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A Microwave Imaging System for the Detection of Targets Hidden behind Dielectric Walls

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Introduction

- Localization of targets in unreachable regions (e.g., inside buildings) is important in many applications [1][2]:
  - Police and military force missions
  - Fire-fighting and rescue operations
- Microwave systems are very promising for such task → Although several methods and systems have been proposed, there is still the need for further advancements.
- A new prototype of imaging system is presented.
- It allows two different working modalities, in order to be able to work remotely from the wall or in direct contact with it.
- Some preliminary validation studies are shown.

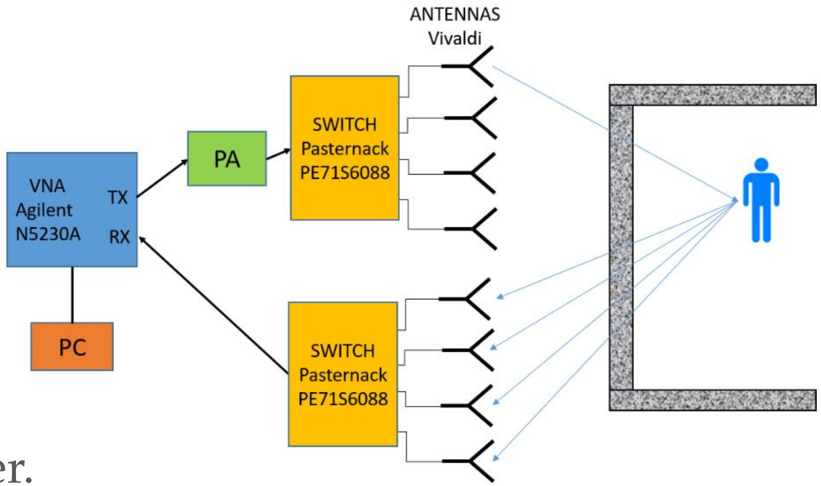
PRIN

Research activity funded by MIUR under the PRIN2015 project U-VIEW, grant no. 20152HWRSL.

[1] M. G. Amin, Through-the-Wall Radar Imaging. Boca Raton, FL: CRC Press, 2011.

[2] M. Pastorino and A. Randazzo, Microwave Imaging Methods and Applications. Boston, MA: Artech House, 2018.

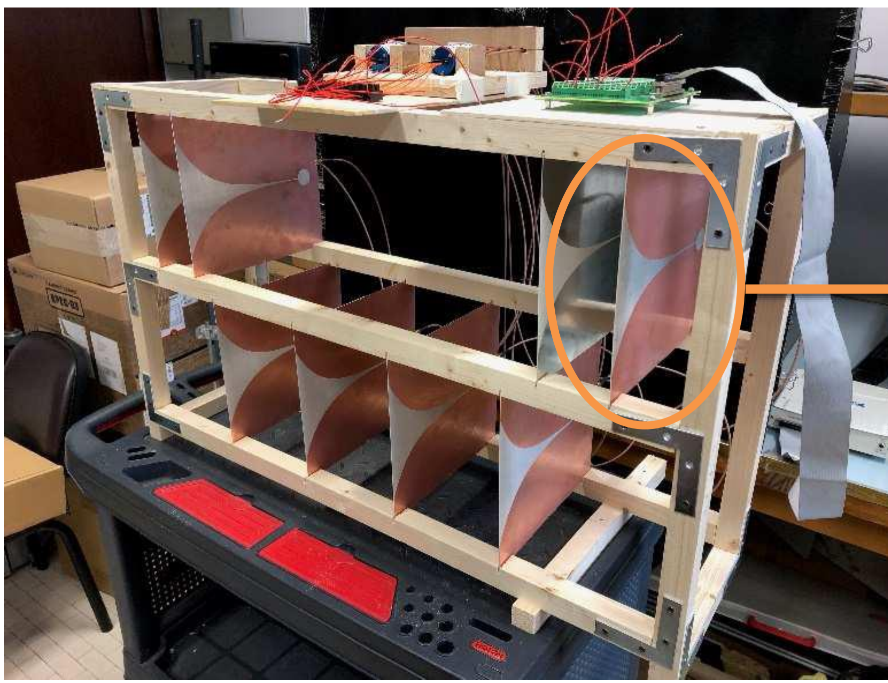
Overview of the developed setup

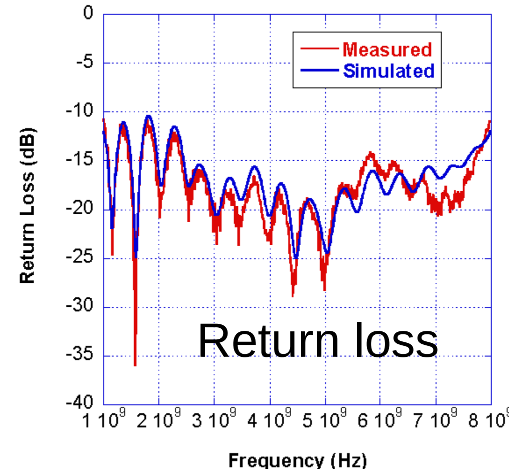


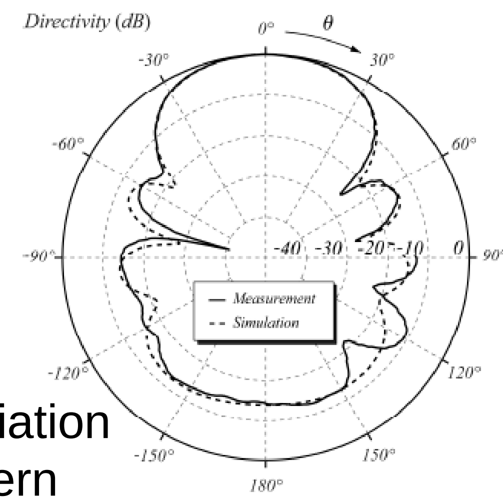
- Two possible operating modalities.
- **Remote modality:**
  - MIMO array of 16 Vivaldi antennas connected to a VNA through a switch.
  - A power amplifier in the transmitting channel is used to increase the TX power.
- **Proximity modality:**
  - Bessel beams are used to focalize in specific regions behind the wall.
  - A circular waveguide equipped with an exciter suitable to generate a Bessel beam @ ~8.7 GHz has been developed.
  - A printed antenna placed in the neighboring of the launcher is used to receive the field scattered by the target.

Overview of the remote system

- The remote system is based on a MIMO structure composed by Vivaldi antennas, which allows to synthesize a monostatic array of 16 elements with spacing 3.75 cm.



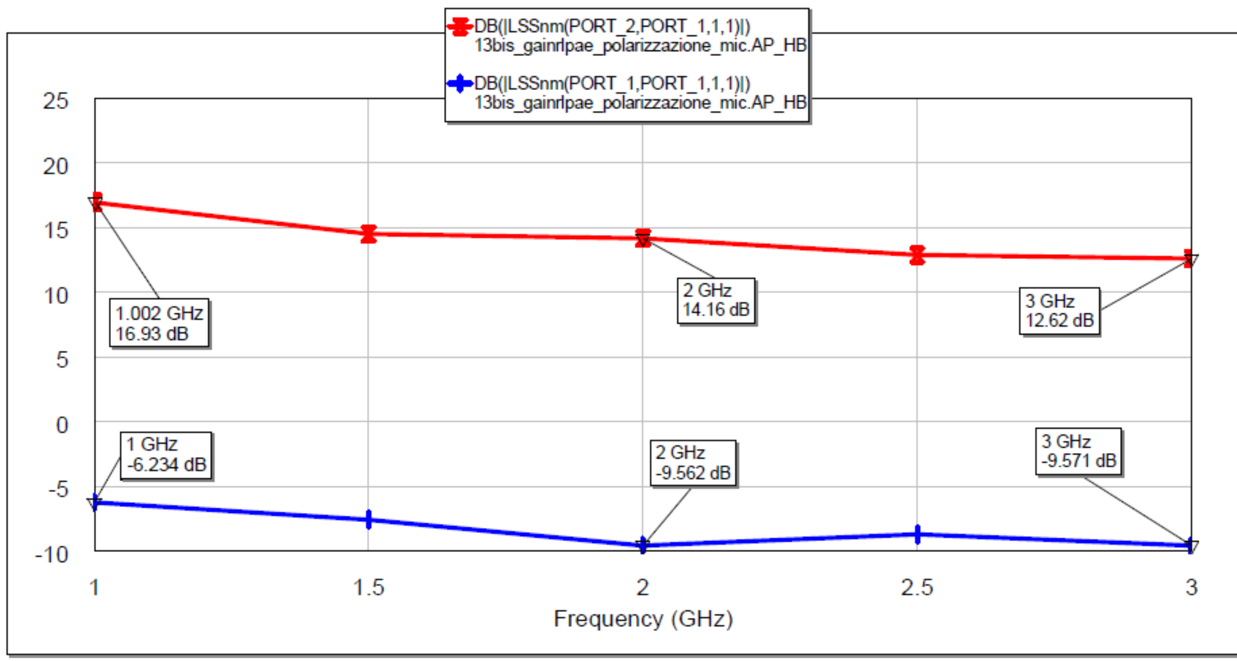




Radiation pattern

Overview of the remote system

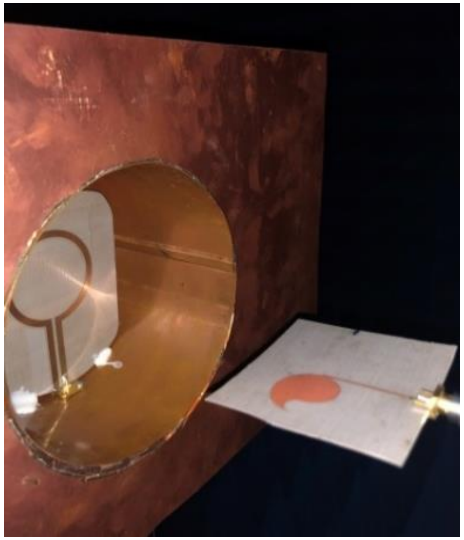
- A class A amplifier based on a GaN transitor (Polyfet GP1441) has been designed to achieve a maximum transmit power of 10 W.

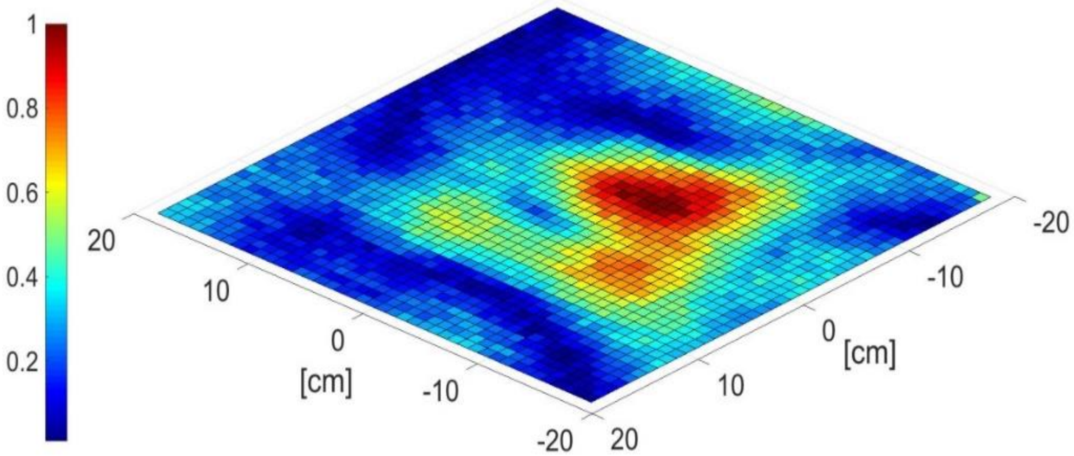


Return loss and gain of the developed amplifier

Overview of the proximity system

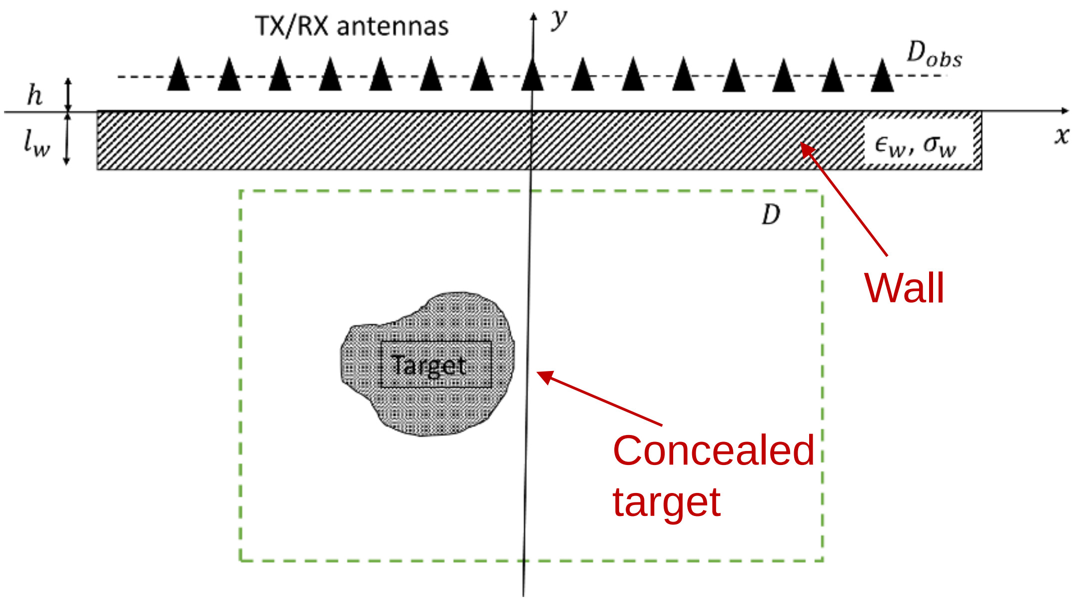
- The proximity system allows to exploit the focusing capabilities of Bessel-beam sources.
- To this end, a Bessel beam lancher based on a circular waveguide containing three anular rings has been developed.





Distribution of the electric field produced by the developed Bessel launcher.

Through-wall scattering modeling

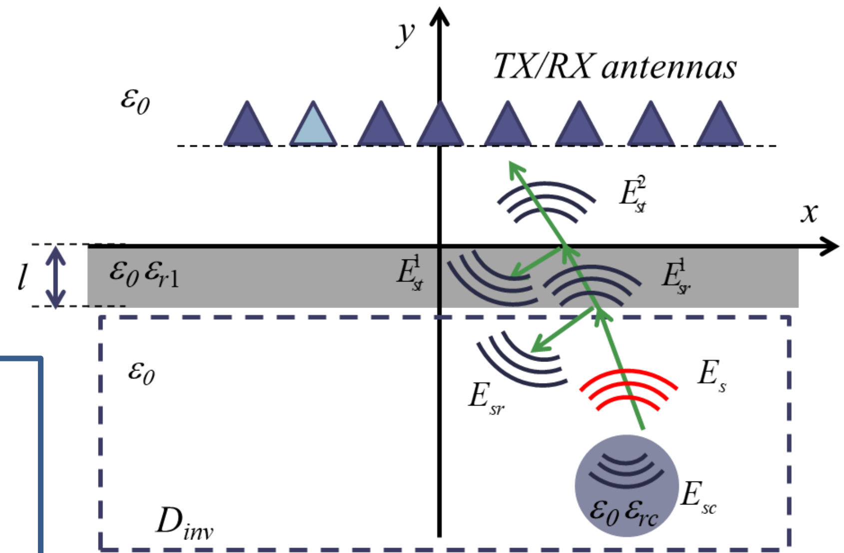


The inverse scattering problem is reduced to a 2D scalar problem ($\mathbf{r} = (x, y)$ and scalar fields)

- Homogeneous wall with thickness l_w and dielectric properties $\epsilon_{r,w}$, σ_w
- Cylindrical targets, located inside a known area D_{inv}
- The scene is illuminated by TMz incident electric fields $e_i(\mathbf{r})$.
- Total field $E_t(\mathbf{r})$ is collected by a receiving antenna in different positions located in the measurement domain D_{obs}

Through-wall scattering: forward modeling

- A forward model based on the cylindrical wave approach [1] has been developed to model the through-wall scenario.



Scattered-transmitted field in medium 0

$$E_s(x,y) = V_0 \sum_{q=1}^{N} \sum_{m=-\infty}^{+\infty} i^m c_{qm} TW_m^{2,0}(x,y;d_q)$$

- The basis functions are Reflected Cylindrical waves, expressed through the plane-wave spectrum

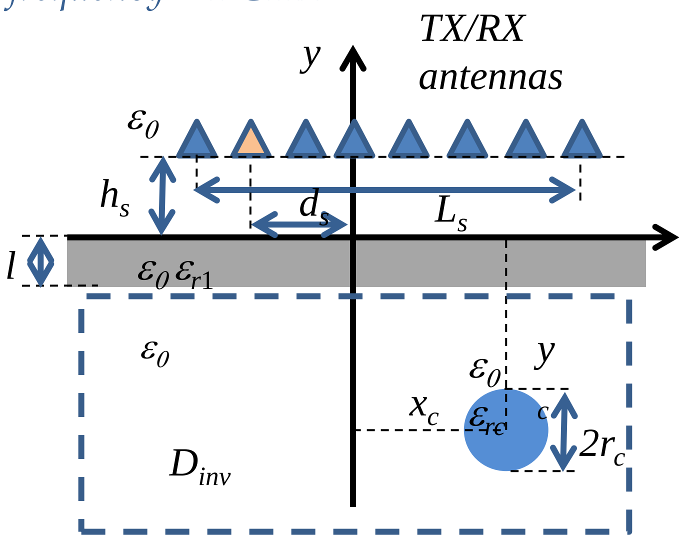
$$TW_m^0(x,y;h_q) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} T_{10}(k_\parallel) T_{21}(k_\parallel)\, F_m[-k_2(h_q-l),k_\parallel]\, e^{i\sqrt{1-(k_2 k_\parallel)^2}\,x}\, e^{i k_2 k_\parallel (y-d_q)}\, dk_\parallel$$

Fresnel reflection coefficient at the interface between medium 1/medium 0 and medium 2/medium 1

[1] C. Ponti, M. Santarsiero, and G. Schettini, "Electromagnetic scattering of a pulsed signal by conducting cylindrical targets embedded in a half-space medium," IEEE Trans. Antennas Propag., 2017.

An example of forward modeling

frequency = 1 GHz



CWA

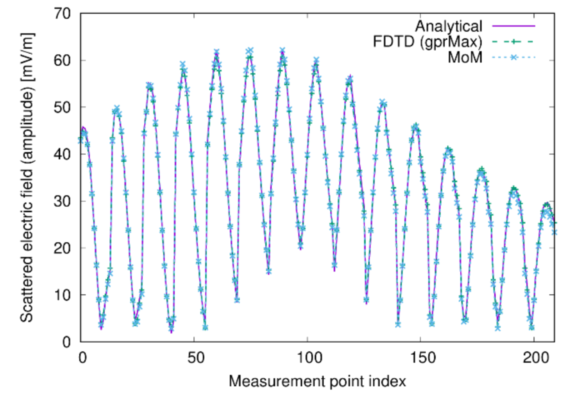
M_t = 9 truncation order

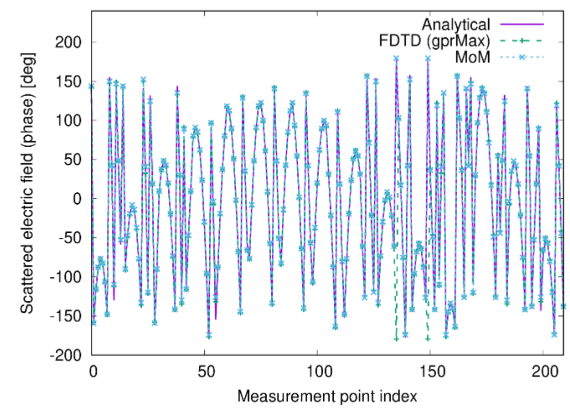
M = 19 system order

MoM

N = 900 square subdomains

side length = 0.005 m





Target

center $(x_c, y_c) = (-20\ \text{cm}, 60\ \text{cm})$

radius $r_c = 7.5$ cm

relative permittivity $\varepsilon_{rc} = 3$

Wall

relative permittivity $\epsilon_{r1} = 4$

thickness $l = 20$ cm

Through-wall scattering: inverse modeling

- The inverse problem is based on the formulation of the TW problem in terms of a first-order linearized integral equations involving a multi-layer 2D Green's function [1][2], i.e.,

$$E_s(\mathbf{r}_{RX}^{s,m}) \cong \int_D \chi(\mathbf{r}')g_{tw}(\mathbf{r}',\mathbf{r}_{TX}^{s})g_{tw}(\mathbf{r}_{RX}^{s,m},\mathbf{r}')d\mathbf{r}' = G_{tw}\chi(\mathbf{r}_{RX}^{s,m})$$

- where

Generalized reflection and transmission coefficients

$$g_{tw}(\mathbf{r},\mathbf{r}') = \frac{j}{4\pi}\int_{-\infty}^{+\infty}\frac{e^{j\zeta(x-x')}}{\gamma_1}\begin{cases} e^{-j\gamma_0|y-y'|} + Re^{-j\gamma_0(y+y')}, & y \geq 0 \\ Te^{j\gamma_0(y+l-y')}, & y \leq -l_w \end{cases} d\zeta$$

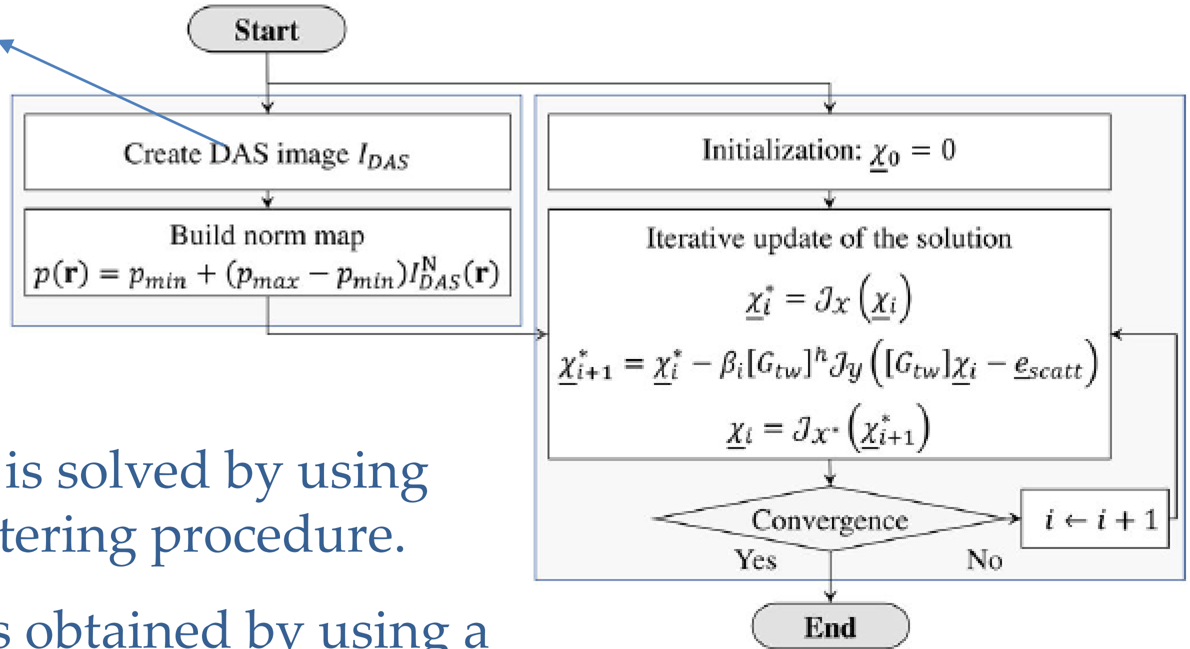
[1] F. Soldovieri and R. Solimene, "Through-Wall imaging via a linear inverse scattering algorithm," IEEE Geosci. Remote Sens. Lett., Oct. 2007.

[2] M. Pastorino and A. Randazzo, Microwave Imaging Methods and Applications. Boston, MA: Artech House, 2018.

Through-wall scattering: inverse modeling

$$I_{DAS}(\mathbf{r}) = \sum_{f=1}^{F}\sum_{s=1}^{S}\sum_{m=1}^{M} E^{s}_{scatt}(\mathbf{r}^{s,m}_{RX})\, e^{j\omega_f\left(\tau^{s}_{TX}(\mathbf{r})+\tau^{s,m}_{RX}(\mathbf{r})\right)}$$

Dealys computed by means of Fermat's principle



- The inverse problem is solved by using a hybrid inverse-scattering procedure.
- A first initial image is obtained by using a Delay-And-Sum scheme with wall compensation [1].
- Such an image is used to define the exponent function for a Landawber iterative scheme in variable-exponent Lebesgue spaces [2].

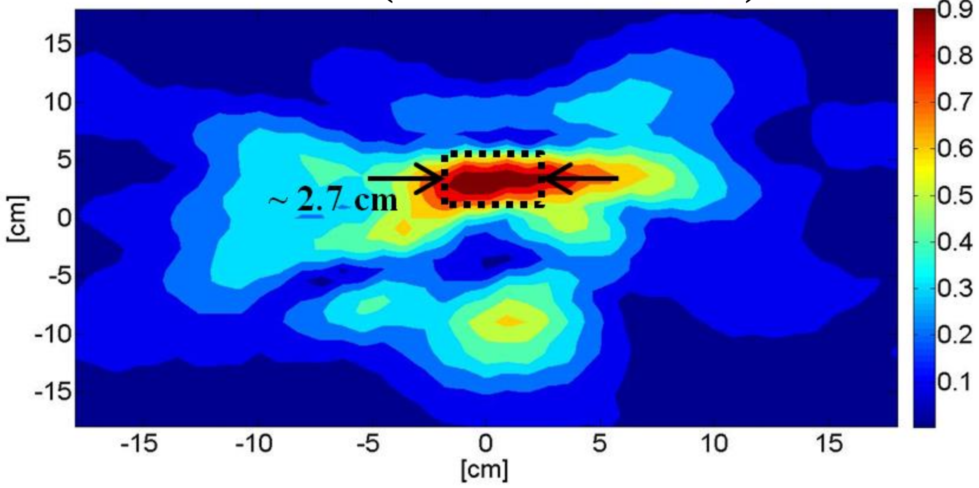
[1] S. Pisa et al., "Comparison between delay and sum and range migration algorithms for image reconstruction in through-the-wall radar imaging systems," IEEE J. Electromagn. RF Microw. Med. Biol., 2018.

[2] C. Estatico, A. Fedeli, M. Pastorino, and A. Randazzo, "Quantitative microwave imaging method in Lebesgue spaces with nonconstant exponents," IEEE Trans. Antennas Propag., 2018.

Experimental results – Proximity modality

- An analysis of the focusing capabilities of Bessel beams in through-the-wall scenarios has been performed.
- A stratified wall composed of a 10 mm plasterboard layer and a 20 mm wood layer has been considered.

Measured field transmitted behind the wall (normalized values).



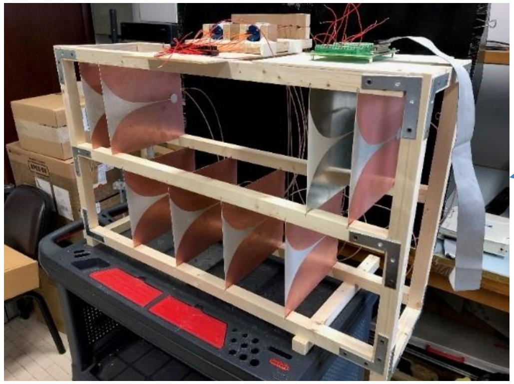
Dielectric properties of the wall layers

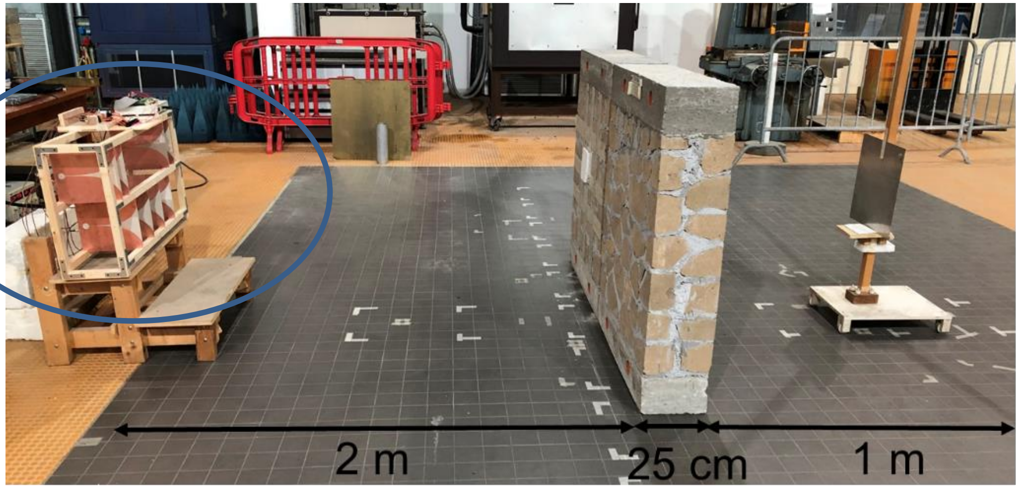
	Dielectric Constant	Loss Tangent
Plasterboard	1.40	0.007
Wood	1.76	0.067

A very good focusing of the transmitted field is obtained.

Experimental results – Remote modality

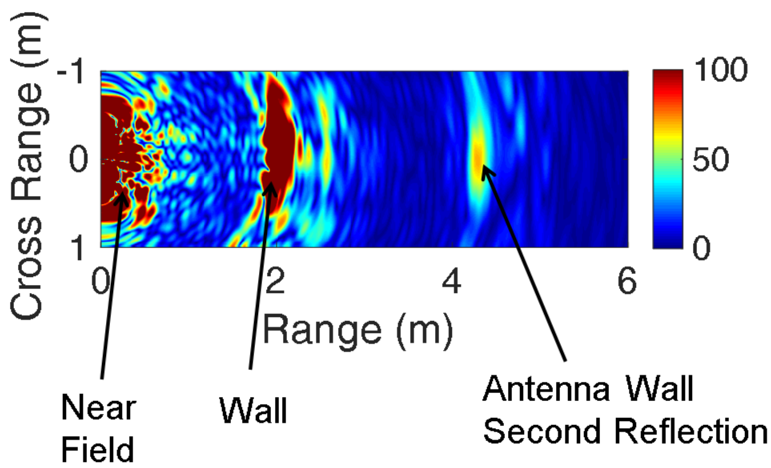
- Measurement parameters
  - Brick wall 1.2 m high, 1.8 wide and 0.25 m tick, with estimated relative dielectric permittivity 4.5.
  - MIMO array with 16 Vivaldi antennas 2 m away from the wall.
  - Frequency-stepped measurements between 1 GHz and 3 GHz with a step of 4 MHz.
- Target parameters
  - Metallic plate with sides 36×42 cm, located 1 m from the wall and 60 cm from the floor.
- Inversion procedure parameters
  - Maximum number of iterations, 100; threshold on the relative variation of the residual, 0.01; range of the norm parameter, [1.4, 2.0].



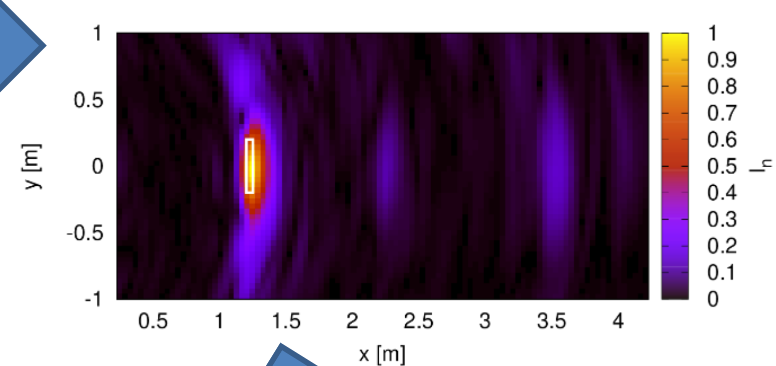


Experimental results – Remote modality

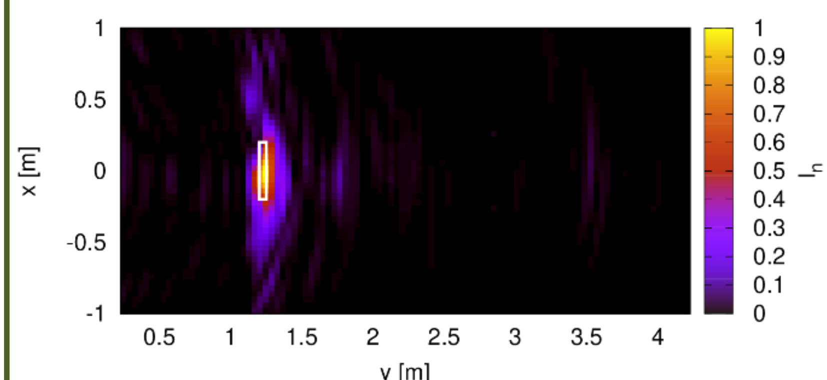
- Raw DAS reconstructions (unfocused)



- DAS reconstructions with wall compensation



- Hybrid approach reconstruction



- The developed hybrid procedure allows to obtain an accurate reconstruction, in which the target is correctly localized and shaped.
- Moreover, the background is clean from artefacts, which are instead present in the DAS image.

Conclusions

- A new prototype of imaging system for through-the-wall imaging has been presented and experimentally validated.
- It allows two different working modalities, in order to be able to work remotely from the wall or in direct contact with it.
- In the remote case, measurements are acquired by using a MIMO array and are processed by an efficient inverse-scattering procedure.
- In the proximity modality, Bessel beams are exploited in order to obtain highly-focused fields behind the wall.
- Further activities will be devoted to a more comprehensive validation of the system.