A compressed sensing approach for detection of explosive threats at standoff distances using a Passive Array of Scatters

Jose Angel Martinez-Lorenzo, Yolanda Rodriguez-Vaqueiro and Carey M. Rappaport
ALERT Center of Excellence for Department of Homeland Security,
Gordon CenSSIS, Northeastern University Boston (MA), USA
{ jmartine ; rappapor }@ece.neu.edu

Oscar Rubinos Lopez, Antonio Garcia Pino
Dept. of Signal Theory and Communications, University of Vigo, Vigo, Spain
{ oscar ; agpino }@com.uvigo.es

***Abstract*—This work presents a new radar system concept, working at millimeter wave frequencies, capable of detecting explosive related threats at standoff distances. The system consists of a two dimensional aperture of randomly distributed transmitting/receiving antenna elements, and a Passive Array of Scatters (PAS) positioned in the vicinity of the target. In addition, a novel norm one minimization imaging algorithm has been implemented that is capable of producing super-resolution images. This paper also includes a numerical example in which 7.5 mm resolution is achieved at the standoff range of 40 m for a working frequency of 60 GHz.**

***Index Terms*—radar, compressive sensing, millimeter wave imaging.**

I. INTRODUCTION

DURING the last decade, new systems based on Millimeter-Wave-Radar technology have been deployed on airport checkpoints all around the world [1]. Millimeter wave systems are preferred to X-ray systems [2]-[4], for this particular application, because the former do not use ionizing radiation. These systems have been proved to be successful on finding explosives concealed underclothing; the success of this technology is mainly due to the short range between the sensing components of the system and the person under test. A new important challenge arises when the same technology is desired for threat detection at standoff distances [5]-[8], which include ranges running between ten to fifty meters.

In this work, a novel configuration based on an array of randomly distributed transmitting/receiving antennas, located on a two dimensional aperture, is used to scan a person at standoff distances. In order to improve the resolution of the radar system, a Passive Array of Scatters (PAS) is also placed near the target region. Under this configuration, the non-linear imaging problem can be linearized if the field produced by the two dimensional array and the PAS is accurately known across the imaging region. As a result, the imaging problem can be written into a matrix form. The sensing matrix, with coefficients representing the propagation from the target to the sensor establishes the linear relationship between the reflectivity value of a pixel on the target and the field measured on the array of receivers. For the particular case in which the number of pixels in the image is much larger than the number of sensors, the sensing matrix may become singular and difficult to invert.

A new approach, based on compressive sensing [9]-[16], can be used to invert the matrix if two conditions are satisfied: 1) the image can be represented by a sparse representation of customized basis functions; and 2) the sensing matrix complies with the mathematical Restricted Isometric Property (RIP) condition. If both conditions are satisfied, the image can be reconstructed by solving a convex problem.

This paper shows how this imaging algorithm has been used to achieve a resolution of 1.5 wavelengths, or 7.5 mm at 60 GHz. The proposed algorithm can accurately reconstruct the reflectivity values of both weak dielectric scatterers, such as explosives, including Tri-Nitro-Toluene (TNT), and strong scatters, like metallic pipes, concealed under clothing.

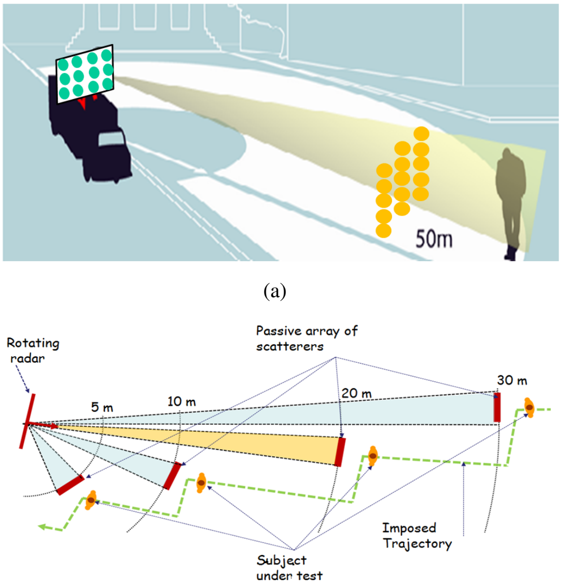
II. SYSTEM CONFIGURATION

A. System Concept of operation

The proposed system configuration is shown schematically in Fig. 1. It is composed of an inexpensive, high-resolution radar system that can distinguish foreign objects hidden on individuals at a distance, and that can still fit in or on a van. Additionally, a PAS is placed between the radar and the person under test in order to be able to achieve a super-resolution radar system. The concept of using multiple PAS over an imposed trajectory (see Fig.1 (b)) for person movement in places like airport terminals or bus stations provides the system with the option of re-configurability so that it might be applicable to indoor scenarios at multiple ranges.

B. System parameters

Fig. 2 represents a top view of the configuration and parameters of the system. The blue dots, on the left, represent the positions of the transmitting and receiving antennas. The radar is located on a square aperture of width L_1, and the total number of transmitting/receiving antennas is n_a. The orange dots, at the center of the image, represent the positions of the elements composing the PAS. The PAS is also located on a square aperture of width L_2, and the total number of elements on the PAS is n_d. The person under test is represented by the red silhouette on the right; and the reconstruction is performed by the imaging algorithm on a two dimensional plane, represented by a red line in Fig. 2, located in front of the person under test with n_p pixels. The distance between the radar and the person under test is Z_0, and the distance between the PAS and the person under test is Z_2. The resolution of the radar system, which is equal to the pixel size of the reconstructed image, is indicated by the parameter l.



(a)

(b)

Fig. 1. (a) General sketch of our van-based, high resolution radar system for standoff detection of potential suicide bombers. (b) Top view of the multiple-range concept of operation.

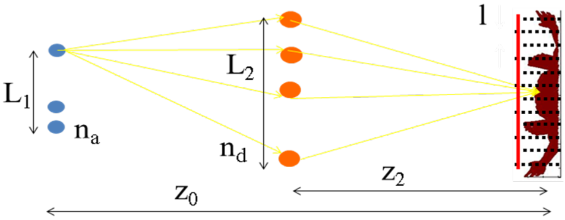


Fig. 2. Top view of the radar configuration. The blue circles on the left represent an thinned array of transmitter/receiver antennas; the orange dots on the center represent the passive array of scatters, which randomly redirect the energy of the radar towards the target; the person under test (target) is represented by the red silhouette on the right, and the two dimensional plane over which the reconstruction is implemented is represented by the red line in front of the person under test.

III. MATHEMATICAL FORMULATION FOR THE IMAGING PROBLEM

A. Sensing matrix

In this particular work, the sensing matrix, used by the imaging algorithm, is computed by using the phase term associated with an electromagnetic wave traveling as follows: 1) from each one of the transmitting antennas to each one of the scatters in the PAS; 2) from each one of the scatters on the PAS to each pixel on reconstruction plane; 3) from each pixel on the reconstruction plane to each one of the scatters on the PAS; and 4) from each one of the scatters on the PAS to each receiving antenna. This approximation is based on the following assumptions: 1) the amplitude attenuation associated with the electromagnetic wave propagation is considered to be constant, since it's impact on the quality of the reconstructed image is negligible; 2) the mutual coupling among pixels in the reconstructed image is not taken into account; 3) the amplitude and phase of the induced currents on the reconstruction plane is proportional to the incident field produced by radar illumination the latter approximation is equivalent to traditional Physical Optics method.

The system works on a multiple mono-static configuration, in which each element of the array transmits and receives on different slots of time without interacting with the radiation of other elements in the array.

Under this configuration, the sensing matrix A establishes a linear relationship between the unknown complex reflectivity vector $x \in C^{n_p}$ and the measured complex field data $y \in C^{n_d}$. This relationship can be expressed in a matrix form as follows:

$$A \cdot x + n = y \tag{1}$$

where $n \in C^{n_d}$ represents the noise collected by each receiving antenna. The matrix A can be rewritten as the product of two matrices: 1) E_b, which is a diagonal matrix accounting for the background incident field produced by a single transmitting/receiving antenna and PAS on the reconstruction plane; and 2) P, which is a full matrix accounting for the propagation from each point on the reconstruction plane to each transmitting/receiving antenna after passing though the PAS. After applying some algebraic operations, the coefficients a_{ij} of the sensing matrix A can be expressed as follows:

$$a_{ij} = \sum_{p=1}^{n_d} \left(e^{-j2k\left|r_i - r''_p\right|} e^{-j2k\left|r''_p - r'_j\right|} \right) \tag{2}$$

where k is the free space wave number; r_i is a vector indicating the position of the i-th transmitting/receiving antenna; r'_j is a vector indicating the position of the j-th pixel in the reconstruction plane; and r''_p is a vector indicating the position of p-th scatter in the PAS.

B. Imaging algorithm using compressive sensing approach

The proposed radar system is designed in accordance with the compressive sensing theory [9]-[16]. In order to apply such principles for standoff detection of explosive related-threats, certain mathematical conditions must be satisfied by the sensing matrix A and the reconstructed reflectivity image x. These conditions can be summarized as follows [13]: 1) the sensing matrix must satisfy the Restricted-Isometry-Property condition, which is related to the independency of the columns of the matrix; and 2) the unknown reflectivity vector must accept a sparse representation as a solution, which related to the number of non-zero entries on the solution vector. The parameters of the systems can be modified until these two conditions are satisfied; the optimized parameters include the following: aperture length of the radar, aperture length of the PAS, resolution in the reconstruction plane, number of antennas on the radar aperture, number of scatters in the PAS, working frequency, separation between the radar and the PAS, separation between the PAS and the target. In this work, this optimization is done manually, but it is expected that in further research contributions such optimization process should be automatized.

If the two aforementioned conditions are satisfied, then the reconstruction of the unknown vector can be performed with a small number of measurements (transmitting/receiving antennas) by solving the following convex problem [15]:

$$\min \|x\|_1 \qquad s.t. \quad Ax = y \tag{3}$$

where $\|x\|_1$ represents the norm-one of the vector x. In the particular case where x is not sparse, the problem can still be solved if one can find a discretized functional W, in which a sparse representation x_p of the unknown vector x can be found through the following relationship: $x_p = Wx$. Therefore, the "Compressive Sensing" problem can be now solved by the following problem:

$$\min \|Wx\|_1 \qquad s.t. \quad Ax = y \tag{4}$$

A Total Variation (TV) functional W is used in this particular work [15]. The TV functional W computes and adds the two directional gradients of the image x for each pixel; thus achieving a sparse representation x_p of the original image x.

IV. NUMERICAL EXAMPLES

A. Radar configuration

The imaging principles described in the previous section are evaluated on two different scenarios (see Table I): configuration #1, in which the distance between the radar and person under test is ten meters; and configuration #2, in which the distance between the radar and person under test is forty meters. Table I also summarizes all the parameters used for the numerical simulations. It is important to realize that in order to increase the range by a factor of four, from ten to forty meters, the length of the radar aperture must also be increased by a factor of four, and the number of antennas in such aperture must also be increased by a 60% factor, from five to eight hundred. The size and the number of scatters of the PAS is the same for both configurations, leading to the same system resolution of 7.5 millimeters. For the simulations in this work, a uniform white noise of 25 dB of signal to noise ratio is considered; and the working frequency of the system is 60 GHz.

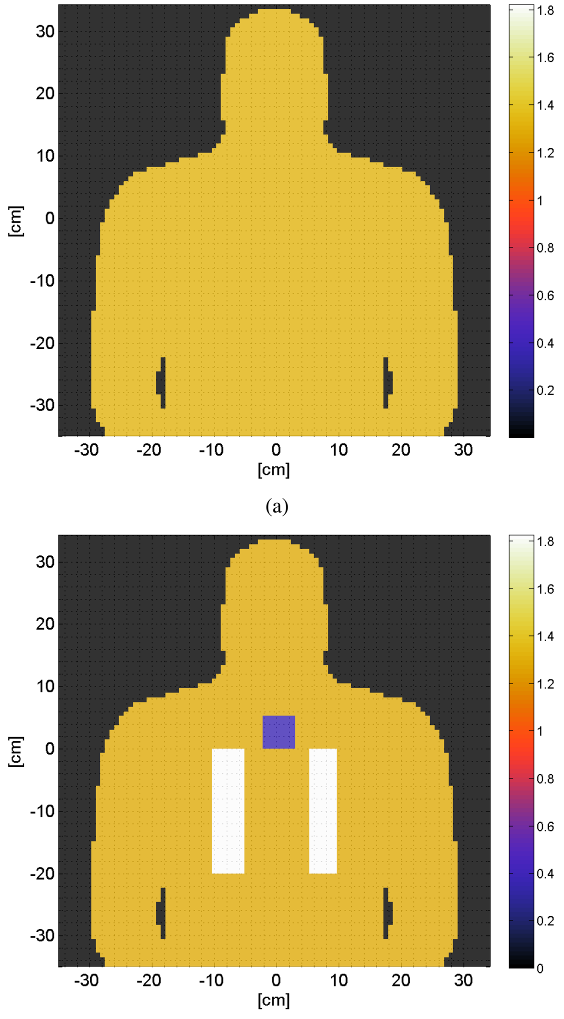
PARAMETER	CONFIG. #1	CONFIG. #2
Z_0	2000λ = 10 m	8000λ = 40 m
Z_2	250λ = 1.25 m	250λ = 1.25 m
L_1	80λ = .4 m	320λ = 1.6 m
L_2	250λ = 1.25 m	250λ = 1.25 m
n_a	500	800
n_d	1000	1000
l	7.5 mm	7.5 mm

TABLE I
PARAMETERS FOR THE NUMERICAL EXAMPLES.

B. Target specifications

In order to test the feasibility of the system, a projection into a two dimensional plane of the three dimensional geometry, –a person with attached explosives– is used as ground truth for the imaging algorithm. This two dimensional simplification of the three dimensional problem allows for a fast reconstruction using only one frequency for the radar configuration, and its extension to the three dimensional problem can be easily implemented in the future.

Fig. 3 (a) shows the two dimensional projection of a person under test; and Fig. 3 (b) shows the same person with two different types of explosive stimulants: two vertical metallic pipes of high reflectivity, and one square made of TNT of low dielectric reflectivity. The colorbar in the image indicate the absolute value of the reflectivity divided by the average reflectivity on the whole image.



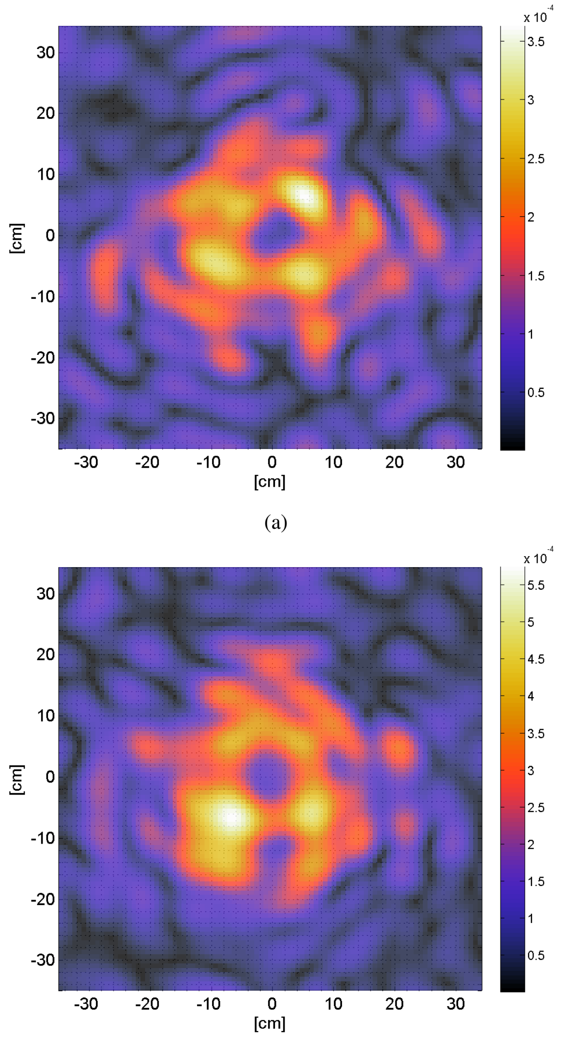
(a)

(b)

Fig. 3. Projection of the person under test used as ground truth by the imaging algorithm: (a) no-threat case, (b) threat case composed of two metallic pipes with high reflectivity and TNT square of low dielectric reflectivity.

C. *Reconstruction results*

Fig. 4 (a) and (b) show the reconstructed image when traditional Fourier-based SAR techniques [1] are used for the case of a person without and with explosive stimulants located at ten meters from the radar system (Configuration #1). This algorithm did not use the PAS; and, therefore, the resolution of the system is limited to that of the radar aperture. The quality of the reconstruction is quite deficient, and it is very difficult to discern the threat from the no-treat cases. Only an amplitude-based algorithm could be used to distinguish between the cases. The threat case, containing metallic pipes, shows some pixels with higher intensity level than those of the no-threat case.



(a)

(b)

Fig. 4. Reconstruction using traditional Fourier-based SAR algorithms for configuration #1: (a) no-threat case, and (b) threat case.

When the PAS is introduced and the norm-one minimization is used for the imaging algorithm, the quality of the reconstructed images, for both threat and no-threat cases, is substantially improved when compared to those produced by traditional SAR imaging algorithms [17][18] as it can be seen on Fig. 5 (a)-(b).

Fig. 5 (c) shows the reconstructed image for configuration #2, in which the radar and the target are separated 40 meters, when the PAS and the norm-one minimization on the imaging algorithm are used. Standoff detection at 40 meters requires that the length of the square radar aperture be increased from 0.4 meters to 1.6 meters, and the number of transmitting/receiving antennas is also increased from 500 to 800. This upgraded version of the system is capable of producing a resolution of 7.5 millimeters at 40 meters range.

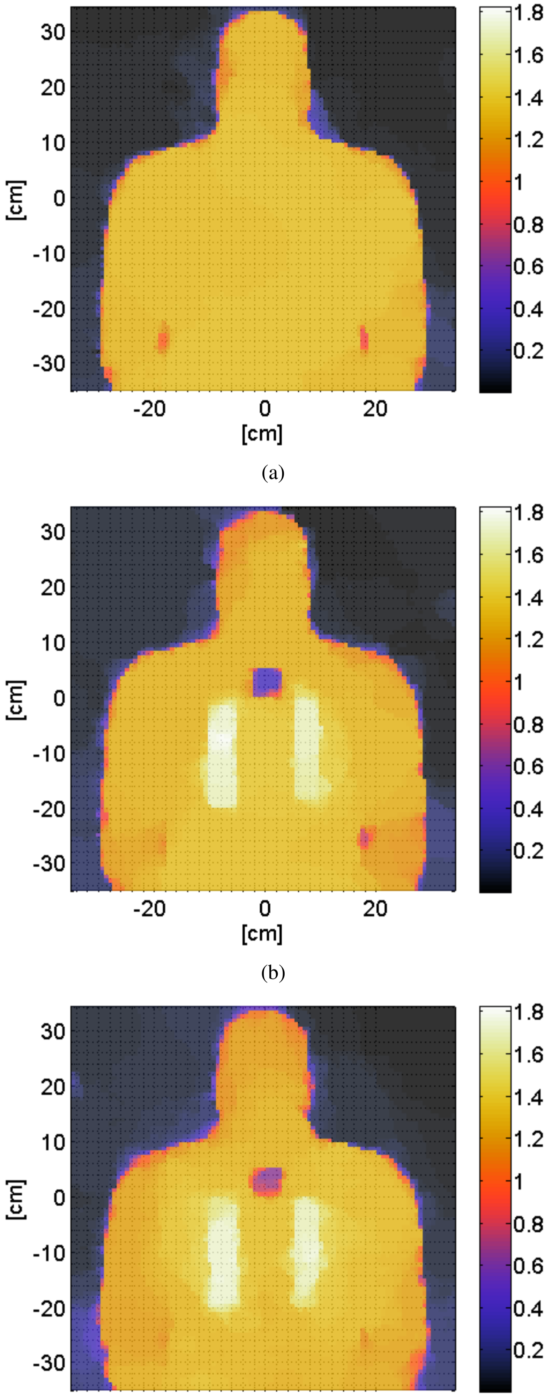
V. Conclusions

This paper describes a new millimeter wave imaging system, which is able to produce super resolution images at standoff distances. Unlike traditional imaging systems in which the radar system directly illuminates the target under test, this system illuminates a passive array of scatters that redirects the energy of the radar towards the person under test. The PAS can be seen as a magnification lens that is located in front of the target, producing a super-resolution image. The imaging algorithm used for this system is based on compressive sensing theory. This imaging algorithm is different than traditional SAR algorithms because instead of just performing a Fourier transform of the measured data, it solves a norm-one minimization problem. Another important feature of this system is that it can be configured to work at multiple ranges if a specified trajectory is imposed on the person under test, making this system well suited for deployment for indoor spaces such as airport terminals or bus stations.

The performance of the system in terms of quality of the reconstructed image was tested for two target range configurations 10 and 40 m. In both cases, the system produced a resolution of 7.5 mm. The same PAS was used for both configurations, but it was necessary to increase the size of the radar aperture for the farther case to achieve the required 7.5 mm resolution.

Acknowledgment

This material is based upon work supported by the Science and Technology Directorate, U.S. Department of Homeland Security, Award No. “008-ST-061-ED0001” By the“Ministerio de Economa y Competitividad” Government of Spain under the project CSD2008-00068 (TERASENSE) and TEC2011-28683-C02-02 (TeraRADAR). The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of DHS.



(a)

(b)

(c)

Fig. 5. Reconstruction using compressive sensing and the passive array of scatters: (a) no-threat case in configuration #1, (b) threat case in configuration #1, and (c) threat case in configuration #2.

REFERENCES

[1] D. M. Sheen, D. L. McMakin, T. E. Hall, *"Three-Dimensional Millimeter-Wave Imaging for Concealed Weapon Detection", IEEE Transactions on Microwave Theory and Techniques*, Vol. 49, No. 9, pp. 1581-1592, September 2001.

[2] US patent 5181234, Steven W. Smith, *"X-ray Backscatter Detection System"*, Issued 1993-01-19.

[3] R. F. Eilbert, Shi Shuanghe, *"Improved imaging for X-ray inspection systems", IEEE Aerospace and Electronic Systems Magazine*, Vol. 20, Issue 3, pp. 23-28, 2005.

[4] TSA X-ray Screening Technology Safety Reports: http://www.tsa.gov/research/reading/xray_screening_technology_safety_reports_march_2011.shtm

[5] J. A. Martinez-Lorenzo, F. Quivira and C. M. Rappaport, *"SAR imaging of suicide bombers wearing concealed explosive threats", Progress In Electromagnetics Research*, 125, pp. 255272, 2012.

[6] J. Fernandes, C. M. Rappaport, J. A. Martnez-Lorenzo, M. Hagelen, *"Experimental results for standoff detection of concealed body-worn explosives using millimeter-wave radar and limited view ISAR processing", 2009 IEEE Conference on Technologies for Homeland Security (HST09)*. Waltham, MA, May 11-12, 2009. pp. 456-460.

[7] A. Angell, C. Rappaport,*"Computational Modeling Analysis of Radar Scattering by Metallic Body-Worn Explosive Devices Covered with Wrinkled Clothing", 2007 IEEE/MTT-S International Microwave Symposium*. Honolulu, HI, June 3-8, 2007. pp. 1943-1946.

[8] K. B. Cooper, R. J. Dengler, N. Llombart, B. Thomas, G. Chattopadhyay, P. H. Siegel, *"THz Imaging Radar for Standoff Personnel Screening", IEEE Trans. Terahertz Science and Tech.*, Vol.1, pp.169-182, Sept. 2011.

[9] E. Candes, J. Romberg, and T. Tao, *"Robust Uncertainly Principles: Exact Signal Reconstruction from Highly Incomplete Frequency Information", IEEE Transactions on Information Theory*, 52, 2, February 2006, pp. 489-502.

[10] E. Candes, J. Romberg, and T. Tao, *"Signal Recovery from Incomplete and Inaccurate Measurements", Communications on Pure and Applied Mathematics*, 59, 2006, pp. 1207-1223.

[11] D. L. Donoho, *"Compressed Sensing", IEEE Transactions on Information Theory*, 52, 4, April 2006, pp. 1289-1306.

[12] R.G. Baraniuk, *"Compressive Sensing", IEEE Signal Processing Magazine*, 24(4), pp.118-121, July 2007.

[13] A. C. Fannjiang, T. Strohmer, and P. Yan, *"Compressed Remote Sensing of Sparse Objects", SIAM J. Imaging Sciences*, Vol. 3, No. 3, 2010, pp. 595-618.

[14] M.D.Migliore, D.Pinchera, *"Compressed Sensing in Electromagnetics: Theory, Applications and Perspectives", Proc. of the EuCAP*, Rome (Italy), 2011.

[15] S. Becker, J. Bobin, E. J. Candes, *"NESTA: A Fast accurate first-order method for sparse recovery" Siam J. on Imaging Sciencies*, Vol. 4, pp. 1-39.

[16] http://www-stat.stanford.edu/ candes/nesta/

[17] Y. Alvarez, J. A. Martinez, F. Las-Heras, C. M. Rappaport, *"An inverse Fast Multipole Method for geometry reconstruction using scattered field information". IEEE Transactions on Antennas and Propagation*, Vol. 60, No. 7, pp. 3351-3360, July 2012.

[18] Y. Alvarez, J. A. Martinez-Lorenzo, F. Las-Heras and C. M. Rappaport. *"An inverse fast multipole method for imaging applications", IEEE Antennas and Wireless Propagation Letters*, 10:12591262, 2011.

ABOUT THE AUTHORS

Jose Angel Martinez-Lorenzo - *jmartine@ece.neu.edu*

Yolanda Rodriguez-Vaqueiro

Carey Rappaport - *rappapor@ece.neu.edu*

ALERT Center of Excellence for Department of Homeland Security,

Gordon CenSSIS, Northeastern University Boston (MA), USA

Oscar Rubinos Lopez - *oscar@com.uvigo.es*

Antonio Garcia Pino - *agpino@com.uvigo.es*

Dept. of Signal Theory and Communications, University of Vigo, Vigo, Spain