PhD in Information Technology and Electrical Engineering

Università degli Studi di Napoli Federico II

PhD Student: Giovanni Cavallo

XXX Cycle

Training and Research Activities Report – Third Year

Tutor: Prof. Annalisa Liccardo

1. Information

PhD Candidate: Giovanni Cavallo

MSc title: Master's degree in Electronic Engineering (cum laude), University of Naples "Federico II"

Doctoral Cycle: XXX - ITEE – University of Naples Federico II

Fellowship type: European Social Fund (ESF)

Tutor: Prof. Annalisa Liccardo

Year: Third

I graduated, cum laude, in Electronic Engineering at University of Naples "Federico II". I am a PhD Student of the XXX cycle of ITEE.
My fellowship is financed by European Social Fund (ESF). My tutor is Prof. Annalisa Liccardo.

2. Study and Training activities

a. Courses

b. Seminars

- *"ItaloGorini 2017"*, Doctoral Summer School promoted by the Italian "Electrical and Electronic Measurement" (GMEE) and "Mechanical and Thermal Measurement" (MMT) associations, Catania, August 28th - September 1st, 2017, ***3 CFU***.

3. CS Summary

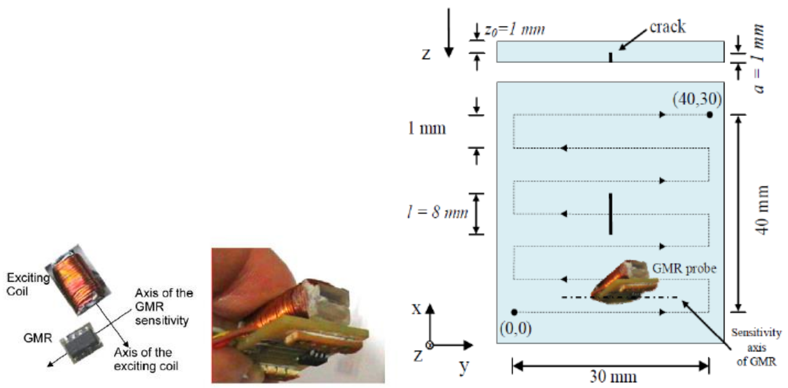
Student: Giovanni Cavallo giovanni.cavallo@unina.it | **Tutor: Prof. Annalisa Liccardo** annalisa.liccardo@unina.it | **Cycle XXX**

	Credits year 1								Credits year 2								Credits year 3									
		1	2	3	4	5	6			1	2	3	4	5	6			1	2	3	4	5	6			
	Estimated	bimonth	bimonth	bimonth	bimonth	bimonth	bimonth	Summary	Estimated	bimonth	bimonth	bimonth	bimonth	bimonth	bimonth	Summary	Estimated	bimonth	bimonth	bimonth	bimonth	bimonth	bimonth	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

4. Research activity

The research activity for the third year has been projected to complete the study involved the analysis of images acquired by THz radiation and reconstructed through CS-solver focused attention on the uncertainty affecting the CS reconstruction and its impact on the overall quality of the reconstructed image, and use Compressive Sampling in Eddy Current testing techniques (*ECT*).

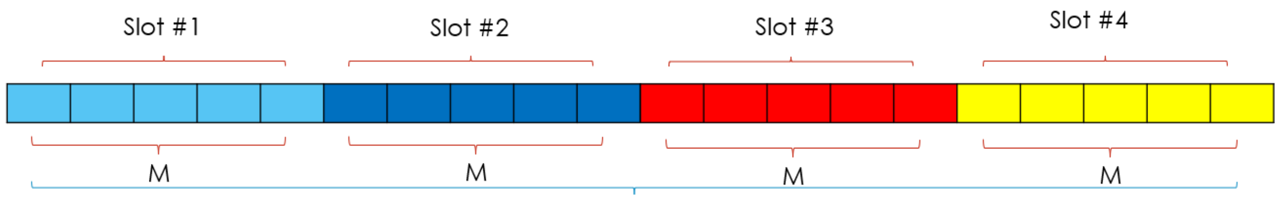
In the last years, in fact, the effort of the research has been focused on the development of eddy current measurement procedures capable of providing as much information as possible about the presence, the location and the geometrical characteristics of a defect. To this aim, newer signals characterized by a wide spectral content able to penetrate in the different layers of the material under test are substituting the older sinusoidal excitation. Firstly, this application is the result of a collaboration with the University of Cassino and Southern Lazio, in fact the research group of Cassino has realized the sensor and the components use to realize the measurements.
The sensor is a *Giant Magneto-Resistance* (*GMR*) sensor, used for eddy-current non-destructive testing on conductive materials. Today, on the market, different technologies are presented and are adopted in the realization of the probe. Among them, the *GMR* seems well suited for the purpose due to their large signal level, physical size, high sensitivity, low power consumption and low cost. Thanks to field-dependent changes in resistance that is possible to be observe in thin-film ferromagnetic/nonmagnetic metallic multilayers, it is possible to know the operation method of *GMR*, in fact, in the absence of an applied field, *GMR* sensitivity shows a high value due to the scattering between oppositely polarized electrons in the anti-ferro magnetically coupled multilayers of the device. To reduce the *GMR* sensitivity, eliminating the scattering mechanism, an external field is applied and this aligns the magnetic moments of the ferromagnetic layers. The main objective of this activity is to realize a crack characterization and estimate both the crack depth and height.
Using this *GMR* sensor, often, a very big area of interest is investigated, with or without the presence of defect and cracks, that sometimes are collocated in the center of the sample under test. In figure a GMR schematic and investigated area are shown:



The area to investigate can be considered as a matrix of *NxN* pixels, where of each pixel two different signals, current and voltage, are acquired with a huge number of samples, about 100000.
This means that memory data are need to be very big, and reconstruction times are too long because the knowing of all the signal is necessary.
Therefore, the purpose of *CS* in *ECT* is to reduce the memory size, reducing the number of samples acquired for each signal, and limit the reconstruction time to a few seconds. So that, the third year of research has focused on the best estimate value of the reconstructed samples, and on the determination of the CS-algorithm/CS-Solver that permits to reduce reconstruction times. In order to realize a detailed analysis, the study of has seen the applications of two different CS-Solver: the basic *Matching Pursuit*, indicated with *MP*, and the evolution *Compressive Sampling Matching Pursuit*, so-called *CoSaMP*.
Both these solvers have been applied with specific parameters criteria.
To apply CS-Solvers, an appropriate sensing matrix has been necessary realized to the operation of reconstruction. In this case, sensing matrix's realization has been developed creating two different sequences, in which the distinction has been made by considering a fixed and a variable sequence. This difference has been placed in order to evaluate some aspects, in fact with the fixed sequence it is possible to study the reproducibility of reconstruction process from the point of view of time by varying several factors, such as PCs, development environment, etc., while with the variable sequence it is possible to analyze the impact of the time on the sequence to reconstruct. Another important aspect is length of the sequence. It is related to the number of samples that are used to carry out the reconstruction; so means that given an signal

with *n* samples, the reconstruction takes place of *m* samples, with *m* smaller than *n*, so that CS has reason to be applied.

The creation of the sequence is realized by a Matlab-script and it is generated in a random manner with *n* samples, where of these *n* samples for the fixed sequence is considered a slot of *m* samples, firmly fixed, which can be in the queue, in the head or in the middle of the sequence, while in the case of variable sequence, several successive slots of *m* samples are considered, as shown in figure:



On current and voltage signal, CS approach is applied, in order to determine the necessary minimum number of samples, called *m*, useful to reconstructed the original signal acquired with a number of samples equal to 100000, called *n*.

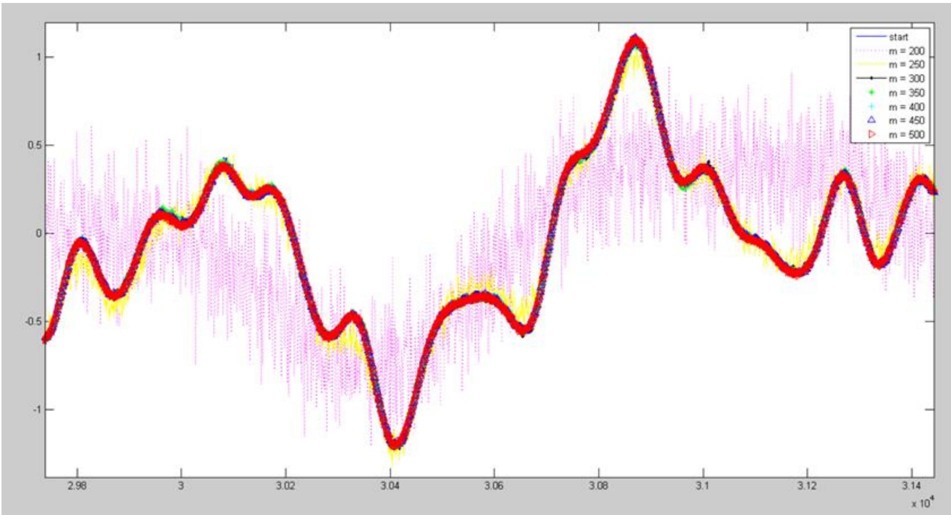
To find the best value of *m*, a parameterization of *m*-quantity is realized, in fact some different values are considered:

$$m = 200{,}250{,}300{,}350{,}400{,}450{,}500$$

In this way, it is important to observe that for *m*-factor selection it is necessary to respect the relation:

$$M \geq C * \mu^2(\Phi, \Psi) * \log(N)$$

in fact a little value of *m*-factor, for example *200 - 250*, are not sufficient to reconstructed the original signal; while a higher value of *m*-factor is not necessary because not interested in having a perfect reconstruction, that permits to have a matching between original and reconstructed signal, but they want to know approximately the *m*-factor value, that is more or less *300-400* according to the type of CS-method/solver applied, as shown in figure:.



After that m-factor value is established, study has been developed the analysis considering the different CS solvers and the two different sequences in order to study time performances, all thanks to application of script file realized with Matlab software. In particular, more attention is focused on studying how much time is necessary to reconstruct the signal considering the different type of sequence and how much are the dimensions of signal that are transferred. Time's value obtained are not excessive, on the contrary values are contained to values under 5 seconds, in general, but with particular parameters' combinations more little values are possible, for example a half of second. Very little time values for reconstruction process are possible because in study it has been possible to consider processes/tools that permits the parallelization of operations, in fact it has been token advantages using *CUDA* and *GPU* operations.

During the simulation campaign another important parameter has been considered. First of all iterations number, called *iter*, that permits to verify when stopped the algorithms, and this is considered in particular for *MP* algorithm, and tones or frequencies number, called *s*, that is the number of tones used to excite samples under test. The setting of *s*-parameter is possible only in the case of *CoSaMP* algorithm because in *MP* the determination of tones number is implicated.
In the following some tables are reported, in particular they show the necessary temporal values to reconstruct signals with *MP* and *CoSaMP* algorithm's taking account the changing of the parameters *m*, *iter*, and *s*:

m-samples/iter	Fixed Seq 50 | 75 | 100 | 125	Variable Seq 50 | 75 | 100 | 125
200	0.6 | 0.943 | 1.307 | 1.702	0.609 | 0.964 | 1.369 | 1.772
250	0.709 | 1.101 | 1.528 | 1.988	0.719 | 1.132 | 1.577 | 2.063
300	0.815 | 1.265 | 1.754 | 2.276	0.827 | 1.299 | 1.820 | 2.368
350	0.945 | 1.425 | 1.969 | 2.543	0.939 | 1.457 | 2.018 | 2.603
400	1.035 | 1.599 | 2.199 | 2.832	1.040 | 1.612 | 2.211 | 2.851
450	1.144 | 1.764 | 2.418 | 3.106	1.148 | 1.770 | 2.425 | 3.115
500	1.257 | 1.933 | 2.645 | 3.394	1.257 | 1.938 | 2.663 | 3.420

Figure 1: MP Algorithm

m-samples/tones	Fixed Seq 30 | 40 | 50	Variable Seq 30 | 40 | 50
200	0.496 | 0.775 | 11.197	5.354 | 12.053 | 33.340
250	0.306 | 1.243 | 3.369	15.163 | 8.399 | 24.133
300	0.294 | 1.045 | 1.311	17.441 | 3.333 | 17.180
350	0.597 | 1.925 | 3.598	43.296 | 2.369 | 13.810
400	0.666 | 1.795 | 3.795	48.130 | 2.343 | 8.095
450	0.736 | 1.289 | 3.139	48.524 | 2.251 | 5.064

Figure 2: CoSaMP Algorithm

About the temporal analysis, it can be seen that reconstruction time values are very fast for both the algorithms, in fact with *MP* one the maximum value is about *1.3 s* for *m = 500*, but in this case it's sufficient an *m = 300 - 350* where the time values pass to *1.0 s*, while with *CoSaMP* algorithm, time values has a significant decrease in fact the considerable value is *0.6 s*. These results refers to a fixed sequence, while for a variable sequence, in the case of *CoSaMP* algorithm time values are lightly greater in fact it's preferable to use the *MP* algorithm where values with a variable sequence are comparable with the values obtained with a fixed sequence.

A same analysis it has been developed to evaluate the error percentage of quality reconstruction, and results are shown in tables:

m-samples/iter	Fixed Seq 50 | 75 | 100 | 125	Variable Seq 50 | 75 | 100 | 125
200	96.94 | 97.98 | 98.24 | 98.32	90.24 | 91.29 | 91.61 | 91.70
250	22.59 | 23.85 | 24.29 | 24.43	23.43 | 17.37 | 17.52 | 17.75
300	9.08 | 4.38 | 4.62 | 4.75	13.65 | 6.32 | 5.84 | 6.08
350	10.46 | 4.48 | 4.43 | 4.64	11.73 | 5.07 | 4.80 | 5.03
400	7.96 | 4.17 | 4.44 | 4.57	10.75 | 4.66 | 4.45 | 4.67
450	9.60 | 4.16 | 4.26 | 4.43	9.98 | 4.38 | 4.25 | 4.45
500	9.69 | 4.19 | 4.19 | 4.37	9.50 | 4.20 | 4.14 | 4.33

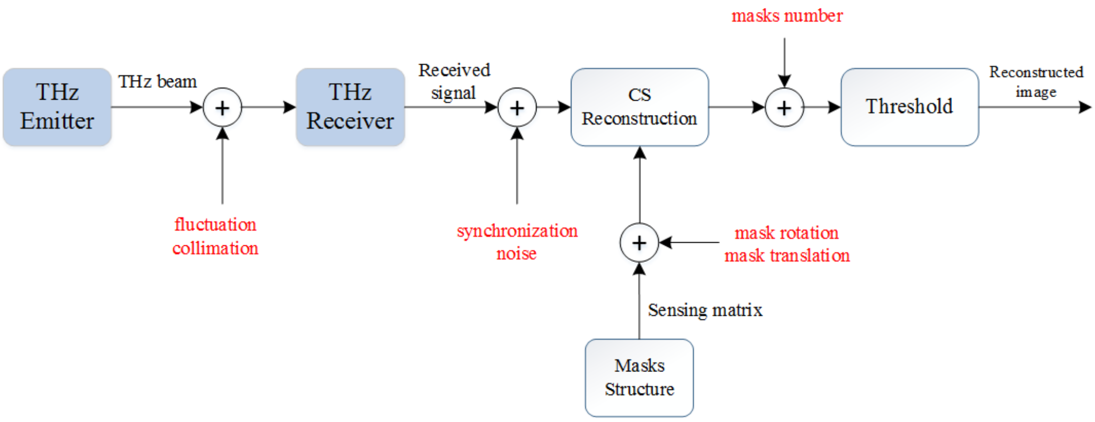
Figure 3: MP Algorithm

m-samples/tones	Fixed Seq 30 | 40 | 50	Variable Seq 30 | 40 | 50
200	84.53 | 103.63 | 126.08	77.27 | 88.05 | 100.71
250	27.42 | 4.26 | 4.43	29.59 | 11.55 | 21.17
300	27.36 | 3.85 | 4.27	27.44 | 3.99 | 4.36
350	27.36 | 3.74 | 4.09	27.37 | 3.87 | 4.17
400	28.13 | 3.61 | 3.88	27.34 | 3.75 | 4.04
450	27.36 | 3.64 | 3.79	27.35 | 3.68 | 3.94

Figure 4: CoSaMP Algorithm

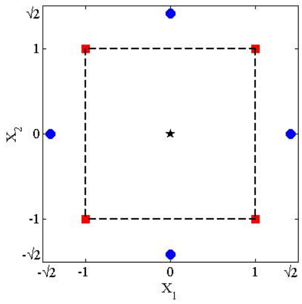
In this case, significant results are obtained with *CoSaMP* algorithm, in fact it permits to the user to determine the tone numbers necessary to realize an acceptable reconstruction. In the case, both sequences are possible considering a tone number values equal to *40*, taking in account of a bilateral spectrum, so in the truth only *20-tones* are necessary, the error percentage is about of *4%*.

About the study involved the analysis of images acquired by THz radiation and reconstructed through CS-solver, a simulated case of study has been developed and a scheme of the possible uncertainty sources that influence results has been created and it is shown in the figure, where each block models an operating step of the measurement process:



Five main blocks can be recognized: (i) *THz Emitter*, that generates the beam; (ii) *THz Receiver*, that provides the signal associated with the radiation that passed through the sample under test; (iii) *CS Reconstruction*, where the received THz signal is manipulated in order to estimate the reconstructed image;

(iv) *Mask Structure*, that provides the sensing matrix and (v) *Threshold*, where, with the aim of de-noising the reconstructed image, the grey pixels are forced to be black or white.
The figure, moreover, highlights in red the uncertainty sources characterizing each operating step, that afflict the related output. About the THz system, researches on the uncertainty source and their effect on the THz image measurements are already available in literature. On the contrary, the literature is lacking as concerns the uncertainty associated with the CS-based approach.
To reduce the computational burden, an approach based on the *Central Composite Design* (*CCD*) has been followed. The CCD, in fact, turns out to be particularly appropriate in response surface design, and allows to estimate a second order (quadratic) model for the response variable without needing of investigating the whole space of the input quantities. To this aim, only a limited number of experiments is needed and, once executed them, linear regression techniques are applied to identify the model. As it can be expected, the complexity of the model/design changes based according to number of considered input quantities; nevertheless, the sampling scheme of the input quantities space remain the same and, for the sake of the clarity, is shown in figure with reference to an example involving two independent variables.



From an operating point of view, CCD can be considered as the union of three distinct sets of experimental runs: (i) a set of centre points (indicated by a star marker in figure) replicated to preliminarily estimate the uncertainty of the experiment. The experimental runs are characterized by the same values of each input quantity; the adopted value turns out to be equal to the mean of the values assumed by the same quantity in the other experimental runs; (ii.) a set of axial points (indicated by blue bullet markers in figure) capable of emulating a one-factor-at-time analysis, i.e. the quantities values are the same of the centre points but for one of them, which assumes either the maximum or minimum value of the variation range; and (iii.) a set of values characterizing a typical factorial design (indicated by red square markers in figure) where each quantity is investigated on a two levels range.
In the case of my study, five inputs are considered and applied to CCD and in order to assess the effect of the considered uncertainty sources on the quality of the image reconstruction, two quality metrics index are introduced and evaluated: MSE and SSIM.
In the following tables, the sweep of the input parameters and the relative values of MSE and SSIM are shown:

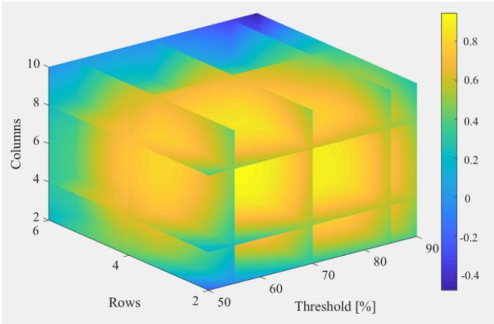
Par.	$-\alpha$	-1	0	1	α
Rotation [°]	0	0.5	1	0.5	2
Translation [mm]	0	0.25	0.5	0.75	1
Rows	2	3	4	5	6
Columns	2	4	6	8	10
Threshold [%]	50	60	70	80	90

Results of MSE and $SSIM$ obtained in CCD-based tests.

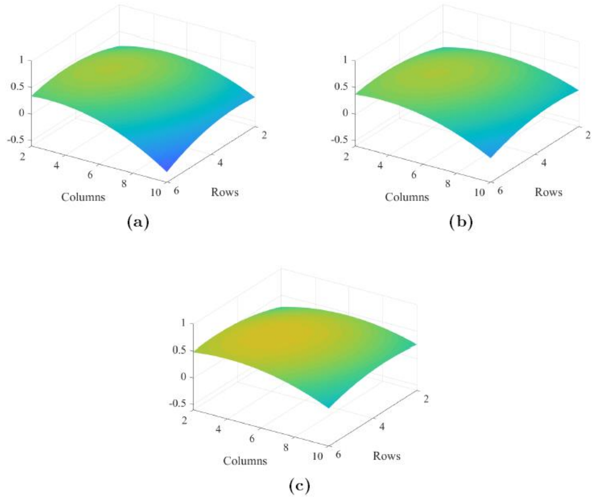
Run	Rot.	Trans.	Rows	Col.	Thr.	$SSIM$	MSE
1	-1	-1	-1	-1	1	0.2530	0.04
2	-1	-1	-1	1	-1	0.5329	0.02
3	-1	-1	1	-1	-1	0.5306	0.03
4	-1	-1	1	1	1	0.1948	0.03
5	-1	1	-1	-1	-1	0.2530	0.04
6	-1	1	-1	1	1	0.1948	0.03
7	-1	1	1	-1	1	0.2424	0.05
8	-1	1	1	1	-1	0.2424	0.05
9	1	-1	-1	-1	-1	-0.0269	0.06
10	1	-1	-1	1	1	-0.0068	0.05
11	1	-1	1	-1	1	-0.0269	0.06
12	1	-1	1	1	-1	0.1661	0.07
13	1	1	-1	-1	1	-0.0068	0.05
14	1	1	-1	1	-1	-0.0068	0.05
15	1	1	1	-1	-1	-0.0457	0.07
16	1	1	1	1	1	-0.0269	0.06
17	-2	0	0	0	0	0.5329	0.02
18	2	0	0	0	0	-0.0068	0.05
19	0	-2	0	0	0	0.2424	0.05
20	0	2	0	0	0	-0.0269	0.06
21	0	0	-2	0	0	-0.0269	0.06
22	0	0	2	0	0	-0.0269	0.06
23	0	0	0	-2	0	-0.0662	0.18
24	0	0	0	2	0	0.2061	0.06
25	0	0	0	0	-2	0.2061	0.06
26	0	0	0	0	2	-0.0269	0.06

Stemming from a deep analysis of the measurement process associated with the operating steps of the CS-based THz imaging, the main uncertainty sources (except those associated with THz beam generation and acquisition) have been singled out and their effect estimated thanks to a suitable design of experiments approach. The first considered source has been the misalignment of the matrix of masks usually adopted in CS-based THz imaging applications with respect with its ideal configuration; to this aim angular rotation and linear translation of the matrix have been taken into account. Moreover, number of different masks adopted to arrange the so-called sensing matrix has been considered. Finally, the effect of threshold level for image enhancement have been investigated. Several tests conducted both in numerical and actual experiments have been carried out to assess the uncertainty sources effects. As regards the numerical tests, two performance factors, referred to as SSIM and MSE, have been considered in order to quantify the quality of reconstructed images. Both factors have been calculated with reference to a common target image consisting of a square hole; MSE is based on pixels difference measurements, while SSIM exploited a human visual approach to estimate quality measurements. Central composite design has been adopted in order to efficiently estimate the evolution response surface of two performance factors versus the considered uncertainty sources.

Obtained results have highlighted that (i.) SSIM provides better performance due to sensitivity values higher than those granted by MSE, (ii.) angular rotation of the masks matrix has been identified as the most influencing source, (iii.) moderated value of horizontal or vertical translation only resulted in translation of the reconstructed images with respect to the ideal center, (iv.) an optimal number of masks could be determined for target reconstruction and (v.) also the position of the masks within the matrix has been assessed as uncertainty sources. With specific regard to the last two items, differently from the ideal application of the CS approach, increasing number of masks adopted for images reconstruction did not correspond to continuous improvement of their quality. Moreover, given the optimal number of masks, the best configuration is given by a "square" of masks in the matrix; this configuration, in fact, minimize the effect of the misalignment uncertainty sources.



Evolution of $SSIM$ index versus threshold, row masks, and column masks.



Evolution of $SSIM$ index versus column masks and row masks for different values of threshold a) 50% b) 70% c) 90%.

5. Products

a. Publications

During my third year I have written an article for a conference realized to Torino (I^2MTC 2017) where I presented during the session poster, also a scientific paper on review Measurements about the effect of uncertainty sources on CS-based THz systems.

- **Publication**

- "Terahertz shielding properties of carbon nanocomposite materials"
  L. Angrisani, G. Cavallo, A. Liccardo, G.P. Papari, A. Andreone, and P. Russo, International Conference on Semiconductor Mid-IR and THz Materials and Optics SMMO2016, Lisboa, Portugal;

- "Experimental Performance Assessment of Compressive Sampling-based THz Imaging Systems"
  International Instrumentation and Measurement Technology Conference (I^2MTC 2017), Turin, Italy;

- "On the Measurement Uncertainties of THz Imaging Systems based on Compressive Sampling"
  L. Angrisani, F. Bonavolontà, G. Cavallo, A. Liccardo, R. Schiano Lo Moriello
  Review on being printed Measurements.

5. Conferences and Seminars

- "Experimental Performance Assessment of Compressive Sampling-based THz Imaging Systems"
  International Instrumentation and Measurement Technology Conference (I^2MTC 2017), Turin, Italy

6. Activity abroad

I have spent no time abroad during the first year PhD course.

7. Tutorship

Exams Assistant for the B. S. course "Fondamenti di Misure (FM)", taught by Prof. Mauro D'Arco,18 hours.

Exams Assistant for B. S course "Misure per l'automazione e la produzione industriale (MAPI)", taught by Prof. Annalisa Liccardo and Prof. Rosario Schiano Lo Moriello, 23 hours.