Investigation and First Experiment of BeiDou-Based Passive Radar Vessel Target Imaging

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Abstract

The passive radar system using global navigation satellite systems (GNSS) as opportunistic illuminator shows its potential in maritime surveillance application owing to its global coverage. However, the main drawback of GNSS-based passive radar stays in the extremely low signal power density near the Earth's surface, which makes the detection and imaging of target in surveillance sea area a challenging task. In this paper, an overview of the signal processing algorithms for GNSS-based passive radar target detection and imaging is provided. Then, a maritime experiment with BeiDou satellites as transmitters and a vessel as the target was carried out, which is the world's first BeiDou-based passive radar vessel target detection and imaging experiment. The results confirm the feasibility of GNSS-based passive radar in vessel target detection and imaging.

1. Introduction

Passive radar has been one of the research lines in the past few decades. Since it does not need a dedicated transmitter, passive radar is actually a low-cost detection approach. The spatially diverse receiver and opportunistic transmitter bring advantages for passive radar system, such as strong concealment and anti-interference ability [1].

There are different kinds of opportunistic signals that can be utilized in passive radar. Currently, most of the researches focus on the passive radar using terrestrial sources, such as FM radio, DAB/DVB-T, et al [2-4]. Owing to the transmitters' positions and their original intentions, these signals only guarantee the coverage of main land. Therefore, such passive radar is primarily applicable to detect the vehicle or airborne targets.

This paper focus on the imaging of vessel target in sea area via passive radar, where the terrestrial sources are apparently unsuitable. Under such circumstance, a feasible alternative for passive radar system is to exploit the signals transmitted from satellite illuminators. And the global navigation satellite system (GNSS) is one of the most promising option, since it provides a global coverage and the transmitted signal has a relatively large bandwidth. Currently, there are four main GNSS constellations in orbit, i.e. GPS, GLONASS, Galileo, and BeiDou. Some of the transmitted GNSS signals are able to provide the range resolution of 15 m (such as GPS L5, BeiDou B3I, and Galileo E5a/b signals) [5], which is apparently smaller than the typical size of a vessel. Thus, the GNSS-based passive radar shows its potential in vessel target detection and imaging. In addition, any point on the Earth is simultaneously illuminated by 4-8 navigation satellites in a single GNSS constellation from different angles [6]. The utilization of the multiple singles from different satellite transmitters is likely to help to increase the target detection and imaging performance.

2. System Concept

The system geometry of GNSS-based passive radar for vessel detection and imaging is shown in Figure 1. The passive receiver is equipped with two antennas. One of them points to the sky, receiving the direct signal from GNSS satellite for signal synchronization [5]. The other antenna receives the reflected signals from the detected area, which are used for the vessel target detection and imaging.

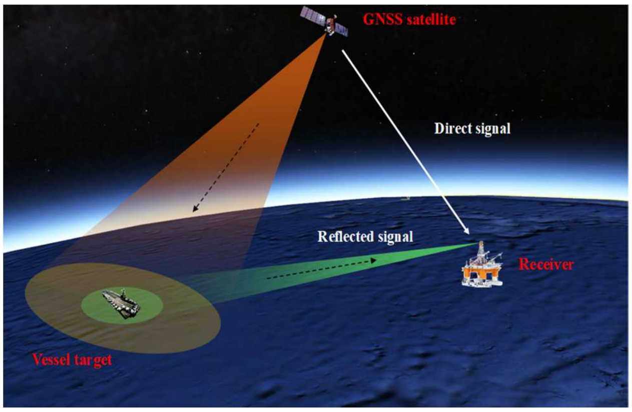


Figure 1. The system geometry of GNSS-based passive radar.

The main drawback of the GNSS-based passive radar is its extremely low power density near Earth's surface. Due to the limited transmitted power and high orbit altitude, the power density can be as low as -135 dBW/m^2 [7]. The conventional target detection and imaging methods in active radar system are no longer available in this condition. Therefore, dedicated and novel detection and imaging methods should be applied for GNSS-based passive radar.

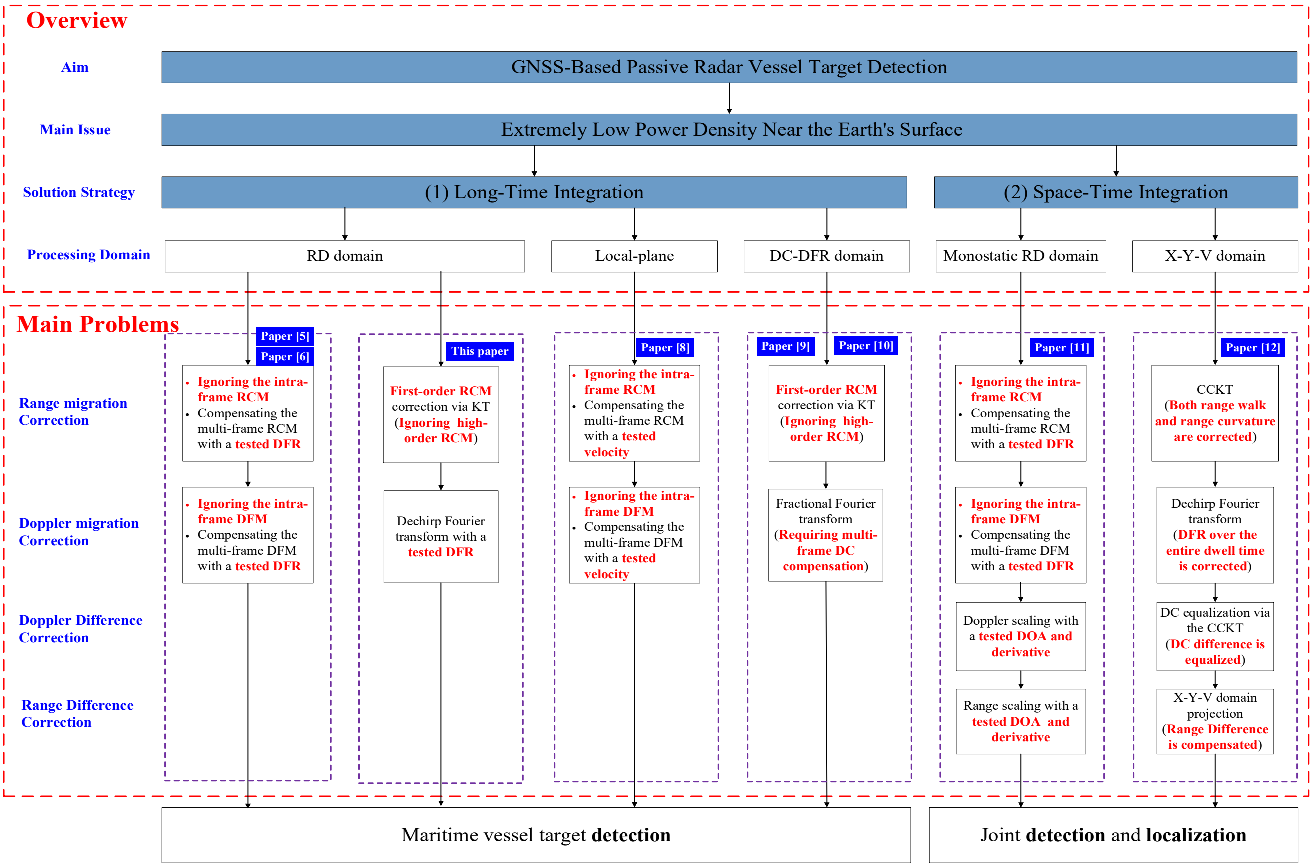


Figure 2. An overview of the maritime vessel target detection and imaging methods via GNSS-based passive radar.

3. Processing Methods

The limited power budget of GNSS-based passive radar causes an extreme signal-to-noise ratio (SNR) of the reflected target echo. In order to increase the SNR value for a reliable target detection and imaging performance, an obvious solution is to integrate the target echo over a long observation time. In addition, since the signals from different GNSS satellite can be simultaneously recorded by the same receiver, the combination of multiple echoes can further increase the SNR, which is defined as the space integration.

The GNSS signals are continuous in time. The received radar data are firstly reformatted into two dimensional fast-time and slow-time domain according to an equivalent pulse repetition interval (PRI). After the signal synchronization via the cross-correlation between reflected signal and the reference signal [5], the bistatic range concerning the range-compressed data is expressed as

$$R(\eta) = R_T(\eta) + R_R(\eta) - R_b(\eta) \tag{1}$$

where η is the slow-time, R_b is the length of baseline, R_T and R_R are the distances between the target and, respectively the satellite transmitter and receiver. Then the Doppler frequency is obtained as

$$f_d(\eta) = \frac{\partial R(\eta)}{\partial \eta} \tag{2}$$

Apparently, owing to the motions of the satellite and the vessel target, the range and Doppler change with time. Usually the integration time for a typical vessel target is in order of several tens of seconds. Thus, the range and Doppler migrations are non-negligible. In addition, when the multiple satellites are considered, the different kinetical parameters of these transmitters bring the differences in range and Doppler parameters between multiple echoes.

An overview of the existing integration methods for GNSS-based passive radar vessel target detection and imaging is summarized and presented in Figure 2. It should be noted that the coherent integration of the entire echo is unprocurable owing to the scattering mechanism of the target. Therefore, a hybrid integration strategy is applied to preferably maximize the target energy. That is, the entire echo is segmented into multiple frames, where the coherent integration is performed on each intra-frame signal, and non-coherent integration of different frames is applied. As shown in Figure 2, the aforesaid problems for target integration are solved via different ways. In this paper, we mainly focus on the vessel target detection and imaging using the GNSS-based passive radar consisting of a single satellite transmitter, and the configuration consisting of multiple GNSS satellites is beyond the scope of this paper. The corresponding long-time integration method is simultaneously shown in Figure 2. Here, the range migration is removed via the keystone transform, and the Doppler migration correction is achieved via the dechirp Fourier transform, which is expressed as

$$S(\tau, f_d) = \int_{-\infty}^{+\infty} s(\tau,\eta) \exp\left\{-j2\pi f_d \eta - j\pi \tilde{f}_{dr} \eta^2\right\} d\eta \tag{3}$$

where $s(\tau,\eta)$ is the signal in fast-time and slow-time domain, and $\tilde{f}_{dr}$ is the tested Doppler rate value. When compared with the methods in [5,6], this method provides a slightly better integration result since it enables the correction of the range and Doppler migrations inside each frame.

4. Experimental results

A maritime experiment was carried out in Lianyungang port to demonstrate the GNSS-based passive radar. As shown in Figure 3, the passive receiver was fixed at the shore, and a container vessel moving in the observed area was regarded as the target. Which is the world's first BeiDou-based passive radar vessel target detection and imaging experiment.

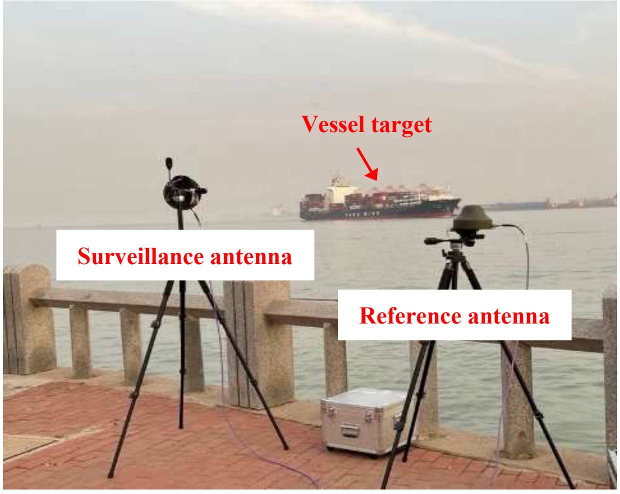


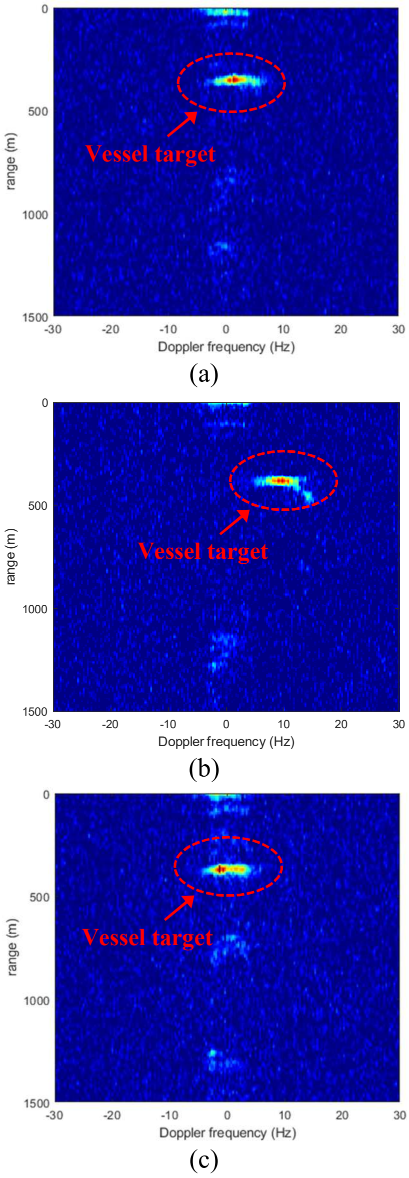
Figure 3. The experimental setup of the BeiDou-based passive radar.

With respect to the transmitter of opportunity, the B3I signals from BeiDou satellites were recorded by the receiver, and the corresponding parameters are shown in Table 1. Compared with the other GNSS constellations, the BeiDou system operates satellites in three orbits, i.e. medium earth orbit (MEO), inclined geosynchronous orbit (IGSO), and geostationary earth orbit (GEO). Thus, more satellites can be selected as the opportunistic transmitters for the passive radar system. In this experiment, three different BeiDou satellites (i.e. C27, C38, and C41) are treated as the transmitters, where C27 and C41 are in MEO at an altitude of 21528 km, and C38 is in IGSO at an altitude of 35786 km.

Table 1. The experimental parameters.

Parameters	Values
Carrier frequency	1268.520 MHz
Signal chip rate	10.23 MHz
Sampling rate	50 MHz
Equivalent PRI	1 ms

The entire observation time on the vessel is 45 s. Following the hybrid integration strategy, the long-time echo is segmented into 15 frames with frame duration of 3 s. By means of the vessel target detection and imaging method provided in this paper, the integration result pertaining to the three different BeiDou satellites are shown in Figure 4. It is observed that the target is well concentrated and isolated from the noise background in all the three maps, providing a reliable vessel detection and imaging performance. These results illustrate the effectiveness of integration method and the feasibility of the BeiDou-based passive radar. Meanwhile, the target is observed to be located at different positions in these three maps, which is caused by the different configurations concerning the different opportunistic transmitters.



(a)

(b)

(c)

Figure 4. The detection and imaging results with respect to different BeiDou satellites: (a) C27, (b) C38, (c) C41.

5. Conclusion

The paper introduces a novel maritime surveillance technology via passive radar which utilizes GNSS as transmitter of opportunity. The global coverage provided by the GNSS makes such radar system applicable in this kind of application. However, the extremely low power density of GNSS signal makes it difficult for target detection and imaging. In this paper, an overview of innovative vessel target detection and imaging methods via GNSS-based passive radar is summarized. All the methods aim at increasing the SNR by integrating the target energy. A new target detection and imaging method is also introduced in this paper, which achieve the long-time integration of target echo via keystone transform and dechirp Fourier transform. The experimental results testify the feasibility of the integration method.

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