Research on navigation and positioning Technology based on opportunity signal of low orbit satellite

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Abstract. Global Navigation Satellite System (GNSS) signals to the Earth's surface are weak, vulnerable to interference, and require significant infrastructure investment to keep them operating. In order to get rid of the dependence on GNSS navigation system and overcome the problems such as shadow occlusion and malicious interference, opportunity signal is used to realize positioning to make up for the shortcomings in this aspect. Aiming at the limitation of coverage and availability of land-based opportunity signals at present, the opportunity signals of low-orbit satellites have the advantages of high signal power, wide coverage and no need to build additional infrastructure, etc. Therefore, space-based opportunity signal positioning by using low-orbit satellite system can be used as an effective backup or supplement to GNSS system. In this paper, the signal communication system of low orbit satellite is studied deeply, and the Doppler frequency information is obtained by using the single tone signal of the pilot frequency of low orbit satellite, and the mathematical model of instantaneous Doppler positioning and its geometric factor of accuracy is established, so as to realize the positioning ability of opportunity signal of low orbit satellite. The simulation results show that the positioning accuracy is better than 200 m using the actual low orbit satellite signals. The research results have reference significance for the theoretical research and application of location technology based on opportunity signal. By studying the communication system of low orbit satellite signal, the mathematical model of instantaneous Doppler positioning is established, and the method of obtaining Doppler frequency information by using the single tone signal of low orbit satellite signal and combining the satellite orbit information calculated by the orbit prediction model to realize low orbit satellite positioning is proposed. The measured data verification results show that the positioning accuracy of 100 meters can be achieved by using the LORB opportunity signal, and the research results have reference significance for the theoretical research and application of positioning technology based on the LORB opportunity signal.

Key Words: Low orbit satellite; Opportunity signal; Doppler location
1. Introduction
The satellite navigation technology has been integrated into all aspects of social life during the 25 years since the world’s first Global Navigation Satellite System (GNSS)-GPS was built to provide services in 1994. The complete-coverage, all-weather and full-range navigation services it provides play a significant role in the fields of national construction, security and economy. The world’s four major navigation systems, including BDS, can provide a regular services of which position accuracy is less than 10m, meeting the navigation and positioning requirements of popular applications.

Although GNSS (Global Navigation Satellite System) developed rapidly because of the increasing demand of position services, GNSS still has some disadvantages such as weak signal and susceptibility to interference. The application of the widespread wireless opportunistic navigation (OpNav) and collaborative opportunistic navigation (COpNav) have received extensive attention in recent years. Typical systems such as All Source Positioning and Navigation (APSN) technology proposed by the U.S., which attempted to use all available signal resources to achieve fusion navigation and positioning. Similarly, the Ministry of Defence of the United Kingdom developed the Navsop (Navigation via Signals of Opportunity) system as well.

![Fig.1 Global Satellite Orbit Distribution](image1)

![Fig.2 Global Satellite Orbital Height Distribution](image2)

In recent years, low-orbit satellite gained gradually attention and favor in the field of navigation enhancement with its unique advantages in orbit and signal as well as wide application potential. It was also expected to become a new increment in the development of next-generation satellite navigation systems. At present, the development and practice of low-orbit satellite technology are flourishing. the world’s major aerospace countries have actively carried out the R&D and deployment of large-scale LEO communication constellations. The application of the LEO satellite technology in combination with the opportunistic navigation has the following advantages in navigation and positioning: firstly, the orbits of the LEO satellites are about one-twentieth of that of conventional GNSS satellites, so the signals received on the ground are stronger; secondly, the speeds of LEO satellites are faster, so their signals in the use of Doppler are more meaningful; thirdly, the increasingly abundant LEO satellite...
resources are denser in both frequency bands and distribution. Positioning technology based on LEO satellite signals of opportunity is in the ascendant. With the large amount of existing satellite resources, it can easily meet the military and civilian positioning service requirements with a small amount of capital investment, and help improve the accuracy and performance of the existing GNSS systems, so it can be used as an effective backup or supplement.

This paper focuses on treating low-orbit satellites as an opportunity signal source, which can be used without authorization then use the low-orbit satellite signals as an opportunity signal to locate. Since only part of the information of the opportunity signal is known, this paper focuses on analyzing the signal regime and giving a method to obtain positioning observation information. A detailed mathematical model of positioning is given and the physical meaning of the geometric accuracy factor of Doppler positioning is explained. By building a satellite signal acquisition platform, the positioning of the actual satellite signal is realized.

2. Low Orbit Satellite Development Trend Analysis
With the increasing demand of current Internet and civil-military integration navigation applications, low-orbit satellites have benefited from their excellent signal characteristics and application potential, which pushed low-orbit satellites to a new climax of development. In combination with the global satellite navigation field, a profound industrial, system and technological change is underway, which has triggered the innovation and expansion of the LEO satellite navigation model and opened a new era of LEO satellite development.

Currently, the United States has taken the lead in deploying thousands of LEO satellites in the field of LEO satellites. Among them, the traditional LEO constellations such as Iridium, Orbcomm and Globalstar have realized the in-orbit operations. The most representative of these is the STL service provided by the Iridium NEXT constellation, which can provide sub-accuracy location, navigation and time services for users anywhere on the earth. It has been incorporated into the national strategic PNT system by the U.S. Department of Defense, to provide backup navigation in order to provide backup navigation in the event of GPS systems gotten impact or interference. The Starlink program of the Space Exploration Technologies Corp (Space X) has the fastest progress in emerging low-orbit constellations. By the end of 2020, Space X has completed more than 1,000 Starlink satellite launches by the end of 2020, which was close to achieving the first phase of 550 km orbital altitude deployment (72 orbital planes, 22 satellites per orbital plane) and started its global service.
As China’s commercial aerospace development is somewhat later than that of the United States, most of our domestic LEO satellite constellations are still in the stage of experiment or planning demonstration. Nevertheless, traditional aerospace systems and commercial aerospace fields are actively carrying out independent research and development of satellite constellation layout work, with the representative examples including State Grid Fusion Star, Hongyan Constellation (CASC), Hongyun Constellation (CASIC), Centispace (Future Navigation), Luojia-1 (Wuhan University), etc. All these constellations plan to engage in navigation augmentation backup services to assist in improving the availability and reliability of GNSS constellations in complex environments.

![Fig. 4 Luojia-1 scientific experiment satellite](image1)

**Fig. 4** Luojia-1 scientific experiment satellite

Luojia-1 and Hongyan constellation have obtained a large amount of measurement data through the launched experiment satellites, and evaluated the improvement of the LEO satellite navigation augmentation performance. The experiment results are shown in Fig.5 and Fig.6. Among them, “Luojia-
1” broadcasts and gives augmentation signals by carrying a dedicated navigation augmentation payload, and has achieved breakthroughs in key technologies such as on-board signal transmission, reception and isolation, on-board high-precision time maintenance, payload miniaturization, and low power consumption design. The user terminal optimizes the reception processing flow according to the characteristics of the LEO navigation augmentation signal, which improves the acquisition sensitivity and tracking accuracy of the LEO satellites, and can simultaneously capture and track GPS, Beidou navigation signals and “Luojia-1” navigation augmentation signals. According to the actual measurement results, the difference between the ground clock obtained by Luojia-1 single satellite time service and the ground clock obtained directly using GPS signals remains among 10-30ns.

Fig.7 The First Satellite of Hongyan Constellation

The first satellite of Hongyan constellation was launched at the end of December 2018 and carried out navigation augmentation related experiments. The navigation augmentation system based on Hongyan’s first satellite can provide users with information enhancement and signal augmentation services. Among them, the information enhancement service broadcasts and sends orbit and clock correction information in the form of broadcasting, realizing dynamic decimeter-level and static centimeter-level global precision point positioning (GPPP), and the user location algorithm convergence time is shortened from about 30 minutes to less than 1 minute.

Fig.8 GDOP of Mixed System with Beidou and Hongyan Scientific Experiment Satellite

At the same time, the signal augmentation service uses Hongyan LEO satellite as the navigation signal source to broadcast and send ranging signals similar to GNSS satellite, and users receive GNSS signals and LEO signals simultaneously for joint positioning and calculation. According to the actual measurement results, the average GDOP of the mixed system with Hongyan and Beidou in one day has
dropped by 9.9% compared to that Beidou constellation alone, which can effectively improve the usability and positioning accuracy of the navigation system.

While domestic LEO satellites have completed the verification of a small number of experimental satellites, a large number of subsequent launch missions are being deployed in full swing. In view of the above analysis and investigation, the research and analysis based on the LEO satellite navigation augmentation system at this stage has shown particularly important practical value and application significance. China is expected to utilize the “late-mover advantage” to fully tap the space resources and strategic value behind the LEO navigation system and grasp the new growth points of the LEO system to surpass the formers in the field of satellite navigation.

3. LEO Satellite Signals of Opportunity and Positioning Technology Research

3.1. System for LEO Satellite Signals of Opportunity

Due to the limitation of business model, profitability and other factors, the vast majority of existing LEO satellites are communication satellites, and there are only a few experimental satellites dedicated to ground-orbiting satellites for navigation augmentation. LEO satellites have become one of the best platforms for supplementation or backup of navigation systems due to their high satellite dynamics, strong landing power, and fast algorithm convergence. Correspondingly, the use of LEO communication satellites to achieve opportunistic navigation has low construction costs and low system overhead due to the large number of existing LEO communication satellites with abundant system resources in frequency bands and power, and the ability to achieve seamless global coverage. It receives great attention.

The use of LEO communication satellites to realize the opportunistic navigation function generally relies on the satellite paging channel, and it minimizes the impact on the original satellite communication function simultaneously. There are pilot channels and paging channels in the satellite communication frame structure. The channels do not transmit data information, but only serve as channel estimation and user paging functions. The paging channel has the characteristics of fixed time and frequency domain resources, one-way broadcast, high landing power, and comprehensive coverage, and is suitable for the broadcast and transmission of navigation augmentation information. Therefore, many LEO augmentation studies including Iridium satellite have modified the paging channel, such as adopting QPSK modulation and broadcasting augmentation information in one channel, while providing navigation augmentation services under the premise of retaining the original paging function and minimizing the impact on the communication system.

![Fig.9 Schematic Diagram of Time-Frequency Resources for LEO Satellite Opportunistic Navigation](image-url)
3.2. Positioning Technology for LEO Satellite Signals of Opportunity

The relative motion between the satellite and the receiver produces a Doppler phenomenon. The Doppler frequency can reflect the relationship between the position and speed of the satellite and the position and speed of the receiver, so frequency measurement information can be used to achieve positioning.

The early transit system is a typical Doppler-based satellite positioning system. Due to the limitation of the space constellation, the number of visible satellites is small. Therefore, the integrated Doppler is used as the observation information, and the measurement information is converted into a hyperboloid of the distance difference, and after multiple accumulations at different times, multiple hyperboloids intersect to obtain the position. In the case where multiple satellites are visible at the same time, instantaneous Doppler-aided frequency can be used to realize instant positioning, that is, the instantaneous iso-Doppler cone of multiple satellites can be intersected to obtain the receiver position.

The linear navigation status update equation for pseudo-range positioning can be expressed as follows:

\[
\ddot{z} = H \dot{x} + \varepsilon
\]

In the equation, \(\ddot{z} = z - z_{\text{d}}\) is the priori pseudo-range measurement deviation vector; \(\ddot{z}\) is the measured pseudo-range vector; \(z_{\text{d}}\) is the predicted pseudo-range vector; \(H\) is the Jacobian matrix, while \(\varepsilon\) is the measurement and linearization deviation vector.

Make \(\delta x = [\delta_x, \delta_y, \delta_z]^T\) denote the state update vector and \(\varepsilon\) denote the deviation change amount. Take the derivative of the above equation and get

\[
\frac{\ddot{z}}{\ddt} - \frac{\ddot{z}_{\text{d}}}{\ddt} = H \frac{\ddot{\delta x}}{\ddt} + \frac{\ddot{H}}{\ddt} \delta x + \varepsilon.
\]

According to the classic linear equation of receiver speed measurement, we will get

\[
H \frac{\ddot{\delta x}}{\ddt} = H \begin{bmatrix} \delta_{k_x} \\ \delta_{k_y} \\ \delta_{k_z} \\ \delta_{k_0} \end{bmatrix}
\]

In the equation, \(\delta_{k_x}, \delta_{k_y}, \delta_{k_z}\) are the update s variables of the receiver’s priori speed, and \(\delta_{k_0}\) is the update variable of the receiver’s frequency deviation.

According to the relationship between Doppler frequency and the receiver’s position,

\[
\frac{\ddot{H}}{\ddt} \delta x = \begin{bmatrix} \frac{\ddot{e}_x^{(1)}}{\ddt} \\ \frac{\ddot{e}_y^{(1)}}{\ddt} \\ \frac{\ddot{e}_z^{(1)}}{\ddt} \end{bmatrix} + \frac{\ddot{e}_x^{(2)}}{\ddt} \begin{bmatrix} \delta_x \\ \delta_y \\ \delta_z \end{bmatrix}
\]

In the equation, \(\frac{\ddot{e}_x^{(1)}}{\ddt} = \frac{\dd}{\ddt} \begin{bmatrix} x_x^{(1)} - x_{x_0} \\ y_x^{(1)} - y_{x_0} \\ z_x^{(1)} - z_{x_0} \end{bmatrix}\), \(x_x^{(1)}\) is the position of the satellite \(k\), \(x_{x_0}\) is the priori position information of the receiver, and \(\dddot{e}_x^{(1)}\) is the line-of-sight unit vector of the satellite \(k\).

Make \(d = \frac{\ddot{z}}{\ddt}\) denote the measured Doppler vector and \(\frac{\ddot{q}_k}{\ddt} \frac{\ddot{y}_k}{\ddt}\) denote the predicted Doppler measurement vector. Combining the above equations, the instantaneous Doppler-aided positioning linear equation is
In the equation, $\frac{\partial e^{(i)}}{\partial t} = \left( \frac{\partial x^{(i)}}{\partial t} - e^{(i)} \cdot \left( e^{(i)} \cdot v^{(i)} \right) \right) \frac{1}{r^{(i)}}$ means the satellite speed minus the speed component of the satellite's line-of-sight direction and then is divided by the upper line-of-sight geometric distance; $v^{(i)}$ means the speed vector of the satellite k.

The above equation is the mathematical model of instantaneous Doppler-aided positioning. The estimators include 7 state variables such as receiver position, speed and frequency deviation. When the position state variable is known, the above equation is the classic mathematical model of receiver speed measurement. For static positioning, positioning can be achieved by using 4 satellites, namely

$$\hat{d} = H \begin{bmatrix} \delta_k \\ \delta_k \\ \delta_k \\ \delta_k \end{bmatrix} + \frac{\partial e^{(i)}}{\partial t} \begin{bmatrix} \delta_s \\ \delta_s \\ \delta_s \end{bmatrix} + \varepsilon$$

$$\begin{bmatrix} \delta_k \\ \delta_k \\ \delta_k \end{bmatrix} = H \begin{bmatrix} \delta_k \\ \delta_k \\ \delta_k \end{bmatrix} + \frac{\partial e^{(i)}}{\partial t} \begin{bmatrix} \delta_s \\ \delta_s \\ \delta_s \end{bmatrix} + \varepsilon$$

The positioning technology based on LEO satellite signals of opportunity used in this paper uses the Doppler shift of the single tone signals of the LEO signals in the LEO satellite downlink as positioning observations, and then uses the public two-line element (TLE) data and the SGP4 prediction model to output the position and speed of the corresponding satellite of the LEO satellite, and finally use...
instantaneous Doppler-aided positioning technology to achieve multi-epoch static positioning. What is actually used is the software developed based on this technology, and the positioning flowchart of the software is shown in the figure:

![Fig.11 Schematic Diagram of Positioning Process of LEO Satellite Signals of Opportunity](image)

4. Experimental Verification of Navigation and Positioning Based on LEO Satellite Signals of Opportunity

This paper analyzes the actual collected LEO satellite signals in the time-frequency domain and estimates the signal Doppler frequency. The acquisition platform mainly includes an antenna, a RF front end and a data processing unit. The block diagram of the collection system is shown in the figure below.

![Fig.12 Schematic Diagram of Acquisition System by LEO Satellite Signals of Opportunity](image)

Use the built hardware acquisition system to acquire the user link simplex downlink 0.5MHz band signals of the actual LEO satellite, the center frequency is set to 1,626.25MHz, the collected intermediate-frequency data frequency is 28.25MHz, and the data length is 20s. After down-conversion,
it is 28.270833MHz. The channel information is sent every 48 frames, that is, the time interval for the same spot beam of the same satellite to repeatedly send the signal is 4.32s. Process a certain LOE signal within 20s, and its time-domain signal is shown in Fig13. Fig14 and Fig15 respectively showing the IQ vector diagram and phase diagram after signal demodulation.

![Fig.13 Time Domain Diagram of LEO Satellite Signals of Opportunity](image1)

![Fig.14 Iq-vector Image of LEO Satellite Signals of Opportunity](image2)

![Fig.15 Phase Image of LEO Satellite Signals of Opportunity](image3)

Through time domain and frequency domain analysis results, it can be seen that the bandwidth of the LEO signal in the actual collected signal is about 26.6667kHz and the duration is 6.8ms. The center frequency of the signal captured by the maximum likelihood estimation method is 28.244935683MHz, that is, the Doppler frequency of the satellite signal is 25897.317Hz. It can be seen from Figure 7 that the LEO satellite signal is mainly composed of three parts: no modulation, BPSK modulation, and QPSK
modulation. Among them, the single-tone continuous wave signal has no information, the independent word uses BPSK modulation, and the data information uses QPSK modulation.

In this paper, the collected LEO satellite signals are used as positioning observation information and there are 25 observation epochs totally; instantaneous Doppler-aided positioning is used for positioning calculation. The real receiving antenna position is calibrated by GPS recorder (accuracy is meter level). The Doppler information of 25 different observation epochs is combined 800 times to perform the positioning error analysis, and the positioning results of each 50 combinations are used for positioning error mean and root mean square error (RMS) statistics.

Fig16 shows the statistical results of the positioning errors. It can be seen that using actual LEO satellite signals can achieve positioning with an accuracy better than 200m. The eastward error fluctuation is larger than the northward error fluctuation, but it has a smaller mean value of positioning error. This is because the inclination of the orbit of the Iridium satellite is relatively large; when the iso-Doppler cone of the satellite moving in the north-south direction is affected by the error, the positioning error is larger in the east-west direction.

![Fig.16 Positioning Result of LEO Satellite Signals of Opportunity](image)

5. Conclusion
Through in-depth research on the communication system of LEO satellite signals, this paper proposes to use LEO satellite pilot tone signals to obtain Doppler frequency information, and then establishes a mathematical model of instantaneous Doppler-aided positioning and its GDOP, so as to realize positioning via the LEO satellite signals of opportunity. The simulation results show that the actual LEO satellite signals can achieve positioning with an accuracy better than 200m. The research results have reference significance for the theoretical research and application of positioning technology based on signals of opportunity. Through the in-depth study on the communication system of LEO satellite signals, an instantaneous Doppler-aided positioning mathematical model is established, and a method that can obtain Doppler frequency information by using the single tone signal of LEO satellite signals and realize LEO satellite positioning in combination with the satellite orbit information calculated by the orbit prediction model is proposed. The measured data verification results show that a positioning with an accuracy of three-digit meters can be achieved by using the LEO satellite signals of opportunity, and the research results have reference significance for the theoretical study and application of positioning technology based on the LEO satellite signals of opportunity.

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