Eco-friendly dual-band AULOS® Passive Radar for air and maritime surveillance applications

Tatiana Martelli, Fabiola Colone
DIET Dept. Sapienza University of Rome,
Via Eudossiana 18, 00184 Rome, Italy
tatiana.martelli@uniroma1.it, fabiola.colone@uniroma1.it

Roberta Cardinali
Leonardo Company
Via Tiburtina Km 12.400, 00131 Rome, Italy
roberta.cardinali@leonardocompany.com

***Abstract* —The last results obtained with the Eco-friendly dual-band AULOS® passive radar sensor carried out within the long-term collaboration between Sapienza University of Rome and Leonardo S.p.A. are here reported. Specifically, FM and DVB-T signals are parasitically exploited for air and maritime surveillance applications. A significant effort concerned the development of signal processing techniques to be efficient in both the investigated applications. To this purpose, the recent processing techniques developed by the research group of Sapienza have been applied. We show that the FM-based AULOS is able to detect with great continuity the typical aerial traffic as well as aircrafts with low RCS. In contrast, the DVB-T based sensor can be successfully employed for monitoring vessel of different dimensions both in the proximity of a port that travel during the day. The reported results confirm that the considered sensor can be usefully employed for improving safety and security of public areas, such as airports and harbors, preserving both the landscape integrity and the electromagnetic health of the population.**

Keywords—passive radar, AULOS® sensor, FM signals, DVB-T transmissions, aerial surveillance, maritime surveillance.

I. Introduction

Nowadays, it is increasingly important to improve the security and the protection of public areas, such as ports, airports and trains station. To this purpose, a compelling alternative to the use of active radar is represented by passive radar (PR) systems. PR exploit existing transmitters as illuminators of opportunity to perform target detection, localization, and also imaging. This means that, due to the lack of a dedicated transmitter, they provide several advantages with respect to the conventional active radar such as reduced costs and facilitated maintenance, as well as intrinsic covert operation and low vulnerability to electronic countermeasures. In addition, due to the fact that they do not emit any e.m. radiation and yield a small impact on the landscape thanks to their reduced size, they are considered eco-friendly systems; hence, they are also called "green" systems. For the aforementioned reasons, they are especially interesting for residential and urban area monitoring preserving both the landscape integrity and the electromagnetic health of the population [1]. Different transmitters for telecommunications, remote sensing and radio navigation applications have been employed in this opportunistic manner and their practicability has been well demonstrated in a number of civil and military applications [2]-[5].

For all the above motivations, PR are of great interest also for the industry world. In this regard, AULOS® is the passive radar family system developed by Leonardo S.p.A.. It is a dual-band system that exploit both FM radio stations [88-108 MHz] and Digital Video Broadcasting-Terrestrial (DVB-T) transmissions [470 862 MHz] for surveillance applications. The exploitation of the FM radio broadcast transmitters represents the best choice for air surveillance applications because they offer high power level and wide coverage. In contrast, the wide horizontal beam and the excellent coverage as well as the wider frequency bandwidth (that allows a range resolution of approximately 20 m) of the DVB-T transmitters make the DVB-T based AULOS system the most attractive solution for maritime surveillance, [6]-[8].

In this contribution, we report the last results obtained with the AULOS system carried out within the long-term collaboration between Sapienza University of Rome and Leonardo S.p.A. A significant contribution concerned the development of signal processing techniques to be efficient in both the investigated applications. Specifically, aiming at enhancing the target detection and localization ability of the considered system, the recent processing techniques developed by the research group of Sapienza have been applied [8]-[9].

With reference to the FM-based AULOS component, recently it has received a renewed interest so much so it was involved in a research collaboration agreement between Nanyang Technological University (NTU) of Singapore and Leonardo S.p.A.. To this purpose, dedicated acquisition campaigns have been performed in a military airport using the high performing FM-based AULOS receiver. Both traffic of opportunity and small cooperative targets have been considered. The obtained results clearly show that the system is able to detect and localize the typical aerial traffic up to very long range distance as well as aircrafts with low radar cross section (RCS). This means that such sensor can be fruitfully integrated within conventional Air Traffic Control (ATC) solutions, with the role of gap-fillers, for providing continuous coverage.

Regarding the DVB-T based AULOS component, we have conducted different test campaigns at different sites along the

Italian coastline. The reported results prove that the system is able to detect vessels of different dimensions located both close to the coast and at long range distances. Therefore, the conceived sensor can be successfully exploited for monitoring the typical maritime traffic travel during the day and for improving the situational awareness in the proximity of a harbor.

The paper is structured as follows. The benefits of using passive radars for air and maritime surveillance applications are illustrated in Section II. In Section III we summarize the developed AULOS® processing schemes by highlighting the main differences given by the exploitation of the two different waveforms of opportunity. The experimental results for both air and maritime surveillance applications are shown in Sections IV and V, respectively. Finally, we draw our conclusions in Section VI.

II. PASSIVE RADARS FOR AIR AND MARITIME MONITORING

As it is well known, in the air transportation field, the security topic represents the main issue. Conventional ATC systems cover large airspace but they do not assure the full coverage in particular geographical areas (like mountains and valleys) and they are unable to detect low altitude targets. Therefore, FM-based PR could be effectively integrated within conventional ATC sensors, with the role of gap-fillers, to extend the conventional surveillance coverage but also to guarantee the detection in case of failure of the conventional surveillance system. This with a reduced cost and a limited impact on the environment. Another possible application of the FM-based sensor is for supporting search and rescue operations in critical scenarios. As an example, for tracking the low RCS aircrafts employed in emergency services (such as air ambulance, Canadair) during fires, landslides, earthquakes (see Figure 1(a)).

With reference to the maritime scenario, the dense maritime traffic requires modern control systems able to enhance the situational awareness in the proximity of a harbour and to strengthen the navigation safety level, with a reduced e.m. pollution level as well as a limited environmental impact. Therefore, the DVB-T based PR represents a valid alternative to the use of active systems that generally are not very accepted from the local resident people. In particular, such sensor could be integrated with the conventional technologies to create a cost-effective sea border surveillance system. To this purpose, it is worth mentioning that, in the last years, the DVB-T based AULOS component has been involved in two European Projects (Seabilla and Closeye) together other different sensors to create an advanced technological surveillance solution for enhancing the security of the European waters [10]-[11].

Otherwise, aiming at the monitoring of marine areas where typical active radars cannot be installed (such as protected areas), a network of passive sensors could be created to provide continuous and complete coverage along the coastline meanwhile to preserve the integrity of the coast (see Figure 1(b)).

Figure 1. Scenarios of potential interest: (a) FM-based PR for supporting search and rescue operation in critical scenarios; (b) DVB-T based PR for monitoring of marine protected areas.

In the following, we illustrate the effectiveness of the AULOS® sensor in the considered surveillance applications.

III. AULOS® PROCESSING SCHEME

AULOS® is a technologically advanced sensor developed entirely on the basis of a “software defined radar” approach, involving signal sampling directly at carrier frequency using COTS (commercial off the shelf) devices for signal reception and digital processing. The resulting bi-band family offers great flexibility for potential use in a variety of operating conditions, along with enhanced target monitoring distance and position estimate performance, [6].

Figure 2 sketches the developed AULOS® processing scheme for the detection and localization of the target echo. Notice that each single block has been opportunely tailored to be effective against both the exploited source of opportunity (FM or DVB-T) and the considered application (air or maritime surveillance). The main blocks are briefly described below.

As it is well known, a surveillance antenna (steered toward the area to be monitored) is used to collect the signal reflected from the target. Obviously, multiple surveillance antennas can be employed. Then, an additional antenna (the reference antenna), steered towards the transmitter of opportunity, is employed to collect the transmitted signal that is unknown at the receiver, [12].

First of all, we perform a disturbance cancellation on the K available surveillance channels for the removal of the direct

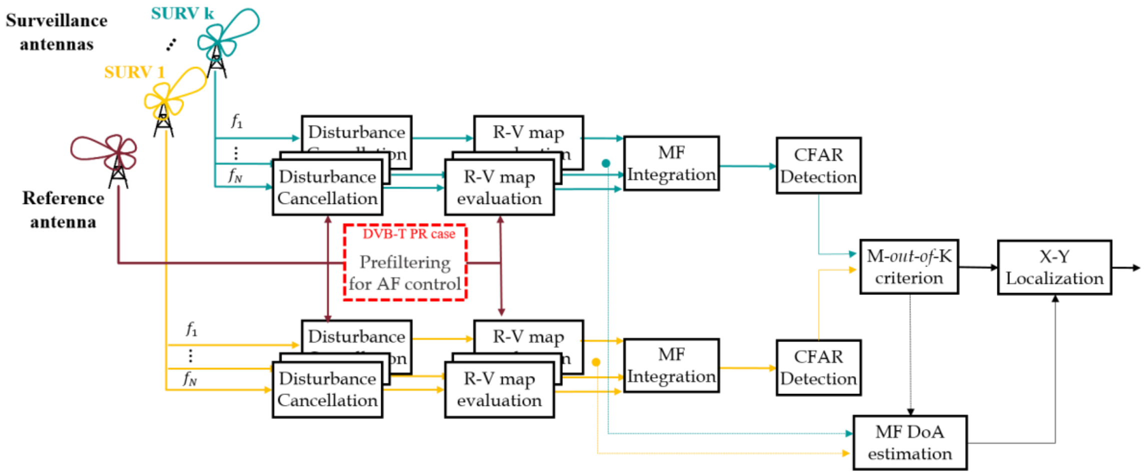


Figure 2. Developed AULOS® processing scheme.

signal, clutter and multi-path returns, received together with the moving target echo. For the purpose, we consider the sliding version of the extensive cancellation algorithm (ECA-S) recently proposed by the same authors in [9]. Then, the output of the above stage and the corresponding reference signal are adopted to evaluate the bistatic Range-Velocity map. Typically, the Range-Velocity map evaluation represents the most costly operation in a conventional PR processing scheme. In fact, in both the considered applications, integration times of order of few seconds (1-2 s) are necessary to extract the target signal, characterized by a low level, from the disturbance (namely, a large number of complex multiplications to perform). Notice that, since the computational load is also proportional to the bandwidth of the specific waveform of opportunity, the DVB-T case corresponds to the most challenging application in terms of computational burden. To reduce the computation load, with limited Signal to Noise (SNR) loss, sub-optimum techniques have been applied following the approaches in [12]. When DVB-T signals are considered, due to their digital nature, high side-lobes and spurious peaks appear in the Ambiguity Function (AF). For the removal of such undesired peaks, the reference signal is properly filtered before it is used for Range-Velocity evaluation (dashed red block in Figure 2), [13].

Despite the efficiency of the above blocks, the detection performance highly depends on the exploited FM or DVB-T frequency channel. Notice that, in both AULOS configurations, the passive sensor is able to collect simultaneously multiple FM or DVB-T channels. Aiming at enhancing the target detection ability of the passive system, multi-frequency (MF) integration strategies, able to jointly exploit multiple channels transmitted by the same transmitter, have been implemented following the approaches in [8], [14]. Once we have evaluated the integrated map at all the available receiving channels, a conventional CA-CFAR threshold is separately applied to each map to detect targets over the bistatic range-velocity plane with a considered probability of false alarm (P_{fa}).

Afterward, an *M-out-of-K* criterion can be adopt to integrate the detection results over the *K* receiving channels. Eventually, the Direction of Arrival (DoA) of the detected echo is estimated with the purpose of localizing it in the X-Y plane. To this purpose, MF approaches could be considered for target DoA estimation to exploit the benefits derived from the availability of multiple frequency channels also for target angular localization [15].

IV. FM-BASED PR FOR AIR SURVEILLANCE APPLICATION

In this work, we show the detection results obtained against the datasets acquired during the test campaigns performed in August 2017 at Pratica di Mare Airport, Rome. Both traffic of opportunity and small cooperative targets have been considered.

A. *Test campaigns and data collection*

Figure 3 reports the acquisition geometry. The reference antenna was steered toward the FM transmitter of Monte Cavo while two log-periodic surveillance antennas (with distance $d = 1.65\ m$) were adopted with a main beam-width of 120°. A sketch of the antenna's configuration is illustrated on the bottom left corner of Figure 3.

For the tests against traffic of opportunity, the surveillance antennas were pointed at 280° clockwise from north in order to include in the main beam most of the civilian air traffic departing or arriving to Fiumicino airport (see yellow lines in Figure 3). Live ATC registrations have been also collected (by means of an ADSB receiver, Automatic Dependent Surveillance - Broadcast). In contrast, the tests with cooperative targets were conducted pointing the surveillance antenna beam in the south direction with respect to the installation, specifically at 165° clockwise from north (see green lines in Figure 3). This area was selected in cooperation with Italian Air Service Provider (ENAV), which prohibited the flight in the area near Fiumicino airport in order not to interfere with Fiumicino traffic. The tests were conducted exploiting the small aircrafts provided by flying school Aviomar located in Urbe airport in Rome (see Figure 3). Both Cessna 172 and Cessna 152 (see Table 1) have been employed as cooperative targets equipped with a GPS receiver. Their dimensions, pictures and additional details are reported in Table 1.

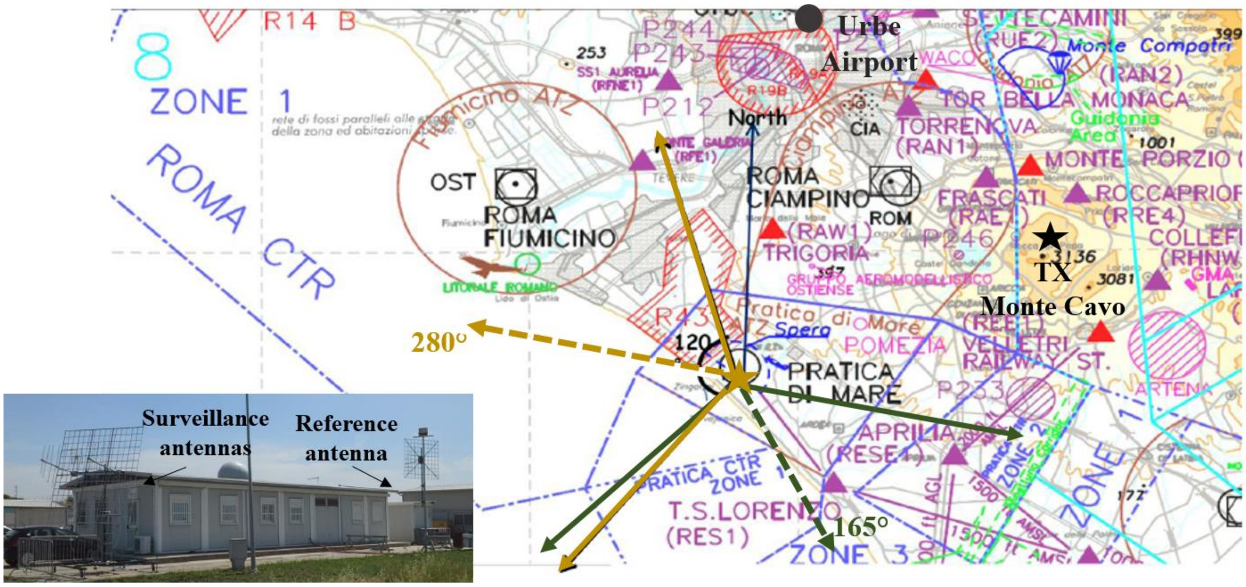


Figure 3. Picture of the test geometry of the acquisition campaigns carried out at Pratica di Mare Airport (Rome).

Different tests have been performed against the above targets and some results are illustrated in the following section.

Table 1. Details of the employed cooperative targets.

	Cessna 152	Cessna 172
Length (m)	7.3	8.28
Wingspan (m)	10.2	11
Height (m)	2.6	2.72
Number of passengers	one	three
Picture		

B. Detection results

The FM-based processing scheme (illustrated in Figure 2) has been applied at all the collected data files. Specifically, we use an integration times of 1.4 s and 2 s for the bistatic range-velocity map evaluation, at both surveillance channels, in the case of traffic of opportunity and cooperative targets, respectively. Then, for the detection of the target, we resort to a CA-CFAR with a nominal $P_{fa} = 10^{-6}$ (against traffic of opportunity) and $P_{fa} = 10^{-5}$ (against cooperative targets) on the final range-velocity plane after a 2-out-of-2 detection criterion across the available receiving channels. In both cases, the joint exploitation of five FM frequency channels has been considered using the centralized approach reported in [8], [14].

As an example, Figure 4 shows the raw detection results, within 205 s of acquisition time, for a test against traffic of opportunity. The red plots are the raw detections of the PR sensor while the black trajectories represent the available air truth, reported for direct comparison. Notice that these are raw detections, namely no tracking or track initiation stage is applied. As it is evident, most of the opportunistic targets moving in the surveyed area are correctly and continuously detected by the FM-based AULOS PR. Specifically, targets are detected at very long bistatic range, till 400 km.

For the case of cooperative targets, Figure 5 reports the detection results for a test against the Cessna 172 along the whole acquisition time (about 61 minutes). The red dots represent the passive detections while the GPS trajectory is reported in black. Notice that, in the considered case, for the passive sensor, we report the correct detections. In detail, at each data file, a detection is defined as ‘correct’ when it appears at the expected range-velocity location based on the available

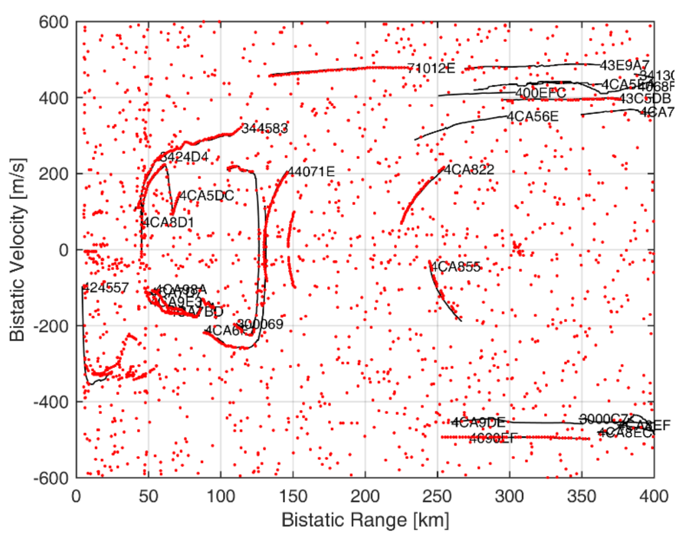


Figure 4. Detection results against traffic of opportunity.

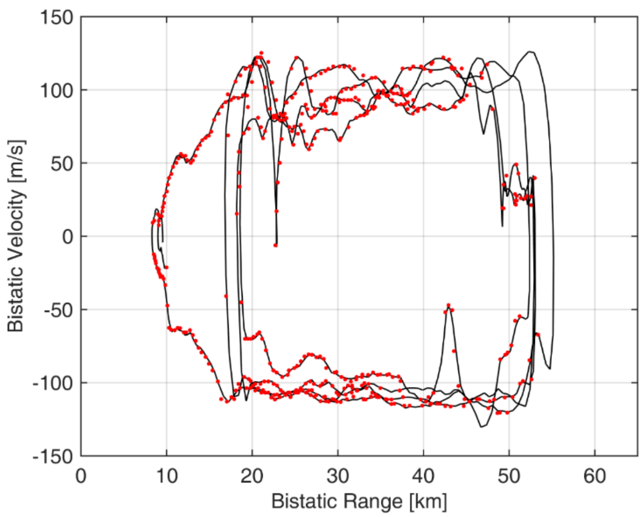


Figure 5. Detection results against the cooperative Cessna 172.

air-truth. Figure 5 shows that the sensor detect continuously the target up to approximately 45 km, despite its low RCS.

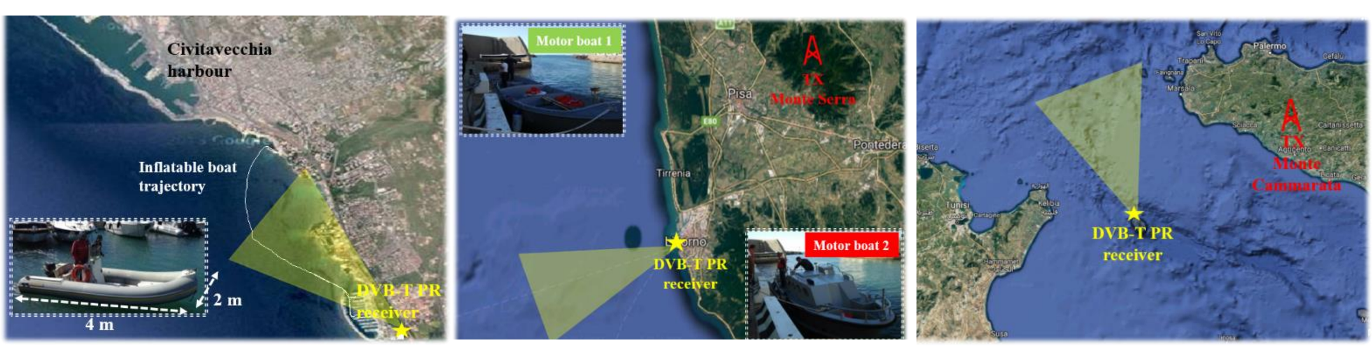
V. DVB-T-BASED PR FOR MARITIME SURVEILLANCE APPLICATION

During the last years, we have conducted several test campaigns at different sites along the Italian coast. In all the performed tests, the passive system includes a reference antenna (a commercial Yagi-Uda antenna steered towards the transmitter of opportunity) and a surveillance antenna array steered toward the area to be monitored. The latter is composed by two or three Yagi Uda antennas arranged in the horizontal plane. In this section, we report some examples of the obtained results.

In the first test, we show the potential of the DVB-T based sensor in the detection of very small boats with low RCS moving close to the coast, [7]. Specifically, we report the results of a test campaign performed in Civitavecchia (Lazio), in the western coast of Italy. As sketched in Figure 6(a), the DVB-T receiver was installed in the closeness of the tourist harbor of Riva di Traiano. A rubber boat (2 m wide and 4 m long) equipped with a GPS receiver was used as cooperative target. Figure 7(a) reports the localization results over the Cartesian plane, obtained along an acquisition time of about 7 minutes (40 sequential data files are available). The GPS trajectory is reported in red while the black plots are the raw passive detections. We observe that the small boat is detected; specifically, the estimated detection rate is 29 over 40.

In the second test, the localization results obtained against a dataset collected during the acquisition campaigns performed in Livorno (Tuscany) are reported, [7]. In this case, we aim at demonstrating the potential of such sensor in monitoring typical maritime traffic around the port area. The test geometry is sketched in Figure 6(b). The sensor was located on the roof of the "G. Vallauri" Italian Navy Institute, located on the coastline, very near to the Livorno port. During the test, we employ two motorboats (of length between 6 m and 9 m), equipped with a GPS receiver, as cooperative targets. Figure 7(b) illustrates the localization results within an acquisition time of about 6 minutes. As it is evident from the two GPS tracks (red and green), the motorboats start to move very close each other, along parallel directions. Then, one of them changes its direction. Again, both small cooperative targets are detected (detection rate: 52 over 62 and 48 over 62 for motorboat 1 and motorboat 2, respectively). Moreover, we can observe that the considered PR sensor correctly detect also many of the opportunistic vessels moving in the monitored area (see the Automatic Identification System (AIS) registrations in blue).

Finally, we illustrate the capability to detect vessels at very long range distances, [8]. For the purpose, we report the results of a test campaign performed in Pantelleria, a small island in the South of Italy. The DVB-T PR receiver has been installed very close to the coast (see Figure 6(c)) with the surveillance antennas steered toward the open sea for the detection of the typical maritime traffic travelling during the day. The obtained detection results over the range-velocity plane are shown in Figure 7(c) in gray dots. Instead, the red tracks identify the maritime traffic of the AIS registrations. As it is apparent, the DVB-T based sensor allows the detection of many targets also at very long bistatic ranges. Indeed, thanks to the low carrier frequency of the exploited signals as well as to the use of long integration times, the targets are detected beyond the standard radar horizon.



(a) (b) (c)

Figure 6. Test campaigns in the Italian coast: (a) Civitavecchia; (b) Livorno; (c) Pantelleria.

VI. CONCLUSIONS

In this paper, the recent results obtained with the dual-band AULOS® passive sensor designed by Leonardo S.p.A. are reported. Specifically, FM and DVB-T signals have been parasitically exploited for air and maritime surveillance applications, respectively. The experimental results obtained in different test campaigns shown that such sensor can be effectively integrated within conventional ATC solution, with the role of gap-fillers, to extend the conventional surveillance coverage as well as to guarantee the detection in case of failure of the conventional surveillance system. In contrast, the DVB-T based PR can be employed for detecting and tracking small boats near to the coast as well as in long range maritime surveillance applications. All this with reduced costs and preserving both the landscape integrity as well as the electromagnetic health of the population.

REFERENCES

[1] A. Farina and H. Kuschel, Eds., Special Issue on Passive Radar (Part I&II) – *IEEE Aerospace and Electronic Systems Magazine*, vol. 27, no. 10-11, 2012.

[2] K. E. Olsen and W. Asen, "Bridging the gap between civilian and military passive radar," in *IEEE Aerospace and Electronic Systems Magazine*, vol. 32, no. 2, pp. 4-12, Feb. 2017.

[3] A. Bhatta and A. K. Mishra, "GSM-based commsense system to measure and estimate environmental changes," in *IEEE Aerospace and Electronic Systems Magazine*, vol. 32, no. 2, pp. 54-67, Feb. 2017.

[4] F. Colone, T. Martelli, C. Bongioanni, D. Pastina and P. Lombardo, "WiFi-based PCL for monitoring private airfields," in *IEEE Aerospace and Electronic Systems Magazine*, vol. 32, no. 2, pp. 22-29, Feb. 2017.

[5] H. Ma, M. Antoniou, D. Pastina, F. Santi, F. Pieralice, M. Bucciarelli, and M. Cherniakov, "Maritime Moving Target Indication Using Passive GNSS-based Bistatic Radar," in *IEEE Transactions on Aerospace and Electronic Systems*, vol. 54, no. 1, pp. 115-130, Feb. 2018.

[6] A. Di Lallo, A. Farina, R. Fulcoli, S. Immediata, M. Sedehi, E. Tilli, and L. Timmoneri, "AULOS: Finmeccanica family of passive sensors," in *IEEE Aerospace and Electronic Systems Magazine*, vol. 31, no. 11, pp. 24-29, Nov. 2016.

[7] D. Langellotti, F. Colone, P. Lombardo, M. Sedehi, and E. Tilli, "DVB-T based Passive Bistatic Radar for maritime surveillance," in *IEEE Radar Conference* 2014, Cincinnati (OH, USA), May 2014, pp. 1197-1202.

[8] T. Martelli, F. Colone, E. Tilli, and A. Di Lallo, "Multi-Frequency Target Detection Techniques for DVB-T Based Passive Radar Sensors," in *Sensors 2016*, Sept. 2016.

[9] F. Colone, C. Palmarini, T. Martelli and E. Tilli, "Sliding extensive cancellation algorithm for disturbance removal in passive radar," in *IEEE Transactions on Aerospace and Electronic Systems*, vol. 52, no. 3, pp. 1309-1326, June 2016.

[10] http://cordis.europa.eu/project/rcn/94732_en.html.

[11] http://www.closeye.eu/.

[12] F. Colone and P. Lombardo, “Advanced processing methods for passive bistatic radar systems,” in *Principles of Modern Radard : Advanced Radar Techniques*, Raleigh, NC: SciTech Publishing, 2012, pp. 739-821.

[13] F. Colone, D. Langellotti and P. Lombardo, "DVB-T Signal Ambiguity Function Control for Passive Radars," in *IEEE Transactions on Aerospace and Electronic Systems*, vol. 50, no. 1, pp. 329-347, Jan. 2014.

[14] F. Colone, C. Bongioanni and P. Lombardo, "Multi-frequency integration in FM radio-based passive bistatic radar. Part I: Target detection," in *IEEE Aerospace and Electronic Systems Magazine*, vol. 28, no. 4, pp. 28-39, April 2013.

[15] F. Colone, C. Bongioanni and P. Lombardo, "Multifrequency integration in FM radio-based passive bistatic radar. Part II: Direction of arrival estimation," in *IEEE Aerospace and Electronic Systems Magazine*, vol. 28, no. 4, pp. 40-47, April 2013.

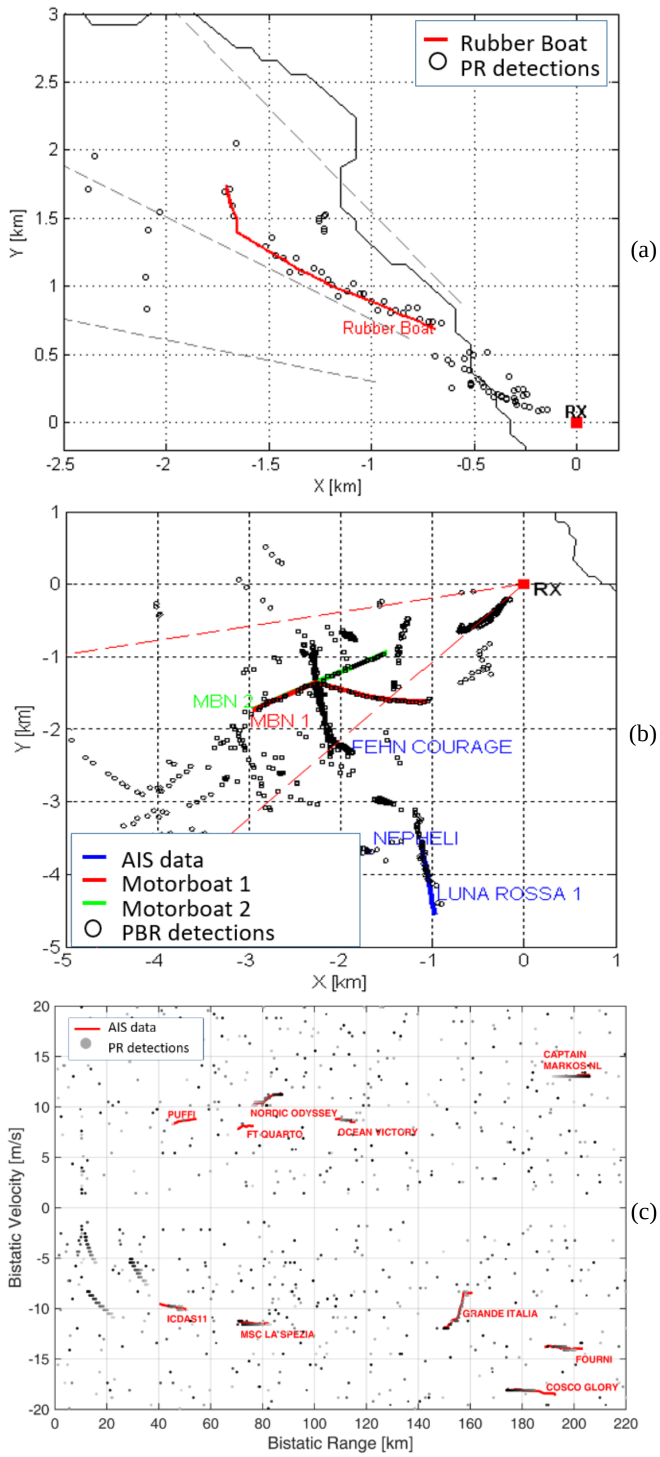


Figure 7. Experimental results:

(a) Localizations results of the test campaign in Civitavecchia;
(b) Localizations results of the test campaign in Livorno;
(c) Detection results of the test campaign in Pantelleria.