Research Networking Programmes

Short Visit Grant ☒ or Exchange Visit Grant ☐

(please tick the relevant box)

Scientific Report

The scientific report (WORD or PDF file – maximum of eight A4 pages) should be submitted online <u>within one month of the event</u>. It will be published on the ESF website.

<u>Proposal Title</u>: Synthesis of array-based focusing systems for microwave imaging

<u>Application Reference N°</u>: 6755

1) Purpose of the visit

The main goal of the visit was to implement advanced techniques for antenna array imaging, with particular reference to the identification of faults in the radiating structure.

Broadly speaking, the presence of radiating elements that do not work properly in array antennas can cause a serious degradation of the performance of the radiating structure, and of the system in which the antenna is present. For this reason identification of faults is of great importance.

In absence of detailed information on the Antenna Under Test (AUT), including the 'active' pattern of the elements, identification of failures requires the reconstruction of the 'image' of the field on the array surface from measurements taken at some distance from the array. In particular, in the case of interest, the data are supposed to be collected on a hemisphere placed in the far field of the AUT.

During the short visit two approaches, the Matrix Method and the Compressed Sensing algorithm, were tested on a reflectarray antenna, in order to compare their performances with the classic 'Backpropagation Method' (BM) algorithm in terms of accuracy and number of measurement points required by the techniques.

2) Description of the work carried out during the visit

The first method implemented during the visit is called 'Matrix Method' (MM), and is based on the inversion of the matrix relating the current on the AUT and the measurement points. Such a matrix is usually strongly ill-conditioned and required a stabilization procedure. In the original approach, developed by Migliore and others, an iterative inversion method based on the Landweberg algorithm was used, and the regularization was obtained stopping the algorithm after a suitable number iterations. The method developed during the visit uses a different approach, based on the Singular Value Decomposition of the matrix. The regularization was obtained truncating the singular values of the matrix at a proper level.

The BM and the MM require a large number of measurements. In order to reduce the number of measurements, and the acquisition time, a second technique based on the Compressed Sensing (CS) theory has been implemented. In the following a short discussion of the CS technique is presented.

Let us consider an equispaced linear array of N=2N'+1 elements. We suppose that there is a number S of faulty radiating elements. The goal is to identify these elements from far-field data using a number M of measurements lower than the one required by other techniques. Instead of considering the excitations of the array we consider the 'innovation vectors' **x** having length N that is obtained considering the difference between the excitation and the field radiated by the AUT, and the excitation of a 'gold array' that has no fault elements. Analogously, for the data we consider the vector **y** having length M whose entries are the difference between the field radiated by the AUT in the measurement positions and the field radiated by the 'gold array' in the same sampling positions. If (as usually happens in practice) the number of faulty elements S is much smaller than the total number of elements N, the vector **x** is sparse. In fact, by formulating the problem as done, only the faulty elements of the original array radiate. This allows to solve the problem using the theory of CS, i.e. using an efficient algorithm for recovery of sparse data with a very small number of measurements.

In the algorithm developed during the visit the sparse data were retrieved using the 1-norm minimization. Since the problem is convex, it can be solved using efficient algorithms. In particular, we used CVX with Sudomi and Mosek.

3) Description of the main results obtained

The algorithms were checked using data measured in the anechoic chamber of the I.E.T.R. on an antenna designed by Thales Alenia Space in the framework of the project R3MEMS.

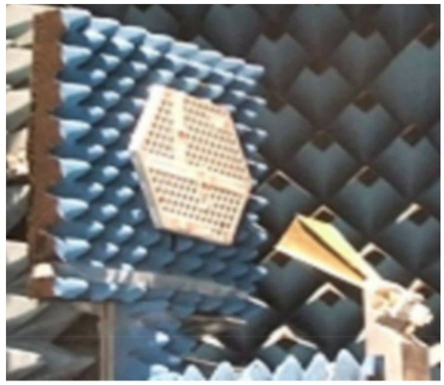

Fig 1: the AUT in the anechoic chamber

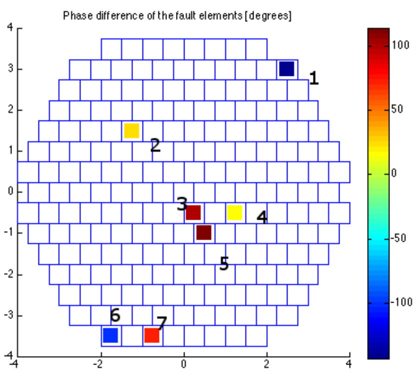

Fig. 2: positions, indexes and phase error [degree] of the fault elements;

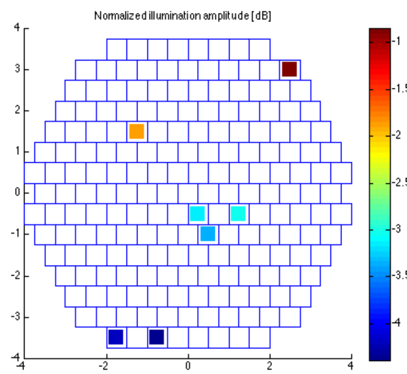

Fig. 3: amplitude [dB] of the illumination on the fault elements

The antenna was a reflect array (Fig. 1) of 193 elements with a highly tilted sidelobe. A number of 5536 co-polar and 5536 cross-polar data were collected on a far-field half-sphere. A number of 7 radiating elements were covered by metallic square patches in order to simulate a phase failure on the element. In the following the elements will be labeled as in Fig. 2. In the same Fig. 2 the value of the phase error is plotted in false color. Furthermore, the reflecting surface was illuminated by a directive horn, as shown in Fig 1. This causes a non uniform illumination of the elements. The amplitude [dB] of illumination on the fault elements (normalized to the maximum) is shown in Fig. 3.

From Fig 2 and 3 we can note that faults n. 2 and 4 have a phase different very small (around 20°, plotted in yellow color elements in Fig 2). Furthermore, faults n. 6 and 7 have a weaker illumination (dark blue in Fig 3) compared to the other fault elements due to the tapering of illumination associated to the horn pattern.

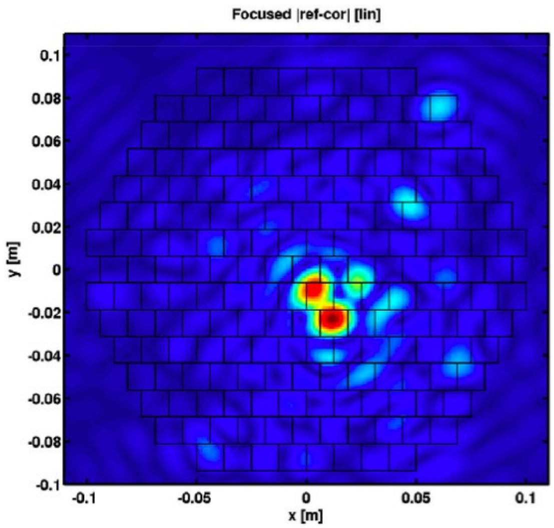

Fig. 4: Backpropagation algorithm using the FFT, 5534 data : the failures n. 3 and 5 are clearly visible; the failures n. 1 and 6 are visible but at a level lower than the one of a number of spots that cause false alarm

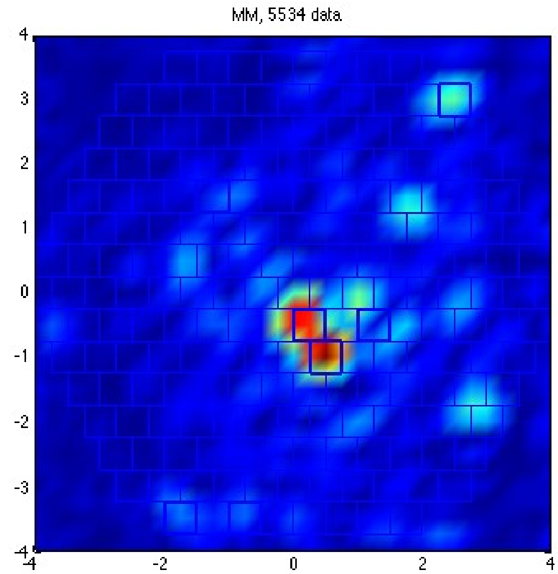

Fig. 5: Matrix Method solution, 5534 data: the failures 3 and 5 are clearly visible; the failures 1, 6 and 7 are barely visible at the same level or at a level lower than the one of a number of spots that cause false alarm

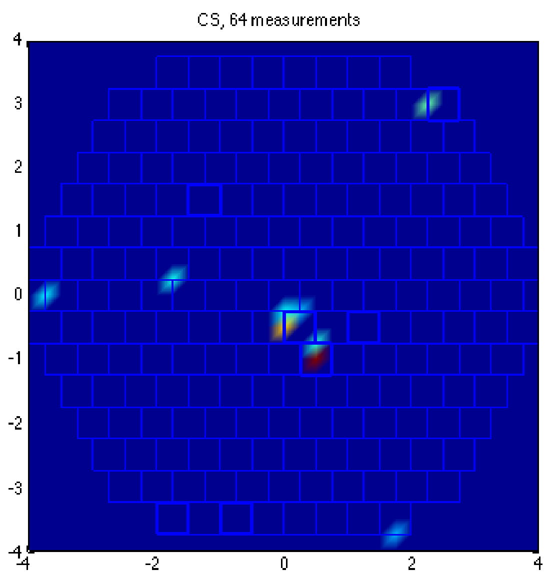

Fig. 6: Compressed Sensing solution using 1.15% of the complete data set (64 measurements): the failures n. 1, 3 and 5 are clearly visible;
some false alarms are also present at a level lower than the one associated to the failures 1, 3, 5

Method	Detected	False alarm	Covered/Invisible
BP	2	≅7	1/4
MM	2	≅6	3/2
CS	2	3	1/4

Table 1

Legend
Detected: amplitude above the false alarms
False alarms: significant level in areas different from the positions of the fault elements
Covered: amplitude below the amplitude of the strongest false alarm amplitude
Invisible: no significant level

In order to have a reference solution, in Fig 4 the result using the BM (obtained during the period of the visit by other researchers) with the whole set of co-polar data (5534) is shown. The failures n. 3 and 5 are clearly visible. The failure n. 1 is visible, but its value is lower than a spot associated to a false alarm. Some other spots causing false alarms are also present.

The result using the MM algorithm considering the whole set of co-polar data data, (5534 data) is shown in Fig 5. We can note that the failures 1, 3 and 5 are clearly visible. Failure 4 is not detected, as well as failure 2. This is an expected result since the phase difference associated to these failures is small. We can note that the failures 6 and 7 are barely visible over the noise. Furthermore, there are some 'inhomogeneities' that are not associated to faulty elements. The positions of these spots is almost the same as the positions of the spots using the BP, and their value is between the value of the spots associated to the faults 1,3 and 5, and the ones of the faults 6 and 7. They could be caused by diffraction of the metallic patches, or by some artifacts associated to the numerical algorithms. The nature of these 'false alarm' spots requires further studies.

The CS sampling method has been applied reducing the set of data from 5534 to 64, i.e. taking only 1.16 % of the original set of measured data. The result using the l1-norm minimization is shown in Fig. 6. In spite of the dramatic reduction of the number of measurements, the presence of the failures 1, 3 and 5 is still clearly visible. Other three spots causing false alarm are also visible. It is interesting to note that the values associated to the faults number 1, 2 and 5 are higher than the one of the false alarm, and a 'smart threshold' could reduce or avoid the false alarm. This suggests the investigations of automatic threshold determination paralleling the methods developed in RADAR signal processing considering the probability of detection and false alarm. It is worth noting that such reduction of measurements is of great interest in practical applications, and represents a significant improvement compared to the other available techniques.

A summary of the results is given in Table 1. The Table reports the number of the signals associated to failures whose amplitude is above the false alarms (denoted as Detected), the number of false alarm, i.e. the number of spots not associated to failures having significant amplitude (denoted as False alarms), the number of failures associated to spots that are still visible, but whose amplitude is lower than the strongest false alarm (denoted as Covered), and the number of failures that are not visible (denoted as Invisible). It must be noted that the level of fault n. 5 is only slightly higher than one of the false alarms in CS solution, and fault n. 5 has been included in the Covered faults following a conservative approach.

The table shows that BP and MM give results not far each to the other. This is related to the fact that the MM does not have information on the patterns of the elements, and hence BP and MM basically have the same information on the array. This suggests that the MM is not particularly advantageous compared to the BM in absence of more detailed information on the array. However, further studies are required to draw clear conclusions. Finally, it is useful to stress again that, in spite of the dramatic reduction of the measurements, the CS gives results not far from the other two techniques.

It is also important to note that these results were obtained during the visit in a limited amount of time, and could be improved continuing the research.

Besides the above described work, the basis of a cooperation to identify optimal sampling strategies of radiating sources has been discussed, and some preliminary work in this field of research has been started.

Finally, a lecture entitled 'Antennas and channel capacity' discussing the relationships between electromagnetics and information theory has been given during the visit.

4) Future collaboration with host institution (if applicable)

The research will continue carrying out accurate numerical simulations and further experimental investigations in order confirm the general results obtained in this short visit and finally to publish the material on an important IEEE electromagnetic journal.

At the same time we will continue also the collaboration, started during the visit, on the development of advanced sampling techniques for the reduction of the acquisition time in antenna measurement.

Furthermore, taking into account the good results obtained in this short visit, the Italian and French partners have agreed to participate to the next call of the Italy-France Galileo program in order to be able to continue this fruitful collaboration in the most effective way

5) Projected publications / articles resulting or to result from the grant *(ESF must be acknowledged in publications resulting from the grantee's work in relation with the grant)*

The short visit was very fruitful. In spite of the small amount of time of the visit, the material obtained and shortly described in this scientific report has a significant degree of novelty, and is appropriate for a publication in an important international conference such as the IEEE Antennas and Propagation Symposium.

6) Other comments (if any)