The Role of Pseudo-Satellite Signals in Precise GPS-Based Positioning

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Abstract

In this paper, three general classes of pseudolite system configurations are discussed. The first is *GPS augmentation with pseudolite(s)*, which is suitable for circumstances where direct GPS signal availability is restricted. The second is *indoor applications of pseudolite-based positioning*, where pseudolites can, in principle, completely replace the GPS satellite constellation. The last class of configurations is *an inverted pseudolite-based positioning system*, where a 'constellation' of GPS receivers with precisely known 'orbits' track a mobile pseudolite. In the case of pseudolite-only or hybrid pseudolite-GPS positioning systems there are some additional issues that need to be addressed. These include multipath, atmospheric delay effects, and location-dependent errors such as receiver and pseudolite location biases. In May 1999, the Satellite Navigation and Positioning (SNAP) Group, The University of New South Wales (UNSW), purchased a pseudolite and commenced research into this technology. In December 2000 some experiments were carried out using NovAtel GPS receivers and IntegriNautics IN200CXL pseudolite instruments (two borrowed from the Dept. of Geomatics Engineering, the University of Calgary, Canada). The experimental results indicate that these pseudolite-based positioning systems are feasible. Their performance will be demonstrated through several case study examples.

1 Introduction

Due to the high precision of the carrier phase measurements, the Global Positioning System (GPS) technology has been widely used for geodetic applications such as measuring crustal motion, for geodetic engineering applications such as monitoring ground subsidence and the deformation of man-made structures such as bridges, dams and buildings, and a wide range of engineering survey applications. As is well known, the accuracy, availability, reliability and integrity of the GPS positioning solutions is heavily dependent on the number, and geometric distribution, of satellites being tracked. However, in some situations, such as in urban canyons, in valleys and in deep open-cut mines, the number of visible satellites may not be sufficient to reliably determine precise coordinates. Furthermore, it is impossible to use GPS for indoor positioning applications. On the other hand, due to limitations of the GPS satellite geometry, the accuracy of the height component is generally 2 or 3 times worse than the horizontal components. These factors make it difficult to address GPS positioning applications in areas where the number of visible satellites is limited or satellite geometry is poor, especially where high accuracy height component determination is needed. Therefore, in order to improve the performance of GPS-only positioningsystems, the integration of GPS with other technologies has been extensively investigated. Some well known examples include the integration of GPS with Glonass, and the integration of GPS and inertial navigation systems. This paper discusses the potential use of pseudolites.

Pseudolites, which are ground-based transmitters of GPS-like signals (i.e. "pseudo-satellite"), can significantly enhance the satellite geometry, and even replace the GPS satellite constellation in some circumstances. Pseudolites generally transmit signals at L_1: 1575.42MHz frequency (though proposals have been made to transmit at other frequencies as well -- Zimmerman et al, 2000). Both pseudo-range and carrier phase measurements can be made on the pseudolite signals.

The use of pseudolites can be traced back to the early stages of GPS development in the late 1970s, at the Army Yuma Proving Ground in Arizona (Harrington and Dolloff, 1976), where the pseudolites were in fact used to validate the GPS concept before launch of the first satellites. In the mid 1980s, the RTCM committee SC-104 ('Recommended Standards for Differential NAVSATR GPS Service') designated the Type 8 Message for the pseudolite almanac, containing the location, code and health information of pseudolites (Kalafus et al, 1986). With the development of the pseudolite techniques and GPS user equipment during the last decade, the pseudolites can now be used to enhance the availability, reliability, integrity and accuracy in many applications, such as aircraft landing (Holden and Morley, 1997; Hein et al, 1997), deformation monitoring applications (Dai et al, 2000; Dai et al, 2001), Mars exploration (Lemaster and Rock, 1999), precision approach applications, and others (Barltrop et al, 1996; Weiser, 1998; Wang et al, 2000; Stone and Powell, 1999; O'Keefe et al, 1999).

In this paper, the potential pseudolite applications for precise positioning are discussed. They include GPS and pseudolite integration, an indoors pseudolite-only system, and the pseudolite-based 'inverted' positioning system concept. Some additional issues, such as multipath, atmospheric delay effects, and location-dependent errors (receiver and pseudolite location biases) have been addressed in the case of the pseudolite-only or hybrid pseudolite-GPS systems. In particular, the effects of additional pseudolite signal(s) on ambiguity resolution and positioning accuracy have been investigated. Several experiments have been carried out using NovAtel GPS receivers and IntegriNautics IN200CXL pseudolite instruments.

2 Pseudolite System Configurations

There are three general classes of pseudolite configurations.

2.1 GPS Augmented by Pseudolite(s)

The augmented GPS positioning system is suitable for such environments as urban canyons, valleys and deep open-cut mines, where the number of visible satellites is limited, or high precision height information is needed. Applications with implementation constraints such as solution reliability and availability can be addressed by the pseudolite augmentation of GPS. The additional pseudolite signal(s) can significantly enhance the performance of the GPS system in a number ways, including reducing the dilution-of-precision and improving the accuracy, integrity, availability and reliability of the final solutions. The general configuration of such a system is illustrated in Figure 1.

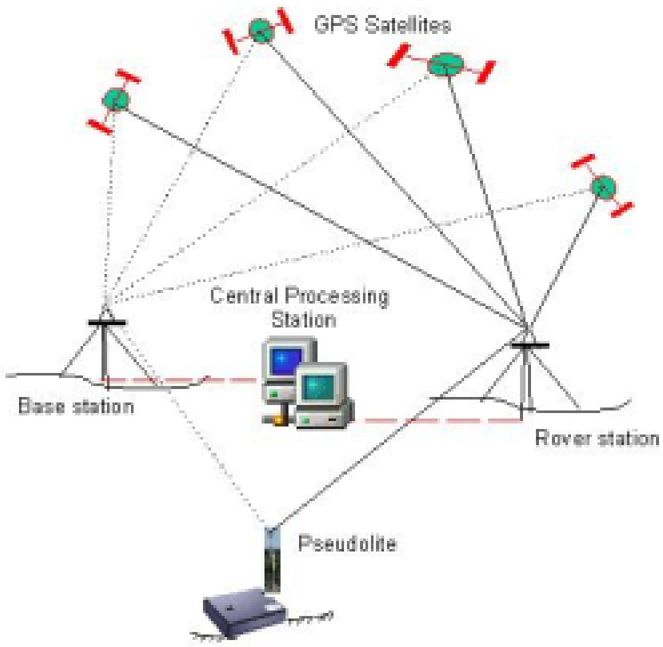

Figure 1. Configuration of a GPS positioning system augmented by pseudolite signal(s).

The geometry of the 'satellite constellation' can be improved by careful selection of the pseudolite location(s). In the case of GPS, the measurements with low elevation angles are usually rejected in order to avoid serious multipath, tropospheric delay and ionospheric bias. However, this is not necessary in the case of pseudolites. For example, in the first experiment (described later in this paper), the quality of the measurements with less than half degree elevation angle from the pseudolite transmitter to the GPS receivers is still very high. Therefore, high quality pseudolite measurements with low elevation angles, when included in data processing, can be expected to significantly improve the ambiguity resolution performance and solution accuracy, especially in the height component. The availability is also increased because a pseudolite(s) provide an additional ranging source (or sources) to augment the GPS constellation. More measurements make it easier to isolate outliers in the carrier phase measurements, and hence enhance the result reliability. Furthermore, the number of the pseudolites can be configured according to the accuracy requirement, the system costs and the environmental conditions.

2.2 Pseudolite-Based Positioning Systems

GPS techniques cannot be used when the signals are completely blocked by obstacles, natural and man-made. However, GPS-type positioning techniques may need to be applied in areas such as canyons, or underground, indoors, and in tunnels. Pseudolite transmitters can, in principle, completely replace the GPS satellite constellation, as shown in Figure 2.

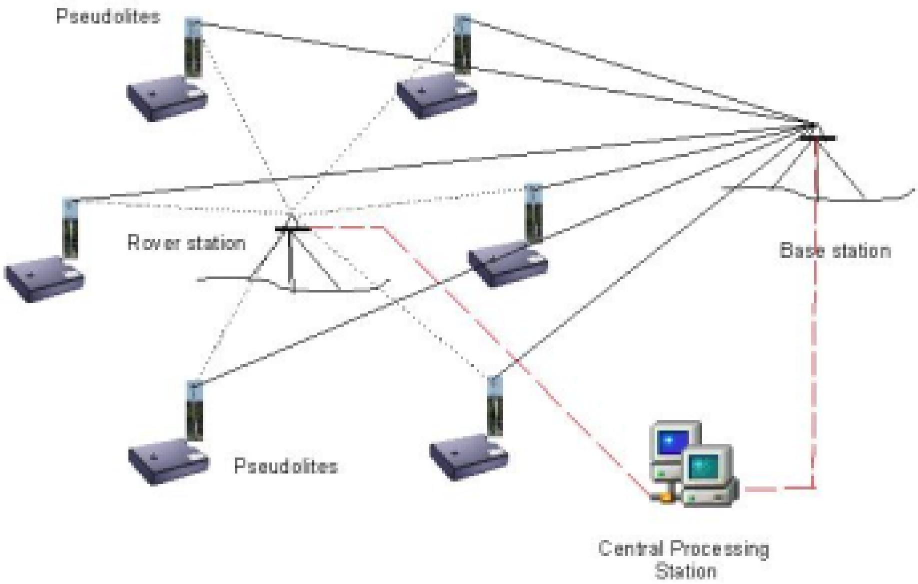

Figure 2. Configuration of a pseudolite-only positioning system.

In the case of an indoor pseudolite-based positioning system, the pseudolite transmitters can be placed at arbitrary locations. Therefore, the pseudolite geometry can be optimally designed in advance so that the highest quality results can be obtained. According to the different requirements of the positioning applications, different design scenarios can be considered. For example, in order to measure ground subsidence, the system configuration may consist of only two receivers and two pseudolites. In this system, one double-differenced carrier phase observable can be used to derive the height information if the constraint of no horizontal movement is applied. Furthermore, due to the potentially low cost of pseudolite instruments, many more pseudolites can be used in the system design. The transmitted frequency can also be selected so that it is optimal for the particular situation. In the pseudolite-based system, all the instruments, including receivers and pseudolites, are under user control, unlike the case with GPS.

In the case of a pseudolite-based system in which both the receivers and the pseudolites are stationary, the geometry doesn't change with the time. Therefore ambiguity resolution becomes a big issue. The simplest way to overcome this problem is to use precise initial coordinates to help 'round off' the ambiguity terms to their likeliest integer values. Because there is the opportunity to customise the pseudolite signals, a promising approach is to expand on the principles employed by dual-frequency GPS receivers and use a multi-frequency system that can instantaneously resolve the ambiguities, even in cases of no motion. A four-frequency pseudolite system which uses two frequencies in the 900MHz ISM band and two in the 2.4GHz ISM band (S-band) has been suggested (Zimmerman et al, 2000). Multi-frequency pseudolite development will make it more feasible to implement a pseudolite-only positioning system.

2.3 Pseudolite-Based 'Inverted' Deformation Monitoring

In this configuration a pseudolite-based inverted positioning system involves a 'constellation' of GPS receivers, with precisely known 'orbits', tracking a static or mobile pseudolite. The system consists of an array of GPS receivers, the reference pseudolite and a mobile pseudolite, as illustrated in Figure 3. The concept of inverted pseudolite positioning was first suggested by Raquet et al (1995). In their experiment, a ground-based test was conducted to investigate the feasibility of using mobile pseudolites for the precise positioning of military aircraft. O'Keefe et al (1999) also discussed the pseudolite-based inverted GPS concept for local area positioning, and presented some experimental results.

Applications with implementation constraints such as solution reliability and availability, and severe design constraints such as space and weight, can be addressed by the pseudolite-based inverted positioning concept. In this configuration, greater flexibility is obtained, and cost is reduced, because all the hardware equipment and software are configured 'on the ground', where the power, size and computational load constraints can be easily resolved. Furthermore, the whole system may operate in the presence of jamming at GPS frequencies.

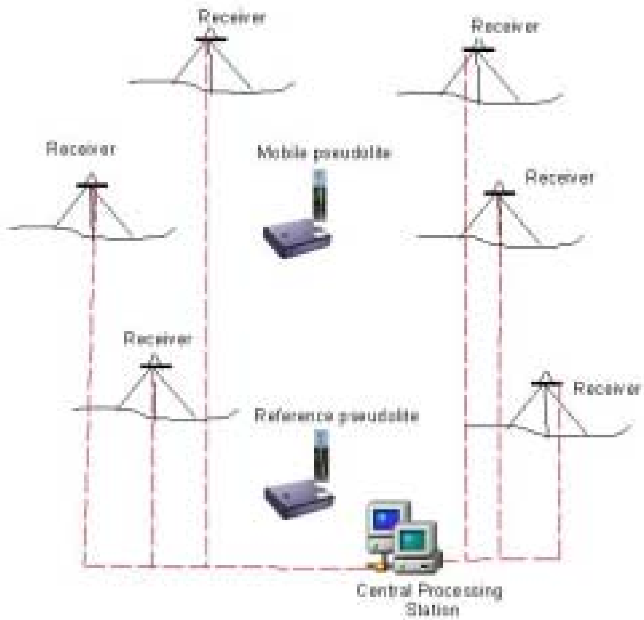

Figure 3. Pseudolite-based 'inverted' positioning system concept

One important issue that needs to be addressed is the optimisation of the locations of the receivers and pseudolites. The carrier phase measurement errors are magnified through the geometry matrix in the final coordinate solutions. A certain configuration can minimise the influence of the geometric sensitivity on the results, and can be expected to improve significantly the accuracy.

3 Practical Challenges and Modelling Issues Relating to the Use of Pseudolites

In the case of pseudolite-only or hybrid pseudolite-GPS systems, there are several additional issues that need to be addressed in comparison to GPS-only systems. These include multipath, atmospheric delay effects, and location-dependent errors such as receiver and pseudolite-location biases. recent UNSW research has focused on studying these issues, see Dai et al (2000), Wang et al (2000) for details.

3.1 Pseudolite Multipath

Pseudolite multipath has characteristics which are different compared to the multipath affecting GPS signals. Firstly, the multipath from pseudolites is not only from reflected signals off a surface, but also from the pseudolite transmitter itself (Ford et al, 1996). Bartone (1999) has shown that the standing-wave multipath in an airport pseudolite ground-to-ground link can essentially be eliminated by the use of a Multipath-Limiting-Antenna for both the pseudolite transmission and reception antennas. Secondly, compared to GPS, multipath from pseudolites is very serious because the elevation angle from the receiver to the pseudolite transmitter is quite small. On the other hand, GPS measurements with low elevation angle (10 or 15 degree) are normally rejected in order to minimise the multipath effect, and to avoid serious tropospheric delay problems as well. Thirdly, if the pseudolite and receiver are both stationary, the multipath bias will be a constant. Hence, the influence of multipath from pseudolites cannot be mitigated to the same extent over time as in the case of GPS. Finally, multipath will significantly increase the noise level of the measurement in a dynamic environment. Therefore, indirect pseudolite signal reception is very difficult to avoid even though precautions may have been taken. However, because of the constant characteristics of the multipath from a pseudolite transmitter in a static environment, it is relatively easy to calibrate it in advance.

3.2 Pseudolite Atmospheric Bias

The atmospheric biases on GPS signals comprise the ionospheric delay and the tropospheric delay. It should be emphasised that no terms need to be introduced to account for ionospheric delay for ground-based pseudolites (unlike the GPS/Glonass satellites transmitting signals through space). For GPS signals, a simple way to compensate for the tropospheric delay is to use a model such as the Saastamoinen, Hopfield, or Black models, to estimate the magnitude of the delay. however, the delay derived from such models is highly dependent on the satellite elevation angle, yet in the case of a pseudolite it is possible that a small difference in height can lead to a few degrees difference in the elevation angle. The standard tropospheric models cannot be used to compensate for pseudolite tropospheric delay because the model parameters are designed for signals from GPS satellites more than 20000km space. A simple troposphere model for pseudolite signals has been derived (Hein et al, 1997; Dai et al., 2000), and the tropospheric delay correction can reach 320.5ppm (32.05cm per km!). It is obvious that local weather conditions have a significant effect on the correction. Barltrop et al (1996) suggests that the local refractivity should be estimated as a slowly varying parameter using the pseudolite measurements. If the pseudolite site can be located with the difference in geometric ranges between the pseudolite transmitter and two receivers as small as possible, the tropospheric error can be significantly reduced.

3.3 Pseudolite-Location Error

Because a pseudolite is essentially a 'satellite-on-the-ground', the influence of pseudolite-location error must be considered in a different way to that of the GPS satellite orbit bias. The pseudolite-location errors have been analysed in detail by Dai et al (2000), and Wang et al (2000). Due to the pseudolite being stationary (unlike the moving GPS satellites) the pseudolite-location error will be a *constant*. If the reference and mobile receiver are both stationary, orbit error will contribute an invarant bias to the differenced observables. In the worst case, the influence of the pseudolite-location error on the differenced range becomes doubled. The pseudolite-location errors can bias significantly the precise carrier phase observation even though they are only of the order of a few centimetres in magnitude. Careful selection of pseudolite location can mitigate the bias. It also should be emphasised that the pseudolite location should be precisely determined beforehand.

Another issue is the effect of the pseudolite signal(s) on ambiguity resolution. Additional pseudolite signals can aid the algorithm to resolve the carrier phase ambiguity quickly and reliably in the moving receiver case. This is because the line-of-sight vector between epochs changes by a large angle, which results in a well-conditioned matrix of ambiguity parameters. Though the geometry doesn't change if observations are made in a static environment, pseudolite ambiguities can still be resolved with the help of extra GPS measurements, measurements from multiple-frequency pseudolites, or using the known precise initial coordinate(s).

4 Experiments

Several static, multi-pseudolite experiments have been carried out at UNSW during the past year and a half. The NovAtel Millennium GPS receivers and the IntegriNautics IN200CXL pseudolite instruments (http://www.integrinautics.com) were used in these experiments. The pseudolites transmitted only GPS L1 signals (Figure 4). In order to avoid signal interference, the RTCM recommended pulsing signals at 1/11 cycle was used, and 32 db attenuation was applied to the signal power.

Figure 4. Three sets of pseudolite hardware used for the UNSW experiments

4.1 Pseudolite Augmentation of GPS

The first experiment was conducted using two GPS receivers and three pseudolite instruments at a factory site on 3 January 2001. Heavy industry, such as steelworks, are very challenging environments for precise positioning due to heat, dust, cramped and dangerous conditions, vibration, moving machinery, elevated sites, line-of-sight obstructions, gas fumes and steam, etc., make both conventional surveying technology, and satellite-based systems such as GPS, sub-optimal. The objective of this experiment was to study the feasibility of integrating GPS and pseudolites for positioning in industrial environments. The three pseudolites were set up on tripods, on the ground, where some GPS satellites were blocked by the buildings (Figure 5 and 6). These three pseudolites were set up to transmit PRN codes 12, 16 and 18. A pair of NovAtel Millennium GPS receivers were used to make measurements on the GPS and pseudolite signals.

The distances from the reference GPS receiver to pseudolites PL12, PL16 and PL18 were 54m, 55m and 109m respectively, and the corresponding elevation angles were 0.02°, 0.39° and 0.26°. During this experiment five GPS satellites were tracked, and about an hour of GPS and pseudolite measurements were collected with one second sampling rate. The pseudolite and GPS data have been processed together, in static mode, using the baseline software developed at UNSW.

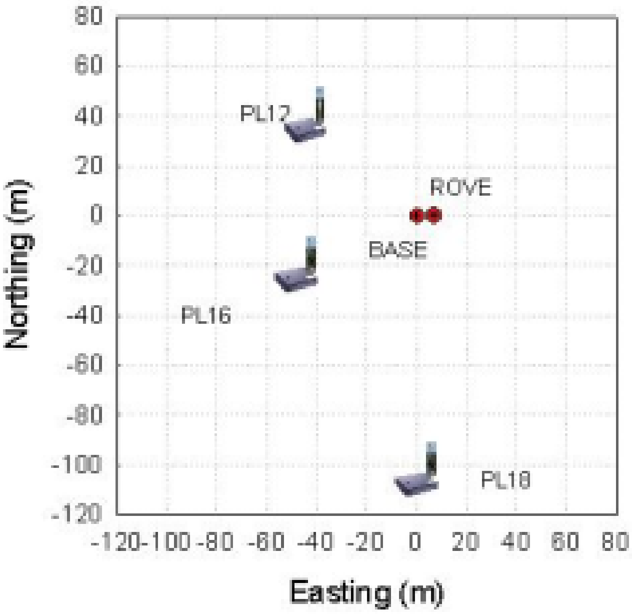

Figure 5. Location of instruments for the multiple pseudolite experiment, 3 January 2001.

Figure 6. Location of three pseudolites (top-left, bottom-left and bottom-right) and two GPS receivers (top-right), 3 January 2001.

The quality of the measurements is very high despite the elevation angles from the pseudolites to the receivers being quite low (less than half degree). The difference in the baseline vector (E, N, U) and length between the static GPS-only fixed solution and the static integrated solution is 0mm, 3mm, 5mm and 0.3mm respectively. Figures 7a, 7b and 7c show the differences between the single-epoch GPS-only solutions and the single-epoch solutions with pseudolite augmentation. Black lines represent the GPS-only solutions, and red denotes the integrated solutions. The standard deviations of the single-epoch solutions for E, N and U are 3.4mm, 2.5mm and 4.4mm for the integrated GPS-pseudolite solutions, and 3.6mm, 4.2mm, 16.2mm for the GPS-only solutions. It can be clearly seen that the accuracy of the horizontal and vertical components from an integrated GPS-pseudolite solution can be significantly improved. The results do indicate that the accuracy of the height component can be improved to almost the same level as the horizontal components. Clearly, pseudolites can be used as additional range information to improve the performance of a GPS-based positioning system, especially where high accuracy height component determination is needed, as in such applications as ground subsidence or for deformation monitoring of man-made structures.

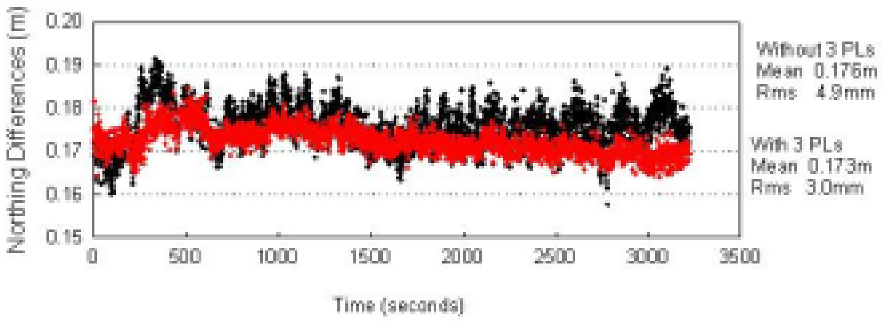

Figure 7a. North component carrier phase solutions with GPS-pseudolite integration (red plot) and GPS-only (black plot).

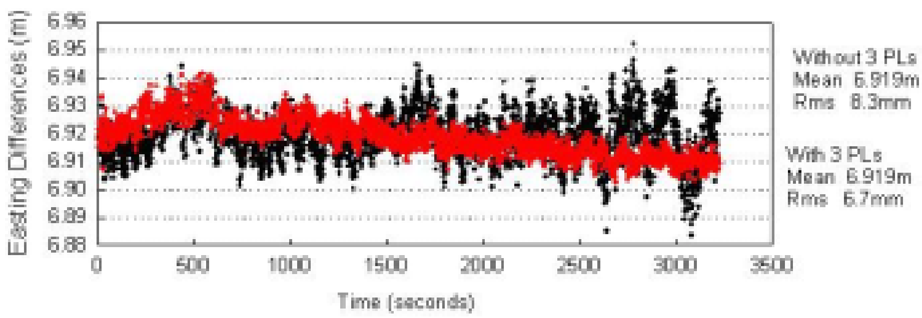

Figure 7b. East component carrier phase solutions with GPS-pseudolite integration (red plot) and GPS-only (black plot).

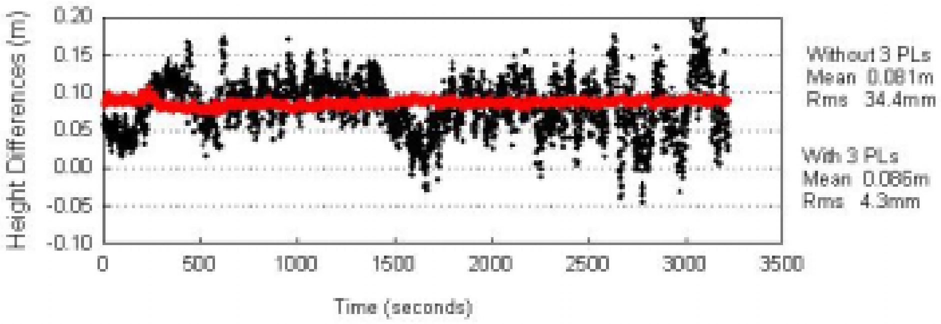

Figure 7c. Height component carrier phase solutions with GPS-pseudolite integration (red plot) and GPS-only (black plot).

4.2 Inverted Pseudolite Positioning Experiment

A further experiment was conducted using six Novatel receivers and two IntegriNautics IN200CXL pseudolite instruments on the UNSW campus, on 20 December 2000. The objective of this experiment was to study the feasibility of the pseudolite-based inverted positioning concept. The two pseudolites were configured as PRN codes 12 and 18. The six receivers were sited on the UNSW cricket ground (Figure 8).

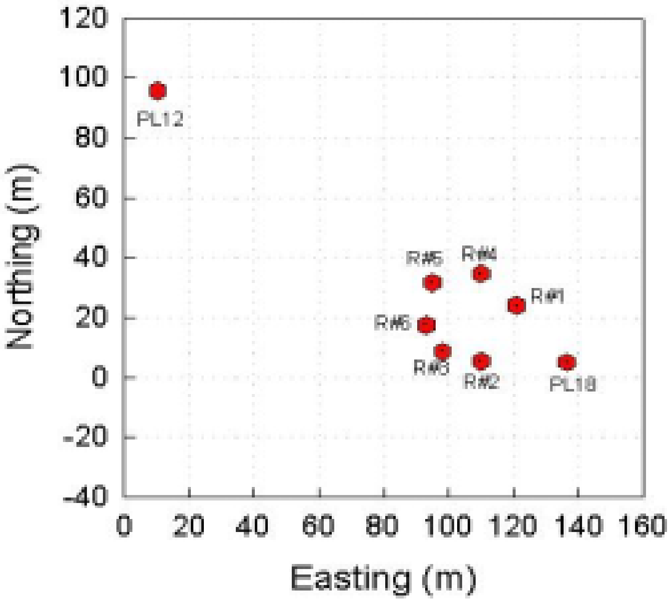

Figure 8. Configuration of GPS receivers (R#1-6) and pseudolites (PL12 and PL18), 20 December 2000.

At the beginning of this experiment, one receiver failed to record data, although the other five receivers tracked the GPS satellites and the two pseudolite signals. About an hour of GPS and pseudolite measurements were collected with a one second sampling rate. The coordinates of the six receivers and pseudolite sites were precisely determined beforehand. Figure 9 is a plot of the XDOP value (North-direction dilution-of-precision) and YDOP (East-direction dilution-of-precision) of pseudolite PL18. The small difference in the heights of the six receivers (the biggest difference is only 15cm) leads to very poor geometry, especially in HDOP. As a result, three-dimensional positioning was not feasible using the data from this experiment. Hence a height constraint was applied during data processing in order to obtain meaningful two-dimensional (horizontal) results. From Figure 9 it can be seen that the XDOP and YDOP values are 5.5 and 11.2 respectively which compared to typical GPS DOP values are still quite large. However, the geometry can be optimised for a particular application through careful selection of pseudolite and GPS antenna locations.

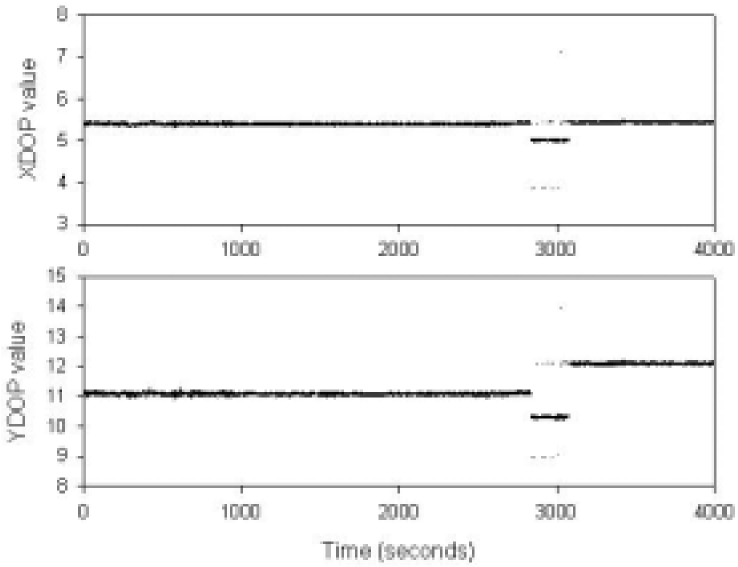

Figure 9. The XDOP and YDOP values at PL18 (number of receivers tracking is 5, except around epoch 3000, when 6 receivers were tracking).

Carrier phase ambiguity resolution could not be attempted in the normal manner because the GPS receivers and pseudolites were stationary. The carrier phase processing was conducted by fixing the double-differenced ambiguities using the first epoch of carrier phase measurements and the known initial position of the mobile pseudolite PL18.

During the data processing, it was found that significant constant biases existed in the pseudolite carrier phase measurements. The constant biases may be due to the invariant multipath disturbance, because the elevation angles from the receivers to the pseudolites are very low (approximately 2-2.5°). The carrier phase multipath for the one-way signal does not exceed approximately one-quarter of the wavelength (5-6cm for L1). However, the double-differenced measurements, involving four one-way signals, could be seriously contaminated by multipath. It is therefore necessary to calibrate the constant biases before data processing. In this experiment, each receiver not only tracks the two pseudolite signals but also the GPS signals. Therefore, GPS measurements can be used to estimate the constant biases in the pseudolite measurements. The biases for receivers 2, 3, 4, 5, 6 are 0.477, -0.251, -0.341, 0.157, 0.476 cycles respectively (receiver 1 is selected as the reference 'satellite'). It should be pointed out that the RMS values for these biases are approximately 5mm (or 0.025 cycle).

The data set was divided into 400 sessions. One solution can be made for each session with a 10-second data span. The residuals from the pseudolite-based inverted positioning solutions are shown in Figure 10. The RMS of the North and East components are 1.3cm and 2.2cm respectively. After calibration of the constant biases in the carrier phase (see above), the final solutions are not biased. It should be pointed out that the positioning accuracy can be dramatically improved if the XDOP and YDOP values were significantly reduced (i.e. by designing a better receiver-pseudolite geometry).

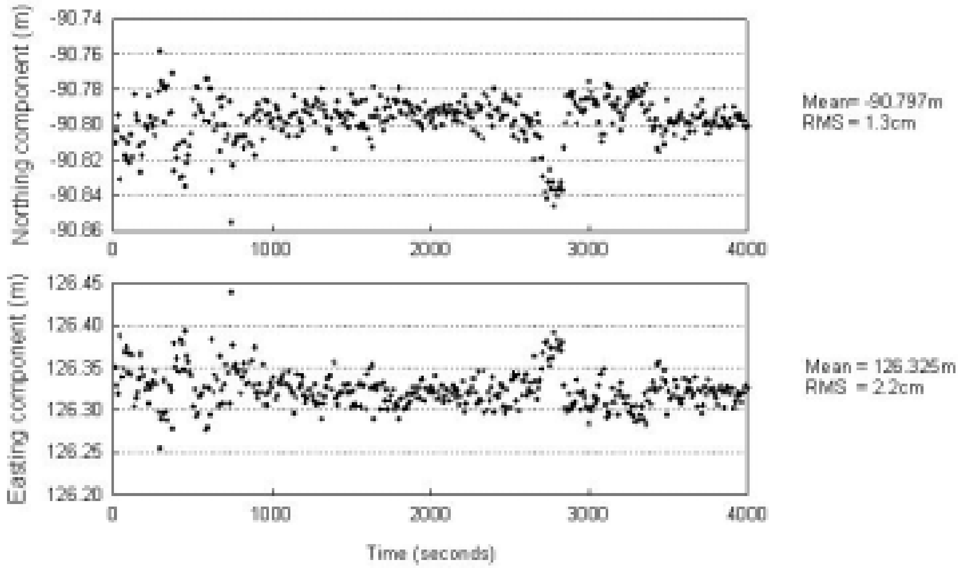

Figure 10. The North and East component solutions based on inverted pseudolite carrier phase positioning with 10 epochs of data each session (400 sessions).

5 Concluding Remarks

In this paper the three different pseudolite configurations (integrated GPS-pseudolite, pseudolite-only, and 'inverted' pseudolite-based positioning) has been described. The results of several experiments using NovAtel GPS receivers and up to three IntegriNautics IN200CXL pseudolites were reported. The first experimental results indicate that the accuracy of the height component can indeed be significantly improved, to the same level as the horizontal components. The accuracy, reliability, availability and integrity of the solutions from an integrated GPS and pseudolite system can also be improved. The second experiment, with severe conditions such as very poor receiver-pseudolite geometry and a high multipath environment, has achieved carrier phase-based positioning results in the 'inverted' pseudolite positioning mode with RMS errors of the order of 1-2cm in the horizontal components. These can be decreased significantly with better designed receiver-pseudolite geometry.

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