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A COMBINED GPS/BEIDOU SIGNAL ACQUISITION ALGORITHM FOR A MULTI-CONSTELLATION GNSS SOFTWARE RECEIVER

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Abstract. *Signal processing in multi-constellation receivers is increasingly important for the compatibility and interoperability of global navigation satellite system (GNSS). This paper proposes a novel acquisition algorithm to combine both the GPS L1 and BeiDou B1 signals together using the combined replica codes based acquisition module in a dual-constellation GNSS software receiver. The proposed algorithm can detect multiple visible satellites and determine their corresponding coarse values of code phase and carrier frequency simultaneously, so as to improve the efficiency of signal acquisition process for GPS L1 and BeiDou B1 signals. In order to test and demonstrate the performance of the proposed acquisition algorithm, semi-physical simulation tests are carried out with a GNSS signal simulator and a software receiver. The test results show that signal acquisition efficiency can be improved by 21% to 30% depending on different combination numbers, compared with the traditional acquisition approach.*

Keywords: GNSS navigation, Software receiver, Signal acquisition, Multi-constellation

1. **Introduction.** Global navigation satellite system (GNSS) receives more and more attention by researchers in recent years due to its comprehensive applications in many areas such as aviation, transport and agriculture. For the next decade, multi-constellation scheme is becoming a trend of future navigation solution, and the compatibility and interoperability of next generation GNSS will become the main issues of future multi-constellation receiver. Moreover, it is still hoped that multi-constellation system will help to offer the GNSS users a better positioning or navigation service. In recent years, many international receiver providers have rolled out dual system receivers. For instance, NovAtel provides GPS/GLONASS dual-frequency receivers in the past two years. Meanwhile, several Chinese producers including OLinkStar released BeiDou/GPS compatible navigation module. Compared with receivers based on one GNSS constellation, multi-constellation receivers have many advantages as follows:

(a) The position accuracy can be improved due to decrease of dilution of precision (DOP);
(b) More visible satellites can be searched in complex environments such as city canyons or forests;
(c) More measurements can be got to detect the abnormal problem in the receiver system.

Although there are clearly many benefits of expected extra satellites and their signals in terms of availability, continuity, accuracy, efficiency and integrity, challenges still exist, for example, multi-constellation receivers need to solve the problem of how to process signals coming from different sources, such as GPS and BeiDou satellites, so as to accomplish positioning and navigation functions.

GNSS software receiver provides full access to base band signals processing inside the receiver, and the first key step in it is signal acquisition implementation that aims to determine all visible satellites and the phase/frequency values of the corresponding signals [1]. In order to reduce the computational load, the conventional acquisition algorithm usually exploits a fast Fourier transform (FFT) method to implement the correlation operation in the frequency domain [2,3]. In order to improve the sensitivity of acquisition algorithm, several different combining techniques such as non-coherent and coherent have been employed for signal acquisition [4-8]. It is noted that the effect of navigation data bit transitions has to be considered when choosing the length of coherent integration time. To solve the issue, the differentially-coherent instead of coherent combining of integration results was proposed for the acquisition of complex code division multiple access (CDMA) signals [9-11]. Although several works mentioned above have investigated new methods to improve signal acquisition performance of GNSS receivers, these acquisition techniques can only determine one satellite existing or not, nor can search multiple satellites. In order to improve the efficiency of signal acquisition, this paper proposes a novel acquisition algorithm based on differentially-coherent technique which can process GPS and BeiDou signals together and determine the visible satellites simultaneously for a multi-constellation GNSS software receiver.

Aside from this introductory section, the rest of this paper is composed of 3 sections. In Section 2 two different multi-constellation receiver architectures are analyzed, and then the combined GPS/BeiDou signal acquisition algorithm is proposed. Experimental results are given in Section 3. The paper finishes with conclusions in Section 4.

2. Combined GPS/BeiDou L1/B1 Signal Acquisition Algorithm.

2.1. Combined GPS/BeiDou receiver architecture. When receivers demodulate signals with not only one frequency-band or even not the same constellation, taking GPS L1 and BeiDou B1 for example, two solutions can be adopted. One solution is to keep each system work independently to avoid interfere with each other. In this strategy, each system can operate and provide navigation solution individually, but the nature correlations between the signals and receiver have been ignored. The other solution is to exploit a multi-constellation strategy to process multiple satellites' signals of different frequencies and constellations, whose architecture can be seen in Figure 1. Combining signals from multiple constellations can provide greater availability and higher reliability than that can be achieved individually.

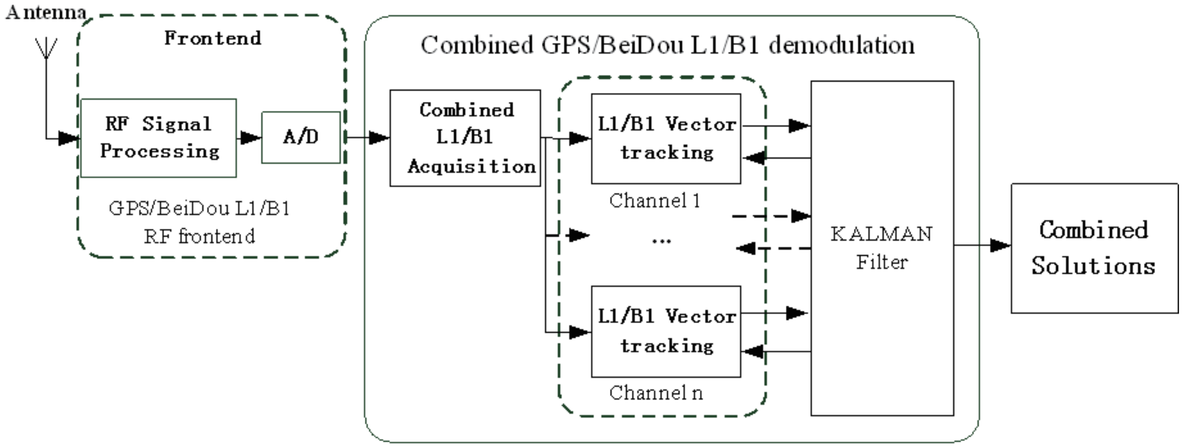

Figure 1. Combined GPS/BeiDou L1/B1 receiver architecture

Since BeiDou B1 has shared many features such as signal structure in common with GPS L1, this paper provides a combined GPS/BeiDou L1/B1 acquisition algorithm in software receiver. In the described combined GPS/BeiDou software receiver architecture that is shown in Figure 1, the acquisition of GPS and BeiDou signals is combined by the proposed acquisition algorithm. After acquisition operation, a vector tracking loop is used to combine the tracking of both GPS and BeiDou signals and the navigation calculation of receiver is completed in the Kalman filter [12].

2.2. **Combined GPS/BeiDou L1/B1 signal acquisition algorithm.** Signal acquisition is a two-dimension search process. The main purpose of acquisition is to determine the visible satellites and coarse values of carrier frequency and code phase of the satellite signals by correlating the GNSS intermediate frequency (IF) signal with the receiver generated signal. In order to determine the visible satellite, a local PRN code has to be generated, when the replica code is perfectly aligned with the incoming code, the code phase has been determined. Similarly, it is necessary to know the frequency to be able to generate a local carrier signal, so this signal can be used to remove the incoming carrier from the received signal. Since the BeiDou B1 signal is the sum of component I (open) and Q (authorization), only the signal acquisition of I component is considered due to that the code demodulation of Q component requires an authorization.

The first step toward the combined signals acquisition goal is to generate and save the GPS and BeiDou replica codes. The generation of GPS PRN code is normal for designing GPS software receivers capable of acquiring and tracking. With 32 different PRN sequences generating, all satellites PRN sequence originating from GPS are created. The BeiDou satellites are differentiated by the 37 different PRN codes. The BeiDou B1 ranging code is a subset of the Gold code family, and is generated by means of Modulo-2 addition of G1 and G2 sequences. Each satellite has a unique ranging code with a different phase shift of G2 sequence. The generation and saving of all possible PRN sequences aim to directly load and produce replica code offline instead of generating every time in proposed acquisition algorithm. Since the BeiDou B1 ranging code for civilian use has a chipping rate of 2.046 Mbps, so the code sequence in one code period which has 2046 chips can be expressed as C_{BeiDou_I}.

For the purpose of realizing a combined GPS/BeiDou L1/B1 acquisition function, the combined GPS/BeiDou code sequences for In-phase (I) component has been designed as follows:

$$C_{Icom}(n) = \sum_{i=1}^{N} C_{GPS}^{i}(sv) + \sum_{i=1}^{N} C_{BeiDou\_I}^{i}(sv) \tag{1}$$

where N is the number of combination, sv denotes the combined satellite prn, and C_{GPS} is the replica pseudo-random noise code of GPS. Moreover, when the receiver is placed outside where the signal strength is good, N can be set to 2, that is, there are two GPS satellites and two BeiDou satellites combining together. On the contrary, N should be set to 1, that is, only one satellite in each constellation is combined.

As the combined code sequences have been generated, the proposed acquisition approach will be explained. Firstly, if the satellite signals collected are In-phase and Quadrature signals, the carrier signal of input signal can be expressed as:

$$\mathrm{S}_c(t) = A(t)e^{j2\pi f_c t} \tag{2}$$

where, $A(t)$ is the amplitude and f_c is the carrier frequency of received signal. If this signal is delayed by time τ, the delayed signal can be expressed as:

$$\mathrm{S}_c(t-\tau) = A(t-\tau)e^{j2\pi f_c (t-\tau)} \tag{3}$$

Secondly, let $S_c(t)$ multiplied by the complex conjugate of $S_c(t-\tau)$ generate a mix signal $S_m(t)$, which is created as follows:

$$S_m(t) = S_c(t)S_c(t-\tau)^* = A(t)A(t-\tau)e^{j2\pi f_c \tau} \tag{4}$$

As the above equation shown, the carrier components of the IF signal have been removed by multiplying operation, so that the mix signal does not have any frequency component. Therefore, only the offset or phase of the ranging code needs to be found.

Thirdly, in order to search the phases of multiple ranging codes simultaneously, the mix signal $S_m(t)$ is correlated with the mix combined code sequence which is generated by multiplying the combined code sequence with itself delayed by a τ time.

Finally, when one PRN code is aligned, the output of correlation will show a distinct peak in magnitude, and the peak location is corresponding to the visible satellite code phase. Once the code phase is found, it is easy to detect the carrier frequency by FFT operation with several milliseconds signal.

The above approach can only be applied to the complex signals. Since the collected satellite IF signal in our laboratory is real format, this paper mainly focused on research of the real signal acquisition algorithm.

Because the BeiDou B1 signal with quadrature phase shift keying (QPSK) modulation can be regarded as two binary phase shift keying (BPSK) signals that respectively modulated on In-phase and Quadrature component added, here, one system is emphasized to analyze the theory and procedure of the combined GPS/BeiDou parallel acquisition approach for the collected real signal. Taking the BeiDou In-phase component signal as example firstly, the real input signal model is:

$$S_I^i(t) = A_C D_I^i(t) C_I^i(t-\tau_I)\cos[2\pi f_c t + \phi_I^i] \tag{5}$$

where, A_C is the amplitude of received BeiDou B1 signal, $D(t)$ is the navigation message containing the ephemerides and other navigation parameters, and ϕ_I is initial phase of the received carrier in In-phase component. Let the above signal be delayed by τ, and the result is:

$$S_I^i(t-\tau) = A_C D_I^i(t-\tau) C_I^i(t-\tau_I-\tau)\cos[2\pi f_c(t-\tau) + \phi_I^i] \tag{6}$$

Then the mix signal can be created by multiplying $S_I^i(t)$ and $S_I^i(t-\tau)$ as follows:

$$\begin{aligned} S_{I\_mix}(t) &= S_I(t)S_I(t-\tau) \\ &= A_C^2 D_{I\_mix} C_{I\_mix}\cos[2\pi f_c t + \phi_I]\cos[2\pi f_c(t-\tau)+\phi_I] \\ &= \tfrac{A_C^2 D_{I\_mix} C_{I\_mix}}{2}\{\cos(4\pi f_c t - 2\pi f_c\tau + 2\phi_I) + \cos(2\pi f_c \tau)\} \end{aligned} \tag{7}$$

Equation (7) is made up of two parts: a high frequency term $\cos(4\pi f_c t - 2\pi f_c \tau + 2\phi_I^i)$ and a direct current term $\cos(2\pi f_c\tau)$. Only the dc term can be used to find the phase of the ranging code. Strictly speaking, the delay time τ cannot be set at random. To keep the delay time just being a complete carrier cycle, we must make the dc term close to +1. So one choose a delay time satisfying that:

$$\begin{aligned} &\cos(2\pi f_c\tau) = 1 \Rightarrow 2\pi f_c \tau = 2n\pi \\ &\Rightarrow \tau = \tfrac{n}{f_c}(s) = \tfrac{n}{f_c} f_s \ (\textit{sample points}) \ (n = 1, 2, 3, \cdots) \end{aligned} \tag{8}$$

Next, in order to complete parallel acquisition operation for multiple satellite signals, the combined code sequences for In-phase component need to be delayed by τ and then be multiplied with the combined code sequences. The mix combined code sequences can be given as follows:

$$C_{Imix}(n) = C_{Icom}(n) \cdot C_{Icom}(n-\tau) \tag{9}$$

After the mix combined code generation, the following correlation between the mix combined code and In-phase mix signal will be performed. In order to improve efficiency of correlation operation, the correlation of the mix combined code and mix signal in the time domain can be transformed to multiplication calculation in the frequency domain. An efficient tool for that is the fast Fourier transform. So the correlation results in the frequency domain are:

$$Z_I(k) = S_{I\_mix}(k) C^*_{Imix}(k) \tag{10}$$

where $S_{I\_mix}(k)$ is the FFT result for $S_{I\_mix}(t)$, $C^*_{Imix}(k)$ is the complex conjugate of the FFT results for $C^*_{Imix}(t)$. When the correlation representation in the frequency domain is computed, the result in time domain can be derived through inverse Fourier transform:

$$Z_I(n) = ifft(Z_I(k)) \tag{11}$$

Since the output from an inverse fast Fourier transform (IFFT) is complex, the output needs to compute the absolute value for the two components. The absolute value of the output of the IFFT represents the correlation between the input and the combined code. The correlation results of I component are then integrated over a period of N samples. If multiple peaks are present in the correlation, the number of peaks is corresponding to the visible satellite number, and the indexes of multiple peaks mark the found code phases of the combined visible satellites. When the combined satellite signal is absent, the correlation results are only made of noises and none peak will appear. From the procedure of combined signals parallel acquisition algorithm, the FFT of correlated signal after multiplying the mix signal needs to be performed only once for multiple combined satellites. Obviously, the more satellites under combination are, the more computational load can be saved in signal acquisition.

3. **Test Setup and Results.** In order to test and verify the performance of proposed combined L1/B1 signal acquisition algorithm, semi-physical simulation tests are carried out. Simulation platform is shown in Figure 2. In order to evaluate the capability and performance of the proposed acquisition algorithm, the GPS and BeiDou IF data is stored in a host computer. In the simulation, PRNs 1∼32 belong to GPS satellites, while PRNs 33∼48 were allocated to BeiDou satellites. There were 5 GPS satellites (PRNs 12, 14, 22, 25 and 31) and 4 BeiDou satellites (36, 41, 43 and 47) that were searched successfully by the proposed approach. The searched visible satellites in the sky at the start of the simulation are shown in Figure 3.

Then, in order to further demonstrate and explain the effectiveness of proposed acquisition algorithm, a combined code sequence is generated by two chosen visible satellites, which contains each GPS and BeiDou satellite. The coherent integration time is chosen

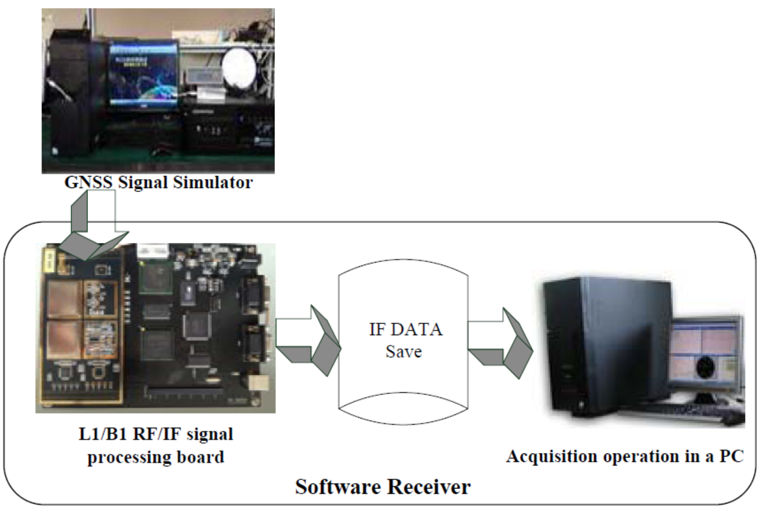

Figure 2. Simulation platform

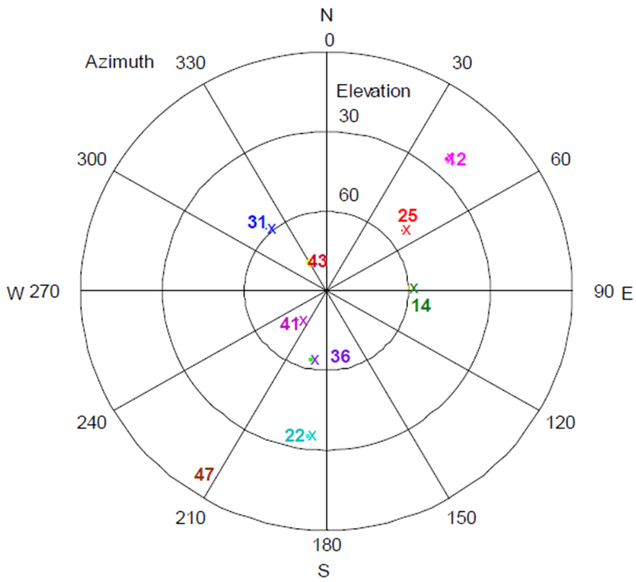

Figure 3. The skyplot of visible satellites

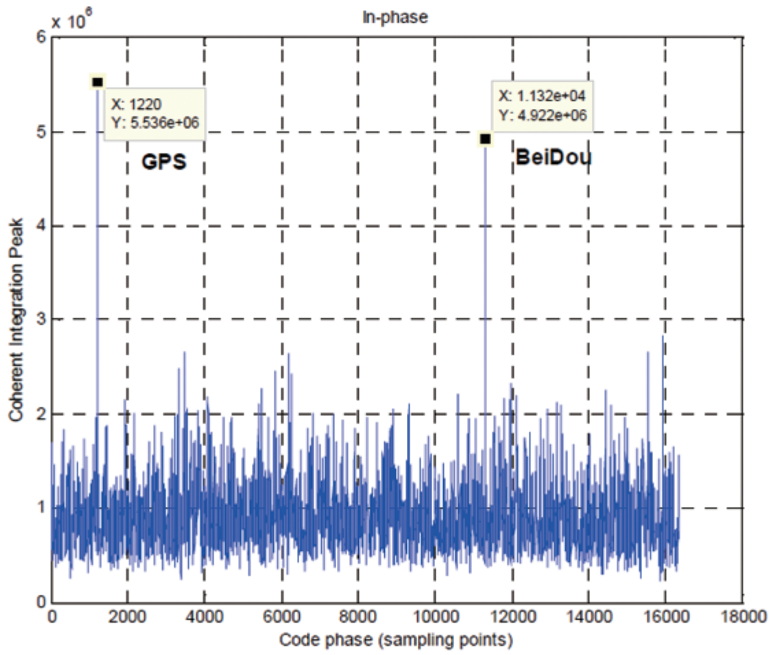

Figure 4. Combined GPS/BeiDou acquisition result using two visible satellites

as 1ms and the combined GPS/BeiDou acquisition result for the two visible satellites is shown in Figure 4. As illustrated in Figure 4, the proposed algorithm can get the code phases of multiple visible satellites according to the corresponding coordinates of correlation integration peaks. However, it is noted that the multiplication operation between incoming signal and delay signal increases noise in the process of combined acquisition. In order to decrease noise of the correlation results, we stack multiple periods of signal together to increase the correlation energy and average down the noise. When the coherent integration time is chosen as 10ms, and the combined code sequence is generated by four visible satellites, the acquisition result is shown in Figure 5. The coherent integration peaks of visible satellites are becoming more obvious by increasing the coherent integration time, which helps to make the proposed algorithm more feasible and stable when multiple satellites are combined to perform the combined acquisition function.

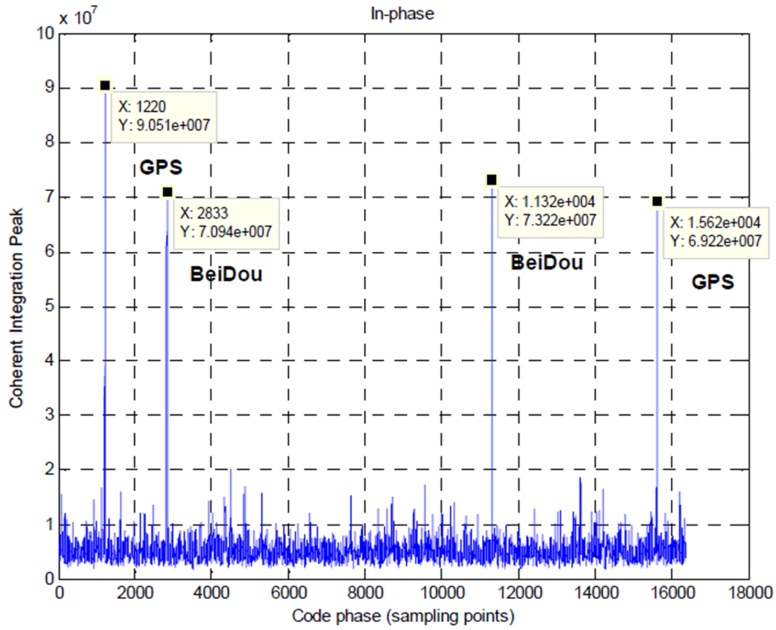

FIGURE 5. Combined GPS/BeiDou acquisition result using four visible satellites

TABLE 1. The execution time of acquisition algorithms

Algorithms \ Satellites sum	1	2	3	4
PFA	2.876s	5.840s	8.563s	10.450s
PCA	1.325s	2.647s	4.012s	5.526s
Proposed algorithm	0.983s	1.851s	3.165s	4.083s

TABLE 2. The computational complexity numerical comparison

Algorithms \ Computation		Multiplications	Sums	Complexity
PFA for GPS		1.071×10^9	1.875×10^9	High
PFA for BeiDou		2.143×10^9	3.750×10^9	High
PCA for GPS		1.113×10^7	1.833×10^7	Medium
PCA for BeiDou		1.636×10^7	2.749×10^7	Medium
Proposed algorithm	**Max**	9.329×10^5	1.735×10^6	Low
	Min	6.710×10^5	1.276×10^6	

Finally, in order to evaluate and compare the cost time of proposed acquisition algorithm with that of the conventional acquisition algorithm, the comparison of execution time of acquisition algorithms for multiple satellites is summarized in Table 1.

As illustrated in Table 1, the cost time needed by the proposed algorithm is obviously less than the parallel frequency search acquisition (PFA) and parallel code phase search acquisition (PCA) methods. Furthermore, the proposed acquisition algorithm can improve efficiency of signal processing by 21% to 30% depending on different combination numbers compared with parallel code phase approach.

The performance of the proposed method in terms of time needed is reduced in two ways: the reduction of search space and high efficiency of FFT module. In order to further analyze the computational complexity of different acquisition methods in Table 1, we provide a numerical example of the computational complexity shown in Table 2.

Considering the probability of the visible satellites in the combination of GPS and BeiDou PRNs, both the best and worst scenarios are calculated. The best scenario is where the combination of non-visible satellites has higher probability; therefore, minimum time is needed due to the high efficiency in exclusion of non-visible satellites. On the other hand, the worst scenario needs maximum time. Table 2 shows that the proposed algorithm needs a fewer multiplications and additions computation than PFA and PCA methods, and it can save lots of search steps in each satellite's code phase and carrier frequency dimensions, which will spend more time by the PFA and PCA methods. So the proposed algorithm can significantly reduce the computational load compared to the other acquisition methods.

4. **Conclusions.** This paper has presented a GPS/BeiDou signal acquisition algorithm based on the differentially-coherent technique for a multi-constellation GNSS software receiver. The main advantage of the proposed algorithm is that multiple satellites' signals can be processed together and multiple visible satellites of GPS and BeiDou can be detected and acquired simultaneously. The experimental results demonstrate that the proposed algorithm can improve the efficiency of signal acquisition. Moreover, the vector tracking algorithm for multi-constellation receivers should be further studied in the future.

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