New Method for Positioning Using IRIDIUM Satellite Signals of Opportunity

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ABSTRACT The global navigation satellite system (GNSS) system has a number of disadvantages such as weak signal strength and high cost, while signals of opportunity (SOPs) can make up for these shortcomings. Non-GNSS satellite SOPs offer some advantages in terms of high signal strength, low cost that belongs to ground-based SOPs and better coverage than ground-based SOPs. We investigate a new method of instantaneous Doppler positioning with Iridium signals that are treated as satellite SOPs. Initially, the Iridium SOPs positioning system is introduced through a description of its characteristics and components. Next, the instantaneous Doppler positioning algorithm is introduced, and the effects of measurement errors and satellite orbital errors on the positioning solution are analyzed by a new method. Furthermore, the influence of constellation geometrical distribution on positioning performance is analyzed based on the relative position relationship between discrete distribution points of the receiver position. Finally, the simulation data are used for theoretical verification, and the real data experiment is implemented with IRIDIUM NEXT signals. The results show that the two-dimensional (2-D) position accuracies of approximately 22 m (1σ) can be achieved with the height aiding when the static receiver has a complete view of the sky.

INDEX TERMS GNSS, signals of opportunity, non-GNSS satellite, Iridium, instantaneous Doppler positioning, Doppler geometric dilution of precision.

I. INTRODUCTION

Global navigation satellite systems (GNSS) have experienced rapid development in recent decades. Their applications have expanded in many aspects of society. However, many scholars devoted themselves to researching other positioning techniques as a backup system of GNSS, which can get rid of depending GNSS, or as a method for solving the situation that GNSS does not work. The main problem faced by the use of GNSS in environments with strong disturbances and other complicated conditions, is performance degradation [1]. Sometimes GNSS cannot provide positioning information when failing to decode the navigation message [2]. Many other techniques are used to mitigate the lack of the GNSS signals, such as inertial [3], et al. The new methods, termed opportunistic navigation (OpNav) [4], [5] and collaborative opportunistic navigation (COpNav) [6], that have emerged in recent years are based on abundant and various frequency signals. The typical system is Navigation via Signals of Opportunity (NAVSO), which was made by the UK defense firm BAE Systems in 2012; it relies on the same signals used by mobile phones, TVs and other radio systems rather than navigation satellites. It has been developed to complement or even replace current technologies such as GPS. It could also be used in a war if the satellite navigation system were turned off. Similarly, the All Source Positioning and Navigation (ASPN) program made by the US Defense Advanced Research Projects Agency (DARPA) seeks to enable low cost, robust, and seamless navigation in any environment, with or without GPS by using all the available signals.

Non-GNSS satellite signals, as the new SOPs, have some important advantages in terms of high signal strength, low cost and better coverage. Plentiful Non-GNSS satellites are operational today; IRIDIUM, GLOBALSARTR and ORBCOMM are typical representatives. The IRIDIUM Company will finish the deployment of the second generation constellation by 2019, and it launched a total 75 IRIDIUM NEXT satellites. In 2016, it also announced that the service termed satellite time and location (STL) based on the Iridium satellite network can provide a solution for assured time and location which can aid GPS or even replace GPS, but the technical details have not been released [7]. The deployment of the
24 new, second generation GLOBALSATR satellites was completed by 2013, and 15 new ORBCOMM satellites were launched by 2015. Numerous scholars have further studied using additional signals to augment GNSS from low Earth orbit [8]–[10]. On the other hand, in 2015, OneWeb and Boeing announced the production of new constellations of large numbers of LEO satellites in the future [8]. China has also presented a similar plan, for example, the HONYAN constellation and HONYUN project.

Available satellite SOPs may have a fully known or partially known characterization. For noncooperation satellite SOPs, the receiver can still measure Doppler-shift when it fails to get range information. Doppler positioning techniques can still provide location services with little information [11]. Hill first introduced the principle of GPS instantaneous Doppler positioning [12]. Different Doppler-shift measurement methods are also analyzed and compared. Sakamoto also performs related research on indoor positioning based on Doppler measurements [13]. It can also be used to improve the time to first fix (TTFF) [14]. Van describes the instantaneous Doppler measurements [13]. It can also be used to improve the time to first fix (TTFF) [14]. Van describes the instantaneous Doppler positioning technique with the A-GNSS technique, as it can be used for frequency assistance and code delay assistance [15]. Chen et al. combined Doppler positioning with the coarse-time navigation technique to solve the problem that the user cannot provide an a priori location, which must satisfy certain conditions in the traditional coarse-time technique [16], [17]. Othieno and Gleason also performed related research [18]. We mainly implement Iridium satellite SOPs positioning using the instantaneous Doppler positioning technique.

Satellite orbital errors and Doppler observation errors are the main error sources for the Iridium SOPs positioning. The satellite velocity information is also used in Doppler positioning, which means positioning error analysis is more complex than that of the traditional pseudorange positioning because the effects of satellite velocity are need to be considered. Doppler geometric dilution of precision (Doppler DOP) is not only related to constellation geometric distribution but also dynamic satellite trajectory, and it is a physical quantity with dimensionality. Decreasing the Doppler DOP by reasonably choosing GNSS satellites has significance for improving position accuracy. There is few research in the current literature on the issues mentioned above. We present deep research on these topics, focusing on the Iridium SOPs positioning technique.

In Sect. 2, we describe the principle of the Iridium satellite SOPs positioning technique. The instantaneous Doppler positioning algorithm and a new method of geometric analysis of positioning error is proposed in Sec. 3. The effect of constellation geometric distribution on position accuracy is discussed in Sect. 4. Experimental results are described in Sect. 5. Finally, the conclusions are presented in Sect. 6.

II. IRIDIUM SATELLITE SOPs POSITIONING TECHNIQUE

The signals from Iridium satellites are generally stronger than GNSS satellite signals. If the satellite antenna radiates a power $p$ isotropically, then the power spatial density at a distance $l$ is $s = P/4\pi l^2$, where $P/4\pi l^2$ is the spreading loss, $l = r_e \sin(\alpha) + \sqrt{r_s^2 (\sin(\alpha))^2 - 1} + r_z$ denotes the distance between the receiver and satellite, $r_e$ is the radius of the earth, and $\alpha$ is the elevation angle. Table 1 shows the spreading losses for Iridium and GPS at different elevation angles. As shown, the spreading loss for Iridium is approximately $-139$ to $-128$ dB. In sharp contrast, the spreading loss for GPS is approximately $-158$ dB. The signal-to-noise ratio (SNR) for the receiver is $S = (P G_R \cdot \lambda^2)/(L N_0 \cdot 4\pi \cdot 4\pi l^2)$, where $L$ denotes the signal power loss due to the atmosphere and receiver, $N_0$ denotes the noise power spectral density, and $G_R$ denotes the gain of the receive antenna. As a result, the Iridium carrier to noise ratio ($C/N_0$) is much stronger than the GPS $C/N_0$. Radio frequency interference and signal blockages downtown can readily introduce $C/N_0$ degradations of tens of dB. Even so, the Iridium $C/N_0$ is still more optimistic than that for GPS. The clocks on board the Iridium satellites have stabilities better than 10 ppb and drift rates less than 3 Hz/second [9]. Actually, Iridium has already been used to demonstrate time transfers with accuracies better than a few microseconds and even nanoseconds [19].

The LEO satellite SOPs can work in severe environments, such as when rushing to deal with an emergency, fire control inside deep buildings and in combat. It can also be a full standalone backup of the GNSS; ASPN, presented by DARPA, is a typical GPS backup research project. The concept of Iridium SOPs positioning is presented in Figure 1. An antenna with a frequency band from 380 MHz to 20 GHz and a 5 dB gain connects to a radio frequency (RF) front end. There are typically three main processes in the software module: Doppler acquisition, satellite orbit reconstruction and positioning solution. The receiver position is obtained with the instantaneous Doppler positioning, and the position accuracy can be further improved by height aiding. The dotted part in Fig. 1 shows the new analysis methods, which include error analysis and the relationship between the geometrical distribution of satellites and positioning error. More details are presented in the following sections.

The measurements are taken from the acquisition process since the Iridium satellite burst signals are discontinuous. Generally, the signals are much stronger than the noise. Doppler coarse and fine measurements are obtained by the fast fourier transform (FFT) and maximum likelihood estimator (MLE) algorithms [20], where the latter can improve measurement accuracy which are effected by the FFT resolution. Iridium satellite orbital data can be provided in NORAD.

![TABLE 1. Spreading loss statistical results for Iridium And Gps.](image-url)

| Elevation [degrees] | IRIDIUM Spreading loss [dB] | GPS Spreading loss [dB] |
|---------------------|----------------------------|------------------------|
| 5                   | -139                       | -159                   |
| 85                  | -128                       | -157                   |
two-line element set format (TLE), which consists of orbital parameters and time information. The SGP4 prediction model is used for the purpose of reconstruction. Iridium TLE sets are periodically updated once or twice every day and can be acquired directly from the NORAD website celestrak.com. The Iridium satellite position errors based on TLE can be from 100 m to several kilometers, and the corresponding satellite velocity errors can be approximately 3 m/s, and their values are rather smaller in the radial direction than for cross and along direction.

III. INSTANTANEOUS DOPPLER POSITIONING AND ANALYSIS OF POSITIONING ERRORS

This section mainly presents a new analysis method for positioning errors: geometric analysis. We begin with a look at the principles of the instantaneous Doppler positioning technique and the corresponding Doppler DOP. Next, the influences of measurement errors and orbital errors on position accuracy are analyzed with the new method, and the mathematical models of position errors are presented.

A. INSTANTANEOUS DOPPLER POSITIONING AND DOPPLER DOP

If satellite Doppler-shift is recorded by a static receiver on the earth surface at some moment, without considering any errors, all points with the same measurement form a circular conical surface, as shown in Fig. 2. Point N denotes the projection of the satellite on the cone undersurface. In the following sections, this special cone is defined as an iso-Doppler circular conical surface (IDCCS), and the angle $\theta$ between the directions of satellite velocity and line-of-sight is defined as the field angle of this IDCCS. The Doppler-shift is expressed as

$$f_d = \frac{1}{\lambda} v_{Sat} \cdot \frac{r_{Sat} - r_{User}}{||r_{Sat} - r_{User}||}$$

where $r_{Sat}$ and $v_{Sat}$ are the satellite position and velocity vectors, respectively, $r_{User}$ is the user position vector, and $\lambda$ is the signal wavelength. Equation (1) is an approximate expression for Doppler-shift in that the satellite line-of-sight velocity is much smaller than the speed of light [21]. With the aid of the expression $v_{Sat} = ||v_{Sat}||$

$$f_d = \frac{1}{\lambda} v_{Sat} \cos(\theta)$$

For a given satellite, as a result of the Doppler-shift measurement process of a static receiver, the user must locate somewhere on the corresponding IDCCS. If the receiver repeats the same process with other satellites simultaneously, the receiver is at the intersection of these IDCCSes. As a result, the receiver position can be calculated by the Doppler measurement equation when enough satellites are available.

The navigation equations of instantaneous Doppler positioning can be obtained by different methods. Van [15] differentiated the linearized pseudorange positioning equations, and the user position is solved by the least squares algorithm. Although the vector expressions of the navigation solution from different methods are different, the scalar expressions are the same. Doppler positioning takes receiver clock frequency-drift as an unknown quantity instead of a receiver-clock error. If one cannot acquire the precise transmitted time of the signal, time error can be regarded as an unknown variable. This method is called the snapshot technique in pseudorange positioning. Fernández-Hernández and Borre studied this in his paper, and the experiments showed that the method was advanced [17].
Generally, at least four satellites are needed for instantaneous Doppler positioning. For the static receiver, Doppler measurements of the same or different satellites at different moments can be used for positioning since the receiver coordinates are unchanged over time. However, the receiver clock frequency drift maybe changed at different moments due to the instability of clock. As a result, it is modeled with a three order polynomial and six unknowns need to be calculated. In this context, at least six Doppler measurements of the same or the different satellites at different moments are needed in this case. With height aiding, the common unknowns can be reduced to five, and five Doppler measurements are enough for positioning.

Hypothetically, the measurement errors have zero mean, are uncorrelated and have equal variance, which is denoted $\sigma_v^2$. Let $\sigma_u^2$ denote the variances of positioning errors; therefore,

$$\sigma_u = DPDOP \cdot \sigma_v$$  (3)

DPDOP is the Doppler position dilution of precision. The IDCCS in 2-D space is shown in the top plot of Fig. 3. Points A and B denote the true and estimated positions of the receiver, respectively. The difference between the directions of the real line-of-sight and measurement is denoted by $\Delta \theta$. Consider that its left half is depicted as the position vector form in the middle plot of Fig. 3. The vector $\vec{AB}$ represents the position error. The vector $\vec{v}_{AB} = \vec{v}_B - \vec{v}_A$ in the bottom plot of Fig. 3 denotes the difference between the true Doppler-shift vector and realistic measurement vector. As a result, measurement errors produce a new velocity vector $\vec{v}_{AB}$. The estimation of the receiver position shifts from the true position A to estimated position B by the velocity $\|\vec{v}_{AB}\|$ after a period of time. The conclusion is still valid if the receiver position estimates are other points on segment SB. Considering the statistical characteristics of measurement errors, the standard deviations $\sigma_v$ and $\sigma_u$ in (3) correspond to $\|\vec{v}_{AB}\|$ and $\|\vec{AB}\|$, respectively. Obviously, DPDOP represents the time; its physical significance is the time spent by the Doppler positioning solution as it shifts from the true position to the estimation due to the existence of measurement errors. The above conclusions still hold true in terms of a 3-D space and are also valid for Doppler horizontal dilution of precision (DHDOP) and Doppler vertical dilution of precision (DVDOP).

**B. GEOMETRICAL ANALYSIS OF THE INFLUENCE OF DOPPLER-SHIFT MEASUREMENT ERRORS**

The measurement errors often come from several sources, such as ionospheric influence, troposphere influence, and receiver noise. It is assumed that the Doppler-shift measurement is $f_{\text{obs}} = f_{\text{Real}} + \Delta f \cdot f_{\text{Real}}$ is the true measurement, and $\Delta f$ is the measurement error. In Fig. 4 top plot, if $\Delta f < 0$, the receiver got an IDCCS2 instead of IDCCS, and its field angle is $\theta_{\text{obs}} = \theta_{\text{real}} + \Delta \theta$; $\theta_{\text{real}} = \theta$ is the true field angle. If $\Delta f > 0$, the receiver got an IDCCS1 instead of IDCCS.

As a result, the influence of measurement errors on IDCCS is the changing of field angle, as shown in the top plot of Fig. 4. When the receiver uses this satellite and other satellites for positioning, the realistic intersections should be on inaccurate IDCCS instead of true IDCCS due to the existing of the Doppler measurement errors. As a result, the positioning solution is at point B instead of true position A.

In fact, $\Delta \theta$ is not a constant. Suppose that IDCCS2 and IDCCS1 correspond to the boundary values of measurement errors, and all the IDCCs obtained by the receiver are between IDCCS1 and IDCCS2 and have the same vertex. As a result, the influence of measurement errors changes the IDCCS to a special geometry, and its bottom is an annulus. We define this regular geometry as Doppler Annulus Cone Geometry (DACG).
Similarly, the position solution should be on IDCCS1 instead of IDCCS. Considering the fact that errors are stochastic, the value and the corresponding direction are uncertain. Let the IDCCS1 revolve about the line SO of IDCCS and the value of \( \theta \) remain unchanged. As a result, the corresponding IDCCS turns into a DACG. It can be seen that the influence of direction error of satellite tangent velocity on IDCCS is similar to that of satellite tangent velocity error. In addition, the effects contributed by the satellite position error must be included. Let \( \Delta r_{\text{Sat}} \) denote the position error vector; with the aid of (4), the field angle of IDCCS has nothing to do with the satellite position vector \( r_{\text{Sat}} \), which means that IDCCS is not out of shape due to \( \Delta \theta = 0 \). However, the position of IDCCS is shifted. The satellite position with errors may be in or on the sphere of radius \( L_{\text{max}} \) corresponding to the boundary of errors, as shown in the bottom plot of Fig. 4. As a result, satellite position errors turn the normal IDCCS into an irregular geometry. In general, Doppler positioning is less sensitive to satellite position errors than satellite velocity errors. Because the former only shifts the position of IDCCS and the latter causes the position errors to be related to the line-of-sight due to the changing of field angle. The effects of orbit errors on IDCCS for a special satellite are the combination of all the effects of satellite positioning errors, satellite tangent velocity errors, and the velocity direction errors. The IDCCS turns into an irregular geometry when the orbital errors exist.

D. MATHEMATIC MODEL OF POSITIONING ERROR

The new geometric analysis method can be intuitive for illuminating the error effects. Here, we present the mathematic model of the effect of the satellite orbital errors and measurement errors. Suppose that \( n \) satellites can be seen by the static receiver at the moment, the Doppler positioning estimation vector is \( \mathbf{X} = [r_{\text{ix}}, r_{\text{iy}}, r_{\text{iz}}, \delta t_{\text{x}}, \delta t_{\text{y}}, \delta t_{\text{z}}]^T \), the satellite position vector is \( r_{1i} = [r_{\text{ix}}, r_{\text{iy}}, r_{\text{iz}}]^T, (i = 1, 2, \ldots, n) \), and the satellite velocity vector is \( v_{1i} = [v_{\text{ix}}, v_{\text{iy}}, v_{\text{iz}}]^T, (i = 1, 2, \ldots, n) \), and let \( \mathbf{G}_{\text{doppler}} \) denote the Jacobian matrix of the Doppler navigation equation; then, the Doppler-shift measurement vector \( \mathbf{d} = [\mathbf{d}_{\text{ix}} \mathbf{d}_{\text{iy}} \mathbf{d}_{\text{iz}} \cdots \mathbf{d}_{\text{nx}} \mathbf{d}_{\text{ny}} \mathbf{d}_{\text{nz}}] \), \( (i = 1, 2, \ldots, n) \), can be written in matrix form as

\[
\mathbf{d} = \mathbf{G}_{\text{doppler}} \mathbf{dX} + d\Gamma
\]

\[
\mathbf{dX} = (\mathbf{G}_{\text{doppler}}^T \mathbf{G}_{\text{doppler}})^{-1} \mathbf{G}_{\text{doppler}}^T (\mathbf{d} \mathbf{\hat{p}} - d\Gamma)
\]

where

\[
\mathbf{d} = \mathbf{K}_{1r} \begin{bmatrix} dr_{1x} \\ dr_{1y} \\ dr_{1z} \end{bmatrix} + \ldots + \mathbf{K}_{nr} \begin{bmatrix} dr_{nx} \\ dr_{ny} \\ dr_{nz} \end{bmatrix} + \mathbf{M}_{1v} \begin{bmatrix} dv_{1x} \\ dv_{1y} \\ dv_{1z} \end{bmatrix}
\]

\[
+ \ldots + \mathbf{M}_{nv} \begin{bmatrix} dv_{nx} \\ dv_{ny} \\ dv_{nz} \end{bmatrix}
\]

Matrices \( \mathbf{K}_{nr} \) and \( \mathbf{M}_{nv} \) are the differential coefficient matrices corresponding to the satellite position and velocity. With the
Then, the position accuracy can be expressed as

$$\mathbf{P}_{dX} = E\left[\mathbf{dX} \cdot \mathbf{dX}^T\right]$$

Equation (9) shows that orbital errors can be seen as measurement errors. More specifically, it is assumed that all visible satellites have the same variances \(\sigma_1, \sigma_2, \sigma_3\) of positioning errors and variances \(\sigma_1^2, \sigma_2^2, \sigma_3^2\) of velocity errors. Let \(d_i\) denotes the line-of-sight distance of satellite \(i\). The measurement errors and orbital errors are zero mean and are not related to each other; then,

$$\mathbf{P}_{dX} = \left(\mathbf{G}^T_{\text{doppler}} \mathbf{G}_{\text{doppler}}\right)^{-1}\mathbf{G}^T_{\text{doppler}} E[\mathbf{d} \mathbf{p} \mathbf{d}^T] \mathbf{G}_{\text{doppler}} E[\mathbf{d} \mathbf{p} \mathbf{d}^T]^T \left(\mathbf{G}^T_{\text{doppler}} \mathbf{G}_{\text{doppler}}\right)^{-1}$$

where

$$d_{i1}^2 = \frac{v_{ix}}{d_i} \frac{r_{ix} - r_{ux}}{d_i^2},$$

$$d_{i2}^2 = \frac{v_{iy}}{d_i} \frac{r_{iy} - r_{uy}}{d_i^2},$$

$$d_{i3}^2 = \frac{v_{iz}}{d_i} \frac{r_{iz} - r_{uz}}{d_i^2},$$

According to (11) and (12), the positioning accuracy is determined by measurement accuracy and geometric factor. The former includes the Doppler measurement errors and orbital errors that are reflected by \(\sigma_1, \sigma_2, \sigma_3\), \(i = 1, 2, \ldots, n\).

Geometric factor is the relative location relationship between the satellites and user, which is reflected by \(a_{i1}^2, a_{i2}^2, a_{i3}^2\), \(i = 1, 2, \ldots, n\) and \(\mathbf{G}_{\text{doppler}}\). Actually, the positioning accuracy is mainly affected by satellite velocity errors, since the values of \((\sigma_1^2 + \sigma_2^2 + \sigma_3^2)\) are generally very small. This conclusion is accord with the geometrical analysis results of the effects of satellite orbital errors above.

### IV. EFFECTS OF CONSTELLATION GEOMETRIC DISTRIBUTION ON POSITION ACCURACY

The effects of constellation geometric distribution on position accuracy are taken into account here. The constellation geometric distribution not only includes the relationship of the relative position of a satellite and receiver but also that of the relative velocity directions of different satellites. We provide the related analysis after introducing a geometrical concept.

#### A. DEFINITION OF DACGPLY

If the receiver is located at the earth surface, the estimations from instantaneous Doppler positioning are distributed in a region that is the intersection between DACGs and the earth surface. The relationship between measurement error \(\Delta v\) and field angle error \(\Delta \theta\) can be written as

$$|\Delta \theta| = \left|\frac{\Delta v}{v_{sat}(-\sin(\theta))}\right|$$

where \(v_{sat}\) is the satellite tangential velocity, and \(\theta\) is the true field angle. The \(v_{sat}\) and \(\Delta v\) are constants for the moment. When the satellite tangential velocity is orthogonal to the line-of-sight, \(\Delta \theta\) achieves the minimum value.

The case in the top plot of Fig. 5 corresponds to an elevation less than 90 degrees, and point B denotes the receiver position. Drawing a plane perpendicular to segment SB, that plane intersects segments SD and SC at points E and F, respectively. Segment EF is defined as the ply of the corresponding DACG (DAGPLY); the expression is

$$\text{DAGPLY} = \tan\left(\frac{\Delta v}{\|v_{Sat}(-\sin(\theta))\|}\right) \cdot \|r_{Sat} - r_{User}\|$$

FIGURE 5. Analyzing the constellation geometrical distribution. Schematic of the DACGPLY definition (top) and schematic of the DACGPLY characteristic analysis (bottom).
According to (14), the greater the distance $\|\mathbf{r}_{\text{Sat}} - \mathbf{r}_{\text{User}}\|$ is, the larger the DACGPLY value is. The effect of measurement error $\Delta v$ on DACGPLY influences the Doppler DOP value indirectly. Since the distance of line-of-sight between the receiver and satellite is always too far, DACGPLY value is large. As a result, the DPDOP is often larger than the geometric dilution of precision (GDOP) of pseudorange positioning.

### B. RELATIONSHIP BETWEEN CONSTELLATION GEOMETRICAL DISTRIBUTION AND POSITION PRECISION

The analysis here considers two aspects, which are the character of single satellite DACGPLY and the relative position relationship of the DACGs of multiple satellites.

Point O is the satellite subpoint, and the solid line L and the dotted line L’ denote the satellite trail and subtrack, respectively, as shown in the bottom plot of Fig. 5. Line UU’ is perpendicular to line L’ and passes through point O. The dotted lines AM and AN are perpendicular to line L’ and line UU’, respectively. The field angle of true IDCCS is denoted by $\theta$. Point C in triangle AMO and point D in triangle ANO are symmetrical with respect to line AO. First, the receiver is on track L’. The larger $\theta$ is, the smaller the distance $\|\mathbf{r}_{\text{Sat}} - \mathbf{r}_{\text{User}}\|$ is, and then DACGPLY will be small. Second, the receiver is on line UU’; then, field angle $\theta$ is constant. The closer the distance between the subpoint and receiver is, the smaller the distance $\|\mathbf{r}_{\text{Sat}} - \mathbf{r}_{\text{User}}\|$ is. As a result, DACGPLY will be small. Third, the receiver at station A moves towards UU’ along AN. The field angle $\theta$ increases, and the distance $\|\mathbf{r}_{\text{Sat}} - \mathbf{r}_{\text{User}}\|$ decreases, which means that DACGPLY will be small. If the receiver moves towards L’ along AM, the field angle $\theta$ and distance $\|\mathbf{r}_{\text{Sat}} - \mathbf{r}_{\text{User}}\|$ decrease. Whether DACGPLY gets larger or smaller is all in accordance with specific conditions. The DACGPLY at point D will be smaller than that at point C. Finally, the LEO satellite DACGPLY is smaller than the MEO satellite DACGPLY when considering the above three conditions due to the characteristics of the LEO orbit. The DACGPLY is also smaller for near-equatorial users, since the influence of the earth rotation on the relative motion of the satellite is greater.

One can conclude that the DACGPLY is small if the receiver is at a direction orthogonal to the satellite velocity direction. Its value is even smaller for the receiver near the subpoint in this case. Conversely, the satellites with corresponding subpoints that are closer to the receiver and corresponding angles between satellite velocity and line-of-sight that are larger have smaller DACGPLY, which means that these satellites are more suitable for instantaneous Doppler positioning.

The analysis above concerns the characteristics of DACGPLY; however, the position errors are also related to the different DACG positions. The intersection region of different DACGs depends on satellite positions and satellite velocity directions. The width of the intersection region between DACG and the earth surface is larger than the corresponding DACGPLY, since satellite elevation is often less than 90 degrees. Three cases are in place to discuss the characteristics of the intersection of different DACGs. First, two satellites are adjacent, and the elevations are almost equal. The corresponding vertical intersection region of two DACGs will be large when the satellite velocity directions approach each other; as a result, larger position errors exist in the vertical direction. Second, considering the same condition, the vertical intersection of DACGs will be larger if two satellite elevations increase, which means that the vertical position error will be larger. At the same time, the width of the intersection arc region between each DACG and the earth surface will be smaller. However, the horizontal intersection region of two DACGs may be large, and it all depends on the satellite velocity directions. Finally, consider the condition that the two satellite elevations are small; for instance, the receiver and two satellites are in the same plane. Then, the vertical intersection of DACGs will be relatively smaller than for the above two cases regardless of the satellite velocity directions. The horizontal intersection will be small if the line-of-sight directions are perpendicular. At the same time, the vertical intersection of DACGs will be even smaller if the receiver is located on the satellite subtrack.

In conclusion, for satellites with high elevations, velocity directions that are equally spaced and satellites with low elevations, the corresponding subtracks are close to the receiver and should be used for instantaneous Doppler positioning. With altitude aiding, low elevation satellites can be ignored when the horizontal positioning precision is in a receivable scope, which means that only satellites with larger elevations are used for positioning.

### V. EXPERIMENTAL RESULTS

We present some experimental results based on simulation data and real data. The simulations are carried out to verify the theoretical analysis of Doppler DOP above, and the real Iridium NEXT data collection and analysis are used to test the Iridium SOPs positioning, as described below.

### A. SIMULATION TEST OF THE ANALYSIS OF DOPPLER DOP

Systems Tool Kit (STK) software of Analytical Graphics Inc. is used to simulate the LEO satellite orbits, and the orbital altitude is 780 km. The receiver is located on the X-axis of the ECI coordinate system, and the altitude is zero during the initial time of the STK project. Three satellites, S1, S2, and S3, are all located above the receiver, the corresponding orbital inclinations are 10 degrees, 45 degrees and 80 degrees, and the anomalies are all 0 degrees. The orbital inclination of S4 is 135 degrees, and the corresponding anomaly is –24 degrees. The constellation of LEO satellites and receiver are shown in Fig. 6. Three cases are presented in the experimental verification.

First, the relationship between DHDP and satellite positions is verified. The positions of satellites S1, S2 and S3 remain unchanged, and the elevation of satellite S4 is changed by adjusting the corresponding true anomaly. The solid line
in Fig. 7 shows the DHDOP as a function of the $S_4$ position. The dotted line represents the changing curve of DHDOP when $S_4$ is located on the top of the receiver, and the true anomalies of $S_1$, $S_2$ and $S_3$ are changed simultaneously. Second, the relationship between DHDOP, DVDOP and the satellite velocities is verified. Keeping the locations of $S_1$, $S_2$ and $S_3$ unchanged, the satellite velocity directions of $S_3$ and $S_1$ are changed simultaneously by adjusting the corresponding orbital inclinations. The curves in Fig. 8 show the relationship between the Doppler DOP and the satellite velocity directions, and the x-axis represents the angular between the orbital inclination of $S_1$ or orbital inclination of $S_3$ and the orbital inclination of $S_2$. Finally, the relationship between Doppler DOP and satellite positions is verified. Without loss of generality, the true anomalies of $S_1$, $S_2$ and $S_3$ are all 3 degrees. The changing curves of Doppler DOP when the $S_4$ elevation is increasing are drawn in Fig. 9.

The changing of true anomaly from left to right in Fig 7 means that the satellite elevation is increasing and then tapering. The solid line shows that the elevation of $S_4$ has almost no influence in DHDOP when other satellites are on the top of the receiver. Because the width of the horizontal intersection region between different DACGs is decided by higher elevation satellites, the horizontal positioning error is restricted within a scope. From the dotted line, we can see that the DHDOP values decrease obviously with increasing $S_1$, $S_2$ and $S_3$ elevations when $S_4$ is on the top of the receiver. The changing trend of DHDOP is in connection with the other three satellite positions and satellite velocities. DHDOP is smaller for the higher elevation satellites because the width of the intersection region between all the DACGs and the earth surface is smaller, which means that the horizontal intersection will not be restricted by only one high elevation satellite. As a result, more satellites near the top of the receiver should be used to constrain the horizontal position errors, since it includes 2-D errors.

Fig. 8 shows that the more dispersive the satellite velocity directions are, the smaller the Doppler DOP is. The curve of DVDOP is almost a straight line since the vertical intersection area is not changing. The results in Fig. 9 show that DPDOP and DVDOP are sensitive to the $S_4$ satellite elevation. The vertical intersection gets larger as the elevation of satellite $S_4$ increases, which means that the elevation variation
primarily affects the up-direction position errors. The DHDOP is almost unchanged since the remaining satellites restricted the horizontal position accuracy. The effects of constellation geometrical distribution on position accuracy are verified by the tests. Using the analysis proposed above, we are able to obtain a better Doppler DOP.

B. EXPERIMENT AND ANALYSIS OF INSTANTANEOUS DOPPLER POSITIONING BASED ON IRIDIUM NEXT SIGNALS

We present some experimental results based on real Iridium data collected. Every IRIDIUM NEXT data blocks are collected by a static receiver in the parking area of BUAA university for 30 min, and the wide antenna with 9 dB gain is under open sky, as shown in Fig. 10. The IF data collector receives the raw data with a sampling rate of 112 MHz at a RF center frequency of 1626.25 MHz, and the center frequency of the recorded data is 28.25 MHz. In practice, the received signals are from two downlink-only channels. However, only one channel signal is used for positioning. Since no orbital information can be decoded from the signals, TLE data will be involved. The results of Iridium signal acquisition and Iridium SOPs positioning are presented, as described below.

1) ACQUISITION OF IRIDIUM NEXT SIGNALS
The IRIDIUM system uses a combination of SDMA, FDMA, TDMA and TDD. The TDMA frame is in total 90 ms long, and the simplex channel is 20.32 ms. The system uses L-band frequencies of 1616 to 1626.5 MHz for the user link. The FDMA scheme divides the simplex channel bandwidth into 12 channels of 41.67 kHz for a total of 0.5 MHz from 1626.0 to 1626.5 MHz [22]. Each IRIDIUM signal burst has an unmodulated tone, unique word and information data [23]. The IRIDIUM NEXT data that were collected by us are the Ring Alert signal and Primer message signal.

The tone signal in each burst is used to measure Doppler frequency shift by identifying the peak of the FFT of the signal and a maximum likelihood estimator (MLE) of frequency [20]. The IF of the Ring Alert signal is 28.270833 MHz. It repeats every 48 frames, which means that the repetition time in the same beam of the same satellite is 4.32 s. The top-left panel of Fig. 11 shows the time domain plot of a burst signal in the collected data. The top-right plot of Fig. 11 shows the result of the frequency estimation by MLE. The bottom-left plot and bottom-right panel of Fig. 11 show the corresponding I-Q diagram and phase angle of the baseband burst, respectively.

The bandwidth of this burst is approximately 26.6667 kHz, and the signal duration is approximately 6.8 ms. The IF acquired by MLE is 28.244935683 MHz, which means that the corresponding Doppler-shift is 25897.317 Hz. We can see that the IRIDIUM NEXT signal consists of three parts, which are tone (no modulation), unique word (BPSK modulation) and information (QPSK modulation), as shown in the bottom-right plot. Similar results can still be obtained after performing the same step for the Primer Message signal. Actually, the duration of the real collected burst signals are between 6.5 ms and 20.32 ms, and the duration of the tone is approximately 2.6 ms. On the other hand, for the ring alert channel, the two bursts with corresponding intervals that are rigorously 90 ms and multiples of 90 ms in the actual data capture means that they are from the adjacent and the non-adjacent beams of the same satellite. If not, they are transmitted by different satellites.

2) POSITIONING BASED ON IRIDIUM NEXT SIGNAL

The entire 30 min of data are divided into 5000 data blocks, and the Doppler-shift will be acquired if the data block contains the burst. The left and right plots in Fig. 12 show the Doppler-shift curves of the 7 and 11 downlink-only channels. The receiver can see 7 IRIDIUM NEXT satellites during 30 min, and at most 2 satellites can be viewed simultaneously. The first visible satellite just passes the top of the receiver. The three longer curves show that the corresponding satellites are on the same track as the first visible satellite. The corresponding subsatellite points of these four satellites...
are near the receiver, while those for the remaining satellites are not. The Doppler curves in the two figures have exactly the same profile since the signals corresponding to every pair of curves belong to the same satellites and show that the Ring Alert signal and the Primary message signal are not synchronous.

The TLE data are obtained as the satellite ephemerides, and the instantaneous Doppler positioning based on the ring alert signals and height aiding are used for receiver positioning. After static receiver acquires Doppler measurements from 30 min IRIDIUM NEXT data, positioning solution equations are formed by total 25 different satellite Doppler measurements at different moments. Receiver position information can be calculated by Least Squares (LS) with different 25 Doppler measurements.

Fig. 13 shows the positioning results with different Doppler measurement combinations from 30 min IRIDIUM data (every combination has 25 Doppler measurements from 6 satellites, the position calculations are run for a total of 800 times). The mean error and Root Mean Square (RMS) are calculated every 50 times. The satellites at low and high elevations are involved, and the mean value of DPDOP is 424 s.

The top left plot of Fig. 13 shows that the north-direction position error has a smaller mean value. However, the solutions are bad in the east direction, the corresponding mean error is relatively large because it is almost 180 m, and the fluctuations in error magnitude can be 380 m. The statistical results of height aiding are shown in the bottom left and right plots of Fig. 13. The largest mean errors of east-direction and north-direction are approximately 46 m and 24 m, respectively, and the east-direction error has a relatively larger fluctuation that is caused by the special IRIDIUM orbital characteristic.

To improve the position accuracy, the Kalman Filtering (KF) is used to process the Least squares (LS) solutions from different Doppler measurement combinations. After testing with multiple IRIDIUM data blocks (a total of 24 h), the 2-D position error of the new method for static receiver can achieve 22 (1σ) m in an open sky.

The experiment presented above is performed in an open sky environment. Then, we show the IRIDIUM signals capture under hostile environment. The IRIDIUM signals and GPS L1 signals are collected together under a dense forest shown in Fig. 14. The GPS signals are processed in real time for positioning by the traditional software receiver that made by our CNT Lab (see the left computer in Fig. 14). The IRIDIUM signal spectrum is shown on the right computer in Fig. 14. Clearly, the power of IRIDIUM Ring Alert signals is higher than the noise for about 8 dB.

The Doppler curves of the IRIDIUM Ring Alert signals and the position result are shown in Fig. 15 and Fig. 16, respectively. Although the visible times of satellites are less than those under open sky, the SNR is still optimistic...
and the Doppler measurements are enough for positioning by the new positioning method. The estimation is 108m from the receiver position. Fig. 17 shows the real-time processing result of GPS L1 signals. At most time, only one satellite can be seen, and it is not kept being tracked by the static receiver, which means sometimes no GPS satellite can be seen by receiver. As a result, the GPS receiver does not work under such circumstances.

Further work on this topic can cover the performance analysis and the positioning experiments on Iridium SOPs positioning at low SNR.

VI. CONCLUSION

This article investigated the use of Iridium signals that are treated as the noncooperative SOPs for positioning. The key innovation was the development of a new geometric analysis method of positioning errors of the instantaneous Doppler positioning and the finding of the relationship between the constellation geometric distribution and the positioning accuracy. The new concept of Iridium SOPs positioning and the effects of constellation geometric distribution on positioning errors were then tested using a real IRIDIUM NEXT data set and STK simulations, respectively. The key findings from this work are described below.

The physical significance of DPDOP, as well as DHDOP and DVDOP, is the time spent by the Doppler positioning solution shifts from the true position to the estimation due to the existence of measurement errors.

The geometric analysis shows that the effects of measurement errors and satellite velocity errors on the instantaneous Doppler positioning are the changing of the IDCCS profile, while the effects of satellites’ position errors shift the position of IDCCS. The positioning accuracy is mainly affected by satellite velocity errors instead of satellite position errors.

The theoretical analysis and simulation results show that the satellites with high elevations and velocity directions that are equally spaced are more suitable for improving the horizontal positioning accuracy, and for the satellites with low elevations, the corresponding subtracks that are close to the receiver should be used to restrict the vertical positioning errors.

The Doppler-shift measurements can be used for Iridium SOPs positioning. Using real Iridium data in an open sky environment, the 2-D position accuracy can achieve 22 m (1σ) with height aiding.

REFERENCES

[1] G. Seco-Granados, J. A. López-Salcedo, D. Jiménez-Baños, and G. López-Risueño, “Challenges in indoor global navigation satellite systems: Unveiling its core features in signal processing,” IEEE Signal Process. Mag., vol. 29, no. 2, pp. 108–131, Feb. 2012. doi: 10.1109/MSP.2011.943410.
[2] B. Peterson, R. Hartnett, and G. Ottman, “GPS receiver structures for the urban canyon,” in Proc. ION GPS, Palm Springs, CA, USA, Sep. 1995, pp. 1323–1332.
[3] A. Abosekeen, A. Noureldin, and M. J. Korenberg, “Improving the RISS/GNSS land-vehicles integrated navigation system using magnetic azimuth updates,” IEEE Trans. Intel1. Transp. Syst., to be published. doi: 10.1109/TITS.2019.2905871.
[4] K. M. Pesyna, Jr., Z. M. Kassas, J. A. Bhatti, and T. E. Humphreys, “Tightly-coupled opportunistic navigation for deep urban and indoor positioning,” in Proc. ION GPS, Portland, OR, USA, Sep. 2011, pp. 3065–3616. doi: 10.1109/GLOCOMW.2011.6162371.
[5] C. Yang and T. Nguyen, “Self-calibrating position location using signals of Opportunities,” in Proc. ION GNSS, Savannah, GA, USA, Sep. 2009, pp. 1055–1063. doi: 10.1109/NAECON.2009.5426658.
[6] Z. M. Kassas and T. E. Humphreys, “Observability analysis of collaborative opportunistic navigation with pseudorange measurements,” IEEE Trans. Intell. Transp. Syst., vol. 15, no. 1, pp. 260–273, Feb. 2014. doi: 10.1109/TITS.2013.2278293.

[7] D. Lawrence, H. S. Cobb, G. Gutt, F. Tremblay, P. Laplante, and M. O’Connor, “Test results from a LEO-Satellite-Based assured time and location solution,” in Proc. ION GNSS, Monterey, CA, USA, Jan. 2016, pp. 125–129. doi: 10.33012/2016.13416.

[8] T. G. Reid, A. M. Neish, T. F. Walter, and P. K. Enge, “Leveraging commercial broadband LEO constellations for navigating,” in Proc. ION GNSS, Portland, OR, USA, Sep. 2016, pp. 2300–2314.

[9] E. Per, B. Ferrell, J. Bennett, D. Whelan, G. Gutt, and D. Lawrence, “Orbital diversity for satellite navigation,” in Proc. ION GNSS, Nashville, TN, USA, Sep. 2012, pp. 3834–3846.

[10] M. Rabinowitz, B. W. Parkinson, C. E. Cohen, M. L. O’Connor, and D. G. Lawrence, “A system using LEO telecommunication satellites for rapid acquisition of integer cycle ambiguities,” in Proc. IEE Position Location Navigat. Symp., Palm Springs, CA, USA, Apr. 1998, pp. 137–145. doi: 10.1109/PLANS.1998.670034.

[11] J. Hill, “The principle of a snapshot navigation solution based on Doppler shift,” in Proc. ION GPS, Salt Lake City, UT, USA, Sep. 2001, pp. 3044–3051.

[12] Y. Sakamoto, H. Arie, T. Ebinuma, K. Fujii, and S. Sugano, “High-accuracy IMES localization using a movable receiver antenna and a three-axis attitude sensor,” in Proc. IPIN, Guimaraes, Portugal, Sep. 2011, pp. 1–6. doi: 10.1109/IPIN.2011.6071915.

[13] M. Kirkko-Jaakkola, J. Parviainen, J. Collin, and J. Takala, “Improving TTFF by two-satellite GNSS positioning,” IEEE Trans. Aerosp. Electron. Syst., vol. 48, no. 4, pp. 3660–3670, Oct. 2012. doi: 10.1109/taes.2012.6324754.

[14] F. Van Diggelen, A-GPS: Assisted GPS, GNSS, and SBAS, Norwood, MA, USA: Artech House, 2009, pp. 206–214.

[15] H.-W. Chen, H.-S. Wang, Y.-T. Chiang, and R. F. Chang, “A new coarse-time GPS positioning algorithm using combined Doppler and code-phase measurements,” GPS Solutions, vol. 18, no. 4, pp. 541–551, 2014. doi: 10.1007/s10291-013-0350-8.

[16] J. Hill, “Orbital diversity for satellite navigation guided and control from Harbin Engineering University, China,” in Proc. ION GNSS, Portland, OR, USA, Sep. 2010, pp. 60–65. doi: 10.1109/plans.2012.6236865.

[17] D. Whelan, G. Gutt, and P. Enge, “Robust time transfer from space to backup GPS,” in Proc. ION GNSS, Portland, OR, USA, Sep. 2010, pp. 907–914.

[18] L. Li, J. Zhong, and M. Zhao, “Doppler-aided GNSS position estimation with weighted least squares,” IEEE Trans. Veh. Technol., vol. 60, no. 8, pp. 3615–3624, Oct. 2011. doi: 10.1109/TVT.2011.2163738.

[19] C. Fossa, R. A. Raines, G. H. Gunsch, and M. A. Temple, “An overview of the Iridium (R) low Earth orbit (LEO) satellite system,” in Proc. Aerosp. Electron. Conf., Dayton, OH, USA, Jul. 1998, pp. 152–159. doi: 10.1109/NAECON.1998.710110.

[20] C. M. R. Shahrizar, “A scheme to mitigate interference from Iridium satellite’s downlink signal captured by omnidirectional antenna array,” in Proc. IEEE Antennas Propag. Soc. Int. Symp., San Diego, CA, USA, Jul. 2008, pp. 1–4. doi: 10.1109/APS.2008.4619788.