iTEE Ph.D
iNFORMATION tECHNOLOGY
eLECTRICAL eNGINEERING

Giovanni Cavallo

Tutor: Prof. Annalisa Liccardo

XXX Cycle - III year presentation

Non Destructive Testing methods based on Terahertz radiation and Compressive Sampling

Università degli Studi di Napoli
Federico II

My background

- I received the MSc Degree in Electronic Engineering (cum laude) from University of Naples, Federico II
- I work within “Measurements Group” of DII-DIETI, in particular:

  Prof. Leopoldo Angrisani
  Prof. Annalisa Liccardo
  Rosario Schiano Lo Moriello
  Francesco Bonavolontà

- My fellowship is financed by European Social Fund (ESF)

Credits Summary

- Credits Table

Student: Giovanni Cavallo Tutor: Prof. Annalisa Liccardo Cycle XXX
giovanni.cavallo@unina.it annalisa.liccardo@unina.it

	Credits year 1								Credits year 2								Credits year 3									
	Estimated	bimonth 1	bimonth 2	bimonth 3	bimonth 4	bimonth 5	bimonth 6	Summary	Estimated	bimonth 1	bimonth 2	bimonth 3	bimonth 4	bimonth 5	bimonth 6	Summary	Estimated	bimonth 1	bimonth 2	bimonth 3	bimonth 4	bimonth 5	bimonth 6	Summary	Total	Check
Modules	20	0	3	7	0	9	0	19	15	4	0	0	0	9	0	13	0	0	0	0	0	0	0	0	32	30-70
Seminars	7	0	3,6	2,1	2,2	0	3	10,9	5	0	0,7	1,2	0,7	0	3,8	6,4	3	0	0	0	0	0	3	3	20	10-30
Research	33	10	3,4	0,9	7,8	1	7	30,1	40	6	9,3	8,8	9,3	1	6,2	41	57	10	10	10	10	10	7	57	128	80-140
	60	10	10	10	10	10	10	60	60	10	10	10	10	10	10	60	60	10	10	10	10	10	10	60	180	180

All the established objects have been reached. No period abroad has been spent.

Table of Courses/Seminars

Year	Lecture/Activity	Type	Credits
1	The Entrepreneurial Analysis of Engineering Research Projects	Ad hoc Course	3
1	Project Management per la Ricerca	Ad hoc Course	3
1	Models, methods and software for Optimization	Ad hoc Course	4
1	Misure su sistemi wireless	Msc Course	9
1	Analisi e generazione di segnali ultra-veloci	Seminars	1.2
1	Efficeint service distribution in next generation cloud networks	Seminars	0.8
1	Three core issues for the Internet: things, security and economics	Seminars	1.6
1	The iCub project: an open platform for research in robotics & artificial intelligence	Seminars	0.3
1	Partial possibilistic regression path modeling	Seminars	0.2
1	Microlease e Keysight: Testing Efficace	Seminars	1.6
1	Rohde & Schwarz: Research and Education Seminar Tour	Seminars	0.8
1	Lagrangean relaxation and Set Covering	Seminars	1
1	V model design: descrizione ed implementazione di un modello di sviluppo nelle realtà aziendali	Seminars	0.4
1	Italo Gorini 2015	Seminars	3
2	Field Computation and Magnetic Measurements for Accelerator Magnets	ccasionally Cour	4
2	Sensori e Trasduttori di Misura	Msc Course	9
2	Perception-based surround sound recording and reproduction	Seminars	0.3
2	Programmable network conjugations	Seminars	0.4
2	Microcontrollori di misura: La piattaforma ST Microelectronics Nucleo™	Seminars	0.4
2	ST Microelectronics Wireless applications of Soft Measurement Transducers for IoT	Seminars	0.4
2	Challenging real-time measurement systems for immersive life-size augmented environment	Seminars Seminars	0.4
2	Medical Robots Research at IPR – KIT Karlsruhe	Seminars	0.4
2	The development of a Fast Pick-and-Place robot with an Innovative Cylindrical Drive	Seminars	0.3
2	Italo Gorini 2016	Seminars	3
2	Half day EMC Design and troubleshooting Course	Seminars	0.8
3	Italo Gorini 2017	Seminars	3

Outline

- ➢ NDT methods based on THz radiation and CS
- ❑ Why?
- ❑ Proposal: CS-THz and CS-ECT
- ➢ Technical details
- ❑ THz Technology
- ❑ Compressive Sampling
- ❑ Central Composed Design (CCD)
- ❑ Results
- ❑ Eddy Current Testing

Problem statement

Cracks and defects can devastate the performance of components and structures. For this, cracks detection is an essential element of quality control in all engineering fields.

Who does it?

Non Destructive and Non-Invasive Tests

- Characterization Solid
- Morphology Study
- Physical and Chemical Analysis
- Realization method

Techniques: Ultrasonic, X-Rays, Penetrant Liquids, Visual Inspection, Magnetic Field and others

Problem statement

😟 The existence of a wide variety of NDT methods suggests that none of them is really complete, but rather one method can be more appropriate than another one respect to the operating conditions.

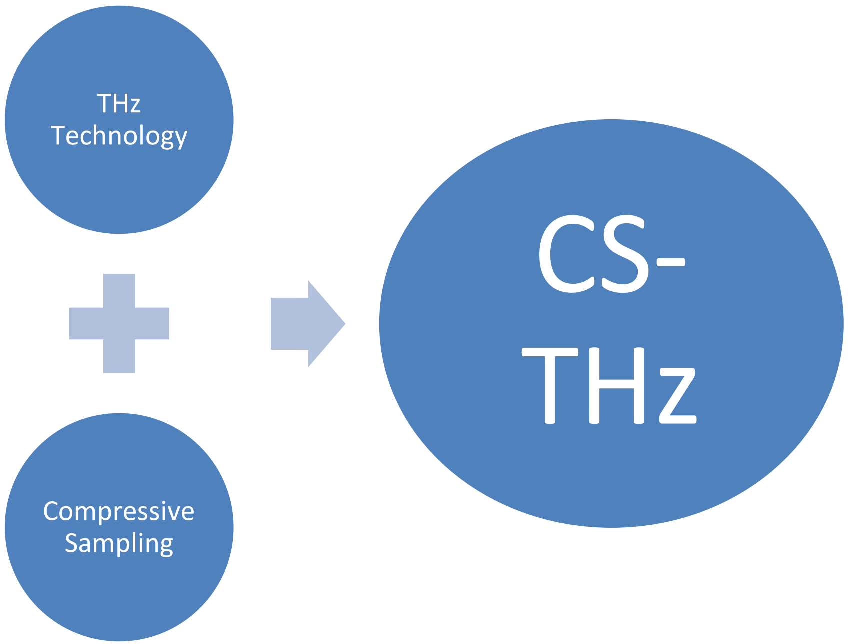
😟 Often, also, more methods are combined in order to ensure the identification as many possible of defects.

😟 Often the areas to be investigated are large, so the take-up times are very long.

😟 The amount of data to be saved is huge.

Proposal

A new technique of detection based on THz technology and Compressive Sampling is proposed, and it goes under name Compressed-THz:



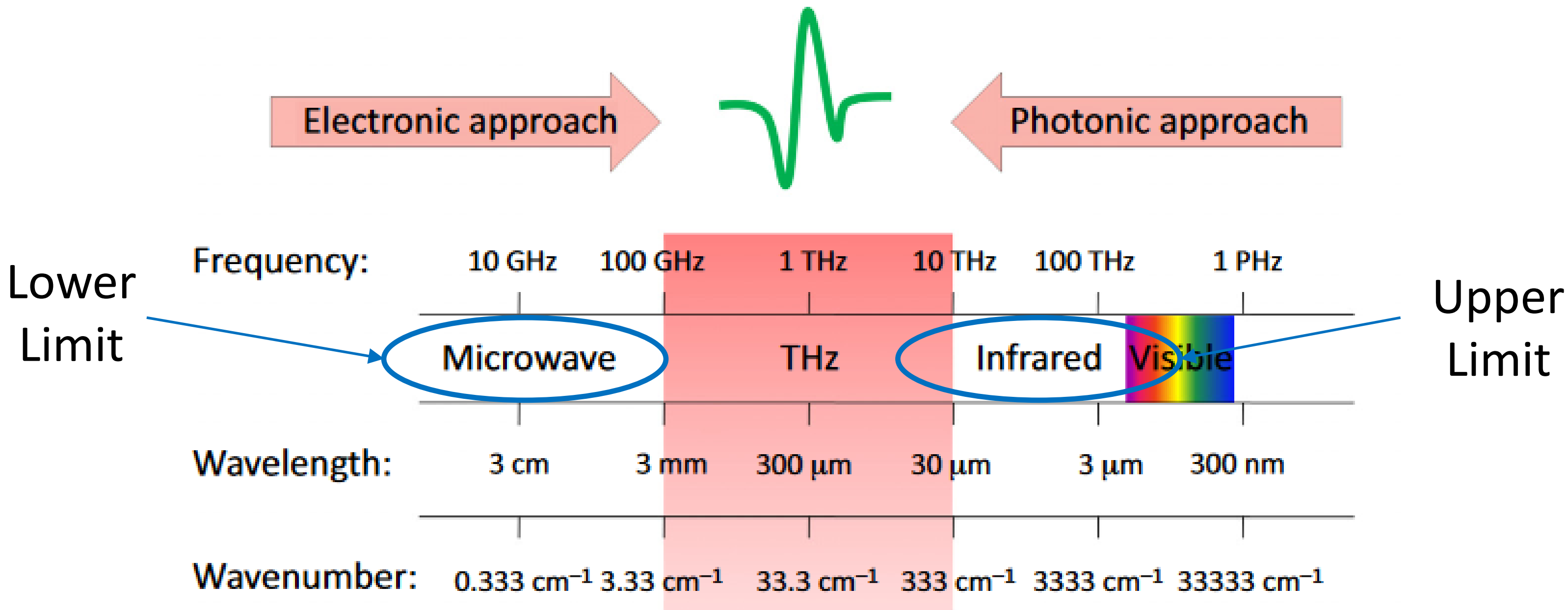
☺ Detection is realized with a new type of waves, so called T-waves.

☺ Reduction of acquisition time because all the area is acquired, and reconstruction time.

☺ Reduction of data to be saved,
so instrument are more light and have the possibility to store more data.

☺ Simple Computing Unit

THz (T-waves) Technology



- ✓ Not perceptible by the human eye
- ✓ Not ionizing
- ✗ Water and metals
- ✓ Ability to cross many nonconducting common materials such as paper, fabrics, wood, plastic, and organic tissues.

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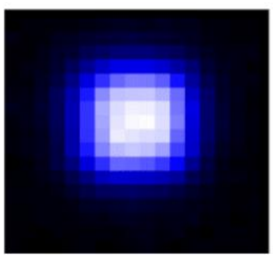
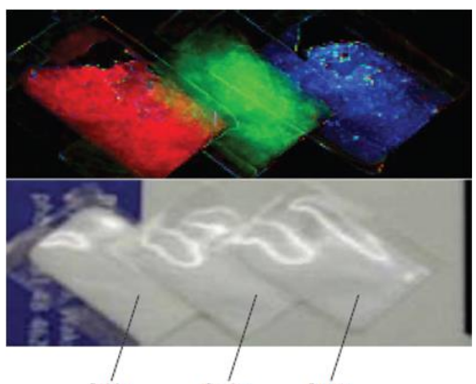
THz Applications

Thanks to the excellent properties, **Spectroscopy** and **Imaging** are the main applications of THz technology.

They give access to the rotational and vibrational modes of many molecules and macromolecules, providing the "*fingerprint*" of unknown samples → Electrodynamic Analysis

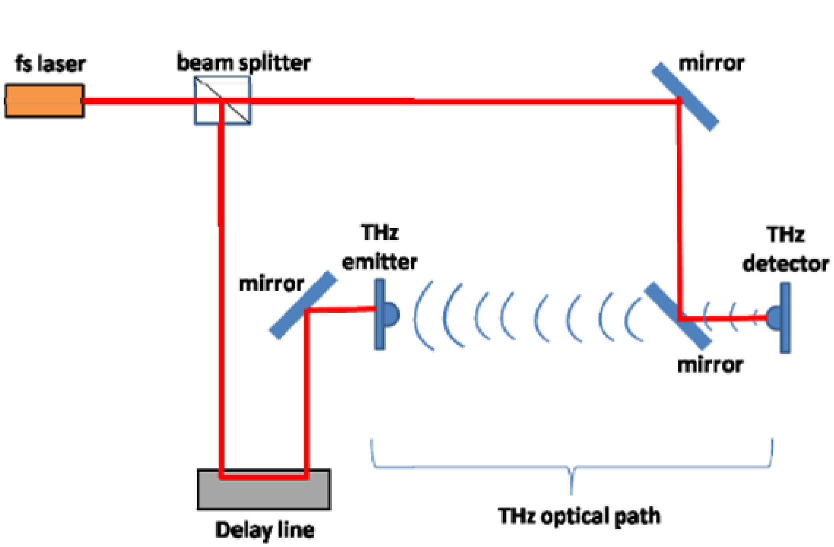
Allows contactless analysis of the materials under investigation, by spatial imaging operations with resolution higher than micro- and millimeter waves. → Imaging (Raster Scan)





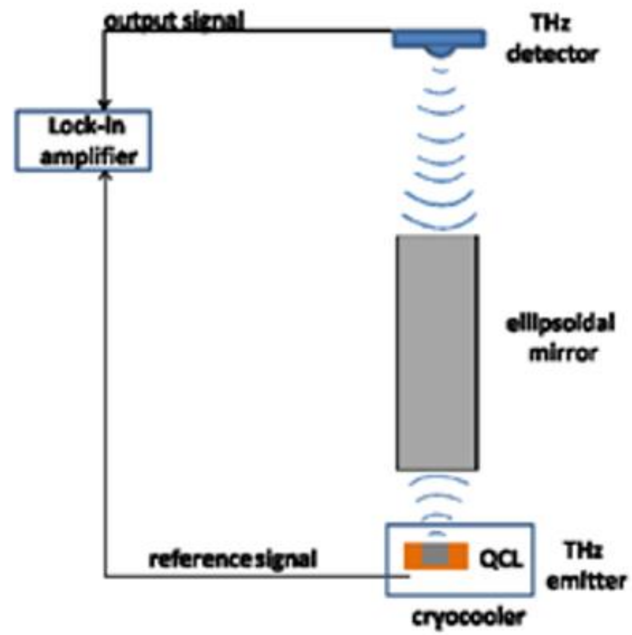
THz Systems

Time Domain (TD)



- ✓ Broadband in nature with emission not continuous.
- ✓ Realizes measurements in both transmission and reflection mode for spectroscopic applications.
- ✓ Optical-to-THz signal conversion technology, based on the generation and detection of an EM transient having duration of few picoseconds.
- ✓ Works to different frequencies thanks to the application of FFT.
- ✓ Low power
- ✓ Amplitude and phase info
- ✓ Active only

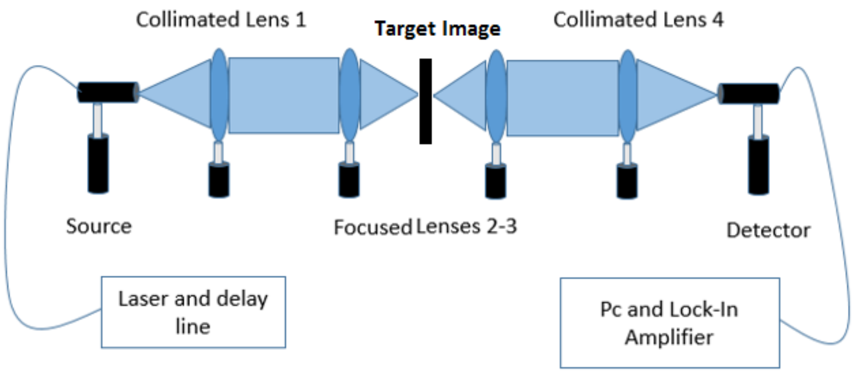
Continuous Wave (CW)



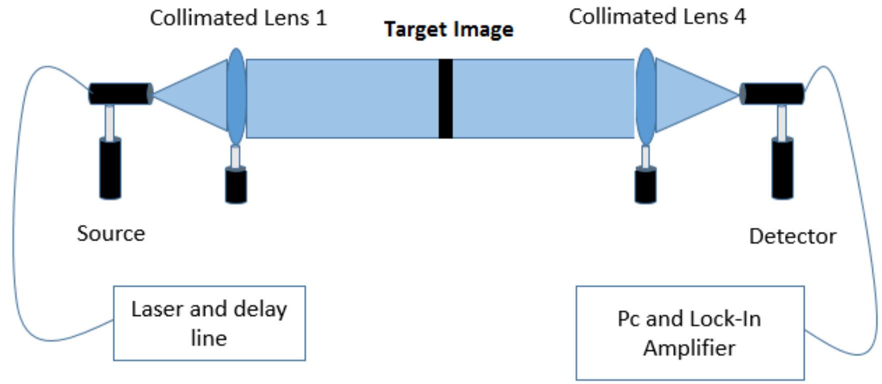
- ✓ Very low tunable
- ✓ Narrowband
- ✓ No immediate spectral data
- ✓ High power available Low power
- ✓ Very sensitive
- ✓ Faster data acquisition
- ✓ Active and passive

THz Configurations

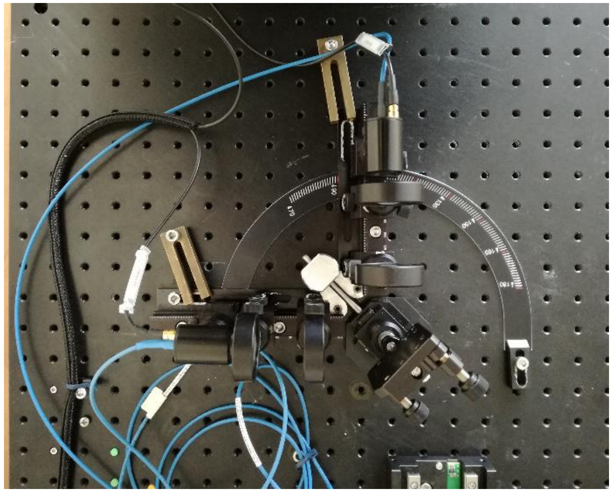
Focused



Collimated



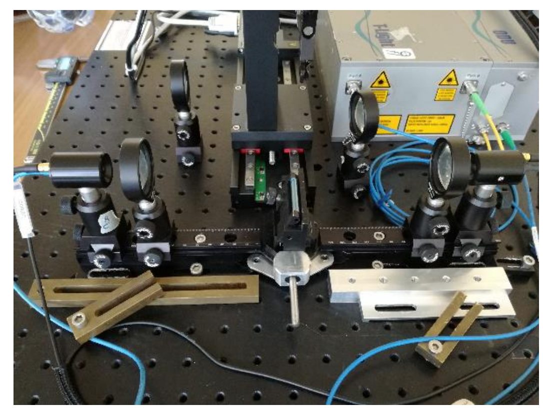
Reflection



Real THz System

Menlo Systems

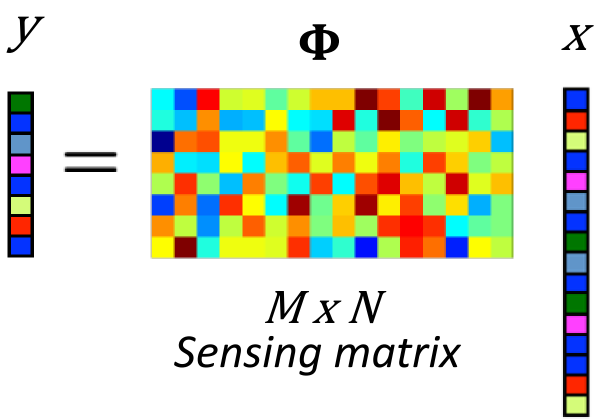
Fiber Laser 1560 nm
Pulse duration < 90 fs
Repetition rate 100 MHz
Low-temperature grown InGaAs/InAlAs–based PCA emitter/detector with hyper-hemispherical high resistivity Si lenses TPX plano-convex lenses (focal length 54 mm)
Spot diameter about 2 mm



Compressive Sampling

Compressive Sampling (CS) is an innovative paradigm of sampling that permits to:

- Acquire a signal of interest ***x*** (of N samples) directly in a compressive form (i.e. M samples << N);
- At a later time, reconstruct it with appropriate algorithms (ex. resolution of a problem of optimal convex).



Underdetermined System

You can not rebuild directly signal ***x***

<u>System admits infinite solutions!!!</u>

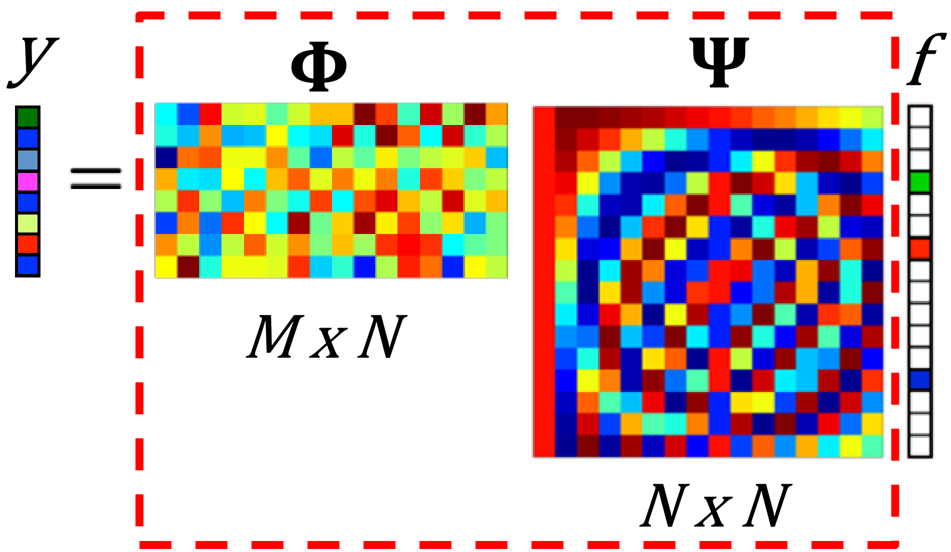
L1-Magic

CVX TVAL3

Compressive Sampling

If ***x*** is sparse, compressible in an opportune basis or spase, a new problem is possible with a new matrix, sensing matrix ***A***:

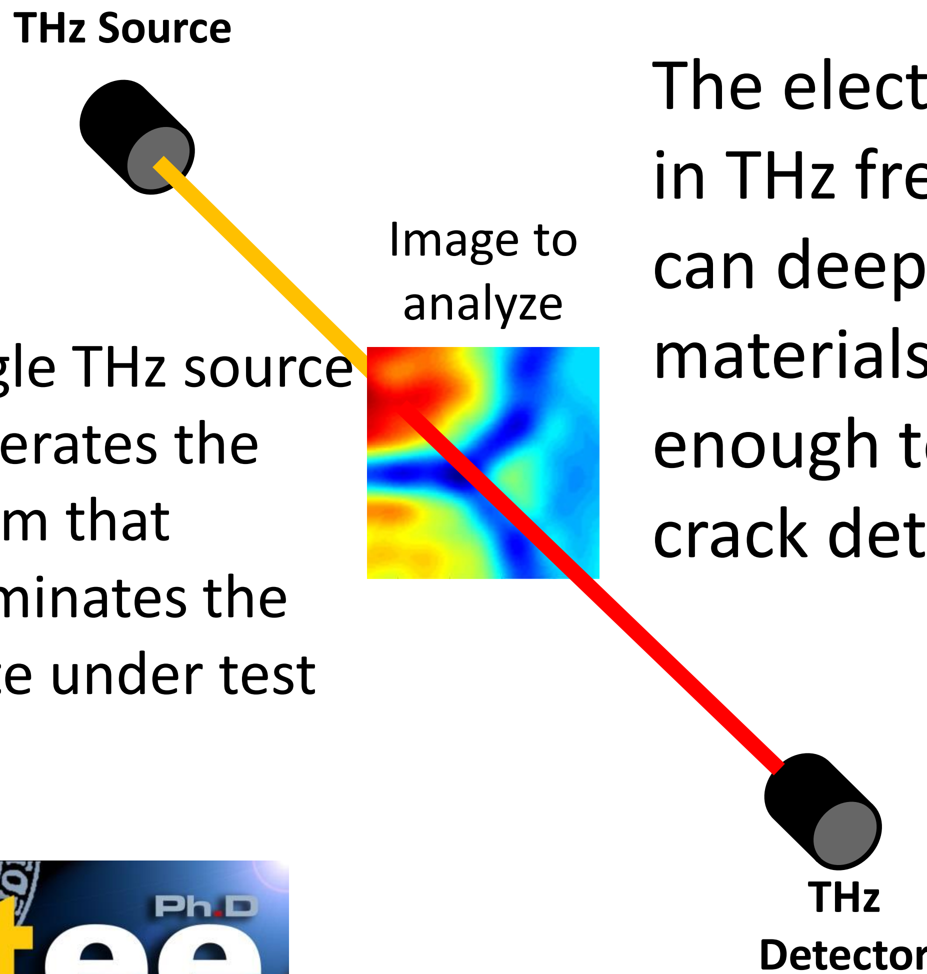
Sensing Matrix $\boldsymbol{A}\,[MxN]$



Although system is still underdetermined,
it is possible to find a sparse solution to the problem by minimizing the L1-norm of ***f***

$$f = \min_{f \in R^N} \| f \|_{\ell_1}$$

Traditional Raster Scan THz Imaging System



Single THz source generates the beam that illuminates the plate under test

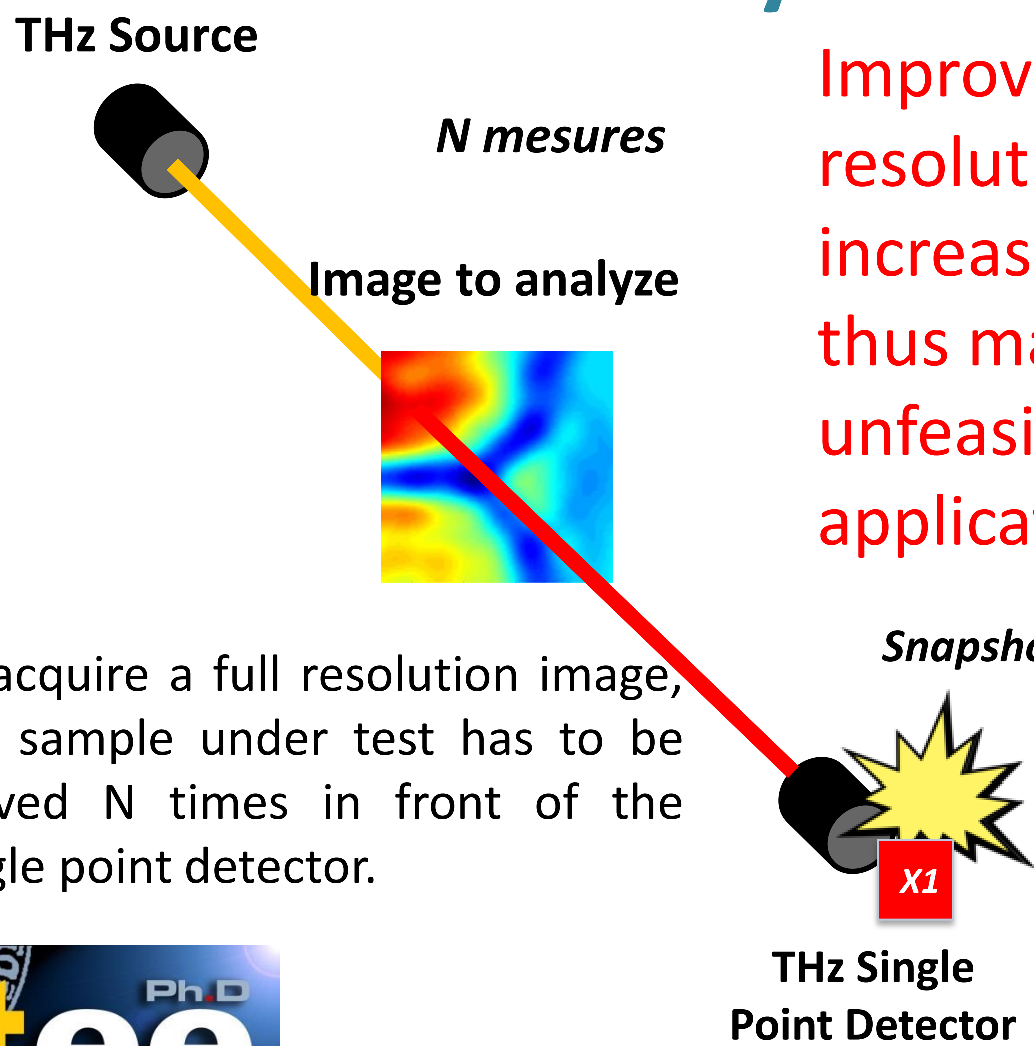
The electromagnetic radiation in THz frequency range (0.1–10 THz) can deeply penetrate inside these materials. Its wavelength is small enough to make it suitable for early crack detection.

Single point detector receives and measures radiations passed through the plate

Traditional Raster Scan THz Imaging System

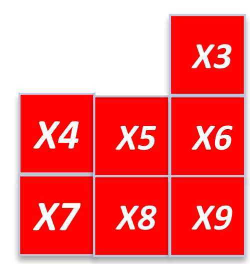
Improving measurement resolution (< 1mm) dramatically increases the acquisition time, thus making traditional systems unfeasible for the required application.

To acquire a full resolution image, the sample under test has to be moved N times in front of the single point detector.



Data acquisition system

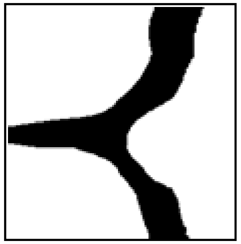
Full Resolution Image with PxQ = N pixels



CS-based THz systems

In order to perform a random sampling of 3 measurements, we need a set of 3 random masks, one for each measurement.

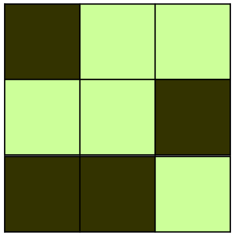
Image to analyze



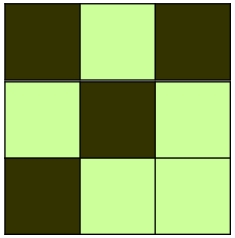
Digitized Image

0	1	0
1	1	0
0	1	0

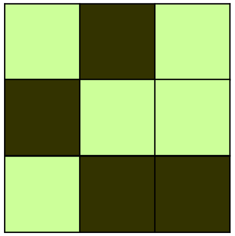
Mask 1



Mask 2

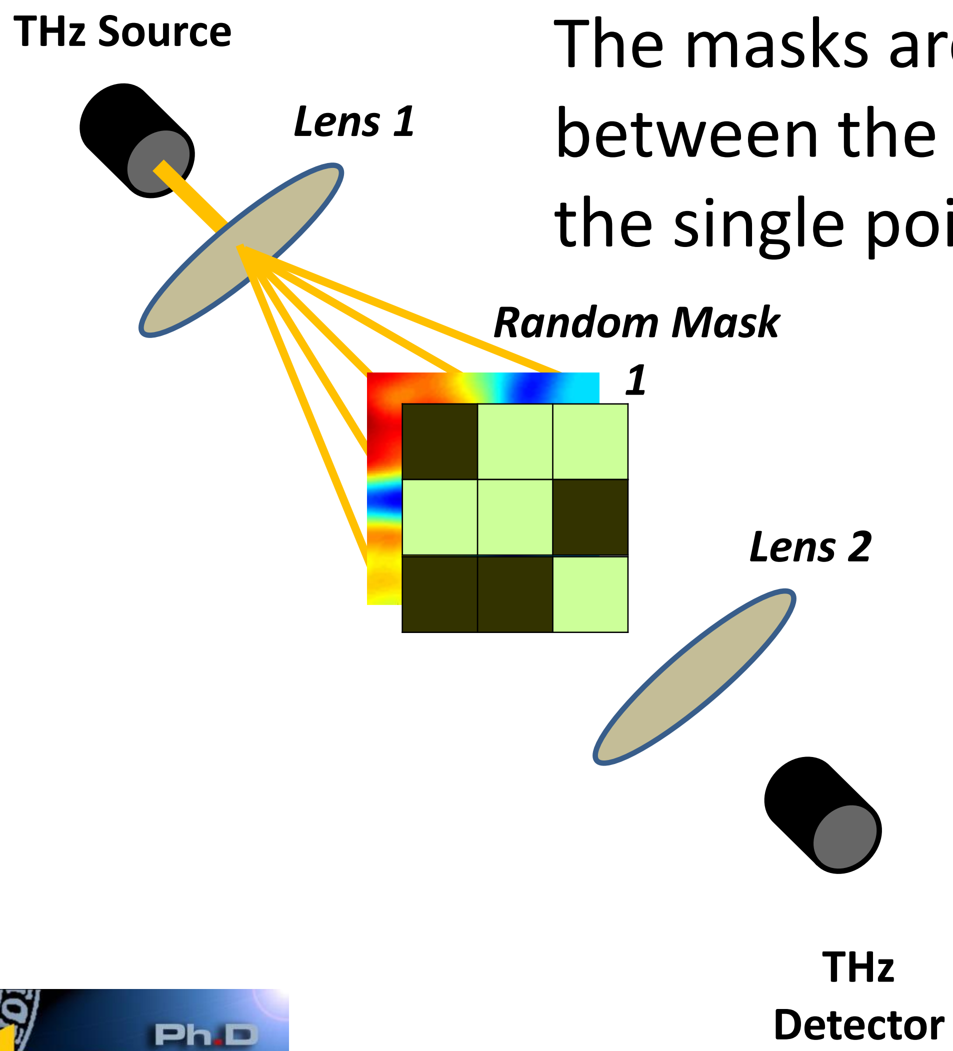


Mask 3



Each mask is a 2D-dimentional matrix, of *N* pixels having random features to transmit or block THz radiation, with equal probability.

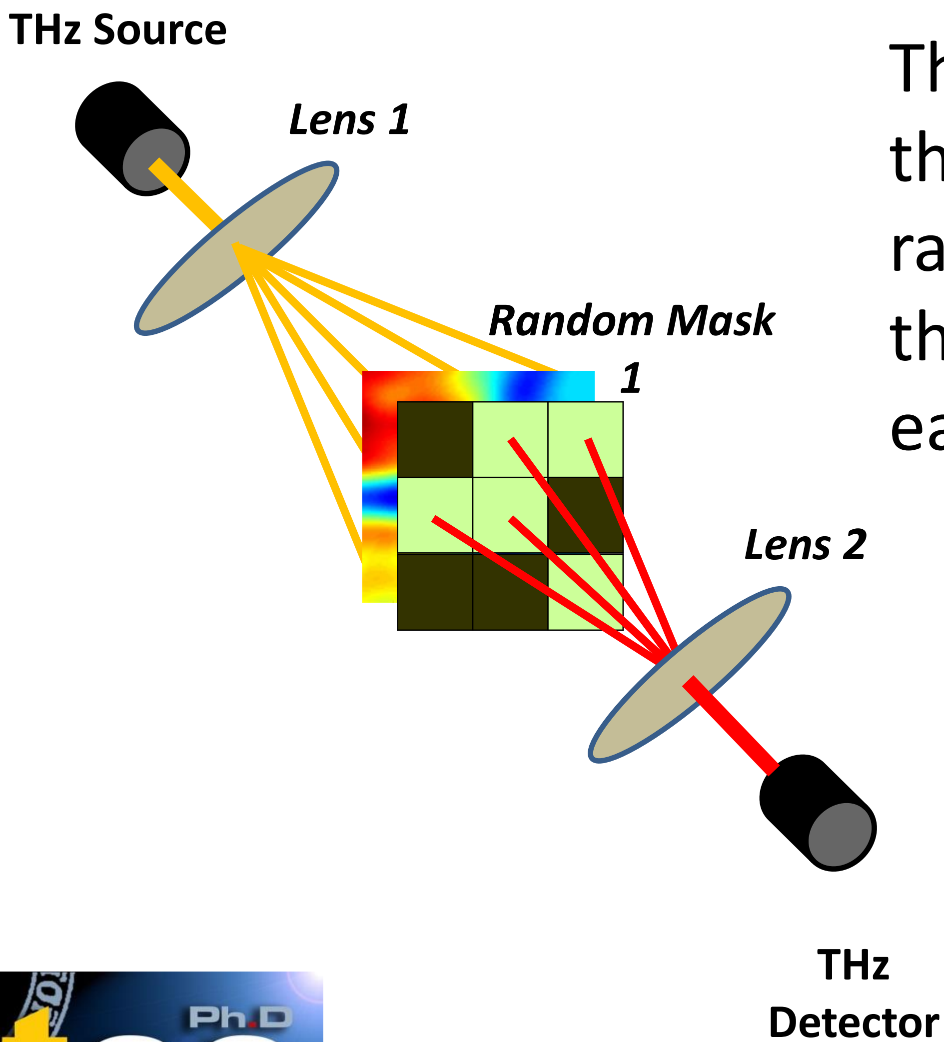
CS-based THz systems



The masks are insert, one at a time, between the image to analyze and the single point detector.

Differently from the raster-scan mode, in CS-based THz system, the THz beam is collimated on the whole area to be analyzed.

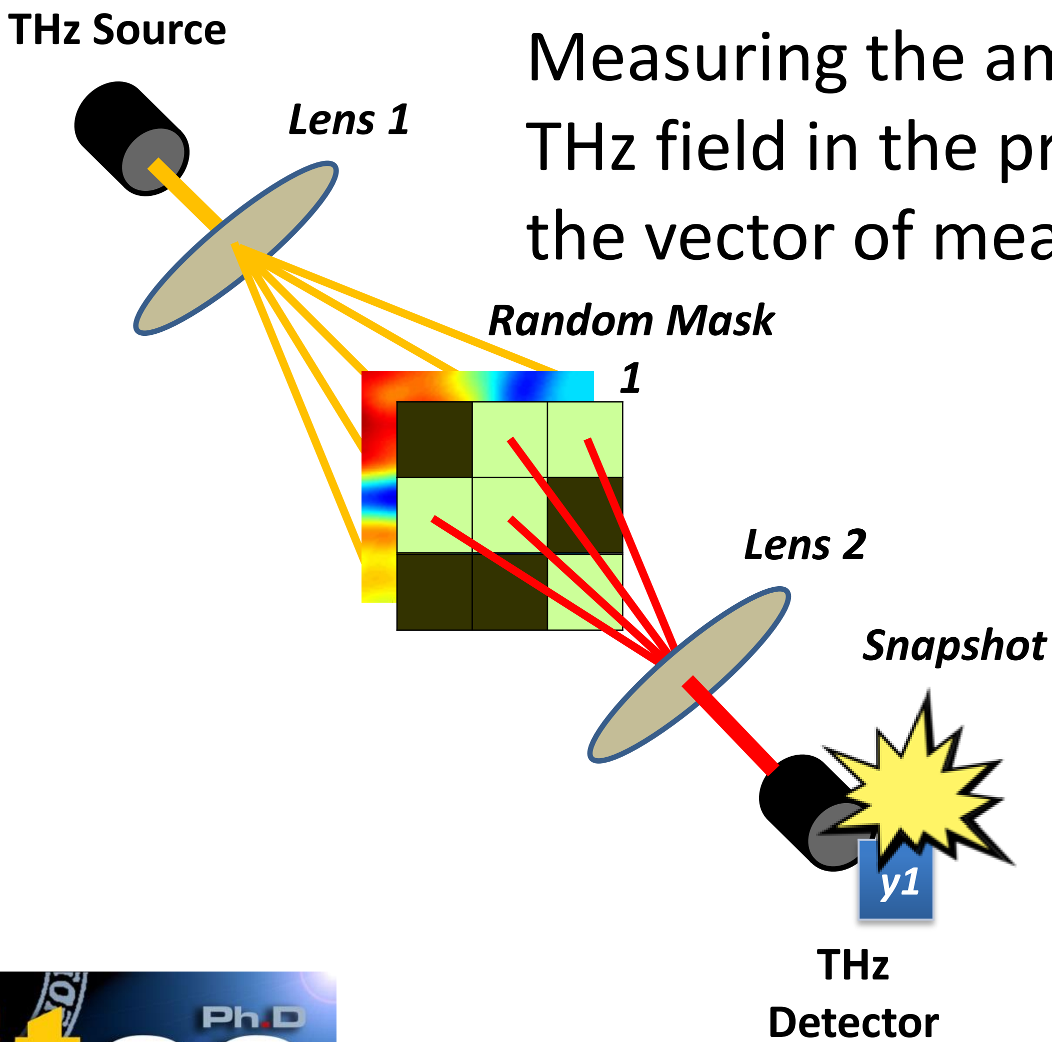
CS-based THz systems



The detected THz radiation is the superposition of radiation that passes through the “transmitting” pixels of each random mask.

CS-based THz systems

Measuring the amplitude of the received THz field in the presence of each mask, the vector of measurements is obtained.

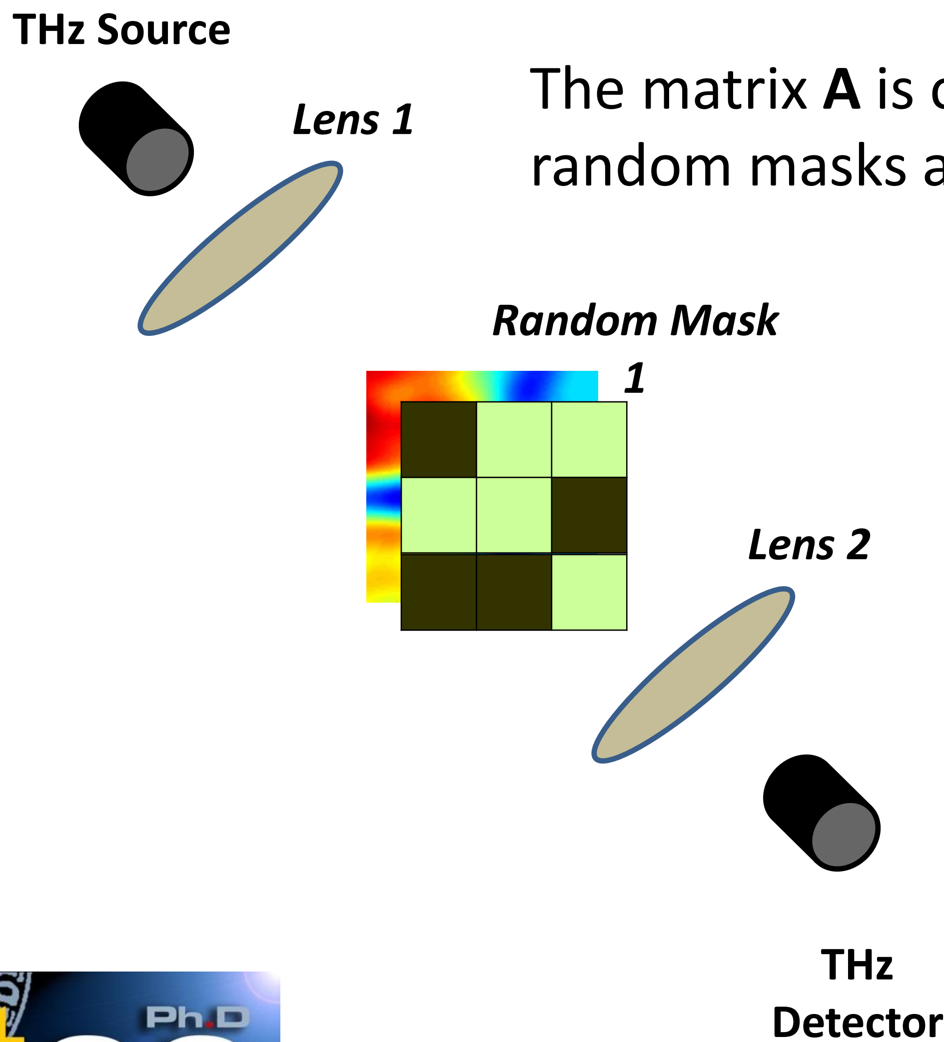


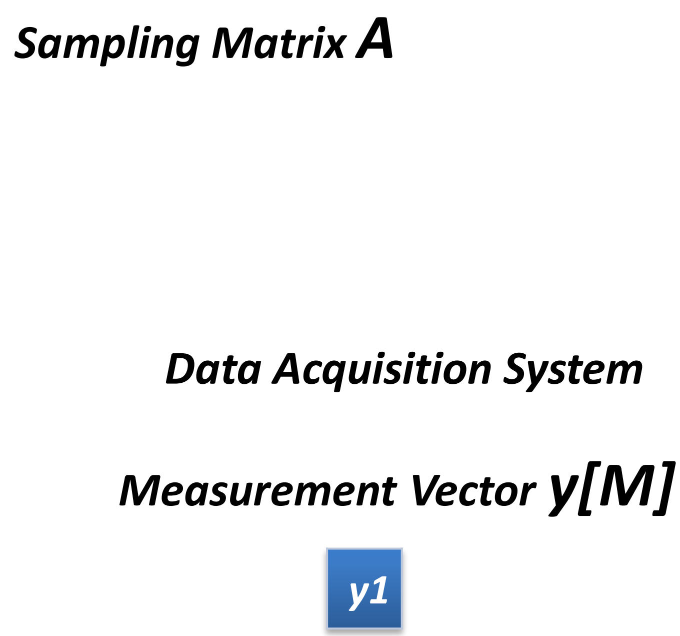
Data Acquisition System

Measurement Vector ***y[M]***

CS-based THz systems

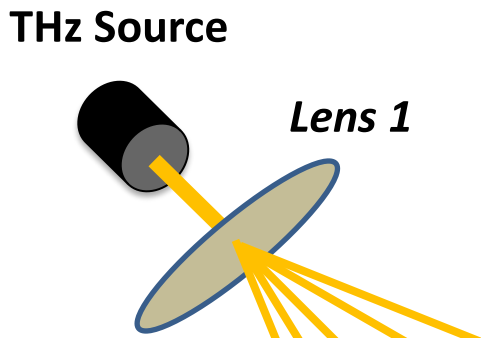
The matrix **A** is obtained by reshaping each of M random masks as row of sampling matrix.

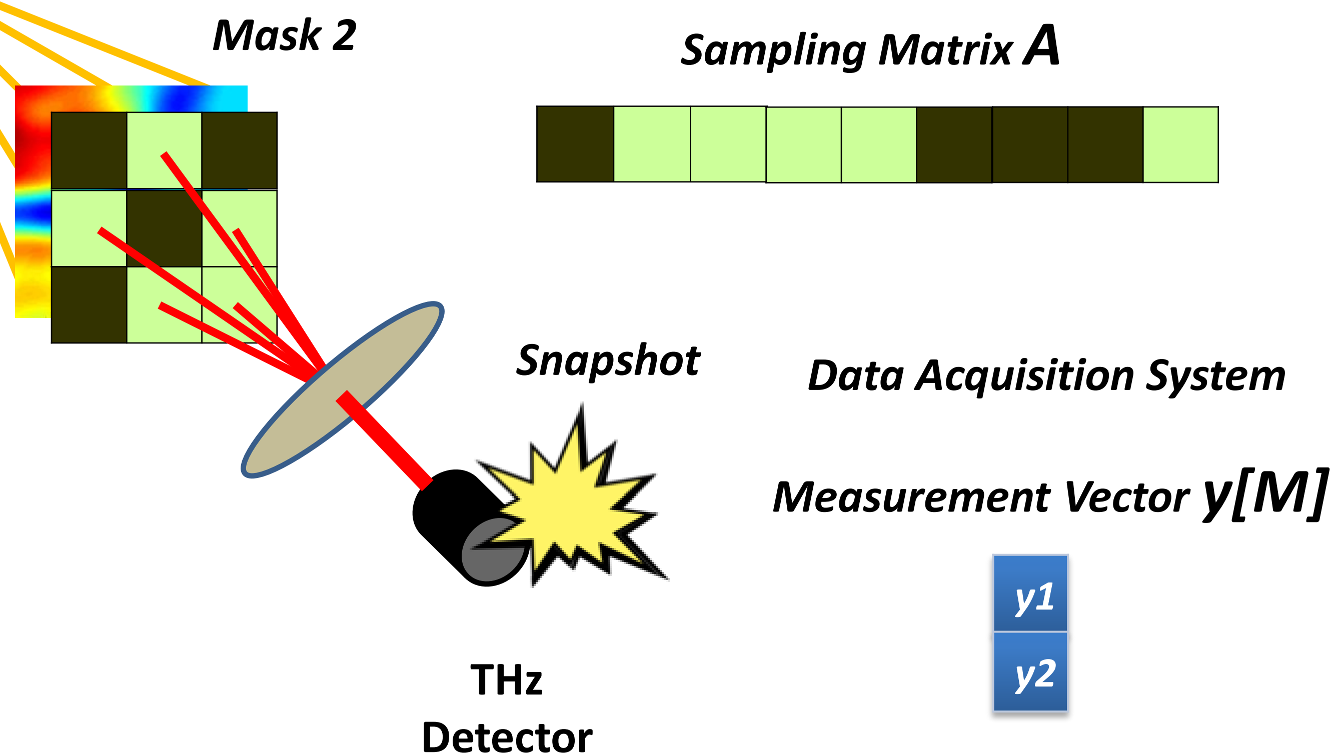




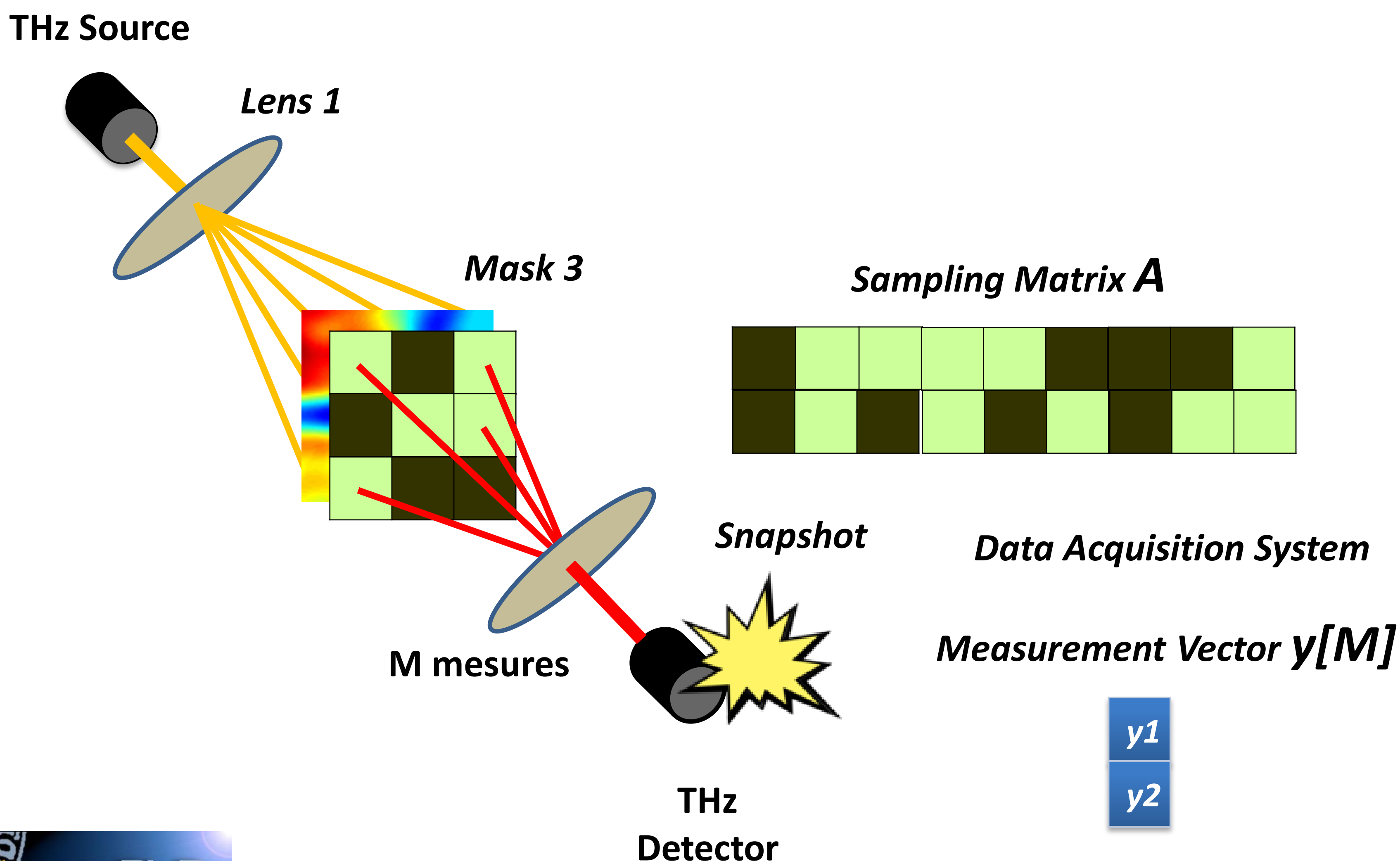
CS-based THz systems

The CS approach requires only to change M times the masks in front of the THz detector and collect the measured values, thus achieving a significant decrease of total acquisition time





CS-based THz systems



CS-based THz systems

Measurement Vector [M] ***Sampling Matrix A*** ***Unknown Vector x[N]***

$$\begin{bmatrix} y1 \\ y2 \\ y3 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 1 \\ 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 1 \\ 1 & 0 & 1 & 0 & 1 & 1 & 1 & 0 & 0 \end{bmatrix} \text{X} \begin{bmatrix} x1 \\ x2 \\ x3 \\ x4 \\ x5 \\ x6 \\ x7 \\ x8 \\ x9 \end{bmatrix}$$

According to the feature of each pixels of the mask, the entries of each row of the sampling matrix A are set equal to 1 (“transmitting” pixel) or 0 (“blocking pixel”).

CS-based THz systems

Measurement Vector y[M] ***Sampling Matrix A*** ***Unknown Vector X***

y1
y2
y3

=

0	1	1	1	1	0	0	0	1
0	1	0	1	0	1	0	1	1
1	0	1	0	1	1	1	0	

X

x1
x2
x3
x4
x5
x6
x7
x8
x9

In order to achieve a sparse solution of the problem, and reconstruct the unknown image x, several CS Solvers can be used.

CS-based THz systems

Sparse solution

$$\hat{x} = argmin\|x\|_1 \ s.t. \ y = Ax$$

$$\|x\|_1 = \sum_{i=1}^{N} |x_i|$$

Reconstructed Vector X →

x1
x2
x3
x4
x5
x6
x7
x8
x9

CS Solvers:

- CVX
- Greedy
- TVM

CS-based THz systems

The reconstructed vector $\hat{\mathbf{x}}$, sparse solution of the problem $\boldsymbol{y} = \boldsymbol{A}\boldsymbol{x}$, has to be reordered to finally reconstruct the original image.

Reconstructed Vector X

Sparse Solution

0
1
0
1
1
0
0
1
0

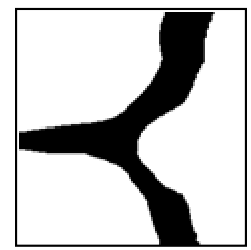
→

Digitized Image

0	**1**	**0**
1	**1**	**0**
0	**1**	**0**

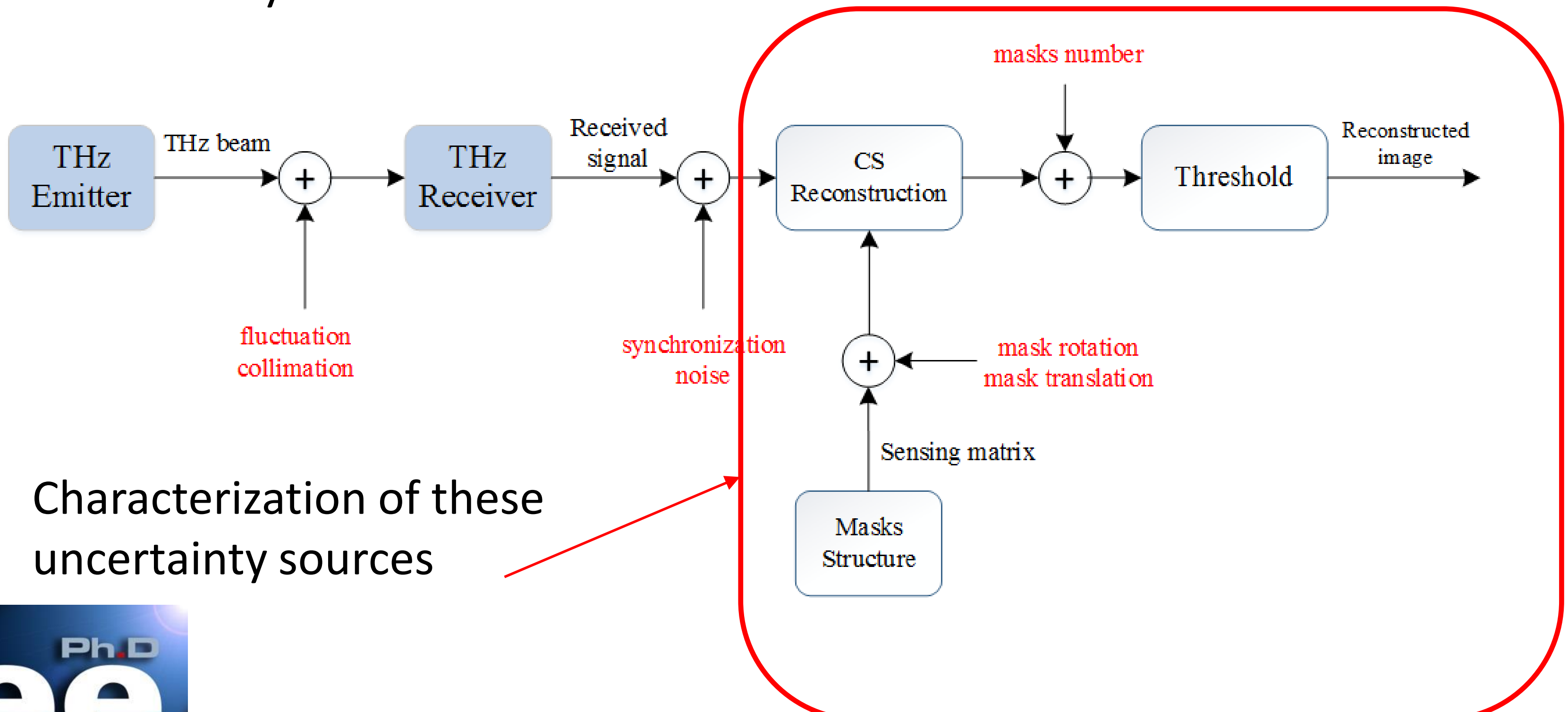
→

Original Image



Uncertainty Sources

Differently from what stated by CS-approach (i.e. the higher the number of masks the better the image reconstruction), it has been experienced that increasing the masks number, a degradation of the reconstruction occurs. In order to highlight problems affecting the experimental application of CS-based method, a characterization of the CS-THz Imaging approach has been performed, focusing on different uncertainty sources.



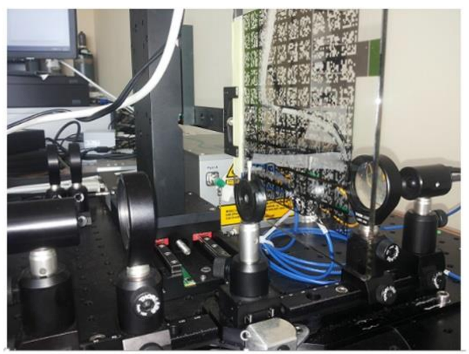
Characterization of these uncertainty sources

Uncertainty Sources

- **Thresholding process**: CS reconstruction returns images in grey scale so that each pixel has to be forced to 1 or 0 with an opportune threshold criteria

- **Number of masks**: how many masks are used to reconstruct an image is a topic already present in literature, where, from a theoretical point of view, it is demonstrated that higher the number of masks, better is the image reconstruction; in experimental tests the increase of the number of masks can also deteriorate the performance

- **Masks positioning**: a perfect alignment THz beam-mask-object is crucial for any application and in particular for CS; usually this issue is not considered in theoretical formulations, but, in experimental application, misalignment or tilt of the mask can hugely affect the performance.



To reduce the computational burden, an approach based on the Central Composite Design (CCD) has been applied.

(Box-Wilson) Central Composite Design

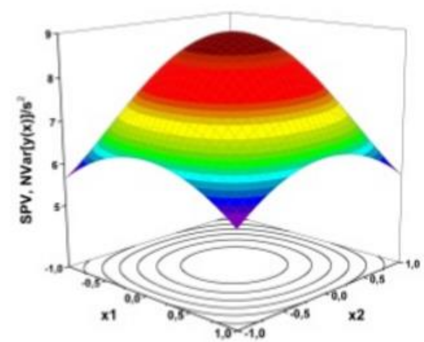
- The Central Composite Design (CCD) is a useful technique particularly appropriate in response surface design.

- CCD allows to estimate a second order (quadratic) model without needing to investigate the whole space of the input quantities (factors).

- In particular, by using a CCD, it is possible to carry-out only a limited number of experiments.

- Once they have been executed than the model is identified by applying a regression linear technique.

response surface design



CCD: Design of Experiments

Uncertainly Source	$-\alpha$	-1	0	1	α
Mask Rotation [°]	0	0.5	1	1.5	2
Mask Translation [mm]	0	0.25	0.50	0.75	1
Rows	2	3	4	5	6
Columns	2	4	6	8	10
Threshold Value [%]	50	60	70	80	90

In order to assess the quality of an image reconstruction, two quality index have been selected. In general, it is possible to distinguish between **Pixel Difference Measurements** and **Human Visual Based Measurements**.

$$MSE = \frac{1}{MN}\sum_{i=1}^{M}\sum_{j=1}^{N}[X(i,j) - Y(i,j)]^2$$

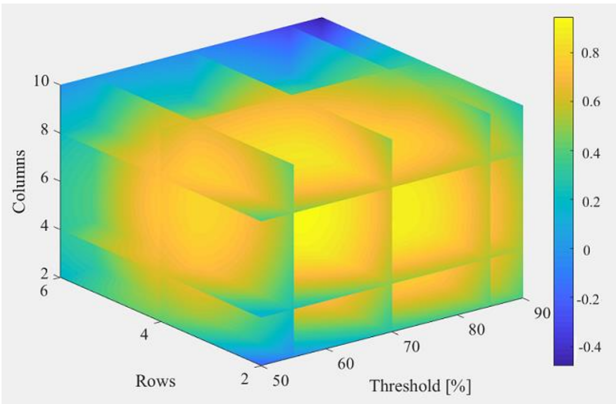
Mean Square Error: is a Pixel Difference Measurements estimate the quality of an image by performing the pixel-to-pixel difference between the reconstructed image and the reference one.

$$SSIM\,(X,Y) = \frac{(2\mu_X\mu_Y + C_1)(2\sigma_{XY} + C_2)}{(\mu^2{}_X + \mu^2{}_Y + C_1)(\sigma^2{}_X + \sigma^2{}_Y + C_2)}$$

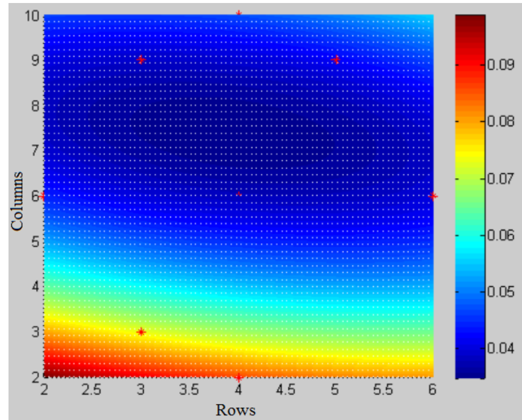
Structural SIMilarity index (SSIM): is a Human Visual Based Measurements uses human perception as a reference, taking into account parameters that can change the perception of an image as brightness, contrast, texture, orientation.

Results

SSIM

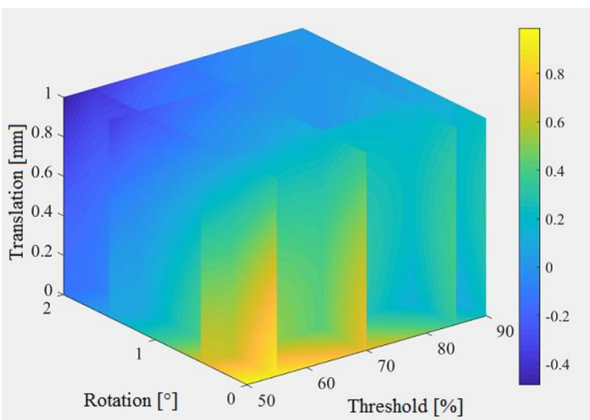


MSE



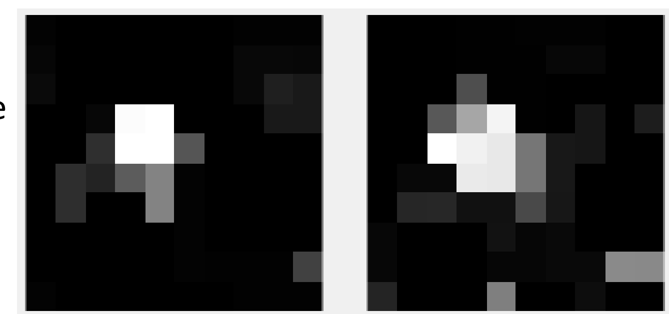
SSIM presents a superior sensitivity, in fact figures show the evolution of SSIM and MSE versus the number masks rows and columns in the same conditions of rotation and translation. SSIM value arrives to 0.6 – 0.8, and it is not suitable influence of the thresholding process. Unfortunately, the MSE ranged within the interval from 0.04 up to 0.09 thus highlighting the limited sensitivity of the performance factor.

Mask rotation = 0.5°   Mask Translation = 1 mm



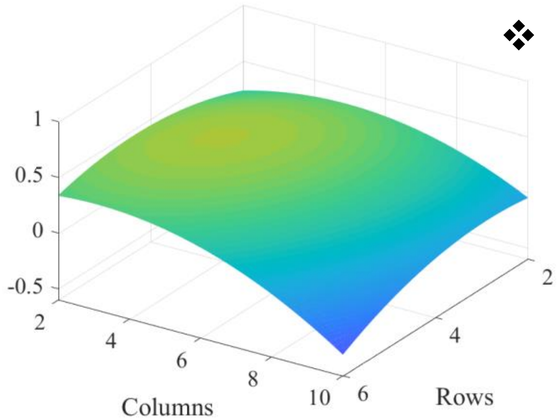
The effect of mask rotation is more significant than the mask translation The maximum value for rotation is of 0.5°, while for translation is possible to arrive to 1 mm.

Reconstruction image of an hole square $2x2\,mm^2$ with 16 measurements. Even if the number of measurements is the same, the difference combination of rows and columns influences the reconstruction process.



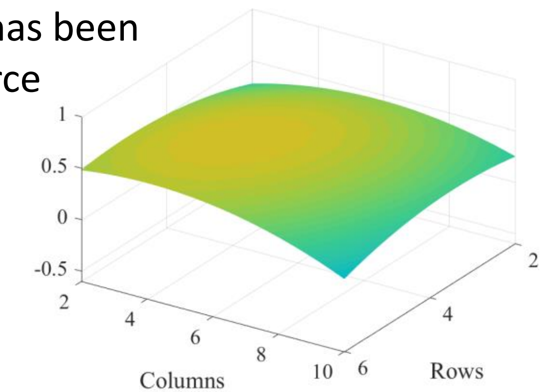
On the left reconstruction is obtained with 4 rows and 4 columns, while on the right by adopting 2 rows and 8 columns.

Results

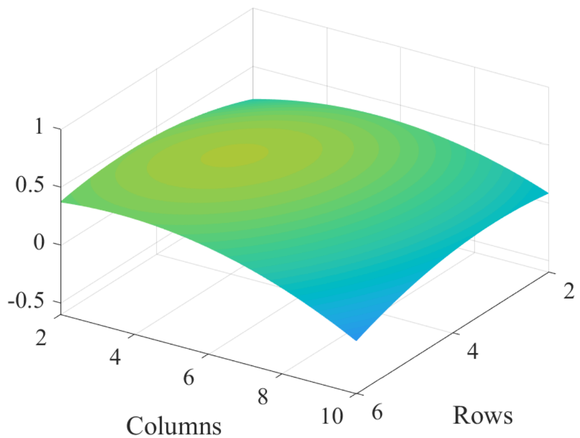


- ❖ SSIM provides better performance due to sensitivity values higher than those granted by MSE.

- ❖ Angular rotation of the masks matrix has been identified as the most influencing source



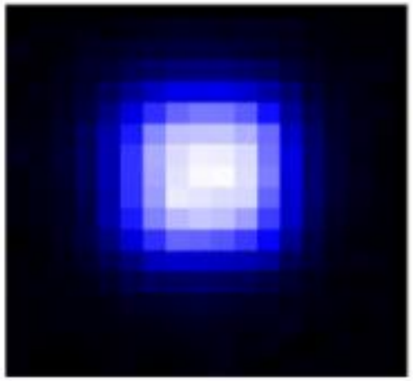
- ❖ An optimal number of masks could be determined for target reconstruction

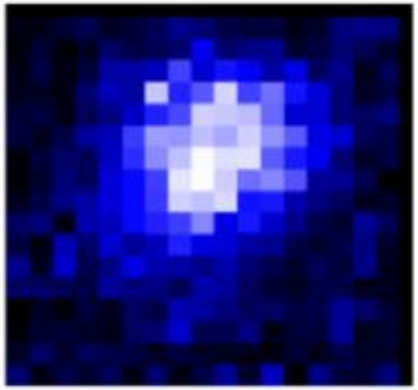
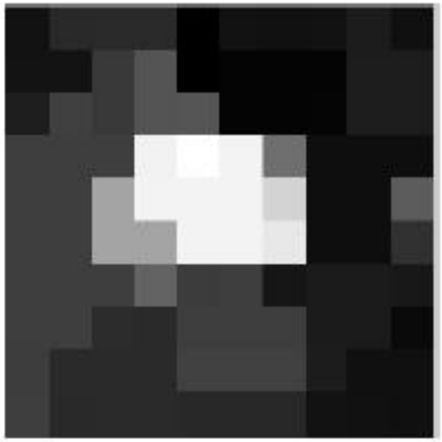


- ❖ The position of the masks within the matrix has been assessed as uncertainty sources

- ❖ Moderated value of horizontal or vertical translation only resulted in translation of the reconstructed images with respect to the ideal center

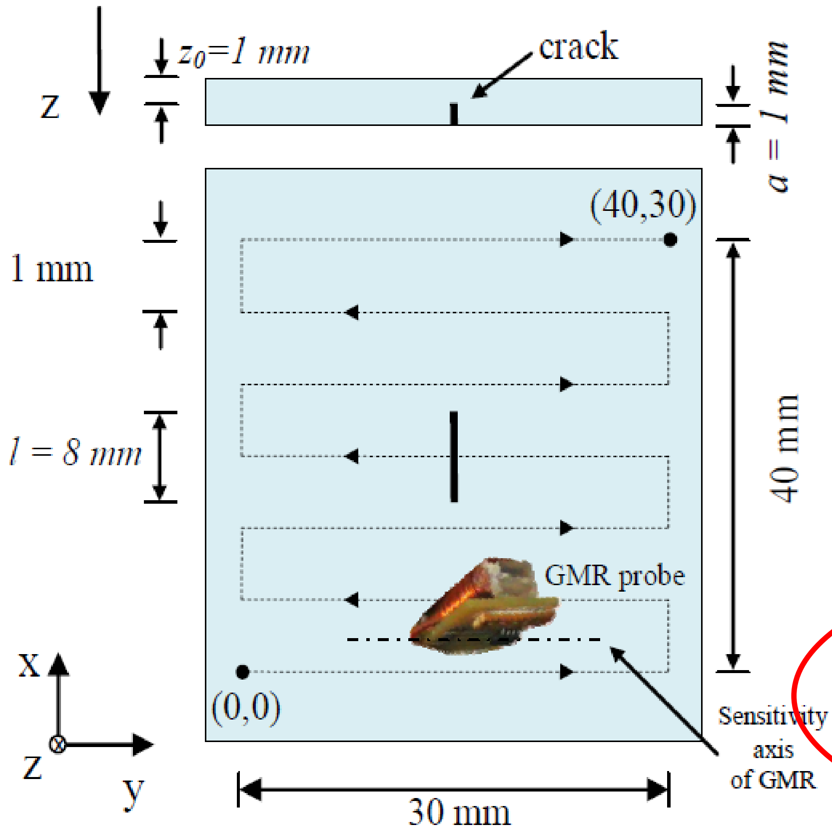
Results



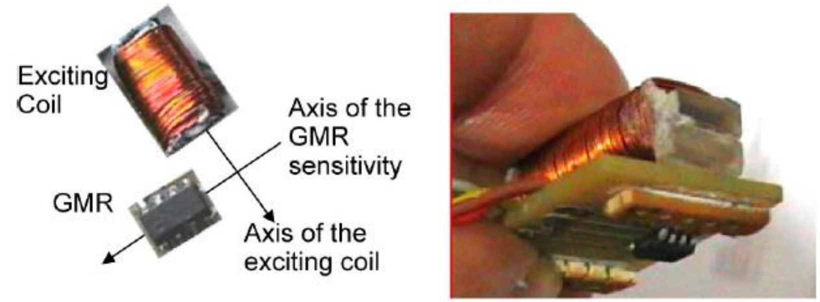



Comparison between the reconstruction of a defect obtained with the simple RS technique and CS-approach are shown. In particular, the defect is represented by a square hole of $3x3\ mm^2$, realized on a piece of Kevlar; the RS is shown and compared with reconstruction obtained with CS-approach considering 9x4 masks. At the same time, the image of the same hole hidden between two layers of concrete wall (total thickness 7.45 mm) is shown. In the case of RS, time to acquire all the area is about 10 h (even if it depends by the resolution selected), while for CS each mask uses only few seconds to acquire the area so that the M acquisition are realized in few minute.

Eddy Current Tests



Zoom of the investigation area, in which the crack is collocated in the centre of the structure



GMR probe

- ✓ Acquisition of Current and Voltage Signals
- ✗ Each signal is acquired with a number of samples equal to 100000
- ✗ Acquisition time very long, up to 10 s

Compressive Sampling
CUDA and GPU

CS based on ECT

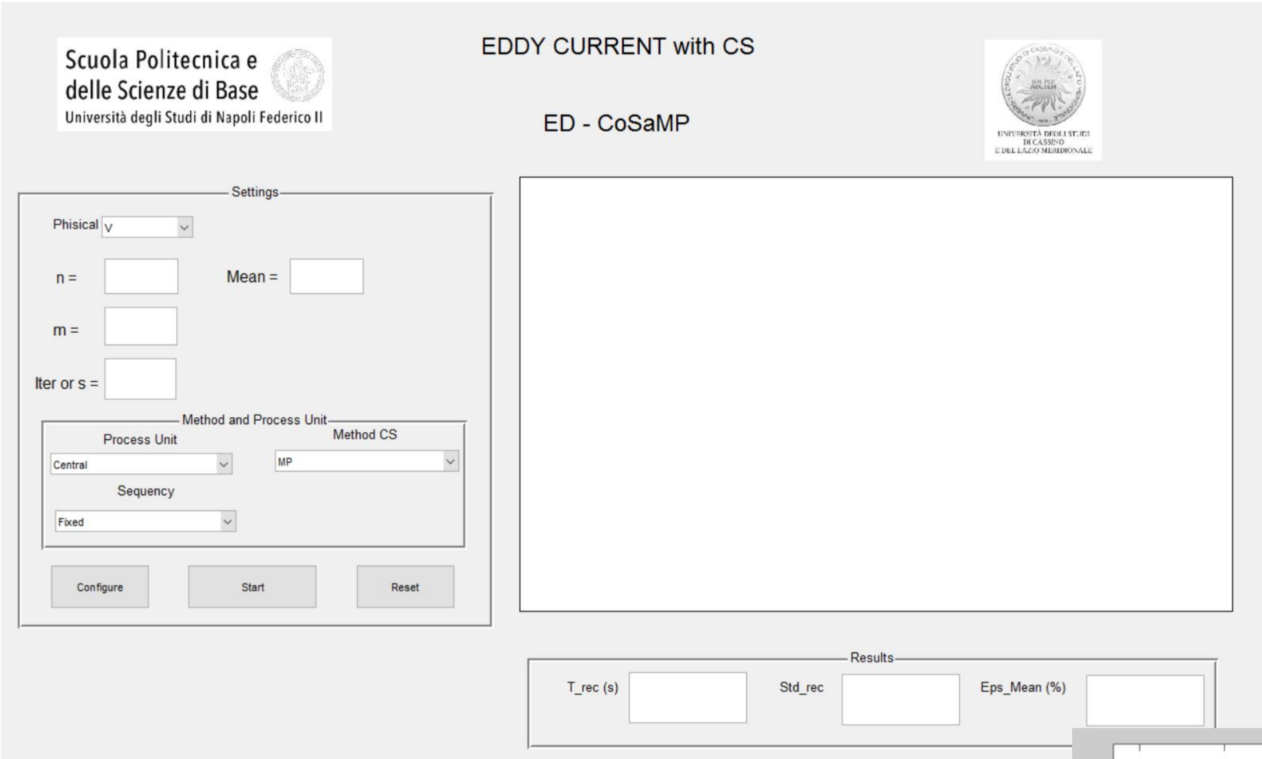
- Physical Quantity
  - Voltage (V)
  - Current (I)
- Sequence (Sensing matrix)
  - Fixed
  - Variable
- CS-Solver
  - MP
  - CoSaMP
- n → Number of samples acquired
- m → Number of samples used for reconstruction
- Process Unit
  - Central (CPU)
  - Graphic (GPU)

INPUTs

- T_rec → Reconstruction Time
- Std_rec → Standard Deviation of Time
- Eps_mean → Quality of Reconstruction

OUTPUTs

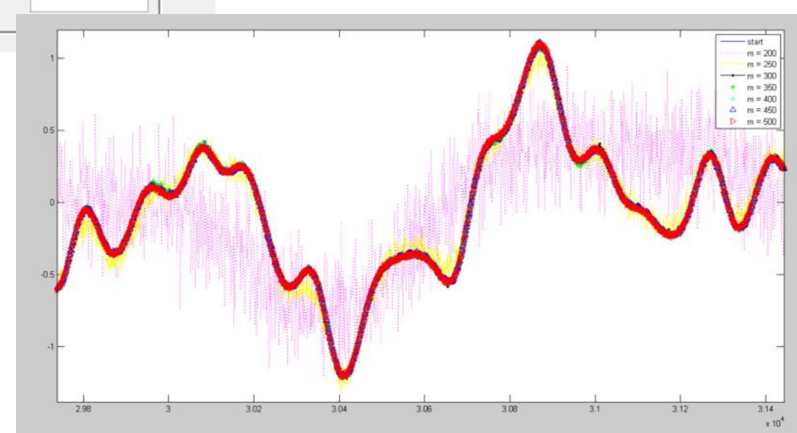
CS based on ECT



A Gui-Matlab has been developed, in which all the Inputs and Outputs presented before are taken into account.

- Iter or s are linked to the Method CS applied.
- Mean parameter for Std_rec

The acceptable value of m is 300 – 350, starting from 100000 samples!!!



CS based on ECT

MP Algorithm

CORRENTE

Fissa	T_rec				Std_rec				Eps_rec			
m/iter	50	75	100	125	50	75	100	125	50	75	100	125
200	0,614704	0,959695	1,323864	1,74094	0,036071	0,063664	0,133826	0,22575	5,581706	5,935897	6,03806	6,080929
250	0,71095	1,108031	1,539269	2,003426	0,0295	0,066805	0,128366	0,217756	4,41916	2,001715	2,199736	2,276786
300	0,815791	1,270806	1,756887	2,28322	0,031883	0,066922	0,129952	0,227752	4,422516	1,943336	1,812021	1,886889
350	0,921454	1,433733	1,967918	2,559967	0,029706	0,067357	0,128923	0,21706	5,068296	2,241127	1,762782	1,878986
400	1,036141	1,601562	2,201438	2,839186	0,034207	0,068675	0,134651	0,232589	4,958088	2,151914	1,945036	1,986399
450	1,145955	1,76729	2,423015	3,112326	0,030355	0,071682	0,141411	0,229683	4,830406	1,897396	1,519021	1,580807
500	1,257202	1,934795	2,643132	3,392909	0,031165	0,075026	0,137085	0,23289	4,337367	1,844272	1,52257	1,574536

Variabile	T_rec				Std_rec				Eps_rec			
m/iter	50	75	100	125	50	75	100	125	50	75	100	125
200	0,624058	0,979292	1,345008	1,751023	0,045916	0,092199	0,139087	0,238988	7,822384	7,618792	7,793789	7,840281
250	0,715742	1,141168	1,589876	2,071568	0,034818	0,076239	0,145005	0,237892	6,274094	4,250233	4,357297	4,43617
300	0,819293	1,271725	1,800286	2,354689	0,030243	0,071299	0,156177	0,2505	5,274528	2,844482	2,808169	2,896769
350	0,937366	1,433274	2,016127	2,624066	0,025341	0,066519	0,145169	0,242727	4,813633	2,499858	2,408967	2,487609
400	1,038015	1,625199	2,242807	2,926347	0,031998	0,085692	0,134969	0,31001	4,303537	2,100473	1,926424	2,000066
450	1,177381	1,78616	2,430909	3,186217	0,037309	0,060188	0,137922	0,26543	4,158661	1,982697	1,706197	1,763817
500	1,273262	1,938663	2,687369	3,42828	0,031693	0,067448	0,145674	0,244104	3,95372	1,881378	1,555613	1,593076

Can I go under 1 s???

YES, I CAN

CS based on ECT

CoSaMP Algorithm

CORRENTE

Fissa	T_rec				Std_rec				Eps_rec			
m/s	20	30	40	50	20	30	40	50	20	30	40	50
200	39,39115	40,65495	41,4624	42,94014	0,396345	0,403925	0,507161	0,556459	10,59543	3,09833	2,147829	5,690513
250	0,252133	48,30775	0,852967	50,9697	0,002415	0,620006	0,005563	0,717354	10,5102	3,227978	1,670172	1,681308
300	0,286243	0,351231	0,757657	1,01897	0,002555	0,002845	0,005444	0,006572	10,46086	3,180845	1,553515	1,591459
350	0,450567	0,896516	4,520382	4,541712	0,006948	0,009048	0,468254	0,02101	10,43971	3,202466	1,52985	1,442062
400	0,65531	1,305922	2,131322	3,141931	0,005527	0,012211	0,012047	0,017477	10,44324	3,202878	1,541961	1,425704
450	0,900359	1,272888	2,198829	3,674011	0,005907	0,007555	0,146236	0,01979	10,40287	3,174456	1,475925	1,343152

Variabile	T_rec				Std_rec				Eps_rec			
m/s	20	30	40	50	20	30	40	50	20	30	40	50
200	6,584994	12,47043	19,21914	42,16249	14,47115	18,49376	19,81698	5,485554	10,59279	3,460059	3,229114	5,839455
250	5,434332	11,10253	6,125417	32,12417	14,67971	20,01216	14,61197	23,52048	10,50955	3,292205	1,825856	1,959445
300	5,681775	3,878554	6,133607	13,31256	16,2457	13,37166	16,08822	22,96179	10,46732	3,241202	1,659358	1,720055
350	13,8124	12,95692	5,220935	15,55415	41,92245	40,15633	21,01016	40,58858	10,44289	3,188975	1,582118	1,552989
400	22,80091	7,498745	5,350609	9,657854	55,05013	31,21793	22,75611	31,86012	10,42547	3,195852	1,534207	1,423021
450	14,79523	10,10826	2,000138	10,38556	47,96455	38,85272	0,502633	35,51317	10,41368	3,179376	1,50561	1,336359

Between a fixed and variable sequence, it is preferable to use a variable ones to obtain a very little time of reconstruction!!!

Remarks

- It is possible to reconstruct the signal with the CS-approach
- Starting from a signal, current or voltage, of 100000 samples, it has reached to one of only 300-400 samples
- Using CUDA and GPU, reconstruction times have been dropped, ranging from value over 10 s to values below the second.

Products

“THz Measurement Systems”
Leopoldo Angrisani, Giovanni Cavallo, Annalisa Liccardo, Gian Paolo Papari and A. Andreone
Chapter InBook:“New Trends and Developments in Metrology” book edited by Luigi Cocco

“Performance and metrological characteristics of THz systems for dual use applications”
G. Cavallo, A. Liccardo, F. Bonavolontà, R. Schiano Lo Moriello, L. Angrisani, G.P. Papari, and A. Andreone
Conference: Second IEEE International Forum on Research and technologies for Society and Industry (RTSI 2016), Bologna (Italy)

“Terahertz shielding properties of carbon nanocomposite materials”
L. Angrisani, G. Cavallo, A. Liccardo, G.P. Papari, A. Andreone and P. Russo
Conference: International Conference on Semiconductor Mid-IR and THz Materials and Optics SMMO20116, Lisboa, Portugal.

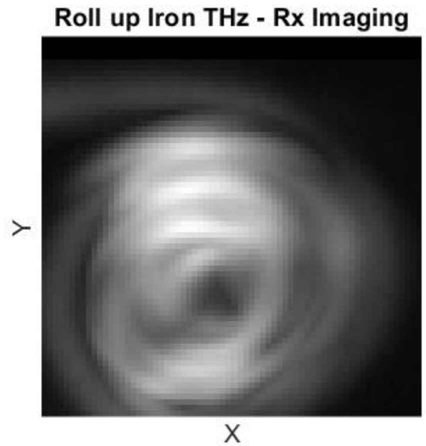
“Experimental Performance Assessment of Compressive Sampling-based THz Imaging Systems”
L. Angrisani, F. Bonavolontà, G. Cavallo, A. Liccardo, R. Schiano Lo Moriello, G.P. Papari, and A. Andreone.
Conference: International Instrumentation and Measurement Technology Conference (I2MTC 2017), Torino (Italy)

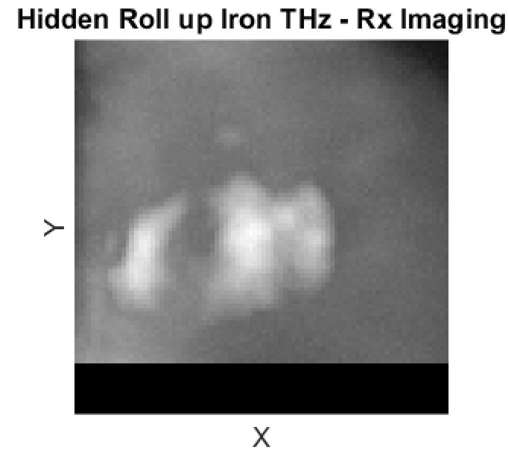
“On the Measurement Uncertainties of THz Imaging Systems based on Compressive Sampling”
Measurement: Journal of the International Measurement Confederation: L. Angrisani, F. Bonavolontà, G. Cavallo, A. Liccardo, R. Schiano Lo Moriello

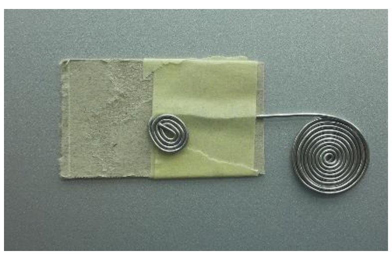
Thanks for the attention!!!

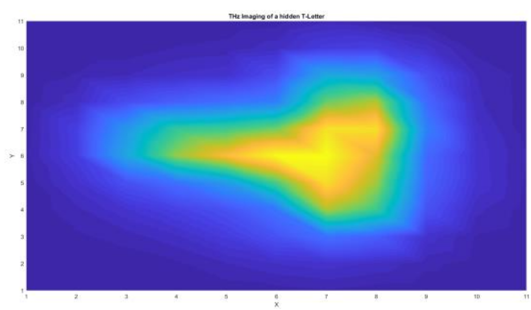
Questions?

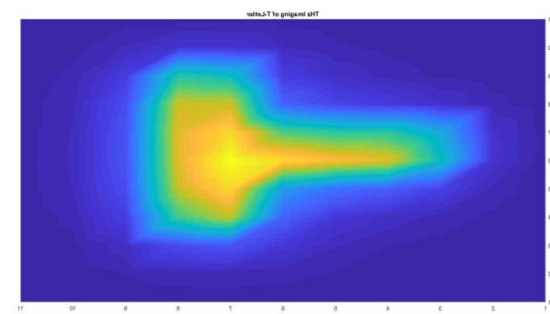
THz Imaging


Roll up Iron THz - Rx Imaging
Y
X

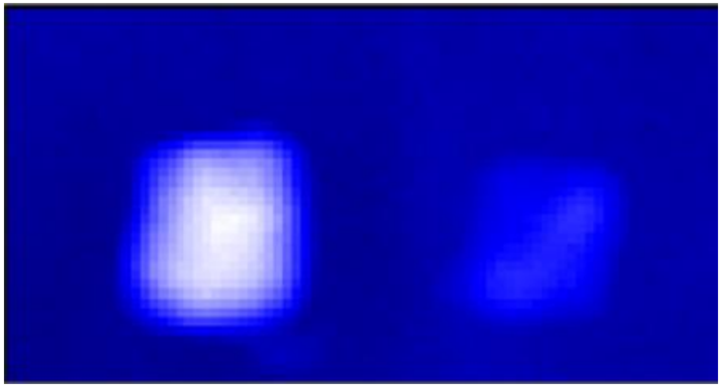

Hidden Roll up Iron THz - Rx Imaging
Y
X

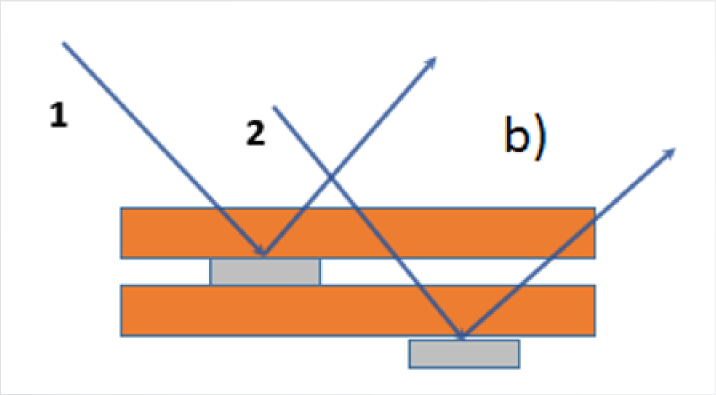


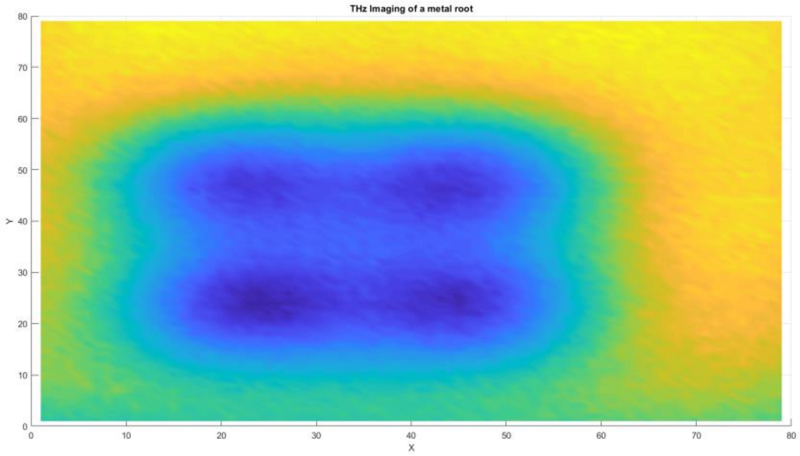


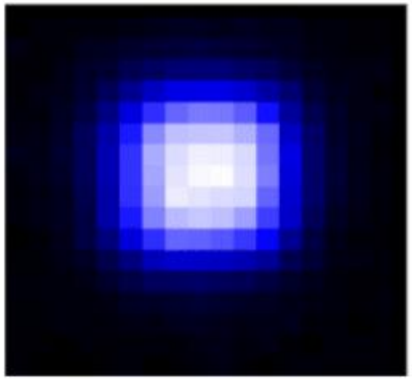


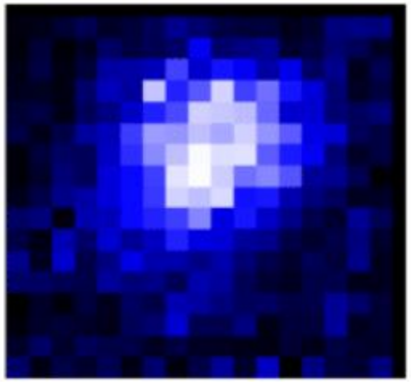
THz Imaging



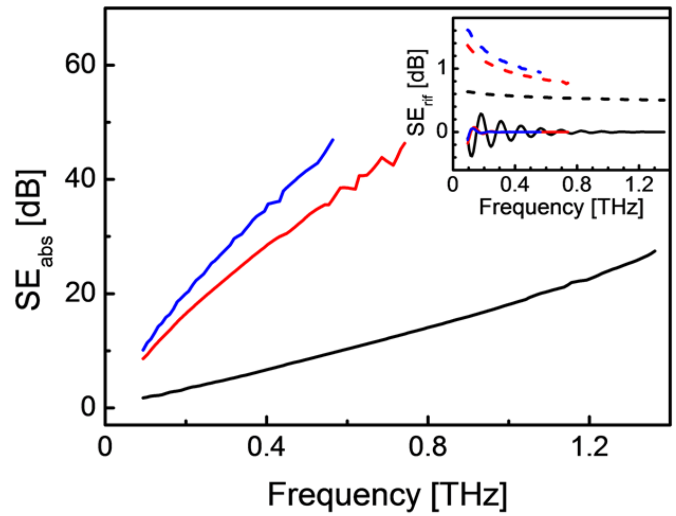


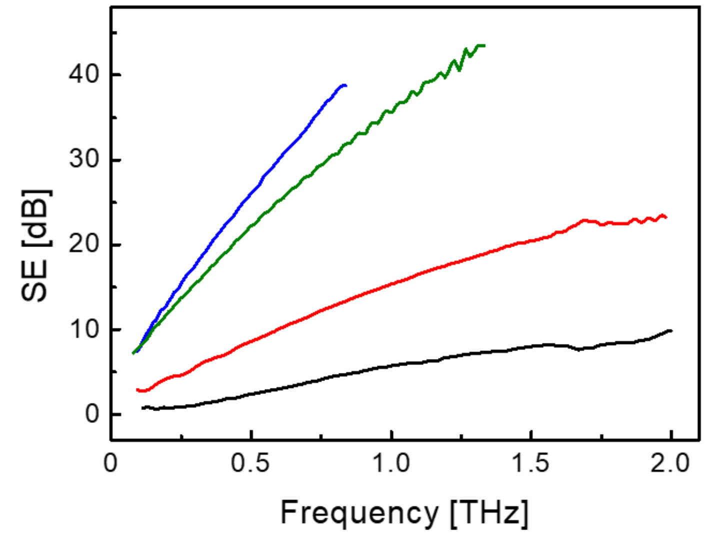


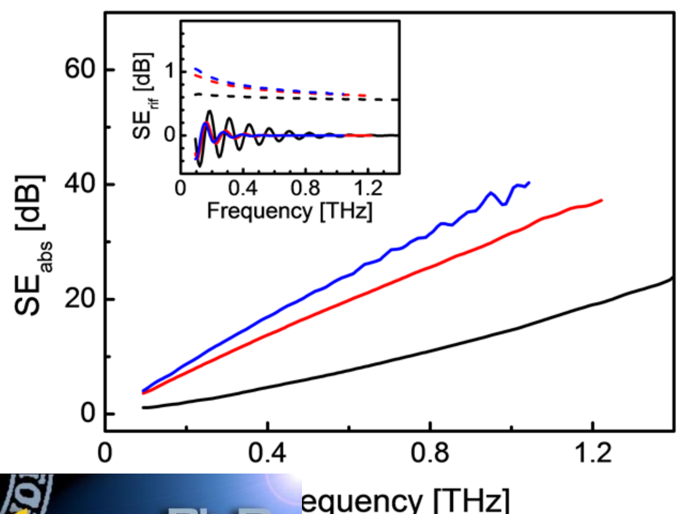


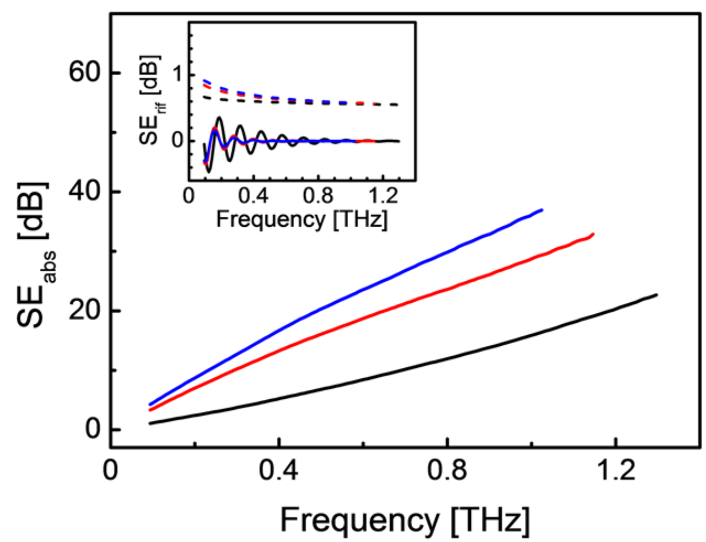


THz Spectroscopy



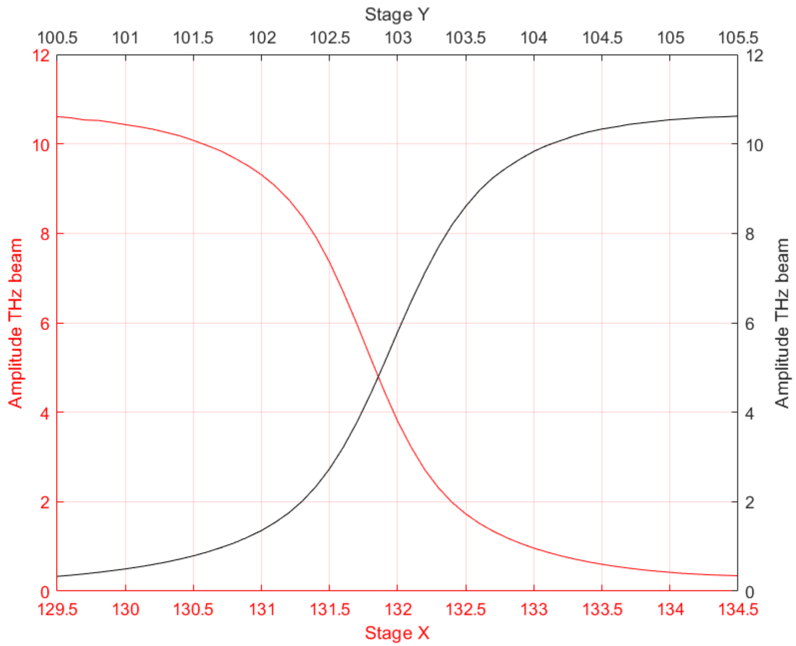




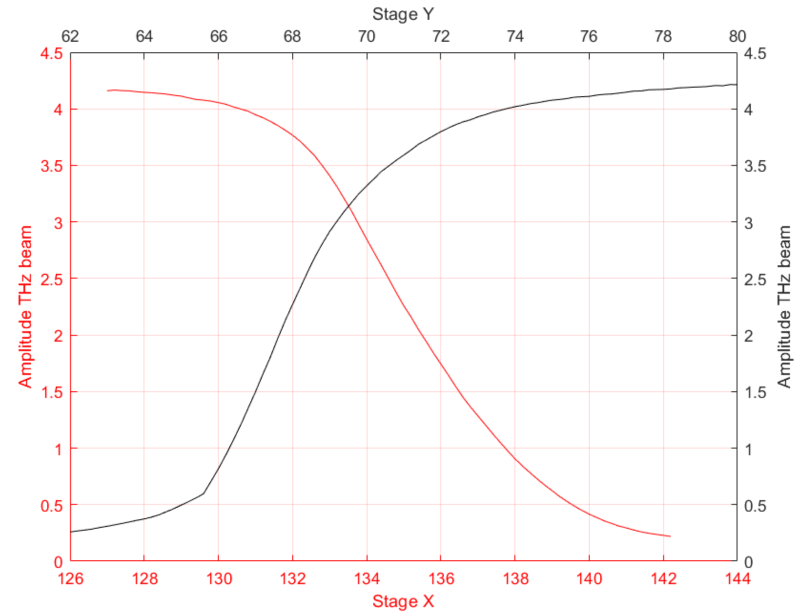


THz beam profile

Knife-Edge Method

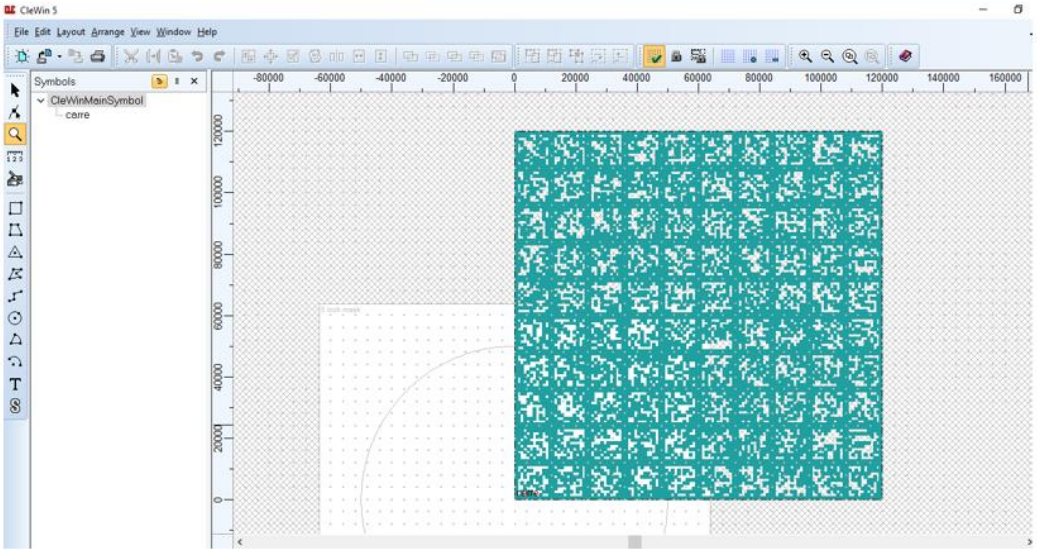


Transmission
Focused THz beam
$2x2\ mm^2$



Transmission
Collimated THz beam
$2x2\ mm^2$

CS-based on THz system



Compressive Sampling

Compressive Sampling (CS) is an innovative paradigm of sampling that permits to:

- Acquire the signal of interest directly in a compressive form;
- At a later time, reconstruct it with appropriate algorithms (ex. resolution of a problem of optimal convex).

L1-Magic
CVX TVAL3

Compressive Sampling vs Traditional Sampling

Sampling according to Nyquist-Shannon requests:

- Bandwidth limited signal
- Uniform sampling
- Sample rate equal to $f_C \geq 2f_{MAX}$

Sampling according to CS requests:

- Sparse Signal
- Not uniform sampling
- Number of samples $M \ll N$

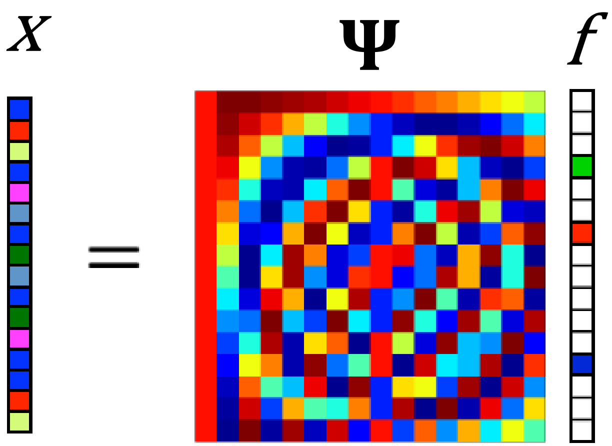
Compressive Sampling

If ***x*** is sparse, compressible, respect to a suitable orthonormal basis ***Ψ***, you can write:

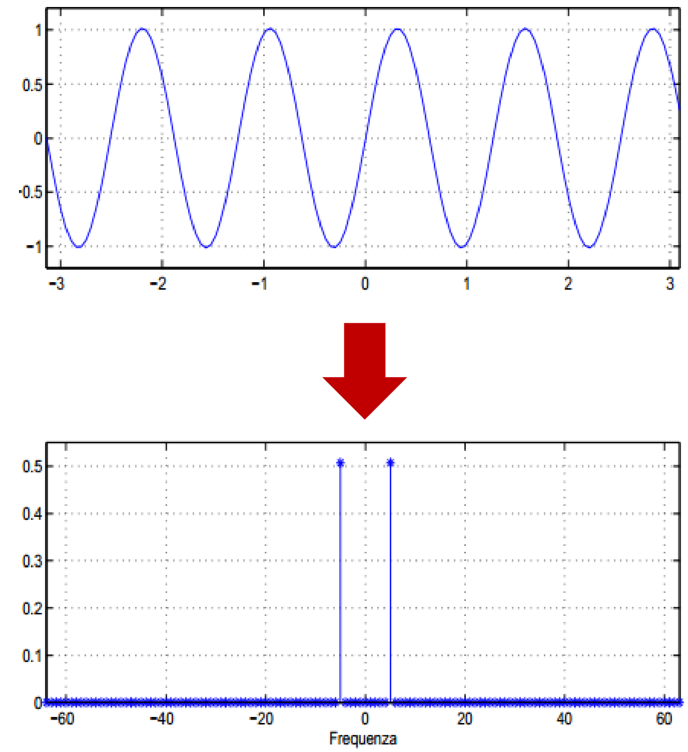
$$x = \Psi f$$

Ψ *[NxN]* *Trasformation matrix*

f [N] *Sparse vector*



Time domain



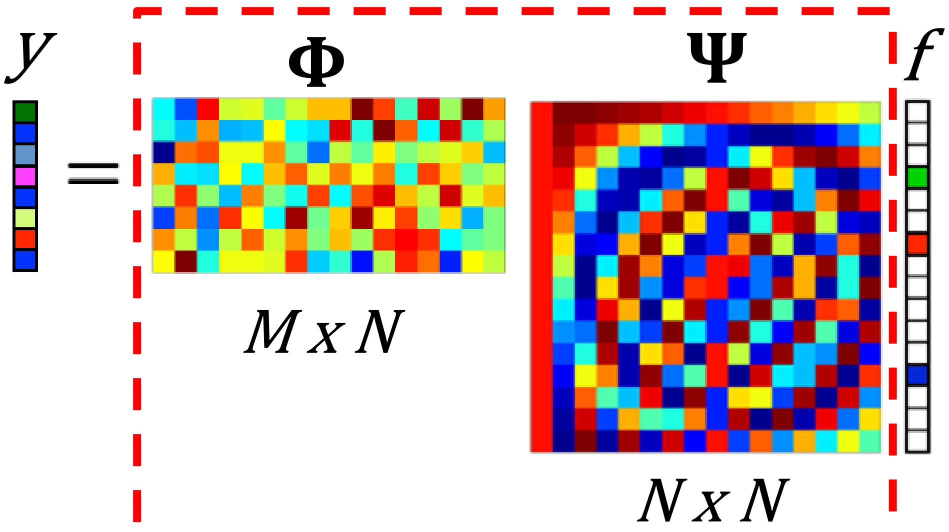
Frequency domain

Compressive Sampling

Combining the two previous expressions, you get a new matrix, sensing matrix ***A*** and a new problem:

$$y = Af \text{ with } \boldsymbol{A} = \boldsymbol{\Phi}\boldsymbol{\Psi}$$

Sensing Matrix $\boldsymbol{A}\ [MxN]$



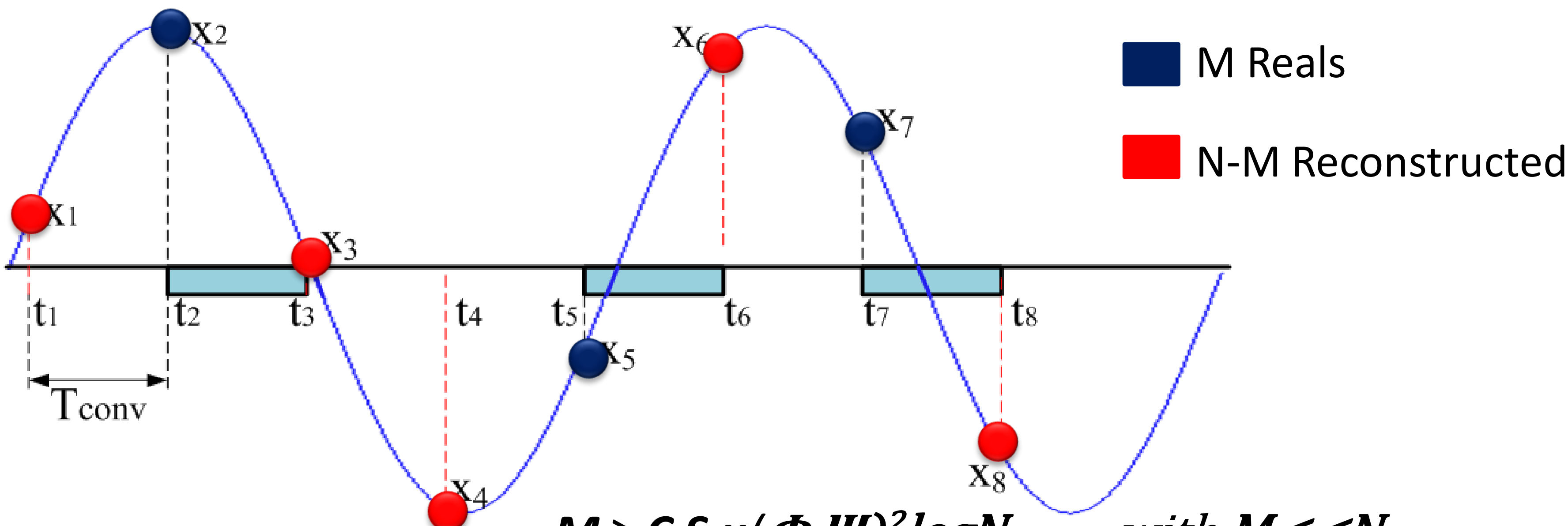
Although system is still underdetermined, it is possible to find a sparse solution to the problem by minimizing the L1-norm of ***f***

$$f = \min_{f \in R^N} \| f \|_{\ell_1}$$

Compressive Sampling

Once the sparse solution $\hat{\boldsymbol{f}}$, the signal being acquired can be reconstructed with N samples using the previous expression:

$$\hat{\boldsymbol{x}} = \boldsymbol{\Psi}\hat{\boldsymbol{f}}$$



$$M \geq C\,S\,\mu(\Phi,\Psi)^2 \log N \qquad \text{with } M \ll N$$

1. ***S***, *sparsity index of signal*
2. $\mu(\Phi,\Psi)$, *coherence between matrixes* Φ,Ψ

Compressive Sampling

- ✓ For an efficient implementation of CS it is necessary to guarantee low levels of ***S*** and $\boldsymbol{\mu}$

- ✓ A low level of ***S*** depends not only by signal, but also to an appropriate choice of the transformation matrix $\boldsymbol{\Psi}$

- ✓ Fixed the transformation matrix $\boldsymbol{\Psi}$, a low level of coherence is assured by any ***Random*** matrix

CCD: Design of Experiments

STEP 1: Design of experiments

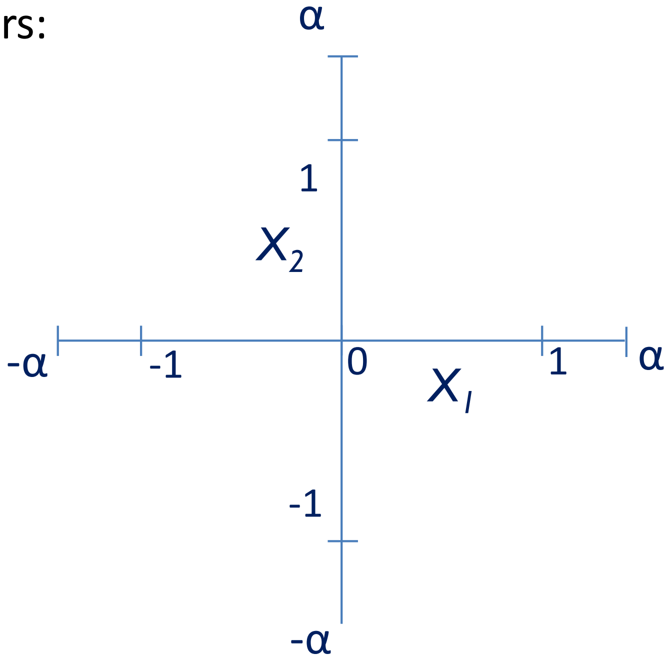
This CCD design has circular, spherical, or hyperspherical symmetry (depending by the number of factors) and require 5 levels for each factor.

The 5 levels of factors are encoded in an arbitrary unit interval [-α, -1, 0, 1, α].

For example, let you consider a CCD design of two factors: X_1 and X_2

X_1 =[-α, -1, 0, 1, α]

X_2 =[-α, -1, 0, 1, α]



CCD: Design of Experiments

STEP 1: Design of experiments

CCD can considered the union of three distinct design point:

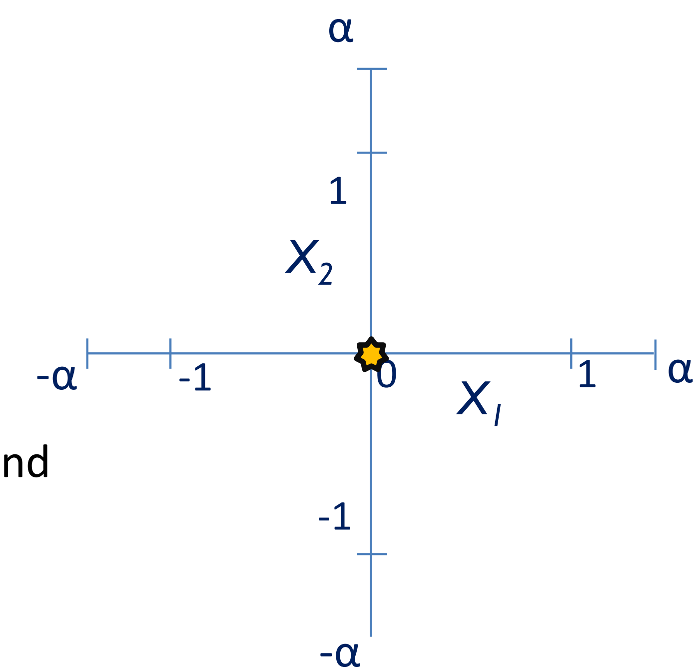
- **A set of center points (indicated by yellow star marker):**

Replicated to preliminary estimate **repeatability and reproducibility** of the experiments.

mean values

Run	IX-XVI
X_1	0
X_2	0

$$X_1 = [-\alpha, -1, 0, 1, \alpha].$$
$$X_2 = [-\alpha, -1, 0, 1, \alpha].$$



The quantities value are the same for each factors and equal to means value of intervals.

CCD: Design of Experiments

STEP 1: Design of experiments

CCD can considered the union of three distinct design point:

$X_1 = [-\alpha, -1, 0, 1, \alpha]$

$X_2 = [-\alpha, -1, 0, 1, \alpha]$

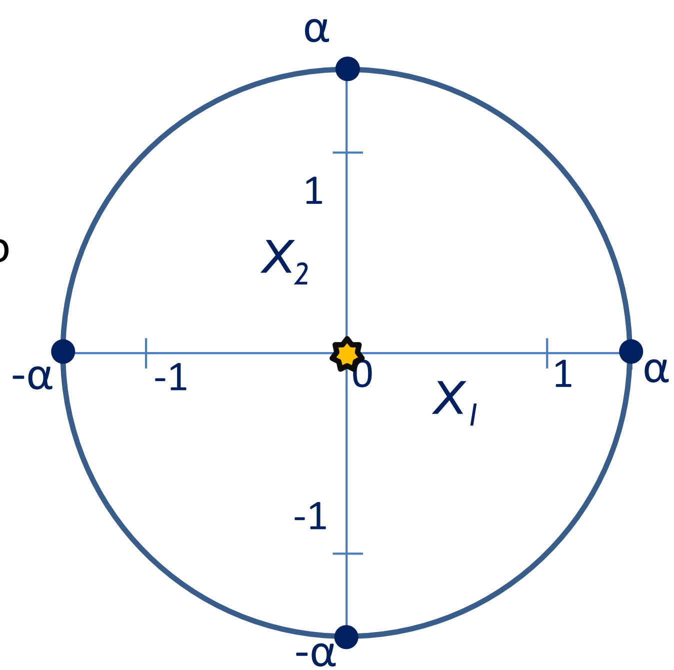
- **A set of axial points (indicated by blue marker)**

Capable of emulating a one-factor-at-time analysis.

The quantities values are the same of the center points but not for one of them which assume either the maximum or the minimum of interval of levels, equal to α.

Run	V	VI	VII	VIII	IX-XVI
X_1	-α	α	0	0	0
X_2	0	0	-α	α	0

Experimental Runs



CCD: Design of Experiments

STEP 1: Design of experiments

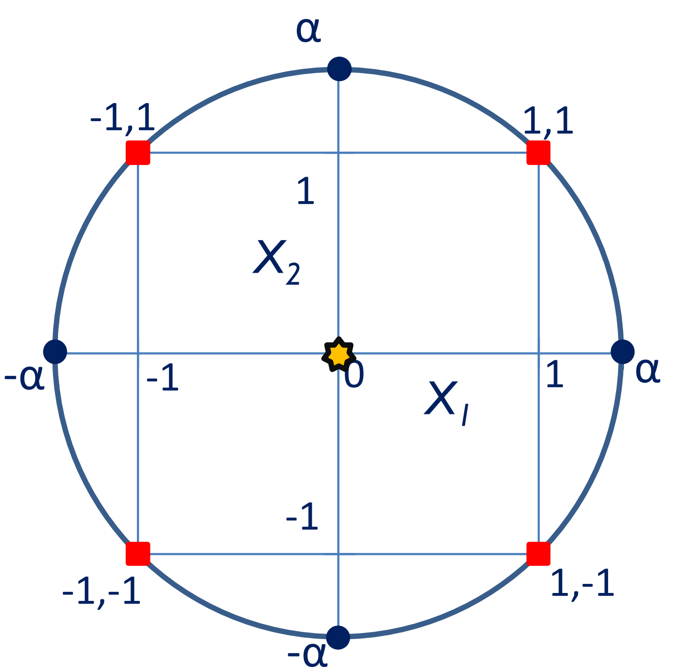
CCD can considered the union of three distinct design point:

X_1 =[-α, -1, 0, 1, α]
X_2 =[-α, -1, 0, 1, α]

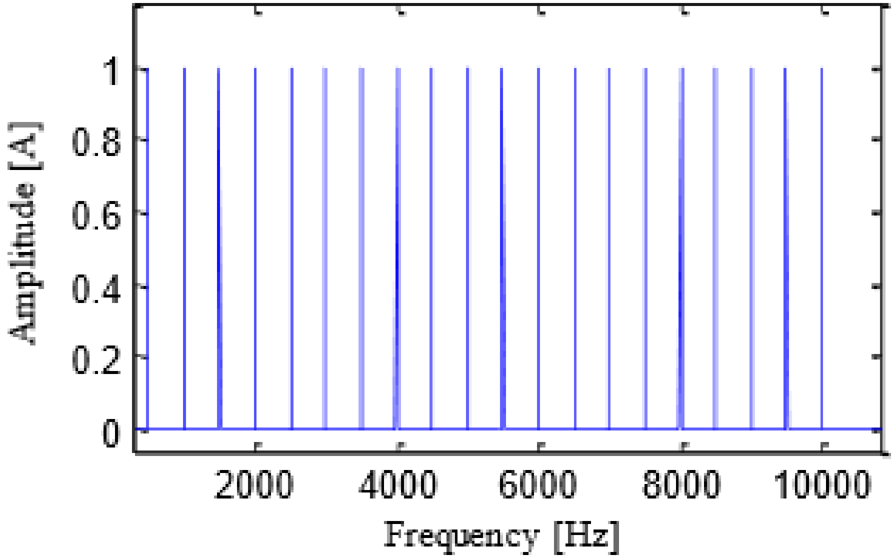
- **A set of edge points (indicated by red square marker)**

A set of values characterizing a typical factorial design where each quantity is investigated on two levels range to study the effects of interactions between factors on the response variable.

Run	I	II	III	IV	V	VI	VII	VIII	IX-XVI
X_1	-1	-1	1	1	-α	α	0	0	0
X_2	-1	1	-1	1	0	0	-α	α	0

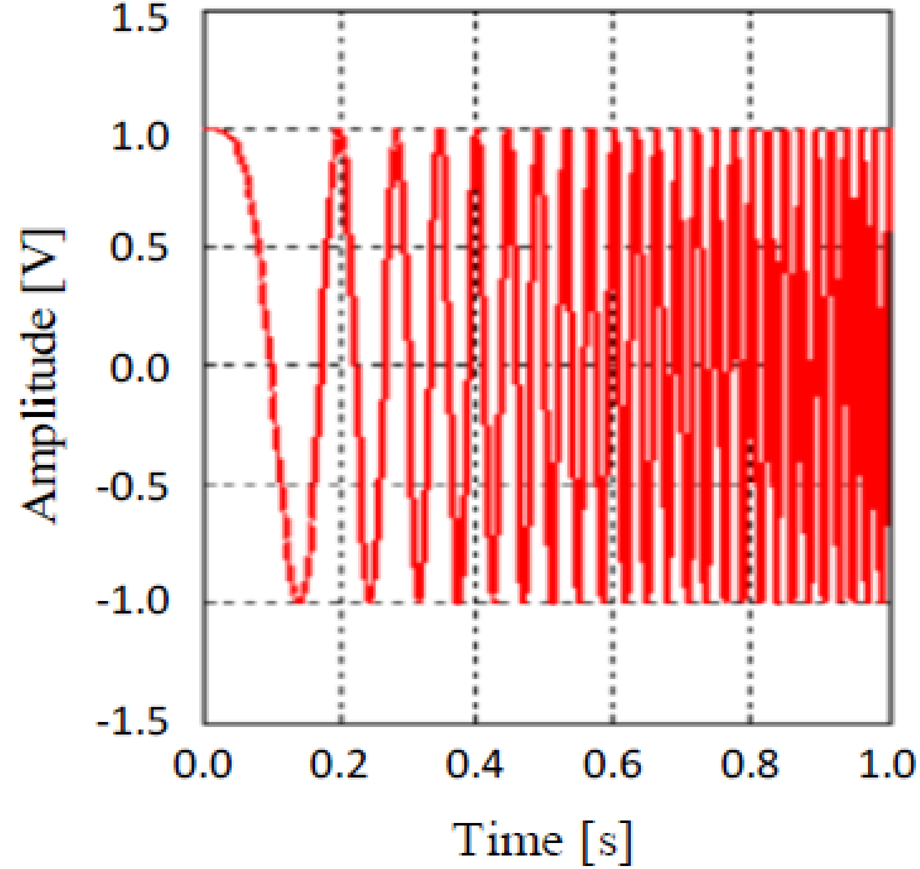


Eddy Current Test



Multi-tone

Chirp



Which kind of excitation is possible?

CS based on ECT

Very often, signals acquired in EC tests are very large in terms of :

- Number of samples considered
- Size (bytes) of the file to be acquired or transferred
- Long acquisition and reconstruction times

CS permits to:

- Reduce of samples to be considered
- Consequence: minor number of bytes
- Reduction of acquisition and construction times