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A two-stage approach for direct signal and clutter cancellation in passive radar on moving platforms

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***Abstract*— This paper addresses the problem of direct signal interference (DSI) and clutter cancellation for passive radar systems on moving platforms using displaced phase centre antenna (DPCA) approach in the presence of receive channels imbalance. First, we show that using the signal emitted by the illuminator of opportunity as a source for channels calibration might be ineffective when DSI and clutter echoes have different directions of arrival. Then, a calibration approach is presented, based on supervised selection of clutter areas in the range-Doppler map. Finally, a two-stage strategy is presented, composed of an ECA-based DSI removal prior to DPCA clutter cancellation, which doesn't require supervised selection of the calibration area. The effectiveness of this scheme in the joint suppression of DSI and clutter is shown against real data.**

Keywords—passive radar, DPCA, STAP, calibration.

I. Introduction

In the last years, passive radar (or passive coherent location - PCL) systems have gained considerable attention in the scientific community, [1]-[3], and currently several research groups are investigating the capabilities of PCL receivers on moving platforms, [4]-[9].

Stationary sensors have widely proved their ability to detect and localize air and ground targets exploiting the signals transmitted by illuminators of opportunity. In the future, this application will also be available for mobile platforms. The obvious strategic advantages of PCL receivers on moving platforms, are paid by the presence of the distortions caused by the Doppler effect: (i) the frequency-shifted reference signal must be reconstructed independently of motion, and (ii) the Doppler spectrum of the clutter echoes is spread by the motion of receiver with respect to stationary scene. This latter effect tends to be even more important at the VHF/UHF bands of the widely used FM radio and DVB-T illuminators of opportunity, because of the typical wide antenna beams available. The detection of slow-moving targets requires a proper suppression of the clutter echoes, which is usually obtained by applying Space-Time Adaptive Processing to the signals collected by multiple on-board receivers, connected to antennas with some along track displacement. The low-cost characteristic of passive radar, the typical size of antennas at VHF/UHF bands and the high data rate of digital broadcast transmissions suggest the use of only few spatial channels and a simple processing scheme. For this reason, a displaced phase centre antenna (DPCA) approach has been primarily considered in [6]-[9].

Conventional DPCA performs a non-adaptive subtraction of radar echoes collected by two receiving antennas at the times that their two-way phase centres occupy the same spatial position [11]. Echoes from stationary background are removed, being the performance only limited by thermal noise, internal clutter motion, waveform variability, and channels imbalance. Conversely, echoes from moving targets, shifted in phase due to their radial motion, are preserved and can be ideally detected. In principle, direct signal interference (DSI) can be seen as a strong stationary scatterer so that DPCA suppresses it together with the other clutter components. The effectiveness of DPCA against simulated data is presented in [6] for a DVB-T based mobile passive radar and against real data in [7] for an airborne FM-based passive radar. Moreover, in [9] a processing scheme is proposed, based on a reciprocal range compression filter and a flexible DPCA, that removes the performance limitations caused by the uncontrolled waveform variability. Its effectiveness has been verified for DVB-T based PCL system against both simulated and experimental data. Since the DPCA is intrinsically sensitive to channels imbalance, the scheme in [9] includes a simple approach for channel calibration that compensates amplitude and phase of the two channels for the global return, which is typically dominated by the DSI from transmitter, assumed as a strong reliable source.

Starting from the solution in [9], this paper shows that channels imbalance can be angle dependent due to non-identical receive antenna patterns (especially outside the main lobe region). This might be a critical problem in PCL systems, typically employing low directivity antennas, especially when clutter echoes and DSI come from different directions of arrival (DoA). In this case the simple calibration proposed in [9] can be ineffective and new solutions should be found for joint suppression of DSI and clutter disturbance.

In this paper, after recalling (Section II) signal model and processing scheme of [9], we give evidence of the limits of channel calibration based on DSI applied before DPCA, by testing it against experimental data from a DVB-T based PCL system on moving platform (Section III). Then, we propose alternative solutions, trying to preserve the paradigm of a simple processing scheme. In Section IV.A we present a supervised approach for channel calibration based on main clutter ridge contributions. In Section IV.B, we introduce a two-stage strategy for combined suppression of DSI and clutter, resorting to a time domain cancellation technique prior to the DPCA stage. Our conclusions are drawn in Section V.

II. Signal model and processing scheme

We assume a passive radar receiver mounted on a moving platform and exploiting a ground-based transmitter as illuminator of opportunity (see Fig. 1). The platform moves at constant velocity v_p on a straight line. Two parallel receiving channels are available, displaced by d in the along-track direction, in a side-looking configuration. They are referred to as leading (LA) and trailing (TA) antenna.

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The discrete time baseband signal representing the clutter contribution at the two antennas can be expressed as the superposition of echoes from stationary scatterers at different bistatic ranges R_q $(q = 1, \dots, N_R)$ and different angles φ:

$$r_C^{(LA)}[l] = \sum_{q=1}^{N_R} \int_{\phi} G^{(LA)}(\varphi)\, A_q(\varphi) \sum_n s_n\left[l - nL - l_{\tau_q}\right] \cdot \cdot\, e^{j2\pi \frac{v_p}{\lambda} \cos\varphi nT}\, d\varphi$$

$$r_C^{(TA)}[l] = \sum_{q=1}^{N_R} \int_{\phi} G^{(TA)}(\varphi)\, A_q(\varphi) \sum_n s_n\left[l - nL - l_{\tau_q}\right] \cdot \cdot\, e^{j2\pi \frac{v_p}{\lambda} \cos\varphi\, nT}\, e^{-j2\pi \frac{d}{\lambda} \cos\varphi} d\varphi \quad (1)$$

where

- φ is the angle between the platform velocity vector and the receiver to scatterer line of sight;
- $A_q(\varphi)$ and $\tau_q = l_{\tau_q}/f_s$ are the complex amplitude and bistatic propagation delay of echo from clutter patch at angle φ and range R_q, f_s being the sampling frequency;
- $G^{(LA)}(\varphi)$ and $G^{(TA)}(\varphi)$ are the complex amplitude gains of the LA and TA channels respectively; they represent the overall receiver chains, including the antenna patterns;
- $f_D(\varphi) = \frac{v_p}{\lambda} \cos\varphi$ is the bistatic Doppler frequency of the generic clutter patch at angle φ, λ being the signal carrier wavelength;
- transmitted signal has been partitioned in fragments of duration $T$and s_n is the n-th fragment, including $L = Tf_s$ samples; correspondingly the Doppler induced phase term within each fragment has been neglected.

It is worth noting that the expressions above might include also the direct signal contribution from the transmitter.

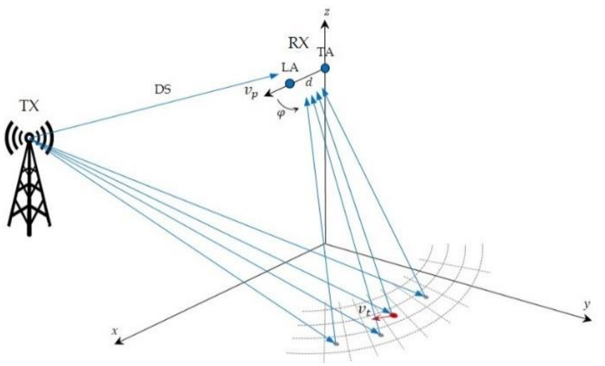

Fig. 1. System geometry for a mobile passive radar.

The processing scheme presented in [9] for a DVB-T based passive radar is sketched in Fig. 2. After a preliminary synchronization stage, the bistatic range-Doppler map is evaluated by means of a batches processing strategy:

i. the received signal is subdivided into short consecutive batches of duration T, deliberately selected to be equal to single OFDM symbols;
ii. range compression is performed on a batch-by-batch basis, using a reconstructed version of the reference signal in a reciprocal filtering strategy;
iii. consecutive batches are coherently combined by means of a DFT to synthesize the Doppler dimension.

A batches processing architecture significantly reduces the computational load in passive radar exploiting wideband digital waveform. Moreover, it recreates the conventional framework of a pulsed radar operating at an equivalent PRF, given by the inverse of the batch length ($PRF = 1/T$).

The use of a reciprocal filter in the range compression stage has a dual function. On one hand, it allows to control the sidelobes level and mitigate undesired structure and grating lobes arising in the signal ambiguity function, which may hinder echo signals of targets, especially when OFDM transmissions are exploited [12]-[13]. On the other hand, reciprocal filter strategy yields significant advantages to the subsequent DPCA stage (see [9]). At the expense of a limited and predictable loss compared to a matched filtering, it allows to remove the temporal variability of the system impulse response, due to the time-varying characteristics of the employed waveform of opportunity, so that an ideal clutter cancellation can be in principle obtained based on subsequent observations of a stationary scene.

DPCA stage is then applied by resorting to a flexible technique, which allows to relax the constraint posed on the equivalent PRF. For bistatic radar employing a stationary transmitter, DPCA condition is given by:

$$T_{DPCA} = K \cdot PRI = K \cdot T = d/v_p \quad (2)$$

where K is the integer number of symbols after which the two-way phase centres occupy the same position. Since this condition is hardly verified in real environment, in flexible-DPCA technique, the required time shift is performed in two steps: a coarse delay T_q quantized to the equivalent PRI is applied in time domain; a residual fine delay T_f is compensated in frequency domain by a linear phase term.

$$T_q = \left\lfloor \frac{d}{v_p T} \right\rfloor T$$
$$T_f = T_{DPCA} - T_q \quad (3)$$

The platform velocity must be measured by means of an Inertial Measurement Unit (IMU) or estimated from the data. Based on this strategy, the proposed architecture can be effective in establishing the DPCA condition also when a batches architecture is adopted.

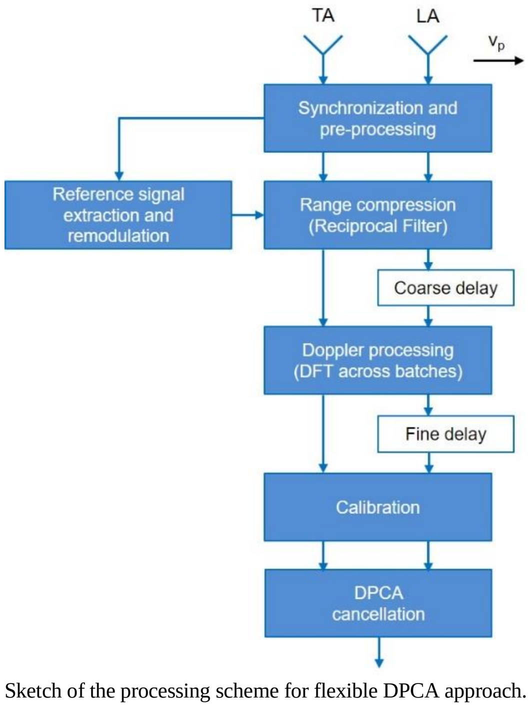

Fig. 2. Sketch of the processing scheme for flexible DPCA approach.

The described processing scheme should in principle provide an ideal cancellation of stationary background, by a simple subtraction of the delayed observations from the two channels, provided that the following conditions are met:

- perfect DPCA condition established by compensation of time delay according to (3);
- negligible internal clutter motion (ICM), i.e. constant amplitude $A_q(\varphi)$ within the processing interval;
- compensation of potential amplitude and phase inter-channel imbalance $\Gamma(\varphi) = G^{(TA)}(\varphi)/G^{(LA)}(\varphi)$.

Therefore, even assuming the first two conditions, DPCA performance strongly relies on the adoption of a proper calibration strategy before channel subtraction.

The simplest model for channel calibration is based on the assumption of a uniform amplitude and phase channel imbalance, $\Gamma(\varphi) = \Gamma_0$, to compensate for by applying a single complex coefficient. Nevertheless, as mentioned, calibration requirements might depend on DoA, due to the effect of non-identical antenna patterns. Consequently, if significant stationary scene contributions arrive from very different directions, more sophisticated calibration strategies should be defined for an effective cancellation.

Specifically, we focus on difference in channel imbalance, and thus in the required calibration, between DSI and clutter echoes under the specific bistatic geometries, that make unfeasible to cancel both with a single calibration coefficient.

III. Application against experimental data

A. *Overview of the acquisition campaign*

The processing scheme and calibration strategies proposed below are applied against a set of experimental data acquired by a DVB-T based multichannel PCL mounted on a ground moving platform. The acquisition campaign was conducted by Fraunhofer FHR in a rural area of the Eifel region, in western Germany. The selected DVB-T illuminator of opportunity was the Eifel/Scharteberg transmitter. The PCL system consisted of four receiving channels, serving as surveillance channels, connected to discone antennas (omnidirectional in azimuth), displaced in the along-track direction. A radar absorbing material (RAM) surface was placed on one side, thus forming a single side-looking configuration. The system was mounted on the back of a van (see Fig. 3). Table I summarizes the parameters of exploited DVB-T transmission and main acquisition and processing parameters.

For the purpose of our study, signals collected by only two adjacent antennas are exploited below, to analyse the effects of different calibration strategies with the considered DPCA scheme. The reference signal is extracted from one of the surveillance channels.

Fig. 3. Multichannel PCL receiver mounted on the back of a van in a side-looking configuration.

In particular, the considered case study is characterized by a bistatic geometry where the transmitter is located in the opposite direction to the observed scene, with direct signal impinging on the antenna back-lobes.

TABLE I. Parameters of experimental test

Symbol	*Description*	*Value*
	DVB-T signal parameters	
	DVB-T Standard	8k 16QAM
f_c	Carrier frequency	690 MHz
N_c	Number of useful carriers	6817
T_u	Useful symbol duration	896 us
T_g	Guard interval duration	224 us
T_s	OFDM symbol duration	1120 us
B	Bandwidth	7.61 MHz
	System and processing parameters	
d_a	Antenna spacing	$0.36\ m$
CPI	Coherent processing interval	$512\ T_s$

B. *Results with calibration on direct signal*

As mentioned, the simplest approach for channel calibration is based on direct signal coming from transmitter. A single complex coefficient is evaluated according to the single range-Doppler bin associated to DSI, to compensate for an assumed angle invariant channel imbalance $\Gamma(\varphi) = \Gamma_0$. Complex correction coefficient is then given by:

$$\widehat{\Gamma_0} = \frac{z^{(TA)}[r_{TX}, f_{TX}]}{z^{(LA)}[r_{TX}, f_{TX}]} \quad (4)$$

where $z^{(\gamma)}[r_{TX}, f_{TX}]$ are the complex values in range-Doppler map corresponding to direct signal. This approach can rely on a strong and reliable source and proved to be effective in the analysis conducted in [9]-[10], where a dominant front DSI contribution was present in a maritime scenario.

Unfortunately, under more general conditions, direct signal can be not representative of the overall clutter distribution in terms of amplitude and phase calibration requirements. This might be the case when the DSI DoA is outside the main antenna beam, where antenna patterns are very likely to differ.

A range-Doppler map obtained at single channel (LA in this case) before DPCA, for a CPI of $512\ T_s \cong 0.57\ s$, is reported in Fig. 4. A strong DSI contribution appears at the first bistatic range bin and Doppler $f_{TX} \cong -3.3\ Hz$. Clutter extends over a Doppler bandwidth of $\pm v_p/\lambda \cong \pm 32\ Hz$ and is characterized by the presence of large discrete contributions. Notice that all range-Doppler maps are scaled to the estimated noise power level to allow a direct comparison of the results. Fig. 5 shows the results after the application of the flexible-DPCA scheme, adopting the DSI-based calibration strategy. It is evident how cancellation only occurs for DSI, while echoes from stationary scene are not suppressed and appear to be even increased.

In order to quantify the effectiveness of clutter suppression and compare the results of different approaches, we define as performance metric a cancellation ratio (CR), which expresses the attenuation in clutter power provided by the DPCA stage:

$$CR[r, f] = \frac{P_c^{in}[r, f]}{P_c^{out}[r, f]} \quad (5)$$

where $P_c^{in}[r,f]$ is the clutter power measured on the range-Doppler map at the LA and TA channels and $P_c^{out}[r,f]$ is that measured after the application of DPCA. Since all maps are scaled to the estimated thermal noise floor, CR can be regarded as Clutter to Noise Ratio reduction. It can be evaluated for each single range-Doppler bin or as an average power reduction in a specific area of the map. Fig. 6 shows the CR for the case in Fig. 5, as function of range-Doppler bin.
As expected, perfect cancellation is obtained for the range-Doppler bin corresponding to DSI and high CR values for its multipath and sidelobes contributions.

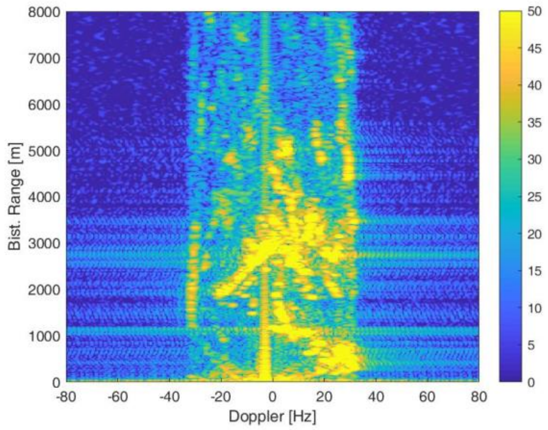

Fig. 4. Single channel Range-Doppler map obtained at LA or TA.

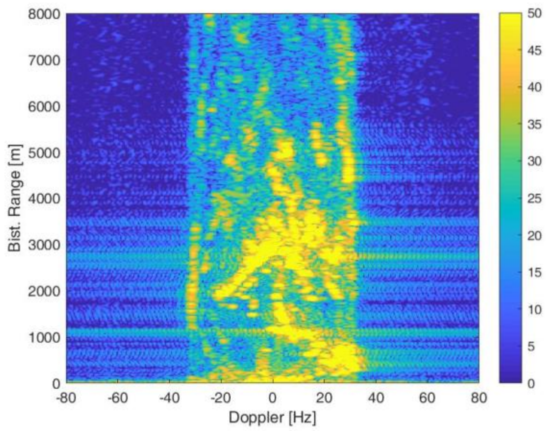

Fig. 5. Range-Doppler map after DPCA with calibration on direct signal.

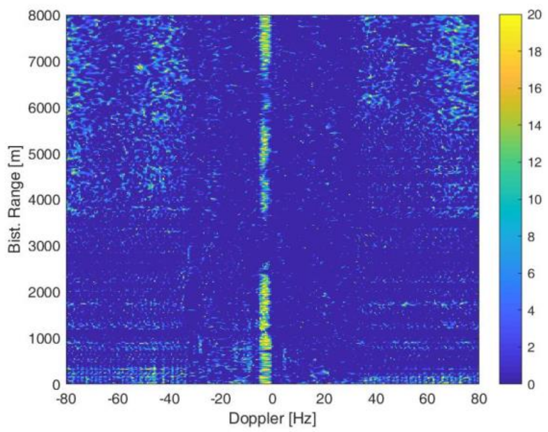

Fig. 6. Cancellation Ratio as a function of Range-Doppler bin given by DPCA with calibration on direct signal.

Conversely, the average CR on an area containing the overall clutter ridge: bistatic range interval [500, 8000] m and Doppler frequency [-35, 35] Hz, is of -2.1 dB, implying increased clutter power.

Apparently, residual channel mis-calibration prevents the clutter echoes from being cancelled. This result can be attributed to differences in back-lobe pattern of surveillance antennas and gives evidence of the limits of a calibration approach based on the DSI and, more in general, of the assumed model of a uniform inter-channel imbalance.

IV. Proposed Alternative Approaches

In this section, a slightly more complex model for inter-channel imbalance is adopted: it is assumed that $\Gamma(\varphi)$ is constant for the clutter contributions, mostly coming from the antenna main lobe, while it possibly has different amplitude and phase values for the DSI, coming from the back-lobes. We present alternative strategies for channel calibration, aimed at providing the maximum attenuation of clutter power, while preserving the paradigm of a simplified approach based on the estimation of a single calibration coefficient. A two-stage approach is then considered, which allows for a joint suppression of DSI and clutter contributions, and its benefits to final cancellation performance are analysed.

A. *Calibration on clutter ridge*

In order to minimize the clutter power at the output of DPCA subtraction, thus maximizing the cancellation ratio, the complex calibration coefficient can be defined as:

$$\Gamma_c = \underset{\Gamma}{\text{argmin}}\left\{E\left\{\left|z^{(TA)}[r,f] - \Gamma\, z^{(LA)}[r,f]\right|^2\right\}\right\} = \frac{E\left\{z^{(TA)}[r,f]\, z^{(LA)^*}[r,f]\right\}}{E\left\{\left|z^{(LA)}[r,f]\right|^2\right\}} \quad (6)$$

where * indicates conjugate. The calibration coefficient that maximizes CR in a selected clutter area is then evaluated as:

$$\widehat{\Gamma_c} = \frac{\frac{1}{N}\sum_{i=1}^{N} z_i^{(TA)} z_i^{(LA)^*}}{\frac{1}{N}\sum_{i=1}^{N}\left|z_i^{(LA)}\right|^2} \quad (7)$$

Moreover, to make calibration more robust, only range-Doppler bins whose power level exceeds an assigned threshold are considered. Notice that, by selecting only the DSI range-Doppler bin, (7) coincides with (4). However, if the overall clutter ridge area is blindly selected for calibration, results are nearly identical to the previous case, due to the high DSI values. In contrast, with a properly supervised selection of a clutter area that does not include cells where the DSI is dominant (typically skipping the first range bins) calibration is correctly performed on clutter echoes, thus minimizing the clutter power.

An example of results achievable with this approach is presented in Fig. 7 and Fig. 8. As expected, significant clutter power attenuation is obtained, with an average CR value of 12 dB across the overall clutter ridge and values up to 30 dB at specific range-Doppler locations. On the other hand, the DSI is not suppressed at all.

The main drawback of this approach is that a supervised selection of calibration area is required: this area might depend on the transmitter power level and position. Moreover, the DSI might remain non-cancelled.

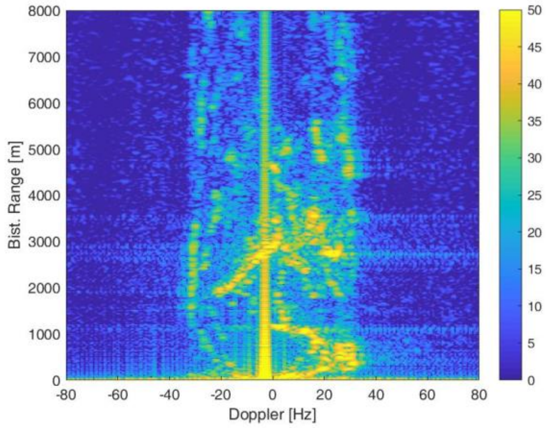

Fig. 7. Range-Doppler map after DPCA with calibration on clutter ridge.

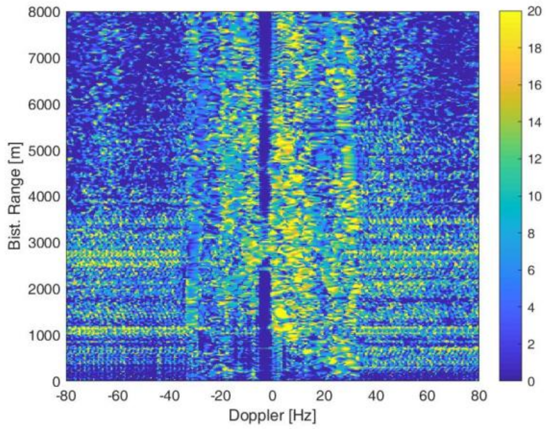

Fig. 8. Cancellation Ratio as a function on Range-Doppler bin given by DPCA with calibration on clutter ridge.

B. *Direct signal removal and calibration on clutter ridge*

A modified version of the processing scheme is sketched in Fig. 9. This architecture adds a DSI suppression stage preceding the DPCA stage, thus forming a two-step cancellation approach. DSI is suppressed on both surveillance channels in time domain, resorting to ECA techniques, while clutter cancellation is performed in space-time domain via DPCA. This approach aims at: (i) achieving a combined cancellation of both DSI and clutter echoes, despite adopting a calibration strategy based on a single coefficient; (ii) allowing a blind selection of the range-Doppler map area used for the evaluation of calibration coefficient.

The Extensive Cancellation Algorithm (ECA) [14] is able to remove DSI by projecting the surveillance signal into a subspace orthogonal to direct signal disturbance. Specifically, we adopt in this case the ECA-CD (ECA by Carrier and Doppler) version of the algorithm [15], which operates carrier by carrier with OFDM waveforms. Preliminary suppression of DSI removes the need for a supervised selection of calibration area. Therefore, the calibration coefficient can be evaluated according to (7), on a blindly selected clutter area.

Fig. 10 shows the range-Doppler map obtained after applying the two-stage cancellation scheme. Calibration is performed based on the overall clutter ridge area. As expected, DSI is successfully suppressed by the ECA-CD stage and clutter power is attenuated by the following DPCA stage. Corresponding CR maps are shown in Fig. 11 and Fig. 12, respectively the CR provided by the ECA-CD at both surveillance channels and the CR given by the final DPCA.

In particular, the average clutter power reduction across the overall ridge exceeds 13.5 dB. Table II compares achieved cancellation values using the different considered approaches. CR is evaluated on the DSI bin and the overall clutter ridge.

Obtained results lead to following considerations: a clutter suppression stage via DPCA approach is clearly still required after the DSI removal and DPCA cancellation capability over clutter can be even improved after DSI suppression, thanks to a more accurate calibration, to an extent that likely depends on the level of DSI. The residual uncancelled clutter power in the final range-Doppler map highlights the presence of further limitations to DPCA performance, possibly related to internal clutter motion (ICM), potential antenna misalignment or mutual coupling effects, or to additional antenna pattern diversity in Doppler/angle domain over the clutter ridge.

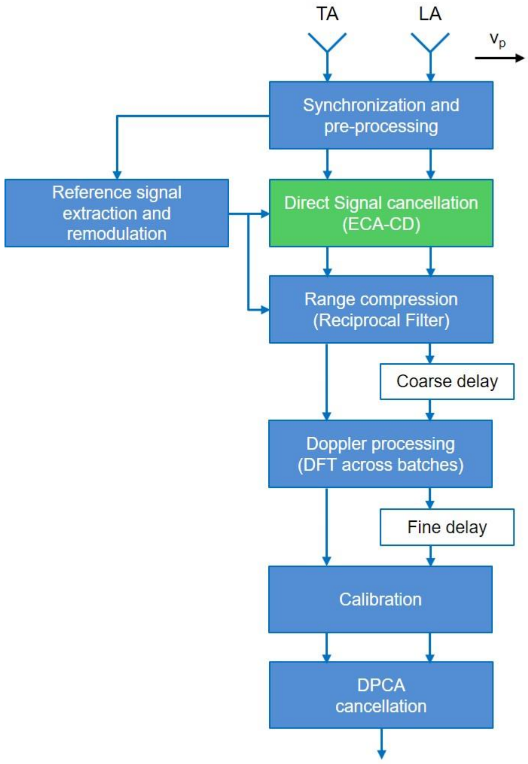

Fig. 9. Modified processing scheme for the two-stage approach: ECA-CD technique for direct signal cancellation and DPCA for clutter suppression.

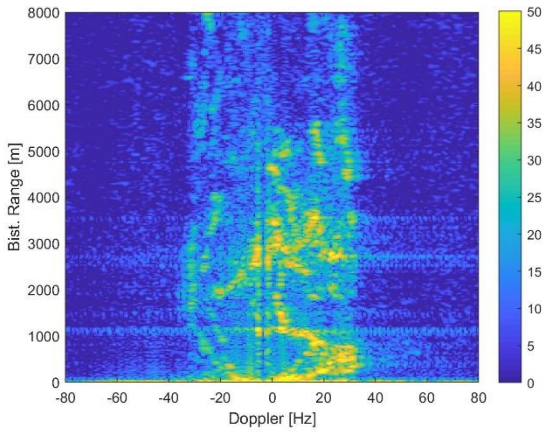

Fig. 10. Range-Doppler map after ECA-CD and DPCA with calibration on clutter ridge.

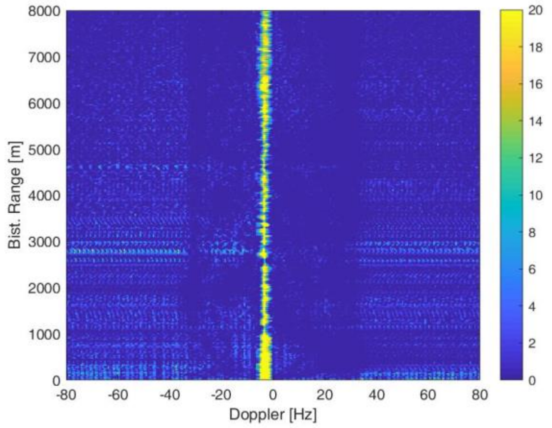

Fig. 11. Cancellation Ratio as a function of Range-Doppler bin given by the ECA-CD stage.

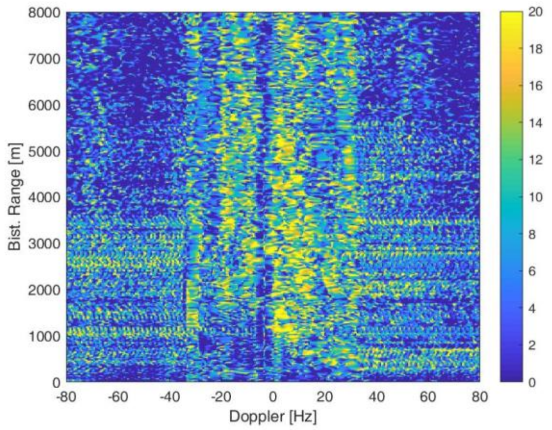

Fig. 12. Cancellation Ratio as a function of Range-Doppler bin given by the DPCA stage with calibration on clutter ridge.

TABLE II. COMPARISON OF OBTAINED CANCELLATION RATIO

Considered area	**Adopted approach**			
	DPCA calibration on DS	*DPCA calibration on Clutter*	*Two-Stage*	
			ECA-CD	*DPCA*
Direct Signal	Inf.	-2.1 dB	56.8 dB	-1.2 dB
Clutter ridge	-2.1 dB	11.9 dB	0.3 dB	13.7 dB

V. CONCLUSIONS

In this paper we addressed the problem of direct signal interference and clutter cancellation for a passive radar on moving platform through DPCA approach.

First, we highlighted the limits of a channel calibration approach based on direct signal, for bistatic geometries where DSI and main clutter echoes have different directions of arrival, due to the effect of unequal antenna patterns on the channel imbalance.

Therefore, we proposed two alternative strategies, by still resorting to a simple model for channel calibration. Firstly, an approach was presented for calibration based on selected areas of range-Doppler map, in order to maximize the cancellation performance on clutter region. Then, a two-stage strategy was proposed, providing an ECA-based DSI removal prior to clutter cancellation via DPCA. This approach allows the joint suppression of direct signal and clutter; it makes the system more robust to the presence of DSI coming from directions affected by different channel imbalance and allows for an unsupervised selection of the calibration area.

Although we reported results for a single case study, the proposed approach proved to be effective for ground moving receiver also in other experimental datasets, characterized by different bistatic acquisition geometries, and it is reasonably expected to be applicable also to other mobile PCL system configurations, e.g. airborne receiver.

Future research will investigate more sophisticated calibration strategies, to compensate for additional angle-dependent channel errors across Doppler bins. An example along this line is reported in the companion paper, [16].

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