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The Self-Verification of GNSS Multi-mode Single Epoch Attitude Determination:Method and Test

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***Abstract*— In recent years, there is a growing interest in GNSS (Global Navigation Satellite System) compass type attitude determination system. Multi-mode single epoch scheme is the point for the current research, since it is insensitive to cycle slips and it has a higher success rate. With this scheme, the coverage, integrity and availability can also be improved for the practical application. As a new type of compass, being different from the magnetic compass and gyrocompass, the correctness of resolved heading and elevation should be verified by internal fitting method or external fitting method. In this contribution, as one internal fitting method, the self-verification of GNSS multi-mode single epoch compass system is studied, based on the double collinear baselines with different lengths. Actual dynamic experiments based on L1/L2/B1 observations have been performed, the relative yaw and relative pitch are computed and the results verify the correctness of GNSS multi-mode single epoch compass system with the self-verification method.**

Keywords—GNSS compass; self-verification; short baseline; integer ambiguity resolution; accuracy

I. INTRODUCTION

In the past decades, for attitude determination of vehicles, there are two widely used and fundamentally different types of compass: the magnetic compass and the gyrocompass. The magnetic compass contains a magnet that interacts with the earth's magnetic field and aligns itself to point to the magnetic poles. The gyrocompass contains a motorized gyroscope whose angular momentum interacts with the force produced by the earth's rotation to maintain a north-south orientation of the gyroscopic spin axis, thereby providing a stable directional reference [1]. However, the accuracy of the magnetic compass is affected by the magnetic field intensity nearby the equipment, and the gyroscopes suffer from the error drift.

In recent years, there is a growing interest in GNSS (Global Navigation Satellite System) compass type attitude determination system. Carrier phase measurements from two antennas and an integer ambiguity resolution method are used to obtain precise attitudes such as yaw and pitch in this system. Compared with the magnetic compass and the gyrocompass, the GNSS compass can point to any desired direction without the above-mentioned shortcomings [2]. For this technique, one antenna is assumed to be a reference and another is assumed to be a rover. By finding the baseline vector defined by two antennas, the vehicle attitude can be determined, namely the heading (or yaw) and elevation (or pitch).

In order to acquire high-precision heading and elevation, the GNSS carrier phase measurements are usually employed. However, the phase observations are in essence affected by integer ambiguities: only the fractional part of the phase of the incoming GNSS signal can be measured [3]. Integer ambiguity resolution (IAR) is the process of resolving the unknown cycle ambiguities of the carrier phase data as integer, and many studies have been carried out to investigate the IAR method. More recent IAR methods make use of the Constrained LAMBDA (CLAMBDA) method to estimate the integer ambiguity, which is proved to be a fast, reliable estimator [4]. With this estimator, the successful ambiguity resolution can be achieved by utilizing instantaneous measurements, namely the single epoch ambiguity resolution, thus making IAR a total independence from carrier phase slips and losses of lock [5]. On the other hand, in order to improve the accuracy, the coverage, integrity and availability in the practical applications, the observables from multiple GNSS constellations (GPS, GLONASS, Galileo and Compass) are often utilized, namely the multi-mode scheme. It is desired from the perspective of users to exploit the possibilities and opportunities of fusing signals from different constellations so as to enhance coverage, accuracy, integrity, and availability. Thus, for modern GNSS compass system, various GNSS multi-mode single epoch schemes are often utilized.

As a new type of compass, the correctness of resolved heading and elevation should be verified. Two approaches can be utilized for validating the correctness: internal fitting and external fitting. For external fitting, other types of compass should be utilized such as gyrocompass, inertial navigation system and heading reference system. The major drawbacks of this method are the higher cost and the error drift of devices. Compared with the external fitting, internal fitting is easier to be achieved and no extra equipment is required, namely the self-verification method.

In this contribution, the self-verification of GNSS multi-mode single epoch compass system is studied, based on the double collinear baselines with different lengths. The assessment of accuracy is also achieved with this scheme. Actual dynamic experiments based on L1/L2/B1 observations have been performed to verify the correctness of GNSS multi-mode single epoch compass system.

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II. THE BASIC MODEL OF GNSS COMPASS

A. Attitude Estimation

For GNSS-based attitude determination, two antennas are often attached to a vehicle, and then a baseline vector defined as a vector from reference antenna to another antenna can be determined using GPS relative positioning technique. The yaw and pitch of the vehicle can thus be computed from the resolved baseline vector $\boldsymbol{b}$. If the baseline vector from reference antenna to another antenna is parameterized with respect to the local East-North-Up frame, the heading ψ and the elevation θ can be computed from the baseline components (coordinates) b_E, b_N and b_U as

$$\psi = \tan^{-1}\left(b_E / b_N\right) \tag{1}$$

$$\theta = \tan^{-1}\left(b_U \Big/ \sqrt{b_N^2 + b_E^2}\right) \tag{2}$$

B. GNSS Compass Model

With a prior baseline length, the GNSS compass model reads as [6]:

$$E(\boldsymbol{y}) = \boldsymbol{Aa} + \boldsymbol{Bb}, D(\boldsymbol{y}) = \boldsymbol{Q}_y, \boldsymbol{a} \in Z^n, \boldsymbol{b} \in R^3, \|\boldsymbol{b}\| = l \tag{3}$$

where $\boldsymbol{y}$ is the given GNSS data vector, and $\boldsymbol{a}$ and $\boldsymbol{b}$ are the ambiguity vector and the baseline vector of order n and 3 respectively. $E(\cdot)$ and $D(\cdot)$ denote the expectation and dispersion operators, respectively, and $\boldsymbol{A}$ and $\boldsymbol{B}$ are the given design matrices that link the data vector to the unknown parameters. The variance matrix of $\boldsymbol{y}$ is given by the positive definite matrix $\boldsymbol{Q}_y$, which fully characterizes the statistical properties of the given GNSS data vector. Since the baseline length is often known in practical applications, this priori given baseline information can be treated as a useful constraint as well. In Equation (3), l denotes the known baseline length, which is assumed to be constant. Note that the GNSS compass model (3) involves two types of constraints: the integer constraints on the ambiguities and the length constraint on the baseline vector. For this model, once $\boldsymbol{a}$ is resolved, the least-squares solution for $\boldsymbol{b}$, namely the conditional least-squares solution, can be written as

$$\hat{\boldsymbol{b}}(\boldsymbol{a}) = \left(\boldsymbol{B}^T \boldsymbol{Q}_y^{-1} \boldsymbol{B}\right)^{-1} \boldsymbol{B}^T \boldsymbol{Q}_y^{-1} (\boldsymbol{y} - \boldsymbol{Aa}) \tag{4}$$

The corresponding variance matrix is given as

$$\boldsymbol{Q}_{\hat{b}(a)} = \left(\boldsymbol{B}^T \boldsymbol{Q}_y^{-1} \boldsymbol{B}\right)^{-1} \tag{5}$$

To solve the GNSS model (3), one usually applies the least-squares principle and this amounts to solving the following minimization problem:

$$\min_{\boldsymbol{a} \in Z^n, \boldsymbol{b} \in R^3, \|\boldsymbol{b}\| = l} \|\boldsymbol{y} - \boldsymbol{Aa} - \boldsymbol{Bb}\|_{Q_y}^2$$
$$= \|\hat{\boldsymbol{e}}\|_{Q_y}^2 + \min_{\boldsymbol{a} \in Z^n} \left(\|\hat{\boldsymbol{a}} - \boldsymbol{a}\|_{Q_{\hat{a}}}^2 + \min_{\boldsymbol{b} \in R^3, \|\boldsymbol{b}\| = l} \left\|\hat{\boldsymbol{b}}(\boldsymbol{a}) - \boldsymbol{b}\right\|_{Q_{\hat{b}(a)}}^2 \right) \tag{6}$$

where $\|(\cdot)\|_{Q_y}^2 = (\cdot)^T \boldsymbol{Q}_y^{-1} (\cdot)$ and $\hat{\boldsymbol{e}}$ is the least squares residuals. Moreover, the following cost function can be formulated [7]:

$$\min_{\boldsymbol{a} \in Z^n} \left(\|\hat{\boldsymbol{a}} - \boldsymbol{a}\|_{Q_{\hat{a}}}^2 + \min_{\boldsymbol{b} \in R^3, \|\boldsymbol{b}\| = l} \left\|\hat{\boldsymbol{b}}(\boldsymbol{a}) - \boldsymbol{b}\right\|_{Q_{\hat{b}(a)}}^2 \right) \tag{7}$$

In this case, the conditional least-squares solution for $\boldsymbol{b}$ and its variance matrix are both required for the estimator. The solution to the minimization problem follows therefore as

$$\breve{\boldsymbol{a}} = arg \min_{\boldsymbol{a} \in \boldsymbol{Z}^n} \left(\|\hat{\boldsymbol{a}} - \boldsymbol{a}\|_{Q_{\hat{a}}}^2 + \min_{\boldsymbol{b} \in R^3, \|\boldsymbol{b}\| = l} \left\|\hat{\boldsymbol{b}}(\boldsymbol{a}) - \boldsymbol{b}\right\|_{Q_{\hat{b}(a)}}^2 \right) \tag{8}$$
$$\breve{\boldsymbol{b}} = \hat{\boldsymbol{b}}(\breve{\boldsymbol{a}})$$

This can be solved by the Constrained (C-) LAMBDA method with high efficiency and high success rate [8].

C. Error Propagation of GNSS Compass

The baseline vector in the local East-North-Up frame can be expressed as follows:

$$\boldsymbol{b} = \begin{bmatrix} b_E \\ b_N \\ b_U \end{bmatrix} = \begin{bmatrix} l \sin\psi \cos\theta \\ l \cos\psi \cos\theta \\ l \sin\theta \end{bmatrix} = \Omega(\Lambda) \tag{9}$$

where Ω is the nonlinear operator and $\Lambda = (\psi \quad \theta \quad l)^T$.

Linearization of these nonlinear observation equations can be given as [9]

$$\begin{bmatrix} \delta b_E \\ \delta b_N \\ \delta b_U \end{bmatrix} = \begin{bmatrix} l_0 \cos\psi_0 \cos\theta_0 & -l_0 \sin\psi_0 \sin\theta_0 & \sin\psi_0 \cos\theta_0 \\ -l_0 \sin\psi_0 \cos\theta_0 & -l_0 \cos\psi_0 \sin\theta_0 & \cos\psi_0 \cos\theta_0 \\ 0 & l_0 \cos\theta_0 & \sin\theta_0 \end{bmatrix} \begin{bmatrix} \delta\psi \\ \delta\theta \\ \delta l \end{bmatrix} \tag{10}$$

where the given Taylor point of expansion is $\Lambda_0 = (\psi_0 \quad \theta_0 \quad l_0)^T$ and terms of second order and higher order have been neglected. The inverse of equation (10) becomes

$$\begin{bmatrix} \delta\psi \\ \delta\theta \\ \delta l \end{bmatrix} = \begin{bmatrix} \dfrac{\cos\psi_0}{l_0 \cos\theta_0} & \dfrac{-\sin\psi_0}{l_0 \cos\theta_0} & 0 \\ \dfrac{-\sin\psi_0 \sin\theta_0}{l_0} & \dfrac{-\cos\psi_0 \sin\theta_0}{l_0} & \dfrac{\cos\theta_0}{l_0} \\ \sin\psi_0 \cos\theta_0 & \cos\psi_0 \cos\theta_0 & \sin\theta_0 \end{bmatrix} \begin{bmatrix} \delta b_E \\ \delta b_N \\ \delta b_U \end{bmatrix} \tag{11}$$

With the law of variance and covariance (v-c) propagation, the v-c matrix of Λ can be calculated by

$$\boldsymbol{Q}_\Lambda = \boldsymbol{J}^{\mathrm{T}} \boldsymbol{Q}_{\hat{b}(a)} \boldsymbol{J} \tag{12}$$

where $\boldsymbol{J}$ is the matrix that link the baseline error vector to the attitude error parameters in (11). Note that $\boldsymbol{Q}_{\hat{b}(a)}$ is determined by the design matrix $\boldsymbol{B}$ and the positive definite matrix $\boldsymbol{Q}_y$, see also (5). With σ_E^2, σ_N^2 and σ_U^2 being the diagonal elements of $\boldsymbol{Q}_{\hat{b}(a)}$, we have the following expressions [10]:

$$\sigma_{\delta\psi}^2 = \frac{(\cos\psi_0)^2 \sigma_E^2 + (\sin\psi_0)^2 \sigma_N^2}{l_0^2 (\cos\theta_0)^2} \tag{13}$$

$$\sigma_{\delta\theta}^2 = \frac{(\sin\psi_0 \sin\theta_0)^2 \sigma_E^2 + (\cos\psi_0 \sin\theta_0)^2 \sigma_N^2 + (\cos\theta_0)^2 \sigma_U^2}{l_0^2} \tag{14}$$

$$\sigma_{\delta l}^2 = (\sin\psi_0 \sin\theta_0)^2 \sigma_E^2 + (\cos\psi_0 \cos\theta_0)^2 \sigma_N^2 + (\sin\theta_0)^2 \sigma_U^2 \tag{15}$$

Equation (13) and (14) indicates that the accuracies of the estimated attitude angles found by using carrier phase are inverse proportional to the length of the baseline used. In other words, the accuracies of heading and elevation can be further improved for the longer baseline. Thus, if the

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baseline is long enough, it can be treated as the reference system with high accuracy.

III. THE SELF-VERIFICATION OF GNSS COMPASS

With the discussion on the error propagation and the accuracy assessment of GNSS compass, a new method is proposed for the self-verification of GNSS multi-mode single epoch compass system. That is, without any other kind of compass, the correctness of GNSS compass attitude determination are achieved by the internal fitting.

A. The Basic Principle

In order to achieve the self-verification of GNSS compass, the proposed method utilizes double collinear baselines but with distinctly different lengths. One is the purpose baseline equipped for the vehicle, and the other is treated as the reference system, which is much longer than the purpose baseline.

Firstly, both baselines should be setup in the collinear way. In general, at least three antennas are employed and set up in the same straight line, which is shown in Fig.1.

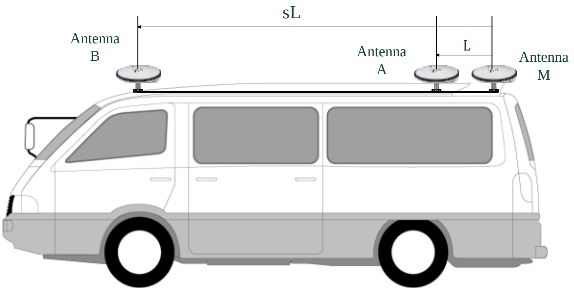

Fig.1 Double collinear baselines with three antennas

The purpose baseline is setup with Antenna M and Antenna A in Fig.1, namely MA, and the baseline length is L. The reference baseline is setup with Antenna M and Antenna B, denoted as MB, and the baseline length is *s* times longer than MA. To make sure that the accuracy of reference baseline is high enough, the length of baseline MB should be long and the times *s* is large.

Second, the phase centers of all the antennas are required to be stable enough, thus making the drift error of phase center minimized. If the drift error is very large, the attitude angles of long baseline may not be close enough to true attitude angles, thus making the reference baseline inaccurate even if all the geometric centers of the three antennas are in the same straight line. Hence, the surveying antennas with very stable phase center are required for the self-verification procedure.

B. The Accuracy Assessment

Note that Equation (5) is nothing to do with the baseline placement and the design matrix $\boldsymbol{B}$ is determined by the satellite geometry and the positive definite matrix $\boldsymbol{Q}_y$ is determined by the noise levels of observables. Thus, with the same type GNSS receivers and the same observing period, both baseline MA and baseline MB have the same variance matrices $\boldsymbol{Q}_{\hat{b}(\boldsymbol{a})}$, indicating that σ_E^2, σ_N^2 and σ_U^2 of the both baseline vector are the same.

For the purpose baseline, with L being the baseline length, the accuracies of yaw and pitch are given by

$$\sigma_{MA,\delta\psi}^2 = \frac{(\cos\psi_{MA})^2\sigma_E^2 + (\sin\psi_{MA})^2\sigma_N^2}{L^2(\cos\theta_{MA})^2} \tag{16}$$

$$\sigma_{MA,\delta\theta}^2 = \frac{(\sin\psi_{MA}\sin\theta_{MA})^2\sigma_E^2 + (\cos\psi_{MA}\sin\theta_{MA})^2\sigma_N^2 + (\cos\theta_{MA})^2\sigma_U^2}{s^2L^2} \tag{17}$$

For the reference baseline, with sL being the baseline length, the accuracies of yaw and pitch are given by

$$\sigma_{MB,\delta\psi}^2 = \frac{(\cos\psi_{MB})^2\sigma_E^2 + (\sin\psi_{MB})^2\sigma_N^2}{L^2(\cos\theta_{MB})^2} \tag{18}$$

$$\sigma_{MB,\delta\theta}^2 = \frac{(\sin\psi_{MB}\sin\theta_{MB})^2\sigma_E^2 + (\cos\psi_{MB}\sin\theta_{MB})^2\sigma_N^2 + (\cos\theta_{MB})^2\sigma_U^2}{s^2L^2} \tag{19}$$

Note that the baseline placement can also affect the accuracy of GNSS compass, since the errors of heading and elevation are related to the direction of baseline vector. By disregarding the installation error of both baselines, we have

$$\psi_{MA} = \psi_{MB}, \theta_{MA} = \theta_{MB} \tag{20}$$

Hence, the accuracies of reference baseline have the following relationships with those of the purpose baseline:

$$\sigma_{MA,\delta\psi}^2 = s^2 \cdot \sigma_{MB,\delta\psi}^2, \sigma_{MA,\delta\theta}^2 = s^2 \cdot \sigma_{MB,\delta\theta}^2 \tag{21}$$

C. The Multi-frequency Single-constellation Model

If either baseline vector from reference antenna to another antenna is parameterized with respect to the local East-North-Up frame, the heading ψ and the elevation θ of both baselines can be computed as follows:

$$\psi_{MA} = \tan^{-1}\left(\frac{b_{MA,E}}{b_{MA,N}}\right), \theta_{MA} = \tan^{-1}\left(\frac{b_{MA,U}}{\sqrt{b_{MA,N}^2 + b_{MA,E}^2}}\right) \tag{22}$$

$$\psi_{MB} = \tan^{-1}\left(\frac{b_{MB,E}}{b_{MB,N}}\right), \theta_{MB} = \tan^{-1}\left(\frac{b_{MB,U}}{\sqrt{b_{MB,N}^2 + b_{MB,E}^2}}\right) \tag{23}$$

Then the relative heading and relative elevation can be computed as follows:

$$\psi_{MA-MB} = \psi_{MA} - \psi_{MB}, \theta_{MA-MB} = \theta_{MA} - \theta_{MB} \tag{24}$$

Hence, the accuracies of relative heading and relative elevation have the following relationship with those of reference baseline:

$$\sigma_{MA-MB,\delta\psi}^2 = (s^2+1)\cdot\sigma_{MB,\delta\psi}^2, \sigma_{MA-MB,\delta\theta}^2 = (s^2+1)\cdot\sigma_{MB,\delta\theta}^2 \tag{25}$$

For the standard deviation, we have

$$\sigma_{MA-MB,\delta\psi} = \sqrt{s^2+1}\cdot\sigma_{MB,\delta\psi}, \sigma_{MA-MB,\delta\theta} = \sqrt{s^2+1}\cdot\sigma_{MB,\delta\theta} \tag{26}$$

Without the true attitude angles, the self-verification procedure can thus be achieved with

$$E(\psi_{MA-MB}) = 0, E(\theta_{MA-MB}) = 0 \tag{27}$$

$$\frac{\sigma_{MA-MB,\delta\psi}}{\sqrt{s^2+1}} = \frac{\sigma_{MA,\delta\psi}}{s} = \sigma_{MB,\delta\psi}, \frac{\sigma_{MA-MB,\delta\theta}}{\sqrt{s^2+1}} = \frac{\sigma_{MA,\delta\theta}}{s}\cdot\sigma_{MB,\delta\theta} \tag{28}$$

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IV. EXPERIMENTS

This section presents the evaluation of the propose self-verification procedure based on actual dynamic tests. The accuracies of yaw and pitch are also compared with different baseline lengths.

A. Platform and Test Environment

In order to achieve the propose self-verification procedure for GNSS single epoch compass, the actual GNSS measurements are collected with three NovAtel's OEM628 boards, which are designed with 120 channel and can tracks all current and upcoming GNSS constellations and satellite signals including GPS, GLONASS, Galileo and Compass. Configurable channels optimize satellite availability in any condition, no matter how challenging. For this experiment, the GPS L1/L2 and Compass (or BDS) B1 are exploited for constructing the GNSS multi-mode single epoch compass model. In order to minimize the multipath interference, three Trimble® Zephyr™ Model 2 antennas are utilized for this experiment, and this type of antenna has outstanding low elevation satellite tracking performance and extremely precise phase center accuracy and it also supports the GPS L1/L2 and Compass (or BDS) B1 bands.

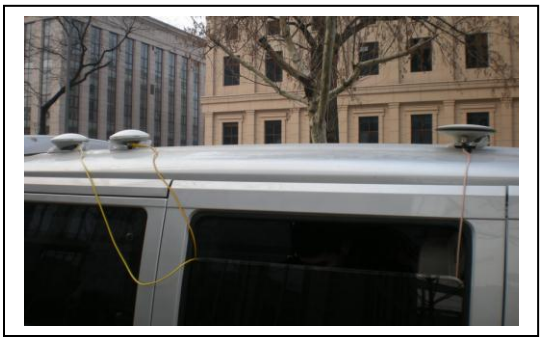

Fig.2 The experiment system and environment

The proposed method has been tested processing actual data collected during a dynamic experiment, in which a car was equipped with three antennas and the shorter baseline length is 0.325m and the longer baseline length is 1.625m, as is shown in Fig.2. The car is moving along a narrow rectangle block about 4 laps and both ends of the rectangle block are arc-shaped. During about 410 seconds observation, the number of available satellites equals eight for GPS and five for Compass most of the time. The constellation of GPS satellites in this experiment is shown in Fig.3 and the constellation of Compass satellites is shown in Fig.4, and each satellite is discernible by its PRN number. Note that the star symbol denotes the geostationary satellites of Compass. The numbers of visible satellites are given in Fig.5.

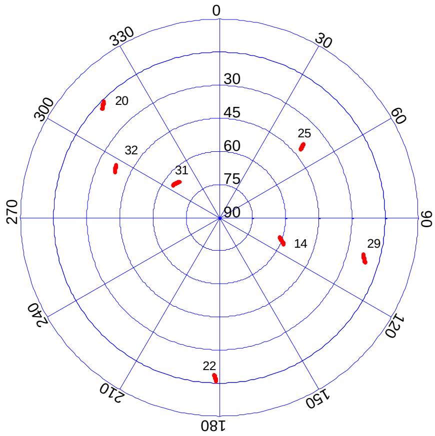

Fig.3 The constellation of GPS satellites

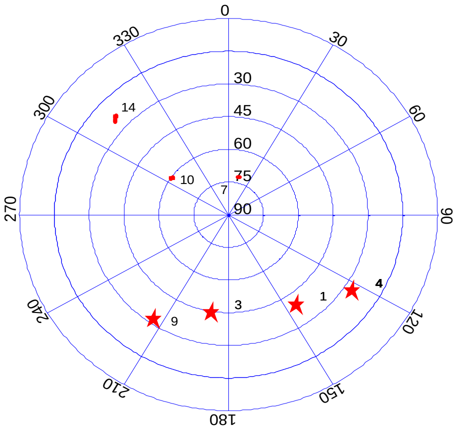

Fig.4 The constellation of Compass satellites

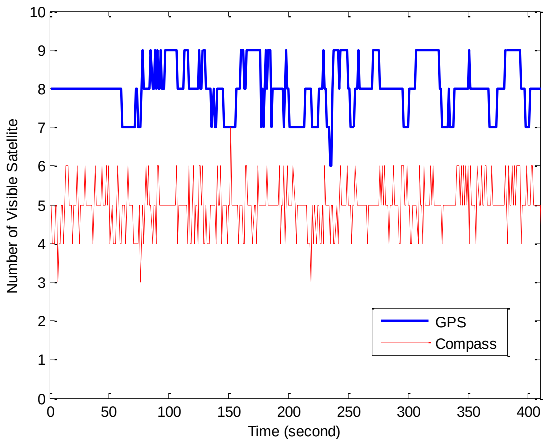

Fig.5 The number of visible satellites

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B. Comparison of Attitude Determination

The heading/yaw and elevation/pitch are resolved based on the model (8) with Constrained (C-) LAMBDA method. The yaw and pitch results are demonstrated in Fig.6 and Fig.7, respectively.

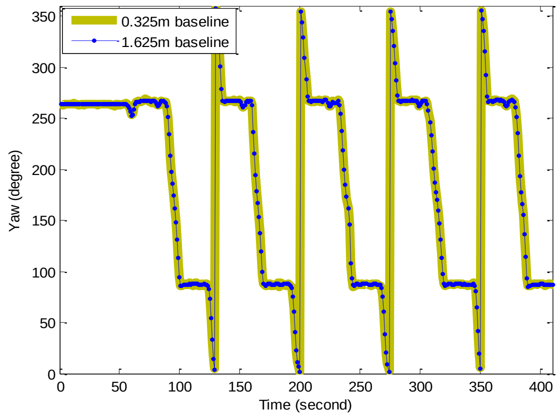

Fig.6 The yaw comparison for 0.325m baseline and 1.625m baseline

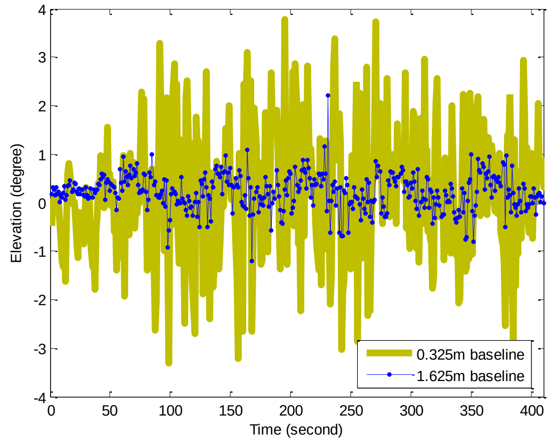

Fig.7 The pitch comparison for 0.325m baseline and 1.625m baseline

As is shown, the accuracy of 1.625m baseline is much higher than that of the 0.325m baseline. However, the yaw and pitch angles of both baselines are consistent. The resolved relative yaw and pitch are also given in Fig.8 and Fig.9, respectively.

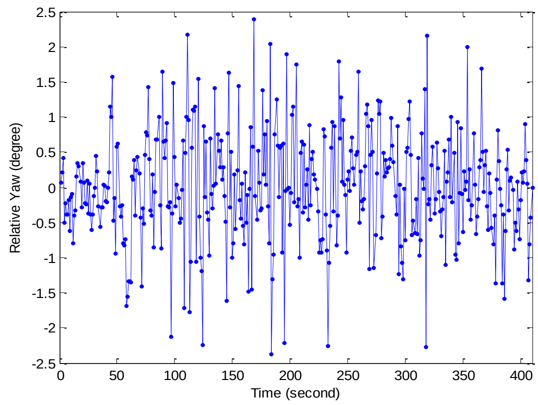

Fig.8 The relative yaw of the purpose baseline and the reference baseline

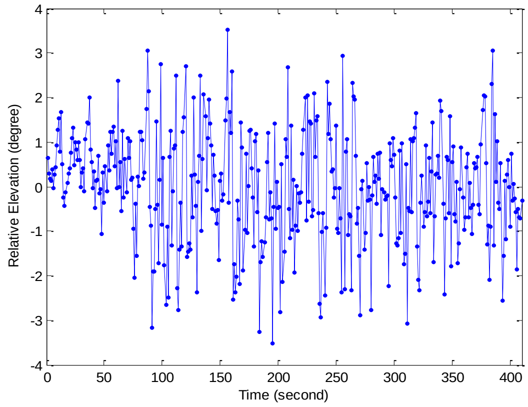

Fig.9 The relative pitch of the purpose baseline and the reference baseline

C. Accuracy Assessment of Relative Attitude Angles

As shown in Table I, the average and standard deviation of relative attitude angle measurements of dynamic this experiment are given.

TABLE I. RELATIVE ACCURACY ASSESSMENT

Table Head	Mean Value (degree)	Standard deviation (degree)
Relative Yaw	0.0088	0.7782°
Relative Pitch	0.0013	1.2539°

Since the mean values of both relative yaw and relative pitch are both close to zero, the consistency of both baselines is thus be verified, see Equation (27). Note that we do not know the true attitude angles of both baselines and no other extra device is utilized for the fitting. It is not difficult to find that the reference baseline is five times longer than the purpose baseline. Thus, with Equation (28), it can also be inferred that the yaw accuracy of reference baseline is 0.156° and the pitch accuracy of reference baseline is 0.251°.

With the actual experimental results above, the correctness of GNSS multi-mode single epoch attitude determination can be proved based on the self-verification scheme.

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