Long-time coherent integration based on intra-partition range-Doppler processing for passive bistatic radar

Luo Zuo | Jun Wang | Jinxin Sui

1 | INTRODUCTION

Passive bistatic radar (PBR) exploits available non-cooperative transmitters as its illuminators of opportunity [1], such as frequency modulation (FM) radio [2,3], digital audio broadcast (DAB) [4], digital television terrestrial multimedia broadcasting (DTMB) [5], global navigation satellite system (GNSS) [6], wireless fidelity (Wi-Fi) [7] and long-term evolution (LTE) [8] etc. Without the need for the deployment and operation of a specialized transmitter, PBR systems can be implemented and operated for low-cost target detection than active radar [9]. Furthermore, with suitable illuminators available, covert surveillance of an area of interest targets is possible. By calculating cross-correlations between the direct illumination and the surveillance signal reflected from the environment in two dimensions (time-delay and Doppler shift), the range and velocity of the target can be obtained [10].

In radar missions, far range detection can be achieved by increasing the transmitted power, antenna gain, signal bandwidth and coherent processing interval (CPI) [11]. However, as the entire transmitter parameters related to the gain are beyond the control of the PBR system designer, increasing CPI is the main method to improve the target’s energy and thus enhance the detection performance of PBR system [12,13]. The PBR cross-correlation results are discretized into range and Doppler cells. The size of the range cell, that is, range resolution, is determined by the bandwidth of the available illuminator of opportunity. As the bandwidth of the PBR signal increases, the range resolution varies from coarse (e.g. 750 m for FM) to fine (e.g. 18.75 m for DTMB, 7.5 m for LTE). Note that the range resolution values are pseudo-monostatic equivalents). Although the finer range resolution can help to resolve targets spatially, it also presents a problem that is for the long-time coherent integration processing, the motions of the manoeuvring target, for example, high velocity and acceleration, induce range migration (RM), including range walk (RW), range curvature (RC) and Doppler frequency migration (DFM) during the CPI. This makes it difficult to improve coherent integration ability and thus result in serious detection performance deterioration [14].

In recent studies, there are mainly the following methods for long-time coherent integration. The method proposed in Ref. [11] utilizes short time correlation and two-step Doppler processing to correct the first order of range cell migration (RW). The standard keystone transform (KT) mitigates the RW...
by rescaling the time axis according to each frequency [15–17].

After that, the Radon–Fourier transform (RFT) via joint searching along the range and velocity dimensions to achieve long-time coherent integration for the moving target with cross-range cells [18]. Besides, in ref. [19], the author presents a more general form of the cross-ambiguity function to extend the integration time of the manoeuvring target. While the four methods support the RW mitigation due to the high speed of the moving target, the RC induced by the target’s acceleration cannot be mitigated; and therefore, it suffers integration gains reduction in the case of RC. To remove RC and make the target’s acceleration contribute to the integration gains, the generalized keystone transformation (GKT) was investigated in refs. [20,21]. However, the GKT does not compensate for the Doppler ambiguity factor. Due to the high-speed and low pulse repetition frequency, the Doppler ambiguity would occur and the integration performance may decrease seriously. The double GKT [21,22] and GKT-RFT [23,24] methods were then proposed to overcome the limitation of Doppler ambiguity and remove the RW. It should be noted that these methods are applicable based on the support of fast and slow time domain concepts, which means that the received continuous-time signals should be divided and processed in pulse mode for PBR. Nevertheless, the PBR signals (such as DTMB, LTE signal) suffer from Doppler mismatch in pulse compression because of the characteristics of the near-ideal thumbtack ambiguity function [25]; thus the long-time coherent integration gain is severely degraded in case of detecting the high-speed and far-distance moving target.

To tackle the problems in the aforementioned methods, the signal model is constructed for target moving with constant acceleration and a novel long-time coherent integration method based on intra-partition range-Doppler (RD) processing is proposed. The presented method firstly applies intra-partition RD processing to realise the two-dimensional pre-accumulation of target energy in each partition and remove the Doppler mismatch, in which the DFM is eliminated using coarse Doppler-filter as the pre-filter. Then, the GKT is employed to correct the RC. After that, the residual RW is removed with the centre frequency of the coarse Doppler-filter related to the target velocity. Furthermore, the matched filtering process (MFP) is utilized to estimate the target’s acceleration, followed by the quadratic phase term compensation. As a result, the method presented applies to a wider range and velocity of PBR systems configurations and better detection performance than previously published methods. Simulations are provided to demonstrate the effectiveness.

The remaining sections are organized as follows. In Section 2, the geometry of the PBR system is described. Based on the geometry relationship, the signal models of the target moving with constant acceleration is constructed. The problem in the coherent integration of PBR is analysed in Section 3. In Section 4, a novel long-time coherent integration method for space moving targets with high speed is derived. Section 5 is devoted to the simulation results and performance analyses of the proposed method. Relevant summary and conclusions are given in Section 6.

![Passive bistatic radar geometry model](image)

2 | PBR SYSTEM MODEL

2.1 PBR geometrmodel

A classical PBR geometry model is presented in Figure 1. It supposes that the transmitter is an omnidirectional antenna in azimuth angle and the receiver has two types of antennas, the dedicated reference antenna directoring toward the transmitter and the surveillance antenna covering the airspace of interest for obtaining the scattered signal. It also supposes that the airplane moves at a far distance relative to the baseline.

2.2 Signal model

In this section, the signal model is constructed. Suppose that the transmitted signal bandwidth is $B$, the carrier frequency is $f_{c}$, the signal CPI is $T$ and the bistatic angle is $\theta$. The reference signal after down-conversion can be stated as:

$$S_{r}(t) = u(t - \tau_{0})\exp\left(-j2\pi f_{c}t\right)$$

(1)

where $u(t)$ is the baseband signal and $\tau_{0}$ is the propagation delay of the direct illumination from the transmitter.

The surveillance signal can be expressed as

$$S_{s}(t) = u(t - 2R(t)/c)\exp\left(-j4\pi f_{c}R(t)/c\right)$$

(2)

where $R(t)$ is the instantaneous delay-range of surveillance signal from the transmitter to the receiver via target reflection, $c$ is the light speed and $t$ denotes the variable of time.

Neglecting the high order components, the target instantaneous delay-range and the velocity satisfies
\[ R(t) = R(0) + v_0 t + \frac{1}{2}a t^2 \] (3)
\[ \nu(t) = \nu_0 + at \] (4)

where \( R(0) \) is the initial range, \( \nu_0 \) is the initial radial velocity of the target and \( a \) denotes the acceleration of the target. Note that the acceleration is assumed absolutely constant during the CPI in target motion model.

Thus, the target signal can be further written as

\[
S_i(t) = u\left( t - \frac{2R(0) + 2\nu_0 t + at^2}{c} \right) \exp\left( -j2\pi f_c \frac{2R(0) + 2\nu_0 t + at^2}{c} \right) \\
= u\left( \rho t - \frac{2R(0)}{c} \right) \exp\left( -j4\pi f_c \frac{R(0)}{c} \right) \exp\left( -j4\pi f_c \frac{\nu_0 t + at^2}{c} \right) \exp\left( -j2\pi f_c \frac{at^2}{c} \right) 
\] (5)

where \( \rho = \frac{c - (2\nu_0 + at)}{c} \) is the time companding factor. Due to the motion of the target, this factor \( \rho \) will cause timescale change (time stretching or shrinking) of the signal \( u(\tau) \). As the CPI, velocity or acceleration increases, the effect of \( \rho \) on signal envelope will be strengthened. The first exponential term in Equation (5) represents the initial phase corresponding to the initial delay of the echo and the second exponential term represents the Doppler frequency shift generated by the target’s velocity. The third exponential term is formed by the target’s acceleration, which may cause target’s Doppler frequency changes \[19,26\].

3 | PBR RECEIVER

3.1 | PBR signal processing

A typical PBR signal processing considers the optimal detection scheme based on the matched filter concept. The surveillance signal is processed by the filter bank, each filter matched to the desired target signal with the propagation delay \( \tau \) and the Doppler frequency \( f_d \). The output of all filters for different \( \tau \) and \( f_d \) generate a two-dimensional RD surface \[27,28\], which can be expressed as

\[
\chi(\tau, f_d) = \int_0^T S_i(t)S_r^*(t - \tau) \exp\left( -j2\pi f_d \tau \right) dt 
\] (6)

A matched filter receiver improves the target signal-to-noise ratio (SNR). Constant false alarm rate (CFAR) detectors declare a peak in Equation (6) as indicative of a detected target by determining a detection threshold dependent on the noise power \[29\].

In general, there is more than one component in the surveillance signal. Direct illumination signal and multipath interference signal will also be received in the surveillance signal, and their energy is higher than the target signal. Therefore, to effectively improve target signal SNR, the adaptive filtering method \[1,30\] should be applied to suppress the interfering signals before performing matched filtering.

3.2 | Signal-to-noise ratio and integration time

The detection probability and maximum detection power are essentially related to SNR in a radar system. The resulting target signal SNR can be improved by performing coherent integration (matched filtering) \[19\], with the SNR after integration given by:

\[
SNR = SNR_{in} BT 
\] (7)

where the SNR prior to integration is the \( SNR_{in} \), \( B \) is the signal bandwidth and \( T \) is the signal CPI. From Equation (7), we note that the expected SNR of any target can be achieved by performing coherent integration. However, the practical limitation constraint is the CPI.

In order to show how the SNR depends on the radar parameters, it is assumed that the PBR exploits an available illuminator with a transmitter antenna of the gain \( G_T \) and power \( P_T \) and the PBR is designed with a receiving antenna of the gain \( G_R \); thus, the target SNR can be expressed as \[31\]:

\[
SNR = \frac{P_T G_T G_R \delta \lambda^2}{(4\pi)^3 R_T^2 R_R^2 k T_{th}} T 
\] (8)

where \( \lambda = c / f_c \) is the transmitter signal wavelength. The target radar cross-section (RCS), distance from the transmitter to target and distance from target to the receiver are given as \( \delta \), \( R_T \) and \( R_R \); \( k T_{th} \) denotes the system noise power.

By Equation (8), it can be seen that to enhance the detectability of the system, one can increase the transmitter power, antenna gain or the CPI. However, in the PBR system, the only parameters under the manipulation of the designer are CPI and receiver antenna gain. Furthermore, for low cost and small PBR, increasing the integration time \( T \) is the predominant scheme of improving SNR \[32,33\].

3.3 | Long-time coherent integration for PBR

RM is a phenomenon occurring when the range resolution \( \Delta R \) is fine compared to the velocity of the target and the CPI. RM induces an energy dispersal in the range correlation, and bistatic RM occurs when the bellow equation is satisfied:

\[
\Delta R = \frac{c}{2B \cos(\theta/2)} \leq R(T) - R(0) 
\] (9)

From Equation (9), a high-speed target can be defined as a target moving through several range cells during a CPI.

According to the analysis in Section 3.1, increasing the coherent integration time can improve the target signal SNR and thus enhance the system detection capability. However,
it will inevitably induce the problem of RM and DFM. As described in Equations (3) and (4), the instantaneous range \( R(t) \) and velocity \( v(t) \) are variables over time. In narrowband radar (such as FM), \( R(t) \) can be treated as a constant because \( R(T) - R(0) = \Delta R \). On the other hand, for wideband PBR, this assumption will be violated in the case of the target moving with high velocity and acceleration. Its trajectory will span multiple range-Doppler cells within one CPI, \( R(T) - R(0) \geq \Delta R \) and \( af'/c \geq 1/T \), which means the timescale change of signal envelope \( u(t) \) caused by the time companding factor \( \rho \) will involve RM and the Doppler phase change caused by the target’s acceleration will involve DFM.

Figure 2 shows the variation of the maximum SNR gain with integration time via traditional RD processing under the condition of different velocities and accelerations. In Figure 2, it can be noted that the SNR gain degrades with the integration time when the RM and DFM exist. Consequently, for the long-time coherent accumulation of the wideband PBR, the correlation processing method in Equation (6) is not the optimal detection method. It cannot be performing MFP and obtaining the desired accumulation result for the manoeuvring target.

To obtain the matched filtering results for the manoeuvring target, the method based on intra-partition RD processing is proposed. In this method, \( R(t) \) and \( v(t) \) can be treated as constant, if \( t \in [-T_0/2, T_0/2] \), where \( T_0 \) is expressed as partition time. Note that the selection of \( T_0 \) is to take the maximum value under the condition of no RM occurs, as

\[
T_0 = \arg \max_{T_0} \left( \frac{vT_0}{2} + \frac{1}{2}aT_0^2 \leq \Delta R \right) \tag{10}
\]

Hence, preparing for proposed method, the received signal is divided into partitions. The intra-partition is called fast time \( t \), and inter-partition is called slow time \( t_m \), expressed as

\[
t_m = mT_0, \quad \left( -\frac{M}{2} \leq m < \frac{M}{2} \right) \tag{11}
\]

where \( T_0 \) is also called pulse repetition time and \( M \) denotes the number of the partitions of the signal. \( R(t) \) is rewritten as the following linear equation by using Equation (11):

\[
R_m(t) = R(t_m) + v(t_m)t \tag{12}
\]

and the surveillance signal based on the division can be written as

\[
S(t, t_m) = u(t - 2R_m(t)/c) \exp(-j4\pi f_R R_m(t)/c) \tag{13}
\]

4 | PROPOSED METHOD

In this section, the detailed processes of the proposed long-time coherent integration method are introduced. The proposed method consists of three main steps: (1) intra-partition RD processing for target energy pre-accumulation; (2) GKT and Doppler processing for RM correction; (3) MFP for DFM compensation. To clarify the method better, Figure 3 represents a simplified illustration of it.

4.1 | Intra-partition range-Doppler processing

The intra-partition RD processing results \( \chi(\tau, f_{dp}, t_m) \), that is, cross-correlation ambiguity function (CAF) between the segmented surveillance and reference signal, written as [34]

\[
\chi(\tau, f_{dp}, t_m) = \int_{-T_0/2}^{T_0/2} u(t) \exp(-j2\pi f_{dp}t) \exp(-j2\pi f_R R_m(t)/c) dt \tag{14}
\]
\[ f_{dp} = \frac{p}{T_0} \left( -\frac{P}{2} \leq p < \frac{P}{2} \right) \]  

where \( P \) is the number of samples in \( T_0 \).

It is worth noting that after the intra-partition RD processing, the target energy is equivalent to accomplish the pre-accumulation in each partition, in which the intra-partition Doppler frequency \( 2v_0/\lambda \), that is, mismatch in the pulse compensation, has been compensated via the coarse Doppler filter. It is an advantage for coherent integration compared with other segmented methods.

Applying the Fourier transform (FT) to Equation (15) with \( \tau \) and the intra-partition CAF in the Doppler-range frequency domain \( f_{dp} - f_c \) can be expressed as:

\[ \chi(f_c, f_{dp}, t_m) = \text{sinc} \left( T_0 \left( f_{dp} + \frac{2v_0 + 2at_m}{\lambda} \right) \right) \exp \left( -\frac{\pi R(t_m)}{\lambda} \right) \]  

Here, the range migration is mitigated in the filter when the below constraint is followed:

\[ T_0 v_{max} + \frac{1}{2} a T_0^2 \leq \frac{c}{2B} \]  

(16)

where \( v_{max} \) is the maximum detection speed of the system. Note that the range resolution is treated as a constant in Equation (16). In addition, the Doppler frequency of the intra-partition CAF can be treated as the coarse Doppler filter, the Doppler resolution is determined by the partition time \( T_0 \), \( f_{dp} \) is the centre frequency of the coarse filter and is written as

\[ f_c = \frac{F_c}{T_0} \left( -\frac{P}{2} \leq p < \frac{P}{2} \right) \]  

(17)
Therefore, Equation (18) can be further represented as

\[
\chi(f_r,f_{dp},t_m) = \text{sinc} \left[ T_0 (f_{dp} + \alpha) \right] \exp \left[ -j4\pi(1 + \gamma) \frac{R(0)}{\lambda} \right] \\
\times \exp \left[ -j2\pi(1 + \gamma)at_m \right] \exp \left[ -j2\pi(1 + \gamma)\beta_t^2 \right]
\]  

(20)

where \( \alpha = 2v_{0}/\lambda \) is the target's Doppler frequency; \( \gamma = f_c/f_r \); \( \beta = a \) is the chirp rate. We note that the DFM can be eliminated by using coarse Doppler-filter as the pre-filter. Therefore, the RM and DFM in each partition have been corrected completely. The remaining problems are only concentrated in inter-partitions.

In Equation (20), the first-order exponential term and quadratic exponential term of slow time \( t_m \) are all coupled with the range frequency \( f_r \), which will lead to RW and RC, respectively. Thus, the target energy will be distributed in cross-range cells within the CPI. In addition, the quadratic term also gives rise to the DFM, which causes the target energy discretized into Doppler cells. Both RM and DFM influence can reduce the target integration gains and thus worsen the radar’s detection ability.

### 4.2 Range curvature correction

As derived in Section 4.1, the quadric coupling term of range frequency should be mitigated. The GKT is applied to remove the RC for the target moving with constant acceleration, which performs scaling \( t_m = [f_{dp}/(f_{dp} + f_r)]^{1/2}t_n \) in \( t_m - f_r \) domain. It is important to note that the GKT is a resampling process and therefore requires to be realised without spectrum aliasing [35]. Substituting the dilation factor into Equation (20) yields:

\[
\chi_r(f_r,f_{dp},t_n) = \text{sinc} \left[ T_0 (f_{dp} + \alpha) \right] \exp \left[ -j4\pi(1 + \gamma) \frac{R(0)}{\lambda} \right] \\
\times \exp \left[ -j2\pi \left( \frac{f_r + f_{dp}}{f_c} \right)^{1/2} \right] \exp \left( -j2\pi\beta t_n^2 \right)
\]  

(21)

Applying the first-order Taylor series expansion on \( [f_{dp}/(f_{dp} + f_r)]^{1/2} \), Equation (21) can be further expressed as

\[
\chi_r(f_r,f_{dp},t_n) = \text{sinc} \left[ T_0 (f_{dp} + \alpha) \right] \exp \left[ -j4\pi(1 + \gamma) \frac{R(0)}{\lambda} \right] \\
\times \exp \left[ -j2\pi \left( 1 + \frac{f_r}{2f_c} \right) \right] \exp \left( -j2\pi\beta t_n^2 \right)
\]  

(22)

By Equation (22), the second-order coupling term has been removed. Whereas part of the linear coupling is still present.

### 4.3 Range walk correction

While the RC has been mitigated by performing GKT, the target energy within the CPI is still scattered on different range cells due to the residual RW. Therefore, the residual RW should be removed, following the below given Doppler compensation scheme.

The residual RW \( \Delta R_n(t_n) \) based on Equation (22) is expressed as

\[
\Delta R_n(t_n) = \frac{f_{dp}}{2f_c} t_n
\]  

(23)

The Doppler compensation function is represented as

\[
H_{\nu u}(f_r,f_{dp},t_n) = \exp \left[ -j2\pi f_{dp} t_n \right] \text{sinc} \left[ T_0 (f_{dp} + \alpha) \right] \exp \left[ -j4\pi(1 + \gamma) \frac{R(0)}{\lambda} \right] \\
\times \exp \left[ -j2\pi \left( 1 + \frac{f_r}{2f_c} \right) \right] \exp \left( -j2\pi\beta t_n^2 \right)
\]  

(24)

where \( \delta(\cdot) \) is Dirac delta function.

Thus, multiplying the conjugate of Equation (24) with Equation (22), the compensated function can be expressed as

\[
\chi_{\nu u}(f_r,f_{dp},t_n) = \chi_r(f_r,f_{dp},t_n) H_{\nu u}(f_r,f_{dp},t_n)
\]  

\[
= \text{sinc} \left[ T_0 (f_{dp} + \alpha) \right] \exp \left[ -j4\pi(1 + \gamma) \frac{R(0)}{\lambda} \right] \\
\times \exp \left[ -j2\pi \left( 1 + \frac{f_r}{2f_c} \right) \right] \exp \left( -j2\pi\beta t_n^2 \right)
\]  

(25)

when the parameters satisfy the below limitation:

\[
\frac{1}{2f_c T_0} T \leq \frac{1}{B}
\]  

(26)

where \( \eta = \alpha - f_{dp} \) is defined and is considered a constant.

In Equation (25), it is significant to observe that the first-order and the quadric coupling term with the range frequency \( f_r \) are removed regardless of the target velocity, which means the proposed method can correct the RM without prior information of the target motion.

### 4.4 Doppler frequency migration elimination

After the RM correction, the quadric phase term in Equation (25), which is induced by the target's acceleration, should be estimated and compensated. Without this process, the target energy distributed in different partitions within the CPI cannot be aligned completely, and then the coherent integration
performance will suffer serious loss. To eliminate the DFM, the matched filtering function is defined as follows:

\[ H_{\text{dim}}(\beta', t_n) = \exp\left(2\pi \beta' t_n^2\right) \tag{27} \]

where \( \beta' \) is the searching chirp rate.

Compensating for Equation (25) with Equation (27) yields

\[ \chi_{\text{ru}}\left(f, f_{dp}, t_n, \beta'\right) = \chi_{\text{ru}}\left(f, f_{dp}, t_n\right)H_{\text{dim}}(\beta', t_n) \]

\[ = \text{sinc}\left[T_0\left(f_{dp} + \alpha\right)\right]\exp\left[-j4\pi(1 + \gamma)\frac{R(0)}{\lambda}\right] \]

\[ \times \exp(-j2\pi\eta t_n)\exp\left[j2\pi(\beta' - \beta)t_n^2\right] \tag{28} \]

when \( \beta' = \beta \), namely, the searching chirp rate are matched with the target’s chirp rate, and performing inverse Fourier transform (IFT) with \( f_r \) on Equation (28), we can get

\[ \chi_{\text{dim}}\left(f, f_{dp}, f_{dn}\right) = \text{sinc}\left[(\tau - 2R(0)/c)\right]\text{sinc}\left[T_0\left(f_{dp} + \alpha\right)\right] \]

\[ \times \exp(-j2\pi\eta t_n)\exp\left(-j4\pi R(0)/\lambda\right) \tag{29} \]

From Equation (29), one can see that the DFM effect resulted from the acceleration could be compensated. Note that in the DFM elimination, the matched filtering is performed to estimate the target acceleration at first. This means such a correction is target parameter-dependent and it is not multi-target processing as above-mentioned RM correction is.

Applying the FT of Equation (29) with \( t_n \) is the fine Doppler filter, we can get

\[ \chi_{\text{dim}}\left(f_r, f_{dp}, f_{dn}\right) = \text{sinc}\left[(\tau - 2R(0)/c)\right]\text{sinc}\left[T_0\left(f_{dp} + \alpha\right)\right] \]

\[ \times \text{sinc}\left[MT_0\left(f_{dn} + \eta\right)\right]\exp\left(-j4\pi \frac{R(0)}{\lambda}\right) \tag{30} \]

where \( f_{dn} \) is the centre frequency of this fine Doppler filter and is written as

\[ f_{dn} = \frac{n}{MT_0} \left(n = \frac{M}{2}, \ldots, 0, \ldots, \frac{M}{2}\right) \tag{31} \]

To improve practicality, the dimensionality reduction processing is applied in the Doppler frequency domain (coarse and fine Doppler), and the Doppler frequency can be expressed as

\[ f_{dl} = f_{dn} + f_{dp}; \left(l = \frac{MP}{2}, \ldots, 0, \ldots, \frac{MP}{2}\right) \tag{32} \]

where \( n_i \) is the round down integer of the quotient of \( l \) and \( M \), \( p_i \) is the remainder of the division of \( l \) by \( M \).

Finally, the proposed method obtains the long-time coherent integration of target via matched filter, expressed as

\[ \chi_{co}\left(f_r, f_{dl}\right) = \text{sinc}\left[(\tau - 2R(0)/c)\right]\text{sinc}\left[T_0\left(f_{dp} + \alpha\right)\right] \]

\[ \times \text{sinc}\left[MT_0\left(f_{dn} + \eta\right)\right]\exp\left(-j4\pi \frac{R(0)}{\lambda}\right) \tag{33} \]

From Equation (33), it can be noticed that the coherent integration reaches its maximum value when the searching chirp rate \( \beta' \) is precisely matched. Thus, the estimated function of \( \beta \), that is, \( \hat{\beta} \) can be obtained as follows:

\[ \hat{\beta} = \arg \max_{\beta'} \left| \text{IFT}\left\{\chi_{\text{ru}}\left(f, f_{dp}, t_n\right)H_{\text{dim}}(\beta', t_n)\right\}\right| \tag{34} \]

In Equation (34), it is observed that for the target moving with constant acceleration, its energy that is discretized into different range-Doppler cells could be concentrated in the same. On the condition that the peak value of Equation (34) exceeds the given threshold, the target could be detected. It should be noted that the searching scope of \( \beta' \) is \([\beta'_{\min}, \beta'_{\max}]\), where the searching interval is \( \Delta\beta' = 1/(2\gamma T_d) \) [36]. Furthermore, the proposed method can overcome Doppler ambiguity constraint and Doppler mismatch after signal division because of the intra-partition RD and Doppler filtering compensation processing. Additionally, similar to the method in [37], the summarized framework of the proposed method is given in Algorithm 1, while the flowchart is shown in Figure 4.

5 | SIMULATION AND ANALYSIS

This section is about the conducted numerical simulations for demonstrating the validity of the proposed method. The performance comparison with the existing popular coherent integration methods is discussed as well. Suppose that the illumination is a DTMB transmitter, the parameters of PBR system are shown in Table 1. A simplified PBR geometry is shown in Figure 5. In this figure, \( \delta \) is the angle between the bistatic angle bisector and the velocity vector, \( \theta \) is the bistatic angle, and \( v \) is the real velocity vector. Note that in this simulation, our focus is on the target’s RM and DFM instead of solving the real parameters of the target, therefore the target angle \( \delta \) is neglected, the initial radial velocity \( v_0 \) is considered only.

5.1 | Results

The surveillance signal of the object moving with constant accelerated rectilinear motion is generated in the scenario. The
FIGURE 4  Flow chart of proposed method

TABLE 1  Parameters of PBR system

| Description          | Parameter | Value |
|----------------------|-----------|-------|
| Carrier frequency (MHz) | $f_c$     | 754   |
| Sample frequency (MHz)   | $f_s$     | 10    |
| Bandwidth (MHz)        | $B$       | 8     |
| Bistatic angle (°)     | $\theta$  | 16    |
| CPI (s)                | $T$       | 1     |

Abbreviations: CPI, coherent processing interval; PBR, passive bistatic radar.

FIGURE 5  Passive bistatic radar analytical geometry in the north-referenced coordinate system

Algorithm 1: Summarize: the main procedures of the proposed method

1. **Input**: raw signals $S_i(t)$ and $S_j(t)$, searching scopes, that is, $[\beta_{\min}, \beta_{\max}]$.
2. **Partition**: Divide signals $S_i(t)$ and $S_j(t)$ into partitions $S_i(t, t_n)$ and $S_j(t, t_n)$, respectively.
3. **Intra-partition RD processing**: Apply RD method in each partition to obtain $\chi(t, \tau_{n}, t_n)$ via Equation (15) then through $\chi(t, \tau_{n}, t_n)$ by Equation (20).
4. **Range curvature correction**: Apply GKT or $\chi(t, \tau_{n}, t_n)$ and achieve $\chi_{GKT}(t, \tau_{n}, t_n)$ by Equation (21).
5. **Range walk correction**: Construct Doppler filtering function $H_{def}(\tau, \tau_{n})$ via Equation (24) then decoder multiply with $\chi_{GKT}(t, \tau_{n}, t_n)$ to achieve $\chi_{def}(t, \tau_{n}, t_n)$ through Equation (25).
6. **Matched filtering processing**: Go through each $\beta$ in $[\beta_{\min}, \beta_{max}]$ with interval $\Delta\beta$.
7. For $\beta = \beta_{\min}, \ldots, \beta_{\max}$, do
8. Multiply the matched filtering function $H_{def}(\tau, \tau_{n})$ and $\chi_{def}(t, \tau_{n}, t_n)$ to obtain $\chi_{def}(t, \tau_{n}, t_n)$ by Equation (28);
9. Apply the range frequency $f_r$ IFT and the slow time $t_n$ FT on $\chi_{def}(t, \tau_{n}, t_n)$
10. Preserve the peak value of $\chi_{def}(t, \tau_{n}, t_n)$.
11. **End**
12. **Find the matched chirp rate**: Find the maximal peak value, then the corresponding $\beta$ is the estimated chirp rate $\hat{\beta}$.
13. **Output**: $\hat{\beta}$.
14. **Doppler frequency migration remove**: Construct $H_{def}(\hat{\beta}, \tau_{n})$ then multiply with $\chi_{def}(t, \tau_{n}, t_n)$ to obtain $\chi_{def}(t, \tau_{n}, t_n)$.
15. **Coherent integration**: Perform the range frequency $f_r$ IFT and the slow time $t_n$ FT on $\chi_{def}(t, \tau_{n}, t_n)$ to obtain $\chi_{def}(t, \tau_{n}, t_n)$ via Equation (30), then synthesize the coarse Doppler $f_{sp}$ and fine Doppler frequency $f_{sl}$ to achieve the coherently $\chi_{co}(t, \tau_{sl})$.

TABLE 2  Positions and motion parameters of target

| Description      | Parameter | Value |
|------------------|-----------|-------|
| Initial range (km) | $R_0$     | 30.3  |
| Initial velocity (km/s) | $v_0$     | 0.36  |
| Acceleration (m/s²) | $a$       | 30    |
| SNR (dB)        | $SNR_{on}$ | $-35$ |
| Partition time (ms) | $T_0$     | 12.5  |
| Number of partitions | $M$       | 80    |

Abbreviation: SNR, signal-to-noise ratio.
the partition time $T_0$ is set to 12.5 ms, which ensures that no RM occurs when the target moves with velocity Mach 2. In addition, there will be no DFM in each partition when maximum acceleration is 30 m/s².

The result of conventional RD processing is represented in Figure 6a, where the integration results in the $\tau$-$\nu$ domain and the result of the 1st and 80th partitions are represented in Figure 6b. It can be seen from Figure 6 that serious RM, including RC and RW, and DM occurs, which causes the target signal energy to be distributed along the curve with a little curvature, where the curvature depending on the acceleration and the total range migration cells is 20, respectively. The proposed method first
performs intra-partition RD processing to achieve the pre-accumulation of the target signal. Then the GKT is applied to remove RC and a part of RW will also be removed. Figure 7a,b shows the result. It can be seen from Figure 7 that the form of the target’s energy distribution becomes more concentrated, is an oblique line, and the total range migration cells are reduced to 10, 10 range cells are less than Figure 6b, respectively. Special attention should be paid to the range migration cells at this time. Theoretically, the numbers of range migration cells induced by the RW are $\Delta R_w = vT/\Delta R \approx 19$, and the range migration cells induced by the RC are $\Delta R_c = aT^2/(2\Delta R) \approx 1$. After the RC correction, the number of range migration cells is reduced by $aT^2/(2\Delta R) + vT/(2\Delta R) \approx 10$. Therefore, the results after RC correction are consistent with the theoretical analysis value, which verifies the correctness of the proposed method. Furthermore, the residual RW is removed with the coarse Doppler filtering compensation scheme and the results are depicted in Figure 8a,b. It is observed that the target energy is

**Figure 7** Result after range curvature correction: (a) Target in the $\tau$-$v$ domain (top view); (b) Target of the 1st and 80th partitions.
distributed on a straight line, that is, the target energy is accumulated in the same range cell, which is helpful to the coherent integration, and the total RM cells are reduced to 0, respectively. Consequently, the RM due to the slow time coupling with the range frequency is mitigated completely, and only the DFM of the target requires to be compensated. Finally, to remove the DFM induced by the acceleration phase of the target's signal, the proposed method applies the MFP to estimate and compensate the chirp rate corresponding to the acceleration of target and the results are represented in Figure 9. It is important to note that the target energy is concentrated in the same range-Doppler cell and accumulated as a distinct peak in the output of the proposed approach, respectively. The detected initial range and velocity of the target are $R_0 = 30$ km, $v_0 = 0.36$ km/s, respectively. Besides,
Figure 10 shows a comparison of the section of Figures 6a, 7a, 8a and 9a at $R_0$. As depicted in Figure 10, the changing trend of integration gains in the proposed method can be clearly observed. The proposed method obtained excellent gains, about 23 dB, as compared with the conventional RD scheme in the long-time coherent integration.

Therefore, these simulations demonstrate the validity of the proposed method.

5.2 | Performance

To demonstrate the performance of the proposed method, the conventional RD, the standard KT [15], the method in [17] (Note that the KT method in [15] is based on the chirp-z transform, method in [17] is based on Lagrange polynomial interpolation), method in [19], the double GKT [21] and the proposed method are conducted with different SNRs (defined
before coherent integration), leaving the target parameters unchanged. Besides, to ensure enough effectiveness of the standard KT, the method [17] and the double GKT, the partition time $T_0$ of these three methods is set to 0.3 ms according to the following Figure 11d. Its efficiency is clearly illustrated in such a figure. The relationship between target energy accumulation gain and input SNR is given in Figure 11a. It can be seen that the benefits of the proposed method are most substantial for different SNRs and precedes the other methods. Meanwhile, two hundred times of Monte Carlo simulations are implemented for the four methods with different input SNR. Subsequently, we set the false alarm probability $P_f = 10^{-5}$ and all echoes are submerged in complex white Gaussian noises, where the strength of noise is 5 dB. Figure 11b illustrates the detection probability with different input SNR for the above-mentioned methods. The SNRs vary from $-60$ to $-15$ dB. It can be seen that the detection probability of the proposed method is up to 0.98 when the input SNR is $-50$ dB, which can effectively detect the target while performing better than the others.

To further demonstrate the applicability of the proposed method in the long-time coherent integration, additional comparisons with these methods are conducted. Figure 11c shows the integration gains of the target signal in terms of input velocity when the remaining parameters of the target are set to be constant for the other methods, except the partition time $T_0$ for the standard KT, the method in [17] and the double GKT, which is still set to 0.3 ms. In Figure 11c, it is observed that as the target’s velocity increases, the improvement in SNR of the standard KT, the method in [17] and the double GKT tapers off, almost close to the conventional RD method, which is not conducive to the detection performance of the system. By contrast, the proposed method not only obtains the desirable integration gain, but the performance does not decrease even with the high speed of the target. The reason is that the transmitted signal (DTMB) is a Doppler-sensitive signal and severe Doppler mismatch in pulse compression occurs when the system detects a high-speed target. The proposed method can compensate for the Doppler mismatch via the intra-partition RD processing. Besides, although the performance of the method in [19] is stabilized, its SNR lower than proposed method due to the RC effect.

Similar to Figure 11c, Figure 11d illustrates the integration gains in terms of input partition time for the proposed method and segmented methods, that is, the standard KT, the method in [17] and the double GKT. It can be seen from the figure that the benefits of the proposed method are desirable with different partition time, which contributes to the improvement of the detection performance of the system. However, as the partition time increases, the performance of the standard KT the method in [17] and the double GKT deteriorates severely, even lower than the conventional RD when partition time is greater than 0.8 ms. This effect occurs for the reason that in the three methods, the maximum detection range depends on the number of sampling points of the pulse, that is, the length of partition determines the maximum detection range in this study. Therefore, the mismatch in pulse compression will be aggravated when detecting far range target.
To sum up, the proposed method can obtain expected integration gains, despite the high speed and far distance of the detection target, having better performance than the others.

6 | CONCLUSION

PBR exploits existing transmitters for sources of illumination and offers an effective, low cost and covert solution for monitoring airspace of interest. However, the dependence on illuminators of opportunity does present a problem that the PBR cannot control transmitter related to the gain. Thus, the target signal SNR is largely constrained by the CPI, which in turn is constrained by RM and DFM [38].

The problem of long-time coherent integration for PBR is addressed, involving RM and DFM within the CPI. A novel method based on the intra-partition RD processing is proposed to realize the long-time coherent integration of space moving targets with high speed. The method first divides the received signals into partitions and applies the intra-partition RD processing to achieve the two-dimensional pre-accumulation of target energy in each partition. Then, without the knowledge of the target’s motion, the method utilizes the GKT to remove the RC, in which the part of RW is removed as well. After that, the Doppler filtering processing is used to correct the residual RW. Finally, the quadric phase term due to the target acceleration is estimated and compensated following the MFP. The method is capable of overcoming the Doppler mismatch in pulse compression and correcting the RM without compensating the Doppler ambiguity under the condition of surveillance signal division processing in PBR. Thus, the long-time coherent integration for PBR can be achieved and the system detection performance is significantly improved, as demonstrated by the simulation results.

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ORCID

Luo Zuo https://orcid.org/0000-0002-3434-6312

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