SAPIENZA
UNIVERSITÀ DI ROMA

# Environmental geophysics


**Giorgio De Donno**


## *4. RADAR methods*

*GPR data processing*


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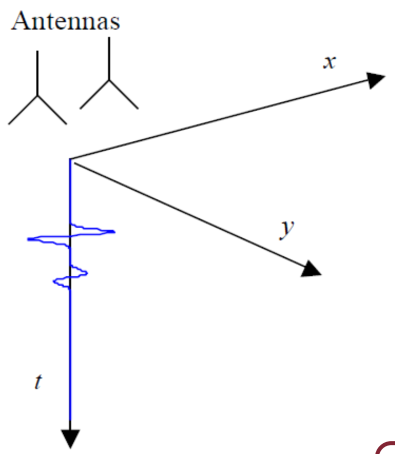
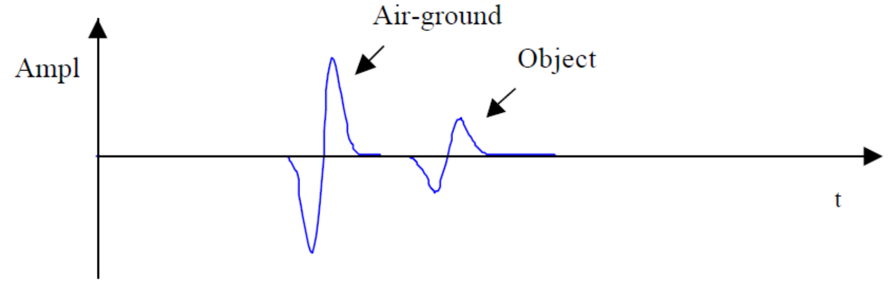
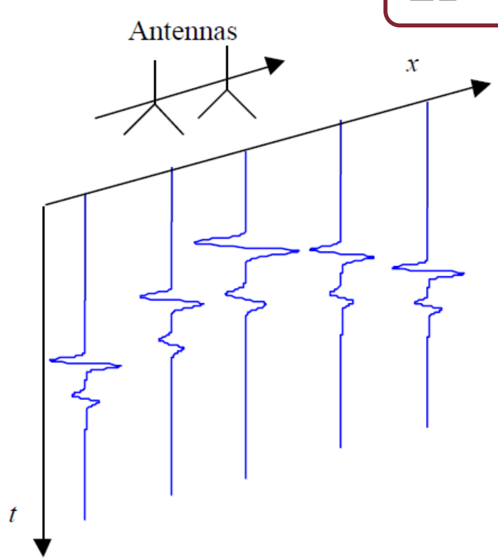
# GPR data processing

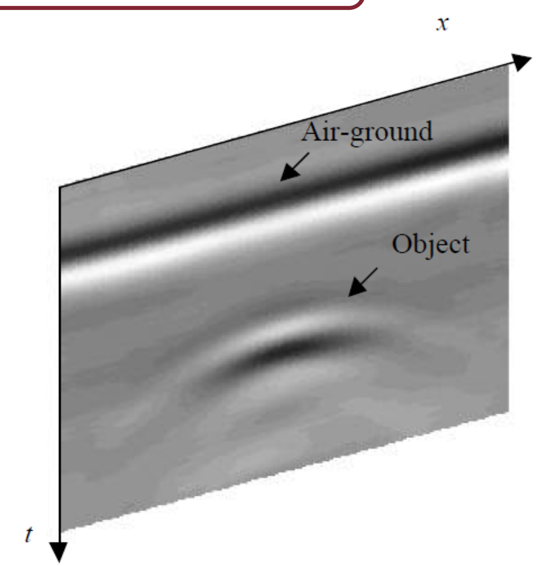



## 1D – A-scan - Trace



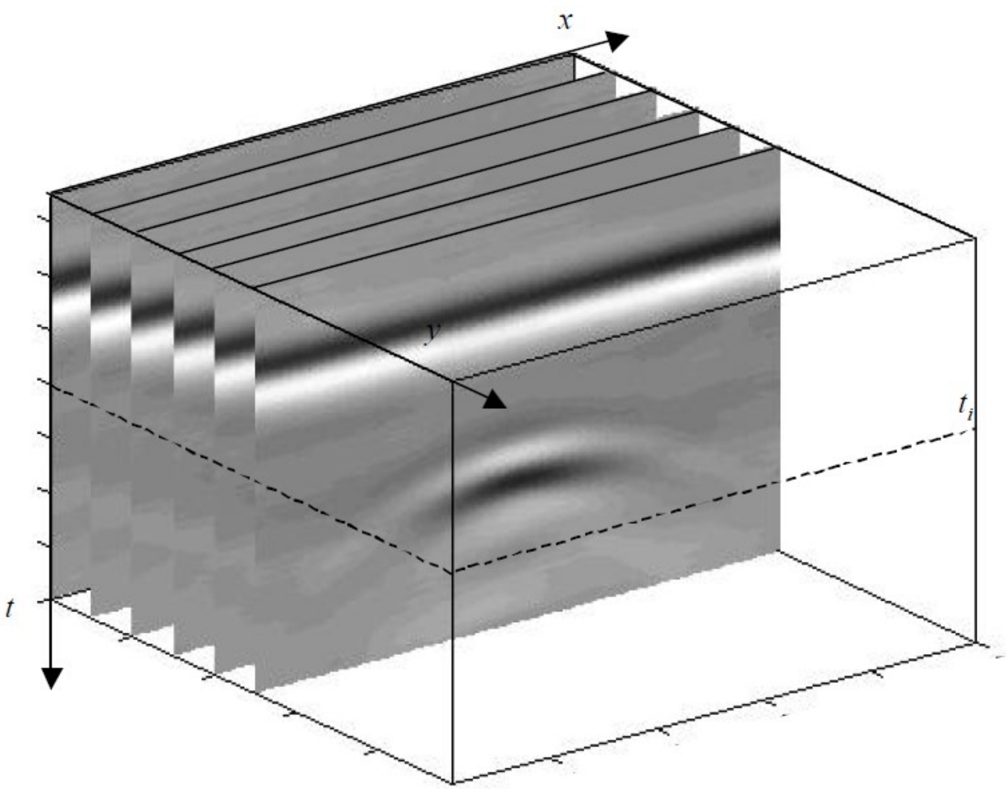

## 2D – B-scan -Radargram



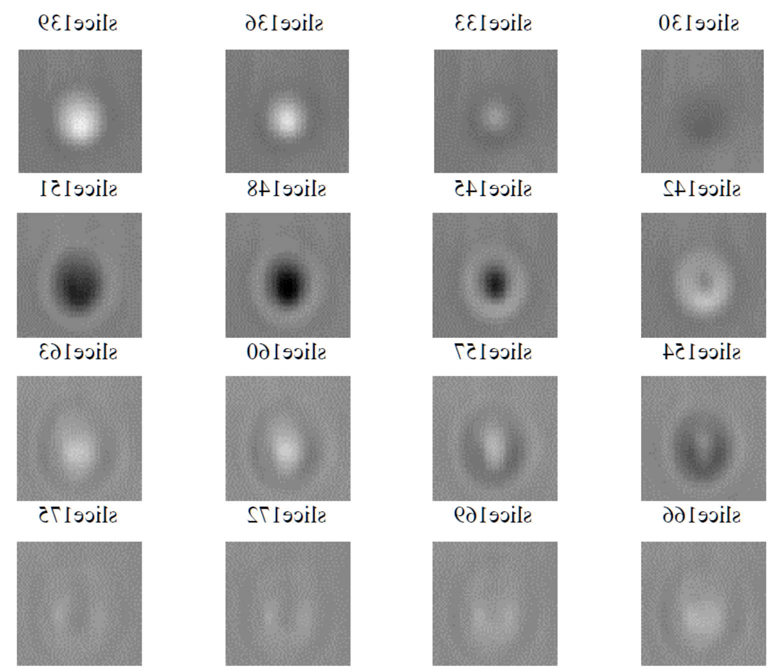



# GPR data processing

**3D – C-scan - Volume**




**3D – C-scan – Horizontal slices**



# GPR data processing

**The principal goal of data processing for a conventional GPR survey is to get a final image which can be as close as possible to the reality: we can get an accurate assessment of type, shape and spatial location (x,y,z) of the anomalies.**

The main purposes of data processing are to:

- **remove system-induced irregularities**
  - ✓zero-time correction
- **increase the signal-to-noise ratio**
  - ✓filtering (background removal, dewow)
  - ✓gain

} **ALWAYS APPLIED**

- ***correct geometrical effects***
  - ✓*migration*

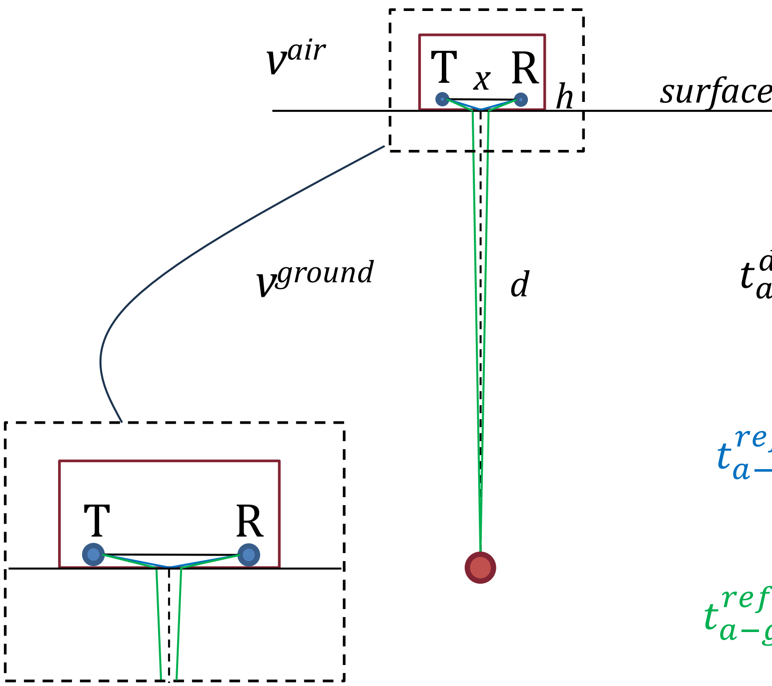
} **ONLY FOR DIFFRACTIONS (i.e. scattering of small targets)**

- **velocity estimation and time-to-depth conversion**

} **ALWAYS APPLIED**

# GPR data processing – Zero-time correction

Zero-time correction is the process of **controlling the vertical position of the surface reflection that is the time where the EM pulse enters the subsurface.**
A proper zero-time adjustment is crucial for accurate depth determination, especially for cases where near-surface features are targeted




$x$ = offset (~ few cm)
$h$ = antenna height (~ few mm)
$r$ = target depth (~ tens cm/few m)

**hp.** $h << x << d$

$$t_{air}^{dir} = \frac{x}{v^{air}}$$

$h << x$

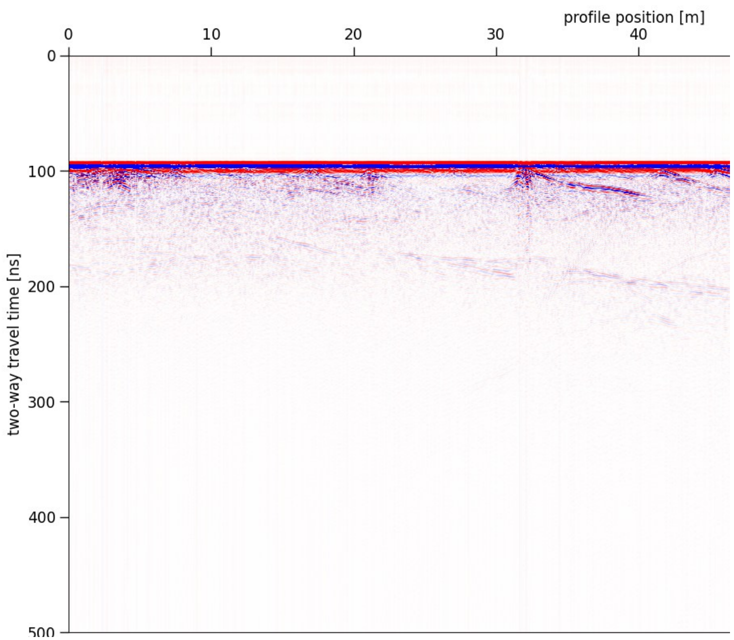
$$t_{a-g}^{refl} = 2\frac{\sqrt{\left(\frac{x}{2}\right)^2 + h^2}}{v^{air}} = \frac{\sqrt{x^2 + (2h)^2}}{v^{air}} \cong \frac{x}{v^{air}} = \boxed{t_{air}^{dir}}$$

$$t_{a-g}^{refr+scatt} \cong \mathrm{d}t^{air} + \frac{2d}{v^{ground}} \cong t_{a-g}^{refl} + t_{ground}^{scatt} = \boxed{t_{air}^{dir}} + t_{ground}^{scatt}$$

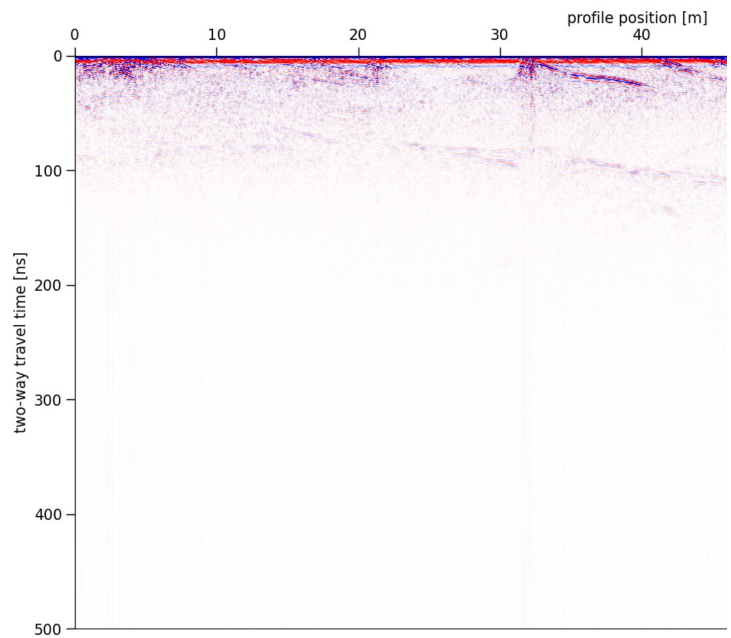
Zero-time correction

Zero-time correction is the process of **controlling the vertical position of the surface reflection that is the time where the EM pulse enters the subsurface.**
A proper zero-time adjustment is crucial for accurate depth determination, especially for cases where near-surface features are targeted

**Raw data**



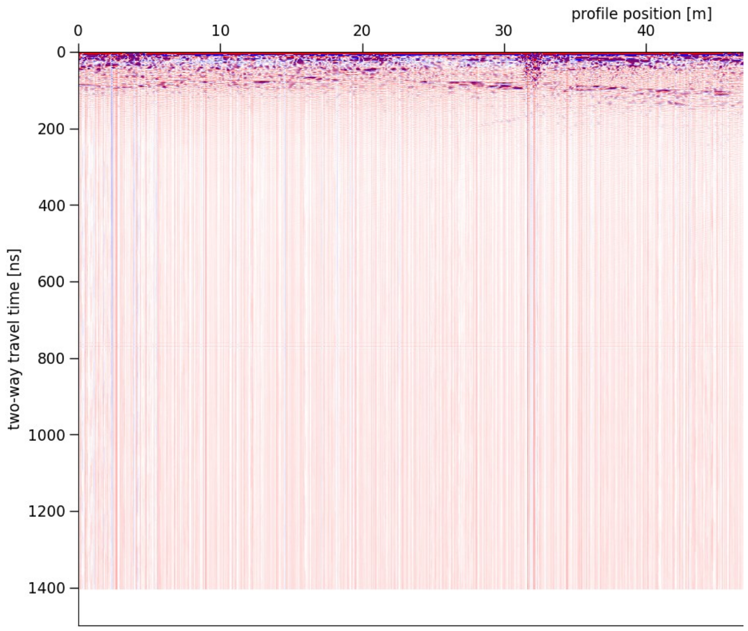

**Zero-time corrected data**



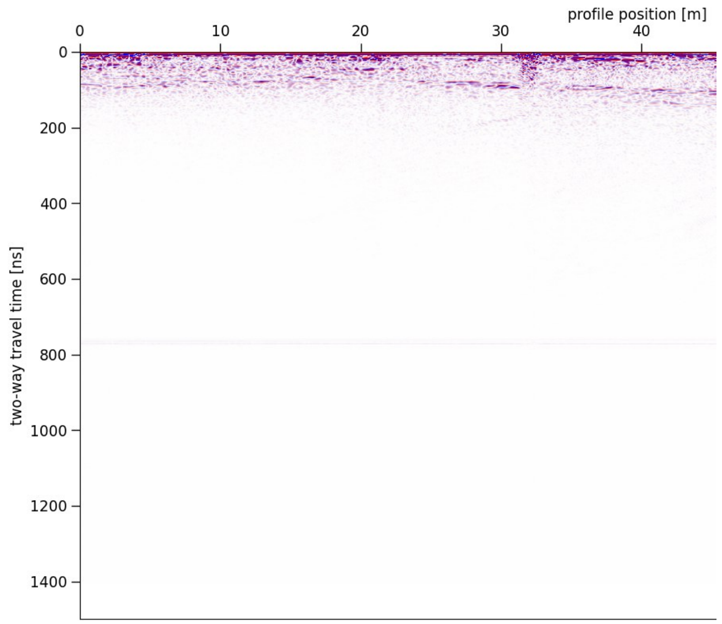
# GPR processing – Dewow

Dewow is typically used to filter out low-frequency noise due to EM induction
To this end we apply a **running median temporal filter** in a fixed window:

**Raw data**



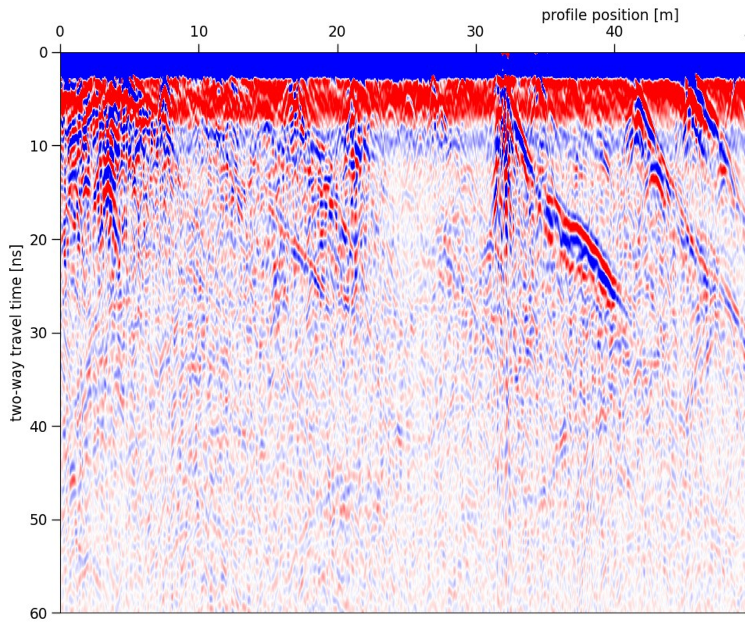

**Dewowed data**



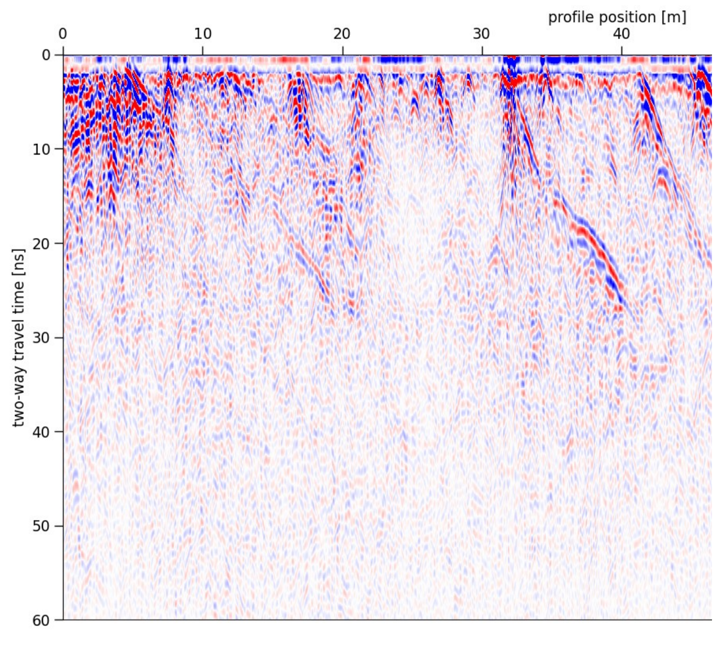
Background Removal (BR) is typically used to filter out residual air waves. For applying BR, we calculate the mean of all traces in a fixed window (on throughout all the radargram) and subtracts it from each trace.

$$A_{i,j}^{BR} = A_{i,j}^{RAW} - \frac{1}{N}\sum_{i=1}^{N} A_{i,j}^{RAW}$$

**Raw data**



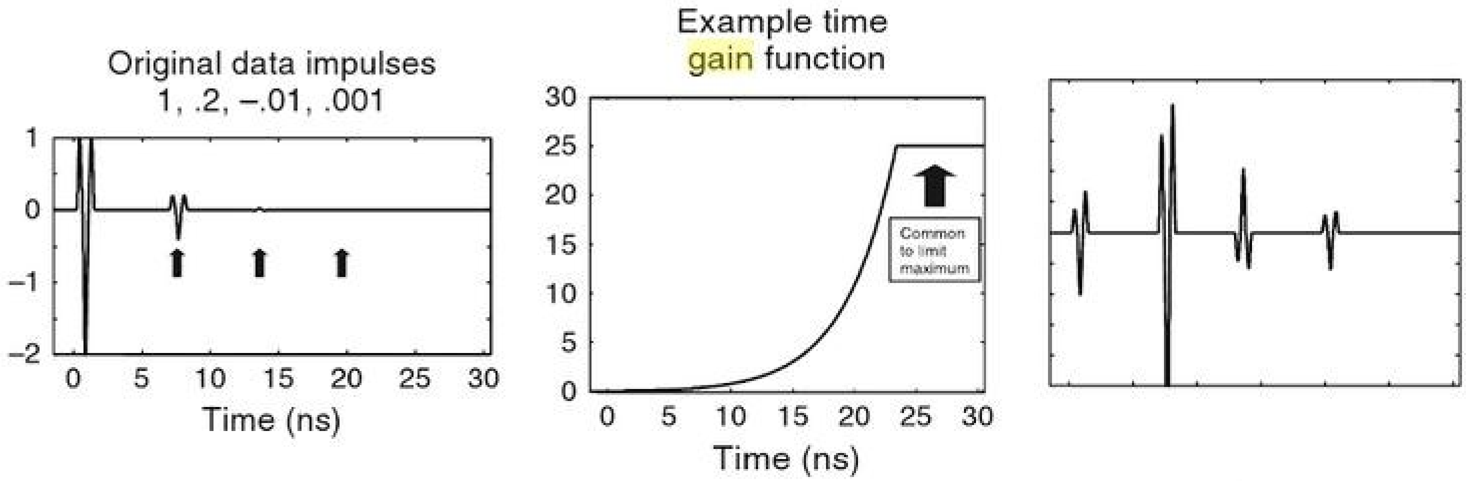

**BR corrected data**



# GPR data processing – Time-varying gain

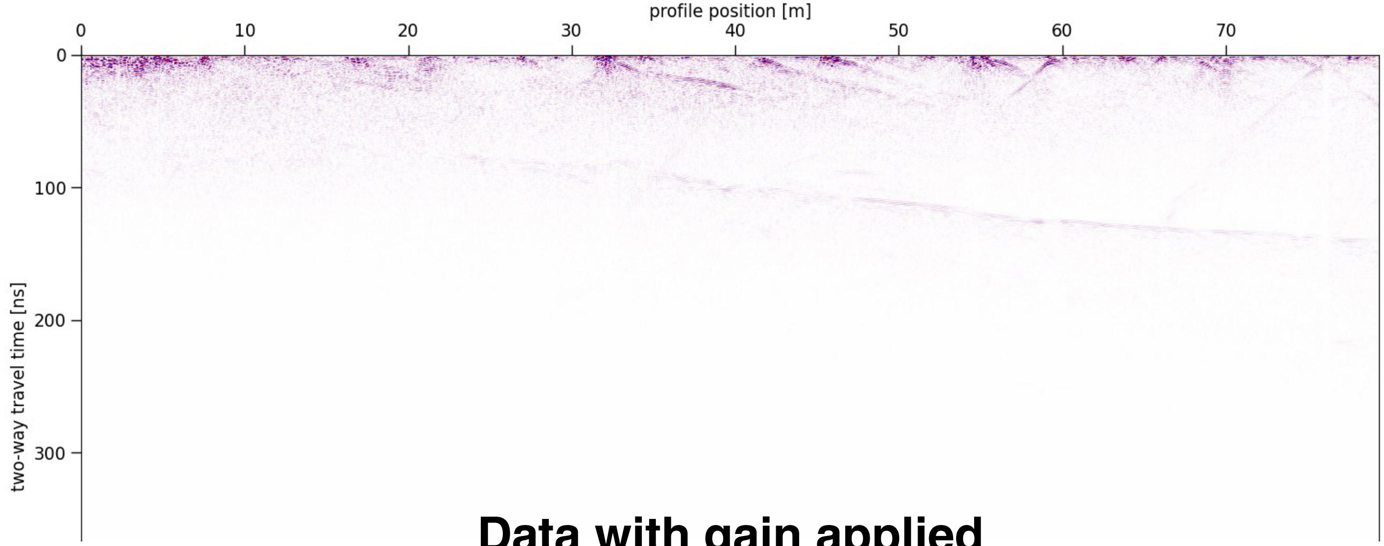
EM waves are rapidly attenuated as they propagate through the different layers. The responses from targets at greater depths can therefore be much smaller in amplitude compared to reflection waves from shallow depths. For a clear display for both responses, time varying gain functions should be applied to the data.

The application of the time-dependent gain functions is expected to compensate for the rapid amplitude decay of EM signals from deeper depths

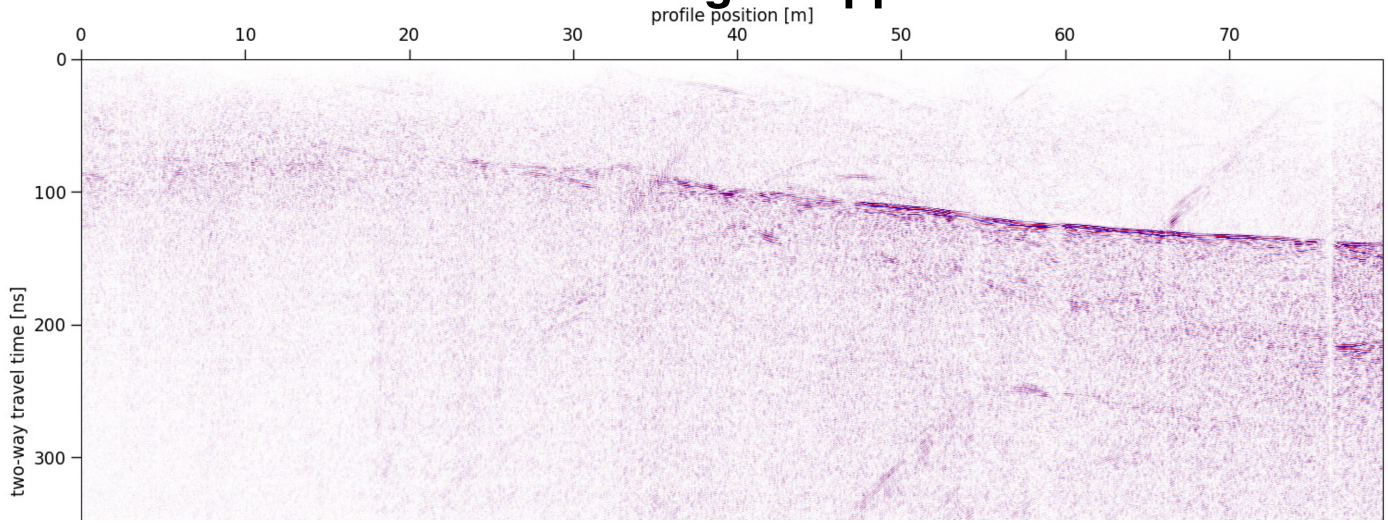


# GPR data processing – Time-varying gain

## Raw data




## Data with gain applied



# GPR data processing – Time-to-depth conversion

For the time-to-depth conversion we need to estimate the EM wave velocity. There are several choices to get information about the velocities of the investigated lithotypes/materials.

- from the curvature of diffraction hyperbola **(fast method)**
- from borehole measurement of the dielectric constant (**accurate method**)
- from literature (**first-approximation method**)

**Once the velocity is known, we can perform the time-to-depth conversion to achieve the final GPR image**

**FINAL PLOTS**

**Radargram**
**(vertcal section distance vs. depth)**

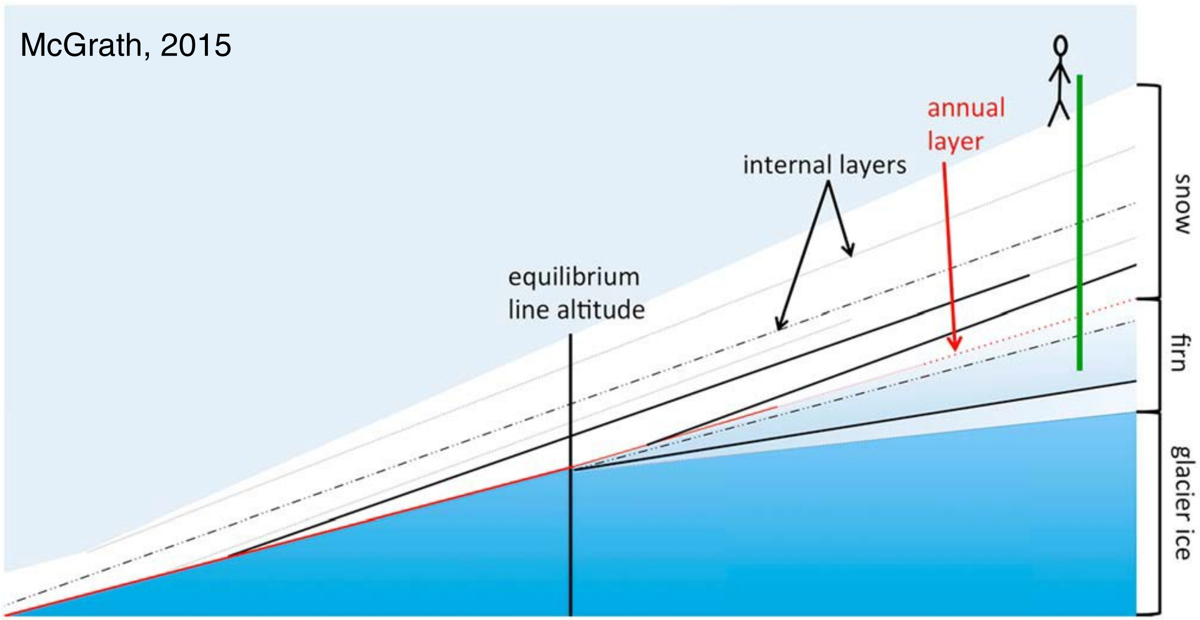
**Depth-slice**
**(horizontal section at a fixed depth)**

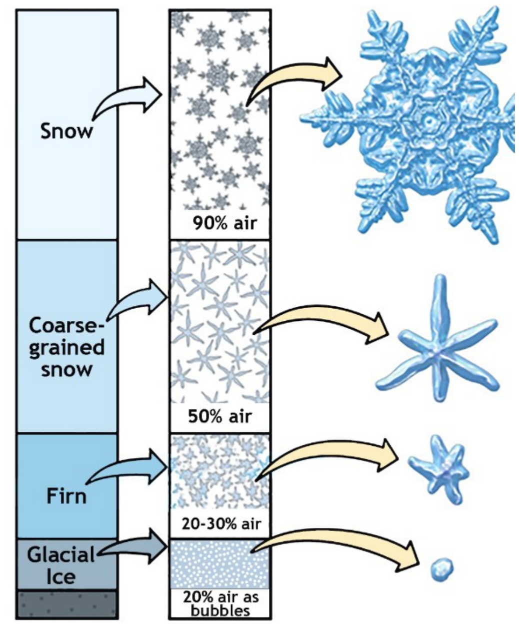
$$z_i = v_k \frac{t_i}{2}$$

$i = 1,2, \dots, P$ Number of time samples

$k = 1, 2, \dots, S$ Number of layers

## Ex. 2 GPR for monitoring snow/firn thicknesses



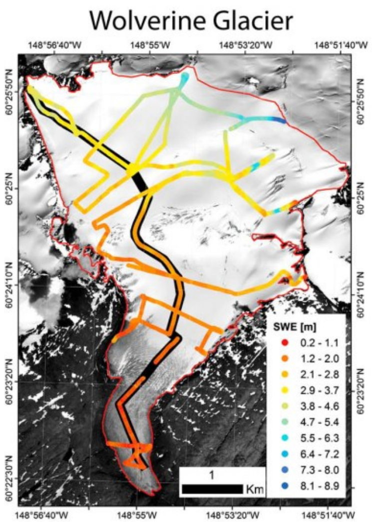




Credit: Department of Geography and Environmental Science/Hunter College

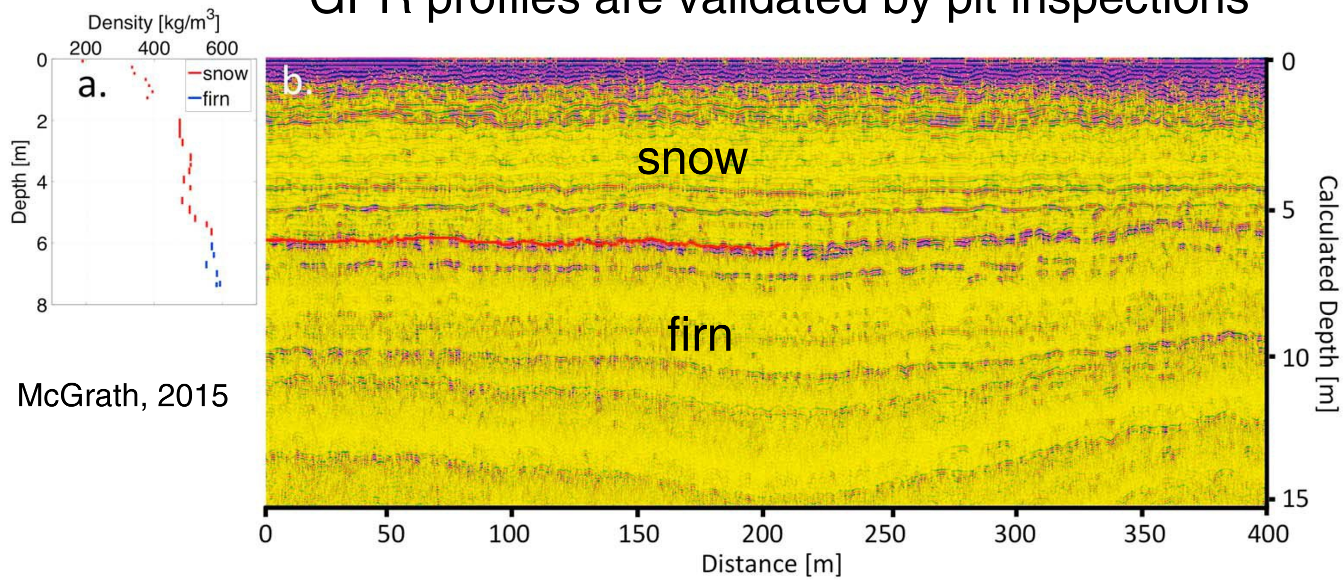
The equilibrium-line altitude (ELA) marks the area or zone on a glacier where accumulation is balanced by ablation over a 1-year period. The ELA is sensitive to several meteorological factors, such as variations in winter precipitation, summer temperature, and wind transport of dry snow. When the annual net mass balance is negative, the ELA rises, and when the annual net mass balance is positive, the ELA falls.

Fluctuations in the ELA provide an important indicator of glacier response to climate change.

## Ex. 2 GPR for monitoring snow/firn thicknesses




GPR profiles are validated by pit inspections




McGrath, 2015

The relative permittivity (dielectric constant) $\varepsilon_r$ is linked to the density of the snow/firn by an empirical equation (Robin et al. 1969, Kovacs et al. 1995):

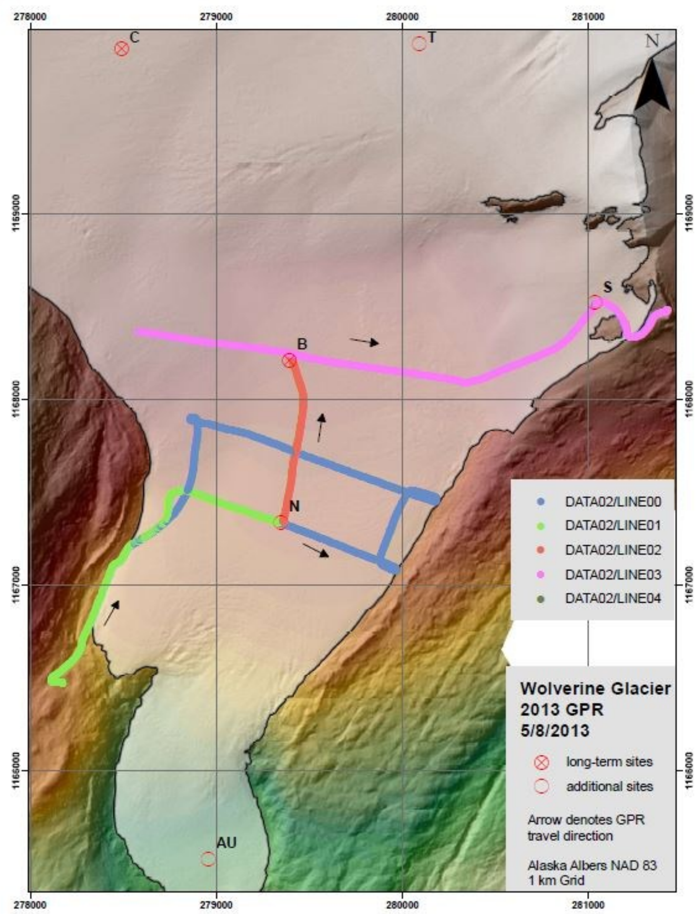
$$\varepsilon_r = (1 + 0.000845\,\delta)^2$$

| Type | Density (kg/m$^3$) |
| --- | --- |
| Fresh snow | 50 - 100 |
| Old snow | 250 - 450 |
| Wet snow | 300 - 500 |
| Firn | 500 - 830 |
| Ice | 830-910 |

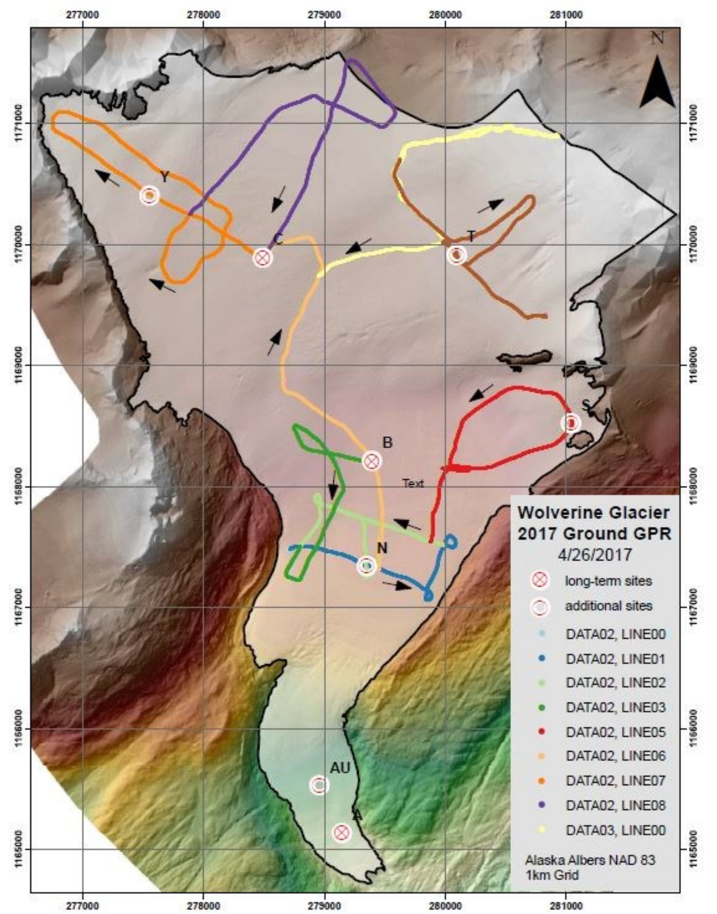
# GPR examples – Glaciers

## Ex. 1 GPR for monitoring snow/firn thicknesses in Alaska (USA)

2013 GPR profiles



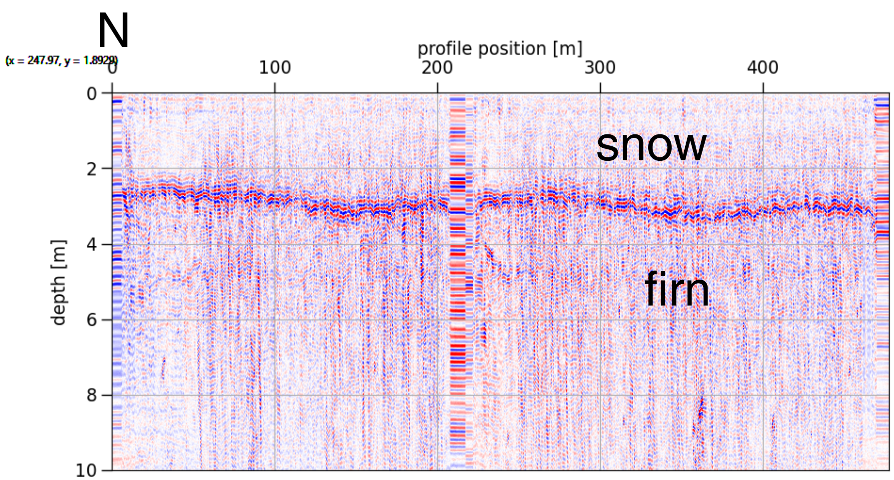

2017 GPR profiles



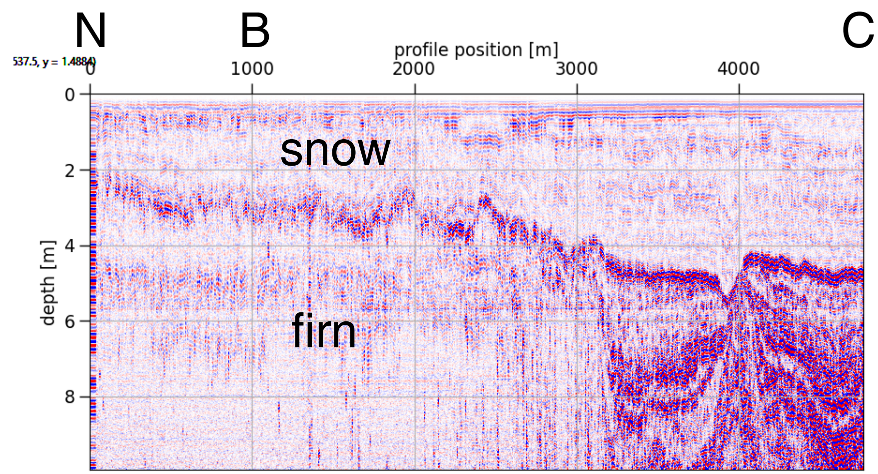
# GPR examples – Glaciers

## Ex. 1 GPR for monitoring snow/firn thicknesses in Alaska (USA)

2013 GPR profiles

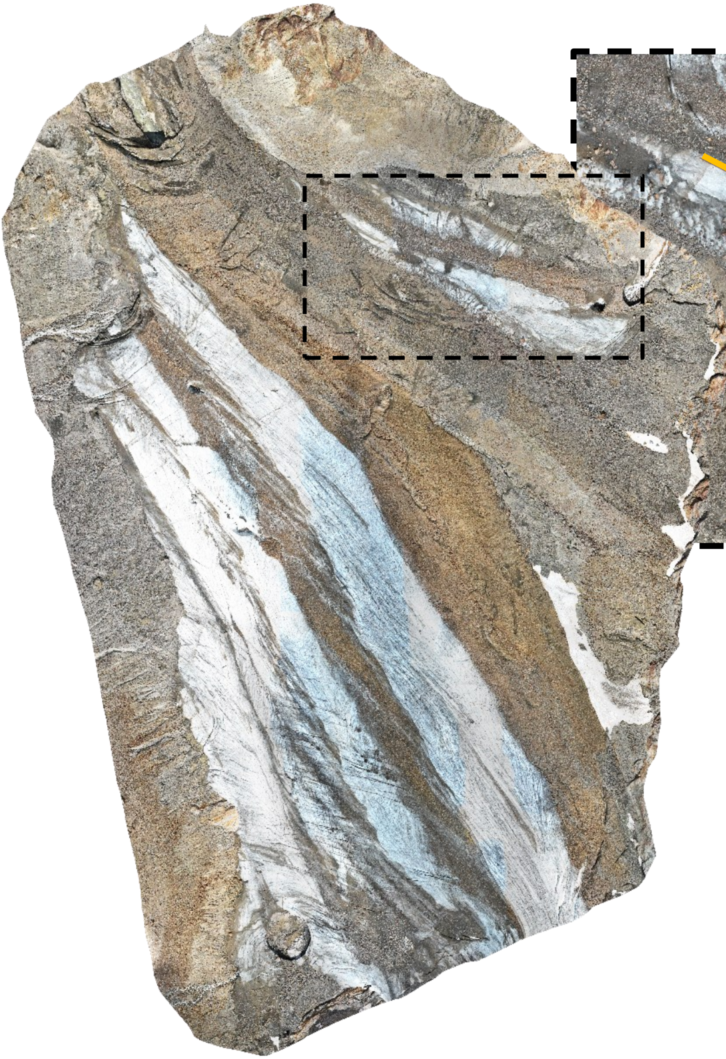



2017 GPR profiles



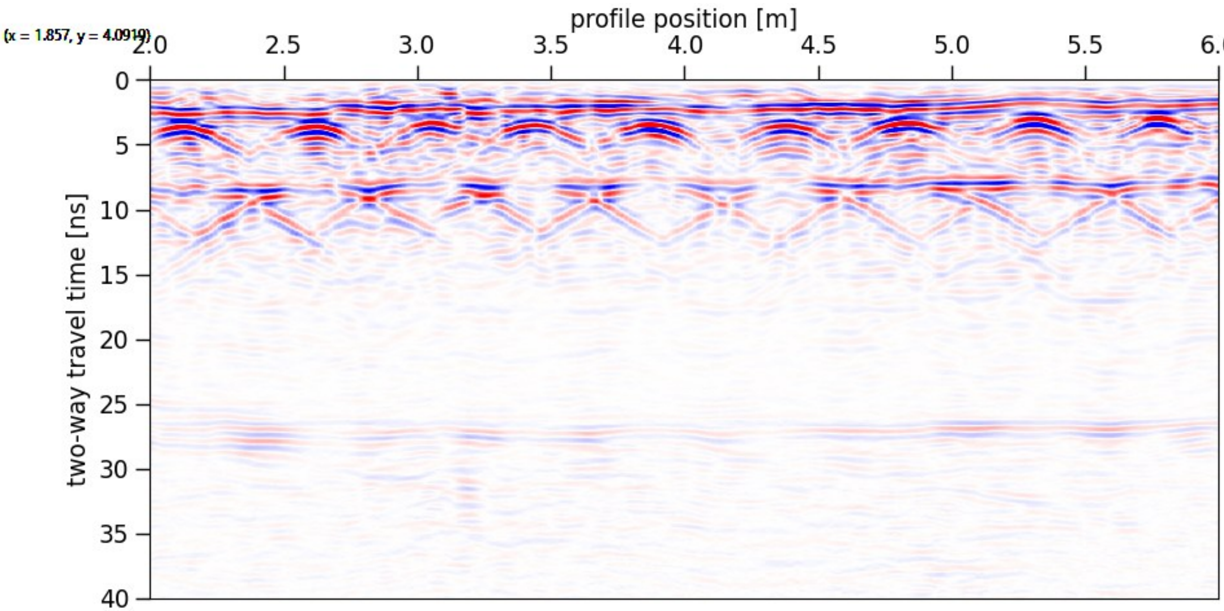
# GPR examples – Glaciers

**Ex. 2 GPR for monitoring ice thickness (Forni Glacier – Italy)**




2024 campaign (Exercise 6)

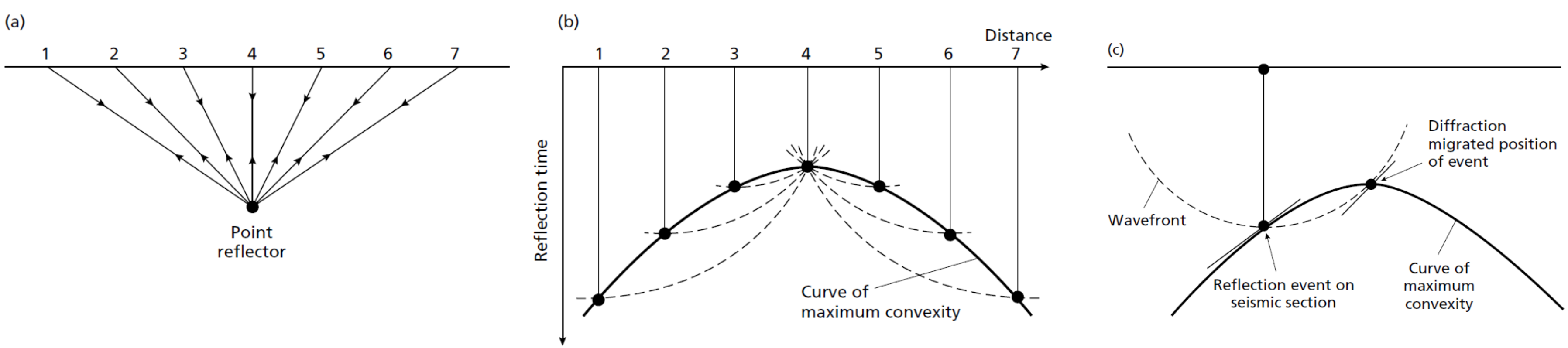
**Ex. 3 Detecting utilities and structural elements (pipes, wires, reinforcements etc.)**




**The diffraction hyperbola should be corrected to get a final GPR radargram that is the image of the subsurface…**

Where EM wave encounters small scatterers or truncated/sloped reflectors, the shape of these object will be biased.
Migration process concentrates the diffracted energy to the apex (vertex) of the hyperbola.
The condition for applying migration is the correct estimation of the EM wave velocity.

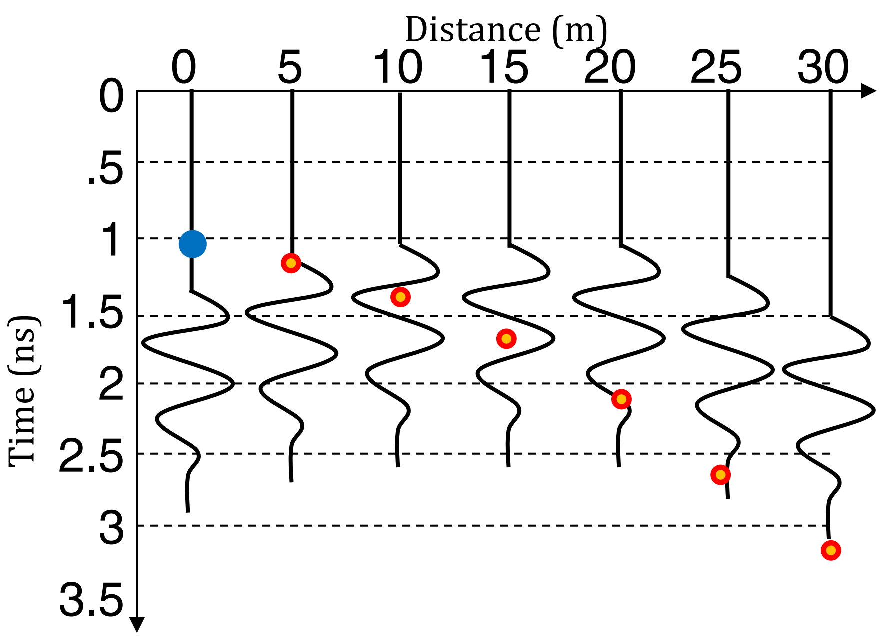
**Acquisition geometry** **Diffraction hyperbola** **Migration**



# GPR data processing - Migration

**Example:** we acquire a GPR profile with a fixed spatial and temporal sampling and we guess the EM wave velocity of the homogenoeus ground.
Each point (*i, j*) of the radargram could be potentially the vertex of a hyperbola:

$$t(x_i) = \sqrt{\left(\frac{2d}{v}\right)^2 + \left(\frac{x_i}{v}\right)^2} = \sqrt{{t_0}^2 + \left(\frac{x_i}{v}\right)^2}$$




Data: $dx$ = 5 cm and $v$ = 10 cm/ns
**First guess**: vertex in (0,1)→ $t_0$ =1 ns

$$t(x_0) = 1 \text{ ns}$$

$$t(x_1) = \sqrt{1 + \left(\frac{0.05}{0.1}\right)^2} = \sqrt{1 + 0.25} \cong 1.2 \text{ ns}$$

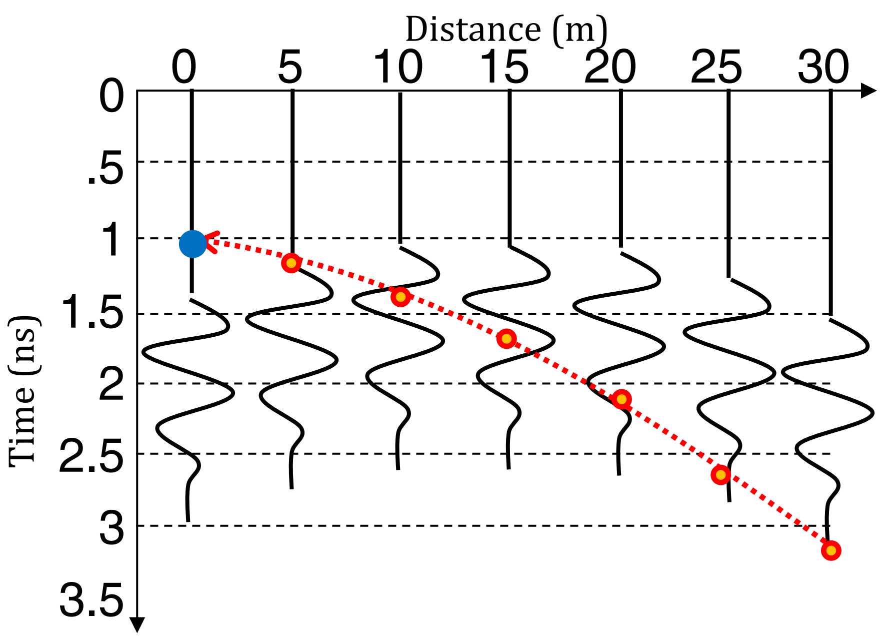
$$t(x_2) = \sqrt{1 + \left(\frac{0.1}{0.1}\right)^2} = \sqrt{1 + 1} \cong 1.41 \text{ ns}$$

⋮

$$t(x_6) = \sqrt{1 + \left(\frac{0.3}{0.1}\right)^2} = \sqrt{1 + 9} \cong 3.16 \text{ ns}$$

**Example:** we acquire a GPR profile with a fixed spatial and temporal sampling and we guess the EM wave velocity of the homogenoeus ground.
Each point (*i, j*) of the radargram could be potentially the vertex of a hyperbola:

$$t(x_i) = \sqrt{\left(\frac{2d}{v}\right)^2 + \left(\frac{x_i}{v}\right)^2} = \sqrt{{t_0}^2 + \left(\frac{x_i}{v}\right)^2}$$



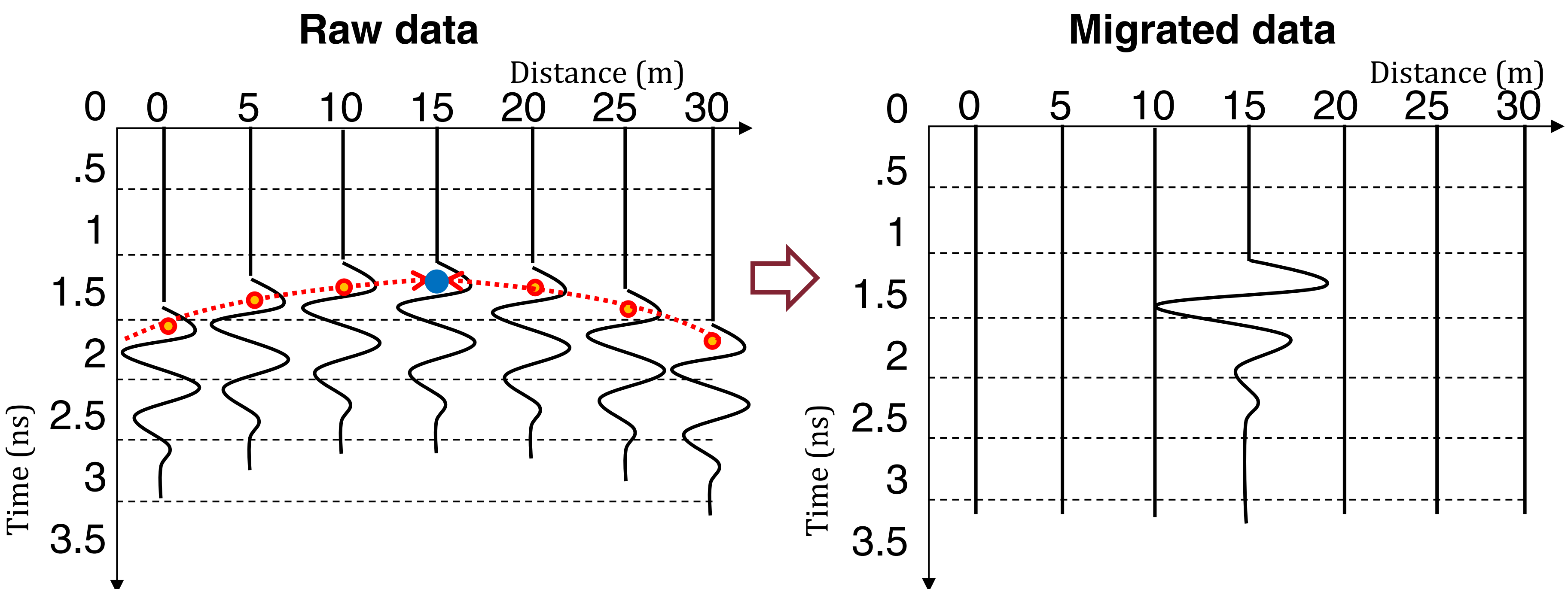

Data: $dx$ = 5 cm and $v$ = 10 cm/ns
**First guess**: vertex in (0,1)→ $t_0$ =1 ns

$$A_{0,1}^{MIGR} = A(x_0, t(x_0)) + A(x_1, t(x_1)) + \cdots + A(x_6, t(x_6))$$

The new migrated amplitude of the point (0,1) will be the sum of the amplitude of the traces that belong to the hyperbola with vertex $t_{1,1}$ and velocity $v$.
**In this case the amplitude is almost zero, because we have a destructive interfecrence.**

**Example:** we acquire a GPR profile with a fixed spatial and temporal sampling and we guess the EM wave velocity of the homogenoeus ground.
Each point (*i, j*) of the radargram could be potentially the vertex of a hyperbola:

If we automatically repeat the same procedure for all the potential vertices (*i, j*) of the hyperbola and for different velocity values *v*, we will have the maximum constructive interference where the *fitting* between the diffraction hyperbola due to the scatterer and the maxima values of amplitude is the best one.

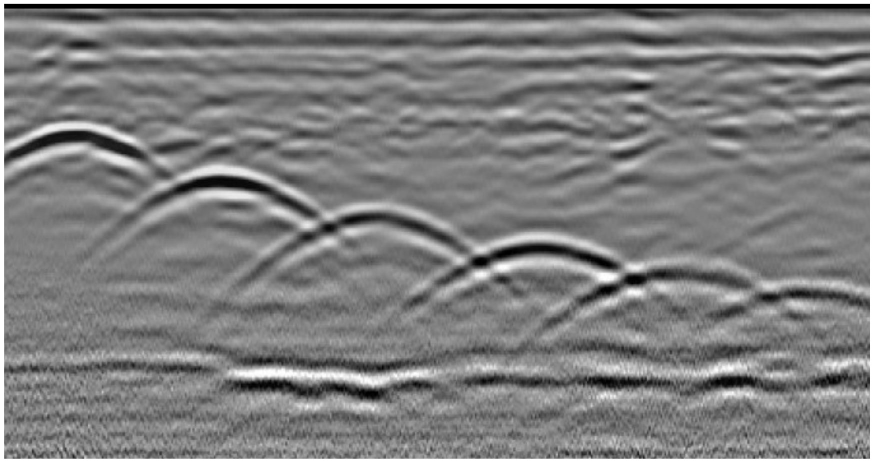


# GPR data processing - Migration

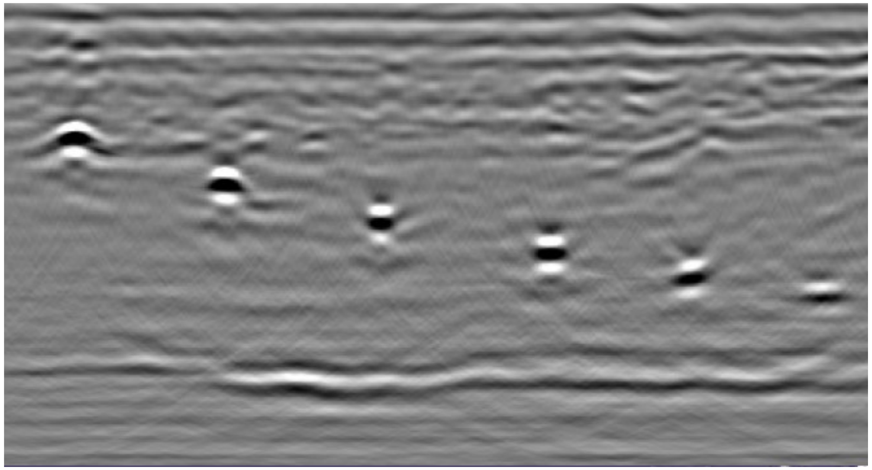
Where encountering small scatterers or sloped reflectors, the EM wave is backscattered to the receiver along the same ray of incidence. Therefore, the shape of these object will be biased.

Migration process can concentrate the diffracted energy in the vertex of the hyperbola and dipped layers will be moved to their correct place. The pre-condition for applying migration is the estimation of the EM wave velocity.

**Raw data**



**Migrated data**



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Where encountering small scatterers or sloped reflectors, the EM wave is backscattered to the receiver along the same ray of incidence. Therefore, the shape of these object will be biased.
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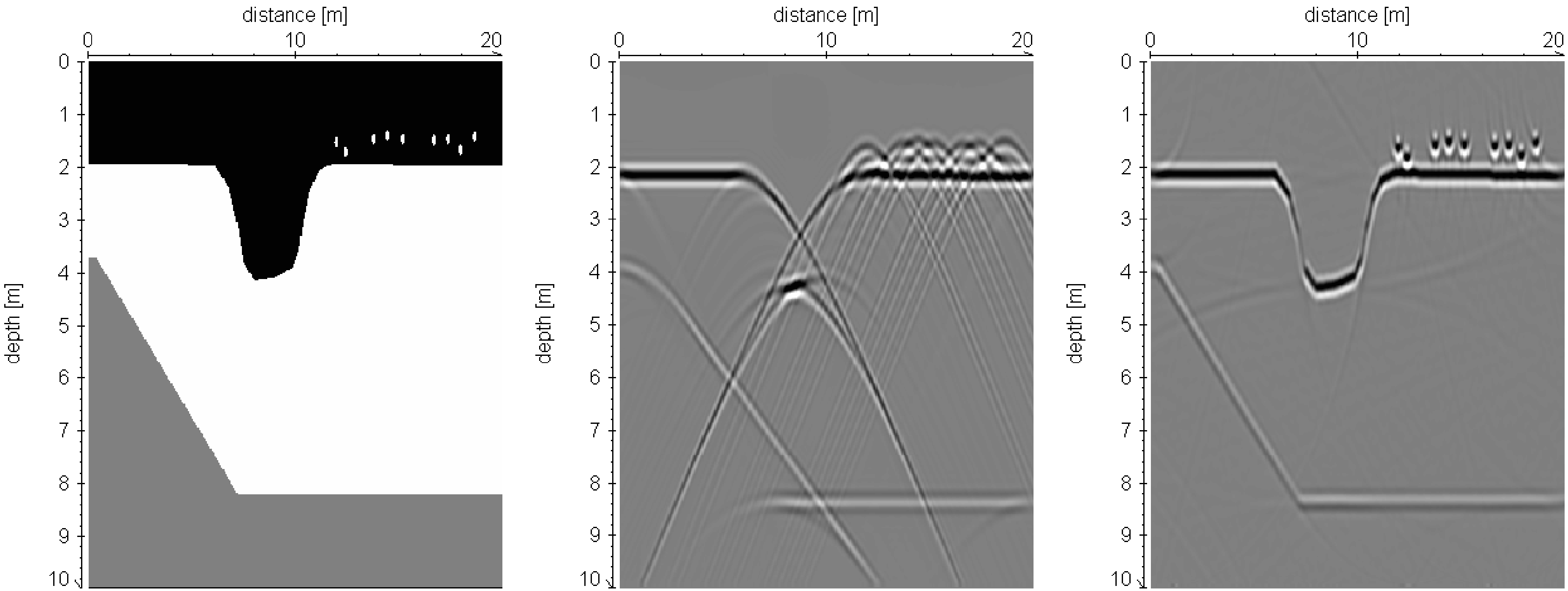

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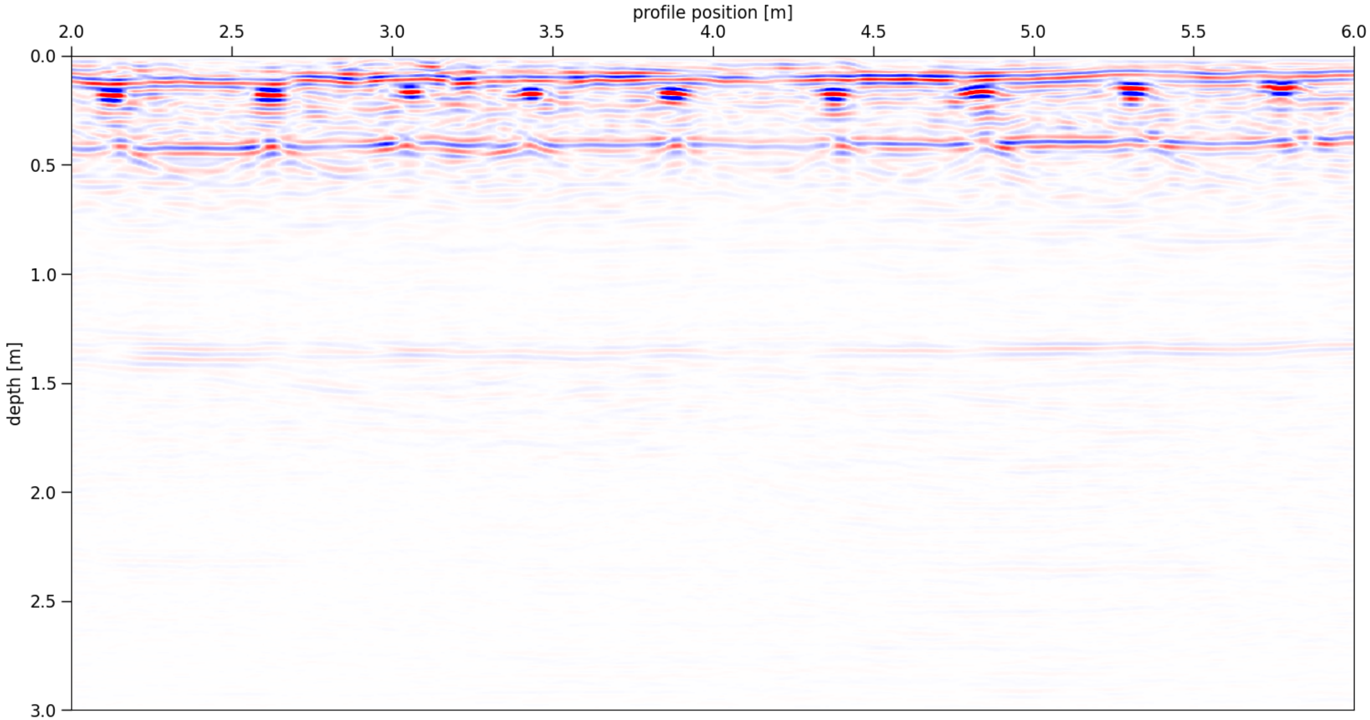
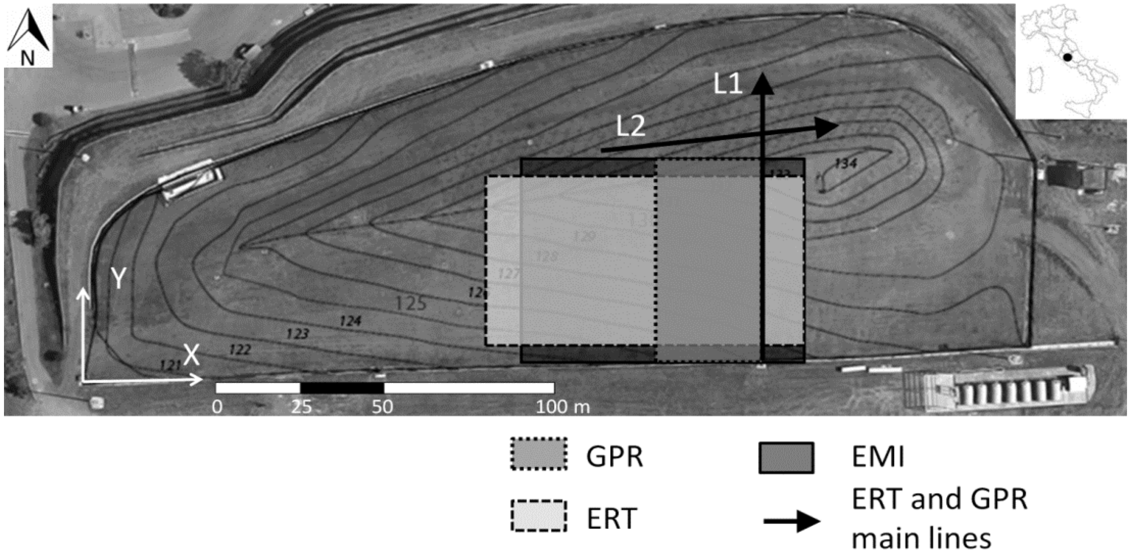
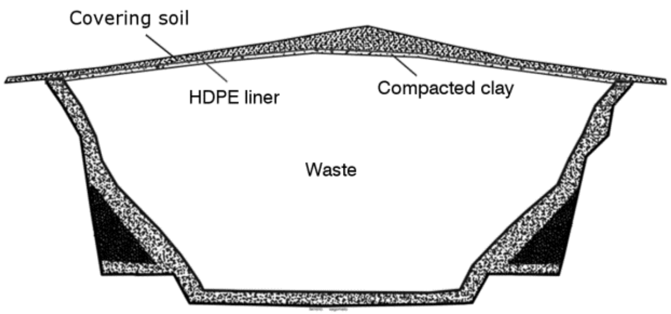


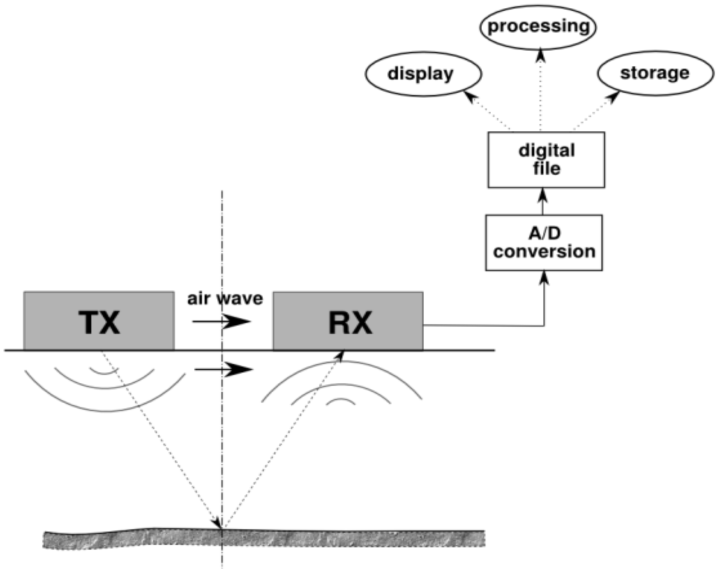

**Migrated data**

## Ex. 4 GPR for the assessment of the liner integrity in a car-fluff landfill




# GPR examples – Car fluff landfill



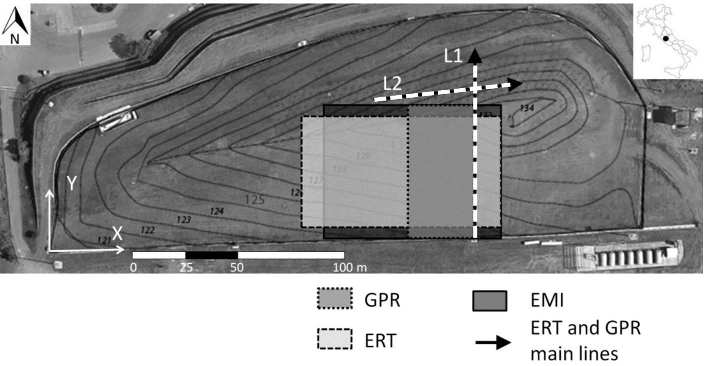

*Device*: IDS Antennas

*Frequency:* 200 - 600 MHz

*Profile spacing:* 1.5 m

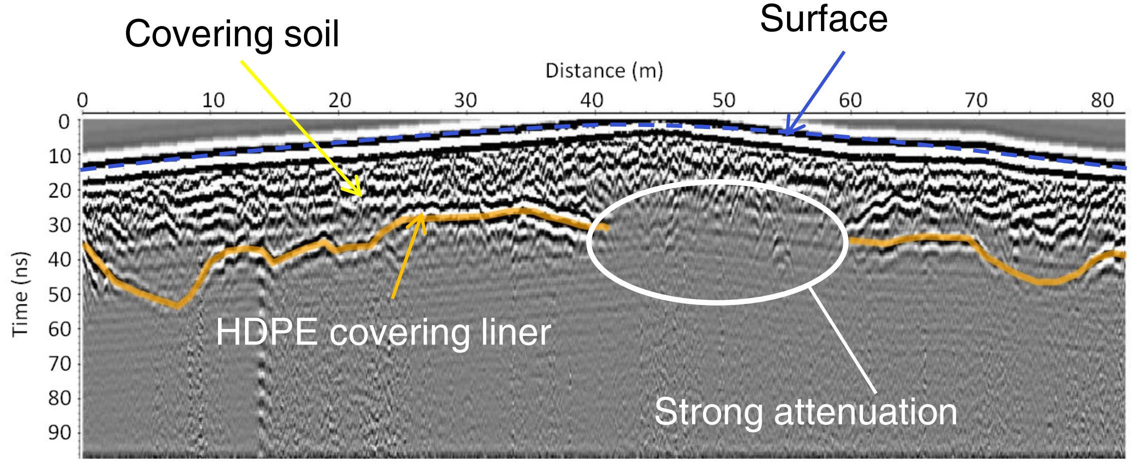
*Investigated area*: 27x46 m + 2 main lines (L1 - L2)

# GPR examples – Car fluff landfill

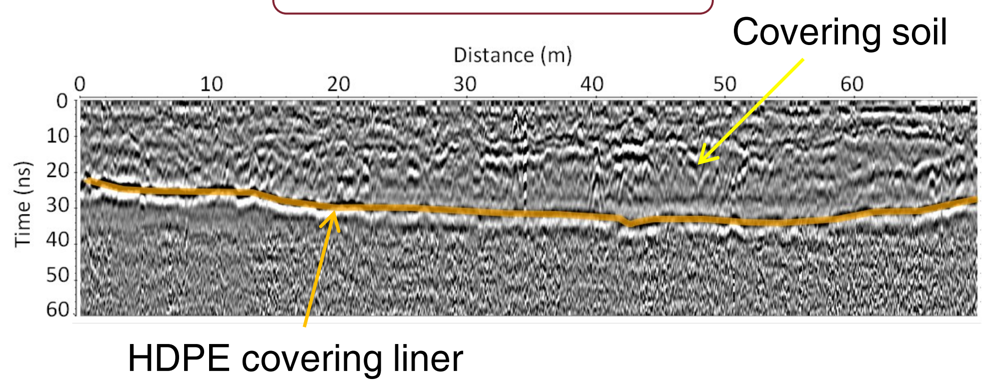



- In the zone ranged between 40 and 60 m on the L1 line, the continuous reflector is no longer detected
- On L2 line the reflection is clearly visible on the whole profile
- Below the GPR signal is strongly attenuated due to the presence of the compacted clay layer (conductive) acting as a regularization surface.

**Radargram - L1**




**Radargram - L2**



# GPR data processing

**Depth-slices**

**Horizontal slices cut at different depths**
Q. What is the parameter to be mapped?
A. The average of the squared amplitude in a fixed window.

$$DS_{i,j} = \frac{1}{N}\sum_{j=1}^{N} A_{i,j}^2 \text{ for } i = 1,2,\dots,M$$

$M$ = number of traces
$N$ = number of samples for each trace that lie within the selected window

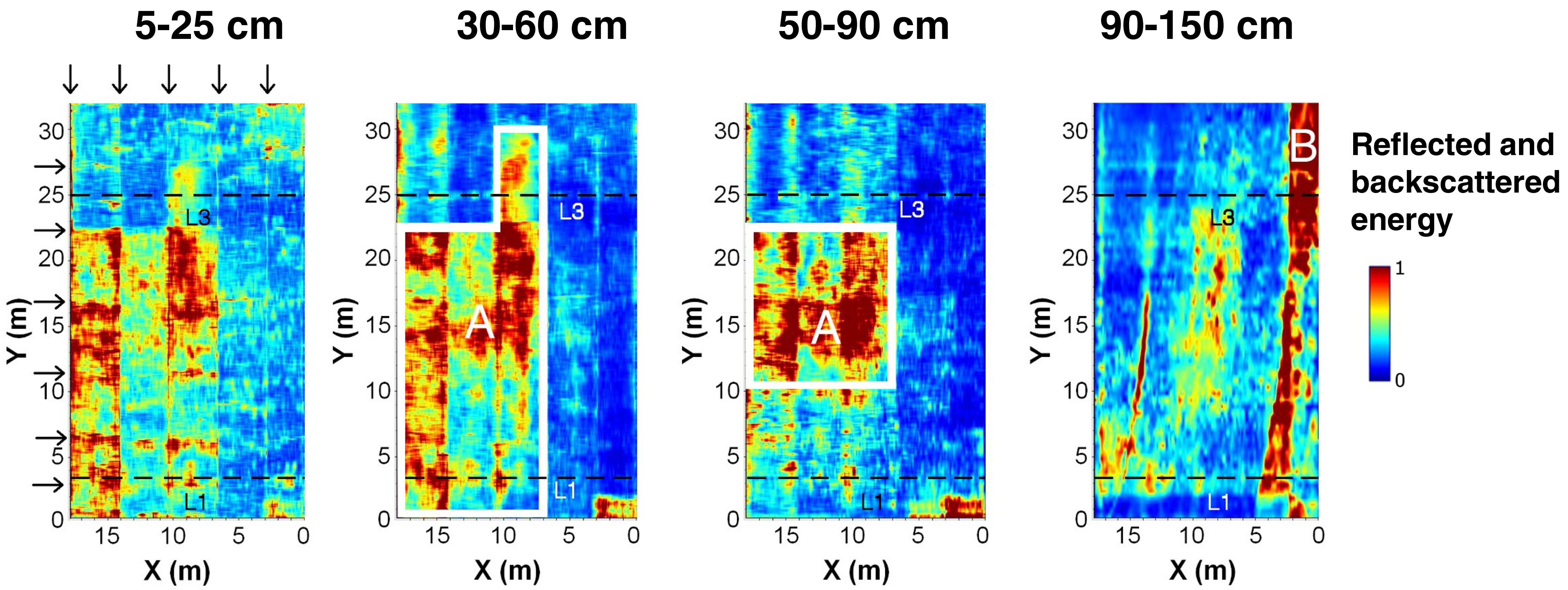
**Example:**
**Depth-slice at 10 ± 10 cm.**
What does it mean?

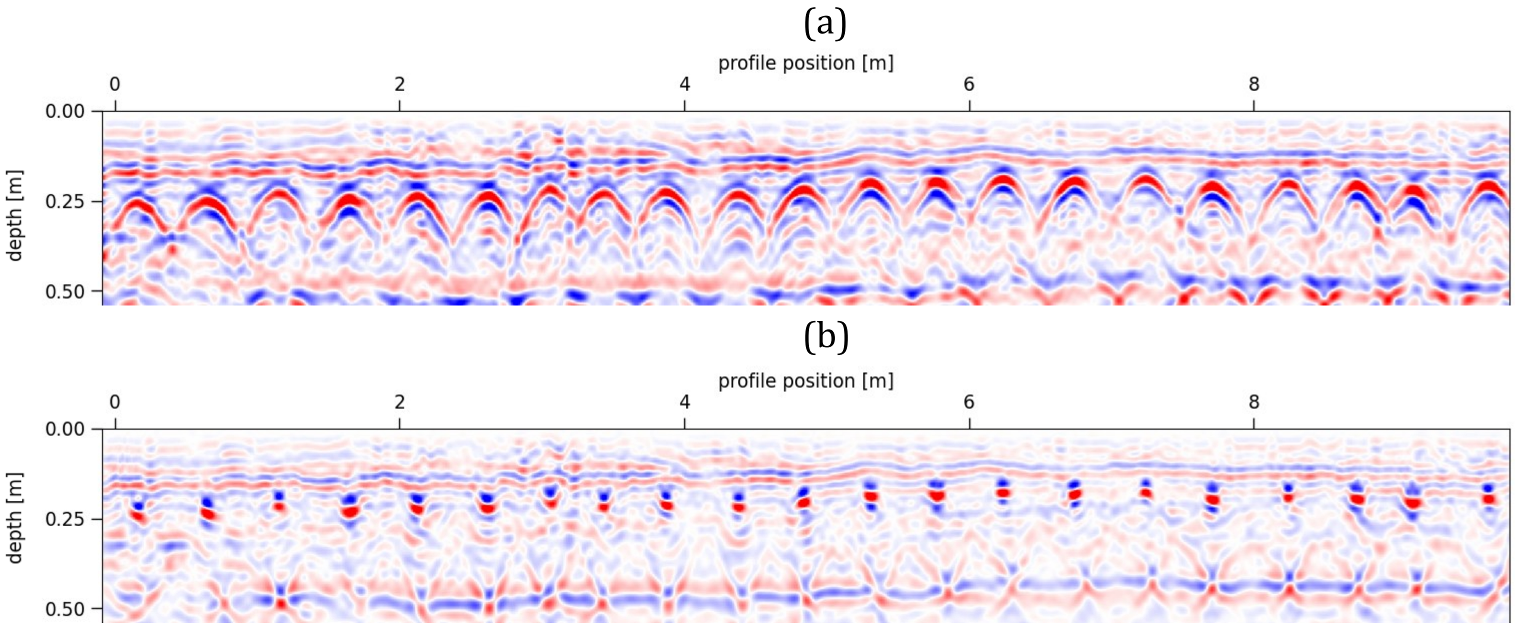
It means that the cut is done at 10 cm by summing the squared amplitude amplitude between 0 and 20 cm

# GPR data processing

## Depth-slices

**The average of the squared amplitude is a measure of energy that is back-scattered and reflected back to the surface in a given portion of the subsurface**




(a)
profile position [m]
0
2
4
6
8
0.00
0.25
0.50
depth [m]
(b)
profile position [m]
0
2
4
6
8
0.00
0.25
0.50
depth [m]