Maritime surveillance via multi-frequency DVB-T based Passive Radar

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***Abstract*—In this paper, we consider the possibility to jointly exploit multiple frequency channels emitted by the same transmitter to improve target detection capability in a DVB-T based passive radar. In particular, appropriate multi-frequency techniques are presented for target detection to be effective in the considered application. The proposed approaches are validated and compared with reference to several experimental data for maritime surveillance applications. The reported results show that the considered multi-frequency techniques yield a significant enhancement in target detection performance with respect to the single frequency operation.**

Keywords—DVB-T signals; passive radar; passive coherent location; multi-frequency.

I. INTRODUCTION

Nowadays Passive Coherent Location (PCL) have reached a point of maturity and they are widely employed for civilian, security and defense applications. PCL exploits transmitter of opportunity for target detection and localization. Since there is no need to build a dedicated transmitter, they offer many advantages such as low cost, covert operation and low vulnerability to electromagnetic countermeasures, [1].

Many transmitters for telecommunications, radio navigation and remote sensing have been considered as waveform of opportunity. Nowadays, a very attractive solution is represented by the Digital Video Broadcasting Terrestrial (DVB-T) transmissions since they are characterized by high level of radiated power, good spatial coverage and wide bandwidth (namely, good range resolution of about 20 m). In addition, by employing orthogonal frequency division multiplexing (OFDM) modulation, the DVB-T signals are noise-like waveforms; thus, they provide more attractive ambiguity function properties that are independent of the signal content [2]-[3].

The exploitation of DVB-T PCL systems in coastal/maritime surveillance applications has recently attracted significant interest from the passive radar community [4]-[7]. For instance, such sensor can be employed for monitoring typical maritime traffic as well as for detecting small boats close to the coast [4]-[5]. In addition, their exploitation by PR receivers on moving maritime platforms has been investigated in [6]. Furthermore, the wide horizontal beam and high power level of the broadcast transmitters allow their exploitation even for long range surveillance. Specifically, due to the low carrier frequencies of the considered waveform, the over the horizon (OTH) capability has been investigated in [7] showing that the DVB-T PCL can be successfully employed even in very long range maritime surveillance applications.

However, target detection highly depends on the employed DVB-T channel. In fact, both the radiating characteristics of the transmitter and the electromagnetic conditions of the propagation channel vary across the wide frequency band allocated to the DVB-T service in the UHF band (from 470 MHz to 862 MHz). In addition, also the target scattering can change with the different considered frequency channesl.

In this paper, in order to enhance the detection performance of the considered PCL system, multiple DVB-T frequency channels emitted by the same transmitter are jointly exploited and integrated making the sensor more robust to the time-varying characteristics of a single channel. This possibility was investigated in [8] for a FM-based PCL. In that case, the concept of a non-coherent multi-frequency (MF) integration was introduced to mitigate the time-varying characteristics of the exploited waveform that largely depend on the radio program content. However, the MF approaches presented in [8] cannot be directly applied to a DVB-T based PCL due to the peculiar characteristics of the waveform of opportunity. Therefore, in this paper, the MF integration detection schemes presented in [8] have been properly modified and extended to be efficient in the newly considered application. The potentialities of the different integration approaches are validated and compared against several experimental data. The considered data sets refer to a maritime scenario and they have been provided by Leonardo-Finmeccanica S.p.A. in the framework of a long-term collaboration with the research group at Sapienza University of Rome.

The paper is organized as follows. The DVB-T-based PCL processing scheme is briefly illustrated in Section II. The MF approaches together with the adopted modifications concerning the exploitation of the DVB-T transmissions are described in Section III while the experimental results are reported in Section IV. Finally, our conclusions are drawn in Section V.

II. SINGLE FREQUENCY DVB-T BASED PCL PROCESSING SCHEME

The DVB-T based PCL processing scheme for target detection to be adopted against a single DVB-T frequency channel is illustrated in Figure 1.

As it is typical in passive radar, the low power signal reflected from the target is collected by the main receiver (surveillance channel) whereas another receiver (reference channel) is exploited to collect the transmitted signal. Obviously, multiple surveillance channels can be considered.

First, the reference signal is adopted to remove the direct signal from the transmitter and the multipath contributions in the surveillance channels. To this purpose, the Extensive Cancellation Algorithm (ECA) is applied [9]. Then the reference signal is properly pre-filtered in order to mitigate the high sidelobes and spurious peaks appearing in the DVB-T signal Ambiguity Function (AF). To this purpose, we resort to the linear approach presented in [3] which is based on the cascade of the pilots signals equalization and a Residual Peaks Removal (RPR) filter to remove the zero-Doppler peaks. Successively, the mismatched reference signal and the output signals from the ECA filter are processed to evaluate the bistatic range-velocity Cross-Ambiguity Function (CAF). In particular, in the maritime scenario, the low velocity of the considered targets allows to increase the integration time duration up to 1-2 seconds without experiencing a significant range cell migration. This also allows to improve the Doppler resolution as well as the capability to discriminate between slowly moving vessels and docked boats. Once the CAF has been evaluated at all the available surveillance channels on the single DVB-T channel, a Cell Average Constant False Alarm Rate (CA-CFAR) threshold is separately applied to each map to detect targets with a given probability of false alarm (P_{fa}). Then, an M-out-of-N detection criterion can be adopted to integrate the detection results obtained at the surveillance channels thus allowing a reduction in the number of false alarms. Finally, a tracking algorithm could be applied on the range-velocity plane to reduce the false alarms while yielding measurements that are more accurate.

Obviously, in order to enhance the target detection performance, multiple DVB-T channels could be jointly exploited as illustrated in the next section.

III. MULTI-FREQUENCY DETECTION APPROACHES FOR A DVB-T BASED PCL

This section describes the MF detection schemes and the adopted modifications concerning the exploitation of the DVB-T transmissions.

A. *MF detection schemes*

Based on the results obtained in [8] for a FM-based PCL system, the integration strategies considered in this paper for a DVB-T based PCL are:

- The *Centralized MF detection scheme* (*CEN-MF-N*): the CAFs obtained at the N_{ch} frequency channels are incoherently summed (after square law detector) pixel-by-pixel aiming at enhancing the SNR on the resulting integrated map. Then a CA-CFAR detection technique is applied. Obviously, as shown in [8], the CFAR threshold should be properly modified to guarantee the same desired P_{fa}. As it is evident, with this approach the characteristics of a bad channel are averaged with the good ones, thus yielding a limited impact on the final performance.
- The *Decentralized MF detection scheme L/N (DEC-MF-L/N):* a binary integration is used after applying a first-detection threshold at each frequency channel. Therefore, a detection is declared at a given range-velocity location when L detections out of N_{ch} channels are obtained for the considered pixel over the single-channel maps. Obviously, this approach yields reasonable detection performance improvement when at least L of the N_{ch} exploited channels are characterized by a reasonable SNR for a given target.

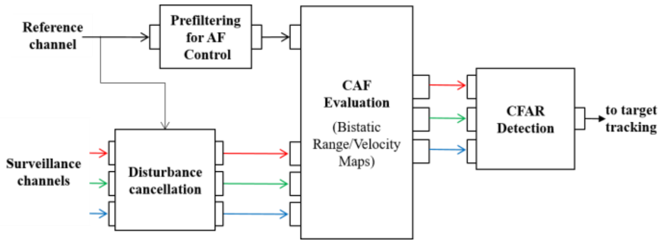

Figure 1. DVB-T-based PCL processing scheme for target detection.

B. *Modifications recquired for DVB-T based PCL case*

For an effective MF integration, the target echoes over the different frequency channels should be perfectly aligned on the range-velocity plane. This hypothesis holds in a FM-based PCL. In contrast, the finer range resolution and the wider frequency separation of DVB-T channels might jeopardize the validity of the above assumptions. Specifically, possible limitations along this line are illustrated in the following sub-sections together with the proposed solutions.

1) *CAF Maps evaluation on a common range-velocity grid*

In order to effectively integrate the target echoes over the different DVB-T channels, their range-velocity maps should be directly comparable. This means that they should be evaluated on a common grid both in range and in velocity.

For the range dimension, the same pixel spacing is guaranteed by the common sampling frequency. In contrast, the pixel spacing in the velocity dimension is a function of the carrier frequency and of the integration time. For this reason, in [8] different integration times have been used at the N_{ch} available channels in order to guarantee a constant velocity spacing across the different channels. This approach has been shown to be robust and effective in the FM-based PCL since the FM frequency band (88-108 MHz) is quite limited and does not yield a significant variation in term of integration gain.

In contrast, when DVB-T transmissions are exploited, the required integration times might correspond to quite different integration gains due to a large diversity among the available carrier frequencies within the DVB-T band (470-862 MHz). In fact, a SNR gain difference equal to 2.6 dB could be achieved at the edges of the UHF band. In order to benefit from the MF integration approaches also in a DVB-T based PCL, the proposed approach is to adopt a constant integration time across the different frequency channels with the aim to guarantee the same integration gain. In detail, the adopted integration time is selected to guarantee the desired velocity resolution at the highest available carrier frequency included in the integration scheme. Then, a zero-padding in the Doppler dimension is performed to obtain the same CAF grid in the velocity dimension.

2) Target echoes misalignment across channels and counteracting strategies

After the application of the above strategies, the resulting CAF maps of the considered frequency channels are directly comparable. However, a displacement of the target echoes received at different frequency channels can be occasionally observed.

As an example, Figure 2 reports the detection results of three different DVB-T channels, for the data set that will be shown in the next section. In detail, the bistatic range values are reported as a function of the scan number for a portion of the vessel track labeled “MSC La Spezia”. Figure 2 clearly shows the range misalignment across the employed DVB-T channels. As is apparent (e.g. scans 45-48), the plots obtained when exploiting the carrier frequencies 682 MHz and 626 MHz show a range displacement up to 100 m (3 range cells). Notice that, the considered target is a cargo ship characterized by remarkable size (365.82 m long and 51 m wide). However, a similar effect was noticed also for other smaller targets.

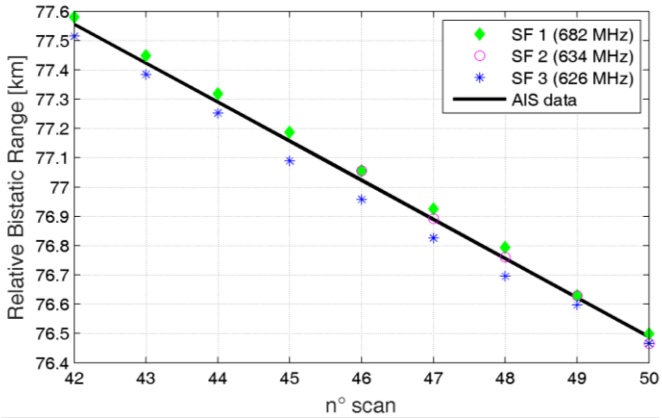

Figure 2. Detection results at few scans of the single frequencies for the target “MSC La Spezia” (see Figure 4**)**.

Among the possible causes of the target echoes misalignment across frequency channels, the following aspects should be considered:

- First of all we have to consider the target physical size. In fact, if the target size is comparable or larger than the resolution cell, its echo could span multiple range bins. Depending on the carrier frequency of the exploited DVB-T channel, different target portions might have different scattering characteristics thus yielding a range displacement of the dominant target echo. This effect is certainly more evident when widely diverse carrier frequencies are employed.
- Another possible cause is the exact position of the transmitting antennas. In fact a transmitting site that broadcast multiple DVB-T channels might be composed by a few masts with multiple transmitting antennas which distance can be in the order of tens of meters. Based on the information available online, multiple DVB-T channels can be broadcasted by the same transmitter from a given site.

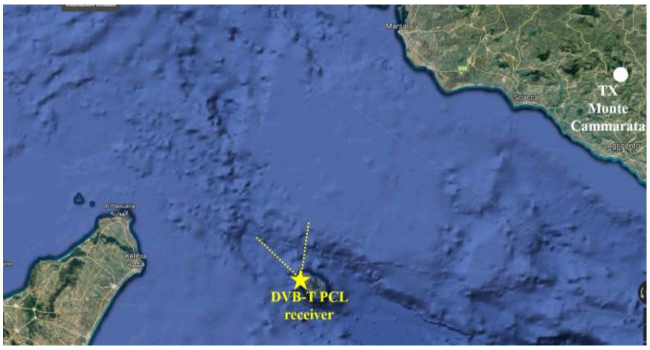

Figure 3. Sketch of the acquisition geometry.

However they might be emitted by largely displaced antennas. In such case, the employed multiple frequency channels are not strictly collected with the same bistatic geometry. Therefore, a given target can be observed at different bistatic ranges and velocity. However, for the considered distance among the transmitting antennas, the impact on the bistatic velocity can be negligible with respect to the velocity resolution.

- Finally, another possible cause could be related to the presence of anomalous propagation effects. For example, when super-refractive conditions occur, the propagation paths of the target echoes can differ from channel to channel thus yielding a displacement on the CAF map.

Certainly, when such range displacement is present, the effectiveness of the proposed MF techniques is limited. However, if the target echoes misalignment is within few cells, a practical solution in the decentralized scheme can be to extend the integration of the binary results (of W cells) after the application of the first threshold so that a few consecutive range bins are included in the sum. Obviously, in order to maintain the desired final false alarm rate, the detection threshold to be used at the first stage has to be properly increased [10]. By properly setting the window size W, limited range misalignments could be managed.

IV. Performance Against Real Data

In this section, we show the benefits resulting from the application of MF approaches against experimental data for maritime surveillance.

A. Acquisition campaign

The acquisition campaign was carried out in Pantelleria, a small Italian island (see Figure 3). The reference antenna was steered toward the DVB-T transmitter of Monte Cammarata (about 170 km away) while the DVB-T-based PCL receiver was installed very close to the coast. In particular, two Yagi-Uda antennas (with distance of 0.63 m in the horizontal plane) pointed at 343° clockwise from north and main beam width of about 36° were employed. In this way, the considered sensor is able to detect the typical maritime traffic that is present in that area.

In the following, we report the results for an experimental test of about 19 min. Specifically, the data set is composed by 93 sequential data files of temporal duration equal to 1.2 s,

Table 1. Detection results with the single DVB-T channels and different MF approaches.

	249801000	256139000	FT Quarto	Nordic Odyssey	256965000	Captain Markos NL	Fourni	477795300	Grande Italia	MSC La Spezia	Total detections
SF1 (682 MHz)	0	14	1	36	**11**	34	18	2	8	58	182
SF2 (634 MHz)	**3**	8	0	**70**	2	79	**37**	**42**	48	54	343
SF3 (626 MHz)	1	**22**	**5**	58	5	**89**	33	36	**55**	**56**	**360**
SF4 (546 MHz)	0	0	0	9	2	75	16	4	25	5	136
CEN-MF-2 (SF2-3)	3	26	**5**	**75**	8	**92**	39	43	**63**	70	424
CEN-MF-3 (SF1-3)	**5**	**28**	**5**	74	**9**	**92**	39	**44**	61	**81**	**438**
CEN-MF-4	0	25	**5**	72	6	90	**40**	**44**	57	74	413
DEC-MF-2/4, W=1	0	**19**	1	70	5	87	35	30	45	52	344
DEC-MF-2/4, W=3	**2**	**19**	**2**	**72**	**10**	**88**	**42**	**44**	**53**	**63**	**395**

spaced by 12 s. Four DVB-T channels have been simultaneously collected, all emitted by the same transmitter, at the following carrier frequencies: 682 MHz, 634 MHz, 626 MHz and 546 MHz.

B. *Target detection results*

First, the performance of each DVB-T channel has been evaluated. To this purpose, the DVB-T-based PCL processing scheme in Figure 1 has been applied to all the available data files of each carrier frequency. Specifically, the ECA [9] is applied with 1000 taps (namely 33 km) and an integration time of 1.2 s is used to evaluate the CAF maps that span a surveillance area of 220 km × 20 m/s. A CA-CFAR with P_{fa}=10^{-4} has been employed and a 2-out-of-2 criterion is adopted at the two surveillance channels allowing a P_{fa}=10^{-8} on the final range-velocity map. Moreover, all the plots whose velocity in module was less than 1 m/s have been discarded assuming that they are due to disturbance residuals.

As an example, Figure 4 shows the detection results over the range-velocity plane of the best single DVB-T channel (f_c=626 MHz). All the raw detection results within the acquisition time have been reported in gray dots. In particular, a gray scale has been adopted to plot the raw detections obtained on consecutive scans. In addition, the maritime traffic recorded by the Automatic Identification System (AIS) during the test campaign has been reported in red. As it is evident, the passive sensor has correctly detected most of the opportunistic targets moving in the surveyed area also at very long bistatic ranges, up to 210 km. In fact, as reported in [7], in the considered maritime applications, the sensor might provide OTH capabilities. In addition, many other detections are provided by the PCL sensor which not correspond with the AIS data. These are likely caused by sidelobes of strong echoes or correspond to ghost targets due to Single Frequency Network (SFN) operation.

In Table 1 a quantitative comparison in terms of target detection capability, provided by the SF operation and after the MF approaches, has been reported. Specifically, the first columns of the table report the number of correct detections of each target of opportunity available while the last column reports the total number of correct detections of the considered configuration. Moreover, the bold font is used to highlight the

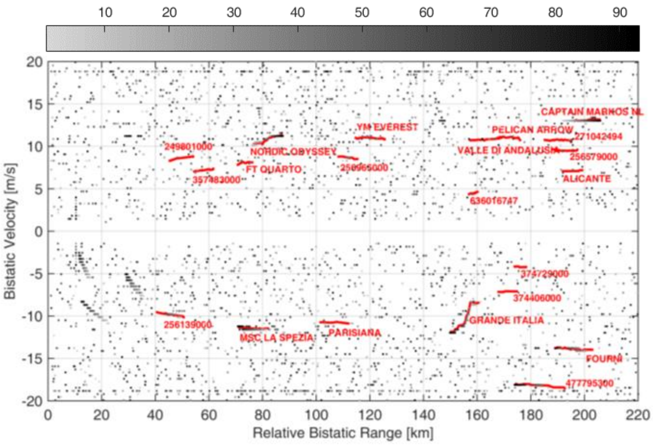

Figure 4. Detection results over the range-velocity plane for the best single DVB-T channel (f_c=626 MHz).

best case of each different solution. In detail, we define a given detection as correct when it appears at both expected range-velocity location and expected time instant based on the availability of accurate AIS. All the remaining plots are then labeled as false alarms. The results after the application of the centralized technique with N=2, 3 and 4 channels and the decentralized DEC-MF-2/4 scheme with range window size of W=1 and W=3 have been reported in Table 1.

First we observe that the target detection performance highly varies with the exploited DVB-T channel. As it is evident, only by applying the proposed MF integration schemes, the number of correct detections significantly increases with respect the best performing channel. We observe that the centralized approach using the first three available channels (CEN-MF-3) yields the best performance among the centralized approaches since the fourth channel does not provide a remarkable contribution. Moreover, among the decentralized configurations, the use of W=3 (DEC-MF-2/4, W=3) provide an higher number of correct detections with respect to W=1. In fact, the exploitation of a degradation by a factor of W in the decentralized scheme allows to recover the detection loss due to target echoes misalignment across different DVB-T channels. As an example, we report in Figure 5 an enlarged view around the target “MSC La Spezia” (the same target of Figure 2) over the range-velocity plane.

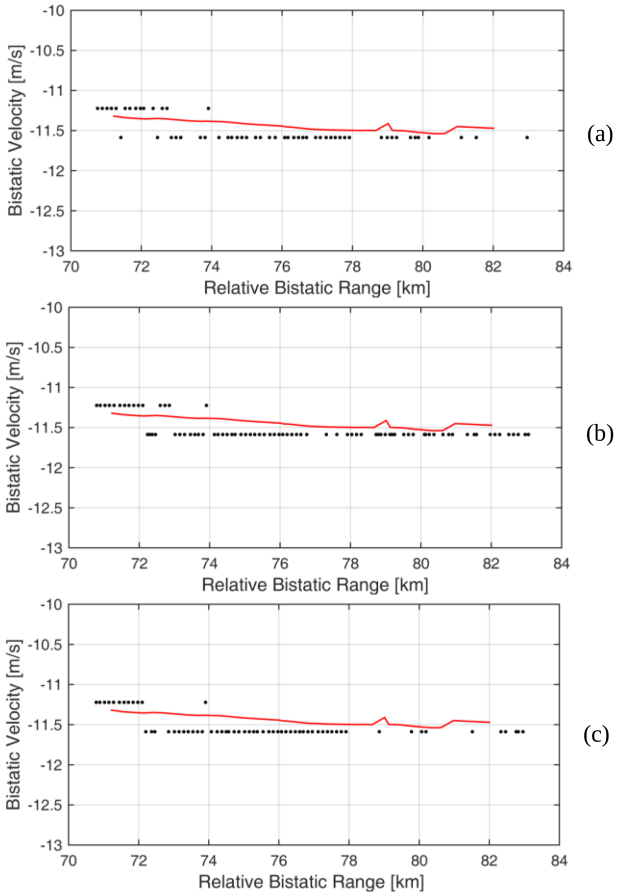

Figure 5. Detection results over the range-velocity plane for the target “MSC La Spezia”. (a) Best single DVB-T channel (f_c=626 MHz); (b) CEN-MF-3; (c) DEC-MF-2/4 with W=3.

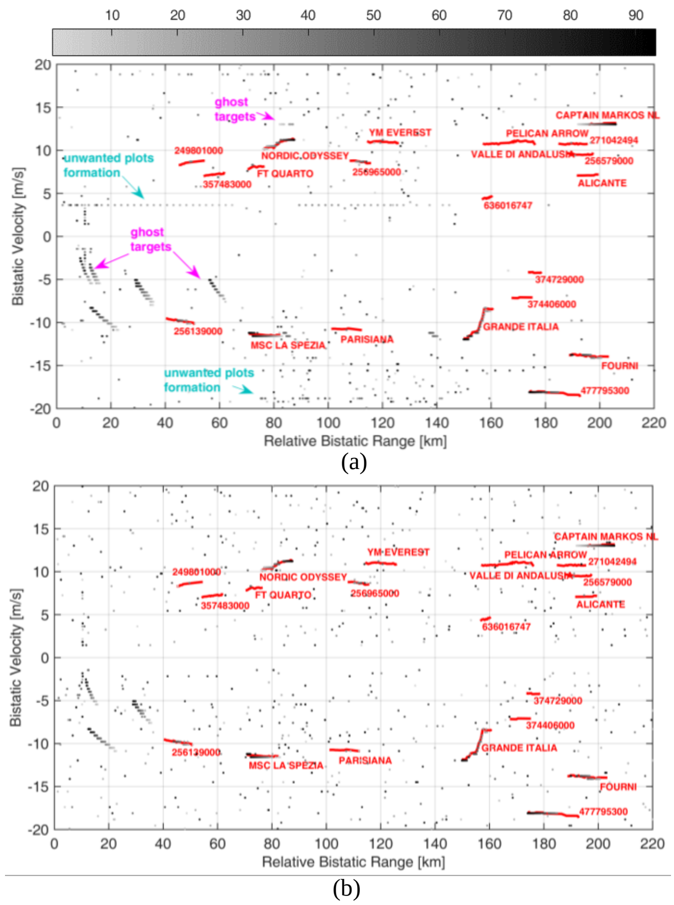

Figure 6. Detection results over the range-velocity plane for the best MF configurations. (a) CEN-MF-3; (b) DEC-MF-2/4 with W=3.

Particularly, Figure 5(a) refers to the best SF channel whereas Figure 5(b)-(c) show the results after the application of the best centralized and decentralized approaches, respectively. It is evident that the considered target is detected with greater continuity when MF schemes are considered. Specifically, the number of possible detections for this target is 93 while the number of correct detections moves from 56 with the best SF channel, to 63 with the DEC-MF-2/4 with W=3, up to 81 with CEN-MF-3.

Finally, the raw detection results of the best centralized and decentralized MF approaches are reported in Figure 6. From the comparison between Figure 4 and Figure 6 we observe that the considered MF schemes allow a better control of the false alarms with respect to the SF operation. Notice that the available data set is not sufficient for the estimation of the false alarm rate. However, we report a quantitative analysis of the false alarm control capability of the proposed MF schemes in [10] for the case of an aerial scenario.

We obtain that the decentralized scheme DEC-MF-2/4 with W=3 yields only a slight loss in term of target detection performance with respect to the CEN-MF-3 (see Table 1). However, it provides the additional capability to suppress the unwanted plots formation and the ghost target tracks due to SFN transmission mode (see Figure 6(b)). In fact, the binary integration in the decentralized approach allows to be more robust to the formation of tracks that do not correspond to targets.

Once a target has been detected on the range-velocity plane, the Direction of Arrival (DoA) of the corresponding echo has to be estimated in order to provide its localization on the Cartesian plane. A preliminary result is reported in Figure 7 after the detection results of Figure 6(a). Specifically, a MF DoA estimation scheme is adopted along the line in [11]. As expected the obtained DoA estimation accuracy is still not precise for target localization especially for target far from the receiver.

V. CONCLUSIONS

In this paper, aiming at jointly exploiting multiple frequency channels emitted by the same transmitter, appropriate MF techniques for target detection have been proposed for the case of a DVB-T passive radar. In particular, the approaches presented in [8] for a FM-based PCL have been modified and extended to be efficient in the considered scenario. Different non-coherent integration schemes have been proposed and extensively compared against experimental data pertaining to maritime surveillance applications. The obtained results showed that the proposed MF integration schemes yield a remarkable enhancement of the target detection capability of the considered sensor with respect to the SF operation.

Moreover, the MF approaches have been proven to guarantee a better control of the false alarm rate as well as the capability to mitigate the problems arising from the possible presence of ghost targets or unwanted plots formation.

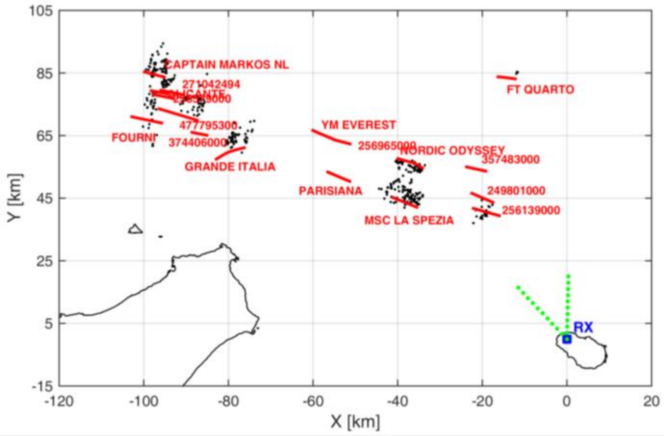

Figure 7. Localization results over the X-Y plane when the CEN-MF-3 detection scheme is employed and MF approaches are considered for DoA estimation.

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