Study on GNSS-R multi-target detection and location method based on consistency checking

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Funding Information
National Natural Science Foundation of China, Grant/Award Numbers: 42074044, 61701481, Unassigned; Young Talent Supporting Programme of the China Association for Science and Technology, Grant/Award Number: 2019QNRC001; China Association for Science and Technology, Grant/Award Number: Unassigned

Abstract
The use of GNSS reflected signals to carry out passive detection of space targets is an emerging technical field. Unlike the traditional GNSS-R in large-scale environments such as oceans, vegetation, ice and snow, it is required to identify different targets within the detection range, which is one of the biggest challenges. To solve this problem, a hyperboloid observation equation based on the TDOA location model is constructed, which can eliminate the GNSS satellite orbit error, the satellite atomic clock error and the detection receiver clock error via differential technique. The consistency checking theory based on hypothesis and test is used to detect and distinguish different targets while locating. The simulation results show that the target detection and location accuracy can reach tens of metres, and when the different space targets are separated by 50 m, 100 m, 150 m, 200 m, and 250 m in sequence, the detection success rate of the method is 67.25%, 87.50%, 95.75%, 99.25%, and 99.75%, respectively, which indicates the feasibility and effectiveness of the method. The study provides a feasible technical approach for solving the multi-target problem in GNSS-R space target passive detection.

1 | INTRODUCTION

GNSS Reflectometry (GNSS-R) technology uses Global Navigation Satellite System (GNSS) satellites as the radiation sources and uses the land-, aviation- or space-based platforms to carry the detection equipment. By receiving and processing the GNSS signals reflected by land, sea or other objects, GNSS-R combines the changing signal waveform, amplitude, phase and frequency information to extract the characteristics of the signal reflection medium. [1–3].

The concept of GNSS-R was first proposed by Martin-Neira of the European Space Agency (ESA) in 1993 [4]. In 1996, in order to verify the feasibility of GNSS-R altimetry, Martin-Neira et al. conducted experiments on the Zeeland Bridge in Netherlands by using the GPS reflected signals from the sea surface, and the results showed that the altimetry error was less than 10 cm [5]. Subsequently, Low and Zuffada of the Jet Propulsion Laboratory (JPL) of the National Aeronautics and Space Administration (NASA) carried out airborne GNSS-R altimetry experiments on lake and sea, with an altimetry accuracy of 5 cm [6]. Among them, in the lake experiment, since the water surface was very calm, the carrier phase measurement was used to achieve a high altimetry accuracy of 2 cm [7]. Due to the success of the above series of experiments, NASA approved the ‘CYGNSS’ plan in 2013, and began to gradually launch a total of 8 micro-satellites since 2016. Each satellite is equipped with a GNSS-R reflected signal receiver, and planned to detect the Hurricane eyes through the inversion...
of sea surface wind fields [8, 9]. At present, in addition to ESA and NASA, the University of Colorado, Purdue University, Hopkins University, NAVSYS, French Space Technology Laboratory, Surrey University, Surrey Satellite Technology Centre, Tokyo University, Japan, Queensland University, New Zealand, The University of South Wales and other institutions have also carried out research on the GNSS-R technology, and extended it to the sea surface wind field detection, tsunami warning, ocean salinity, land humidity and forest cover remote and other application fields. China is also actively developing GNSS-R research and applications. Yang Dongkai et al. systematically studied the principles and methods [10–12], and actively carried out experimental verification and application in marine altimetry, and participated in the CYGNSS plan. Jin Shuanggen et al. realized the effective application of GNSS-R in ice and snow height measurement and remote sensing [13, 14]. Yin Cong et al. [15], Zhang Yun et al. [16] and others carried out the simulation and experimental verification of GNSS-R in the sea ice remote sensing. However, in addition to the remote sensing and feature inversion towards the ground, GNSS-R can also be used to detect and locate the air and ground targets to realize the function of a passive radar. The ‘Opportunity Illumination Source Radiation Detection and Ranging System’ of VTT Technical Research Centre of Finland uses satellite TV signals from Germany and France as the radiation source to verify the theoretical design of the system [17]. Cherniakov, Nezlin & Kubik et al. of Russia used low-orbit communication satellites as radiation sources to discuss the characteristics of the reflected signals [18]. Griffiths & Baker of the University College London (UCL) carried out research using the TV signal of the ‘Marco Polo I’ satellite as a radiation source [19]. Compared with the television or communication satellites, the passive detection technology research using GNSS satellites as the radiation source is more advanced. One of the current representative systems is the passive multi-base air defence radar developed by Diehl Defence Inc. of Germany. It uses GPS and GLONASS satellites as the radiation sources and uses the phased array antennas for reception. In addition to the advantages of the traditional passive detection radars such as high electromagnetic silence and high concealment, the passive detection approach based on GNSS-R also has its own unique advantages. In August 2020, with the full completion of China’s BeiDou Global Navigation Satellite System (BDS-3), four major GNSS core constellations currently have been found to have more than 100 satellites in orbit, providing us with the rich, stable and reliable illumination sources. Secondly, the GNSS satellites are evenly distributed in different azimuths, forming a multistatic radar between satellites and detection equipment, which is easy to obtain a good DOP (Dilution of Precision) [4]. Third, the GNSS satellites located in the middle and high orbits have a wide beam range and a large coverage airspace, which can provide a sufficient observation time. Finally, the PRN (Pseudo Random Noise) code with precise ranging ability is modulated on the GNSS satellite signals, where the satellite orbital coordinates can be accurately calculated through the broadcast ephemeris message, and the time of the satellites have been synchronized with the on-board precise atomic clock. Therefore, it is possible to use a new detection scheme that is different from the traditional PCL (Passive Coherent Location) [20–22]. In addition, the use of the autonomously and controllable BDS as the external radiation source has additional benefits. For example, the pilot channel of the new signal of the BDS-3 (e.g. the BIC or B2a signal) can be used to increase the integration processing time of the receiver (BDS ICD 2017) [23], thereby further improving the detection capability. However, the use of GNSS-R for space target detection also has some significant challenges. Unlike the traditional applications of GNSS-R remote in large-scale environments such as oceans, land, hydrology, vegetation, ice and snow, the use of GNSS-R for space target detection requires a faster response and processing, so it cannot achieve high-resolution imaging through long-term integration. Therefore, apart from the fact that the detection range is easily limited due to the weak power of GNSS reflection signals, one of the biggest problems is how to simultaneously locate and distinguish multiple targets within the detection range. To solve the problem, we construct a hyperboloid observation equation based on the pseudorange difference between the direct signal and the reflected signal of GNSS, which uses a time difference of arrival (TDOA) location model. On this basis, it is proposed to use the consistency checking theory to effectively detect and distinguish different targets in an algorithmic manner, thereby reducing hardware requirements for the detection equipment. Finally, the simulation of the propose method is performed. The simulation result shows that by comparing and judging the consistency of different GNSS received signal combinations, the method can effectively detect and distinguish different spatial targets with a good spatial resolution. Specifically, the target detection and location accuracy based on the TDOA method can reach tens of metres. And when the different space targets are separated by 50 m, 100 m, 150 m, 200 m, and 250 m in sequence, the detection success rate of the method is 67.25%, 87.50%, 95.75%, 99.25%, and 99.75%, respectively. The remainder of this article is structured as follows. Section 2 introduces the basic principles of the GNSS-R passive detection and the composition of the detection system. In Section 3, the TDOA hyperboloid observation equation based on the pseudorange difference between the direct signal and the reflected signal of the GNSS satellite is proposed and constructed, which eliminates the GNSS satellite orbit error, the satellite atomic clock error and the detection receiver clock error via differential technique. Therefore, it is beneficial to improve the detection and location accuracy. Section 4 proposes to use the consistency detection theory to test and compare different GNSS received signals to determine and extract the correct signal combination to achieve the purpose of multi-target detection and identify. On this basis, a consistency test quantity based on the Sum Squares Error (SSE) of pseudorange difference and its corresponding fast detection algorithm are proposed. Finally, the method is simulated and analysed in Section 5 and the conclusions are summarized in Section 6.
2 | BASIC PRINCIPLE OF GNSS-R PASSIVE DETECTION

The basic principle of using GNSS satellites as the opportunistic radiation sources to carry out the passive detection of space targets is similar to the traditional GNSS-R altimetry technology. All of them use pseudorange observations of GNSS satellites (which can be code pseudoranges or carrier phase pseudoranges) as raw observations to obtain the propagation distance difference between the direct signals and the reflected signals, and construct geometric observation equations for solution. The basic composition of the detection system is shown in Figure 1.

In the detection system, both the reference channel and the detection channel include the antennas, radio frequency front-ends (including low-noise amplification, filters, frequency mixing, A/D converters, etc.), digital signal processing basebands (including correlators, carrier loops, code Ring, CNC oscillator, pseudo code generator, etc.) and other components. The difference is that the reference channel uses a Right-Hand Circular Polarized (RHCP) antenna to receive GNSS direct signals and serves as a reference, and the detection channel uses a Left-Hand Circular Polarization (LHCP) antenna with a high polarization isolation and gain to receive GNSS reflected signals.

The reference channel and the detection channel use a same time-frequency crystal oscillator (OSC) to trace the source to a unified time reference, synchronously generate the pseudo code and carrier of the local receiver, and realize the detection of the arrival time difference of the signals. The two-channel signal processing results are transmitted to a computing module (which can be an ARM or a PC) for calculation, and finally achieve positioning, speed measurement and multi-target detection goals.

Similar to a GNSS-R altimetry receiver, the GNSS-R passive detection receiver can also be implemented on the basis of the existing commercial geodetic receiver, thereby reducing the equipment costs.

3 | LOCATION MODEL

GNSS-R passive detection is realized based on the TDOA location model [24, 25]. As shown in Figure 2, the threedimensional spatial coordinates of the receiving antenna R, the target T and the satellite \( S_i (i = 1, 2, \cdots, n) \) are \((x_R, y_R, z_R)\), \((x_T, y_T, z_T)\) and \((x_{S_i}, y_{S_i}, z_{S_i})\), respectively. The pseudorange measurements of the direct signal and the reflected signal of the satellite \( S_i \) are \( \rho_i \) and \( \rho'_i \), respectively. The geometric distance from the satellite \( S_i \) to the target \( T \) is \( L_i \), and the Line-of-Sight (LOS) distance from the satellite \( S_i \) to the receiving antenna \( R \) is \( D_i \). The geometric distance from the target \( T \) to the receiving antenna \( R \) is \( D \).
First, the pseudorange difference between the reflected signal measurement \( \rho_i' \) and the direct signal measurement \( \rho_i \) can be calculated as follows:

\[
\Delta \rho_i = \rho_i' - \rho_i. \tag{1}
\]

Taking into account the residual \( \Delta \epsilon \) of the atmospheric transmission delay difference between the reflected signal and the direct signal, \( \Delta \rho_i \) is equal to the difference in the geometric distance between the reflected distance and the direct distance, that is

\[
\Delta \rho_i = L_i + D - \rho_i + \Delta \epsilon \tag{2}
\]

Due to the similarity of the geometric distance between the detection receiver and the target, the magnitude of \( \Delta \epsilon \) can be negligible, thus equation (2) can be further written as:

\[
\sqrt{(x_i - x_T)^2 + (y_i - y_T)^2 + (z_i - z_T)^2} \\
+ \sqrt{(x_R - x_T)^2 + (y_R - y_T)^2 + (z_R - z_T)^2} = \Delta \rho_i \\
+ \rho_i
\]

where

\[
\rho_i = \sqrt{(x_i - x_R)^2 + (y_i - y_R)^2 + (z_i - z_R)^2},
\]

and it can be calculated by using the known coordinate positions of the receiver and each GNSS satellite.

Equation (2) and Equation (3) constitute a hyperboloid observation equation form [26]. Through the differential processing of the direct signals and the reflected signals from the same GNSS satellites, the effects of system deviations such as the GNSS satellite orbit error, the satellite atomic clock error, and the detection receiver clock error \( \Delta \tau \) are eliminated. In addition, the ionosphere, troposphere and other atmospheric delay errors in signal propagation are also partially eliminated.

In summary, the satellite orbit coordinates can be calculated in real-time by using broadcast ephemeris messages, the receiver coordinates can be obtained via GNSS positioning, and the receiver clock error have been eliminated by differential processing. Therefore, there are only three unknown coordinate parameters \((x_T,y_T,z_T)\) left in the equations. By observing more than four GNSS satellites and their effective reflection signals, we can solve the equations iteratively after the Taylor expansion. Thus, Equation (3) can be sorted into:

\[
\left(\frac{x_S - x_T}{\hat{r}_{S,T}} + \frac{x_R - x_T}{\hat{r}_{R,T}}\right) \Delta \hat{x}_T + \left(\frac{y_S - y_T}{\hat{r}_{S,T}} + \frac{y_R - y_T}{\hat{r}_{R,T}}\right) \Delta \hat{y}_T \\
+ \left(\frac{z_S - z_T}{\hat{r}_{S,T}} + \frac{z_R - z_T}{\hat{r}_{R,T}}\right) \Delta \hat{z}_T = \Delta \hat{\rho}_i + \hat{\rho}_i - \hat{D} - \hat{L}_i
\]

where \((\hat{x}_T,\hat{y}_T,\hat{z}_T)\) is the approximate coordinate at which the iterative calculation of the detection target \( T \) starts,

\[
\hat{r}_{S,T} = \sqrt{(x_S - \hat{x}_T)^2 + (y_S - \hat{y}_T)^2 + (z_S - \hat{z}_T)^2}
\]

is the calculated distance from the satellite \( S \) to the target \( T \), and

\[
\hat{r}_{R,T} = \sqrt{(x_R - \hat{x}_T)^2 + (y_R - \hat{y}_T)^2 + (z_R - \hat{z}_T)^2}
\]

is the calculated distance from the detection receiver \( R \) to the target \( T \). The left part represents the residuals of the single-difference pseudo-range of the direct and reflected signal, in which \( \Delta \rho_i \) is the pseudorange difference of the satellite, \( \hat{\rho}_i \) is the estimated distance between satellite \( i \) and the receiver, \( \hat{D} \) is the estimated distance between the target and the receiver, and \( \hat{L}_i \) is the estimated distance between the satellites and target.

On this basis, by measuring the Doppler frequency shift of the reflected signal and the direct signal, the pseudorange changing rate difference \( \Delta \hat{\rho}_i \) between the two can be obtained, and the observation equation about the three-dimensional velocity \((\hat{x}_T,\hat{y}_T,\hat{z}_T)\) of the target \( T \) can be constructed in the same way:

\[
\sqrt{(x_S - \hat{x}_T)^2 + (y_S - \hat{y}_T)^2 + (z_S - \hat{z}_T)^2} \\
+ \sqrt{(x_R - \hat{x}_T)^2 + (y_R - \hat{y}_T)^2 + (z_R - \hat{z}_T)^2} = \Delta \hat{\rho}_i + \hat{\rho}_i
\]

Similarity, the linear form of equation (5) is

\[
\left(\frac{x_S - \hat{x}_T}{\hat{r}_{S,T}} + \frac{x_R - \hat{x}_T}{\hat{r}_{R,T}}\right) \Delta \hat{x}_T + \left(\frac{y_S - \hat{y}_T}{\hat{r}_{S,T}} + \frac{y_R - \hat{y}_T}{\hat{r}_{R,T}}\right) \Delta \hat{y}_T \\
+ \left(\frac{z_S - \hat{z}_T}{\hat{r}_{S,T}} + \frac{z_R - \hat{z}_T}{\hat{r}_{R,T}}\right) \Delta \hat{z}_T = \Delta \hat{\rho}_i + \hat{\rho}_i - \hat{D} - \hat{L}_i
\]
the target. The calculation for \( \hat{L}_2 \) and \( \hat{D} \) is similar with that for \( \hat{p}_1 \).

Equation (4) and Equation (6) can be solved together, and the matrix form is denoted as

\[
G\Delta x = b
\]  

(7)

where the coefficient matrix \( G \) is:

\[
G = \begin{bmatrix}
\frac{x_s - \hat{x}_T}{r_{s,T}} & \frac{x_r - \hat{x}_T}{r_{r,T}} & \frac{y_s - \hat{y}_T}{r_{s,T}} & \frac{y_r - \hat{y}_T}{r_{r,T}} & \frac{z_s - \hat{z}_T}{r_{s,T}} & \frac{z_r - \hat{z}_T}{r_{r,T}} \\
\frac{x_s - \hat{x}_T}{r_{s,T}} & \frac{x_r - \hat{x}_T}{r_{r,T}} & \frac{y_s - \hat{y}_T}{r_{s,T}} & \frac{y_r - \hat{y}_T}{r_{r,T}} & \frac{z_s - \hat{z}_T}{r_{s,T}} & \frac{z_r - \hat{z}_T}{r_{r,T}} \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\]  

(8)

The unknown vector \( \Delta x \) of the target's position and velocity is

\[
\Delta x = \begin{bmatrix}
\Delta x_T \\
\Delta y_T \\
\Delta z_T \\
\Delta \dot{x}_T \\
\Delta \dot{y}_T \\
\Delta \dot{z}_T
\end{bmatrix}
\]  

(9)

and the measurement vector \( b \) is

\[
b = \begin{bmatrix}
\Delta \rho_1 + \hat{\rho}_1 - \hat{D} - \hat{L}_1 \\
\Delta \rho_2 + \hat{\rho}_2 - \hat{D} - \hat{L}_2 \\
\vdots \\
\Delta \rho_n + \hat{\rho}_n - \hat{D} - \hat{L}_n \\
\Delta \dot{\rho}_1 + \hat{\dot{\rho}}_1 - \hat{\dot{D}} - \hat{\dot{L}}_1 \\
\Delta \dot{\rho}_2 + \hat{\dot{\rho}}_2 - \hat{\dot{D}} - \hat{\dot{L}}_2 \\
\vdots \\
\Delta \dot{\rho}_n + \hat{\dot{\rho}}_n - \hat{\dot{D}} - \hat{\dot{L}}_n
\end{bmatrix}
\]  

(10)

The unknown vector \( \Delta x \) can be solved by the Least-squares (LS) algorithm as follows:

\[
\Delta x = (G^T G)^{-1} G^T b
\]  

(11)

When the number of GNSS satellites opportunistic radiators is greater than 4, and the hyperboloid observation equations are over-determined, the weighted least squares (WLS) algorithm can be used to solve the problem. At this time, equation (11) has the following form:

\[
\Delta x = (G^T C G)^{-1} G^T C b
\]  

(12)

where \( C = W^T \), and \( W \) is a diagonal weight matrix composed of the weights of the pseudorange difference observations \( \Delta \rho_i (i = 1, 2, \cdots, n) \) and pseudorange difference rate observations \( \Delta \dot{\rho}_i (i = 1, 2, \cdots, n) \) of each hyperboloid, and it has

\[
W = \text{diag}(W_1, W_2, \cdots, W_n, \omega_1, \omega_2, \cdots, \omega_n)
\]  

(13)

The weights \( W_i \) and \( \omega_i \) can be the reciprocals of \( \sigma_i \) and \( \sigma'_i \), respectively, where \( \sigma_i \) is the standard deviation of the satellite
pseudorange difference measurement error, and $\sigma'_i$ is the standard deviation of the satellite pseudorange difference rate measurement error. That is:

$$
\begin{align*}
W_i &= \frac{1}{\sigma_i} \\
\omega_i &= \frac{1}{\sigma'_i}
\end{align*}
$$

(14)

The values of $\sigma_i$ and $\sigma'_i$ can be comprehensively determined by the carrier-to-noise ratio and altitude angle of the signal [27].

Finally, the above hyperboloid observation equations can be further integrated with the detection target motion state model (such as static, uniform motion, uniform acceleration motion model, etc.), and use a Kalman filter or other dynamic filters to optimise the solution.

4 | MULTI-TARGET CONSISTENCY CHECKING

This section describes the multi-target problem in GNSS-R passive detection. To solve this problem, the consistency checking theory is introduced. Combined with the TDOA observation equations, a test quantity based on the pseudorange difference residual is constructed, and its corresponding fast detection algorithm is proposed.

4.1 | Multi-target problem description

When performing GNSS-R altimetry of the sea surface or detecting a single space target, the above-mentioned TDOA model can be better applied. However, when there are multiple detection targets in space, the problem of cross interference appears.

Suppose that at a certain observation moment, the number of space targets within the detection range of the receiver is $m$, and the number of GNSS satellite radiation sources is $n$. Then, each GNSS satellite may illuminate multiple space targets and form multiple reflected signals. At this time, the detection receiver will receive at most $m \times n$ effective reflection signals at the same time, as shown in Figure 3 (the signals of the same colour indicate that they are from the same GNSS satellite). For each GNSS satellite, the maximum $m$ reflection signals may be generated, and they have the same PRN code. Therefore, when the detection receiver does not use a multi-array or phased array antenna for scanning and tracking, and does not have a function of angle measurement, it will be difficult to distinguish which group of reflected signals are from a same target and which group of reflected signals are from another. This phenomenon of multiple GNSS reflected signals limits the multi-target location capability of the detection system.

4.2 | Multi-target identify based on consistency checking

4.2.1 | Construction of the detection quantity

The consistency checking technology has gradually become one of the standard features of GNSS receivers, which includes many consumer-grade terminals. Receiver Autonomous Integrity Monitoring (RAIM) and Random Sample Consensus (RANSAC) are the two most popular consistency checking methods for GNSS satellites, and they are actually the application of fault detection and elimination theory (FDE) in GNSS field [28–30]. The principle of consistency checking is that NLOS and multipath-contaminated measurements produce a less consistent position solution than clean direct-LOS measurements. In other words, if position solutions are computed using combinations of signals from different satellites, those obtained using only the multipath-free signals should be in greater agreement than those that include NLOS and multipath-contaminated measurements [31, 32]. Thus the fault measurements can be evaluated and a more accurate and reliable position solution can be obtained.

The consistency checking theory can also be used to detect and distinguish multiple targets. First, we can make the hypothetical combinations of the effective reflection signals from the targets, and construct the TDOA equations. Then, the test quantity corresponding to the equations can be calculated and tested, and the correct combination of the reflection signals can be determined by comparison.

Referring to the RAIM algorithm, the pseudorange difference residual vector $\Delta \mathbf{b}$ of the hyperboloid equations can be used to construct the consistency checking quantity. $\Delta \mathbf{b}$ is obtained by subtracting the calculated pseudorange difference value $\mathbf{b}$ after positioning from the actual measured pseudorange difference value $\mathbf{b}$ [33]:

![Figure 3](image-url)
\[ \Delta b = b - \hat{b} \]  

The constructed SSE test quantity \( \varepsilon_{\text{SSE}} \) of the pseudorange residual difference \( \Delta b \) is

\[ \varepsilon_{\text{SSE}} = \Delta b^T \Delta b \]  

If the WLS solution is used, the Weighted Sum Squares Error (WSSE) detection quantity can be further constructed as [34].

\[ \varepsilon_{\text{WSSE}} = (W\Delta b)^T (W\Delta b) = \Delta b^T C \Delta b \]  

Since the solution of the unknown vector \( \Delta x \) is given in equation (12), the residual vector \( \Delta b \) can be directly written as [33].

\[ \Delta b = b - G\Delta x = b - G(G^T CG)^{-1} G^T C b = Sb \]  

where \( S \) is the conversion matrix, and it has

\[ S = I - G(G^T CG)^{-1} G^T C \]  

Equation (18) and Equation (19) show that the coefficient matrix \( G \) can be used to directly convert the pre-positioning pseudorange difference residuals into post-positioning residuals without solving the hyperboloid equations, thereby reducing the amount of calculation.

4.2.2 Detection algorithm flow

The values of the test quantity \( \varepsilon_{\text{SSE}} \) and \( \varepsilon_{\text{WSSE}} \) indicate the degrees of consistency between the pseudorange difference measurements. As shown in Figure 4, for the TDOA location model, when the measurements are accurate, the hyperboloid defined by the observation equations will intersect at a point in space, and the value of \( \Delta b \) is zero at this time; when there is error in the measurements (i.e., poor consistency), the intersection area of the hyperboloid will become larger, and the value of \( \Delta b \) will increase. \( \varepsilon_{\text{SSE}} \) and \( \varepsilon_{\text{WSSE}} \) indicate the size of this intersection area, so we can perform TDOA solution by all possible combinations of direct and reflected signals, and select the combination with the smallest value of \( \varepsilon_{\text{SSE}} \) or \( \varepsilon_{\text{WSSE}} \) as the correct matching combination.

Obviously, although this approach is effective, it brings a larger amount of calculation. Therefore, we can refer to RAIM and define a detection threshold. Assuming that the errors of the pseudorange difference measurements are independent of each other and have a Gaussian normal distribution with a mean value of zero, since there are four independent and effective governing equations (the rest are redundant observations), \( \varepsilon_{\text{SSE}} \) and \( \varepsilon_{\text{WSSE}} \) conform to a \( \chi^2 \) distribution with a DOF (Degrees of Freedom) of \( N - 4 \) (\( N \) is the number of the GNSS satellite opportunistic radiation sources) [33, 35]. Once the probability distribution of the detection quantity \( \varepsilon_{\text{SSE}} \) or \( \varepsilon_{\text{WSSE}} \) is obtained, the corresponding threshold value \( T_{\text{SSE}} \) or \( T_{\text{WSSE}} \) can be determined according to the given False Alarm rate (FA). For example, assuming that there are seven GNSS satellite reflection signals from a same space target, then \( \varepsilon_{\text{SSE}} \) and \( \varepsilon_{\text{WSSE}} \) conform to a \( \chi^2 \) distribution with a DOF of 3, as shown in Figure 5.

The lower right corner of Figure 6 shows the probability that \( \varepsilon_{\text{SSE}} \) or \( \varepsilon_{\text{WSSE}} \) is greater than 11.3448 times \( \sigma_{\Delta \rho} \) when the GNSS reflected signals are correctly matched, where \( \sigma_{\Delta \rho} \) is the Mean Square Error (MSE) of the pseudorange difference measurement. In the same way, the threshold corresponding to other DOFs can be obtained. Since the MSE of pseudorange difference measurement is difficult to estimate, the threshold \( T_{\text{SSE}} \) and \( T_{\text{WSSE}} \) can usually be set based on experience.

When the test quantity is within the threshold \( T_{\text{SSE}} \) or \( T_{\text{WSSE}} \), it is considered that all the received signals are correctly matched; otherwise, they are incorrectly matched and the adjustment should be performed. A fast algorithm is to calculate the ratio of the residual vector \( \Delta b \) to the corresponding element \( z_i \) in the conversion matrix \( S \) (denote as \( \frac{\Delta b}{z_i} \)), and consider that the reflected signal corresponding to the largest \( \frac{\Delta b}{z_i} \) value is incorrectly matched, so as to replace it [36, 37]. Among them, \( z_i \) represents the square (or the weighted

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**Figure 4** Pseudorange difference residual of time difference of arrival
square) of the $i$-th element of the vector $\Delta \mathbf{b}$, and $S_i$ represents the $i$-th row and column element of the matrix $\mathbf{S}$. In summary, the GNSS-R multi-target detection and identify algorithm flow is shown in Figure 6.

5 | SIMULATION AND ANALYSIS

In order to verify the feasibility and effectiveness of the method, the simulation is performed in this section. The simulation result shows that by comparing and judging the consistency of different GNSS received signal combinations, the method can effectively detect and distinguish different spatial targets with a good spatial resolution.

\[
\sigma_{\text{DDL}} = \begin{cases} 
\frac{B_L}{C} D \left( 1 + \frac{2}{(2-D)T_{\text{coh}^*} C N_0} \right), \\
\frac{B_L}{C} \left( \frac{1}{B_{\text{rf}}T_C} + \frac{B_{\text{rf}}T_C}{\pi - 1} \right) \left( D - \frac{1}{B_{\text{rf}}T_C} \right)^2 \left( 1 + \frac{2}{(2-D)T_{\text{coh}^*} C N_0} \right), \\
\frac{B_L}{C} \left( 1 + \frac{1}{T_{\text{coh}^*} C N_0} \right), \\
\frac{B_L}{2 C} \left( 1 + \frac{1}{B_{\text{rf}}T_C} \right) \frac{1}{C N_0}, \end{cases}
\]

\[D \geq \frac{\pi}{B_{\text{rf}}T_C} \]

\[\frac{1}{B_{\text{rf}}T_C} < D < \frac{\pi}{B_{\text{rf}}T_C} \]

\[D \leq \frac{1}{B_{\text{rf}}T_C} \]

where $B_{\text{rf}}$ is the bandwidth of the RF front-end, $B_L$ is the bandwidth of the loop noise, $T_C$ is the pseudo code width of GNSS satellites (e.g. the C/A code width is $\frac{1023}{1024} \text{ns}$, and $T_{\text{coh}}$ is the coherent integration time.) For a typical geodetic receiver, $B_L$ can be set to 0.1 Hz, and can be set to 17 [33]. In the case of limiting the coherent integral frequency error loss (caused by the change of the signal Doppler frequency), $T_{\text{coh}}$ can be performed for a few seconds at most, here it is taken as 0.7s. Thus, the change of $\sigma_{\text{DDL}}$ with the carrier-to-noise ratio ($C/N_0$) at different early-late correlator interval $D$ can be obtained, as shown in Figure 7.

Similarly, for a typical commercial geodetic receiver, the interval of the early-late correlator can be set to $D = 1/8$ chip, and the $C/N_0$ output from the receiver system to the baseband processing loop is about 9.7db Hz [40]. Therefore, take the value of $\sigma_{\text{DDL}}$ according to Figure 7, and convert and express it as a distance (unit: m), there is

\[
\sigma_{\text{DDL}} = 0.029 \times 293m \left( \text{length of the } \frac{C}{A} \text{ chip} \right) = 7.9m
\]

### 5.1 GNSS reflected signal measurement error

Assuming that the GNSS-R detection receiver adopts the currently widely used configuration of auxiliary code-loop with the carrier-loop. At this time, the carrier-loop can help the code-loop to eliminate the main dynamic stress effects such as target motion and receiver reference frequency drift, and the code-loop measurement error of the receiver is mainly caused by the code phase jitter (thermal noise), which can be estimated by the following formula [38, 39]:

\[\sigma_{\text{DDL}} = 0.029 \times 293m \left( \text{length of the } \frac{C}{A} \text{ chip} \right) = 7.9m\]
commercial GNSS receiver, and the MSE of the direct signal pseudorange measurement is known to be about $\sigma = 2m$. On this basis, two stationary space targets A and B separated by a certain distance are given, and the GNSS reflected signal pseudorange measurements are generated with an MSE of $\sigma_{DDL} = 7.9m$.

In order to verify the spatial resolution of the multi-target detection algorithm, the distance between targets A and B is set to 250, 200, 150, 100 and 50 m in turn from far to near. The positions of the GNSS Receiver are obtained by the mean value of the output from the receiver. The satellite positions are calculated from the broadcast ephemeris recorded by the GNSS receiver. The positions of the target are set in the local navigation frame (ENU) with the origin point at the position of the GNSS receiver. The true position of target A was set to be $\mathbf{U}_0 = [50 \ 0 \ 0]^T$, and target B was set to $\mathbf{U}_i = [50 + 50i \ 0 \ 0]^T$, where $i = \{1, 2, 3, 4\}$ for different target distances, respectively. Finally, the $\varepsilon_{SSE}$ of the pseudorange difference after solution when the reflected signals are matched correctly and incorrectly are calculated and presented, respectively, as shown in Figure 8.

It can be seen from Figure 8 that when the reflected signals are judged to be matched correctly, the value of $\varepsilon_{SSE}$ is also significantly smaller, and it will significantly different from the value of $\varepsilon_{SSE}$ when the reflected signals are matched incorrectly, which shows that the consistency checking algorithm can effectively distinguish the reflected signals from different spatial targets.

According to the different distances between the targets, the detection success rates are shown in Figure 9. It presents the spatial resolution ability of the algorithm to a certain extent.

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**Figure 6** Multi-target detection algorithm of Global Navigation Satellite System Reflectometer

**Figure 7** Thermal noise variance of code-loop

In the simulation, an equal-weight model is used for the direct signals and reflected signals of GNSS satellites, respectively.

### 5.2 Multi-target detection and location

The simulation is carried out by combining the actual data output and simulation data generation. Raw observations such as satellite broadcast ephemeris and C/A code pseudorange measurements are actually output at a frequency of 1 Hz by a
It can be seen from Figure 9 that when the distance between the spatial targets in the detection range increases, the detection success rate of the method will increase accordingly. This is also consistent with our intuitive experience. Specifically, when the two space targets A and B are separated by 50, 100, 150, 200, and 250 m in sequence, the detection success rate of the method is 67.25%, 87.50%, 95.75%, 99.25%, and 99.75%, respectively, which shows a good spatial resolution.

The position and velocity for two static targets in the local navigation frame (ENU) with different distance from 50 and 200 m are also simulated, as shown in Figures 10 and 11. The estimated positions for two targets with a distance of 50 m are partly overlapped, while the estimated positions can be clearly distinguished for the 200 m case, which are consistent with the success rate obtained by multi-target detection. The positioning accuracy can be increased depends on the number of the satellites in the observation. We compare the positioning performance of the target using GPS and multi-constellation (GPS and BeiDou), respectively. The positioning error for north, east, and up components in GPS only simulation are 15.4306, 4.6946, 12.9653 m, respectively, while the positioning accuracy for multi-constellation simulation was increased by 28.7%, 6.2%, 38.1%, respectively. The positioning result for two targets with the distance at 200 m in a multi-constellation simulation can be seen in Figure 11. The velocity for the static target in the simulation was shown in Figure 12, and the result was consistent with the static assumptions with the simulation condition where the pseudorange rate noise is 0.05 m.
6 | CONCLUSIONS

The use of GNSS reflected signals to carry out passive detection of space targets is an emerging technical field. Thanks to the abundant GNSS satellite resources and the pseudo-code spread spectrum technique with precise ranging function, it can use a new passive detection scheme different from the traditional PCL, which has its own unique advantages.

However, the use of GNSS-R for space target detection also has some significant challenges. One of the biggest problems is how to simultaneously locate and distinguish multiple targets within the detection range. To solve the problem, we construct a hyperboloid observation equation based on the pseudorange difference between the direct signal and the reflected signal of GNSS, which uses a Time Difference of Arrival (TDOA) location model. Through the differential processing of the direct signal and the reflected signal, the system deviations such as the GNSS satellite orbit error, the satellite atomic clock error, and the detection receiver clock error can be eliminated, thus to improve the accuracy of the detection and location. On this basis, it is proposed to use the consistency checking theory to effectively detect and distinguish different targets in an algorithmic manner, thereby reducing hardware requirements for the detection equipment. In the end, the simulation is carried out by combining the actual data output and the simulation data generation. The result shows that by comparing and judging the consistency of different GNSS received signal combinations, the method can effectively detect and distinguish different spatial targets with a good spatial resolution. Specifically, the target detection and location accuracy based on the TDOA method can reach tens of metres, and when the two space targets A and B are separated by 50, 100, 150, 200, and 250 m in sequence, the detection success rate of the method is 67.25%, 87.50%, 95.75%, 99.25%, and 99.75%, respectively. Thus, a feasible
Figure 12 The velocity for the target in the simulation

technical approach which does not increase in the hardware cost is provided for solving the multi-target identify problem in GNSS-R space target passive detection.

ACKNOWLEDGEMENT

This work was supported by the Young Talent Supporting Programme of the China Association for Science and Technology (Grant Number: 2019QNRC001), and the Natural Science Foundation of China (Grant Numbers: 42074044, 61701481).

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