data collection times
- Generally........Second
  - Methods with more definitive sensing capabilities

Check List For Considering Geophysical Survey

- Define problem
- Research history
- Find area of concern
- Note site conditions
- Describe target(s)
- Estimate depth
- Will geophysics help?
- List methods that will show most contrast
- How will you use this information?

A Note About Contracting Geophysical Jobs

- Use source that is knowledgeable about all geophysical methods
- Write contract to assume several “what if” scenarios to deal with special issues
- Obtain copies of raw data & notebooks
- Be aware that interpretation & reports may be optional



MAGNETIC METHODS

by
Jim Ursic
Region 5, U.S. Environmental Protection Agency
Ursic.James@EPA.gov or (312) 353-1526

December 3, 2009 – Northern Kentucky University

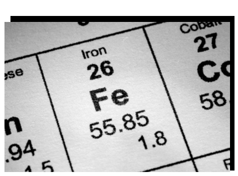
Metal Detector ≠ Magnetic Method

photo credit: Wikipedia

METAL DETECTORS use internal power to create an electromagnetic field to locate metal

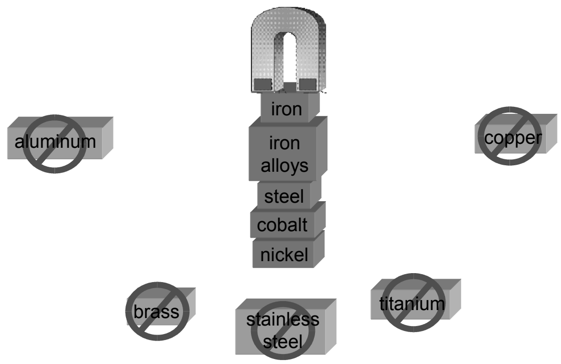
MAGNETOMETERS are passive instruments and only sense ambient magnetic fields

The Magnetic Method



- Senses presence of iron
- Measures magnetic fields
- Easy to apply and interpret

Ferrous & Non Ferrous Metals



Why Is Magnetics Important?

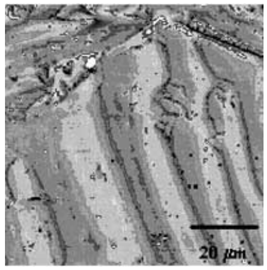
- Non-invasive, passive detection method
- Quantitative results
- Large masses detectable at significant depths
- Complements other geophysical methods

Optimal Detectable Features Unique to Magnetics

- Buried drums, tanks, pipes, valves
- Steel casing (abandoned wells)
- Mixed ferrous wastes (landfills)
- Steel reinforced foundations
- Natural occurring ferrous minerals
- Fired clays (bricks, clay pots)

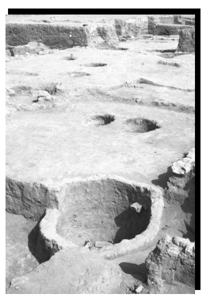
Why Are Baked Clays Magnetic?

- Magnetic force microscopy image showing magnetic domains
- Heated beyond curie point & when cooled domains realign



NDT Resource Center

Fire Pit
Negev Desert



What Tools are Used to Measure Magnetic Fields?

- Instruments called magnetometers
- Several types & configurations available
- Measures strength of magnetic intensities

Magnetic Survey Tools for Hazardous Waste Sites

- Generally 1 of 3 tool types used
  - Proton precession
  - Overhauser precession
  - Alkali vapor (cesium)
- All measure magnetic intensity
- Detects ferrous materials - minerals
- Tools are portable - independent systems

Selecting An Instrument

- Proton precession
  - Slow sampling cycle times: 3 – 6 seconds
  - Rugged system can be linked to GPS
- Overhauser
  - Faster cycle times: 1s – GPS link possible
  - Sensors sensitive to extreme heat (120°)
- Alkali Vapor
  - Fastest cycle times: 0.1s
  - Sensors have high sensitivity but are fragile & $
  - Most systems have direct hook-ups for GPS

Magnetometer Tool Options

- Several types available
  - Proton precession (2 types)
  - Alkali vapor
- Each configurable
  - Total field mode
  - Gradient mode
  - Base station mode
- Sensor option alignments
  - Vertical
  - Horizontal

Selection Options

- ☐ Standard precession
- ☐ Overhauser precession
- ☑ Alkali Vapor

- ☐ Total field (TF)
- ☐ TF + Base Station
- ☑ Gradient*

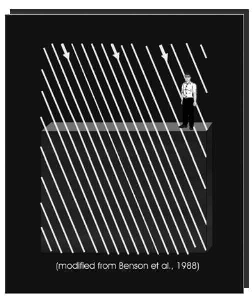
- ☑ Vertical gradient*
- ☐ Horizontal gradient*

What Exactly Is Measured?

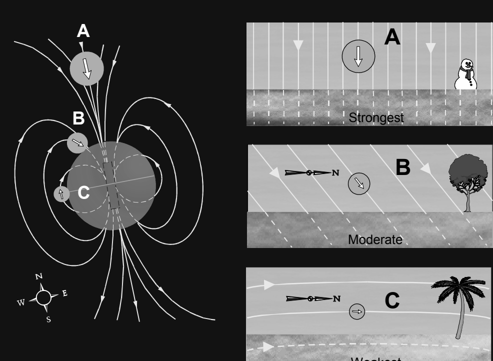
- An integration of magnetic properties
  - Earth's magnetic field intensity
  - Natural magnetic intensity rock/soil
  - Cultural magnetic intensities
- Values either attractive or repulsive
  - Represented by + or - numbers
  - (+) values same direction of inducing field
  - (-) values oppose direction of inducing field

Earth's Magnetic Field

- Always present
- Invisible to senses
- Viewed as background
- Sensitive to other ferrous influences
- Changes with latitude

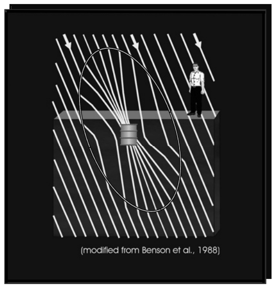

(modified from Benson et al., 1988)

Earth's Magnetic Background



Ferrous Interactions

- Ferrous metal has its own magnetic field
- Capable of altering Earth's field
- Limited influence
- Easily measured
- Provides accurate location method



(modified from Benson et al., 1988)

Measurement Units

- Units measured in gammas or nano Teslas
- 1 gamma = 1 nano Tesla
  - 55 gallon drum lid about 40 γ or nT
  - 250 gallon tank about 1000 γ or nT

Sensor Configurations

- Most systems can operate 1 or 2 sensors at same time
- 1 sensor
  - Obtains total field data
- 2 sensors
  - Collects total field & gradient data

Total Field Configuration: One Sensor

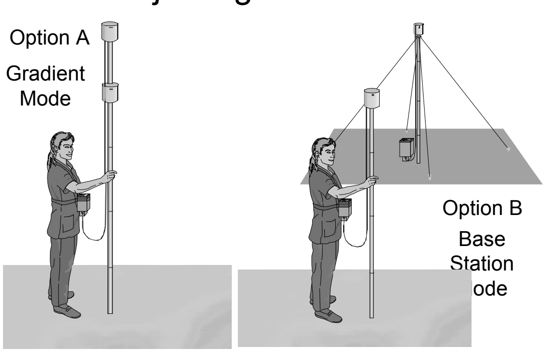
- Intensity measured from a single sensor
- Tool's latitude defines background
- Anomalies: > or < than background
- Solar activity will influence data

Photo: Geometrics

Gradient Configuration: Two Sensors

- Intensity measured from two sensors
- Background is defined as "0"
- Anomalies: > or < than background
- Solar activity will not influence data

Gradient Configurations: Adjoining or Remote



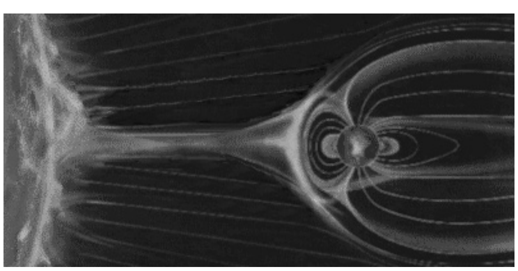
Gradient Readings

- Total field (bottom sensor) minus vertical gradient (top sensor) noted as γ or nT per unit of distance between sensors
- 55,900 - 55,200 = 700 γ /meter or nT/M
- Negative values are also possible

Why is Gradient Data Significant?

- Earth's background fluctuates due to solar disturbances
- Failure to neutralize a rapid background change will result in misleading data
- Gradient data ignores solar changes

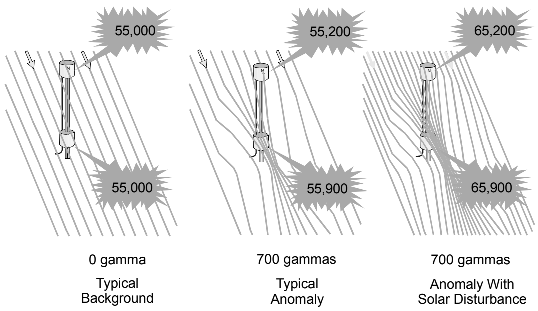
Solar Disturbances



Solar Forecasts: http://www.swpc.noaa.gov/today.html

Gradient Measurements

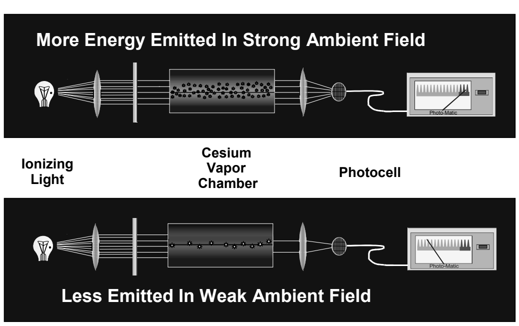
(Vertical Gradient)



Cesium Magnetometer

- Ionizing light “pumps” elections to higher energy levels
- Magnetic fields affect rate energy gain/loss
- Constant “pumping” allows continuous data acquisition
- Accuracy of .1 gamma (detect several nails)

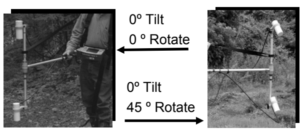
Cesium Mag Measurements

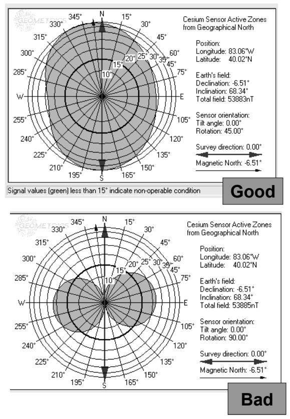


(modified from Bloom, 1960)

Alkali Vapor Sensor Orientation

Tilt = parallel plane to direction of travel
Rotate = perpendicular plane to direction of travel



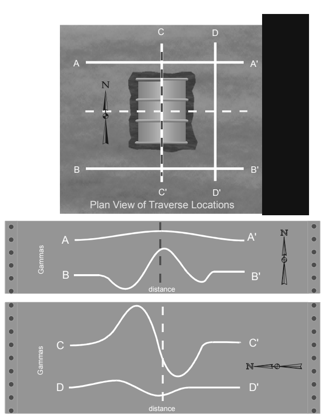


Data Interpretation

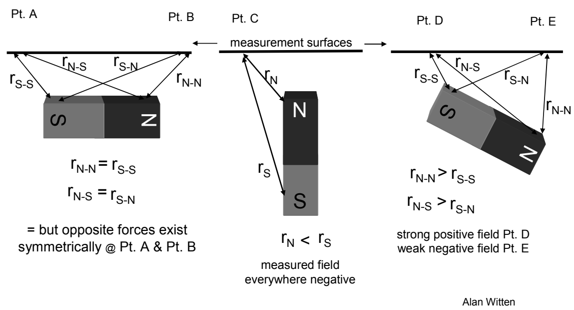
- Data analyzed by computer program
- Typically by some contouring method
  - Lines connecting equal values at specific intervals
- Displayed as 2D or pseudo 3D graphic

Data Values

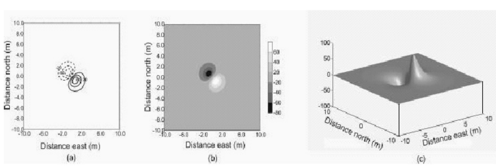
- Location over target effects data
- Strongest values closest to target



Data Signatures



Data Display Options



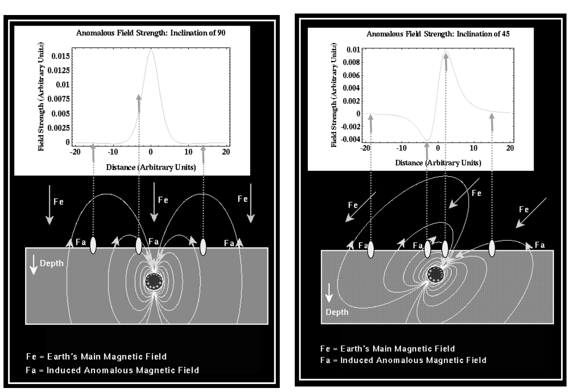
Alen Witten – In Press

Examples of synthetic magnetic data for a horizontally oriented dipole

a) Contour plot: dashed = (-); Solid = (+)

b) Gray-scale plot: dark = (-); light = (+)

c) Surface plot (3D)



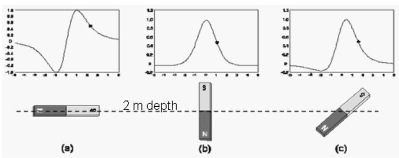
Modified from The University of Melbourne

Estimating Target Depths

$$d = 1.3\ \Delta\chi_{1/2} - h$$

d = Depth
$\Delta\chi_{1/2}$ = Half maximum value
h = Distance above ground surface at which measurements are made

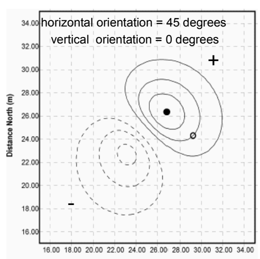
	½ Max.	d
a)	2.4 m	3.12 m
b)	1.0 m	1.30 m
c)	1.6 m	2.08 m



Credit: Alan Witten

Depth Estimate Calculation From Contour Map

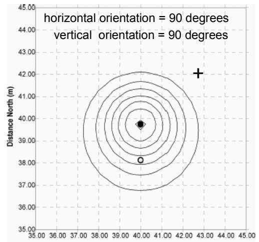
- Solid & open circles are locations of max. value & ½ max. value: 3.6m (as measured from map scale)
- Contour interval 20 nT
- Target = horiz. metal bar
  - Depth: actual = 5m
  - Depth: est. = 4.68m



Credit: Alan Witten

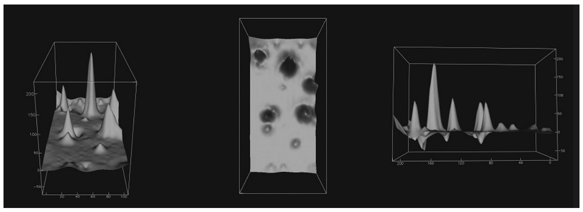
Another Depth Estimate

- Solid & open circles are locations of max. value & ½ max. value: 1.8m (as measured from map scale)
- Contour interval 20 nT
- Target = vert. metal bar
  - Depth: actual = 3m
  - Depth: est. = 2.34m

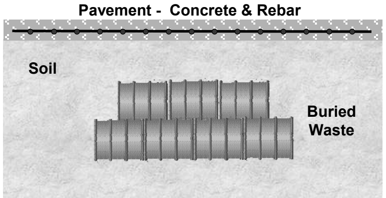


Credit: Alan Witten

Mag Data Example – 3D From Chicago Test Site



Multiple Magnetic Sources

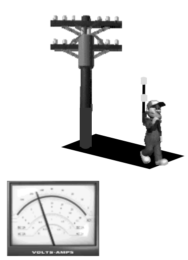


Drum Mass ≈ Rebar Mass: Difficult to Distinguish

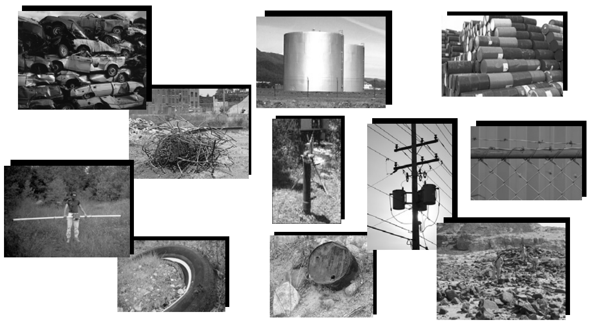
Drum Mass > Rebar Mass: Easier to Distinguish

Dealing With Noise Issues

- Accounting for un-wanted Interferences
  - Power lines, fences, cars
- Apply a “walk-away” test
  - Start at source
  - Walk-away until readings normalize – note distance



Unwanted Magnetic Noise Examples

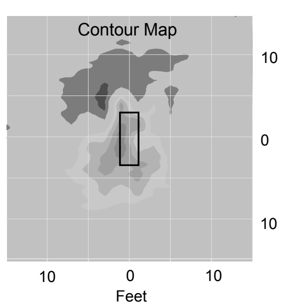


Data Interpretation Pitfalls

- Incorrect grid spacing
- Contour interval too large or small
- Cultural noise not properly addressed
- No data maps or reference points
- Use of color maps in reports that are photocopied in B&W

Mag Anomaly Example 1

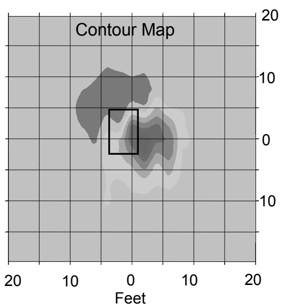
- 1 Crushed drum (lying vertical)
- Depth: -4.5' to -8.5'
- Values: +26 to -54
- Contour interval: 10
- Blues: pos. values
- Reds: neg. values



Example 1 Source

Mag Anomaly Example 2

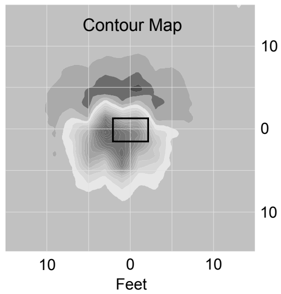
- 5 Crushed drums
- Depth: -5’ to -6’
- Values: +78 to -171
- Contour interval: 35
- Blue: pos. values
- Reds: neg. values



Example 2 Source

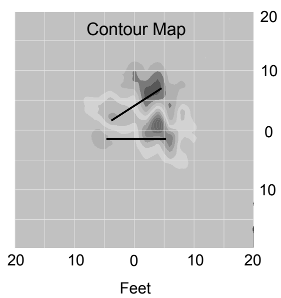
Mag Anomaly Example 3

- 1 Drum (horizontal)
- Depth: -3' to -6'
- Values: +111 to -572
- Contour interval: 35
- Blues: pos. values
- Reds: neg. values



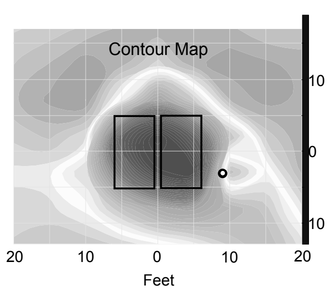
Mag Anomaly Example 4

- 2 Iron pipes: 10' x 4"
- Depth: -1.7' to -2'
- Values: +129 to -238
- Contour interval: 35
- Blues: pos. values
- Reds: neg. values



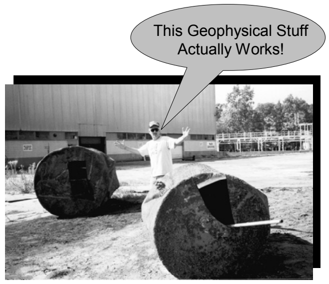
Mag Anomaly Example 5

- Two 500 gal. tanks
- Depth: -2' to -7'
- Values: +1114, -120
- Contour interval: 35
- Blues: pos. values
- Reds: neg. values



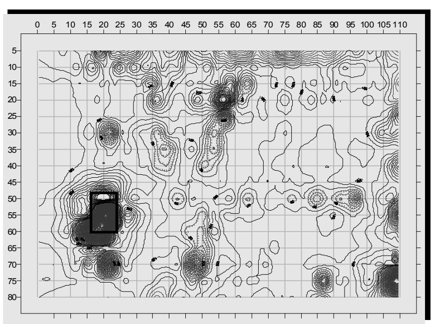
Tank Removal

In-Situ



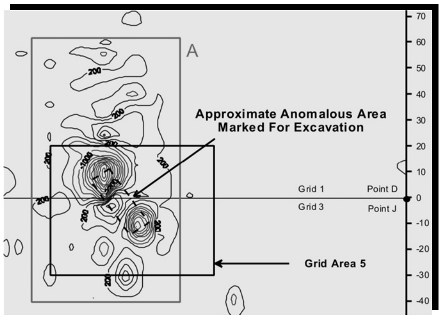
500 Gallon Tanks

Mag Anomaly Example 6



Example 6 Tank Removal

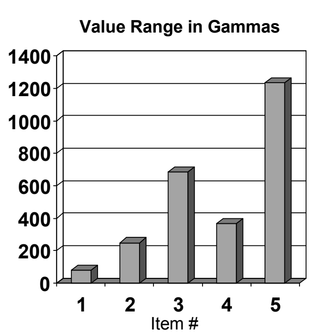
Mag Anomaly Example 7



Mag Anomaly 7 Removal

Environmental Anomaly Comparisons

1) 1 crushed drum
   -4.5' to -8.5' depth
2) 5 crushed drums
   -5' to -6' depth
3) 1 whole drum horiz.
   -3' to -6' depth
4) 2 pipes 10' x 4"
   -1.7' to -2' depth
5) 2 tanks 500 gal. ea.
   -2' to -7' depth



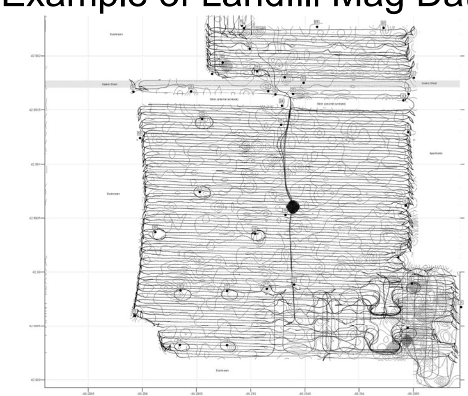
Confirmatory Methods for Magnetics

Magnetics
Rapid Data Collection
Establish Amount of Mass
General Lateral Dimensions

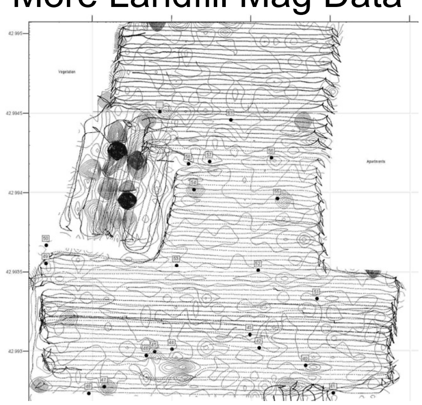
GPR
Depth to Target
Top of Target Shape
(dependent on soil conditions)

Electromagnetics
Detailed Lateral Dimensions
Generalized Depth Information
(dependent on Tx & Rx range)

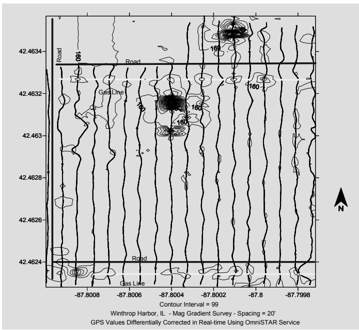
Example of Landfill Mag Data



More Landfill Mag Data



Vacant Field Mag Data



Marine Cesium Magnetometer

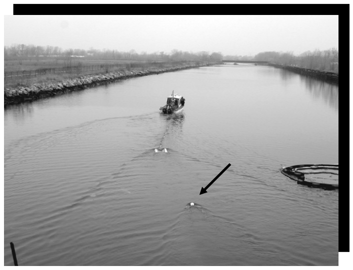
- Towed by boat
- X-Y location control by GPS
- Depth control by line & speed or floatation device

Geometrics

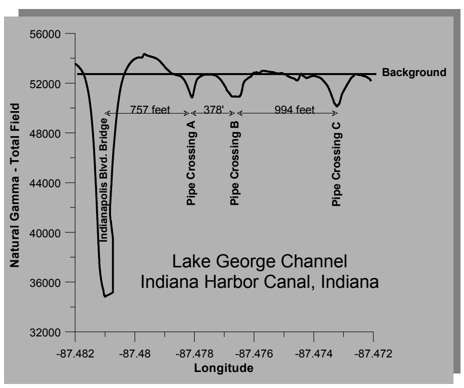
Surface Mag in Aluminum Boat

Marine Applications

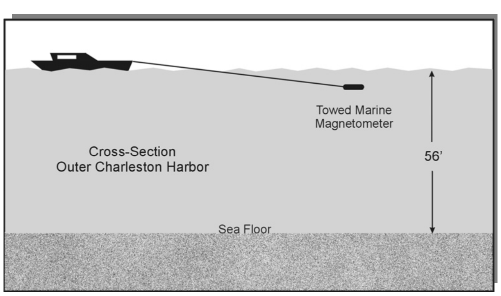
- Lake George Channel
- Indiana Harbor Canal
- Looking south Indianapolis blvd. bridge



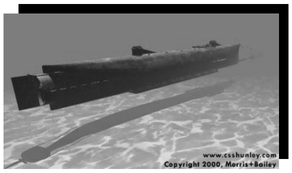
Marine Cesium Magnetometer Data

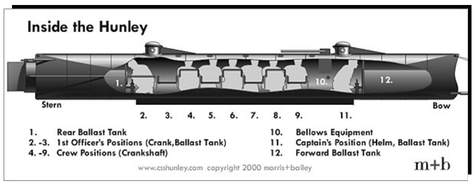


Search for CSS Hunley Using Magnetics

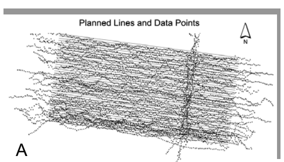


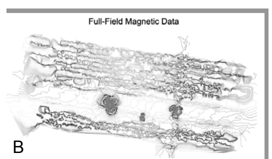
CSS H. L. Hunley – USS Housatonic



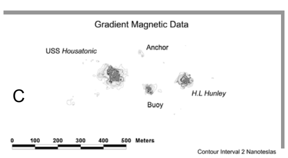


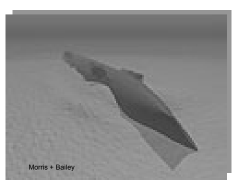
Battle Site Mag Anomalies





A, B, C Courtesy: Submerged Cultural Resources Unit - National Park Service – Santa Fe, NM





What's Wrong With This Picture?

Requesting A Survey

(Questions Provider Should Ask You)

- How big is the site
- Composition of targets
- Orientation & size of targets
- Depth or burial method of targets
- Describe terrain & site conditions
- Explain special circumstances

Provider Submits Plan

(Questions You Should Ask)

- Why are selected method(s) appropriate?
- What tool & configurations will be used?
- Method to ensure data location accuracy?
- What deliverables will be provided?
- Will data be presented for the layperson?
- How can I relocate area at a later date?

Limitations

- Subject to cultural noise
- Detection of small objects reduced with depth
- Depth estimates most difficult for non-homogenous masses
- Masses cannot be uniquely characterized

Summary & Conclusion

- Magnetometers detects ferrous metal & fired clays
- Non-invasive, passive detection method
- Quantitative results relative to amount of mass
- Large masses detectable at significant depths
- Complements other geophysical methods
- Note: Magnetometers are different from metal detectors
  - metal detectors emit energy to detect metal
  - magnetometers passively measure ambient conditions

ELECTROMAGNETIC (EM) METHODS

Module Goals

- Describe electromagnetic methods in general
- Explain the differences between these two types of electromagnetic instrumentation
- Describe the application of the two types in the field of environmental geophysics

EM Methods

- Often used with magnetics
- Fast and inexpensive
- Measures conductivity
- Frequency Domain
- Time Domain

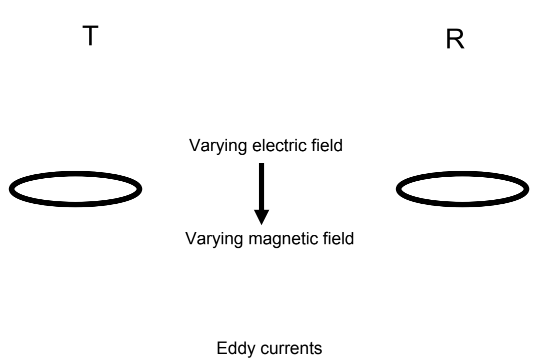
Frequency Domain EM (FDEM)

- Fixed Frequency - Fixed Depth
- Multiple Frequency - Variable Depth
- Reads Conductivity Directly
- Metal Detection

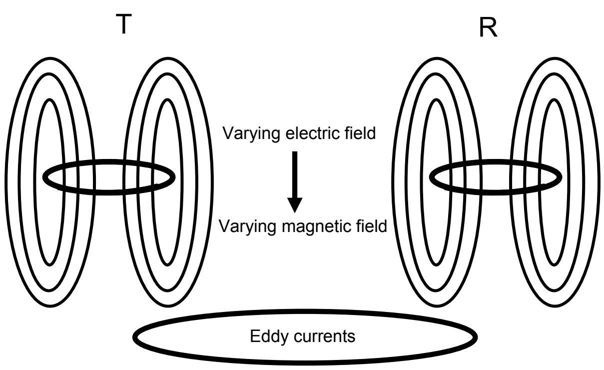
Time Domain EM (TDEM)

- Square Wave signal - Variable Depth
- Conductivity at depth
- Metal Detection

Frequency-Domain EM



Frequency-Domain EM



Depth of Penetration

- ~1.5 x coil spacing for vertical dipole
- ~.75 x coil spacing for horizontal dipole

FDEM Signal Components

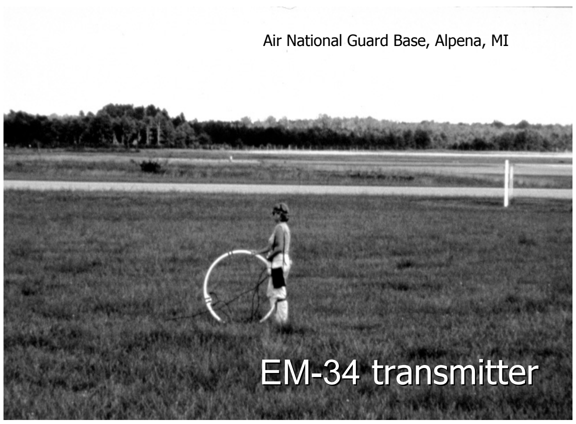
- The secondary magnetic field has two components
  - Quadrature phase - used to measure ground conductivity - 90° out of phase with primary field
  - In-phase - used to detect excellent conductors (metal) - 180° out of phase with primary field

EM-31

- ~ 4.5 meter maximum depth (3.66 m coil spacing)
- Operating frequency 9.8 kHz
- Soil conductivity (mS/m) - quadrature phase
- Metal detection (ppt) - in-phase component

EM-34

- Three coil spacings –
  - 10 m. (6.4 kHz)
  - 20 m. (1.4 kHz)
  - 40 m. (0.4 kHz)
- Soil conductivity - quadrature phase
- Coil spacing - in-phase component



Gem-2 and 3

- Multi-frequency signal
- Variable depth of investigation
- Output is secondary magnetic field (ppm) to the primary magnetic field

Conditions Affecting Conductivity

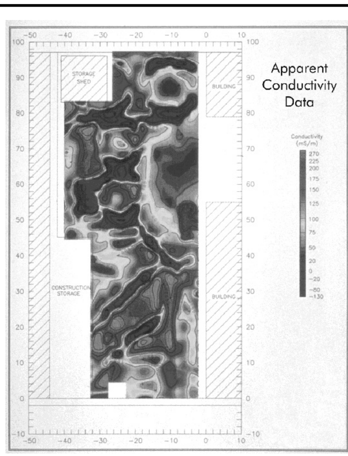
- Soil type
- Moisture
- Cultural debris
- Pore fluid

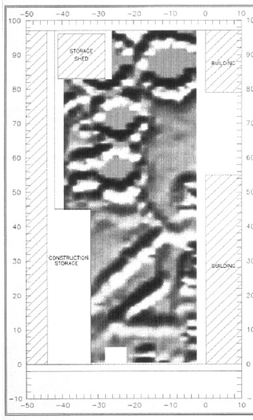
Advantages/Limitations of FDEM Detectors

- Advantages
  - Fast, inexpensive
  - Reasonable lateral resolution
- Limitations
  - Limited depth of penetration
  - Sometimes difficult to interpret
  - Many noise sources

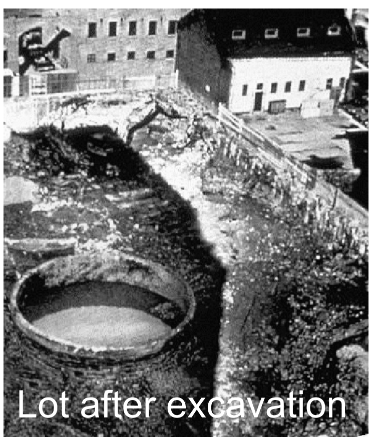
Frequency Domain EM

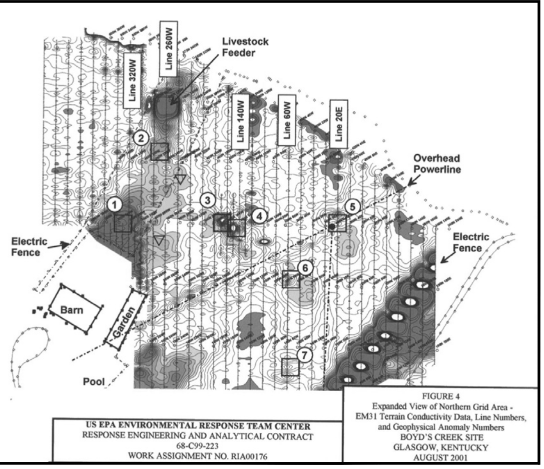
Case Studies



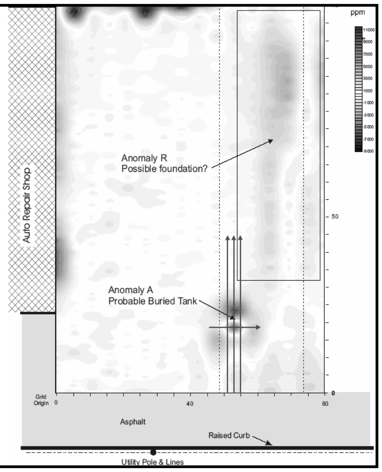


Inphase Shaded Relief Map

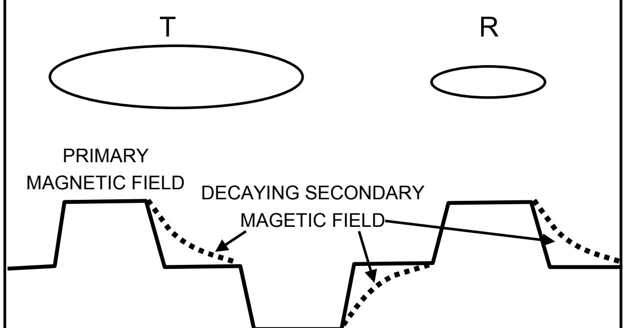




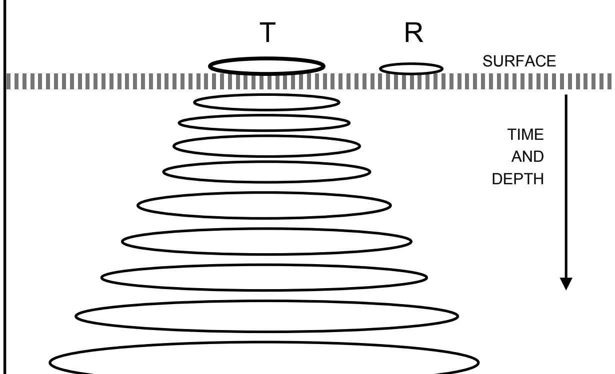
EPA Gem2 data
Northridge, IL
21030 Hz
In phase data

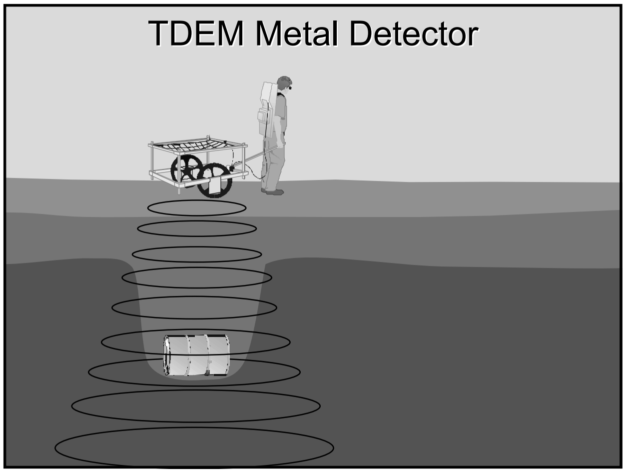


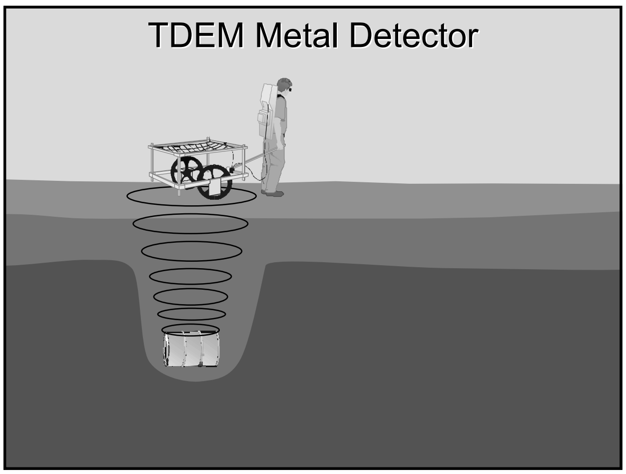
Time Domain EM (TDEM)



TDEM




TDEM Metal Detector


TDEM Metal Detector


EM-61 MK2
Site near Dayton, OH

Time Gates EM-61 MK2

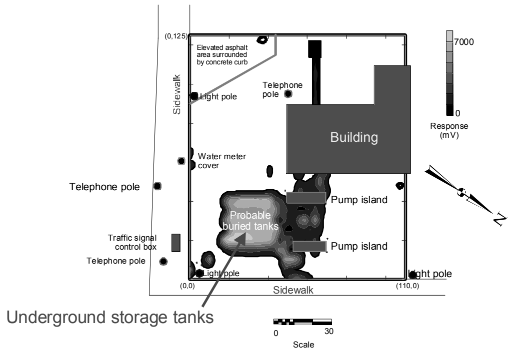
- Channel 1 – 216 μ seconds (bottom coil)
- Channel 2 – 366 μ seconds (bottom coil)
- Channel 3 – 660 μ seconds (bottom coil)
- Channel 4 – 1266 μ seconds (bottom coil)
- Channel T – 660 μ seconds (top coil)

TDEM Metal Detector

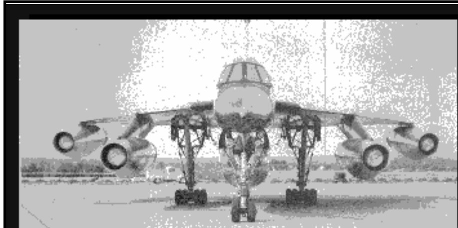
- One transmitting coil
- Two receiving coils
- Ability to discriminate depth and screen surface metal
- Depth of detection about 3.5 meters

Advantages and Limitations of TDEM Detectors

- Advantages
  - Fast and inexpensive
  - Easy to interpret
  - Excellent lateral resolution
  - Unaffected by conductive soil
- Limitations
  - Limited depth of penetration - 3.5 meters
  - No geologic data



Abandoned Gas Station, East St. Louis, Illinois



B-58
Hustler

Before Takeoff Crash
December, 1964
Bunker Hill
(Grissom) AFB
Indiana

SEISMIC METHODS

Seismic Refraction
Seismic Reflection

Seismic Methods

- Acoustic energy induced in the ground
- Refraction relies on increasing acoustic velocities in each layer to refract energy
- Reflection relies on velocity contrasts of each layer to reflect the energy

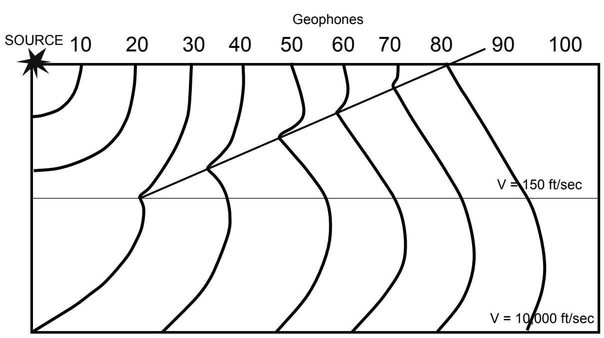
Environmental Seismic Methods

- Shallow targets
- Simple geometry/geology
- Generally only P waves (compressional wave) used

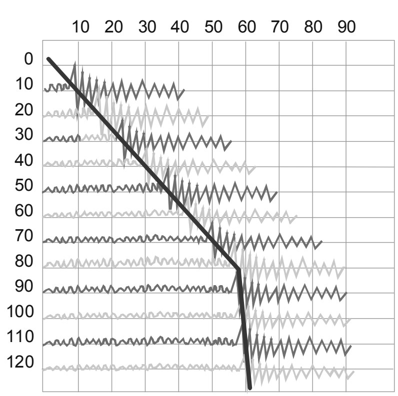
Seismic Refraction

- Acoustic energy (wave) encounters a boundary between two geologic layers
- If the velocity is higher in the lower layer, some energy is reflected and some is refracted
- If the velocity is lower in the lower layer the layer is "hidden" from the refraction method

First Arrival



Wave Signatures



Refraction Equipment

- Seismometer - instrumentation
- Geophones - acoustic sensors
- Source - acoustic energy generator

Common Velocity Ranges

Sand and gravel (dry)	1,500–3,000 ft/sec
Sand and gravel (saturated)	2,000–6,000 ft/sec
Clay	3,000–9,000 ft/sec
Water	4,800 ft/sec
Sandstone	6,000–13,000 ft/sec
Limestone	7,000–20,000 ft/sec
Metamorphic rock	10,000–23,000 ft/sec

Reference: Bison Instruments, Inc.

Seismic Refraction Uses

- Depth to groundwater
- Top of bedrock
- Mapping unconsolidated alluvial deposits
- Rippability
- Determination of rock types from seismic velocities

Refraction Advantages

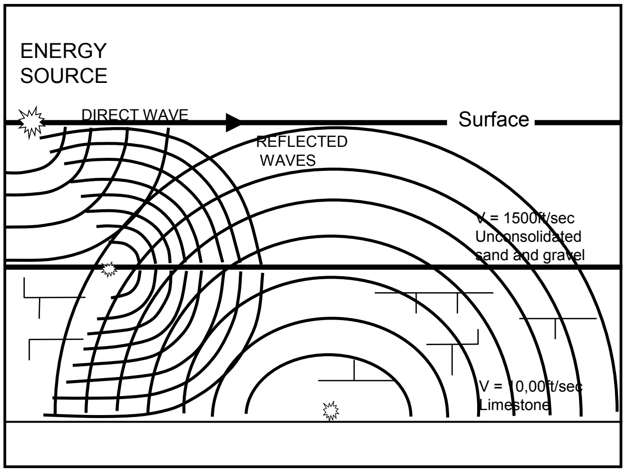
- Simple field procedure
- Rapid data collection
- Fast preliminary interpretation
- Useful in a wide variety of geologic settings

Refraction Limitations

- Velocities of layers must increase
- Poor resolution for simple surveys
- Complex interpretation in dipping formations
- Lateral velocity variations complicate interpretations
- Weathered layer absorbs acoustic energy and may be hidden

Seismic Reflection

- Acoustic energy encounters a boundary between two geologic layers
- If the acoustic impedance contrast is large enough some of the energy is reflected and the rest is transmitted
- Resolution of the thickness may be difficult for thin beds



Seismic Reflection Equipment

- In most cases identical to refraction equipment
- Geophone arrangement may be different
- Data is taken from later in the seismic record

Seismic Reflection Uses

- Subsurface geometry/geology
- Finding faults and intrusions
- High resolution mapping of beds

Seismic Reflection Advantages

- No problem with low velocity layers
- Better resolution of thin beds
- Higher resolution overall
- Deeper imaging with same source

Seismic Reflection Limitations

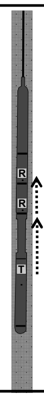
- More complex to interpret
- May be more expensive than refraction
- Works only in some environments
- Generally for deeper investigations
- High resolution requires high frequency signal

Acoustic Velocity Logging

- Downhole seismic technique
- Used for fracture studies and stratigraphic determinations
- Very high resolution

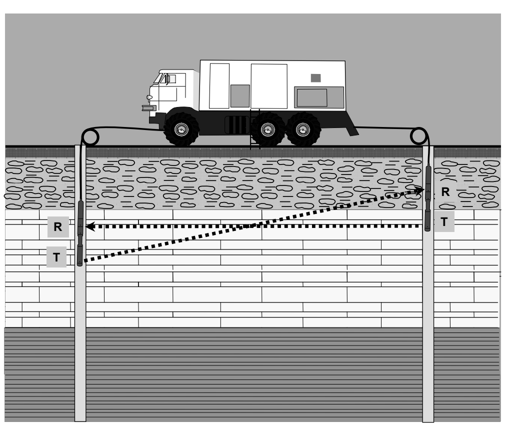
Acoustic Velocity Logging

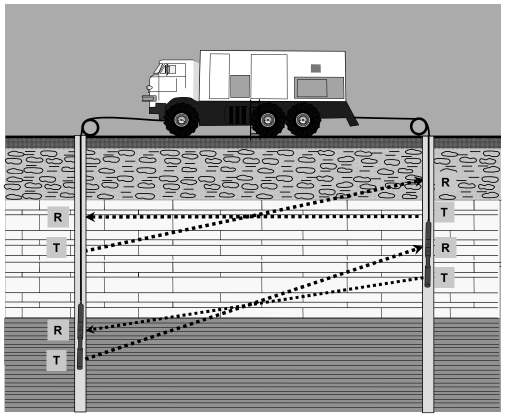
- Downhole seismic technique
- Used for fracture studies and stratigraphic determinations
- Very high resolution



Crosshole Seismic

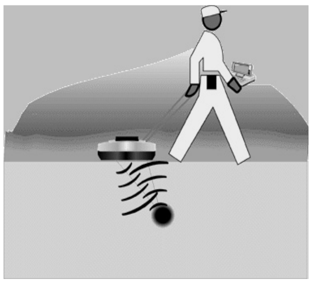
- Three dimensional imaging
- Velocity and stress determinations
- Very high resolution





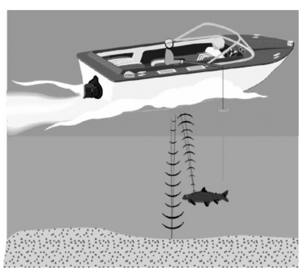
Additional Seismic Methods

What is GPR?



- acronym for **G**round **P**enetrating **R**adar
- ground can be soil, rock, concrete, wood
  - anything non-metallic
- emits a pulse into the ground
- records echoes
- builds an image from the echoes

GPR is Just Like a Fish Finder & Echo Sounder



- sends out a ping
- signal scattered back from fish
- signal scattered back from bottom
- in this example a single record has 2 blips at different times

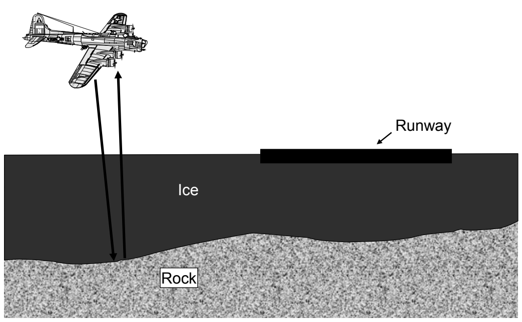
Ground Penetrating Radar

- Electromagnetic technique
- Same principles and theory as radar used to detect aircraft
- Sensitive to changes in electrical properties

A Little History!!

- First GPR survey was performed in Austria, 1929
- Sound depth of a glacier
- Technology then largely forgotten

1950's USAF Greenland



Apollo 17 Surface Electrical Properties Experiment

NASA

- December 1972
- Transmitting antenna (1-32.1 MHz) near Lunar Module
- Receiver on Lunar Rover
- Results: Upper 2 km lunar surface extremely dry

Commercial Systems

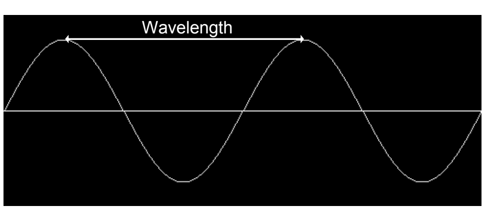
- 1960's had to build your own system
- Changed in 1972
- Geophysical Survey Systems Inc.
- Sell first commercial GPR system
- Several companies now make systems

GPR: A True Wave-Based Technique

Wave energy travels at a characteristic wave speed that depends on the material through which it travels. This is the main difference between GPR and EMI.

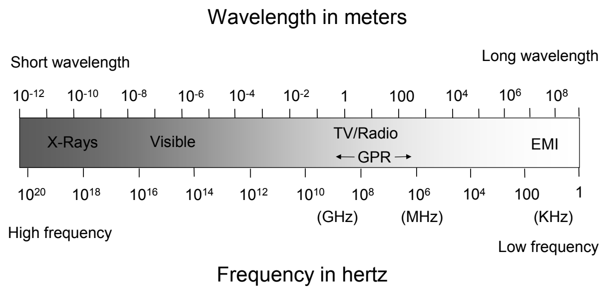
Wave Properties

The wavelength of a wave is the distance between any two adjacent corresponding locations on the wave train.



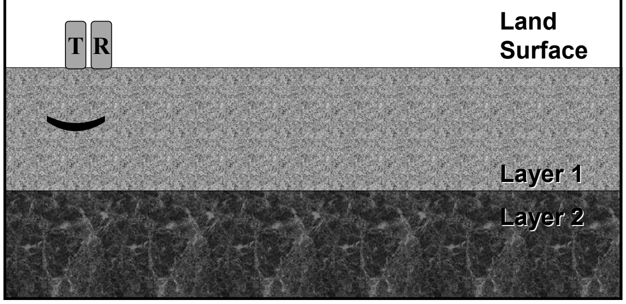
Frequency refers to how many waves are made per time interval. This is usually described as how many waves are made per second, or as cycles per second.

Electromagnetic Spectrum

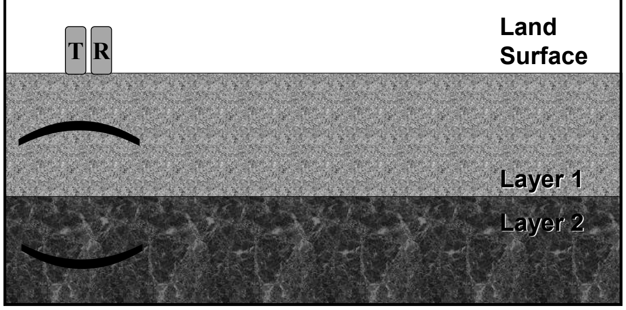


GPR = 10 to 1000 MHz range

Ground Penetrating Radar (GPR) Data Collection



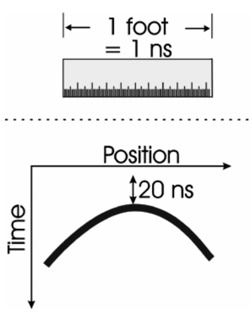
Ground Penetrating Radar (GPR) Data Collection



Two-Way Travel Time

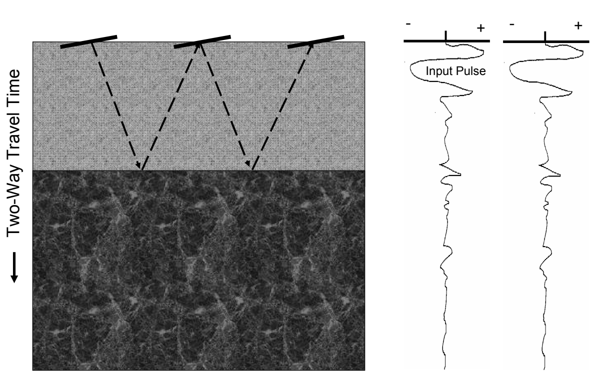
- Amount of time for the radio wave to make round-trip from the surface down to the reflector and back
- Greater for deeper objects
- Can be converted to depth if velocity is known
- Measured in nanoseconds

What Are Nanoseconds?

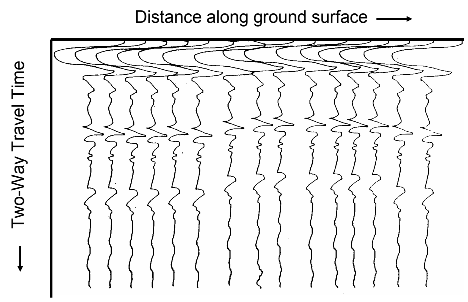


- GPR time is measured in units of nanoseconds
- 1 nanosecond is 1 billionth of a second =1/1,000,000,000 second
- GPR signals travel 1 ft (0.3m) in air in 1 nanosecond
- *ns* is the abbreviation for nanosecond

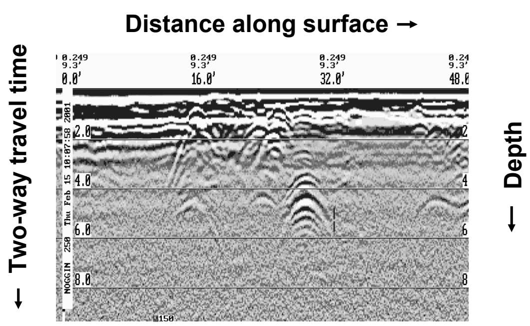
GPR Trace



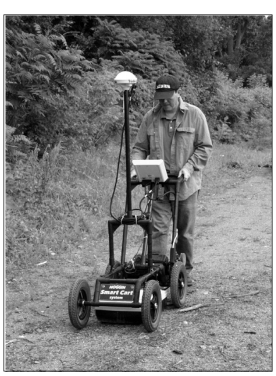
GPR Record



GPR Display/Record

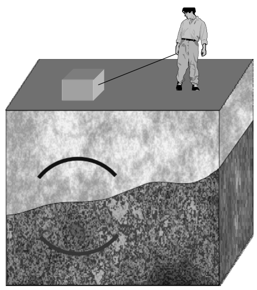


Typical GPR System



- Digital video logger
- Transmitter & Receiver antenna
- Odometer controlled
- GPS

What Creates GPR Reflections?



- Caused by an abrupt change in electrical properties of the subsurface
- Primarily the relative dielectric permittivity

Relative Dielectric Permittivity

- aka: Dielectric Constant
- Measure of the capacity of a material to store charge when an electric field is applied
- Controls wave velocity
- Reflections occur when radio waves encounter a change in velocity
- Values range from 1 to 81

Typical RDP Values (K)

Air	1
Water	81
Dry Sands	4
Saturated Sands	25
Silts	5-30
Clays	5-40
Limestone	6
Granite	5
Ice	3-4

Reflection Strength

$$r = \frac{\sqrt{K_2} - \sqrt{K_1}}{\sqrt{K_2} + \sqrt{K_1}}$$

K_1 = relative dielectric permittivity of first layer
K_2 = relative dielectric permittivity of second layer

Reflection Strength

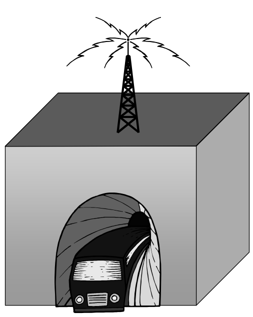
r = 0 to 0.2 weak reflections

r = 0.2 to 0.3 moderate reflections

r = greater than 0.3 strong reflections

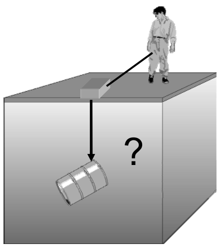
Metal reflects nearly 100% of a radar wave

How Deep Can GPR See?



- Radio waves do not normally penetrate far through most materials
- Loss of radio reception or cell phone connection in a tunnel attests to this
- GPR works because of very sensitive measuring systems and specialized circumstances

How Deep Can GPR See?



- Conductivity prime factor
- Higher conductivities limit depth
- Conductivity controlled by material type
- Frequency

Conductivity

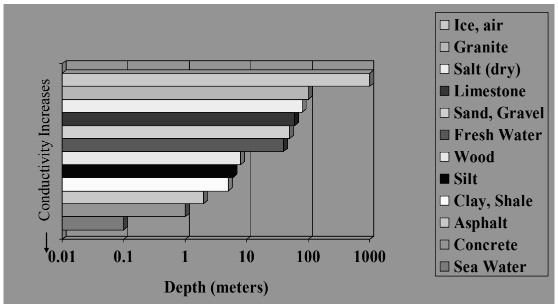
- Ability of a material to conduct electric current
- Conductivity increases with increase in water and/or clay content
- Higher conductivities limit depth
- Conversion of EM energy to heat

Estimating Exploration Depth

$$\text{Depth} = \frac{35}{☞} \text{ meters}$$

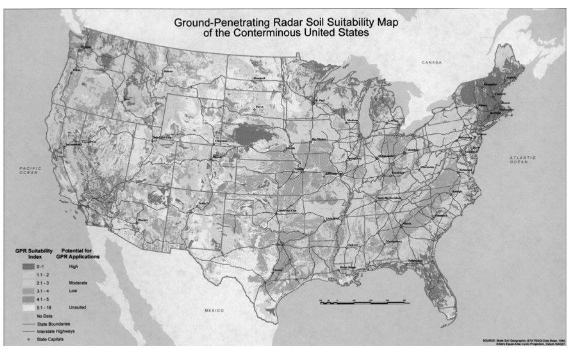
☞ = conductivity in mS/m

Material Type

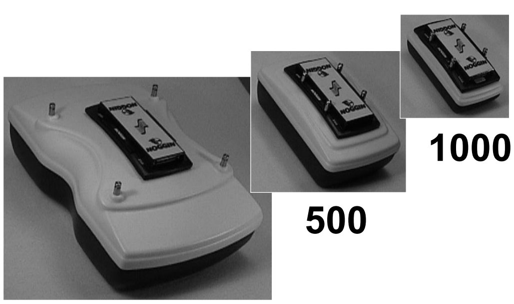


Sensors & Software Inc.

GPR Suitability Map



Antenna Frequency



1000

500

250 MHz

Antenna Characteristics

Frequency (MHz)	Depth (feet)	Resolution (feet)
250	5-45	0.5
500	1.5-12	0.3
1000	0-1.5	0.05

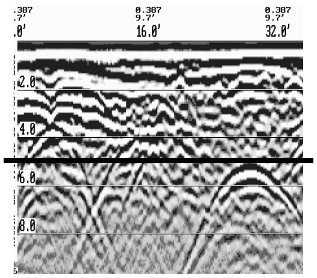
Depth Calibration
How Do I Measure Depth?

- Measure travel time
- Need material speed
- depth =velocity x time / 2
- How ?

Method 1
Estimate

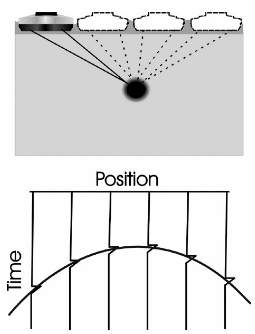
Material	Velocity (ft/ns)
Air	1.0
Ice	0.56
Dry Soil	0.43
Dry Rock	0.39
Moist Soil	0.33
Concrete	0.33
Wet Soil	0.22
Water	0.11

Method 2
Depth to Known Target



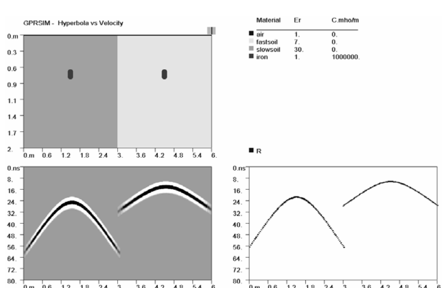
- **Know depth**
- **Adjust velocity**

Method 3
Point Target Hyperbola



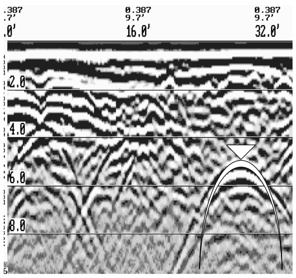
- **Wide beam**
- **Localized features**
- **Hyperbolas (inverted U's)**
- **Shape determine velocity**

Method 3
Point Target Hyperbola



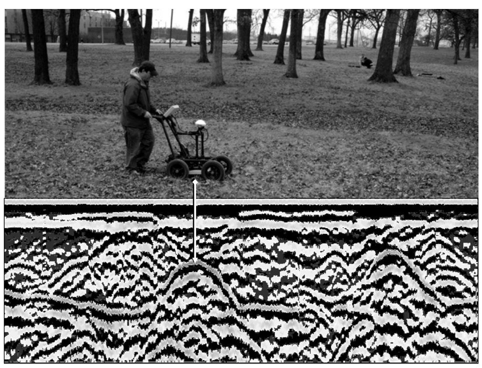
Dean Goodman

Method 3
Point Target Hyperbola

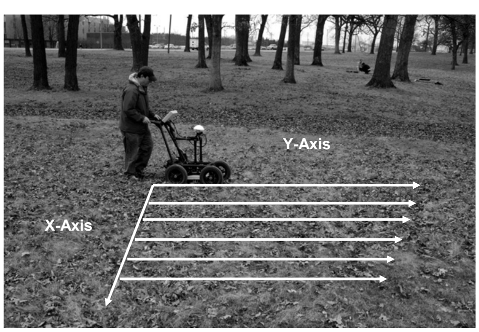


- **Adjust shape**
- **Determines velocity**

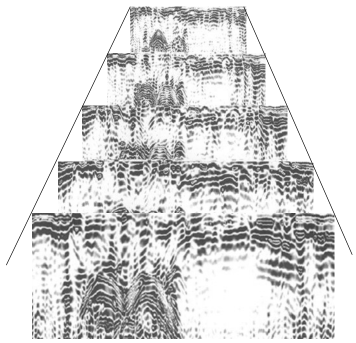
Profile and Mark



Survey Grid

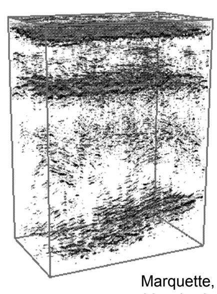


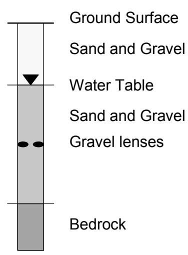
Series of GPR Profiles



Grumman Exploration

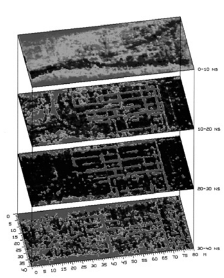
3-D GPR





Marquette, MI
30 m by 6 m area
6 - 8 m depth

Grumman Exploration

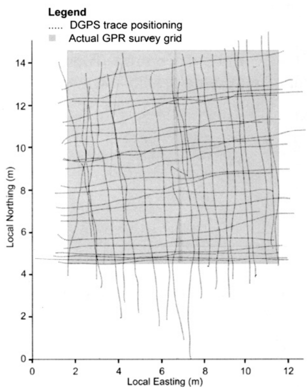


Time Slices

- GPR dataset from Forum Novum site in the Tiber Valley, Italy.
- Site is a Roman market place and church that were built in the 2nd century A.D.
- GPR time slices revealed buried walls and foundations from the ancient Roman buildings.

Dean Goodman

GPR and GPS

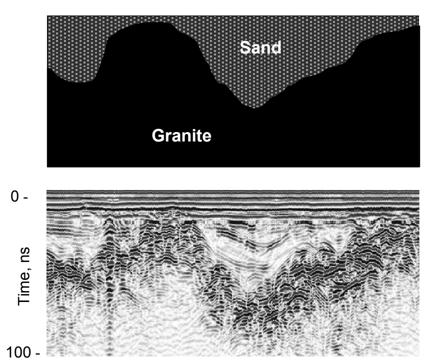


- 10 m by 10 m grid
- 0.5 m line spacing
- Differential GPS
- Area wide open
- Ideal conditions
- Not accurate

GPR Applications

- Mapping subsurface geology
  - Bedrock
  - Water Table
  - Faults and Fractures
- Locating cultural objects
  - Drums and Tanks
  - Landfills and pits
  - Contamination

Bedrock

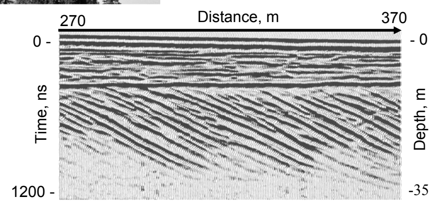


GSSI

Stratigraphy

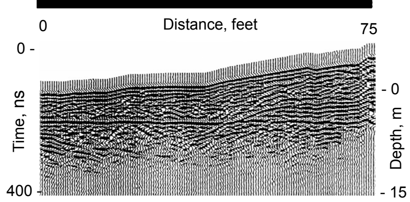
Peyto Lake Delta
Banff National Park

GPR data
Delta
Sediments
25 MHz



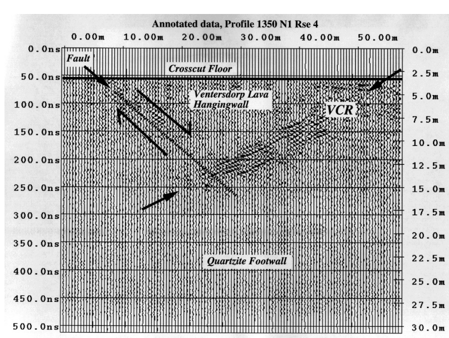
Derald Smith, University of Calgary

Water Table Mapping



Glacial sand and gravel deposits near Lake Superior, Ontario, Canada, 100 MHz, Sensors and Software, Inc.

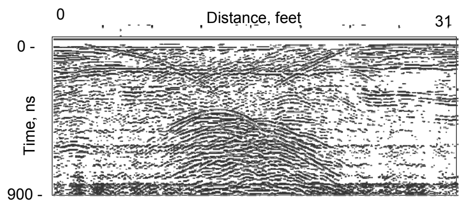
Faults and Fractures



Ventersdorp Contact Reef - South Africa

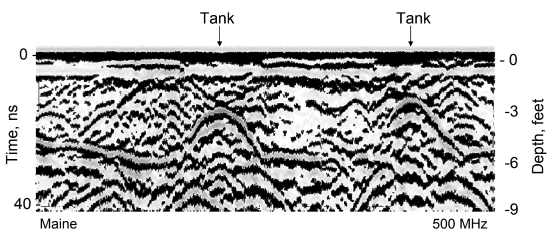
Sinkholes

Sinkhole at Winter Park, Florida



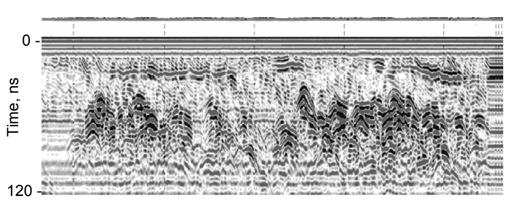
80 MHz GPR data showing developing sinkhole, Florida. GSSI

Underground Storage Tanks



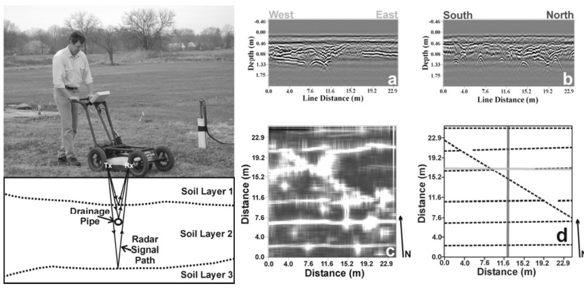
Geophysical Survey Systems, Inc.

Trench with Drums



Geophysical Survey Systems, Inc.

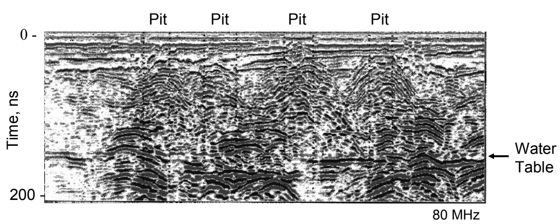
Drainage Pipe Detection



72% Success Rate in Ohio

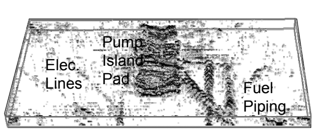
Barry Allred, USDA/OSU

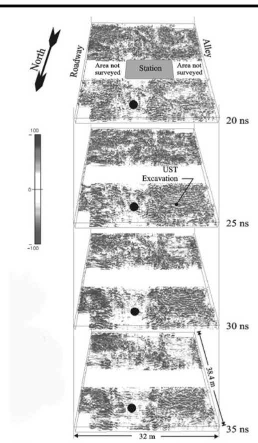
Laboratory Waste Pits



OSU - Brookhaven National Laboratory

Gas Station-Petroleum Product

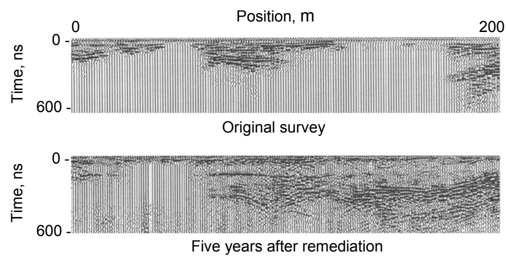




Time Slices

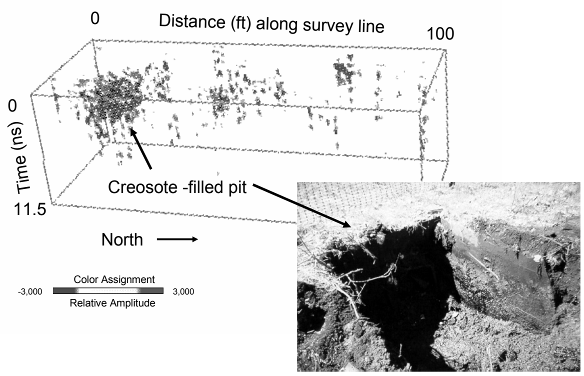
Jeff Daniels and Dave Grumman, OSU

Contaminated Groundwater

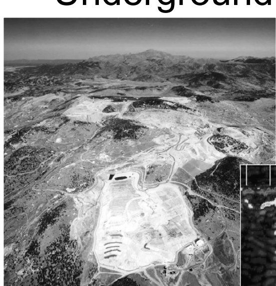


Sensors & Software Inc.

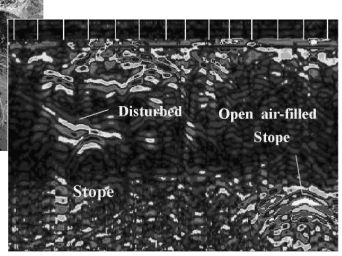
Creosote Pit



Underground Mine Workings



Cresson Open-Pit Mine
Cripple Creek, Colorado

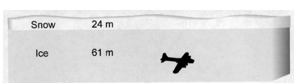


Pikes Peak Mining Co./ GSSI

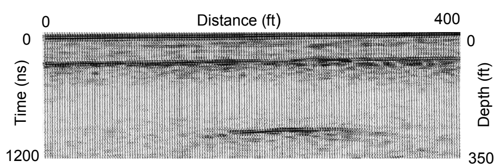
Ice / Glaciology

- Ice very transparent to GPR signals
- RDP = 3-4
- Penetration depth as much as 500 meters
- Used to study thickness and structure of glaciers

The Lost Squadron



GPR locates aircraft at depth of 279 feet below surface in Greenland



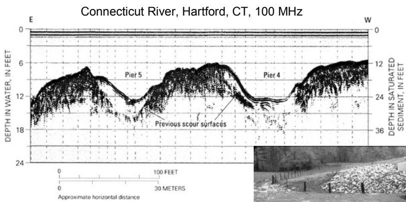
Sensors & Software Inc./Greenland Expedition Society

Water-borne GPR

Antenna

Control Unit

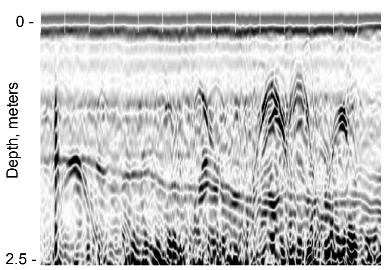
Bathymetry & Sub-bottom Profiling



Riverbed scour near bridge piers is a widespread problem throughout the United States

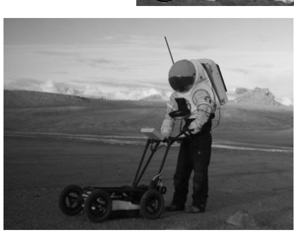
Archaeology
Burials

Iceland

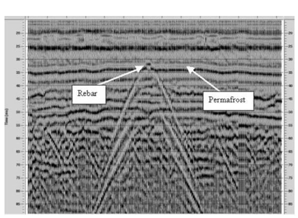


Ho Chunk Nation, Wisconsin

The Haughton-Mars Project



Haughton Meteorite Impact Structure
Devon Island, Canada
Mars Analog
2002

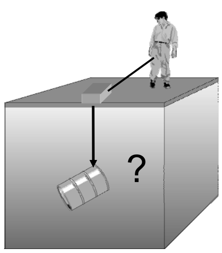


Objective to image permafrost layer similar to that presumed on Mars

Survey Design

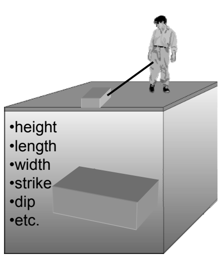
- Proper design of GPR surveys is critical to success.
- The most important step in a GPR survey is to clearly define the problem.
- There are five fundamental questions to be asked before deciding if a radar survey is going to be effective.

What is the target depth?



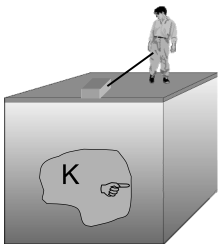
- The answer to this is usually the most important.
- If the target is beyond the range of ideal GPR conditions, GPR can be ruled out.

What is the target geometry?



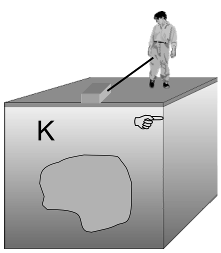
- Most important target factor is size
- If target is non-spherical, target orientation should be qualified.

What are the target electrical properties?



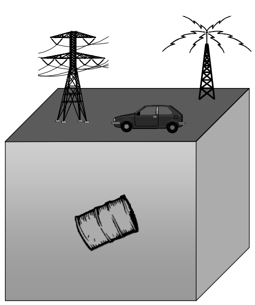
- What is relative dielectric permittivity and electrical conductivity of target?

What is the host material?



- Electrical properties of the host need to be defined.
- Need contrast in electrical properties with host environment.
- Variations of electrical properties in the host material can create noise.

What is the survey environment like?



- GPR method is sensitive to surroundings
- Extensive metal structures
- Radio frequency EM sources and transmitters
- Site accessibility

GPR Summary

- Reflection technique which uses radio waves to detect changes in subsurface electrical properties
- Limited exploration depth in conductive soils
- GPR provides the highest resolution of any surface geophysical method
- The most important step in a GPR survey is to clearly define the problem