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Civil Engineering Applications
of Ground Penetrating Radar

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**SPOT-GPR: a freeware tool for target
detection and localization in GPR data**

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SPOT-GPR:

1. Introduction

What?

- SPOT-GPR is a freeware processing tool for 2D-GPR raw data, aiming to provide an estimation of target position (spotting)
- It takes a collection of A-scans as input, obtained by using a linear array of sensors
- Each scan is the digitized acquisition of a single sensor within the time window, at a given sample frequency

How?

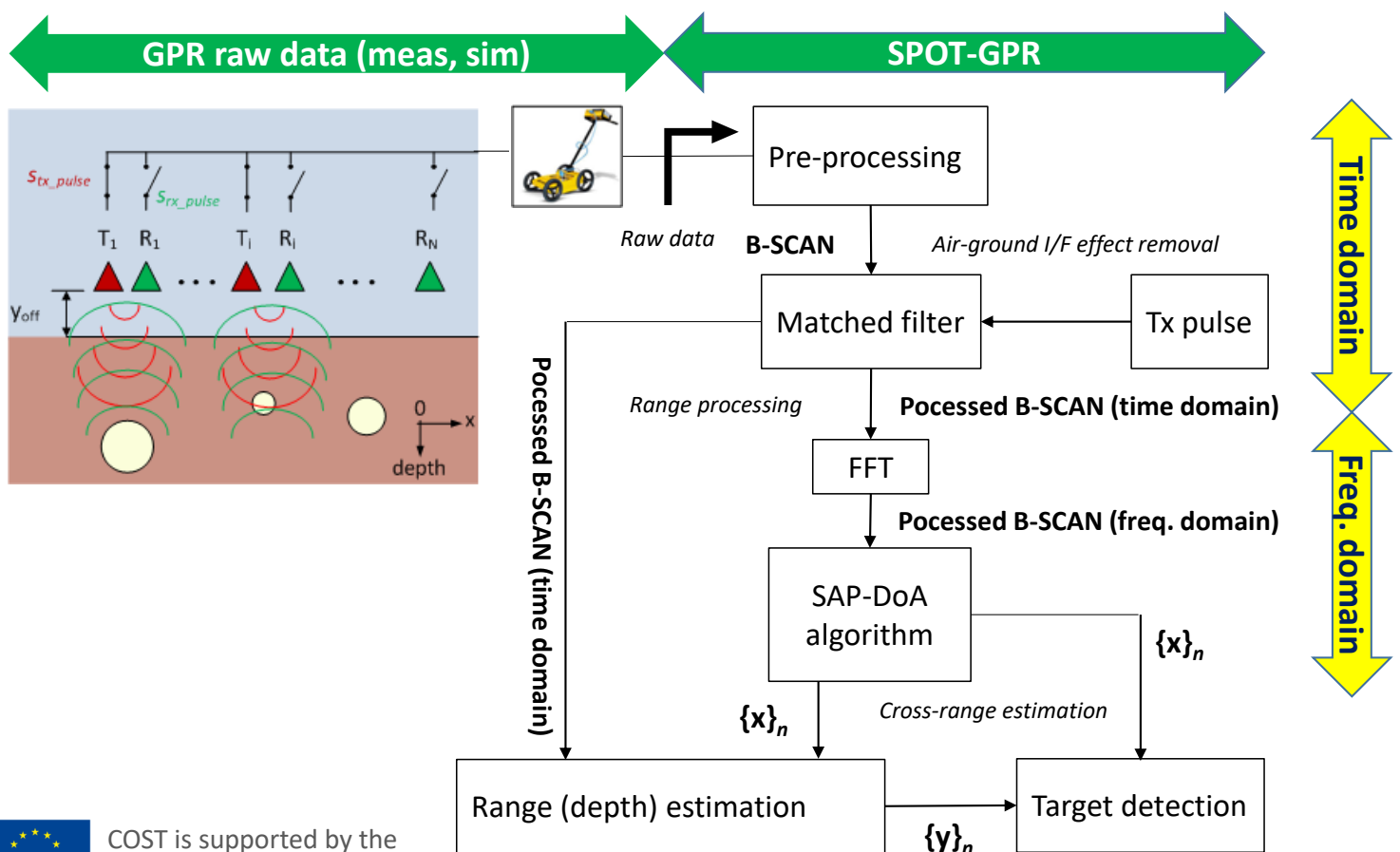
- The initial dataset is pre-processed to remove the effect of the air-ground interface, by using a dataset of only-ground measurements (no target)
- A two-stage processing algorithm is then applied, both in time (range) domain and in frequency (cross-range) domain



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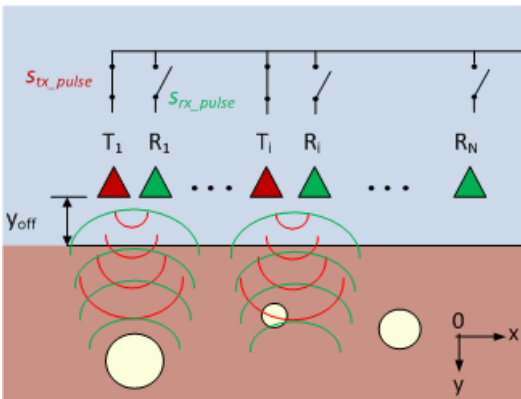
SPOT-GPR:

2. Processing layout



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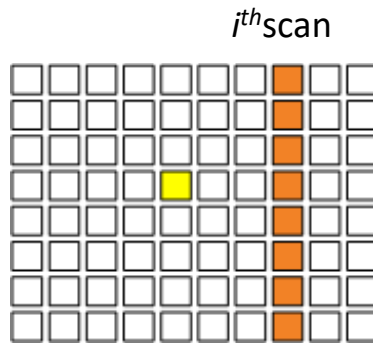
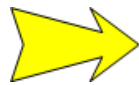
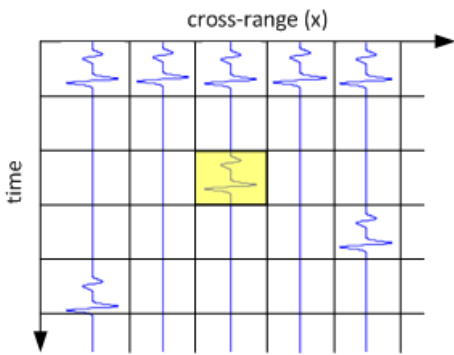
SPOT-GPR: 3. Dataset acquisition



δ_{cr} (cross-range spacing) and δ_{τ} (time window) define a patch of signal energy \propto signal energy [W·sec] in the patch $\delta_{\tau} \times \delta_{cr}$.

δ_{cr} = spacing in cross-range (d)

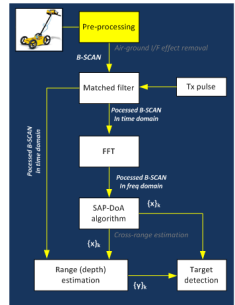
δ_{τ} = time window (τ) / no. of scan per sample (S)



B-SCAN [S x M]

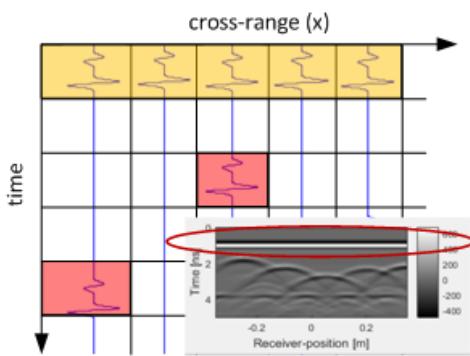
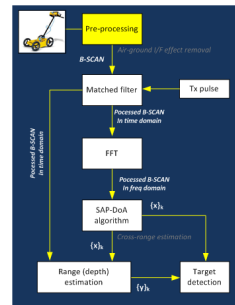
S: no. of samples per scan

M: no. of sensors

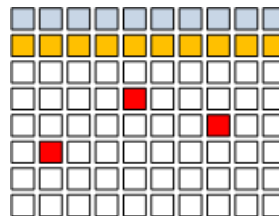


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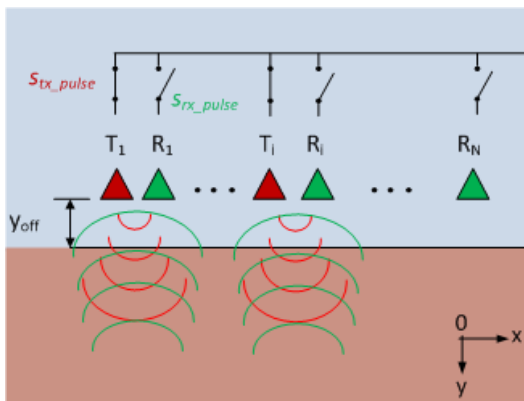
SPOT-GPR Step 1 : 4. Air-ground I/F effect removal



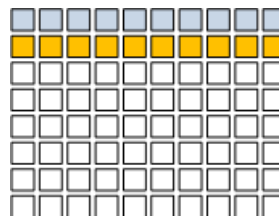
The air-ground interface spreads over all the cross-range dimension.



air-ground I/F return
targets



A target-free B-SCAN with same dimension can be acquired in order to filter the I/F effect out

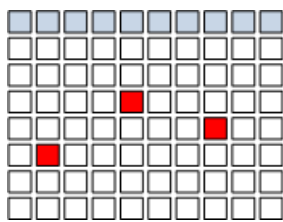
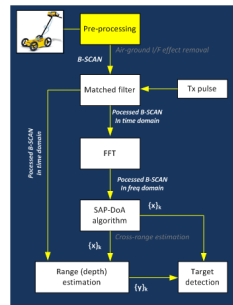
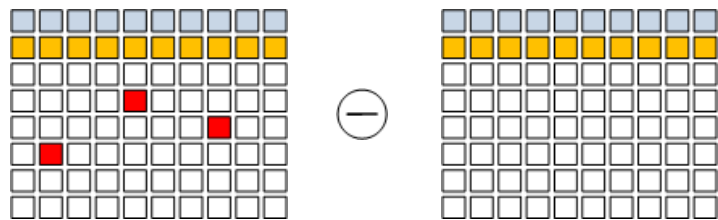
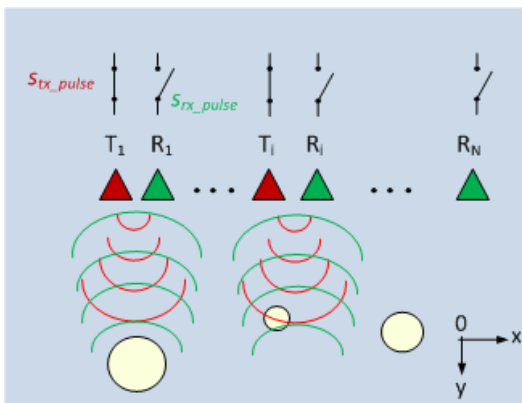


Air/interface/ground dataset



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SPOT-GPR Step 1 : 4. Air-ground I/F effect removal



only-target dataset

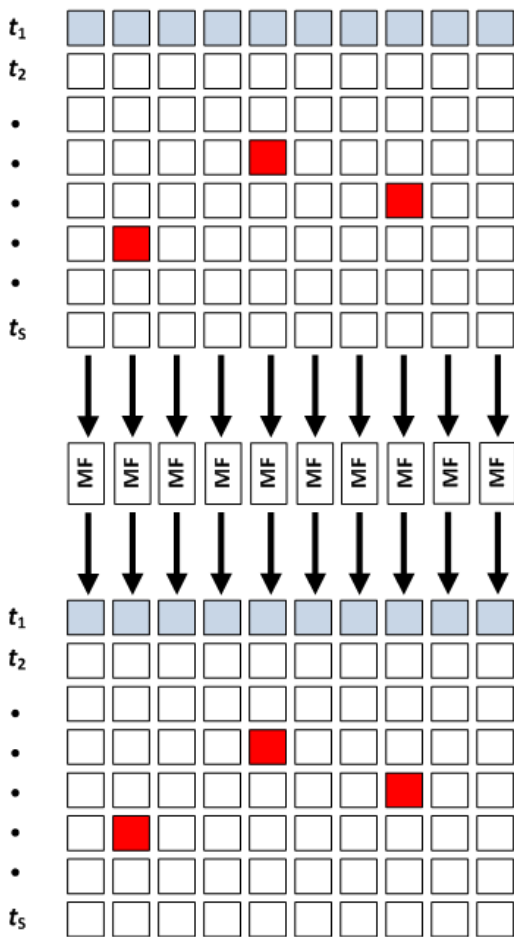
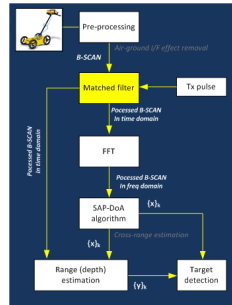
Note: if an air gap is present, the corresponding range bins are larger than other ground range bins and it has to be taken onto account in post-processing.



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SPOT-GPR Step 2 :

5. Range processing (matched filter)



Transmit waveform

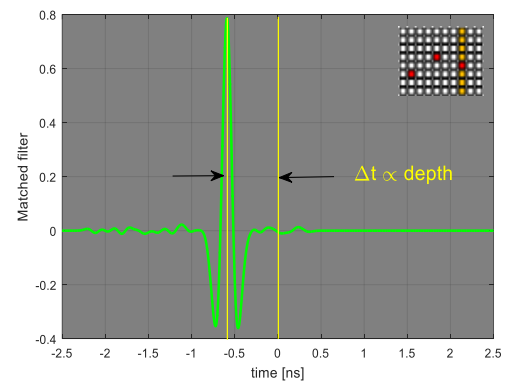
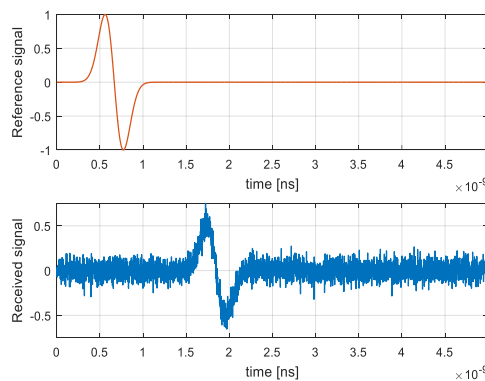
$$x(t) \quad 0 \leq t \leq \tau$$

Matched filter

$$h(t) = ax^*(-t) \quad 0 \leq t \leq \tau \quad a \text{ is a constant}$$

The filter operation is defined in terms of a convolution integral (i.e. between range lines and reference Tx signal)

$$y(t) = \int_{-\infty}^{\infty} x(\rho)h(t - \rho)d\rho = a \int_{-\infty}^{\infty} x(\rho)x^*(\rho - t)d\rho$$

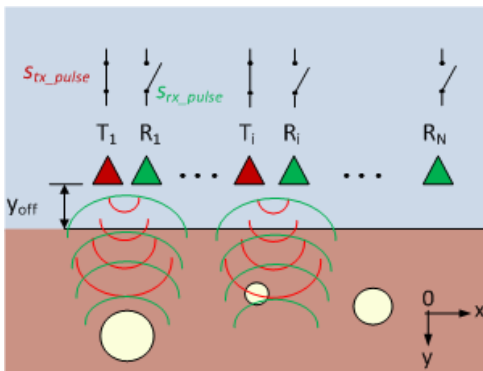
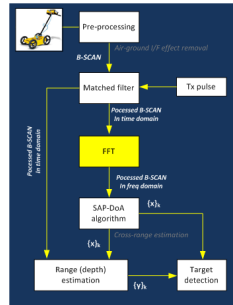


SPOT-GPR Step 3 :

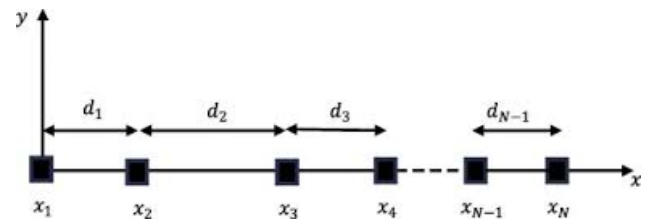
6. Cross-range processing (SAP-DoA)

SAP-DoA method principal characteristics:

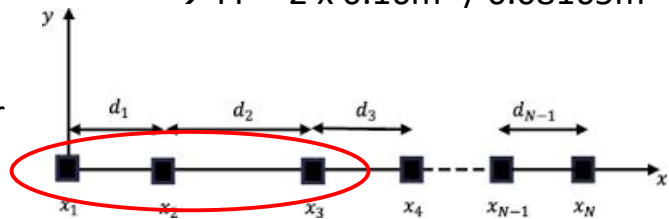
- **Subarray processing (SAP) of the original array**
- DoA estimation from each subarray
- DoA triangulation and crossin pattern extraction
- Statistical filtering



For ULA the FF distance is $2L^2/\lambda$



es. $f = 1.5 \text{ GHz}$, $\epsilon_r = 6$, $d = \lambda/2$, $M = 11$
 $\rightarrow L = 10 \times 0.08165\text{m} \times 0.5 \approx 40 \text{ cm}$
 $\rightarrow \text{FF} \approx 2 \times 0.16\text{m}^2 / 0.08165\text{m} \approx \mathbf{3.9\text{m!}}$



By partitioning the whole array into smaller subarrays, the e.m. field received by each subarray, is a **plane wave**.

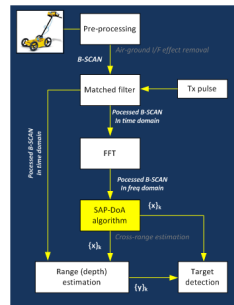
Considering a 3-element array, $L \approx 8 \text{ cm}$, and near targets can be properly detected



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SPOT-GPR Step 3 : 6. Cross-range processing (SAP-DoA)

➤ DoA estimation from each subarray



If the impinging signal at each subarray is a plane wave, a narrow-band signal model can be applied for each frequency component...

... So that, a dominant DoA can be estimated for every subarray and for a number of frequency points, representing the direction of the maximum received power (target) over frequency...

... Adjacent subarrays will probably see the same target at different aspect angles and their DoAs can be collected and processed to obtain information about target cross range position!

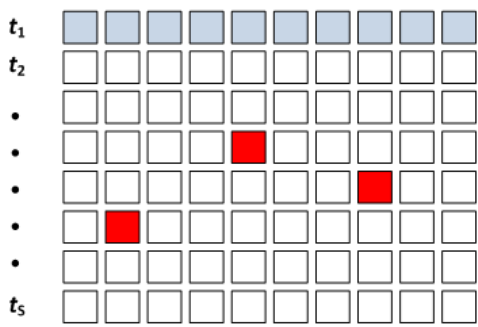
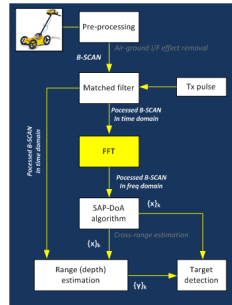


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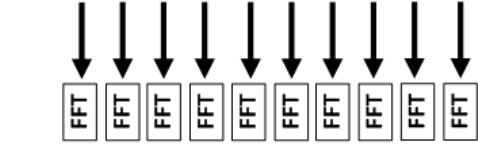
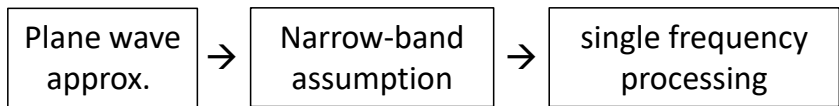
Some plants or trees
can cause allergic reactions

SPOT-GPR Step 3 :

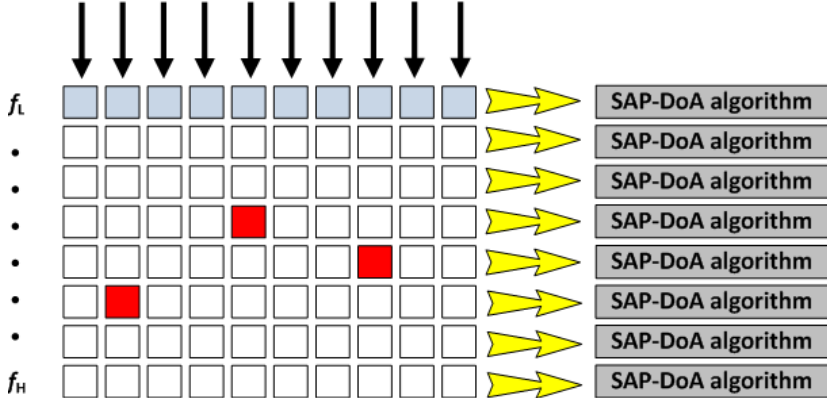
6. Cross-range processing (SAP-DoA)



Processed B-SCAN in time domain (Range processing)



Processed B-SCAN in frequency domain



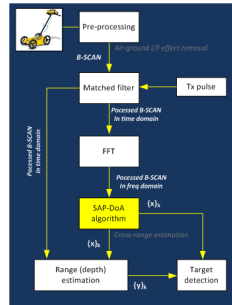
$f_L : f_{\text{step}} : f_H$ (N values)
 $BW = f_H - f_L$

Cross-range processing (angular filtering)

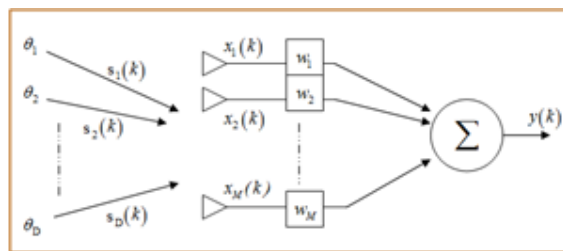


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SPOT-GPR Step 3 : 6. Cross-range processing (SAP-DoA)



Signal model



$$y(k) = \mathbf{w}^T \cdot \mathbf{x}(k)$$

$\mathbf{x}(k)$ – vector of received signals at the k^{th} time instant

\mathbf{a} – steering vector

\mathbf{w} – weight vector (angular filter) es. MUSIC

$$\mathbf{x}(t) = \sum_{d=1}^D \mathbf{a}(\theta_d) s_d(t) + \mathbf{n}(t)$$

$$\mathbf{a}_{\text{ULA}}(\theta) = [1 \quad \dots \quad e^{-(M-1)jkd \cos \theta}]^T$$

$$\mathbf{w}(\vartheta) \quad ?$$

\mathbf{R}_{xx} – array correlation matrix

$P(\mathbf{w})$ – average power

$$\begin{aligned} \mathbf{R}_{\text{xx}} &= E[\mathbf{x} \cdot \mathbf{x}^H] = \\ &= E[(\mathbf{A} \cdot \mathbf{s} + \mathbf{n}) \cdot (\mathbf{A} \cdot \mathbf{s} + \mathbf{n})^H] = \\ &= \mathbf{A} \cdot E[\mathbf{s} \cdot \mathbf{s}^H] \cdot \mathbf{A}^H + E[\mathbf{n} \cdot \mathbf{n}^H] = \\ &= \mathbf{A} \cdot \mathbf{R}_{\text{ss}} \cdot \mathbf{A}^H + \mathbf{R}_{\text{nn}} \end{aligned}$$

$$\begin{aligned} P(\mathbf{w}) &= E\left\{ \frac{1}{K} \sum_{k=1}^K |y(t)|^2 \right\} = \\ &= \frac{1}{K} \sum_{k=1}^K \mathbf{w}^H \cdot E\left\{ \mathbf{x}(t) \mathbf{x}^H(t) \right\} \mathbf{w} = \\ &= \mathbf{w}^H \cdot \mathbf{R}_{\text{xx}} \cdot \mathbf{w} \end{aligned}$$

SPOT-GPR Step 3 :

6. Cross-range processing (SAP-DoA)

The most intuitive approach consists of a beam steering in all the direction ϑ_i of interest. In this case the weight vector is a replica of the steering vector calculated in ϑ_i .

$$w_b(\vartheta_i) = a(\vartheta_i) = [1, \dots, e^{-(M-1)kd \cos \vartheta_i}]$$

$$P(w_b) = w_b^H R_{xx} w_b = \left| \sum_d a^H(\vartheta_i) \cdot a(\vartheta_d) s_d(t) + n(t) \right|^2$$

→ $P(\mathbf{w})$ peaks occur for $\vartheta_i = \vartheta_d$. This sounds like a kind of an angular matched filter!!!

Unfortunately this simple beamforming suffers of poor angular resolution. More sophisticated super-resolution algorithms can be implemented (i.e. **MUSIC**, ESPRIT, etc.).

Given N_{SUB} subarray, the principal N_{SUB} DoAs are then estimated:

$$DOA_j = \max_{\vartheta} \{P(\mathbf{w}_b)\} \\ j = 1, \dots, N_{SUB}$$



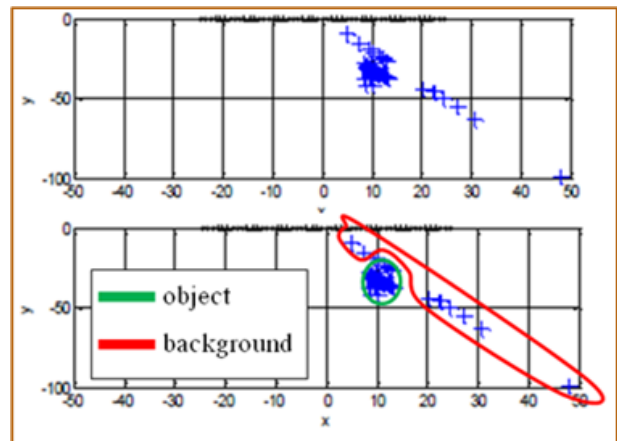
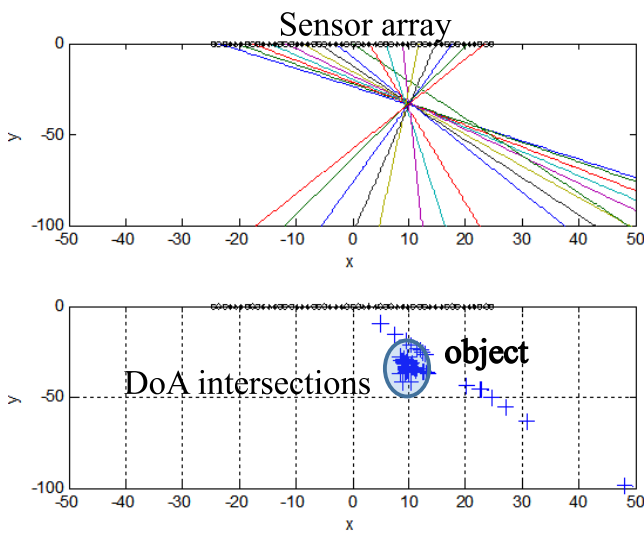
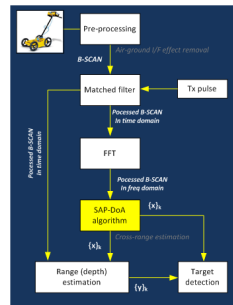
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SPOT-GPR Step 3 : 6. Cross-range processing (SAP-DoA)

➤ DoA triangulation and crossin pattern extraction

The interception of all the N_{SUB} DoAs combine to form a **crossing pattern**.

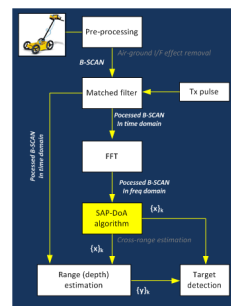
The crossing pattern contains both target spots and noisy samples. In order to extract precise information about target, **the undesired noise crosses must be cleaned out.**



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SPOT-GPR Step 3 : 6. Cross-range processing (SAP-DoA)

➤ Statistical filtering



A nice property of crossing pattern is that **spots have different density**. Target crossings are greater and more dense than background crossings.

This property can be properly exploited by using the **Poisson distribution** function

$$P_{\lambda}\{X = k\} = p_{\lambda}(k) = \frac{e^{-\lambda} \lambda^k}{k!}$$

k is the number of crossing in a given window and λ is the density rate

$$P(X = k | \text{Background}, \hat{\lambda}_b) = \frac{1}{k!} e^{-\hat{\lambda}_b} - \hat{\lambda}_b^k$$

False alarm probability

$$P_{fa} = \sum_{k=\mathcal{K}}^{\infty} f_X(k | H_0, \hat{\lambda}_b)$$

$$P(X = k | \text{Target}, \hat{\lambda}_t) = \frac{1}{k!} e^{-\hat{\lambda}_t} - \hat{\lambda}_t^k$$

Detection probability

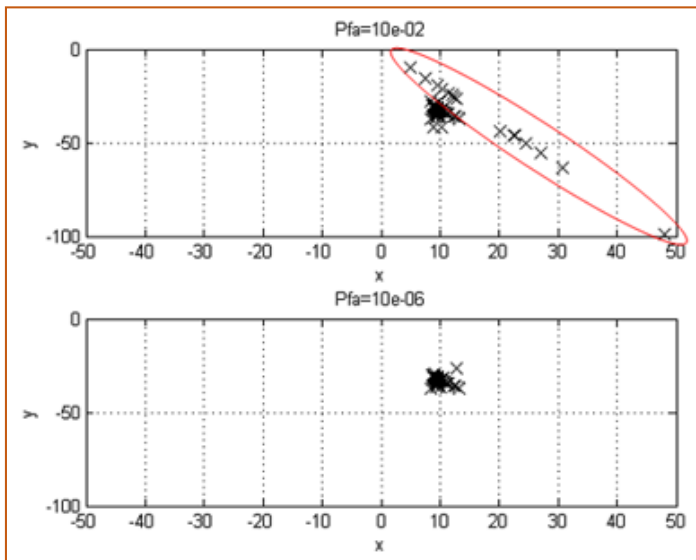
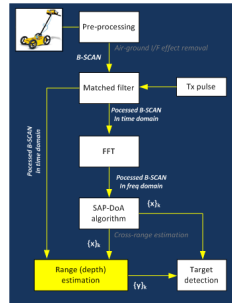
$$P_d = \sum_{k=\mathcal{K}}^{\infty} f_X(k | H_1, \hat{\lambda}_t)$$



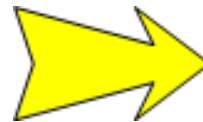
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SPOT-GPR Step 4 :

7. Parameter extraction (cross-range)

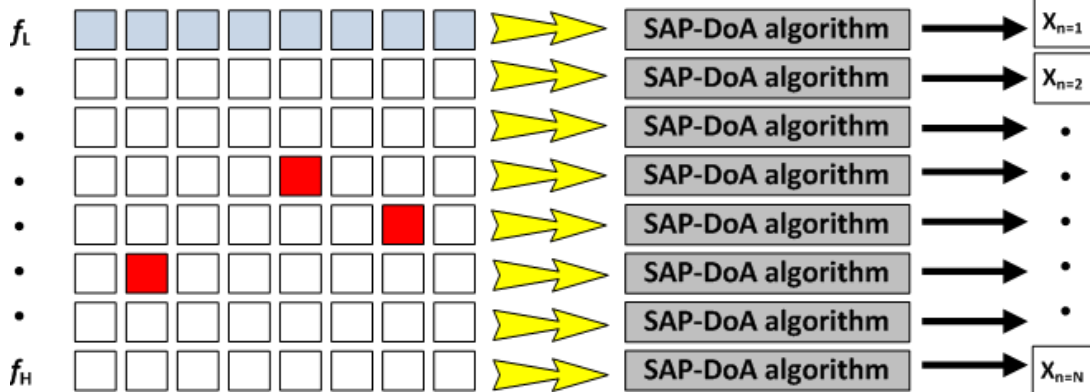


Statistical filtering for every processed frequency line



Simple average of the x coordinates

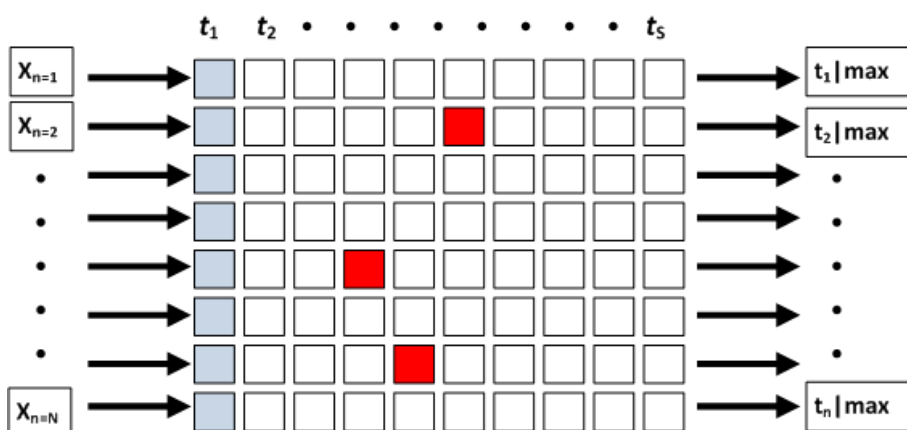
$$x_n = \frac{1}{P} \sum_{p=1}^P x_p$$



N = no. freq. points

P = no. crossings in every single crossing pattern

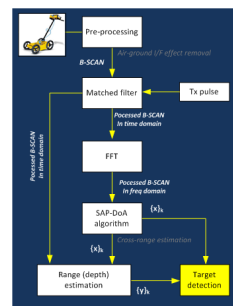
SPOT-GPR Step 4 : 7. Parameter extraction (range)



$t_n | \max$ ($n = 1, \dots, N$) is the time sample corresponding to the maximum value in the processed B-SCAN, addressed by the n^{th} coordinate in cross-range x_n .

$$y_n = \frac{\left(y_{off} - \frac{c \cdot t_n}{\sqrt{\epsilon_r}} \right)}{2}$$

Where y_{off} is the length of the in-air propagation path



8. SPOT-GPR example

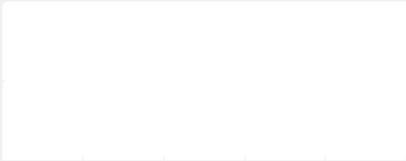
STEP 1 - LOAD INPUT FILES

Background input file

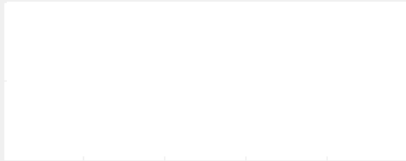
Simulation input file

Pulse input file

B SCAN



Processed B SCAN



STEP 2 - SETTINGS

Centre frequency [MHz]

Bandwidth [MHz]

Frequency resolution [MHz]

No. of samples per scan

Time window [ns]


Scan spatial sampling [m]

Antenna-ground distance [m]

Dielectric constant of ground

False-alarm probability

STEP 3 - SPOTTING



Bottom left

Bottom right

Top left

Top right

X-estimation

Depth estimation



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8. SPOT-GPR example

Step - 1. **Load input files:** relevant input files (background, simulation/measurement, Tx-pulse).

Step - 2. **Settings:** simulation settings.

Step - 3. **Spotting:** interactive spotting.

Background input file format (.txt)

The COST_DOA tool is based on a two-dimensional geometry objects of arbitrary shape are embedded in a host medium.

The background input file is a matrix of real values, representing a collection of M traces (A-scans) measured by the GPR in the absence of the targets (M has to be equal to the number of A-scans included in the B-scan that the user wants to process).

Each A-scan has to be a vector of T real values, where T is no. of samples per scan. Such matrix has to be saved as a .txt file, formatted in the following way:

```
(v1, 1) space (v1, 2) space (v1, 3) . . . space (v1, N)
(v2, 1) space (v2, 2) space (v2, 3) . . . space (v2, N)
. . .
(vT, 1) space (vT, 2) space (vT, 3) . . . space (vT, N)
```



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8. SPOT-GPR example

Simulation/measurement input file format (.txt)

The simulation/measurement input file contains the B-Scan that the user is willing to process, i.e., the collection of M traces (A-scans) measured by the GPR along the interface between the air and the host medium.

Each A-scan has to be a vector of T real values, T is the no. of samples per scan.

Hence, the background input file has to contain a matrix of $T \times M$ real values.

Such matrix has to be saved as a .txt file, formatted in the following way:

```
(v1, 1) space (v1, 2) space (v1, 3) . . . space (v1, N)
(v2, 1) space (v2, 2) space (v2, 3) . . . space (v2, N)
. . .
(vT, 1) space (vT, 2) space (vT, 3) . . . space (vT, N)
```

Pulse input file format (.txt)

The pulse input file contains a vector of T' samples of the pulse emitted by the GPR.

In other words, the pulse input file has to contain a $1 \times T'$ vector of real values, where $\tau = 1, \dots, T'$ is the sampling time and T' is **not necessarily** equal to T .

The vector has to be saved as a .txt file, formatted in the following way:

```
(v1, 1) space (v1, 2) space (v1, 3) space (v1, 4) . . . space (v1, T)
```



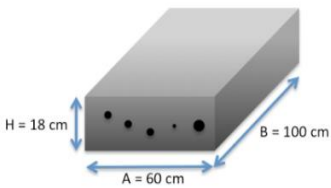
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Setting name	Unit	Description	Comments
Center frequency	MHz	Center frequency f_c of the Tx pulse	GPR system parameter
Bandwidth	MHz	Bandwidth of the Tx pulse [$f_c - BB/2$; $f_c + BB/2$]	GPR system parameter We suggest to consider a -10 dB bandwidth
Frequency resolution	MHz	Frequency step to be used by the SAP-DoA algorithm [$f_c - BB/2$: f_{RES} : $f_c + BB/2$]	For each point within the range, the SAP-DoA procedure is executed and the relevant crossing pattern is processed
No. of samples per scan	N/A	Sample frequency of the ADC	GPR system parameter Typ. 512, 1024, 2048
Time window	ns	Tx/Rx time window	GPR system parameter Assumed to be the same in Tx and Rx
Scan spatial sampling	m	Distance between consecutive A-scan traces	Ideally this is the spacing of a linear uniform array collecting all the A-scans together. For time-invariant scenarios, the A-scans can be collected in different instants
Antenna-ground distance	m	Distance between Tx/Rx antennas and the air-ground I/F	GPR system parameter Assumed to be the same in Tx and Rx
Dielectric constant of ground	N/A	Relative permittivity of ground	In release 1.0, this is a real value, i.e., losses are not considered by the SAP-DoA procedure
False-alarm probability	N/A	Probability of false alarm used by SAP-DoA procedure for the crossing pattern filtering	Typically between 10^{-3} and 10^{-6} , depending on f_{RES} . For a coarse f_{RES} , a lower number of crossings has to be expected and a lower false-alarm probability is recommended

8. SPOT-GPR example

Concrete 1

Cells 1.1 – 1.3 can be simulated in 2D and 3D. In 2D, the concrete cell size is $A \times H$; in 3D, the cell size is $A \times B \times H$.



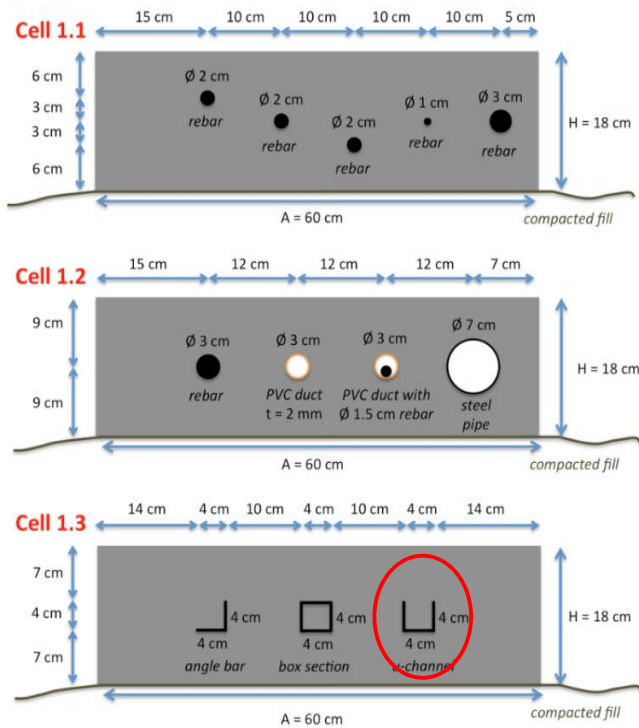
Transmitter:

- ✓ Central frequency: $f = 1.5$ GHz
- ✓ Pulse time-shape: Ricker
- ✓ 2D source: line of current
- ✓ 3D source:
 - Hertzian dipole // B or // A
 - Bow tie antenna // B or // A
 - GSSI antenna

- ✓ Rx and Tx are at 2 cm from concrete-air interface
- ✓ The distance between Tx and Rx is $d = 10$ cm

Output:

- ✓ B-Scan with step 5 mm
- ✓ A-Scan above the center of each scatterer
- Total field and back-scattered field
- Time window: 5 ns



Cross-range: 15 ÷ 19 cm
Range: 7 ÷ 9 cm

L. Pajewski, A. Giannopoulos, “Electromagnetic modelling of Ground Penetrating Radar responses to complex targets”, Short Term Scientific Missions and Training Schools – Year 1, COST Action TU1208, L. Pajewski & M. Marciniak, Eds., Aracne Editrice, Rome, Italy, May 2014, ISBN 978-88-548-7225-7, pp. 7-45.



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8. SPOT-GPR example

STEP 1 - LOAD INPUT FILES

Load background input file
C:\Users\Simol\Desktop\COST_A
 CTION_TU1208ISMSTS_0120171
 COST_DOA\input\backgroundE
 sfondo_13_a.txt

Load simulation input file
C:\Users\Simol\Desktop\COST_A
 CTION_TU1208ISMSTS_0120171
 COST_DOA\input\cell_13\cell13
 2D concrete_a.txt

Load Tx pulse input file
C:\Users\Simol\Desktop\COST_A
 CTION_TU1208ISMSTS_0120171
 COST_DOA\input\myPulse.txt

B SCAN

Processed B SCAN

STEP 2 - SETTINGS

1.5e3 Done

6e3 Done

300 Done

256 Done

5 Done

5e-3 Done

2e-2 Done

6 Done

1e-4 Done

START

STEP 3 - SPOTTING

	actual [cm]	estimate [cm]
x-rg	15÷19	18.57
rg	7÷9	8

0.185759 Done

-0.0798719 Done

NEW SPOT

0.271,-0.104 Done

0.108,-0.104 Done

0.271,-0.073 Done

0.108,-0.073 Done



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Conclusions

- SPOT-GPR can be used to post-process GPR raw data in order to estimate the position of targets
- SPOT-GPR is based on a two-stage processing scheme: in time domain (range) and in frequency domain (cross-range)
- In time domain, the received B-SCAN is at first manipulated to remove the I/F effects, and then, each A-SCAN is cross-correlated with the transmitted pulse
- The obtained processed B-SCAN is FFT-transformed and the SAP-DoA algorithm is applied for a discrete number of frequency points
- For each frequency point a dominant DOA is estimated for all the subarrays and the overall DOA collection is used to derive the cross-range estimated position
- The cross-range estimation is then matched with the corresponding time domain values of the processed B-SCAN in order to estimate the position in range (depth)





**For detailed references and any other
business feel free to contact me**

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Thank you

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