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A Microwave Diagnostic Technique for Early-Stage Brain Stroke Characterization

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Introduction

- **Brain stroke** is well known as one of the leading causes of death and disability worldwide.
- Within **electromagnetic diagnostic techniques** [1, 2] an increasing interest is attracted by **brain stroke detection** [3 – 6].
- A novel **tomographic multistatic system** where the acquired data are processed by an **inexact Newton** scheme in **variable-exponent L^p spaces** is presented.
- Simulated and experimental results are shown.

[1] J.-C. Bolomey, "Advancing Microwave-Based Imaging Techniques for Medical Applications in the Wake of the 5G Revolution," **in 2019 13th European Conference on Antennas and Propagation (EuCAP), 2019**, pp. 1–5.

[2] O. M. Bucci, G. Bellizzi, S. Costanzo, L. Crocco, G. Di Massa, and R. Scapaticci, "Assessing detection limits in magnetic nanoparticle enhanced microwave imaging," **IEEE Access**, vol. 6, pp. 43192–43202, 2018.

[3] A. E. Stancombe, K. S. Bialkowski, and A. M. Abbosh, "Portable microwave head imaging system using software-defined radio and switching network," **IEEE J. Electromagn. RF Microw. Med. Biol.**, 3, 4, Dec. 2019, pp. 284–291.

[4] V. L. Coli, P.-H. Tournier, V. Dolean, I. E. Kanfoud, C. Pichot, C. Migliaccio, and L. Blanc-Féraud, "Detection of simulated brain strokes using microwave tomography," **IEEE J. Electromagn. RF Microw. Med. Biol.**, 3, 4, Dec. 2019, pp. 254–260.

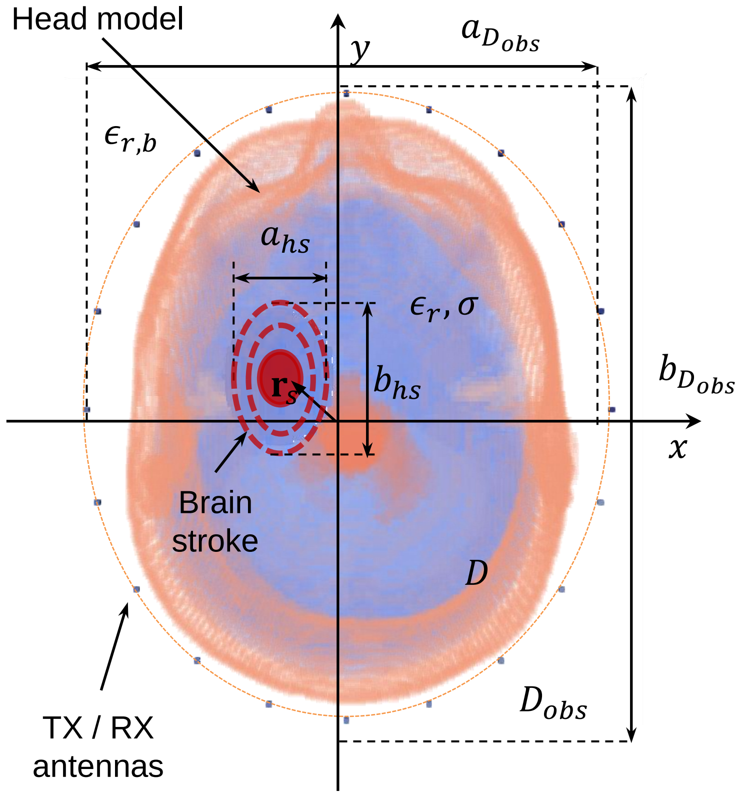
[5] R. Scapaticci, J. Tobon, G. Bellizzi, F. Vipiana, and L. Crocco, "Design and numerical characterization of a low-complexity microwave device for brain stroke monitoring," **IEEE Trans. Antennas Propag., 66, 12, Dec. 2018**, pp. 7328–7338.

[6] L. Crocco, I. Karanasiou, M. James, and R. C. Conceição, Eds., **Emerging electromagnetic technologies for brain diseases diagnostics, monitoring and therapy**. Springer International Publishing, 2018.

Inverse problem configuration & assumptions

- A simplified 2D scalar model with dielectric properties independent from the axial coordinate z has been assumed [1]
- The head, located in a known investigation domain D, is illuminated by a known time-harmonic TMz incident electromagnetic field e_{inc}
- Head is surrounded by a lossy coupling medium with complex dielectric permittivity ϵ_b
- Estimation of the reference dielectric profile of the head characterized by a contrast function $\tilde{c} = (\tilde{\epsilon} - \epsilon_b)/\epsilon_b$ ($\tilde{\epsilon}$ being the complex dielectric permittivity of the reference profile)

Configuration of the considered model and measurement system



[1] I. Bisio, C. Estatico, A. Fedeli, F. Lavagetto, M. Pastorino, A. Randazzo, and A. Sciarrone, "Variable-exponent Lebesgue-space inversion for brain stroke microwave imaging," **IEEE Transactions on Microwave Theory and Techniques**, vol. 68, no. 5, pp. 1882–1895, May 2020. https://doi.org/10.1109/TMTT.2019.2963870.

Inverse scattering problem formulation

- The scattering problem is formulated as

$$\begin{cases} \Delta e(\mathbf{r}) = \overbrace{-k_b^2 \int_{D_{inv}} x(\mathbf{r}')\, e_{tot}(\mathbf{r}') g(\mathbf{r},\mathbf{r}') d\mathbf{r}'}^{G_{data} x e_{tot}}, & \mathbf{r} \in \mathcal{M} \\ e_{tot}(\mathbf{r}) = e_{ref}(\mathbf{r}) \underbrace{-k_b^2 \int_{D_{inv}} x(\mathbf{r}')\, e_{tot}(\mathbf{r}') g(\mathbf{r},\mathbf{r}') d\mathbf{r}'}_{G_{state} x e_{tot}}, & \mathbf{r} \in \mathcal{D} \end{cases}$$

Scattered field: $\Delta e(\mathbf{r})$

Total field: $e_{tot}(\mathbf{r})$

Reference field due to c_{ref}: $e_{ref}(\mathbf{r})$

Differential contrast function
$x(\mathbf{r}') = c(\mathbf{r}') - c_{ref}(\mathbf{r}')$

Green's function: $g(\mathbf{r},\mathbf{r}')$

where

- $c = (\epsilon - \epsilon_b)/\epsilon_b$ is the contrast function of the actual configuration (which gives rise to the field e_{tot})
- $c_{ref} = \left(\epsilon_{ref} - \epsilon_b\right)/\epsilon_b$ represent the contrast function of the reference configuration (related to the field e_{ref})

- By combining the two equations, we obtain the scattering model

$$\Delta e(\mathbf{r}) = F(x)(\mathbf{r}) = G_{data} x \left(I - G_{state} x\right)^{-1} e_{ref}(\mathbf{r})$$

Inversion procedure

- To solve this nonlinear equation, an inexact-Newton iterative method is applied to minimize the residual functional $\Psi: X \rightarrow \mathbb{R}$

$$\Psi(x) = \frac{1}{2} \|F(x) - \Delta e\|_Y^2 ,$$

where $x \in X$, $\Delta e \in Y$, $F: X \rightarrow Y$, and $\|\cdot\|_Y^2$ denotes the square of the norm of the functional space Y

- In particular, variable exponent Lebesgue spaces $L^{p(\cdot)}$ [3] are considered, in which the power p used in the norm is not constant, but it is a function $p(\cdot)$.

[3] C. Estatico, A. Fedeli, M. Pastorino, and A. Randazzo, "Quantitative microwave imaging method in Lebesgue spaces with nonconstant exponents," **IEEE Trans. Antennas Propag.**, vol. 66, no. 12, pp. 7282–7294, Dec. 2018.

Inversion procedure

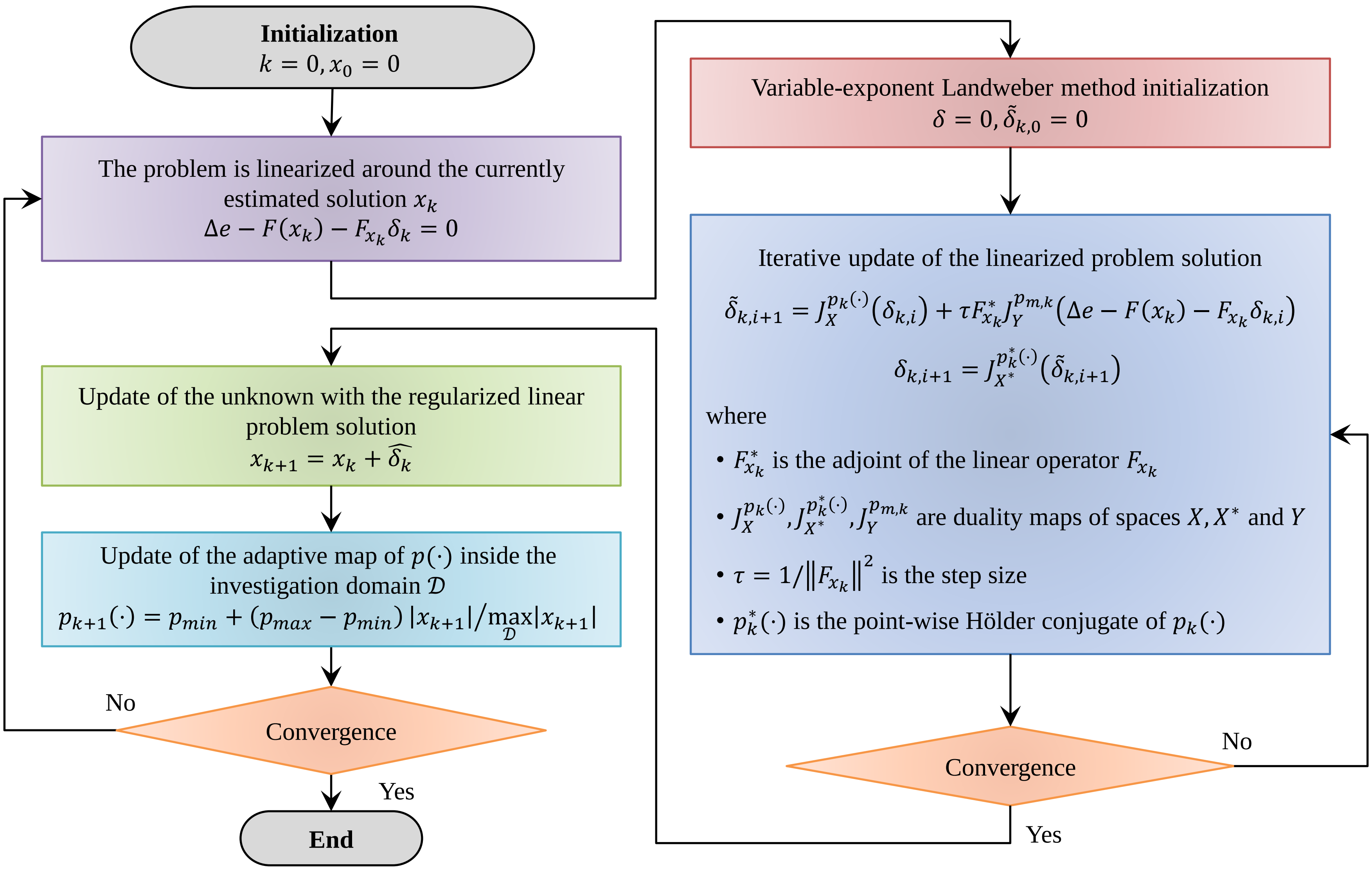
- The exponent function for the space of the unknowns X depends upon the position inside the investigation domain, allowing to set different values of the parameter p to each point.
- The function $p(\mathbf{r})$ is updated at each step as

$$p_k(\cdot) = p_{min} + (p_{max} - p_{min})\, |x_k| / \max_{\mathcal{D}} |x_k|$$

- Two possible initializations are considered:
  - A fixed value is used, i.e., $p_0(\mathbf{r}) = p_{start}$
  - A delay-and-sum qualitative scheme is used to build the initial map, i.e.,

$$I(\mathbf{r}) = \int_M \int_\Omega E_s(\mathbf{r}', \omega) e^{j\frac{2\omega}{v}\|\mathbf{r}-\mathbf{r}'\|} d\omega d\mathbf{r}' \rightarrow p_0(\mathbf{r}) = p_{min} + (p_{max} - p_{min}) \frac{|I(\mathbf{r})|}{\max_{\mathbf{r} \in D} |I(\mathbf{r})|}$$

Inversion procedure

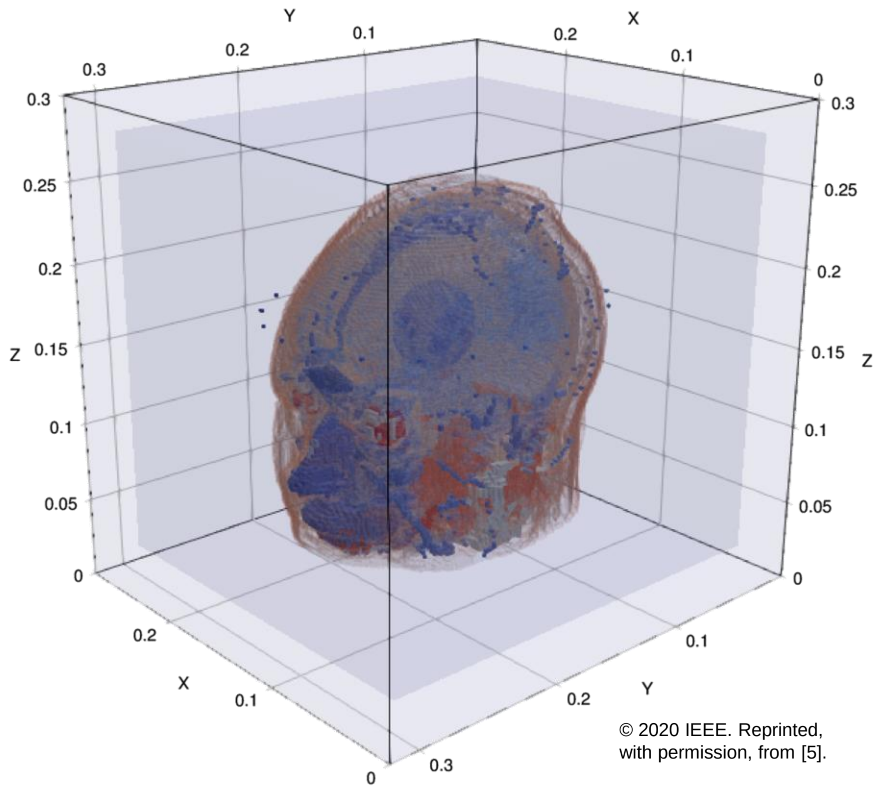


Brain stroke detection – Numerical results

Simulation parameters

- Head of the *AustinWoman* 3D model [1] with 2-mm voxel size
- Time-domain forward simulation by using gprMax FDTD [2]
- Dispersive tissue properties [3, 4]
- Domain size: 28.4 × 32 × 30 cm (3.4×10^6 cells of 2 mm side)
- PML boundary (10 cells)
- Time step: 3.85×10^{-12} s
- Time window: 3×10^{-8} s
- $S = 21$ antennas (Hertzian dipoles) on an ellipse of semi-axes 9.2 cm and 11 cm.
- Excitation signal: Gaussian derivative centered at 1 GHz
- Background coupling medium: glycerin/water mixture 70%
- Scattered field data corrupted by additive white Gaussian noise with $SNR = 25$ dB.

Three-dimensional FDTD simulation domain



[1] J. W. Massey et al., **38th Ann. Int. Conf. of the IEEE EMBS**, 2016.
[2] C. Warren et al., **Comput. Physics Comm.**, 209, 2016.
[3] J. M. Fujii, **IEEE MWCL**, 22, (2), 2012.
[4] S. Mustafa et al., **IEEE TAP**, 62 (3), 2014.
[5] I. Bisio, C. Estatico, A. Fedeli, F. Lavagetto, M. Pastorino, A. Randazzo, and A. Sciarrone, "Variable-exponent Lebesgue-space inversion for brain stroke microwave imaging," **IEEE TMTT**, 68(5), 2020.

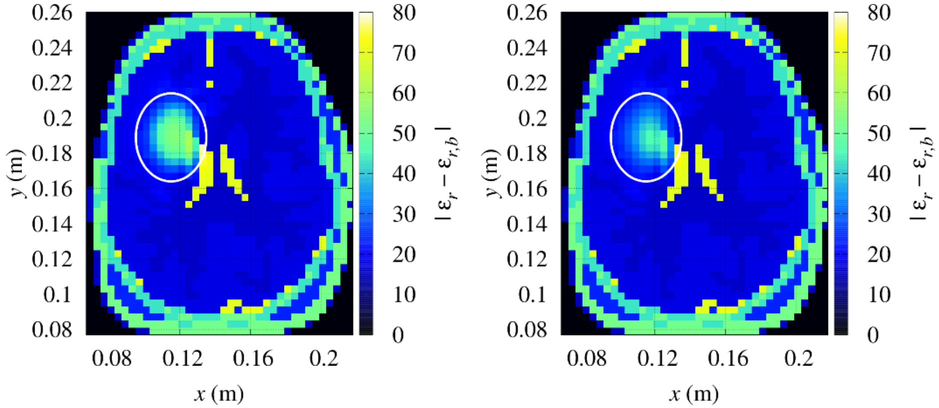
Brain stroke detection – Numerical results

Measurement configuration

- Ellipsoidal inclusion: hemorrhagic brain stroke at (11.7, 17.2, 17.5) cm
- **Healthy head profile** used as reference model
- Investigation domain composed by 1485 cells with 4 mm side
- Frequency hopping started from 500 Mhz and with step 50 MHz.
- Range of values of the exponent function: [1.4,2].
- Initial exponent map: constant value equal to 1.4.

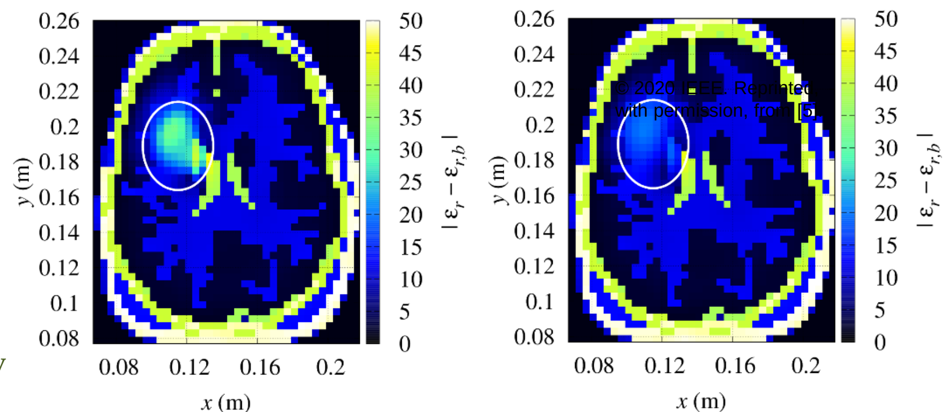
Reconstructed dielectric properties at 0.5 GHz

Variable-exponent approach | Fixed-exponent approach ($p_{opt} = 1.2$)



Reconstructed dielectric properties at 0.8 GHz

Variable-exponent approach | Fixed-exponent approach ($p_{opt} = 1.4$)



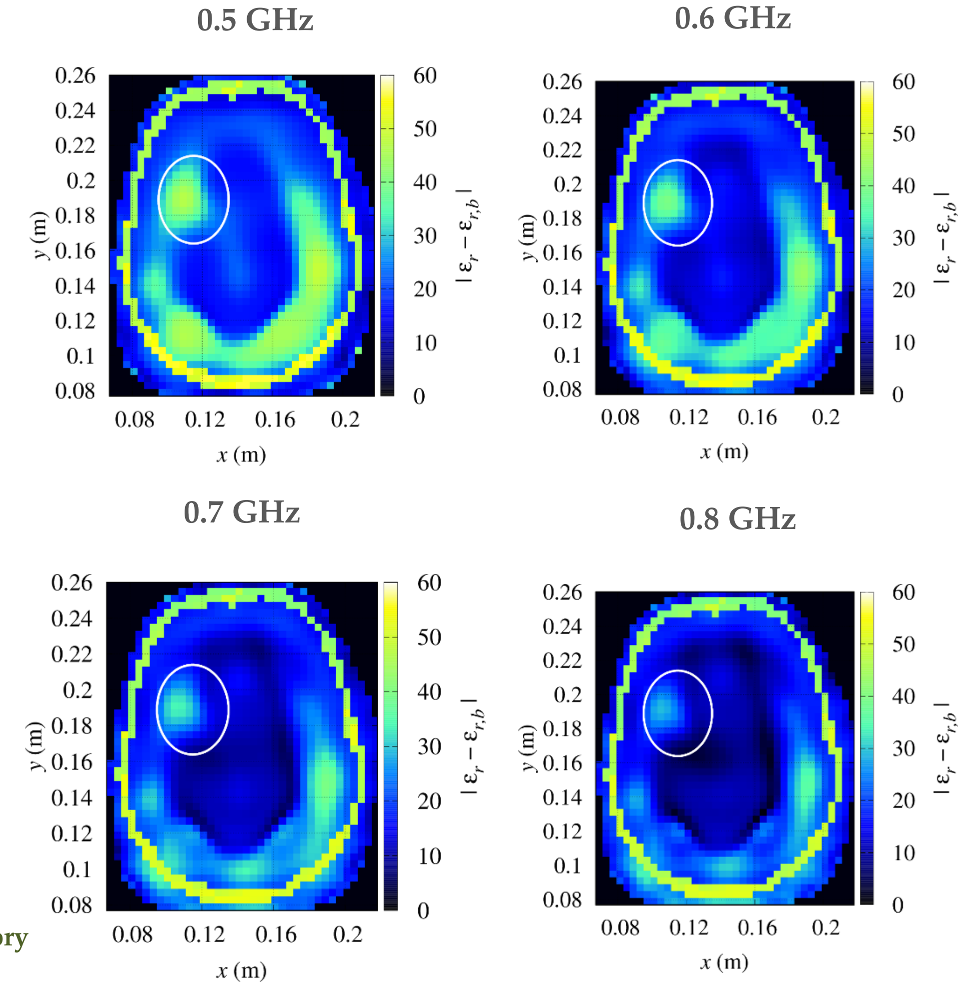
[1] I. Bisio et al., “Variable-exponent Lebesgue-space inversion for brain stroke microwave imaging,” **IEEE Transactions on Microwave Theory and Techniques**, vol. 68, no. 5, pp. 1882–1895, May 2020.

Brain stroke detection – Numerical results

Measurement configuration

- Ellipsoidal inclusion: hemorrhagic brain stroke at (11.7, 17.2, 17.5) cm
- **Partially homogeneous configuration** (except skull) used as reference model
- Investigation domain composed by 1485 cells with 4 mm side
- Frequency hopping started from 500 Mhz and with step 50 MHz.
- Range of values of the exponent function: [1.4,2].
- Initial exponent map: constant value equal to 1.4.

Reconstructed dielectric properties (variable exponent approach)



[1] I. Bisio et al., "Variable-exponent Lebesgue-space inversion for brain stroke microwave imaging," **IEEE Transactions on Microwave Theory and Techniques**, vol. 68, no. 5, pp. 1882–1895, May 2020.

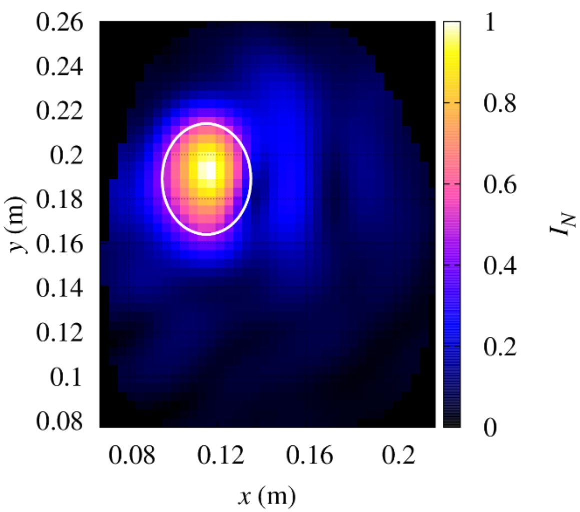
Brain stroke detection – Numerical results

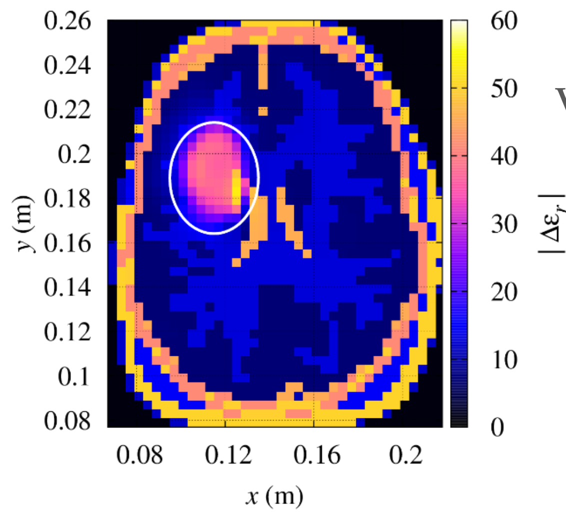
Measurement configuration

- Ellipsoidal inclusion: hemorrhagic brain stroke at (11.7, 17.2, 17.5) cm
- **Healthy head profile** used as reference model
- Investigation domain composed by 1485 cells with 4 mm side
- Frequency hopping started from 500 MHz and with step 50 MHz.
- Range of values of the exponent function: [1.4,2].
- Initial exponent map: **obtained by applying the DAS scheme**.

Reconstructed dielectric properties at 0.7 GHz

DAS reconstruction (initial map)

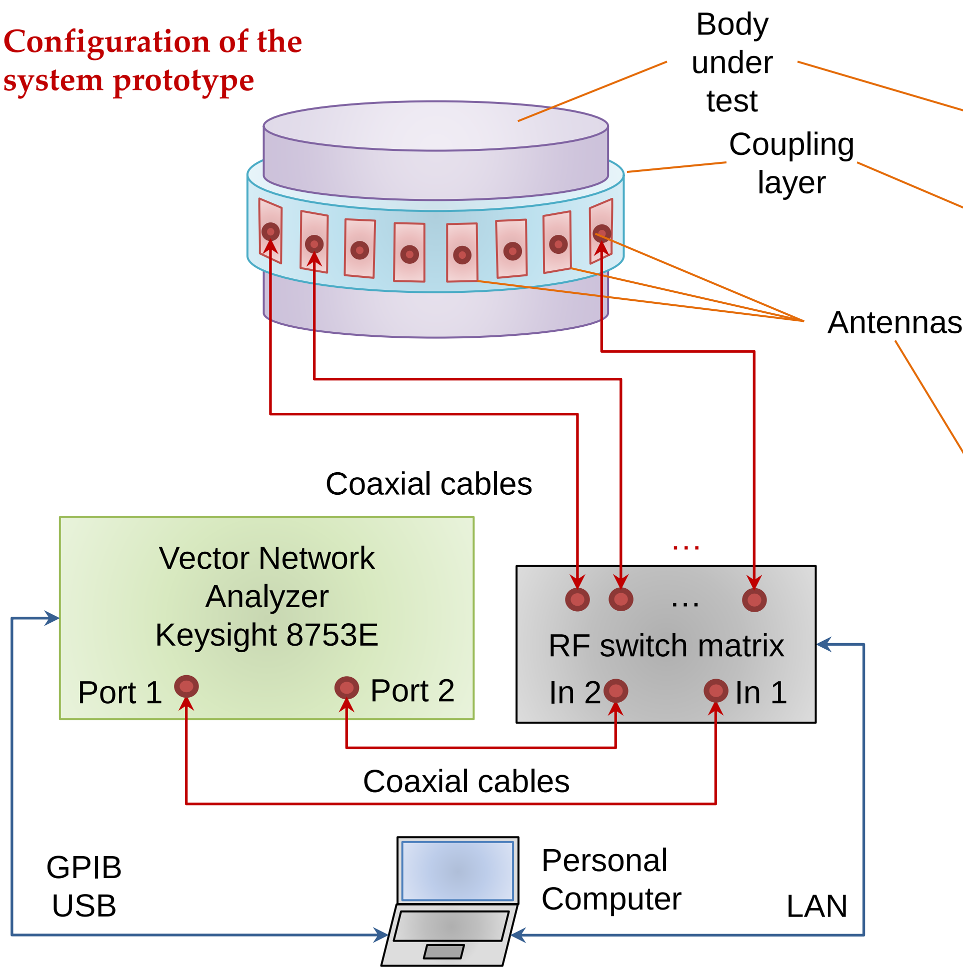




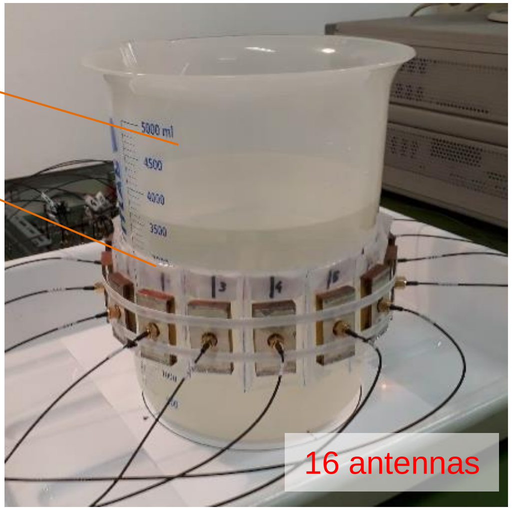
Variable-exponent approach

Brain stroke detection – Experimental results

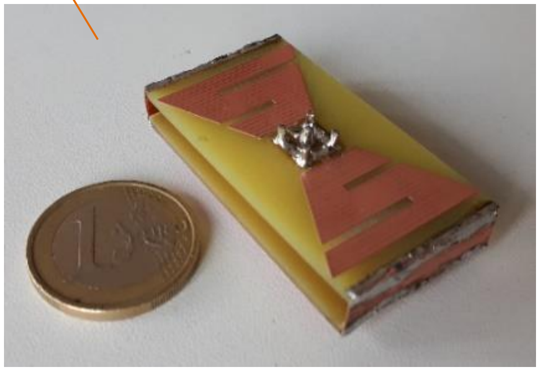
Configuration of the system prototype



Cylindrical test target



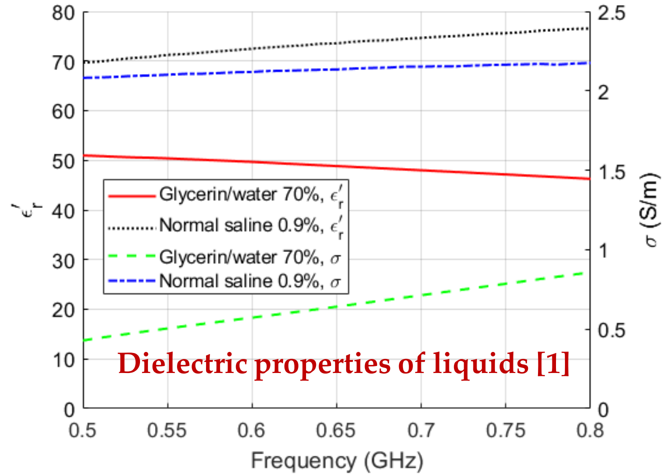
Bowtie-like antenna structure [1]



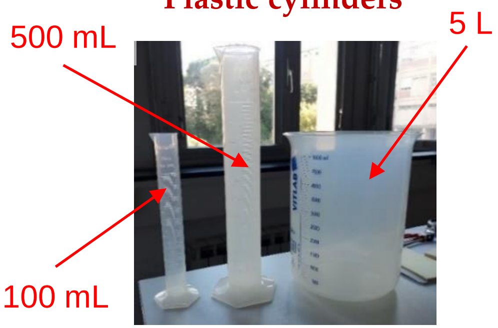
[1] I. Bisio et al., "Brain stroke microwave imaging by means of a Newton-conjugate-gradient method in Lp Banach spaces," **IEEE Transactions on Microwave Theory and Techniques**, vol. 66, no. 8, pp. 3668–3682, Aug. 2018.

Preliminary experimental results

- Target properties
  - Outer structure (filled with 70% glycerin/water mixture)
    - 5 L PP beaker (external diameter of 180 mm, 4 mm thickness) filled with 70% glycerin/water mixture
  - Cylindrical inclusions (filled with 0.9% saline solution)
    - 100 mL PP circular cylinder, 20 mm diameter
    - 500 mL PP circular cylinder, 52 mm diameter
- Configuration parameters
  - Coupling medium (70% glycerin/water mixture) in PE bags (40 x 80 mm, 100 μm thick, 20 ml volume) around the outer cylinder
  - Investigation domain partitioned into $N_i = 1264$ square cells of side $d_i = 4.5$ mm
- Parameters of the inverse solver
  - $p_{start} = p_{min} = 1.4$, $p_{max} = 2.0$
  - Number of maximum allowed inner and outer iterations to $N_{IN} = N_{LW} = 100$, minimum residual variation $r_{IN} = r_{LW} = 0.35$



Plastic cylinders



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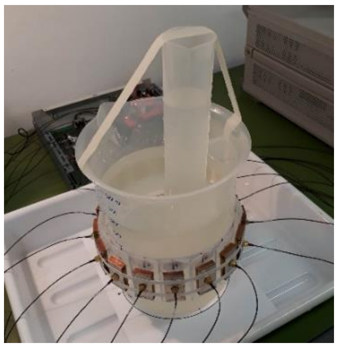
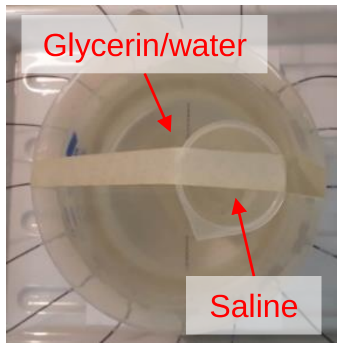
Preliminary experimental results

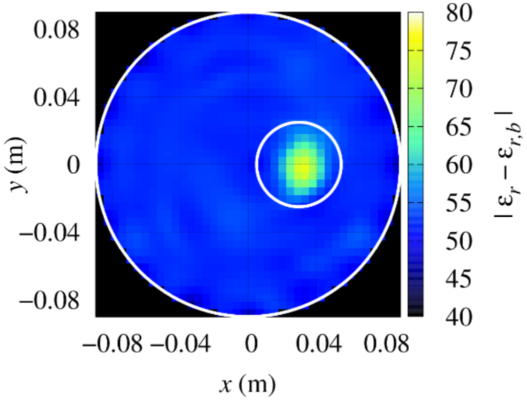
Target configuration – Single circular inclusion
(Ø 52 mm cylindrical inclusion)



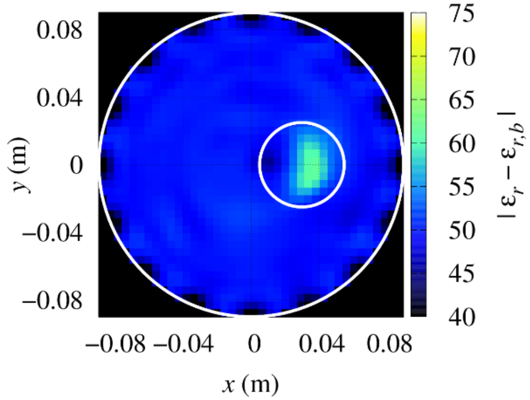


Reconstructed relative dielectric properties (variable exponent)

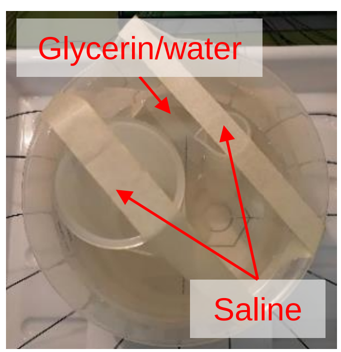
***f* = 600 MHz**



***f* = 900 MHz**

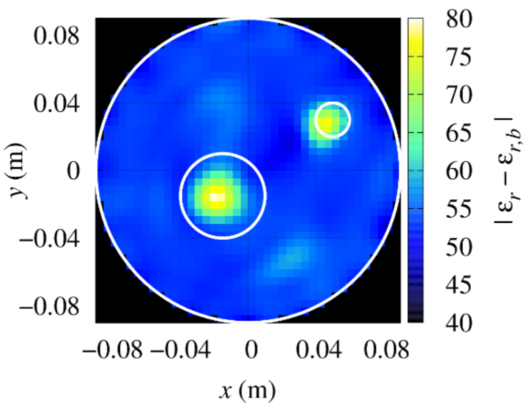


Target configuration – Two circular inclusions
(Ø 20 mm and Ø 52 mm cylindrical inclusions)

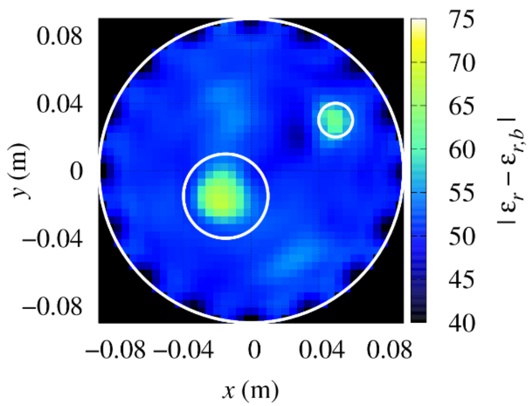


Reconstructed relative dielectric properties (variable exponent)

***f* = 600 MHz**



***f* = 900 MHz**



[1] I. Bisio, C. Estatico, A. Fedeli, F. Lavagetto, M. Pastorino, A. Randazzo, and A. Sciarrone, "Variable-exponent Lebesgue-space inversion for brain stroke microwave imaging," **IEEE Transactions on Microwave Theory and Techniques**, vol. 68, no. 5, pp. 1882–1895, May 2020.

Conclusions

- A novel **tomographic multistatic microwave imaging system** for **brain stroke detection** has been designed
- A variable-exponent Lebesgue-space inversion scheme is adopted for processing the acquired data.
- Two initialization strategies have been considered:
  - Constant exponent function
  - Variable exponent function obtained by a delay-and-sum scheme.
- Numerical simulations and preliminary experimental results have been carried out
- Further activities will be devoted to
  - Improve the measurement system
  - Test the method in more realistic configurations, also with clinical data