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DVB-T Airborne Passive Radar: clutter block rejection

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Abstract—Passive radar systems generally receive direct path, ground echoes and potential target echoes. As the first two are much more powerful than the target signals, they have to be rejected. Numerous solutions are proposed in the literature. The algorithm introduced by [1] has become a reference. Due to the airborne passive clutter spread, this algorithm faces limits. In this article, we derive two solutions in order to be able to reject a large amount of clutter and therefore to reduce detrimental secondary sidelobes. Experimental results prove that the proposed method performs only 4 dB worse than in a ground configuration.

Index Terms—airborne passive radar, DVB-T, clutter rejection

I. INTRODUCTION

The radar system literature devotes various studies to the passive radar detection, that is to say detection using already existing transmitters. These non-cooperative transmitters may broadcast television, radio or other services. The aim of passive detection consists in seeking for echoes of the scattered signal from potential targets.

The composite nature of the received signal, containing in general the direct path and multiple ground echoes, that is to say clutter, imposes to filter these interferences out so as to obtain proper detection performance. The optimal coefficients according to the minimum mean square error (MMSE) correspond to the Wiener-Hopf filter [2]. But this solution is generally too complex to be computed. Consequently, several articles propose suboptimal approaches such as Least Mean Square (LMS), Normalised LMS (NLMS) or Recursive Least Square [3]. These algorithms are relevant for stationary environment but less efficient for a time varying one. Otherwise, the article [4] adapts to radar the CLEAN method introduced initially for astronomic purposes. However this processing generates artefacts especially in case of diffuse backscatterers [5]. Moreover, the author of [6] uses the OFDM signal properties to reject direct path frequency by frequency. Finally the authors of [1] proposes a Least Square approach. This solution will be used as the reference rejection method due to its proper ability to cancel direct path and clutter.

A. The RIVERA radar

To overpass the imperfections of simulation, the authors have developed an airborne passive radar in order to obtain real experimental data. RIVERA is a dedicated project to aiRborne passIVE Radar, led in partnership between SONDRA, ONERA and the French Air Force. A whole system has been developed. It is composed of a 3-channel antenna array and a radio-frequency receiver embedded in a pod of the BUSARD (Banc Ultraléger pour Systèmes Aéroportés de Recherche sur les Drones) motorglider, which is the ONERA testbed dedicated to air experiments, such as remote sensing and specifically SAR imaging [7], [8]. The BUSARD cruise speed is comprised between 30 m/s and 55 m/s. It can load up to 60 kg in its two under wing pods. One pod is in charge of electrical power generation, and the other, which is transparent to electromagnetic waves, carries the payload as it is shown in figure Fig.1.

RIVERA is especially designed to deal with Digital Video Broadcasting - Terrestrial (DVB-T) signal. The DVB-T signal uses to Orthogonally Frequency Division Multiplexing (OFDM) modulation [9]. It means that each OFDM symbol is composed of equispaced subcarriers that do not interfere with one another. Each subcarrier conveys an elementary symbol picked from a particular constellation such as Quadrature Amplitude Modulation (QAM). Besides, each DVB-T channel is about 8 MHz wide. It implies that such a signal provides a very accurate range resolution. As detailed in [10], the range resolution is:

$$\Delta_r = \frac{c}{2B_w \cos(\beta/2)}, \quad (1)$$

where B_w is the signal bandwidth, c the speed of light and β the bistatic angle.

Two experimental campaigns have been performed in Salon de Provence, south of France. The first one took place in 2015, and aimed at validating the passive radar system in its environment. It allowed, first, to observe the level of signals recorded at different altitudes and ranges in order to quantify the signal to noise ratio, and second, to measure the impact of the platform mobility on the reference signal reconstruction. The second campaign, in 2017, took advantages of the first

results, and guided the parameter choice such as speed and altitude, in order to observe the impact of clutter spread on mobile target detection. In France, to our knowledge, the only DVB-T airborne passive radar experimentations have been conducted in common by Sondra, Onera and the French Air Force.

Fig. 1. RIVERA on BUSARD

The paper is organized as follows. In section II, we expose the standard rejection method and point out its limits in case of an airborne configuration. The third section introduces the principle of block rejection and shows some experimental results. The fourth section explains the evolution from block processing to sliding block processing. It also gives a general overview of the RIVERA system rejection ability. The last section concludes the paper.

II. STANDARD REJECTION METHOD LIMITS

A. Passive radar standard processing

A passive radar system uses non-cooperative transmitters such as television, radio, mobile phone or even Wifi [11]. Consequently, it consists of a receiver only. The received signal can be decomposed into several components : the direct path from the transmitter, in case it is actually in line-of-sight, reflections on ground obstacles that form the clutter, and finally reflections on potential targets. Consequently, at time t , the received signal is:

$$\mathbf{z}(t) = \mathbf{z}_{DP}(t) + \sum_{i=1}^{N_{CL}} \mathbf{z}_{CL,i}(t) + \sum_{k=1}^{N_{TG}} \mathbf{z}_{TG,k}(t) + \mathbf{u}(t), \quad (2)$$

where physical values indexed by DP , CL and TG respectively refer to direct path, clutter and targets. $\mathbf{z}$ corresponds to the whole received vector whereas $\mathbf{z}_{XX}$ indexed values refer to each received signal component. N_{XX} is the number of paths, $\mathbf{u}$ a white Gaussian additive noise.

All the paths are characterised by an attenuation α_{XX} , a delay τ_{XX} , a phase shift ϕ_{XX} and a Doppler shift f_D^{XX} . For $i = 1 \dots N_{CL}$, for $k = 1 \dots N_{TG}$:

$$\begin{cases} \mathbf{z}_{DP}(t) &= \alpha_{TDS}(t) e^{j\phi_{TD}} \\ \mathbf{z}_{CL,i}(t) &= \alpha_{CL,i} \mathbf{s}(t - \tau_{CL,i}) e^{j2\pi f_D^{(CL,i)} t} e^{j\phi_{CL,i}} \\ \mathbf{z}_{TG,k}(t) &= \alpha_{TG,k} \mathbf{s}(t - \tau_{TG,k}) e^{j2\pi f_D^{(TG,k)} t} e^{j\phi_{TG,k}} \end{cases} \quad (3)$$

To sum up, the received signal has a composite nature: it is a sum of attenuated, delayed and Doppler shifted copies of the transmitted signal $\mathbf{s}$. Passive radars consists in detecting target despite all the other components.

First of all the transmitted signal has to be estimated. It then becomes our reference signal, denoted as $\mathbf{s}_{ref}$. This estimation may be easy for terrestrial non moving platform, but reveals to be much more difficult in case of an airborne platform as precised in [12]. Then, direct path and clutter have to be rejected. Their contributions are in general much more powerful than the target signal. So it may mask the potential target. Finally radar target detection is performed via a correlation between the received signal and the transmitted signal that scans the different variable states. If τ and ν denotes respectively the delay and the Doppler frequency, then the matched filtering correlation can be written:

$$\chi_{(\tau,\nu)}(\mathbf{z}, \mathbf{s}) = \int_0^{T_{int}} \mathbf{z}(t) \mathbf{s}_{ref}^*(t - \tau) e^{-j2\pi\nu t} dt, \quad (4)$$

where T_{int} is also called integration time.

B. Passive airborne clutter spread

As detailed in [13], a geometrical analysis can explain the clutter spread. Let us consider a flat earth. On the one hand, the projection of isorange curves on the ground are ellipsis whose focii are the transmitter and the receiver. These ellipsis are symmetrical with respect to the baseline between the two focii.

On the other hand, the projection of isodoppler curves on the ground would be half straight lines concurrent at the receiver position if the receiver lied on the ground. But the radar elevation distorts the half straight lines into hyperboles, whose center lies at the receiver. These hyperboles are also symmetrical about the axis defined by the platform velocity vector.

As a consequence, for a given range, the Doppler frequency shift limits can be derived from the two isodoppler curves that are tangent to the corresponding ellipse. The lack of symmetry between isodoppler and isorange curves induces a dissymmetry between the Doppler shift limits. The Doppler clutter spread is indeed range dependent.

Figure Fig.2 provides the output of the matched filter for one experimental dataset. The direct path has been rejected to better visualize the clutter. Red lines indicate the predicted of clutter bounds inferred from the above detailed reasoning.

Contrary to a ground passive radar, where the clutter concentrates along the 0 Hz-Doppler axis, this figure points out the very large clutter spread. It obviously implies that its rejection will be much more complex.

C. Rejection complexity

In order to reject direct path and clutter, the authors of [1] proposes a Least Square approach to estimate the rejection coefficients $\mathbf{g}$. These filter coefficients are solution of:

$$\mathbf{g}_{LS} = \arg \min_{\mathbf{g}} \|\mathbf{z} - \mathbf{S}_{ref}^{(\tau,D)} \mathbf{g}\|^2. \quad (5)$$

Fig. 2. Matched filter output after direct path cancellation - Clutter spread predicted bounds in red line.

where $S_{ref}^{(\tau,D)}$ corresponds to the rejection mask. The columns of this matrix are delayed and Doppler shifted copies of the reference signal of length N_s . As K_τ and K_D denote respectively the number of range and Doppler hypotheses (that is bins to be rejected), the matrix size is $N_s \times K_\tau K_D$. The solution of equation (5) is:

$$\mathbf{g}_{LS} = \left((S_{ref}^{(\tau,D)})^H S_{ref}^{(\tau,D)} \right)^{-1} (S_{ref}^{(\tau,D)})^H \mathbf{z}. \quad (6)$$

It corresponds to an orthogonal projection to the rejection mask $S_{ref}^{(\tau,D)}$ subspace. Figure Fig.3 summarizes the principle.

Fig. 3. Rejection algorithm principle.

This algorithm imposes to precise the range and Doppler cells where to cancel clutter. The rejection mask contains as many delayed and Doppler shifted copies of the reference signal as there are selected range-Doppler cells. Yet, the previous section points out the large bistatic aeronautical passive clutter spread. First, let us assume that it extends beyond 50 km. Considering the accurate range resolution of DVB-T signal as defined by (1), it corresponds to about $K_\tau = 1500$ range bins. Besides it is roughly 100 Hz to 150 Hz Doppler wide.

The Doppler resolution depends on the observation time T_{int} , so that:

$$\Delta_{Doppler} = \frac{1}{T_{int}}. \quad (7)$$

Considering an integration time of 160 ms, the Doppler resolution is about 6 Hz. It means that $K_D \simeq 20$ Doppler bins have to be taken into account. Moreover, as recommended by [14], the Doppler must be oversampled by at least a factor of 3, to improve algorithm efficiency. It results in $K_\tau \times (K_D \times 3) = 90000$ cells.

As the reference signal is about $N_s = 1500000$ samples long, it represents more than 8 To memory considering that we use the 64 bytes double float number representation. We conclude that the standard method [1] is not applicable here to cancel the whole clutter.

III. BLOCK REJECTION

A. Principle

Even though the standard rejection is unable to address the whole clutter, it proves to be efficient to cancel direct path and limited part of clutter. So it is necessary to find a method able to reduce the rejection mask size in order to be able to cancel large quantities of clutter.

Therefore we propose to divide the received signal into small blocks $\mathbf{z}_i$, for $i = 1, \dots, n_{block}$, of duration T'_{int} where n_{block} denotes the number of blocks. Rejection is then performed on every blocks, leading to different $\mathbf{g}_{LS,i}$ filter coefficients. The rejected signal $\mathbf{z}_{rej}$ is build by concatenating all rejected blocks: $\mathbf{z}_{rej} = [\mathbf{z}_{rej,1}, \dots, \mathbf{z}_{rej,n_{block}}]$. Rejection over small blocks cancels a wider Doppler spectrum, as $1/T'_{int} < 1/T_{int}$. In our case, it reduces the rejection mask $S_{ref}^{(\tau,D)}$ size by approximately a factor of T_{int}/T'_{int} , so that farther range cells can be rejected.

The authors of [15] have proposed to implement a batch version of the rejection method of [1]. Initially they introduced it to reduce computation load. In our case, we propose it to monitor the rejection notch fineness.

B. Experimental results

For practical reason, blocks correspond to groups of OFDM symbols. Table Tab.I compares the Doppler notch width for different block sizes. It shows that the block rejection method can reduce Doppler hypotheses by a factor from 6 to 18. This allowed us to reject large amount of clutter as it can be seen on figure Fig.4. To evaluate the rejection algorithm we measured the secondary sidelobes signal-to-noise ratio, denoted as SNR_{SSL} . The five listed block configuration provide SNR_{SSL} .

Figure Fig.5 plots the evolution of SNR_{SSL} as the number of rejected range cells increases. We notice that the SNR_{SSL} first sharply decreases. However, after 1500 range bins, the decrease slope tends to slow. For instance, rejecting 3000 range bins provides only a 1 dB decrease of the SNR_{SSL} compared to rejecting 1500 range bins. As a consequence, we assume that significant clutter may be restricted only to the 1500 first range cells.

TABLE I
DOPPLER NOTCH COMPARISON FOR DIFFERENT BLOCK SIZE

Symboles / blocks	32	20	16	10	8
T'_{int} ms	32.3	20.2	16.1	10.1	8.1
$\Delta_{Doppler}$ Hz	31	49	62	99	124
Clutter spread [Doppler bin]	3	2	2	2	1

Fig. 4. Range-Doppler matched filter output after block rejection - 8 symbols / block

Fig. 5. Secondary sidelobes SNR vs number of rejected range cells

IV. SLIDING BLOCK REJECTION METHOD

A. Motivation and principle

As detailed in article [16], block processing introduces some artefacts due to the filter coefficients $\mathbf{g}_{LS,i}$ discontinuities. These artefacts present a Doppler period inverse to the block duration T'_{int} . Figure Fig.6 illustrates such a phenomenon, with peaks at 46.5 Hz, 170.5 Hz and 294.5 Hz. The frequency interval between two peaks is exactly $1/T'_{int} = 124$ Hz.

Therefore we propose to smooth the rejection filter coefficients estimation by using sliding blocks that overlap from one to the next. The whole block duration T'_{int} is used to estimate the coefficients. However only the central part of the considered block is exploited to form the output rejected signal over the whole T_{int} duration. Successive blocks overlap one another. This procedure enables to smoothe coefficients, and mitigate artefacts.

Fig. 6. Block processing artefact highlights - 8 symbols / block

The article [16] also proposes a sliding batch version of the standard rejection algorithm they have introduced in [1]. However their goal was quite different. On the one hand, the authors notice that rejecting over a smaller period allows the algorithm to better take into account the environment fluctuations. So short blocks must be preferred to permit rapid update of filter coefficients. But, in the other hand, it needs enough data to accurately estimate the coefficients, that is to say long blocks. As these two requests are conflicting, they have introduced a sliding version that allow them to dissociate it. The coefficient update duration (central part of the block) is decorrelated from the needed coefficient estimation duration (whole block).

B. Space filtering

During our research, we observe that space filtering helps reducing the secondary sidelobes. It aims at roughly filter out the direction of the transmitter in order to help cancelling the direct path, but also to suppress all distortions introduced by the transmitter that can not easily be modelled by the reference signal. The filter notch is built toward the eigenvector $\mathbf{a}_{FOC}$ of the main eigenvalue λ_{max} of the received signals over the RIVIERA antennas. Let us consider $\mathbf{z}_a = [\mathbf{z}_1, \mathbf{z}_2, \dots, \mathbf{z}_{N_{RX}}]^T$ the vector of received signals on each elementary antenna, where N_{RX} is the number of antenna. $\mathbf{z}_a$ is a matrix of size $N_{RX} \times N_s$. The eigenvalue λ_{max} is defined as :

$$\lambda_{max} = \max_{i=1, \dots, N_{RX}} \lambda_i, \quad (8)$$

where $[\lambda_1, \lambda_2, \dots, \lambda_{N_{RX}}]$ corresponds to the eigenvalue decomposition of the covariance matrix $\hat{R}_{\mathbf{z}_a \mathbf{z}_a} = E[\mathbf{z}_a \mathbf{z}_a^H]$.

Finally the orthogonal projector toward $\mathbf{a}_{FOC}$ is:

$$\Pi_{\mathbf{a}_{FOC}} = I_{N_{RX}} - \frac{\mathbf{a}_{FOC} * \mathbf{a}_{FOC}^H}{(\mathbf{a}_{FOC}^H * \mathbf{a}_{FOC})} \quad (9)$$

where $I_{N_{RX}}$ represents the identity matrix of size N_{RX} .

C. Experimental results

The chart Fig.7 presents an overview of several processing performances. It compares the SNR_{SSL} when there is no rejection, with the standard algorithm, the block rejection and finally the sliding rejection. We also combine these rejection solutions with a space filter (SF). The space filter precedes

the rejection. Finally the chart indicates the SNR_{SSL} we measured during ground tests with the RIVERA system in its final configuration.

We observe that the sliding rejection solution provides a supplementary 4 dB sidelobe SNR decrease. The smoothed estimation of rejection and the induced mitigation of undesired artefact structure may partly explain this improvement. But these results also confirm the ability of the method to properly update the rejection coefficients in accordance with environment fluctuations as illustrated by [16], [17]. The spatial filter provides a substantial decrease from 3 dB to 6 dB depending on the case. Ground comparative measures have been made with RIVERA system, during the before flight radar ground validation. It allows to compare both configuration, that is to say ground and airborne. The best combination in the airborne case, that is space filter combined with sliding rejection, leads to an SNR_{SSL} only 4 dB worse than the ground passive detection configuration. This especially confirms the efficiency of the method.

Fig. 7. Performance in terms of SNR_{SSL} for various rejection methods

Nonetheless, the performance indicator is only based on the secondary sidelobes SNR. We have not characterised the sliding block rejection impact on potential targets, especially because we can not confirm any detection at the present time. This method may indeed filter out targets that stand close to the clutter bound. Similarly, the spatial filter must lower targets echoes coming from a direction close to the transmitter's direction, in particular because the RIVERA radar includes only three wide-beam antennas.

V. CONCLUSION

To overpass restriction of standard rejection algorithm, we have proposed to cancel direct path and clutter with a block rejection method. The block size directly regulates the Doppler filter notch width, and therefore allows to reduce the rejection mask. As a consequence, large amount of clutter can be rejected. These tests highlight the fact that clutter is spread over almost about 1500 range cells, that is to say 50 km.

However the estimation of the rejection filter coefficients suffers from the discontinuity from one block to the other. Therefore we introduce a sliding block version of our method.

Combined with space filtering, this solution performs only 4 dB worse than the standard rejection method in a ground non moving configuration.

These results may however be deepened. Especially, it could be interesting to measure the impact of both block filtering and space filtering on a confirmed detected target.

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