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SPECIAL SESSION URSI IN ITALY
Commission B – Fields and Waves

Electromagnetic Imaging: Methods and Applications

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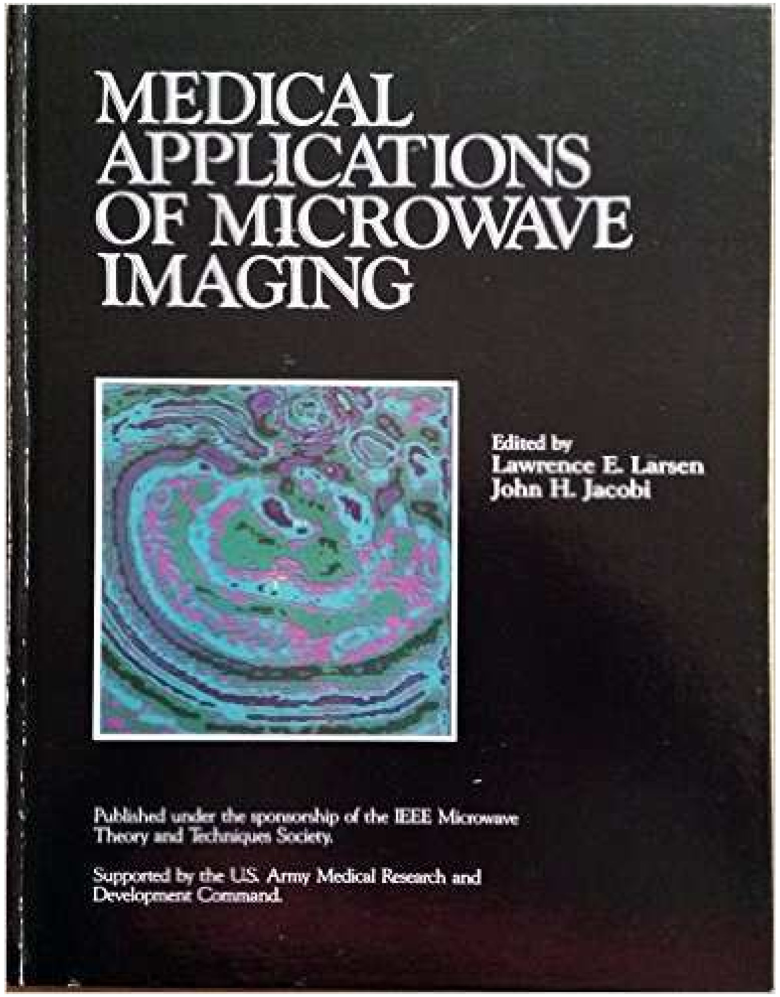
Introduction

- Some recent developments in the field of electromagnetic inverse scattering methods for nondestructive evaluation and imaging are discussed …
- … with particular reference to approaches for which the Italian electromagnetics community has provided some contributions.
- Linear, quadratic, and fully nonlinear models are considered, whereas some new ideas and trends are delineated with reference to specific applications proposed for imaging and diagnostics in several area.

Introduction



- The preliminary ideas concerning the application of microwave imaging to medical imaging have been summarized in this book (1986).
- When that pioneering work appeared, it seemed that techniques based on interrogating microwaves would have provided in a short time new and powerful tools for medical diagnostics.
- However, several years later, microwave medical imaging is often still considered an emerging technique, since accurate and effective dielectric reconstructions are still very difficult to obtain.

Introduction

- One should consider, for comparison, the developments in the area of X-ray Computerized Tomography.
- The Radon transform, considered to be useless for some decades, has been *rediscovered* in the 1970s and, few years later, tomographs were already available in several advanced diagnostic units of important hospitals, whereas, about ten years later, Computerized Tomography has become a routine diagnostic methodology.
- The *history* of medical microwave imaging is clearly far different…
- Nevertheless, if you look at number of recently appeared scientific publications (including this edition of ICEAA – IEEE APWC) … an ever increasing attention is devoted to microwave imaging.

Introduction

- Another pioneering paper is ...

(European Microwave Conference, 1983)

A MICROWAVE DIFFRACTION TOMOGRAPHY SYSTEM FOR BIOMEDICAL APPLICATIONS

G. PERONNET*, Ch. PICHOT*, J.Ch. BOLOMEY*, L. JOFRE*, A. IZADNEGAHDAR*
C. SZELES**, Y. MICHEL**
J.L. GUERQUIN-KERN***, M. GAUTHERIE***

ABSTRACT

This paper describes a 3 GHz experimental set-up for quasi real time tomography of biological media. Experiments on animal organs illustrate the main features of this imaging process.

INTRODUCTION

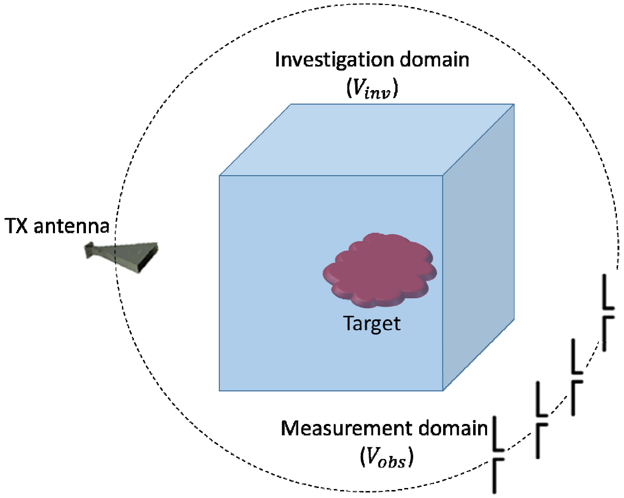
Microwaves have been used for many years in biomedical applications such as hyperthermia or diagnostic and remote temperature control by thermography. Microwave active imaging only started recently, after the deci-

- The important fact is that some of the factors that have so far limited the real applicability of microwave medical imaging tend to reduce more and more their impact on the development of imaging systems.
- This delineates an *optimistic perspective*, which is supported by the significant achievements concerning both the design and realization of efficient illumination/measurement systems and the development of fast, effective, and reliable reconstruction procedures

Electromagnetic scattering basics (dielectric targets)

To fix ideas…..

- A target, characterized by a complex relative dielectric permittivity ϵ is located inside a predefined volume V_{inv}.
- The object is illuminated by one or more incident electric fields $\mathbf{E}_{inc}(\mathbf{r})$ (generated by one or more TX antennas).
- The electric field $\mathbf{E}_{tot}(\mathbf{r})$, resulting from the interaction between the target and the illuminating radiation, is collected by means of RX antennas located in a known measurement domain V_{obs}.



- Basic equation governing EM scattering:

$$\mathbf{E}_{tot}(\mathbf{r}) = \mathbf{E}_{inc}(\mathbf{r}) + \int_{V_{inv}} c(\mathbf{r}')\mathbf{E}_{tot}(\mathbf{r}') \cdot \overline{\mathbf{G}}_0(\mathbf{r},\mathbf{r}')d\mathbf{r}'$$

- $\overline{\mathbf{G}}_0$: Free-space Green's dyadic
- $c = \frac{\epsilon}{\epsilon_0} - 1$: dielectric contrast

Electromagnetic scattering basics (dielectric targets)

- This formulation is usually used in 3D near-field imaging.
- Approximations can be adopted working in far-field condition (plane wave illumination is assumed, etc…)
- Other formulations are possible (e.g., the Contrast Source Integral Equation and several modified versions).
- For inspect bodies with high conductivities or PEC bodies other formulation can be used (e.g., PO approximation and surface currents, …).
- For inspecting buried objects or targets in stratified media, the proper Green's function must be used. Sometimes the Green's function is also numerically computed (e.g., in some approaches for through-the-wall inspection).

Electromagnetic inverse scattering problem

- **Objective**: starting form measures of the electric field, find an approximation of some model parameters describing the electromagnetic properties of the investigated area (e.g., the distribution of the dielectric permittivity ϵ_r)

Electromagnetic **inverse scattering problem**

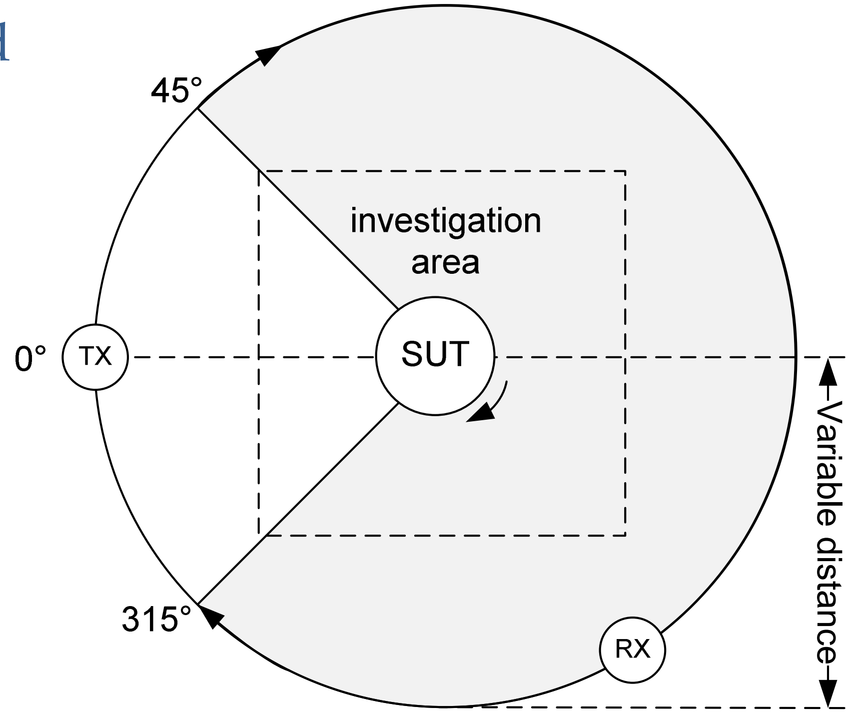
- In a mathematical form: given a data function y (the electric field), find an approximation of the unknown function x (e.g., the dielectric contrast) such that

$$F(x) = y$$

- being F a nonlinear operator describing the scattering phenomena.

Tomographic imaging

- Cylindrical scatterers are assumed
- A multiview arrangement is considered
- The area under test is illuminated from V different directions
- For each view, the electric field is collected at M points.
- A TM illumination is assumed



- The inverse problem is reduced to a 2D scalar problem.

Basic Mathematical Formulation – Tomography

- For the 2D problem the fundamental scalar scattering equation (EFIE) is now

$$e_{tot}^{(v)}(\mathbf{r}) = e_{inc}^{(v)}(\mathbf{r}) + e_{scatt}^{(v)}(\mathbf{r}) = e_{inc}^{(v)}(\mathbf{r}) - k_0^2 \int_{D_{inv}} c(\mathbf{r}') e_{tot}^{(v)}(\mathbf{r}') g_0(\mathbf{r}, \mathbf{r}') \mathrm{d}\mathbf{r}'$$

$$c(\mathbf{r}) = \varepsilon_r(\mathbf{r}) - j\frac{\sigma(\mathbf{r})}{\omega\varepsilon_0} - 1$$

$$\mathbf{r} \in D_{obs}, v = 1,..,V$$

$$\mathbf{r} = x\mathbf{x} + y\mathbf{y}$$

It is worth noting that the **total electric field** inside the investigation area is **unknown**

A second EFIE for $\mathbf{r} \in D_{inv}$ is used and combined with the first one

In order to retrieve the distribution of the scattering potential c, a nonlinear inverse problem must be solved

Imaging Methods

- Key problems associated to the solution of this equation:
  - **Nonlinear equation** with **two unknowns** (the total electric field and the contrast function).
  - Very **ill-posed** inverse problem (Fredholm equation of the first kind)

- The various proposed imaging techniques can be categorized in several ways:
  - Classification based on the dimensionality of the problem (one-, two-, and three-dimensional reconstructions).
  - Classification based on the objective of the inspection and includes qualitative and quantitative methods.

Some comments

- The current trend is to address 3D problems.
- The reconstruction of 3D scenarios without modifications of the imaging formulation is one of the advantages of this diagnostic technique.
- But computational aspects remain an issue.
- Sometimes 2D models are still preferred.
- Some recent contributions on this topic:
  - W. Zhang and Q. H. Liu, “Three-Dimensional Scattering and Inverse Scattering from Objects With Simultaneous Permittivity and Permeability Contrasts,” IEEE Transactions on Geoscience and Remote Sensing, vol. 53, no. 1, pp. 429–439, Jan. 2015.
  - G. Gennarelli, I. Catapano, F. Soldovieri, and R. Persico, “On the Achievable Imaging Performance in Full 3-D Linear Inverse Scattering,” IEEE Transactions on Antennas and Propagation, vol. 63, no. 3, pp. 1150–1155, Mar. 2015.
  - M. A. Ali and M. Moghaddam, “3D Nonlinear Super-Resolution Microwave Inversion Technique Using Time-Domain Data,” IEEE Transactions on Antennas and Propagation, vol. 58, no. 7, pp. 2327–2336, Jul. 2010.

Qualitative and quantitative imaging methods

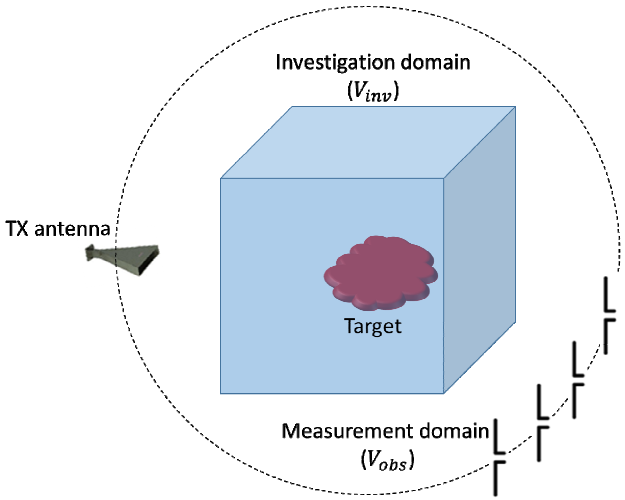
- Concerning the inversion algorithm a classification concern the objectives of the inspection.

- Qualitative imaging:
  - Methods aimed at obtaining only some information about the scatterers under test (e.g., shapes and locations), but not the distributions of the unknown electromagnetic parameters
  - Methods based on certain approximations in scattering models (e.g., those based on Born- and Rytov-type approximations)

- Quantitative imaging:
  - Methods aimed at providing the values of the electromagnetic parameters (usually dielectric permittivity and electric conductivity) of the inspected investigation domain, without approximations on the electromagnetic model

Electromagnetic scattering basics (dielectric targets)

Born Approximation



$$\mathbf{E}_{tot}(\mathbf{r})$$

$$= \mathbf{E}_{inc}(\mathbf{r}) + \int_{V_{inv}} c(\mathbf{r}')\mathbf{E}_{inc}(\mathbf{r}') \cdot \overline{\mathbf{G}}_0(\mathbf{r},\mathbf{r}')d\mathbf{r}'$$

- $\overline{\mathbf{G}}_0$: Free-space Green's dyadic
- $c = \frac{\epsilon}{\epsilon_0} - 1$: dielectric contrast

Qualitative imaging methods

- There are essentially two kinds of qualitative methods.

- Methods based on model approximations:
  - diffraction tomography
  - filtered backpropagation
  - iterative approaches based on the Born or Rytov approximations
  - ...

- Methods able to provide some relevant features of the body to be inspected (e.g., shape, location,…)
  - Linear Sampling Method
  - Level Set Method → See for example the paper M. Benedetti, D. Lesselier, M. Lambert, and A. Massa, "Multiple-Shape Reconstruction by Means of Multiregion Level Sets," IEEE Transactions on Geoscience and Remote Sensing, vol. 48, no. 5, pp. 2330–2342, May 2010.
  - MUSIC → See for example the paper by R. Solimene and A. Dell'Aversano, "Some Remarks on Time-Reversal MUSIC for Two-Dimensional Thin PEC Scatterers," IEEE Geosci. Remote Sens. Lett., vol. 11, no. 6, 2014.
  - …..

An example: The Linear Sampling Method

- Linear Sampling Method (LSM) is a technique able to find the external shape of unknown objects starting from measurements of the scattered electric field performed on circle surrounding the target.
- It is based on the solution of the so-called far-field equation [1]

$$\int_0^{2\pi} E_\infty(\hat{\mathbf{r}},\hat{\mathbf{d}})\,g(\hat{\mathbf{d}})\,d(\hat{\mathbf{d}}) = \Phi_{B,\infty}(\hat{\mathbf{r}},\mathbf{z})$$

E_∞ - far-field pattern
$\Phi_{B,\infty}$ - far-field pattern of the Green's function

- It has been proven that the function g, which depends on the point $\mathbf{r}' \in D_{inv}$, is such that $\|g\|^2$ blows up when $\mathbf{r}'$ approaches the boundaries of the target.

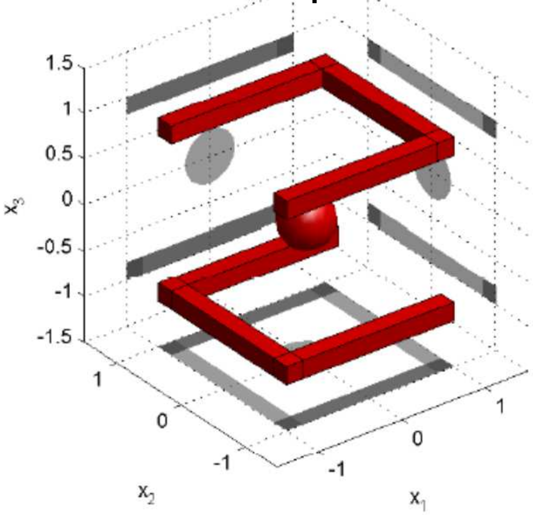
[1] M. Brignone, G. Bozza, R. Aramini, M. Pastorino, and M. Piana, "A fully no-sampling formulation of the linear sampling method for three dimensional inverse electromagnetic scattering problems," Inv. Probl. Vol. 25, 2009.

An example: The Linear Sampling Method

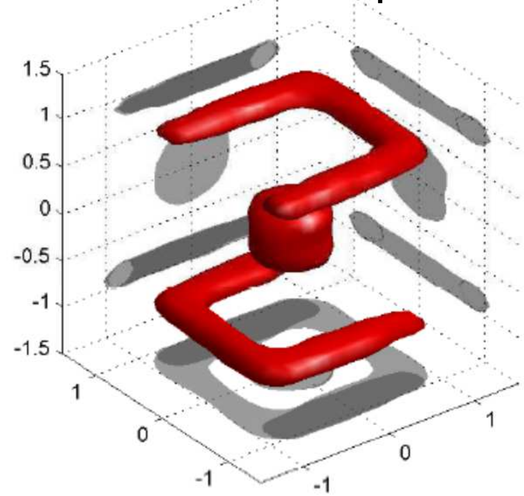
Shaping example

- $V = 162$ illumination directions and $M = V$ observation directions
- Synthetic data (7% Gaussian noise)
- Target characterized by $\epsilon_r = 2$
- Frequency: 286 MHz

Actual profile



Reconstructed profile



Some advances on Linear Sampling Method

- Linear Sampling Method (LSM) was initially developed for detecting target boundaries in free space and starting from far-field data.
- Some recent advancements:
  - Formulation of the method in **near field** [1] – A modified far- field equation is used. The incident fields are modeled as cylindrical waves and the scattered field is collected in the near-field region of the target
  - Use of a priori information about an eventual inhomogeneous **background medium** [2] – The presence of the inhomogeneous background is taken into account by its Green's function, which is numerically computed and used as the right hand side of the (eventually modified) far- field equation.

[1] G. Bozza, M. Brignone, M. Pastorino, M. Piana, and A. Randazzo, "Crack detection in dielectric structures by a linear sampling approach," Int. J. Signal Imag. Syst. Eng., vol. 3, no. 2, pp. 73-80, 2010.
[2] G. Bozza, M. Brignone, A. Randazzo, M. Pastorino, and M. Piana, "Imaging of unknown targets inside inhomogeneous backgrounds by means of qualitative inverse scattering," Inv. Probl. Imag., vol. 3, no. 2, pp. 231-241, 2009.

Generalized linear sampling method

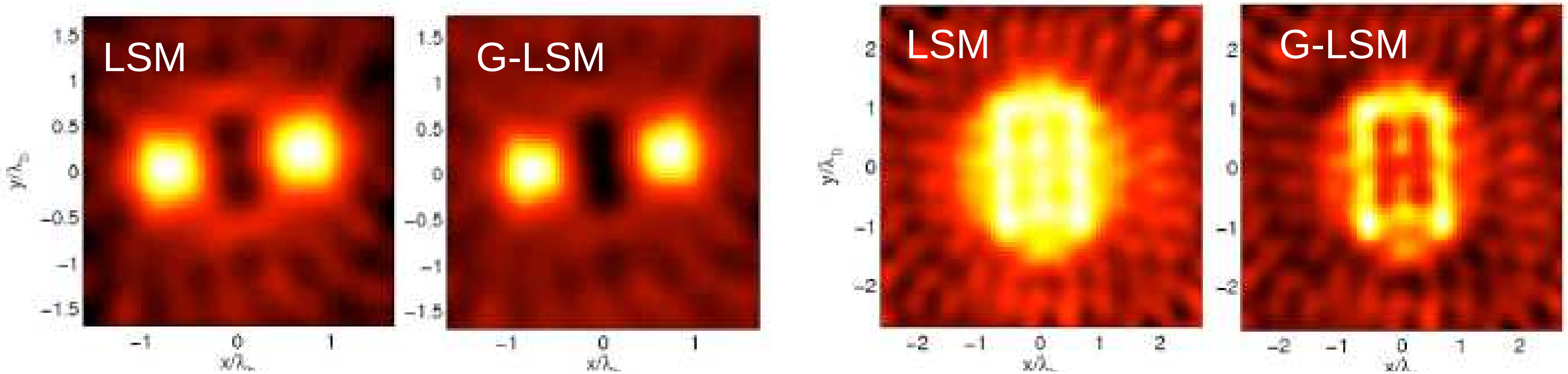
$$\int_{\Gamma} E_s(\theta, \underline{R})\xi(\theta, \underline{r}_s)d\theta = \mathcal{F}[\xi] = G(\underline{r}_s, \underline{R})$$

Changing the right hand side
(from monopole to multipoles)

$$\int_{\Gamma} E_s(\theta, \underline{R})\xi_n^p(\theta, \underline{r}_s)d\theta = \mathcal{F}\left[\xi_n^p\right] = \Phi_n^p(\underline{r}_s, \underline{R}), \quad p = x, y$$

A physics inspired combination formula

$$\mathcal{I}_P(\underline{r}_s) = \prod_{n=1}^{P} \frac{\Upsilon_0(\underline{r}_s)}{\Upsilon_n^x(\underline{r}_s)} \frac{\Upsilon_0(\underline{r}_s)}{\Upsilon_n^y(\underline{r}_s)}, \quad P = k_b a$$



Crocco et al. IEEE Trans. Antennas Propagat. Vol. 61(2), 843-851, 2013

(by courtesy of L. Crocco, IREA-CNR, Napoli, Italy)

Beamforming methods

- Another class of imaging methods, which has already provided very good reconstruction results and seems to exhibit great potentialities for further developments concern techniques based on beamforming concepts.
- Beam summation represents the basic approach for a ray-based local construction of spectrally uniform solutions in complex configurations.

  - R. Tuvi and E. Heyman, "The propagating frame with applications to local inverse scattering," Proc. of The 2015 URSI Atlantic Radio Sci. Conf. (URSI AT-RASC 2015), Canary Islands, May 18-22, 2015.

- Wide applications in microwave tomography and ultra-wide band imaging, and for extending the ground penetrating radar (GPR) capabilities in sensing and retrieving objects buried in the ground.

  - I. Catapano, A. Randazzo, E. Slob, and R. Solimene, "GPR imaging via qualitative and quantitative approaches," in Civil Engineering Applications of Ground Penetrating Radar, A. Benedetto and L. Pajewski, Eds. Cham: Springer, 2015, pp. 239–280.

Buried object detection

- This topic is covered at MMS 2015 by the Special Session:

Radar imaging and subsurface sensing

(Dec. 2, Room Raffaello, **8:30 – 10:00)**

Organizers:

Raffaele Persico, Institute for Archaeological and Monumental Heritage IBAM-CNR.

Francesco Soldovieri, Institute for the Electromagnetic Sensing of the Environment IREA-CNR, Italy.

- COST Action TU1208 "Civil engineering applications of Ground Penetrating Radar", 2013-2017 (Chairman: Lara Pajewski, University of Roma III, Roma, Italy).

Beamforming methods

- Inverse scattering methods have been exploited in conjunction with radar techniques in different areas, e.g., in the detection of debris in several conditions and environments.
  - K. Mazouni, A. Zeitler, J. Lanteri, C. Pichot, J.-Y. Dauvignac, C. Migliaccio, N. Yonemoto, A. Khomura, and S. Futatsumori, “76.5 GHz millimeter wave radar for foreign objects debris detection on airport runways,” Int. J. Microwave Wireless Technolog., vol. 4, pp. 317–326, 2012.

- Very interesting results using UWB imaging and beamforming approaches have been obtained in the field of biomedical imaging
  - E. C. Fear et al., “Microwave breast imaging with a monostatic radar-based system: A study of application to patients,” IEEE Trans. Microw. Theory Tech., vol. 61, pp. 2119-2128, May 2013.
  - Xu Li, and S. C. Hagness, “A confocal microwave imaging algorithm for breast cancer detection,” IEEE Microw. Wireless Compon. Lett., vol. 11, pp. 130-132, March 2001.
  - Hooi Been Lim et al., “Confocal microwave imaging for breast cancer detection: Delaymultiply- and-sum image reconstruction algorithm,” IEEE Trans. Biomed. Eng., vol. 55, pp. 1697-1704, June 2008.

- Finally, beamforming has also successfully used in conjunction with inverse scattering techniques in order to devise hybrid approaches
  - M. J. Burfeindt, J. D. Shea, B. D. Van Veen, and S. C. Hagness, "Beamforming-Enhanced Inverse Scattering for Microwave Breast Imaging," in *IEEE Transactions on Antennas and Propagation*, vol.62, no.10, pp.5126-5132, Oct. 2014

Linear and quadratic models

- Linear and quadratic models are still adopted.
- They are computationally efficient and do not pose local minima issues.
  - F. Ciaramaglia, A. Dell'Aversanoy, G. Leoney, W. Mellanoz, R. Pierriy, R. Solimene, "A two step linear inversion strategy for imaging simple shapes", ICEAA 2015, Torino, 2015.
- An interesting experimental validation has been recently proposed
  - V. Picco, G. Gennarelli, T. Negishi, D. Erricolo, F. Soldovieri, «Quadratic Forward Model for RF Tomography: Experimental Validation», ICEAA 2015, Torino, 2015.
  - F. Soldovieri, G. Gennarelli, I. Catapano, D. Erricolo, V. Picco, T. Negishi, «A Quadratic RF Tomography Inverse Model for Reflection Configuration», Proc. URSI AT-RASC, Gran Canaria, 2015.

Quantitative imaging methods

- If the distributions of the dielectric properties of strong scatterers are needed, the "exact" formulation must be considered (nonlinear equations).
- Various methods can be categorized as follows.

- Deterministic methods
  - Gradient-based methods (several versions)
  - Newton-type methods (several versions) -> See for example the paper by A. Abubakar, T. M. Habashy, G. Pan, and M.-K. Li, "Application of the Multiplicative Regularized Gauss-Newton Algorithm for Three-Dimensional Microwave Imaging," IEEE Transactions on Antennas and Propagation, vol. 60, no. 5, pp. 2431–2441, May 2012.
  - ...

- Stochastic methods
  - These methods are potentially able to find a global solution (GA, DEM, PSO, ACO, …)

Deterministic methods

- Deterministic approaches usually start from an initial guess and modify it according to some deterministic rule (e.g., by moving towards a local minimum of the data residual function).
- Two strategies are usually employed:
  - both the contrast function and the internal field are searched for simultaneously (or at least in an alternate way), usually by applying iterative approaches ⇒ contrast source inversion, conjugate-gradient procedures
  - only the contrast function is considered as an unknown and, at each iteration, the internal total electric field is computed by solving a direct scattering problem ⇒ distorted-Born iterative method, Gauss-Newton approaches
- Main advantage: they allow obtaining quantitative reconstructions of the distributions of dielectric parameters
- Main disadvantage: they can be trapped in local minima, corresponding to false solutions; the final reconstruction strongly depends on the initial solution

An example of deterministic procedure: IN/LW scheme

- The IN/LW scheme is a reconstruction procedure based on Inexact-Newton methods that can be used for solving the nonlinear integral equations of the inverse scattering problem.
- In particular, the scheme proposed in [1]-[3] is an outer/inner iterative algorithm which can be summarized as follows:
  1. Outer steps (IN): Linearization of the scattering equations by means of a Newton's first-order expansion involving the Fréchet derivative of the operator
  2. Inner steps (LW): The obtained linear equations are not exactly solved, but rather the solutions are only approximated, as the word "inexact" suggests; a regularized solution is obtained by using the truncated Landweber method.

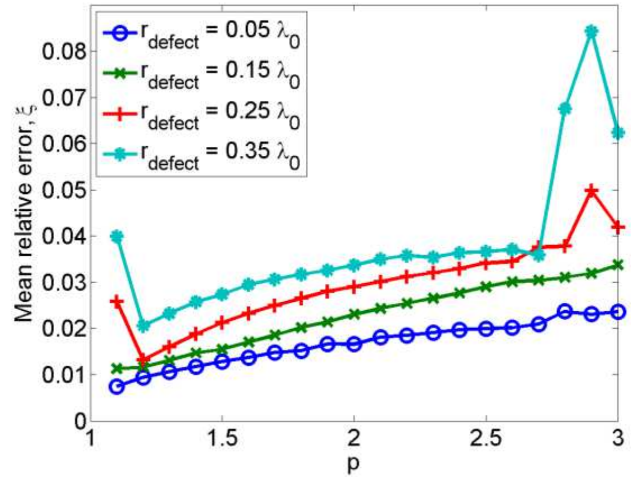
[1] C. Estatico, et al.,"An Inexact-Newton method for short-range microwave imaging within the second order Born approximation," IEEE Trans. Geosci. Remote Sens., 43, 2593-2605, 2005.
[2] G. Bozza and M. Pastorino, "An Inexact Newton-based approach to microwave imaging within the contrast–source formulation," IEEE Trans. Antennas Propagat., 57, 1122-1132, 2009.
[3] C. Estatico et al., "An Inexact-Newton method for microwave reconstruction of strong scatterers," IEEE Antennas Wireless Propagat. Lett., 5, 61-64, 2006.

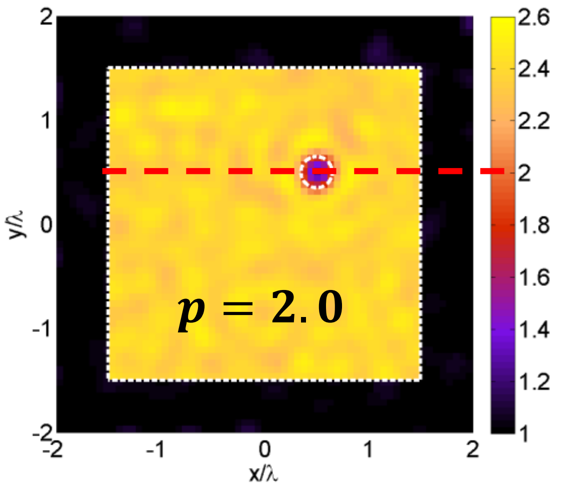
A new paradigm: Inversion in Banach spaces

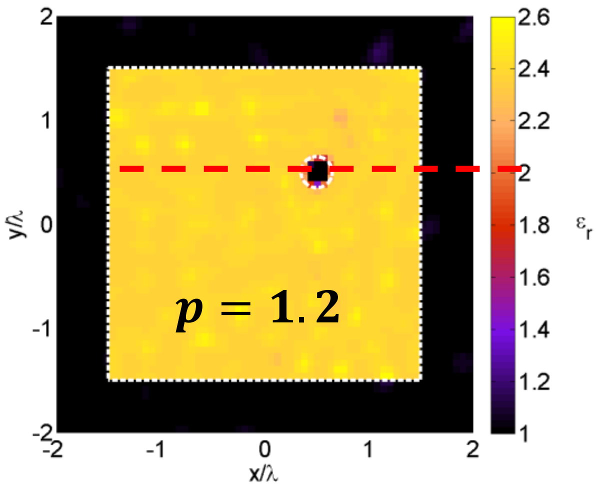
- In order to face the ill-posedness, regularization algorithms are needed.
- Regularization has been extensively studied in the last years in the framework of Hilbert spaces.
  - Benefits: Convergence and regularization properties can be studied with standard mathematical tools (e.g., spectral theory)
  - Drawbacks: Regularization methods in Hilbert spaces usually give rise to smooth (and sometimes oversmoothed) solutions
- More recently, some regularization methods have been introduced and investigated in Banach spaces.
  - Benefits: Thanks to the geometrical properties of Banach spaces, they usually provide solutions endowed with low over-smoothness (resulting in a better localization and reconstruction), especially when dealing with "small" localized objects.
  - Drawbacks: The "Mathematics" is much more involving

A new paradigm: Inversion in Banach spaces

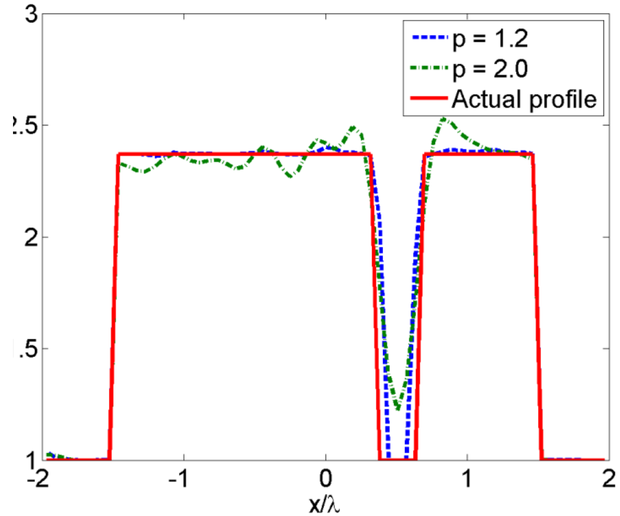
- Example of reconstruction (identification of cracks)
  - Cement pillar (side W=3λ, ϵ_r=2.37−j0.0035) with circular void crack (centered in (0.5λ,0.5λ)).
  - S=36 RX/TX points on a circumference of radius R=5λ (M=35 measurement point for every view)
  - Synthetic data (f=3 GHz, SNR=20 dB)
  - Max outer and inner iterations $N_{IN} = 30$ and $N_{LW} = 30$
  - Algorithm initialized assuming a defect-free cylinder (square area of side 4λ, discretized in 63×63 square subdomains)





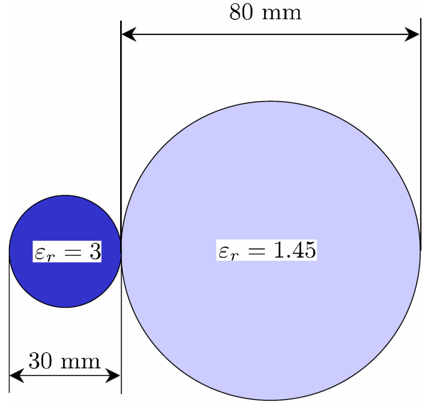


Horizontal cut

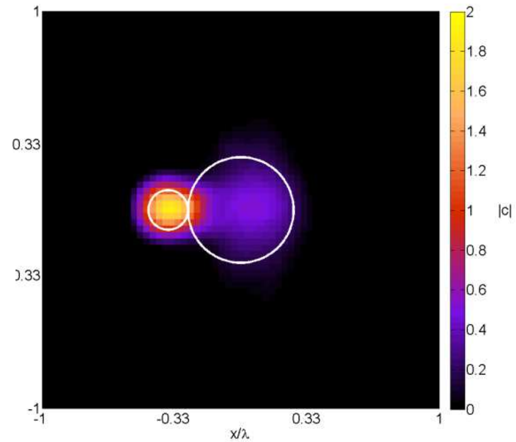


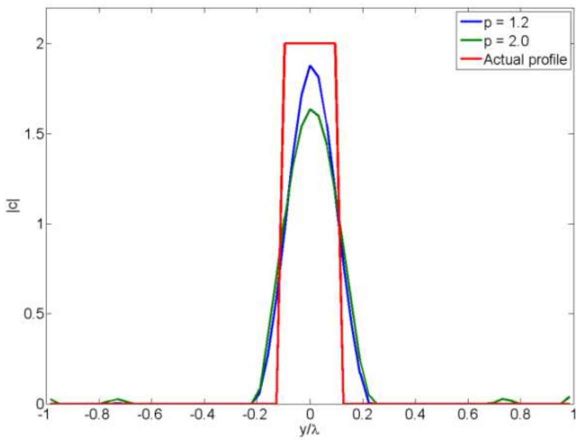
A new paradigm: Inversion in Banach spaces

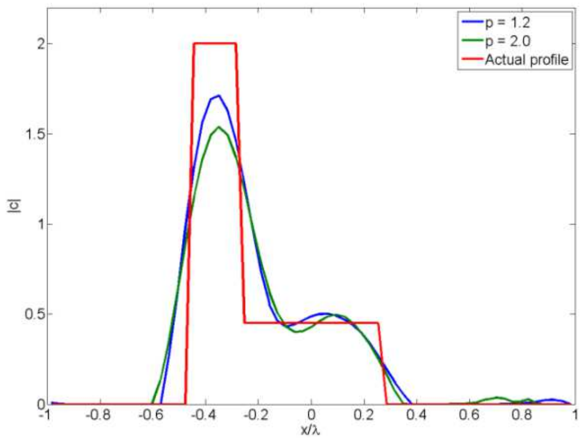
- Example of reconstruction
  - Two adjacent cylinders as shown in the figure
  - Real measured data (microwave-imaging facility at the Institut Fresnel, Marseille, France).
  - Frequency 2 GHz
  - Max outer iterations $N_{IN} = 20$; max inner iterations $N_{LW} = 20$; Algorithm initialized assuming an empty investigation domain (square area of side 2λ discretized in 35×35 square subdomains)



Mean relative reconstruction error ($p = 1.2$) = 0.040
Mean relative reconstruction error ($p = 2,0$) = 0.045







Hybrid approaches

- The current trend concerns the combination of two or more methods (both qualitative and quantitative), in order to develop hybrid approaches able to
  - Take into account sparsity concepts.
  - Take advantages of various nice features of existing methods.
  - To reduce the computational load and the occurance of local minima.

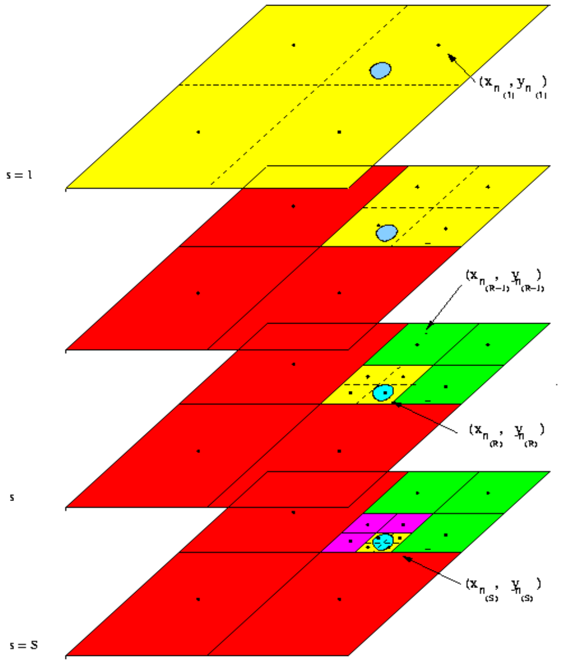
- See for example

  - F. Ciaramaglia, A. Dell'Aversanoy, G. Leoney, W. Mellanoz, R. Pierriy, R. Solimene, "A two step linear inversion strategy for imaging simple shapes", ICEAA 2015, Torino, 2015.
  - M. R. Eskandari, R. Safian, and M. Dehmollaian, "Three-Dimensional Near-Field Microwave Imaging Using Hybrid Linear Sampling and Level Set Methods in a Medium With Compact Support," IEEE Trans. Antennas Propag., vol. 62, no. 10, 2014.
  - T. Moriyama, Z. Meng, and T. Takenaka, "Forward-backward time-stepping method combined with genetic algorithm applied to breast cancer detection," Microw. Opt.Technol. Lett., vol. 53, no. 2, 2011.
  - M. J. Burfeindt, J. D. Shea, B. D. Van Veen, and S. C. Hagness, "Beamforming-Enhanced Inverse Scattering for Microwave Breast Imaging," in IEEE Trans. Antennas Propag., vol.62, no.10, pp.5126-5132, Oct. 2014

Multi-scale techniques

- Another idea is to «focus» the reconstruction only to a certain region of interest.
- An example is reprensented by the so-called Iterative Multiscale Approach (IMSA) [1][2].

> ➢ At each iteration, IMSA evaluates a new Region of Interest (RoI)
>
> ➢ The center and the side of the RoI are estimated on the basis of the current solution (center of mass and variance of τ).
>
> ➢ Once the domain discretization has been set up, a reconstruction method (e.g., the Inexact Newton method) is applied to obtain a new estimate of the contrast function.



[1] M. Donelli, et al. "A new methodology based on an iterative multi-scaling for microwave imaging," IEEE Trans. Microwave Theory Tech., vol. 51, pp. 1162-1173, 2003.
[2] M. Benedetti, D. Lesselier, M. Lambert, A. Massa, "Analysis of the potentialities and limitations of the integration between the IMSA and the level set method for inverse scattering", Proc. EuCAP 2006.

Compressive sensing

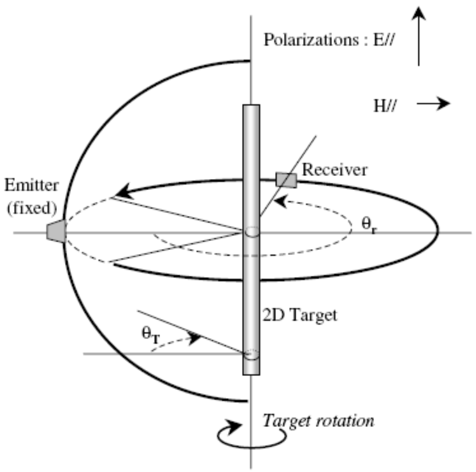
- The principles of compressive sensing have been widely applied in electromagnetic inverse scattering in order to take into account the sparsity properties in certain domains and applications, with a potential great computational saving.

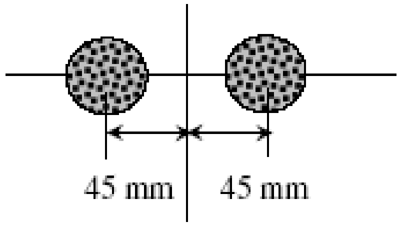
- A. Massa, P. Rocca, and G. Oliveri, "Compressive sensing in electromagnetics - A review," IEEE Antennas Propag. Mag., vol. 57, pp. 224 -238, 2015.
- M. T. Bevacqua, L. Crocco, L. Di Donato, and T. Isernia, "Microwave imaging of nonweak targets via compressive sensing and virtual experiments,« IEEE Antennas Wireless Propag. Lett., vol. 14, 2015.
- F. Soldovieri, G. Gennarelli, I. Catapano, D. Erricolo, V. Picco, and T. Negishi, "A quadratic RF tomography inverse model for reflection configuration," Proc. of The 2015 URSI Atlantic Radio Sci. Conf. (URSI AT-RASC 2015), Canary Islands, May 18-22, 2015.
- L. Guo and A. M. Abbosh, "Microwave stepped frequency head imaging using compressive sensing with limited number of frequency steps," IEEE Antennas Wireless Propag. Lett., vol. 14, pp. 1133-1136, 2015.

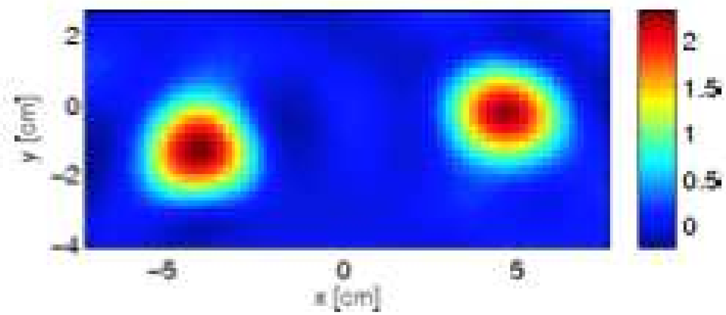
An innovative framework: The virtual experiments

- Basic concepts
  - In a sampling point $\mathbf{r}_s \in V_{inv}$ a «**virtual**» **incident wave**, formed as a linear combination of the physical incident fields, forces the target to scatter on the measurement points in V_{obs} the field of a point source located in $\mathbf{r}_s$.
  - A new set of «**virtual experiments**» can be formed exploiting the **linearity** of Maxwell equations. The information contained in the new data remains the same.
  - This preprocessing step allows to **recast the inverse scattering problem in a different form**, suitable for various kinds of inversion methods.
  - The virtual incident field can be defined by solving the **Linear Sampling Method** equation in $\mathbf{r}_s$.
- Key point: physical interpretation of the Linear Sampling Method
  - Crocco, L.; Catapano, I.; Di Donato, L.; Isernia, T., "The Linear Sampling Method as a Way to Quantitative Inverse Scattering," in *Antennas and Propagation, IEEE Transactions on* , vol.60, no.4, pp.1844-1853, April 2012
- Applications: nonlinear inverse scattering, contrast source inversion, compressive sensing, GPR imaging
  - Bevacqua, M.T.; Crocco, L.; Di Donato, L.; Isernia, T., "An Algebraic Solution Method for Nonlinear Inverse Scattering," in *Antennas and Propagation, IEEE Transactions on* , vol.63, no.2, pp.601-610, Feb. 2015
  - Bevacqua, M.T.; Crocco, L.; Di Donato, L.; Isernia, T., Palmeri, R. "Exploiting virtual experiments for the solution of inverse scattering problem", ICEAA 2015, Torino, 2015.

A Virtual Experiments Linearized Inversion*







Freq = 4 GHz

validation against **single** frequency Frésnel data

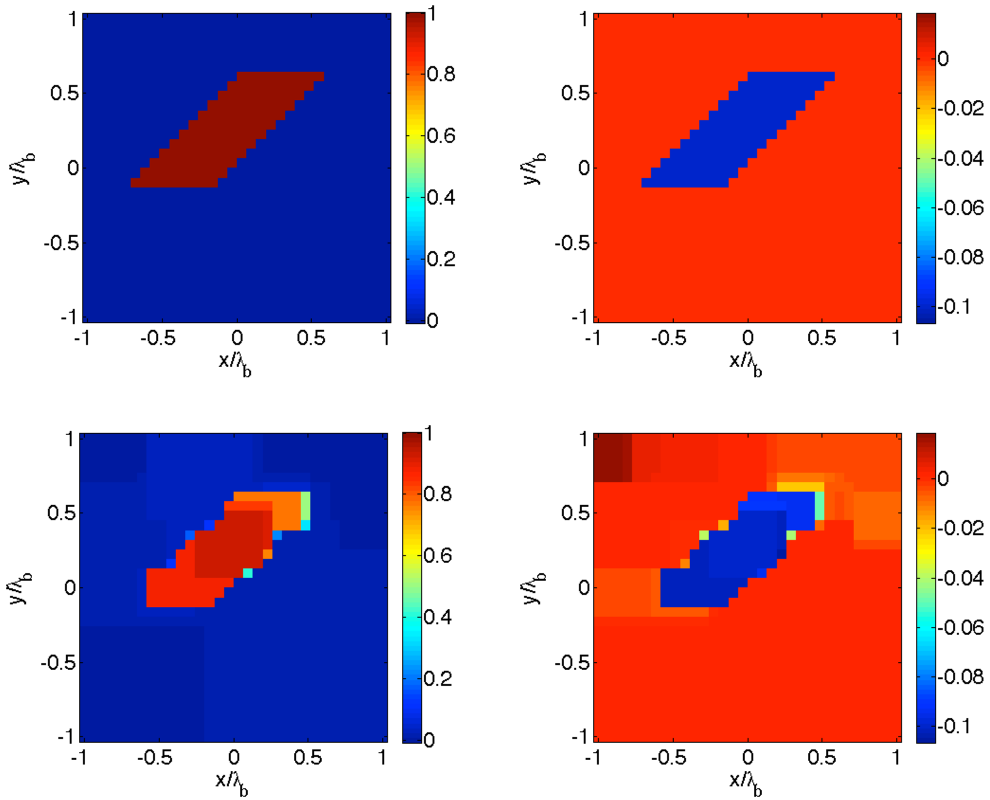
[*] L. Crocco et al., "The linear sampling method as a way to quantitative inverse scattering", IEEE Trans. Antennas Propag., 60(4):1844-1853, Apr. 2012.

(by courtesy of T. Isernia, Mediterranean Univ. of Reggio Calabria, Italy)

A Virtual Experiments Linearized Inversion via Compressive Sensing*

real profile

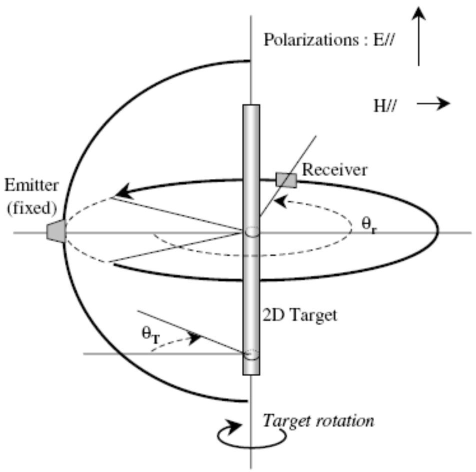
reconstructed profile

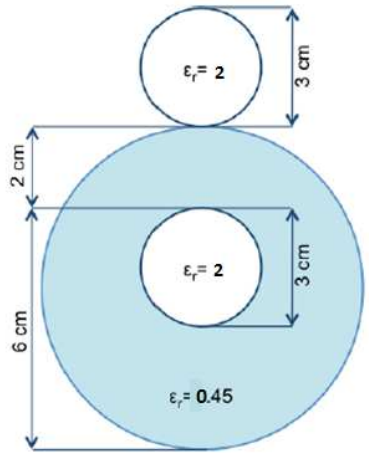


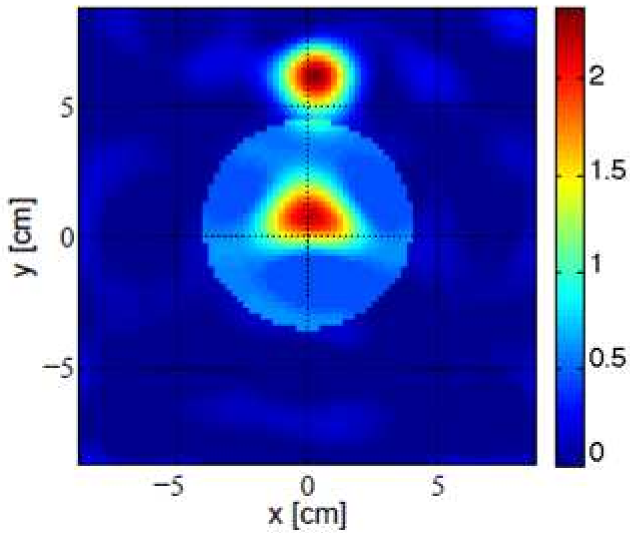
[*] Bevacqua et al., "Microwave Imaging of Non-Weak Targets Via Compressive Sensing and Virtual Experiments," Antennas and Wireless Propagation Letters, IEEE, 2015, vol.14, no., pp.1035-1038, 2015.

(by courtesy of T. Isernia, Mediterranean Univ. of Reggio Calabria, Italy)

A Virtual Experiments Distorted Wave Inversion*





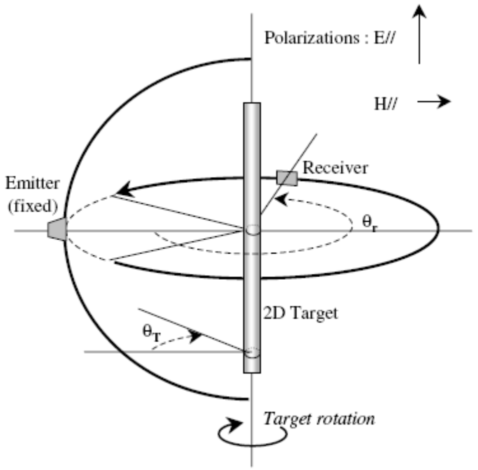


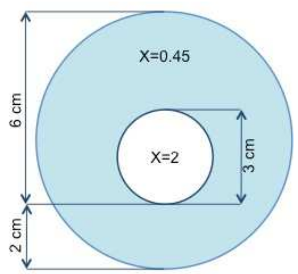
validation against **single** frequency Frésnel data **Freq = 4 GHz**

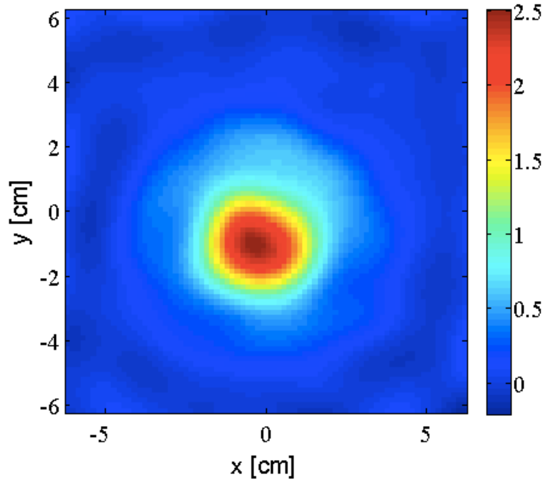
[*] Di Donato et al., “A new linear distorted wave inversion method fot microwave imaging via virtual experiments”, Microwave Theory and Techniques, submitted..

(by courtesy of T. Isernia, Mediterranean Univ. of Reggio Calabria, Italy)

An Iterated Virtual Experiments Inversion *







validation against **single** frequency Frésnel data

Freq = 4 GHz

[*] Bevacqua et al., "Microwave Imaging via Iterated Virtual Experiments," Antennas and Propagation (EuCAP), 2016, 10th European Conference on, submitted.

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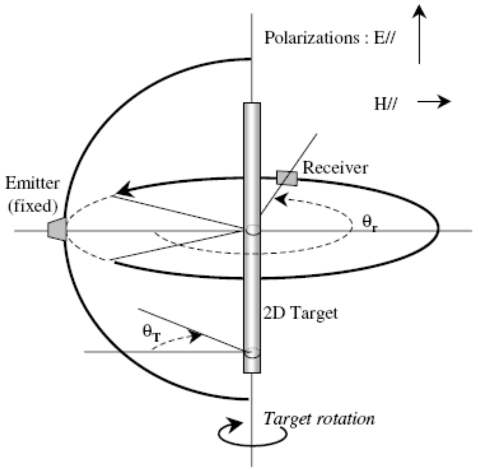
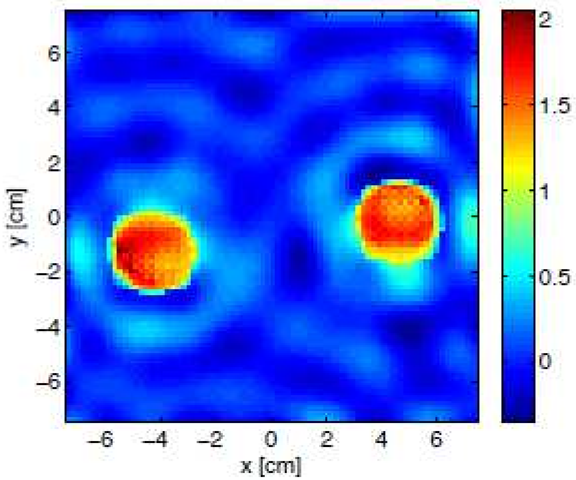
(by courtesy of T. Isernia, Mediterranean Univ. of Reggio Calabria, Italy)

Virtual Experiment: Contrast Source*





validation against **single** frequency Frésnel data

Freq = 5 GHz

[*] Di Donato et al., "Inverse Scattering via Virtual Experiments and Contrast Source Regularization," Antennas and Propagation, IEEE Transactions on, vol.63, no.4, pp.1669-1677, April 2015.

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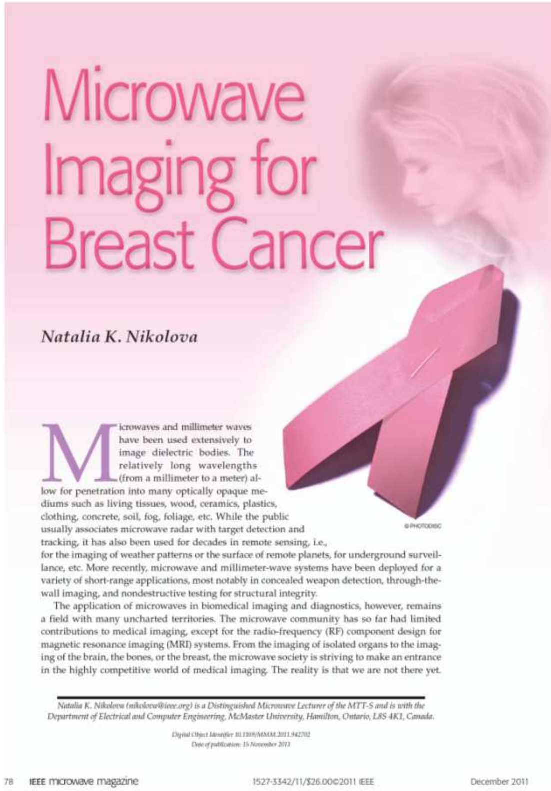
(by courtesy of T. Isernia, Mediterranean Univ. of Reggio Calabria, Italy)

Applications of microwave imaging in medical areas

- In the biomedical field, electromagnetic imaging based on inverse scattering have been widely studied, mainly for breast cancer detection.
- Excellent results have been provided.
- A good overview can be found in
  - N. K. Nikolova, «Microwave Imaging for Breast Cancer», IEEE Microwave Magazine, vol, 12, 2011.
- Beamforming methods are usually adopted and recently they are combined with quantitative methods in order to devise specific hybrid techniques.



Microwave Imaging for Breast Cancer

Natalia K. Nikolova

Microwaves and millimeter waves have been used extensively to image dielectric bodies. The relatively long wavelengths (from a millimeter to a meter) allow for penetration into many optically opaque mediums such as living tissues, wood, ceramics, plastics, clothing, concrete, soil, fog, foliage, etc. While the public usually associates microwave radar with target detection and tracking, it has also been used for decades in remote sensing, i.e., for the imaging of weather patterns or the surface of remote planets, for underground surveillance, etc. More recently, microwave and millimeter-wave systems have been deployed for a variety of short-range applications, most notably in concealed weapon detection, through-the-wall imaging, and nondestructive testing for structural integrity.

The application of microwaves in biomedical imaging and diagnostics, however, remains a field with many uncharted territories. The microwave community has so far had limited contributions to medical imaging, except for the radio-frequency (RF) component design for magnetic resonance imaging (MRI) systems. From the imaging of isolated organs to the imaging of the brain, the bones, or the breast, the microwave society is striving to make an entrance in the highly competitive world of medical imaging. The reality is that we are not there yet.

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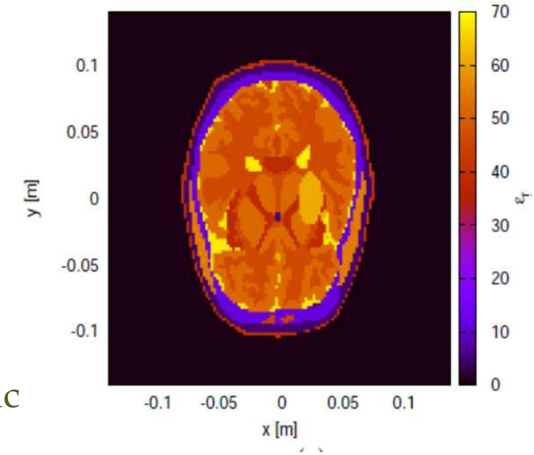
Date of publication: 15 November 2011

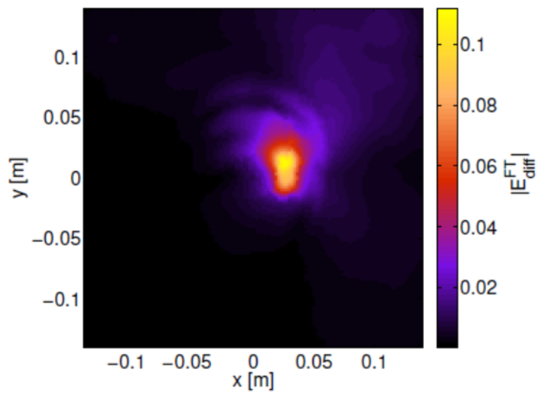
78 IEEE microwave magazine 1527-3342/11/$26.00©2011 IEEE December 2011

Recent new medical applications of microwave imaging

- Recently new medical applications have been exploited.
- Some examples are given in the following.

- Brain stroke detection.
  - L. Guo, A. M. Abbosh, “Microwave Stepped Frequency Head Imaging Using Compressive Sensing With Limited Number of Frequency Steps”, IEEE AWPL, vol. 14, 2015.
  - M. Cerruti, F. Lavagetto, G. Mancardi, M. Pastorino, A. Randazzo, “A numerical simulation for brain stroke microwave imaging by using the FVTD,” Proc. URSI-France 2015 Scientific Days on “Probing the materials by Electromagnetic Waves”, Paris, France, 24-25 March, pp. 171-174, 2015.
  - S. Semenov, B. Seiser, E. Stoegmann, and E. Auff, “Electromagnetic tomography for brain imaging: From virtual to human brain,” in Proc. 2014 IEEE Conference on Antenna Measurements & Applications (CAMA), Antibes Juan-Les-Pins, France, 2014, pp. 1–4.
  - R. Scapaticci, O. M. Bucci, I. Catapano, and L. Crocco, “Robust microwave imaging for brain stroke monitoring,” in Proc. 7th European Conference on Antennas and Propagation (EuCAP), Gothenburg, Sweden, 2013, pp. 75-78.





Recent new medical applications of microwave imaging

- Use of nanoparticles to improve the contrast of the biological tissues.
  - O. M. Bucci, L. Crocco, R. Scapaticci, «On the Optimal Measurement Configuration for Magnetic Nanoparticles-Enhanced Breast Cancer Microwave Imaging», *IEEE Trans. Biomedical Eng.*, vol. 2, no. 62, 2015.
- Legs, arms, and bones imaging
  - M. Ostadrahimi, P. Mojabi, A. Zakaria, J. LoVetri, and L. Shafai, "Enhancement of Gauss-Newton Inversion Method for Biological Tissue Imaging," *IEEE Trans. Microw. Theory Tech.*, vol. 61, no. 9, Sep. 2013.
  - A. Zakaria, A. Baran, and J. LoVetri, "Estimation and Use of Prior Information in FEM-CSI for Biomedical Microwave Tomography," *IEEE Antennas Wirel. Propag. Lett.*, vol. 11, pp. 1606–1609, 2012.
  - P. M. Meaney, D. Goodwin, A. H. Golnabi, T. Zhou, M. Pallone, S. D. Geimer, G. Burke, and K. D. Paulsen, "Clinical Microwave Tomographic Imaging of the Calcaneus: A First-in-Human Case Study of Two Subjects," *IEEE Trans. Biomedical Eng.*, vol. 59, no. 12, pp. 3304–3313, 2012
- Wireless capsule endoscopy (localization of an in-body RF source)
  - R. Chandra, A. J. Johansson, M. Gustafsson, and F. Tufvesson, «A Microwave Imaging-Based Technique to Localize an In-Body RF Source for Biomedical Applications», IEEE Trans. Biomedical Eng., vol. 62, no. 5, May 2015.

Magnetic Nanoparticle Enhanced Imaging for breast cancer imaging

Goal & key concepts

Enhance the contrast between the tumor and the surrounding tissues using a tunable contrast agent

Magnetic Nanoparticles (MNP) as contrast agent:

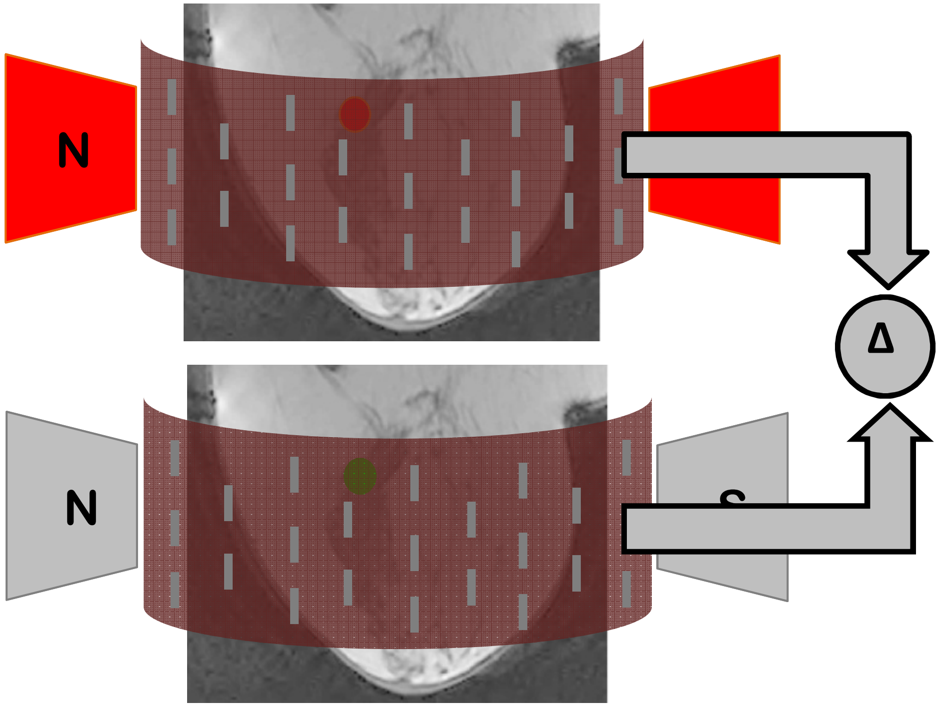
- already approved in clinics (MRI, magnetic hyperthermia)
- allow selective targeting (via functionalization)
- induce a specific contrast (non-magnetic environment)
- tunable by an external magnetic field (switch on/switch off)

G. Bellizzi et al. IEEE Trans. Biomedical Eng, 58 (9), 2528-2536, 2011.
O. M Bucci et al., IEEE Antennas Wireless Propagat Lett. 11, 1630-1632, 2012.
R. Scapaticci et al., IEEE Trans. Biomedical Eng. 61 (4), 1071-1079, 2014.

(by courtesy of L. Crocco, IREA-CNR, Napoli, Italy)

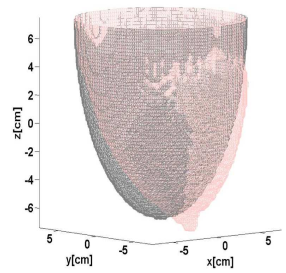
Magnetic Nanoparticle Enhanced Imaging for breast cancer imaging

Basic working principle



ΔE_{scatt}

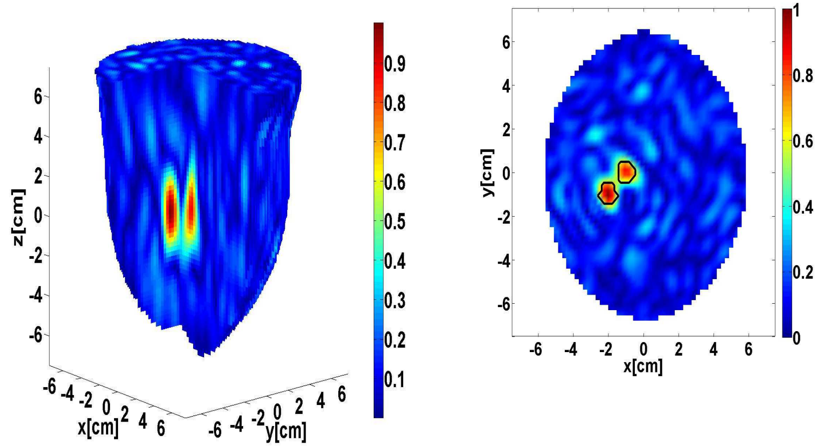
Simplified reference scenario



magnetic contrast reconstruction $\rightarrow \Delta\chi_m$

Differential measurement strategy

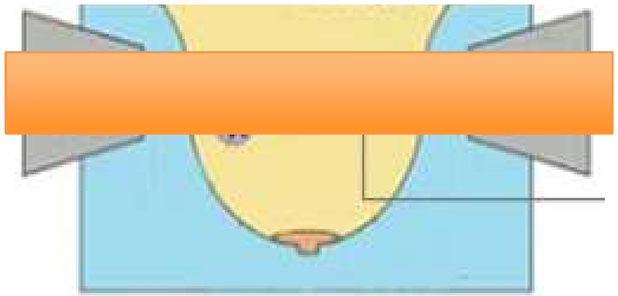
LINEAR inversion
(low magnetic contrast)

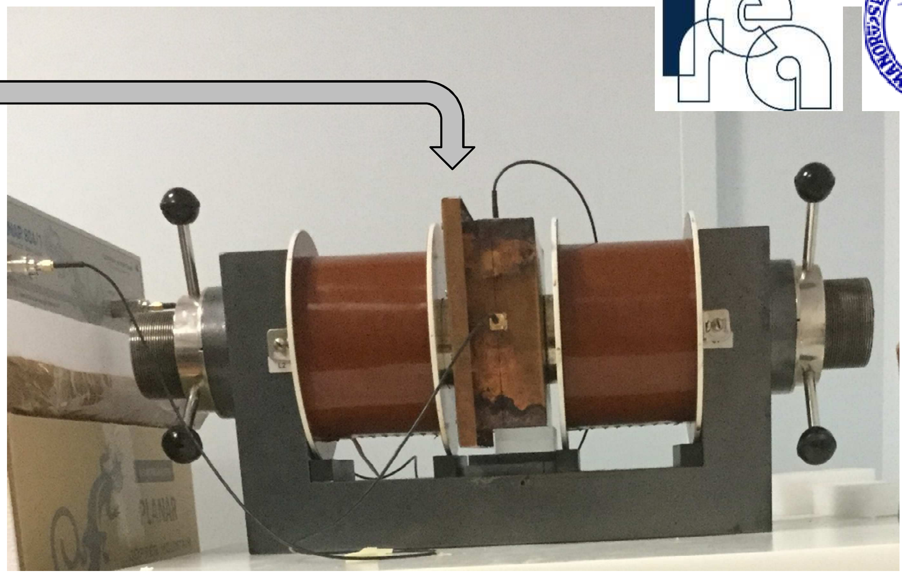


(by courtesy of L. Crocco, IREA-CNR, Napoli, Italy)

Magnetic Nanoparticle Enhanced Imaging
for breast cancer imaging

UNIVERSITÀ DELLA CALABRIA





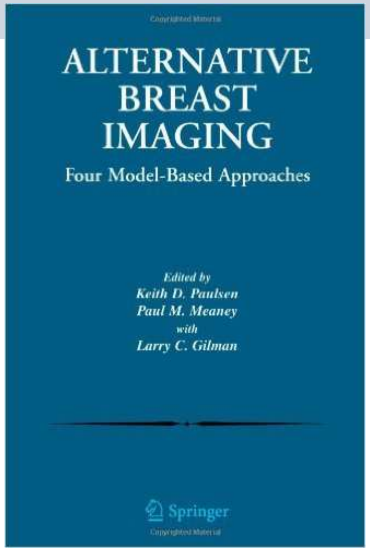
Experimental proof-of-concept

The copper box embeds a breast phantom hosting MNP and surrounded by a coupling medium.
Cavity backed antennas are mounted on the sides of the box

Experimental results will be presented at EUCAP2016

(by courtesy of L. Crocco, IREA-CNR, Napoli, Italy)

Experimental apparatuses for microwave imaging



- Very interesting development have been obtained in the field of experimental systems for microwave imaging.

  - R. Zoughi, Microwave non-destructive testing and evaluation. 2000.
  - M. T. Ghasr, M. A. Abou-Khousa, S. Kharkovsky, R. Zoughi, and D. Pommerenke, “Portable Real-Time Microwave Camera at 24 GHz,” IEEE Trans. Antennas Propag., vol. 60, no. 2, 2012.
  - X. Zeng, A. Fhager, Z. He, M. Persson, P. Linner, and H. Zirath, “Development of a Time Domain Microwave System for Medical Diagnostics,” IEEE Trans. Instrum. Meas., vol. 63, no. 12, 2014.
  - R. D. Monleone, M. Pastorino, J. Fortuny-Guasch, A. Salvade, T. Bartesaghi, G. Bozza, M. Maffongelli, A. Massimini, A. Carbonetti, and A. Randazzo, “Impact of Background Noise on Dielectric Reconstructions Obtained by a Prototype of Microwave Axial Tomograph,” IEEE Trans. Instrum. Meas., vol. 61, no. 1, 2012.
  - V. Tobon, et al., “Design and modeling of a microwave imaging system for breast cancer detection”, 9th Proc. European Conference on Antennas and Propagation (EuCAP), 2015. V. Zhurbenko, T. Rubæk, V. Krozer, and P. Meincke, “Design and realisation of a microwave three-dimensional imaging system with application to breast-cancer detection,” IET Microw. Antennas & Propag., vol. 4, no. 12, 2010.
  - T. Henriksson, N. Joachimowicz, C. Conessa, and J.-C. Bolomey, “Quantitative Microwave Imaging for Breast Cancer Detection Using a Planar 2.45 GHz System,” IEEE Trans. Instrum. Meas., vol. 59, no. 10, 2010.
  - M. Ostadrahimi, A. Zakaria, J. LoVetri, and L. Shafai, “A Near-Field Dual Polarized (TE -TM) Microwave Imaging System,” IEEE Trans. Microw. Theory Tech., vol. 61, no. 3, 2013.
  - K. D. Paulsen, P. M. Meaney, L. Gilman (Eds) “Alternative Breast Imaging: Four Model-Based Approaches”, 2005.

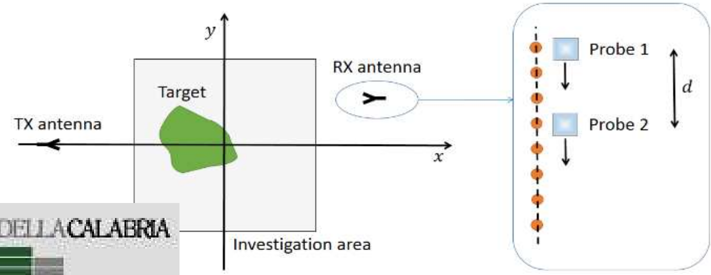
Inversion of amplitude-only data

Real measured data (University of Calabria, Cosenza, Italy [*]).

- S = 9 sources; M = 53 measurement points.

Frequency 10 GHz

Max outer iterations $N_{IN} = 20$; inner iterations $N_{LW} = 5$;
Algorithm initialized assuming an empty investigation domain (square area of side 15 cm discretized in 63×63 square subdomains)



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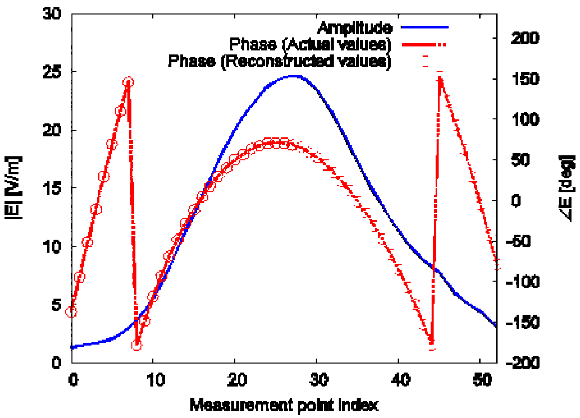
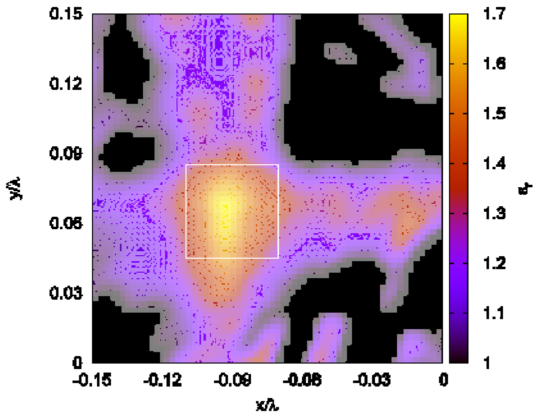
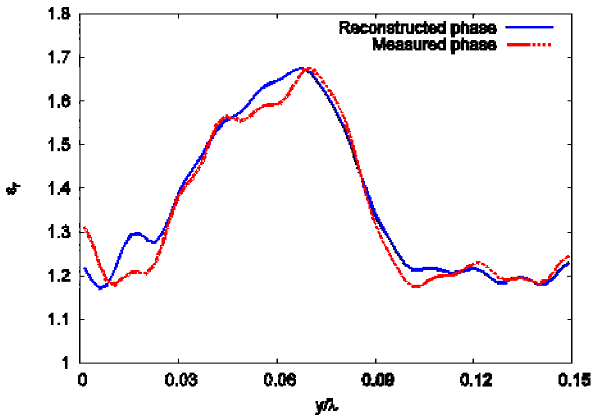






[*] S. Costanzo and G. Di Massa, "An integrated probe for phaseless near-field measurements," *Measurement*, vol. 31, no 2, pp. 123-129, Mar. 2002.

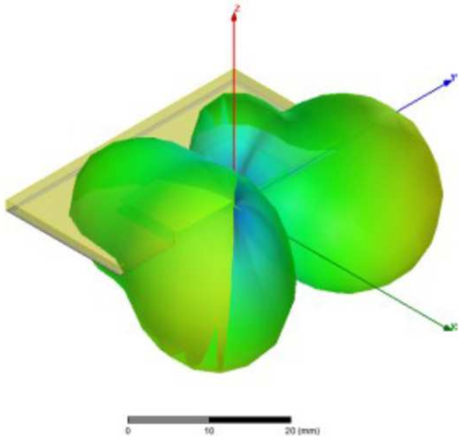
Antennas for microwave imaging

- The development and analysis of antennas for microwave imaging is another research topic of great interest.
- Several proposal have been presented, especially in the field of medical imaging (but not only).
- Some examples:
  - Design and performance analysis of the miniaturized water-filled double-ridged horn antenna for active microwave imaging applications
    - S. L. Latif, D. Flores-Tapia, S. Pistorius, L. Shafai, «Design and performance analysis of the miniaturized water-filled double-ridged horn antenna for active microwave imaging applications» IET Microw. Antennas Propag., vol. 9, no. 11, 2015.
  - Analysis of the impact of polarization on imaging performances
    - R. O. Mays, N. Behdad, S. C. Hagness, "A TSVD Analysis of the Impact of Polarization on Microwave Breast Imaging Using an Enclosed Array of Miniaturized Patch Antennas ", IEEE Antennas Wirel. Propag. Lett., vol. 14, 2015
  - Mathematical formulations of inverse problems taking into account antennas
    - M. Haynes and M. Moghaddam, "Vector Green's function for S-parameter measurements of the electromagnetic volume integral equation," IEEE Trans. Antennas Propag., vol. 60, no. 3, pp. 1400–1413, Mar. 2012.

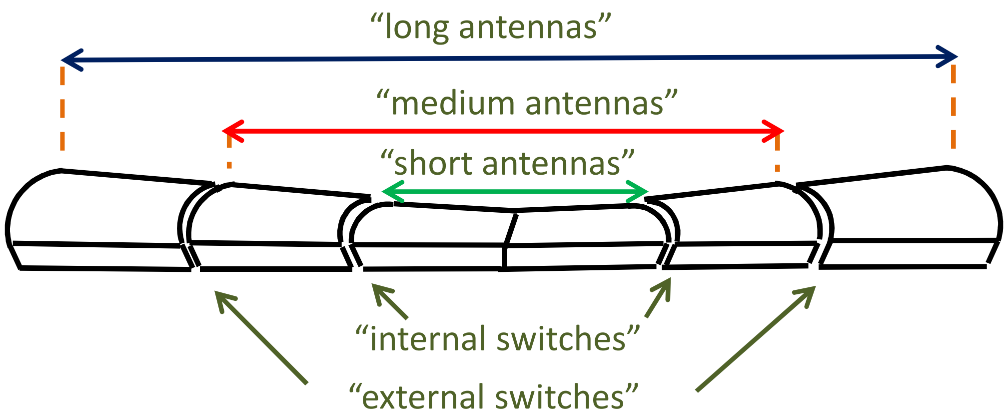
Antennas for microwave imaging

- Development of ultra-wide band antennas for imaging systems
  - T. A. Denidni and G. Augustin, Ultrawideband antennas for microwave imaging systems. Artech House, 2014.
  - S. Ahdi Rezaeieh, A. Zamani, and A. M. Abbosh, “3-D Wideband Antenna for Head-Imaging System with Performance Verification in Brain Tumor Detection,” IEEE Antennas Wirel. Propag. Lett., vol. 14, 2015.
  - M. Lanini, S. Poretti, A. Salvadè, and R. Monleone, ”Design of a slim wideband-antenna to overcome the strong reflection of the air-to-sample interface in microwave imaging”, ICEAA, Torino, 2015.

A slim wideband-antenna for microwave imaging (Lanini et al., 2015),



Reconfigurable GPR system (Italian Patent n. 00013952319)



Scheme of the antenna

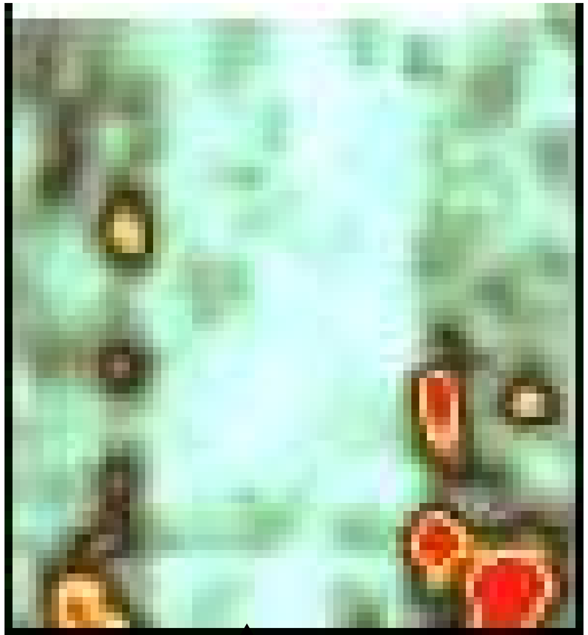
The system can prolong or shorten the antennas by switching on and off two series of PIN diodes along its arms. It has three pairs of equivalent antennas with the same gap and works in the band 50 MHz-1 GHz. It is a stepped frequency system and allows also to reconfigure the integration time of the harmonic tones. This last option has been recently used for an effective rejection of narrow band interferences.

Prototypal reconfigurable system

(by courtesy of Dr. R. Persico, IBAM-CNR, Italy)

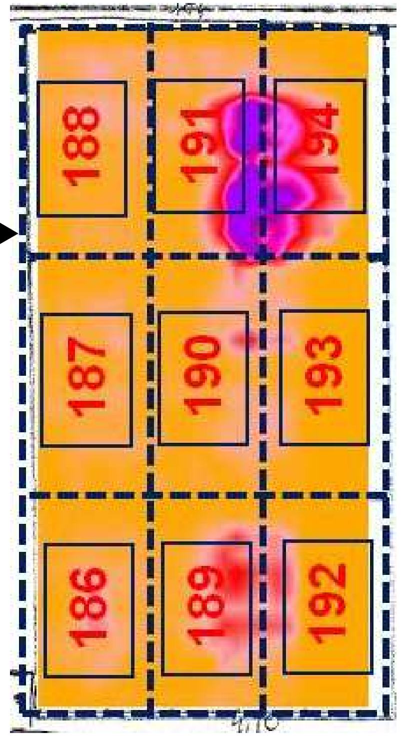
Reconfigurable GPR system

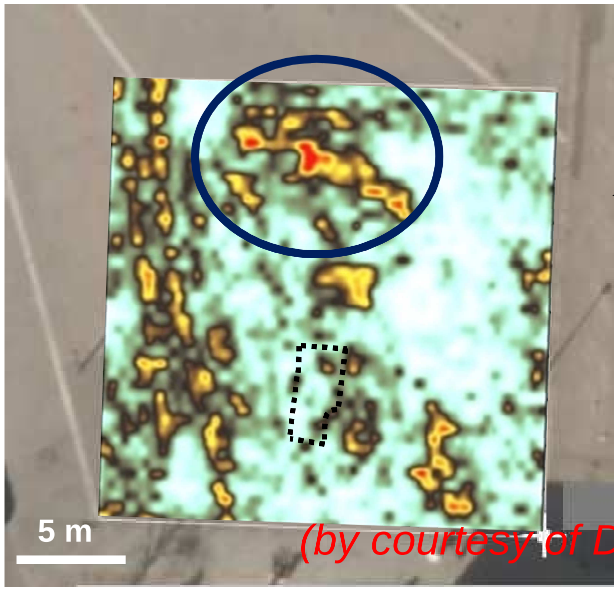
The system can gather in a unique going through three sets of data, suitable to investigate different depths



Bottom of the moat (nowadays filled up) of the Messapic town of Manduria (Italy), 8th-3rd century B.C., at the depth of about 3.5 m. The area is about 10x10 m^2.

Chapel of Aragon in the Cathedral of St. John at Valletta (Malta). The numbered areas corresponds to headstones, but only part of them correspond to sepulchres of knifes. The depth is about 30 cm. The area is about 7x4.5 m^2.





Probable Viking remains in Tondrehim (Norway), at the depth of about 1.8 m. The area is about 20x20 m^2.

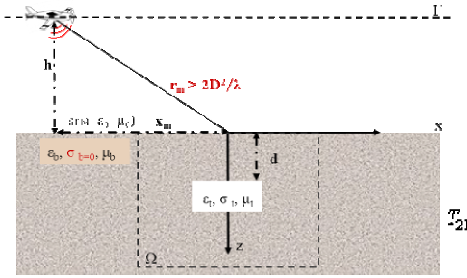
(by courtesy of Dr. R. Persico, IBAM-CNR, Italy)

Microwave tomography via non conventional measurement setups

- **Born Approximation** (linear) $E_s(x_s,z_s,f) \propto \int_\Omega \underbrace{G(x_s,z_s,x',z',f)}_{\text{Green function}} \underbrace{E_{inc}(x',z',f)}_{\text{Incident field}} \chi(x',z') d\Omega = L[\chi]$
- Flexible formulation easily adaptable whatever is the adopted measurement configuration and the reference scenario

Airborne GPR

rapid surveys of large, even inaccessible, areas with high data density



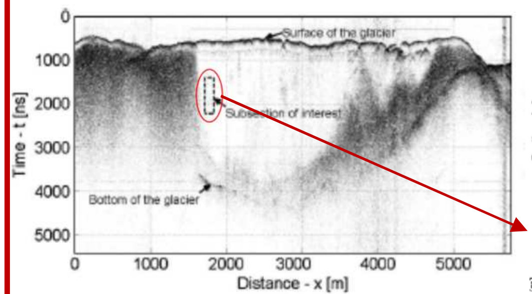
$$E_{inc}(\mathbf{r},\mathbf{r}_m) \approx T_{21} \exp\{-jk_0 \cdot (R_1 + \sqrt{\varepsilon_b} R_2)\}$$

$$G(\mathbf{r}_m,\mathbf{r}) \propto T_{12} \exp\{-jk_0 \cdot (R_1 + \sqrt{\varepsilon_b} R_2)\}$$

$$T_{21} = \frac{2\cos\theta_1}{\cos\theta_1 + \sqrt{\varepsilon_b}\cos\theta_2}, \quad T_{12} = \frac{2\sqrt{\varepsilon_b}\cos\theta_2}{\cos\theta_1 + \sqrt{\varepsilon_b}\cos\theta_2}$$

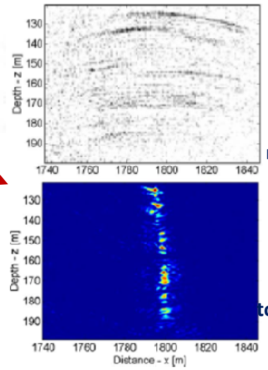
Experimental validation

in collaboration with RST GmbH



GPR surveys on a Swiss glacier – radargram

f	55-150MHz
Δf	2MHz
Tx/Rx height	43.5m
ε_{ice}	3
σ_{ice}	0 S/m



row data

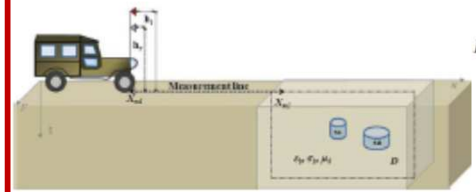
tomographic image

focused image allowing an accurate localization

I. Catapano, L. Crocco, Y. Krellmann, G. Triltzsch, F. Soldovieri, A tomographic approach for helicopter-borne ground penetrating radar imaging, IEEE Geosci. and Remote Sens. Lett., 9, 378-382, 2012

Forward looking GPR

on surface and buried targets imaging while assuring a safety distance



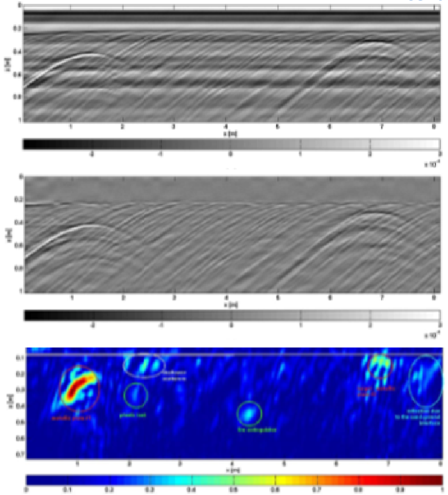
$$E_{inc}(x_t,z_t,\omega,\underline{r}) = \frac{-\mu_0\omega}{2\pi}\int_{-\infty}^{+\infty} \frac{\exp\{-jk_{zb}(u)z\}\exp\{jk_{z0}(u)h_t\}}{[k_{zb}(u)+k_{z0}(u)]} \times \exp\{ju(x_t - x)\}\, du$$

$$G(x_r,z_r,\omega,\underline{r}) = \frac{-j}{2\pi}\int_{-\infty}^{+\infty} \frac{\exp\{-jk_{zb}(v)z\}\exp\{jk_{z0}(v)h_r\}}{[k_{zb}(v)+k_{z0}(v)]} \times \exp\{jv(x_r - x)\}\, dv.$$

Experimental validation

in collaboration with IDS Spa

test site



row data

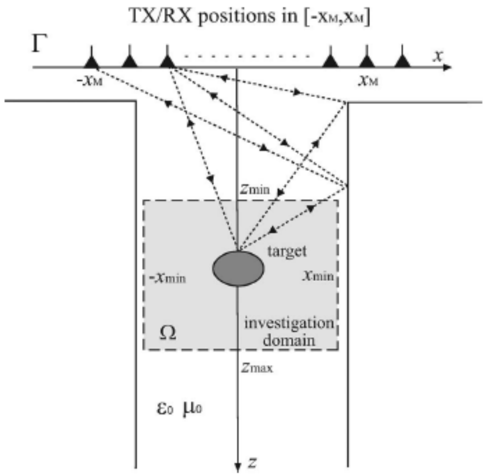
filtered data

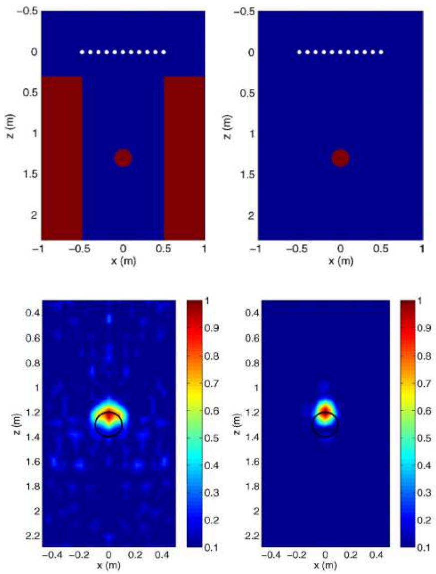
tomographic image

I. Catapano, A. Affinito, A. Del Moro, G. Alli, F. Soldovieri, Forward-Looking Ground-Penetrating Radar via a Linear Inverse Scattering Approach, IEEE Trans. Geosci.and Remote Sen., 53, 5624-5633, 2015

(by courtesy of F. Soldovieri, IREA-CNR, Napoli, Italy)

Radar imaging in complex scenarios



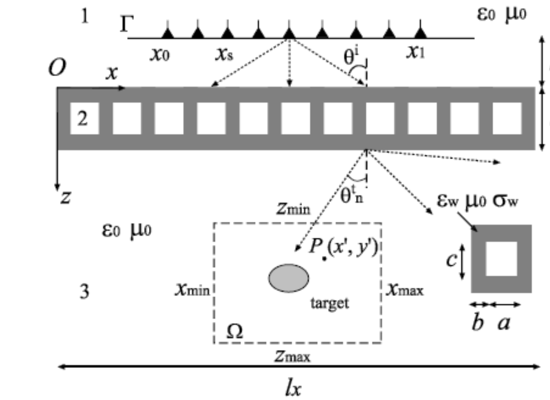


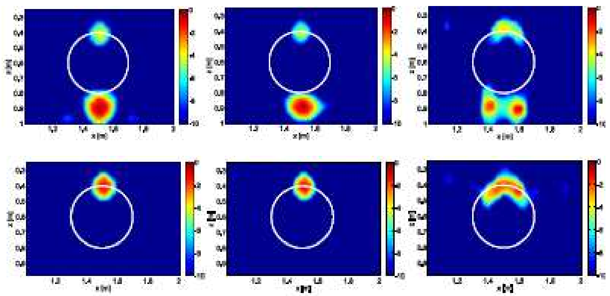
- Target imaging in urban areas (e.g. canyons)
- Rich multipath environment
- Targets in NLOS region

Multipath modeling and exploitation increases resolution and mitigates the ghosts' problem

G. Gennarelli, F. Soldovieri, "A linear inverse scattering algorithm for radar imaging in multipath environments," IEEE Geosci. Rem. Sens. Lett., vol. 10, no. 5, pp. 1085-1089, 2013.

(by courtesy of F. Soldovieri, IREA-CNR, Italy)





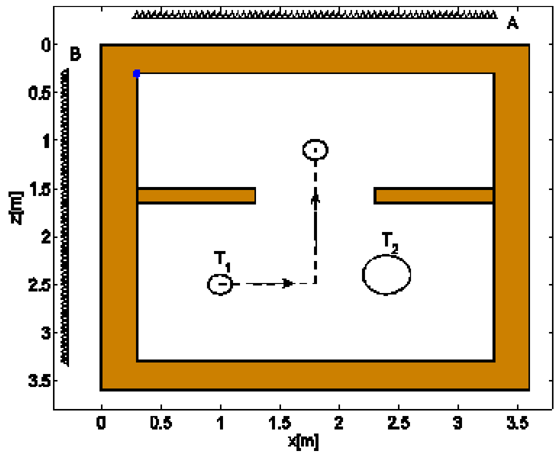
free-space homogeneous wall cinderblock wall

- Imaging through periodic structures (cinderblock walls)
- Multiscattering environment

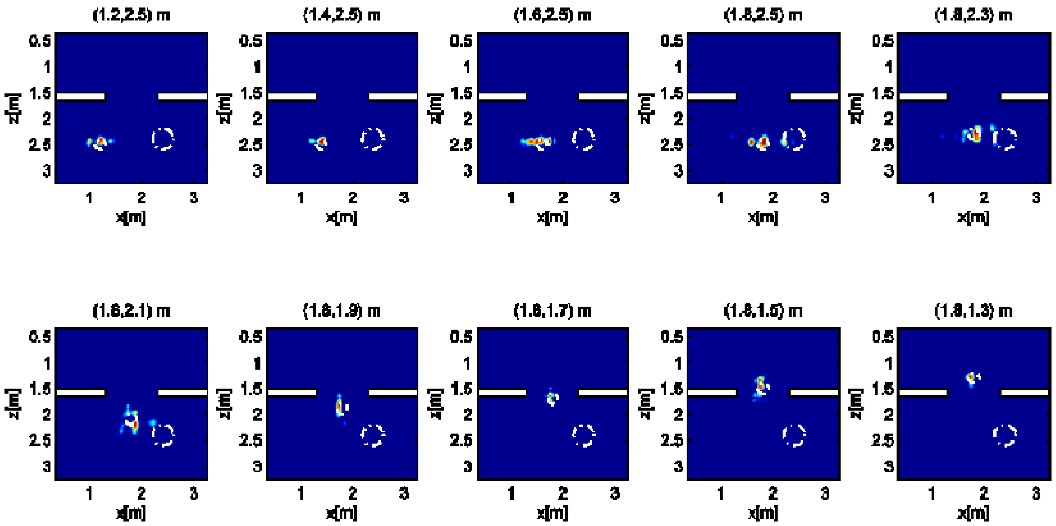
Multipath related to Floquet modes increases the information content of data enhancing resolution

- G. Gennarelli and F. Soldovieri, "Radar imaging through cinderblock walls: Achievable performance by a model-corrected linear inverse scattering approach," IEEE Trans. Geosci. Rem. Sens., vol. 52, no. 10, pp. 6738–6749, 2014.
- G. Gennarelli, R. Persico, F. Soldovieri, "Effective imaging systems based on periodic lattices," Applied Physics Letters, vol. 104, 194103, 2014.

Passive RF tomography



- Opportunistic sources (e.g. Wi-Fi)
- Passive multistatic arrays
- Inverse source formulation
- Moving target imaging

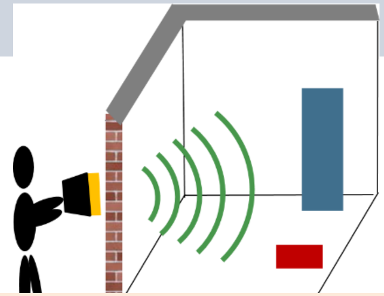


Change detection results

G. Gennarelli, M. G. Amin, F. Soldovieri, and R. Solimene, "Passive multiarray image fusion for RF tomography by opportunistic sources," IEEE Geosci. Rem. Sens. Lett., vol. 12, no. 3, pp. 641-645, 2015.

(by courtesy of F. Soldovieri, IREA-CNR, Napoli, Italy)

Through Wall simulation by a scattering solver

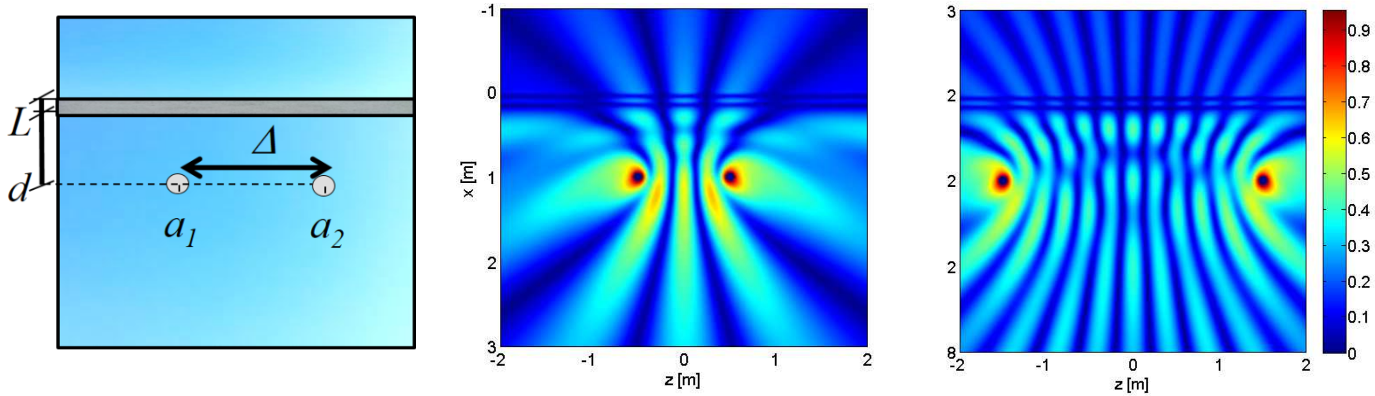


Innovative direct scattering solvers for Through Wall radar applications

- fast and accurate, with low computer memory requirements
- a better understanding of the scattering scenarios
- a benchmark for new imaging techniques and general e.m. solvers

EMLAB[3] Laboratory
«Roma Tre» University, Department of Engineering,
Director: Prof. G. Schettini

Solution to Through Wall scattering with the Cylindrical Wave Approach (CWA)

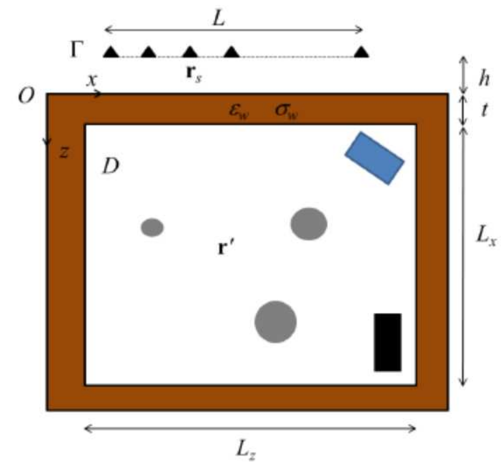


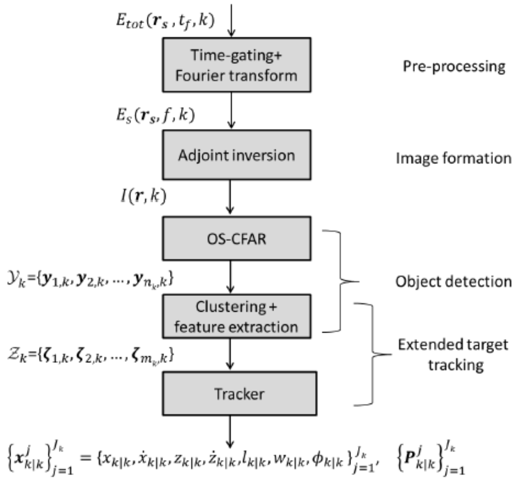
F. Frezza, L. Pajewski, C. Ponti, and G. Schettini, "Through-wall electromagnetic scattering by N conducting cylinders," *J. Opt. Soc. Am. A,* Vol. 30, pp. 1632-1639, Aug. 2013.

C. Ponti, and S. Vellucci, "Scattering by conducting cylinders below a dielectric layer with a fast noniterative approach," *IEEE Transactions on Microwave Theory and Technique*, vol. 63, no.1, Jan. 2015, pp. 30-39.

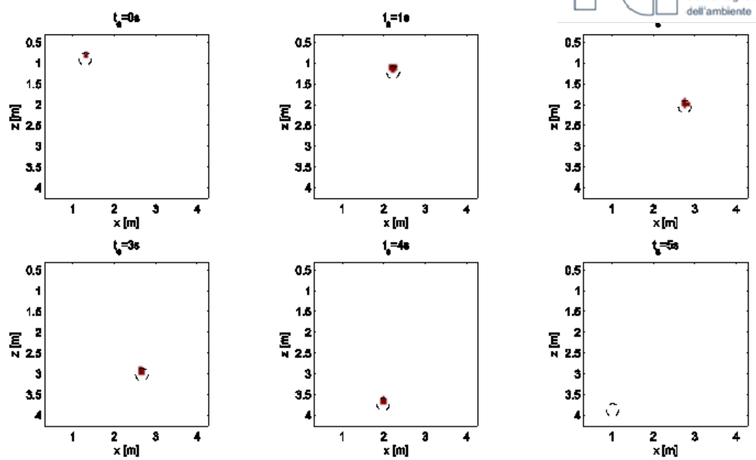
(by courtesy of G. Schettini, Univ. Roma III, Roma, Italy)

Target tracking using through wall radars

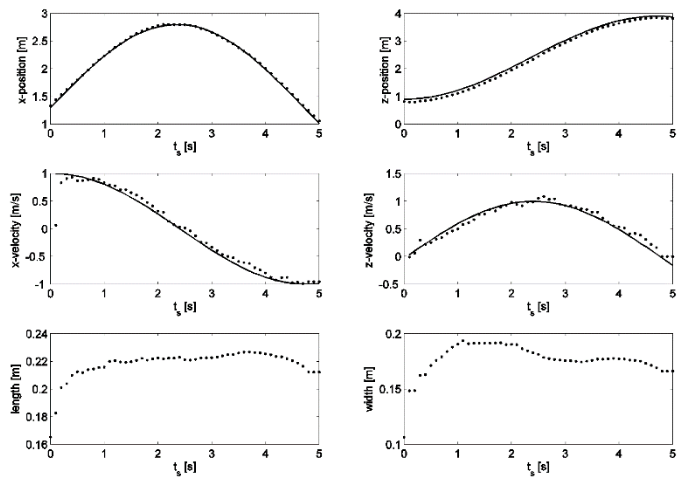




Data processing chain



Detector output



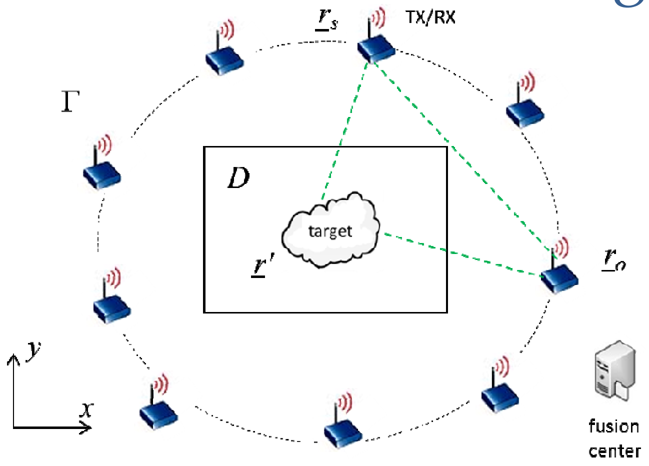
Tracker output

- Ground based monostatic through wall radar
- Complex multipath environment
- Target dynamics evaluation
- False targets mitigation
- Multiple Extended Target Tracking
- Real-time signal processing

G. Gennarelli, G. Vivone, P. Braca, F. Soldovieri, and M. G. Amin, "Multiple Extended Target Tracking for Through Wall Radars," IEEE Trans. Geosci. Rem. Sens., vol. 53, no. 12, pp. 6482–6494, 2015.

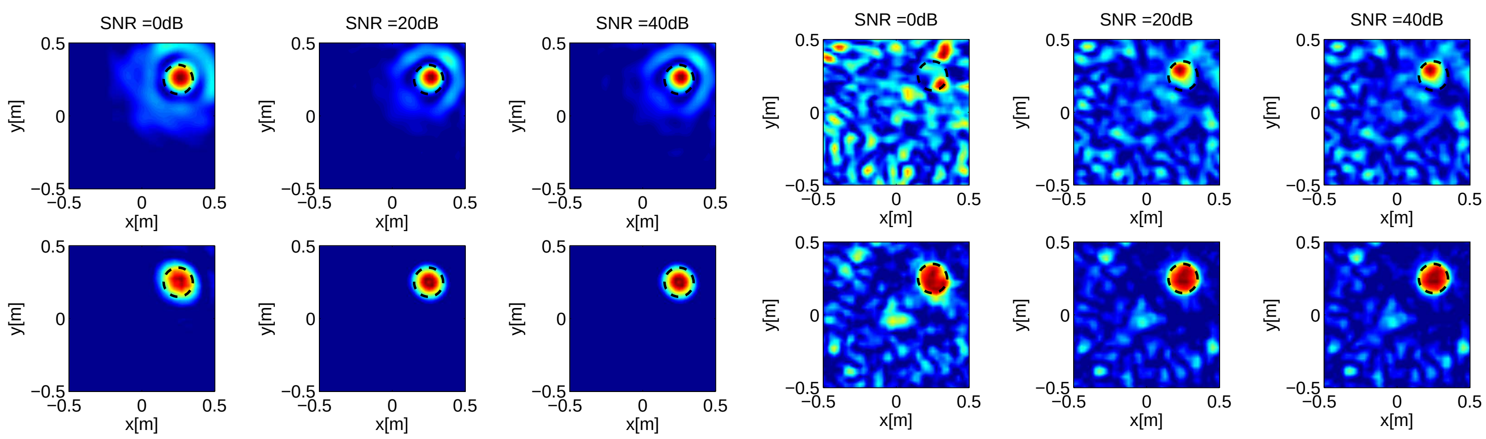
(by courtesy of F. Soldovieri, IREA-CNR, Napoli, Italy)

Incoherent RF tomography by Wireless Sensor Networks



- Simple sensor nodes (e.g. Wi-Fi cards)
- Received power measurements
- Rytov-based inverse scattering model
- Multiview/multistatic measurement configuration
- Performance analysis of incoherent vs. coherent RF tomography

Low contrast target



Densely populated WSN **Poorly populated WSN**

G. Gennarelli and F. Soldovieri, "Performance Analysis of Incoherent RF Tomography using Wireless Sensor Networks," IEEE Trans. Geosci. Rem. Sens., (accepted).

(by courtesy of F. Soldovieri, IREA-CNR, Napoli, Italy)

Other applications

- Microwave imaging has been proposed for many other applications.
- Some examples:
  - Reconstruction of velocity profiles in pipes
    - M. Brignone, M. Raffetto, A. Randazzo, «Reconstruction of non-constant velocity profiles in pneumatic pipelines by microwave inverse scattering Techniques,» ICEAA 2015, Torino, Italy, 2015.
  - Imaging of microwave absorbers
    - J.-M. Geffrin, C. Eyraud, A. Litman, «3-D Imaging of a Microwave Absorber Sample From Microwave Scattered Field Measurements», IEEE Microwave and Wireless Components Letters, vol 25, no. 7, 2015.
  - Detection of debris
    - F. Nsengiyumva, Ch. Pichot, I. Aliferis, J. Lanteri, C. Migliaccio, «Detection of Debris (FOD) on Runways in W-Band: Relevance and Validity Domain of Two-Dimensional Approaches”, ICEAA 2015, Torino, Italy, 2015.

Other applications

- Some other examples:
  - Imaging of strips on reflecting planes
    - M. A. Maisto, R. Solimene, and R. Pierri, "Linear inverse scattering of strip objects above a reflecting plane," Proc. of The 2015 URSI Atlantic Radio Sci. Conf. (URSI AT-RASC 2015), Canary Islands, May 18-22, 2015.
  - Inspection of startified media.
    - M. Fallahpour, J. T. Case, M. T. Ghasr, and R. Zoughi, "Piecewise and Wiener Filter-Based SAR Techniques for Monostatic Microwave Imaging of Layered Structures," IEEE Trans. Antennas Propag., vol. 62, no. 1, pp. 282–294, Jan. 2014.
    - S. Caorsi and M. Stasolla, "A Layer Stripping Approach for EM Reconstruction of Stratified Media," IEEE Geosci. Remote Sens. Lett., vol. 52, pp. 5855-5869, 2014..

- Further application can be found at MMS 2015 in the following special session:

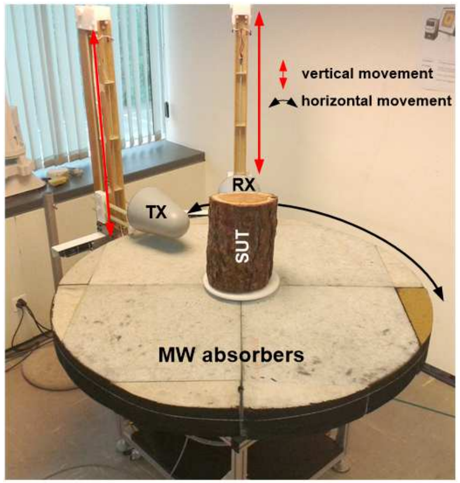
Electromagnetic Inverse Scattering and its Applications to Detection, Diagnostic, and Imaging

Organizer:

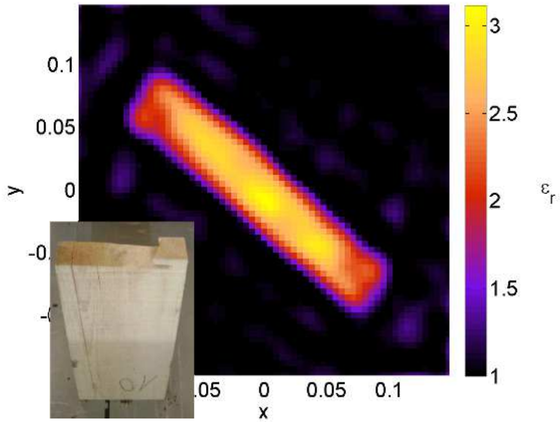
Salvatore Caorsi, University of Pavia.

Other applications

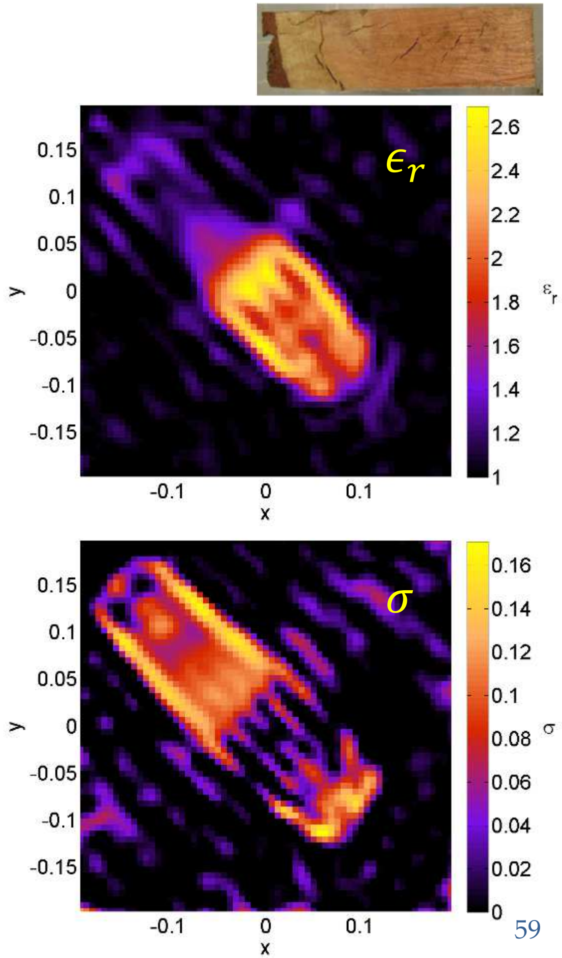
- Microwave imaging in the wood industry
  - Real measured data (SUPSI prototype)
  - $S = 8$ sources uniformly spaced on a circumference with radius $R = 73$ cm and $M = 91$ measurement points over the same circumference
  - Frequency hopping (11 frequencies between 1 GHz – 5 GHz)
  - Max outer iterations $N_{IN} = 30$; max inner iterations $N_{LW} = 30$
  - Algorithm initialized assuming an empty investigation domain (side 0.4 m, discretized in 63×63 square subdomains)



White fir sample
without defects



Larix sample with rotten parts (higher conductivity)



…. THAT'S ALL …
THANK YOU VERY MUCH FOR YOUR ATTENTION