Research on Time to First Fix of a Space-based Positioning Technology based on IRIDIUM Signals of Opportunity

SUN GUIYU[1] ("Author"). QIN HONGLEI. ZHAO CHAO.

Abstract. Utilizing the space-based opportunity signal positioning technology of the IRIDIUM system as an emerging autonomous navigation technology, it can be used as an effective backup or supplement of the GNSS system. Time to First Fix (TTFF) is one of the main indicators for measuring positioning systems and reflects the responsiveness of positioning systems to achieve positioning. In order to investigate the TTFF of the space-based opportunistic signal positioning technology based on the IRIDIUM system and its influencing factors, this paper gives the definition of the TTFF of the technology, builds a set of test platforms, and the positioning results under different preset position deviations and different DOP of IRIDIUM satellites are compared through using actual collected data. The changes in positioning accuracy over a period of time after the first positioning were observed, and the factors affecting TTFF and accuracy were analyzed.The actual measurement results show that the TTFF based on the space-based opportunity signal positioning technology of the IRIDIUM system is better than 15 minutes, and the horizontal positioning accuracy is generally better than 500 meters. The positioning accuracy changes slowly after the first fixing. This study indicates that the TTFF is a meaningful index for evaluating the response capability of the positioning system, and lays the foundation for the continued research and application of positioning technology based on space-based opportunity signals.

Keywords: Opportunity signal. IRIDIUM Satellite. Space-based. Instantaneous Doppler Position. Time to First Fix.

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[1]SUN GUIYU (✉)
Beihang University, Beijing 100191, China.
e-mail: sunguiyu96@gmail.com

1 Introduction

The Beidou satellite navigation system is about to be completed, marking a new era in global navigation and positioning services. With the continuous progress and development of satellite navigation systems that provide a large number of users with global, all-weather convenient positioning services, the needs of various industries for positioning services are more urgent and stringent than ever.

However, under the influence of some natural environments or man-made activities, Global Navigation Satellite System (GNSS) signals tend to become untrustworthy. In addition, building a complete GNSS costs huge material and financial resources. Yet, positioning technologies based on opportunity signals (including AM / FM, mobile communication signals, radio of television, and low-orbit satellites, etc.) proposed in recent years have great potential to make up for the above shortcomings.

Compared with other signal sources, the application of low-earth orbit (LEO) satellite signals in navigation and positioning has the following advantages: First, the orbit of a LEO satellite is about one-twentieth of that of a conventional GNSS satellite, so the LEO satellite signals received on the ground are stronger; second, the low-orbit satellite is faster, so the use of Doppler witch is from the signal transmitted by it is more meaningful; third, the increasingly abundant LEO satellite resources are more dense in both frequency band and azimuth [9][11]. It is also based on the above points that the positioning technology based on the IRIDIUM satellite opportunity signal has been realized [12], and the research on the use of low-orbit satellite signals to achieve navigation and positioning has gradually received attention and attention. However, as it is still an emerging positioning technology, the current testing system is not complete, the testing process is not clear, and the testing standards are not uniform.

Time to First Fix (TTFF) usually refers to the time from when the receiver receives the signal to when it outputs the first reliable position. As one of the key indicators to measure the performance of the receiver [7], TTFF can reflect the rapid response capability of the receiver. This indicator has a significant role in evaluating the actual availability of the positioning technology [1].

Therefore, this paper conducts relevant research on the TTFF based on IRIDIUM satellite opportunity signal positioning technology which has been realized at present [8]. In addition, this paper makes use of actual IRIDIUM satellite signal to complete relevant experimental tests.

In this paper, the positioning technology using the IRIUDM satellite opportunity signal is researched and tested about its TTFF. The structure of the article is as follows: Firstly, a brief description is made of the constellation distribution and signal system of IRIDIUM satellite, and then an introduction is made to the technology of using IRIDIUM satellite to realize instantaneous doppler positioning based on multi-epoch. Then the platform construction and process design for the

TTFF test are completed. Finally, the TTFF of the technology is tested, analysed and summarized by using the IRIDIUM satellite signals actually received.

2 Positioning Technology Based-on IRIDIUM Signal

2.1 IRIDIUM Satellite System Overview

The main object of this paper is the actual downlink signal of IRIDIUM constellation, which is part of the second generation of global telecommunication satellite network. In January 2017, the first 10 IRIDIUM NEXT satellites were launched successfully. The constellation and the corresponding second-generation terminals and services have been put into use since 2018. On January 11, 2019, SpaceX launched another 10 satellites. By May 2019, IRIDIUM NEXT had been successfully launched to 75 satellites, and all but two of the first-generation satellites were ready for use [2].

IRIDIUM NEXT will consist of 81 satellites, including 66 LEO satellites to replace the existing IRIDIUM constellation, 6 in-orbit backup satellites and 9 ground-based backup satellites, providing signal coverage of the entire earth, including the north and south poles [10]. Of the 75 satellites launched, the orbit of 70 satellites are at an altitude of 625 km and 5 are at 720 km, with an average orbital period of 97 minutes. The IRIDIUM NEXT constellation currently in orbit are divided into six orbital planes with an inclination of 86.6 degrees. The interorbital intervals, except one of about 22 degrees, are all about 31.6 degrees. Approximately 11 satellites are evenly distributed in each orbit. The satellites in the five orbits fly in the same direction, while the satellite in the other orbit is in the opposite direction, as shown in Fig. 2.1 of its orbit distribution.

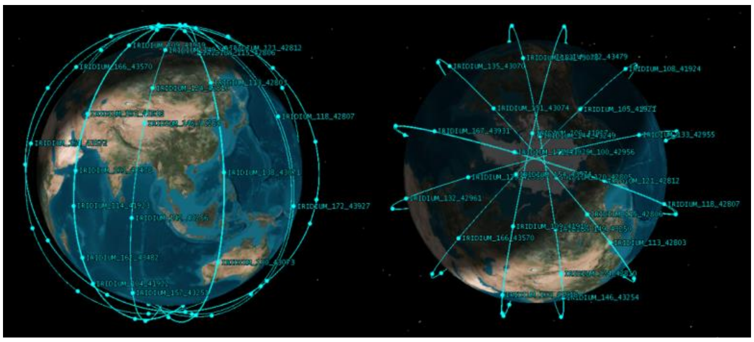

Fig. 2.1 IRIDIUM constellation orbit distribution main view (left), bottom view (right)

The scheme of IRIDIUM satellite system user link signal using multiple modulation methods: the 48 spot beams transmitted by satellite antenna are divided into 4 groups, that is, each group realizes Space Division Multiple Access (SDMA) for the adjacent 12 beams in the total distribution frequency band. Each beam of the band again according to the Frequency Division Multiple Access (FDMA) way is divided into Multiple channels, and at the same Time, the channel according to the Time Division Multiple Access (TDMA) is divided into Multiple carrier, and finally using Time Division duplex (TDD) will be the same TDD user has link respectively under the same carrier in different Time slots of the same frame.

In the actual IRIDIUM signal, the single frame length of TDMA is 90ms, which is allocated to downlink user link slots of the shortest 6.5ms and the longest 20.32ms for simplex channels, and the rest is constituted by the 8.28ms length of the upper and lower downlink slots of the four duplex channels [6]. The specific structure of a single frame is shown in Fig. 2.2:

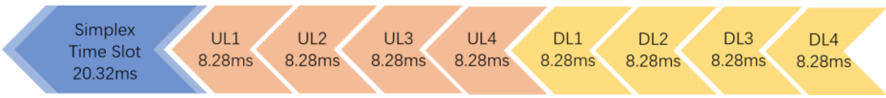

Fig. 2.2 IRIDIUM signal single frame structure

By IRIDIUM satellite system transmission of information by the Differential Quadrature Phase Shift Keying (DQPSK) modulation, again with Binary Phase Shift Keying (BPSK) modulation after independent word combination, a pulse shaping root ascending cosine filter, then 2.6ms long single tone in front of the signal by the combination of plastic, the final will be processed on the signal of variable frequency get 90ms sudden signal, That is, the IRIDIUM satellite system user downlink transmitted a burst signal with a length of 90ms [3].

2.2 Instantaneous Doppler Positioning Technology Based on IRIDIUM Opportunity Signal

The relative motion of the transmitting source and receiving end of the signal is the cause of doppler phenomenon, while the doppler frequency shift is the reflection of the relative relation between the position and velocity of the satellite and the receiver [5]. When multiple satellites are visible at the same time, the location of the receiver can be obtained by crossing the Iso-doppler Circular Conical Surface (IDCCS) of multiple satellites.

The instantaneous doppler positioning technology, adopted by this subject, based on IRIDIUM satellite opportunities signal takes single tone signal doppler frequency shift as a positioning observation which persists in downlink link burst signal, through acquisition IRIDIUM downlink actual signal processing, doppler information has been obtained, then use and open Two-Line Element (TLE) data and the SGP4 model output corresponding IRIDIUM satellite position and velocity [4]. Finally, the multi-epoch static positioning based on IRIDIUM constellation is realized by using instantaneous doppler positioning technology [8]. Actually, the software developed by ourselves based on this technology is adopted, and the positioning flow chart of the software is shown in Fig. 2.3:

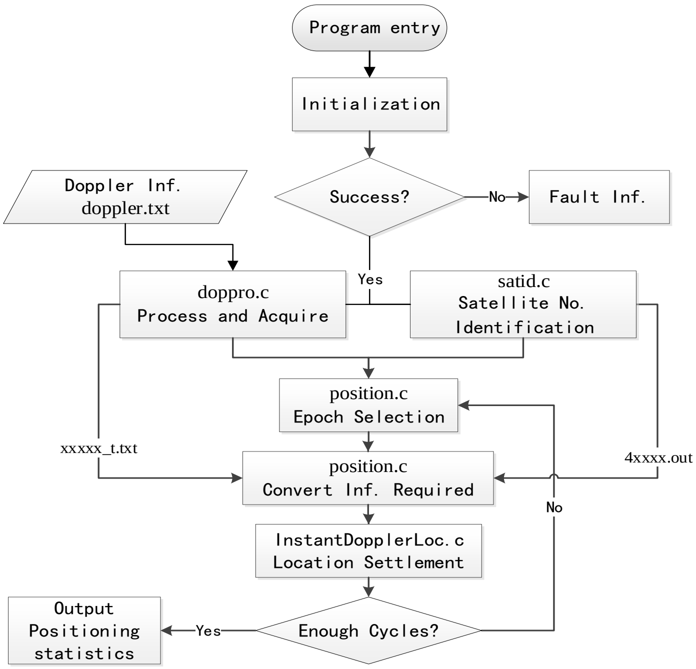

Fig. 2.3 Flow chart of positioning procedure

3 TTFF Test of Positioning Based on IRIDIUM signal

3.1 The Definition and Test Platform of TTFF

TTFF of the positioning technology based on IRIDIUM opportunity signal refers to the time length of IRIDIUM satellite signals used when the mean 2D positioning error of the repeated positioning results reaches within 500 meters for the first time, by taking advantage of existing TLE and applying the instantaneous doppler positioning software for 1 minute step continuous positioning results from statistical IRIDIUM satellite signals with different length, under the condition that the distance between the preset and the actual position is more than 50 kilometers but no more than 1000 kilometers.

Because of the particularity of multi-epoch instantaneous doppler positioning method based on IRIDIUM satellite signal, In this paper, a test platform for the TTFF using the above software is designed, which realized the software cooperation function of extracting and dividing doppler information, predicting satellite orbit, positioning settlement and evaluating by using the actual collected IRIDIUM satellite signals information and downloaded TLE files. The platform module connection is as shown in Fig. 3.1:

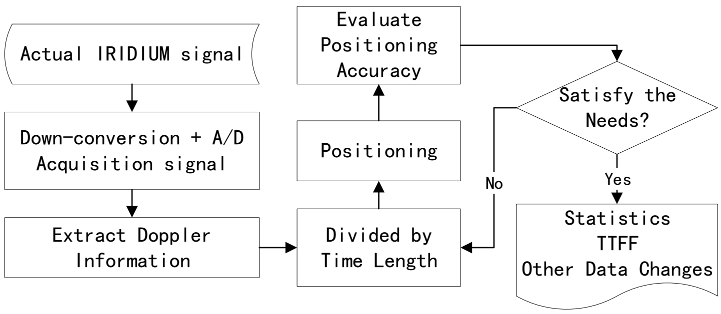

Fig. 3.1 Actual test platform connection

The specific test process is as follows:

1. Collect actual IRIDIUM satellite signals.
2. Processing the actual signal, using the signal time-domain detection technology to continuously detect the data. Each data block is 90ms long. When the signal is detected in the data block, doppler information is extracted. Then it is divided into Doppler frequency information of different time length according to one minute.
3. Input the above Doppler information and the downloaded TLE file into the positioning software, and use the SGP4 orbit prediction model to predict the satellite position and speed information at the required time. Initialize the preset position, run the positioning settlement software, and get the positioning statistical results. The Doppler information of 25 observation epochs is used as the location observation in a single location. Among them, each location result is the result of several times of single location

results obtained passed smooth filtering. The real receiving end position is calibrated by GPS recorder (the error is in meter level).

4. Input the positioning results into the evaluation system. If the conditions are met, record the corresponding time length. If not, input the IRDIUM signal Doppler information of the next time length. Repeat step 3 and 4 until the requirements of the TTFF are met.
5. Count and output the positioning error and the data change of relevant test variables in the process per minute.

3.2 The Test of TTFF

Three groups of tests were carried out according to the above-mentioned test flow with the actual signals collected. The constraints of preset position deviation on the TTFF and accuracy were studied respectively. The accuracy changes in a period of time after the first positioning and the influence of satellite distribution on the TTFF and accuracy were analyzed.

3.2.1 *The Test of TTFF*

According to the above test flow, the location technology based on IRIDIUM opportunity signal is tested, and its TTFF and accuracy are measured.

1. Time and Place of Test

The IRIDIUM signal acquisition system platform was placed in the Northeast corner of the track and field of Beihang University (39.979706 N, 116.339296 E) to collect data. The time is about 17:00 on September 10, 2019.

2. Test Results and Analysis

The 15 minutes Doppler information is shown in Fig. 3.2 below:

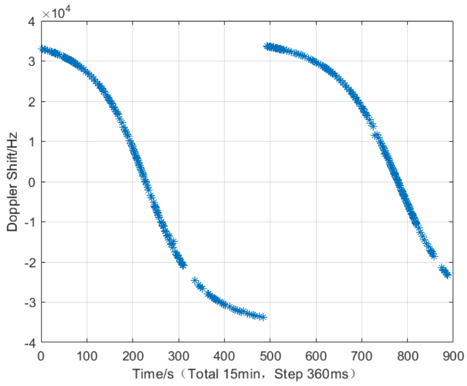

Fig. 3.2 Curve: IRIDIUM signal doppler shift

It can be seen that in this test, only 2 satellites is visible in 15 minutes is, and the maximum number of visible satellites at the same time is 1. In the Fig. 3.2, the first visible satellite is a satellite just entering the visible range, which has been visible for the first 8 minutes; the second satellite and the first satellite belong to the same orbit, which can be seen for 9-15 minutes, and the lower point track of the two satellites is close to the receive end position.

IRIDIUM signals with different lengths of 6-15 minutes (in steps of 1 minute) are used for 10 times of multi-epoch positioning respectively. The preset initial position of the receiver is 58.9 kilometers away from the real position. The positioning results of different time length are obtained for statistics and processing, and the results are as follows:

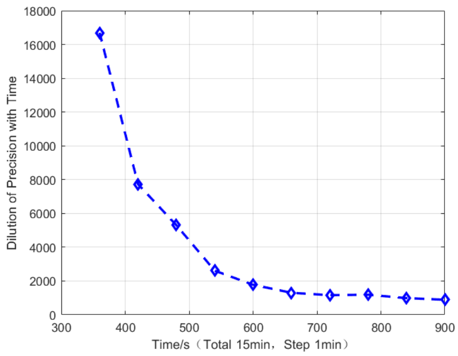

Fig. 3.3 The change of doppler DOP with time

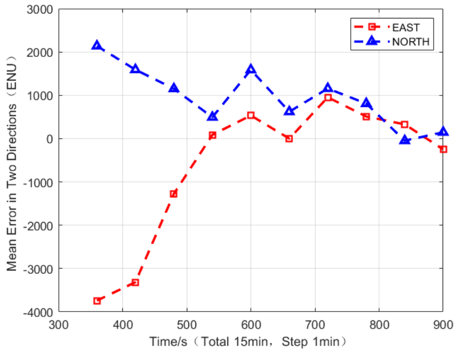

Fig. 3.4 Mean error in east and north directions (ENU)

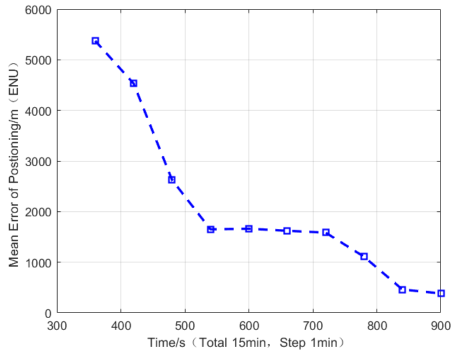

Fig. 3.5 Mean error of 2D positioning distance (ENU)

The results show that with the increase of location time, the DOP of location decreases obviously, which means that the reliability of location results increases correspondingly. At 6-9min, the two-dimensional positioning error rapidly reduces from more than 5 km to less than 2 km. At 9-12 minutes, the positioning error does not change much and fluctuates around 1.6 km. At more than 14 minutes, the mean value of positioning error is less than 500 m. In the whole process, the error difference in northeast direction is not big. To sum up, at 14 minutes, the positioning results meet the requirements of the first positioning for the first time, that is, the TTFF of this test is 14 minutes.

3.2.2 *Test of Relationship between Preset Position and TTFF*

On the basis of the first positioning test mentioned above, change the initial conditions, and use IRIDIUM signals of different lengths for positioning under different initial conditions that the distance between the preset receiver position and the real position is from 20km to 3000km. The positioning results are as follows:

Table 3.1 Relationship between Preset Position and TTFF

	Preset deviation/km	*TTFF/min*	*Accuracy/m*
1	8.87	14	357.81
2	58.89	14	357.81
3	135.43	14	357.81
4	429.30	14	357.81
5	1613.23	14	357.81
6	2154.09	\	\
7	2770.87	\	\
8	3131.50	\	\

It can be clearly seen from table 3.1 that when the preset position deviation is within 1000 km, TTFF and accuracy are not affected; after the error exceeds 1000 km, the technology is restricted by the position deviation, and in most cases, it is in failure state.

3.2.3 Test of the Influence of DOP on the TTFF

In the case of receiving IRIDIUM downlink signals with different geometric distribution, the comparison test is carried out according to the above test procedure.

1. Time and Place of Test

The IRIDIUM signal acquisition system platform was placed in the in the parking lot in front of the swimming pool of Beihang University (39.979768 N, 116.342275 E) to collect data. The time is about 16:00 on November 14, 2019.

2. Test Results and Analysis

The 15 minutes Doppler information is shown in Fig. 3.6 below:

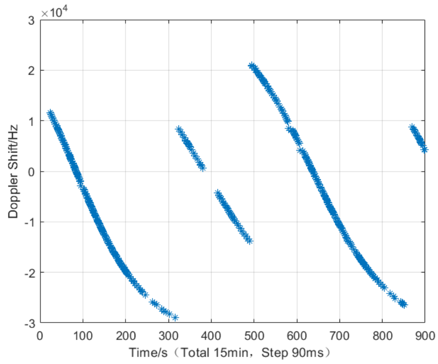

Fig. 3.6 Curve: IRIDIUM signal doppler shift

It can be seen that the geometric distribution of the satellite in this test is obviously different from that in the previous one. There are 4 visible satellites in 15 minutes, and the maximum number of visible satellites at the same time is 2. In the picture, the first satellite is visible for the first 5 minutes; the third satellite and the first satellite are in the same orbit and visible for 8-14 minutes. In the figure, the second satellite can be seen in 6-8 minutes, with short viewing time; the fourth satellite can be seen in 14-15 minutes, with the same orbit as the second satellite, different from the first and third satellites.

The preset initial position of the receiver is 68.9 km away from the real position. Among them, the IRIDIUM signal positioning with 5-15 minutes length is tested 50 times respectively, and the positioning results with different time length are obtained. The positioning results are as follows:

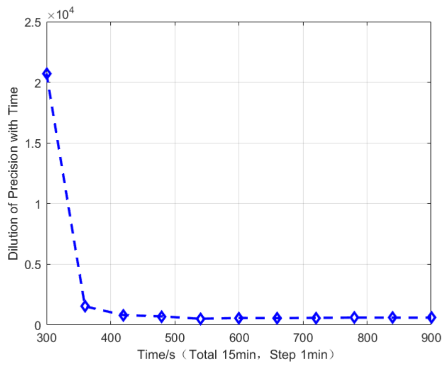

Fig. 3.7 The change of doppler DOP with time

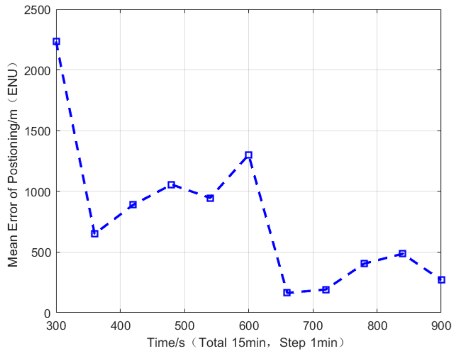

Fig. 3.8 Mean error of 2D positioning distance (ENU)

The positioning results show that the signal of IRIDIUM satellite in this test comes from two orbiting IRIDIUM satellites. After the signal of the second satellite is added, the value of DOP decreases precipitously, and the positioning accuracy also increases rapidly. After the third satellite (in the same orbit with the first satellite) is added, the DOP of the positioning does not does not show the improvement after the addition of the second satellite in the previous test. In 5-10 minutes, the two-dimensional positioning error rapidly reduces from more than 2 km to less than 1 km; in 7-10 minutes, the positioning error fluctuates around 1 km; in 11-15 minutes, the positioning error is less than 500 m. To sum up, the TTFF of this test is 11 minutes. When the observation information includes the signals from two satellites in different orbits, the TTFF is obviously improved.

3.2.4 Test on the Change of Positioning Accuracy after First Fix

The real signal of IRIDIUM satellite in 30 minutes is tested, and the change of positioning accuracy in a long time after the first positioning is compared. Whether the TTFF is significant to evaluate the response ability of positioning system is analyzed.

1. Time and Place of Test

The IRIDIUM signal acquisition system platform was placed in the Northeast corner of the track and field of Beihang University (39.979706 N, 116.339296 E) to collect data. The time is about 22:00 on October 9, 2019.

2. Test Results and Analysis

The 30 minutes Doppler information is shown in Fig. 3.9 below:

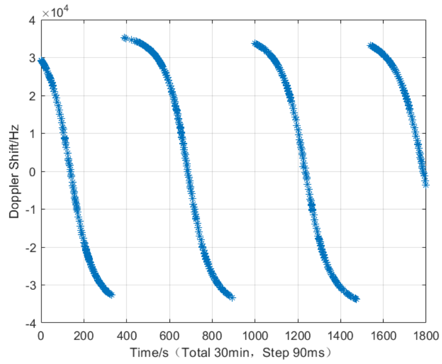

Fig. 3.9 Curve: IRIDIUM signal doppler shift

As can be seen from Fig. 3.9, the number of visible satellites within 30 minutes is 4, and the maximum number of visible satellites at the same time is still 1 in this test. The first satellite is always visible in the first 6 minutes; the second satellite is visible in 7-15 minutes; the third is visible in 17-25 minutes and the satellite is visible in 26-30 minutes. The four satellites in the figure all belong to the same orbit, and the orbit under the satellites is close to the receive end position.

The preset initial position of the receiver is 58.6km away from the real . If the length of test data is extended to 30 minutes (in steps of 1 minute), the location results of different length of time are obtained. The location results are as follows:

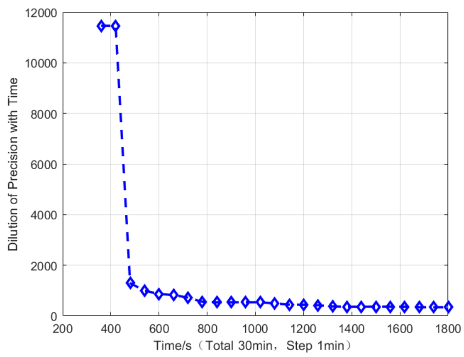

Fig. 3.10 The change of doppler DOP with time

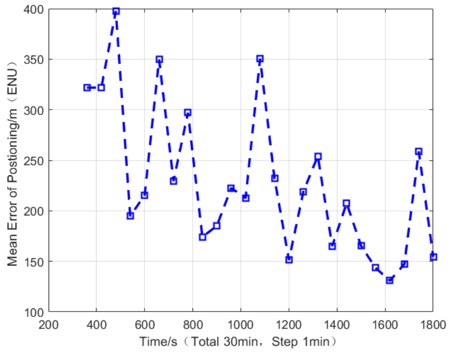

Fig. 3.11 Mean error of 2D positioning distance (ENU)

The positioning results show that the overall positioning results are good. With the increase of time, the value of DOP decreased obviously in 6-8 minutes and slowly in 9-30 minutes. On the whole, the positioning error shows a downward trend with the increase of time. In 6-7 minutes, the positioning error is relatively large, the mean error is more than 500 meters; in 8-13 minutes, the positioning error fluctuates around 450 meters; in 14-20 minutes, the positioning accuracy is significantly improved to within 300 meters, and in 23 minutes, the positioning accuracy is basically kept within 200 meters. To sum up, the TTFF of this test is 9 minutes. After 9 minutes, the positioning accuracy will slowly rise to 200 meters within 20 minutes, but the speed of accuracy improvement is slow. This test shows that the TTFF is significant to evaluate the response ability of positioning system.

4 Concluding Remarks

It can be seen from the test results that the TTFF based on IRIDIUM opportunity signal is about 14 minutes. The instantaneous Doppler positioning technology based on the actual signal of IRIDIUM satellite basically needs at least two IRIDIUM satellites passing through the top of the head. Only when the receiver collects two relatively complete IRIDIUM satellite signals, it can get a high-precision positioning result that basically meets the requirements. According to the coverage of IRIDIUM constellation and the positioning algorithm based on instantaneous Doppler, the TTFF of it is longer than that of current GNSS receiver, but this does not hinder its application or the great potential of its combination with other mature navigation methods when GNSS is interfered.

From several factors of each positioning result and the TTFF, a better DOP of satellites used improves the positioning accuracy in a short time, correspondingly, the improvement of the TTFF is also relatively obvious, but it is not essential for a long-term positioning accuracy improvement. When the preset position deviation is within 1000 km, the deviation does not have a great influence on the TTFF and accuracy. All tests above show that the TTFF is one of the significant indexes to evaluate the response ability of positioning system. Based on this, it can be developed to improve the orbit prediction which reduces the estimation error of satellite velocity and position, or improve the accuracy of satellite position and velocity measurement. The breakthrough in the TTFF will also make the application of navigation technology based on space-based opportunity signals has been greatly ameliorated.

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