GEOFIT
SMART GEOTHERMAL

WP2+WP5+WP6

RADAR TECHNOLOGIES:

An overview on **Ground Penetrating Radar** (GPR),

and **Ground-Based Syntethic Aperture Radar** (GBSAR) interferometry

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AGENDA of the training session

***PART 1*: GEORADAR for underground mapping** *(20' duration)*

- The GPR working principle
- State of the art and 3D imaging
- GPR Data interpretation
- Future development of the GPR technology
- Q+A

***PART 2*: High Definition SAR for Building Monitoring** *(20' duration)*

- The GBSAR working principle
- State of the art and 3D imaging
- GBSAR Data interpretation for displcement measures
- Future development of the GBSAR technology
- Q+A

THE WORKING PRINCIPLE OF GPR TECHNIQUE

PART 1

- **GPR** (*Ground Penetrating Radar*) or ***Georadar*** is a ***Non Destructive Technique*** (NDT), based on the transmission of electromagnetic (EM) energy to investigate the subsoil or manmade manufacts.

- **EM** signal emitted by the **GPR** and reflected back form the subsoil, is detected and recorded by the **GPR** hardware itself, and provides information about the characteristics of any object embedded in the ground, causing the **EM** signal to be reflected, with its burial depth.

- Basic radar output (radar maps or ***radargrams***) presents this as patterns of signals at depth against the distance travelled through the ground. Any **GPR** measures depth in terms of the time it takes for a signal to return after emission. The depth in cm or metres depends on soil conditions and how fast the electromagnetic waves can travel through the ground

- Being a contactless and Non-Destructive Technique, GPR is faster and cheaper respect traditional dig surveys. Typical GPR applications are:
  - Utility detection (pipes, cables).
  - Archaelogical sites recognition.
  - Evaluation of civil structures integrity (walls, tunnels, paves).
  - Geological applications (research of cavitis, fractures).
  - Foundations evaluation.
  - Forensics

THE WORKING PRINCIPLE OF GPR TECHNIQUE

PART 1

- Typically, **GPR** uses high frequency electromagnetic pulses (from 25 MHz to 3,000 MHz, depending on Dipoles and HW characteristics) to gather subsurface information.

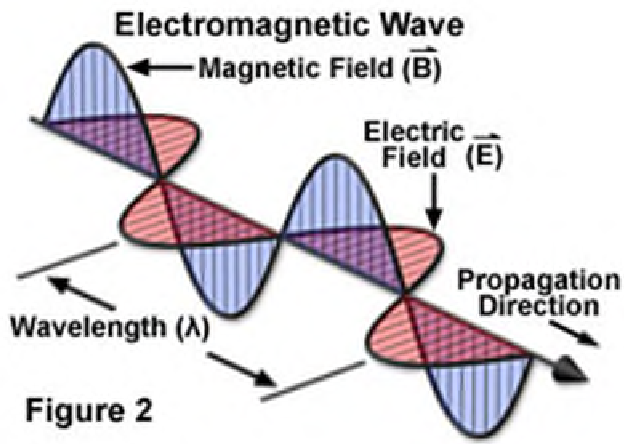


Figure 2

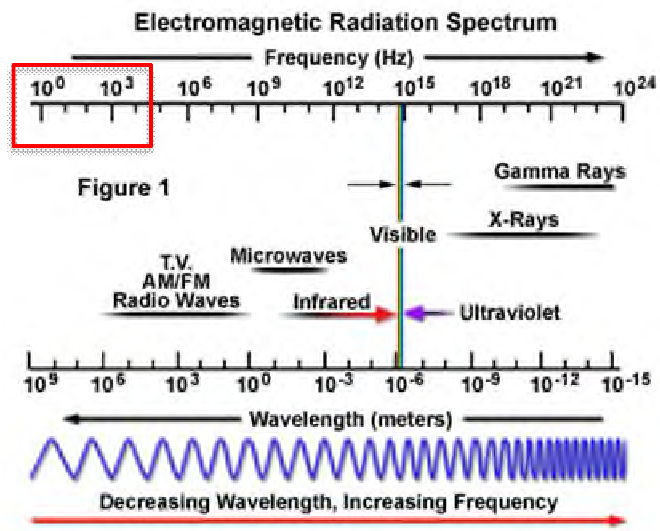
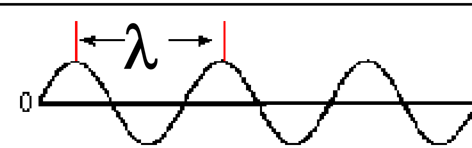


Figure 1

- On each perpendicular plan to x axis, ***E*** and ***H*** have the same value (wave plan).
- The wave lenght is $\lambda = c/f$

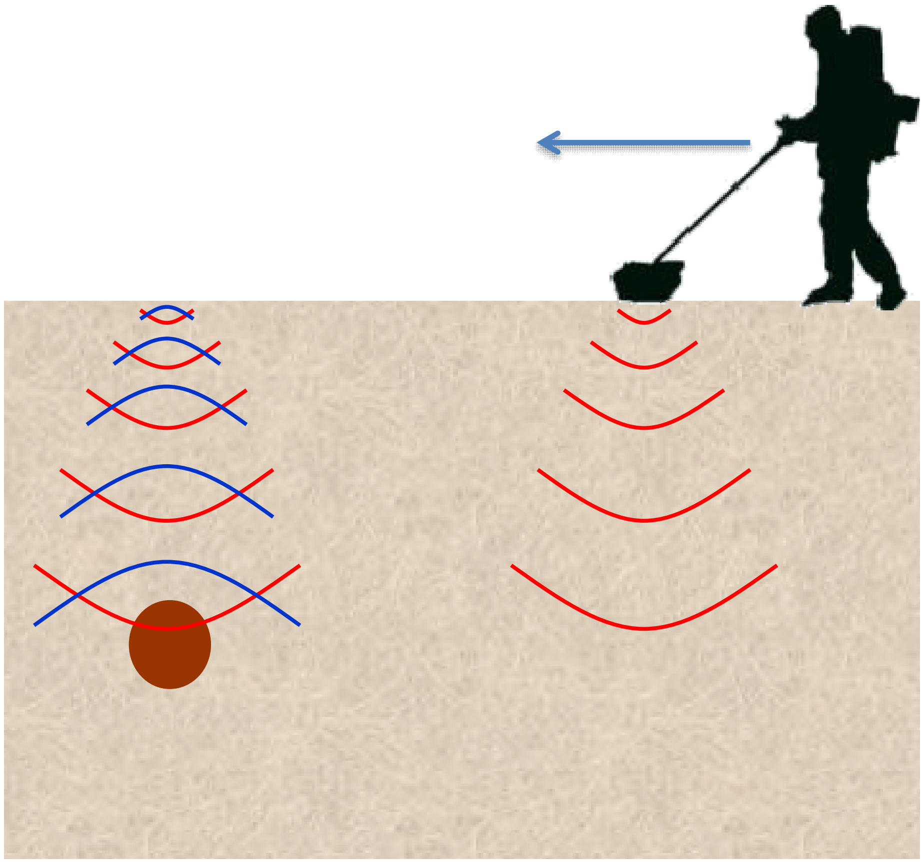
$$\lambda_{meter} = \frac{3\text{x}10^8}{f_{Hz}} \quad or \quad f_{Hz} = \frac{3\text{x}10^8}{\lambda_{meter}}$$



THE WORKING PRINCIPLE OF GPR TECHNIQUE

PART 1

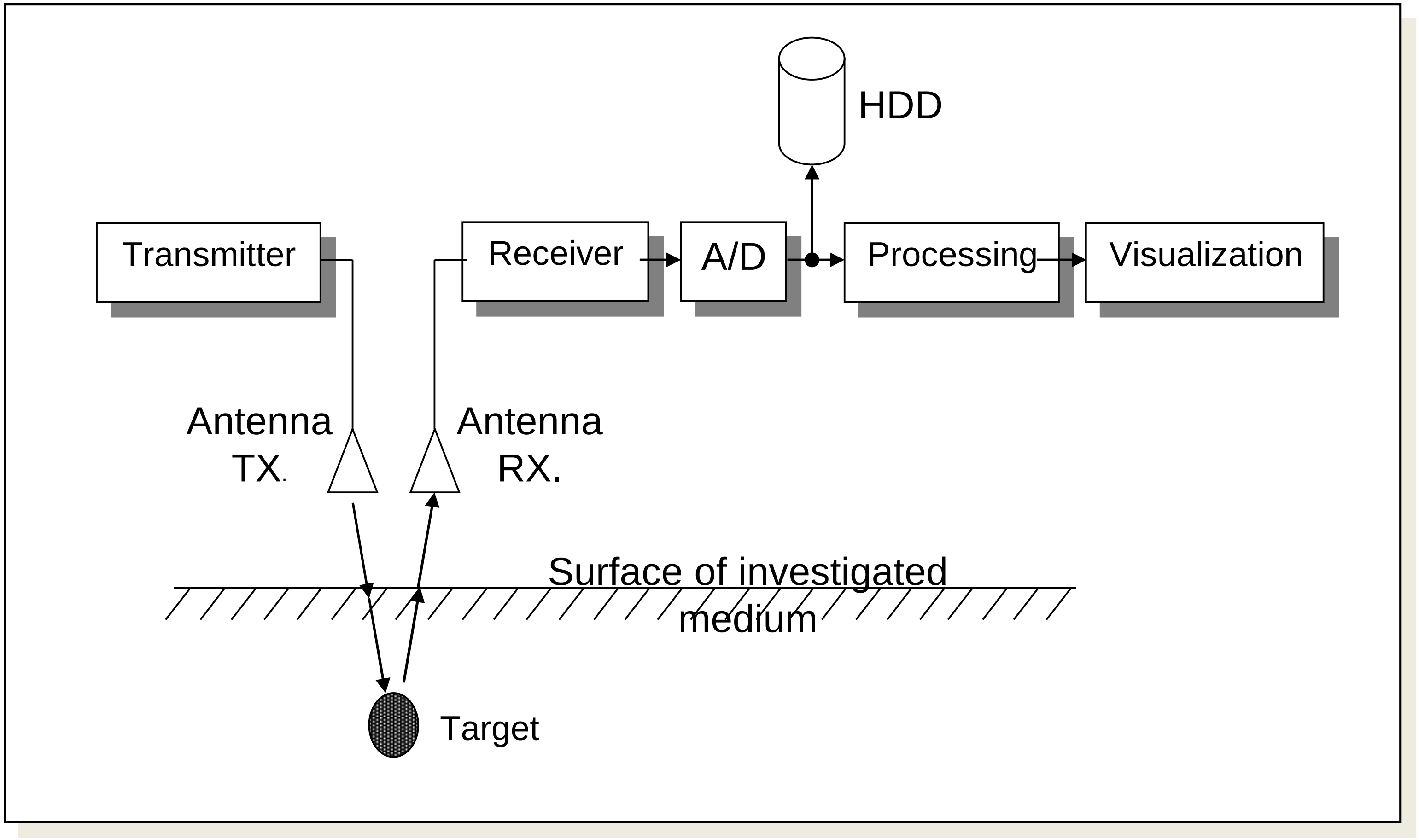
- ✓ *The radar transmits a pulse of EM wave through an antenna transmitter (TX)*
- ✓ *The EM energy reflected back from any discontinuity (target) is detected and recorded by the antenna receiver (RX).*
- ✓ *The time delay (in nsec) contains information on the target depth; time delay depends on subsoil velocity of propagation of EM wave*
- ✓ *The penetration depth of any EM signal and its resolution depends on antenna frequency, the power the EM wave transmitter, and the electrical properties of the ground.*



THE WORKING PRINCIPLE OF GPR TECHNIQUE

PART 1

THE TRANSMITTER-RECEIVER SCHEME



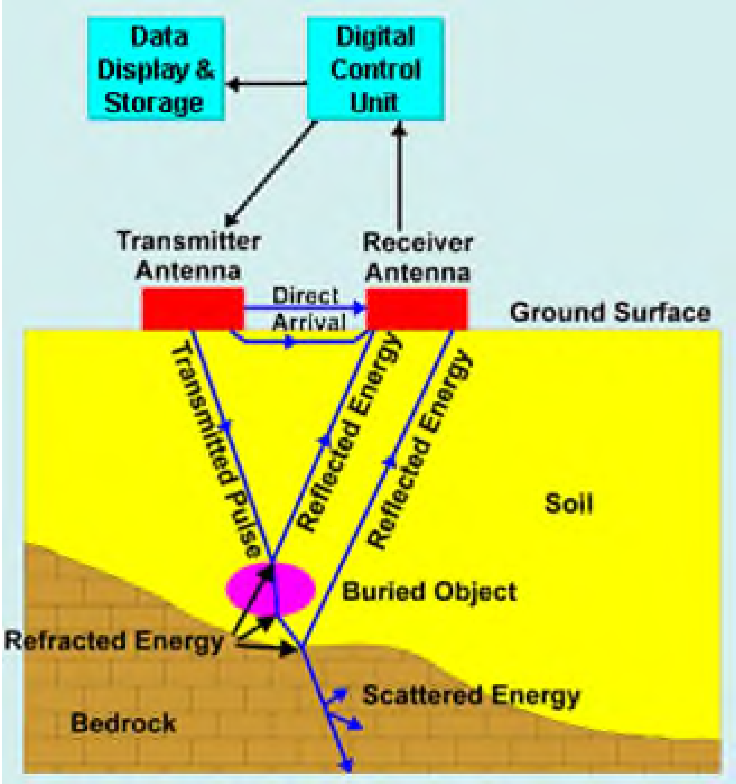
THE WORKING PRINCIPLE OF GPR TECHNIQUE

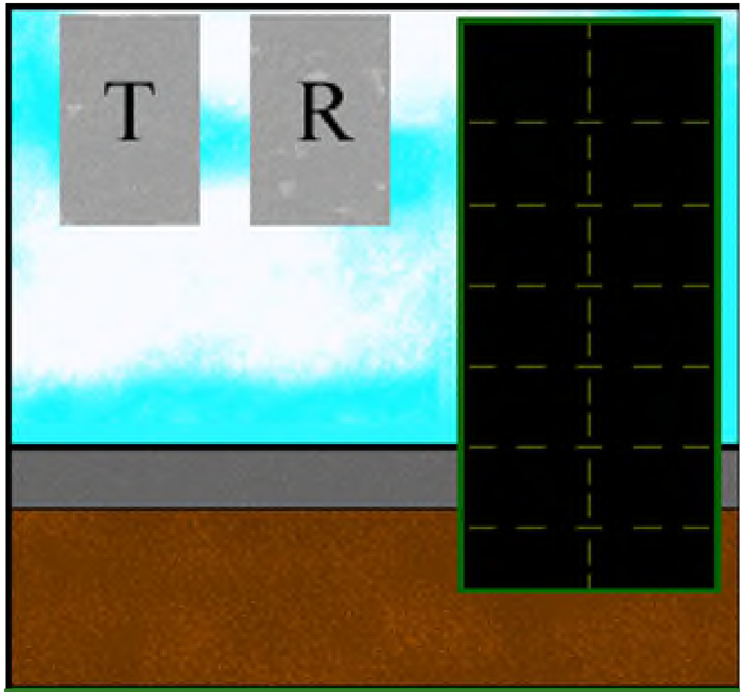
PART 1

Radar Map Generation

GPR is a method for shallow, high-resolution, subsurface investigations of the earth.

GPR uses high frequency pulsed electromagnetic waves (from 25 MHz to 3,000 MHz) to collect subsurface information, to outline the geometry of the subsoil.





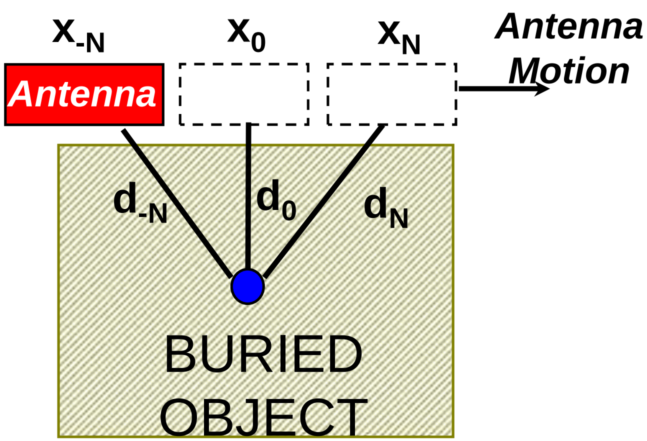
G P R Principle

THE WORKING PRINCIPLE OF GPR TECHNIQUE

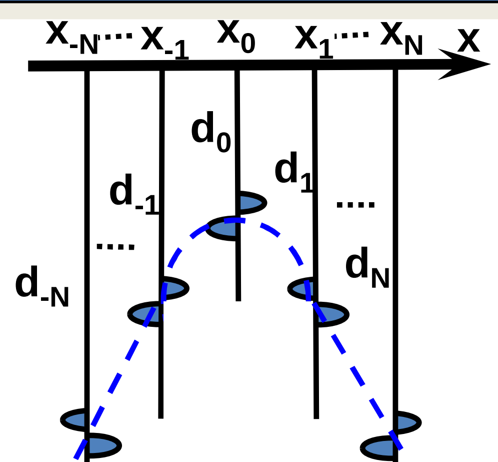
PART 1

Radar Map Generation

Buried object is seen by GPR in deformed shape



Acquisition



Hyperbola generation

Radar map

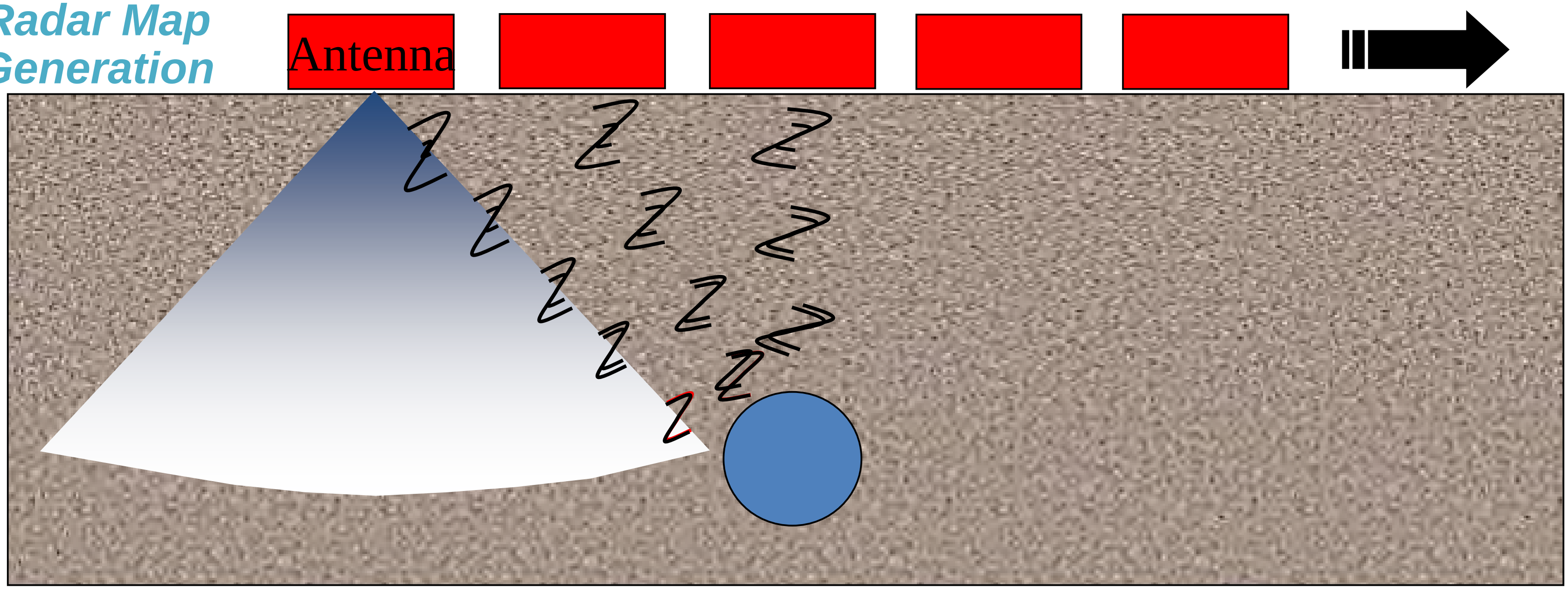
RADAR "sees" the target around a location at a minimum distance

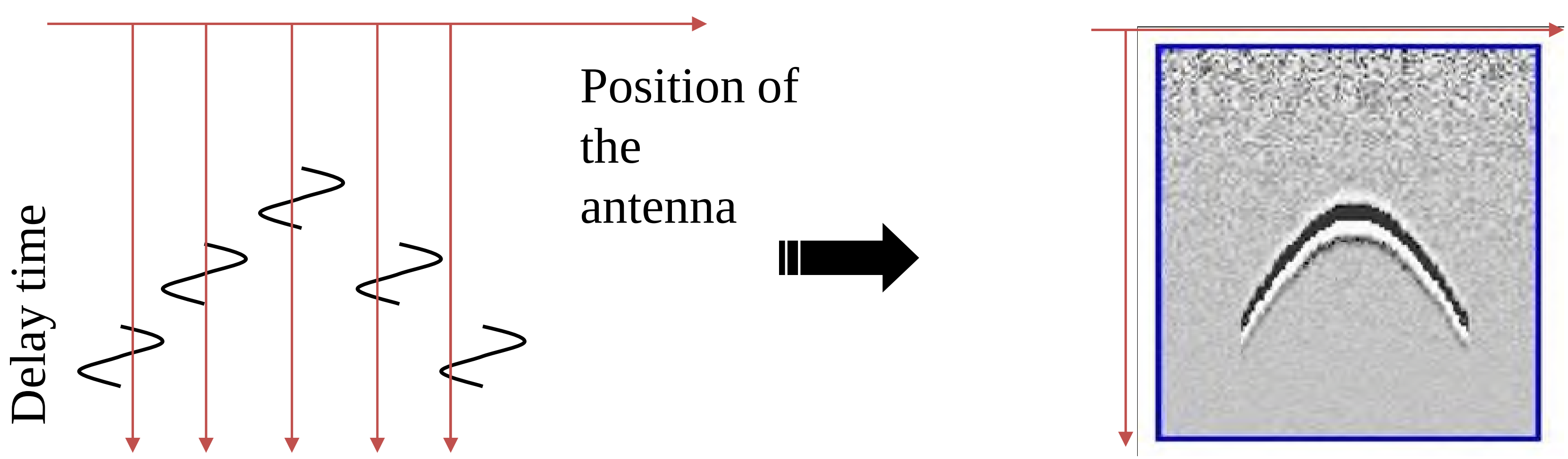
Buried object is detected if:
- it is in the antenna irradiation cone
- ratio signal/clutter > minimum value sufficient to reveal that

THE WORKING PRINCIPLE OF GPR TECHNIQUE

PART 1

Radar Map Generation





The Penetration Depth

- Decreases as:
  - ✓ Electrical Conductivity Increases
  - ✓ Water Content Increases
  - ✓ Clay Content Increases
  - ✓ Scattering Increases
  - ✓ Conductive Contaminant Increases

  GPR user **has no control** over the above factors, these are site specific characteristics.
- Increases as:
  - ✓ Antenna Frequency Decreases
  - ✓ Receiver Sensitivity Increases (Stacking)
  - ✓ Transmitter Power Increases (this is limited by regulations like FCC)

  GPR user **has control** over the above factors to some degree

THE WORKING PRINCIPLE OF GPR TECHNIQUE

PART 1

Characteristics of the Antenna

Low freq

Long wavelength

Bigger antenna size

More depth penetration

Lower resolution

High freq

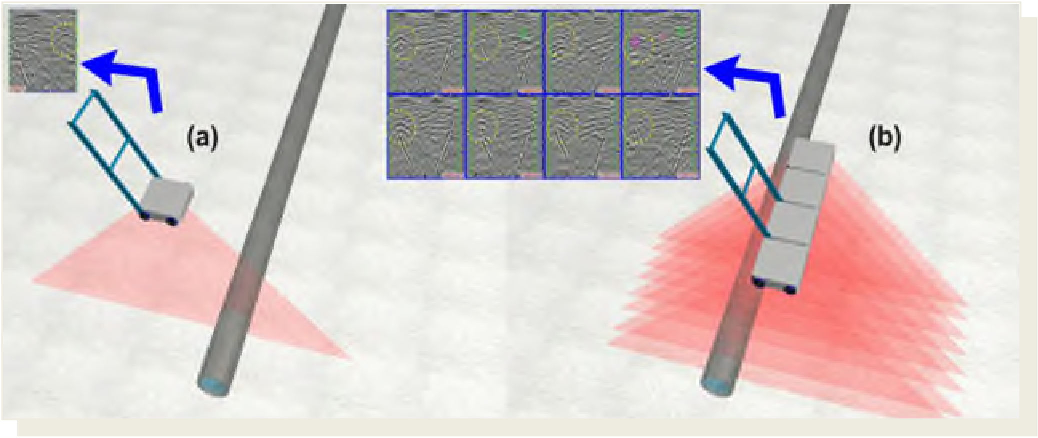
Short wavelength

Smaller antenna size

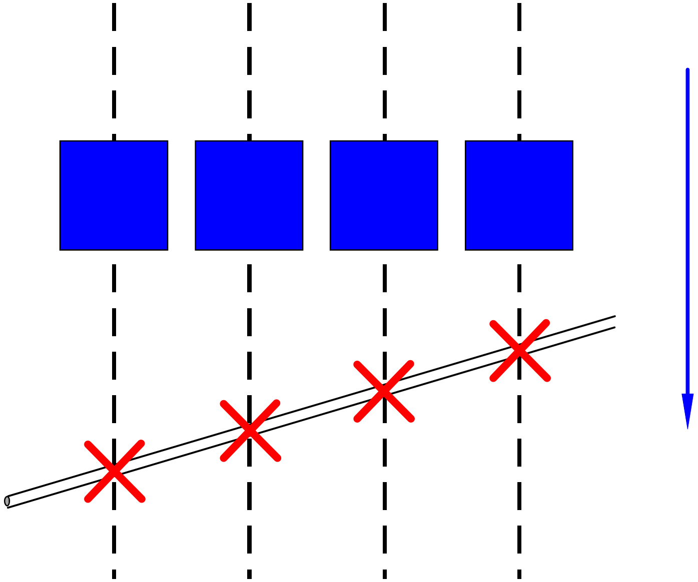
Less depth penetration

Higher resolution

Improving subsoil imaging through the use of antenna Array



Covering with array

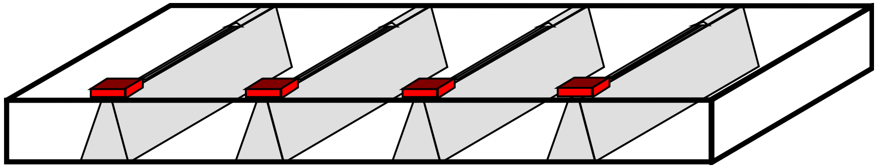


STATE OF THE ART OF GPR TECHNOLOGY

PART 1

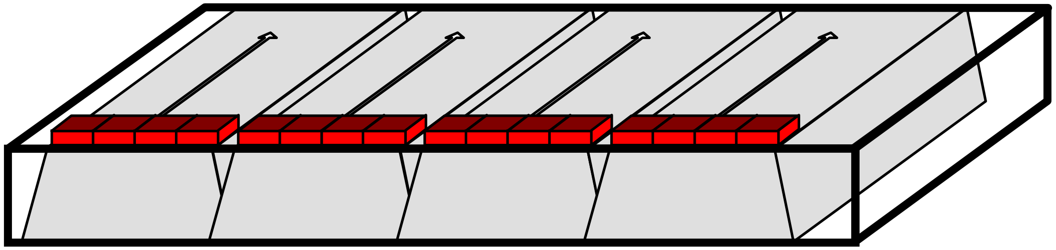
Improving subsoil imaging through the use of antenna Array

«Single line» data acquisition



Bidimensional acquisition on single line

«Array» data acquisition



Array of antennas: volumetric covering (tridimensional acquisition)

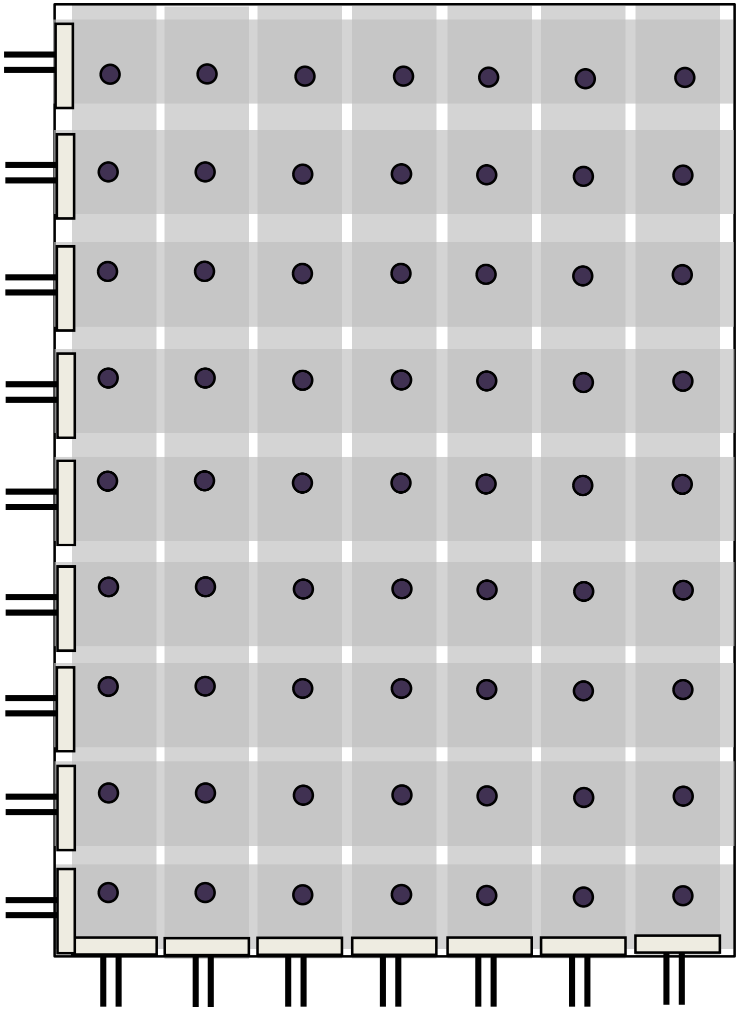
Improving subsoil imaging through the use of antenna Array

«Single line» data acquisition

«Array» data acquisition

Improving subsoil imaging through the use of antenna Array

Area to be mapped



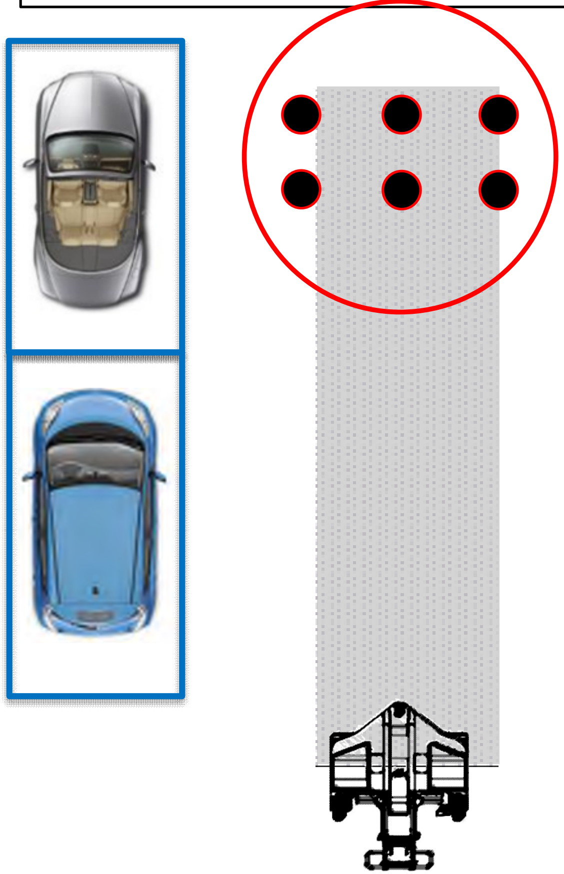
Traditional Mapping:

- Longitudinal acquisition;
- Transversal acquisition;
- Antenna spacing: ~50 cm.

Improving subsoil imaging through the use of antenna Array

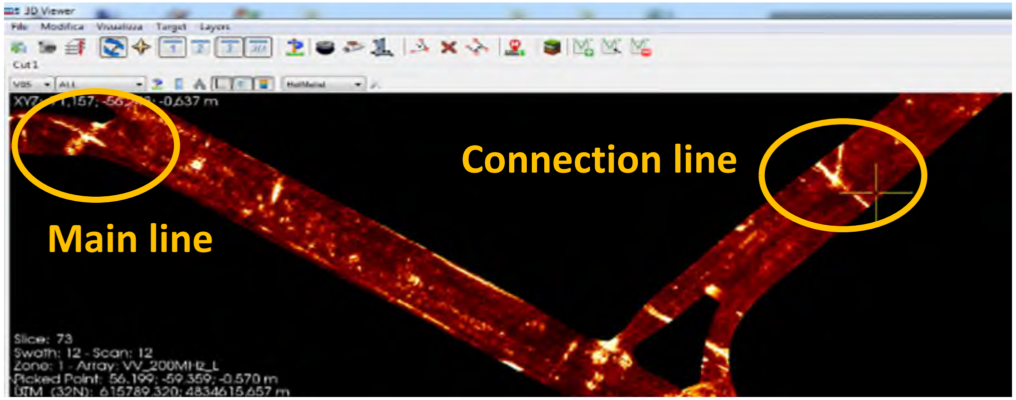
High Productivity

Area to be mapped (e.g. sidewalk)



Stream C

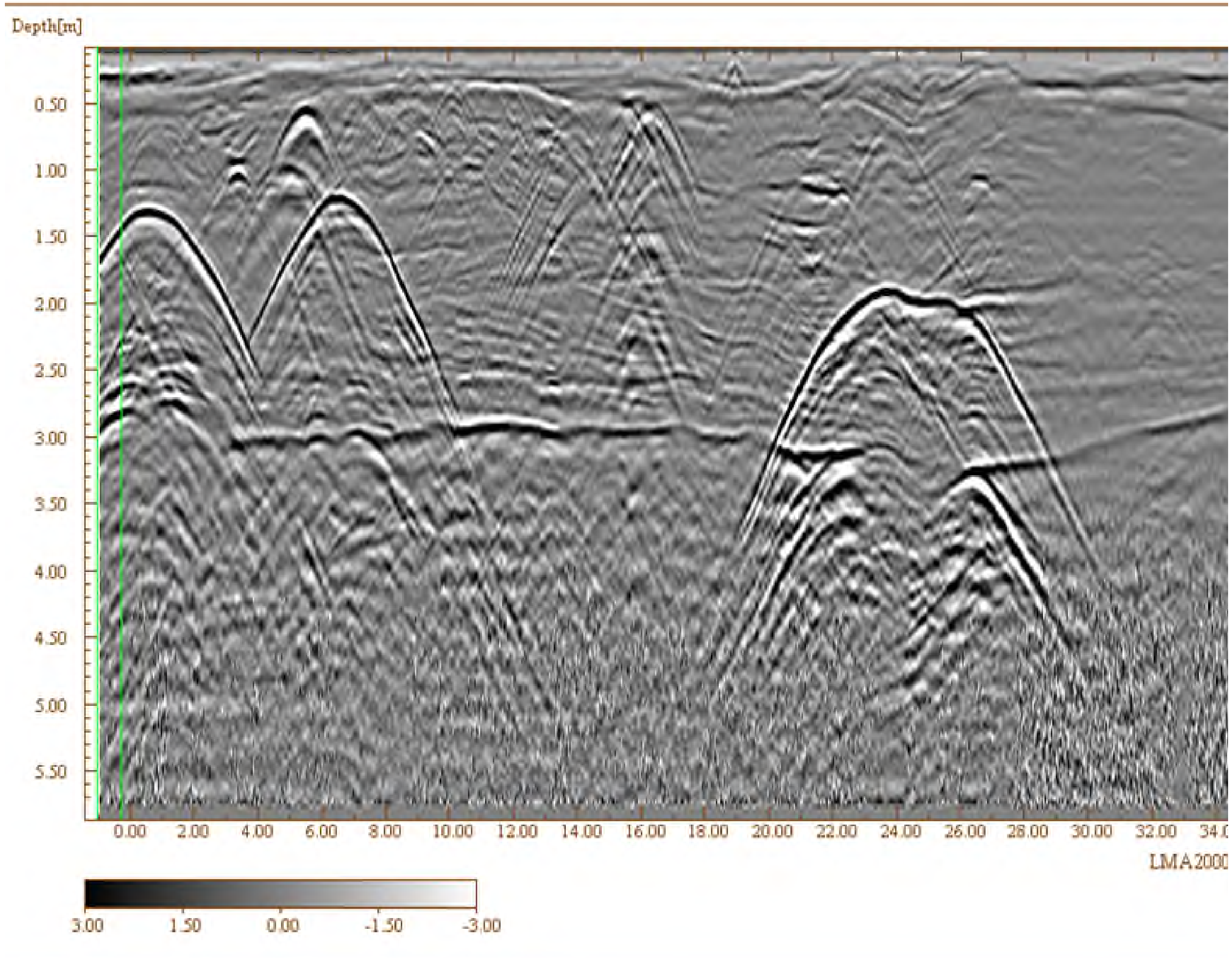
- only longitudinal acquisition;
- antenna spacing: 4.4 cm;
- high quality map.



GPR DATA INTERPRETATION

PART 1

Data interpretation of geological features

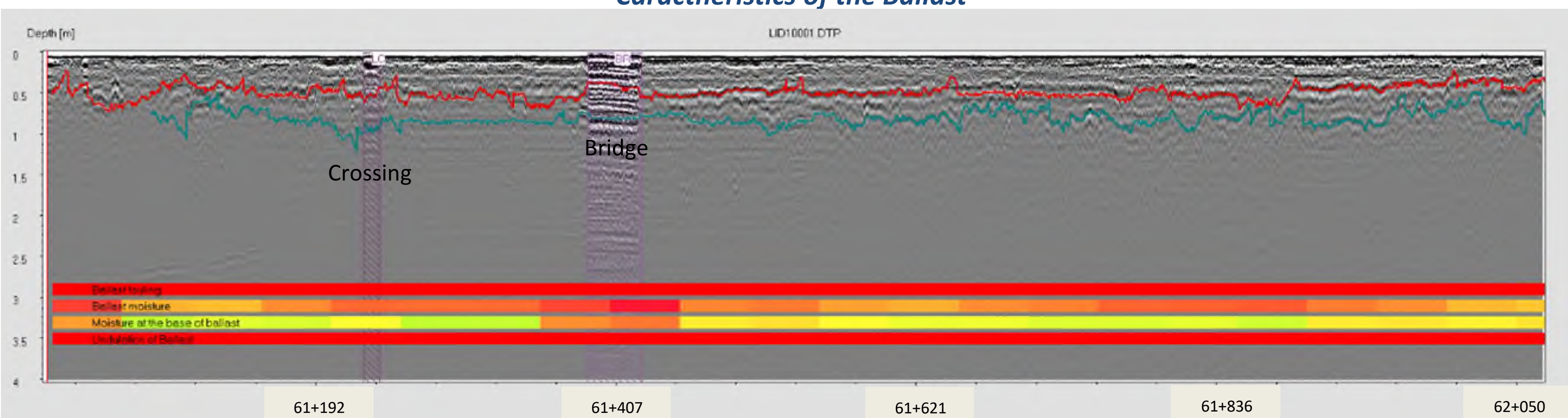


GPR DATA INTERPRETATION

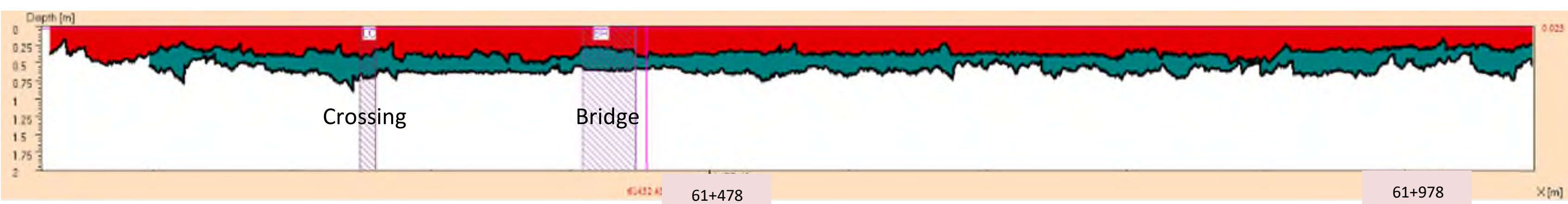
PART 1

Data interpretation: railways ballast evaluation

Caractheristics of the Ballast



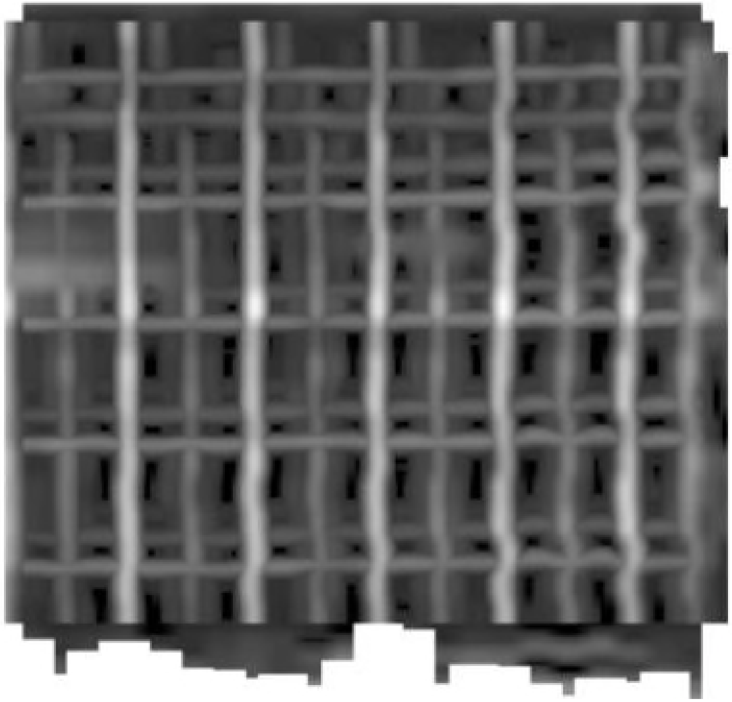
Tickness of the Ballast

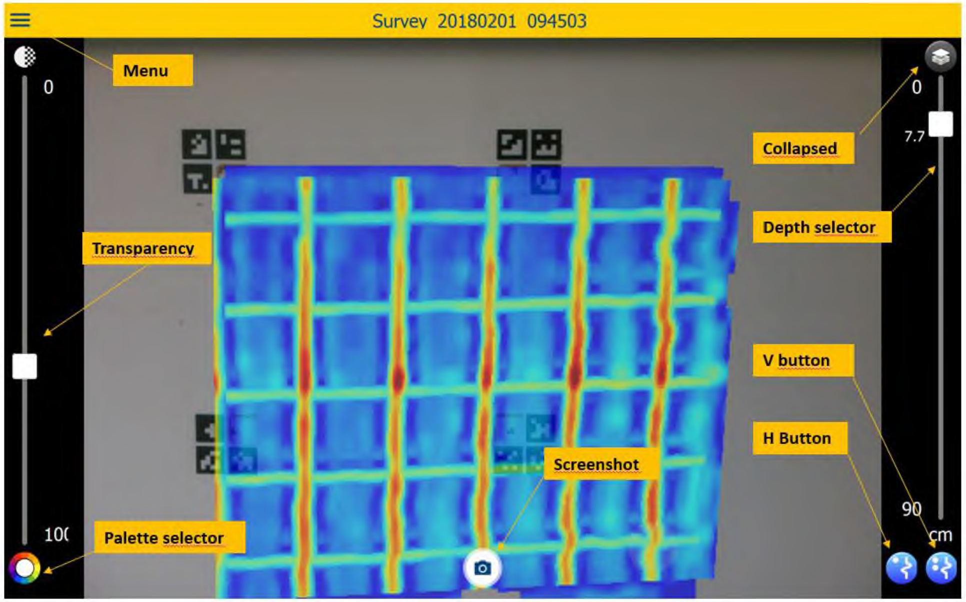


GPR DATA INTERPRETATION

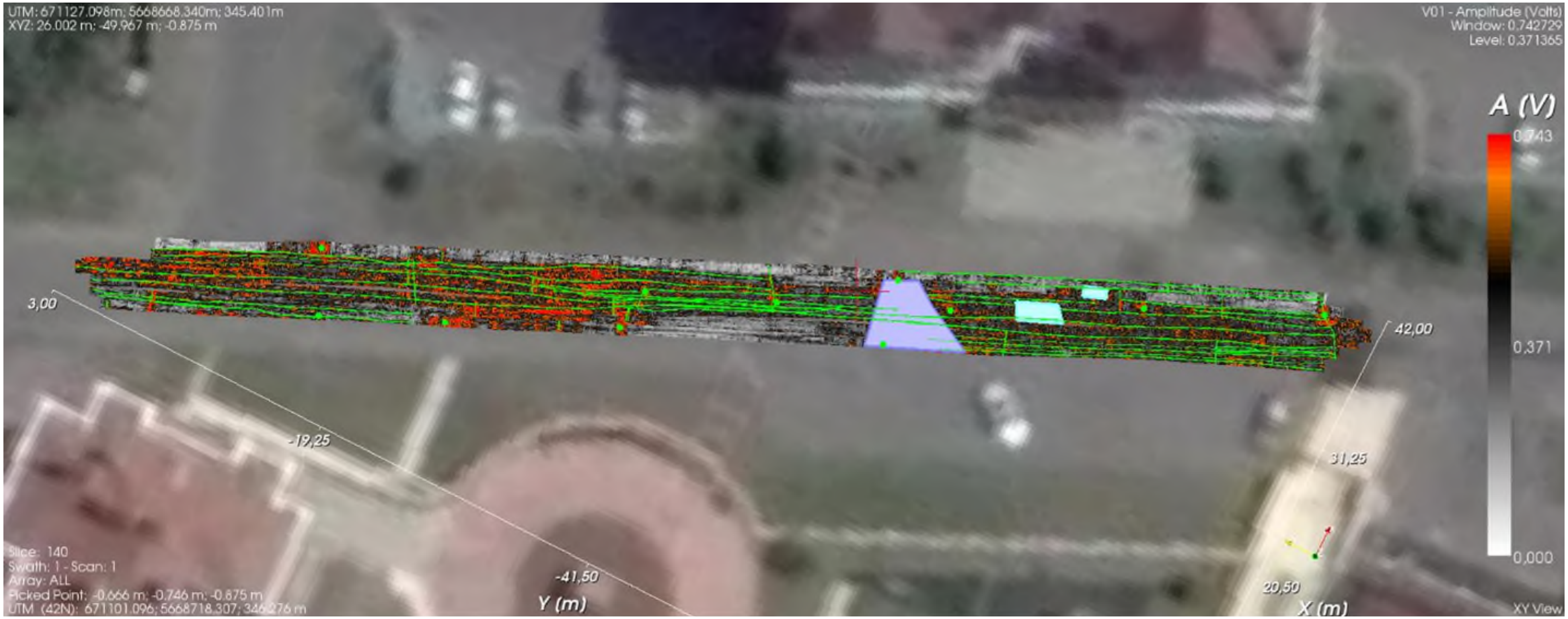
PART 1

Data interpretation: rebars detection



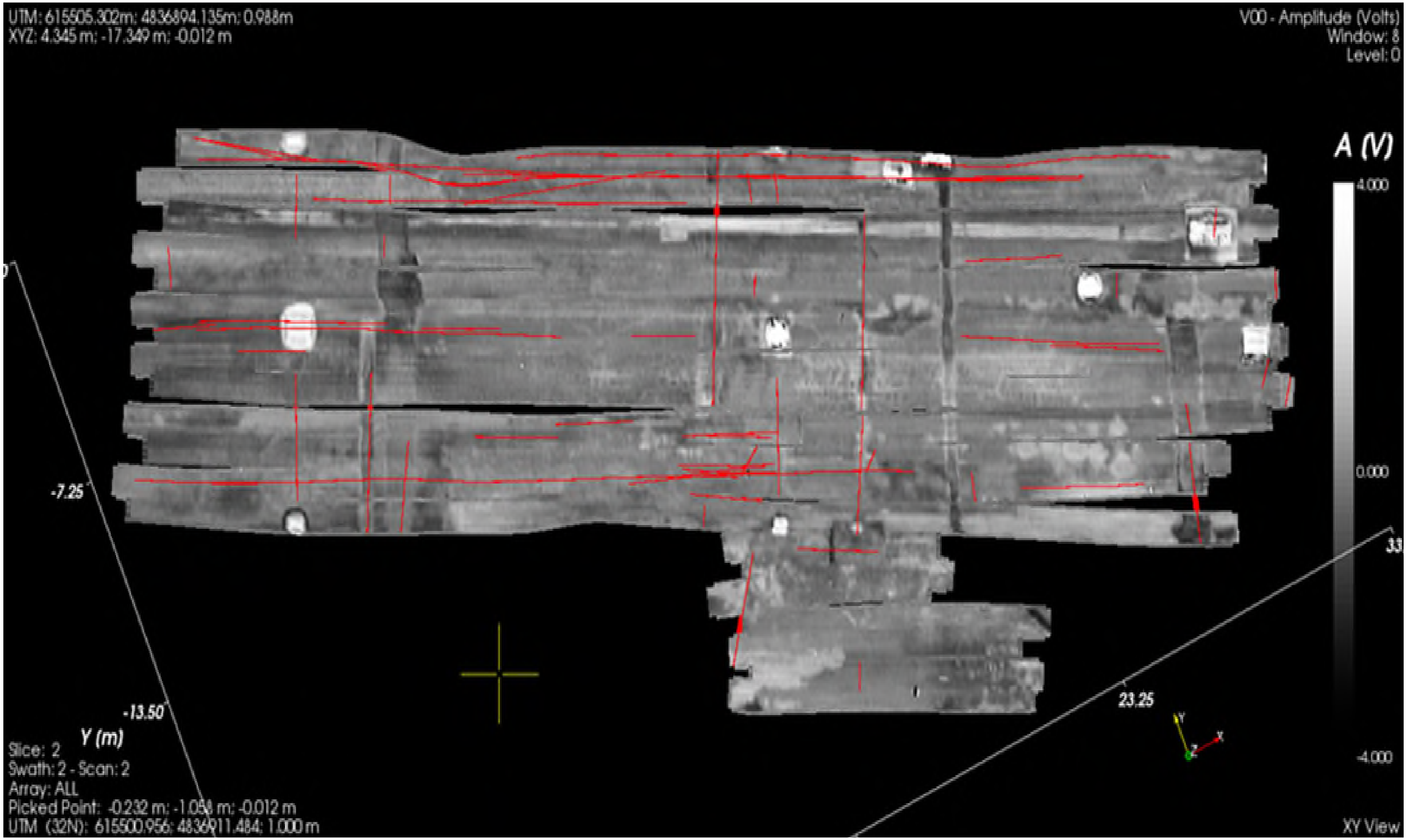


Data interpretation: Utility mapping



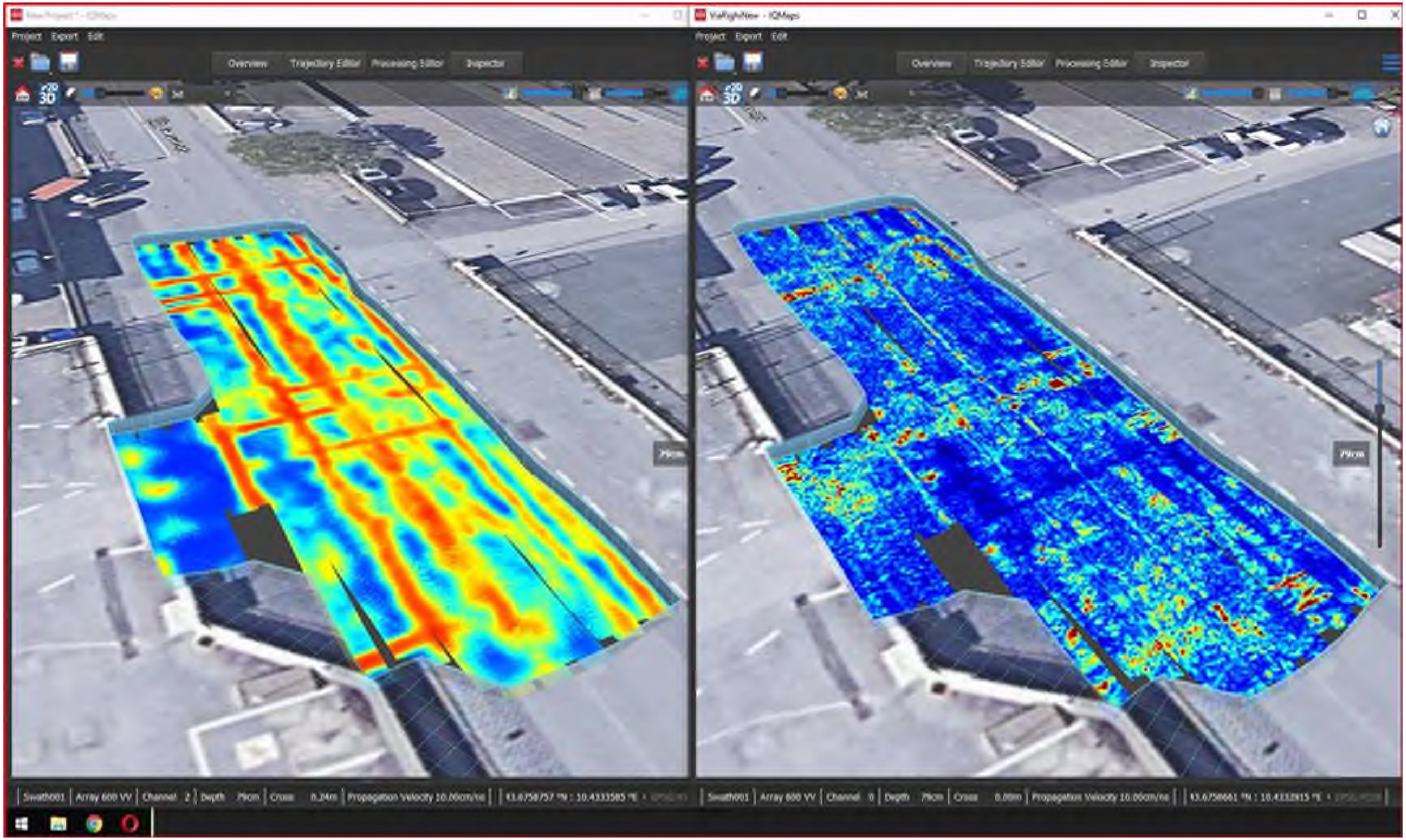
GPR DATA INTERPRETATION: OUTCOME FROM GEOFIT (KER #6 and #7) PART 1

Data interpretation: Utility mapping



GPR DATA INTERPRETATION: DEEP LEARNING (AI)

PART 1

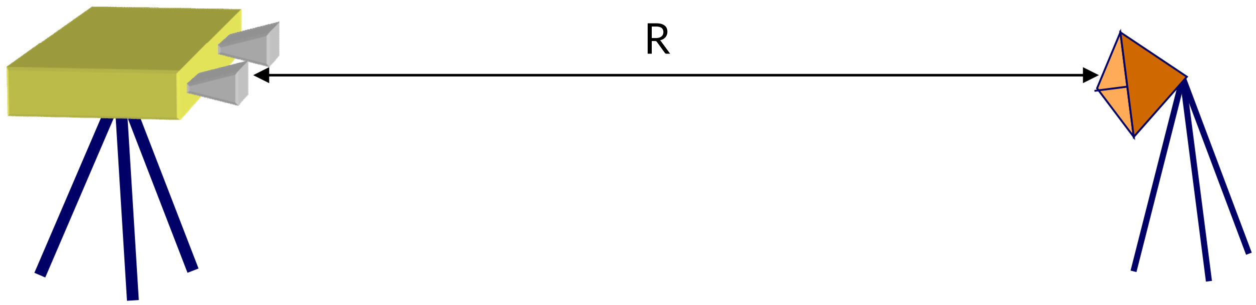


END OF PART 1

Radar stands for

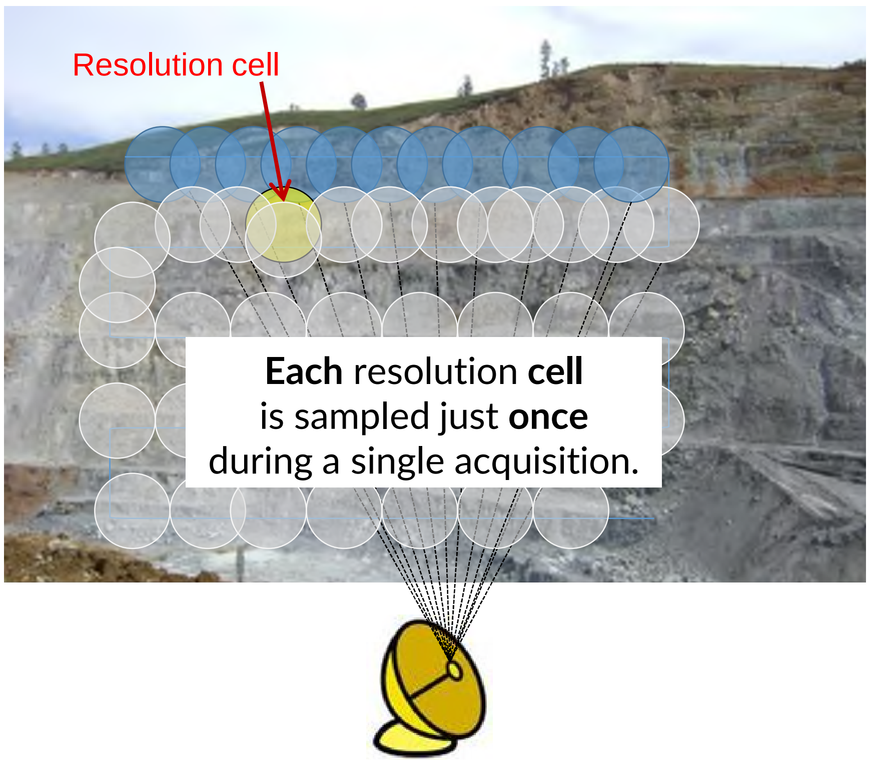
RAdio Detection And Ranging

An instrument able to detect a distant object
measuring the distance
between itself and the target

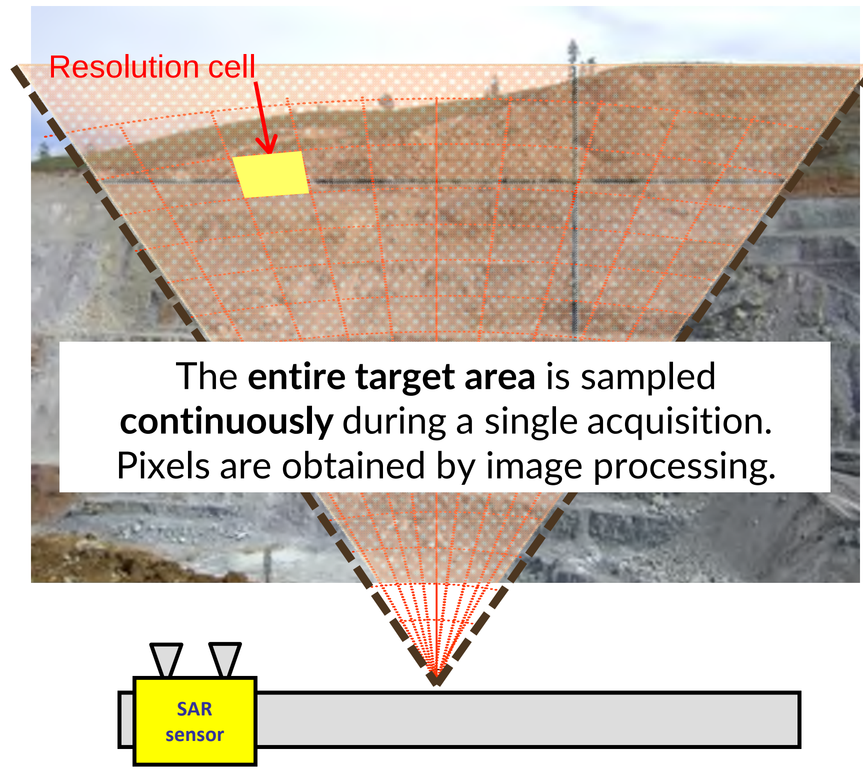


THE GBSAR WORKING PRINCIPLE

PART 2



Real Aperture Radar

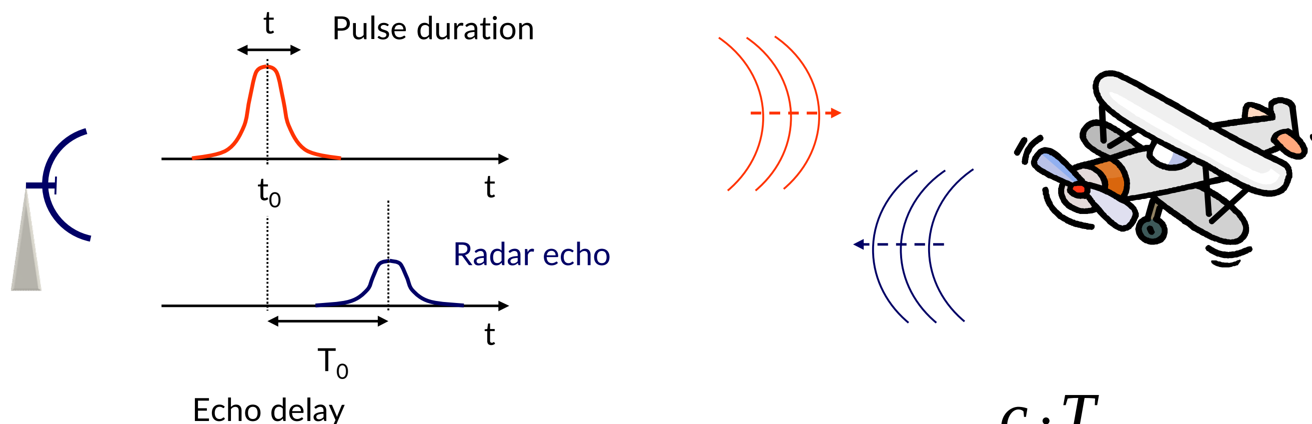


GBSAR

THE GBSAR WORKING PRINCIPLE

PART 2

Pulse Radar working principle

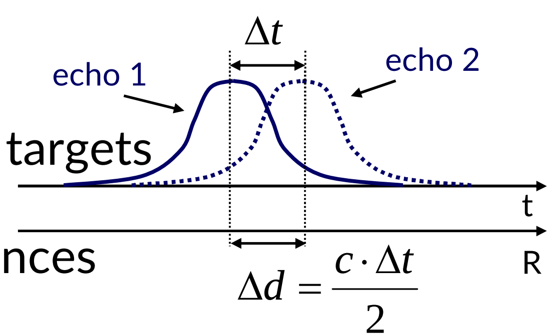


Range calculation

$$T_0 \quad \Rightarrow \quad R_0 = \frac{c \cdot T_0}{2}$$

Range Resolution

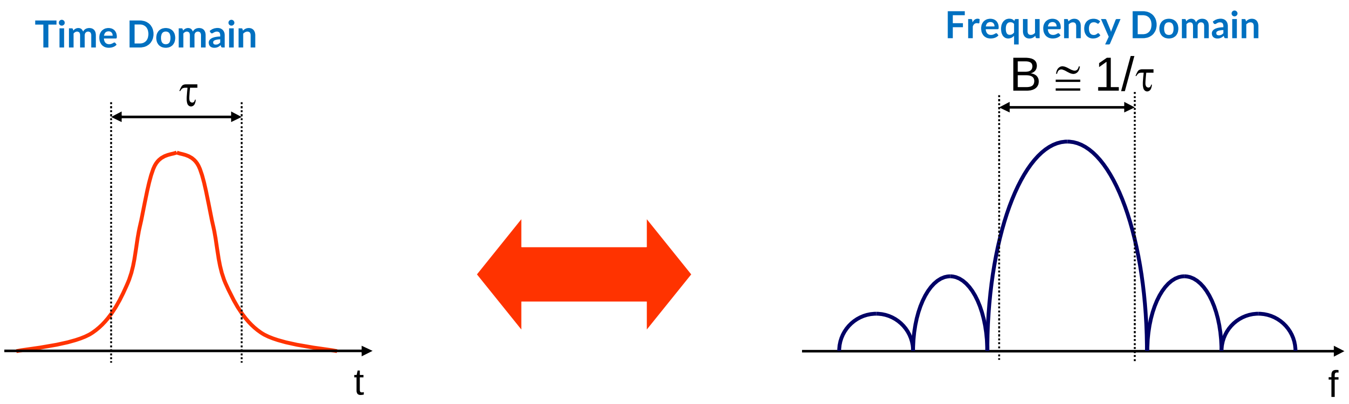
The ability to separate targets
(to see them as distinct)
at different radial distances



$$\Delta R = \frac{c \cdot \tau}{2}$$

THE GBSAR WORKING PRINCIPLE

PART 2

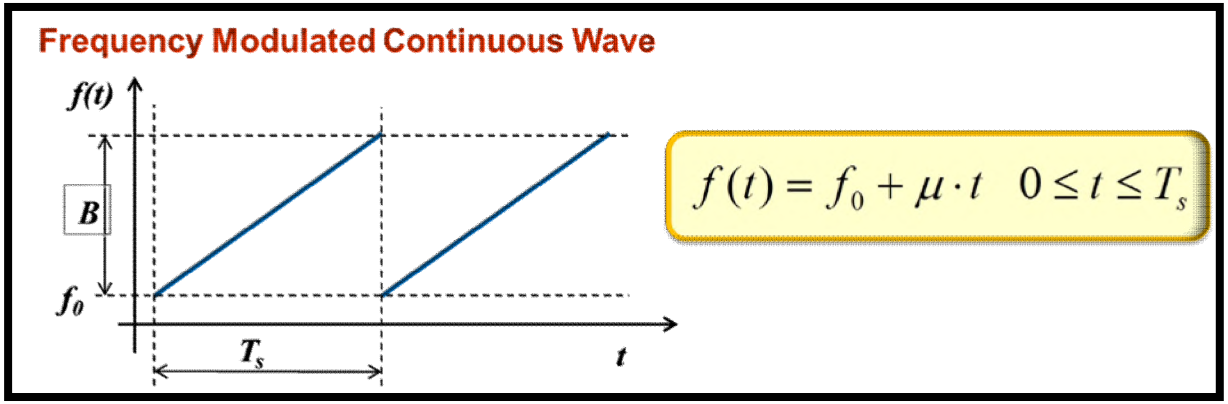


$$\Delta R = \frac{c\tau}{2} = \frac{c}{2B}$$

Range Resolution is a function of the radar Bandwidth <u>only</u>

THE GBSAR WORKING PRINCIPLE

PART 2

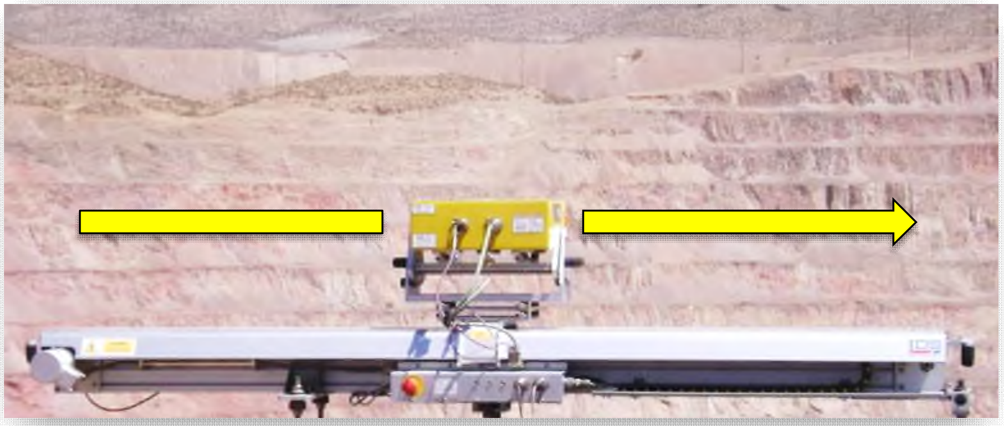


Radar Bandwidth is obtained using a modulation technique called FMCW.
EM emissions are strictly controlled by government regulations

THE GBSAR WORKING PRINCIPLE

PART 2

SAR technique enables the system to provide high *Cross-Range Resolution* exploiting the movement of the physical antenna along a straight trajectory (linear scanner)



Cross-Range Resolution

The ability to separate targets at different azimuth angles

Cross-Range Resolution is a function of the Linear Scanner length

SAR processing allows GBSAR to synthesize a 2m antenna whose azimuth beamwidth is given by the simple formula:

$$\Delta\varphi = \frac{\lambda}{2 \cdot L} = 4.36 mrad$$

Hence the name of *Synthetic Aperture Radar*

THE GBSAR WORKING PRINCIPLE

PART 2

Radar beam

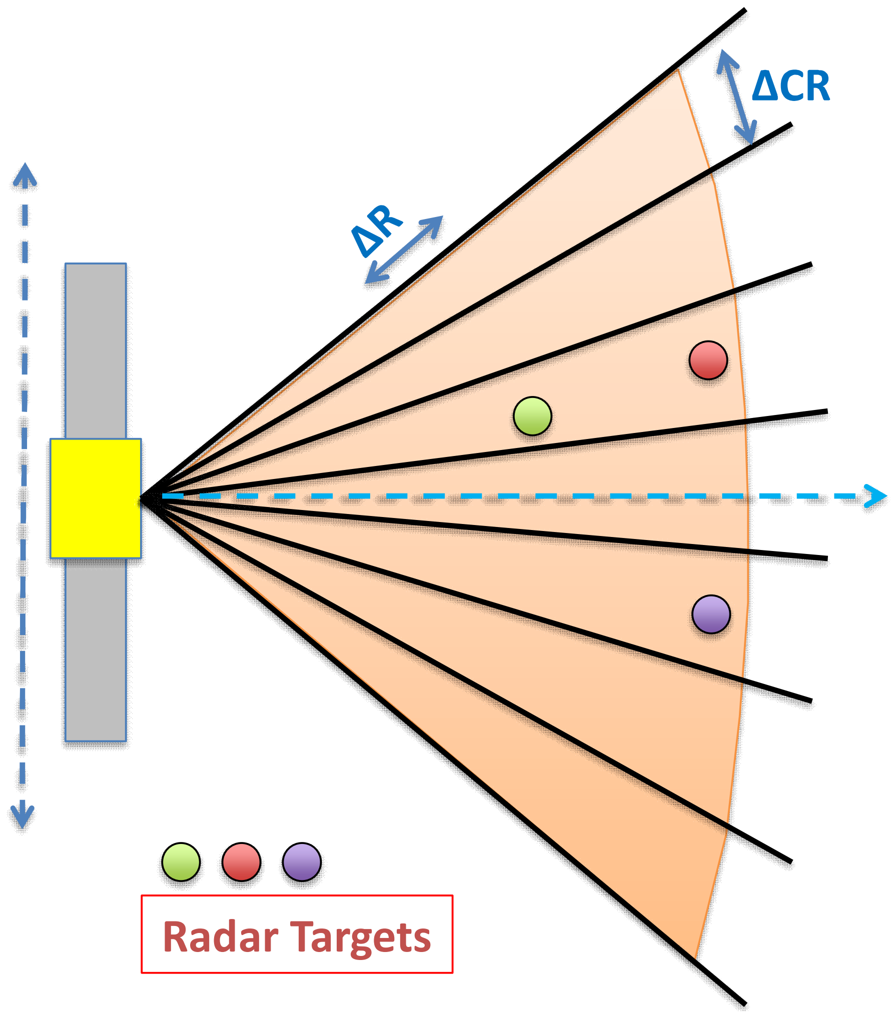
- **Max distance: up to 4 km**
- H-V coverage: given by antenna type (~80°x60° std)

FMCW

- Adds *Range Resolution*
- Related to Bandwidth
- **ΔR does not change with distance**

SAR

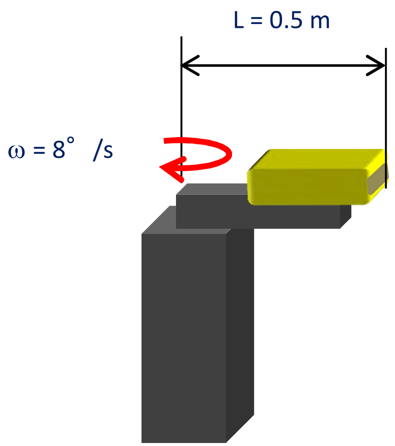
- Adds *Cross-Range Resolution*
- Related to scanner length
- **ΔCR is an angle**!

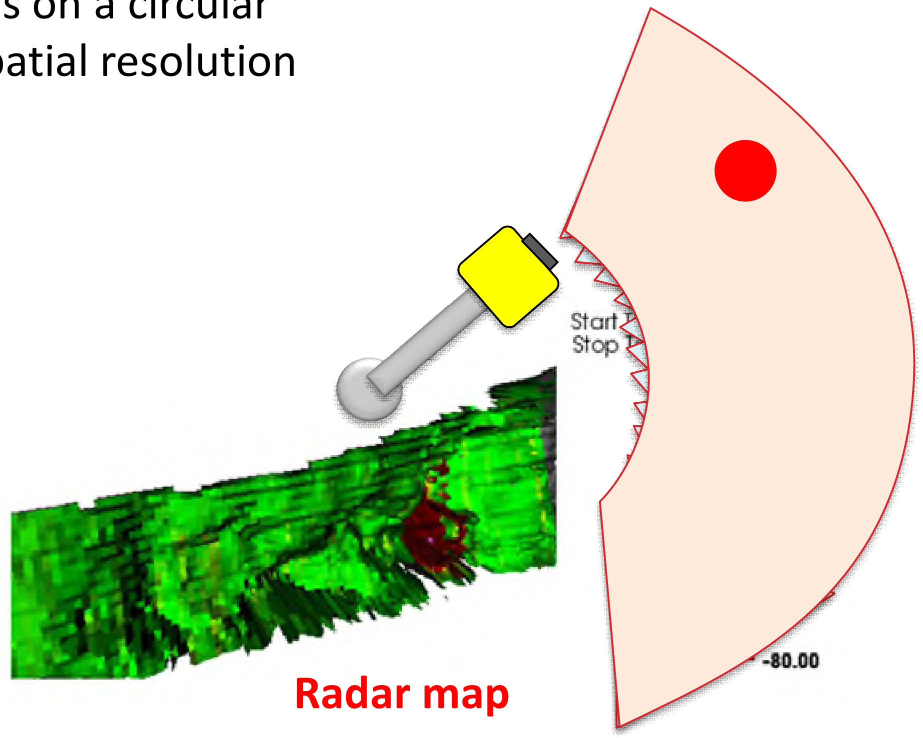


THE GBSAR WORKING PRINCIPLE

PART 2

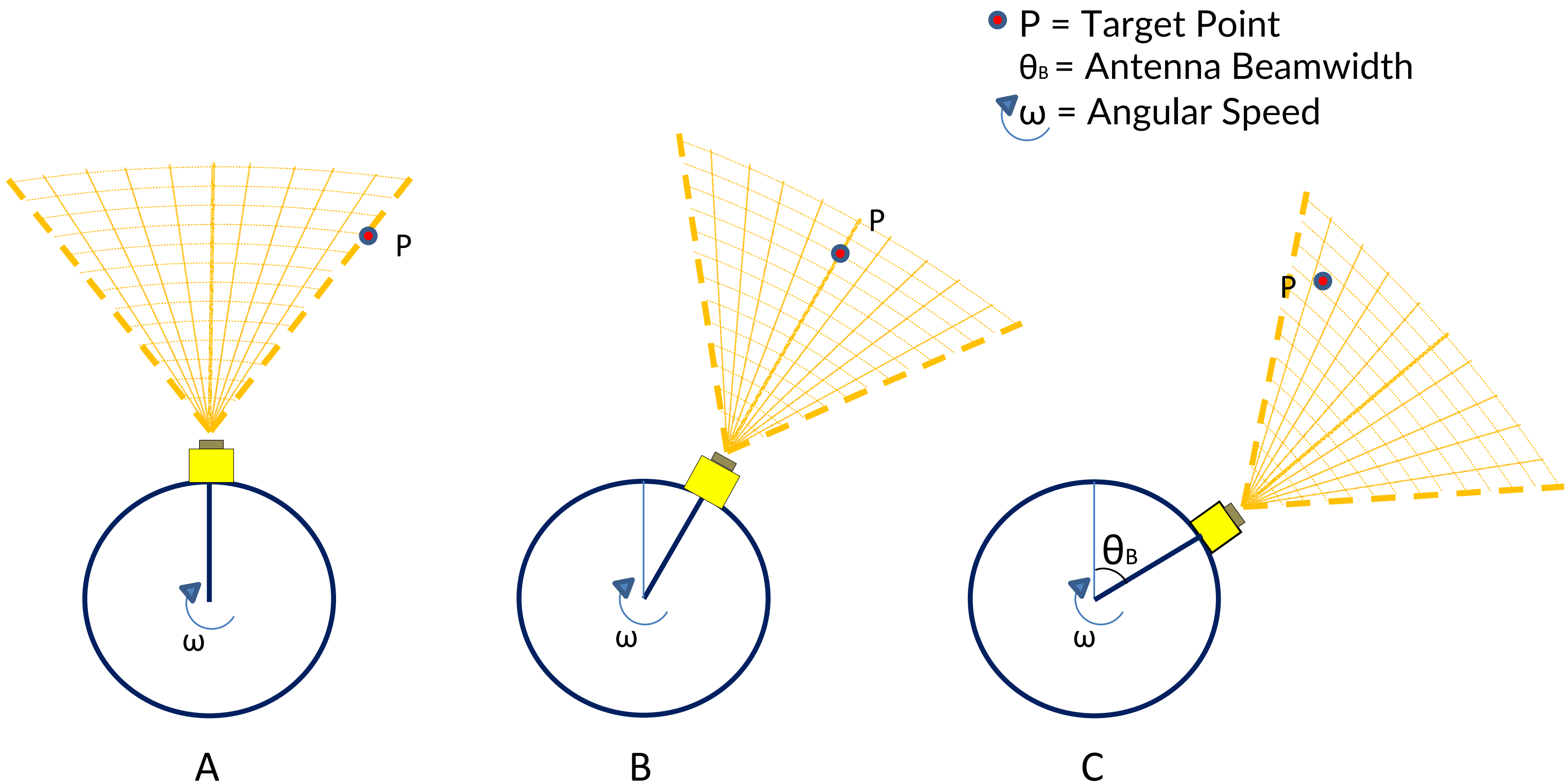
- **ArcSAR technology**: the antenna moves on a circular trajectory in order to obtain a high spatial resolution





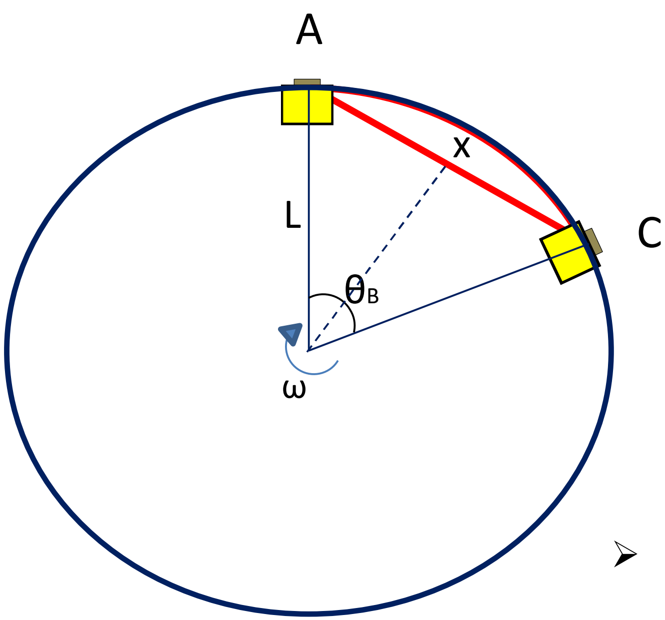
THE GBSAR WORKING PRINCIPLE

PART 2



THE GBSAR WORKING PRINCIPLE

PART 2



- The point is continuously monitored within an angle θ_B which is the antenna beamwidth. Approximating the Arc needed to complete this angle to the rope underlying the arc:

$$X = 2L \cdot \sin\left(\frac{\theta_B}{2}\right)$$

- The **cross range resolution** can be easily calculated using the formula:

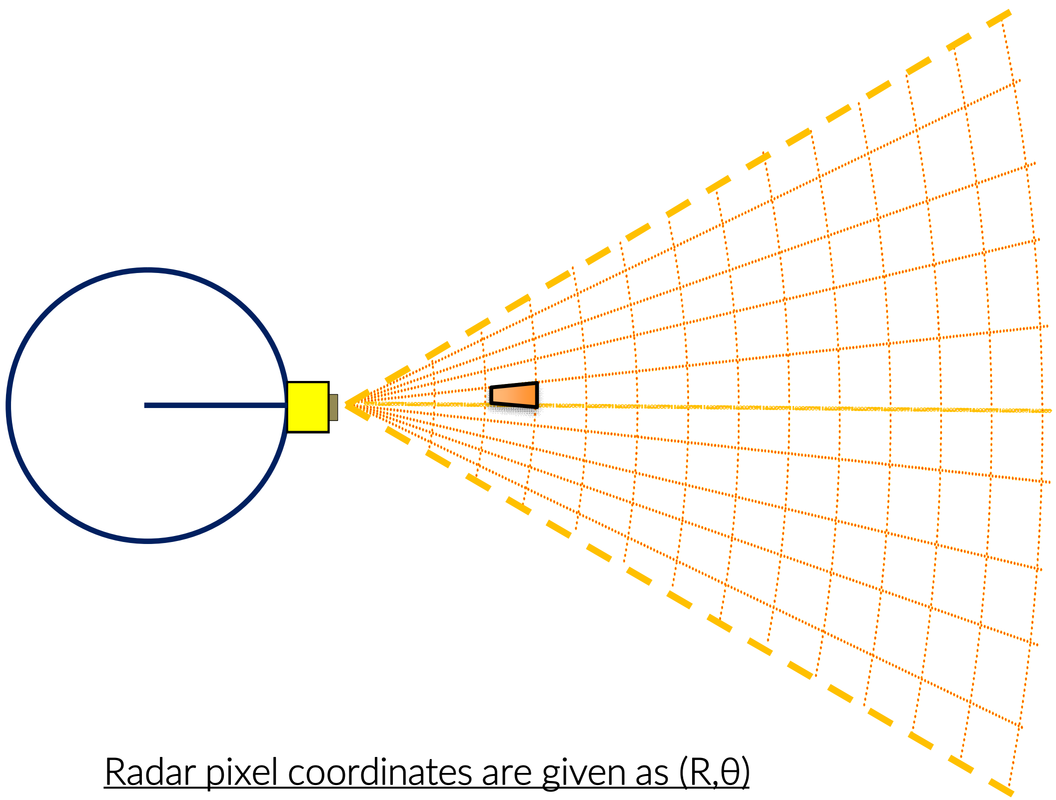
$$\Delta\varphi = \frac{\lambda}{2 \cdot L}$$

$$\boxed{\Delta CR = \frac{\lambda}{4 \cdot L \cdot \sin\left(\frac{\theta_B}{2}\right)} = 14\ mrad}$$

- **Better cross range resolution** is obtained with **longer Arc SAR arm** or **wider antenna beamwidth**, because the target is acquired by the radar during a longer movement.

THE GBSAR WORKING PRINCIPLE

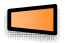
PART 2



Radar pixel coordinates are given as (R,θ)

0.15m x 0.14

Distance = 10 m



0.15m x 0.28

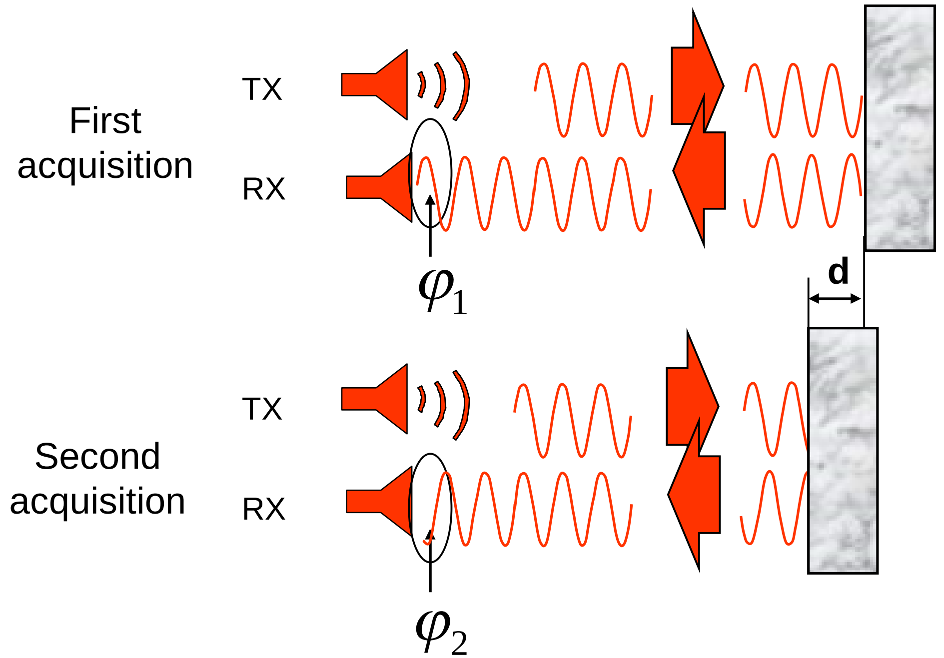
Distance = 20 m

Warning: Not to scale!

THE GBSAR WORKING PRINCIPLE

PART 2

The **interferometric analysis** provides data on object displacement by comparing phase information, collected in different time periods, of reflected waves from the object.



$$d = -\frac{\lambda}{4\pi}(\varphi_2 - \varphi_1)$$

...where λ is the radar wavelength (c/f)= 3,92mm

How can we prevent the *Phase Ambiguity* from happening?

WE CAN'T!

There is a physical limitation to the maximum displacement <u>any interferometric radar</u> can follow between two acquisitions

$$\boxed{d = -\frac{\lambda}{4\pi}(\varphi_2 - \varphi_1)} \quad \& \quad \boxed{|\varphi_2 - \varphi_1| = \pi}$$

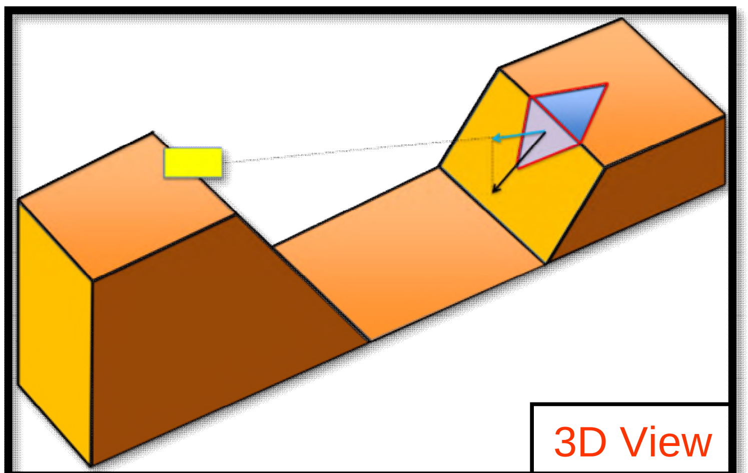
Knowing that the maximum allowed phase difference is π,
the maximum unambiguous displacement detectable by the radar is

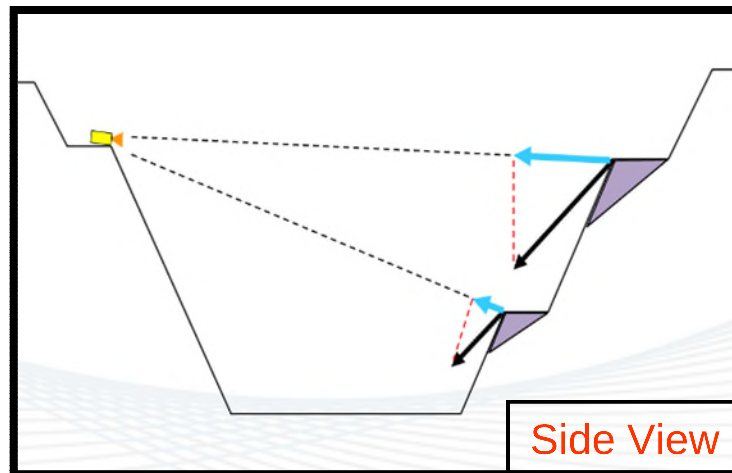
$$\boxed{\pm\lambda/4 = \pm 0.98mm}$$

Any target whose displacement exceeds the *Phase Ambiguity* value can't be resolved by the radar, thus providing ambiguous results.

Line of Sight

Displacement measurement





Failure Surface

--------- Hydra LoS

Real displacement vector

Displacement measured by the radar

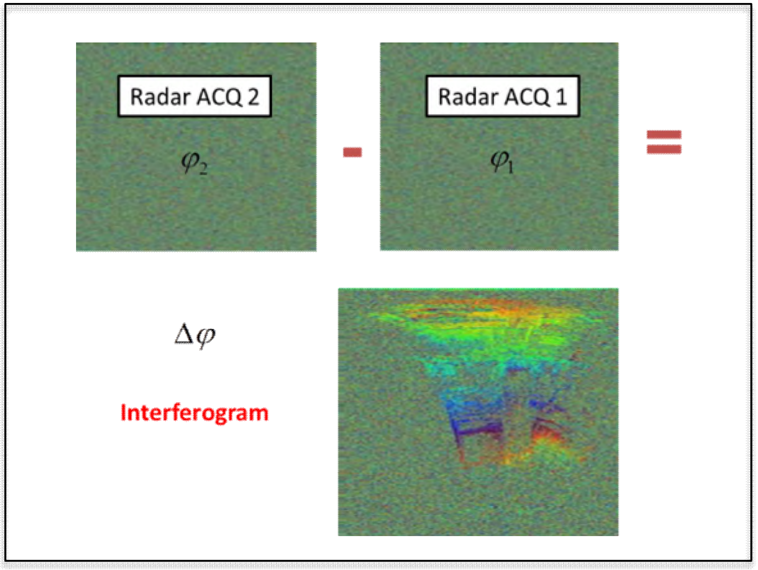
The displacement value is calculated in the direction of the system *Line of Sight (LoS)*

WARNING: Movements orthogonal to radar LoS will show **ZERO** displacement

THE GBSAR WORKING PRINCIPLE

PART 2

- During every GBSAR acquisition, a radar "echo" is collected from each pixel
- This echo brings back to GBSAR an information of signal amplitude |A(n)| and a phase φ
- ***Amplitude*** is related to the pixel backscattered power (high amplitude means good reflector)
- ***Phase*** is an angle that ranges in the interval $[-\pi;\pi]$
- An ***Interferogram*** is a map of the phase difference between any two acquisitions ($\Delta\ \varphi$).
- **An Interferogram is a map that provides information about the deformation of each and every pixel**

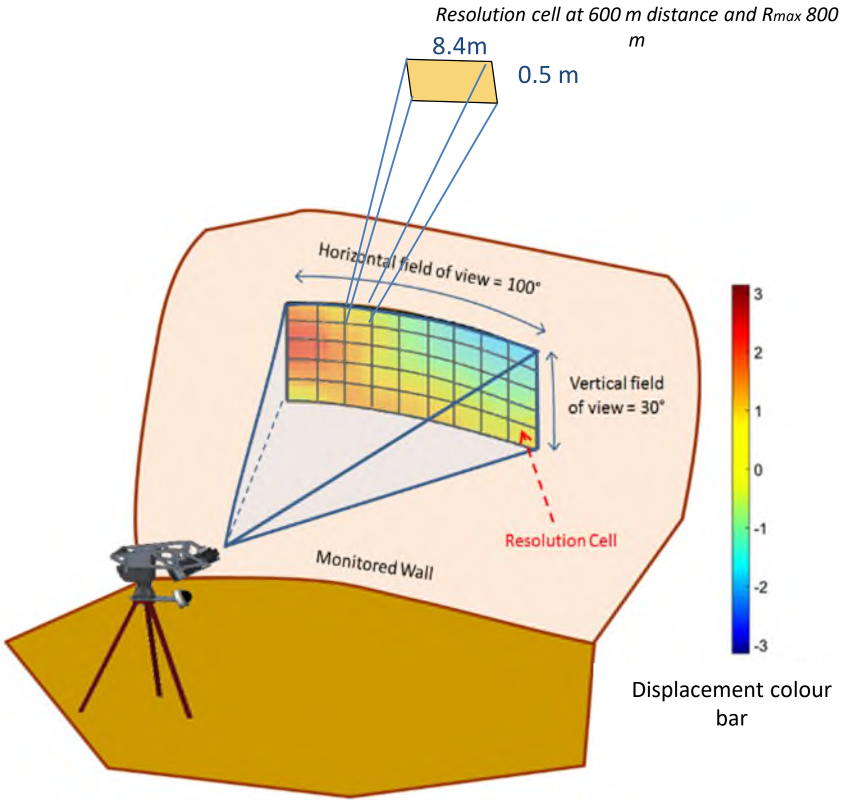


STATE OF THE ART (HYDRA G)

PART 2

- **Accuracy:** Line-of-sight displacement with an accuracy better than 0.1 mm
- On-site **data processing**
- **Integrate GNSS**
- **DTM survey** through Radar sensor
- **Coverage:** 120° horizontal x 30° vertical
- **Scan range:** between 2m - 800m
- **Spatial resolution:** 14 mrad, resolution cells 0.2 m × 1.4m @ 100 m
- **Frequency Band:** W-band (76-77 GHz)
- **Minimun Scan time:** 30 secs

Max Range	Scan Time
100, 200, 400 m	30 sec
600, 800 m	1 min

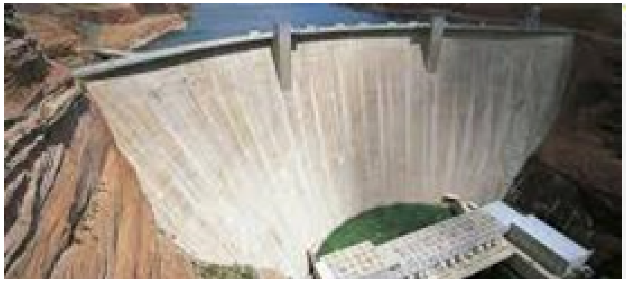


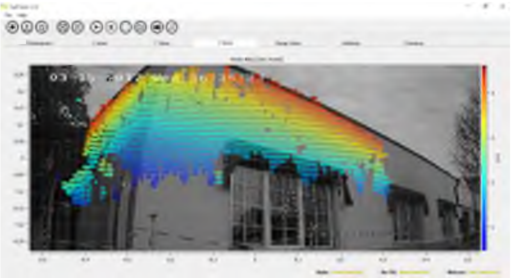
STATE OF THE ART (HYDRA G)

PART 2

Hydra-G is designed for **monitoring applications** in a variety of different application fields, including:

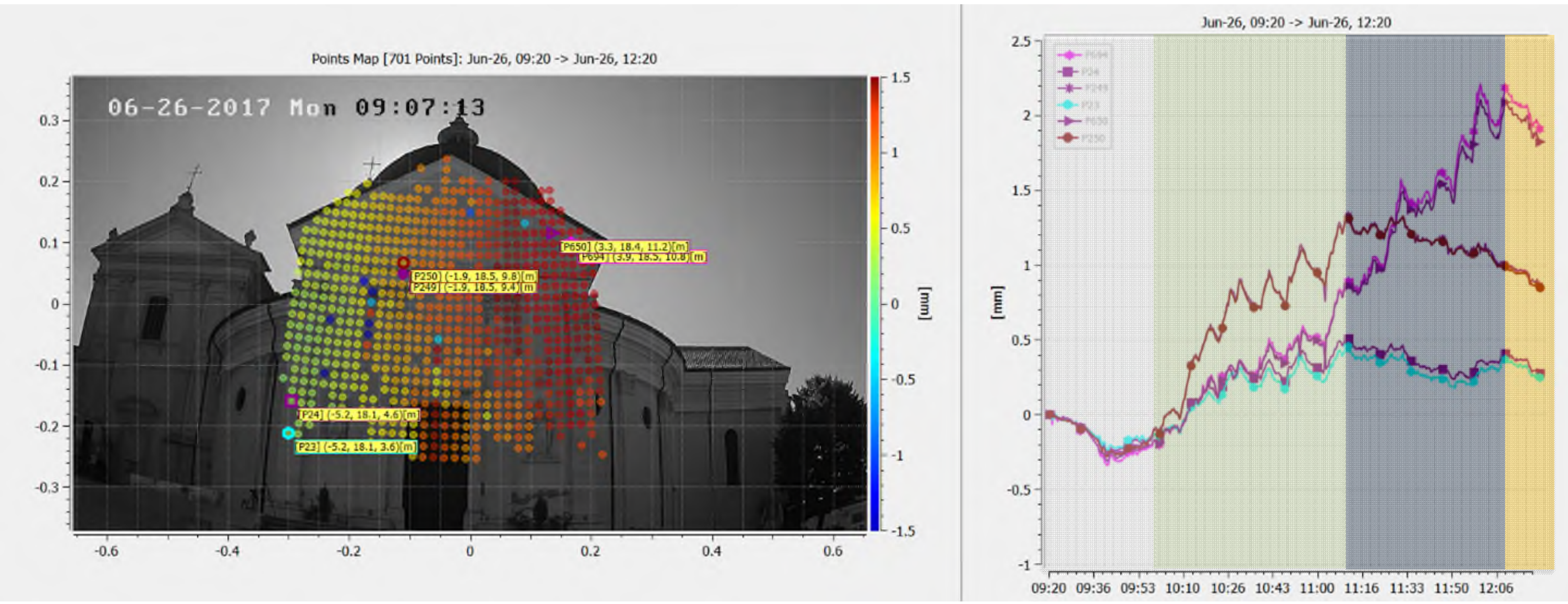
- buildings;
- dams;
- tunnels;
- cut-slopes.





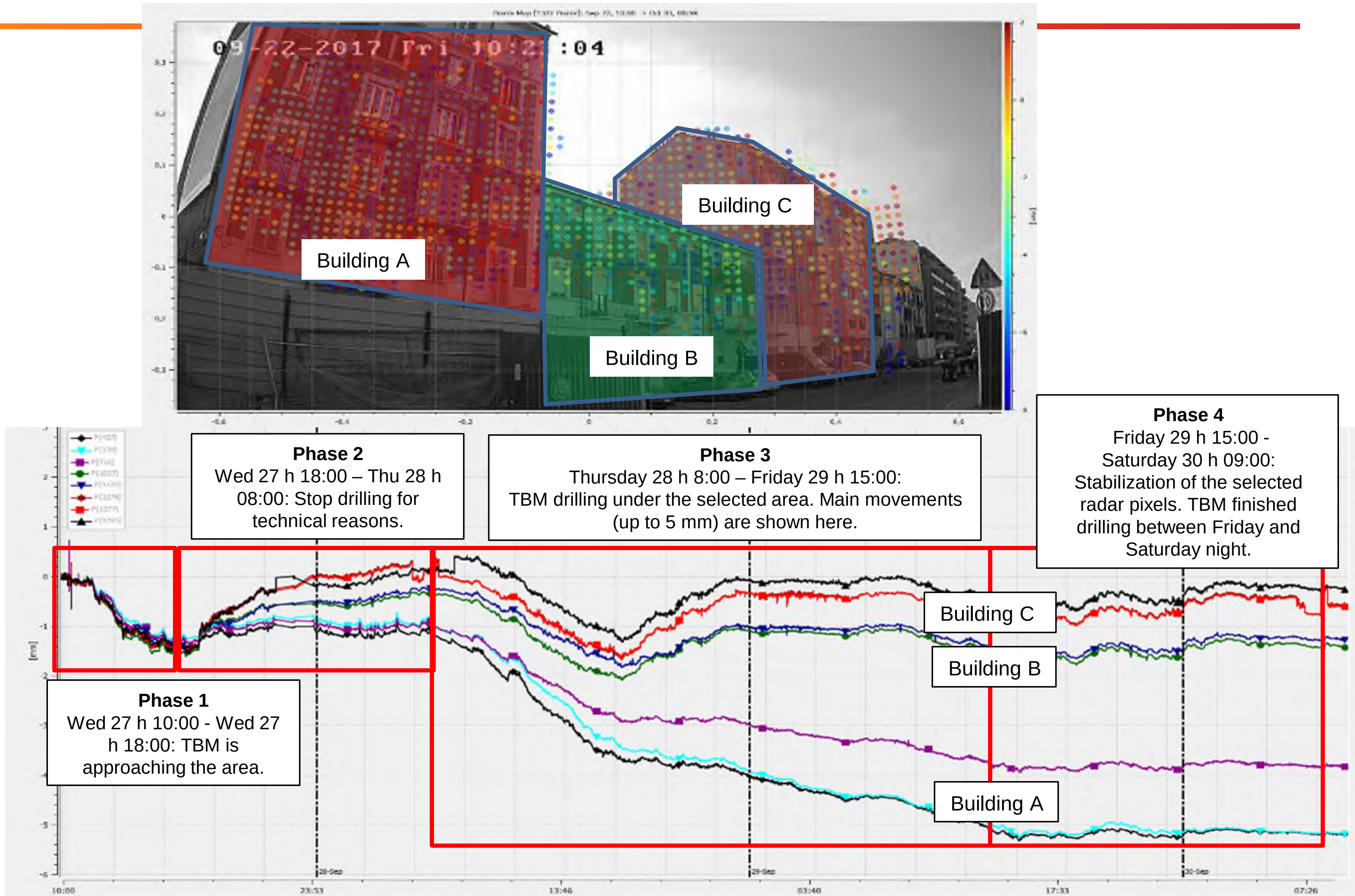
STATE OF THE ART (HYDRA G)

PART 2



STATE OF THE ART (HYDRA G)

PART 2

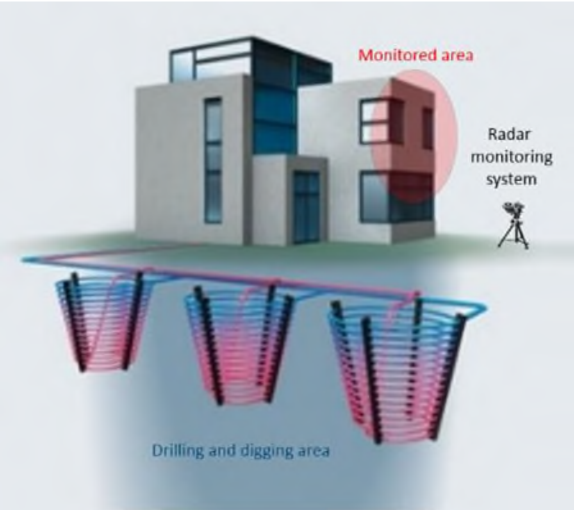


GBSAR DATA INTERPRETATION FOR DISPLACEMENT MEASURES

PART 2

- Interferometric GB-InSAR is nowadays is a key tool able for remotely monitoring **sub-millimeter displacements** at **large distance** (up to several kilometers).

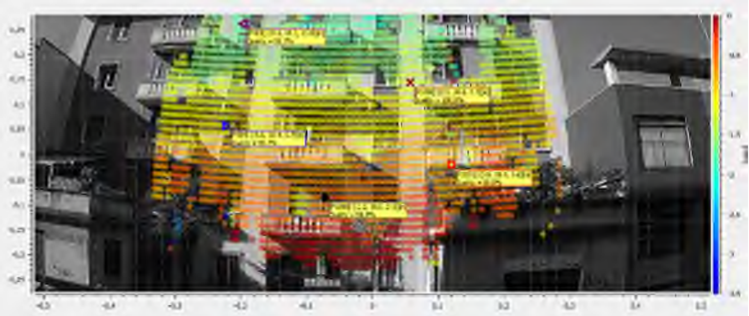
- **Typical applications** are: slope stability monitoring in mining plants, landslide monitoring in risk areas close to civil buildings, bridge load testing and stability monitoring.



Installation geometry example

- **Objectives in GEOFIT:**
    1. Evaluate GB-InSAR technology as a possible tool for building monitoring during retrofitting operations

    2. Improve radar interferometry state-of-art:
        a) Study of a fast 3D -resolution monitoring technique
        b) Reduce the effects of phase-ambiguity → capability of measuring large displacements (> 1 mm) even occuring in a short time (< 30 s)



Displacement can be shown as a heat map projected over the building surface

Thank You

GEOFIT

SMART GEOTHERMAL