Performance Analysis of Long-Time Coherent Integral Acquisition Algorithm for Weak GNSS Signals

Faqin Gao$^{1,2}$

$^1$ School of Information Science, Zhejiang Sci-Tech University, Hangzhou, Zhejiang, China
$^2$ State Key Laboratory of Geo-information Engineering, Xi’an, Shanxi, China.
Email: gfqzjlg@126.com

Abstract. Autonomous navigation places an extremely high demand on the acquisition sensitivity of the global navigation satellite system (GNSS) receivers. To increase the efficiency and sensitivity of the acquisition algorithm of GNSS weak signal, we improve the acquisition algorithm named Improved Acquisition Algorithm with Doppler Frequency Compensation (IAADFC) proposed in our previous study. The bottleneck restricting the performance improvement of the IAADFC algorithm is that it is difficult to estimate Doppler frequency and navigation message bit flip estimation in a very weak signal environment. We provide a detailed analysis and comparison among the proposed IAADFC algorithm, non coherent integration (NCI) algorithm. Simulation results demonstrate that our IAADFC acquisition algorithm can effectively realize the acquisition of GNSS signal with a signal-to-noise ratio that down to 15 dB•Hz which is the current most advanced level of signal acquisition.

1. Introduction
The global navigation satellite system (GNSS) is a satellite-based radio navigation system. Many researchers expect that GNSS can also be used in weak signal environments. After examining the present published papers on this topic, the long-time coherent integration method is the preferred method to improve acquisition sensitivity. However, there are many problems that need to be overcome.

First, since the navigation message bit sign transition tends to degrade gains in signal processing, the coherent integration time (CIT) is limited by the navigation message bit length [1]. Some studies have proposed many methods to prolong CIT, but these methods have high computational complexity [2-5]. Second, the complexity of acquisition algorithm will increase rapidly with the increase of CIT [6]. Third, under long-time coherent integration calculation, a large Doppler frequency will produce a large impact on the PRN code rate and will result in a shift of the code phase, which produces a correlating power loss [7].

Square loss has become the major factors that affect the acquisition performance in low SNR environments [8-19]. Therefore, we studied and designed a long CIT acquisition algorithm named IAADFC algorithm in our previous study and relevant achievements have been published in a SCI journal named GPS Solutions in 2018. Based on that achievement. This paper further investigates the long CIT acquisition method to improve both the sensitivity and efficiency of acquisition algorithms.

The rest of this paper is organized as follows. Section 2 analyse the model method of GNSS signal acquisition algorithm. Section 3 simulated IAADFC algorithm and also makes a comparison among the IAADFC algorithm, NCI algorithm and DBZP algorithm. Section 4 discuss about Doppler effect.
on IAADFC algorithm. Finally, Section 5 gives some conclusions and provides some areas for future work.

2. Acquisition Algorithm Modeling

We will improve a long CIT acquisition algorithm we proposed [12] that called improved acquisition algorithm with Doppler frequency compensation (IAADFC) algorithm in this paper, which can estimate the carrier Doppler frequency and the bit sign transition of the navigation message in a low SNR environment [12]. Figure 1 shows the functional structure of the IAADFC algorithm.

![Function Structure of IAADFC Algorithm](image)

**Figure 1. Function Structure of IAADFC Algorithm**

In IAADFC algorithm, Doppler Frequency Estimation Algorithm (DFEA) is designed to estimate the carrier Doppler frequency and Data Bit Sign Transition (DBST) Estimation algorithm is designed to estimate the bit sign transition of the navigation message, which will be Analyzed first as follows.

DFEA algorithm proposed in our former papers can estimate the Doppler frequency [12]. The unknown PRN Code and navigation message data Bit are removed from IGIFS via square operation after DBSP operation. Therefore, the result signal IGIFS only contains carrier signal and noise. When \( \bar{r}_{LN}(n) \) is converted to \( \bar{R}_{LN}(f) \) in frequency domain by FFT calculation, the frequency of each visible satellite signal can be easily to find through searching the maximum value in \( \bar{R}_{LN}(f) \). Obviously, the Doppler frequency can be estimated using DFEA.

![Graphs](image)

(a) ADV without DBST  (b) ADV with DBST correcting

**Figure 2. The Impact of DBST Correcting**

The basic idea of data bit sign transition (DBST) estimation for a navigation message is described as follows. Assume that the data length of IGIFS used in the DBST estimation is \( T_I = (KL + t) \), where
$t$ is the time length of the data block, specifically, the number of PRN code periods in a data block. By selecting the $T_i$ ms data, we can obtain $(T_i - t + 1)$ correlation results, which reflect the correlation between IGIFS and local signal. Because the data bit sign transition will lead the correlation reduced significantly. Therefore, we can get the serial number of data block where DBST occurs by searching the minimum value in $(T_i - t + 1)$ correlation results. Therefore, the proposed DBST method \cite{12} can detect DBST. The impact of DBST is removing from IGIFS data by multiplying the corresponding data by -1 after each DBST points. Then, the acquisition results after DBST correction are obtained, some of which are shown in Figure 2.

3. Simulation Results

Simulation was done based on the GPS software receiver platform SoftGNSS V3.0, developed by Darius Plausinaitis and Dennis M. Akos. et al \cite{10}. We define the acquisition decision variable (ADV) as the ratio of the maximum value to the second maximum of the coherent integration output. The IGIFS used in our simulation comes from sampling data of a real GPS IF signal. Its frequency is 9.548MHz and the search range of the Doppler frequency is $7kH\tilde{z}$.

Taking computational complexity and sensitivity as the measurements, eight typical satellite signal acquisition methods are analyzed \cite{9} and the DBZP algorithm is considered to have the best acquisition performance in a weak-signal environment among them. In terms of the rapid acquisition of a weak signal, non-coherent integration (NCI) is preferred because of its low complexity. For the above reasons, we will demonstrate that our IAADFC algorithm can detect a weaker signal than that of the NCI or DBZP algorithm can and it run fast than DBZP algorithm.

For Doppler frequency estimation algorithm and IAADFC algorithm, some simulation and experimental results have been published in the journal GPS Solutions, as detailed in the references Gao and Xia (2018) \cite{12}. Only some improved simulation results are listed here.

In order to further illustrate that the increase of CIT can effectively improve the acquisition sensitivity of the IAADFC algorithm, we simulated in different SNR environment. When the SNR of GNSS signal decreases by 25dB, some simulation results are listed in Figure 3. It can be seen that the number of acquired satellite signals rise from 2 to 5 when the CIT is increased from 30ms to 60ms. With the increase of CIT, the acquisition sensitivity of the IAADFC algorithm is improved. It can also be seen that NCI algorithm cannot detect any signal with 80ms incoming data, whereas with only 30ms incoming data, the IAADFC algorithm can detect signals of two satellites, as shown in the upper panels. Additionally, as shown in the bottom panels, the IAADFC algorithm can detect five satellite signals with CIT=60ms, whereas the DBZP algorithm can only detect four satellite signals. Therefore, the IAADFC algorithm can achieve a higher sensitivity than the NCI algorithm or the DBZP algorithm. It can be seen that the acquisition sensitivity of the DBZP algorithm is lower than that of the IAADFC algorithm but it is higher than that of the NCI algorithm.
4. Discussion

The impact of carrier Doppler frequency is large when CIT is long. A small frequency error can lead to a large phase shift when the time of the coherent integration is long. Theoretical analysis is made and some results are list in Figure 4. It can be seen from Figure 6 that:

1) When the phase difference between the input signal and local carrier signal is \( \pi/2 + n \cdot \pi, n = 0, \pm 1, \pm 2, \cdots \) or \( 90^\circ + 180^\circ \cdot n, n = 0, \pm 1, \pm 2, \cdots \) degrees, the correlation coefficient of these two signals is zero. Therefore, the coherent integration output curve has extreme points that exist around these points;

2) When the phase difference between the input signal and local carrier signal is \( \pi + 2n \pi, n = 0, \pm 1, \pm 2, \cdots \) or \( 0 + 360^\circ \cdot n, n = 0, \pm 1, \pm 2, \cdots \), the correlation between the two signals reaches its positive maximum. In contrast, when the phase difference is \( 0 + 2n \pi, n = 0, \pm 1, \pm 2, \cdots \) or \( 180^\circ + 360^\circ \cdot n, n = 0, \pm 1, \pm 2, \cdots \), the correlation between the two signals reaches its negative maximum. Correspondingly, the correlation output curve around these points either rises or declines rapidly.

![Figure 3. Comparison of IAADF, NCI and DBZP algorithms when SNR decreases by 25dB](image)

![Figure 4. The Relationship between the Coherence and Phase Difference](image)
In order to verify the above analysis results and find the relations between the coherent integration output and phase difference, some simulation is carried out, which results are shown in Figure 5. In these simulations, the Doppler frequency estimation accuracy is set as 16.7Hz, and there are no searches in frequency domain.

![Figure 5. Relationship between the Coherent Integration Output and Phase Differences of IGIFS and Local Signal](image)

The right panels of Figure 7 show the curve of maximum coherent integration output, while the left panels show the phase difference between IGIFS and local signal. Figure 7 show the acquisition results for the PRN = 21 satellite signal. As the left panel shows, when CIT = 130ms, the phase difference is about -97 degrees. According to the above theoretical analysis results, the correlation becomes negative as the phase difference continues to increase, which leads to the coherent integral output showing a decreasing trend. Based on this analysis result, the coherent integral output curve shown in the right panel should reach its maximum around CIT = 130ms, and will decrease gradually as CIT increases. It can be seen from the right panel that the variant trend of the curve of the integral output is basically in line with this theoretical analysis result.

Similarly, when CIT = 260ms, the phase difference is about -270 degrees. The coherent integration output reaches an extreme point, which coincides with the above theoretical analysis results. When CIT = 195ms, the phase difference is about -180 degrees. The above theoretical analysis shows that the coherent integration output should change the fastest at this point, which is basically consistent with the curve-changing trend around CIT = 195ms that is shown in the right panel.

5. Conclusion
In this paper, the IAADFC algorithm based on long-time coherent integration is analyzed at different SNR environments and different Doppler frequency estimation accuracy is simulated. It is found that in a weak signal environment, the IAADFC algorithm improves the acquisition sensitivity.

From the above analysis we can also see that, if the Doppler frequency estimation accuracy of the DF EA algorithm is improved, the computational complexity of the acquisition algorithm can be reduced and the upper limit of the CIT will rise to enhance the sensitivity of the acquisition algorithm. Therefore, we will also plan to research the DF EA algorithm in the future.

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