BulTrans-2013
Proceedings
16-18 October 2013
Sofia

A NEW METHOD FOR GNSS BASED ATTITUDE DETERMINATION

BORIS VASSILEV
Department of Aeronautics, Techmical University, Sofia, Bulgaria
borisv@tu-sofia.bg

BORIANA VASSILEVA
bvassil@bas.bg

Abstract:
Obtaining an accurate moving objects attitude (pitch, roll and heading) is essential for object navigation and control applications. In this work GNSS (Global Navigation Satellite System) Based Attitude Determination (GBAD) technique is presented. GBAD assumed one or two shuttled antennas. It uses antenna velocity vector information in the body coordinate system (a priori known) and in the geographic coordinate system (provided by the GNSS receiver). This technique assumes unit with low cost realization and wide area of applications in air, land and water during the open-, commercial- and safety of life- GNSS services. GBAD simulation analysis is realized in MATLAB computational environment. The obtained results show possibility for high accuracy performance. They are a good base for further hardware simulations.

Keywords: *navigation, angular coordinates, Global Navigation Satellite Systems.*

1. Introduction

Attitude is the term used to describe a rigid body's orientation in three-dimensional space. In a more general sense, it is the description of the relative orientation of two coordinate frames. In vehicle guidance, navigation, and control applications the two coordinate frames of interest are sometimes referred as the body and navigation reference frames. Attitude determination systems are used to measure or estimate the relative orientation of these two frames.

Traditional units for attitude measurements—such as gyroscopes and accelerometers—provide high-precision information for navigational calculations. They are, however, expensive and bulky. The current status of the means for measuring pitch, roll and heading can be summarized as follows:

- Inertial Navigational Systems (INS) – Widespread, high precision, reliable. Very expensive, problems with gyro drift, necessity of magnetic sensor of heading, high computational requirements.
- Attitude heading reference systems (AHRS) - utilization of MEMS sensors. Low cost, small sizes, reliable. All disadvantages of INS are typical also for AHRS.
- Gyro methods - reliable, high precision, give attitude information without power supply after critical for the crew period of time. Gyro drift is critical for heading determination, heavy, high technology.
- Magnetic sensors of heading - very simple, reliable. Problems with deviation and inclination. Low precision, dependence of object maneuvers.
- GNSS receiver with three and more antennas. Information for pitch, roll and heading, no problems with latitude of the object, theoretically high precision, high computational requirements, necessity of high base line between antennas, problems with structural deviations because of big distance between antennas and hence additional noises, necessity of very precise carrier phase tracking, ambiguity resolution and detection of cycle.

The below presented GNSS Based Attitude Determination (GBAD) technique exploits velocity information acquired by GNSS receivers. For this purpose, velocities of one or two receiver antennas, which shuttled within the body coordinate system, are measured. The Euler angles (pitch, roll and heading) are then determined based on the relation among the antenna velocity components in the body coordinate system and geographic coordinate system.

2. GBAD description

Two coordinate systems are considered: the body coordinate system XYZ and the geographic coordinate system ENH (East-North-Up). The orientation between the both systems is arbitrary and is determined by three Euler angles – pitch (θ), heading (ψ) and roll (ϕ) (see figure 1.). The proposed idea is to determine these three angles using velocity information from GNSS receiver. To do this receiver antenna which shuttled forward-backward along the axis X in the body coordinate system with a priory known relative velocity V_a is used. If the body moves in coordinate system ENH with velocity V_b and the both velocities coincide in direction, the receiver will measure velocity vector:

$$\begin{vmatrix} V_{E\ for} \\ V_{N\ for} \\ V_{H\ for} \end{vmatrix} = \begin{vmatrix} V_{b\ E} \\ V_{b\ N} \\ V_{b\ H} \end{vmatrix} + \begin{vmatrix} V_{a\ E} \\ V_{a\ N} \\ V_{a\ H} \end{vmatrix} \qquad (1)$$

In the case when the antenna moves backward, the receiver will measure velocity vector:

$$\begin{vmatrix} V_{E\ back} \\ V_{N\ back} \\ V_{H\ back} \end{vmatrix} = \begin{vmatrix} V_{b\ E} \\ V_{b\ N} \\ V_{b\ H} \end{vmatrix} - \begin{vmatrix} V_{a\ E} \\ V_{a\ N} \\ V_{a\ H} \end{vmatrix} \qquad (2)$$

Adding and subtraction the equations (1) and (2) velocity components of the body and antenna along axes of geographic coordinate system ENH can be determined respectively:

$$2 \times \begin{vmatrix} V_{b\ E} \\ V_{b\ N} \\ V_{b\ H} \end{vmatrix} = \begin{vmatrix} V_{E\ for} \\ V_{N\ for} \\ V_{H\ for} \end{vmatrix} + \begin{vmatrix} V_{E\ back} \\ V_{N\ back} \\ V_{H\ back} \end{vmatrix} \qquad (3)$$

$$2 \times \begin{vmatrix} V_{a\ E} \\ V_{a\ N} \\ V_{a\ H} \end{vmatrix} = \begin{vmatrix} V_{E\ for} \\ V_{N\ for} \\ V_{H\ for} \end{vmatrix} - \begin{vmatrix} V_{E\ back} \\ V_{N\ back} \\ V_{H\ back} \end{vmatrix} \qquad (4)$$

Then using velocity components of antenna along axes of the geographic coordinate system ENH, and the existing geometrical relations, the object heading, and pitch can be determined as follow:

$$\theta = arcsin\frac{V_{aH}}{V_X}, \quad \psi = arccos\frac{V_{aN}}{V_{Xhor}}, \quad V_{Xhor} = \sqrt{V_{aE}^2 + V_{aN}^2} \qquad (5)$$

where V_X is the relative antenna velocity in 0X direction.

For determination of roll angle it is necessary existence of second antenna, which moves forward and backward along Y axis with velocity V_Y. Then:

$$\phi = \arccos\frac{V_{aN}\,sin(\psi) + V_{aE}\,cos(\psi)}{V_Y} \qquad (6)$$

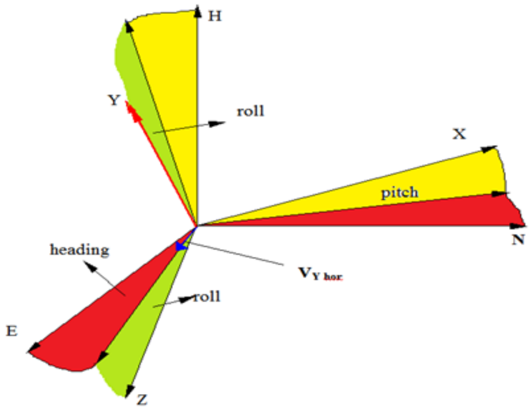

Figure 1

There are different variants for GBAD realization:

- using a rotating GNSS receive antenna;
- using several receive antennas switched at different times in such a way that to simulate the rotation effect;
- using several receive antennas switched at different times in such a way that to simulate forward and backward motion in a straight line of one antenna.

3. GBAD simulation analysis

Simulation tool, suitable for modeling and evaluating the performance of GBAD algorithm variants is developed and realized in MATLAB computational environment. It supports numerical design choices with selectable parameters so that different designs can be traded-off or optimized.

Before Monte Carlo runs, input parameters that describe the simulation scenario and input parameters of the tested algorithm are assigned. Then signatures of the GNSS velocity measurements are generated. The tested algorithm consists of program files which represent separate functions with their own input and output parameters. After execution of the tested algorithm collection of data for each set of angles is carried out. These data are processed in block for statistical analysis of the algorithm performance. The so obtained results are graphically depicted.

Some results produced using the above presented simulation tool are presented below. They concern *heading*, *pitch* and *roll* determination accuracy for given: antenna and body velocities, Euler angles and velocity accuracy of the GNSS receiver.

Figures 2 and 3 show experimental results for measurement error standard deviation (std) for heading and pitch determination in the cases of:

- Velocity measurement error (std) [m/s]: 0.1
- Relative antenna velociry (OX direction) [m/sec]: 10, 20, 40 and 100
- Body velocity (linear) [m/sec]: 100

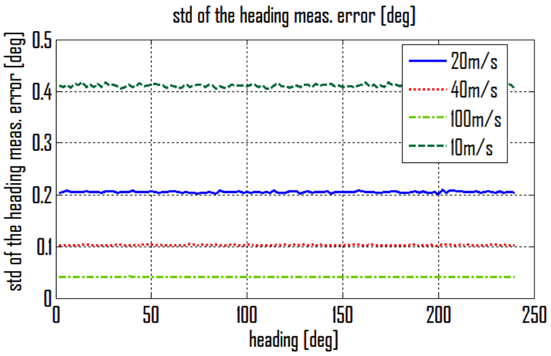

Figure 2**:** std (1σ) of the heading measurement error for different antenna relative velocities and GNSS antenna velocity measurement accuracy 0.1 m/sec

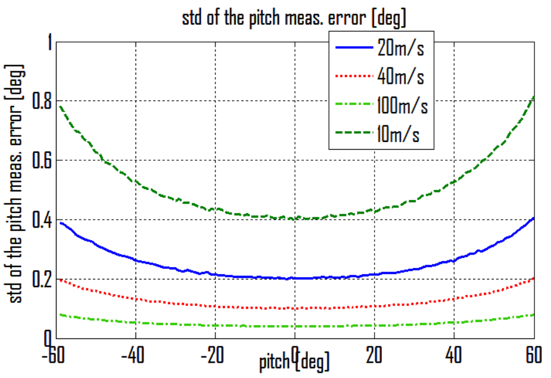

Figure 3: std (1σ) of the pitch measurement error for different antenna relative velocities and GNSS antenna velocity measurement accuracy 0.1 m/sec

- Angle of inclination [deg]: 3
- Sliding angle [deg]: 3
- Pitch angle (for heading model) [deg]: 10
- Heading angle (for pitch model) [deg]: 30
- Runs number: 10000

It must be noted that the choice of different scenario values of angles do not influence the behavior of the below presented graphics.

The graphics show that at a relative velocity of the antenna equal to 20 m/s very good results can be achieved. Therefore, the accuracies of determining heading, pitch and roll have been investigated at velocities of antennas equal to 20 m/s and various velocity accuracies of the GNSS receiver, as follow:

- Velocity measurement error (std) [m/s]: 0.01, 0.1, 0.2
- Relative antenna velocity (OX direction) [m/sec]: 20
- Relative antenna velocity (OY direction) [m/sec]: 20
- Body velocity (linear) [m/sec]: 100
- Angle of inclination [deg]: 3
- Sliding angle [deg]: 3
- Pitch angle (for heading model) [deg]: 10
- Heading angle (for pitch model) [deg]: 30
- Runs number: 10000

Figures 4-9 show results *for heading*, *pitch* and *roll* determination using the complex GBAD algorithm.

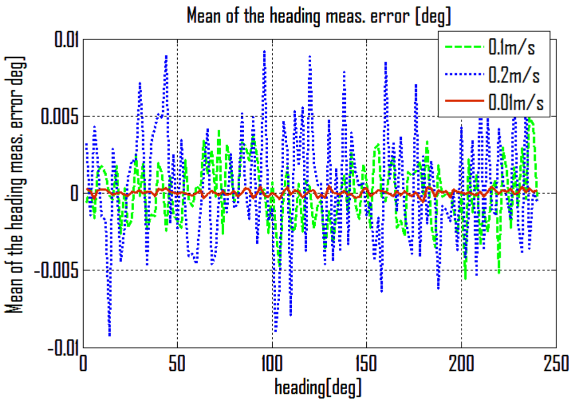

Figure 4: Mean of the heading measurement error for antenna relative velocity 20 m/sec and different std (1σ) of the receiver measurement error

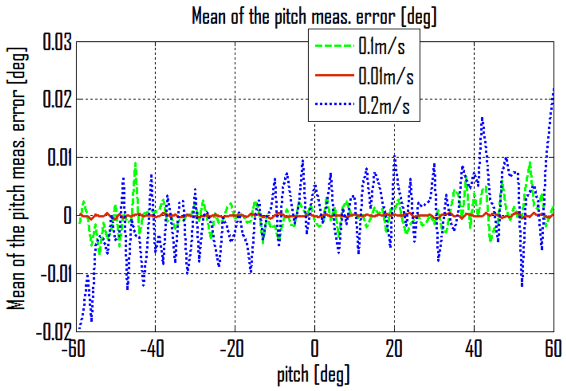

Figure 5: Mean of the pitch measurement error for antenna relative velocity 20 m/sec and different std (1σ) of the receiver measurement error

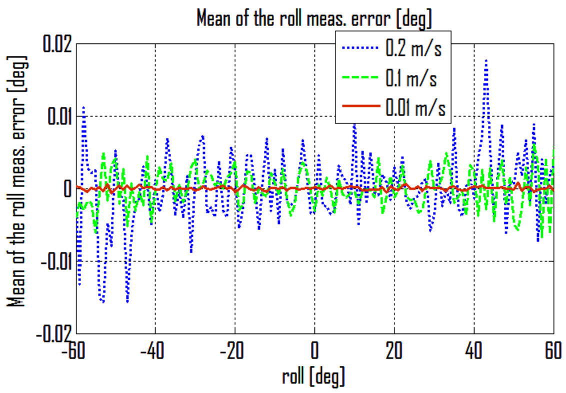

Figure 6: Mean of the roll measurement error for antenna relative velocity 20 m/sec and different std (1σ) of the receiver measurement error

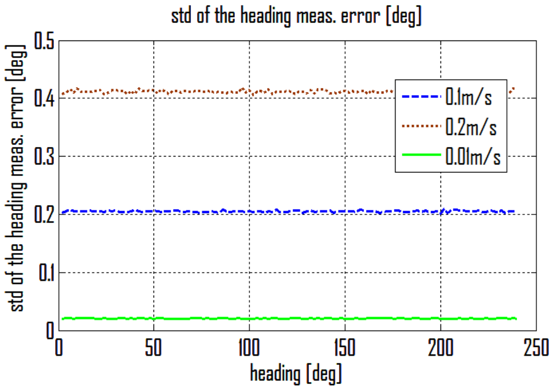

Figure 7: std (1σ) of the heading measurement error for antenna relative velocity 20 m/sec and different std of the receiver measurement error

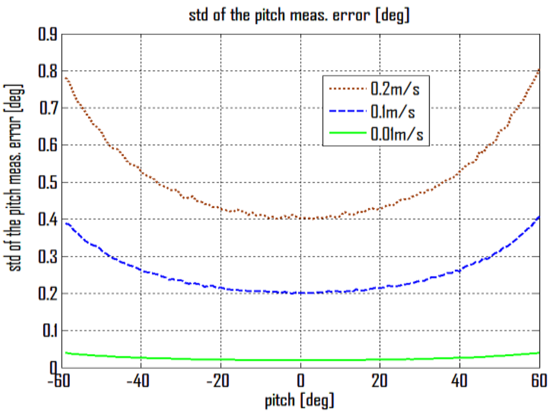

Figure 8: std (1σ) of the pitch measurement error for antenna relative velocity 20 m/sec and different std of the receiver measurement error

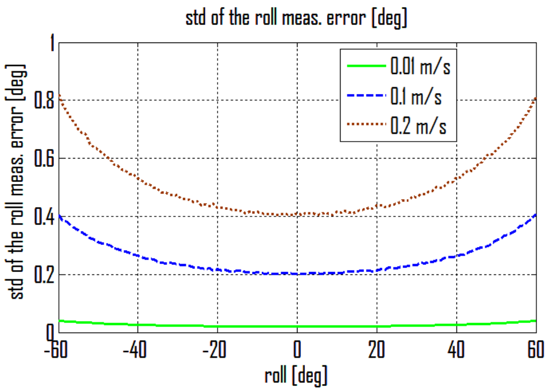

Figure 9: std (1σ) of the roll measurement error for antenna relative velocity 20 m/sec and different std of the receiver measurement error

All results, related to accuracy performance of the GBAD, show:

- Strong dependence on the antenna relative velocity;
- Strong dependence on the accuracy of the GNSS antenna velocity measurements;
- Independence for different values of the heading angle;
- Dependence for different values of the pitch/roll angle. It must be noted that for practical range of interest $[-40^o \div 40^o]$ this dependence is negligible;
- Independence for different values of the body velocity;
- Unbiased Euler angles determination. Mean value of the error is close to zero;
- Possibility to achieve results close to or better of those of INS.

4. Concluding remarks

GBAD is very simple algorithm for attitude determination. It implies high accuracy, as the velocity error measured by GNSS professional receiver has standard deviation within mm/sec and the algorithm will be affected of small noise errors. There is possibility for increasing accuracy of body velocity measurements. The velocity of the antenna is known. The module of this velocity in both coordinate systems is constant and known. There is possibility for filtering the velocity errors, which could be common for the antenna velocity and the body velocity. GBAD may conduct GNSS integrity monitoring. The module of antenna velocity in geographic coordinate system is good information for the integrity of the system.

Acnowledgement

This work was partially supported by the OP “Competitiveness” under grant BG161PO003-1.1.06.0075-C0001.

References

[1] D. Gebre-Egziabher, G. Elkaim, MAV Attitude Determination by Vector Matching, IEEE AES Vol. 44, No. 3 July 2008, pp. 1012-1028

[2] P.J.G. Teunissen and C.C.J.M. Tiberius , Integer least-squares estimation of the GPS phase ambiguities, Proceedings of KIS’94. Banff, Canada, 1994, pp. 221-231.

[3] P.J.G. Teunissen, P.J. de Jonge, and C.C.J.M. Tiberius; “The LAMBDA method for fast GPS surveying”; Proceedings of International Symposium 'GPS technology applications', Bucharest, Romania, September 26-29, pp. 203-210 (1995).

[4] Kaplan, E., Understanding GPS – Principles and Applications, Second Edition, Artech House Inc., London, 2006г.

[5] James B-Y. Tsui, Fundamentals of Global Positioning System Receivers : A Software Approach, 2008

[6] B. Vassilev, B Vassileva, GNSS Based Attitude Determination, Presentation of the idea winner of the DLR special prize, ESNC12, Munich, Germany, 26 September 2012.

[7] Configuring the PolaRx2/2e@ for optimal attitude performance, http://www.septentrio.com/sites/default/files/PolaRx2e_HowTo_Optimal%20Attitude%20Performance.pdf