Algorithm for Multipath Interference Restraint Based on Blind Source Separation in Passive GNSS-Based Bistatic Radar

Yuanyuan Wen[1](✉), Lin Bai[2], Xi Zhang[2], She Shang[1], Dawei Song[1], and Shuai Guo[3]

[1] National Key Laboratory of Science and Technology on Space Microwave, Xi'an 710100, China
wyy031980@163.com
[2] Academy of Space Information Systems, Xi'an 710100, China
[3] National Laboratory of Radar Signal Processing, Xidian University, Xi'an 710070, China

Abstract. Passive bistatic radar belongs to passive radar systems and is a variant of bistatic radar that exploit non-cooperative'illuminators of opportunity' as their sources of radar transmission. Passive bistatic radar has a lot of advantages such as double-base system, silent acceptance, inherently low cost and so on, and hence attractive for a broad range of applications in recent years. The Passive GNSS-Based bistatic Radar system exploits Global Navigation Satellite System as the illuminators of opportunity to detect the potential targets and is inevitable affected by multipath interference due to the reflection effect of mountains and near-earth buildings. If reference signal containing multipath interference is directly used for matching filter processing, the range-Doppler diagram will show the false target formed by matching multipath interference with echo signal. In this paper, a novel blind source separation method is proposed to recovering multipath interference from reference channel data in Passive GNSS-Based bistatic Radar. The elementary reflection matrix is used as a rotation matrix to transform the cumulant matrix to realize the purpose of diagonalization. Finally the direct wave signal and multipath interference signals were separated successfully. Both theoretical analysis and simulation result verify multipath interference can be well suppressed by the proposed method.

Keywords: The Passive GNSS-Based Bistatic Radar · Multipath interference · Direct wave signal · Blind source separation · Elementary reflection matrix

1 Introduction

For nearly twenty years, passive bistatic radar (PBR) has appealed to more and more people to study it at home and abroad because of its unique advantages of double-base system and silent acceptance [1]. The PBR obtains the target information by correlative processing between the target scattering echo signal and the direct wave signal received by non-cooperative transmitters as the illuminators of opportunity, so as to complete the detection, location and tracking of the target. The illuminators of opportunity used

B. Li et al. (Eds.): IoTaaS 2020, LNICST 346, pp. 371–379, 2021.
https://doi.org/10.1007/978-3-030-67514-1_30

include all kinds of wireless signals existing in space (such as FM [2, 3], civil TV [4], mobile communication, Global Navigation Satellite System(GNSS) and other digital video broadcast-terrestrial [5–8]), with good concealment and anti-destruction performance [9]. These systems can realize the features of low-cost network layout [10], wide coverage and flexible layout, and the radar of radiation sources outside the low-frequency segment can also realize anti-stealth, low-altitude detection and anti- “radio silence” [11].

GNSS uses one or more systems in Global Positioning System (GPS) [12], the GLObal Satellite Navigation System (GLONASS) [13], Beidou Satellite Navigation System [14], or Galileo Satellite Navigation System [15] for navigation and positioning. The passive GNSS-based bistatic radar system has many advantages. First, the passive radar is a multi-base radar system, and the stealth equipment cannot absorb microwave signals in the same direction, so passive radar has certain advantages in anti-stealth. Moreover, the passive radar without transmitter has portability and concealment and is difficult to be detected. At present, the worldwide user receives the GNSS by spread spectrum communication signal processing and carrier modulation signal after processing, the launch of the space at the same time, GNSS will remain on the surface of the earth or in the near-earth space of a point to provide 24-hour uninterrupted satellite signal to the world, based on the analysis of these signals using can realize positioning, navigation and timing services [16]. However reference channel of passive GNSS-based bistatic radar system is susceptible to multipath interference. The passive GNSS-based bistatic radar system is inevitable affected by multipath interference due to the reflection effect of mountains and near-earth buildings. When reference channel is affected by multipath interference, reference signals received by reference channel include direct wave signal, multipath interference and channel noise. If reference signal containing multipath interference is directly used for matching filter processing, the range-Doppler diagram will show the false target formed by matching multipath interference with echo signal. How to suppress multipath interference in reference channel of passive GNSS-based bistatic radar has become a difficult problem.

Because the mixed model of multipath interference and direct wave in the channel of the passive GNSS-based bistatic radar system is very similar to the model of blind source separation(BSS), the BSS method can be considered to separate the multipath interference and direct wave [17]. BSS refers to the estimation of each source signal only based on the observed signal received by the receiver when neither the source signal nor the mixed signal can be known [10]. The elementary reflection matrix is used as a rotation matrix to transform the cumulant matrix to realize the purpose of diagonalization and finally the direct wave signal and multipath interference signals were separated successfully.

The rest of the article follows. Section 2 the Passive GNSS-Based Bistatic radar system model is introduced. Section 3 the proposed novel multipath interference restraint algorithm based on BSS in passive GNSS-based bistatic radar is presented in detail. The capability of the proposed algorithm is verified by simulation results in Sect. 4. The conclusions are provided in Sect. 5.

2 Passive GNSS-Based Bistatic Radar System Model

The passive GNSS-based bistatic radar system model is shown in Fig. 1. The GNSS signals are used to detect airborne targets.

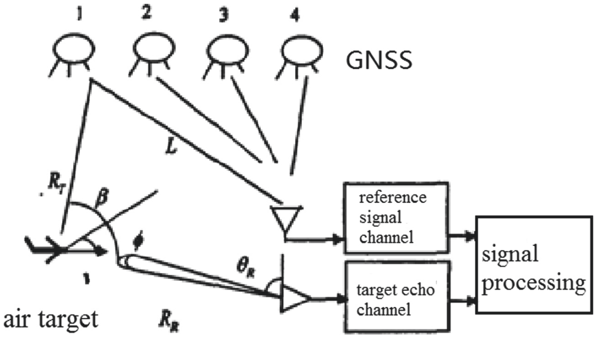


Fig. 1. Passive GNSS-based bistatic radar system model.

Using the traditional GNSS receiver multipath interferences, GNSS direct wave signal and channel noise are received through the reference channel. The signal received by the target channel can be represented as [10, 18, 19]

$$X_{tar}(t) = \underbrace{A_d s(t)}_{\text{directpath}} + \underbrace{\sum_{i=1}^{N} c_i s(t-\tau_{mi})}_{\text{multipathecho}} + \underbrace{a_d s(t-\tau_d)e^{j2\pi f_d t}}_{\text{targetecho}} + \underbrace{n_{tar}(t)}_{noise} \tag{1}$$

The signal received by the reference channel can be rewritten as

$$X_{ref}(t) = \underbrace{A_{d1} s(t)}_{\text{directpath}} + \underbrace{\sum_{i=1}^{M} d_i s(t-\tau_{pi})}_{\text{multipath}} + \underbrace{n_{ref}(t)}_{noise} \tag{2}$$

where $s(t)$ is the direct wave, A_d and A_{d1} are the coefficient of the direct wave signal; $\sum_{i=1}^{N} c_i s(t-\tau_{mi})$ and $\sum_{i=1}^{M} d_i s(t-\tau_{pi})$ are the multipath signals, N and M are the number of the multipath signals, c_i and d_i are the amplitude of the multipath, τ_{mi} and τ_{pi} are the time delay of the multipath signal; $a_d s(t-\tau_d)e^{j2\pi f_d t}$ is the echo signal, a_d, τ_d and f_d respectively is the amplitude, the time delay and the Doppler frequency of the target echo signal; $n_{tar}(t)$ is the noise at the target echo channel, $n_{ref}(t)$ is the noise at the reference channel receiver antenna, $n_{tar}(t)$ and $n_{ref}(t)$ are independent and uncorrelated of the GNSS signal.

3 Multipath Interference Restraint Algorithm Based on BSS

We consider the multipath interferences suppression in the reference channel. The spectra of the sources are heavily overlapped in the reference channel of the passive GNSS-Based bistatic radar, so array antennas are often used to receive signals. In general, the receiving antenna is assumed to be an arbitrarily shaped array structure. Let's think about the common case that the mixture model of the system is overdetermined, namely, the number of receivers is M, and the number of sources is N (N), the received signals can be rewritten as:

$$\begin{bmatrix} \boldsymbol{x}_1(t) \\ \vdots \\ \boldsymbol{x}_{\mathrm{M}-1}(t) \\ \boldsymbol{x}_M(t) \end{bmatrix} = [\,\alpha_1(\theta_1), \quad \alpha_2(\theta_2), \quad \alpha_3(\theta_3), \quad \cdots, \quad \alpha_N(\theta_N)\,] \begin{bmatrix} A_1 s(t) \\ d_1 s(t-\tau_1) \\ d_2 s(t-\tau_2) \\ \vdots \\ d_{N-1} s(t-\tau_{N-1}) \end{bmatrix} + \begin{bmatrix} \boldsymbol{n}_1(t) \\ \boldsymbol{n}_2(t) \\ \vdots \\ \boldsymbol{n}_M(t) \end{bmatrix} \tag{3}$$

we can see that the mixed model of multipath interference and direct wave in the channel of the passive GNSS-based bistatic radar system is very similar to the model of BSS. Therefore, BSS method can be considered to separate the multipath interference and direct wave.

BSS refers to the estimation of N source signal only based on the M observed signal received by the receiver when neither the source signal nor the mixed signal can be known [20, 21].

Suppose an instantaneous linear mixing system in the presence of noise, in which there $M \geq N$. The signal received by the received channel can be expressed as:

$$x_j(t) = \sum_{i=1}^{N} a_{ij}(k) s_j(t) + n_i(t), \quad j = 1, 2, \ldots, M \tag{4}$$

where x_j is the j-th observed signal, s_i is the i-th source signal, $a_{ij}(k)$ is the mixed matrix. We assume that the system is a causal finite filter model throughout this article. $n_i(t)$ is the noise. Suppose $\boldsymbol{S}(t) = [s_1(t), \cdots, s_N(t)]^T$ and $\boldsymbol{X}(t) = [x_1(t), \cdots, x_M(t)]^T$ respectively represent the source signals and the observed signals in matrix form. Formula (4) can also be expressed as the matrix form.

Defining $\boldsymbol{Y}(t) = [y_1(t), \cdots, y_N(t)]^T$ represent the estimated signals in matrix form and $\boldsymbol{W}$ is unmixing matrix. By computing the values of the matrix elements of the unmixing matrix $\boldsymbol{W}$ an individual element is mutually independent estimate vector $\boldsymbol{Y}(t)$ of the source signals vector $\boldsymbol{S}(t)$ is computed [22, 23]. The approximate joint diagonalization process of the signals of received channel is the solution process of $\boldsymbol{W}$.

The elementary reflection matrix is used as a rotation matrix to transform the cumulant matrix to realize the purpose of diagonalization. Finally the direct wave signal and multipath interference signals were separated successfully. Below is the detailed process of diagonalization.

Suppose X be made of matrices $x_1, x_2, \cdots, x_n$ of size $n \times n$. The process of joint diagonalization of X using the elementary reflection matrix can be described to minimize the following equation [24, 25]

$$H'XH = \min \sum \|X - diag(X)\|^2 \tag{5}$$

If $s = 1$, the process of the joint diagonalization is the same as the process of the normal unitary diagonalization. The solution to the matrix H is the process of joint diagonalization of X. And then we make a somewhat rule, through which approximate jointly diagonalizing matrix is realized.

Defining $\boldsymbol{H} = \boldsymbol{I} - \boldsymbol{2ww}^T$ is the elementary reflection matrix, where $\|\boldsymbol{w}\|_2 = 1$.We can have a 0 in a vector through the elementary reflection matrix. Vector $\boldsymbol{x}$ can be transformed into a new vector that has zero entries except for the first entry.

4 Simulation Results

Let us suppose a simplified model of three inputs and three outputs and three source signals s_1, s_2, s_3 is independent. s_1 is the expected signal, s_2, s_3 is multipath reflection of the expected signal. We artificially mix the three sources via the mixing matrix in the following:

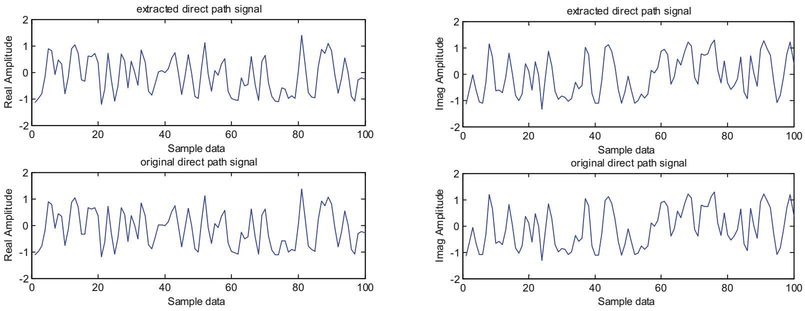
$$\boldsymbol{H}(z) = \begin{bmatrix} 1 + 0.2z^{-1} + 0.1z^{-2} & 0.5 + 0.6z^{-1} + 0.3z^{-2} & 0.3 + 0.6z^{-1} + 0.5z^{-2} \\ 0.5 + 0.6z^{-1} + 0.3z^{-2} & 0.2 + 0.6z^{-1} + 0.2z^{-2} & 0.2 + 0.1z^{-1} + 0.4z^{-2} \\ 0.3 + 0.1z^{-1} + 0.1z^{-2} & 0.5 + 0.2z^{-1} + 0.4z^{-2} & 0.4 + 0.2z^{-1} + 0.3z^{-2} \end{bmatrix} \tag{6}$$

To further measure the separation capability of the proposed method, we evaluate the separation capability of the proposed method using the comparable coefficient. The closer the value of comparable coefficient is to one, the better the capability of the proposed algorithm. The comparable coefficient can be defined as follows:

$$\lambda_{ij} = \lambda(y_i, s_j) = \frac{\left|\sum y_i * s_j\right|}{\sqrt{\sum y_i^2 * \sum s_j^2}} \tag{7}$$

where, s_j and y_i respectively represent two signal vectors; λ_{ij} represents the degree of similarity between two signal vectors.

The original signal and extracted signal are shown in Fig. 2. Figure 2(a) shows the real part comparison of the original signal and extracted signal and Fig. 2(b) shows the imaginary part comparison of the original signal and extracted signal.



(a) Real part (a) Imaginary part

Fig. 2. Original signals and extracted direct wave signal.

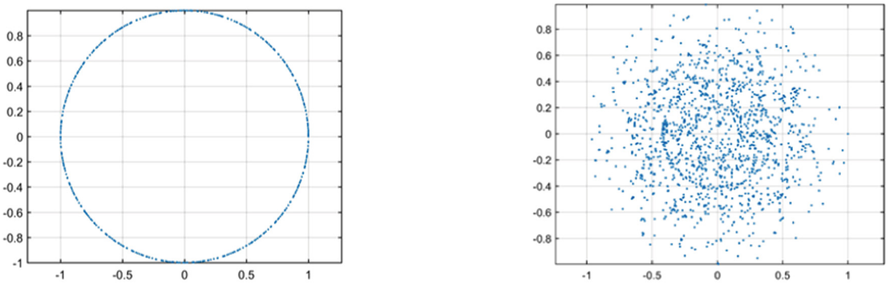
From the figure above we can see that the waveform of the extracted signal and the original direct wave is very similar. We can further verify the separation capability of the proposed method in this paper by calculating the resemble coefficient under different SNR. The resemble coefficient are shown in Table 1.

Table 1. Comparable coefficient.

SNR/dB	−20	−15	−8	−5	0
Comparable coefficient	0.8543	0.9048	0.9439	0.9789	0.9990

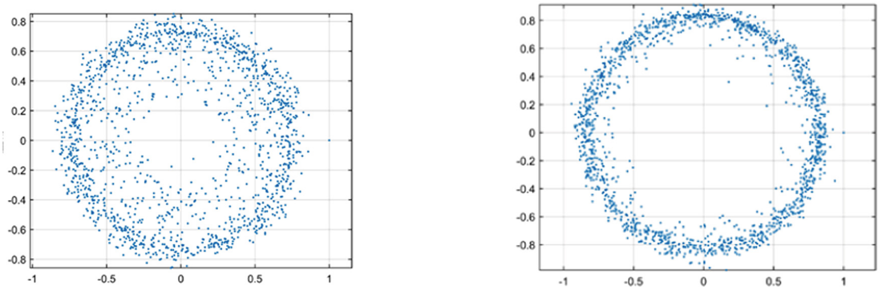
It can be seen from Table 1 that the direct wave signal can be extracted even at a low SNR.

The performance of the algorithm to suppress multipath interference is further verified by comparing the constellations of direct wave signal under different conditions. For the convenience of comparison, this simulation normalizes the direct wave signal under different conditions. When the signal modulus is constant, the signal point trace is distributed as a standard circle with radius 1. When the signal modulus fluctuates with time, the signal point trace distribution is disorganized. By comparing the stray degree of the point trace distribution in the constellation maps, the degree of the signal modulus floating is measured. Therefore, the signal constellation map can directly reflect the distribution of the signal modulus. The comparison results are shown in Fig. 3.



(a) Pure direct wave signal

(b) Contains multipath



(c) Blind beamforming algorithm

(d) BSS interference suppression algorithm

Fig. 3. Comparison of the constellation maps.

As you can see from the Fig. 3 that the stray point trace of the proposed algorithm converges further to the constant modulus circle than the blind beamforming algorithm, which indicating that the proposed method can better suppress multipath interferences.

5 Conclusions

A blind source separation algorithm with the statistical independence of the direct wave signal and multipath interference signals is proposed to suppress multipath signals in the reference channel of the passive GNSS-Based bistatic radar system in this paper. The elementary reflection matrix is used as a rotation matrix to transform the cumulant matrix to realize the purpose of matrix diagonalization and finally the direct wave signal and multipath interference signals were separated successfully. The numerical simulations have demonstrated the validity of the proposed method. Using the proposed method multipath interference signals can also be suppressed at lower SNR and the performance of multipath interference restraint of the proposed method is better than that of the blind beamforming algorithm.

References

1. Guo, S., Wang, J., Chen, G., Wang, J.: Method for multipath interference restraint of the reference channel in passive bistatic radar. J. XIDIAN Uni. **45**(3), 18–23 (2018)
2. Colone, F., Bongioanni, C., Lombardo, P.: Multifrequency integration in FM radio-based passive bistatic radar. Part I: target detection. IEEE Aerosp. Electron. Syst. Mag. **28**(4), 28–39 (2013)
3. Colone, F., Bongioanni, C., Lombardo, P.: Multifrequency integration in FM radio-based passive bistatic radar. Part II: target detection of arrival estimation. IEEE Aerosp. Electron. Syst. Mag. **28**(4), 40–47 (2013)
4. Edrich, M., Schroeder, A., Meyer, F.: Design and performance evaluation of a mature FM/DAB/DVB-T multi-illuminator passive radar system. IET Radar Sonar Navig. **8**(2), 114–122 (2014)
5. Howland, P.E.: Editorial: passive radar systems. IEE Proc. Radar Sonar Navig. **152**(3), 105–106 (2005)
6. Griffiths, H.D., Baker, C.J.: Passive coherent location radar systems. Part 1: Performance predication. IEE Proc. Radar Sonar Navig. **152**(3), 153–159 (2005)
7. Poulin, D.: Passive detection using digital broadcasters (DAB, DVB) with COFDM modulation. IEE Proc. Radar Sonar Navig. **152**(3), 143–152 (2005)
8. Howland, P.E., Maksimiuk, D., Reitsma, G.: FM radio base d bistatic radar. IEE Proc. Radar Sonar Navig. **152**, 107–115 (2005)
9. Nordwall, B.D.: Silent Sentry-A New Type of Radar. Aviation Week & Space Technology (1998)
10. Wen, Y., Sun, W., Shang, S.: Weak signal extraction based on blind source separation in passive radar. In: 2019 International Symposium on Signal Processing, pp. 26–30 (2019)
11. Griffiths, H.D, Long, N.R.W: Television based bistatic radar. Radar Signal Process. **133**(7), 649–657(1986)
12. Navstar IS-GPS-200E, Interface Specification, Science Applications International Corporation, El Segundo, CA, USA. Technical Report IRN-IS-200H-003 (2015)
13. Global Navigation Satellite System GLONASS Interface Control Document (Edition 5 .1), Russian Institute of Space Device Engineering, Nizhnyaya Salda, Russia (2008)
14. BeiDou Navigation Satellite System Signal in Space Interface Control Document, Open Service Signal (Version 2.0). China Satellite Navigation Office, Beijing, China, December 2013
15. Galileo Open Service, Signal in Space Interface Control Document (OS SIS ICD). European Space Agency/European GNSS, Paris, France, November 2015
16. Pastina, D., Santi, F., Pieralice, F.: Maritime moving target long time integration for GNSS-based passive bistatic radar. IEEE Trans. Aerosp. Electron. Syst. **54**(6), 3060–3083 (2018)
17. Colone, F., Cardinali, R., Lombardo, P.: Cancellation of clutter and multipath in passive radar using a sequential approach. In: 2006 IEEE Conference on Radar, Verona (NY), USA, p. 7 (2006)
18. Tsai, P.H.E., Ebrahim, K., Lange, G., Paichard, Y., Inggs, M.: Null placement in a circular antenna array for passive coherent location systems. In: 2010 IEEE International Radar Conference, Washington, DC, USA, pp. 1140–1143 (2010)
19. Feng, B., Wang, T., Liu, C.: An effective CLEAN algorithm for interference cancellation and weak target detection in passive radar. In: 2013 Asia-Pacific Conference on Synthetic Aperture Radar (APSAR), vol. 5, no. 2, pp. 160–163 (2013)

20. Fu, W., Zhou, X., Nong, B., Li, C., Liu, J.: Blind estimation of underdetermined mixing matrix based on density measurement. Wireless Pers. Commun. **104**(4), 1283–1300 (2018). https://doi.org/10.1007/s11277-018-6080-z
21. Li, C., Zhu, L., Xie, A., Luo, Z.: Blind separation of weak object signals against the unknown strong jamming in communication systems. Wireless Pers. Commun. **97**(3), 4265–4283 (2017). https://doi.org/10.1007/s11277-017-4724-z
22. Mohanaprasad, K., Singh, A., Sinha, K.: Noise reduction in speech signals using adaptive independent component analysis (ICA) for hands free communication devices. Int. J. Speech Technol. **3**(22), 169–177 (2019)
23. Liu, S., Gao, X., Qi, W.: Soft sensor modelling of propylene conversion based on a Takagi-Sugeno fuzzy neural network optimized with independent component analysis and mutual information. Trans. Inst. Measur. Control **41**(3), 737–748 (2019)
24. Rader, C., Steinhardt, A.: Hyperbolic householder transformations. IEEE Trans. Acoust. Speech Signal Process. **34**, 1589–1602 (1986). Also in the SIAM Journal on Matrix Analysis and Applications 8(4), 1–5 (1988)
25. Li, Y., Wei, M., Zhang, F., Zhao, J.: Real structure-preserving algorithms of Householder based Transformations for quaternion matrices. J. Comput. Appl. Math. **305**, 82–91 (2016)