

Ground Penetrating Radar

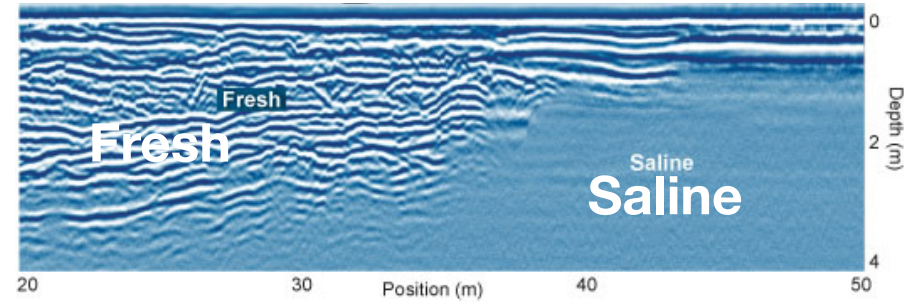


Motivation

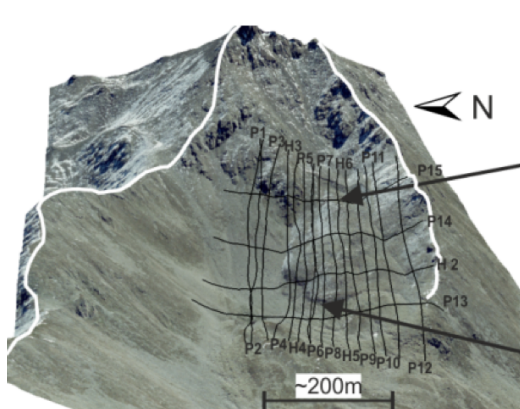
Sink holes



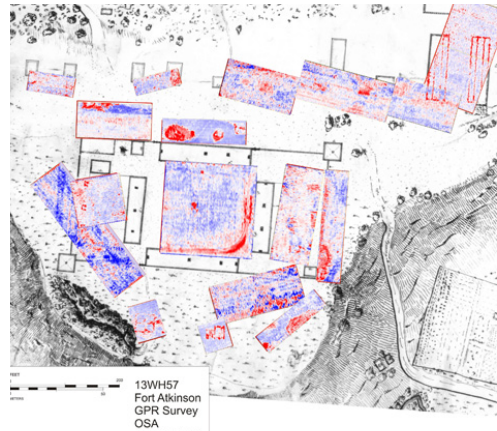
Salt Water Intrusions



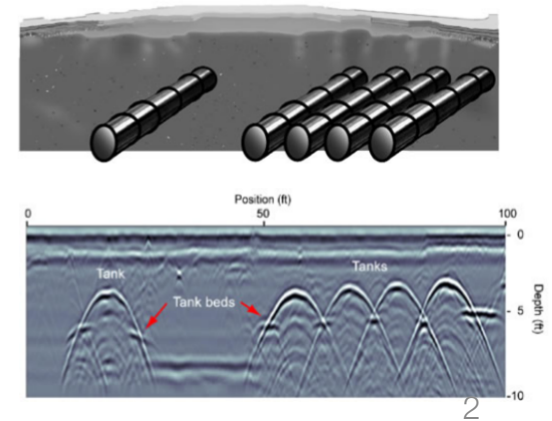
Rock glacier



Archeology



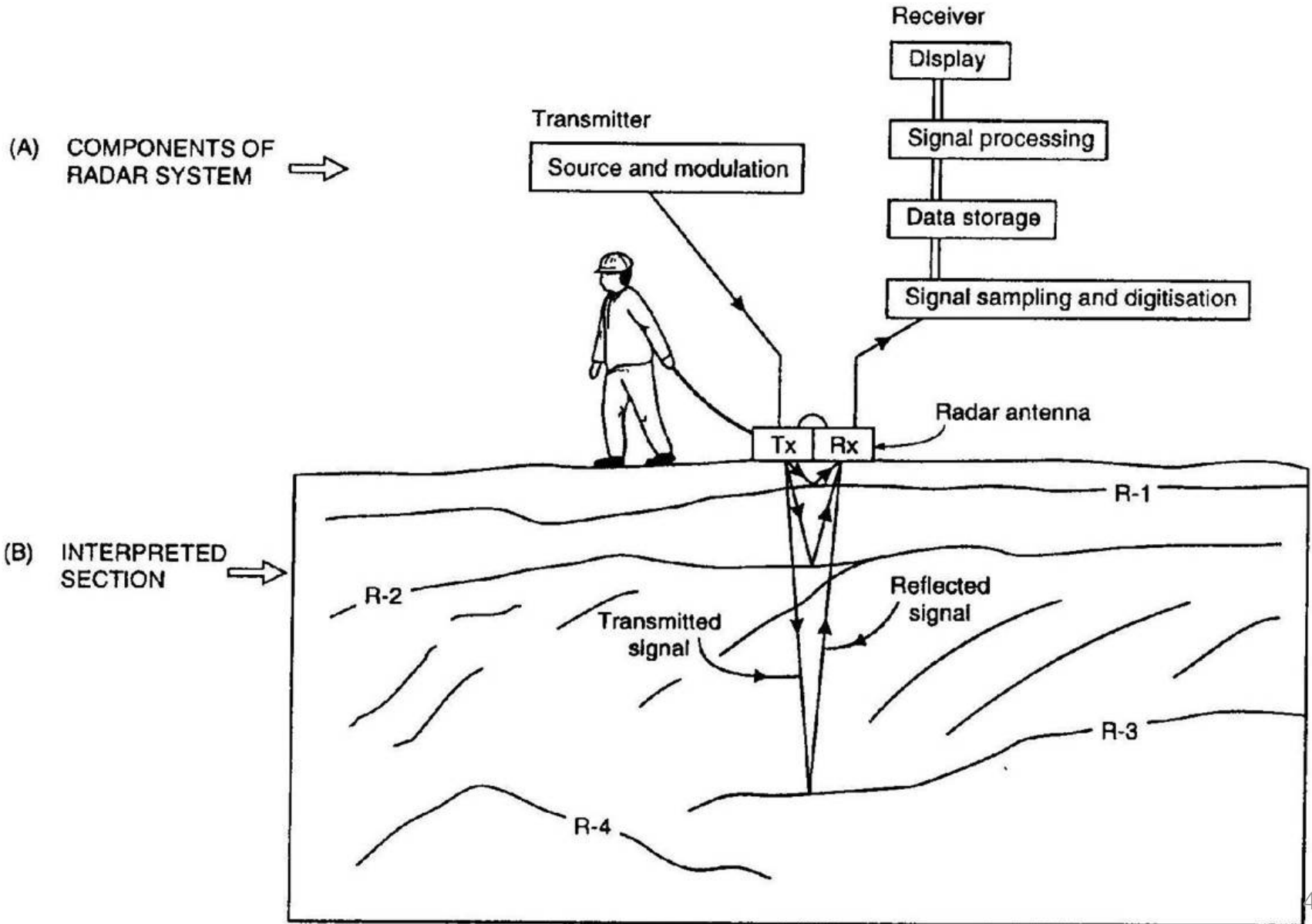
Underground tank



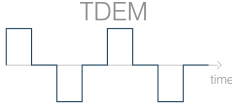
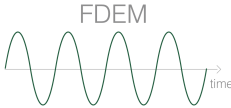
Outline

- Basic experiment
- Physical property
- Physics
- Data and Processing
- Field examples
- Driverless Vehicles
- Case History: Rock Glacier

Basic Experiment



Basic Equations

	Time 	Frequency 
Faraday's Law	$\nabla \times \mathbf{e} = - \frac{\partial \mathbf{b}}{\partial t}$	$\nabla \times \mathbf{E} = - i\omega \mathbf{B}$
Ampere's Law	$\nabla \times \mathbf{h} = \mathbf{j} + \frac{\partial \mathbf{d}}{\partial t}$	$\nabla \times \mathbf{H} = \mathbf{J} + i\omega \mathbf{D}$
No Magnetic Monopoles	$\nabla \cdot \mathbf{b} = 0$	$\nabla \cdot \mathbf{B} = 0$
Constitutive Relationships (non-dispersive)	$\mathbf{j} = \sigma \mathbf{e}$ $\mathbf{b} = \mu \mathbf{h}$ $\mathbf{d} = \epsilon \mathbf{e}$	$\mathbf{J} = \sigma \mathbf{E}$ $\mathbf{B} = \mu \mathbf{H}$ $\mathbf{D} = \epsilon \mathbf{E}$

* Solve with sources and boundary conditions

Basic Equations: Wave Equation

First order equations

$$\begin{aligned}\nabla \times \mathbf{e} &= -\frac{\partial \mathbf{b}}{\partial t} & \mathbf{j} &= \sigma \mathbf{e} \\ \nabla \times \mathbf{h} &= \mathbf{j} + \frac{\partial \mathbf{d}}{\partial t} & \mathbf{b} &= \mu \mathbf{h} \\ & & \mathbf{d} &= \epsilon \mathbf{e}\end{aligned}$$

Second order equations

$$\nabla^2 \mathbf{h} - \underbrace{\mu \sigma \frac{\partial \mathbf{h}}{\partial t}}_{\text{diffusion}} - \underbrace{\mu \epsilon \frac{\partial^2 \mathbf{h}}{\partial t^2}}_{\text{wave propagation}} = 0$$

In frequency

$$\begin{aligned}\nabla^2 \mathbf{H} + k^2 \mathbf{H} &= 0 \\ k^2 &= \omega^2 \mu \epsilon - i \omega \mu \sigma\end{aligned}$$

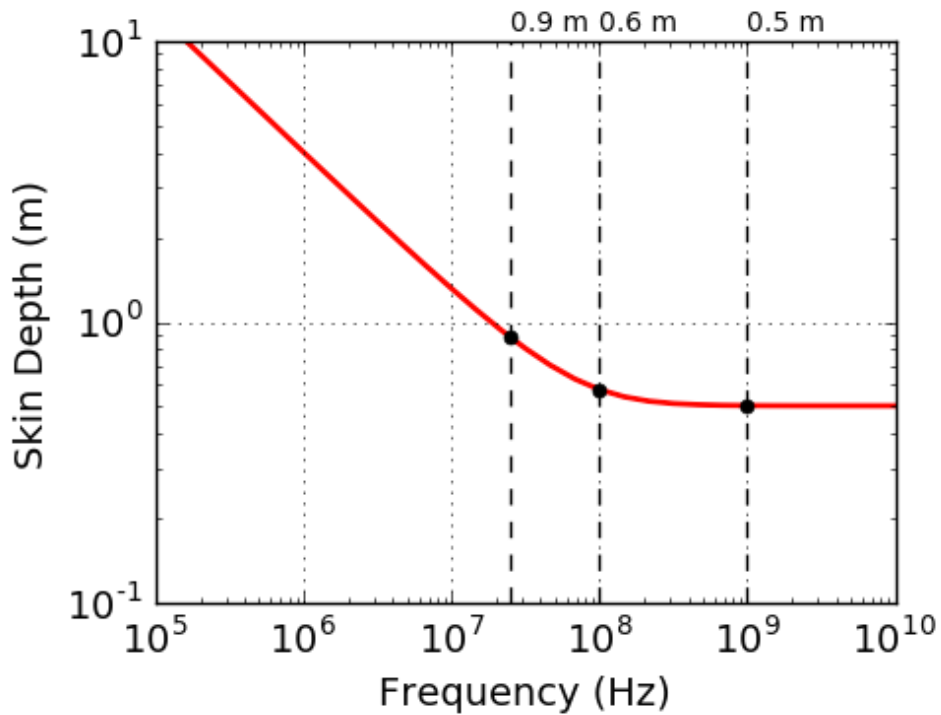
Physical properties

$$v = \frac{c}{\sqrt{\epsilon}}$$



Material	ϵ_r	V_{avg} (m/ns)	σ (ms/m)	Penetration Depth (m)
Air	1	3	0	∞
Fresh Water	80	0.033	0.5	285
Sea Water	80	0.01	3000	< 0.1
Ice	3 - 4	0.16	0.01	3000
Dry Sand	3 - 5	0.15	0.01	3200
Saturated Sand	20 - 30	0.06	0.1 - 1	145
Limestone	4 - 8	0.12	0.5 - 2	30
Shales	5 - 15	0.09	1 - 100	1
Silts	5 - 30	0.07	1 - 100	1.3
Clays	5 - 40	0.06	2 - 1000	0.2
Granite	4 - 6	0.13	0.01 - 1	65
Anhydrites	3 - 4	0.13	0.01 - 1	55

Attenuation: Skin Depth

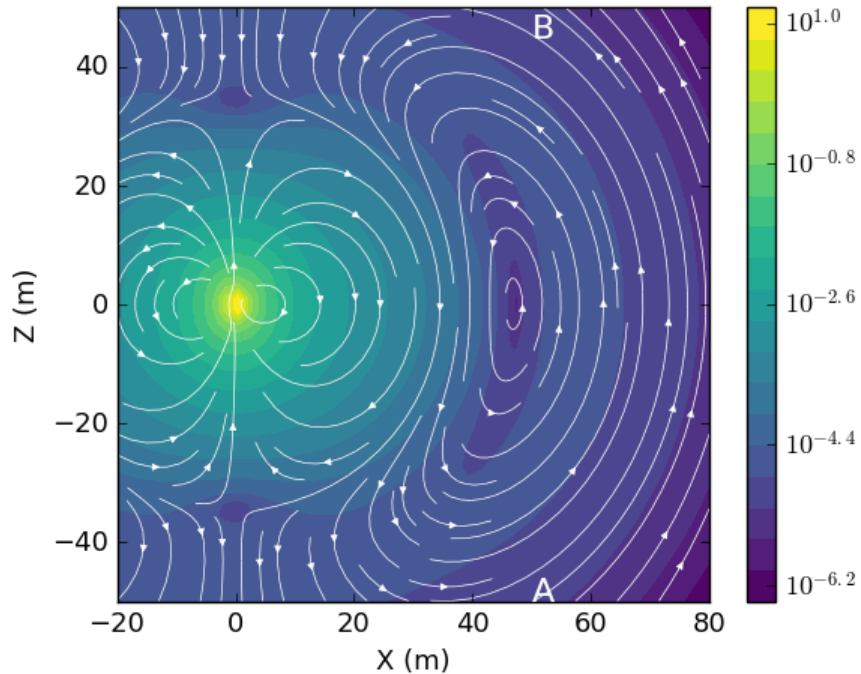


δ : skin depth

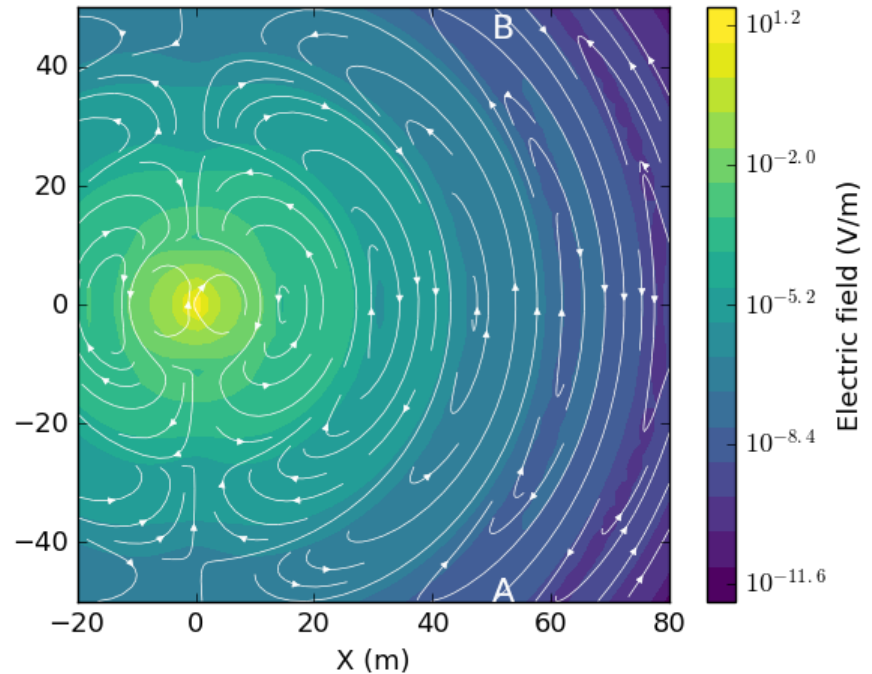
$$\delta \approx \begin{cases} 503 \sqrt{\frac{1}{\sigma f}} & \text{for } \omega \epsilon \ll \sigma \\ 0.0053 \frac{\sqrt{\epsilon_r}}{\sigma} & \text{for } \sigma \ll \omega \epsilon \end{cases}$$

Electric Dipole in a Whole Space

10^5 Hz



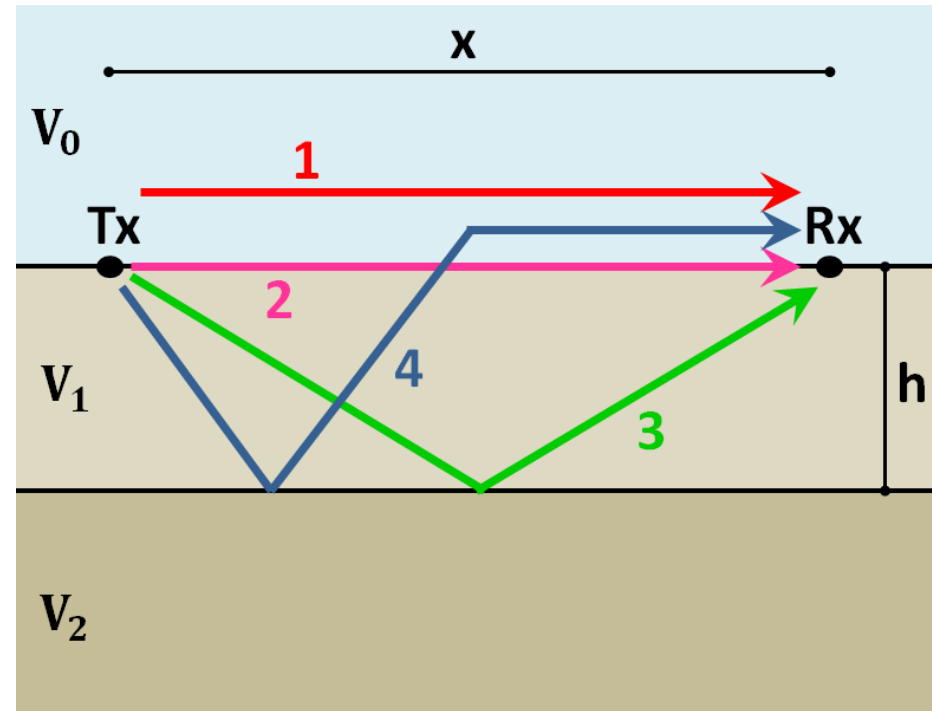
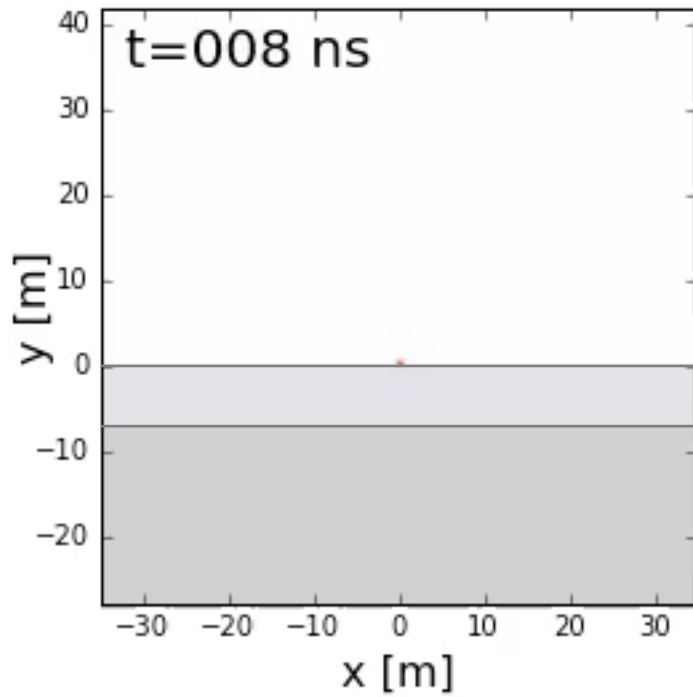
10^6 Hz



$$\lambda = \frac{v}{f}$$

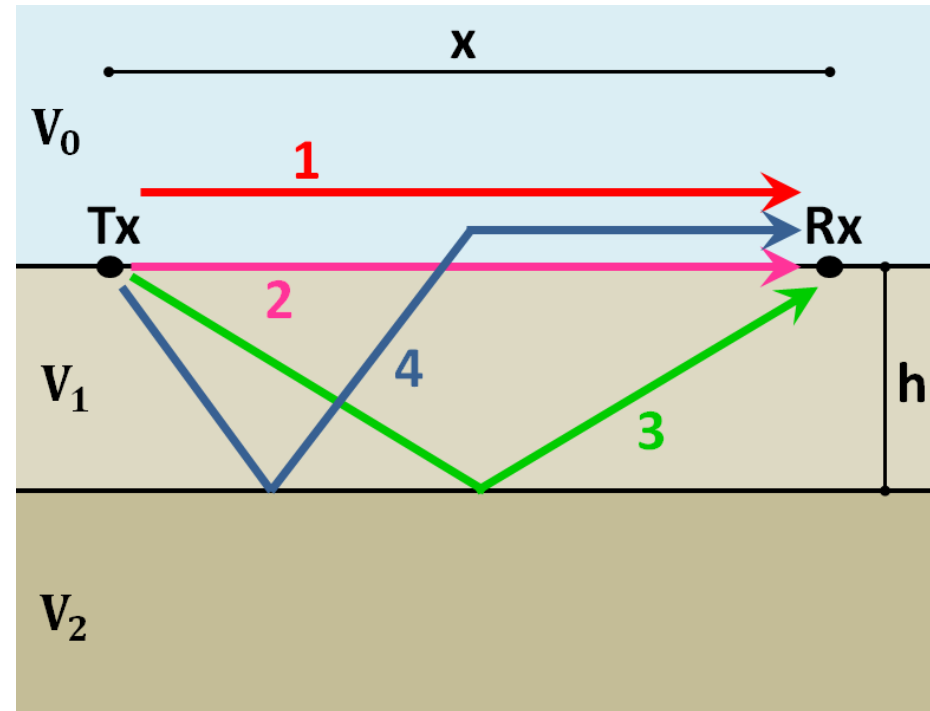
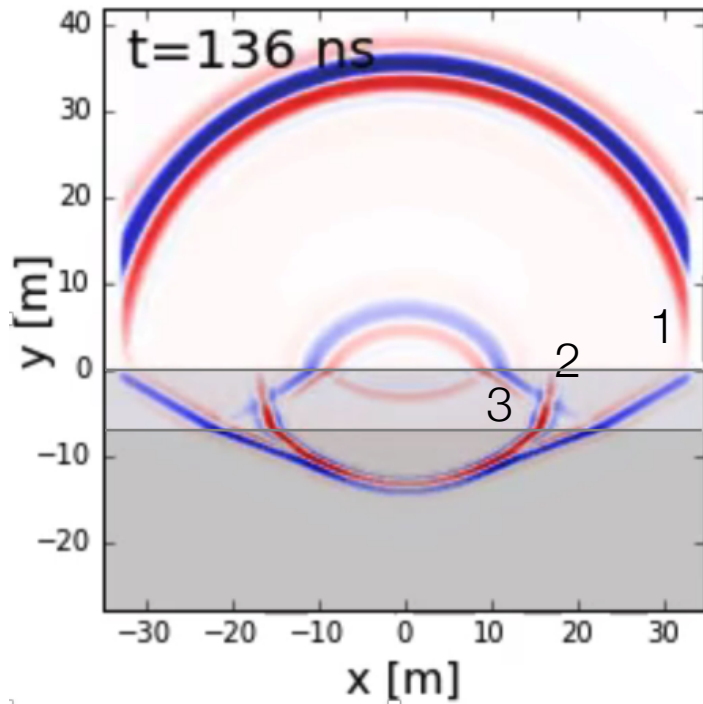
Waves and Rays

$$v = \frac{c}{\sqrt{\epsilon}}$$



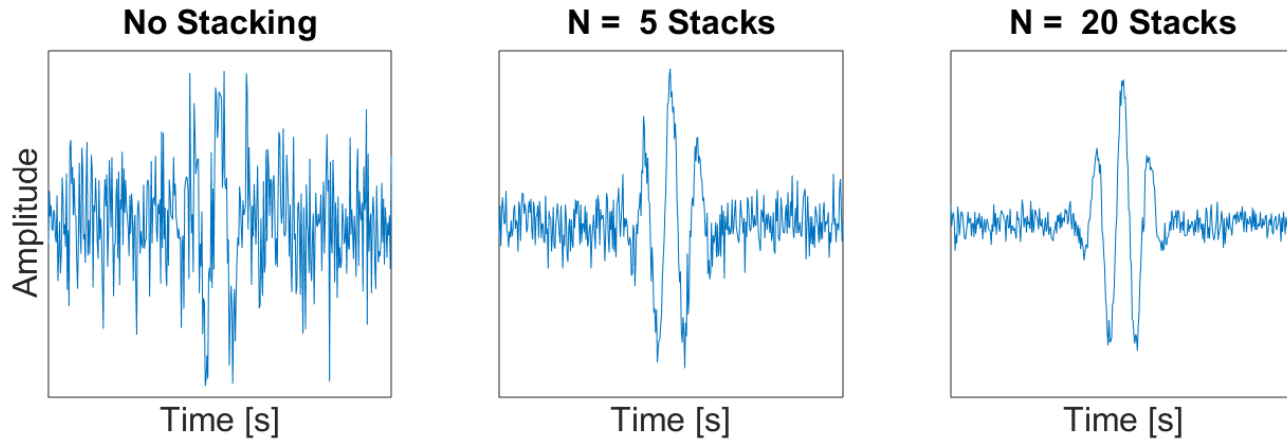
Waves and Rays

$$v = \frac{c}{\sqrt{\epsilon}}$$

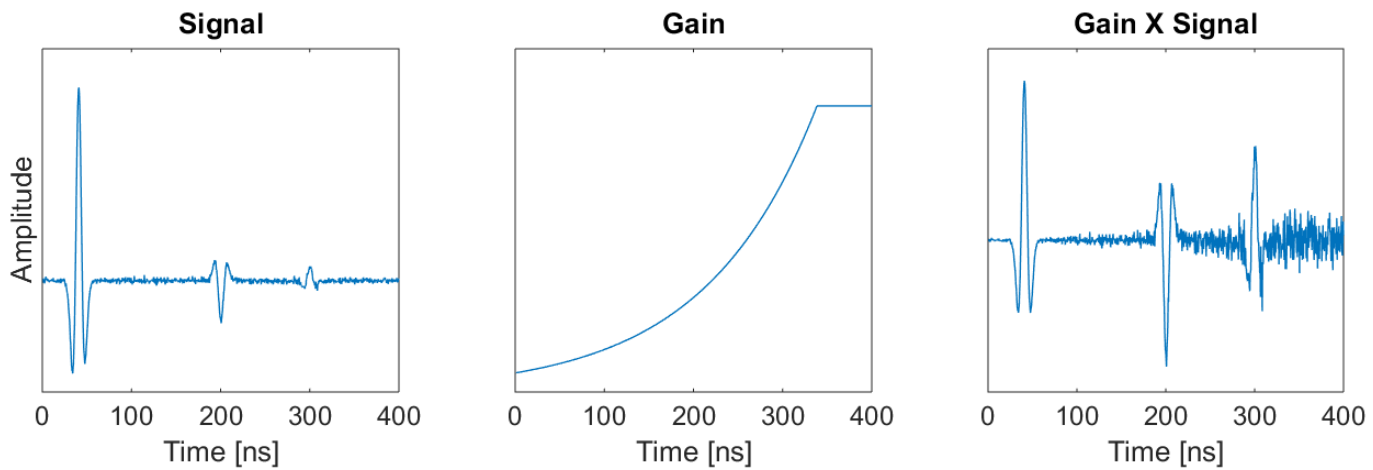


Processing

Stacking

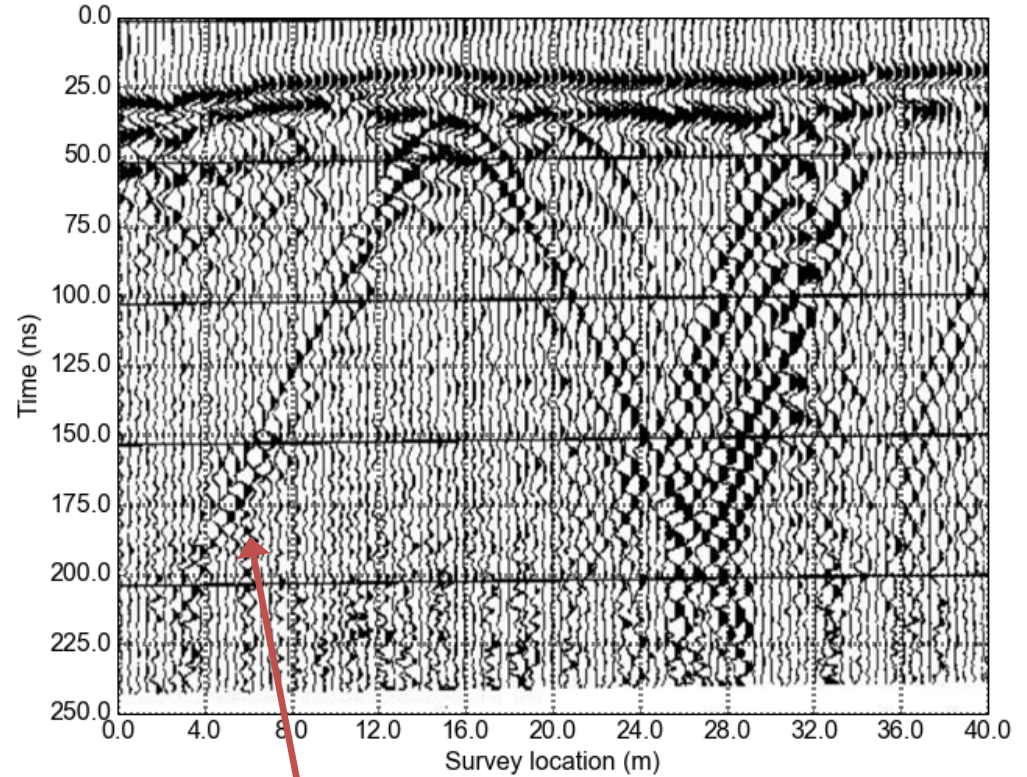
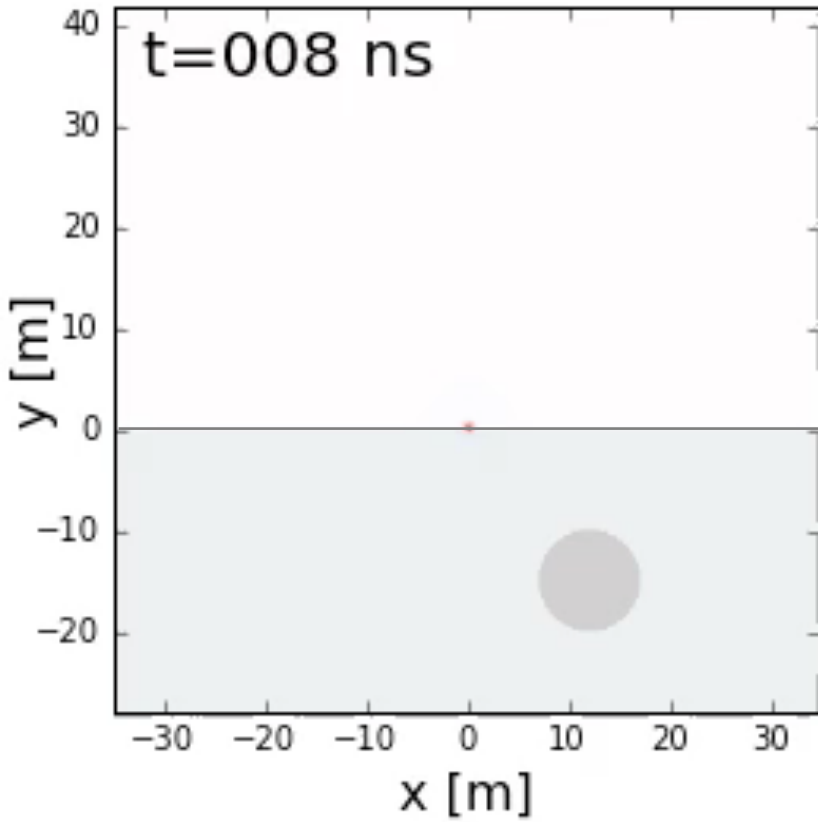


Gain Control



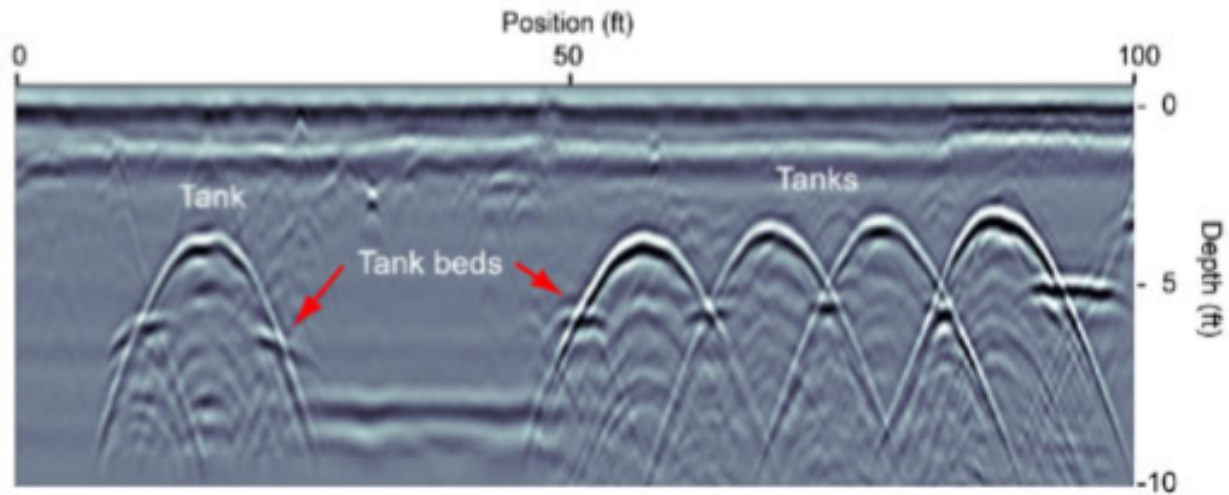
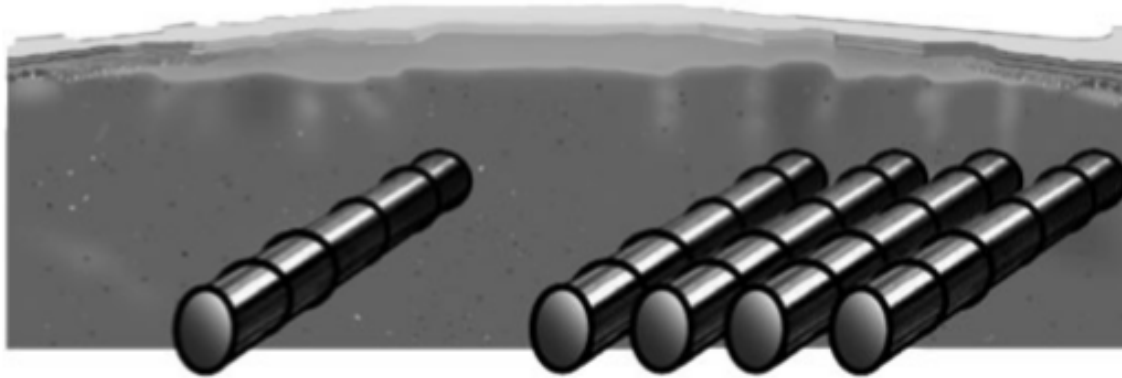
Radargrams

$$v = \frac{c}{\sqrt{\epsilon}}$$

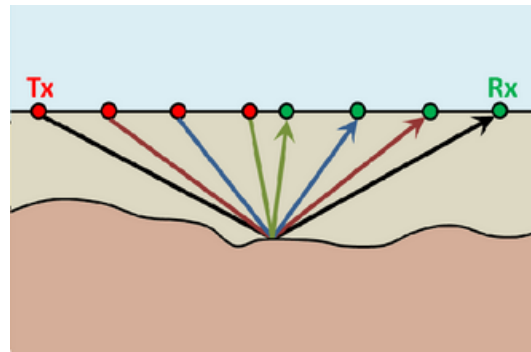


Hyperbola
slope $\sim 2/v$

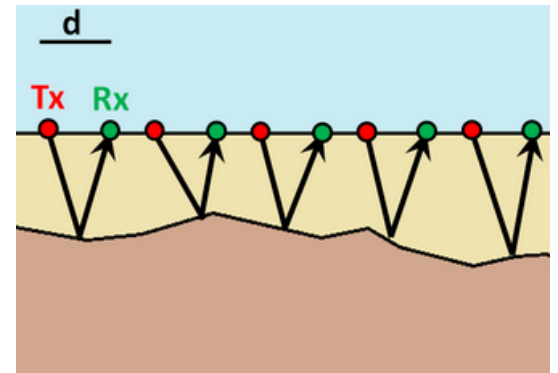
Radargrams



GPR systems



Common midpoint



Common offset

Outline

- Basic experiment
- Physical property
- Physics
- Data and Processing

- Questions?

- Field examples
- Driverless Vehicles
- Case History: Rock Glacier

Environmental Test Survey

Problem

- Characterize soil and identify potential aquifers

Why use GPR?

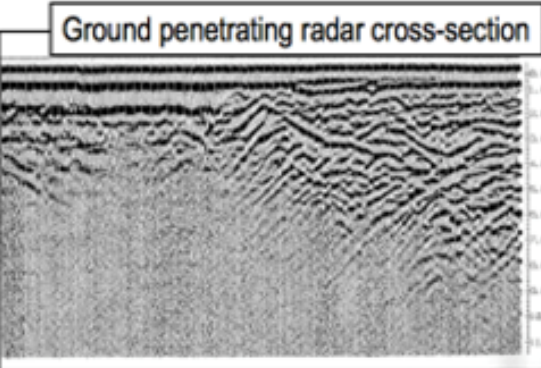
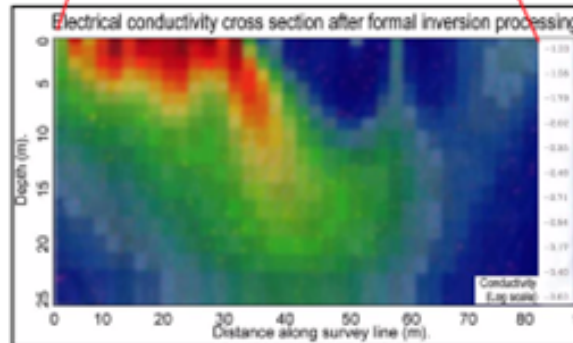
- Dielectric permittivity varies with
 - Water content
 - Lithologies

Survey and Data

- Zero offset data colocated with DC resistivity

Processing and Interpretation

- Attenuation of GPR signals on western side: higher conductivity
- Near surface structure from reflecting events



Locating Underground Storage Tanks

Problem

- Locate buried storage tanks and tank beds

Why use GPR?

- Conductive tanks, tank beds are strong reflectors

Survey and Data

- Zero offset data (250 MHz)

Processing and Interpretation

- Hyperbolic signatures from tanks
- Flat tank-bed reflectors
- 3D image constructed from radargrams

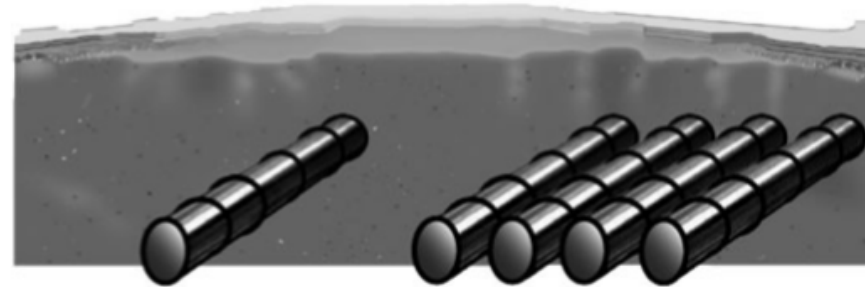


Fig. Geophysical problem

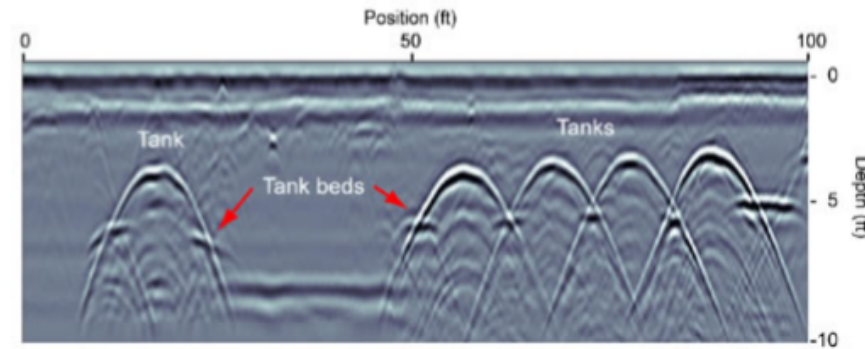


Fig. 2D Radargram profile perpendicular to storage tanks

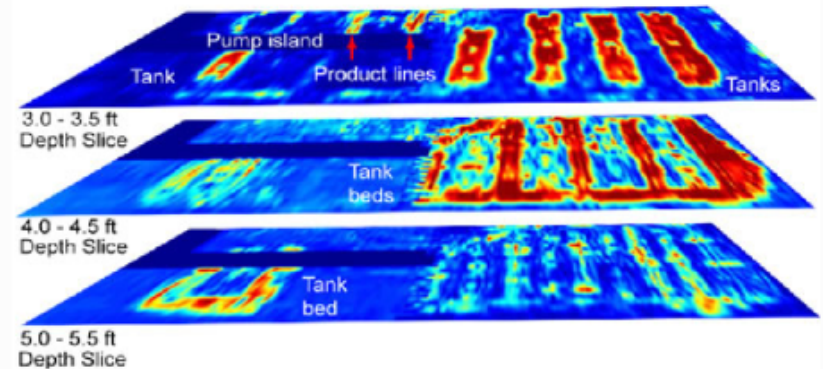


Fig. 129 3D interpolation from several GPR survey lines.

Mapping Peat Thickness

Problem

- Estimate peat thickness

Why use GPR?

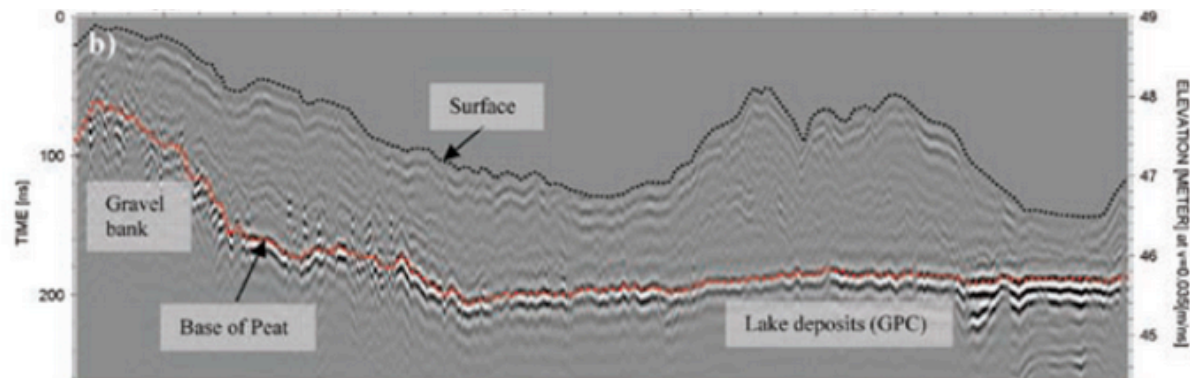
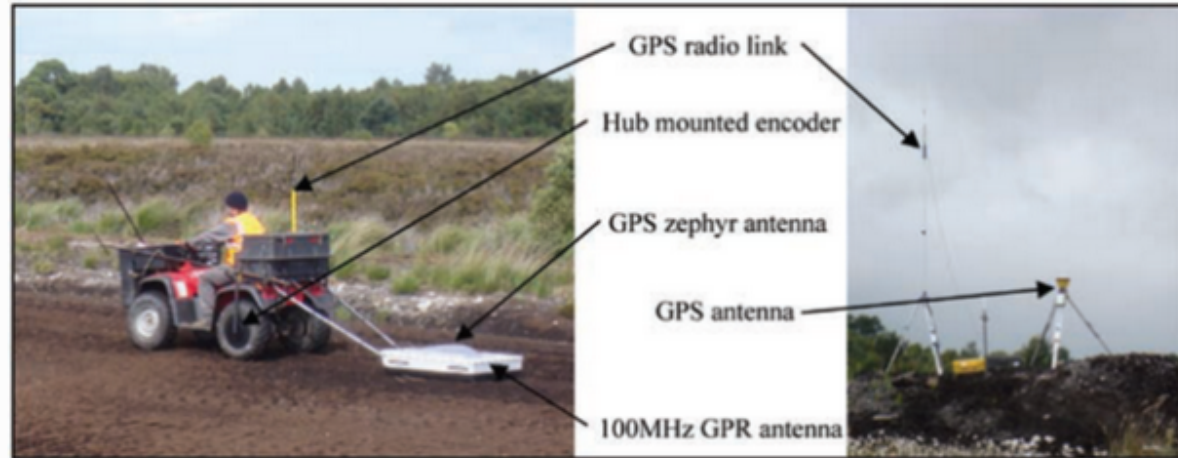
- Strong reflector at base of the peat

Survey and Data

- Zero offset data (100 MHz)
- Profiles every 60m
- LIDAR collected for local topography

Processing and Interpretation

- Arrival time to depth conversion
- Topography correction with LIDAR
- Peat layers up to 2m thick
- Additional reflectors indicate internal structure of peat



Subsurface Utility Mapping

Problem

- Locate iron-cased water pipes and PVC-cased gas lines at an intersection

Why use GPR?

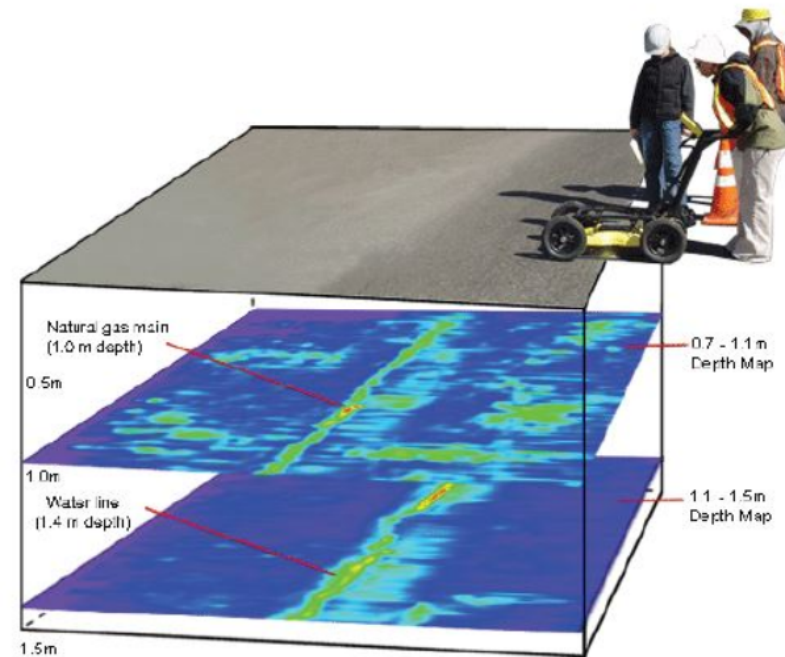
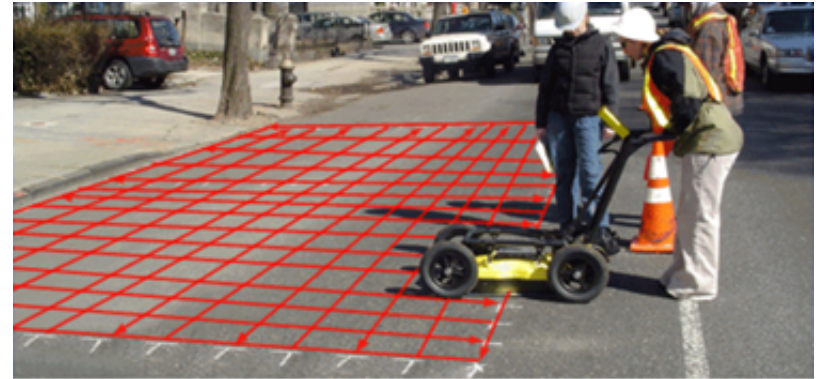
- Iron pipes very conductive → strong GPR reflector
- PVC v. low dielectric permittivity → GPR reflector

Survey and Data

- Zero offset data (250 MHz)
- 0.5m line spacing, 8m x 23m grid

Processing and Interpretation

- Arrival time to depth conversion
- Natural gas main at 1m depth
- Water line at 1.4m depth



Underground Potash mines

Problem

- Locate water/brine leaking into potash mine

Why use GPR?

- Potash has low relative permittivity (~ 5).
- Water/brine has high dielectric permittivity (~ 80).

Survey and Data

- Zero offset data along mine shaft

Processing and Interpretation

- Arrival time to depth conversion using velocity of 0.13 m/ns for anhydrites



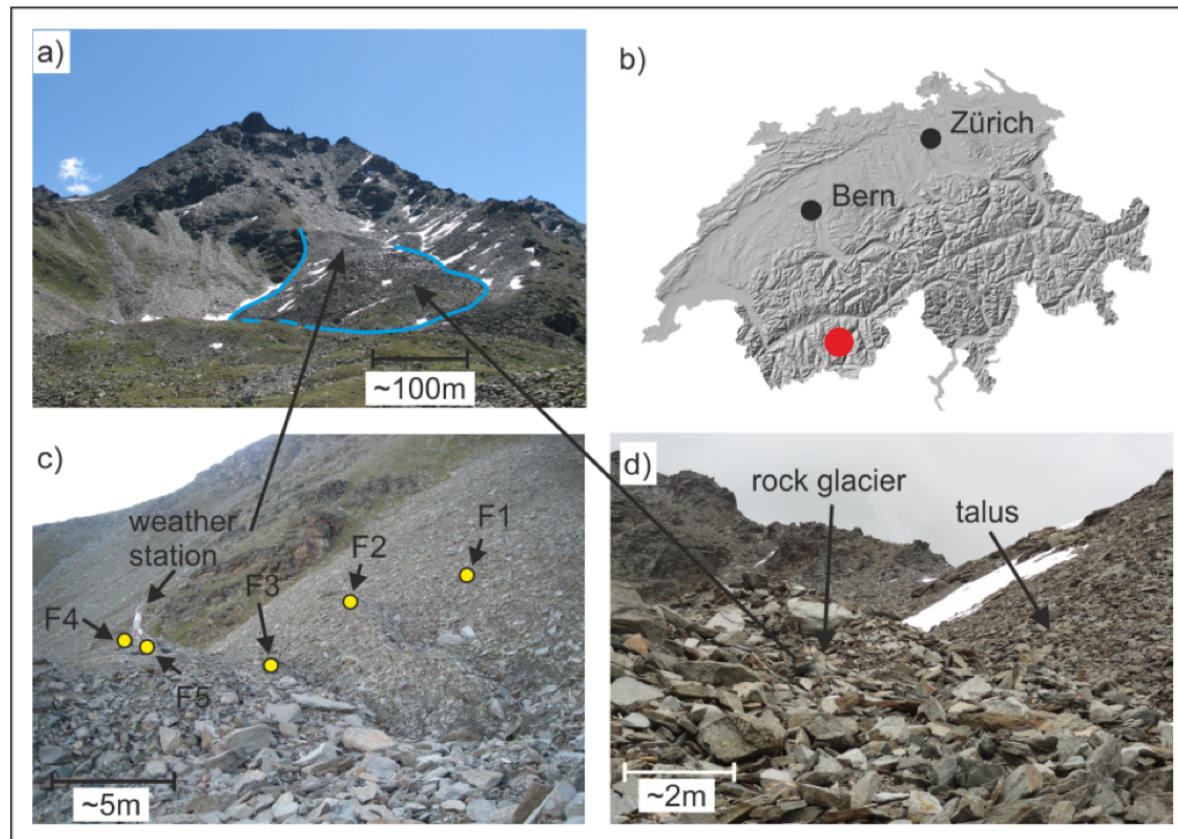
Fig. Inflow problems in a mine



Fig. GPR survey along ceiling of a mine shaft. Courtesy of: <https://www.sensoft.ca/>

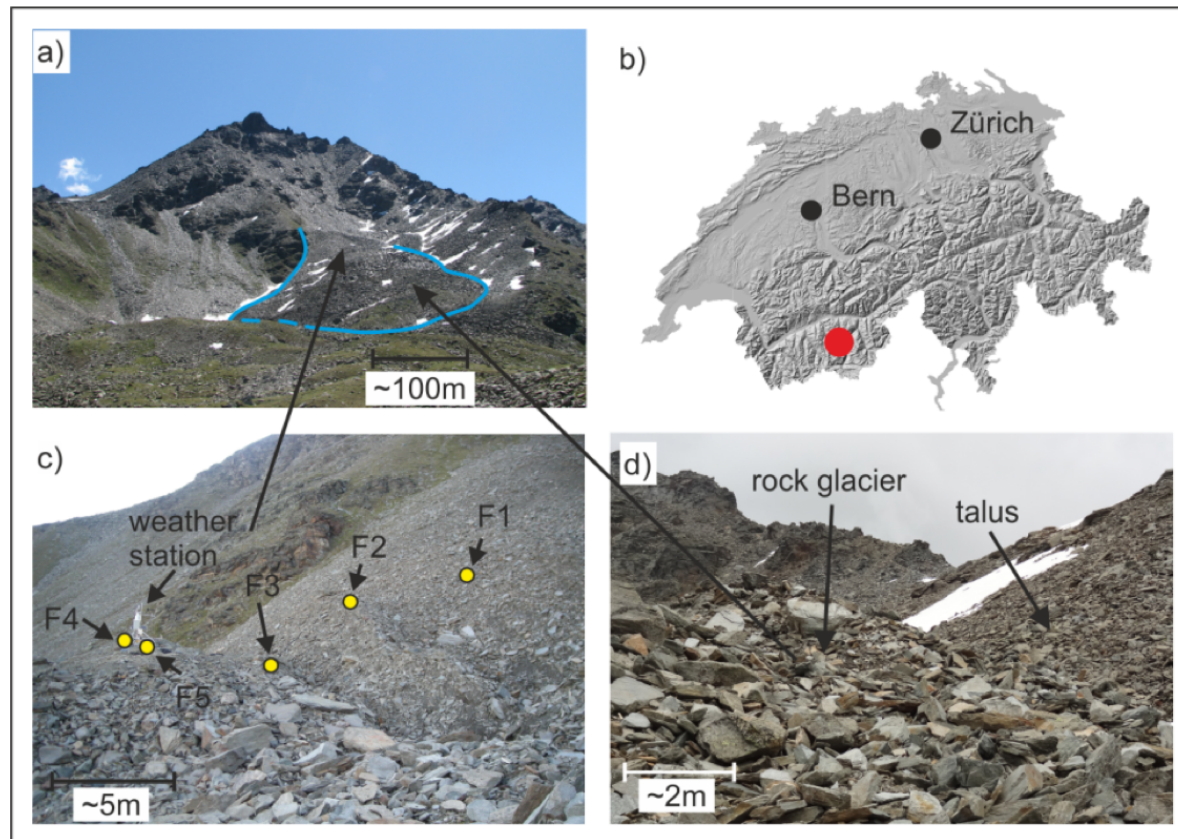
Case History: Furggwanghorn

Merz et al, 2015



Setup

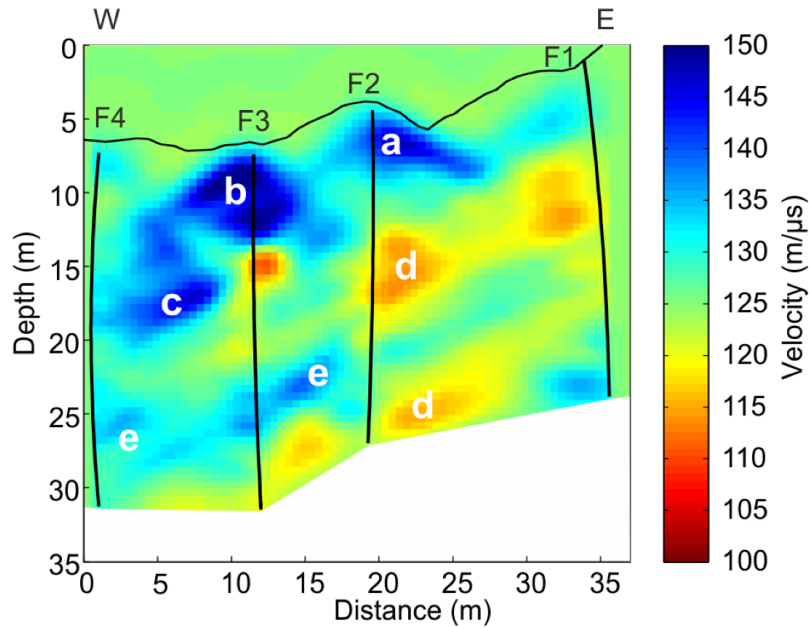
- Downslope movement shown to increase from 1.5 m/yr to 4.0 m/yr.
- Aim: characterize rock units and evolution of glacier
- Surface GPR: unsuccessful (too close to scatterers)
- Helicopter GPR used



Properties

$$v = \frac{c}{\sqrt{\epsilon}}$$

Velocity from cross well GPR

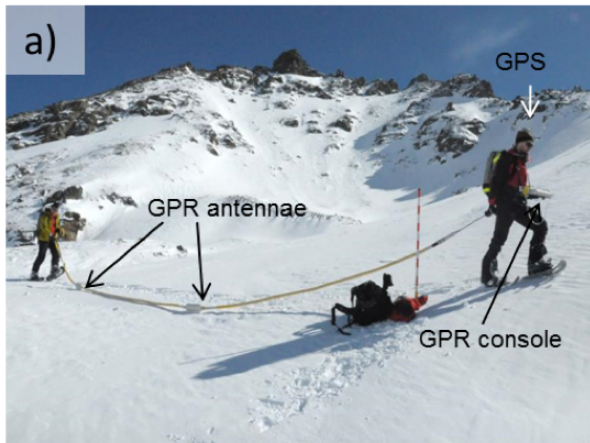


Material	Velocity (m/μs)
(a & b) Unconsolidated sediments	> 140
(c) Ice	> 140
(d) Ice + partial melt	110 - 130
(e) Compact debris	130 - 140
Saturated sediments	80 - 100
Bedrock	110 - 130

Survey

- Initial Ground-Based Survey
 - 2 systems
 - Frequencies: 25 MHz and 50 MHz
- Heli-GPR
 - Frequency: 60 MHz
 - Flight height: 15-20 m
 - Line separation ~15 m

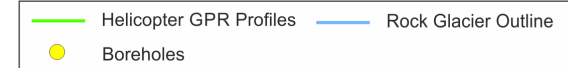
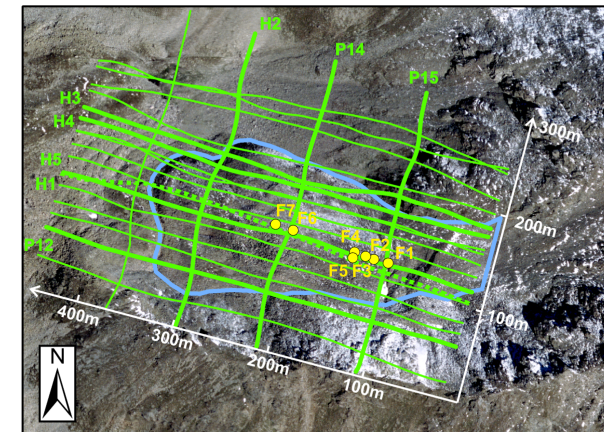
Ground-GPR



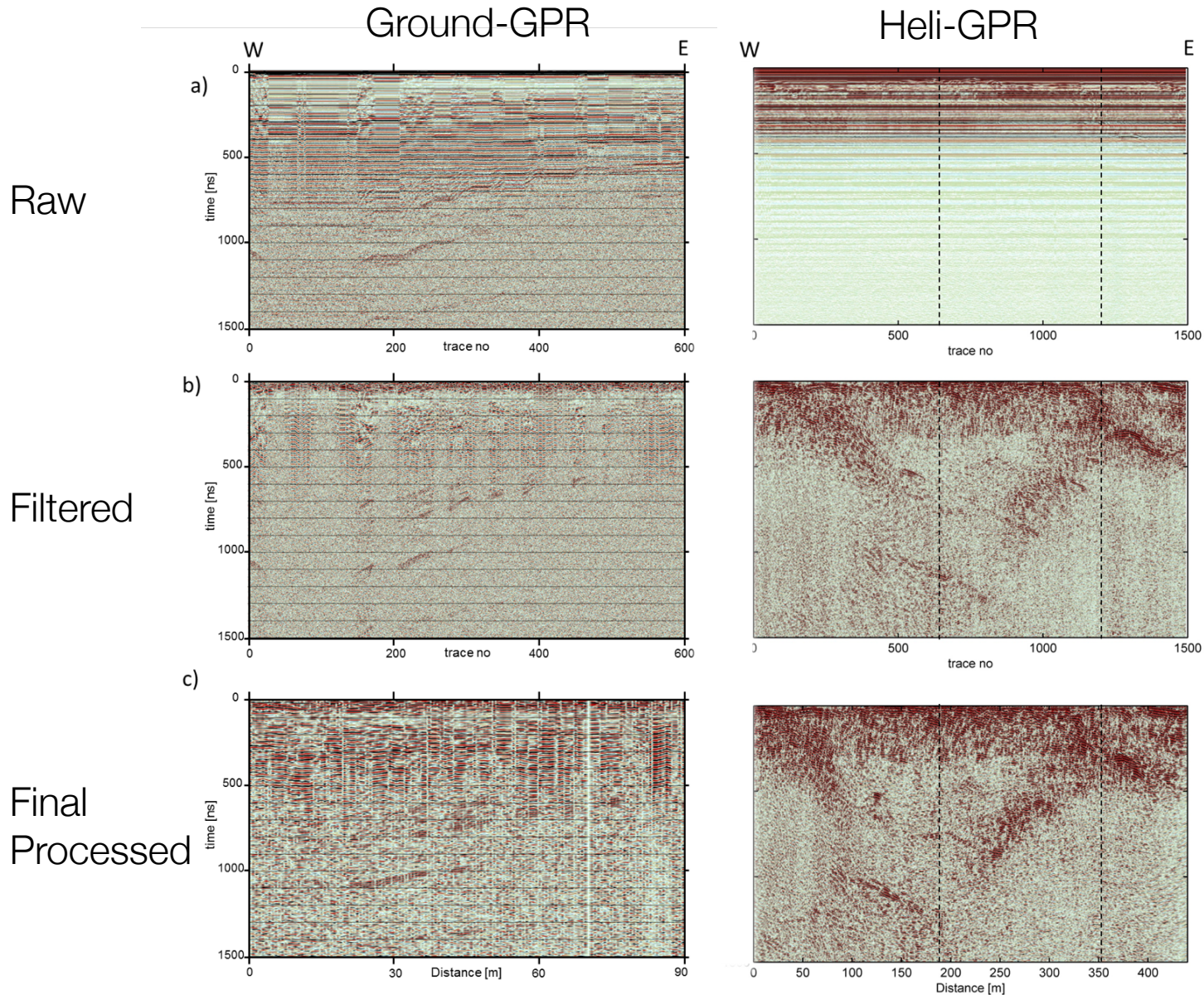
Heli-GPR



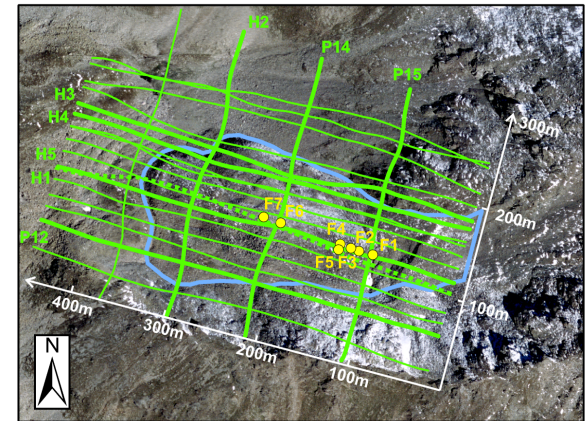
Survey lines



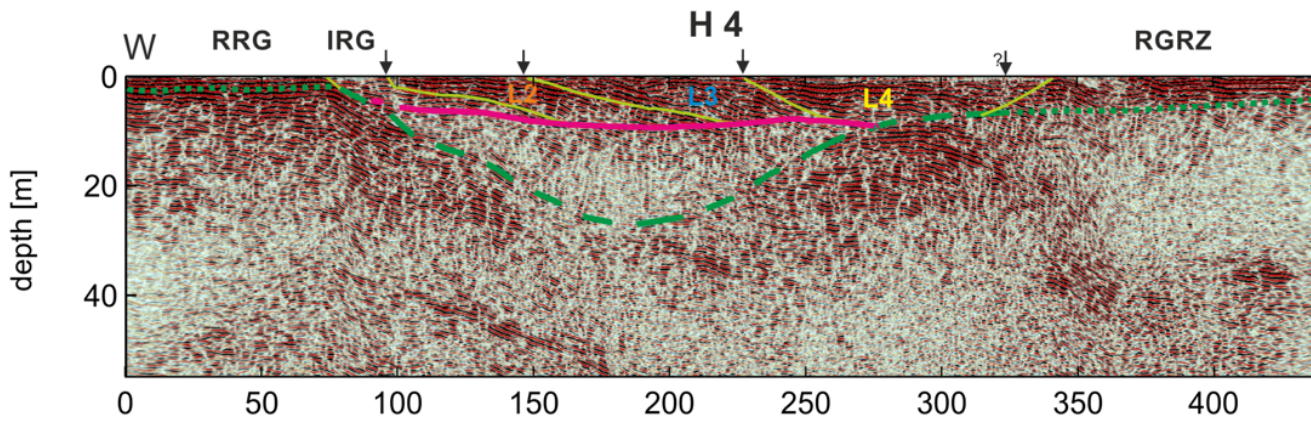
Data and Processing



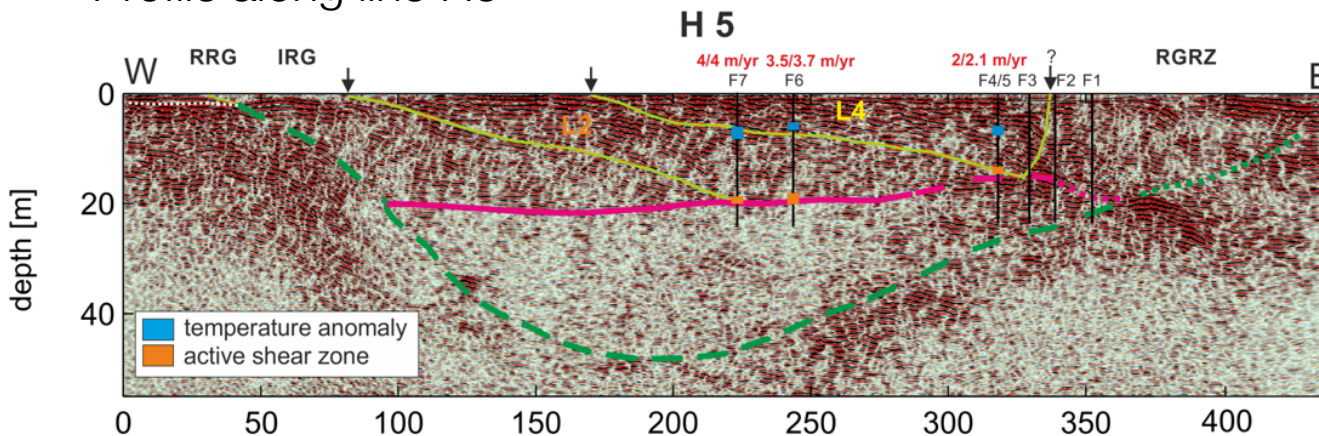
Interpretation



Profile along line H4



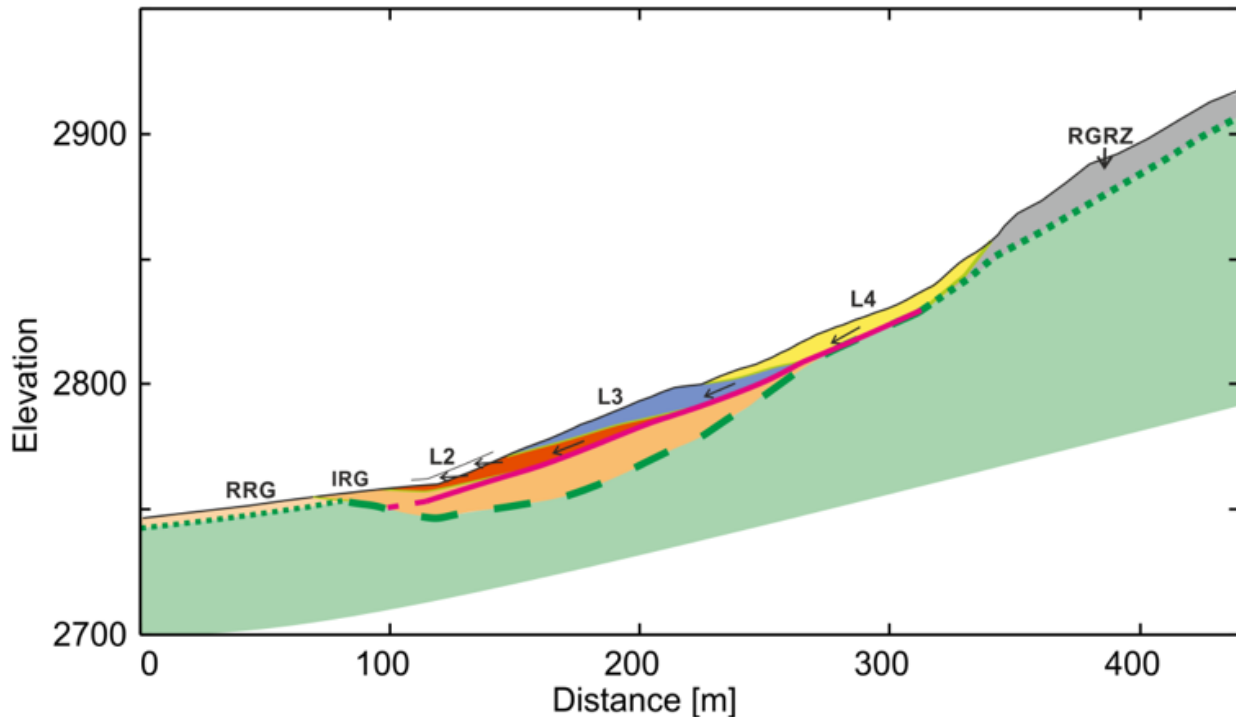
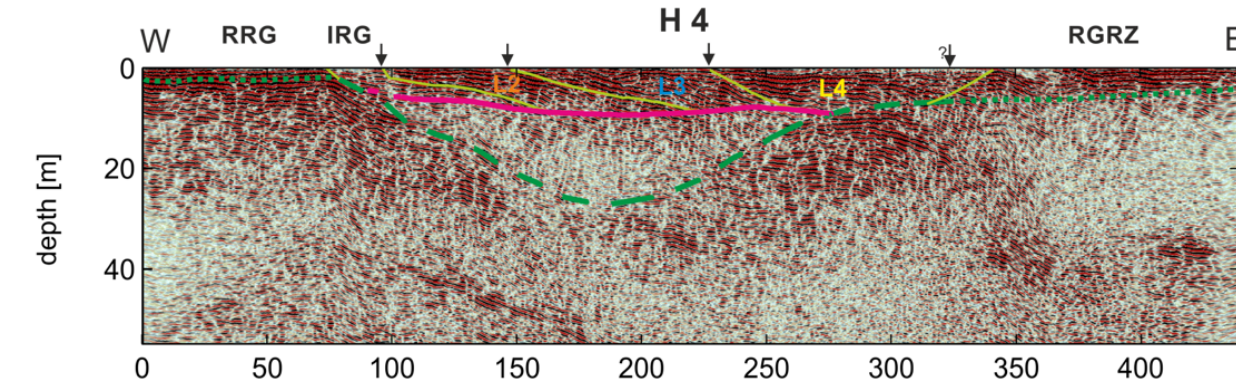
Profile along line H5



- - Bedrock surface
- Major shear zone between ice-rich and ice-poor regions
- Fault zone boundaries of rock lobes

Synthesis

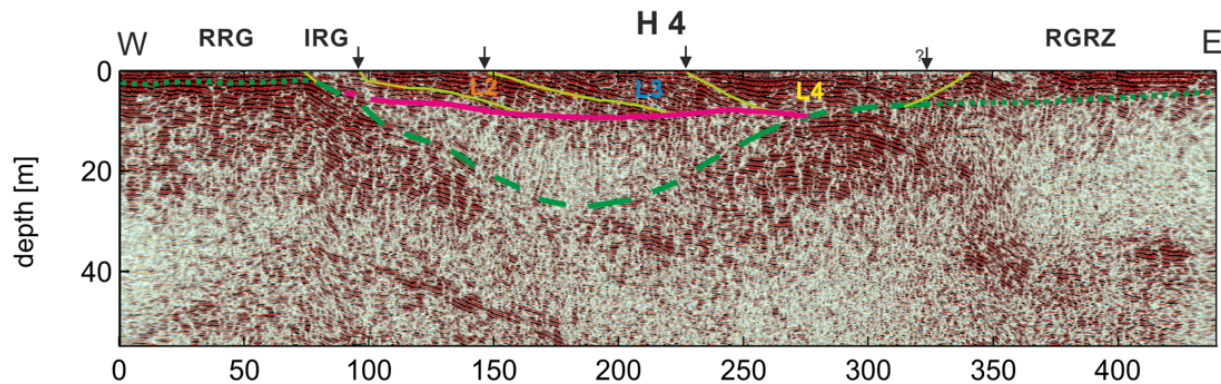
Final Structural and Kinematic Model



- Interpreted with thin-skinned tectonic model
- Major shear zone acts as a décollement
- Rock glacier lobes act as nappes
- Lobes appear to move down-slope
- Tectonic model applicable to other glaciers

Summary

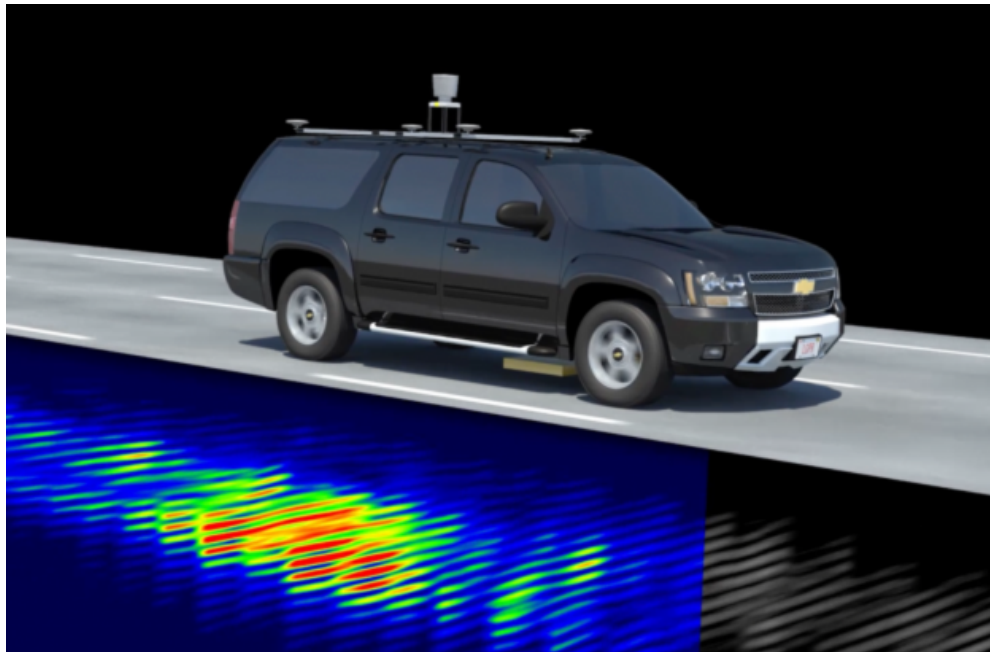
- Basic experiment
- Physical property
- Physics
- Data and Processing
- Case history: rock glacier



LGPR

Localizing GPR for driverless vehicles

MIT Lincoln Labs with GSSI



Journal of Field Robotics

Volume 33, Issue 1, pages 82-102, 27 MAY 2015 DOI: 10.1002/rob.21605

<http://onlinelibrary.wiley.com/doi/10.1002/rob.21605/full#rob21605-fig-0003>

Typical Sensors

Sensors

- GPS
- Lidar
- Camera
- Work fine in good weather

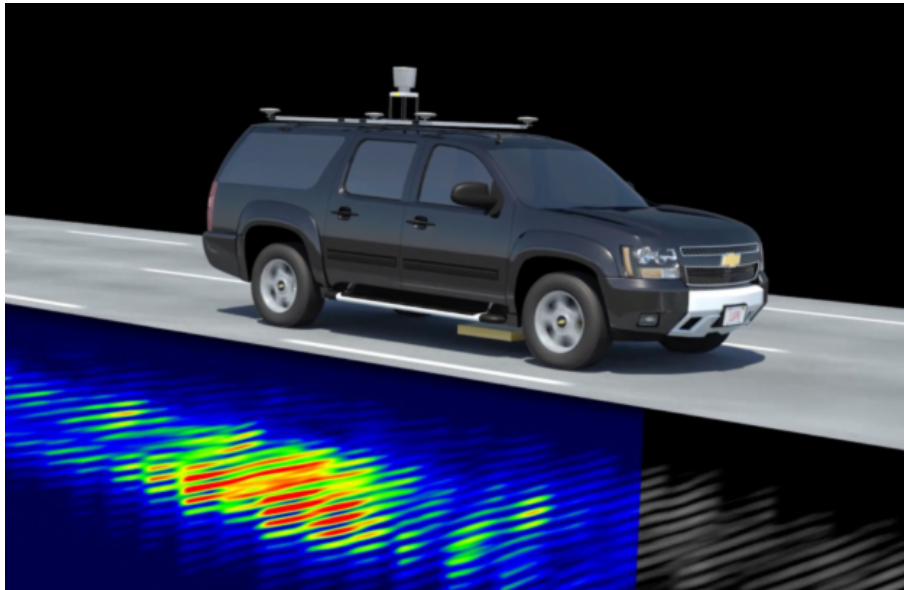
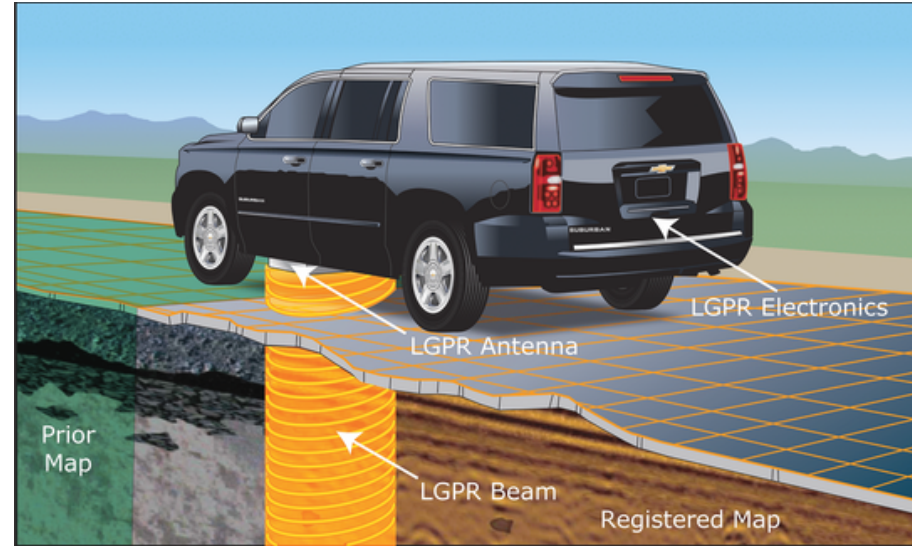
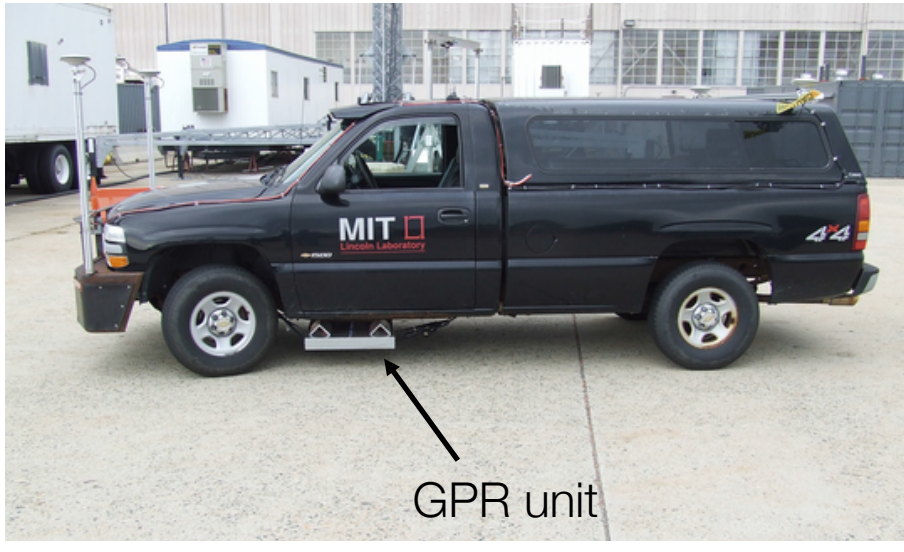
What happens when

- Bad weather
 - rain, snow, sleet, fog, ...
- Changes
 - signs, road stripes, vegetation, ...

Need additional sensor data

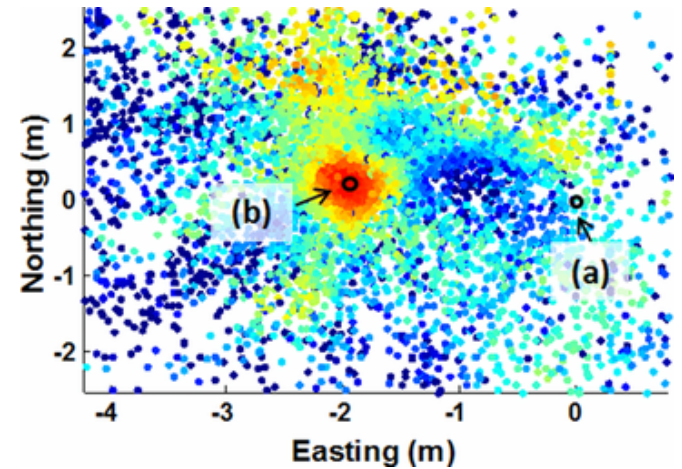
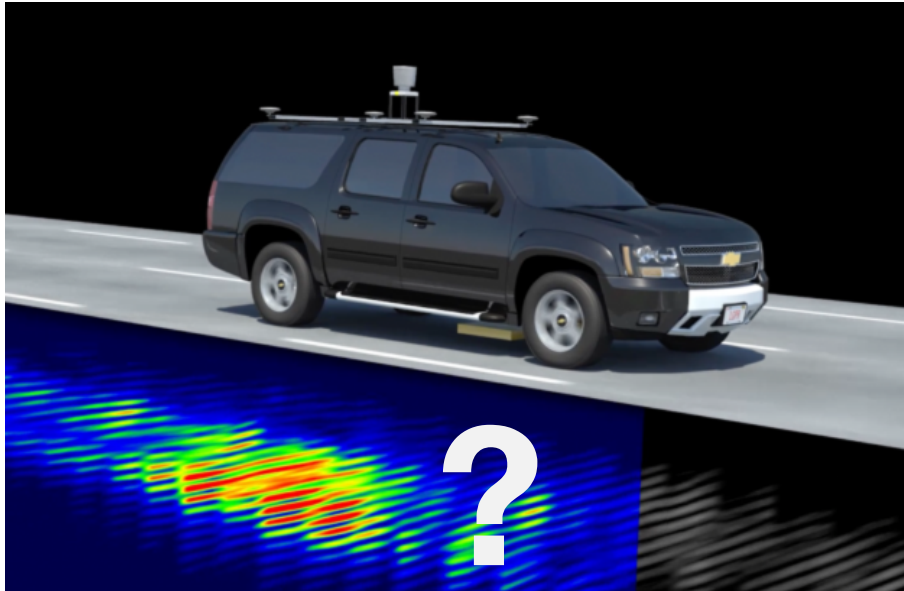


Localizing Ground Penetrating Radar



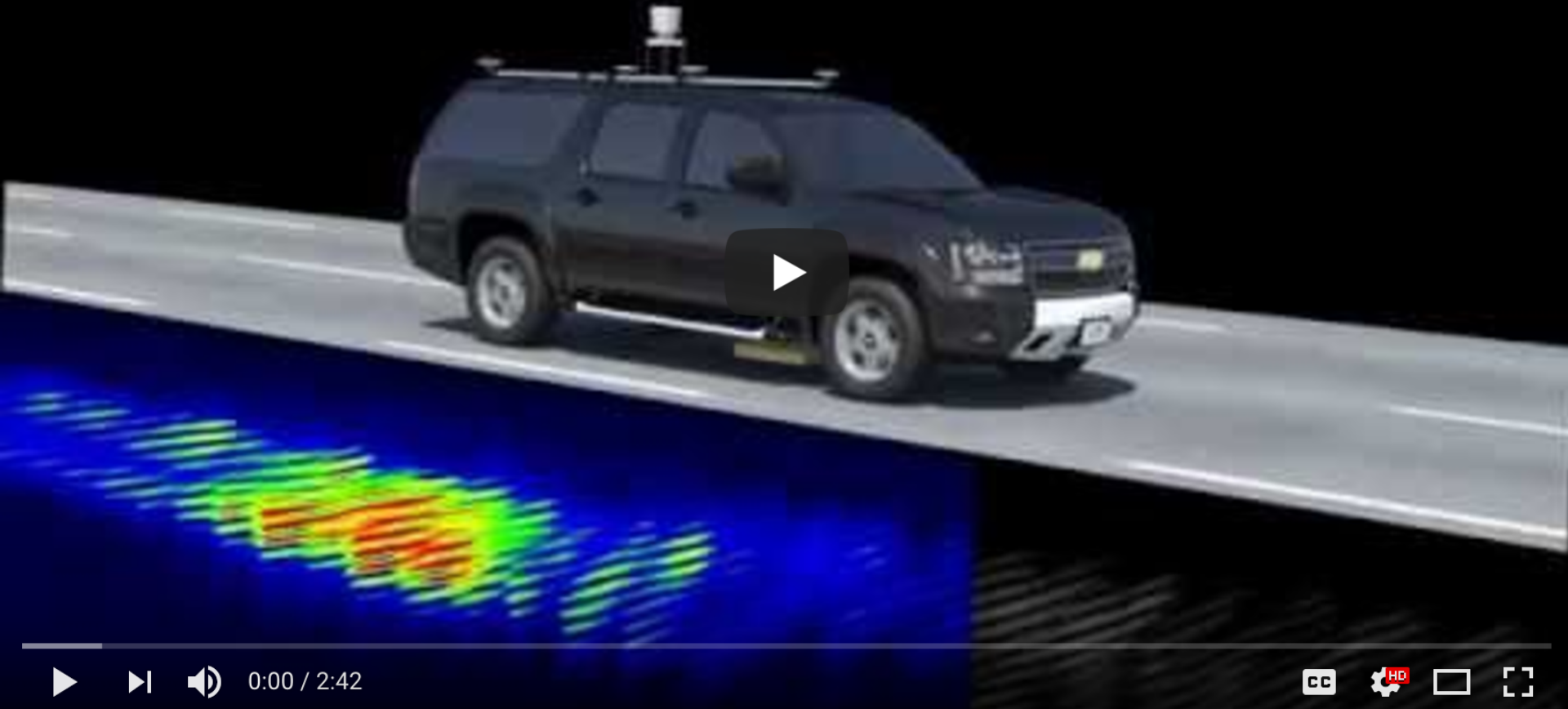
- Collect reference GPR data on clear day
- Store reference data set

Localizing Ground Penetrating Radar



Cross correlate real-time data with reference data to find location

LGPR complements existing technology to achieve the vision of safe autonomous vehicles.



<https://youtu.be/rZq5FMwl8D4?t=20s>

End of GPR

