Attitude Determination Method Based on GNSS Signals Null Steering Technology

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Abstract. GNSS signals are usually used for positioning, but some applications also use them to determinate direction, such as geography north. The attitude of a vehicle could be determined by using multiple short baselines. However, the measurement accuracy is limited by the length of the baseline, so it also limits its application. This paper demonstrates an attitude determination method using GNSS Signals Null Steering (GSNS) technology by a miniaturized phase controlled antenna array. The error of DOA estimation is simulated and analyzed under the condition of received signal's amplitude quantization error and the radiation patterns of antenna cells are inconsistent. The results show that the method has certain engineering feasibility.

Keywords: DOA (Direction of Arrival) · GNSS antenna array · ADM (Attitude Determination Module) · Null steering

1 Introduction

In recent years, with the deployment and operation of giant constellations such as OneWeb and Starlink, as well as the development of Xingwang constellation, telecommunication satellite constellations have become one of the current research hotspots in the space and communications field [1, 2], and present characteristics such as broadband interconnection, and integration of communication and navigation [3].

According to ITU, satellite telecommunication services are divided into fixed satellite service (FSS) and mobile satellite service (MSS). With the development of satellite communication technology, Earth station In Motion (ESIM) [4] communication technology between users and geostationary orbit (GEO) satellites has emerged. Generally speaking, the target satellite of ESIM is GEO satellite, and beacons can be used. It is relatively simple for ESIM users to capture and track the target satellite with narrow beam antenna (hereinafter referred to as pointing access) [5]. For non-GEO communication satellites, due to the low orbit and the fast motion speed relative to the user, the user's pointing access needs to be completed by pointing calculation instead of beacon, and there are some problems such as the low updating frequency of almanac data used in calculation, and the inconsistent coordinates of body attitude and almanac data, which are more difficult than ESIM. Navigation satellite systems (including BD-3 and other global and LEO enhanced navigation satellite systems) can provide body attitude by GNSS signals [6], which solves the problem of inconsistent coordinates to a

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certain extent. However, there are constraints such as the long baseline required and unfavorable miniaturization application.

By the popularity of GNSS receiver, if can the user via the navigation satellite broadcast nearly real-time update of non-GEO satellite almanac data, and users can be implemented through miniaturization of equipment GNSS on board, the user to obtain the goal of the almanac data and body attitude with the same space-based coordinate system (such as BDCS) as a reference, will be able to solve the above problems. For this reason, this paper proposes a method of connecting non-GEO satellite with user pointing assisted by navigation satellite. The core of this method is a miniaturized GNSS multi-DOA (Direction of Arrival) attitude determination method using phase-controlled null steering technology. Preliminary simulation results show that this method has certain engineering feasibility.

2 Beam Access by GNSS Attitude Determination Module

To enable users' high gain antenna beam to access the non-GEO satellite through the auxiliary of the GNSS signals, as shown in Fig. 1, it mainly includes 3 steps: first, the GNSS Attitude Determination Module (ADM) receive GNSS signals from GNSS Antenna array, and second, calculates the body attitude through the measurement of GNSS signals, and finally calculates the beam direction and drives the antenna beam to point to the target non-GEO satellite.

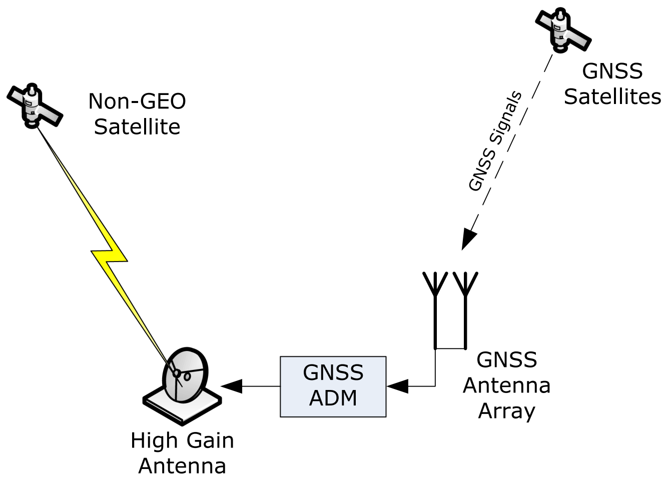

Fig. 1. User beam access to non-GEO satellite by GNSS ADM

After obtaining the almanac data of the target satellite, the direction of the target satellite can be calculated as long as the body attitude is determined (i.e. the attitude determination). Most users adopt inertial equipment (gyro) or radio direction measurement technology [6, 7] to determine the body attitude.

Unmanned aerial vehicle (UAV), for example, is widely used in combined attitude sensor [8], such as MEMS gyroscope (angular velocity), MEMS accelerometer (gravity direction), and magnetometer (geomagnetic measurement direction). The method of attitude determination uses accelerometer to determine horizontal plane and uses magnetometers to determine magnetic north. It is enough for uses of the stability control of flight in a short time, but is insufficient for satellite communications as its inconsistence to space-based coordinates system.

GNSS attitude determination mainly uses the short baseline method to calculate the geographic true north [9]. Combined with gravity measurement, the accuracy of the shot baseline method could be about 0.1°–0.2°/1 m [10, 11], which basically meet the application requirements of pointing access for medium UAV and other platforms. However, the baseline length is still the main bottleneck for minimization application.

Therefore, we need to research and development of miniaturization GNSS attitude determination technology, in order to solve the current problem of the long baseline. It could also be achieved by improving navigation signal carrier frequency, but in this paper the L band is concerned to carry out the analysis in view of the current use.

3 GNSS Attitude Determination Technologies

Assuming that the user body coordinate system is $\mathbf{A} = [\hat{x} \quad \hat{y} \quad \hat{z}]$, and the space-based coordinate system is $\mathbf{G} = [\hat{X} \quad \hat{Y} \quad \hat{Z}]$, and the coordinate transformation relationship between them is: $\mathbf{A}^{\mathrm{T}} = \mathbf{T}_{\mathrm{G2A}}\mathbf{G}^{\mathrm{T}}$. Attitude determination is to determine the transformation matrix $\mathbf{T}_{\mathrm{G2A}}$. Where, the hat ^ means a unit vector, and the superscript $^{\mathrm{T}}$ means the transpose of a matrix.

3.1 Multi-baseline and Multi-DOA Attitude Determination Methods

As shown in Fig. 2, suppose the direction of the satellite i is $\hat{r}_i$, and the vector of the baseline j is $\vec{L}_j$. In the body coordinate system and space-based coordinate system, there are respectively: $\hat{r}_i = \boldsymbol{\rho}_i\mathbf{A}^{\mathrm{T}} = \mathbf{r}_i\mathbf{G}^{\mathrm{T}}, \vec{L}_j = \boldsymbol{\lambda}_j\mathbf{A}^{\mathrm{T}} = \mathbf{L}_j\mathbf{G}^{\mathrm{T}}$, i.e. $\boldsymbol{\rho}_i\mathbf{T}_{\mathrm{G2A}} = \mathbf{r}_i, \lambda_j\mathbf{T}_{\mathrm{G2A}} = \mathbf{L}_j$.

It can be seen that in order to determine the attitude of the body, two methods can be used: one is to measure the baseline vector of the body in the space-based coordinate system, and compare it with the known baseline vector in the body coordinate system; the other is to measure the direction vector of the navigation satellite in the body coordinate system, and compare with the known direction vector of the satellite in the space-based coordinate system.

The first method is the common called multi-baseline method, when there are multiple baselines, we have $[\boldsymbol{\lambda}_j]\mathbf{T}_{G2\mathrm{A}} = [\mathbf{L}_j]$. In the calculation, $\boldsymbol{\lambda}$ is the local measurable quantity and $\mathbf{L}$ is the real measurement. In particular, for the case of three baselines, such as the three antenna method and the four antenna method [9], it can be solved directly:

$$\mathbf{T}_{\mathrm{G2A}} = [\lambda_j]^{-1}[\mathbf{L}_j] \tag{1}$$

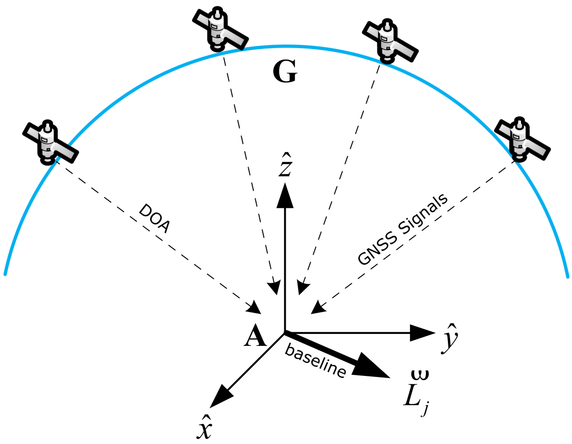

Fig. 2. GNSS attitude determination

The second method is the so-called multi-DOA attitude determination method, when several satellites are observed we have $[\boldsymbol{\rho}_i]\mathbf{T}_{\mathrm{G2A}} = [\mathbf{r}_i]$. In the calculation, $\boldsymbol{\rho}$ is the local observation and $\mathbf{r}$ can be calculated according to the almanac data. It can be solved by the least square method:

$$\mathbf{T}_{\mathrm{G2A}} = \left([\boldsymbol{\rho}_i]^{\mathrm{T}}[\boldsymbol{\rho}_i]\right)^{-1}[\boldsymbol{\rho}_i]^{\mathrm{T}}[\mathbf{r}_i] \tag{2}$$

3.2 Limitation of Carrier Phase Measurement

The carrier phase measurement (CPM) of conventional GNSS receiver can be used for both short-baseline method and multi-DOA method, but there is a limitation of the required baseline length.

In the space-based coordinate system, the carrier phase of multiple satellites (≥ 4) is observed to measure the j-th baseline:

$$\mathbf{P} + 2\pi\mathbf{N} = k\mathbf{R}\mathbf{S}^{\mathrm{T}} + \boldsymbol{\varepsilon} \tag{3}$$

Where $\mathbf{P}$ is the carrier phase vector, $\mathbf{N}$ is the integer ambiguity resolution, $\mathbf{R} = [\mathbf{r}\ 1]$ is the direction matrix, $\boldsymbol{\varepsilon}$ is the error vector, $\mathbf{S} = [\mathbf{L}\ c\tau]$ is the baseline vector with clock difference, c is the velocity of light in free space, τ is the clock offset of GNSS receiver, and k is the carrier wave number. $\mathbf{P}$, $\mathbf{N}$, $\mathbf{R}$ and $\boldsymbol{\varepsilon}$ are expanded according to the number of satellites in the column direction. It can be obtained from formula (3) that:

$$\mathbf{S}^{\mathrm{T}} = \left(\mathbf{R}^{\mathrm{T}}\mathbf{R}\right)^{-1}\mathbf{R}^{\mathrm{T}}(\mathbf{P} + 2\pi\mathbf{N} - \boldsymbol{\varepsilon})/k \tag{4}$$

Then the baseline vector $\mathbf{L}$ is taken out from $\mathbf{S}$ and solved $\mathbf{T}_{\mathrm{G2A}}$ by formula (1).

In the body coordinate system, the direction of the i-th satellite is measured by multi-baseline method:

$$\mathbf{P} + 2\pi\mathbf{N} = k\mathbf{V}\mathbf{W}^{\mathrm{T}} + \boldsymbol{\varepsilon} \tag{5}$$

Where $\mathbf{V} = [\boldsymbol{\lambda}\ 1]$ is the baseline matrix and $\mathbf{W} = [\boldsymbol{\rho}\ c\tau]$ is the direction vector with clock difference. $\mathbf{P}$, $\mathbf{N}$, $\mathbf{V}$, and $\boldsymbol{\varepsilon}$ are expanded according to the baseline number in the column direction. When the number of baselines is 3, formula (5) shows that:

$$\mathbf{W}^{\mathrm{T}} = \mathbf{V}^{-1}(\mathbf{P} + 2\pi\mathbf{N} - \boldsymbol{\varepsilon})/k \tag{6}$$

Then the direction vector $\boldsymbol{\rho}$ is taken out from $\mathbf{W}$ and $\mathbf{T}_{\mathrm{G2A}}$ solved by formula (2).

It should be pointed out that the above two methods are equivalent. In general, the baseline vector and the satellite vector are related by the attitude. In the GNSS carrier phase observation Eq. (3) or (5), the carrier phase just relates the baseline vector and the satellite vector, too. Therefore, the measurement of the carrier phase is equivalent to the attitude. Whether the baseline vector or the satellite vector is regarded as a known quantity, the effect is equivalent.

Further more, to obtain the carrier phase a phase-locked loop (PLL) is usually necessary and the phase precision is difficult to increase. High-precision measurements both rely on long baselines, and there is also the problem of solving the integer ambiguity resolution, which is not conducive to miniaturization application.

In view of the current development level of high-precision phase shifting technology, such as a high-precision phase shifter equivalent to 24 bits implemented in 1 GHz [12], this paper further proposed the attitude determination method based on GNSS signals null steering (GSNS) technology uses multi-DOA method for miniaturization applications.

3.3 GSNS Technology for DOA Estimation

A simple idea of miniaturization is to use a half wavelength spaced GNSS antenna array to scan the DOA of GNSS signals by phased differential beam. For L-band the size of the 4 cells array antenna can be controlled at about 200 mm*200 mm. The 4 cells array can be simplified to 2 cells array for DOA estimation. The unit spacing d of cells is half wavelength, has gain pattern of $f(\theta)$, and cell2 has a B-bit digital phase shifter, as shown in Fig. 3 below.

For a certain DOA θ_0, when the phase shifter is searched step by step, the received signal amplitude is a function of the phase shift quantity ϕ_v:

$$p(\phi_v) = f(\theta_0) + f(\theta_0)\exp(\mathrm{j}(kd\sin\theta_0 + \phi_v)) \tag{7}$$

When the null point appears in the above formula, the DOA can be obtained:

$$\theta_0 = \arcsin((\pi - \phi_v)/k/d) \tag{8}$$

so it is called GNSS Signals Null Steering (GSNS) technology. The relationship between the angular resolution and the phase-shifting resolution can be obtained as:

$$\mathrm{d}\phi_v/\mathrm{d}\theta_0 = -kd\cos\theta_0 \tag{9}$$

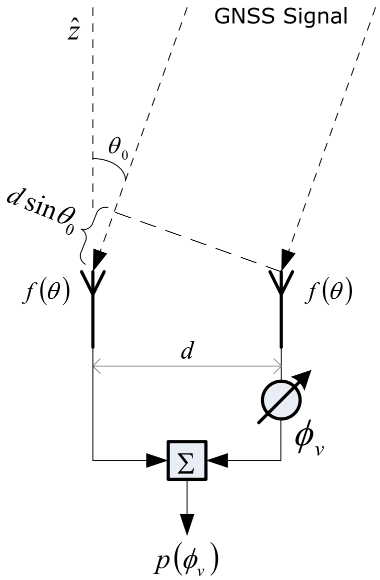

Fig. 3. 2 cells array for DOA estimation

It can be deduced that in order to achieve 0.2° angle DOA estimation accuracy, when the incoming wave is approximate to the vertical incidence, it needs at least 0.6° stepped phase shifting; when the incoming wave is approximately 70° incident, it needs at least 0.2° stepped phase shifting. Though the required phase shifter bits number B could be calculated by:

$$B \geq \log_2\left(180^{\circ}/0.2^{\circ}\right) \approx 10 \tag{10}$$

For this bits number it is feasible in engineering.

For an actual example, the cell is a micro-strip fed patch antenna and both the amplitude and phase radiation pattern is simulated by HFSS®. The cell space is 1/3 wavelength, and the received signal has an amplitude error(pp) of 0.5 dB and phase error(pp) ±1°, and the receiver gets the signal power by C/N0 estimation which has a quantization error of 0.5 dB. Assumed the DOA is 1.2°, we could get the phase scanning curve as shown in Fig. 4, in which the x-axis is marked as varied phase shifter (ϕ_v) and y-axis is marked as received signal amplitude calculated by Eq. (7), thus the null point indicates the estimation of θ_0 which could be calculated by Eq. (8). Though as shown in Fig. 4, the phase scanning curve has a random but zigzag noise and strongly shakes near the null point, it makes the DOA estimation difficult, but we could use a template curve to eliminate the noise and get a more accurate DOA estimation.

The template curve $T(\phi_v)$ is drawn in Fig. 4 as a red or a more smooth curve, which just comes from Eq. (7) by applying ideal cell pattern so

$$T(\phi_v) = A\cos(\theta_0')\left[1 + \exp\left(j\left(kd\sin\theta_0' + \phi_v\right)\right)\right] \tag{11}$$

Where, A and $\theta_0{}'$ are variables to be optimized aimed to make the template curve most reach the curve under test, and $\theta_0{}'$ is just the DOA estimation we pursuing when optimization is obtained.

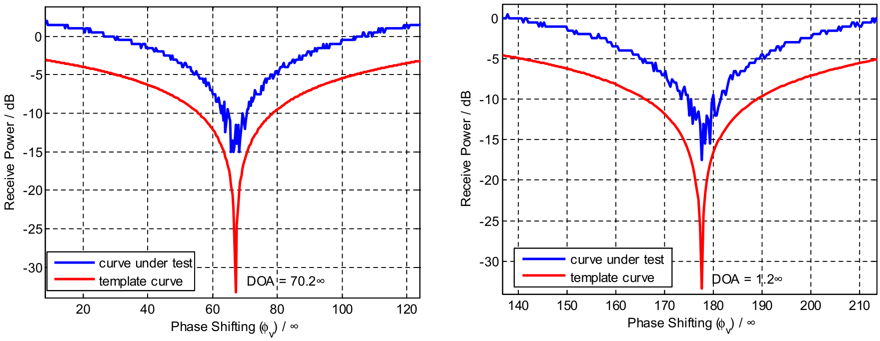

Fig. 4. Phase scanning curve, left: DOA 71.2°, right: DOA 1.2°

For common phase shifters the range of phase variety is 0° to 180°, but it should make the phase scanning curve asymmetric when DOA is near 0° because the null point appears as phase shifter touches its limit 180°. Thus, a wide range phase shifter is used which has a phase variety of 0° to 250° and only ±60° phase scanning around null point is reserved to get a symmetric phase scanning curve. For example as shown in Fig. 4 right, when DOA is 1.2°, the phase scanning curve null point is near 180°, but the actual phase scanning range is up to 120° to 240°.

Except for finding the minimum value of the GSNS curve to determinate $\theta_0{}'$, we could use least-square method move the template curve by searching A and $\theta_0{}'$ in two dimensions grade calculation, and this is called template curve optimization method, which could significantly improve the accuracy of DOA estimation.

To illustrate this, for an example of the same configuration of Fig. 4, using a phase shifter of 9 bits and 100 times statistics per DOA, we could get the DOA estimation error (1σ) shown as Fig. 5.

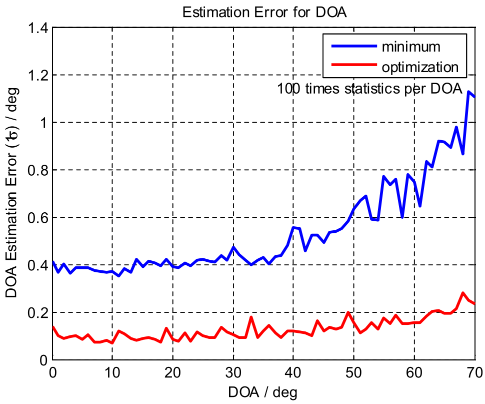

Fig. 5. Estimation error for DOA (Color figure online)

In Fig. 5, the blue curve is the DOA estimation error using minimum method to find null point, and the red curve using the template curve optimization method mentioned above. It could be seen that the estimation error is decrease to about 1/5 of the minimum method after using the template curve optimization method. So, we could get about 0.2° accuracy in 0° to 70° DOA range only by a 1/3 wavelength cell space and 9 bits phase shifter, and it has an advantage of miniature and engineering.

Furthermore, the direction vector ρ of the target satellite can be obtained by using two orthogonal 2 cells arrays, and then $\mathbf{T}_{G2A}$ can be solved by using formula (2).

4 Typical Applications

The miniaturized GNSS multi-DOA ADM enables users to realize positioning and attitude determination without relying on inertial navigation, accelerometer, magnetometer and other means. For example, the miniaturized GNSS multi-DOA ADM can be widely used for attitude measurement and attitude control of mobile platforms such as automobiles, UAVs, micro/nano satellites, etc., and can also be used for attitude measurement independent of gravity and geomagnetism, and play a role in special geological conditions.

Typical application scenarios such as a high gain flat antenna integrated with four elements GNSS multi-DOA ADM can independently sense its body attitude and adjust its beam direction, so as to realize pointing access with target non-GEO satellite.

With the completion of BD-3 global navigation satellite system and the development of non-GEO constellations, the planning of the next generation navigation satellite system is put on the agenda under the background of telecommunication and navigation integration. Taking full advantage of the popularity of navigation signal and GNSS receiver, the miniaturized GNSS multi-DOA ADM technology can provide systematic solutions for the user's antenna beam access of non-GEO constellation, which will further promote the development of telecommunication and navigation integration.

5 Conclusion

In this paper, the method of attitude determination using GNSS signal is researched and analyzed, in which the short baseline method has some disadvantages in miniaturization, and the GNSS Signals Null Steering (GSNS) technology is proposed in this paper which is suitable for miniaturization. Now we could sum up the following conclusions:

1) The attitude determination method based on GNSS signal could be divided into two forms: multi-baseline attitude determination and multi-DOA attitude determination, and both of them are equivalent;
2) The common short baseline method belongs to multi-baseline attitude determination, and the GSNS method proposed in this paper belongs to multi-DOA attitude determination, and thus they are equivalent, too. But because of the difference of the observation means, the GSNS method has better performance;
3) According to the characteristics of GSNS curve, this paper proposes a universal GSNS template curve optimization method which greatly improves the accuracy of DOA estimation.

In this paper, the DOA estimation accuracy of a 2 cells GNSS antenna array is simulated and analyzed. The simulation results show that the DOA estimation error will decrease to 1/5 of the original after using the template curve optimization method, even if the received signal has an amplitude quantization error and the radiation patterns of antenna cells are inconsistent. So it is possible to reduce the number of phase shifters and the cell space, which makes the miniaturization of GNSS ADM more practical.

However, it should be recognized that there are still some key technologies, such as more powerful algorithm to decrease the DOS estimation error, which still needs further research.

References

1. Liu, Y.: Research on the development of foreign LEO high-throughput communication satellite constellation. Int. Space (461) (2017)
2. Guan, Z., He, M.: Hongyan constellation communication system opens a new era of mass satellite communication consumption. In: 2016 Aerospace International Development Forum, Beijing (2016)
3. Wang, Y., Li, X., Wang, X.: Preliminary design of ground communication application system of LEO constellation. Commun. Technol. **52**(3) (2019)
4. Tian, W., Han, Z., Mu, X.: Analysis of frequency rules of Ka band mobile to China Communication. In: The 12th Annual Conference of satellite communication, Beijing (2016)
5. Cui, X., Xi, X., Zhang, Y.: High dynamic Ku/ka dual antenna civil aviation communication system design. Comput. Meas. Control **27**(5) (2019)
6. Li, S., Liu, L., Yan, G.: Determination of spacecraft attitude using GPS carrier coherent measurement technology. Aerosp. Control (4) (1998)
7. Liu, J., Zhu, X.: Comparative study on multiple methods of radio direction finding. Inf. Commun. (11) (2017)
8. Xue, Y.: Attitude fusion and navigation method of small rotor UAV. University of Electronic Science and Technology (2016)

9. Wu, M., Hu, X., Fu, L.: Satellite orientation technology. National defense science and Technology Industry Press, Beijing (2013)
10. Um482 Product Manual of Multi Frequency High Precision Positioning and Orientation Module of The Whole System. https://www.unicorecomm.com
11. He, X., Wu, M.: Low cost GNSS receiver chip carrier phase measurement technology. Navigat. Control **17**(5) (2018)
12. Wang, X., et al.: Design of high precision numerical control microwave phase shifter. J. Microwave **25**(3) (2009)