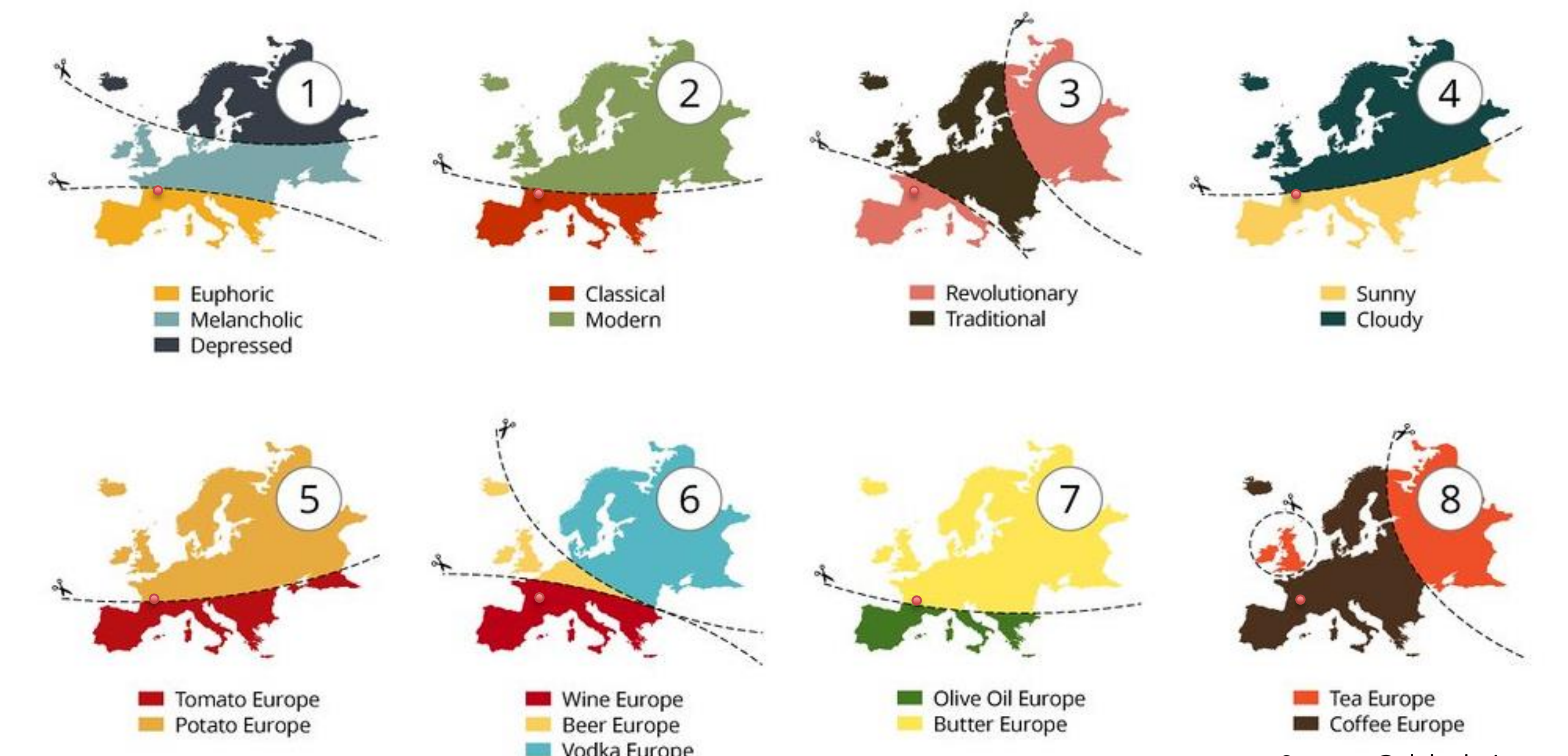
Microwave and millimeter-wave computational imaging

Thomas Fromentèze
Xlim and Collaborations

INSTITUT DE RECHERCHE
xlim



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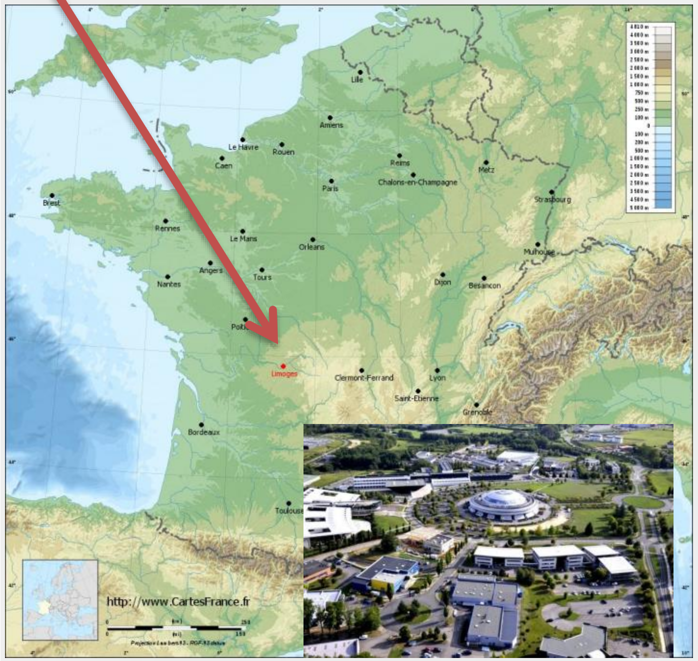

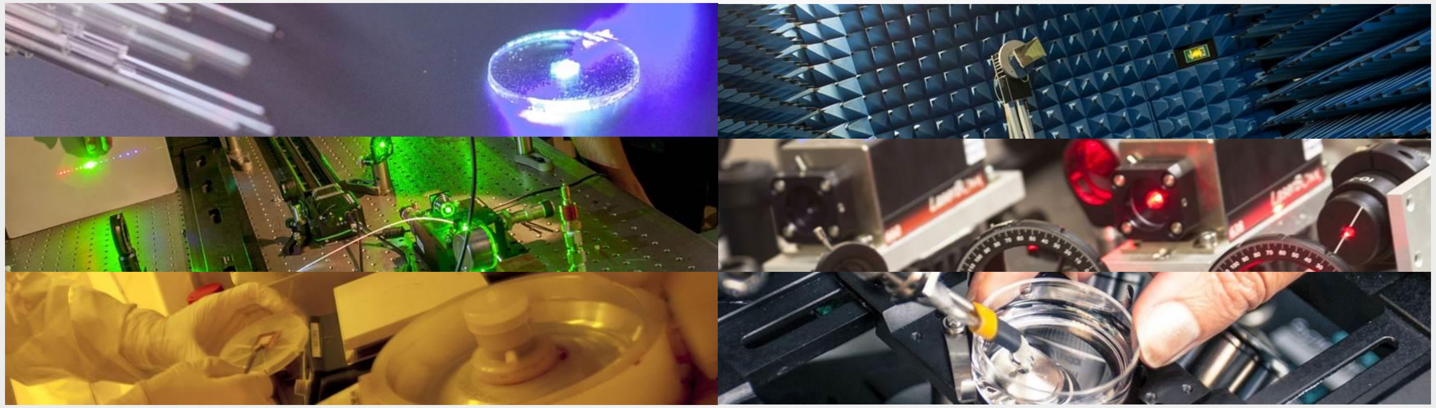

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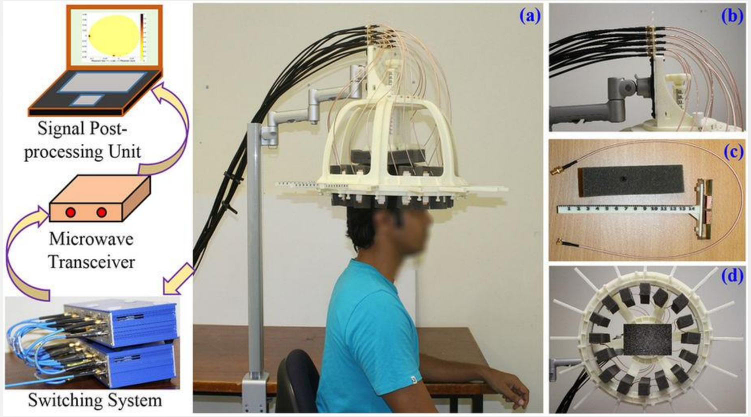
Limits of conventional imaging systems

Resolution – Frame rate - Sensitivity

https://omnirole-rafale.com/avionique/rbe2/

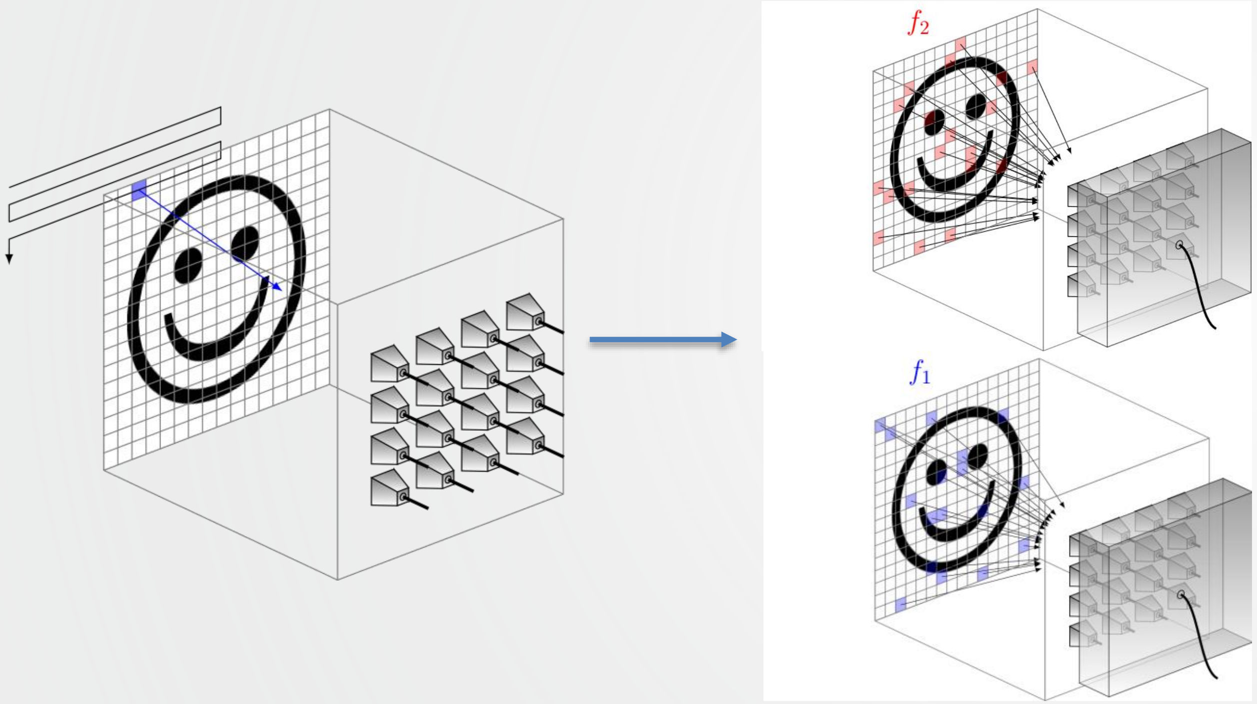
https://www.science-et-vie.com/archives/le-scanner-corporel-22514



Mobashsher, Ahmed Toaha, and A. M. Abbosh. "On-site rapid diagnosis of intracranial hematoma using portable multi-slice microwave imaging system." Scientific reports, 2016

Computational imaging

Computational method: The spatial information is encoded in the physical layer



IEEE TRANSACTIONS ON ULTRASONICS, FERROELECTRICS, AND FREQUENCY CONTROL, VOL. 52, NO. 9, SEPTEMBER 2005 1489

Building Three-Dimensional Images Using a Time-Reversal Chaotic Cavity

Gabriel Montaldo, Delphine Palacio, Mickael Tanter, and Mathias Fink

Science Current Issue First release papers Archive About Submit manuscript

HOME > SCIENCE > VOL. 340, NO. 6134 > 3D COMPUTATIONAL IMAGING WITH SINGLE-PIXEL DETECTORS

REPORT

3D Computational Imaging with Single-Pixel Detectors

B. SUN, M. P. EDGAR, R. BOWMAN, L. E. VITTERT, S. WELSH, A. BOWMAN, AND M. J. PADGETT Authors Info & Affiliations

SCIENCE · 17 May 2013 · Vol 340, Issue 6134 · pp. 844-847 · DOI: 10.1126/science.1234454

C. R. Physique 11 (2010) 37–43

Contents lists available at ScienceDirect

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ELSEVIER

Propagation and remote sensing / Propagation et télédétection

Focusing and amplification of electromagnetic waves by time reversal in an leaky reverberation chamber

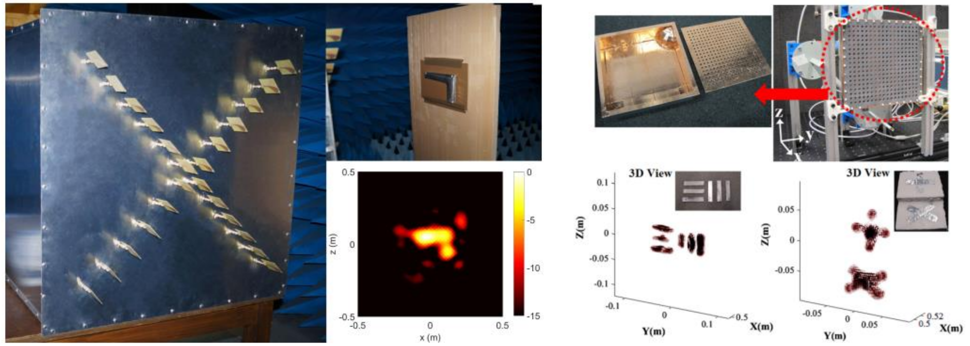
Focalisation et amplification d'ondes électromagnétiques par retournement temporel dans une chambre semi-réverbérante

Matthieu Davy [a,*], Julien de Rosny [a], Jean-Christophe Joly [b], Mathias Fink [a]

[a] *Institut Langevin, ESPCI ParisTech, CNRS UMR 7587, laboratoire ondes et acoustique, 10, rue Vauquelin, 75231 Paris cedex 05, France*
[b] *Centre d'études de Gramat, 46500 Gramat, France*

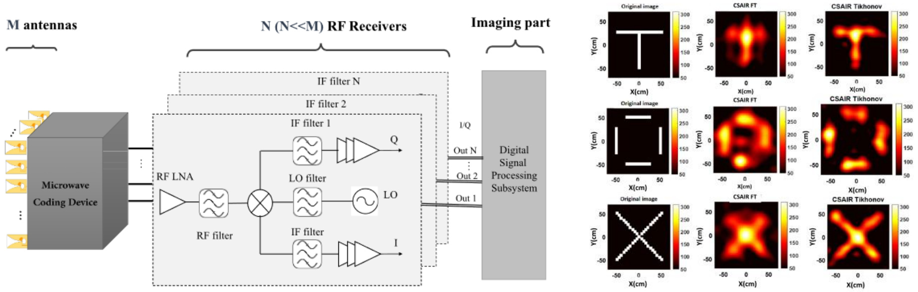
Background: The rise of computational microwave and millimeter imaging

2015 – Scalar multistatic/MIMO imaging



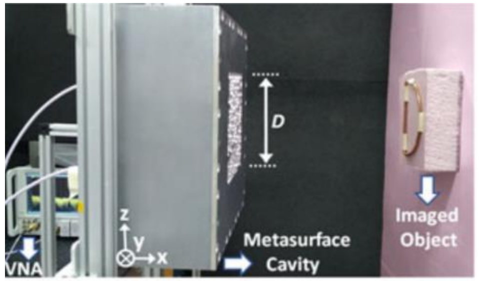
Fromenteze, T., Yurduseven, O., Imani, M. F., Gollub, J., Decroze, C., Carsenat, D., & Smith, D. R. (2015). Computational imaging using a mode-mixing cavity at microwave frequencies. *Applied Physics Letters*, *106*(19), 194104.
Fromenteze, T., Kpré, E. L., Carsenat, D., Decroze, C., & Sakamoto, T. (2016). Single-shot compressive multiple-inputs multiple-outputs radar imaging using a two-port passive device. *IEEE Access*, *4*, 1050-1060.

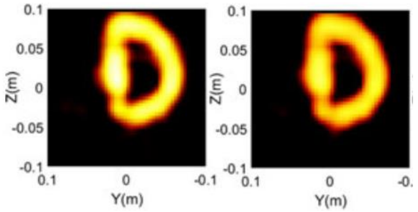
2016 – Interferometric imaging



Kpré, E. L., & Decroze, C. (2016, October). Synthetic aperture interferometric imaging using a passive microwave coding device. In *2016 IEEE Conference on Antenna Measurements & Applications (CAMA)* (pp. 1-4). IEEE.
Kpré, E., Decroze, C., Mouhamadou, M., & Fromenteze, T. (2018). Computational imaging for compressive synthetic aperture interferometric radiometer. *IEEE Transactions on Antennas and Propagation*, *66*(10), 5546-5557.

2016 – Phaseless imaging

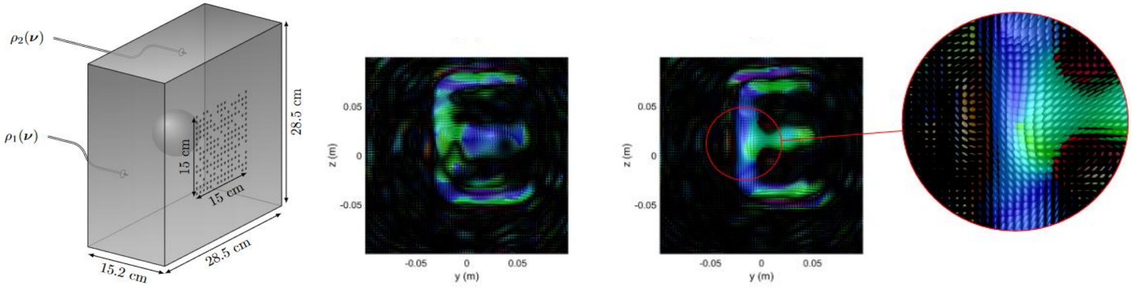




Complex Phaseless

Fromenteze, T., Liu, X., Boyarsky, M., Gollub, J., & Smith, D. R. (2016). Phaseless computational imaging with a radiating metasurface. *Optics express*, *24*(15), 16760-16776.
Yurduseven, O., Fromenteze, T., Marks, D. L., Gollub, J. N., & Smith, D. R. (2017). Frequency-diverse computational microwave phaseless imaging. *IEEE Antennas and Wireless Propagation Letters*, *16*, 2808-2811.

2017 Polarimetric imaging

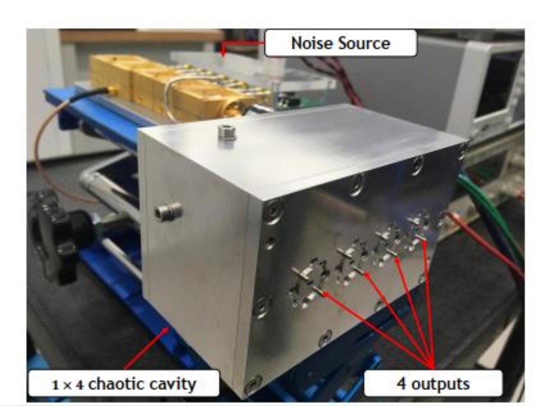


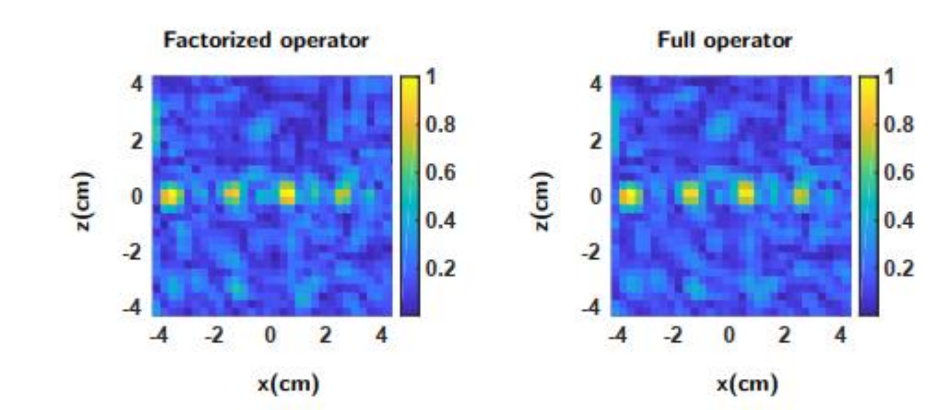
Fromenteze, T., Yurduseven, O., Boyarsky, M., Gollub, J., Marks, D. L., & Smith, D. R. (2017). Computational polarimetric microwave imaging. *Optics express*, *25*(22), 27488-27505.

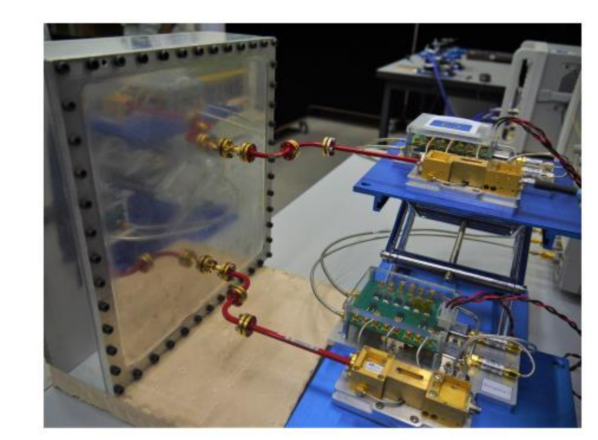
Recent (non exhaustive) works

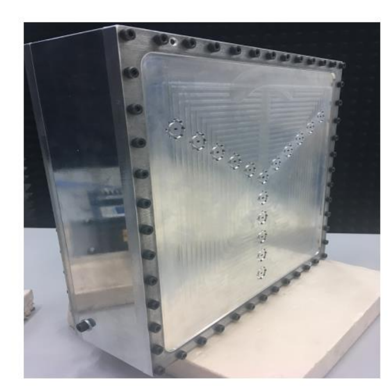
Interferometric computational imaging – W band

Sana Abid









ANR Pixel – Collaboration MC2 Tech. CEA Gramat

Abid, S., Decroze, C., Mouhamadou, M., & Fromenteze, T. (2020). Enhancing millimeter-wave computational interferometric imaging. *IEEE Access*, *8*, 101416-101425.

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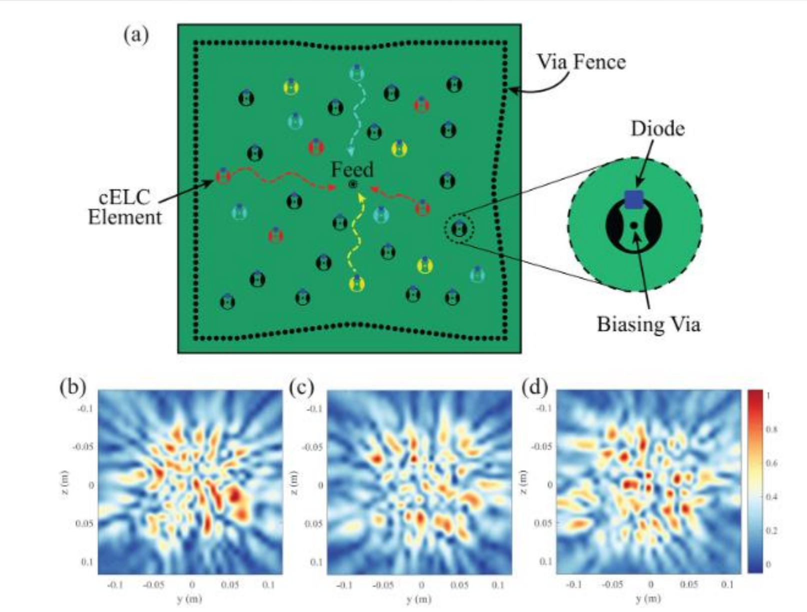
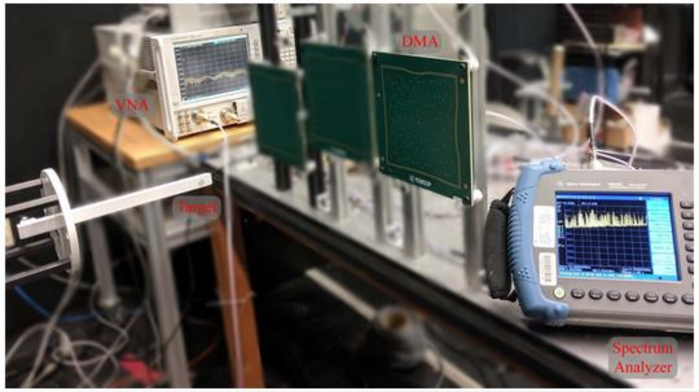
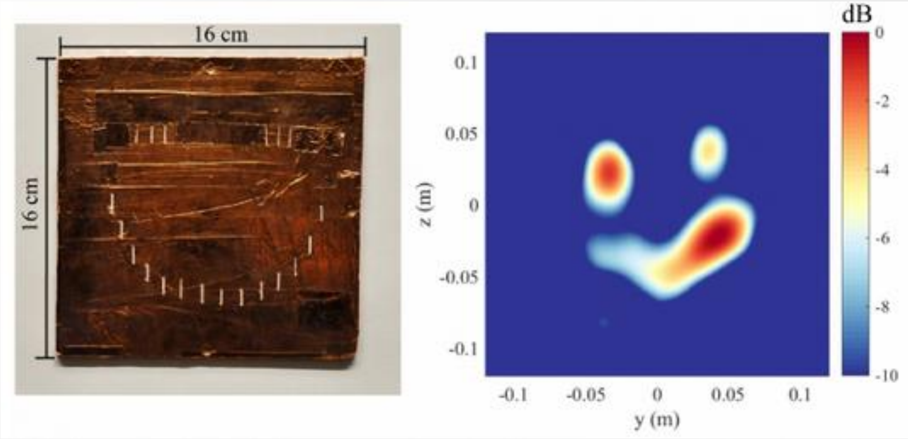
Phaseless computational imaging – K band

Aaron Diebold
Duke University



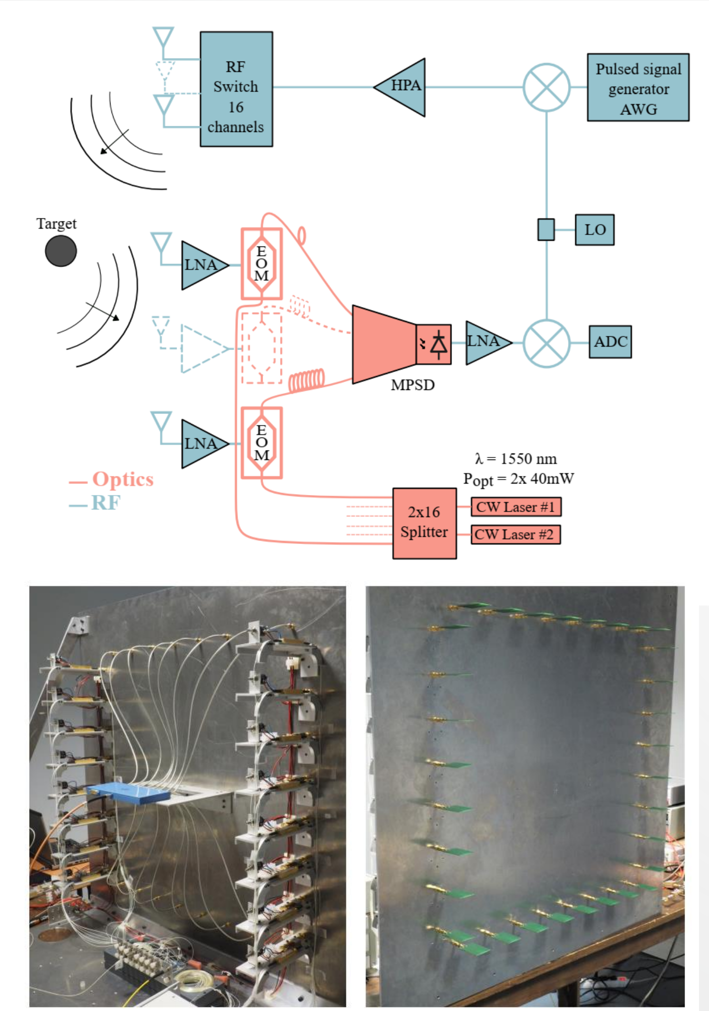
Diebold, A. V., Imani, M. F., Fromenteze, T., Marks, D. L., & Smith, D. R. (2020). Passive microwave spectral imaging with dynamic metasurface apertures. *Optica*, *7*(5), 527-536.

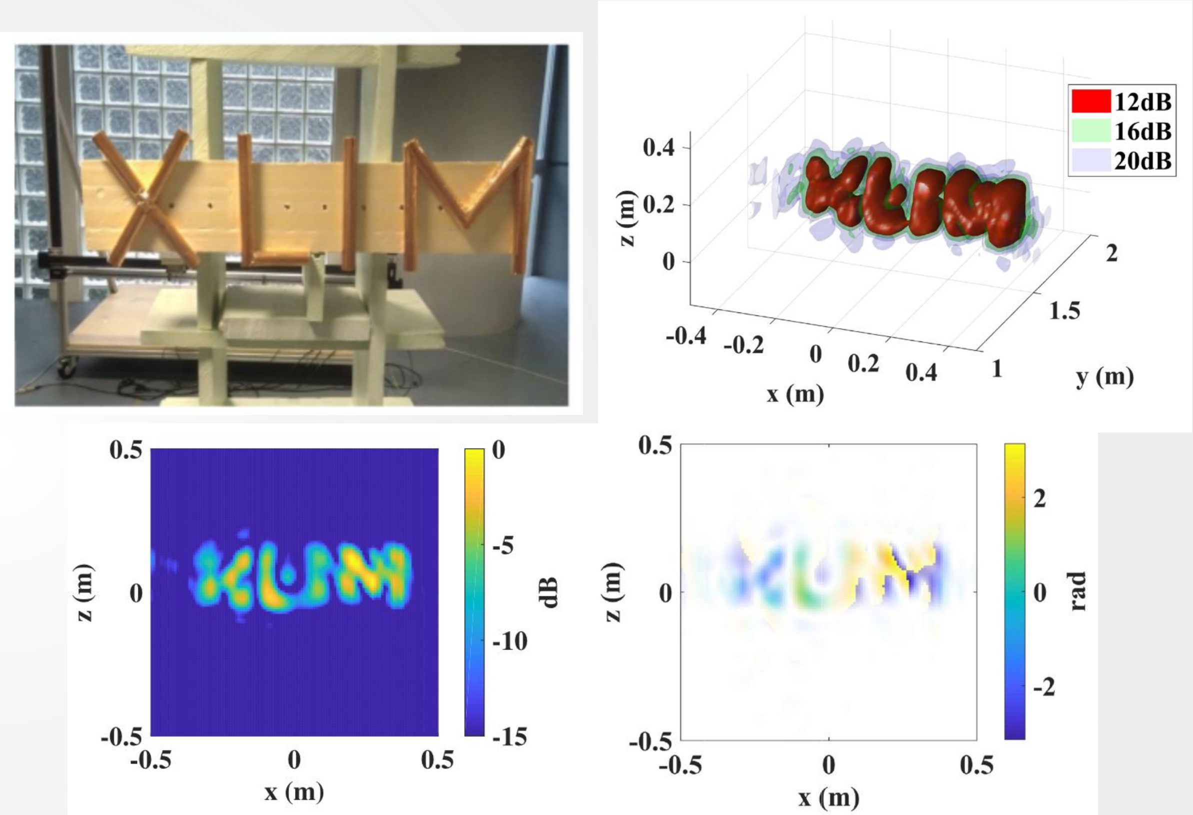




Microwave photonic radar imaging – C band

Fabien Berland





ANR Obiwam – Collaboration C2N, MC2, Vectrawave, STM

Berland, F., Fromenteze, T., Boudescoque, D., Di Bin, P., Elwan, H. H., Aupetit-Berthelemot, C., & Decroze, C. (2020). Microwave Photonic MIMO Radar for Short-Range 3D Imaging. *IEEE Access*, *8*, 107326-107334.

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Focus on a recent work in direct link with the GDR Complex

PHYSICAL REVIEW APPLIED

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Spatiotemporal Analysis of Electromagnetic Field Coherence in Complex Media

Thomas Fromenteze, Matthieu Davy, Okan Yurduseven, Yann Marie-Joseph, and Cyril Decroze

Phys. Rev. Applied **17**, 054039 – Published 24 May 2022

More

Article | References | No Citing Articles | PDF | HTML | Export Citation

Related work

Mounaix, M., & Carpenter, J. (2019)
Control of the temporal and polarization response of a multimode fiber.
Nature communications, *10*(1), 1-8.

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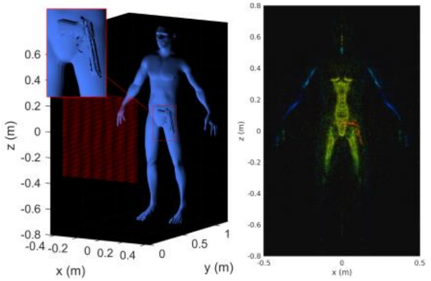
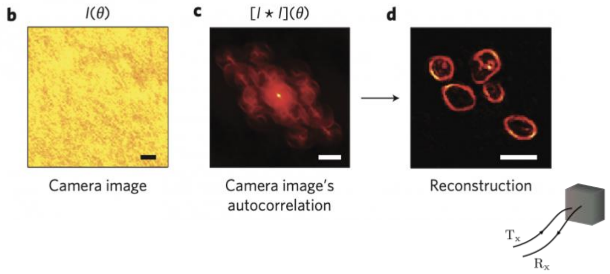
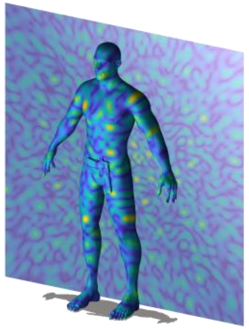
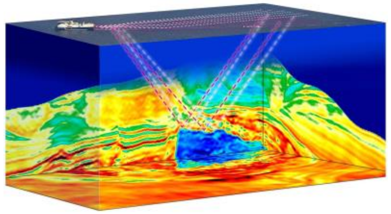
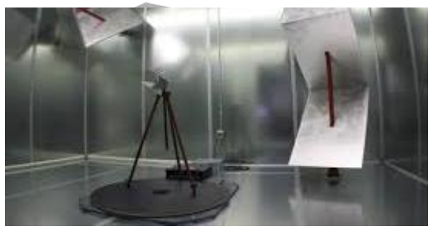
Problem: Digital processing is generally based on approximations





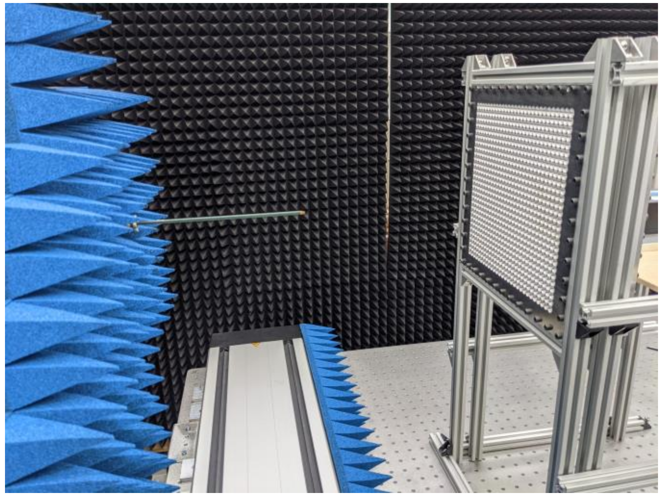


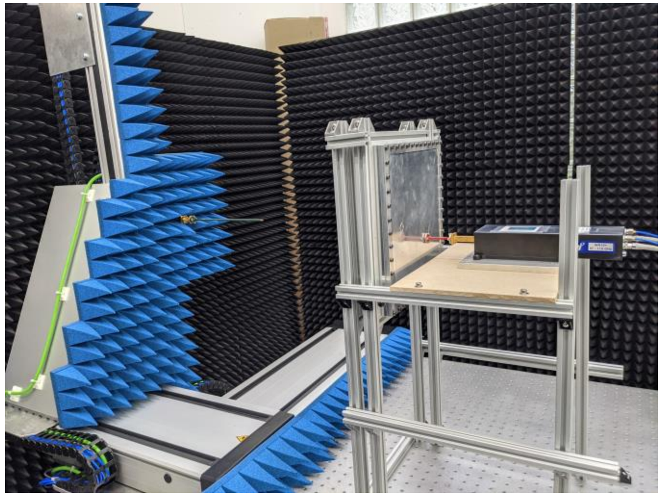




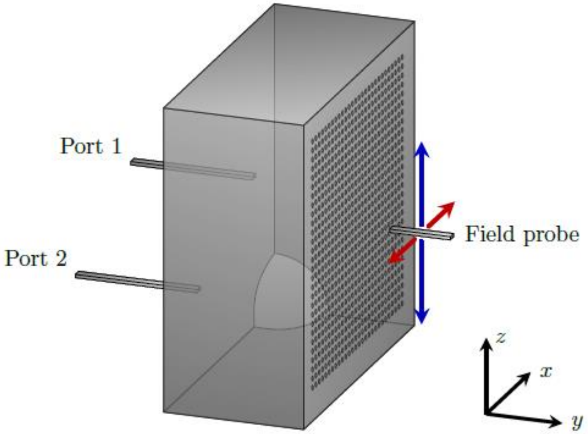
Coherent fields → **Diffuse fields**

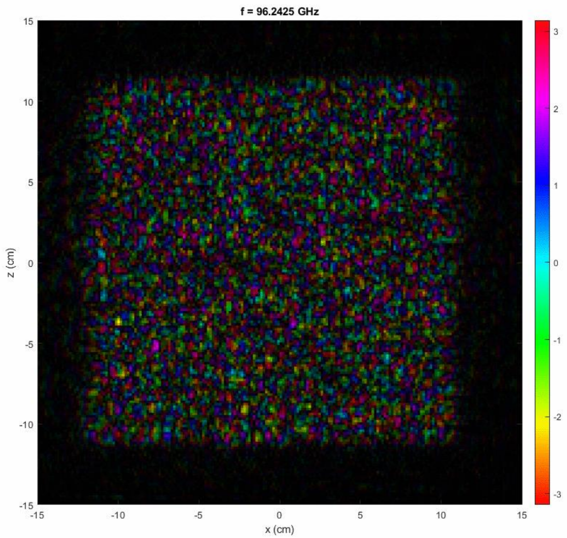
Sources: mvg-world.com - beteirconl.cluster026.hosting.ovh.net - trends.aeroexpo.online - unilim.fr/pages_perso/thomas.fromenteze - faradayshielding.com.au - lkb.upmc.fr/opticalimaging/imaging/ cgg.com

Background: : Radiation of frequency-diverse and spatially diffuse fields



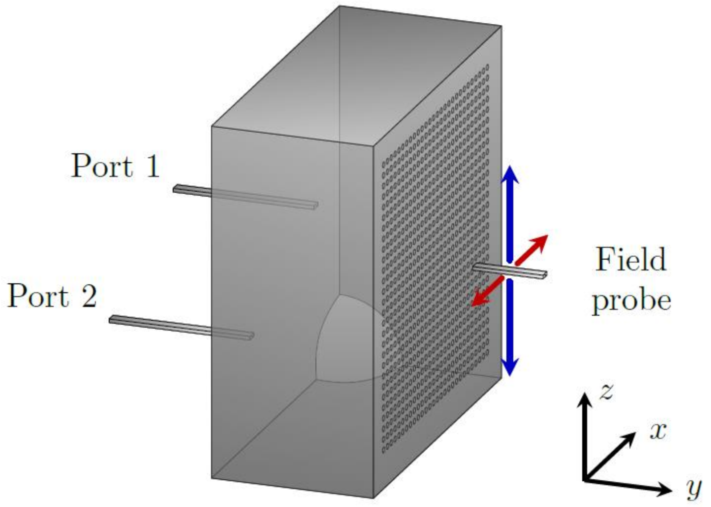


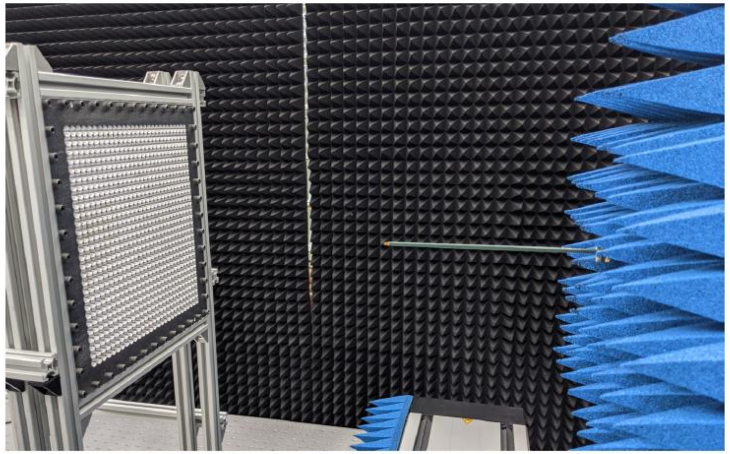




Frequency band: 70-100 GHz
Dimensions: 251 x 66 x 251 mm^3
Feeding: Two z-polarized WR-10 ports
Radiation: 28 x 28 circular irises

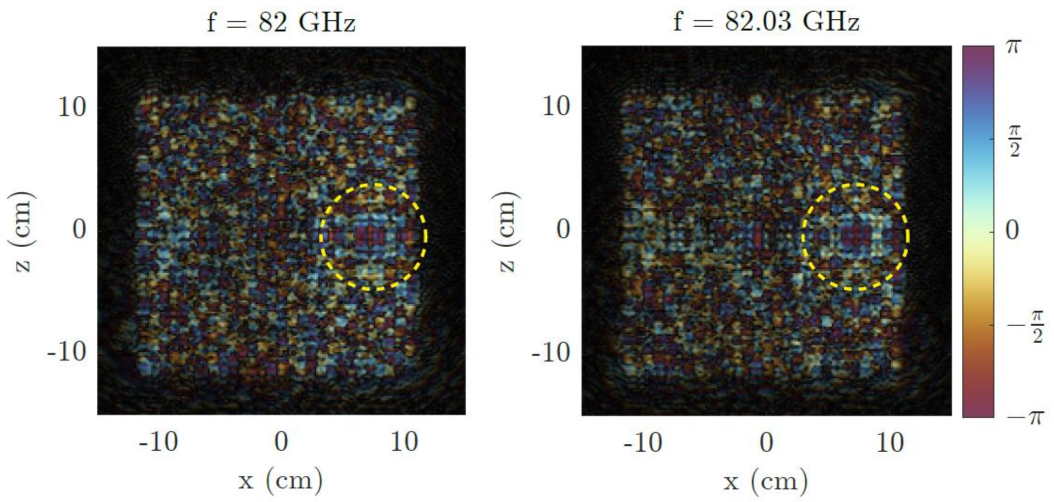
Background: Radiation of frequency-diverse and spatially diffuse fields





Frequency band: 70-100 GHz
Dimensions: 251 x 66 x 251 mm³
Feeding: Two z-polarized WR-10 ports
Radiation: 28 x 28 circular irises

Direct coupling with the feeding probe



Contributions coherent in time and space that should be removed

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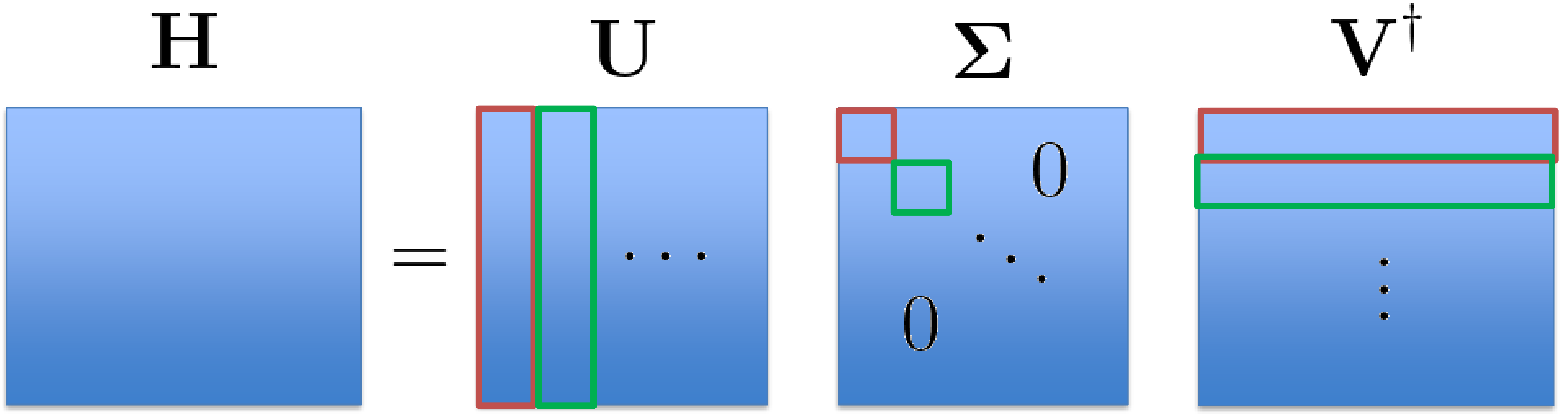
Method: Feature extraction by Singular Value Decomposition



$\mathbf{U}$ $\mathbf{V}^{\dagger}$ Unitary matrices

$\mathbf{\Sigma}$ Diagonal matrices

Structures

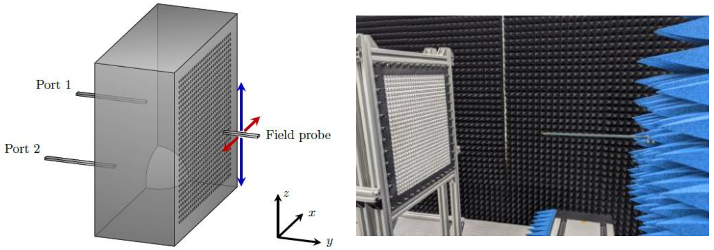
Weights

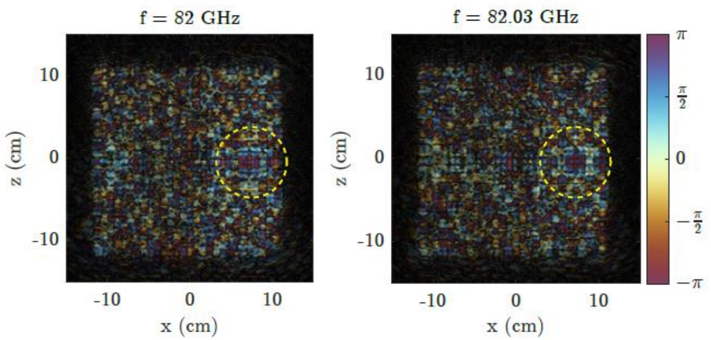
Matlab
```
[U,S,V] = svd(H);
```

Julia
```
U, S, V = svd(A);
```

Python-Numpy
```
U, S, V = np.linalg.svd(H, full_matrices=True)
```

Method: Feature extraction by Singular Value Decomposition





Feeding port index

$$\mathbf{E}_z^{(1)} \in \mathbb{C}^{n_\nu \times n_r}$$

Spatial samples

Frequency samples

Polarization

Factorization of a near-field matrix

$$\mathbf{E} = \sum_n \sigma_n \mathbf{u}_n \mathbf{v}_n^\dagger \rightarrow \begin{matrix} \mathbf{u}_n \in \mathbb{C}^{n_\nu \times 1} \\ \mathbf{v}_n \in \mathbb{C}^{n_r \times 1} \end{matrix}$$

$\mathbf{u}_n \in \mathbb{C}^{n_\nu \times 1}$ → Frequency domain structures

$\mathbf{v}_n \in \mathbb{C}^{n_r \times 1}$ → Spatial structures

Effect of a Fourier transform

Time domain near-field scan

Discrete Fourier transform matrix

$$\begin{aligned} \mathbf{E}_t &= \mathbf{W}^\dagger \mathbf{E} \\ &= \mathbf{W}^\dagger \mathbf{U}\mathbf{S}\mathbf{V}^\dagger \\ &= \mathbf{U}_t \mathbf{S}\mathbf{V}^\dagger \end{aligned}$$

Spatial structures

Time domain structures

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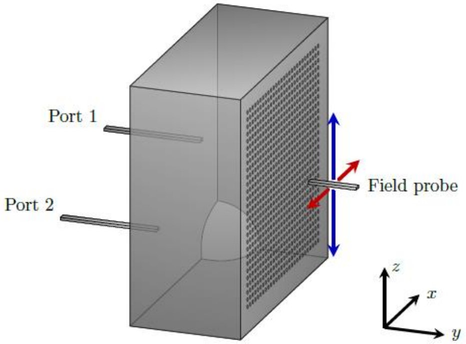
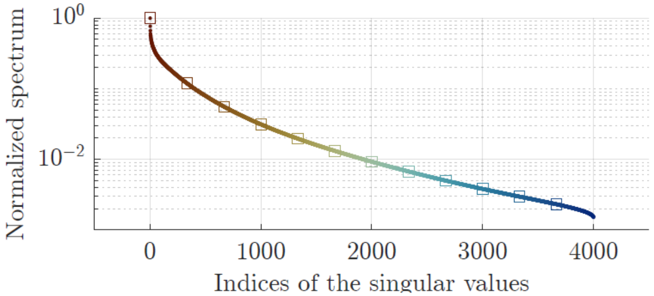
Results: Time domain structures

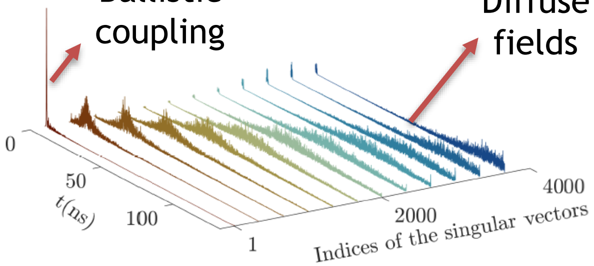


$$\mathbf{E}_t = \mathbf{W}^\dagger \mathbf{E} = \mathbf{W}^\dagger \mathbf{U}\mathbf{S}\mathbf{V}^\dagger = \mathbf{U}_t \mathbf{S}\mathbf{V}^\dagger$$

Singular value spectrum

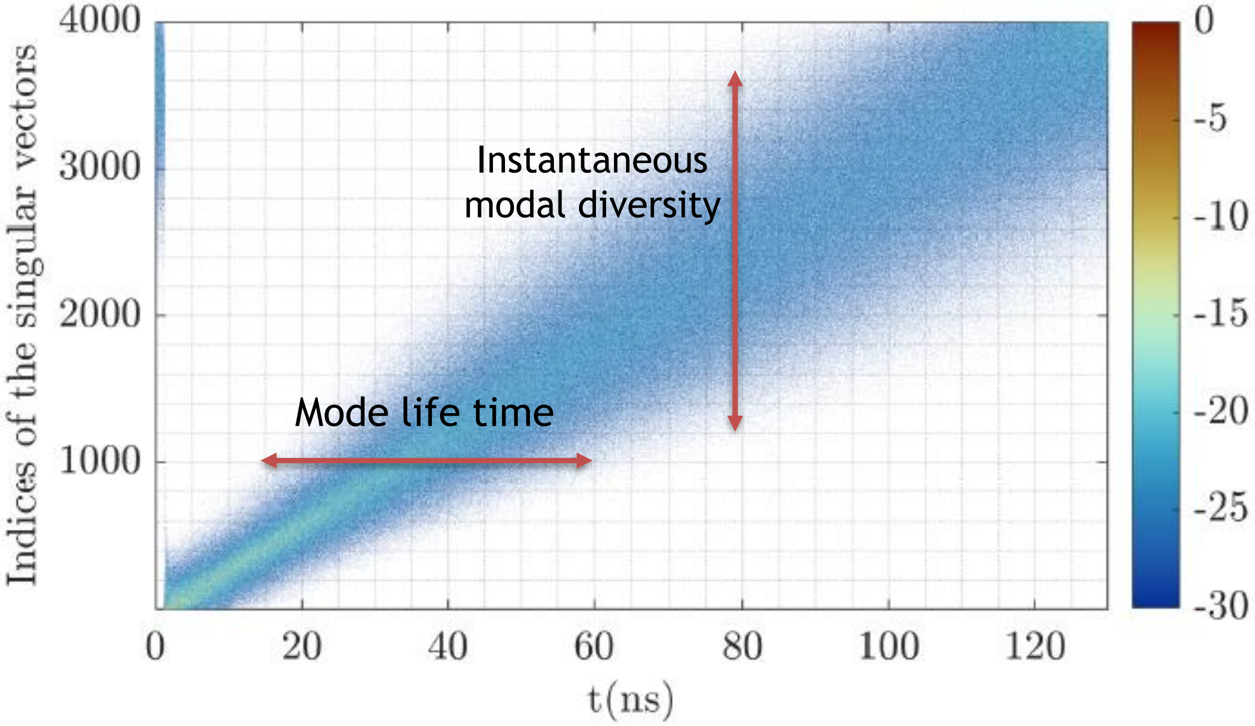


Time domain singular vectors



Discrete Fourier transform matrix

$$\mathbf{U}_t = \mathbf{W}^{-1}\mathbf{U}$$



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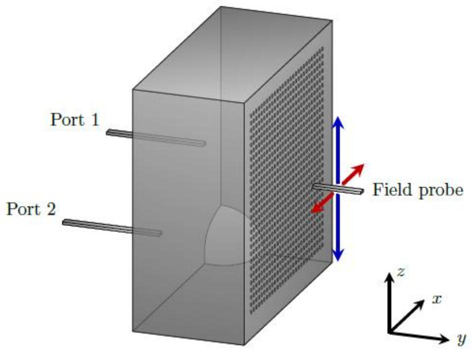
Results: Spatial structures



$$\mathbf{E}_t = \mathbf{W}^\dagger \mathbf{E} = \mathbf{W}^\dagger \mathbf{U}\mathbf{S}\mathbf{V}^\dagger = \mathbf{U}_t \mathbf{S}\mathbf{V}^\dagger$$

Matrix of spatial singular vectors

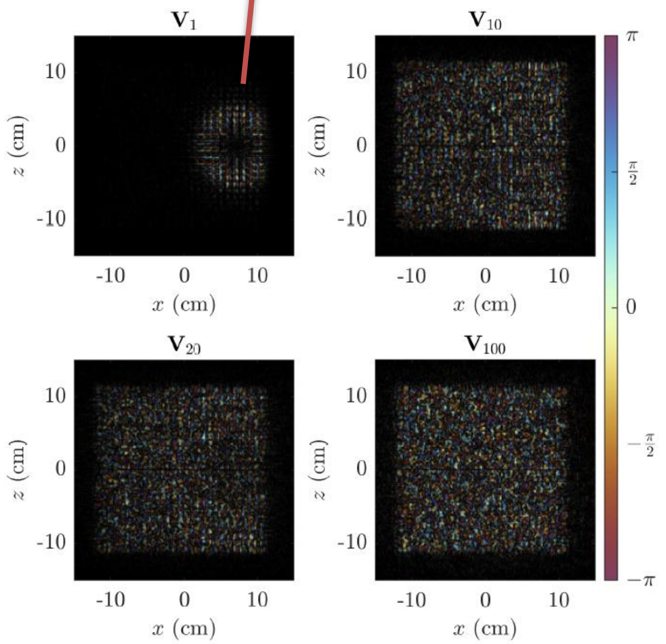
Extraction of the spatial singular vectors

$$\mathbf{v}_n = \mathrm{vec}(\mathbf{V}_n)$$

Reconstruction of the spatial structures by “de-vectorization”

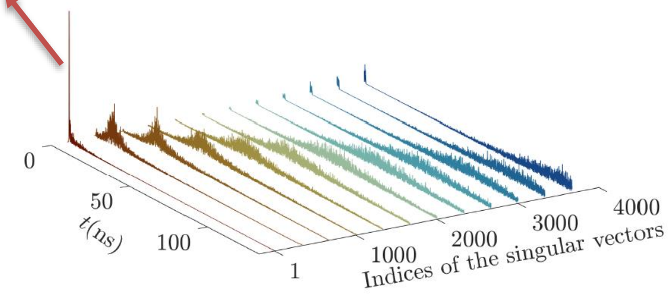
Reshaped spatial singular vectors

Ballistic coupling



Ballistic coupling

Associated time domain singular vectors



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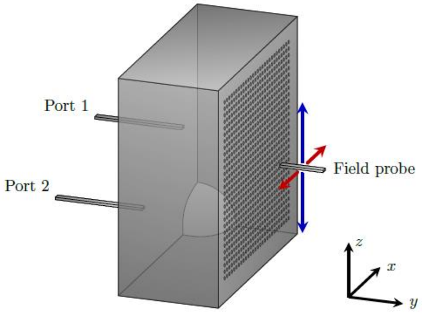
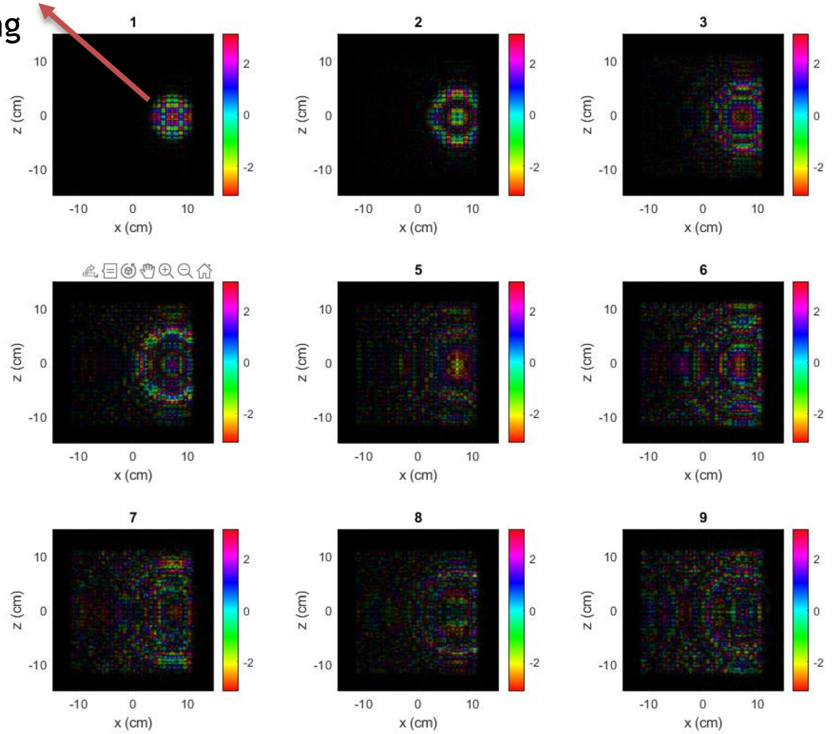
Results: On the effect of polarization



Observation of the first spatial singular vectors

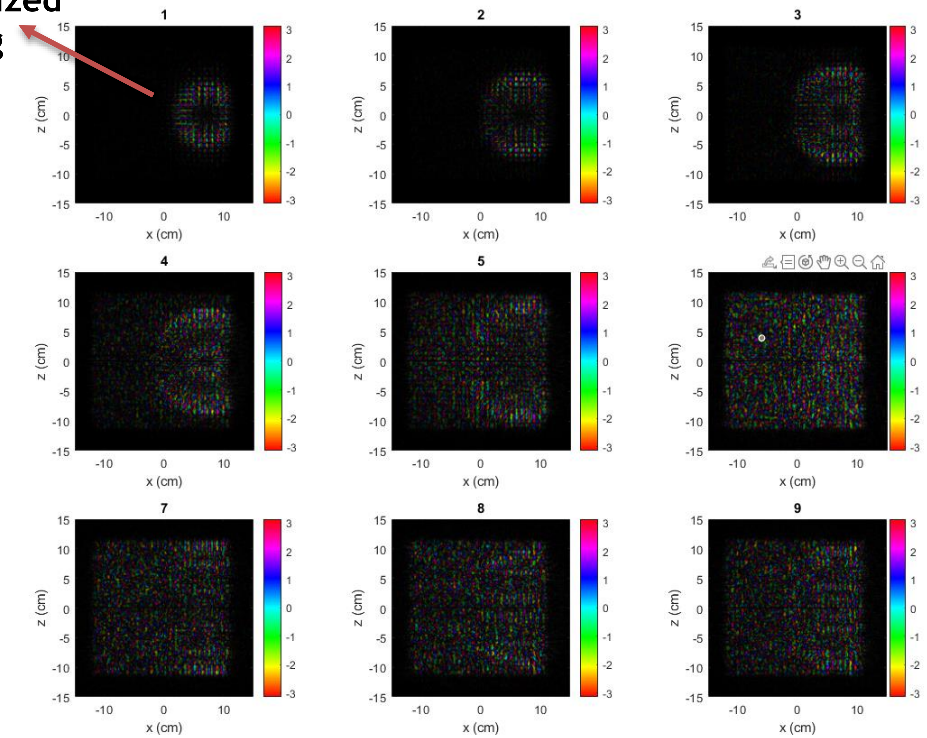
Ballistic
co-polarized
coupling

Excitation port: V-Pol
Field Probe: V-Pol



Ballistic
cross-polarized
coupling

Excitation port: V-Pol
Field Probe: H-Pol



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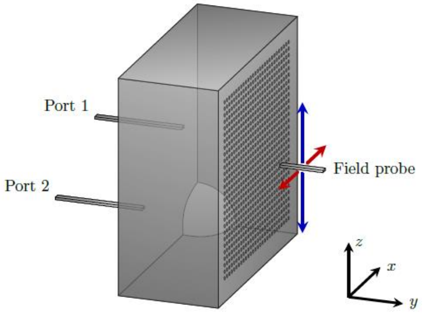
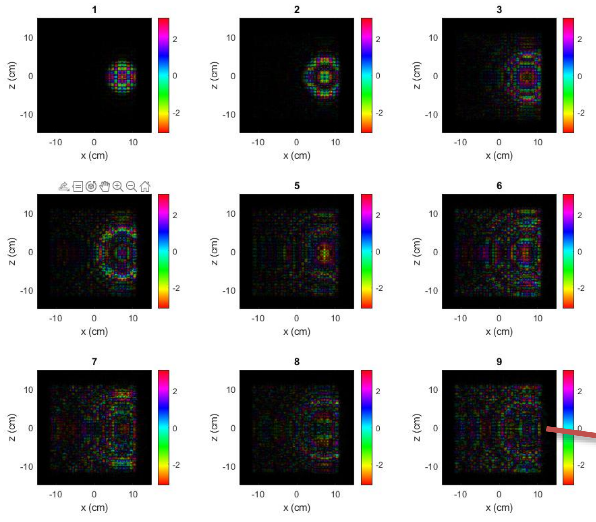
Results: On the effect of polarization

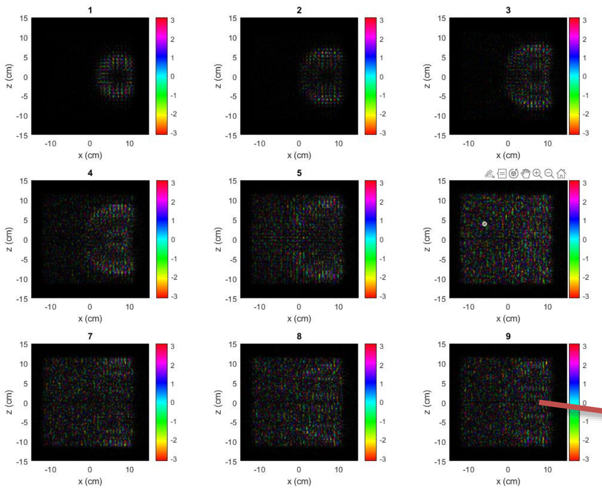


Co-polarized measurements



Remain spatially coherent

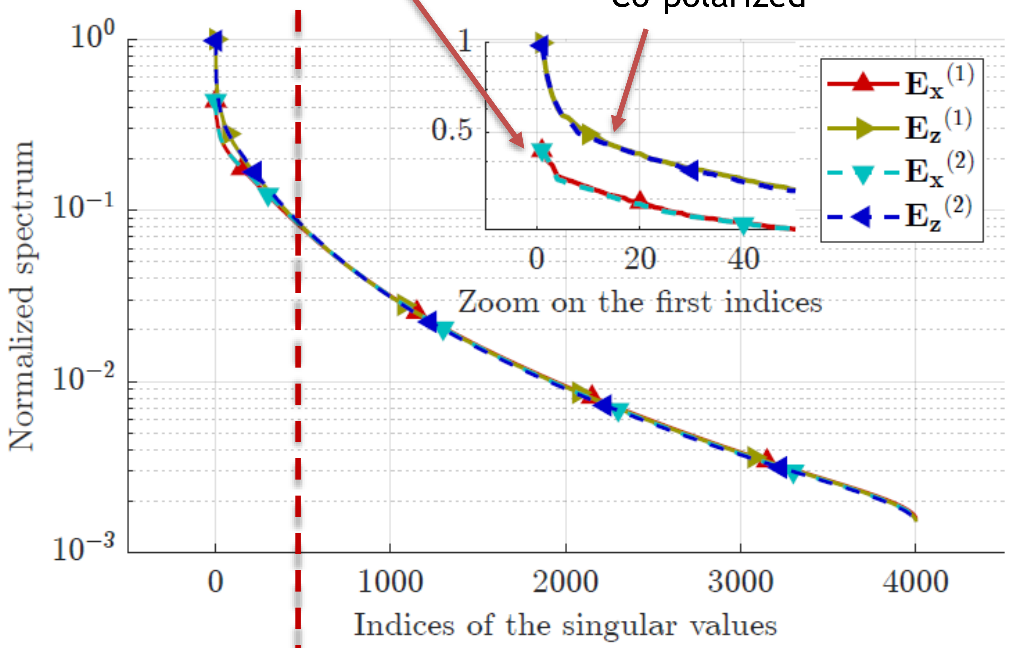
Cross-polarized measurements



Closer to a diffuse field distribution

Cross-polarized

Co-polarized



Feeding port polarization

Cavity boundary conditions

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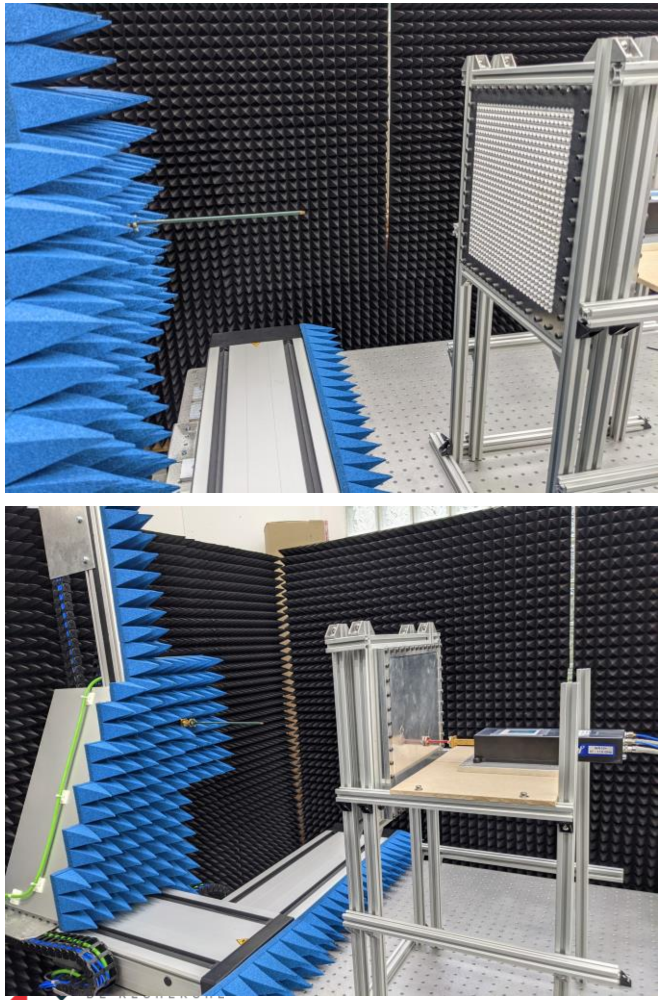
Results: Application to computational imaging

Antenna localization



1. Near-field to dipole conversion

$$\mathbf{m} = \frac{2}{i2\pi\nu\mu_0} \int \hat{\mathbf{n}} \times \mathbf{E}_{\tan} \, da$$

2. Computation of the radiated field

$$\mathbf{E}(\mathbf{r}_j) = -Z_0 \, k^2 \sum_i (\hat{\mathbf{r}}_{ij} \times \mathbf{m}_i) \frac{e^{-ik\mathbf{r}_{ij}}}{4\pi \mathbf{r}_{ij}} \left(1 - \frac{i}{k\,\mathbf{r}_{ij}}\right)$$

3. Forward problem: Measurement of the transfer function

Feeding port index

$$\mathbf{s}^{(q)} = \mathbf{E}_0 \, \boldsymbol{\rho}^{(q)}$$

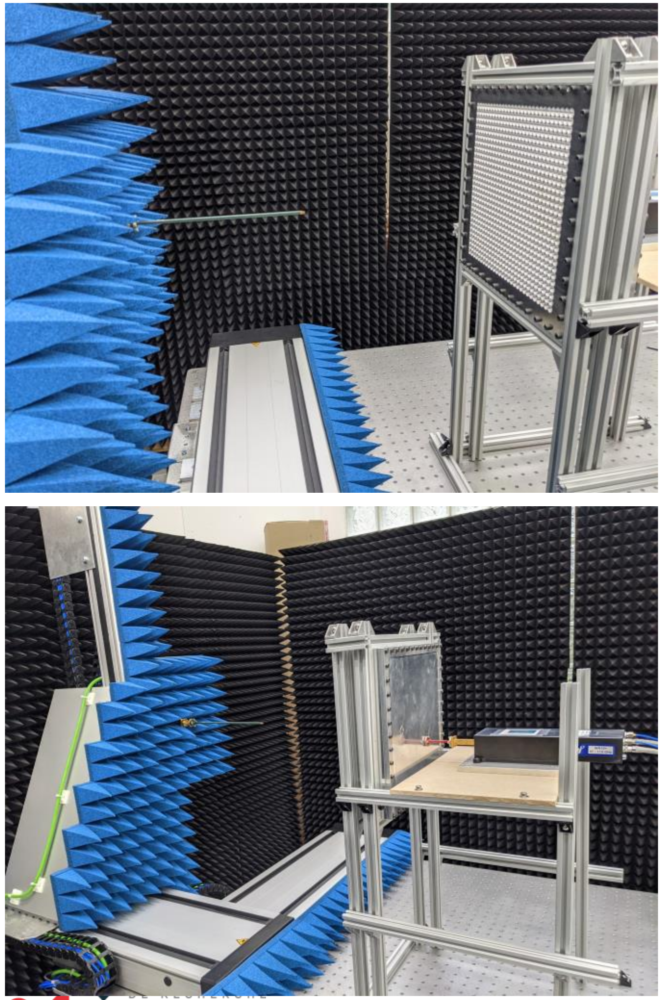
4. Inverse problem: Source localization

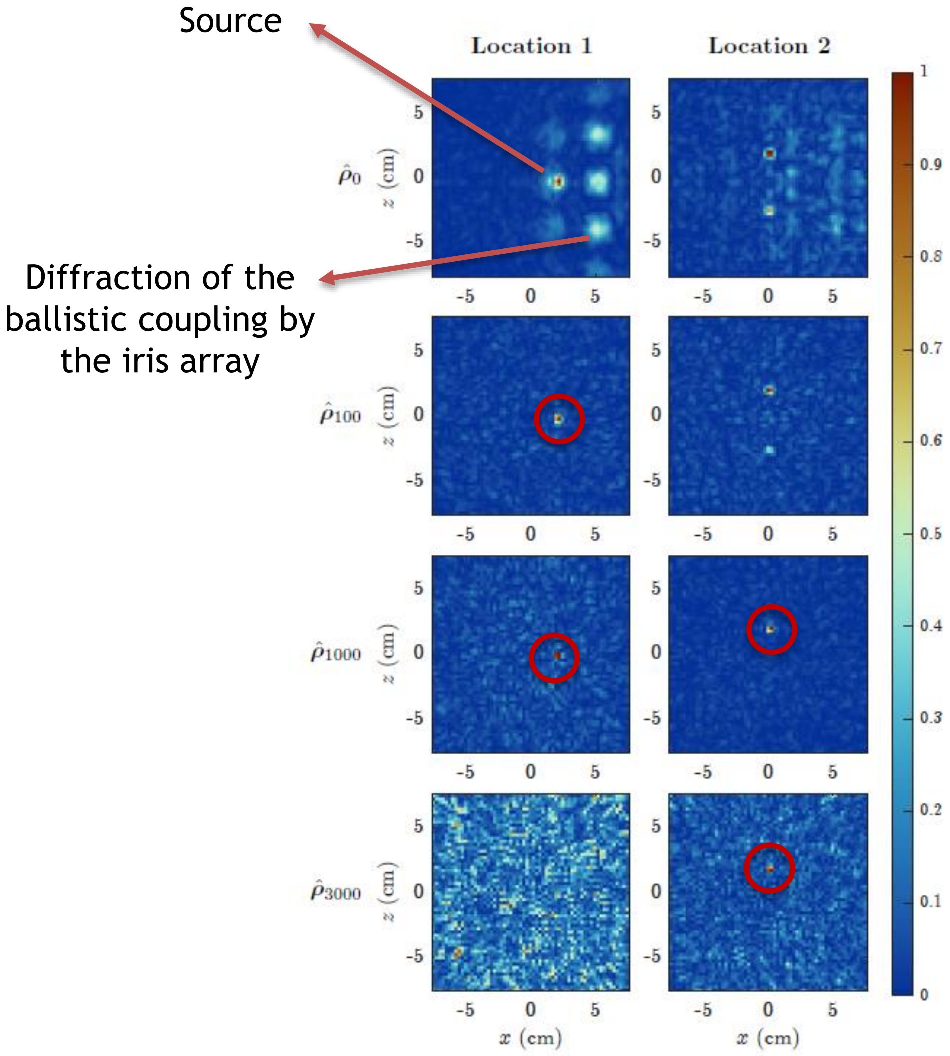
$$\hat{\boldsymbol{\rho}}_m^{(q)} = \mathbf{E}_m^\dagger \, \mathbf{s}^{(q)} = \mathbf{E}_m^\dagger \mathbf{E}_0 \, \boldsymbol{\rho}^{(q)}$$

Removing the m first singular values and vectors

Results: Application to computational imaging

Antenna localization





Filtering of the *m* most coherent subspaces

$$\mathbf{E}_{x,z}^{[m]} = \sum_{n=m+1}^{n_\nu} \sigma_n \mathbf{u}_n \mathbf{v}_n^\dagger$$

Inverse problem: Source localization

$$\hat{\boldsymbol{\rho}}_m^{(q)} = \mathbf{E}_m^\dagger \, \mathbf{s}^{(q)} = \mathbf{E}_m^\dagger \mathbf{E}_0 \, \boldsymbol{\rho}^{(q)}$$

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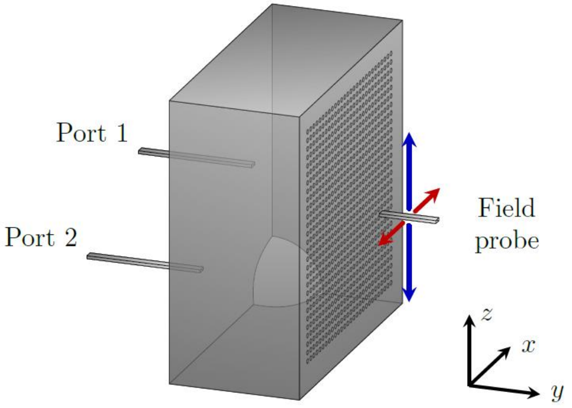
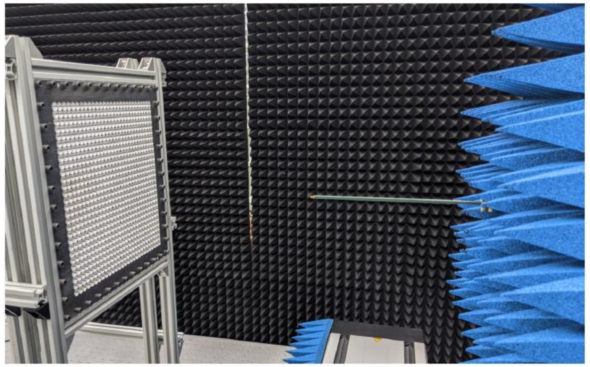
Conclusion

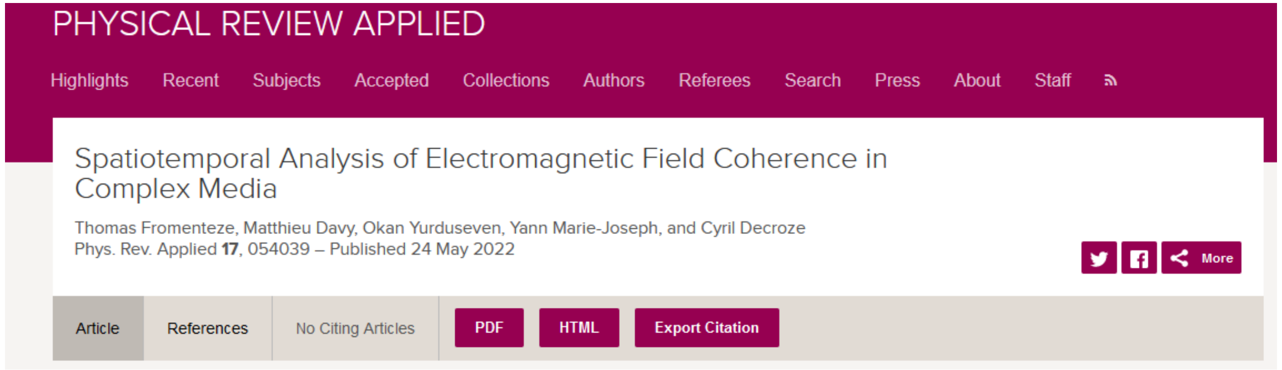




Related work

Mounaix, M., & Carpenter, J. (2019)
Control of the temporal and polarization response of a multimode fiber.
Nature communications, *10*(1), 1-8.

Extended version published in Physical Review Applied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Spatiotemporal Analysis of Electromagnetic Field Coherence in Complex Media

Thomas Fromenteze, Matthieu Davy, Okan Yurduseven, Yann Marie-Joseph, and Cyril Decroze
Phys. Rev. Applied **17**, 054039 – Published 24 May 2022

More

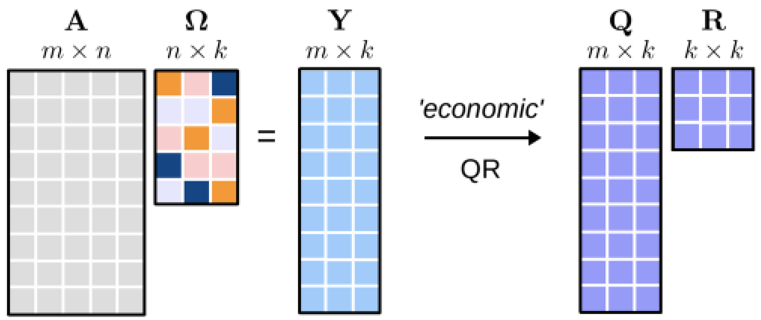
Article References No Citing Articles PDF HTML Export Citation

What is different from this presentation?

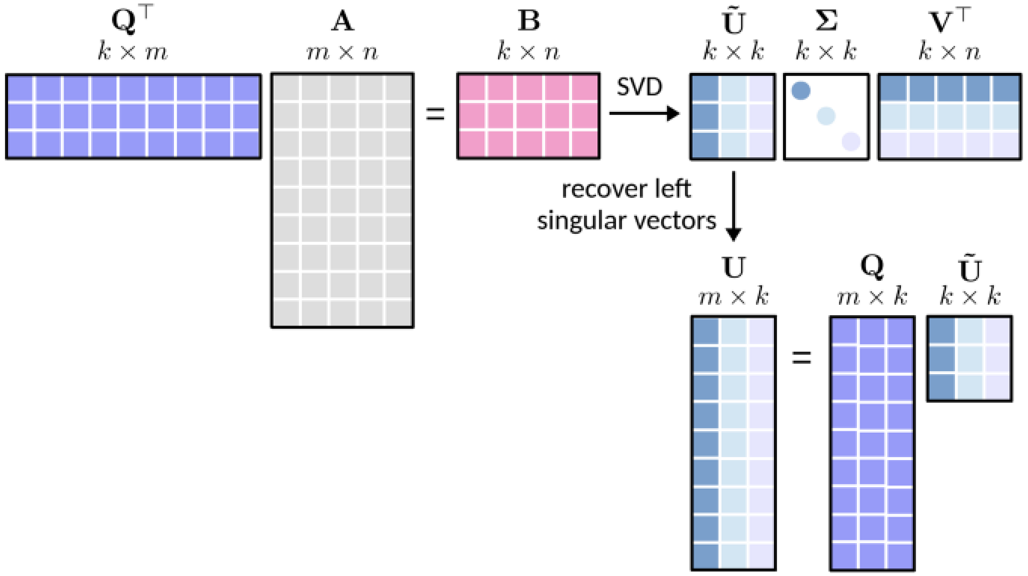
Introduction of coherence metrics
Evolution of spatial vs temporal coherence
SVD-based filtering vs Time-gating

Implementation with large matrices : **Randomized SVD**

1. Multiplication by a random matrix et QR decomposition



2. Multiplication by the initial matrix and SVD



Sources : https://towardsdatascience.com/intuitive-understanding-of-randomized-singular-value-decomposition-9389e27cb9de