Posterior Estimation of Receiver Platform Motion Azimuth Using GPS Velocity Measurements

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Abstract

Azimuth information of moving carriers is crucial for navigation and positioning. It is widely recognized that satellite positioning systems such as the Global Positioning System (GPS) are incapable of performing angular measurements using a single receiver, and therefore cannot directly obtain relevant angular information of single-receiver carriers. Although GPS and similar systems themselves cannot perform attitude determination for user terminals, they can determine real-time azimuth angles of moving receiver carriers based on velocity measurement. This principle is studied and elaborated, and its accuracy level is analyzed. Through field experiments based on vehicle positioning and comparison with angle measurement results from magnetometer sensors, the feasibility and accuracy level of the method are verified. The results demonstrate that although the method of using GPS velocity measurement cannot estimate the receiver' s attitude azimuth angle, it is feasible for estimating the receiver' s motion azimuth angle, and its accuracy is related to the carrier' s motion speed; when the receiver carrier reaches a certain motion speed, a relatively high accuracy level can be achieved. The azimuth information obtained from this estimation can also serve as a state variable in models such as Kalman filtering for positioning results, further improving the accuracy of the filtering model.

Full Text

Estimating the Azimuth of a Moving Receiver by GPS Speed Measurement

Abstract: Azimuth information of moving carriers is crucial for navigation and positioning. It is generally believed that satellite positioning systems such as the Global Positioning System (GPS) cannot measure angles using a single receiver, and thus cannot directly obtain angular information about a single receiver carrier. Although GPS itself cannot measure the attitude of user terminals, it can calculate the real-time azimuth of a moving receiver carrier based on velocity measurements. This paper investigates and elaborates on this principle and analyzes its accuracy level. Through field experiments based on vehicle positioning and comparison with angle measurements from a magnetometer sensor, the feasibility and accuracy of the method are verified. Results demonstrate that while the GPS speed measurement method cannot estimate the attitude azimuth of the receiver, it is indeed feasible for estimating the motion azimuth of the receiver, with precision related to the carrier' s speed. When the receiver carrier reaches a certain speed, high accuracy can be achieved. The azimuth information obtained through this estimation can also serve as a state variable in Kalman filtering models for positioning results, further improving the accuracy of the filtering model.

Keywords: satellite navigation; speed measurement; angle measurement; magnetometer

1. Introduction

Azimuth information plays a vital role in navigation and positioning. After obtaining the azimuth of a moving carrier, one can determine the heading direction of vehicles and vessels, better perform map matching and correction by incorporating angle information to determine motion trajectories, and introduce angle information into error filtering models for post-processing positioning solution data. In vehicle navigation and other fields, azimuth information can also be combined with electronic maps to obtain richer state variables, thereby optimizing filtering models for more ideal results. It is generally believed that GPS can solve for a user' s three-dimensional coordinates and three-dimensional velocity, but cannot measure angles in real time, and thus cannot directly obtain the instantaneous azimuth of a moving receiver carrier. Traditional approaches calculate azimuth between two positioning points after the fact, which lacks real-time capability and suffers from poor accuracy due to large single-point positioning errors. Many satellite positioning terminals integrate gyroscopes, magnetometers, and other sensors to obtain real-time azimuth information with certain accuracy. Although GPS itself cannot measure user terminal attitude, it can measure and calculate the motion azimuth information of the receiver carrier. This enables cost reduction in many situations and applications, allowing estimation of the receiver carrier' s motion azimuth through simple principles and methods without relying on additional hardware. This paper addresses this problem, proposes a method for estimating receiver motion azimuth based on GPS speed measurement, analyzes and predicts the estimation accuracy through error propagation principles, and validates the method through field vehicle experiments.

2. GPS Velocity Measurement Principle

GPS receiver velocity measurement methods can be divided into passive and active categories based on their principles, with passive velocity measurement being more widely used. Passive velocity measurement enables all-weather, full-range, and high-precision speed measurement without requiring the moving carrier to transmit any signals. As long as a GPS receiver is installed on the moving carrier, the velocity at each point along the entire trajectory can be measured in real time during dynamic positioning at user-specified time intervals.

The relative motion between satellites and the user receiver causes a frequency shift in the observed satellite signal. This Doppler shift is typically measured by the carrier tracking loop in the satellite receiver. Given the satellite velocity, the Doppler shift can be used to calculate the receiver velocity. The Doppler shift, also called the range rate, can be viewed as the projection of the relative velocity vector onto the satellite line-of-sight direction. Since the receiver clock drift rate (frequency offset) biases the measurement results, what is actually measured is the pseudorange rate. The pseudorange increment obtained from carrier phase measurements is proportional to the average pseudorange rate, which is proportional to the three-dimensional velocity of the receiver carrier over the time interval, or equivalently, proportional to the projection of the user' s velocity relative to the satellite onto the satellite line-of-sight direction.

The relationship between the receiver carrier' s three-dimensional velocity and the range rate $\dot{\rho}_j$ to satellite j is given by:

$$\dot{\rho}_j = \frac{(X_j - X_u)(\dot{X}_j - \dot{X}_u) + (Y_j - Y_u)(\dot{Y}_j - \dot{Y}_u) + (Z_j - Z_u)(\dot{Z}_j - \dot{Z}_u)}{r_{ju}} + c(\dot{d\tau}_r - \dot{d\tau}_s) + \dot{L}^j_{ion} + \dot{L}^j_{trop} \quad (1)$$

where the parameters are defined as follows: $(\dot{X}_j, \dot{Y}_j, \dot{Z}_j)$ and (X_j, Y_j, Z_j) are the three-dimensional velocity and position of satellite j, respectively, which can be considered known quantities calculated from GPS signals; r_{ju} is the geometric distance from the user to satellite j; $\dot{d\tau}_r$ is the receiver clock drift rate; $\dot{d\tau}_s$ is the satellite clock drift rate; and $\dot{L}^j_{ion}$ and $\dot{L}^j_{trop}$ are the ionospheric and tropospheric delay rates, respectively.

The pseudorange rate $\dot{\rho}_j$ is measured by the GPS receiver according to:

$$\dot{\rho}_j = \frac{c}{f_u}\Delta f = \frac{c}{f_u}\frac{\Delta\phi}{T} \quad (2)$$

where f_u is the actual carrier frequency received by the receiver, f_j is the carrier frequency transmitted by satellite j, $\Delta\phi$ is the measured integrated Doppler shift count, c is the speed of electromagnetic wave propagation, and T is the GPS receiver velocity update rate (the time interval between the velocity measurement moment t_2 and the previous moment t_1). All these parameters are known.

When velocity measurement accuracy is required to reach sub-meter per second or even 0.1 ns/s, the effect of receiver clock drift rate $\dot{d\tau}_r$ must be considered.

The satellite clock drift rate $\dot{d\tau_s}$ is a known quantity for GPS satellites. Since the velocity measurement interval is typically short, the ionospheric and tropospheric delay rates can be considered zero: $\dot{L}^j_{ion} = \dot{L}^j_{trop} = 0$.

With four or more visible satellites, the receiver’ s three-dimensional velocity $(\dot{X}_u, \dot{Y}_u, \dot{Z}_u)$ and receiver clock drift rate $\dot{d\tau_r}$ can be solved from the above process using four equations. In single-point positioning, GPS receivers solve according to this principle, from which acceleration, jerk, and other parameters can be further obtained.

3. Estimating Moving Carrier Azimuth Using Velocity Components

From the discussion in the previous section, velocity components in east, north, and up directions can be solved with four or more satellites. These velocity components can be used to estimate the spatial direction angle information of the moving carrier.

For vehicles, vessels, and other carriers that can be considered moving in a two-dimensional plane, only the east and north velocity components are needed. By synthesizing the east velocity vector $\vec{v}_{east}$ and north velocity vector $\vec{v}_{north}$, a resultant velocity vector $\vec{v}_{resultant}$ can be obtained:

$$\vec{v}_{resultant} = \vec{v}_{east} + \vec{v}_{north} \quad (3)$$

Ignoring hardware and data output delays, during the observation instant, the carrier travels a distance of $\vec{v}_{east} \cdot d\Delta$ in the east direction and $\vec{v}_{north} \cdot d\Delta$ in the north direction. The angle α between the resultant vector and the true north direction can be calculated as:

$$\alpha = \arctan\left(\frac{v_{east}}{v_{north}}\right) \quad (4)$$

Using this formula, the azimuth α of the receiver carrier at each observation instant can be calculated.

[Figure 1: see original paper] Determining azimuth angle by velocity component

4. Analysis of Error Sources in GPS Velocity Measurement

The main error sources affecting GPS velocity measurement include Selective Availability (SA) policy-induced satellite clock frequency jitter $\dot{d\tau_s}$. Since the SA policy has now been revoked, this error can generally be ignored. For receivers moving at medium or low speeds, the primary error source in velocity measurement is the error in predicted satellite positions. Tropospheric delay and multipath effects change little over short time periods.

The impact of satellite orbit error on the range rate can be estimated as:

$$\Delta\dot{\rho}_j = \frac{(\Delta X_j - \Delta X_u)(\dot{X}_j - \dot{X}_u) + (\Delta Y_j - \Delta Y_u)(\dot{Y}_j - \dot{Y}_u) + (\Delta Z_j - \Delta Z_u)(\dot{Z}_j - \dot{Z}_u)}{r_{ju}} \quad (5)$$

Assuming a station-satellite distance r_{ju} of 20,000 km and satellite velocity of 3.2 km/s, when the satellite orbit error is 100 m, the maximum impact on the range rate is about 1.6 mm/s. When the orbit error is 1.6 m, the impact increases to 1.6 cm/s. The International GNSS Service (IGS) publishes GPS satellite orbit accuracies of 1.6 m, and broadcast ephemeris accuracies are also at this level. It can be seen from the equation that satellite orbit errors directly affect the range rate through direction cosines.

For satellite velocity errors, the velocity accuracy calculated using broadcast ephemeris is better than 1 mm/s. If the user is highly dynamic, high acceleration and sudden velocity changes will introduce errors. Due to these error sources, the U.S. Department of Defense has not specified concrete performance metrics for GPS velocity estimation. According to empirical data, most current commercial GPS single-frequency navigation receivers have velocity accuracies in the horizontal direction generally within 0.3 m/s (1). Differential GPS (DGPS) and Real-Time Kinematic (RTK) carrier phase differential techniques can achieve centimeter-level or even higher accuracy. Since the range increment only provides the average velocity over a time interval, this high dynamics also introduces additional receiver phase noise errors.

5. Azimuth Estimation Accuracy Analysis

In a two-dimensional plane, the accuracy of obtained azimuth depends primarily on the velocity measurement accuracy in the east and north directions. Performing partial differentiation on the arctan function yields:

$$d\alpha = \frac{v_{north}}{v_{east}^2 + v_{north}^2} dv_{east} - \frac{v_{east}}{v_{east}^2 + v_{north}^2} dv_{north} \quad (6)$$

From the error covariance propagation law, the variance of azimuth α is:

$$\sigma_\alpha^2 = \frac{v_{north}^2}{(v_{east}^2 + v_{north}^2)^2} \sigma_{east}^2 + \frac{v_{east}^2}{(v_{east}^2 + v_{north}^2)^2} \sigma_{north}^2 \quad (7)$$

To simplify the formula, assuming the velocity errors in the east and north directions are equal ($\sigma_{east} = \sigma_{north} = \sigma_v$), we have:

$$\sigma_\alpha^2 = \frac{\sigma_v^2}{v_{east}^2 + v_{north}^2} = \frac{\sigma_v^2}{v_{resultant}^2} \quad (8)$$

where $v_{resultant}^2 = v_{east}^2 + v_{north}^2$ is the resultant motion speed of the carrier in the two-dimensional plane. The formula can be further simplified to:

$$\sigma_\alpha = \frac{\sigma_v}{v_{resultant}} \quad (9)$$

It can be seen that the accuracy of the estimated azimuth depends on the magnitude of the carrier' s speed in the two-dimensional plane and the velocity measurement error σ_v in the north and east directions.

From the above analysis, for general GPS single-frequency navigation receivers, the velocity error in the north and east directions generally does not exceed 0.3 m/s (1), while DGPS and RTK carrier phase differential techniques can achieve centimeter-level or even higher accuracy. To examine the estimation accuracy of σ_α, let us take $\sigma_v = 0.3$ m/s and $\sigma_v = 0.05$ m/s, and calculate the predicted azimuth accuracy σ_α for different $v_{resultant}$ values according to equation (9).

Prediction of estimated azimuth' s accuracy

$v_{resultant}$ (m/s)	σ_α (°) $\sigma_v = 0.3$ m/s	σ_α (°) $\sigma_v = 0.05$ m/s
1	17.19	2.86
2	8.59	1.43
5	3.44	0.57
10	1.72	0.29
20	0.86	0.14
30	0.57	0.10

The table shows that when this method is applied to determine pedestrian motion direction, the $v_{resultant}$ value is small (average walking speed of 1-2 m/s), resulting in larger azimuth estimation errors. However, when applied to vehicle navigation, where the average driving speed is about 10-20 m/s, more accurate azimuth estimation can be obtained. For general single-frequency single-point GPS civilian receivers, the azimuth estimation error is better than 0.5° (1) when the speed exceeds 30 m/s.

6. Field Experiment and Results Analysis

To verify the feasibility and effectiveness of the method, a vehicle positioning experiment was conducted in Beijing in May. A typical magnetometer module was fixed on the vehicle roof with its north direction parallel to the vehicle' s heading direction.

[Figure 2: see original paper] A magnetometer mounted on the car

To measure the true angle measurement error of the magnetometer module, it was kept stationary for one hour. The data output window is shown in the figure. After calculation, the angle measurement accuracy of this magnetometer module was found to be 0.88° (1). During the experiment, magnetometer output data also required magnetic declination correction, with a declination value of approximately 5.833°.

[Figure 3: see original paper] The output window of magnetometer angle data

After completing the above preparations, the vehicle began driving at approximately 5 m/s, 10 m/s, and 20 m/s for roughly equal time durations. Real-time data from a typical GPS single-frequency receiver module was read through a serial port, including ephemeris and pseudorange information. The instantaneous azimuth of the vehicle was calculated using the above method and compared with the azimuth information output by the magnetometer. The difference between the two is shown in the figure.

[Figure 4: see original paper] Comparison of calculated azimuth angle and azimuth angle output by the magnetometer

In practice, there is always a fixed deviation of about 0.5° between the calculated azimuth and the magnetometer output azimuth, primarily caused by coordinate system deviations, system measurement bias of the magnetometer itself, deviation when mounting the module on the vehicle relative to the vehicle' s axis direction, and residual magnetic declination correction errors. This fixed deviation does not affect the experimental results.

The statistical results in Table 2 were obtained by subtracting the fixed deviation from the measured results. Let the azimuth calculated by this method be α_{GPS} and the azimuth output by the magnetometer be α_{mag}. The difference between them is $\Delta\alpha = \alpha_{GPS} - \alpha_{mag}$. The root mean square error $\sigma_{\Delta\alpha}$ is calculated by:

$$\sigma_{\Delta\alpha} = \sqrt{\frac{\sum_{i=1}^{n}(\Delta\alpha_i)^2}{n}} \quad (10)$$

where n is the number of observation epochs. According to error propagation law:

$$\sigma_{\Delta\alpha}^2 = \sigma_{\alpha_{GPS}}^2 + \sigma_{\alpha_{mag}}^2 \quad (11)$$

Given that $\sigma_{\alpha_{mag}} = 0.88°$, the azimuth error $\sigma_{\alpha_{GPS}}$ calculated by this method at different driving speeds can be obtained from equation (11). The experimental results in Table 2 are basically consistent with the theoretical analysis in Table 1, verifying the feasibility and accuracy of the method.

Azimuth calculation error with different velocity

Speed (m/s)	$\sigma_{\alpha_{GPS}}$ (°)
5	4.45
10	2.32
20	1.19

7. Conclusions

Due to the inherent limitations of GPS in angle and attitude measurement, gyroscopes, magnetometers, and other sensors have been integrated into positioning terminals to obtain various attitude angles for angle measurement of receiver terminals. Although GPS itself cannot measure the attitude of user terminals, it can calculate the motion azimuth of the receiver carrier in real time based on velocity measurements. This paper investigates and elaborates on this principle, derives and analyzes its accuracy level and error indicators, and validates the method through comparison with magnetometer angle measurements in vehicle positioning experiments.

Experimental and analytical results show that the method of using single-frequency GPS speed measurement to estimate the motion azimuth of a receiver is feasible. The accuracy of the method is related to the motion speed of the receiver carrier—when the carrier reaches a certain speed, higher accuracy can be obtained. Based on this characteristic, the method is particularly suitable for vehicle and vessel navigation applications, where it can achieve certain azimuth measurement accuracy without relying on magnetometers, gyroscopes, or other external equipment, and has good application value due to its simple principle. Additionally, it is worth noting that since relatively high accuracy can be obtained, the azimuth information estimated by this method can also serve as a state variable in Kalman filtering models for post-processing positioning solutions, thereby optimizing the filtering method to achieve more ideal results. This is also a direction worthy of further research and exploration.

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Note: Figure translations are in progress. See original paper for figures.