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LEAT
LABORATOIRE D'ELECTRONIQUE, ANTENNES ET TÉLÉCOMMUNICATIONS

Introduction to Millimetre wave imaging

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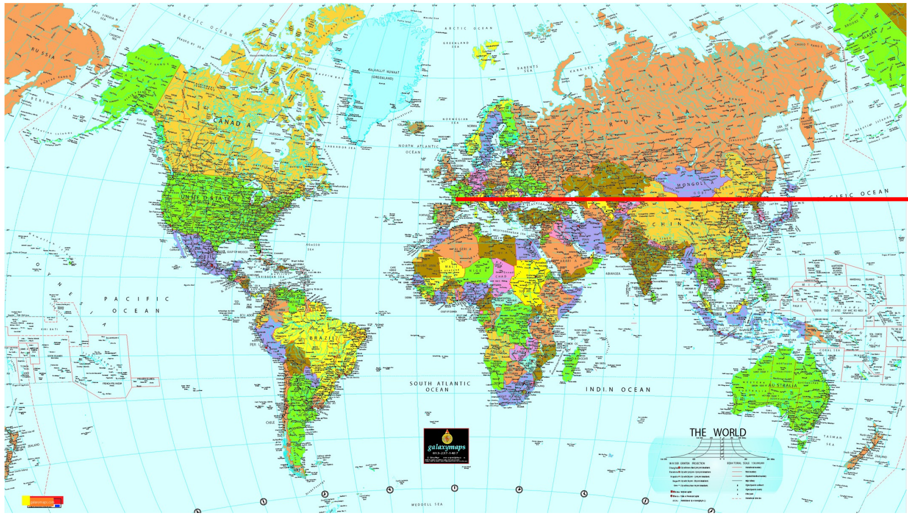
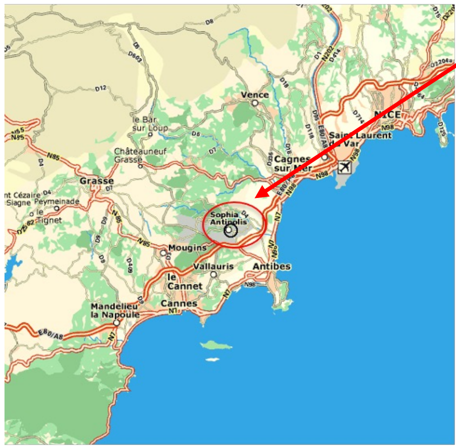
*Laboratoire d'Electronique Antennes et Télécommunications

Université Côte d’Azur : campus SophiaTech



French Riviera

Alpes Maritimes



Electronics @ Université Côte d'Azur

Bachelor and Master
Nice campus : Valrose

Polytech Nice Sophia
Campus Sophia Tech

LEAT

IUT GEII
Nice campus : Fabron

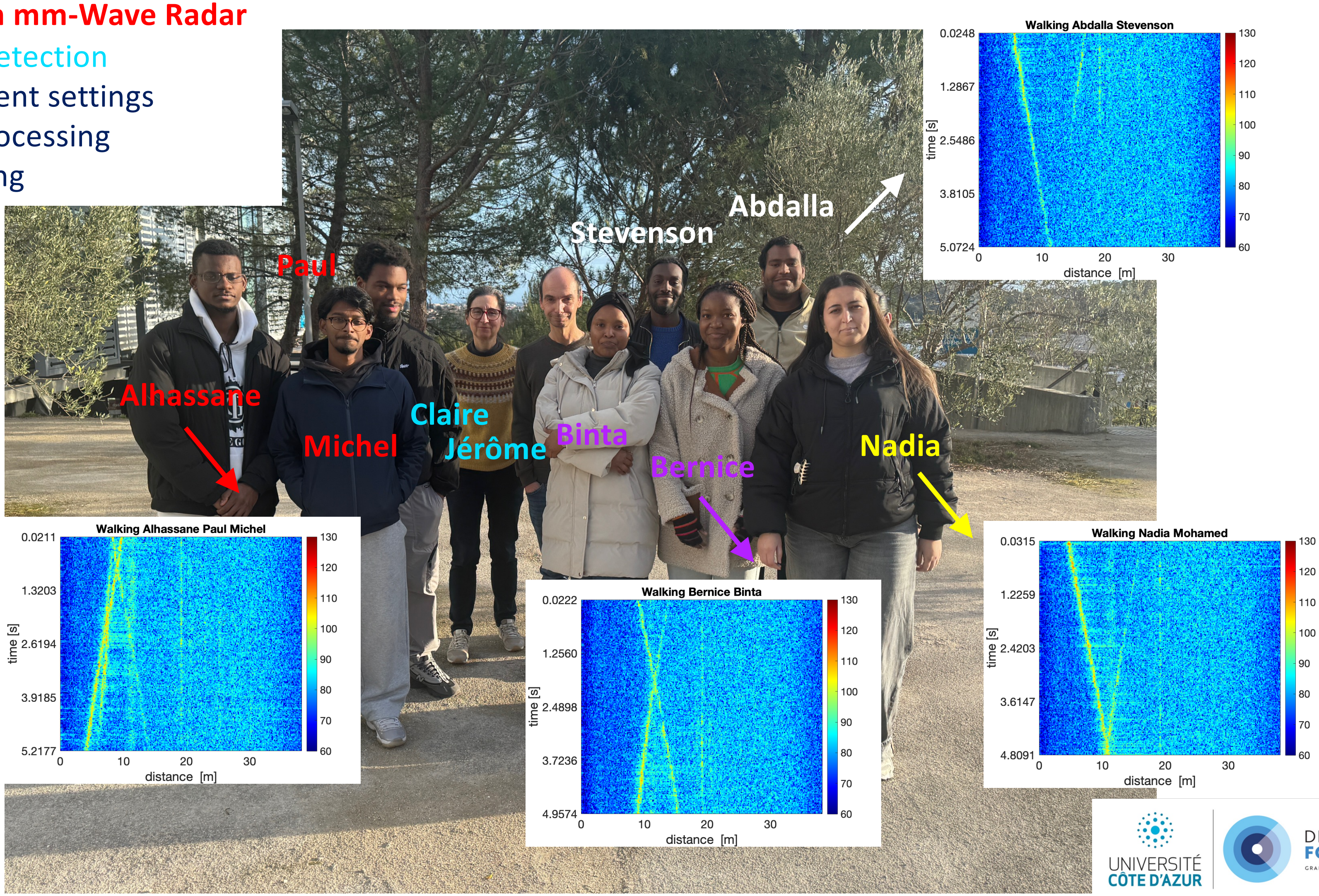
IUT R&T
Campus Sophia Tech

Share the radar experience of Master students at Université Côte d'Azur!

Lab. course on mm-Wave Radar

Pedestrian's detection

- Measurement settings
- Doppler processing
- Path tracking



UNIVERSITÉ CÔTE D'AZUR

DIGITAL SYSTEMS FOR HUMANS

GRADUATE SCHOOL AND RESEARCH

The LEAT :laboratoire d'électronique, Antennes et Télécommunications

Location: The SophiaTech Campus

The LEAT in short

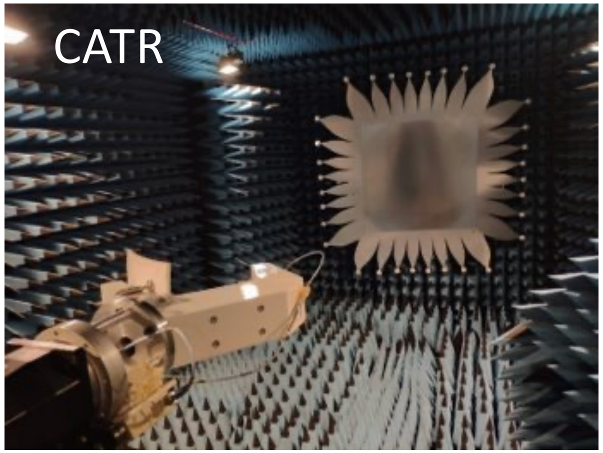
28 permanent staff, 37 PhD students, 8 post-doc, 12 Master students

3 research teams

- CMA : Conception and Antenna Modeling
- EDGE Edge Computing and Digital Systems
- ISA Imaging and Antenna Systems => here I am!

A large set of equipment for antenna testing

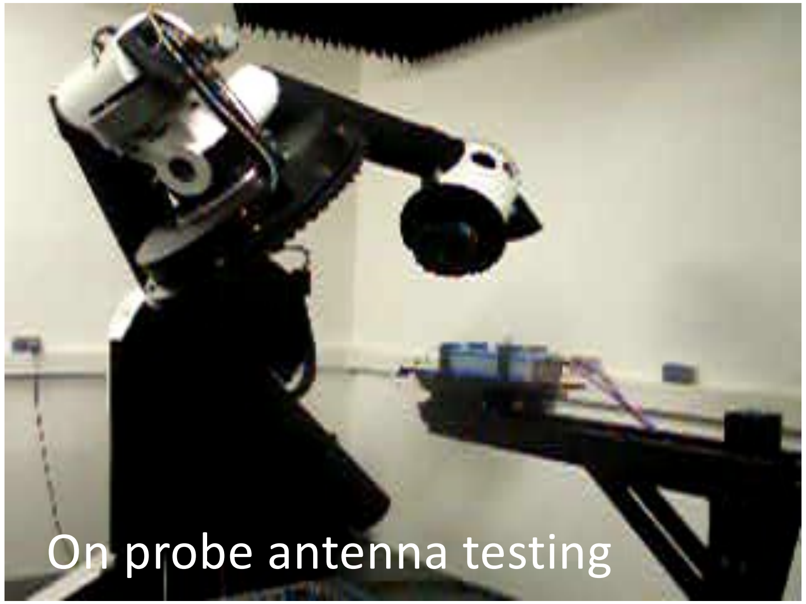
The anechoic chamber
820MHz à 260GHz

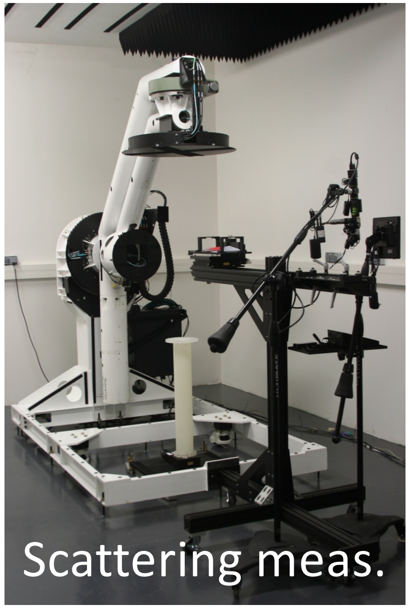


The LEAT in short

3D Scanner : Radiation and scattering measurements

- Up to 260 GHz
- Near Field (NF)and Far Field (FF) capacities
- On probe S_{11} and radiation pattern measurements





Who am I?

Full Prof. Claire Migliaccio, born on 17/01/1970, 2 children

Academic qualifications

- 2006 HDR (Habilitation à Diriger des Recherches), Université Nice Sophia-Antipolis (UNS), France
- 1996 Ph.D., INPG - Institut National Polytechnique de Grenoble, Grenoble, France
- 1993 Engineer degree., INPG, Grenoble, France

Research topics

- MMW electrically large antennas for radar applications, ULB antennas
- Millimeter-wave scattering measurements and millimeter-wave imaging systems
- AI for radar, microwave and millimeter-wave imaging
  - ✓ Large field of applications: medical, non-destructive testing, security and surveillance

Teaching and Supervision

- Teaching : electronics, telecomm. basics, antennas, radar, millimeter-wave imaging
- Until now : 16 PhD, 2 ongoing; more than 20 master students

Who am I? Supervision and collaborations

My deep thanks to

My colleagues

Christian Pichot, Jérôme Lanteri, Jean-Yves Dauvignac, Nicolas Fortino and Ioannis Aliferis

The PhD students and Post-docs

Eirini Linardou, Binh Duong Nguyen, Matthieu Multari, Jérôme Lanteri, Karim Mazouni, Armin Zeitler, Peter Feil, Bin Zawawi Nazrol, Christophe Jendrzejczak, Ibtissam El Khanfoud, Cheick Diakité, Yasmine Ibrahim, Flora Zidane, Sahar Borzooei, Rémi Grisot, Ali Drawish, Maha El Abed, Esteban Geenons Guillaume Clementi, Ngoc Tihn Nguyen, Florence Nsengiyumva, Michael Lebegue.

Who am I?

Main leading and management positions

At University level

- 2017-2022 Head of Doctoral school
- 2020-2023 Member of Academic Council of University Côte d'Azur

At National level

- 2024-2027 Elected member of the French National Council of Universities
- 2023-2025 Vice-President of one of the French Research Grants program (ANR)

At international level

Since 2022 : Founder and Chair IEEE AP-S ECE in 2025

- 2017-2022 : Track Editor of IEEE TAP
- Since-2022 : Associate Editor of IEEE TRS
- Since 2024 : Associate Editor of IEEE AP-Magazine
- TPC member : EuRAD-EUMW, IEEE AP-S URSI, IEEE CAMA

Outline

I. Microwave and MMW* imaging
II. MMW scattering measurements
III. Agricultural and food safety applications
IV. Archaeology
V. Biomedical applications

* MMW = Millimeter-wave

I. Microwave and MMW imaging : definition

Imaging is the "process of producing an exact picture of something, especially on a computer screen"*

Microwave/MMW Imaging is the "process of producing an exact picture of something, based upon measurements conducted at Microwave/Millimeter-Waves"

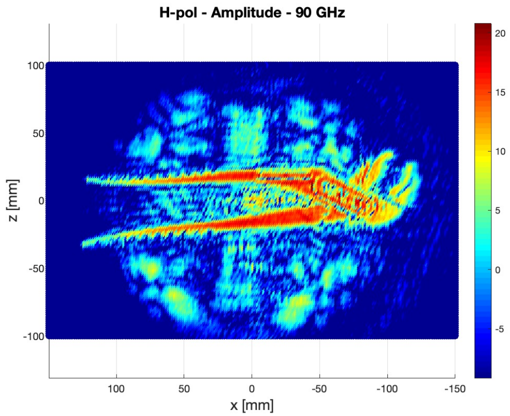
Scattering : interaction between the object and the electric field that illuminates it

Scattered field : $E_{scat} = E_{total} - E_{inc}$

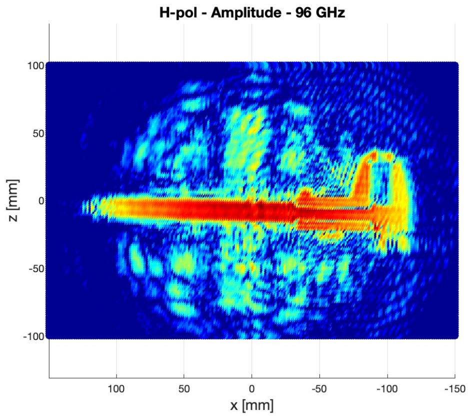
- E_{scat} : scattered field
- E_{total} : total field = object + incident field
- E_{inc} : incident field = empty scene

* Cambridge dictionary

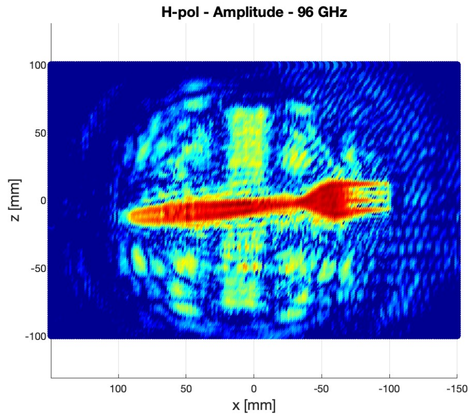
I. What about microwave and MMW images?



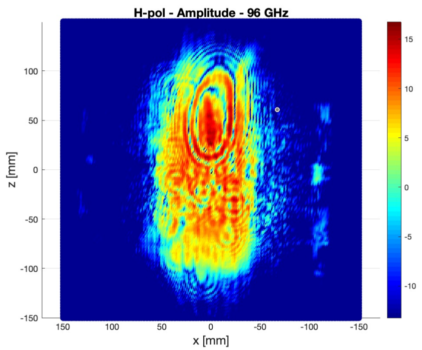
Pliers



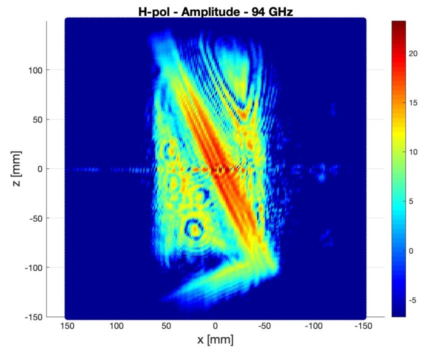
Caliper



Fork

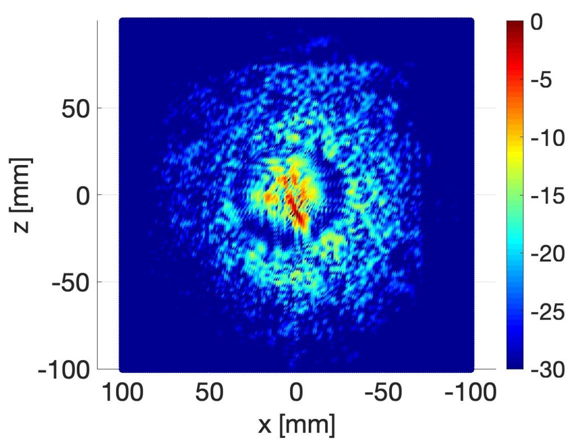


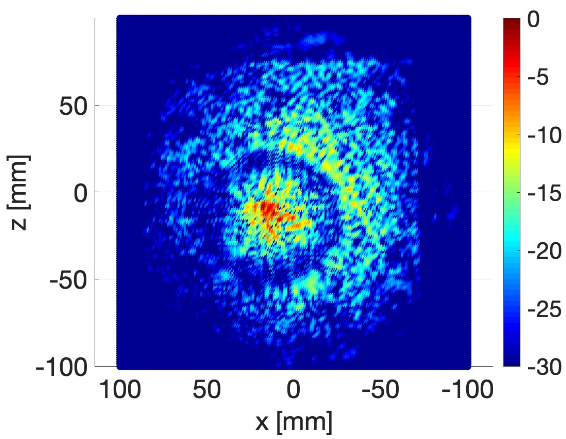
Liquids

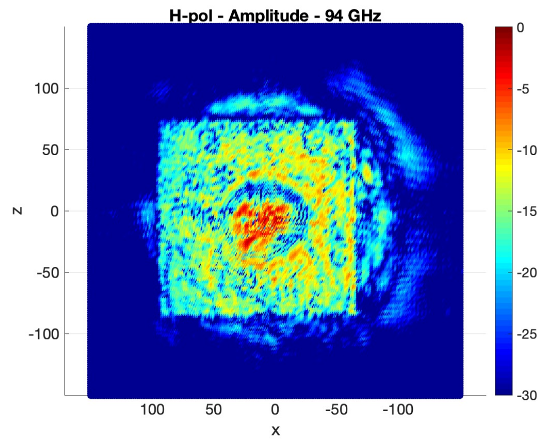


Liquids + metal

I. MMW images : Fruits

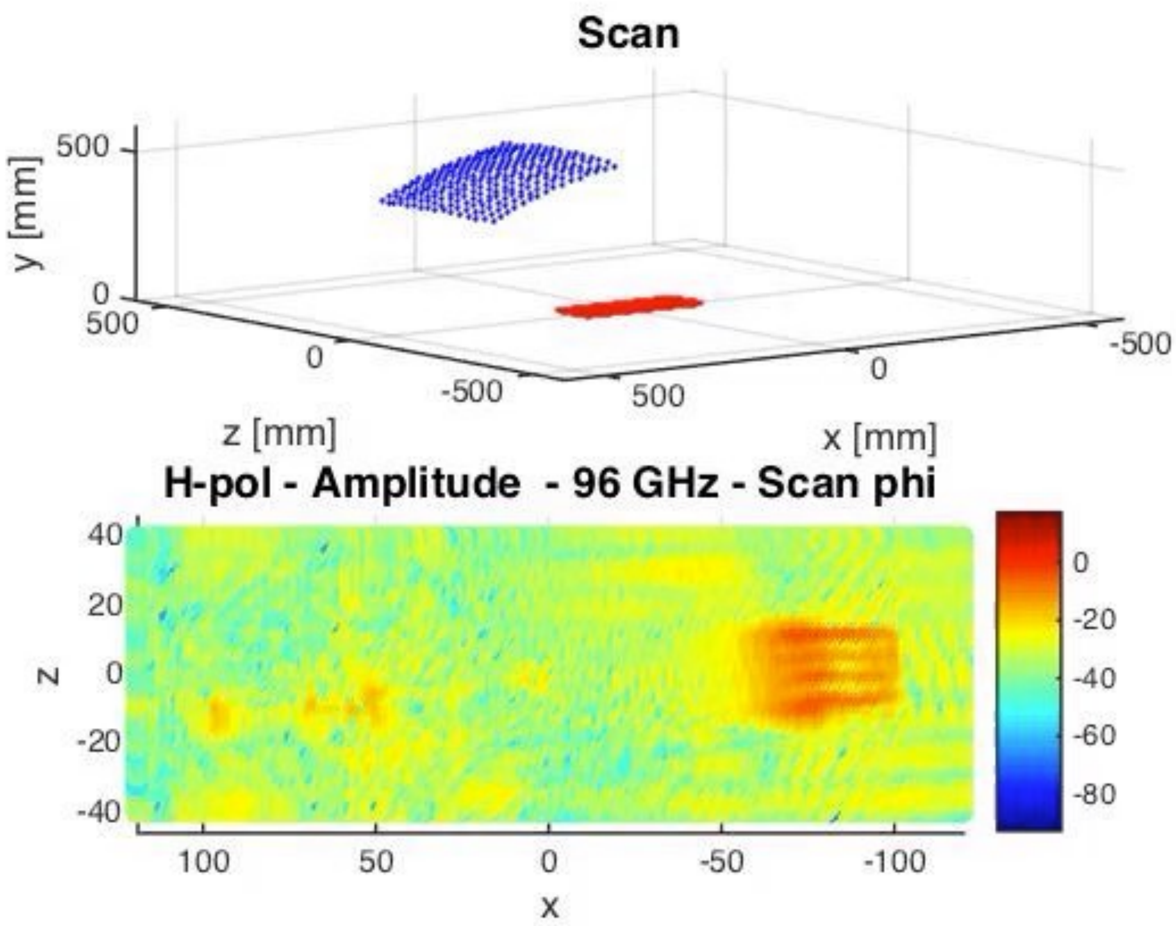




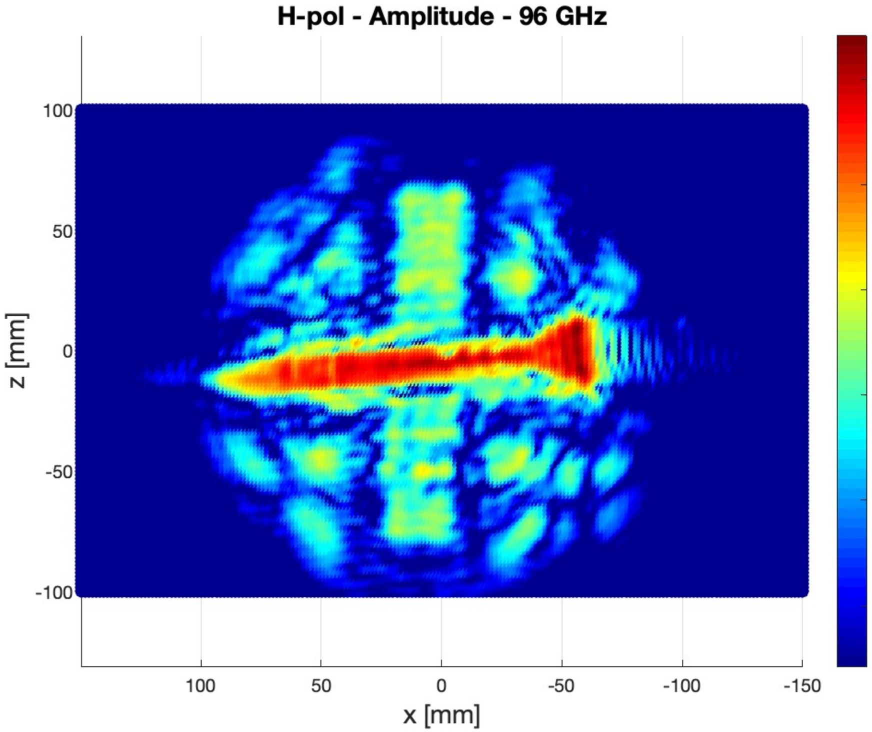


The reflectivity is material-dependent but not only!

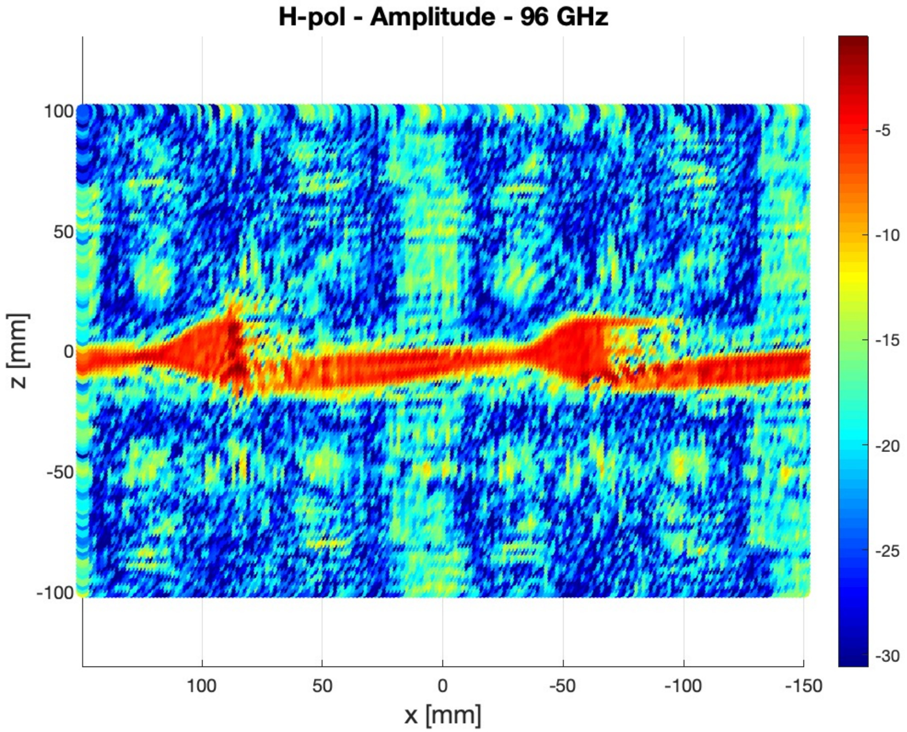
I. MMW images : View angles



I. MMW images : Other issues



Scan size



Scan step

I. MMW images : Trajectories

I. Microwave and MMW imaging : why?

A growing need of Non-destructive Evaluation (NDE) :

- Detection
- Identification
- Classification

For a set of applications (non-exhaustive list):

- Diagnosis => Microwaves
- Food safety => Microwaves and MMW
- Archaeology => MMW and sub-THz
- Homeland security => MMW and sub-THz

I. Imaging : detection, identification, classification

Detection

- Identify the presence of an object
- Passive : radiometry, passive radar
- Active : radar

=> Signal processing

Identification

- Object's shape
- Object's properties such as dielectric properties

=> Electromagnetic inverse problems

Classification

- Identify specific characteristics
- Categorize objects

=> Signal and image processing, Artificial intelligence

I. What is microwave/MMW imaging?

Maxwell's equations

$$\overrightarrow{div}\,\vec{E}\,(\vec{r},\omega) = \frac{\rho(\vec{r},\omega)}{\varepsilon}$$

$$\overrightarrow{div}\vec{H}(\vec{r},\omega) = 0$$

$$\overrightarrow{rot}\vec{E}(\vec{r},\omega) = -j\omega\mu\vec{H}$$

$$\overrightarrow{rot}\vec{H}(\vec{r},\omega) = \vec{J}(\vec{r},\omega) + j\omega\varepsilon\vec{E}(\vec{r},\omega)$$

Direct problem

$$(\varepsilon,\mu) \Rightarrow (\vec{E},\vec{H})$$

Inverse problem

$$(\vec{E},\vec{H}) \Rightarrow (\varepsilon,\mu)$$

I. Inverse problems : a difficult task

Well-posed problem in the sense of Hadamard

- a solution exists
- it is unique
- the solution's behavior changes continuously with the initial conditions

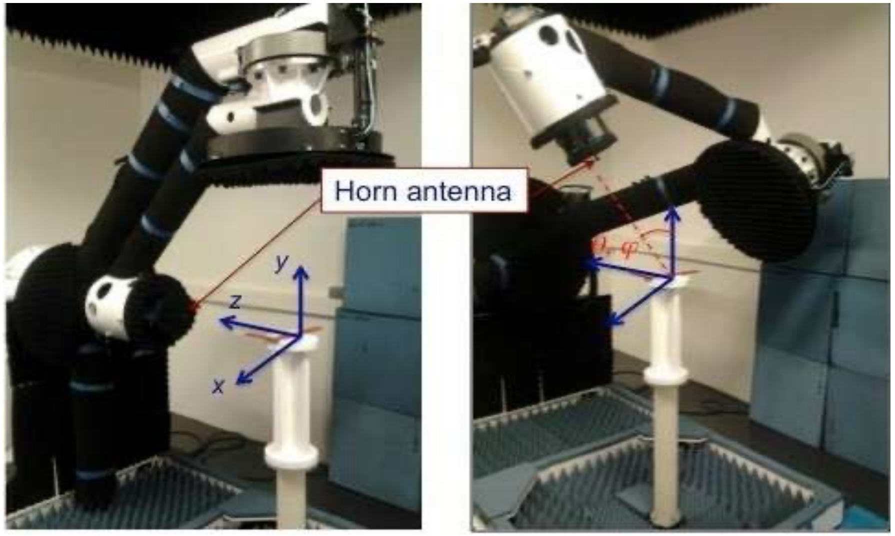
The EM inverse problem is ill-posed

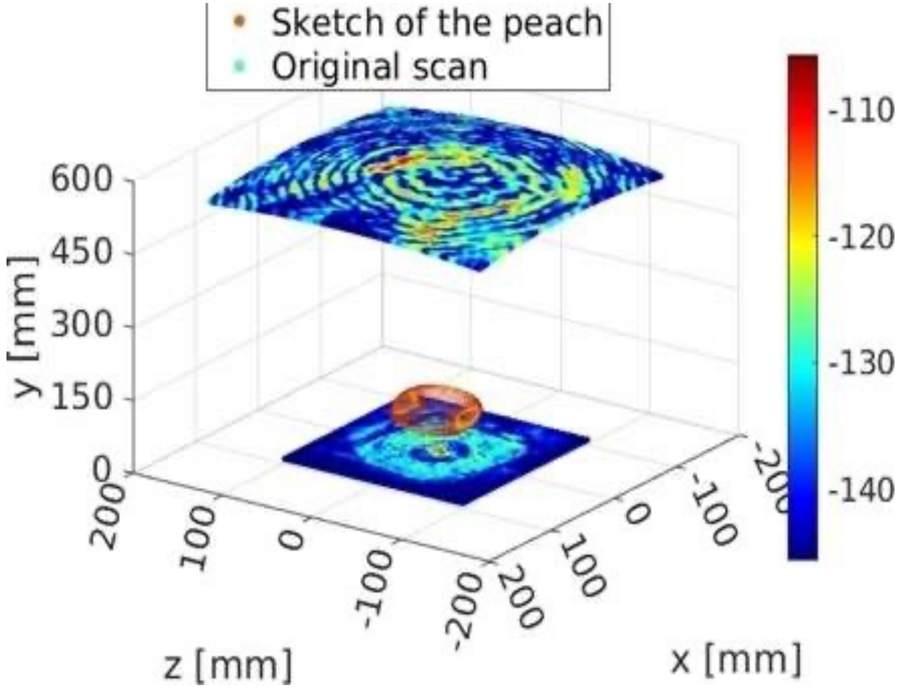
- No uniqueness of the solution
- Initial conditions : evanescent waves are not captured by the measurement system

The inverse problem is a difficult one but if we aim to track the changes in the dielectric permittivity => qualitative imaging

I. Qualitative imaging

Measurements





Complex Electric field => => => Back-propagation algorithm (BPA)

$$E_m = |E_m| e^{\mathrm{j}\arg(E_m)}$$

$$\mathrm{Image(P)} = \sum_{i,j}^{N,M} E_m e^{j2kdij}$$

I. Qualitative imaging

Back-propagation / alternatively 2D-FFT

$$\text{Image(P)} = \sum_{i,j}^{N,M} E_m e^{j2kdij}$$

Maximum expected resolution

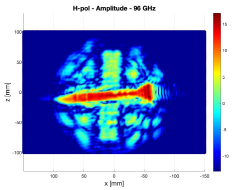
- Half a wavelength (propagative spectrum)

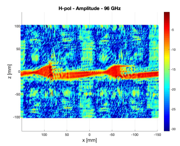
The scan size defines

- The equivalent array aperture
- The image resolution
- The measurement field of view

The scan step defines

- The measurement time
- The maximum image field of view without aliasing



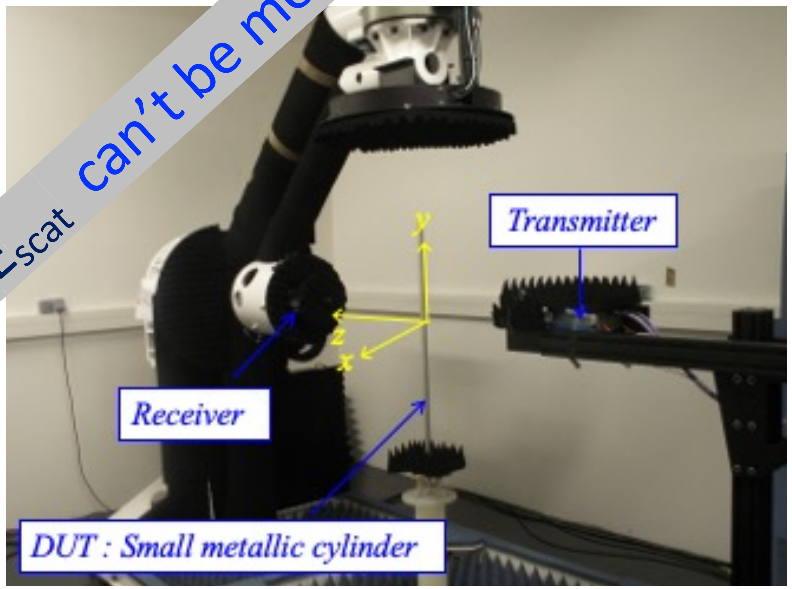


II. MMW scattering measurements

Scattered field : E_{scat} = E_{to}… E_{inc}

- E_{scat} : scattered field
- E_{total} : total field = ob… + incident field
- E_{inc} : incident fiel…

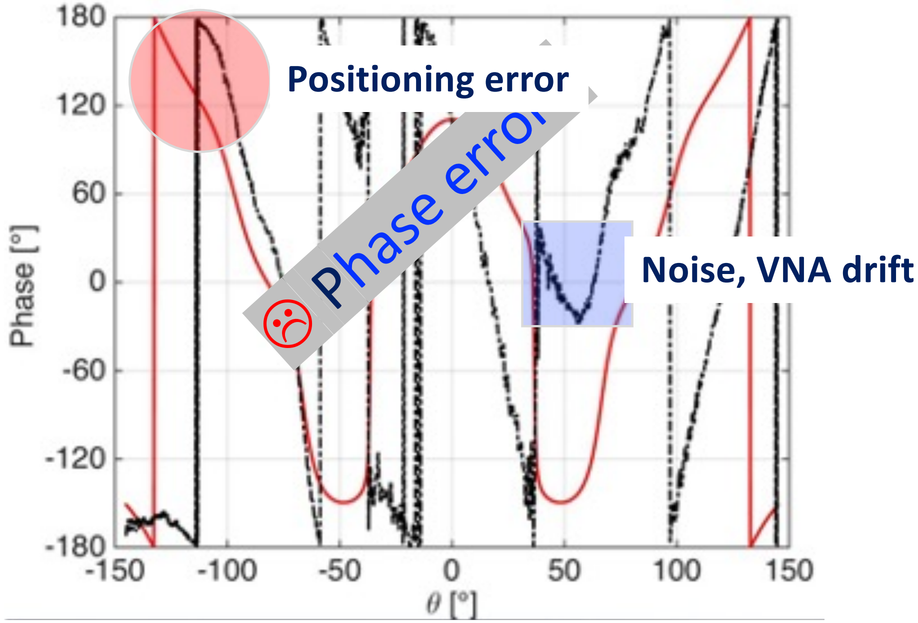
☹ E_{scat} can't be measured directly!



Measurement setup

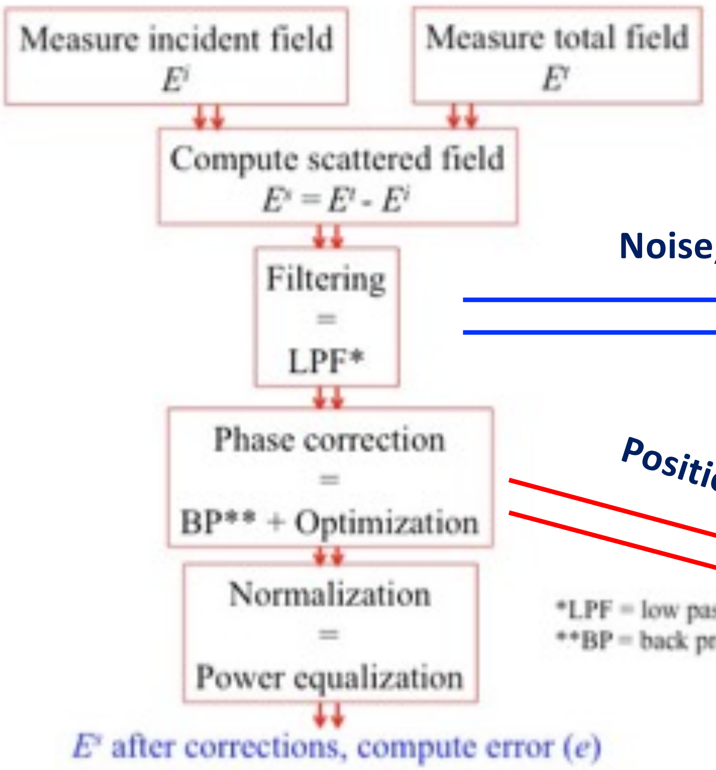
Example : metallic cylinder

- Analytical expression of E_{scat} exists
- Helps to calibrate the system
- Scattered field above the noise floor



☹ Phase error

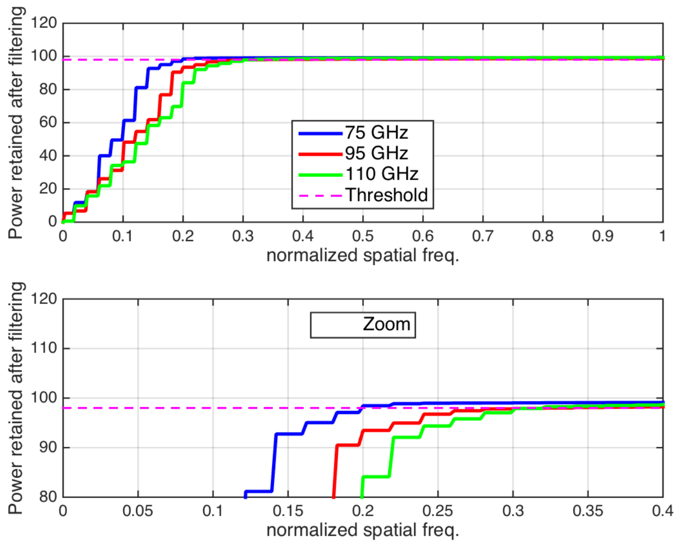
II. MMW scattering measurements

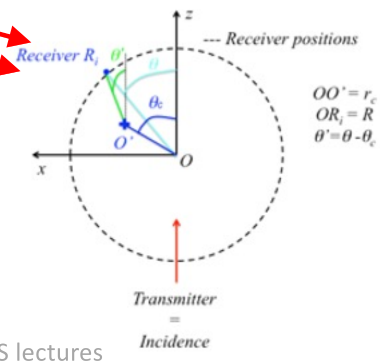


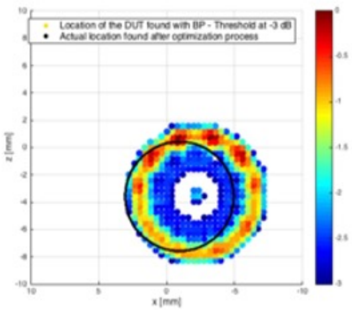
*LPF = low pass filter
**BP = back propagation

Noise, VNA drift

Positioning error

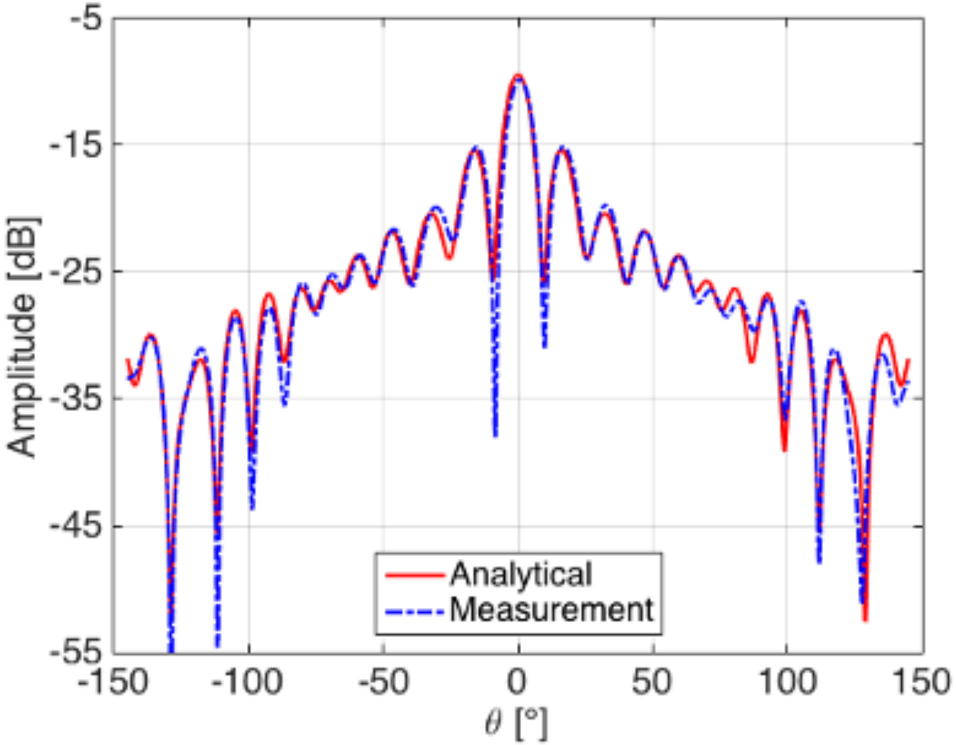


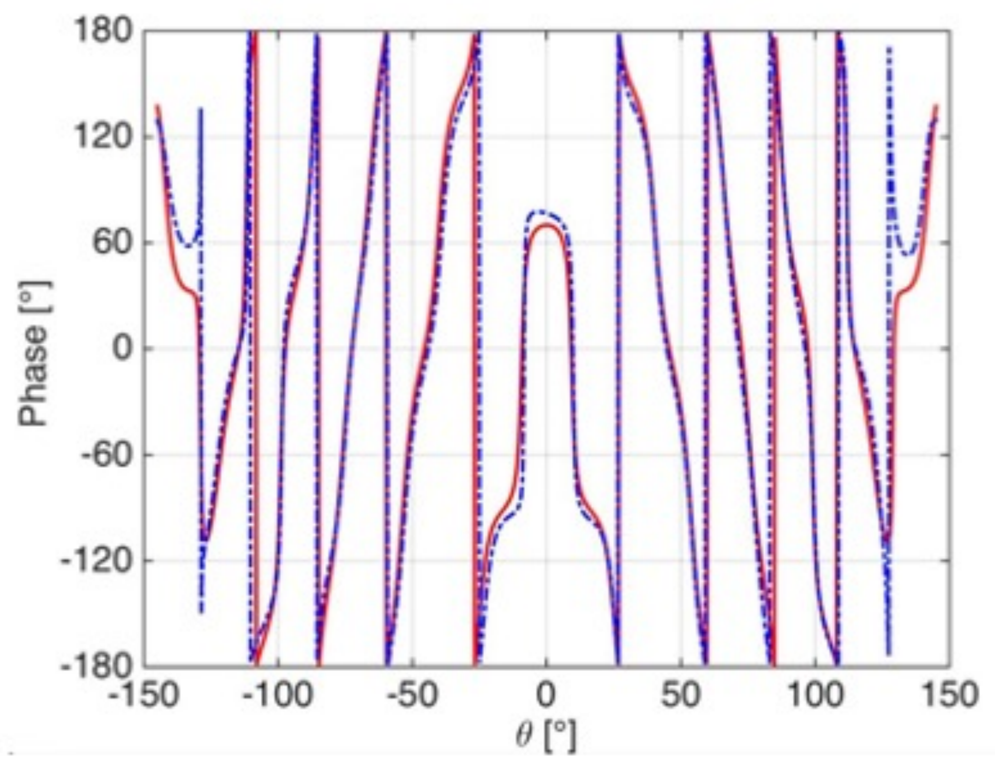




Measurement workflow

II. MMW scattering measurements



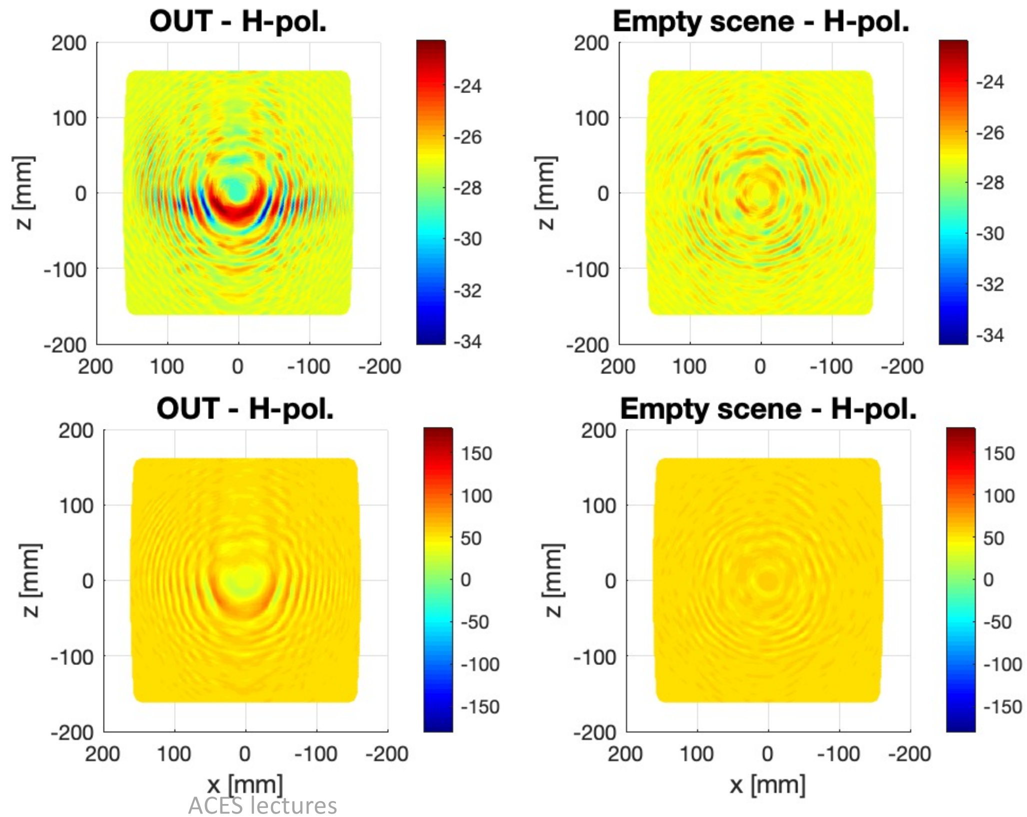


Measurement after correction – Plexiglas cylinder @ 95 GHz

[1] F.Nsengiyumva,C.Migliaccio,L.Brochier,J.-Y.Dauvignac,I.AliferisandC.Pichot,"New W-Band Scattering Measurement System : Proof of Concept and Results for 2-D Objects,"in IEEE Transactions on Antennas and Propagation,vol.66,no.12,pp.7224-7236,Dec.2018. doi:10.1109/TAP.2018.2870429.

II. MMW scattering measurements

- What if we don't have theoretical scattered field?
- What if the can't measured E_{inc}? => Alternative calibration methods



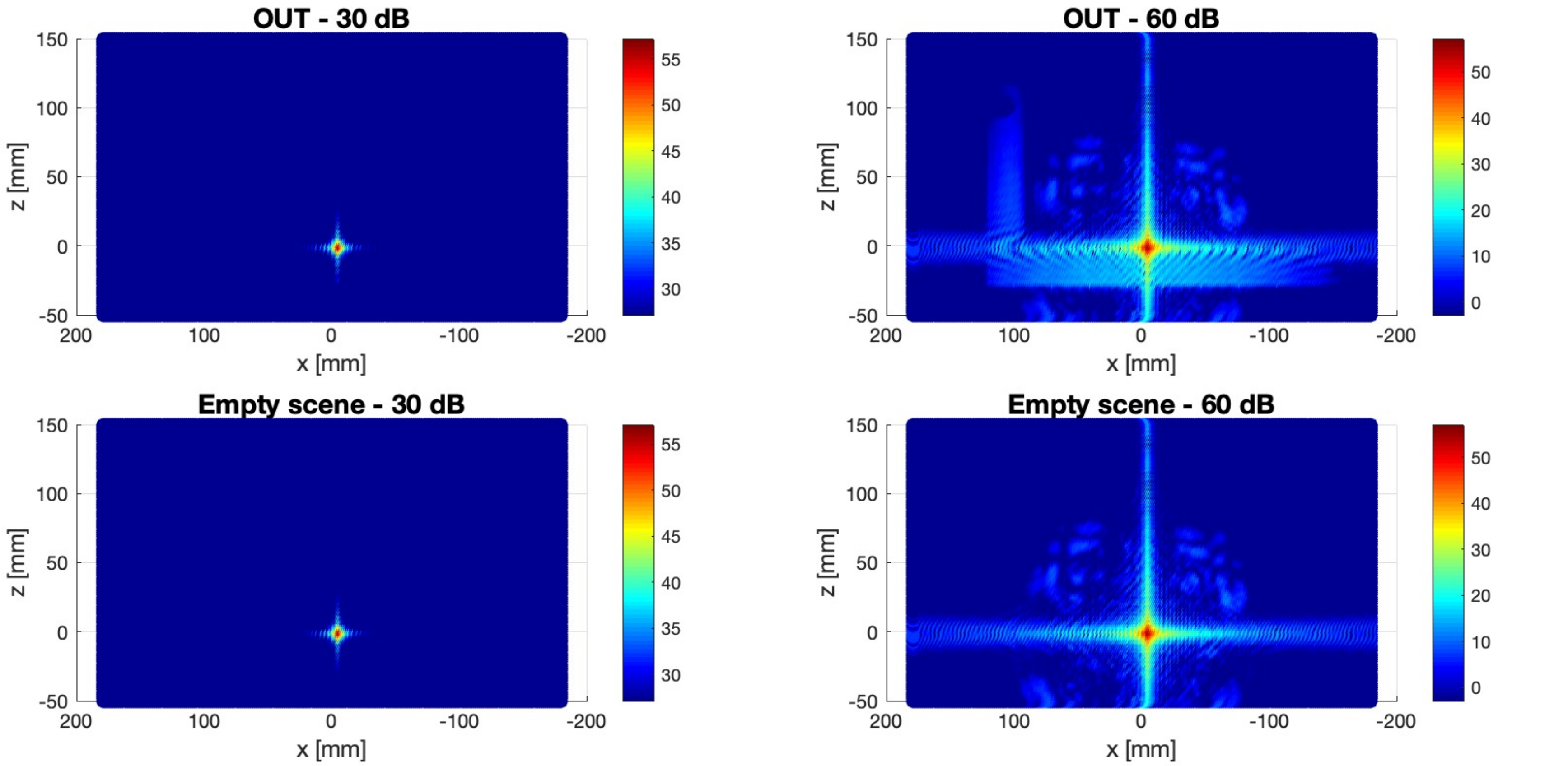
Challenge :

- E_{tot} and E_{inc} are close
- OUT acts as a modulation of E_{inc}

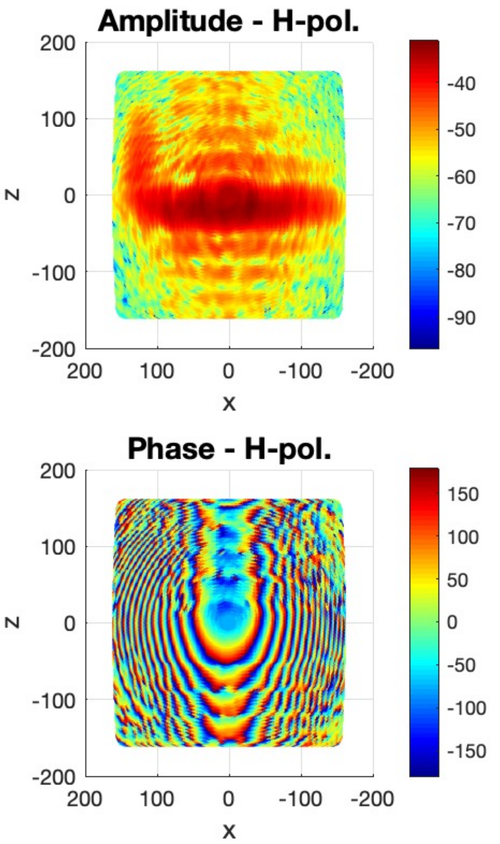
* OUT Object Under Test

II. MMW scattering measurements

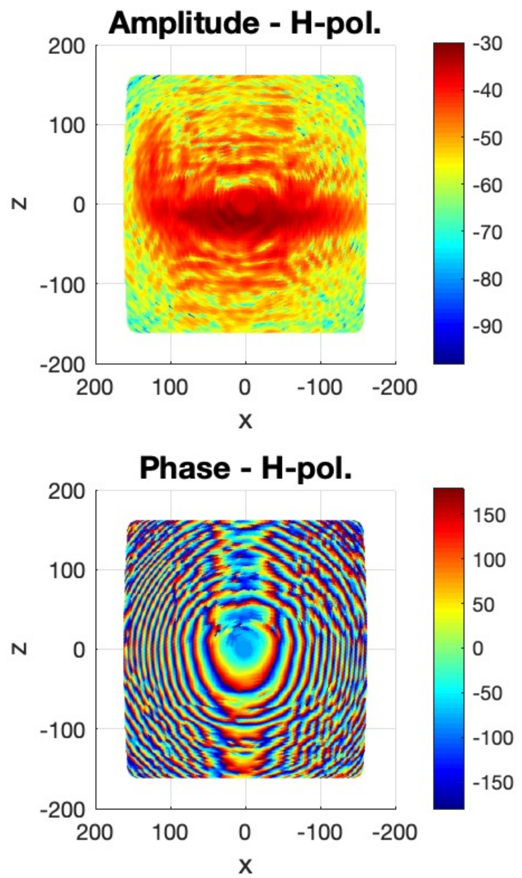
Images with E_{tot} ☹ the object is invisible unless dynamics increases



II. Image calibration schemes



E_{scat}



Mean value

Calibrated measurements

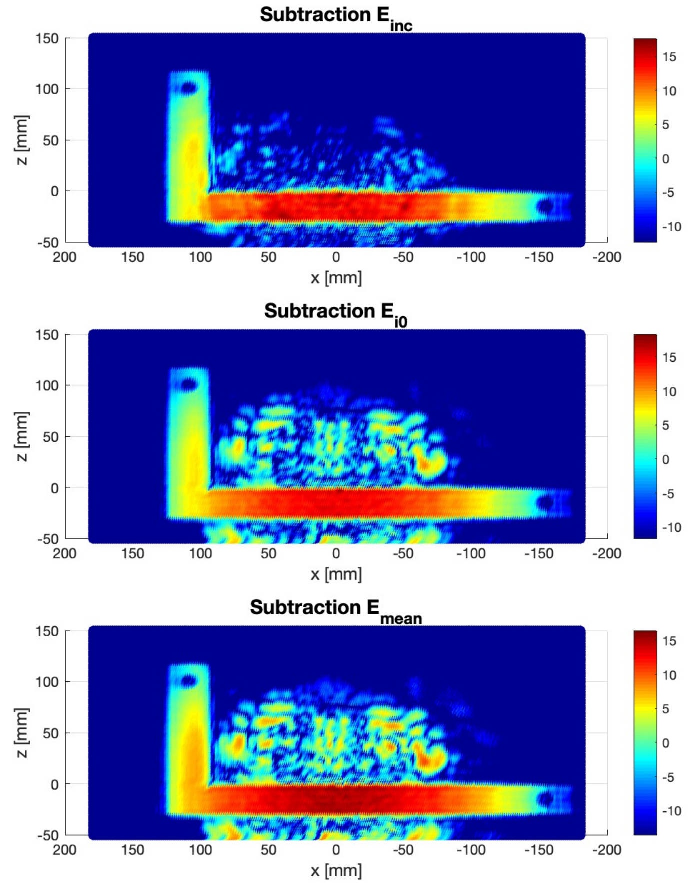
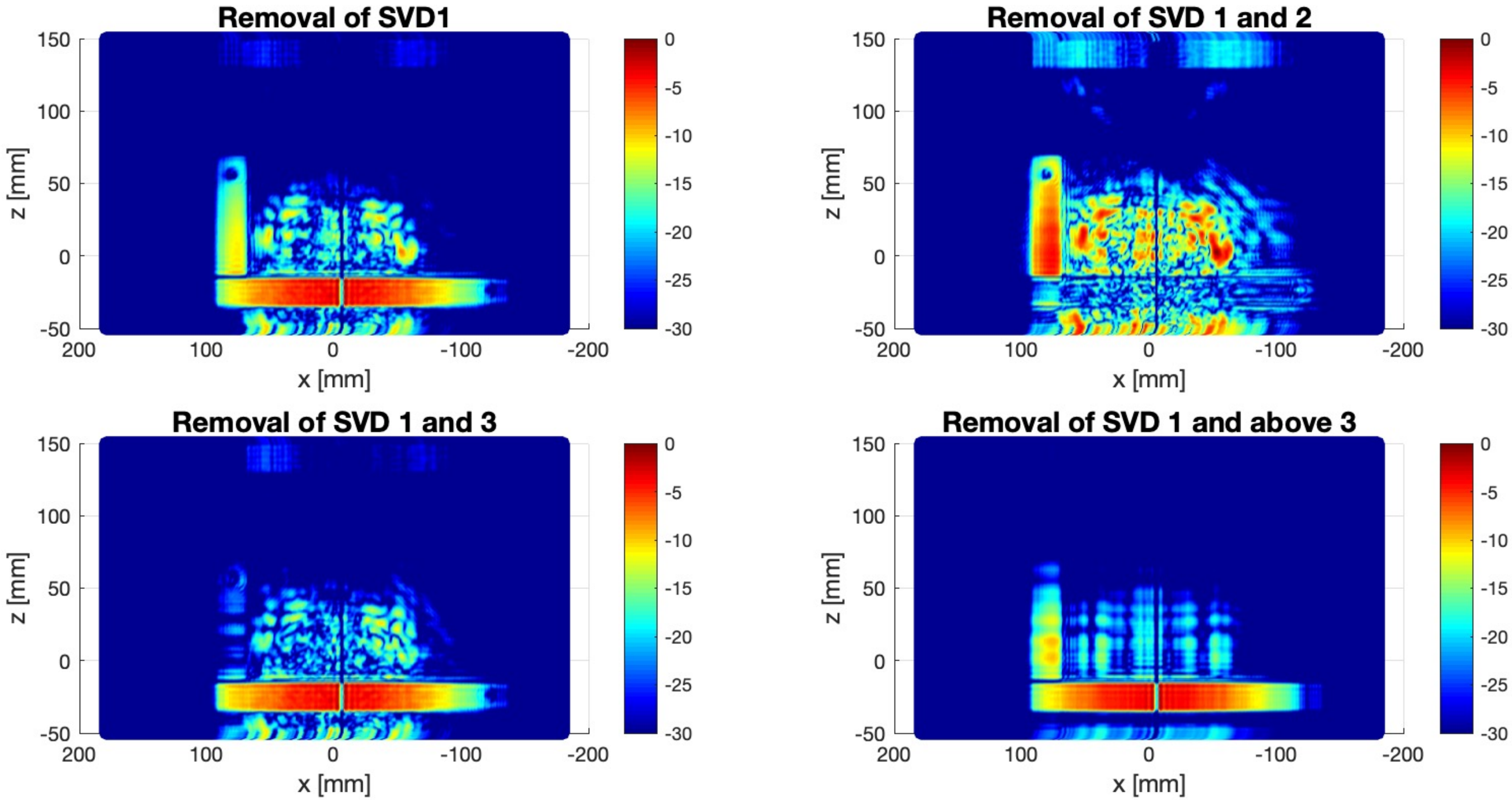


Image (BPA)

II. Image calibration schemes



[Singular Value Decomposition calibration]()

III. Agricultural and food safety applications

NDE for agricultural and food products

- Monitoring fruits and vegetable growth
- Identifying defects : contaminants, damages…

Why microwaves or MMW?

- Good compromise between the resolution and penetration depth
- Non invasive process compared to X-rays
- Low cost

Two applications

- Detection of fruit’s damages
- Detection of contaminants in packaged hazelnut cocoa cream

In collaboration with

- Detection of fruit’s damages
- Apples, peaches and hazelnuts

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Wavision Research Group Politecnico di Torino

III. Detection of fruit’s damages

Current solutions

☹ **Destructive Evaluation**

☺ **Non-Destructive Evaluation**:

- Visual inspection => time consuming
- Optical system => superficial defect
- X-ray system => bulky and expansive

New option:

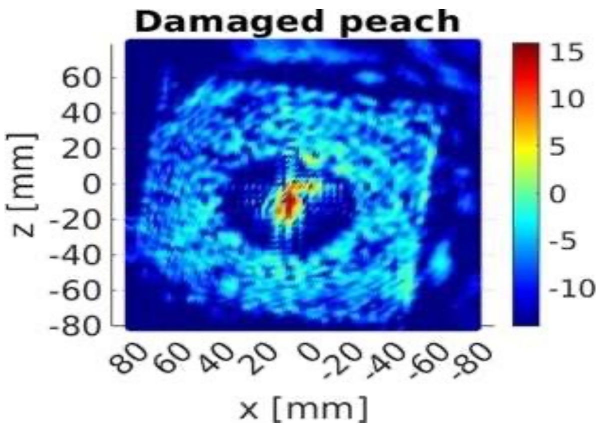
Automated NDE to sort healthy from damaged fruits with MMW imaging

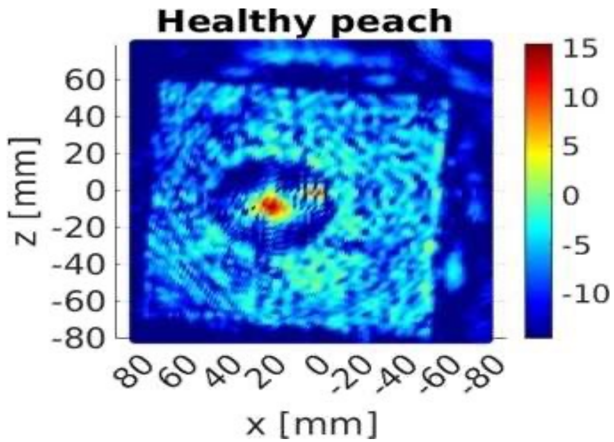
Flora Zidane, Jérôme Lanteri, Laurent Brochier, N. Joachimowicz, Hélène Roussel, C.Migliaccio,"Dam-aged Apple Sorting with mmWave Imaging and Non-Linear Support Vector Machine". IEEE Transactions on Antennas and Propagation 68(12) pp.8062-8071. doi:10.1109/TAP.2020.3016184.5

F. Zidane, J. Lanteri, J. Marot, L. Brochier, N. Joachimowicz, H. Roussel, C.Migliaccio,“Non destructive Control of Fruit Quality via Millimeter Waves and Classification Techniques : Investigations in the Automated Health Monitoring of Fruits”, IEEE Antennas and Propagation Magazine, Volume:62, Issue : 5,Oct.2020, pp.43-54. doi:10.1109/MAP.2020.3003222.4

III. Detection of fruit's damages : measurements

Qualitative imaging => changes in ε are included in the images





How to extract these changes?

=> Machine learning

III. Detection of fruit's damages : SVM

Why Support Vector Machine?

- Performs well for small datasets
- Simple classifications problems, typ. binary classification
- Two classes : + 1 healthy fruit, -1 damaged one

Linear/ non-linear SVM?

- Linear SVM : for linearly separable data => one hyperparameter C
- Non-linear SVM
  - two hyperparameters C an γ
  - RBF kernel

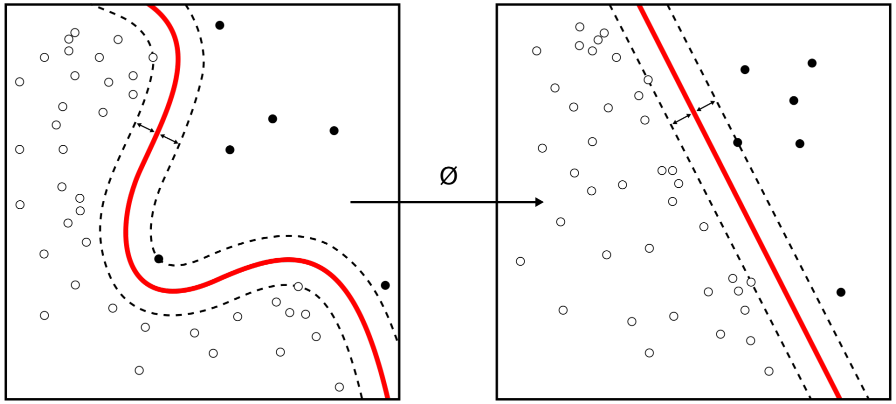
Challenges

- Find the optimal hyperparameters
- Time consuming process
- Optimization : Bio-inspired => Grey Wolf optimizer (GWO)

III. Detection of fruit’s damages : SVM

Binary SVM

- Defines an hyperplane for separating the two classes
- Aims to maximize the margin between classes



Linear SVM

- One hyperparameter : C
- C : sets the margin

Non-linear SVM

- Two hyperparameter : (C,γ)
- Kernel : different functions to map data into a higher-dimensional space
- Most common kernels : linear, polynomial, Radial basis function, Sigmoid
- γ : sets the grouping of the samples with respect to the margin

III. Detection of fruit's damages : SVM

The Grey Wolf Optimizer : a bio-inspired optimization method [2]

Exploration phase

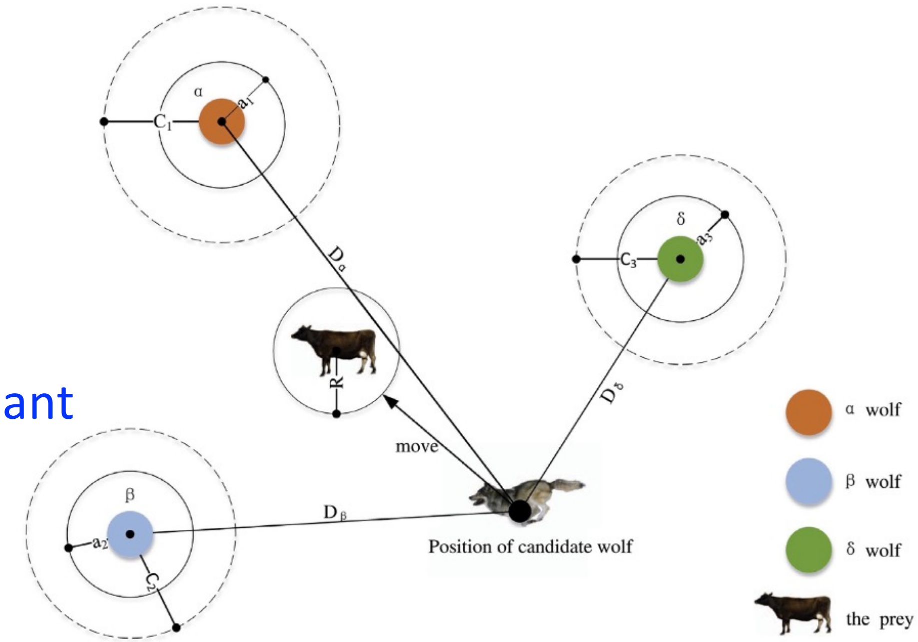
- Wolfes follow the dominant α wolf

=> estimation of prey position

Exploitation phase

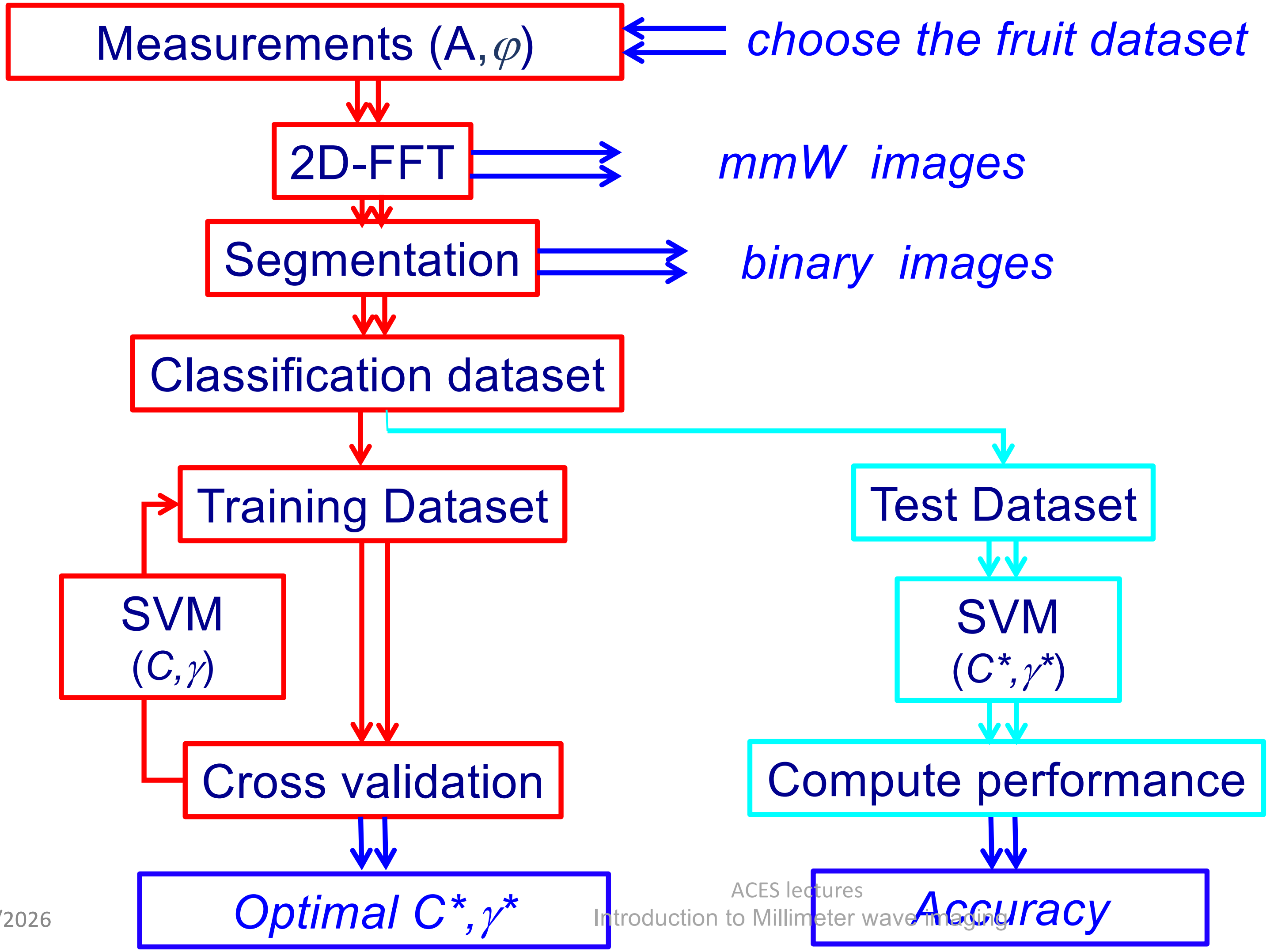
- Wolfes surround the prey under the the dominant α wolf guidance

=> prey position : parameters to be evaluated



Niu, P., Niu, S., & Chang, L. (2019). The defect of the Grey Wolf optimization algorithm and its verification method. *Knowledge-Based Systems*, *171*, 37-43.

III. Detection of fruit’s damages : workflow



III. Detection of fruit’s damages : datasets

6 apples - May 2019 : 3 different sizes

- Measurements : W-band
- Training dataset : a pair of big and medium apples
- Test dataset : pair of small apples

* Pair : contains a healthy fruit and a damaged one

5 apples - October 2020

- Measurements : D-band
- Training dataset : 1 healthy + 1 damaged
- Test dataset : 4 damaged

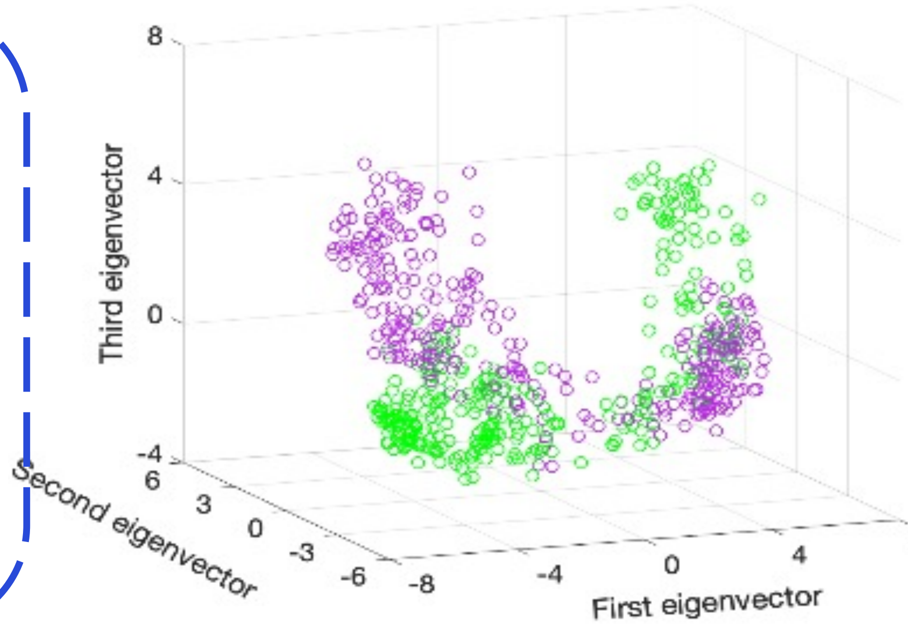
5 peaches : 3 in July 2019 and 5 in July 2020

- Measurements : W-band
- Training dataset : 1 damaged and 1 healthy peach (2019)
- Test dataset : peaches from 2020 + 1 damaged peach from 2019

III. Detection of fruit's damages : PCA

Support Vector Machine (*SVM)* => **suitable** for a small dataset.

- Linear SVM : for linearly separable data => one hyperparameter C
- Non linear SVM:
  - two hyperparameters C an γ
  - RBF kernel
- Two classes :
  - +1 healthy fruit
  - -1 damaged one



PCA training dataset prior to classification

Find optimal values of C and γ => Grid search ☹, later replaced by GWO ☺

III. Detection of fruit's damages : results

6 apples - May 2019 : 3 different sizes

- Measurements : W-band
- Training dataset : a pair of big and medium apples
- Test dataset : pair of small apples
- Accuracy : 100%

* Pair : contains a healthy fruit and a damaged one

5 apples - October 2020

- Measurements : D-band
- Training dataset : 1 healthy + 1 damaged
- Test dataset : 4 damaged
- Accuracy : 100%

5 peaches : 3 in July 2019 and 5 in July 2020

- Measurements : W-band
- Training dataset : 1 damaged and 1 healthy peach (2019)
- Test dataset : peaches from 2020 + 1 damaged peach from 2019
- Accuracy : 100%

III. Detection of fruit’s damages

- ☺ Successful method for sorting healthy from damaged fruits
- ☺ Robustness of the method : over time, fruits and frequency
- ☺ Classification time : 19ms for apples and 12ms for the peaches
- ☹ 22801 measurement points => 2hours (scan step 0.2°)
- ☹ Amplitude and phase measurements

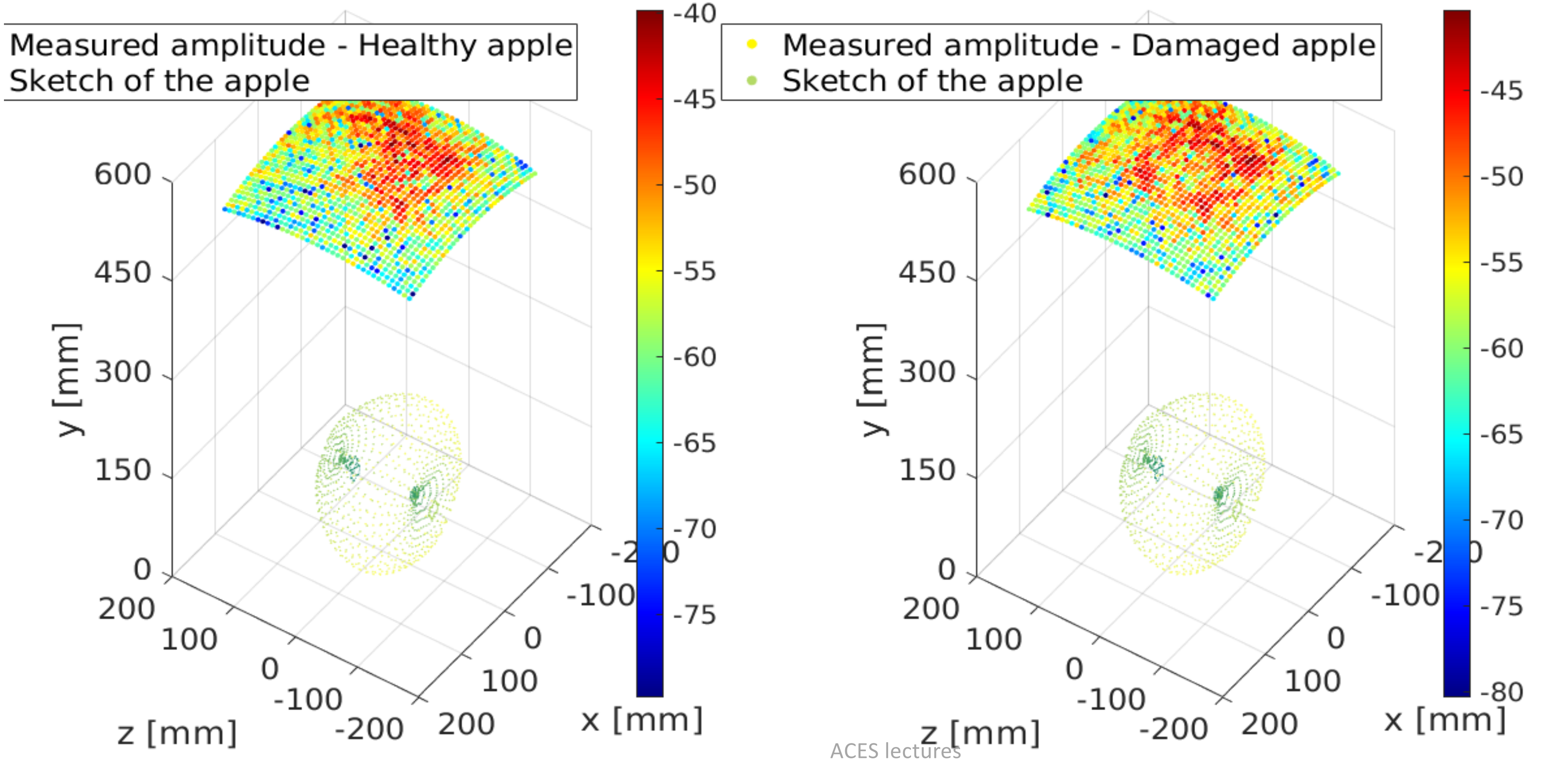
↓↓↓

Reduction of measurement time and complexity

III. Detection of fruit's damages : amplitude only

Amplitude-only measurement

=> ☺ 100% accuracy with 94% reduction of measurement points



III. Detection of fruit’s damages : is it always working?

Motivation

- Contaminants cause billions of dollars in product recall losses
- Current systems fail to detect defaults caused by bugs in hazelnuts

Challenge

- Hazelnuts are in-shell seeds with low water contents

Investigated solution

- Millimeter-wave scanning

What spoils the hazelnuts?

Hazelnuts makes the taste!

III. Detection of fruit's damages : is it always working?

Curculio nucum

Gonocerus acuteangulatus

Devil's bug

→ ☺ Eye detection

→ ☹ In-shell damage

https://www.terrevivante.org/contenu/noisettes-attaquees/

III. Detection of fruit's damages : is it always working?

Method => Same as for peaches and apples

Material => Almonds and hazelnuts : all healthy due to the season

Objective => Separate almonds from walnuts

	Dataset 1		**Dataset 2**		**Dataset 3**	
	Almond	Walnut	Almond	Walnut	Almond	Walnut
Almond 1	281	22	303	0	298	5
Almond 2	252	51	303	0	302	1
Almond 3	242	61	302	1	286	17
Almond 4	43	260	0	303	3	300
Almond 5	68	235	9	294	2	301
Walnut 1	146	157	150	153	278	25
Walnut 2	143	160	103	200	270	33
Walnut 3	121	182	84	219	63	240
Walnut 4	258	45	302	1	302	1

Results

☹ 66% accuracy

Conclusion

Shell has to be removed

IV. Archaeology : pottery shard's classification

Why investigating shard' identification?

6000 to 3000 years before common area (B.C.)

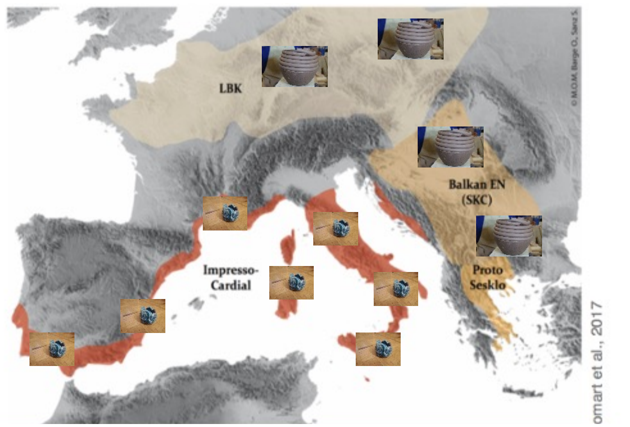
- No writing => historical investigations rely on fabrication techniques
- Issue : introduction of farming into Europe and mediterranean area

<= Material investigation
Mobility & exchanges

Technical gestures =>
Traditions & social groups

Potteries

- Main cultural marker in the Neolithic
- Coiling : Central and western Europe
- Spiral patch : Western mediterranean



IV. Archaeology : pottery shard’s classification

- 2 fabrication techniques as geographical markers
- Remains : shards

Coiling technique

Remains : shards

Differences

=> Air bubbles lines

Spiral patch technique

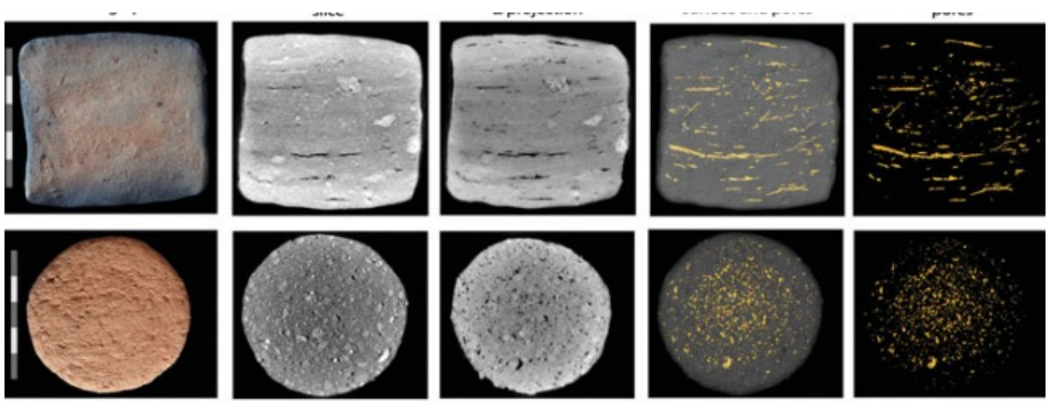
IV. Archaeology : pottery shard’s classification

Archaeologists make use of

- Experimental shards : made by archaeologists for getting familiar with fabrication techniques
- Archaeological shards : dated to between 8000 and 3000 B.C.

Coiling

Spriral



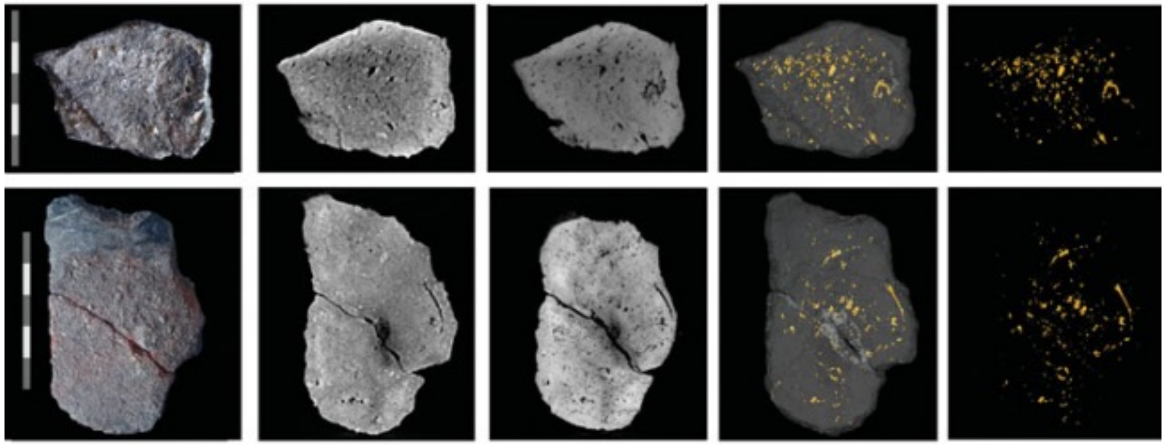
Sorting: air bubbles lines(air)

- linear : coiling
- non-linear : spiral

Expérimental shards [1]

Gomart, Louise, et al. "Spiralled patchwork in pottery manufacture and the introduction of farming to Southern Europe." *Antiquity* 91.360 (2017): 1501-1514.

IV. Archaeology : pottery shard's classification



Unknown archaeologocal shards [1]

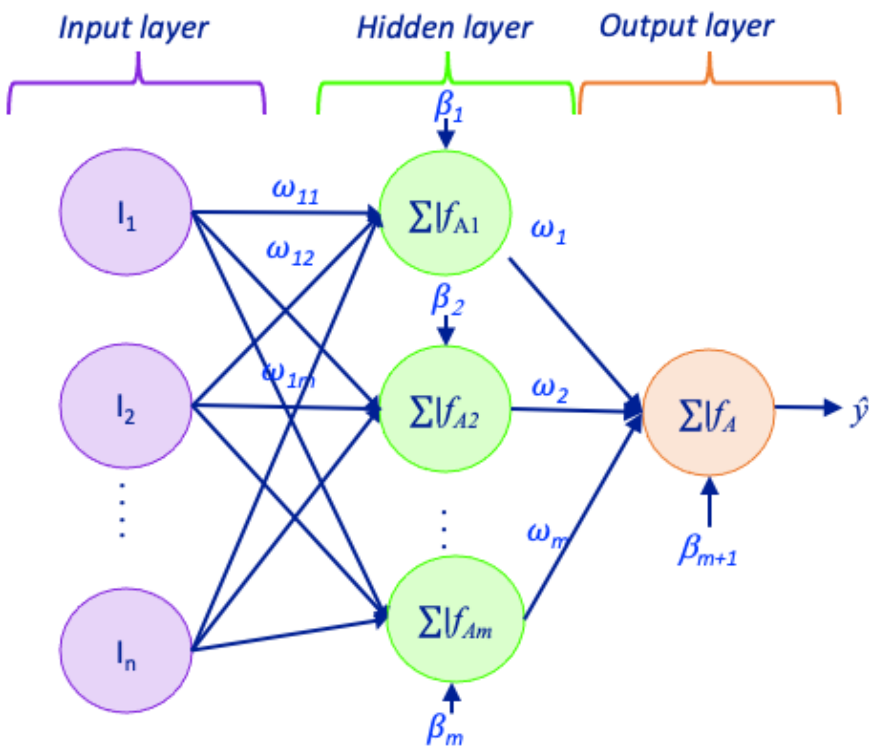
How to sort shards?

- Visual inspected + gesture-based learning=> weakly reliable ☹
- CT-scan, synchrotron => high cost + no straightforward results interpretation ☹

New imaging modality => sub-THz imaging (110-170 GHz)

IV. Pottery shard's classification : MLP

Multi Layer Perceptron (MLP)



MLP

- Artificial Neural Network (ANN)
- Choice : 1 hidden layer

Issues

- Find the optimal number of neurons (*m*) in the hidden

Solution

- Use an optimization algorithm
- GWO => avoids local minima

IV. Pottery shard’s classification : results

After optimization of measurement time with GWO

- Scenario 1 : measurements on the whole D-band
- Scenario 2 : measurements at a single frequency (140 GHz)

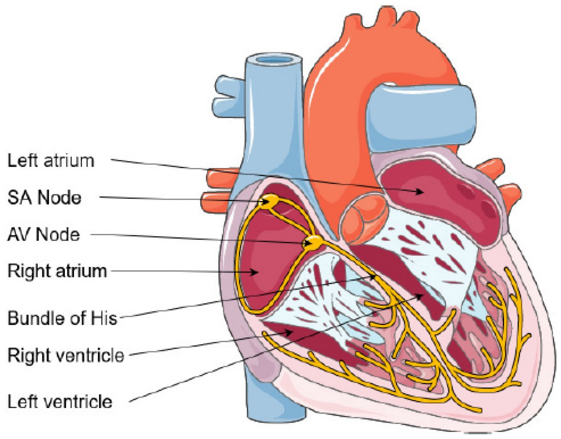
Scenario	*m*	Number of Meas. points	Meas. time reduction	Performance
1	16	37	99%	> 85%
2	27	217	95%	> 77%

F. Zidane et al.,"Artificial Intelligence-Based Low-Terahertz Imaging for Archaeological Shards’ Classification,"in IEEE Transactions on Antennas and Propagation, vol.70, no.8, pp.6300-6312, Aug.2022. doi:10.1109/TAP.2022.3189553

V. Biomedical applications : monitoring vital signs

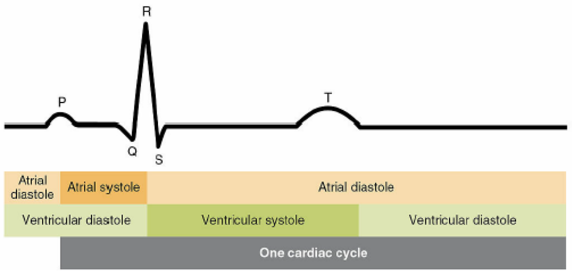
What about MMW systems for medical application?

- Detects small movements due the high resolution
- Benefits from the development of MMW MIMO Radars
- Monitoring vital signs

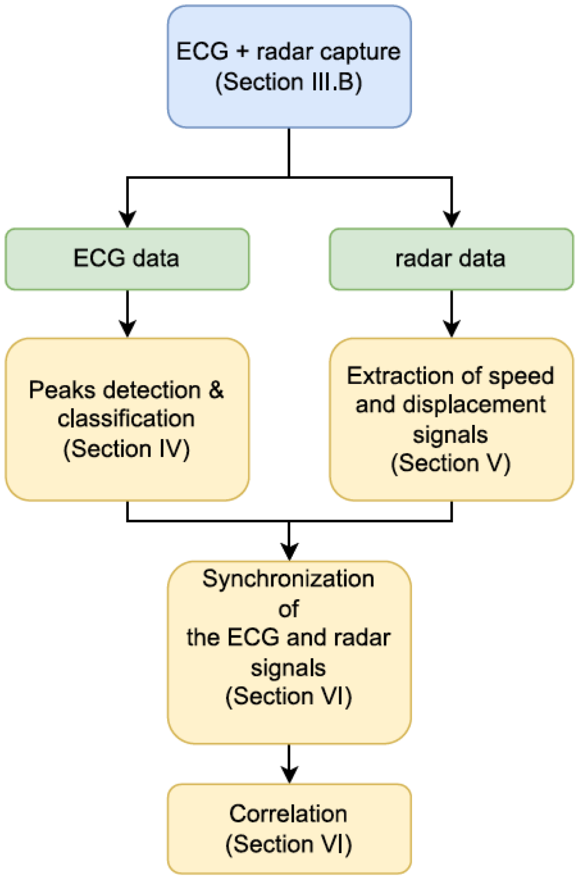


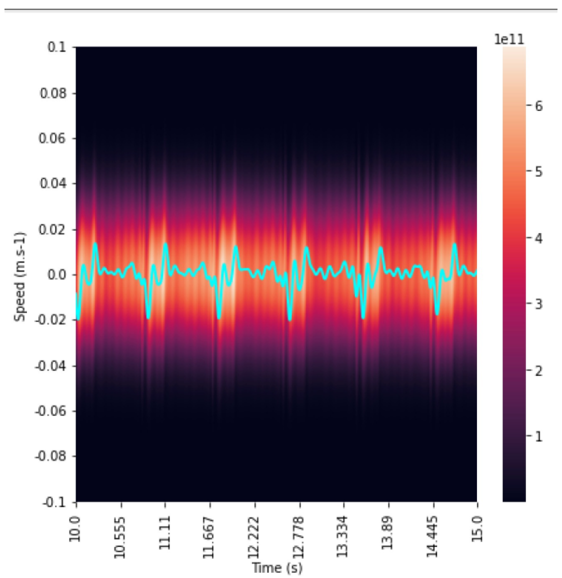
Heart monitoring

- Issue : is it possible to detect the heart's cycle with a MMW Radar?
- System : MIMO radar developed for automotive applications
- Outcome : we have proved that it correlates with ECG

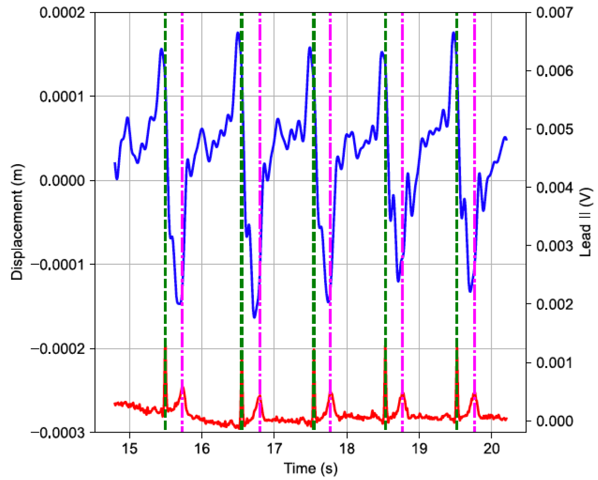


V. Biomedical applications : monitoring vital signs





Radargram



Correlation with ECG

-- R peaks -- Radar

-- T peaks -- ECG

Grisot, Rémi, Pierre Laurent, Claire Migliaccio, Jean-Yves Dauvignac, Mélanie Brulc, Camille Chiquet and Jean Paul Caruana. “Monitoring of Heart Movements Using an FMCW Radar and Correlation With an ECG.” IEEE Transactions on Radar Systems 1 (2023): 423-434. doi:10.1109/TRS.2023.3298348.

Conclusions

In this talk we have seen that MMW imaging is a powerful tool for :

- Detection => MMW for monitoring vital signs
- Identification => Biomedical applications
- Classification => Archaeological and Food safety applications

But domains of applications are much wider

- AI opens new perspectives for real time operation
- Take physical parameters into account
- Continue to improve measurements
- The rapid development of THz components and systems pushes new applications

THANK YOU ☺

AND NOW IT IS YOUR TURN !

RÉPUBLIQUE FRANÇAISE
Liberté
Égalité
Fraternité

UNIVERSITÉ CÔTE D'AZUR

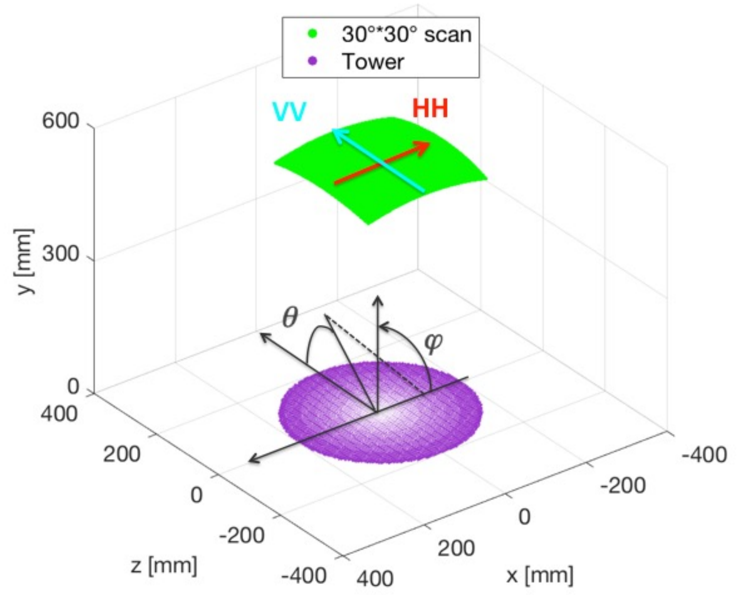
LEAT
LABORATOIRE D'ELECTRONIQUE, ANTENNES ET TÉLÉCOMMUNICATIONS

The lab course 1/3

The Back-propagation algorithm

- Back-propagation (BPA)
  - *P:* pixel (reconstruction plane)
  - *M* :measurements
  - *k*: wavenumber
  - Monostatic measurements: S_{11}

$$A(P) = \sum_{m \in M} \frac{1}{MP^2} S_{11,M}(\theta, \phi) e^{2jkMP}$$



- Possible alternative: 2D-FFT
  - Directly perform a 2D-FFT on complex S_{11}
  - Valid for a scan facing the object

Example

The lab course 2/3

Be sure that you have received the file : .mat

Identify the measurement scenario

- Open it and identify the variables =>
- Plot the portion of the measurement sphere in 3D
- Plot the amplitude
- Plot the phase

Process the field with 2DFFT

- Use function *fft2* and look et the documentation
- Plot the magnitude of the result in dB *

* recommendation: normalize the image to its maximum and use a scale between 0 and -30 dB

The lab course 3/3

Process the field with the back-propagation algorithm

- Define the observation plane
- Define the distance MP
- Apply the back-propagation
- Plot the magnitude of the result according to the same scale as for the 2D-FFT

If you have time

- Plot the real and imaginary parts and try to interpret the result

FFT vs Fourier Transform

Let's take the cos(ω_0t) as example, with $\omega_0 = 2\pi f_0$ and T=1/f_0

Fourier transform (*FT*) :

$$FT(f) = \int_{-\infty}^{+\infty} \cos(\frac{2\pi t}{T})\, e^{-j\omega t} dt$$

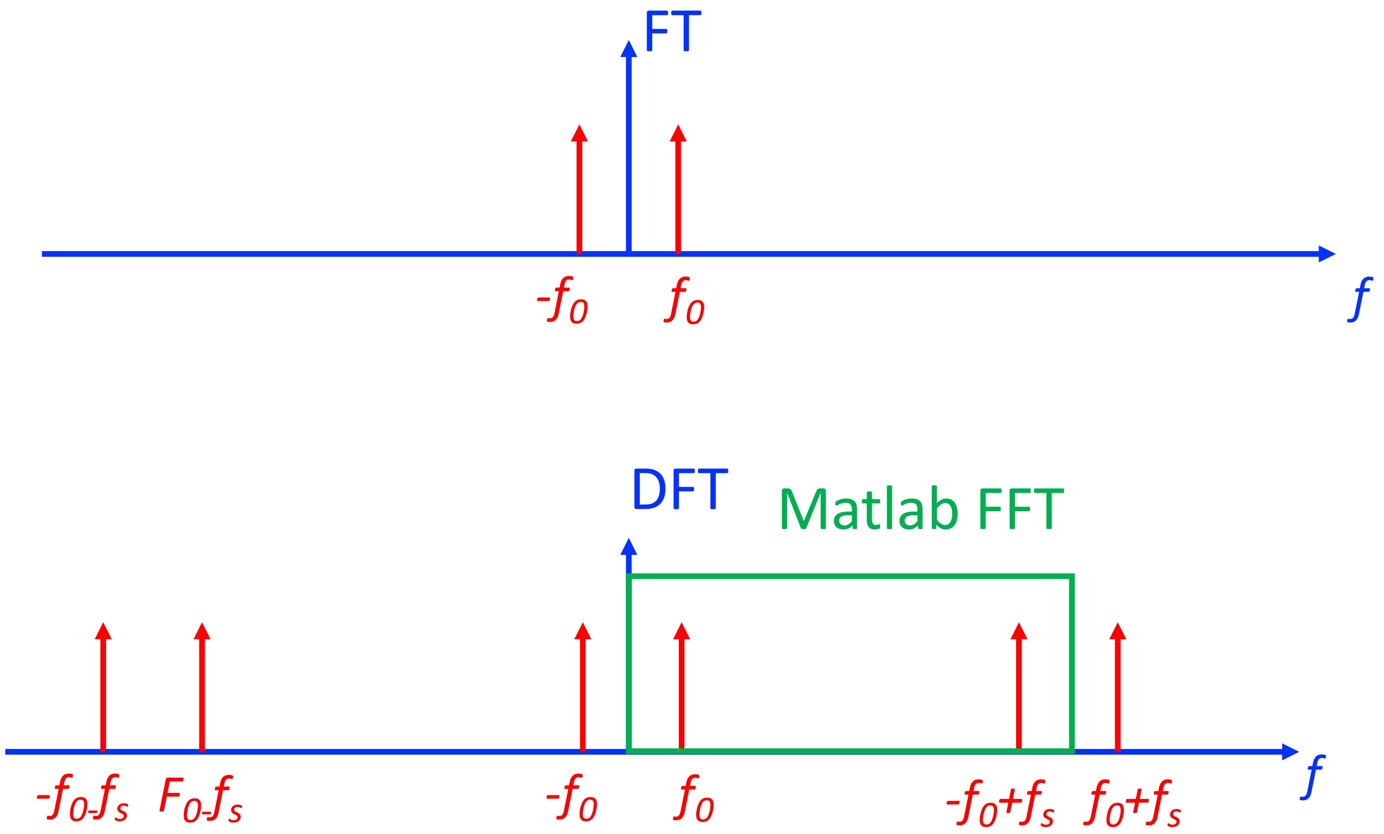
FFT : let's assume *n* samples per period T, the sampling frequency is *n*/T

⇒ the discrete times are : $t_i = \frac{in}{T}$

⇒ the integral becomes a sum => DFT (Discrete Fourier Transform)

⇒ $DFT(f_k) \approx \sum_{i=0}^{N-1} \cos(\frac{2\pi f_0 ni}{T})\, e^{-j\frac{2\pi f_k ni}{T}}$ => it become periodic!

FFT vs Fourier Transform



2DFFT