Abstract—This paper presents the main results of air target imaging obtained by the authors within the frame of the MAPIS (Multichannel Passive ISAR imaging for military applications) project. These results have been obtained by processing the data collected during the MAPIS trials that were carried out in June 2017 in Livorno, Italy. The results presented in this paper represent a first attempt to image an aerial target by using a multistatic and multichannel passive radar system. The results obtained by processing the measurements have been supported by means of simulated data that faithfully reproduce the acquisition geometry.

Keywords—passive ISAR; Multistatic Passive ISAR; Multichannel Passive ISAR; MAPIS.

I. INTRODUCTION

ISAR (Inverse Synthetic Aperture Radar) imaging using active radars is a well-known and mature technology that allows for high resolution images of moving targets to be obtained. ISAR images are commonly used in the next steps of processing as input data for systems that perform target classification and recognition [7][8][9][10].

The ISAR system range resolution is limited by the radar bandwidth. Thanks to recent technological advances, modern active radar are able to transmit wide bandwidth signals of several GHz, which provide a resolution of a few centimeters. The problem is to allocate such a wide bandwidth in congested and contended spectrum conditions.

For very high frequencies, like commercial bands operating at 120 GHz, there is no problem to transmit wide bandwidth. The limitation in this case is the very short range coverage due to the low transmitted power of the transmitters which are currently available on the market operating in these frequency bands. In the lower radar bands, like L, S, C, X, the usage of available radar bands is strongly limited by international spectrum regulations.

The solution might be the use of passive radar technology, which does not require bandwidth allocation as it relies on sources of illumination already available, such as radio, TV, navigation (GPS) or mobile communications transmitters.

The problem of using passive ISAR technology for air target imaging has been studied by the authors within the frame of the MAPIS (Multichannel Passive ISAR imaging for military applications) project, [11], [12], [13], [14], [15]. The objective of the MAPIS project was to study, define, and analyse a new system concept for implementing and demonstrating ISAR imaging capability in a plug-in multistatic array passive radar finalized to target recognition.

This paper presents the main results of the MAPIS project and a feasibility study of using a multichannel PCL (Passive Coherent Location) system in multistatic configurations for air target image formation.

As an introduction to the obtained results an analysis of SISO (Single Input, Single Output) and MIMO (Multiply Input, Multiply Output) configurations is shown in the next section of this paper.

II. PASSIVE ISAR IMAGING – FROM SISO TO MIMO CONFIGURATIONS

Within the MAPIS project, two main architectures have been identified and analyzed: SISO and MIMO architecture.

SISO stands for Single Input Single Output. The PCL system resorts in this case to a bistatic system since the transmitter and the receiver are not co-located. Passive ISAR imaging in this scenario exploits the results from bistatic ISAR theory. Passive Bistatic ISAR feasibility has been well investigated in the literature theoretically [1], and also proven by using measurements. [2], [3].

MIMO stands for Multiple Input Multiple Output and in general it refers to a multi-bistatic PCL system where the receivers and/or the transmitters are spatially distributed.

In this paper SIMO (Single Input, Single Output) architecture will be considered, and therefore a case with a single transmitter and multiple receivers. Fig. 1 represents the
multi-bistatic PCL geometry where spatially separated receivers observe the target from different aspect angles.

As MIMO can be seen as a combination of a number of SISO systems, the main difference of the MIMO imaging architecture with respect to the SIMO architecture is the possibility to combine ISAR image/data from a number of SIMO.

A net of distributed PCL systems has a number of obvious advantages over conventional bistatic geometry, particularly reduced shadowing effects and robustness over aspect angle changes. The main problem to be addressed is how to combine data from each receiver. Data combination can be performed either at raw-data level (coherent fusion) or at image level (incoherent fusion). The authors in [4] and [6] have discussed and provided reasoning on these points. The fusion scheme to use depends on a number of technological and theoretical issues, namely:

1) Synchronization and/or phase coherence must be kept high. Specifically, phase coherence is necessary in the case of raw-data level fusion.
2) Image/data precise co-registration.
3) Fore-shortening effects due to the different receiver LoS (Line of Sight). An ISAR raw-data or image is available at each receiver. The 2D ISAR image (or the corresponding raw data in the Fourier domain) represents the projection of the 3D target reflectivity function onto a 2D plane whose orientation depends on the radar-target geometry and the target’s own motions. Because of the spatial diversity, the two dimensional ISAR images may lay on different 2D planes, thus complicating their combinations. To effectively combine such raw-data or ISAR images a priori information of the target motions (or an estimate of them) is needed.

In this paper some of the issues previously discussed have been addressed, while others were overcome due to the fact that the geometry was completely a priori known during the measurements and the target and the receivers were equipped with GPS/IMU systems. As a consequence, synchronization and phase coherence were guaranteed by the fact that receivers have the same clock reference, which allows simultaneous acquisitions. Precise co-registration is guaranteed via a multistatic autofocusing algorithm which exploits the actual target motions. Finally, since the receivers were located at similar altitude the bistatic pairs share similar geometries apart from the rotation angle, and this condition makes the raw-data combination easier.

The results presented in this paper have been obtained by implementing a raw-data level fusion algorithm. The proposed algorithm is represented in Fig. 2.

As it can be noted each receiver locally computes the RD (Range-Doppler) map, \( R_i(\tau, \omega) \), where \( i = 1, 2, \ldots, N_r \) and \( N_r \) is the number of receivers, \( \tau_i \) and \( \omega_i \) represent the delay-time and Doppler axis which refer to the \( i \)-th receiver. Then, the motion compensation algorithm is applied at each receiver by using information on the target motions which are a priori known or estimated. The result is an ISAR image at each receiver, \( I_{ISAR}(\tau, \omega) \), which can be converted into raw-data by means of an inverse Fourier transform. Then, by using the receiver, target and transmitter position vectors, the local ISAR images are projected back into a data domain, namely the k-space domain, which is common to each receiver, where

\[
\mathbf{k} = \frac{2f}{c} \left( \mathbf{x}_{T \rightarrow g} + \mathbf{x}_{R \rightarrow g} \right)
\]

are the position vectors of the target with reference to the transmitter and the receiver, respectively, and \( f \) denotes carrier frequency and \( c \) is the speed of light. Finally the raw data are coherently added and a discrete Fourier transform applied to obtain the multibistatic ISAR image, \( I_{MBAISAR}(\mathbf{x}) \). Further details about the proposed algorithm can be found in [5].

### III. MAPIS RESULTS

In this section, selected results of passive ISAR imaging obtained within the MAPIS projects are presented. In the first phase of the project the system concept was validated using
Simulations described and analyzed in the next subsection, then the MAPIS trials were carried out to verify the simulations’ results using real measured data.

**Simulation Results**

The simulated scenario is depicted in Fig. 3. In the scenario the isotropic transmitter is placed at [0, 0, 0]. The receiving antennas are respectively positioned at:

- Rx 1A = [-20313.7, -23935.1, -741.5] [m],
- Rx 2 = [-19794.3, -24687.2, -754.5] [m],
- Rx 3A = [-1.8983.0, -2.6734.2, -713.4] [m];

and the portion of trajectory under analysis is highlighted in red colour. As the distance from Tx to Rx is much longer than the analysed target trajectory, the red colour trajectory in Fig 3 appears as an almost single dot. To show a more detailed view of the target trajectory, the corresponding close up is presented in Fig. 4, where the target trajectory is depicted in white and the positions of the receivers are marked by red circles.

The waveform of opportunity is represented by a previously recorded real DVB-T signal containing 7 adjacent channels (Fig. 5). In particular, it is characterized by the following parameters:

- central frequency = 634 MHz;
- sampling frequency = 60 MHz;
- duration = 10 s.

In the first set of simulations, a 35 omni-directional point model of the plane was used. The movement of the target is presented in Fig. 6. In the final simulations, the simple model was replaced with an over 15.5 thousand directional point model of the Cessna aircraft. The simulation includes an over 11.5 million point DTM (Digital Terrain Model), representing the area spanning from Corsica to the western part of the Italian Peninsula. The target trajectory is visualized in Figure 6, with five groups of points representing a simple model of the plane every 2.5 seconds. During the simulation, which is 10 seconds long, the plane traveled about 400 meters with a slight curvature.
Fig. 6. Target trajectory and orientation.

Fig. 7 shows the final obtained results of the representations of the spatial frequency domain and the ISAR image of the target obtained using the signal simulated for one of the receivers (SISO configuration), depicted in Fig 4 as Rx2.

Fig. 8 presents the combined k-space representations for all three receivers depicted in Fig. 4 (Rx1, Rx2 and Rx3). In this case a wider representation in the spatial frequency domain has been obtained. Therefore, its Fourier transform will provide better resolution k-space representation and ISAR image of the target in the receiver (compare results presented in Fig. 7 and Fig. 8).

Results from MAPIS Trials

In this section the analysis of selected real data acquired with one of the passive radar sensors used during the MAPIS trials - the WUT (Warsaw University of Technology) PARADE (Passive Radar Demonstrator) is shown. PARADE is a modular passive radar system constructed at the WUT. Specifically for the MAPIS project, a system consisting of three receivers was constructed based on National Instruments equipment. Fig. 9 presents photos of one of the receivers during measurements.

One target of interest during the trials was an Airbus A319 plane landing. As an example the recorded trajectory of the Airbus A-319 with marked positions of the WUT receivers (Rx1-3) and transmitter of opportunity (Tx) is shown in Fig. 10.

During the trials multiple DVB-T channels were used in the processing. The spectrum of the recorded signal is shown in Fig. 11.

In Fig. 12 the target echo in the k-domain is presented.
As can be seen, the representation of target echo in k-space strongly depends on Tx-Rx geometry. Each receiver station fills a different k-space region. Thanks to this, merging the signals from different passive radar receivers allows one to get a better filling of the k-space (see Fig. 12d), which results in better resolution of the final ISAR image created using multi receiver stations. The final passive ISAR images obtained using DVB-T channels 35, 36, 39, 40, 41 and 42 are presented in Fig. 13.

For comparison, Fig. 14 presents the images for simulated target echo. The simulated target trajectory, transmitters’ and receivers’ positions were the same as in the real measurements. In this case all images obtained for each transmitter – receiver pair were combined coherently and noise was not considered.

Comparing the images in Fig. 13 and Fig. 14 it can be found that the ISAR images of the A-319 target obtained from the real data collected during the MAPIS trials correspond well to the simulated results which creation also helps to understand and explain certain features of ISAR images obtained in real measurements. Presented results shows high potential in the multistatic ISAR imaging. However, there are still some points which need to be improved in future. Further study is needed on the method of coherency reconstruction between multi-receiver data. The fully coherent summation of the images from independent passive radar receivers should give more precise ISAR imaging. To get such images, autofocus techniques with higher order motion parameters estimation have to be applied to the collected data. Due to the limited time for data processing, this topic will be the subject of further research in multistatic image creation.

IV. CONCLUSIONS

This paper presents a first attempt to obtain a multistatic passive ISAR image of aerial targets. Multichannel passive bistatic ISAR imaging has been proven feasible both theoretically and experimentally, and a number of real data results and papers prove it. Conversely, multi-bistatic passive ISAR imaging has never been proven with real measurements.

With the aim to demonstrate the feasibility of the multi-bistatic ISAR concept a measurement campaign was carried out in Livorno, Italy, by using a multi-bistatic PCL system. During the experiment, both the receivers and the target were equipped with GPS/IMU systems and therefore the geometry was completely a priori known. The proposed algorithm was applied to the acquired data by exploiting a priori knowledge about both the transmitter, receivers and target position.

To assess the results obtained by processing the real data, a simulation was carried out which faithfully reproduced the acquisition geometry.

The simulated data results are comparable with the real data results, thus confirming the feasibility of the multi-bistatic passive ISAR concept and the validity of the proposed algorithm.

However, a number of points need to be further investigated and more deeply addressed in the future. In particular, further study is needed on the multistatic autofocusing algorithm which is now implemented by making
use of a priori information about the target motions and by considering only the target velocity [16]. Higher order motion parameters should be considered to improve the ISAR image co-registration and focus degree.

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