

Dear editor,

The authors would like to thank the reviewer #2 for the careful and thorough review of the manuscript "Motion compensation for long integration times and DoA processing in passive radars" and providing us comments and suggestions to improve the quality of the work. The following responses have been prepared to address all comments in a point-by-point fashion.

Author's reply to the Review Report #2

In this work, the authors address the problems arising when long integration times are required. In particular, in the case of the study, a satellite is used as the illuminator of opportunity, and long integration times make sense to compensate for the significant propagation losses. Therefore, during these periods, the target can change the range and/or Doppler cells. The proposed method performs tracking of the target and compensates for these effects in the cross-ambiguity functions. The topic is interesting and the paper is nicely written. However, this reviewer suggests some minor changes to improve the overall quality of the work:

1. In the introduction, a deeper analysis of the advantages and disadvantages of the competitor methods might be useful to the reader. In general, the novel aspects of the work compared to state-of-the-art and their own work [8] should be better motivated.

Reply: The state-of-the-art has been updated to explain the previous work and highlight the novelty of the proposed methodology to use long integration times to exploit DVB-S signal in passive radar systems. The presented solution allows an improvement in detection and tracking capabilities for non-collaborative targets with unknown dynamic implementing target motion compensation in both Doppler and bistatic range domains:

Paragraphs of section "Introduction" has been updated:

"Focus-before-detection (FBD) methods are able to perform long-time coherent integration for weak targets without prior knowledge of the target motion parameters. One of the best well-known methods to solve this type of problem is the Radon Fourier Transform (RFT), which achieves high integration times of the target whose range migration is significant, by searching for the distance and velocity of the target. On the other hand, there is also the generalized RFT method (GRFT) which provides a general method for high coherent integration times. However, these methods do not solve the Doppler migration problem. To solve this problem, the Modified Radon Fourier Transform (MRFT) for long-time coherent integration is presented in [19], which searches the Doppler rate during the integration of pulses. The MRFT integrates

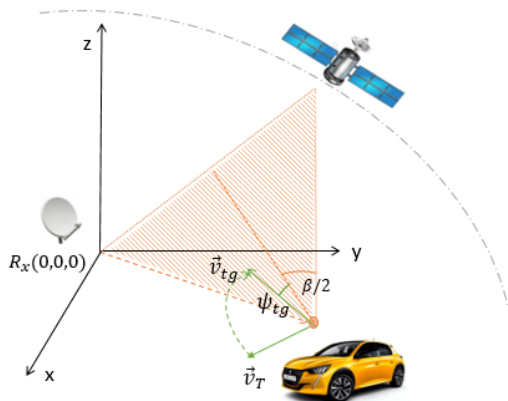
the target echo energy by searching for the range, Doppler and Doppler rate of the target. This algorithm is able to correct both range and Doppler migration problems and significantly improve the signal-to-noise ratio of the signal echo.

In [20] classical compensation methods are compared such as the use of Keystone transform (KT), which is used in a multitude of applications like SAR (Synthetic Aperture Radar), or the envelope alignment based on envelope correlation for range compensation and the Chirp-Fourier Transform (CFT) in Doppler compensation. The CFT is also proposed in [21] and [11]. According to the paper [22], for high integration times, it is proposed to make use of Long-time Integration Fourier Transform (LIFT) to obtain high coherent processing gain. After clutter cancellation, the LIFT is proposed to achieve azimuth compensation. In addition, the Doppler shift is defined as the relative acceleration, which must be calculated before applying for Doppler compensation. If the estimation of this parameter is not precise, a residual white dispersion will be obtained.

The presented solution in this work allows an improvement in detection and tracking capabilities for non-collaborative targets with unknown dynamic implementing target motion compensation in both Doppler and bistatic range domains. The signal processing scheme is based on a multistage range-Doppler migration compensation architecture that combines detection, tracking and feature extraction techniques to provide automatically adaptation to each target dynamic in the bistatic scenario of interest. Main steps are the following:”

2. The notation to introduce the speed and the angles could be improved and better motivated by introducing a figure at the beginning of Section 3. Also, I recommend the use of a bold case for vectors, to clarify equations.

Reply: The following Figure is added to define projection angles considering the passive radar, illuminator of opportunity and target plane:



A paragraph of section “Bistatic scenarios with stationary PR and IoO” has been updated

“In the study case, the PR receiver and the IoO are stationary. Target bistatic Doppler shift depends on the projection of the target speed vector $\vec{v}_T = \hat{v}_T$ on the bistatic plane, $\vec{v}_{tg} = \hat{v}_{tg}$, and it is calculated as $f_D \text{ (Hz)} = (2 \cdot v_{tg} / \lambda) \cdot \cos(\psi_{tg}) \cdot \cos(\beta/2)$, being ψ_{tg} defined by the projected target speed vector, $\hat{v}_{tg}$, and

the bistatic bisector and β_{tg} the target bistatic angle \cite{Willis2005} (**Figure \ref{fig:proyeccion}**). In this case the target bistatic delay depends on time: $t_{tg}(t) = t_T(t) + t_R(t) - t_L = (R_{bis}(t)/c) - t_L$."

3. Some of the acronyms are not defined, thus complicating the readability of the text.

Reply: The definition of the used acronyms in the paper are detailed to improve the readability.

4. The steps leading to eq. (7) could be given in more detail and the differences concerning conventional CAF highlighted.

Reply: Equation (7) is detailed from conventional discrete CAF formulation to the resulted CAF with spreading effects when integration time leads to range and Doppler walks:

$$\begin{aligned} S^{CAF}[m_{tg0}, p_{tg0}] &= \sum_{n=0}^{N-1} S_{ref}^*[n - m_{tg0}] \cdot S_{surv}[n] \cdot \exp\left(-j2\pi \frac{p_{tg0}}{N} n\right) = \\ &= \sum_{n=0}^{N-1} \xi_{ref}^* \tilde{s}^*[n - m_{tg0}] \cdot \xi_{surv}^* \tilde{s}^*[n - m_{tg0}] \exp\left(j2\pi f_c \frac{m_{tg}}{f_s}\right) \cdot \exp\left(-j2\pi \frac{p_{tg0}}{N} n\right) = \\ &= \xi_{ref}^* \xi_{surv} \exp(\phi_{t0}) \sum_{n=0}^{N-1} \tilde{s}^*[n - m_{tg0}] \tilde{s}\left[n - m_{tg0} + \frac{f_{D0} n}{f_c f_s}\right] \exp\left(j\pi \frac{f_{Dr} n^2}{f_s}\right) \end{aligned}$$

A paragraph of section "Long integration time passive radar processing" has been updated:

"If T_{int} is higher than $T_{int,max}$ and the target bistatic acceleration is higher than $a_{bis,max}$, $S^{CAF}[m_{tg0}, p_{tg0}]$ has to be modified, **equation (\ref{eq_CAF3})** where $m_{tg} = (\tau_{tg} f_s)$, to include the spreading effects."

5. As p is not relevant in equations 9, 10 and 11, it can be removed from the IDFT notation.

Reply: To facilitate the readability of the mathematical formulation of the proposed algorithm where DFTs and IDFTs are applied in different dimensions, the following notation is defined:

- DFTp or IDFTp means that the transform is performed in the p-axis or Doppler dimension of the RDM
- DFTm or IDFTm means that the transform is performed in the m-axis or bistatic Range dimension of the RDM

Paragraphs of section "Multi-stage range-Doppler migration compensation" has been updated:

"For one specific value f_{Dr}^i , the compensation technique is based on applying Inverse Discrete Fourier Transform (IDFT) expressed in equation (\ref{IDFT1}). **In other words, IDFT performing across the p -axis ($IDFT_p$) or Doppler axis of the RDMs.**"

" Third Stage: Before range migration correction is performed, the Discrete Fourier Transform (DFT) of expression (\ref{eq_IFTCAF2}) is used and detailed in (\ref{R1}). **In this case, DFT is performed across the m -axis (DFT_m) or bistatic range axis of the RDMs.** With a change

of variable $y=n-m$, the result ($\ref{R2}$) can be expressed in function of the DFT of the surveillance signal corrected version.”

6. The tracking results are combined using a weighted centroid. Can the authors provide more details regarding this method?

Reply: The methodology to obtain the weighted centroid has been detailed in the paper.

Paragraphs of section “Multi-stage range-Doppler migration compensation” has been updated:

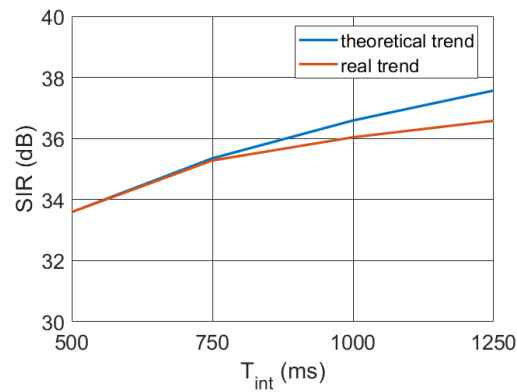
“At the output of the considered detector, the detection matrix is generated, and a target can be observed in a set of cells depending on its size and kinematics. The target position (range-Doppler in the RDM) could be estimated by the data extractor. This extractor applies algorithms such as the flood-fill algorithm that connect all the hints associated with a target and estimate the target position in the system coordinates. These estimated values define a point in the input 2D space, which is denoted as the plot associated with the target. Once the connected hints are detected, the centroid related to each blob is calculated as its center of mass considering the corresponding pixels intensity or outputs of the envelope detector.”

7. Are the indices for S_{ref} the same in eqs. 12 and 13? What is the meaning of the DFT notation in 14?

Reply: The notation of equation 14 is explained in comment 5. For equations 12 and 13, as n and m have N possible values (a variation interval from 0 to $N-1$), it can be assumed that y , $y=n-m$, will have also N possible values and can be assumed, for simplification purposes, the same variation interval from 0 to $N-1$.

8. The validation experiments are conducted in a practical environment, which is very nice. However, it is not clear to this reviewer if some alternatives could be also used to compensate for the movement of the target. If some other methods are feasible, it would be interesting to compare the performance with that of the proposed method.

Reply: The SIR after the coherent signal processing is related to the SIR before the integration, the signal bandwidth, and T_{int} [2]. As input SIR and bandwidth are constant, the SIR improvement with respect $T_{int}=500\text{ms}$ should be 1.76, 3 and 3.98dB for $T_{int}=750\text{ms}$, 1000ms and 1250ms respectively with the proposed solution when the target dynamics are characterized by constant acceleration and linear movement in RDM domain. Results presented in the following Figure confirm that controlled long time intervals can be considered with the proposed methodology to obtain SIR improvements very close to the theoretical ones. The best relationship between CPI value, integration gain, and SIR improvement is obtained for $T_{int}=500\text{ms}$ and 750ms.



[2] D. Pastina et al., "Maritime Moving Target Long Time Integration for GNSS-Based Passive Bistatic Radar," in *IEEE Transactions on Aerospace and Electronic Systems*, vol. 54, no. 6, pp. 3060-3083, Dec. 2018, doi: 10.1109/TAES.2018.2840298.

Paragraphs of section "Experimental results":

"In Figure \ref{fig:SIRvalues}, SIR values estimated for the target detections in the CAFs generated for the 0° -steered beam in the first and third stages of the proposed methodology during the 80 CPIs are presented. Results confirm that the target motion compensation provide a SIR improvement of around 10 dB with $T_{int}=500$ ms. SIR values for CPIs=4, 41, and 72, and the corresponding DoA accuracy are summarized in Figure \ref{fig:Tabla}. **The SIR after the coherent signal processing is related to the SIR before the integration, the signal bandwidth, and T_{int}** \cite{Pastina2018}. As input SIR and bandwidth are constant, the SIR improvement with respect $T_{int}=500$ ms should be 1.76, 3 and 3.98 dB for $T_{int}=750$, 1000 and 1250 ms respectively with the proposed solution when the target dynamics are characterized by constant acceleration and linear movement in RDM domain. Results presented in Figure \ref{fig:SIRt} confirm that controlled long time intervals can be considered with the proposed methodology to obtain SIR improvements very close to the theoretical ones. The best relationship between CPI value, integration gain, and SIR improvement is obtained for $T_{int}=500$ ms (Figure \ref{fig:TintCPI4}) and $T_{int}=750$ ms (Figure \ref{fig:Tint750}).

The final estimated collaborative target trajectory **provided by the proposed solution with $T_{int}=500$ ms** is depicted in Figure \ref{fig:DoA} on 2D map coordinates and compared with GPS data acquired on the collaborative vehicle during the acquisition time confirming the suitability of the proposed scheme for the DVB-S based-on passive radar signal processing."