IAG

Study Group 4.1 (2003-2007):

Pseudolite Applications in Positioning and Navigation

Final Report

Jinling Wang
School of Surveying and Spatial Information Systems
University of New South Wales
Sydney, NSW 2052, Australia

Email: Jinling.Wang@unsw.edu.au
Tel: 61-2-9385 4203
Fax: 61-2-9313 7493

Introduction

Applications of artificial satellites in positioning and navigation can be traced back to as early as the 1960's, just shortly after the launch of the first artificial satellite in 1957, when the era of satellite geodesy started. Over the past four decades, particularly since the inception of the Global Positioning System (GPS), satellite-based positioning techniques have been playing an increasingly important role in surveying and geodesy.

In satellite-based precise positioning, dominant factors are the number *and* geometric distribution of the satellites tracked by receivers. In the case of Global Navigation Satellite Systems (GNSS), such as GPS, Glonass, and the forthcoming European Galileo system as well as Chinese Compass system, four visible satellites are the minimum requirement for precise three-dimensional positioning. In general, the more satellites that are tracked, the more reliable the positioning solutions. However, in some situations, such as in downtown urban canyons, engineering construction sites, and in deep open-cut pits and mines, the number of visible satellites may not be sufficient. In the worst situations, such as in underground tunnels and inside buildings, the satellite signals may be completely absent.

Such problems with existing GNSS systems can be addressed by the inclusion of additional ranging signals transmitted from ground-based "pseudo-satellites" (pseudolites). Pseudolites are an exciting technology that can be used for a wide range of positioning and navigation applications, either as a substantial augmentation tool of space borne systems, or as an independent system for indoor positioning applications.

To promote the applications of pseudolite in engineering geodesy, a working group on pseduolite applications was set up in 2001 within the IAG Special Commission SC4 (Application of Geodesy to Engineering 1999-2003). In 2003, the IAG established Study Group 4.1 on "Pseudolite Applications in Positioning and Navigation" within the IAG Commission 4 Positioning and Applications.

Website of the SG4.1
http://www.gmat.unsw.edu.au/pseudolite/

Objectives of the SG4.1

The goal of this study group was to investigate new concepts of pseudolite-related positioning and navigation applications. The objectives of the research activities were to study:
(a) Pseudolite augmentation of GPS.
(b) Pseudolite-only positioning scenarios.
(c) Integration of pseudolites with other sensors, such as Inertial Navigation Systems (INS).

To achieve these objectives, the members of the Study Group 4.1 have been actively involved in a variety of activities over the past 4 years:
- Promoting dialogue between SG members.
- Encouraging/participating symposia and sessions at conferences with the theme of pseudolite technology and applications.
- Setting up a SG website providing a focus for pseudolite research and applications with the relevant links.
- Developing a comprehensive bibliography for pseudolite research and applications.

Members of the SG4.1

Jinling Wang (Chair, Australia)
Gethin Roberts (Vice Chair, UK)
Dorota Grejner-Brzezinska (Vice Chair, USA)
Joel Barnes (Australia)
Elizabeth Cannon (Canada)
Paul Cross (UK)
Peter Dare (Canada)
Fabio Dovis (Italy)
Xiufeng He (China)
Gunter W. Hein (Germany)
Jonathan P. How (USA)
Changdon Kee (South Korea)
Edward LeMaster (USA)
Jingnan Liu (China)
Paolo Mulassano (Italy)
Xiaolin Meng (UK)
Ilir F. Progri (USA)
Chris Rizos (Australia)
Fredrick von Schoultz (Finland)
Toshiaki Tsujii (Japan).

Activities of the SG4.1

Over the past 4 years, there have been significant progresses in pseusolite research and applications in positioning and navigation, which are briefly summarized in the following sections.

Advances in modeling and algorithms development

Theoretical analysis and algorithm development have been conducted for pseudolite applications. Systematic errors introduced by pseudolites have been investigated by both theoretical and numerical analyses, which reveal that errors of troposphere delay modelling, differential nonlinearity and pseudolite-location are sensitive to pseudolite system geometry. Optimal geometry design for pseudolite-augmented systems has been proposed in airborne surveying scenarios. A new method for pseudolite tropospheric delay modelling has been proposed, which is based on single-differenced GPS tropospheric delay models. The performance of different models has been investigated through simulations and field testing. The advantages and limitations of each method have been analyzed. In addition, it has been found that for a high accuracy pseduolite-based navigation system, compensating for right-hand circularly polarized effects on the carrier phase measurements is essential.

For the integration of GPS, pseudolites and INS, an effective procedure for single frequency carrier phase integer ambiguity resolution has been proposed. With the inclusion of pseudolites and INS measurements, the proposed procedure can speed up the ambiguity resolution process and increase the reliability of the resolved ambiguities.

Innovative algorithms and methodologies are being developed for autonomous network installation, network integrity and quality control of Locata positioning system, which uses a network of terrestrial based signal transmitters (pseudolites) and GPS satellites, to provide ubiquitous positioning (indoors and outdoors) in difficult environments.

Integration of GPS/INS/Pseudolite to geo-reference surveying and mapping platforms

A new integration concept to include pseudolites into the tightly integrated GPS/INS system has been proposed. Land-based experimental studies on this concept have demonstrated potential benefits of the tight integration of GPS/INS/Pseudolites.

In a joint research project between the University of New South Wales and Qasco Survey Ltd., a pseudolite augmented airborne GPS/INS integration system for large scale airborne mapping has been tested. In this test, a ground based pseudolite was set up on the ground, and two GPS/Pseudolite antennas were mounted on an aircraft to receive signals from GPS satellites in the sky and the pseudolite. To evaluate overall navigation performance, flight tests were carried out in October 2006 at the Royal Sydney Golf Club, Australia. The results have shown that the pseudolite signal can strengthen the signal availability and the satellite geometry. Significant geometry enhancement was observed in the vertical component. However, the actual positioning accuracy improvement in the vertical component was not as much as expected, which is primarily due to the unmodelled errors in the integrated system. Several potential error sources in pseudolite measurements and the system have been identified:

- Errors in pseudolite transmission antenna location measurement;
- Serious multipath in pseudolite measurements;
- Pseudolite measurements modelling error;
- Surveying error of the lever arm between the two airborne antennas;

One GPS/Pseudlite data set from this experiment has been made available at the website of SG4.1 http://www.gmat.unsw.edu.au/pseudolite/TwoDataSets.html, for other researchers.

Ultra-tight Integration of GPS/INS/Pseudolite sensors

Ultra-tight integration of GPS, pseudolites and inertial sensors has been investigated, to develop efficient algorithms and quality control procedures for signal acquisition and tracking, which can effectively suppress interferences and enhance the weak ranging signal tracking.

In ultra-tight integration, the design of the integration Kalman filter is critical. Due to the complex measurement model, the computational requirements for a centralised filter approach are high. Therefore, decentralised techniques based on federated Kalman filter approach have been proposed for efficient real-time implementation. The performance of the Kalman filter has been proposed. Depending on the observations utilised by the Kalman filter, the linear or nonlinear Kalman filter based ultra-tight configurations have been investigated. Compared with the pseudorange and pseudorange-rate data used as observations in the linear Kalman filter, the in-phase and quadrature data from the GPS/Pseudolite signal correlators are highly nonlinear, therefore it is necessary to utilise nonlinear Kalman filter techniques.

In a ‘pseudolite-only’ constellation, by increasing the number of pseudolite transmitters and placing them appropriately, the operating environment can be optimised for both geometry and availability of signals. The problem of tracking higher Doppler changes in indoor environment by combining the pseudolite signals with INS data in ultra-tight configuration has been investigated, indicating that the higher Doppler changes require higher tracking loop bandwidths and higher order loop filters. By integrating the INS-derived Doppler with the tracking loops, the dynamics on the pseudolite signals can be effectively reduced. This integration strategy also results in lower tracking loop bandwidths which provide better immunity to multipath signals. The simulation studies have shown a significant improvement in the performance of the integrated system.

Novel uses of pseudolites in positioning and navigation

The researchers at Stanford University has proposed and developed a self-calibrating pseudolite array for potential uses on the Mars. The pseudolites used in such a system are actually transceivers, which can transmit and receive ranging signals to determine the relative locations of all the pseudolites in the array. A transceiver consists of a transmitter and a receiver, which can essentially receive the signals from all the transmitters including the one inside the transceiver itself. This hardware design enables the cancellation of both transmitter and receiver clock errors without using a separate reference station, which is normally required for typical differential satellite positioning.

Research teams at the University of New South Wales, University FAF Munich, Japan Aerospace Exploration Agency (JAXA), and the Seoul National University have conducted several flight tests with the use of pseudolites in positioning and navigation applications. In such applications, pseudolites can provide extra ranging signals to guarantee the stringent integrity requirements or provide a test of GNSS signal performance.

At Worcester Polytechnic Institutethe in the USA, a pseudolite-based indoor geo-location system has been investigated, designed and tested for firefighting applications. In this research, a variety of ranging frequency structures have been considered and compared. Precise (sub-meter) three dimensional personal tracking in the indoor high multipath environment has been achieved.

Research teams in Australia, China, Canada and UK have investigated the applications of pseuolites in deformation monitoring for dams, bridges, open pit mines and high rise buildings. Due to the limited number of satellites in the constellation, GPS positioning precision varies. It is typical that GPS positioning precision is the three times worse in vertical than in horizontal components and varies significantly with the changes of geometry within the visible satellites, particularly where the satellite signals are frequently blocked (by dams or high rise buildings, etc.). The investigations have found that the combined use of GPS and pseudolites can improve the efficiency and reliability of a deformation monitoring system.

Discussions on the definition of pseudolite

Although the term of pseudolite, or pseudo-satellite, was originally from the very first GPS signal validation test, it has since been widely used for any GNSS, for example, Galieo pseudolite, Compass pseudolite, or even Japanese QZSS pseuolite using BOC signals. However, beyond the role of GNSS signal validation, pseudolites can significantly extend positioning and navigation service availability into areas where direct line of sight to satellites is blocked. For this purpose, the frequency used in a pseduolite may be different from the frequencies used in any GNSS systems. For example, IntegriNautics (now called Novariant: http://www.novariant.com/mining/products/index.cfm) has proposed a four-frequency pseudolite system which uses the frequencies in the Industrial, Scientific and Medical (ISM) band: two frequencies in the 900MHz ISM band and two in the 2.4GHz ISM band. Similarly, a new pseudolite design from Locata Corporation in Canberra, Australia (http://www.epicorp.com.au/index/locatacorporation) has also used the frequencies in the (ISM) band to avoid the so-called legal concerns of using officially defined GNSS frequencies which are supposed to be legally protected worldwide. Some researchers have classified such new pseudoites transmitting a non-GNSS signal into terrestrial-based RF positioning technologies, while there is a general trend in the literature that the term of pseudolite is widely used to describe a radio-ranging signal transmitter (and/or) transceiver for positioning and navigation applications.

A time-synchronized pseudolite *transceiver* called a *LocataLite* developed by Locata Corporation is a significant milestone in pseudolite applications in that a precise single point positioning scenario, without the use of any reference station, becomes a reality.

Challenging issues

As shown above, there have been some exciting developments in pseudolite research and applications, which are, without any doubt, of particular interest for positioning and navigation community. However, there are still ome challenging issues to deal with, such as

- Developing realistic tropospheric error models for pseudolite measurements;
- Selecting the optimal frequency bands and the best ranging signal structure;
- Optimal design of pseudolites locations: strengthening the positioning geometry (especially for pseudolite-only positioning scenarios) and minimizing the impact of reminding errors on the positioning results;
- Modelling the pseudolite signal penetrating delays in indoor positioning scenarios;

- Better understanding the pseudolite signal dynamics under different positioning environments;
- Integrating pseudolites with INS and/or imaging sensors
- Novel uses of pseudolites (for example, navigating spacecraft, on Mars/Moon).

List of the selected conferences relevant to SG4.1 (2003-2007)

6th Int. Symp. on Satellite Navigation Technology Including Mobile Positioning & Location Services, Melbourne, Australia, 22-25 July 2003.

16th Int. Tech. Meeting of the Satellite Division of the U.S. Institute of Navigation, Portland, Oregan, 9-12 September 2003

11th Int. Assoc. of Institutes of Navigation (IAIN) World Congress, Berlin, Germany, 21-24 October, 2003

2003 International Symposium on GPS/GNSS, Tokyo, Japan, 15-18 November 2003

1st FIG Int. Symp. on Engineering Surveys for Construction Works & Structural Eng., Nottingham, U.K., 28 June - 1 July 2004

2004 International Symposium on GPS/GNSS, Sydney, Australia, 6-8 December 2004.

Workshop on Geolocation Technology to Support UXO Geophysical Investigations, Annapolis, Maryland, 1-2 June 2005.

18th Int. Tech. Meeting of the Satellite Division of the U.S. Institute of Navigation, Long Beach, California, 13-16 September 2005

2005 International Symposium on GPS/GNSS, Hong Kong, 8-10 December 2005.

US Institute of Navigation's National Technical Meeting 2006, Monterey, California, USA, 18-20 January 2006.

3rd IAG Symp. on Geodesy for Geotechnical & Structural Engineering and 12th FIG Symp. on Deformation Measurements, Baden, Austria, 22-24 May 2006.

19th Int. Tech. Meeting of the Satellite Division of the U.S. Inst. of Navigation, Fort Worth, Texas, 26-29 September, 2006

12th IAIN Congress & 2006 International Symposium on GPS/GNSS, Jeju, Korea, 18-20 October, 2006.

US Institute of Navigation's National Technical Meeting 2007, San Diego, California, USA, 22-24 January 2007.

FIG Working Week, Hong Kong, 13-17 May 2007.

Selected Bibliography

(More publications relevant to the SG4.1 can be found at the website of SG4.1: http://www.gmat.unsw.edu.au/pseudolite/biblio.html)

BIBERGER, R. J.; TEUBER, A.; PANY, T.; HEIN, G. W.; 2003, Development of an APL Error Model for Precision Approaches and Validation by Flight Experiments. In: Proceedings of ION GPS GNSS 2003, Portland, Oregon, Sept. 09-12.

BABU, R., & WANG, J., 2005. Ultra-tight GPS/INS/PL integration: Kalman filter performance analysis. *Int. Symp. on GPS/GNSS*, Hong Kong, 8-10 December, paper 6A-05.

BABU, R., & WANG, J., 2006. Ultra-tight integration of pseudolites and INS. *IEEE/ION PLANS*, San Diego, California, 25-27 April, 705-714.

BARNES, J., RIZOS, C., KANLI, M., & PAHWA, A., 2006b. A solution to tough GNSS land applications using terrestrial-based transceivers (LocataLites). *19th Int. Tech. Meeting of the Satellite Division of the U.S. Inst. of Navigation*, Fort Worth, Texas, 26-29 Sept., 1487-1493.

BARNES, J., RIZOS, C., WANG, J., SMALL, D., VOIGHT, G., & GAMBALE, N., 2003. Locatanet: A new positioning technology for high precision indoor and outdoor positioning. *16th Int. Tech. Meeting of the Satellite Division of the U.S. Institute of Navigation*, Portland, Oregan, 9-12 September, 1119-1128.

COSSER, E., MENG, X., ROBERTS, G.W., DODSON, A.H., BARNES, J., & RIZOS, C., 2004. Precise engineering applications of pseudolite augmented GNSS. *1st FIG Int. Symp. on Engineering Surveys for Construction Works & Structural Eng.*, Nottingham, U.K., 28 June - 1 July, paper TS10.1, CD-ROM procs.

DODSON, A.H., COSSER, E., MENG, X., ROBERTS, G.W., BARNES, J., & RIZOS, C., 2003. Integrated approach of GPS and pseudolites for bridge deformation monitoring. *GNSS2003*, Graz, Austria, 22-25 April, CD-ROM proc., paper 205.

GREJNER-BREZINSKA, D. and YI, Y., 2004, Experimental GPS/INS/Pseudolite system for kinematic positioning, *Survey Review,* Vol. 37, No. 290 October 2003.

HE, X., 2005 Pseudolite-Augmented GPS For Deformation Monitoring: Analysis and. Experimental Study, International Symposium on GPS/GNSS, Hong Kong, 08/12~10/12/2005.

HE X.; CHEN, Y.Q.; SANG, W.; YANG, G., 2007, Pseudolite-augmented GPS for Deformation Monitoring: Analysis and Experimental Study *Acta Geodaetica et Cartographica Sinica*, No.1.

JUN H and C. KEE, 2006, High Accuracy Pseudolite-based Navigation System: Compensating for Right-hand circularly Polarized Effect. The Journal of Navigation, 59, 307–320.

LEE, H.K., WANG, J., & RIZOS, C., 2005. An integer ambiguity resolution procedure for GPS/Pseudolite/INS integration. *Journal of Geodesy*, 79, 242-255.

LEE, H.K., WANG, J., RIZOS, C., & GREJNER-BRZEZINSKA, D., 2004. Analysing the impact of integrating pseudolite observations into a GPS/INS system. *Journal of Surveying Engineering*, 130(2), 95-103.

LEE, H.K., WANG, J., RIZOS, C., & TSUJII, T., 2005. Augmenting GPS by ground-based pseudolite signals for airborne surveying applications. *Survey Review*, 38(296), 88-99.

LI, D., & WANG, J., 2006. Kalman filter design strategies for code tracking loop in ultra-tight GPS/INS/PL integration. *U.S. Institute of Navigation National Tech. Meeting*, Monterey, California, 18-20 January, 984-992.

LI, D., WANG, J., & BABU, R., 2006. Enhancing the performance of ultra-tight integration of GPS/PL/INS: A federated filter approach. *Journal of Global Positioning Systems*, 5(1-2), 96-104.

MENG, X., ROBERTS, G.W., DODSON, A.H., COSSER, E., BARNES, J., & RIZOS, C., 2004. Impact of GPS satellite and pseudolite geometry on structural deformation monitoring: Analytical and empirical studies. *Journal of Geodesy*, 77, 809-822.

PROGRI, I.F., ORTIZ, W., MICHALSON, W.R., & WANG, J., 2006. The performance and simulation of an OFDMA pseudolite indoor geolocation system. *19th Int. Tech. Meeting of the Satellite Division of the U.S. Inst. of Navigation*, Fort Worth, Texas, 26-29 September, 3149-3162.

RIZOS C. 2005, Pseudolite Augmentation of GPS, *Workshop on Geolocation Technology to Support UXO Geophysical Investigations,*Annapolis, Maryland, 1-2 June.

SOON, B.K.H., BARNES, J., LEE, H.K., ZHANG, J., RIZOS, C., WANG, J., & LEE, H.K., 2004. Real-time flight test results of an integrated GPS/INS/pseudolite autolanding system. *GNSS2004*, Rotterdam, The Netherlands, 16-19 May, CD-ROM proc., paper 16.

TSUJII, T, H. TOMITA, Y. OKUNO, S. KOGURE, M. KISHMOTO, K. OKANO, M. DINESH, I. PETROVSKI, M. ASAKO, 2007, Development of a BOC/CA Pseudo QZS and Multipath Analysis Using an Airborne platform, The Institute of Navigation National Technical Meeting, San Diego, US, 22-24 January, 2007, pp.446-451.

WANG W; LIU, Z., XIE, R., 2005, Study on Pseudolite-augmented "Bei dou" Double-star Positioning System and Algorithm, *Chinese Space Science and Technology*, No. 3.

WANG, J., BABU, R., LI, D., CHAN, F., & CHOI, J., 2006. Integrating GPS/INS/PL for robust positioning: The challenging issues. *12th IAIN Congress & 2006 Int. Symp. on GPS/GNSS*, Jeju, Korea, 18-20 October, 127-132.

WANG, J.J., WANG, J., KEARSLEY, A.H.W., & LEE, H.K., 2004. Pseudolite augmentation for GPS aided aerial photogrammetry: An analysis of systematic errors. *Geomatics Research Australasia*, 81, 30-44.

WANG, J.J., WANG, J., SINCLAIR, D., & WATTS, L., 2006. High-accuracy airborne GPS/INS positioning augmented by pseudolite. *U.S. Institute of Navigation National Tech. Meeting*, Monterey, California, 18-20 January, 515-522.

WANG, J.J., WANG, J., SINCLAIR, D., WATTS, L., & LEE, H.K., 2005. Tropospheric delay estimation for pseudolite positioning. *Journal of GPS*, 4(1-2), 106-112.