Integration of GNSS and Pseudo-Satellites: New Concepts for Precise Positioning

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Abstract. Current Global Navigation Satellite Systems (GNSS), such as the GPS and Glonass systems, have been widely used in surveying and geodesy. It is well known that for such spaceborne satellite positioning systems the accuracy, availability and reliability of the positioning results is very dependent on both the number and geometric distribution of satellites being tracked. However, under some harsh observing environments, such as in urban canyons and deep open-cut mines, the number and geometry of visible satellites may not be sufficient to reliably carry out the positioning operations. In the worst situations, such as in underground tunnels or inside buildings, the satellite signals are completely lost.

Such problems with GNSS systems can be addressed by the inclusion of additional ranging signals transmitted from ground-based "pseudo-satellites" (pseudolites). In this paper, the current status of high precision pseudolite applications will be briefly reviewed. Various pseudolite-related positioning concepts, including pseudolite augmentation of GPS, pseudolite-only scenarios, and integration of pseudolites with INS, will be discussed. Both geometric analyses and experimental results will be presented to demonstrate the capabilities of such new positioning systems

Keywords. GPS, Pseudolites, GPS/Pseudolite Integration, GPS/INS/Pseudolite Integration

1 Introduction

Since the launch of the first artificial satellites, satellite-based positioning and navigation techniques have been playing an increasingly important role in surveying and geodesy. However, for positioning systems that use signals at radio frequencies (RF) one major limitation is signal attenuation. In the case of modern Global Navigation Satellite Systems, such as the GPS and Glonass systems, the navigation satellites are orbiting the Earth at about 20,000km altitude. The ranging signals (on the frequencies of about 1.2 and 1.6GHz) from the satellites are relatively weak when they reach ground-based receivers, and thus can be easily obstructed by buildings, walls, trees and terrain. Therefore performance of the spaceborne systems will be severely degraded under poor operational environments such as in urban canyons, deep open-cut mines, etc. In the worst situations the satellite ranging signals may be completely lost. These problems can be addressed by the inclusion of additional measurements from "pseudo-satellites" (pseudolites).

A GPS pseudo-satellite can be considered as a satellite-on-the-ground that transmits GPS-like ranging signals (Elrod & Van Dierendonck, 1996). The use of pseudolites can be tracked back as early as the 1970's. Even before the launch of the GPS satellites, pseudolites had been used to test the initial GPS user equipment (Harrington & Dolloff, 1976). Klein and Parkinson (1984) analysed the geometric advantages of integrating GPS and pseudo-satellites.

The use of pseudolites has been investigated for applications of differential GPS (DGPS) by, for example, Barltrop et al. (1996), Kalafus et al. (1986), Parkinson & Fitzgibbon (1986), Holden & Morely (1997). In the DGPS applications, a pseudolite can be used to provide not only an additional ranging signal, but also a differential data link.

During the last decade investigations into pseudolites have intensified in aviation for precision approach and landing (Brown, 1992; Cobb et al., 1995; Hein et al., 1997), as well as other more general positioning and navigation applications (Dai et al., 2001; Ford et al., 1996; Lemaster & Rock, 1999; Stone & Powell, 1998; Tsujii et al. 2001; Zimmerman et al. 2000; Wang et al., 2001).

Pseudolites are a new, complementary technology that offers opportunities to address a range of robust positioning and navigation applications. It can be expected that such augmentation of GPS will improve the performance of the whole system because the availability and geometry of positioning solutions can be significantly strengthened. On the other hand, a pseudolite-only positioning system is possible, which can replace the GNSS constellation where the use of spaceborne satellite signals is not feasible, such as underground and indoors (Kee et al., 2000).

In principle, pseudolites can transmit their ranging signals on different frequencies, just as the Glonass satellites do. Zimmerman et al. (2000) proposed a design of a pseudolite which uses up to five frequencies (two in the 900MHz ISM band, two in the 2.4GHz ISM band, and the GPS L1 frequency). An advantage of such multi-frequency pseudolite systems is that the integer carrier phase ambiguities can be resolved instantaneously, due to redundant measurements and the extra wide-lane observables that can be constructed from the different frequencies. Currently the majority of the pseudolites transmit GPS-like signals at the frequencies of L1 (1575.42MHz) and possibly on L2 (1227.6MHz). With this configuration, with the modification of the firmware, standard GPS receivers could be used to track pseudolite signals. However, there is a potential interference with the satellite signals due to the pseudolite transmitter(s) being very close to the receiving antenna compared to the GPS satellites, referred to as the 'near-far' problem (Klein & Parkinson, 1984). One solution to this problem is to pulse the pseudolite signals at fixed cycle rates.

The concepts of pseudolite-based positioning are still under development. Pseudolites can be even designed to be capable of both receiving and transmitting ranging signals at GPS L1/L2 or other frequencies. This type of pseudolite can ‘exchange’ signals, which can be used to self-determine the geometry for a pseudolite array. These pseudolites are referred to as *transceivers* (Lemaster & Rock, 1999). Similarly, it is also possible to synchronise the pseudolite ranging signals to the GPS signals. This kind of pseudolites is called a *Sychrolite* (Cobb, 1997).

Compared with satellites in space, pseudolites are much closer to the receivers and usually have a lower elevation angle relative to the receivers. Therefore, there are some challenging issues in modelling and geometric design that need to be addressed, such as non-linearity, tropospheric delays, multipath, pseudolite location errors and in defining the optimal positioning scenarios (Dai et al., 2001; Wang et al., 2001).

This paper will discuss various concepts of precise positioning with the use of GPS pseudo-satellites, including GPS and pseudolite integration, pseudolite-only positioning, and GPS/INS/pseudolite integration. Both geometric analysis and experimental results are presented.

2 GPS and Pseudolite Integration

For spaceborne satellite positioning systems the accuracy, availability and reliability of the positioning results is very dependent on both the number and geometric distribution of satellites being tracked. However, sufficient number of ‘visible’ satellites cannot be guaranteed everywhere. For example, for deep open-cut mines, as shown in Fig.1, the number of visible satellites is limited.

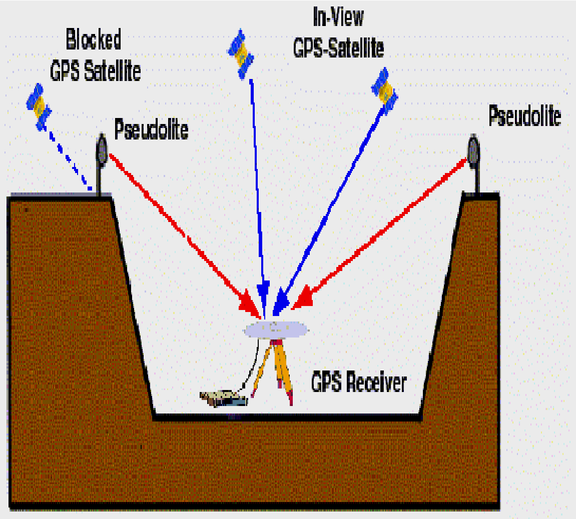

Fig. 1 Integrating GPS and Pseudolite Signals for PosItioning in Deep Open-Cut Mines.

Even when some low elevation satellites can be tracked, the measurements from these satellites are contaminated by relatively high atmospheric noise. Therefore, this *significant drawback of existing systems results in poor accuracy in the vertical coordinates* of positioning -- up to three times worse than that of the horizontal coordinate components. These issues can be addressed by the integration of GPS and pseudolites.

The pseudolite ranging signals can contribute to the GPS positioning systems by enhancing the geometric strength, improving the availability, integrity, and reliability, and increasing the accuracy of the height components of the positioning solutions. To demonstrate the contribution of pseudolite measurements for height component determination, a data set collected on 16 April 2000 at UNSW is analysed. In this data set, four GPS satellites and one pseudolite were observed. The elevation angles for these satellites were 30, 48, 55, and 60 degrees respectively, while the pseudolite elevation was just about 5 degrees. Fig. 2 shows the variations of the DOP value for the height component (RHDOP) for both the GPS-only and the integrated GPS/pseudolite scenarios. It can be seen that the precision of the height components can be significantly improved by including pseudolite observations.

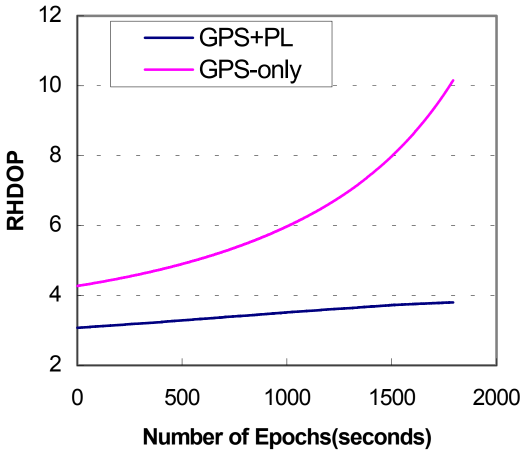

Fig. 2 Geometric Comparison between GPS-only and Integrated GPS and Pseudolite Solutions

In integrated GPS and pseudolite positioning, the optimal locations of pseudolites should be identified so as to maximise the contributions of these additional signals. A geometric analysis can be carried out with appropriate optimisation criteria, such as Position Dilution of Precision (PDOP) and Relative Position Dilution of Precision (RDOP).

3 Pseudolite-Based Positioning

As pseudolites broadcast GPS-like ranging signals, pseudolites can, in principle, replace the satellite constellation. Such a positioning concept has been proposed for indoor positioning (e.g., Kee et al., 2000). Although the concept is straightforward, such challenging issues as multipath and pseudolite location errors need to be addressed. To reduce the multipath errors, helical antennas are usually employed for transmission of pseudolite signals. In some situations the precise determination of the transmitter antenna phase centre position could be a difficult task. Therefore, pseudolite locations should be calibrated. More detailed discussions in this regard can be found in Kee et al. (2000) and LeMaster & Rock (1999).

Pseudolite-only postioning can also be based on the so-called inverted positioning concept (Raquet et al., 1995). In such a positioning scenario (Fig. 3) a reference pseudolite, a user/mobile pseudolite and four or more receivers are needed. Similar to GPS relative positioning, the double-differenced measurements between pseudolites and receivers can be formed to remove most of the systematic errors, such as transmitter and receiver clock errors. The receiver and reference pseudolite locations should be precisely pre-determined. With the known coordinates for the receivers and the reference pseudolite, the coordinates for the user pseudolite can be determined.

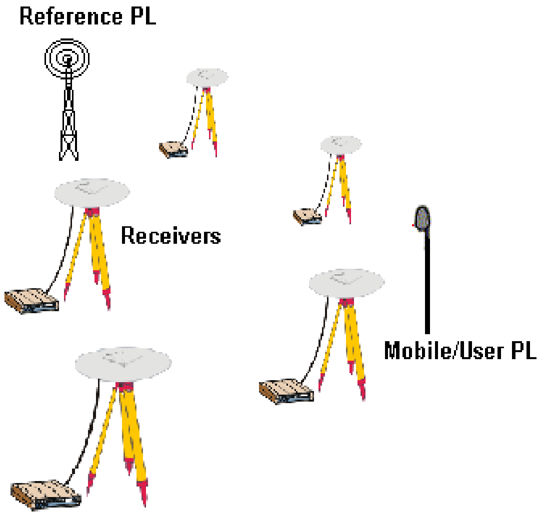

Fig. 3 Inverted Pseudolite Positioning Concept.

As with satellite-based positioning systems, the reliability of an inverted pseudolite positioning system is very dependent on the strength of geometry of the receivers and pseudolites used in the system. For an inverted pseudolite positioning system, a poor geometry will be one in which all the receivers and pseudolites lie approximately in the same plane (Pachter & Mckay, 2000). Such poor geometry will amplify the errors in the positioning solutions. Also, 'unfavorable' geometry may occur, for example, when the transmitter antenna stays directly over the centre of a planar four-receiver square. In this situation the design matrix of the measurement equations will become singular, and thus there is no unique positioning solution. Such situations should be identified through a full simulation for all possible trajectories and excluded from positioning operations.

An optimal geometry can be defined by using appropriate optimisation criterion such as PDOP or RDOP. For an array of four receivers used for inverted static positioning, the optimal geometry as shown in Fig. 4 will have a minimum PDOP value of 1.63 (Dai et al., 2001). In this geometry, three receivers (R1, R2, R3) are equally spaced in the azimuthal plane, and at the zero elevation angle related to the mobile pseudolite (PL), and the fourth receiver (R4) is located at the zenith.

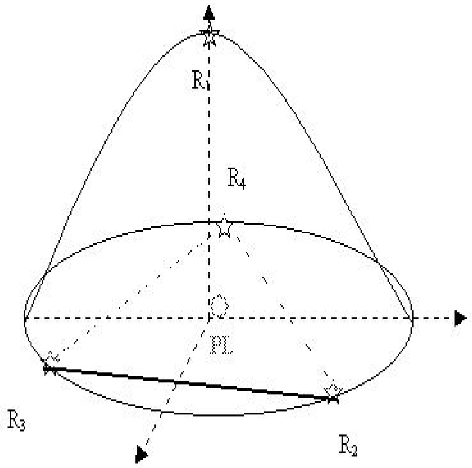

Fig. 4 The Optimal Four-Receiver Array Minimizing the PDOP Value (Dai et al. 2001).

In real applications, other factors need to be taken into account in geometric optimisation. These factors may include observing conditions, specific terrains, number of receivers used, possible ranges for the receiver locations and so on. These factors will impose constraints on the geometric optimisation problem, resulting in a more complicated procedure. However, taking these constraints into account during optimisation ensures that an optimal geometry can be identified for practical applications.

4 GPS, Pseudolite and INS Integration

In contrast to satellite-based positioning systems, Inertial Navigation Systems (INS) are self-contained and autonomous. Thus, INS systems are independent of any external signals. However, one of main drawbacks of INS, when operated as a stand-alone system, is the time-dependent growth of systematic errors. GPS measurements are typically used to calibrate INS systematic errors. As discussed in section 2, GPS signals might be obstructed for extended time periods under difficult operational conditions, during which the performance of integrated GPS/INS systems may degrade rapidly. This issue can be addressed by the inclusion of pseudolite signals. An integrated GPS/INS/pseudolite or INS/pseudolite system will be able to improve system performance under a wide variety of poor operational environments.

An experiment was conducted to investigate the performance of an integrated GPS/INS/pseudolite system in May 2001. Figs. 5 and 6 show the set-up and trajectory for the experiment, in which a Litton LN-100 IMU sensor, an IntegriNautics IN200 pseudolite and two NovAtel GPS receivers were used. During the experiment there were 6 visible satellites (above the cut-off angle of 15 degrees). The elevation angles for these satellites were 16, 20, 26, 50, 44 and 80 degrees respectively. Because of the movement of the rover receiver, the pseudolite elevation varied from 9 to 2.5 degrees at the different rover receiver locations.

Fig. 5 Setting-up for the Integrated GPS/INS/PL Experiment

In the data analysis, the L1 carrier phase measurements were processed together with the IMU measurements in a Kalman filter. The software package AIMS, developed at the Ohio State University, has been modified at The University of New South Wales to include the pseudolite measurements. Both GPS/INS and GPS/INS/PL solutions have been obtained. A comparison between these two solutions are shown in Figs. 7 and 8. As indicated in Fig.7, the inclusion of the pseudolite measurements improves the precision for all three-dimensional coordinates, particularly for the height component. It is noted from Fig. 8 that the coordinate differences between the two types of solutions may reach a few centimetres.

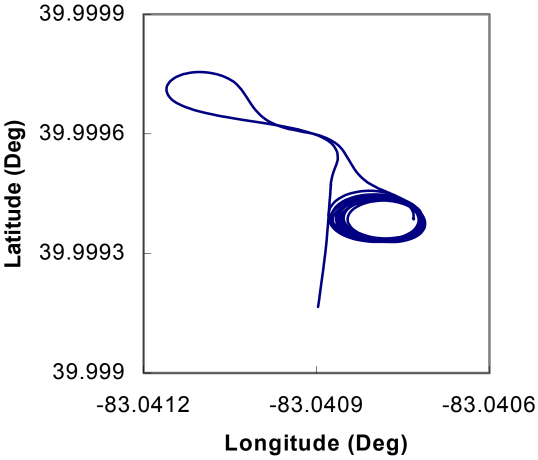

Fig. 6 Trajectory for the Integrated GPS/INS/PL Kinematic Experiment

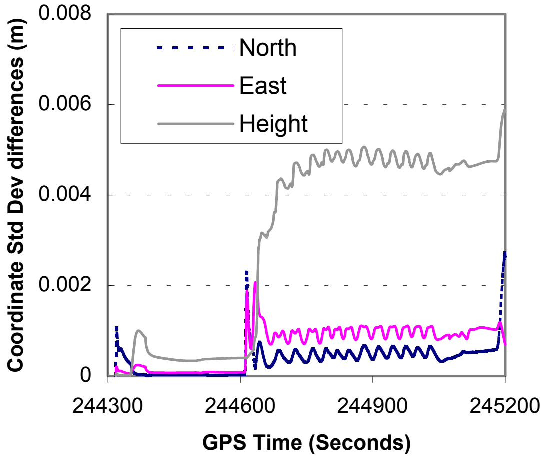

Fig. 7 Precsion Comparsion between the GPS/INS and GPS/INS/PL Solutions.

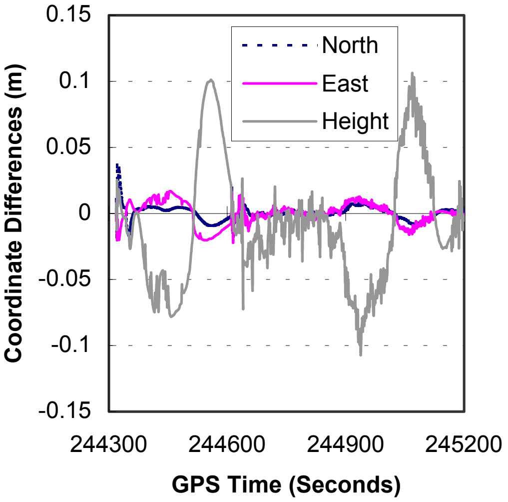

Fig. 8 Coordinate Differences between the GPS/INS and GPS/INS/PL Solutions

In previous studies, there have been some concerns about the systematic biases in pseudolite measurements (e.g., Wang et al., 2001; Dai et al., 2001). In static positioning, these biases appear to be constant. In this kinematic experiment, the possible biases are most likely being randomised because there do not appear to be any significant constant biases in the solutions.

5 Concluding Remarks

Although the role of GNSSs is becoming more and more important in modern positioning and navigation, there are two shortcomings of such technologies: signal attenuation and dependence on the geometric distribution of the satellites. Consequently the performance of such satellite-based positioning systems can decrease significantly under some harsh observing conditions. Satellites orbiting in space are not under users' control. In contrast, pseudolites are ground-based transmitters, which can be easily installed wherever they are needed. They therefore offer great flexibility in precise positioning applications.

New positioning concepts based on the use of pseudolites have been discussed in this paper. The results from a GPS/INS/pseudolite experiment have been presented, which demonstrate the feasibility for the integration of pseudolites with other sensors to improve the performance of precise positioning systems.

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