United States
Environmental Protection
Agency

Office of Emergency and
Remedial Response
Washington, DC 20460

Superfund

EPA

Introduction to Environmental Geophysics (165.20)

Student Manual

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FOREWORD

This manual is for reference use of students enrolled in scheduled training courses of the U.S. Environmental Protection Agency (EPA). While it will be useful to anyone who needs information on the subjects covered, it will have its greatest value as an adjunct to classroom presentations involving discussions among the students and the instructional staff.

This manual has been developed to provide the best available current information; however, individual instructors may provide additional material to cover special aspects of their presentations. Because of the limited availability of the manual, it should not be cited in bibliographies or other publications.

References to products and manufacturers are for illustration only; they do not imply endorsement by EPA.

Constructive suggestions for improvement of the content and format of the Introduction to Environmental Geophysics (165.20) manual are welcome.

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
ENVIRONMENTAL RESPONSE TEAM CENTER
CINCINNATI, OHIO 45268

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, Bruce Potoka, at (513) 569-7537.

OVERVIEW OF GEOPHYSICAL METHODS

Geophysical Surveys

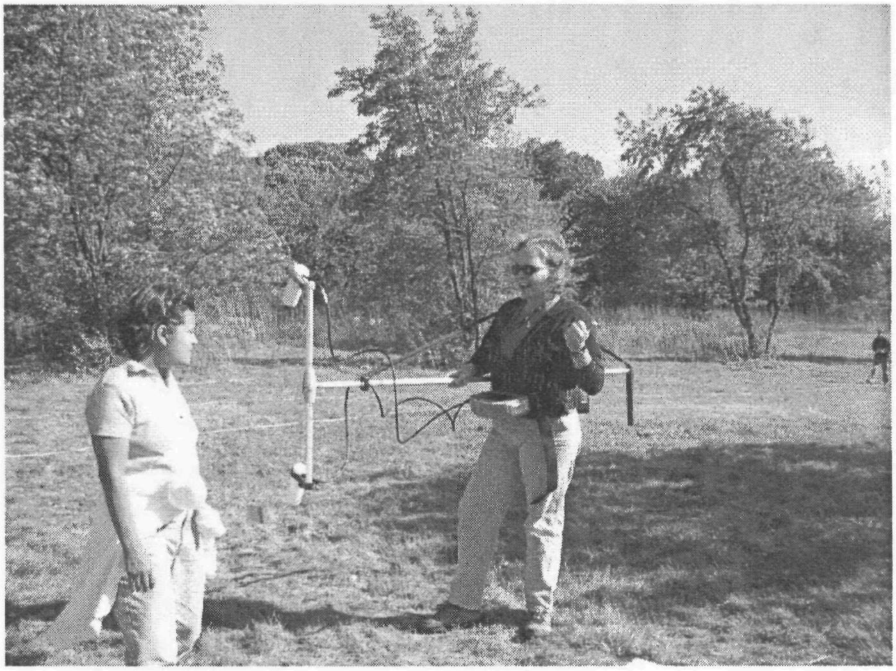
- Characterize geology
- Characterize hydrogeology
- Locate metal targets and voids

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

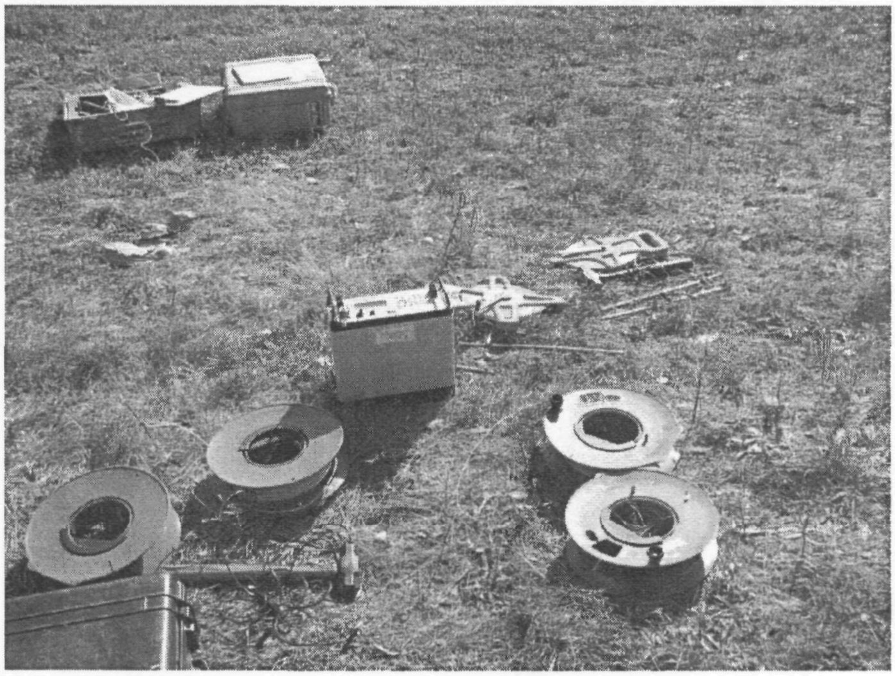


Electromagnetics (EM)

- 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

Gravity

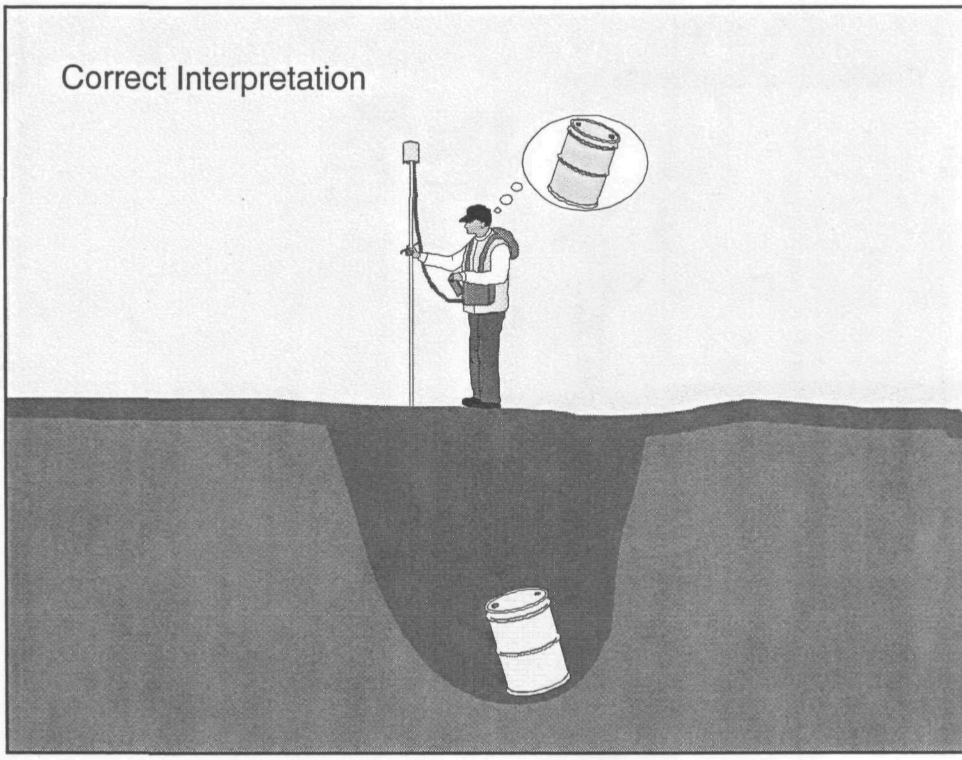
- Measures gravitational field
- Used to determine density of materials under instrument
- Maps voids and intrusions

Ground Penetrating Radar

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

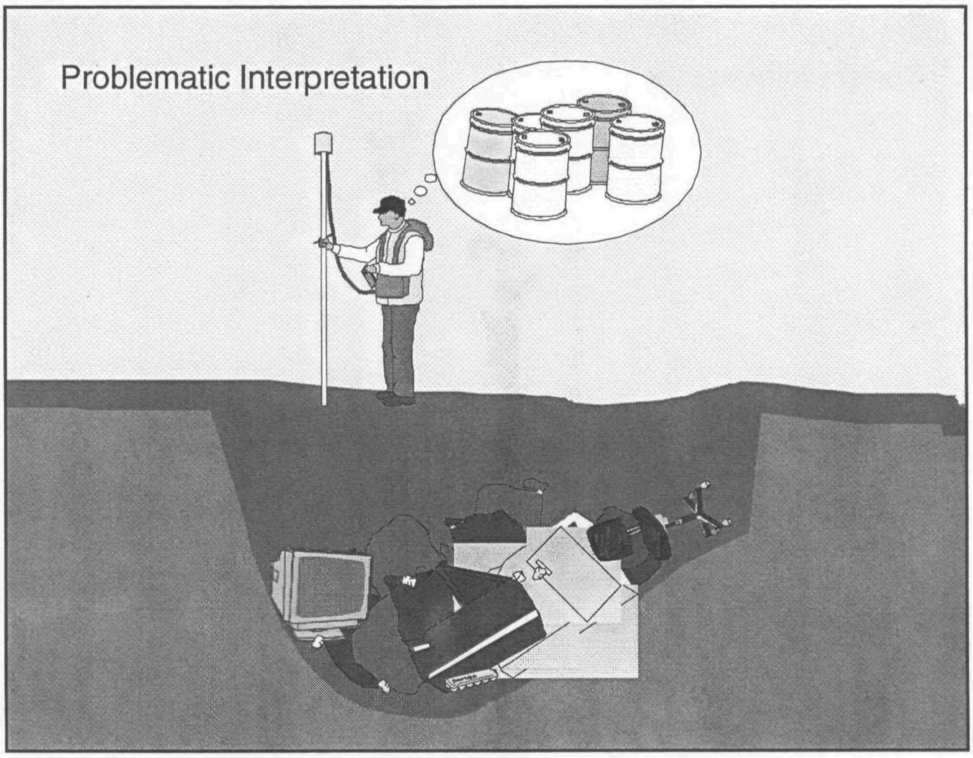
Geophysical Methods
Advantages

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



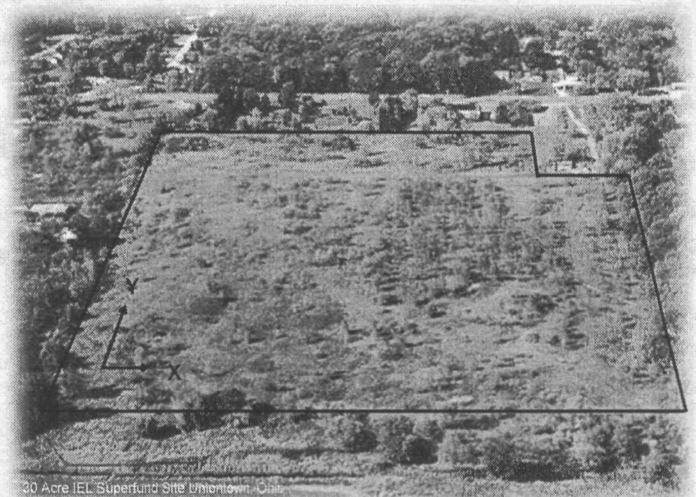
Geophysical Methods
Limitations

- 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

October 17, 2007 Kansas City, MO
Jim Ursic – Region 5, U.S. Environmental Protection Agency
Ursic.James@epa.gov - 312.353.1526

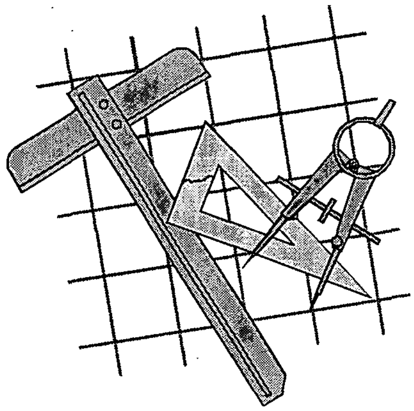


A Good Survey Results In…

- 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

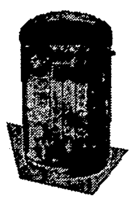
Survey Design Rationale

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



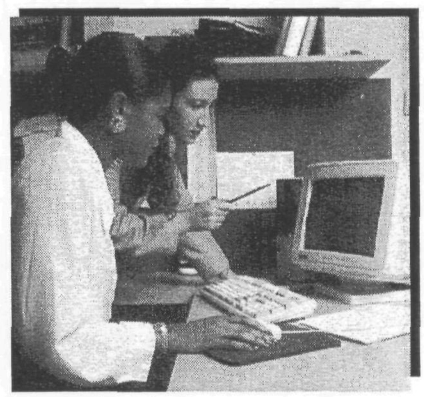
Pre-survey Planning: Garbage IN – Garbage OUT

- 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

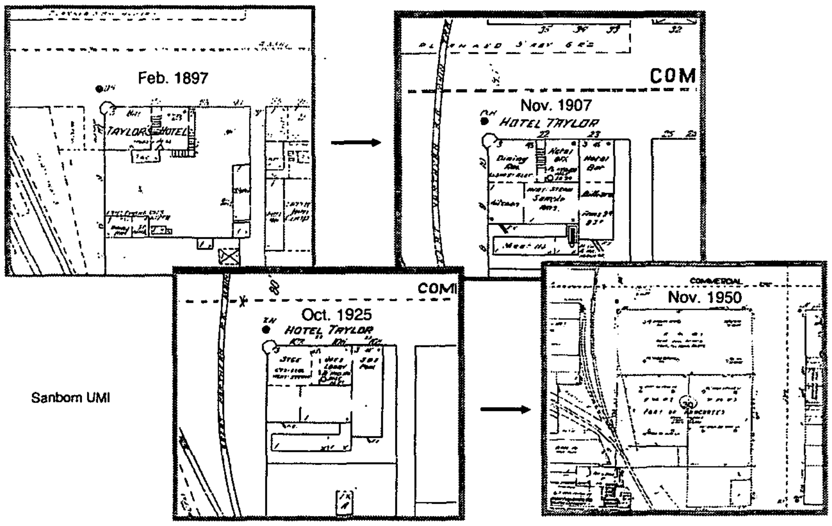
- Site history
- Previous studies
- Geology
- Geohydrology
- Geographic issues
- Health, safety & QAPP issues

Background Map Review

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

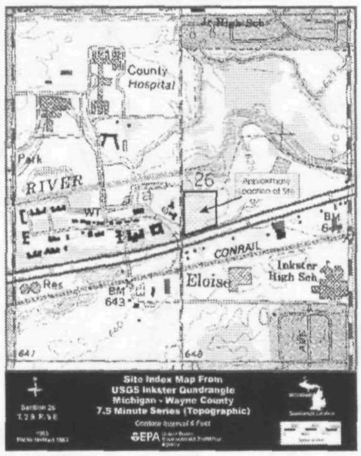
- Topographic Maps
  - Terrain conditions
- Geologic Maps
  - Indirect conditions

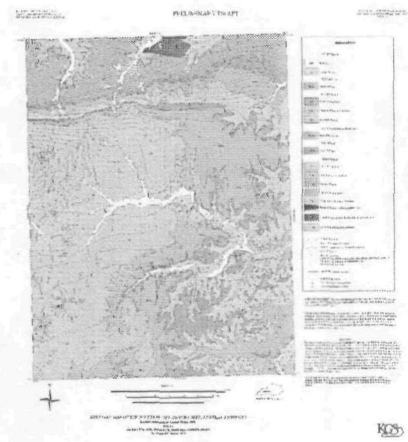
Sanborn Maps: Anacortes, Washington State



Sanborn UMI

Topographic & Geologic Maps

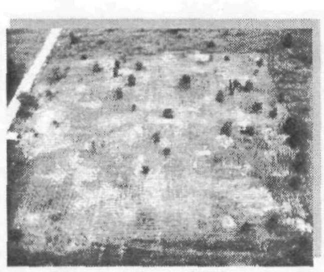




Background Photo Review

Recent Site Photo

Historical Site Photo



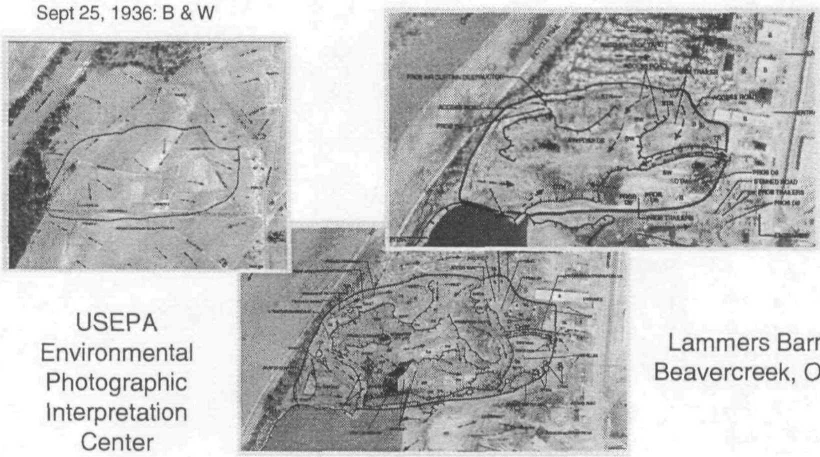
Recent Aerial Photo

Historical Aerial Photo

Photo Interpretation

May 7, 1981: Color Infrared

Sept 25, 1936: B & W



USEPA Environmental Photographic Interpretation Center

Lammers Barrel Beavercreek, Ohio

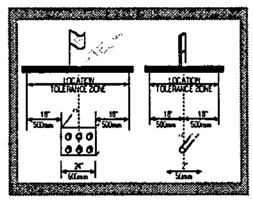
April 5, 1988: Color

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

National Historic Preservation Act

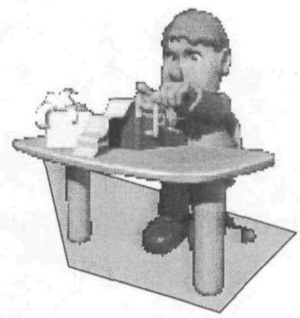
- Why should we care?
  - It's the law
  - Regulations require it
  - It's EPA's policy
  - It's a good idea

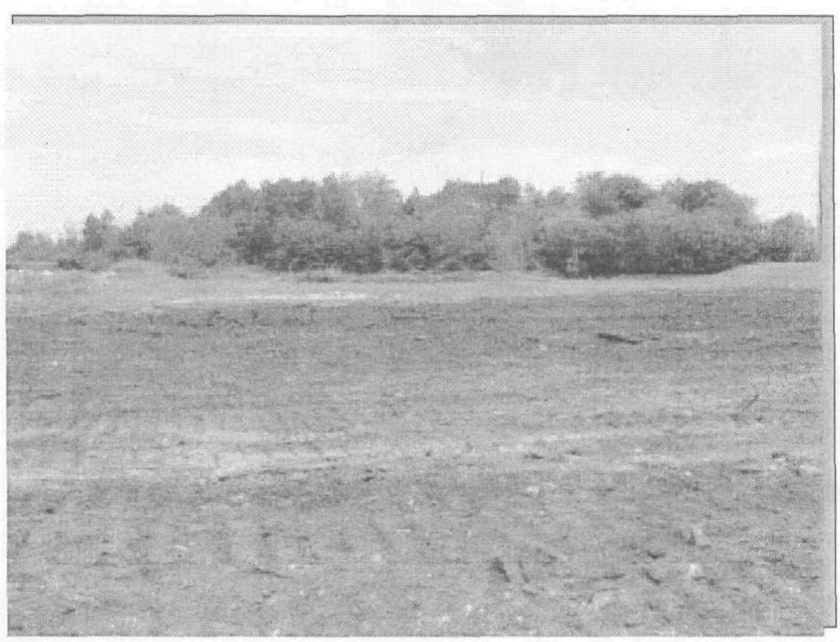
Public Law 89-665; 16 U.S.C 470 & Subsequent Amendments

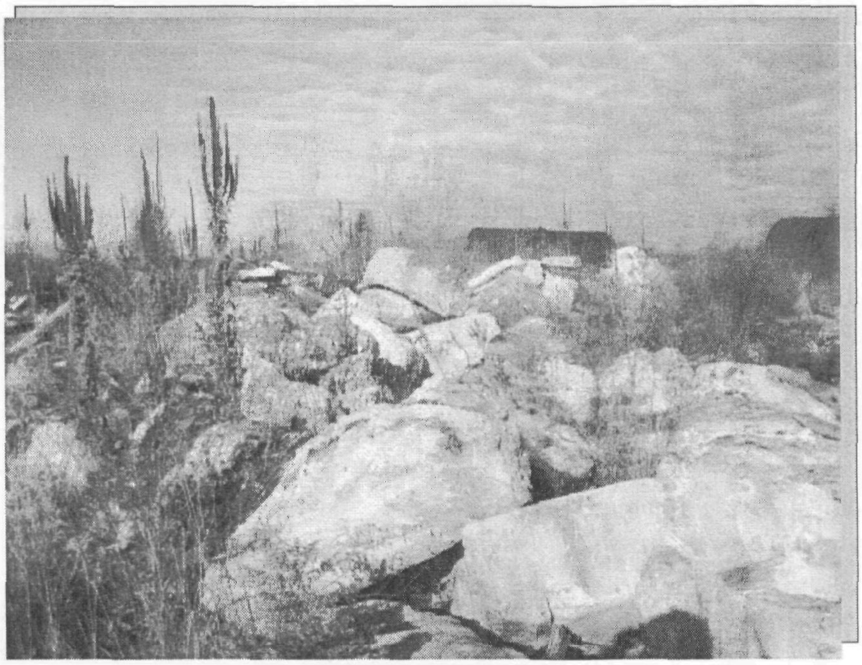
EPA Contact: Loichinger.Jamie@epa.gov - State Contacts: www.ncshpo.org

Analyze Background Information to Determine..

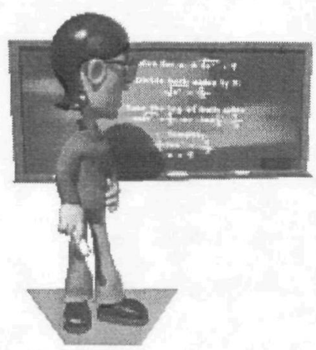
- Area to be surveyed
- Size - number of suspect targets
- Potential problems
- Site reconnaissance needed?



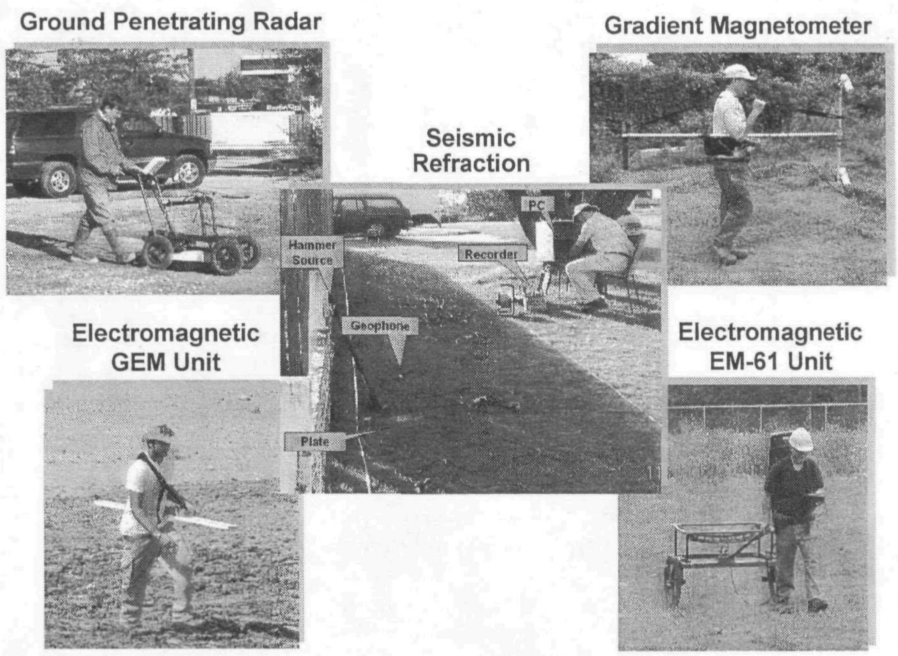




Match Most Favorable Geophysical Techniques to Problem



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



Optimize Data Collection

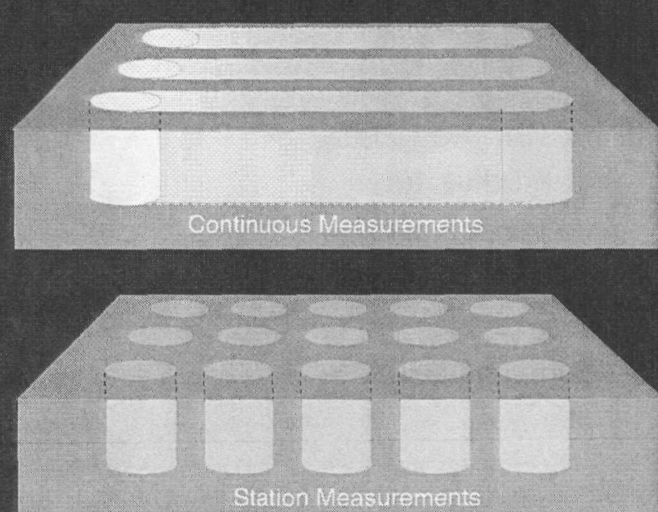
- Establish how data will be collected
  - Traverse pattern
  - Grid spacing
  - Axis labeling
  - Data Location ID

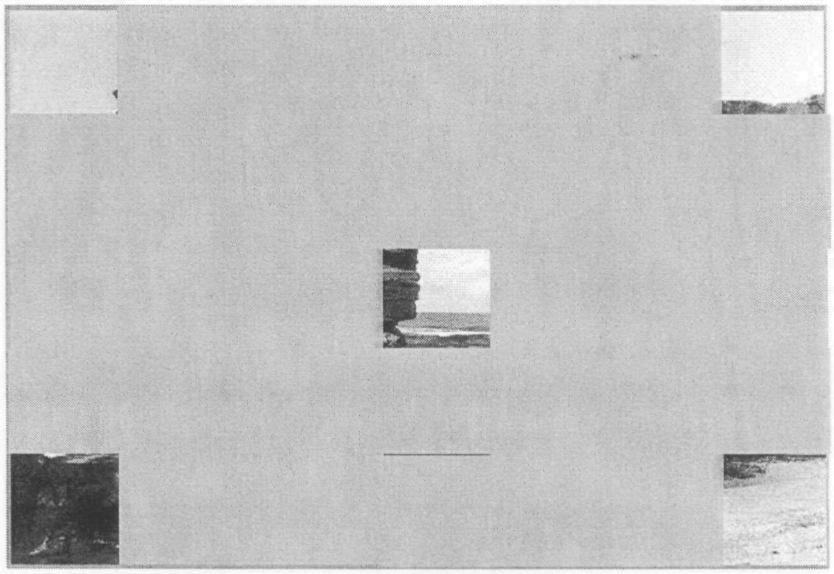
Key Issues For Collecting Data

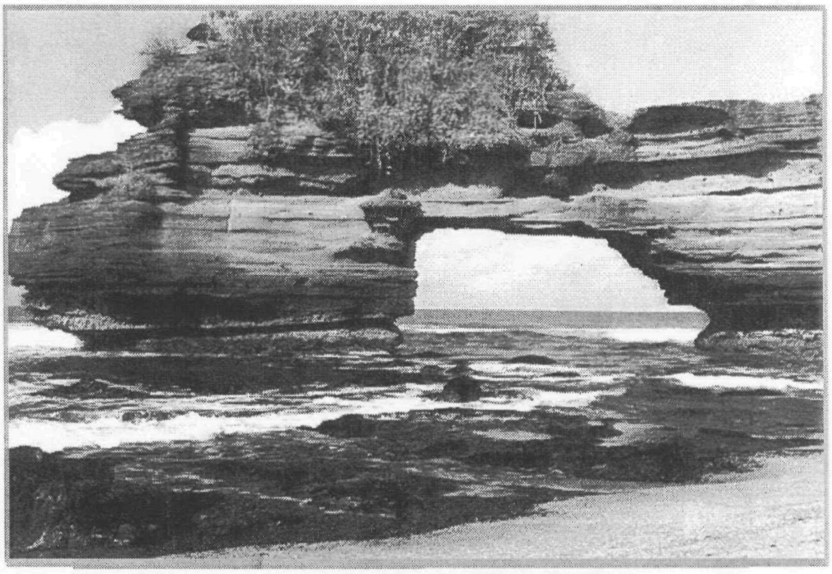
- Systematic collection (grid or lines)
- Spacing dependent on target size
- Accurate grid or line establishment
- Method to ensure location accuracy
- Label grids or lines reasonably
- Maintain good field notes

Data Collection

(magnetics, electromagnetics, ground penetrating radar)







Detection Probability

(Using Individual Station Measurements)

O At = Area of Target
43

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

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

a x Probability Factor = Sampling Points (Approx.)

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

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

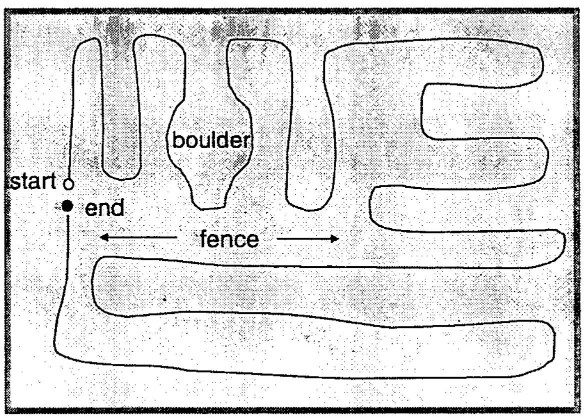
Probability Factors

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)

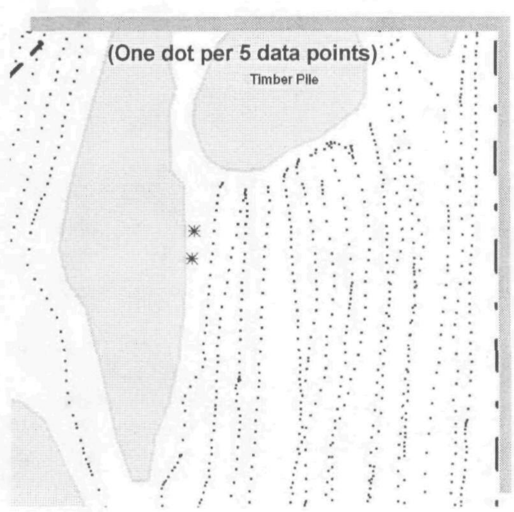


Random Survey Using GPS
(Large Area)

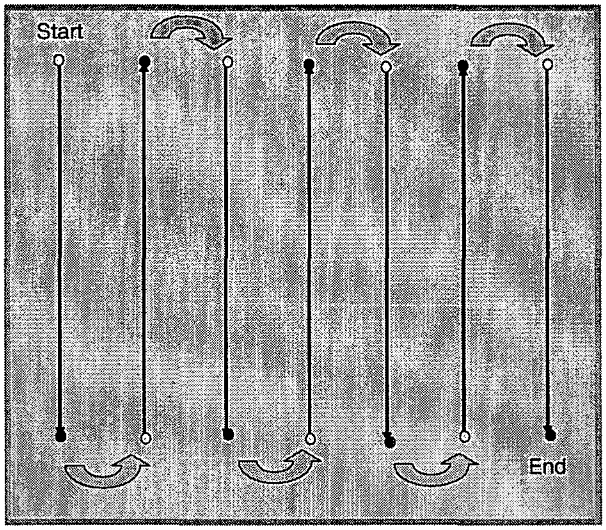
- Maximize productivity
- Data linked to GPS
- Best in obstructed areas
- Areas must be free of:
  - Vegetative canopies
  - Tall buildings
  - Major power lines

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

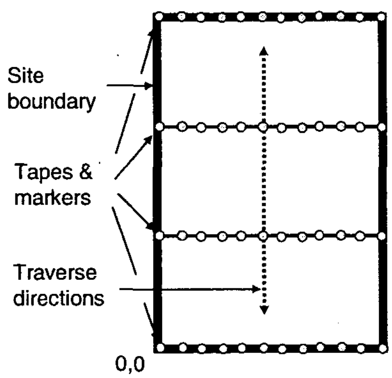


Alternating Traverse
No GPS

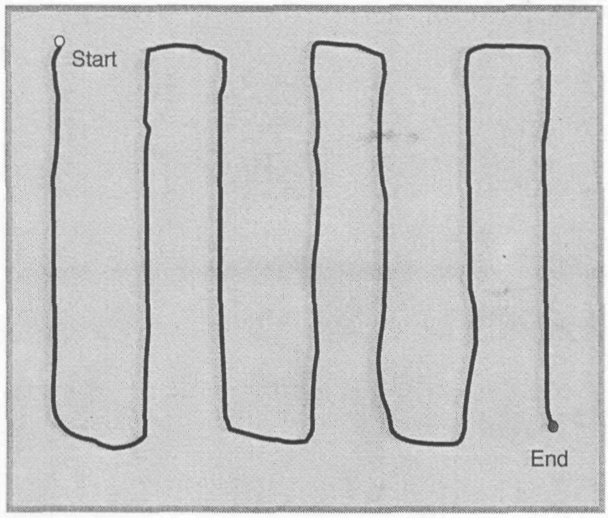


Alternating Traverse Grid Setup
No GPS

- 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



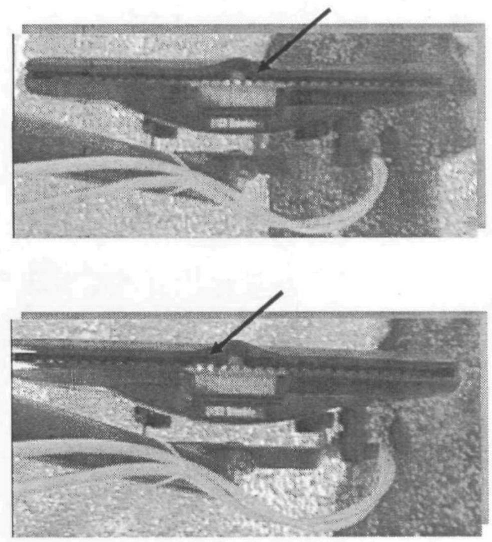
Parallel Swathing GPS

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

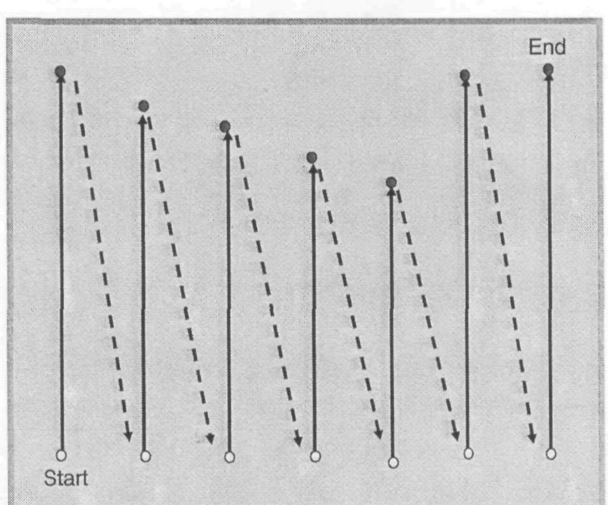
Photo: Geometrics

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

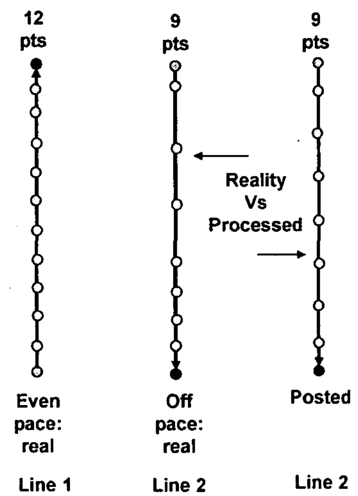
- Station position
- Time – distance
- Encoder wheel
- GPS

Correcting for Position (Y)

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

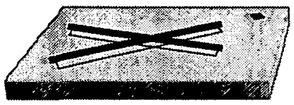
Continuous Data Acquisition Issues for Y Axis

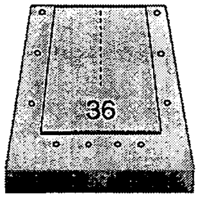
- Operator inputs start & end points per line
- Unit auto "fits" data to input distance
  - Assumes same pace
- Obstacles usually slows pace



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

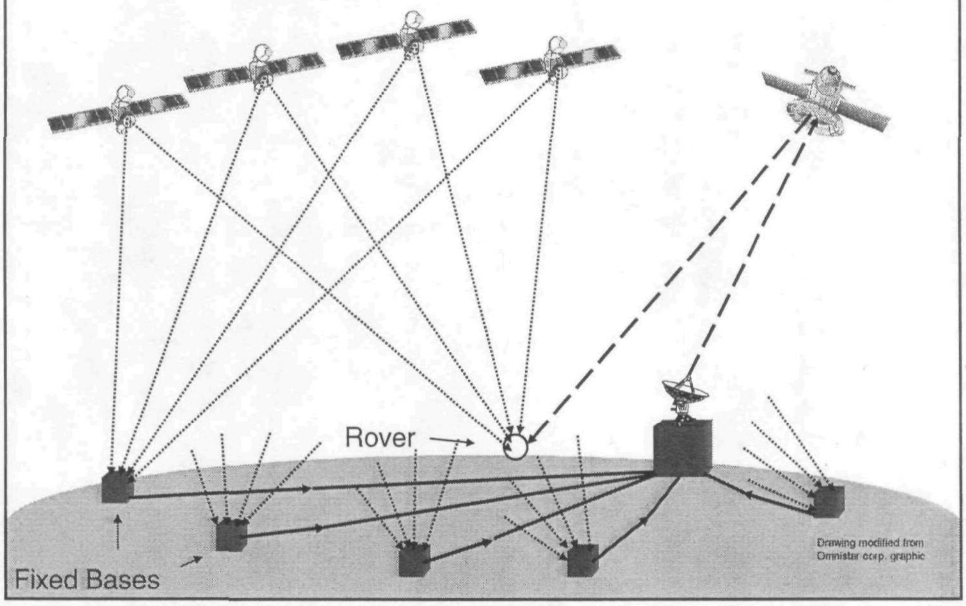




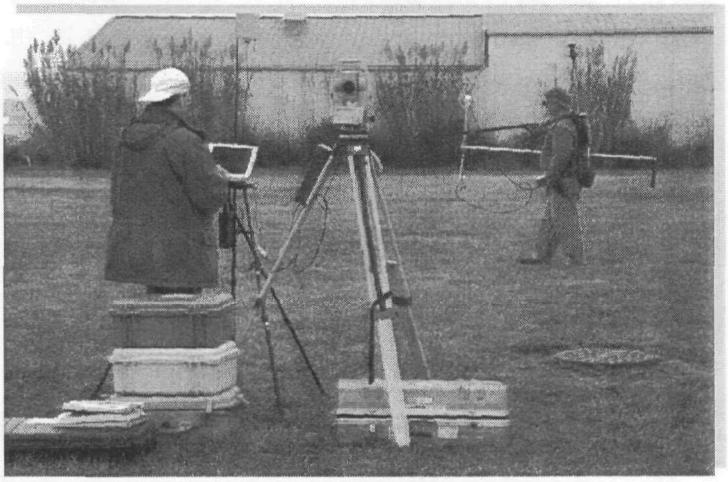
Several GPS Methods

- 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



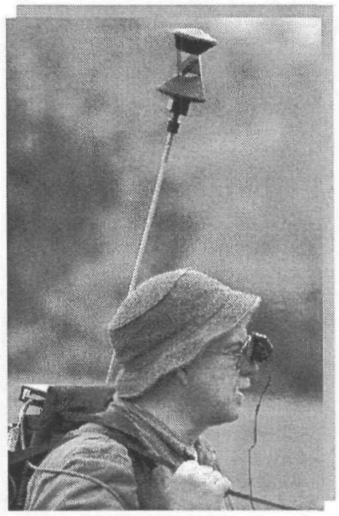
System Overview

- 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

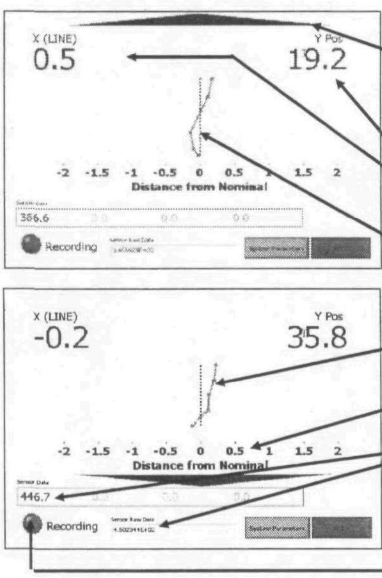
Auto Tracking & Guidance

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

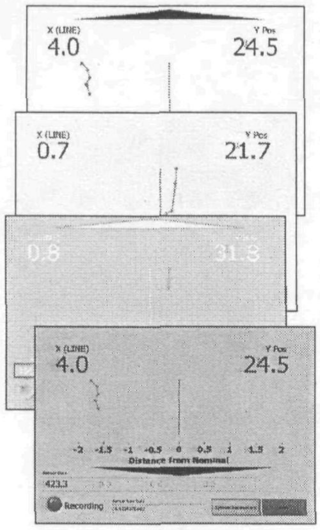


2 Screen Views of HUD



- 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

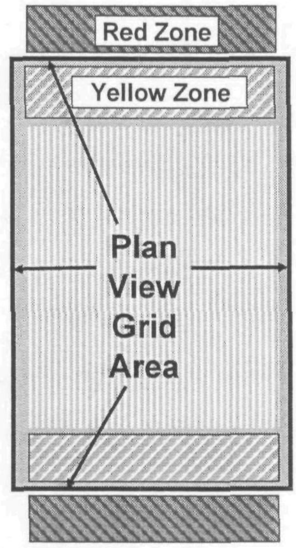


White: Normal

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?

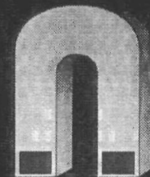
- Dependent on site goals
- Generally........First
  - Methods having larger sensing areas
  - Rapid data collection times
- Generally........Second
  - Methods with more definitive sensing capabilities

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
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October 17, 2007 – Kansas City, MO

Metal Detector ≠ Magnetic Method

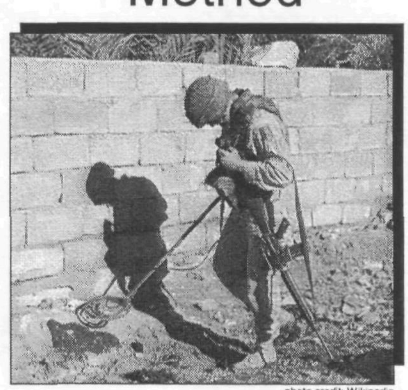
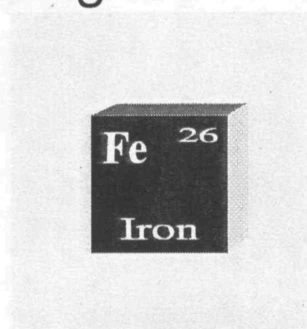


photo credit: Wikipedia

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

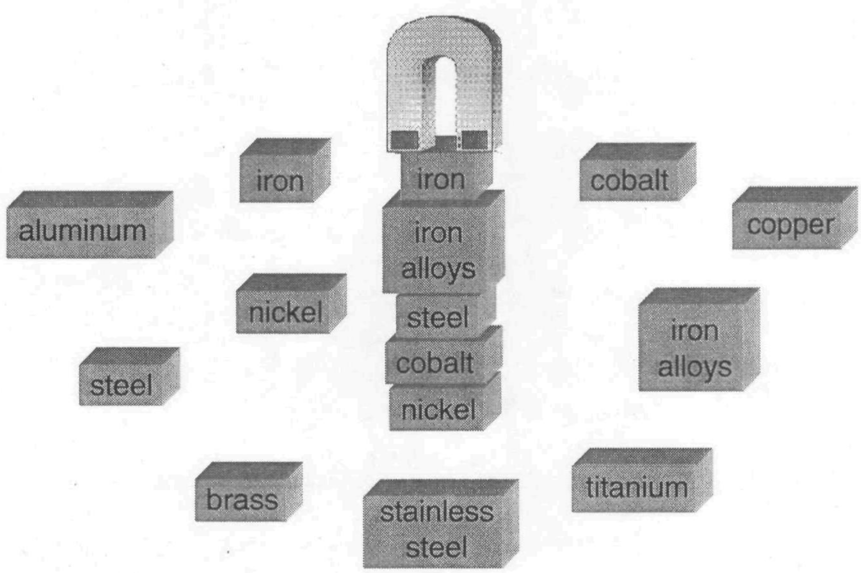
MAGNETOMETERS are passive instruments and only sense ambient magnetic fields

The Magnetic Method

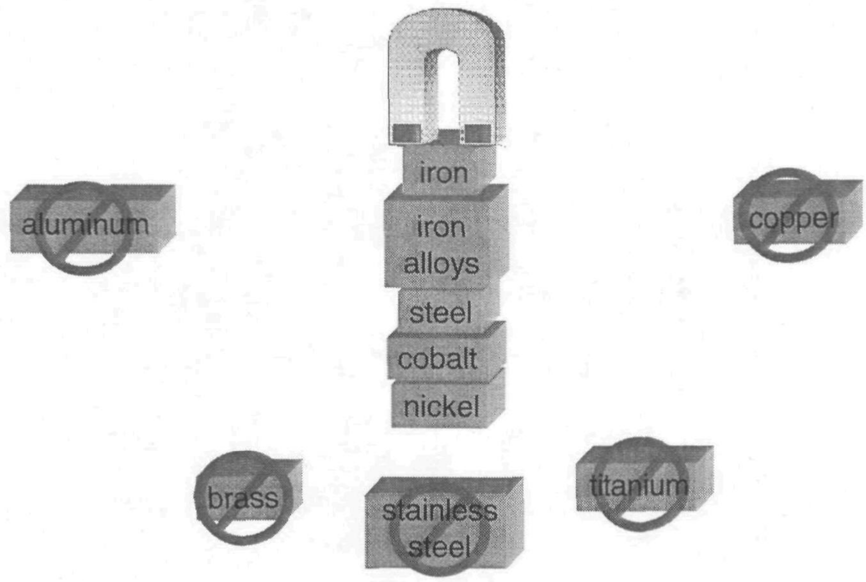


- Senses presence of iron
- Measures magnetic fields
- Easy to apply and interpret

Ferrous & Non Ferrous Metals



Ferrous & Non Ferrous Metals



Why Is Magnetics Important?

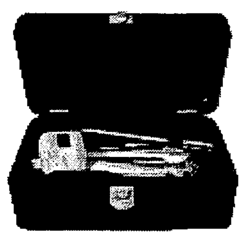
- Non-invasive, passive detection method
- Quantitative results
- Large masses detectable at significant depths
- Complements other geophysical methods

Optimal Detectable Features Unique to Magnetics

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

What Tools are Used to Measure Magnetic Fields?

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

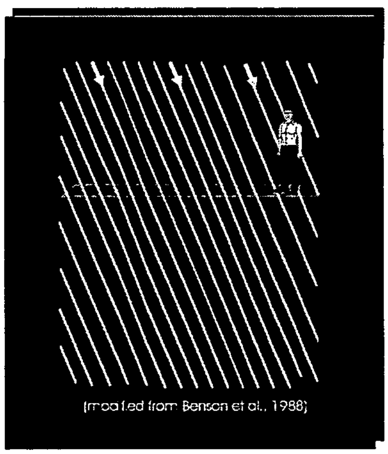


What Exactly Is Measured?

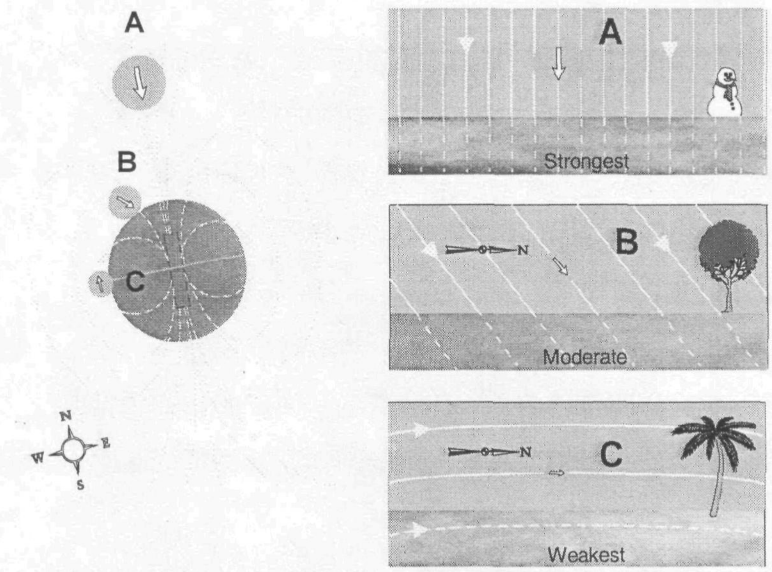
- An integration of magnetic properties
  - Earth's magnetic field intensity
  - Natural magnetic intensity rock/soil
  - Cultural magnetic intensities
- Values either attractive or repulsive
  - Represented by + or - numbers
  - (+) values same direction of inducing field
  - (-) values oppose direction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

Earth's Magnetic Field

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

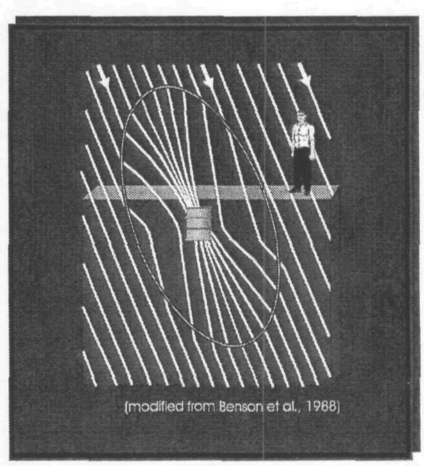


Earth's Magnetic Background



Ferrous Interactions

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

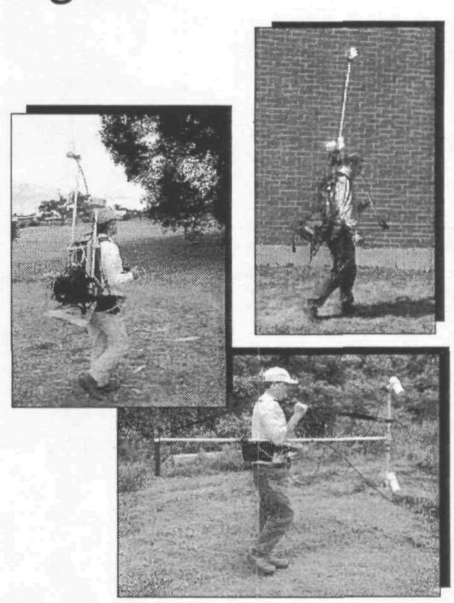

(modified from Benson et al., 1988)

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



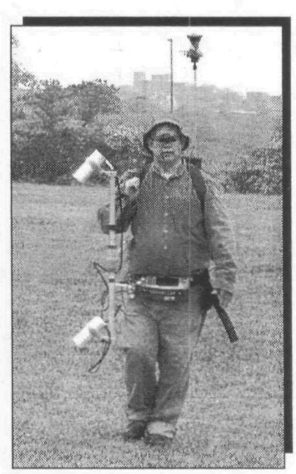
Total Field Configuration: One Sensor

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

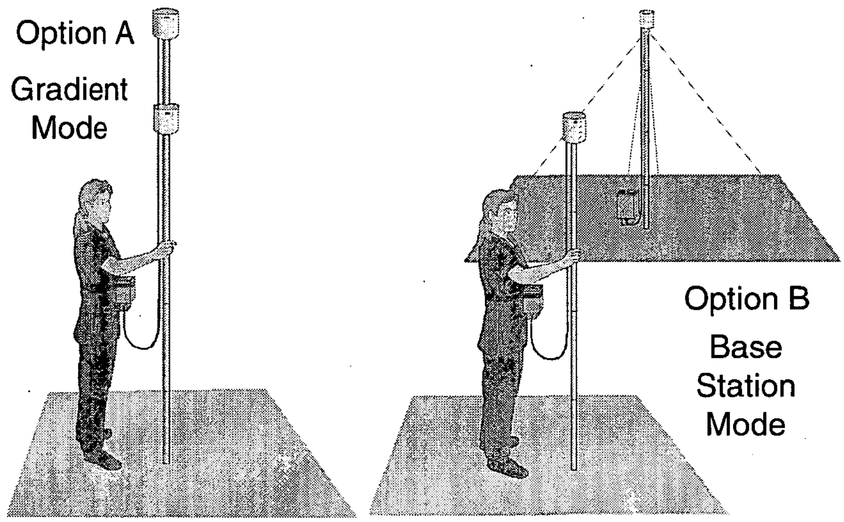
Photo: Geometrics

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



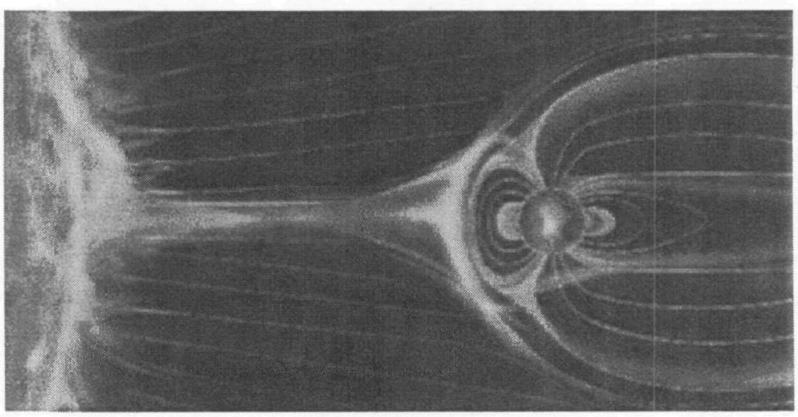
Gradient Readings

- 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

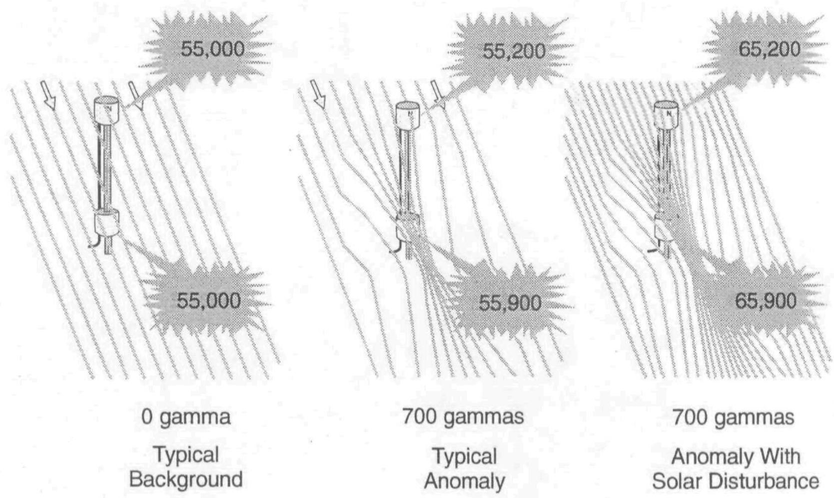
Solar Disturbances



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

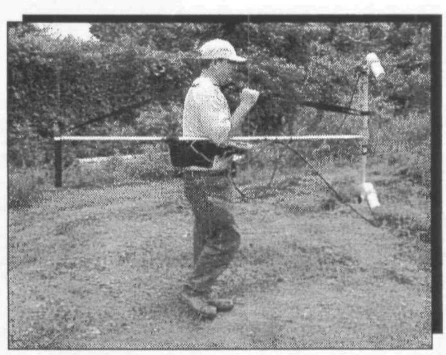
Gradient Measurements

(Vertical Gradient)

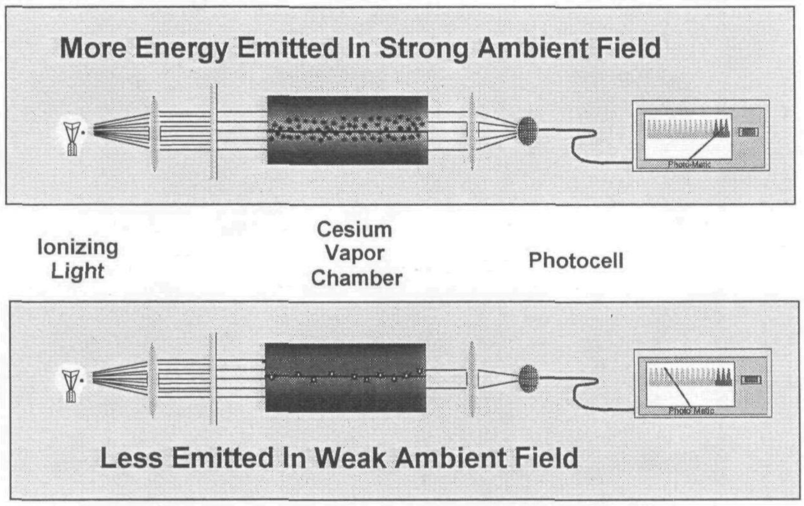


Cesium Magnetometer

- 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

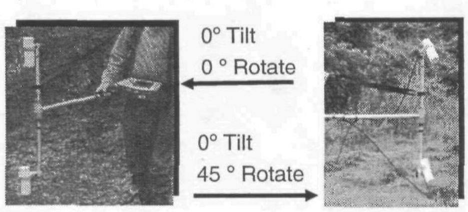


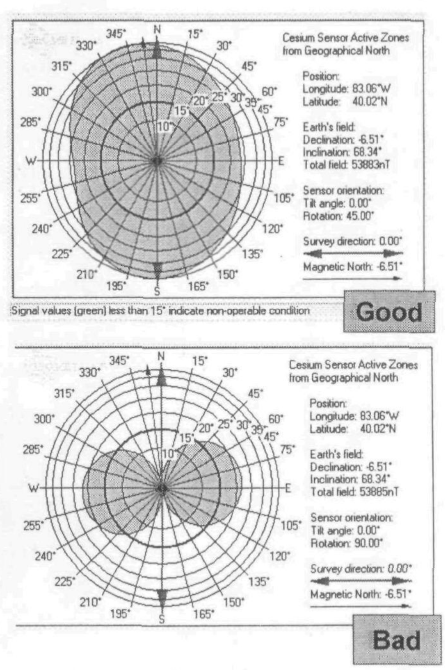
(modified from Bloom, 1960)

Alkali Vapor Sensor Orientation

Tilt = parallel plane to direction of travel

Rotate = perpendicular plane to direction of travel

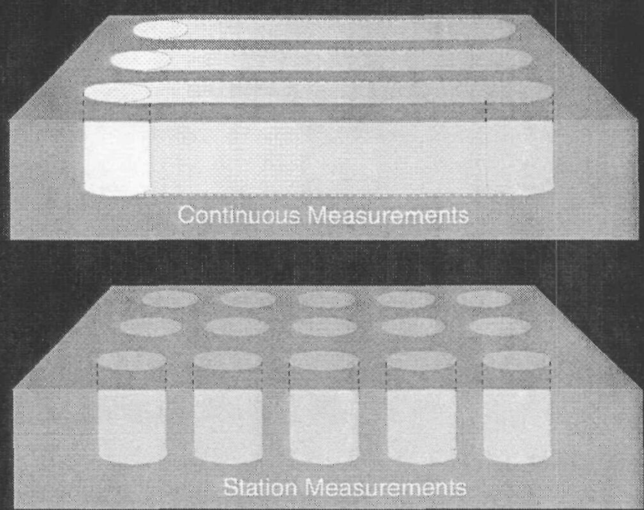




Key Issues For Collecting Data

- 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



Detection Probability

At = Area of Target
43

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 = Approx. Sampling Points

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

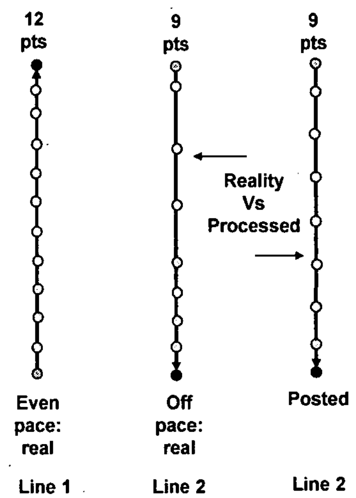
$$\sqrt{b} = \text{Grid Spacing in Feet}$$

Probability Factors

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

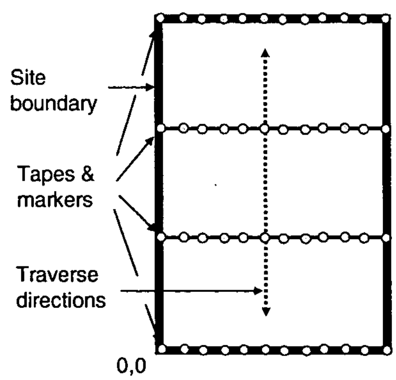
Continuous Data Acquisition Issues

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



Establishing A Grid

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



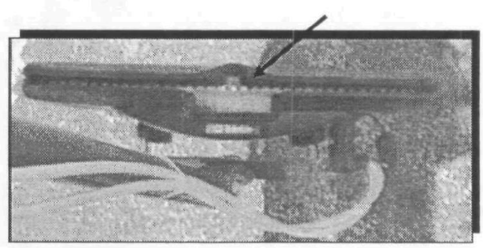
Using GPS For Grid Establishment

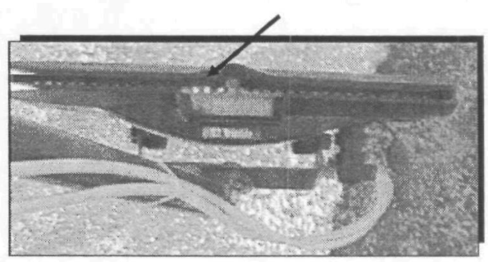
- Initialize start & end points of line
- GPS maintains parallel lines
- Operator follows cursor on lightbar
- Lat. - Long. output to mag data

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



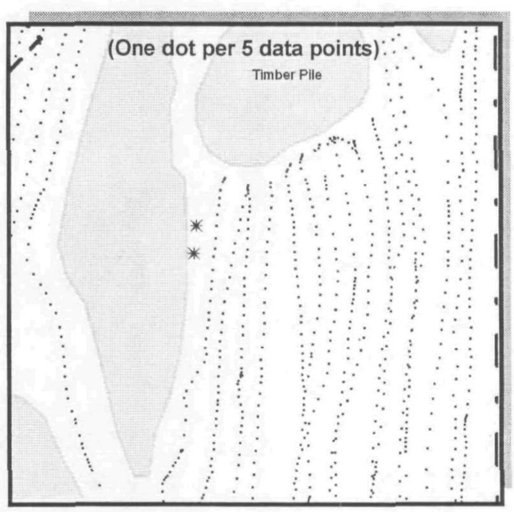


Random Survey Using GPS

- Used for large areas
- Maximize productivity
- Data linked to GPS
- Best in obstructed areas
- Areas must be free of:
  - Vegetative canopies
  - Tall buildings
  - 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

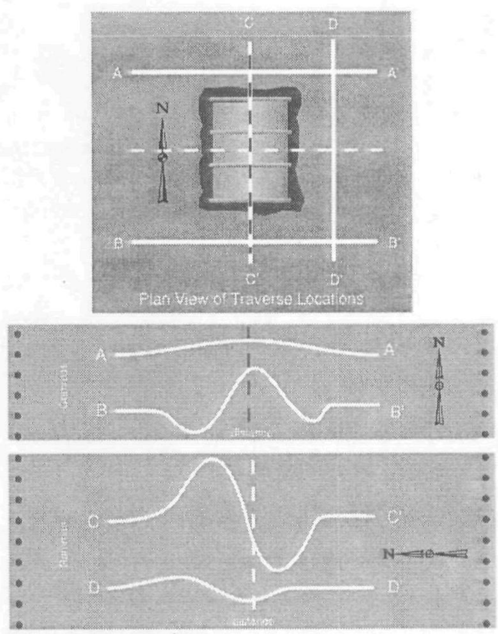


Data Interpretation

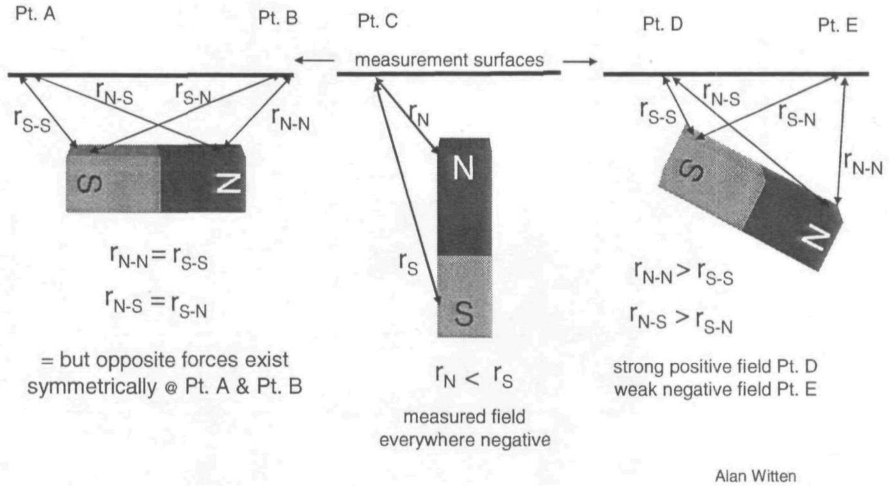
- Data analyzed by computer program
- Typically by some contouring method
  - Lines connecting equal values at specific intervals
- Displayed as 2D or pseudo 3D graphic

Data Values

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

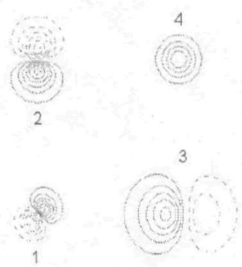


Data Signatures



Contoured Data Signatures

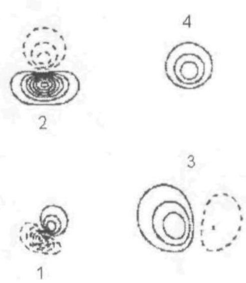
Anomaly #	Depth	Dipole Moment: Magnitude	Dipole Moment: Horizontal ∠	Dipole Moment: Vertical ∠
1	1	150	-135	0
2	1.5	500	0	0
3	2.5	1500	90	-15
4	2	400	0	-90



Signatures – 0° Dip Angle

dash = neg.
solid = pos.

Credit: Alan Witten



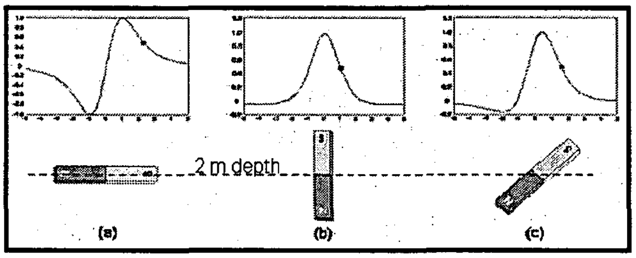
Signatures – 75° Dip Angle

Estimating Target Depths

$d = 1.3\ \Delta\chi_{½} - h$

d = Depth
$\Delta\chi_{½}$ = Half maximum value
h = Distance above ground surface at which measurements are made

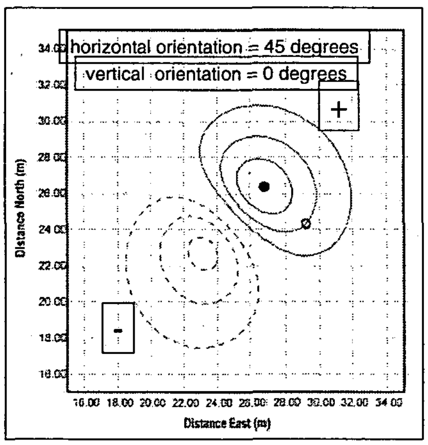
	½ Max.	d
a)	2.4 m	3.12 m
b)	1.0 m	1.30 m
c)	1.6 m	2.08 m



Credit: Alan Witten

Depth Estimate Calculation From Contour Map

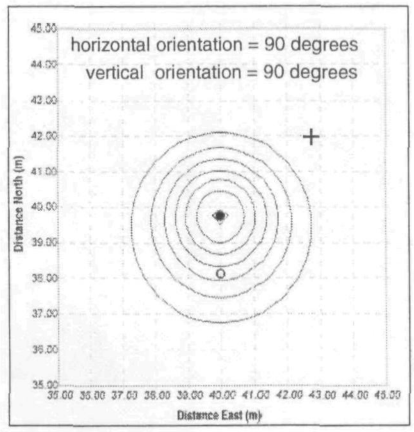
- Solid & open circles are locations of max. value & ½ max. value: 3.6m
- Contour interval 20 nT
- Target = horiz. metal bar
  - Depth: actual = 5m
  - Depth: est. = 4.68m



Credit: Alan Witten

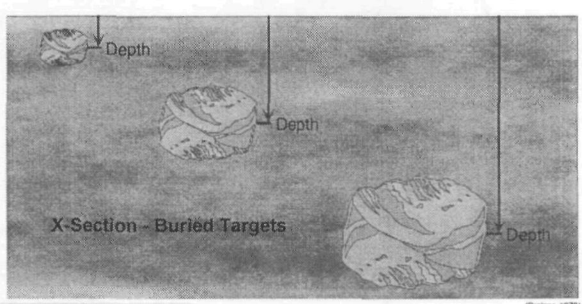
Another Depth Estimate

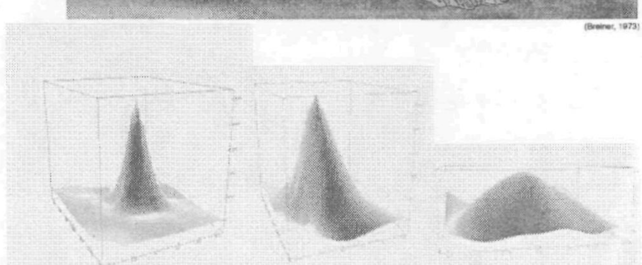
- Solid & open circles are locations of max. value & ½ max. value: 1.8m
- Contour interval 20 nT
- Target = vert. metal bar
  - Depth: actual = 3m
  - Depth: est. = 2.34m



Credit: Alan Witten

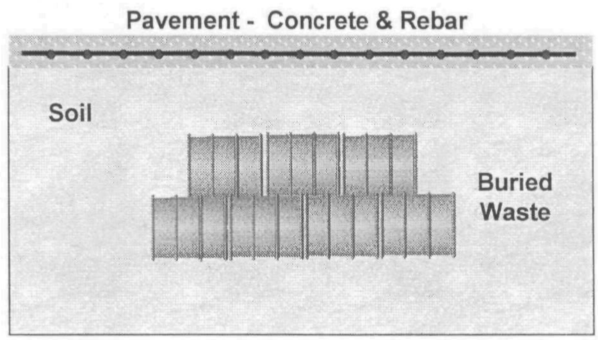
Mass & Depth Examples





Data Plots of Buried Targets

Multiple Magnetic Sources

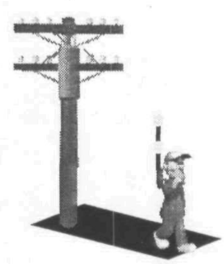


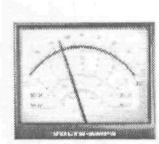
Drum Mass ≈ Rebar Mass: Difficult to Distinguish

Drum Mass > Rebar Mass: Easier to Distinguish

Dealing With Noise Issues

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



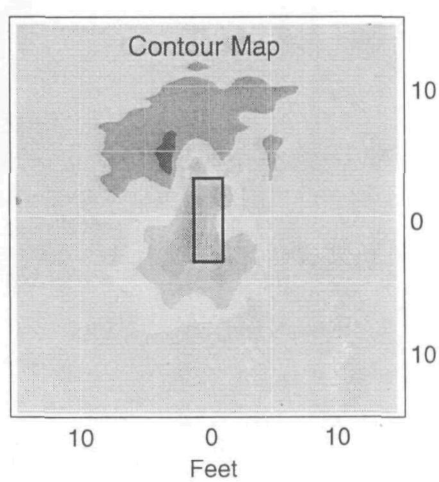


Data Interpretation Pitfalls

- 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

Mag Anomaly Example 1

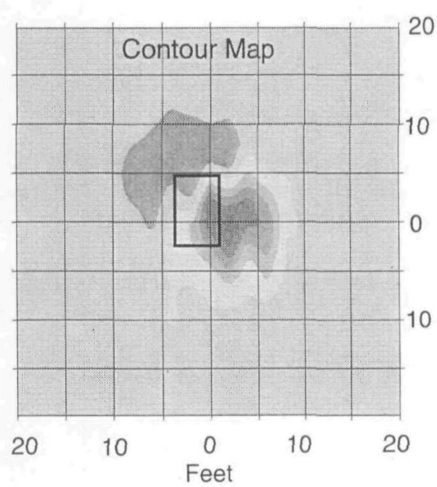
- 1 Crushed drum (lying vertical)
- Depth: -4.5' to -8.5'
- Values: +26 to -54
- Contour interval: 10
- Blues: pos. values
- Reds: neg. values



Example 1 Source

Mag Anomaly Example 2

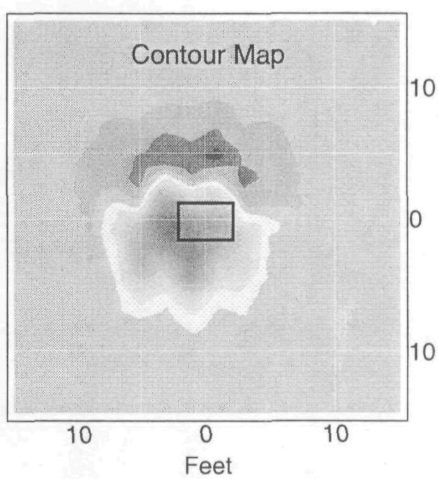
- 5 Crushed drums
- Depth: -5' to -6'
- Values: +78 to -171
- Contour interval: 35
- Blue: pos. values
- Reds: neg. values



Example 2 Source

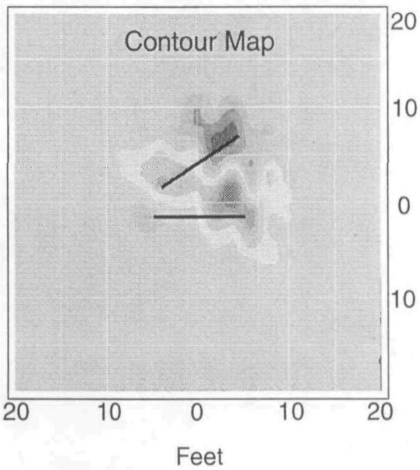
Mag Anomaly Example 3

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



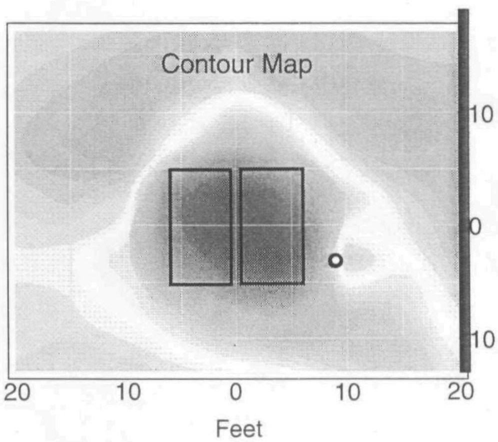
Mag Anomaly Example 4

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



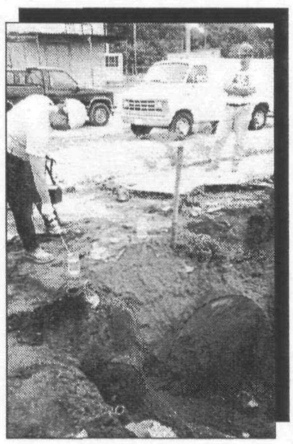
Mag Anomaly Example 5

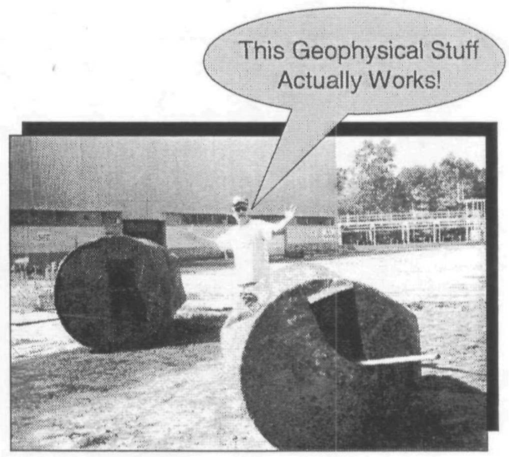
- Two 500 gal. tanks
- Depth: -2' to -7'
- Values: +1114, -120
- Contour interval: 35
- Blues: pos. values
- Reds: neg. values



Tank Removal

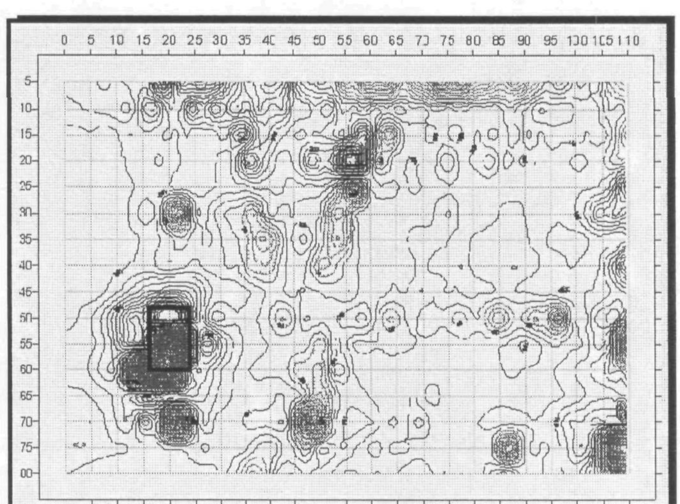
In-Situ



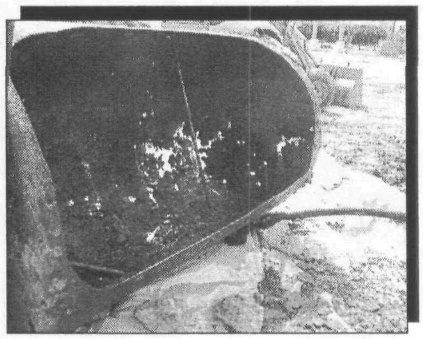


500 Gallon Tanks

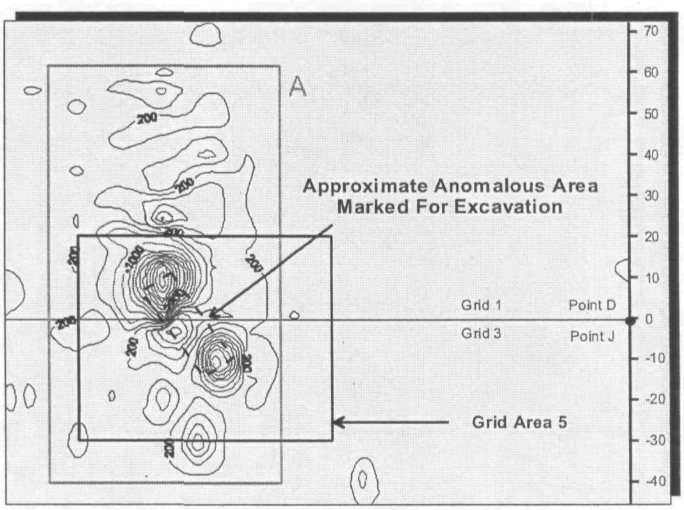
Mag Anomaly Example 6



Example 6 Tank Removal



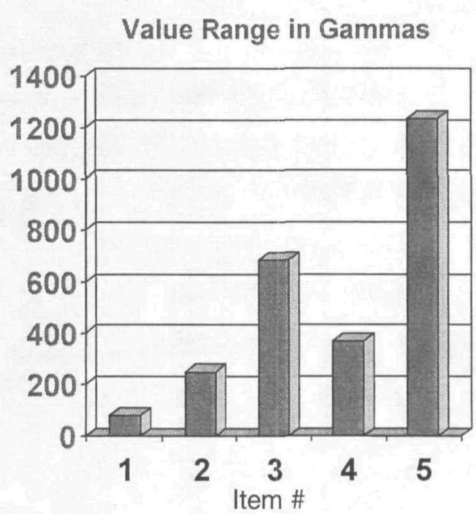
Mag Anomaly Example 7



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

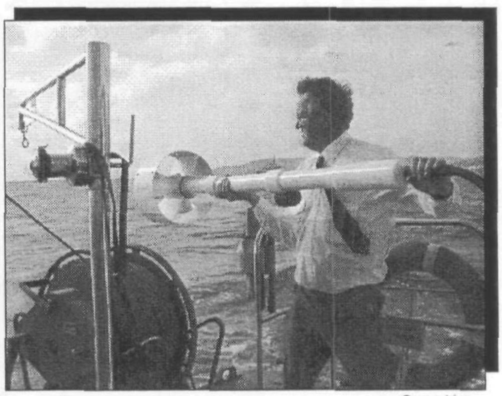
Magnetics
Rapid Data Collection
Establish Amount of Mass
General Lateral Dimensions

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

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

Marine Cesium Magnetometer

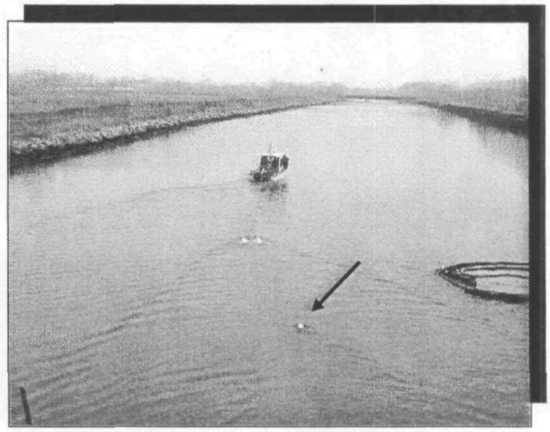
- Towed by boat
- X-Y location control by GPS
- Depth control by line & speed or floatation device



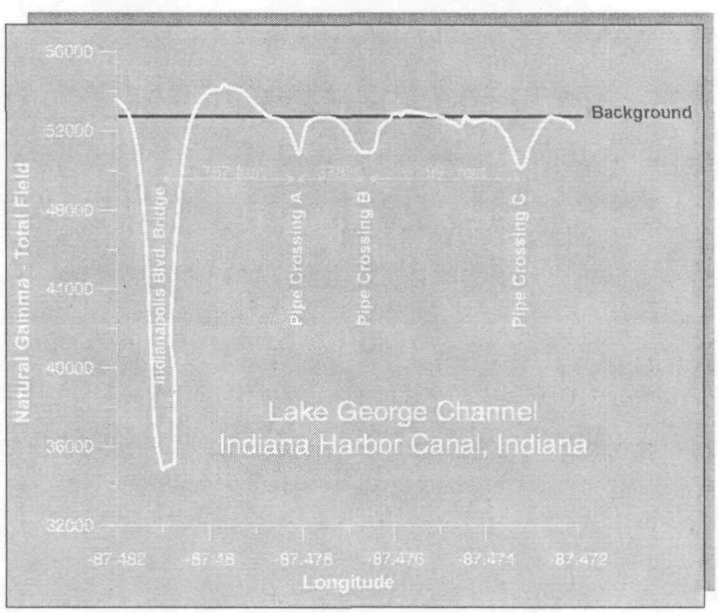
Geometrics

Marine Applications

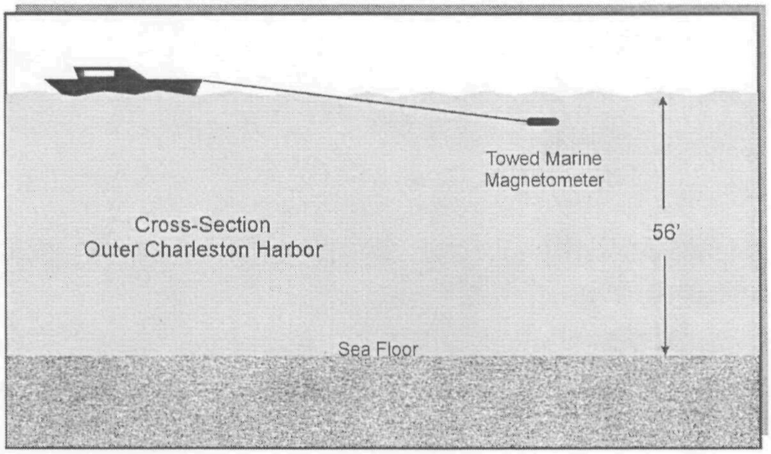
- Lake George Channel
- Indiana Harbor Canal
- Looking south Indianapolis blvd. bridge



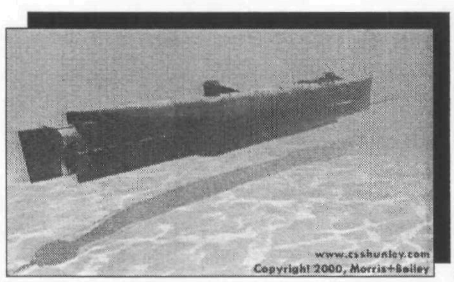
Marine Cesium Magnetometer Data

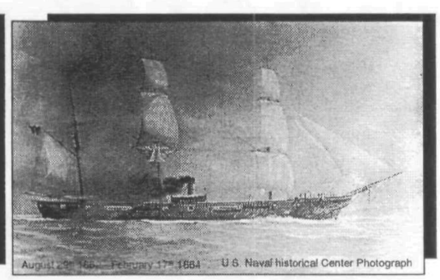


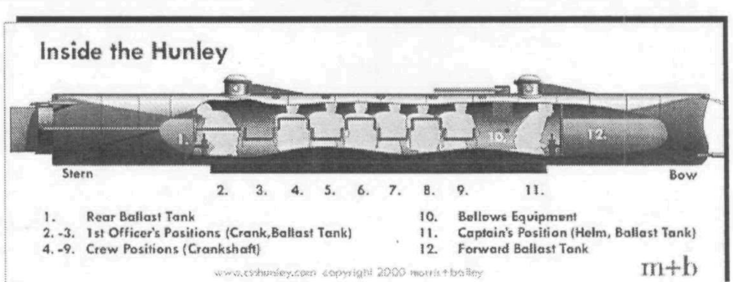
Search for CSS Hunley Using Magnetics



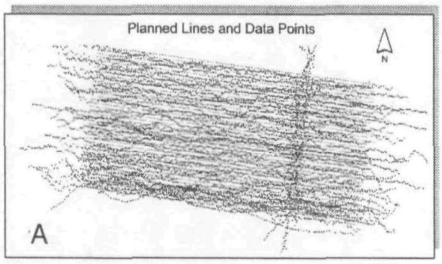
CSS H. L. Hunley – USS Housatonic

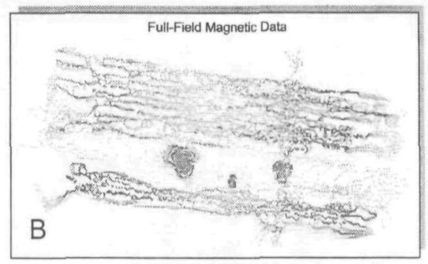




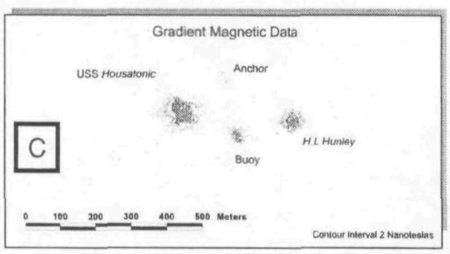


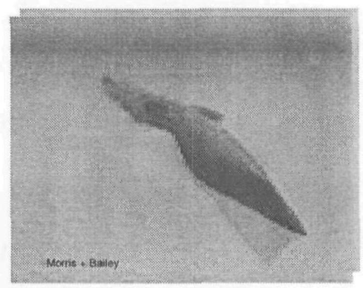
Battle Site Mag Anomalies





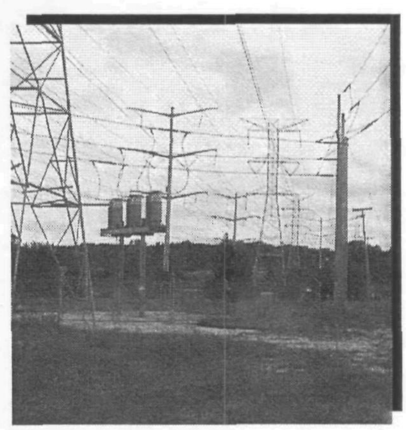
A, B, C Courtesy: Submerged Cultural Resources Unit - National Park Service – Santa Fe, NM





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



Advantages

- Magnetics ideal for ferrous targets
- Method fast, simple and easy to interpret
- Targets identified by area and mass
- Use of other geophysical methods can increase value of magnetic data

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 the two major 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

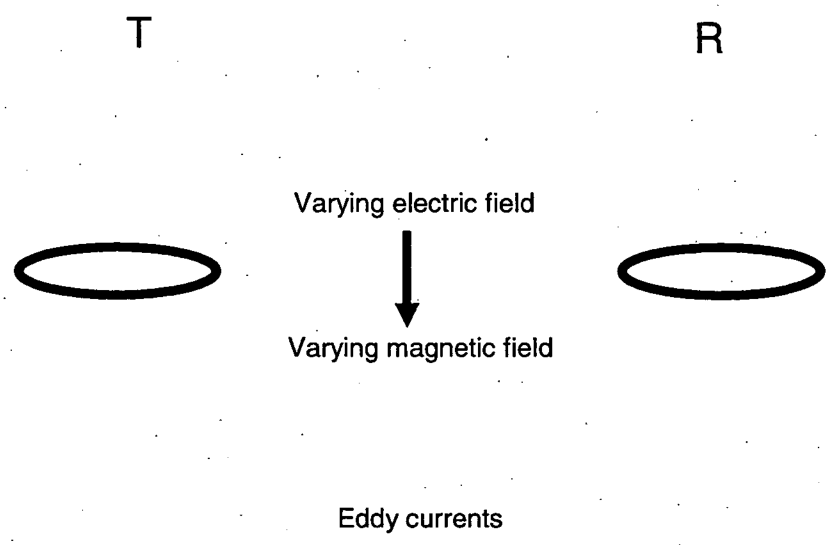
Frequency Domain EM (FDEM)

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

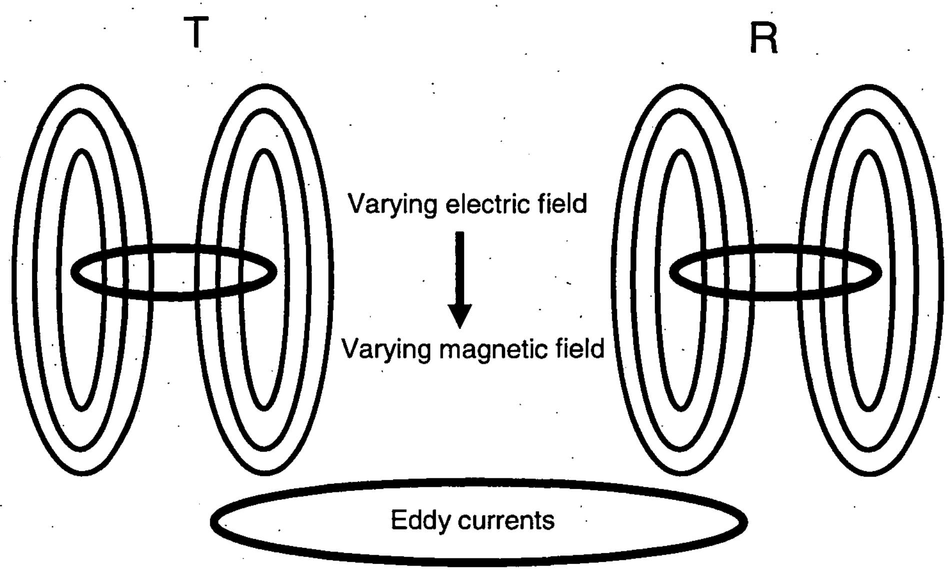
Time Domain EM (TDEM)

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

Frequency-Domain EM



Frequency-Domain EM



Depth of Penetration

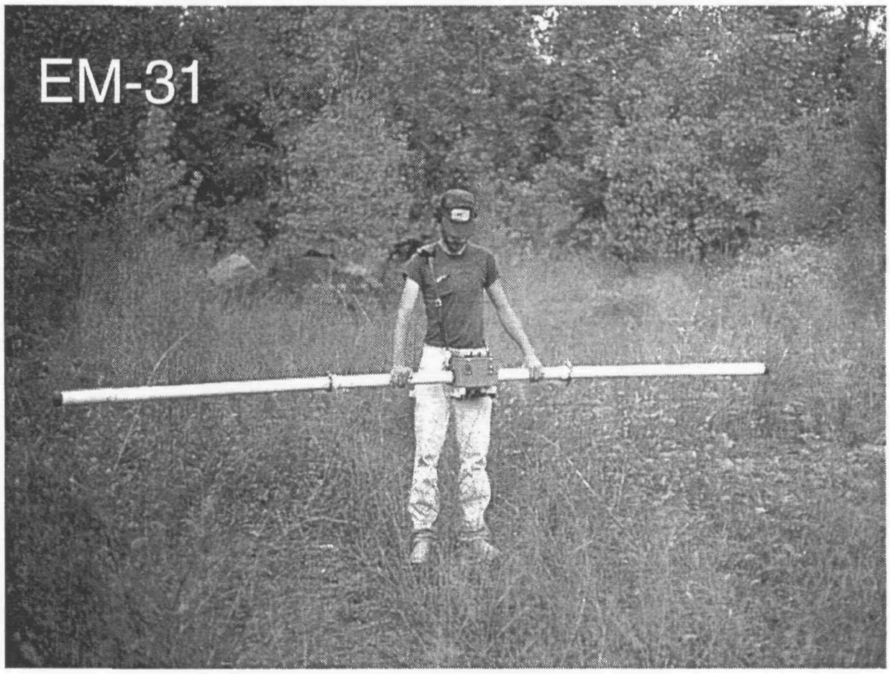
- ~1.5 x coil spacing for vertical dipole
- ~.75 x coil spacing for horizontal dipole

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

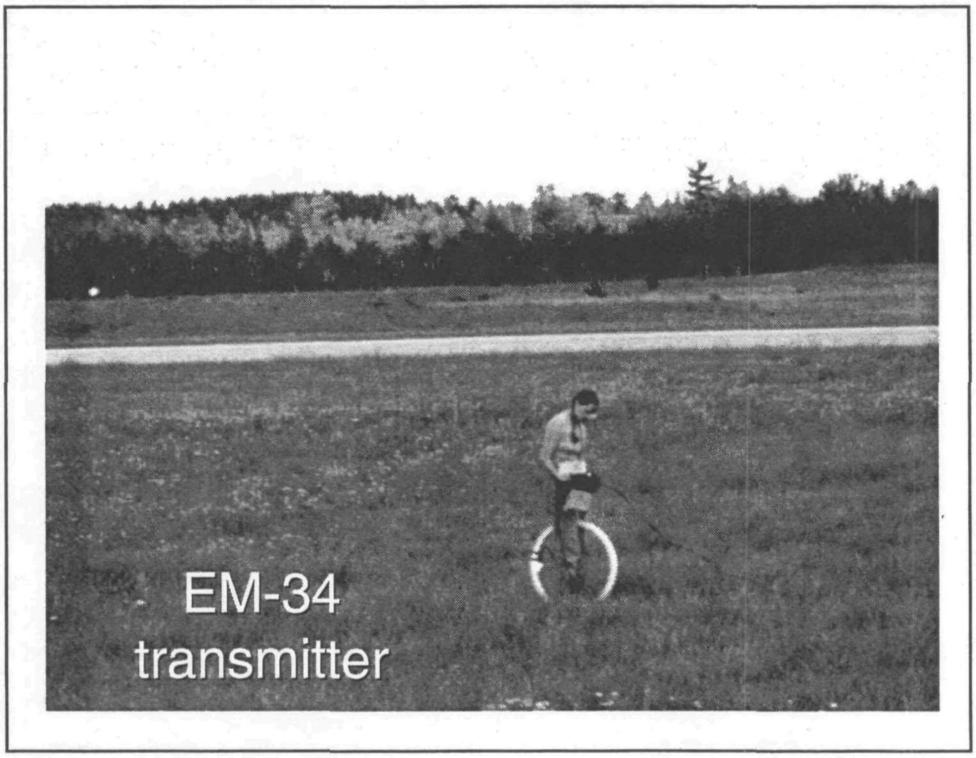
EM-31

- ~ 4.5 meter maximum depth
- Soil conductivity - quadrature phase
- Metal detection - in-phase component



EM-34

- Three coil spacings - 10 m., 20 m., 40 m.
- Soil conductivity - quadrature phase
- Coil spacing - in-phase component


EM-34
transmitter


EM-34 receiver

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

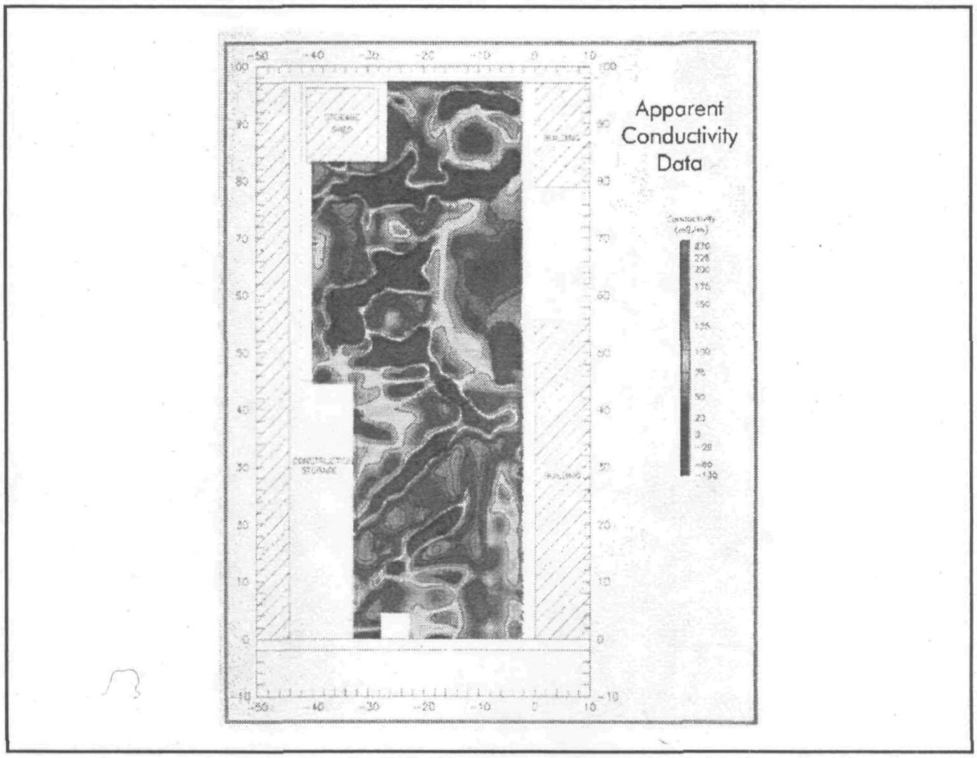
- Soil type
- Moisture
- Cultural debris
- Pore fluid

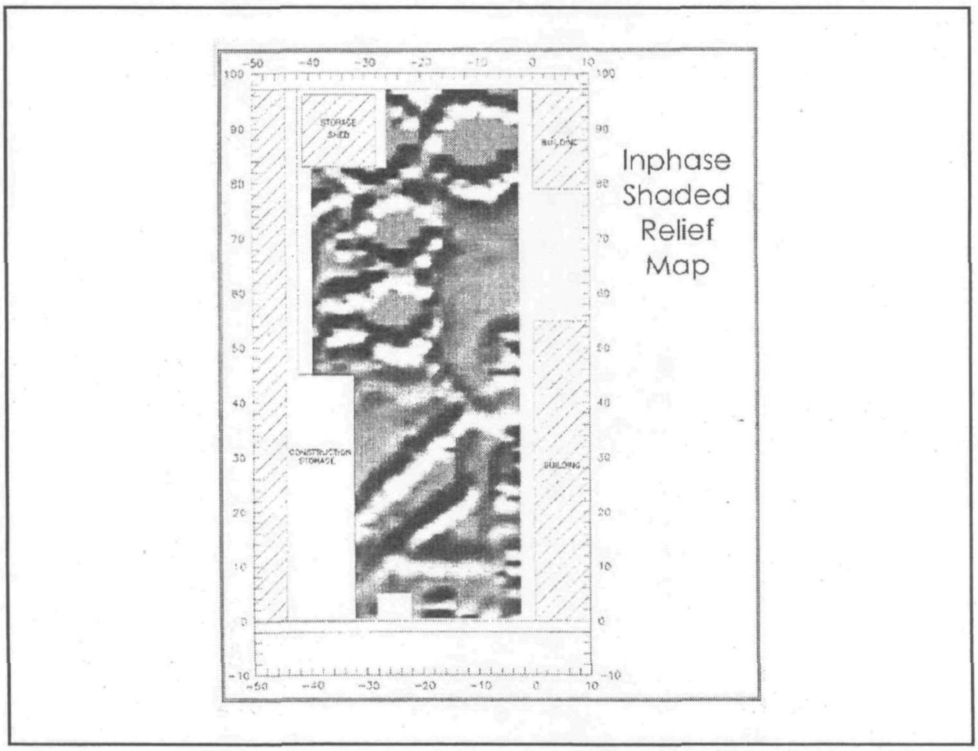
Advantages/Limitations of FDEM Detectors

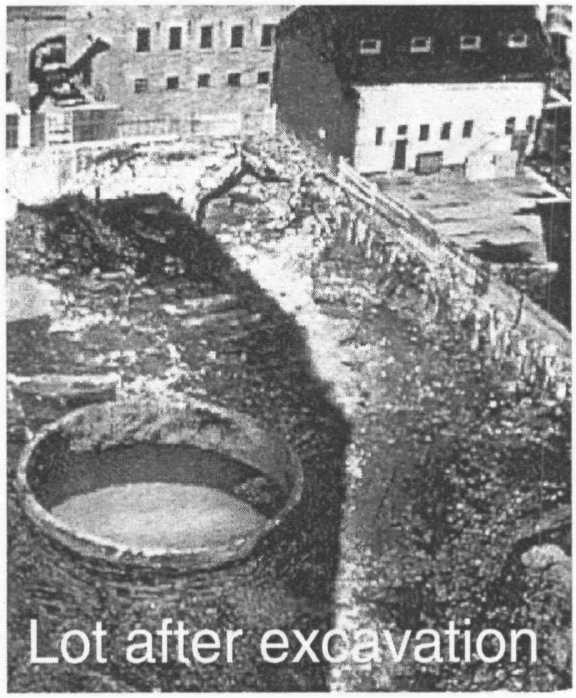
- Advantages
  - Fast, inexpensive
  - Reasonable lateral resolution
- Limitations
  - Limited depth of penetration
  - Sometimes difficult to interpret
  - Many noise sources

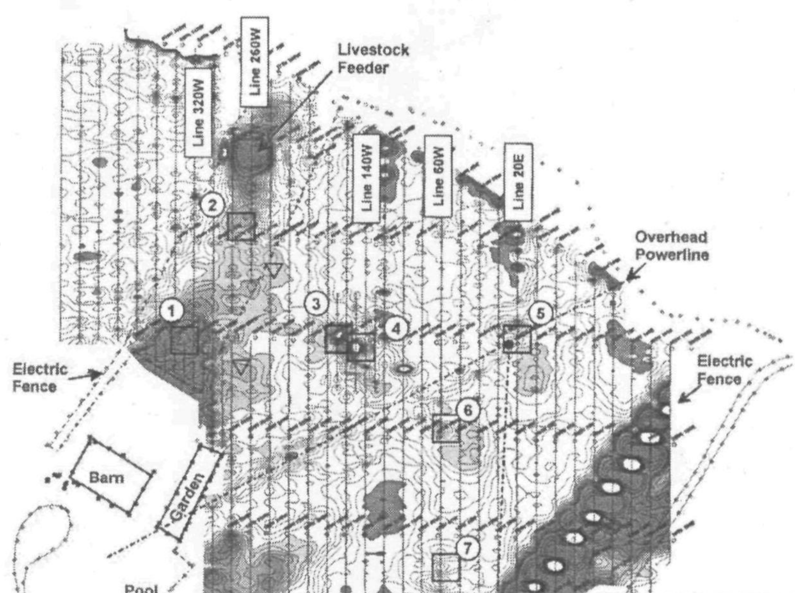
Frequency Domain EM

Case Studies


Apparent
Conductivity
Data


Inphase
Shaded
Relief
Map

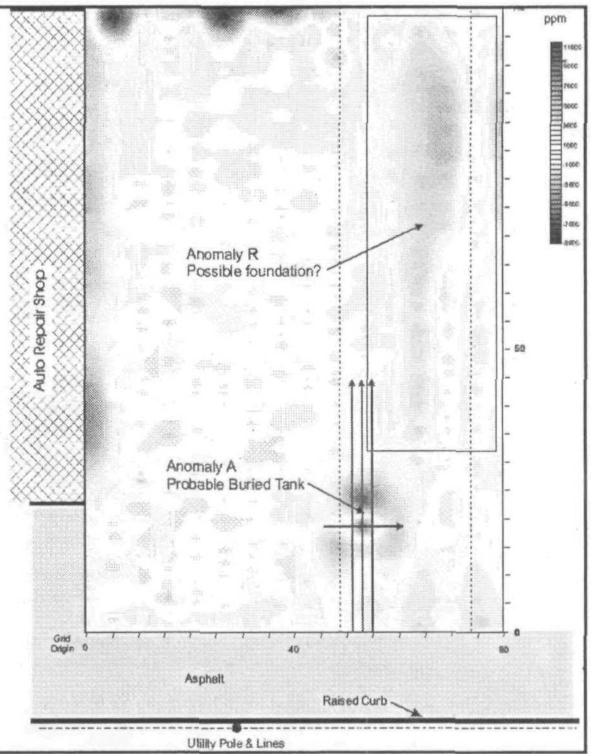




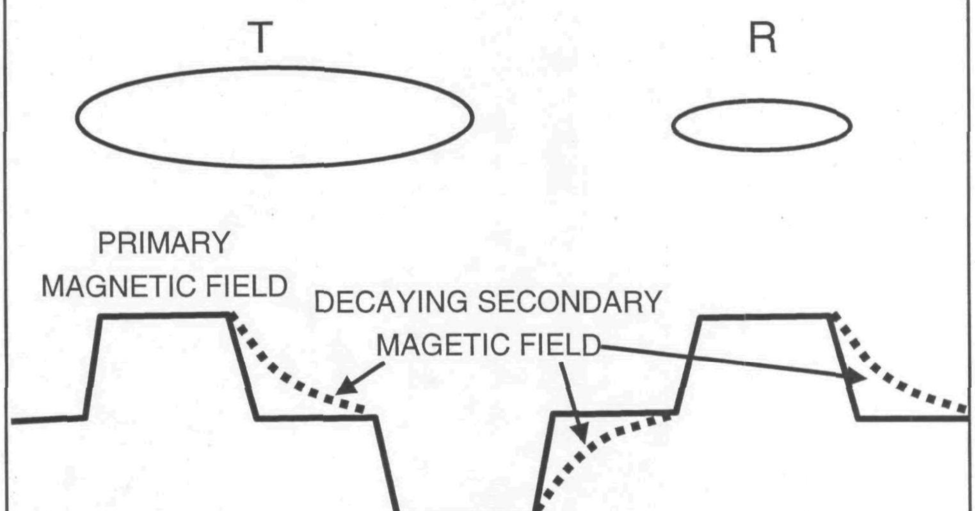
US EPA ENVIRONMENTAL RESPONSE TEAM CENTER
RESPONSE ENGINEERING AND ANALYTICAL CONTRACT
68-C99-223
WORK ASSIGNMENT NO. RIA00176

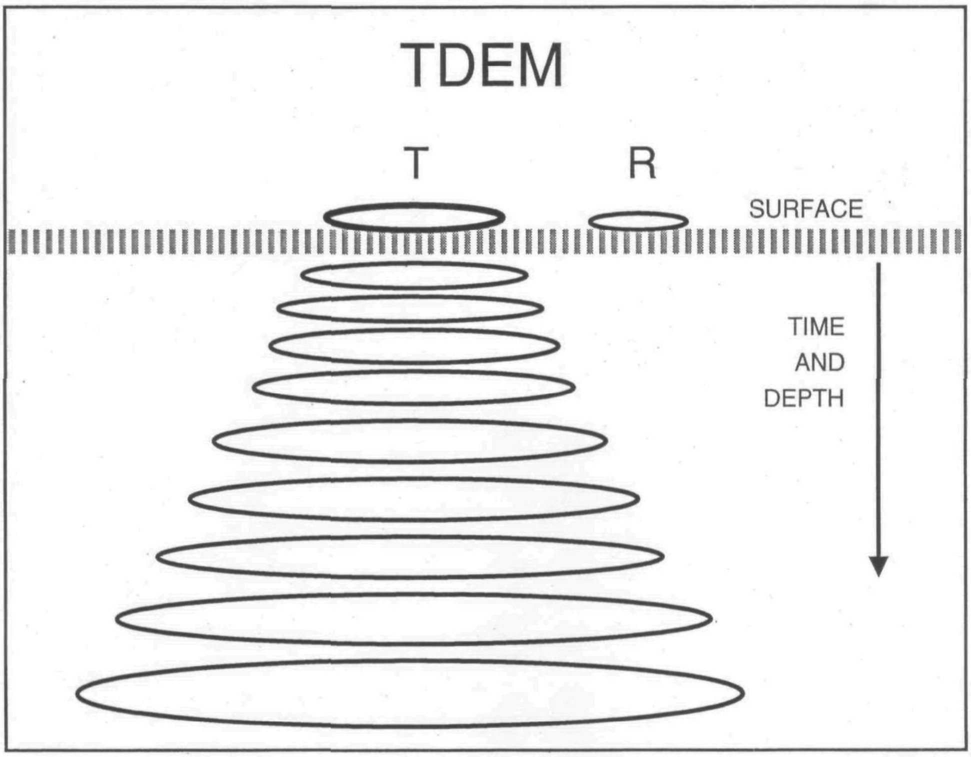
FIGURE 4
Expanded View of Northern Grid Area - EM31 Terrain Conductivity Data, Line Numbers, and Geophysical Anomaly Numbers
BOYD'S CREEK SITE
GLASGOW, KENTUCKY
AUGUST 2001

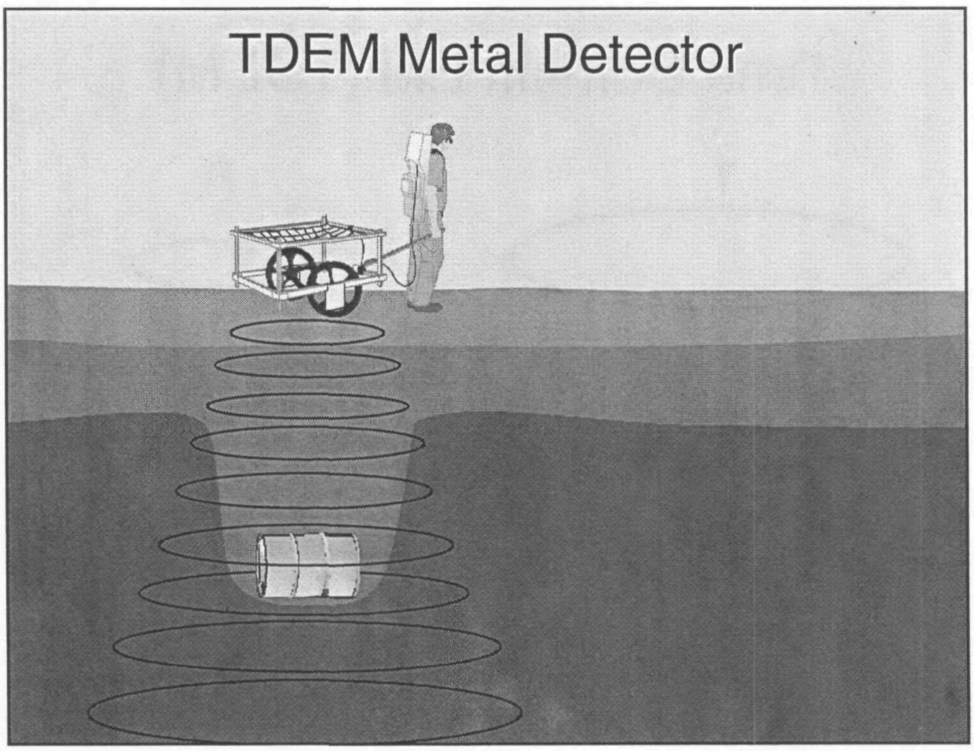
EPA Gem2 data
Northridge, IL
21030 Hz
In phase data

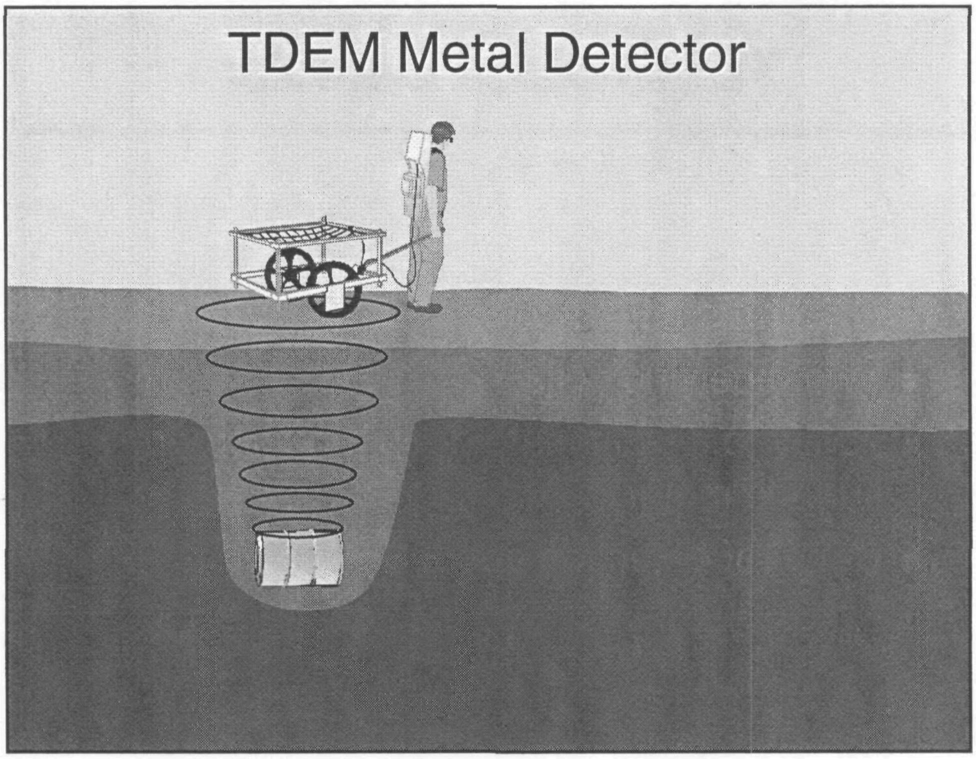


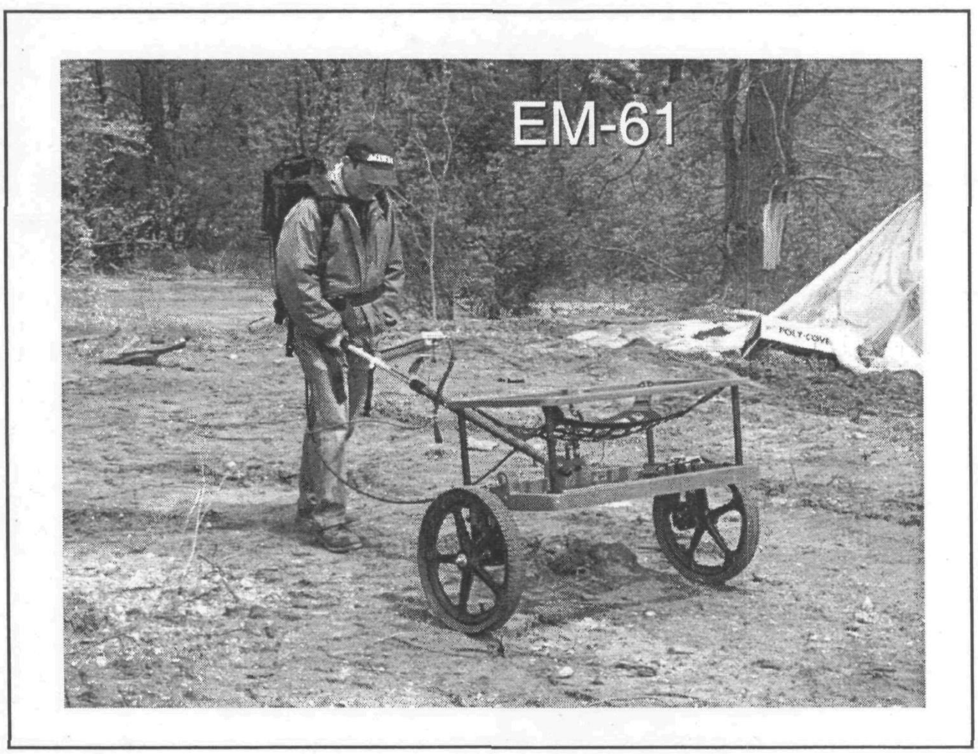
Time Domain EM (TDEM)




TDEM
T
R
SURFACE
TIME
AND
DEPTH


TDEM Metal Detector


TDEM Metal Detector

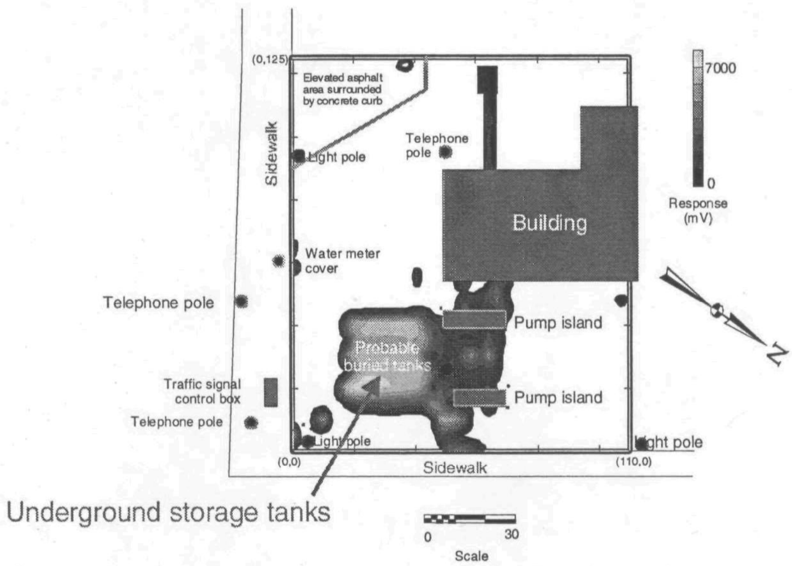

EM-61

TDEM Metal Detector

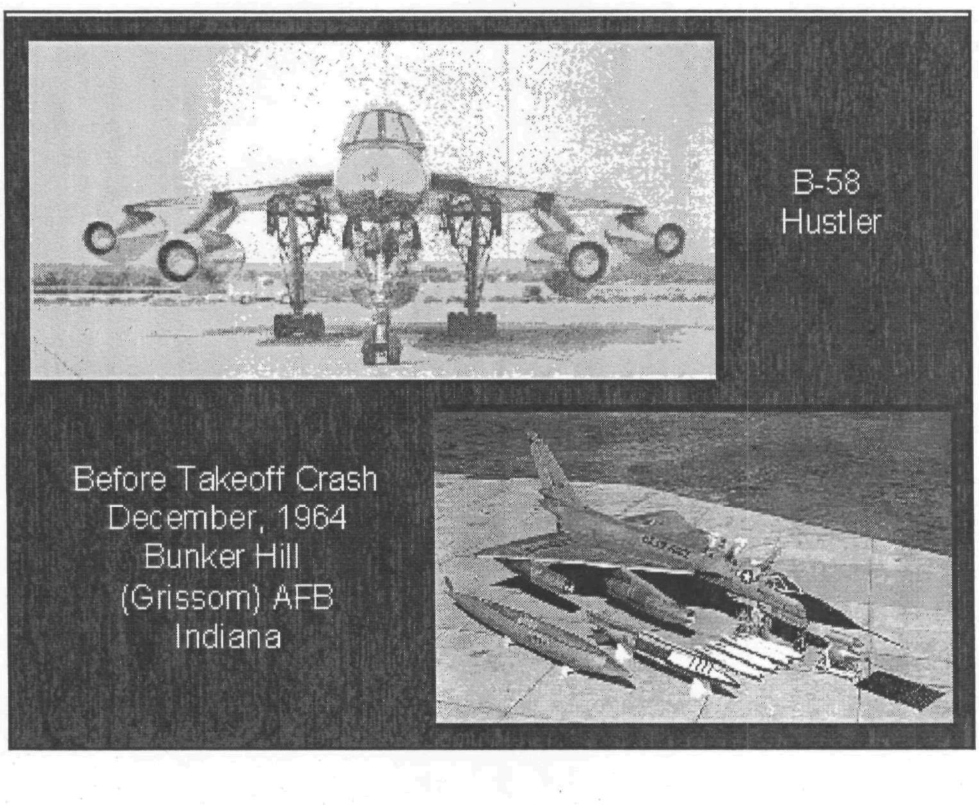
- One transmitting coil
- Two receiving coils
- Ability to discriminate depth and screen surface metal
- Depth of detection about 3.5 meters

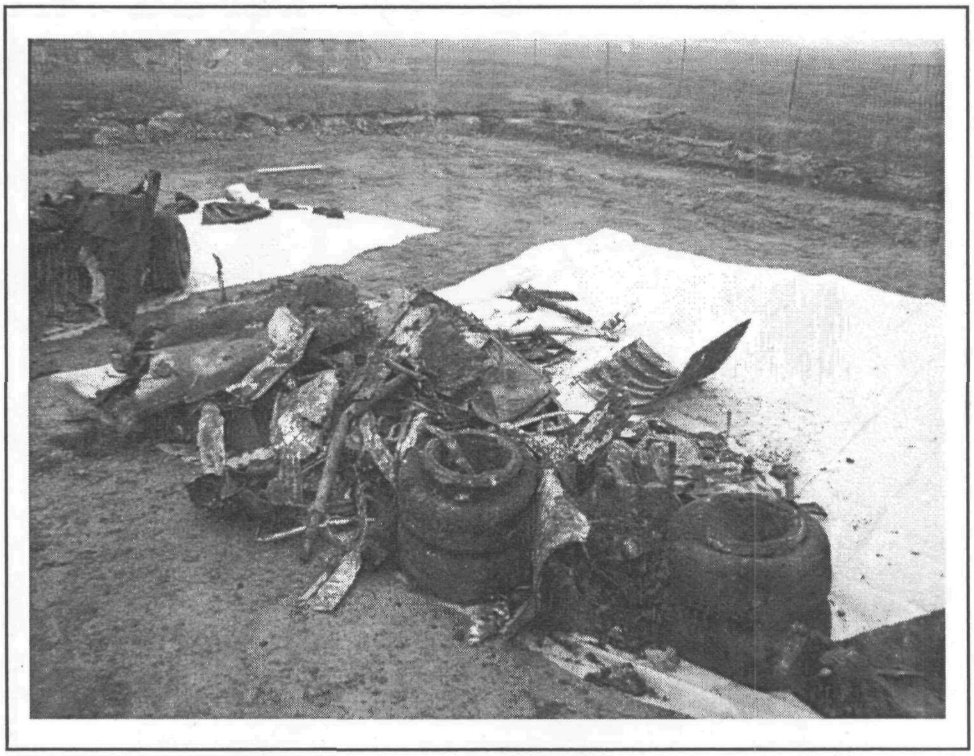
Advantages and Limitations of TDEM Detectors

- 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





SEISMIC METHODS

Seismic Refraction
Seismic Reflection

Seismic Methods

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

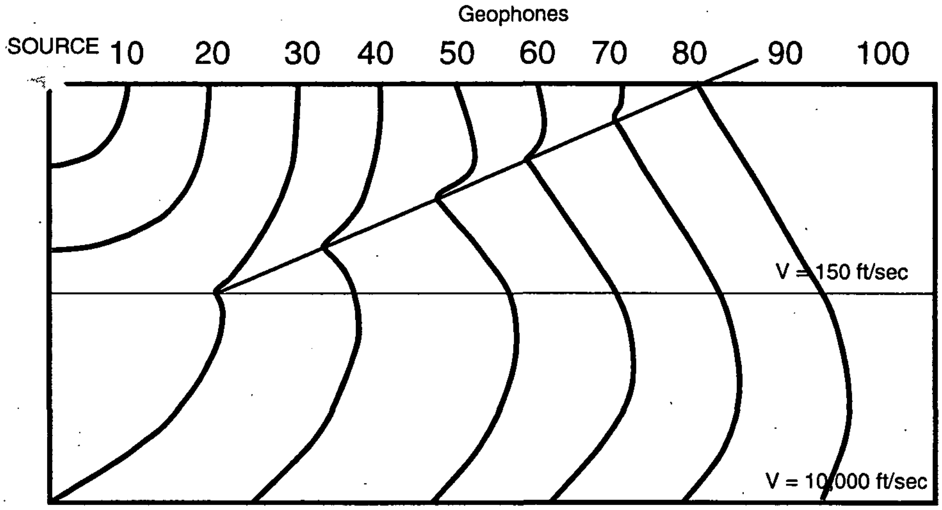
Environmental Seismic Methods

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

Seismic Refraction

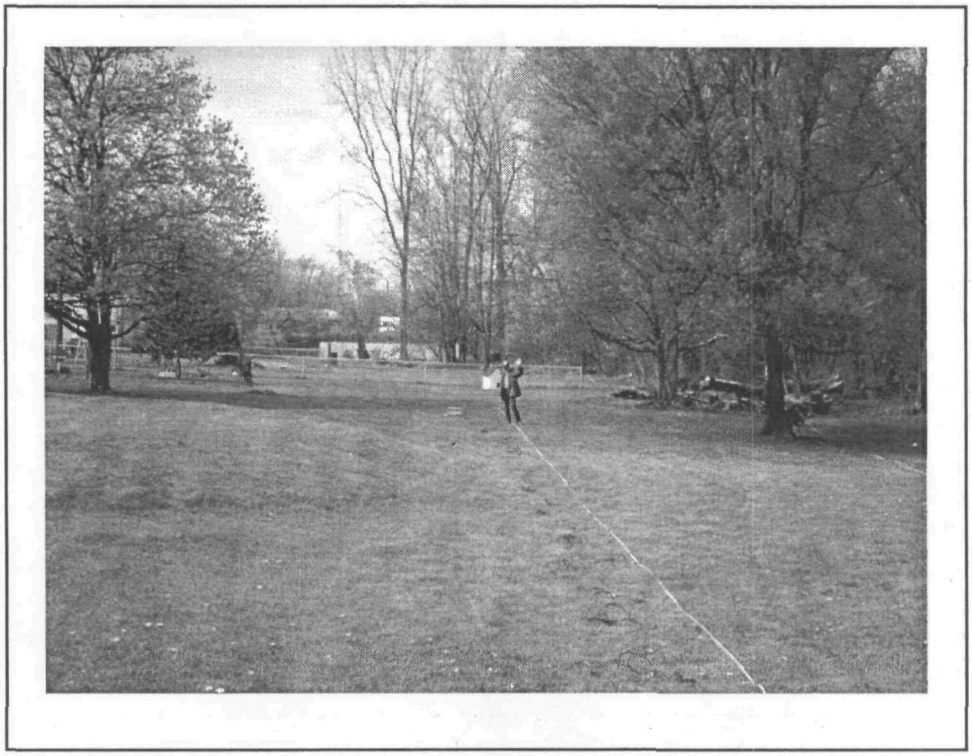
- Acoustic energy (wave) encounters a boundary between two geologic layers
- If the velocity is higher in the lower layer, some energy is reflected and some is refracted upward
- If the velocity is lower in the lower layer the layer is "hidden" from the refraction method

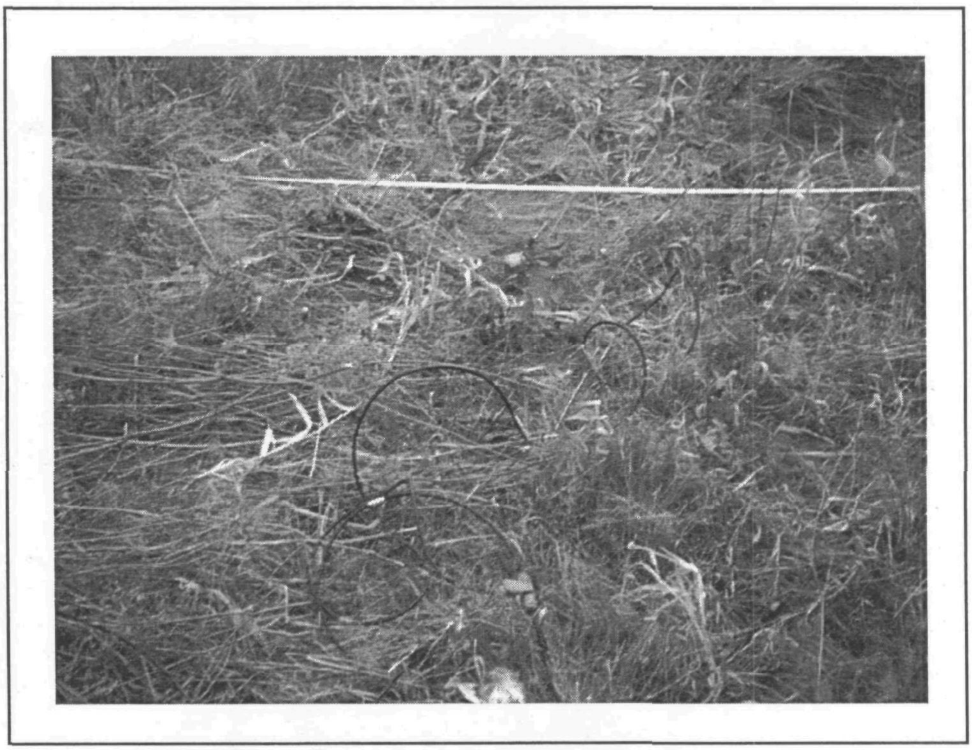
First Arrival



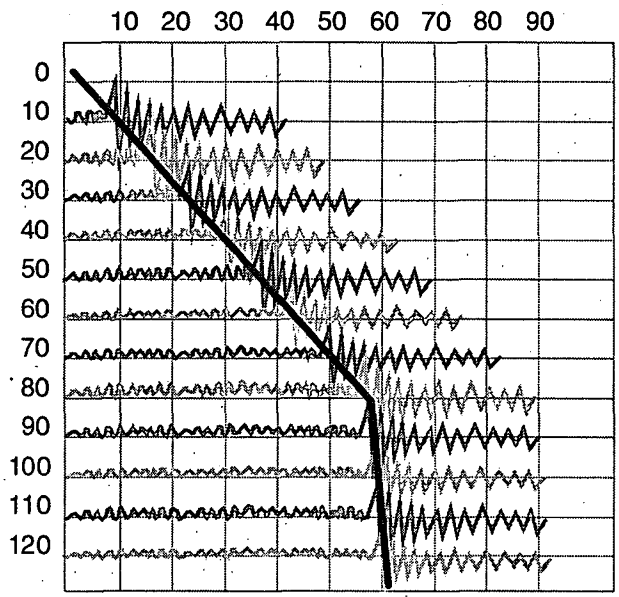
Refraction Equipment

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





Wave Signatures



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

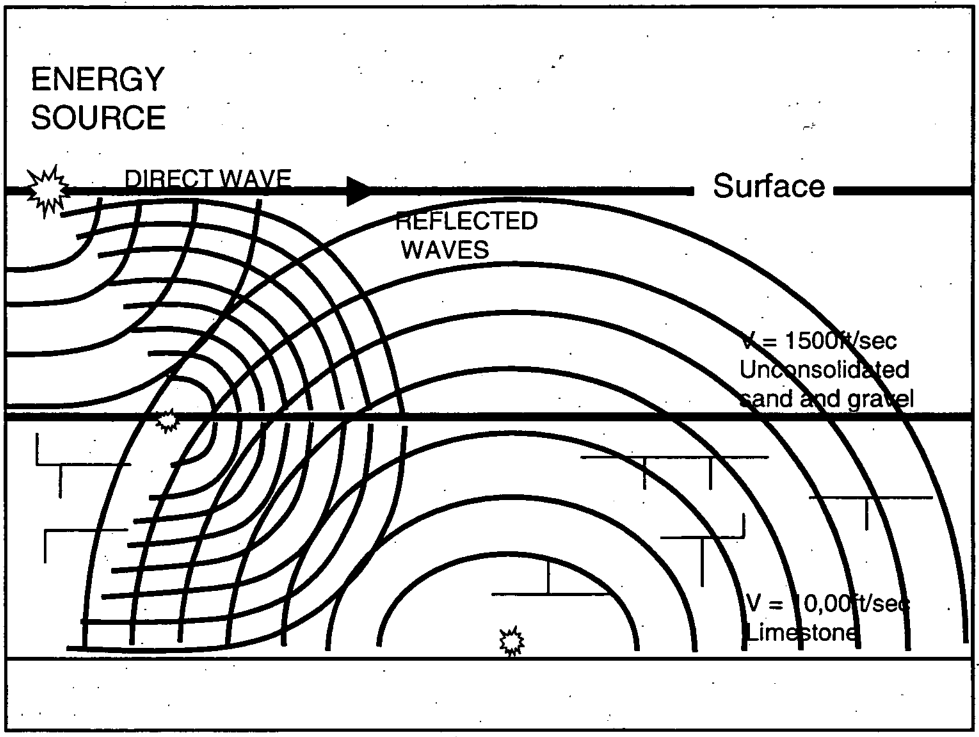
- Rapid data collection
- Simple field procedure
- Fast preliminary interpretation
- Useful in a wide variety of geologic settings

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 is hidden

Seismic Reflection

- Acoustic energy encounters a boundary between two geologic layers
- If the contrast is high enough some of the energy is transmitted and some is reflected
- Thickness of the layer determines if it is detected or "hidden"



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

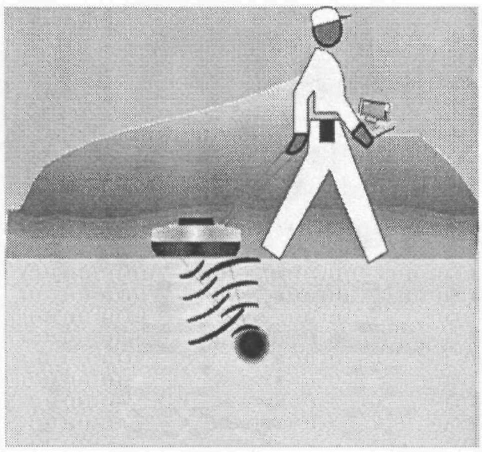
Acoustic Velocity Logging

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

Crosshole Seismic

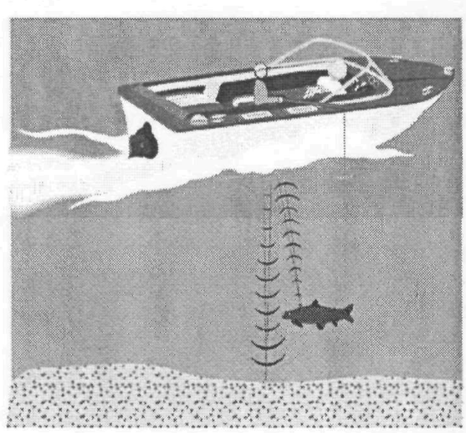
- Three dimensional imaging
- Velocity and stress determinations
- Very high resolution

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

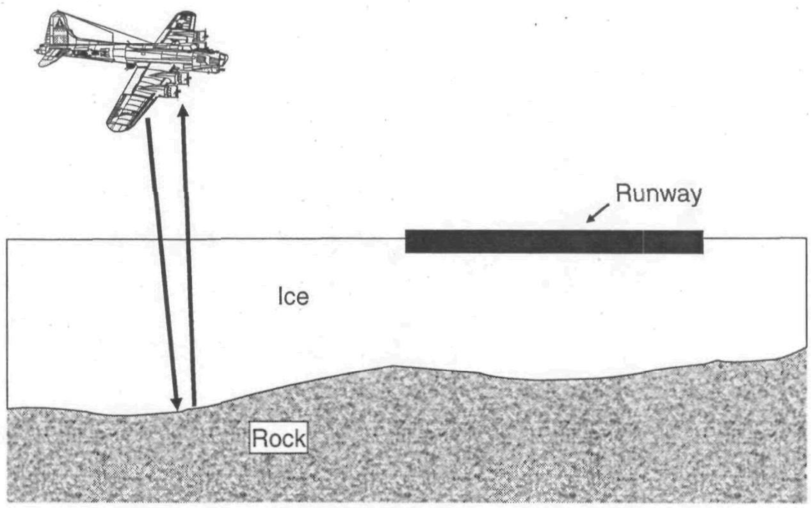
Ground Penetrating Radar

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

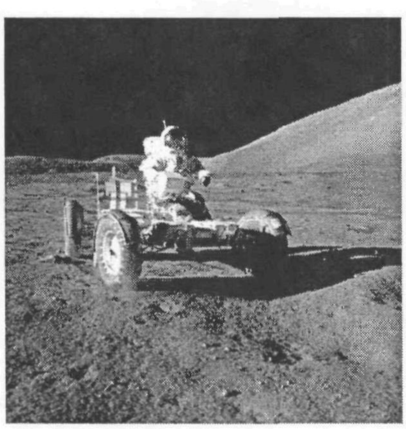
A Little History!!

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

1950's USAF Greenland

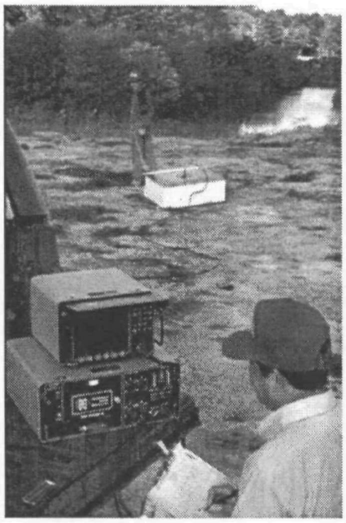


Apollo 17 Surface Electrical Properties Experiment


NASA

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

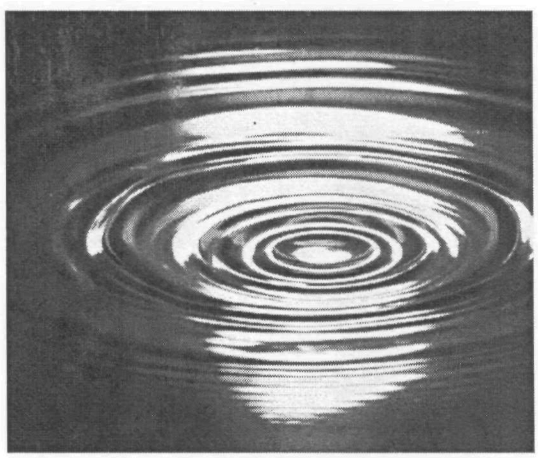
Commercial Systems



GSSI

- 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

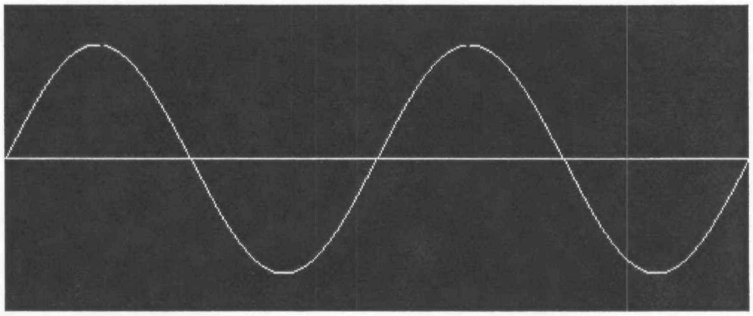
GPR: A True Wave-Based Technique



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.

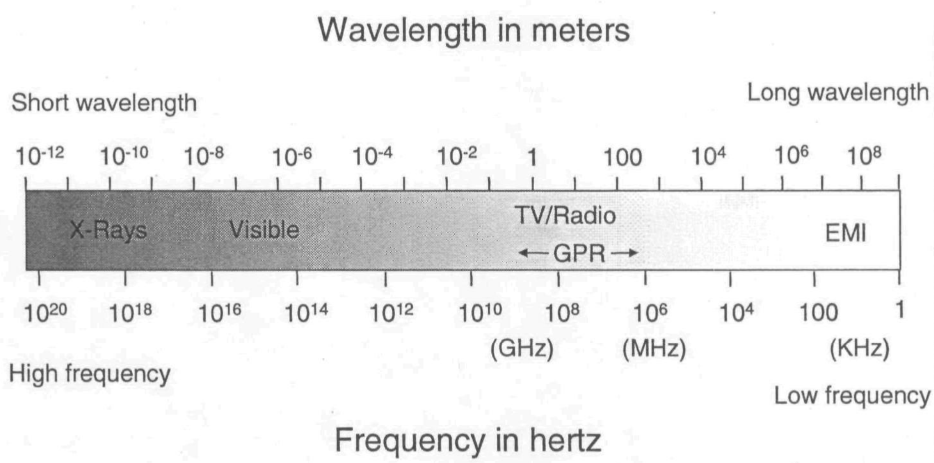
Wave Properties

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

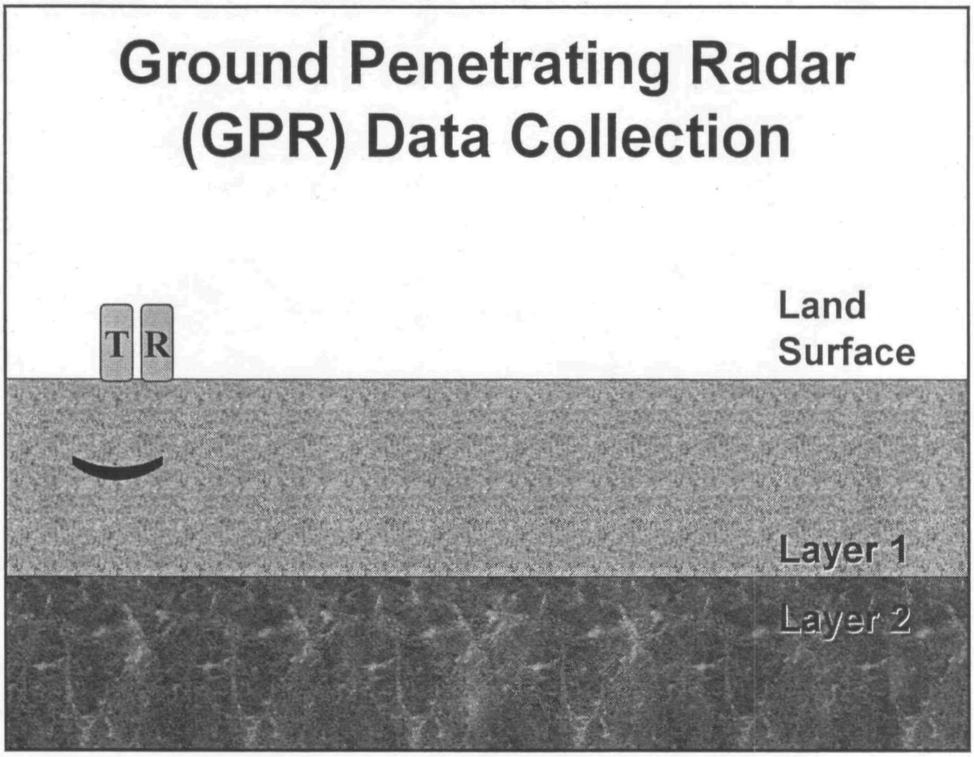


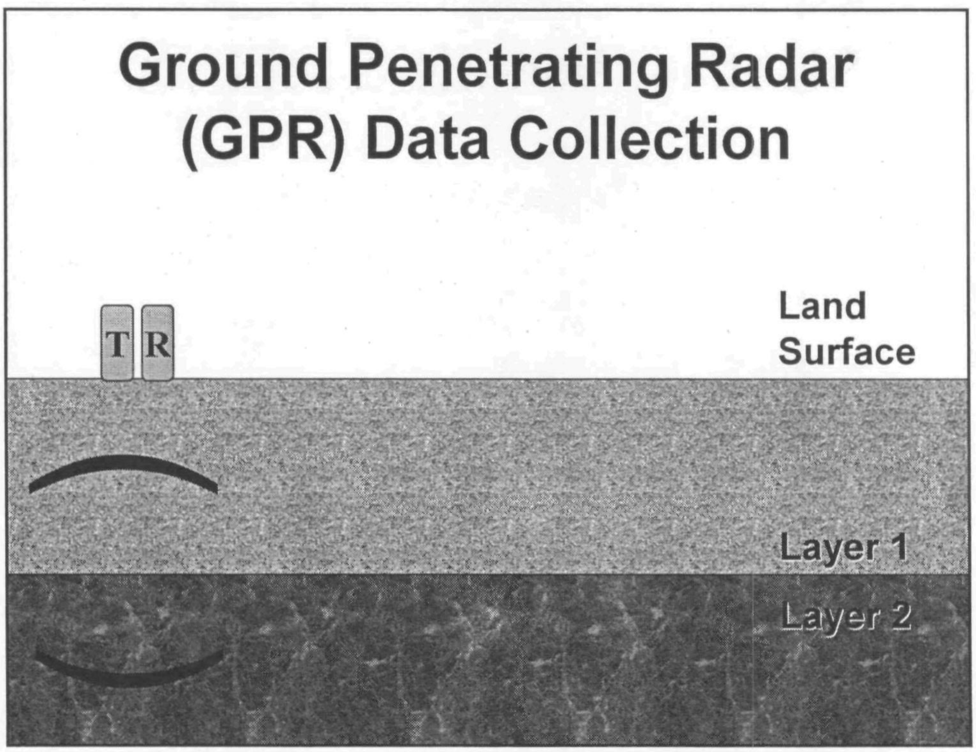
Frequency refers to how many waves are made per time interval. This is usually described as how many waves are made per second, or as cycles per second.

Electromagnetic Spectrum



GPR = 10 to 1000 MHz range

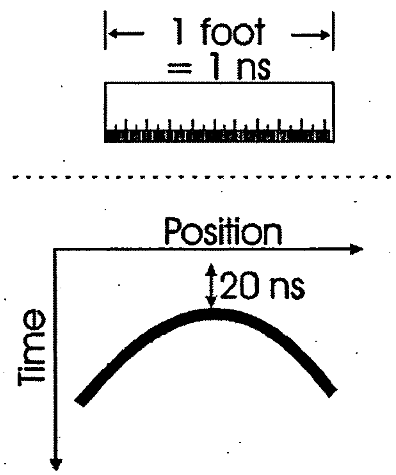

Ground Penetrating Radar
(GPR) Data Collection
T
R
Land
Surface
Layer 1
Layer 2


Ground Penetrating Radar
(GPR) Data Collection
T
R
Land
Surface
Layer 1
Layer 2

Two-Way Travel Time

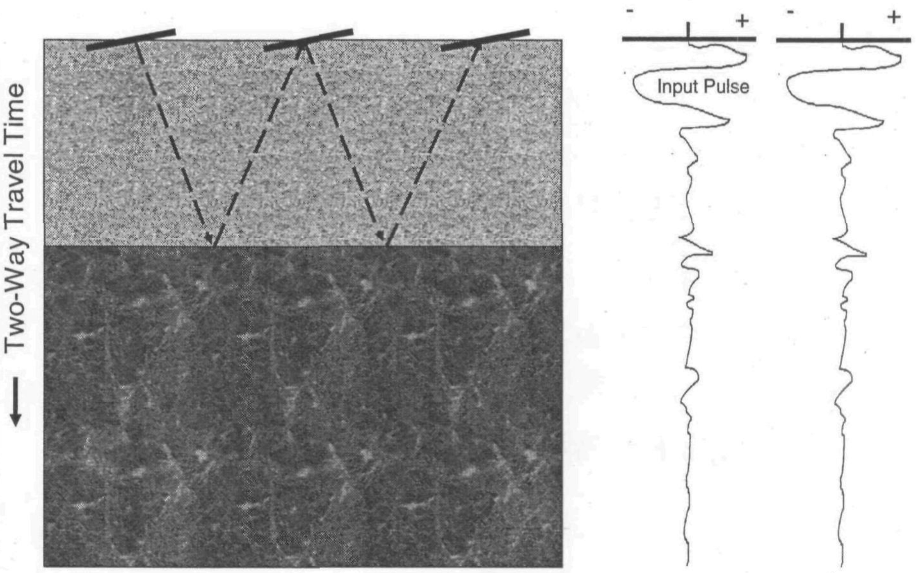
- Amount of time for the radio wave to make round-trip from the surface down to the reflector and back
- Greater for deeper objects
- Can be converted to depth if velocity is known
- Measured in nanoseconds

What Are Nanoseconds?

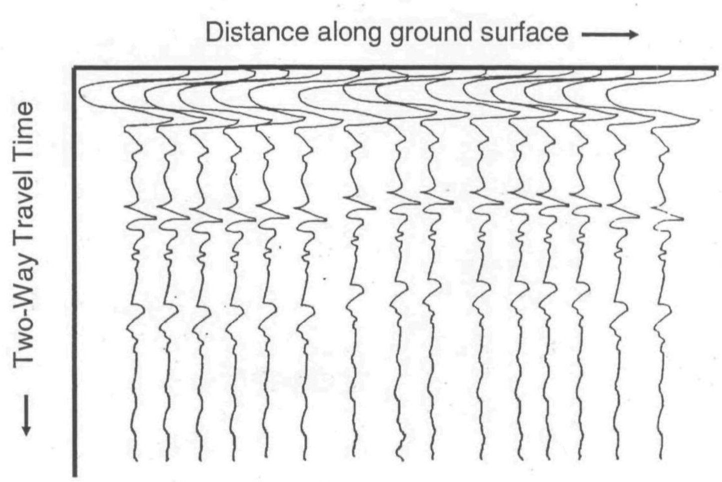


- GPR time is measured in units of nanoseconds
- 1 nanosecond is 1 billionth of a second =1/1,000,000,000 second
- GPR signals travel 1 ft (0.3m) in air in 1 nanosecond
- *ns* is the abbreviation for nanosecond

GPR Trace



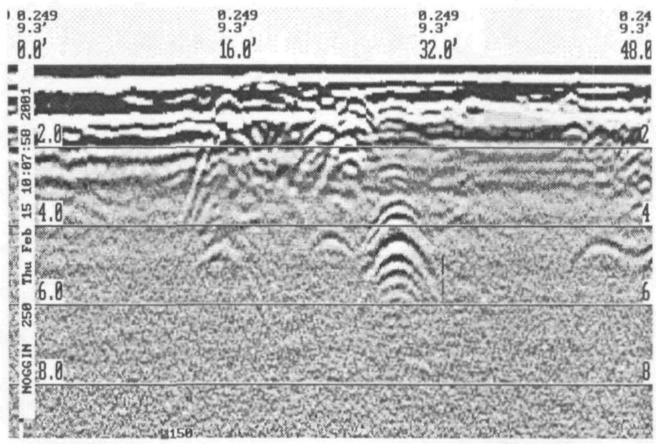
GPR Record



GPR Display/Record

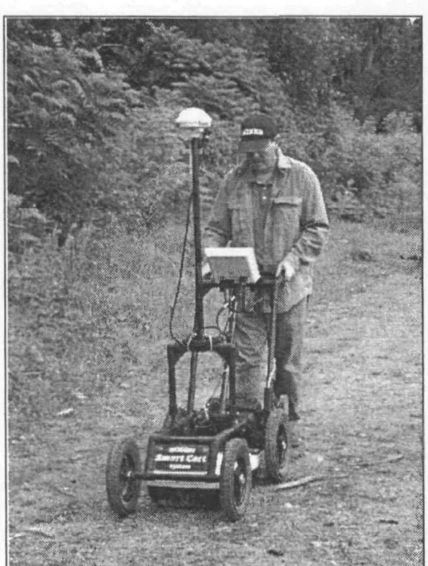
Distance along surface →

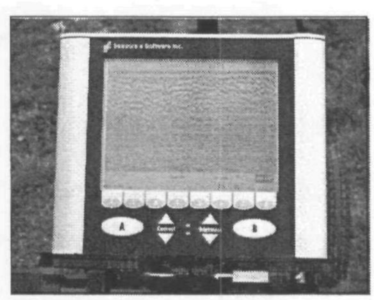
↓ Two-way travel time



↓ Depth

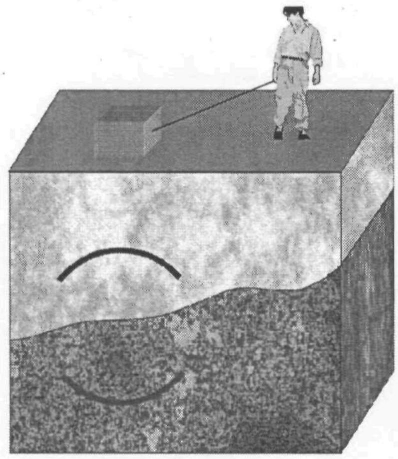
Typical GPR System





- 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

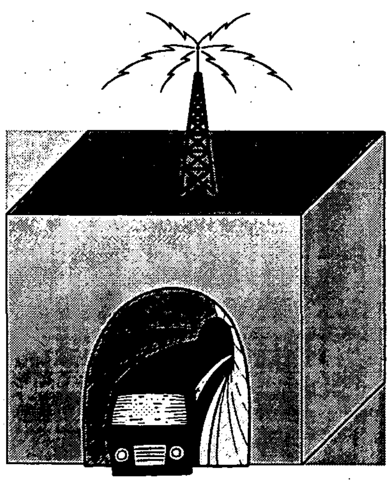
r = 0 to 0.2 weak reflections

r = 0.2 to 0.3 moderate reflections

r = greater than 0.3 strong reflections

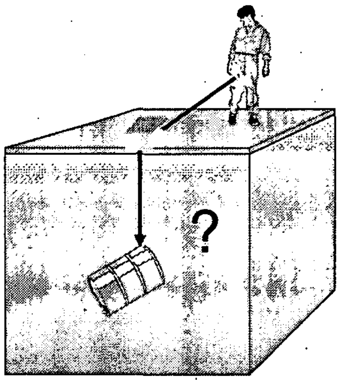
Metal reflects nearly 100% of a radar wave

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

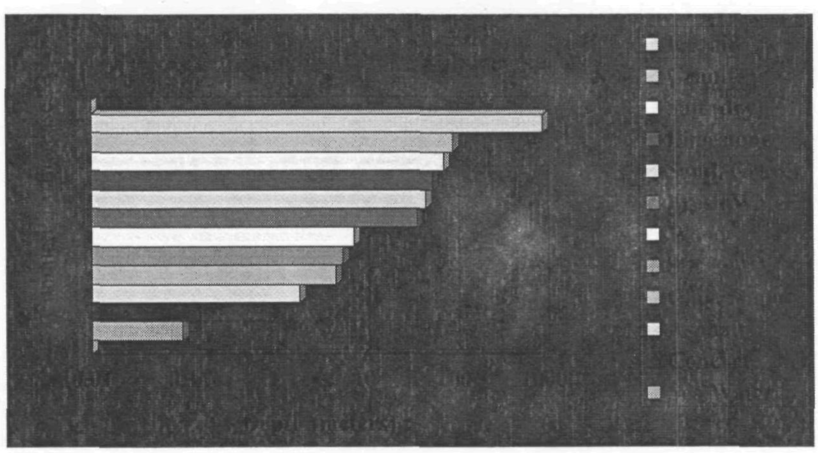
- Ability of a material to conduct electric current
- Conductivity increases with increase in water and/or clay content
- Higher conductivities limit depth
- Conversion of EM energy to heat

Estimating Exploration Depth

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

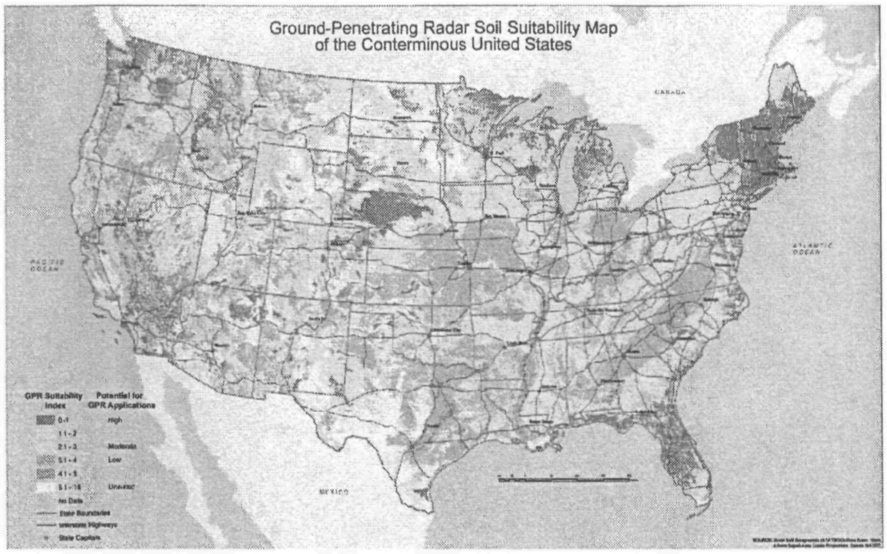
σ = conductivity in mS/m

Material Type

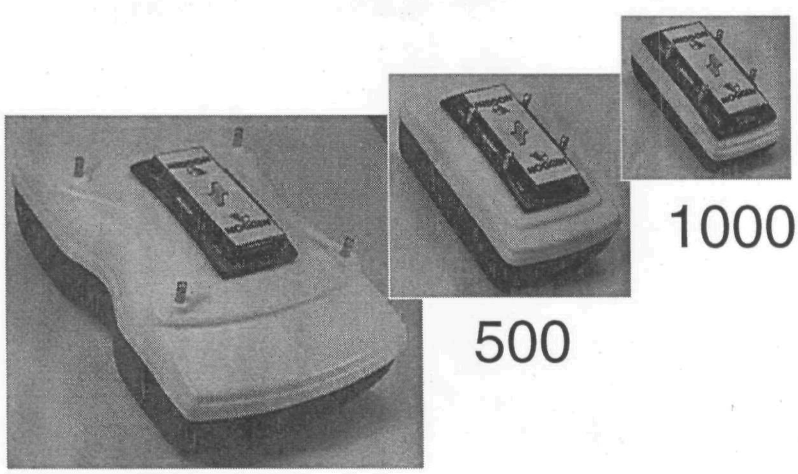


Sensors & Software Inc.

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

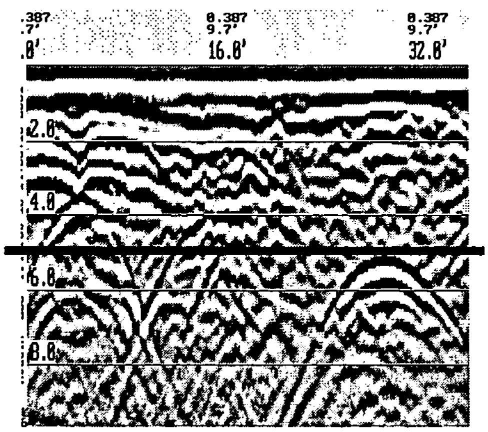
Depth Calibration
How Do I Measure Depth?

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

Method 1
Estimate

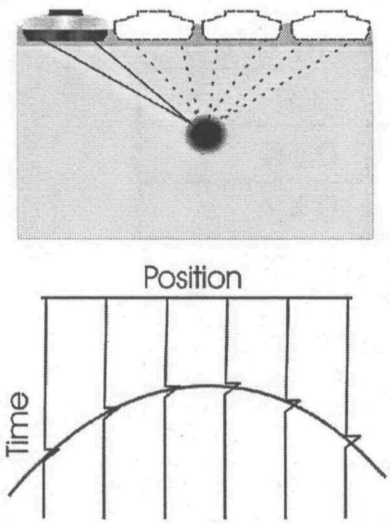
Material	Velocity (ft/ns)
Air	1.0
Ice	0.56
Dry Soil	0.43
Dry Rock	0.39
Moist Soil	0.33
Concrete	0.33
Wet Soil	0.22
Water	0.11

Method 2
Depth to Known Target



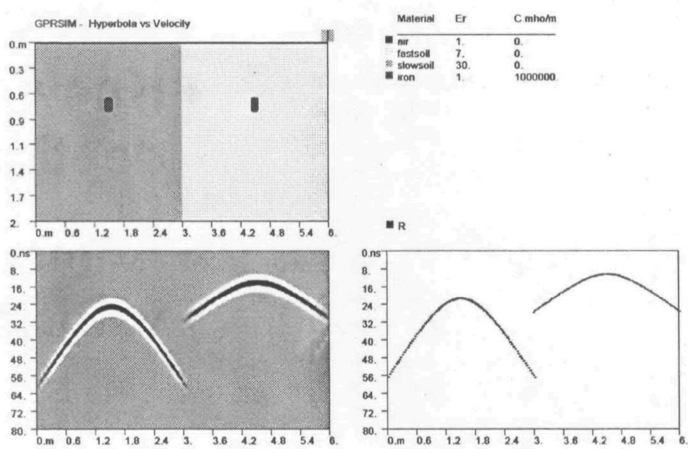
- **Know depth**
- **Adjust velocity**

Method 3
Point Target Hyperbola



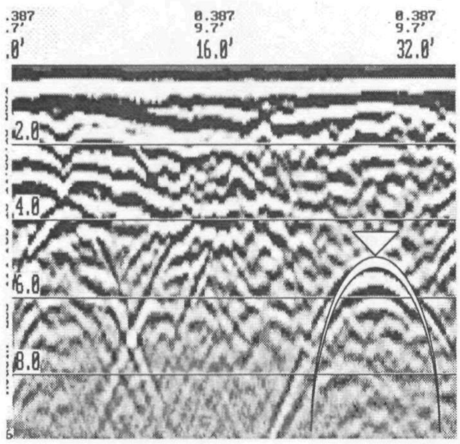
- **Wide beam**
- **Localized features**
- **Hyperbolas (inverted U's)**
- **Shape determine velocity**

Method 3
Point Target Hyperbola



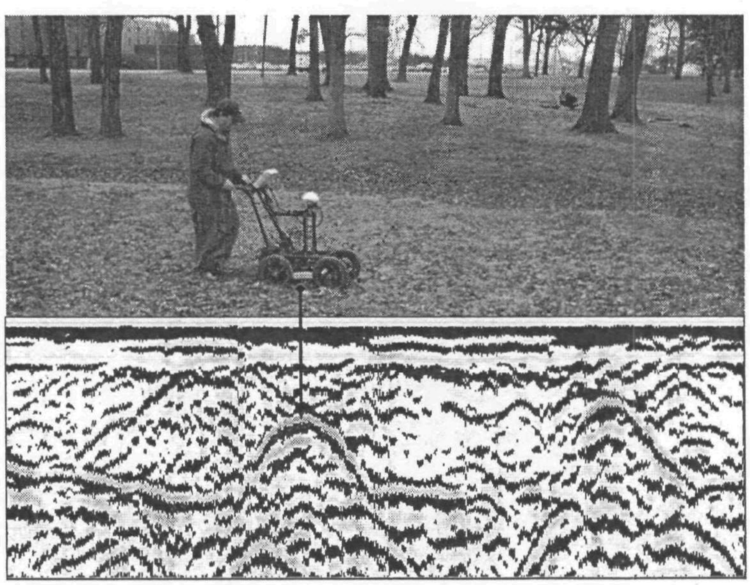
Dean Goodman

Method 3
Point Target Hyperbola

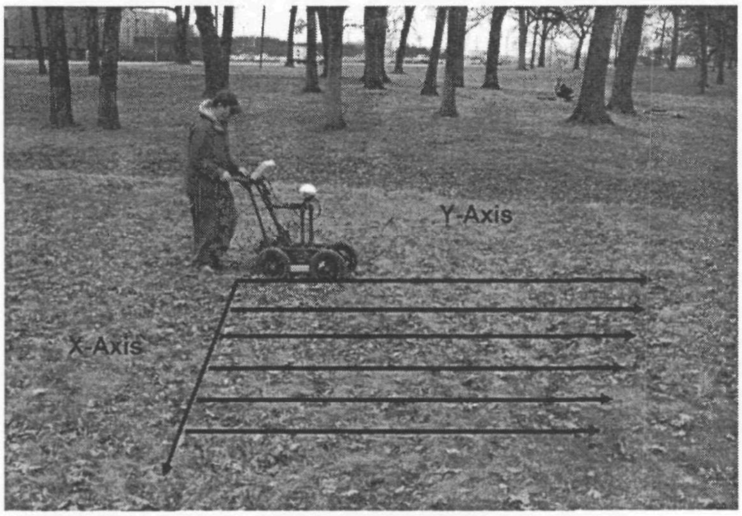


- Adjust shape
- Determines velocity

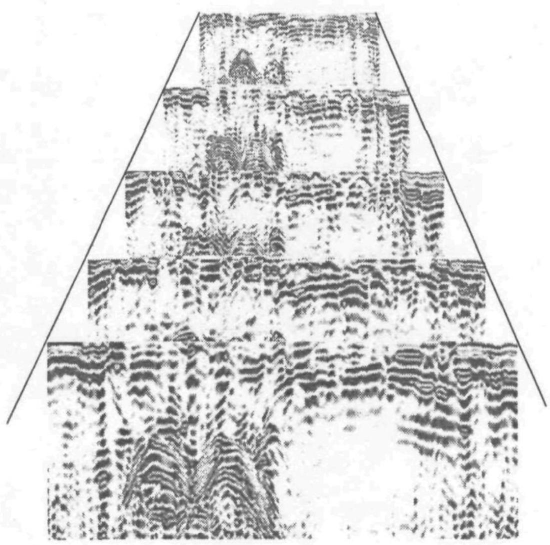
Profile and Mark



Survey Grid

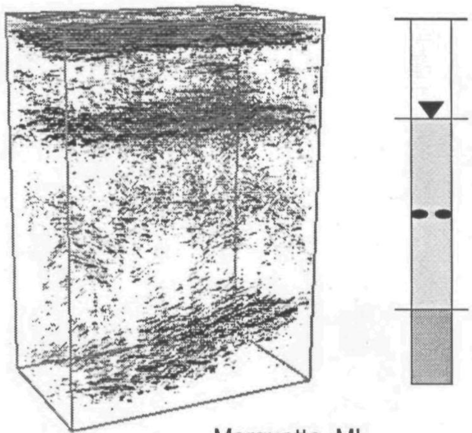


Series of GPR Profiles



Grumman Exploration

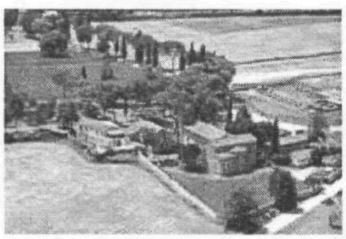
3-D GPR

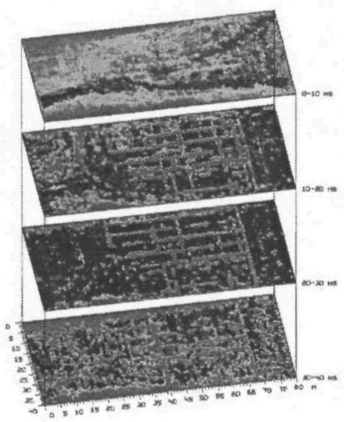


Marquette, MI
30 m by 6 m area
6 - 8 m depth

Grumman Exploration

Time Slices

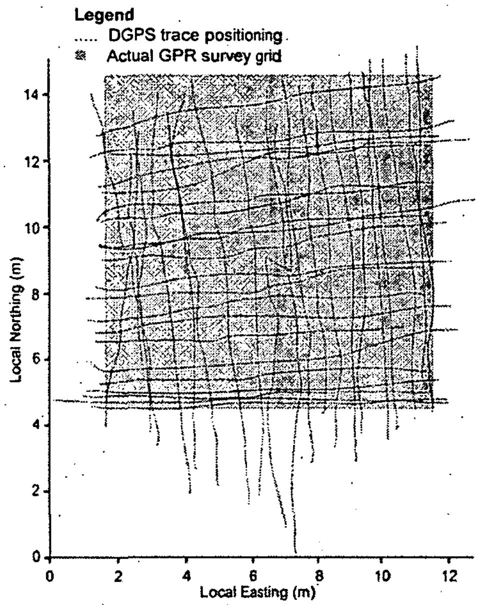




- GPR dataset from Forum Novum site in the Tiber Valley, Italy.
- Site is a Roman market place and church that were built in the 2nd century A.D.
- GPR time slices revealed buried walls and foundations from the ancient Roman buildings.

Dean Goodman

GPR and GPS

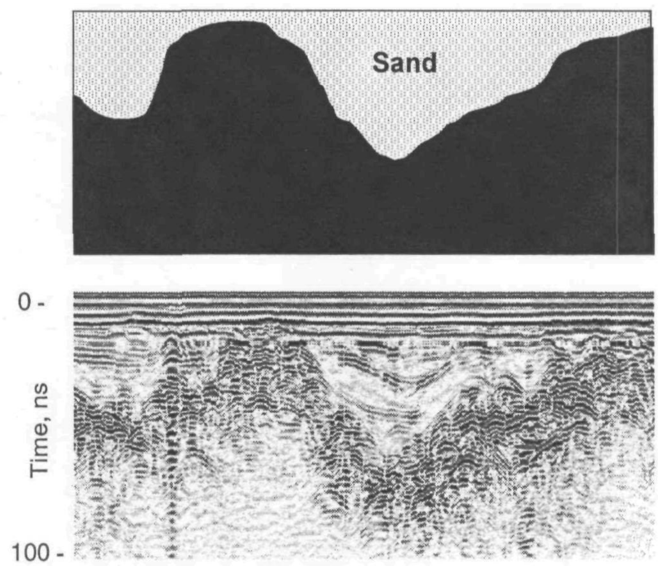


- 10 m by 10 m grid
- 0.5 m line spacing
- Differential GPS
- Area wide open
- Ideal conditions
- Not accurate

GPR Applications

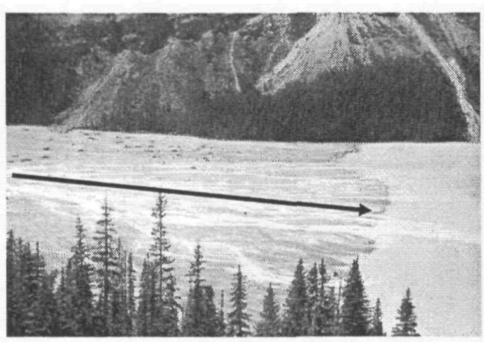
- Mapping subsurface geology
  - Bedrock
  - Water Table
  - Faults and Fractures
- Locating cultural objects
  - Drums and Tanks
  - Landfills and pits
  - Contamination

Bedrock



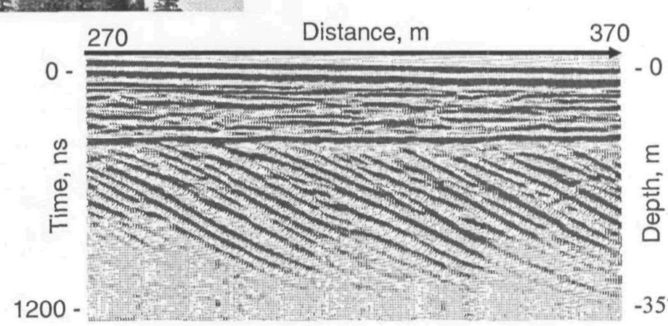
GSSI

Stratigraphy



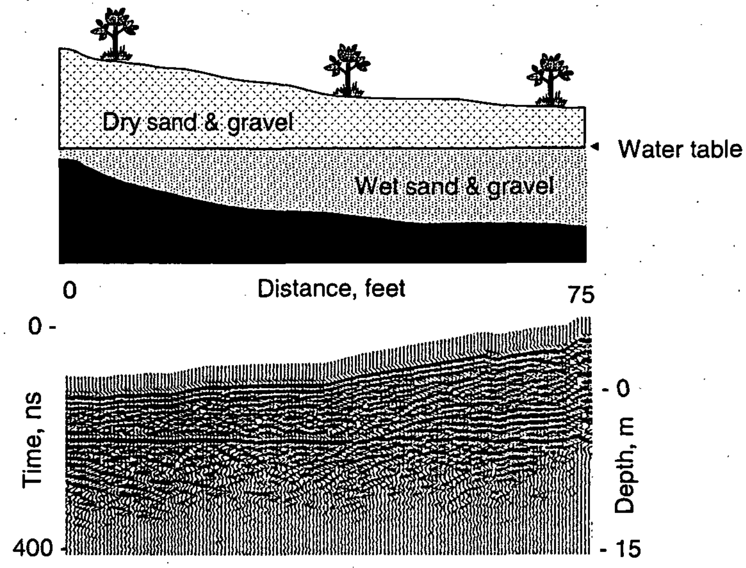
Peyto Lake Delta
Banff National Park

GPR data
Delta
Sediments
25 MHz



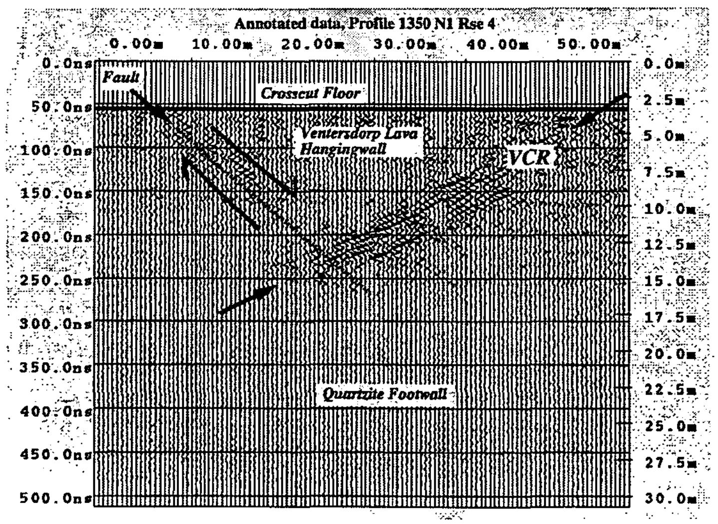
Derald Smith, University of Calgary

Water Table Mapping



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

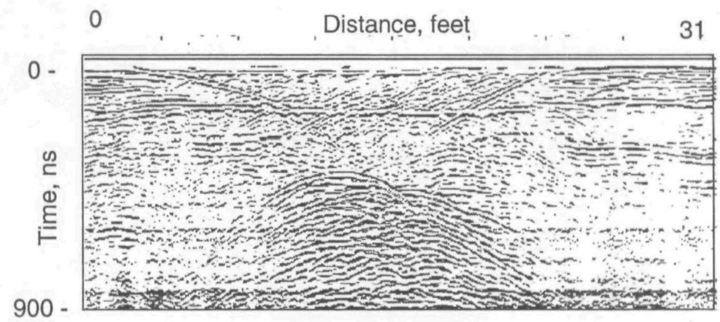
Faults and Fractures



Ventersdorp Contact Reef - South Africa

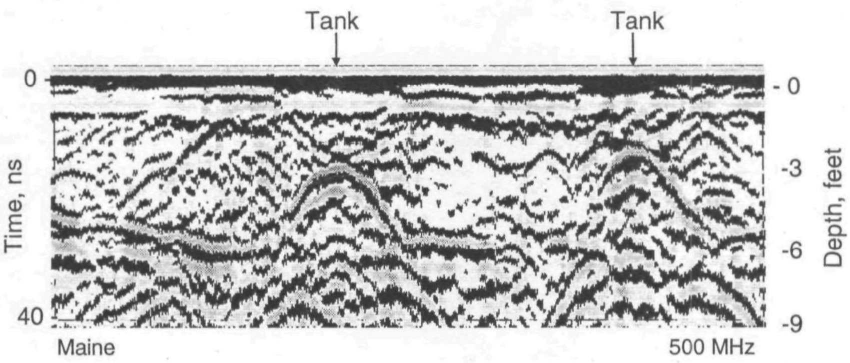
Sinkholes

Sinkhole at Winter Park, Florida



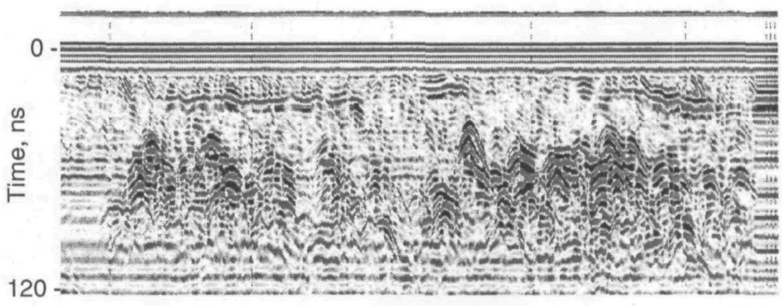
80 MHz GPR data showing developing sinkhole, Florida. GSSI

Underground Storage Tanks



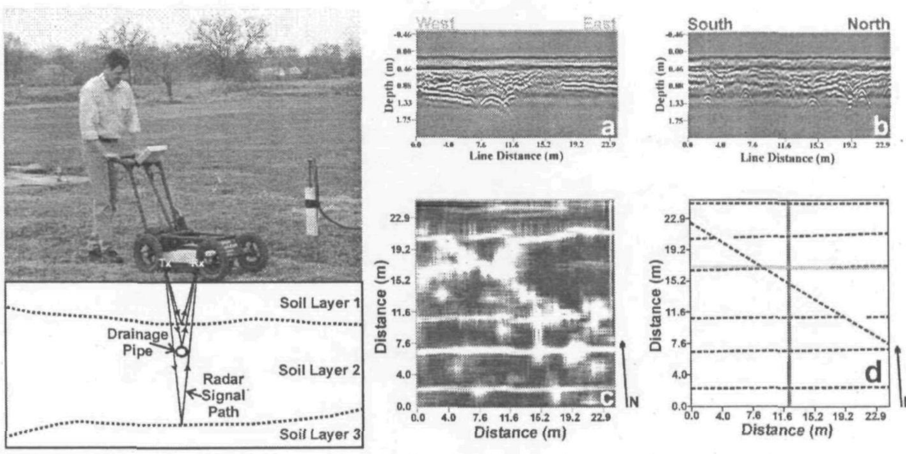
Geophysical Survey Systems, Inc.

Trench with Drums



Geophysical Survey Systems, Inc.

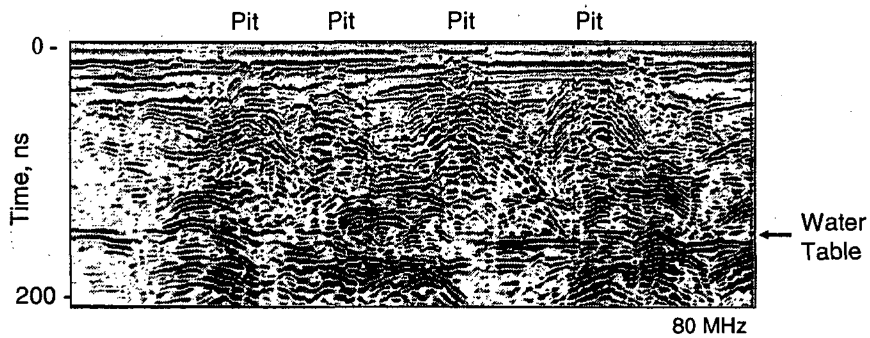
Drainage Pipe Detection



72% Success Rate in Ohio

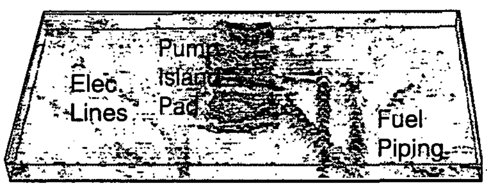
Barry Allred, USDA/OSU

Laboratory Waste Pits

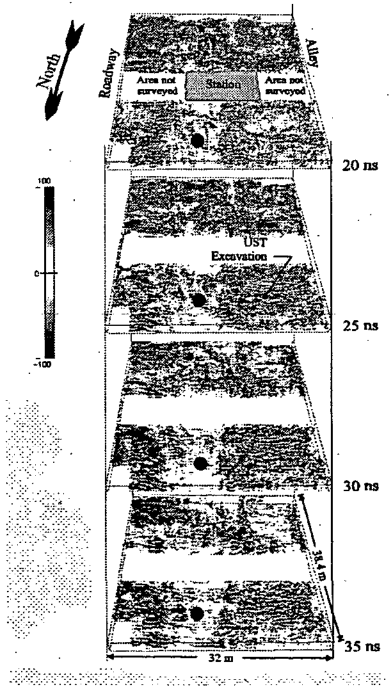


OSU - Brookhaven National Laboratory

Gas Station- Petroleum Product

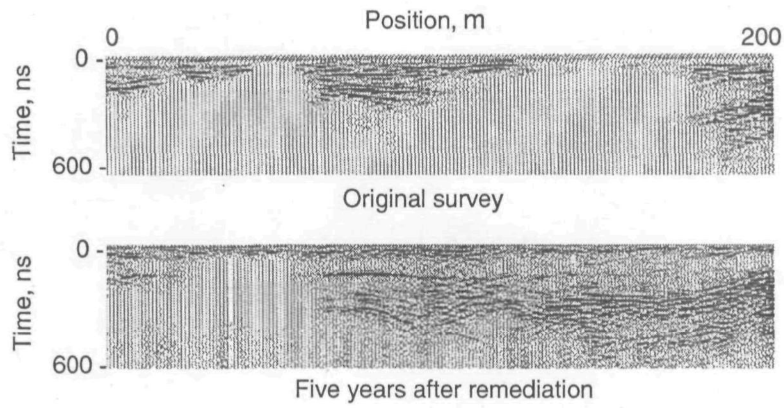


Time Slices



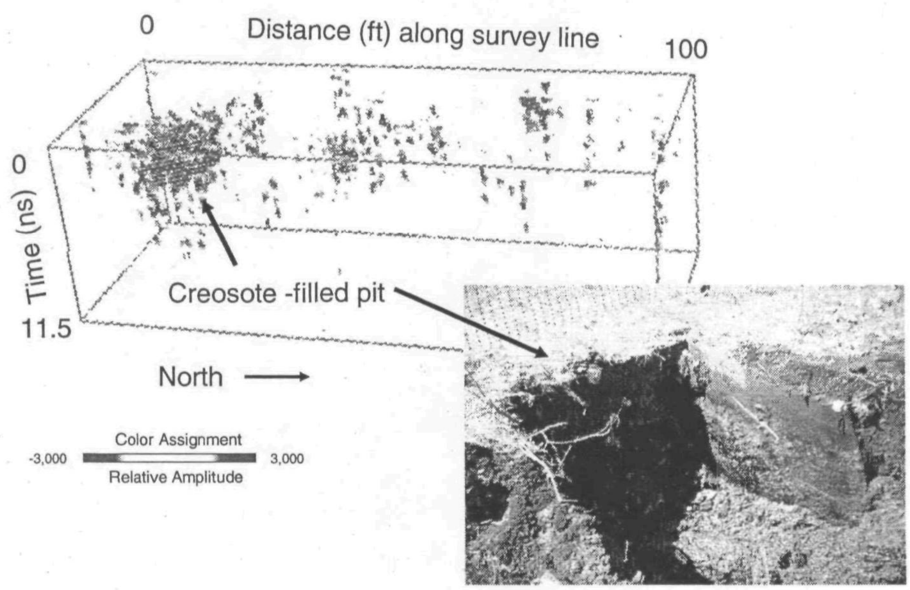
Jeff Daniels and Dave Grumman, OSU

Contaminated Groundwater



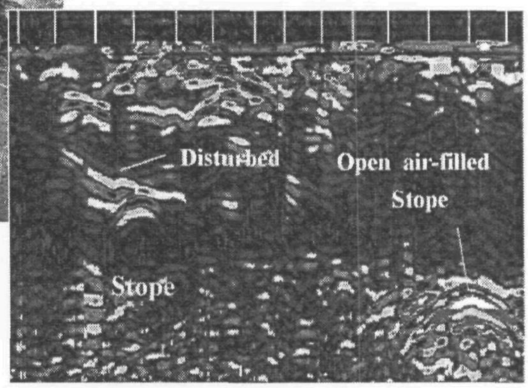
Sensors & Software Inc.

Creosote Pit



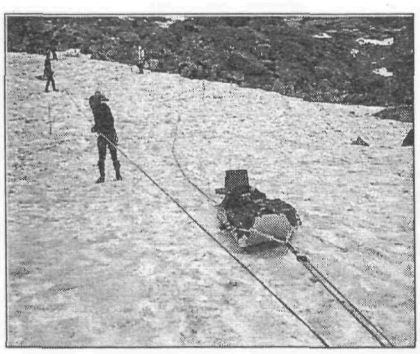
Underground Mine Workings

Cresson Open-Pit Mine
Cripple Creek, Colorado



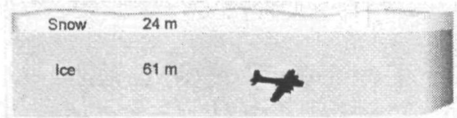
Pikes Peak Mining Co./ GSSI

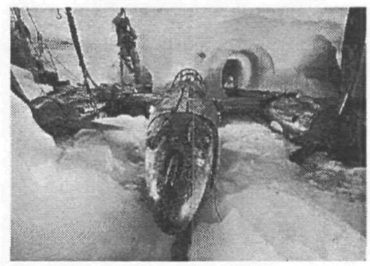
Ice / Glaciology



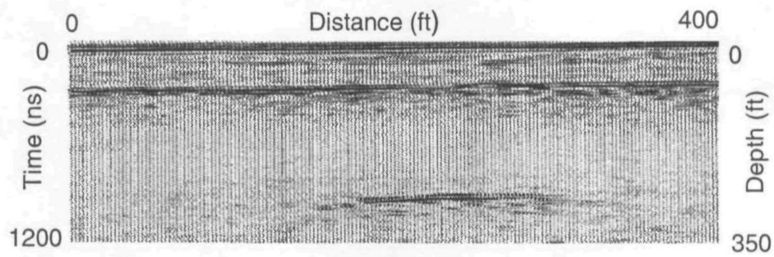
- Ice very transparent to GPR signals
- RDP = 3-4
- Penetration depth as much as 500 meters
- Used to study thickness and structure of glaciers

The Lost Squadron



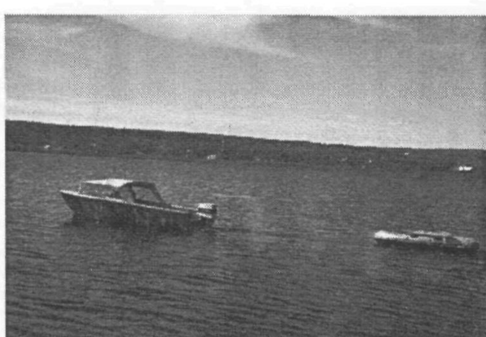


GPR locates aircraft at depth of 279 feet below surface in Greenland



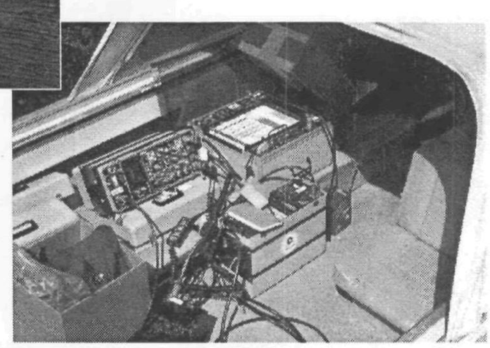
Sensors & Software Inc./Greenland Expedition Society

Water-borne GPR

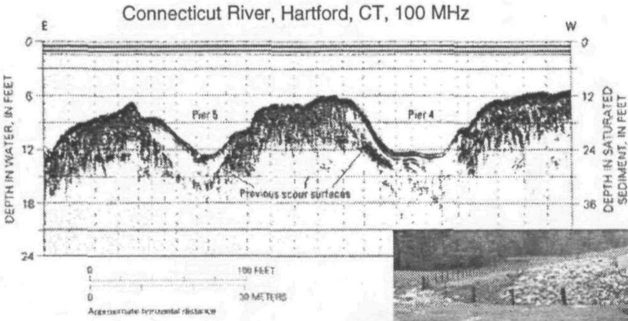


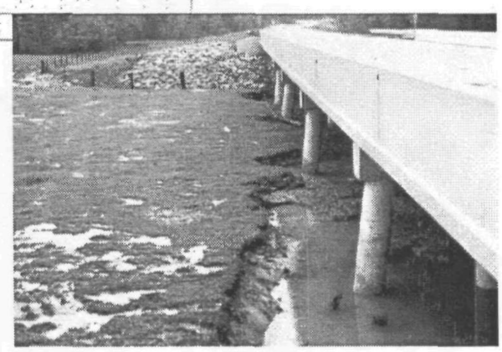
Antenna

Control Unit



Bathymetry & Sub-bottom Profiling

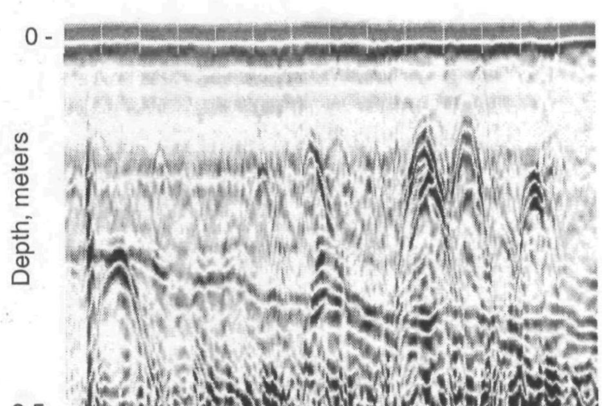




Riverbed scour near bridge piers is a widespread problem throughout the United States

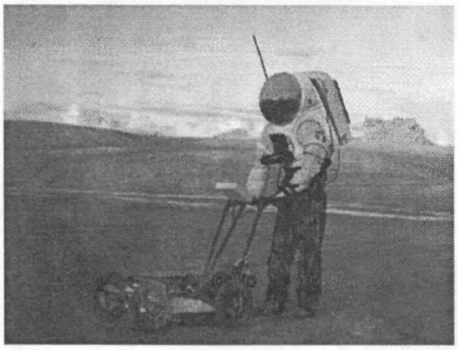
Archaeology Burials

Iceland



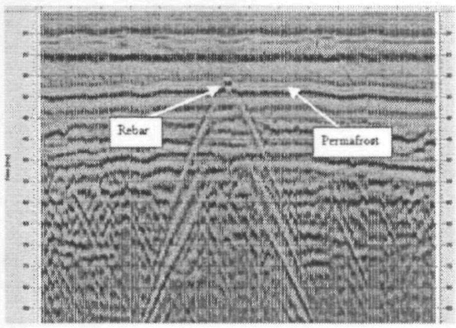
Ho Chunk Nation, Wisconsin

The Haughton-Mars Project NASA



Haughton Meteorite
Impact Structure
Devon Island, Canada
Mars Analog
2002

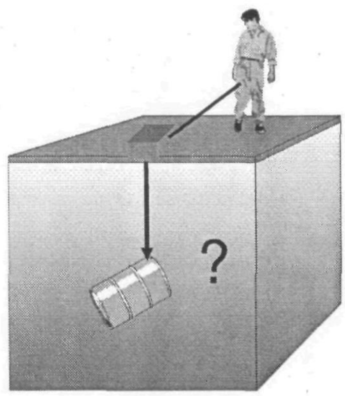
Objective to image permafrost layer similar to that presumed on Mars



Survey Design

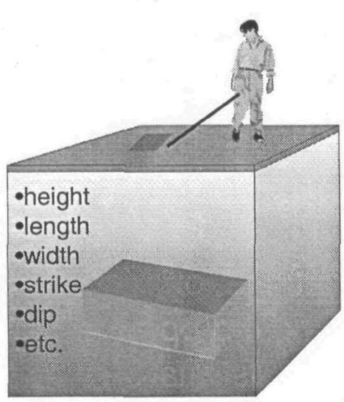
- Proper design of GPR surveys is critical to success.
- The most important step in a GPR survey is to clearly define the problem.
- There are five fundamental questions to be asked before deciding if a radar survey is going to be effective.

What is the target depth?



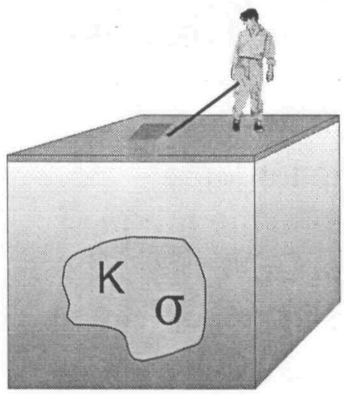
- The answer to this is usually the most important.
- If the target is beyond the range of ideal GPR conditions, GPR can be ruled out.

What is the target geometry?



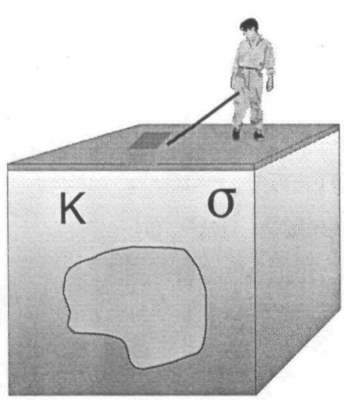
- Most important target factor is size
- If target is non-spherical, target orientation should be qualified.

What are the target electrical properties?



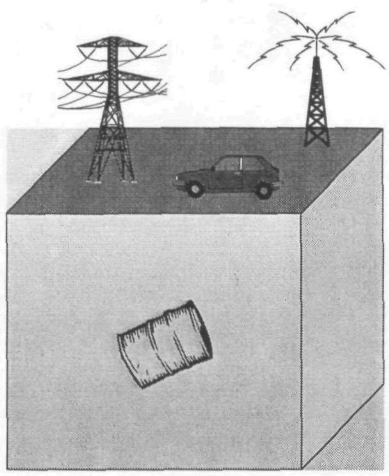
- What is relative dielectric permittivity and electrical conductivity of target?

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