International Journal of Business, Human and Social Sciences
ISSN: 2517-9411
Vol:7, No:7, 2013

Exploring the Ambiguity Resolution in Spacecraft Attitude Determination Using GNSS Phase Measurement

Lv Meibo, Naqvi Najam Abbas, and Li YanJun

Abstract**—**Attitude Determination (AD) of a spacecraft using the phase measurements of the Global Navigation Satellite System (GNSS) is an active area of research. Various attitude determination algorithms have been developed in yester years for spacecrafts using different sensors but the last two decades have witnessed a phenomenal increase in research related with GPS receivers as a stand-alone sensor for determining the attitude of satellite using the phase measurements of the signals from GNSS. The GNSS-based Attitude determination algorithms have been experimented in many real missions. The problem of AD algorithms using GNSS phase measurements has two important parts; the ambiguity resolution and the determining of attitude. Ambiguity resolution is the widely addressed topic in literature for implementing the AD algorithm using GNSS phase measurements for achieving the accuracy of millimeter level. This paper broadly overviews the different techniques for resolving the integer ambiguities encountered in AD using GNSS phase measurements.

Keywords**—**Attitude Determination, Ambiguity Resolution, GNSS, LAMBDA Method, Satellite.

I. Introduction

THE Attitude of a spacecraft is its orientation in space. Attitude determination is the process of computing the orientation of the spacecraft relative to either an inertial reference or some other object of interest, such as the Earth. This typically involves several types of sensors on each spacecraft and sophisticated data processing procedures. The accuracy limit is usually determined by a combination of processing procedures and spacecraft hardware [1].

Attitude determination and control subsystem (ADCS) is one of the crucial subsystems of the satellite. It involves the representation of attitude using Euler angles, direction cosine matrix, Rodriguez parameters or Quaternions. Attitude representation is elaborated in detail along with the significance of each representation by Shuster [2]. Shrivastava and Modi [3] have explained the various environmental forces, torques and their effects on the satellite dynamics.

Determination of attitude includes attitude sensors like sun sensor, magnetometer, horizon sensor, Earth sensor, Star Sensors, Inertial Measurement units (IMU), gyroscope, GPS receiver etc and then applying point to point or recursive attitude determination algorithms to predict the attitude using satellite kinematics and dynamics models along with the environmental models.

Attitude control and stabilization is obtained by applying active or passive techniques and using linear, non linear, adaptive or fuzzy control scheme and using the actuators like magnetic coils, momentum wheels, reaction wheels, permanent magnets, thrusters, jets or control moment gyros. A detailed description and comparison of sensors and actuators is given in [1].

In the past four decades, various attitude determination algorithms for non GNSS-Based AD have been developed and tested. The original concept based on least square estimation was given by Wahba [4]. The first category is point to point estimation algorithms like Triad [1], QUaternion ESTimator QUEST [5], Singular Value Decomposition (SVD) [6] and Fast Optimal Attitude Matrix (FOAM) [7]. The recursive attitude determination algorithms were reviewed by Crassidis et al. [8] in detail and these algorithms include REQUEST [9], OPTIMAL-REQUEST [10], Minimum Model Error (MME) [11], Euler-q [12], Optimal-REQUEST [13], Adaptive Optimal-REQUEST [14] and Kalman Filtering algorithm [15], [16].

The paradigm of Global Navigation Satellite System (GNSS) includes the constellation of navigational satellites in the Medium Earth Orbit (MEO).Currently, GPS is the only fully functional navigation system but the future has promises for the upgraded GLONASS by Russia, Galileo by European Union, Beidou by China and regional navigation systems like GAGAN by India and QZSS by Japan. The origin, evolution and future of GNS are described in detail by Parkinson [17].

The application areas of GNSS are diverse and imagination dependent. They encompass PVT information, aviation and aerospace industry, emergency and rescue, location based services, mining, agriculture and civil engineering, environmental monitoring and hazard management, transportation, e-banking, commerce, geodesy, and many more.

One of the application areas of GNSS is the attitude determination of satellites that is the focus of this contribution especially a problem of resolving the integer ambiguities while using the phase measurements of the GNSS signal for determining the attitude of the satellite and in particular,

Lv Meibo is a lecturer at School of Astronautics, Northwestern Polytechnical University, Xi'an, China with specialization in navigation, guidance and control (Phone: 0086-15829682227; e-mail: nwpuiet@nwpu.edu.cn).

Naqvi Najam Abbas is a PhD candidate at School of Astronautics, Northwestern Polytechnical University, Xi'an, China (Phone: 0086-15129299607; e-mail: najm_naqvi@yahoo.com).

single-frequency, single-epoch GNSS-based attitude determination. Section II elaborates the method of attitude determination using GNSS phase measurements and identifies the ambiguity resolution problem while Section III describes GNSS-based AD algorithms and Section IV presents GNSS based attitude determination models. Section V overviews the methods of resolving the integer ambiguities and paper concludes with some recommendations and conclusions.

II. Attitude Determination Using GNSS Phase Measurements

Attitude determination (AD) of the satellite using GNSS measurements involve two types of measurements namely the code measurements and the phase measurements. The accuracy and precision achieved by the phase measurements is far better than the code or pseudo range based measurements. The basic principle underline the attitude determination using phase measurements is the Interferometric Principle as given by [18], that is, with a pair of GPS antenna, a user can determine phase difference between like signals of that antenna pair and this gives the attitude of the platform. With two antennae/single baseline one is able to estimate the pointing direction, namely the compass solution, while configuration of three or more non-collinear antennae allows the user to estimate the full attitude of a platform [19]. Although the accuracy of a stand-alone GNSS attitude system might not be comparable with the one obtainable with other modern attitude sensors, a GNSS-based system presents several advantages: it is inherently driftless, minor maintenance is required and it is not as expensive as other high- precision systems, such as INS and Star Trackers[20].

Attitude Determination of spacecraft can be done by using space borne GPS receivers or the commercial off-the-shelf (COTs) GPS receivers. GNSS-based AD is dedicated or non-dedicated. In dedicated AD system, a single exclusively GPS receiver is used while in non-dedicated AD system, a set of independent , general purpose independent receivers are used for the attitude determination of the satellite [21].

Bauer et al. [22] presented an overview of the Space borne GPS receivers and the GPS flight experiments. In literature, various GNSS Phase based AD missions have been discussed namely GADACS [23], SPARTAN [24], RADCAL [25], REX II [26], Gravity Probe B [27], UNISAT [28], Gyrostat [29], UOSAT-12 [30] and ALSAT-1 [31]. Bauer et al. [22] and Chu et al. [32] have reviewed the Technology experiments of Attitude Determination with GPS.

Many GPS receiver manufacturing companies like Trimble Navigation [33], [34], Texas Instruments [35], [36], Ashtech [37]-[39], Adroit Systems [40], and others are developing GPS receivers with multiple antennas for attitude determination.

III. GNSS-Based Attitude Determination Algorithms

AD algorithms using GNSS Phase measurements are expressed by Bar-Itzhack [41]. Three-axis AD by Kalman filtering of GPS signals are presented in [42]. Crassidis et al. [43] presented another Algorithm named as attitude-lean-loping-estimator (ALLEGRO) using GPS recursive operations. Park et al. [44] describes a set of numerical gradient-based optimization algorithms for solving the GPS-based AD problem. Madsen et al. [45] presented a new algorithm that utilizes signal to noise ratio measurements from canted antennas to produce three-axis attitude solutions. Three new algorithms were developed by Nadler et al. [46] for solving the attitude estimation problem, a discrete Newton–Raphson-based algorithm, a continuous Newton–Raphson algorithm, and an algorithm that is based on the Eigen problem structure of the nonlinear equations, which are related to the minimization of the quartic cost function. Chun et al. [47] formulated the Attitude determination problem as an optimization problem. Li et al. [48] present an algorithm based on iteration method to resolve the Wahba's problem through the small-angle approach. Kuang et al. [49] proved that QUEST provides the good solutions of attitude for the gyrostat satellite by using the GPS signals. Li et al. [50] cited the AMES algorithm for attitude determination using single and double difference phase measurements. Tsai [51] formulated the problem of AD as a constrained total least-square (CTLS) problem.

IV. GNSS-Based Attitude Determination Models

An overview of GNSS models and their applications in various fields are given in textbooks such as [52]–[57]. GNSS models have two main categories; non-positioning or geometry-free models and the positioning or geometry-based models .Different GNSS models can also be distinguished based on the differencing that is applied. By differencing, we mean to take the differences between observations from different receivers and/or different satellites. It is often applied in order to eliminate some of the parameters from the observation equations [58]. The Single Difference and double difference Methods are explained in [59]. Unconstrained baselines are baselines for which a-priori information about the length is not available and constrained baselines are baselines for which the length is known and constant [60].

In principle all the GNSS baseline models can be cast in the following frame of linearized observation equations, by a Gauss-Markov model [61]

$$E(y) = Aa + Bb; \quad D(y) = Q_{yy} \tag{1}$$

where y is the given GNSS data vector of order m, a and b are the unknown parameter vectors of order n and p respectively. E(:) and D(:) denote the expectation and dispersion operator, and A and B are the given design matrices that link the data vector to the unknown parameters. Matrix A contains the carrier wavelengths and the geometry matrix B contains the receiver-satellite unit line-of-sight vectors. The variance matrix of y is given by the positive definite matrix Q_{yy}.

The model given by (1) is termed as the unconstrained model and its Integer Least Squares (ILS) solution is found in

[61]. For attitude determination applications, usually one can benefit from the knowledge of the additional constraint on the baseline vector length and the Integer Least-Squares minimization problem can be reformulated as a Quadratically Constrained Integer Least-Squares (QC-ILS) problem [61].

V. Methods for Ambiguity Resolution

The carrier phase measurements are inherently corrupted by unknown integer numbers and these numbers must be found to take full advantage of the carrier phase measurements. This problem is referred as the Ambiguity Resolution (AR).

Many algorithms have been proposed for ambiguity resolution. One category of these algorithms is referred to as a *SERACH* Method, independent of receiver –satellite geometry and the other one is referred as *MOTION-BASED* Method, which makes use of the information contained in the motion of the platform or the GPS satellites, dependent on receiver – satellite geometry.

In literature , different ambiguity resolution methods have been discussed [62] like Least-Squares Ambiguity Search Technique (LSAST) [63], Fast Ambiguity Resolution Approach (FARA) [64], Modified Cholesky decomposition [65], most widely used Least-squares AMBiguity Decorrelation Adjustment (LAMBDA) [66], Null method [67], Fast Ambiguity Search Filter (FASF) [68], Three Carrier Ambiguity Resolution (TCAR) [69], Integrated TCAR [70], Optimal Method for Estimating GPS Ambiguities (OMEGA) [71],Cascade Integer Resolution (CIR) [71].A comparison of LAMBDA with CIR, TCAR, ITCAR and the Null-method is presented in [72]-[74].

The estimation process consists of three steps. First a standard least-squares adjustment is applied in order to arrive at the so-called float solution. All unknown parameters are estimated as real-valued. In the second step, the integer constraint on the ambiguities is considered. This means that the float ambiguities are mapped to integer values. Different choices of the map are possible. The float ambiguities can simply be rounded to the nearest integer values or conditionally rounded so that the correlation between the ambiguities is taken into account. The optimal choice is to use the integer least-squares estimator, which maximizes the probability of correct integer estimation. Finally, after fixing the ambiguities to their integer values, the remaining unknown parameters are adjusted by virtue of their correlation with the ambiguities [62].

The integer estimators mostly used in practice [75] are Integer least squares (ILS) [76], Integer Bootstrapping (IB) [77], Integer Rounding (IR) [78] and Best Integer Equivariant estimator (BIE) [62].

The LAMBDA method is currently the standard method for solving unconstrained GNSS ambiguity resolution problems. For nonlinearly constrained ambiguity resolution problems, the single baseline constrained LAMBDA method [79] was presented and the newly proposed The Multivariate Constrained LAMBDA method [21], [80], [81] algorithm solves for the integer ambiguities and body attitude in an integral manner.

VI. Conclusion and Recommendations

Attitude determination of a spacecraft using GNSS phase based measurement for the millimeter level accuracy has been overviewed while addressing the inherent problem of resolving the ambiguities due to the phase measurements. GNSS models for ambiguity resolution are presented and different existing and previous ambiguity resolution algorithms and methods are mentioned. Different GNSS-based attitude determination algorithms are also presented to describe the basic principle of GNSS based attitude determination. The latest Baseline Constrained LAMBDA version of the LAMBDA method for resolving the ambiguity in the GNSS-based AD of satellites is also presented. This broad overview can be helpful for the researchers in the field of attitude determination of satellites using GNSS phase measurements.

Acknowledgment

The authors are thankful to Northwestern Polytechnical University, Xi'an, China and Institute of Space Technology, IST, Pakistan for research support.

References

[1] Wertz, J.R., ed., "Spacecraft Attitude Determination and Control," D. Reidel Publishing Company, Library in Astrophysics and Space Sciences, 1978.
[2] M.D.Shuster,"Survey of Attitude Representations", Journal of Astronautical Sciences, vol.4, pp 439-517, Oct-Dec 1983.
[3] S.K.Shrivastava and V.J.Modi, "Satellite Attitude Dynamics and Control in the Presence of Environmental Torques — A Brief Survey," Journal of Guidance, Control, and Dynamics, vol. 6, Nov.-Dec. 1983.
[4] Wahba, G., "A Least Squares Estimate of Spacecraft Attitude," SUM Review, vol. 7, No. 3, p. 409. July 1965.
[5] Shuster, M.D. and Oh, S.D., "Three-Axis Attitude Determination from Vector Observations." J. of Guidance and Control, vol. 4, No. 1, pp. 70-77. Jan.-Feb. 1981.
[6] Markley, F. L., "Attitude Determination Using Vector Observations and Singular Value Decomposition", Journal of the Astronautical Sciences, No. 36, pp. 245-258, July-Sep. 1988.
[7] Markley, F. L., "Attitude Determination Using Vector Observations: A Fast Optimal Matrix Algorithm," Journal of the Astronautical Sciences, vol. 41, No. 2, pp. 261-280, 1993.
[8] Crassidis, Markley and Cheng, "Survey of Nonlinear Attitude Estimation Methods," Journal of Guidance, Control and Dynamics, vol. 30, No. 1, 2007.
[9] Bar-Itzhack, I.Y., "REQUEST- A Recursive QUEST Algorithm for Sequential Attitude Determination," J. Guidance, Control, and Dynamics, vol. 19, No. 5, pp. 1034-1038, Sept.- Oct., 1996.
[10] D. Choukroun, I. Y. Bar-Itzhack and Y. Oshman, "Optimal-REQUEST Algorithm for Attitude Determination," Journal of Guidance, Control, and Dynamics, Vol. 27, No. 3, May–June 2004.
[11] Crassidis, J. L., & Markley, F. L., "Minimum Model Error Approach for Attitude Estimation," Journal of Guidance, Control, and Dynamics, vol. 20, No.6, 1241-1247, 1997.
[12] Mortari, D. "Euler-q Algorithm for Attitude Determination from Vector Observations," Journal of Guidance, Control, and Dynamics, vol. 21, pp. 328-334, 1998.
[13] D. Choukroun, I. Y. Bar-Itzhack, and Y. Oshman, "Optimal-REQUEST Algorithm for Attitude Determination," Journal of Guidance, Control, and Dynamics, vol. 27, No. 3, May–June 2004.

[14] Choukroun, D. “Adaptive Optimal-REQUEST Algorithm for Attitude Determination,” AIAA Guidance, Navigation and Control Conference and Exhibit. 20-23 August 2007, Hilton Head, South Carolina.
[15] Lefferts, Markley and Shuster, “Kalman Filtering For Spacecraft Attitude Estimation,” AIAA, 20th Aerospace Science Meeting, Orlando Florida, January, 11 -14, 1982.
[16] Martel F., Pal P. K. and Psiaki M. L., "Three- Axis Attitude Determination via Kalman Filtering of Magnetometer Data," Journal of Guidance, Control and Dynamics, vol. 13, No. 3, pp. 506-514, 1989.
[17] W.Parkinson, “Origins, Evolution and Future of satellite Navigation,” Journal of Guidance, Control, and Dynamics, vol.20, 1997.
[18] Garrick, J, “Investigation of Models and Estimation Techniques for GPS Attitude Determination,” NASA Report, 1992.
[19] Gabriele Giorgi and Peter J. Buist, “single-epoch, single-frequency, standalone full attitude determination: experimental results” NAVITECH 2008.
[20] Giorgi, G., Teunissen, P. J., Verhagen, S., Buist, P. J., G, “Testing a New Multivariate GNSS Carrier Phase Attitude Determination Method for Remote Sensing Platforms,” Advances in Space Research, Accepted Manuscript, 2010.
[21] SungPil Yoon, “Real Time Attitude Determination Using GPS,” PhD Thesis, Auburn University, 1999.
[22] Bauer, F. H., Hartman, K., & Lightsey, “Spaceborne GPS Current Status and Future Visions,” AIAA, 1998.
[23] F.H. Bauer, E.G. Lightsey, J. O' Donmfll and R. Sdmurr, “GADACS: A GPS Attitude Determination and Control Experiment on a Spartan Spacecraft,” Control Eng. Practice, vol. 3, No. 8, pp. 1125-1130, 1995.
[24] C.E.Cohen, Lightsey and Parkinson, “Space Flight Tests Of Attitude Determination Using GPS,” International Journal of Satellite Communications, vol. 12, 427-433, 1994.
[25] Axelrad, P., & Ward, L. M. “Spacecraft Attitude Estimation Using the Global Positioning System: Methodology and Results for RADCAL,” Journal of Guidance, Control, and Dynamics, vol. 19, No. 6, November-December 1996.
[26] Lightsey, E. G. “Flight Results of GPS Based Attitude Control on the REX II Spacecraft”.
[27] H. Uematsu, L. Ward, B. W. Parkinson, “Use Of GPS For Gravity Probe B Relativity Experiment and Co-Experiment,” Advances in Space Research, vol. 25, No.6, pp. 1199-1203,2000.
[28] Tortora, P. “A GPS Based Attitude Determination Algorithm for the Spin-Stabilized Microsatellite UNISAT”. Acta Astronautica, vol. 47, Nos. 2-9, pp. 139-146. 2000.
[29] Jinlu Kuan and Soonhie Tan, “GPS-Based Attitude Determination of Gyrostat Satellite by Quaternion Estimation Algorithms,” Acta Astronautica, vol. 51, No. 11, pp. 743–759, 2002.
[30] Dr Martin Unwin, P.Purivigraipong, Alex da Silva Curiel and Prof. Martin Sweeting, “Stand-alone Spacecraft Attitude Determination Using Real Flight GPS Data from UOSAT-12,”Acta Astronautica, vol. 51, No. 1-9, pp. 261-268, 2002.
[31] Elizabeth Rooney, Martin Unwin, Scott Gleason “Demonstration of GPS on the ALSAT-1 Disaster Monitoring Satellite,” AIAA Guidance, Navigation, and Control Conference and Exhibit 11-14 August 2003, Austin, Texas.
[32] Q.P. Chu and P.Th.LM. van Woaicom, “GPS for Low Cost Attitude Determination - A Review of Concepts, In-Flight Experiences, and Current Developments,” Acta Astronautica, vol. 41, No. 4-10, pp. 421-433. 1997.
[33] Clark Emerson Cohen, “Attitude Determination Using GPS,” PhD Thesis, Stanford University, 1992.
[34] Kruczynski, L.R., P.C. Li, A.G. Evans, and B.R.Hermann, "Using GPS to Determine Vehicle Attitude: U.S.S. Yorktown Test Results," ION GPS 89, Colorado Springs, September, 1989.
[35] J. Rath and P. Ward, "Attitude Estimation using GPS," National Technical Meeting, ION, San Mateo, CA, January 1989.
[36] K.A. Brown and A.G. Evans, "GPS Pointing System Performance," ION GPS-90, Colorado Springs, CO, September 1990.
[37] K. Ferguson, et al., "Three-Dimensional Attitude Determination with the Ashtech 3DF 24-Channel GPS Measurement System," Proceedings of the ION National Technical Meeting, Phoenix, **,**Jan. 1991.
[38] F. van Graas and M. Braasch, "GPS Interferometric Attitude and Heading Determination: Initial Flight Test Results," Navigation, Vol. 38, winter 1991-92.
[39] Gang Lu, et al., "Attitude Determination in a Survey Launch Using Multi-Antenna GPS Technologies." National Technical Meeting of the ION, San Francisco, Jan. 1993.
[40] R.D. Jurgens and C.E. Rodgers. "Advances in GPS Attitude Determining Technologies as Developed for the Strategic Defense Command," ION-GPS 9 1, Albuquerque, Sept. 1991.
[41] Bar-Itzhack, I. Y., Montgomery, P. Y., & G, J. C., “Algorithms for Attitude Determination Using the Global Positioning System,” Journal of Guidance, Control, and Dynamics, vol. 21, No. 6, November–December 1998.
[42] Stephen J. Fujikawa, “Spacecraft Attitude Determination by Kalman Filtering of Global Positioning System Signals,” Journal of Guidance, Control, and Dynamics, vol. 18, No. 6, November-December 1995.
[43] Crassidis, J. L., Lightsey, E. G., & Markley, F. L., “Efficient and Optimal Attitude Determination Using Recursive Global Positioning System Signal Operations,” Journal of Guidance, Control, and Dynamics, vol. 22, No. 2, March–April 1999.
[44] Park, F. C. Kim, J. & K, C., “Geometric Descent Algorithms for Attitude Determination Using the Global Positioning System,” Journal of Guidance, Control, and Dynamics, vol. 23, No. 1, January–February 2000.
[45] Jared Madsen and E. Glenn Lightsey, “Attitude Determination Using GPS Signal to Noise Ratio and Carrier Phase Measurements,” AIAA Guidance, Navigation, and Control Conference and Exhibit, 11-14 August 2003, Austin, Texas.
[46] Nadler, A. Bar-Itzhack, I. Y. & Weiss, H., “Iterative Algorithms for Attitude Estimation Using Global Positioning System Phase Measurements,” Journal of Guidance, Control, and Dynamics, vol. 24, No. 5, September–October 2001.
[47] Chun, C., & Park, F. C., “Dynamics-Based Attitude Determination Using the Global Positioning System,” Journal of Guidance, Control, and Dynamics, vol. 24, No. 3, May–June 2001.
[48] Li, Y., & Yuan, J., “Attitude Determination Using GPS Vector Observations”.
[49] Kuang, J., & Tan, S. “GPS-Based Attitude Determination of Gyrostat Satellite by Quaternion Estimation Algorithms,” Acta Astronautica, vol. 51, No. 11, pp. 743–759, 2002.
[50] Y. Li , K. Zhang , C. Roberts & M. Murata, “On-the-fly GPS-based attitude determination using single- and double-differenced carrier phase measurements,” GPS Solutions, vol.8,pp.93–102, 2004.
[51] Chin-Lang Tsai, Wei-Wen Kao, “Constrained total least-square solution for GPS compass attitude determination,” Applied Mathematics and Computation, vol.183, pp.106–118, 2006.
[52] Parkinson and Spilker, Global Positioning System: Theory & Applications”, Progress in Astronautics and Aeronautics, AIAA (American Institute of Aeronautics & Ast), 1st edition, 1996.
[53] Strang and Borre, “Linear Algebra, Geodesy, and GPS”, Wellesley College, 1997.
[54] P.J.G. Teunissen and A Kleusberg, “GPS for Geodesy”, Springer, Berlin Heidelberg ,New York, 1998.
[55] Leick, “GPS Satellite Surveying”**,** Wiley, 3rd edition, 2004.
[56] Misra and Enge, “Global Positioning System: Signals, Measurements and Performance”, Ganga-Jamuna Pr , 2001.
[57] Hofmann-Wellenhof et al., “Global Positioning System: Theory and Practice”, Springer; 5th edition 2001.
[58] Peter Buist ,“ The baseline constrained LAMBDA method for single Epoch, single Frequency Attitude Determination Applications”,
[59] Y. Li , K. Zhang , C. Roberts and M. Murata, “On-The-Fly GPS-Based Attitude Determination Using Single- And Double-Differenced Carrier Phase Measurements,”GPS Solutions, 2004.
[60] P.J. Buist, P.J.G. Teunissen, G. Giorgi, S. Verhagen, “Instantaneous GNSS-based Kinematic Relative Positioning and Attitude Determination using Multi-Antenna Configurations”.
[61] P.J.G. Teunissen, “GNSS Ambiguity Resolution for Attitude Determination: Theory and Method”.
[62] Gabriele Giorgi and Peter J. Buist, “ Single-epoch, single-frequency, standalone full attitude determination: experimental results” , NAVITECH 2008.
[63] Verhagen, Sandra, “The GNSS integer ambiguities: estimation and validation”, PhD Thesis, Delft Institute of Earth Observation and Space Systems, Delft University of Technology, Netherlands.
[64] Hatch R, “Instantaneous ambiguity resolution”. Proc. of KIS'90, Ban, Canada, 1990.

ISSN: 2517-9411
Vol:7, No:7, 2013

[65] Frei E, Beutler G, "Rapid static positioning based on the fast ambiguity resolution approach FARA: theory and first results". Manuscripta Geodaetica, 15: 325-356, 1990.
[66] Euler HJ, Landau H "Fast GPS ambiguity resolution on-the-fly for real-time application", Proc. of sixth International Geodetic Symposium on Satellite Positioning, 1992.
[67] Teunissen PJG, "Least squares estimation of the integer GPS ambiguities. Invited lecture, Section IV Theory and Methodology", IAG General Meeting, Beijing, 1992.
[68] Martfin-Neira M, Toledo M, Pelaez A "The null space method for GPS integer ambiguity resolution". Proc. of DSNS'95, Bergen, Norway, paper no.31. 1995.
[69] Chen D, Lachapelle G "A comparison of the FASF and least-squares search algorithms for on-the-fly ambiguity resolution", Navigation, 42(2): 371-390., 1995.
[70] Harris RA "Direct resolution of carrier-phase ambiguity by 'Bridging the wavelength gap'. ESA publication "TST/60107/RAH/Word", 1997.
[71] Vollath U, Birnbach S, Landau H, Fraile-Ordofnez JM, Martfin-Neira M " Analysis of Three-Carrier Ambiguity Resolution (TCAR) Technique for precise relative positioning in GNSS-2" Proc. of ION GPS-1998, Nashville TN: 417- 426.
[72] Kim D, Langley RB "An optimized least-squares technique for improving ambiguity resolution performance and computational efficiency", Proc. of ION GPS-1999, Nashville TN: 1579-1588.
[73] Jung J, Enge P, Pervan B "Optimization of Cascade Integer Resolution with three civil GPS frequencies". Proc. of ION GPS-2000, Salt Lake City UT: 2191-2200.
[74] Joosten P, Verhagen S "Analysis of ambiguity resolution algorithms and quality control parameters for Global Navigations Satellite Systems" ESA publication, contract no. "16793/02/NL/LvH".2003.
[75] Verhagen S, Joosten P "Analysis of ambiguity resolution algorithms". Proc. of the European Navigation Conference GNSS Rotterdam NL, 2004.
[76] P.J.G. Teunissen and S. Verhagen, "Challenges and Open Problems",
[77] Teunissen PJG "An optimality property of the integer least-squares estimator", Journal of Geodesy, 73: 587-593, 1999.
[78] Teunissen PJG, "A class of unbiased integer GPS ambiguity estimators". Artificial Satellites, 33(1): 4-10, 1998.
[79] Buist, P. J. Teunissen, "The Baseline Constrained LAMBDA Method for Single Epoch, Single Frequency Attitude Determination Applications". Proceedings of ION GPS, Fort Worth, TX, US, 2962-2973. 2007.
[80] Gabriele, Peter J. G. Teunissen , "Single-frequency, Single-epoch, Carrier Phase GNSS Attitude Determination with the Multivariate Constrained LAMBDA Method"
[81] Teunissen, P. J. G. "A General Multivariate Formulation of the Multi-Antenna GNSS Attitude Determination Problem", Artificial Satellites 42 (2), 97-111,2007.

Lv Meibo is a lecturer at School of Astronautics, Northwestern Polytechnical University, Xi'an, China with specialization in navigation, guidance and control. (Phone: 0086-15829682227; e-mail: nwpuiet@nwpu.edu.cn).

Naqvi Najam Abbas is a PhD candidate at School of Astronautics, Northwestern Polytechnical University, Xi'an, China (Phone: 0086-15129299607; e-mail: najm_naqvi@yahoo.com).