Determinating Relative Motion Trajectory and Orientation Angles by GNSS Phase Measurements and Micromechanical Gyroscope Data

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Abstract—A short review of the existing methods for resolving phase measurement ambiguity is given. The general structure of the developed algorithms for solving relative navigation and attitude determination problems by means of GNSS phase measurements is presented. Two GNSS receivers and the azimuthal angular velocity data generated by a strapdown inertial module are used in the attitude determination problem. The original techniques for phase measurement cycles integer search are revealed for both problems. These make it possible to reduce computational costs of ambiguity resolution as compared to existing methods. The results from processing phase single-frequency measurements and micromechanical gyroscope data recorded on board a car and a vessel are presented.

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INTRODUCTION

Application of the phase measurements of global navigation satellite systems (GNSS) opens up the possibility of achieving positioning accuracy at the level of centimeters or even millimeters. In addition to navigational purposes, such measurements may be applied to determine vehicle attitude. Phase measurement precision potential is revealed when at least two receivers are used, allowing the organization of differential mode processing. In a navigation problem, one receiver (an onboard receiver, OR) is installed in a vehicle, while the other (a reference receiver, RR) is installed at a stationary base. In an orientation determination problem, the receivers are located in a vehicle at a certain fixed distance (a baseline) from each other. As a rule, measurement double-differences are processed. It should be noted that single differences are formed between measurements from the same GNSS satellite vehicle (SV) for different receivers. At the same time, the errors caused by ephemeris inaccuracy, signal propagation delays in the ionosphere and troposphere, and SV time scale shift in regard to GNSS system time are compensated for. Double differences are formed between the single differences for various SV to compensate for the measurement error associated with nonsynchronous OR and RR time scale.

In an attitude determination problem, specialized equipment enabling the formation of multiple antenna measurements using a single reference generator may be applied. As an example, we can cite the three-antenna MRK-11 goniometrical system [1] developed by the Krasnoyarsk State Technical University Radio Engineering Research Institute and the Radiosvyaz federal state research and development enterprise; the Javad Duo-G2D (two-antenna) and Quattro-G3D (four-antenna) Duo-G2 GNSS boards [2], and the Delta and Sigma receivers based on these boards; and the four-antenna Triumph-4x-G2T system. Using a common reference generator, measurements from different antennas are synchronized and the first order measurement differences can be directly applied in problem solving. Nevertheless, the use of two one-antenna boards or receivers for heading determination remains a fairly common practice. The Javad GNSS boards are thus now provided with an option that allows one to solve a heading problem using another board from this company, while NovAtel [3] and Trimble [4] are producing specialized receiver attachments that determine one’s heading in combination with one’s main receiver. The results presented in this paper were obtained using two receivers. The simultaneous application of different manufacturers’ receivers was also considered, allowing us to demonstrate the universal nature of the developed algorithmic software.

EXISTING METHODS OF GNSS PHASE MEASUREMENT AMBIGUITY RESOLUTION

The most acute problem that arises during phase measurement processing is phase measurement ambiguity resolution, i.e., integer cycles of the phase measurements determination. Without the use of additional navigation information from measuring sensors external to the receivers, it is impossible to directly search and verify the compliance of all possible integer
cycles with the obtained measurements if the number of measurements is excessive. The amount of required calculations is too large even for modern processors.

At present, the two-step approach to ambiguity resolution [5–9, 16] is widely used in relative navigation problems. At the first stage, measurements are processed using the least mean square (LMS) method or the Kalman filter without taking phase cycles integer into account (the so-called float solution). At the second step, the float solution result is specified with regard to integer (the so-called fixed solution). At this step, an \(N^*\) value of \(m\)-dimensional vector \(N\) of the phase measurement integer cycles is sought that minimizes the quadratic form \(q(N) = (N - \hat{N})^T P_N^{-1} (N - \hat{N})\), where \(\hat{N}\) and \(P_N\) are, respectively, the estimation and its covariance error matrix obtained from the float solution. A detailed theoretical justification of such a two-stage solution scheme can be found in [8, 16]. The reliability of phase measurement ambiguity resolution is usually estimated by various statistical criteria [5–7, 9] or the a posteriori probability of a selected cycles integer [8, 16].

The float solution stage is thus standard, while the fixed solution procedure has many options. Let us examine the most common techniques for reducing the computational load for this stage. First, we consider the methods used in the relative navigation problem that may also be applied to the attitude determination problem as basic procedures.

In [5], it was suggested that calculations of minimized quadratic form \(q(N)\) be performed only for those values of vector \(N\) whose components \(N_j, j = 1, m\) satisfy the conditions

\[
|N_j - \hat{N}_{ji1}| \leq \sigma_{ji1} \sqrt{q}, \quad j = 1, m, \tag{1}
\]

where \(\hat{N}_{ji1}\), \(\sigma_{ji1}\) are the conditional with respect to the earlier components of \(N_1, \ldots, N_{j-1}\) estimations of \(N_j\) and its root-mean-square error, calculated from \(\hat{N}, P_N, \sqrt{q}\) is a pre-determined threshold.

The application of Cholesky decomposition to the matrix \(P_N^{-1}\) [6], i.e., \(P_N^{-1} = C^T C\), where \(C\) is the subdiagonal matrix, was an important development in ambiguity resolution methods. The decomposition of \(P_N^{-1}\) allows us to calculate the quadratic form \(q(N)\) on the recurrence formula

\[
q_j = q_{j-1} + \left( \sum_{i=1}^{j} C_{ji} (N_i - \hat{N}_i) \right)^2, \quad j = 1, m, \quad q_0 = 0, \quad q = q_m, \tag{2}
\]

where \(C_{ji}\) are the elements of matrix \(C\) (\(j\) is the row number, and \(i\) is the column number). If \(q_j > \sqrt{q}\), then in view of \(q_1 \leq \ldots \leq q_{m-1} \leq q\), it is clear that \(q > \sqrt{q}\). In this case, the calculation of \(q\) for the given values of \(N_1, \ldots, N_j\) is interrupted.

An even more successful method of searching for phase cycles integer was proposed in [7]. It essentially combines the positive features of the above methods. Here, component \(N_j\) values selection is performed in regard to conditional estimates \(\hat{N}_{ji1}\) and considering the intermediate value \(q_{j-1}\) of quadratic form \(q\)

\[
|N_j - \hat{N}_{ji1}| \leq \sigma_{ji1} \sqrt{q - q_{j-1}}, \quad j = 1, m. \tag{3}
\]

These intervals are obviously narrower than those in (1) and thus more effective in the selection of \(N\) values. A disadvantage of using (3) is the repeated application of the relatively labor-intensive square-rooting operation.

In [9], an efficient \(N\) value search method was presented that minimized the quadratic form \(q(N)\): the threshold \(\sqrt{q}\) for the quadratic form \(q\) is lowered as the \(N\) vector values are found for which \(q\) is less than the \(\sqrt{q}\) value selected earlier. The \(N\) integer value search organization is still far from perfect, however: it is necessary to recalculate the interval boundaries of the sought \(N\) component values at each change of the \(\sqrt{q}\) threshold value, and the search is either carried out without \(N\) component value ordering (the so-called Depth-First method) or requires labor-intensive sorting and storing of large amounts of intermediate data (the so-called Best-First method).

Similar methods of cycles integer search are applied in resolution phase measurement ambiguity in the attitude determination problem, but the information on the distances between antennas (the baseline length) is still used. On the basis of this additional information, inequalities are formed that are used to reject searched cycles integer. Of the selected \(N\) values, the one that minimizes the loss function is chosen [10, 11].

Attitude determination according to phase GNSS measurements is often supplemented by the use of gyroscopes. The gyroscope data are utilized not only to refine the angles obtained from phase measurements, performed with the use of standard filtering methods, but also to reduce the search of cycles integer, checked against the received measurements [12, 13]. It should be noted that the strapdown measurement module [18] software, developed by the Elektrpribor research institute makes it possible to effectively integrate the inertial data and multiantenna phase GNSS measurements in order to improve the accuracy of orientation angle and navigation parameter generation.

The vehicle angular motion model [14] may also be used as an additional information source that allows us to reduce the cycles integer search. The most practical application of such a noninvariant approach is SV orientation determination. Practical examples of such a problem solution were considered in [14].