Preliminary Experimental Results of Polarimetric Detection Schemes for DVB-T based Passive Radar

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***Abstract*— Suitable methods to jointly exploit the diversity of information conveyed by different polarimetric channels in Passive Coherent Location (PCL) systems are a topic of current research. Possible signal processing strategies were devised for FM radio based PCL with the purpose of enhancing the target detection capability and their benefits were largely demonstrated. This paper presents the results from a preliminary investigation carried out considering a multi-channel PCL system exploiting DVB-T signals. The performance improvements yield by different polarimetric detection schemes are analyzed comparatively using an experimental data set. The employed multichannel PCL system PARASOL, from Fraunhofer FHR, features two linearly orthogonally polarized receiving channels. The results obtained show that a polarimetric-Generalized Likelihood Ratio Test (P-GLRT) detection scheme yields a remarkable improvement in terms of detection capability, with respect to both the exploitation of a single polarization and to the non-coherent integration of the information conveyed by the different polarimetric channels.**

I. Introduction

The Passive Coherent Location (PCL) technology has been a topic of conspicuous research in the last decade [1]-[3]. As well known, PCL systems parasitically exploit illuminators of opportunity (IOs) to perform target detection and localization. Among the considered waveforms of opportunity, broadcast signals, both analog and digital, have always been attractive for PCL purposes, thanks to their potentially wide coverage. Moreover, digital broadcast IOs (such as DVB-T or DAB) also present a constant bandwidth and a stationary ambiguity function with a thumbtack shape i.e. they allow the achievement of good resolution in both range and Doppler [4].

Despite the effectiveness of the signal-processing techniques specifically developed for such IOs, target detection and localization capability of the resulting PCL systems may still be strongly limited by many effects that are not under the control of the PCL radar designer. Hence, the relevant technical literature continuously reports new attempts to identify advanced solutions, which aim at increasing the reliability of such systems against the aforementioned undesired effects.

Among the most recently proposed approaches, the exploitation of the diversity of information conveyed by multiple receiving channels connected to differently polarized antennas has been considered in [5]-[9]. In fact, assuming that target echoes typically show a random polarization, we can expect that the joint exploitation of the signals received at differently polarized antennas might generally result in a performance improvement for the system. In particular, with reference to the target detection stage, a very preliminary polarimetric processing scheme was investigated in [5] where a simple non coherent integration (NCI) of the results obtained at orthogonally polarized surveillance antennas was proposed for FM radio based PCL. However, the extensive analysis in [6] has shown that, besides the expected improvement of target echoes received on multiple channels, the NCI is not able to mitigate the disturbance contributions that still limit the achievable performance

To this purpose, by resorting to a Generalized Likelihood Ratio Test (GLRT), an adaptive polarimetric detection scheme was derived in [6] and the capability of the proposed approach to counteract the disturbance thus improving the performance was demonstrated for a FM radio based PCL system.

Based on the successful results obtained in the FM radio band, there is a strong motivation in understanding the potential benefits of the use of polarization diversity also in DVB-T based PCL systems.

First experimental results have been reported in [8], where it was confirmed that the use of different polarizations on receive leads to different Signal to Interference plus Noise power Ratio (SINR) values for the target echoes. Therefore, we can expect that a suitable method to exploit the polarimetric diversity would provide an improvement in target detection. However, in [8], only a simple polarimetric NCI was considered.

In this paper, we extend the work in [8] by comparing different polarimetric detection schemes for DVB-T based PCL systems. Specifically, the polarimetric-GLRT (P-GLRT) proposed in [6] is considered in order to successfully exploit the polarization diversity between the target echoes and the competing background. The experimental analysis is performed using data collected by the experimental passive radar system PARASOL, developed at Fraunhofer FHR [10] and equipped with two linearly orthogonally polarized surveillance antennas. Aerial and maritime cooperative targets were employed in the experimental tests and enabled a reliable comparative analysis of the achievable detection performance.

The paper is organized as follows. Section II summarizes the basic processing scheme for a multi-channel DVB-T based PCL system and the considered polarimetric detection schemes. The experimental tests and the exploited data set are described in Section III. We report the results obtained in Section IV while some conclusions are drawn in Section V.

II. Polarimetric DVB-T Based PCL Processing Scheme

Let us consider a DVB-T based PCL system, equipped with L receiving channels, connected to differently polarized surveillance antennas. We assume that the signals collected by different antennas are firstly separately processed according to a conventional single-channel processing scheme. Its main stages are sketched in Fig. 1 and briefly summarized in sub-section A (see also [4]). Afterwards, various approaches are adopted to jointly exploit the L outputs obtained for target detection purposes. Sub-section II.B illustrates the polarimetric approaches that are considered and compared in the following.

A. *Single-Channel Processing Scheme*

As is apparent by observing Fig. 1, the signals collected by different receiving channels separately undergo three main processing stages.

1) *Direct Signal Reconstruction*

When exploiting a digital coded signal (such as DVB-T) as IO, one can exploit the synchronization features in order to reconstruct the transmitted signal, instead of steering a reference antenna directly towards the IO. The first step of this operation is the synchronization to the transmitter. Then, the synchronized signal is decoded down to a sequence of bits. Eventually, it is remodulated according to the DVB-T standard. When properly operated, this operation produces a cleaned replica of the direct signal, while requiring a reduced numbers of receiving channels [14]. Of course, in order for it to be possible, a small bit error rate in the decoding of the bit stream, i.e. a high SNR in the direct signal, is required. Once we have obtained a copy of the direct signal, the latter is used in the two following stages, namely the disturbance cancellation stage and the evaluation of the range-velocity map.

2) *Disturbance Cancellation*

In order to remove the clutter contribution in the surveillance signal, the Extensive Cancellation Algorithm by Carrier and Doppler shift (ECA-CD) is used. This approach consists in applying the ECA filter in the range-frequency domain and expanding the clutter subspace in the Doppler domain by adding replicas of the reference signal shifted by fractions of the Doppler resolution bin. Further details can be found in [11]. In this work, first, the ECA filter is applied to the Doppler bin that collects the most interference power and then the process is repeated on the output of the first ECA stage.

3) *Range – Velocity Map Evaluation*

This third stage is performed in order to create a bistatic range-velocity map $\chi[r,v]$ that will allow the system to identify weak target contributions in the surveillance signal, delayed and Doppler shifted. When the exploited IOs are digital communications transmitters, i.e. emitting signals with a known structure, an efficient implementation of this stage is possible by exploitation of the signal structure [12].

B. *Polarimetric Detection Schemes*

Once the stages described above have been performed at each receiving channel, separately, L range-velocity maps $\chi_l[r,v]$ ($l = 1 \dots$ L) will be available. As is well known, beside the effectiveness of the adopted signal-processing stages, a typical range-velocity map is likely to include targets echoes as well as disturbance sources, such as thermal noise, cancellation residuals and interferences.

In case of L =1, the detection stage is typically performed by applying a Cell Average - Constant False Alarm rate (CA-CFAR) threshold to the resulting map in order to detect targets with a given probability of false alarm (P_{FA}). We will refer to this scheme as the conventional single-pol operation.

In contrast, when multiple receiving channels are available (L>1), connected to differently polarized surveillance antennas, two alternative detection schemes can be considered to jointly exploit the outputs of the L polarimetric channels, depending on the assumptions that are made on the statistical polarimetric properties of the disturbance affecting the received signals.

1) *Polarimetric non-coherent integration (P-NCI)*

Under the simplifying assumption of statistically independent and identically distributed interference affecting different channels, the first approach consists in a simple NCI of the outputs obtained at the L polarimetric channels after square law detector. Specifically, for a given Cell Under Test (CUT) at range bin r_0 and velocity bin v_0, we collect the results of the L maps in a complex vector $\boldsymbol{x}_0 = [\chi_1[r_0, v_0] \; \dots \; \chi_L[r_0, v_0]]^T$. The output of the NCI stage is obtained by summing up, after square law detector, the components of vector $\boldsymbol{x}_0$:

$$z[r_0, v_0] = \|\boldsymbol{x}_0\|^2 = \sum_{l=1}^{L} |\chi_l[r_0, v_0]|^2 \quad (1)$$

Then, target detection is sought by comparing the result with the average intensity estimated over Q range-velocity bins surrounding the CUT [5]:

$$z[r_0, v_0] \underset{H_0}{\overset{H_1}{\gtrless}} G \cdot \sum_{q \in I_{[r_0, v_0]}} z[r_q, v_q] \quad (2)$$

where $I_{[r_0,v_0]}$ is a set of indices that identify properly selected range-velocity bins around the CUT and the threshold G is readily found by inverting the P_{FA}'s theoretical expression [6]. The benefits that such an approach can provide have been studied for both FM radio [5]-[6] and DVB-T [8] based PCL systems. Specifically, these advantages are mainly due to the target echo enhancement resulting from the NCI of its contributions on different channels. However, it has been shown that the P-NCI also yields a scarce capability of controlling the actual false alarm rate [6]. This reveals the weakness of the simplifying hypothesis made. In fact, assuming the disturbance mainly related to clutter cancellation residuals, interferences, etc., it cannot be assumed as uncorrelated at the different polarimetric channels.

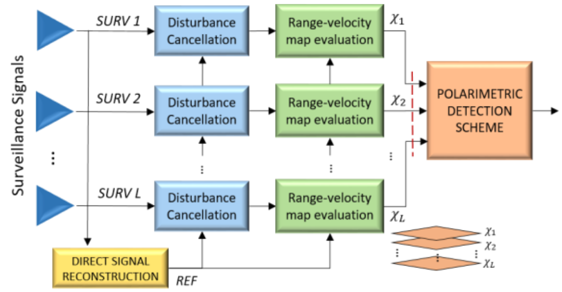


Fig. 1 Polarimetric DVB-T based PCL processing scheme

For this reason, an adaptive detection scheme would be better suited to mitigate such effects, by exploiting the aforementioned correlation.

2) Polarimetric generalized likelihood ratio test (P-GLRT)

Assuming that the target polarimetric characteristics might be very different from the disturbance, an adaptive detection scheme was derived in [6] for FM radio based PCL by resorting to a Generalized Likelihood Ratio Test (GLRT [13]).
The resulting detection test is:

$$\boldsymbol{x}_0{}^H \widehat{\boldsymbol{D}}^{-1} \boldsymbol{x}_0 \underset{H_0}{\overset{H_1}{\gtrless}} \lambda \qquad (3)$$

where $\widehat{\boldsymbol{D}} = \sum_{q=1}^{Q} \boldsymbol{x}_q \boldsymbol{x}_q^H$ is the sample covariance matrix, estimated on a set of Q secondary vectors, $\boldsymbol{x}_q$ $(q = 1, .., Q)$, which contain the output of the L maps at range-velocity locations adjacent to the CUT. The threshold λ is properly selected according to the theoretical expression of the P_{FA}[6]. Notice that the adopted model does not rely on any specific assumption for the polarimetric characteristics of target's echoes. Correspondingly, it results in a NCI of its echoes after a disturbance whitening stage based on the Cholesky decomposition of $\widehat{\boldsymbol{D}}$ (i.e. $\boldsymbol{y}_0 = \boldsymbol{L}^{-1}\boldsymbol{x}_0$ being $\widehat{\boldsymbol{D}} = \boldsymbol{L}\boldsymbol{L}^H$). This scheme is able to extract the polarimetric signature of such disturbance contribution from matrix $\widehat{\boldsymbol{D}}$ to mitigate its effects at the detection stage, therefore improving the discrimination capability by exploiting the polarimetric differences between the target and the competing background. The extensive analysis in [6] has shown that, in FM radio based PCL, the proposed P-GLRT approach not only provides better results with respect to a single-pol operation but it also yields a remarkable improvement with respect to the P-NCI approach. Thus, the purpose of this work is to investigate whether the observed benefits are confirmed in DVB-T based PCL systems.

III. Acquisition Campaign and Methodology

In order to illustrate the benefits of the proposed approach, we have processed a real data set. Specifically, the acquisition campaign has been carried out on September 24th 2014, in Eckernförde, Germany (see Fig. 3). The exploited IO is located in Kiel (approximately 20 km away from the receiver site) and broadcasts DVB-T signals in a single frequency network. It is working in 8k transmission mode, with 6817 OFDM carriers employed, in a 16-QAM (Quadrature Amplitude Modulation) scheme and a guard interval of 1/4. We used the DVB-T signal broadcasted at 666 MHz with an equivalent radiated power (ERP) of 47 kW. The considered data have been collected by means of the PCL system PARASOL [10], developed at Fraunhofer FHR. It features two parallel receiving channels, the receiver front-end and the data and signal-processing unit. For the purpose of our analysis, the two available receiving channels were connected to two cross-polarized antennas. In particular, two linearly polarized log-periodic antennas were used, manufactured by Schwarzbeck, with a gain of 7 dBi in the frequency band under test during the trials (see more specifications in Fig. 2). The antennas were closely spaced and rotated by 90 degrees one to the other, in order to collect the horizontally and vertically polarized versions of the received echoes. The system PARASOL was mounted on a moving platform (namely a military boat approx.. 15 meters long). Specifically, during the acquisition period considered in the analysis, it moves on an approx. rectilinear trajectory covering a global distance of 500 m (see the black trajectory in Fig. 3).
In this paper, 168 consecutive data files (i.e. a total acquisition duration of approx. 95 seconds) have been extracted from the entire acquisition. Pre-processing of the data includes the first three main stages of a DVB-T based PCL processing scheme, briefly discussed in sub-section II.II.A. Then, both the considered polarimetric detection schemes, namely P-NCI and P-GLRT, were applied and the results are compared to those obtained with a single-pol operation using either the Vertical (V) or the Horizontal (H) polarimetric channel, separately. Three cooperative targets, equipped with GPS receivers, were available during the trials. Specifically, one ultra-light aircraft from Fraunhofer FHR (Delphin, see Fig. 4a), and two identical 7 m long rubber boats (see Fig. 4b). Their true trajectories are reported in Fig. 3 in blue, red and green, respectively. The availability of truth-data for the cooperative targets allowed us to evaluate the performance of the PCL system, in terms of correct detections. Specifically, thanks to the a priori knowledge of the bistatic geometry, the available target true trajectories are projected onto the bistatic range-velocity plane. Thus, a given PCL detection obtained at a specific data file is considered a "correct detection" when its bistatic range-velocity location is the same occupied by one of the cooperative targets at the considered time instant. To make the procedure robust to the inaccuracies of both the PCL measurements and the GPS data projection onto the bistatic plane, proper confidence intervals in range (±100 m) and velocity (±3 m/s) were defined for the described association stage.

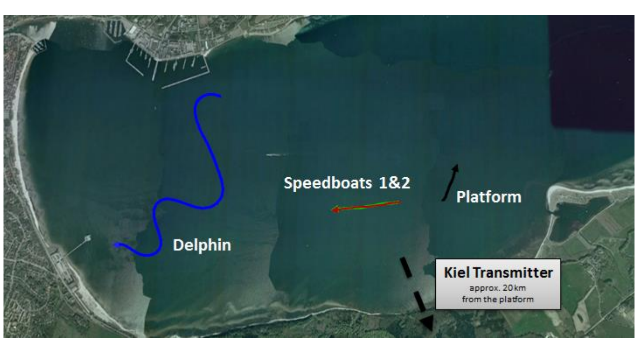


Fig. 3 Sketch of acquisition geometry

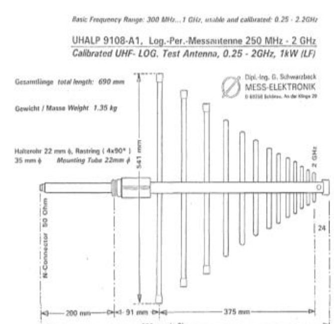


Fig. 2 Sketch of the antenna unit of PARASOL system

a

b

Fig. 4 Cooperative Targets
(a) Delphin aircraft (b) One of the two identical speedboats

When the false alarm rate is kept sufficiently low, this counting procedure allows obtaining a reasonably accurate estimate of the detection rate.

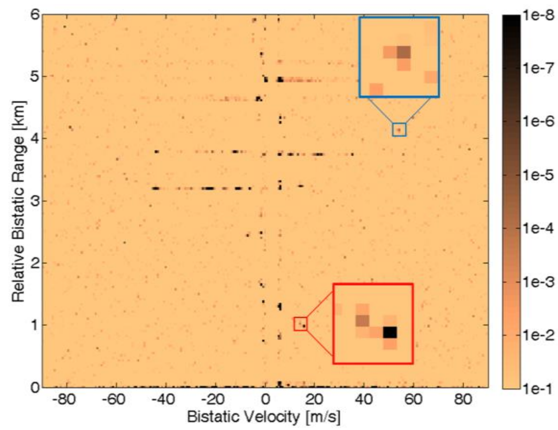
IV. Experimental Results

The results presented in the following have been obtained by applying the processing stages presented in sub-section II.II.A and sketched in Fig. 1 on the received data. In particular, four different approaches were employed at the target detection stage: (a) single-pol operation using the horizontally polarized channel only (single-pol H), (b) single-pol operation using the vertically polarized channel only (single-pol V), (c) P-NCI and (d) P- GLRT.

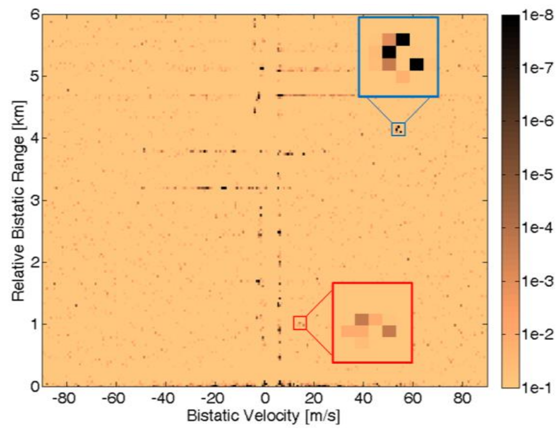
In Fig. 5(a-d) the four approaches are compared for a single scan. For each technique, we report the test statistic over the bistatic range-velocity plane before the application of a proper threshold, selected according to a desired value of nominal P_{FA}. For a fair comparison, in each case, the test statistic is mapped into the P_{FA} setting that would allow the corresponding threshold exceeding. In other words, each pixel in the map has been scaled so that it represents the minimum value of nominal P_{FA} to be set for that pixel to yield a detection. The blue and red squares in Fig. 5 represent the GPS-based positions of two of the cooperative targets, namely the aircraft Delphin and the Speedboat 1, respectively, at the considered scan. An enlarged view of the range-velocity areas around the targets locations is also reported in the square boxes. Incidentally, we notice that at the considered scan the Speedboat 2 exhibits a very low bistatic velocity that prevents its detection.

By observing Fig. 5, we can see that:

a) Targets echoes at the two orthogonally polarized surveillance antennas do not appear as equally strong peaks.



a



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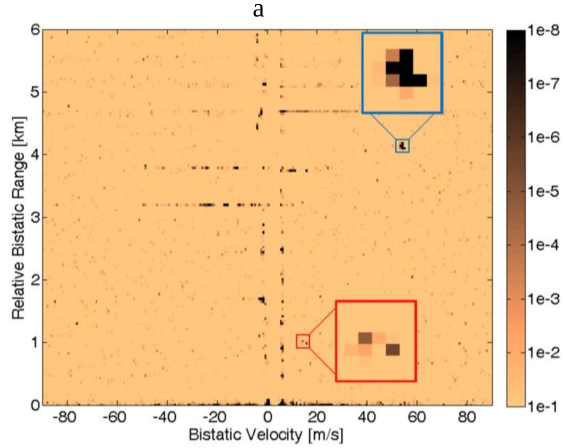
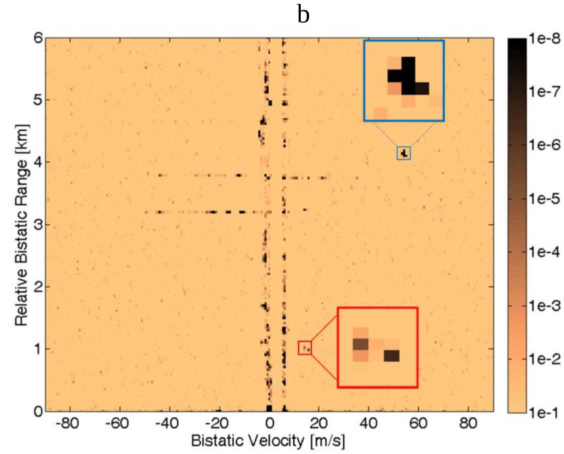


c



d

Fig. 5 Maps of minimum values of nominal $\boldsymbol{P_{FA}}$ to be used in order to detect each pixel, using:
(a) single-pol H (b) single-pol V (c) P-NCI (d) P-GLRT

In fact, the signals received at the two single-pol channels (a-b), processed according to a conventional single-pol scheme, lead to different results. Specifically, single-pol V (b) would be able to detect the aircraft Delphin also for very strict values of desired P_{FA}, while single-pol H only receives a weak echo from that target, i.e. a very high P_{FA} value would be necessary for it to be detected. An opposite behaviour is observed for the small speedboat, that is surely more apparent when the horizontally polarized antenna is used (a).This confirm the hypothesis that, depending on the complex structure of the target, the signal polarization may change in the reflection. Incidentally, we recall that the exploited IO uses H polarization.

b) The P-NCI (c) enhances the echoes of both targets. Nevertheless, as expected, it does not succeed in rejecting the disturbance, i.e. the disturbance sources different from thermal noise also benefits from the integration. This confirms what stated in Section II and already largely demonstrated for a FM based PCL [6]. In fact, we can mostly attribute the inability to provide an effective control of the false alarm rate to the weakness of the hypothesis of statistically independent disturbance affecting the L range-velocity maps. This results in a considerably high number of false alarms throughout the considered range-velocity area.

c) The P-GLRT (d) allows detecting both targets also when very strict values of desired P_{FA} are required. This advantage is obtained while still guaranteeing a good control of the number of false alarms compared to the setting of the nominal P_{FA}. In this regard, despite a quantitative comparison was not possible for the available data set, we observe that, for any given value of the nominal P_{FA}, the actual number of false alarms provided by different approaches usually exceeds the expectations since many detections are produced by cancellation residuals and other interfering sources. However, the P-GLRT always yields the lowest number of false alarms compared to the P-NCI and the single-pol solutions.

After analyzing a single scan, the entire amount of 168 scans has been jointly considered. Specifically, being interested in the detection capability of the system we focus the attention on the correct detections against the cooperative targets. In Fig. 6 (a-d) we report the sequence of detected plots (black dots) provided by different detection schemes. Specifically, we compared the corresponding velocity measurements to the bistatic velocity tracks of the cooperative targets, as a function of time. In Fig. 6, the truth-data of the aircraft Delphin and of the two speedboats are sketched as blue, red, and green continuous lines, respectively. Notice that true target trajectories fluctuate due to the rough velocity estimation obtained via a differentiation of the range information provided by the GPS.

First, by observing Fig. 6, we can confirm the first consideration made on Fig. 5. In fact, the use of a single-pol operation leads to quite different results depending on the employed polarization. For this particular data set, we can say that, on average, the single-pol H yields better results in terms of number of correct detections against all the considered targets. Nevertheless, this trend is not stable and it may change with time, namely since targets echoes typically show random polarizations, the single-pol V occasionally provides correct detections at scans where the single-pol H experiences a missed detection. This was already shown in Fig. 5 but it can also be confirmed by observing, for instance, Fig. 6 (a) and (b), focusing between 50 and 60 seconds.

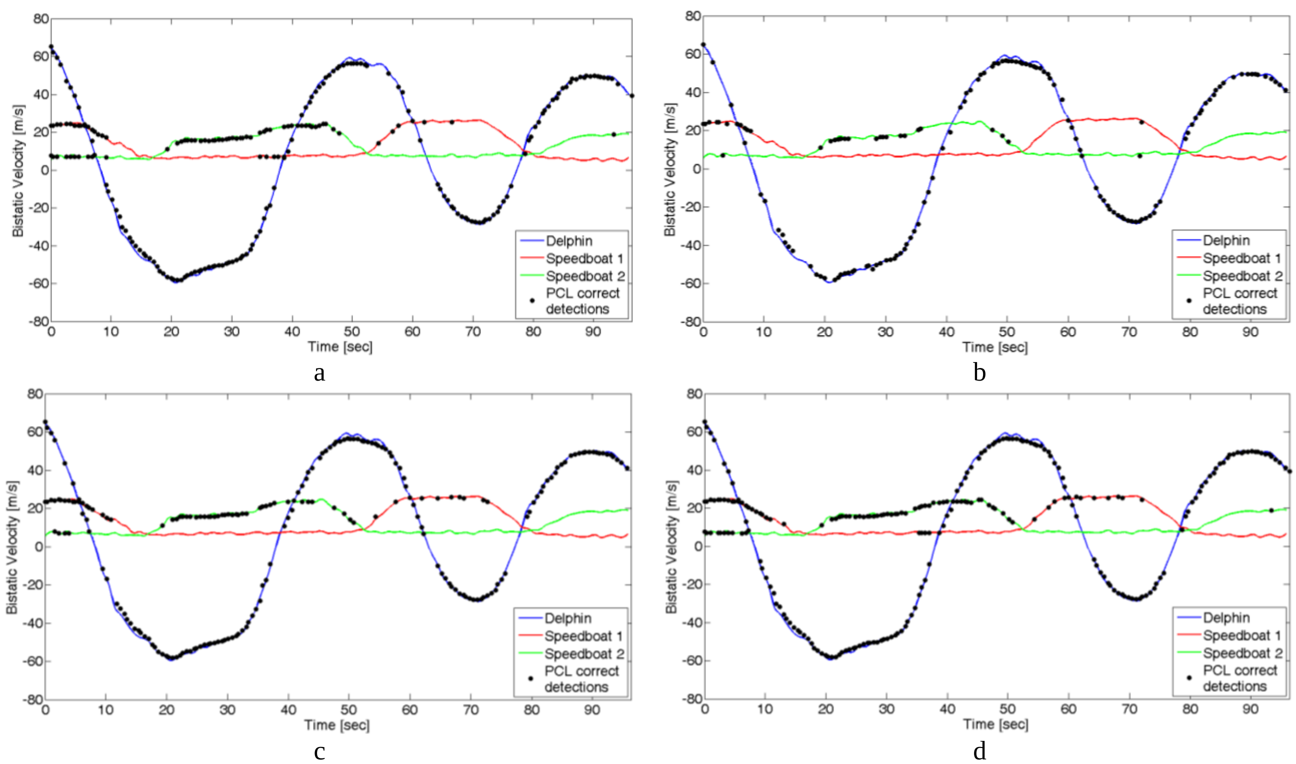


Fig. 6 Extracted sequence of correct detections reported in the velocity-time domain for 168 consecutive scans and nominal $\boldsymbol{P_{FA} = 10^{-6}}$ with: (a) single-pol H (b) single-pol V (c) P-NCI (d) P-GLRT

Similar observations were made in [5]-[6] for a FM based PCL and they were confirmed for a DVB-T based PCL [8]. Thus, it is not possible to establish a priori the best performing polarimetric channel on average.

Then, the two available polarimetric channels are jointly processed according to the polarimetric detection schemes presented in sub-section II.B. The results obtained are reported in Fig. 6 (c-d), where the P-NCI and the P-GLRT detection schemes are compared. First, we can observe that the P-NCI still experiences some missed detections at scans where the best performing single-pol channel provides correct detections. For instance, compare Speedboat 2 detections in Fig. 6 (a) and (c) between 40 and 50 seconds. Moreover, thanks to its capability to reject adaptively the disturbance based on the polarimetric information, the P-GLRT detection scheme (see Fig. 6 (d)) offers the best performance with respect to any other approach.

This is illustrated in Table I, where we collect the number of correct detections provided by each considered detection scheme against the three cooperative targets, by setting a nominal P_{FA} equal to 10^{-6}. We recall that the total number of available scans is 168. As is apparent, the P-GLRT approach yields the highest amount of correct detections. For the three targets, the performance improvement is substantial with respect to the P-NCI and the single-pol H and tremendous with respect to the worst single-pol channel (V). Specifically, with respect to the latter, the P-GLRT offers an improvement of 22%, 70% and 64% on Delphin, Speedboats 1 and 2, respectively. Moreover, the enhanced continuity of the obtained plot sequences potentially simplifies a subsequent track initiation stage. The absence of missed detections for the P-GLRT with respect to any other detection scheme considered shows that it is unlikely that target echoes are removed with the disturbance, i.e. the polarimetric characteristics of the targets and the competing background are different, as expected.

TABLE I. CORRECT DETECTIONS OF THE COOPERATIVE TARGETS WITH $P_{FA} = 10^{-6}$, USING DIFFERENT POLARIMETRIC DETECTION SCHEMES.

Target	**Correct detections using different polarimetric detection schemes**			
	Single-Pol H	***Single-Pol V***	***P-NCI***	***P-GLRT***
Delphin	141	117	144	**150**
Speedboat 1	26	11	27	**37**
Speedboat 2	50	20	40	**56**

V. CONCLUSIONS

Following the successful results obtained for FM radio based PCL, this work investigates the benefits that then joint exploitation of the different polarizations on receive yields in a PCL system exploiting DVB-T signals. Specifically, an adaptive approach, namely the P-GLRT detection scheme, has been used. The results obtained using an experimental data set, including cooperative targets, show that:

a) The signals received with two orthogonally polarized surveillance antennas, processed in a conventional single-pol scheme, lead to different results. Moreover, it is difficult to identify an effective way to a priori establish the best antenna polarization to be employed.

b) A simple non coherent integration of the information conveyed by the two single polarimetric channels, according to a P-NCI detection scheme, leads to an enhancement of target echoes. However, the P-NCI still experiences some missed detections at scans where other approaches provide correct detections. Moreover, this advantage is obtained while accepting a worse control of the false alarm rate.

c) The exploitaion of polarization diversity by means of an adaptive approach, namely the P-GLRT detection scheme, has improved the performance of the systen. In fact, it has been shown that it is possible to exploit the polarimetric differences in order to improve the target discrimination capability. The results obtained using experimental data have shown that this processing scheme allows a significant enhancement of the target detection capability of the system system. Specifically, it leads to the highest number of detections with respect to the single-pol approaches and to the P-NCI. Furthermore, it results in the best control of the actual false alarm rate.

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