APPLICATIONS OF PSEUDOLITES IN DEFORMATION MONITORING SYSTEMS

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Abstract

Due to the high precision of the carrier phase observables, the Global Positioning System (GPS) technology has been widely used for measuring crustal motion and ground subsidence, and more recently for monitoring deformation of man-made structures such as bridges, dams, buildings, etc. It is well known that for such GPS-based deformation monitoring systems, the accuracy, availability, reliability and integrity of the positioning solutions is heavily dependent on the number and geometric distribution of satellites being tracked. However, in some situations, such as in urban canyons, dam monitoring in valleys and in deep open-cut mines, the number of visible satellites may not be sufficient to reliably determine precise position. Indoors the task is impossible. Pseudolites, which are ground-based transmitters of GPS-like signals, can significantly enhance the satellite geometry, and even replace the GPS satellite constellation in some situations (such as deformation monitoring indoors). There are three general classes of the potential pseudolite applications in deformation monitoring systems. The first case is *GPS augmentation* with pseudolite(s), which is suitable for circumstances such as urban canyons, or monitoring in valleys and deep open-cut mines. The second case is *indoor applications* of pseudolite deformation monitoring systems. Pseudolite arrays can, in principle, replace completely the GPS satellite constellation. This could extend the 'satellite-based' deformation monitoring applications into tunnels or underground, where GPS satellite signals cannot be tracked. The last case is an *inverted pseudolite-based* deformation monitoring system, where a 'constellation' of GPS receivers with precisely known 'orbit' tracks a mobile pseudolite. The system consists of an array of GPS receivers, the base reference pseudolite and the mobile pseudolite. However, in the case of such pseudolite-only or hybrid pseudolite-GPS deformation monitoring systems, there are some additional issues that need to be addressed. These include the near-far problem, signal interference, multipath, atmospheric delay effects, and location-dependent errors such as receiver and pseudolite location biases. In this paper, the results of a detailed analysis of these factors are presented. Some practical procedures to mitigate or eliminate their influence are suggested. Some experiments have been carried out using NovAtel GPS receivers and IntegriNautics IN200CXL pseudolite instruments. The experimental results indicate that these three classes of potential pseudolite applications for deformation monitoring systems are feasible. Their performance will be demonstrated through some 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 measuring crustal motion, river level and ground subsidence, and more recently for monitoring deformation of man-made structures such as bridges, dams, buildings, etc. (Ashkenazi et al, 1998; Behr et al, 1998; Çelebi et al, 1998; Duffy & Whitaker, 1999; Moore et al, 2000). It is well known that for such GPS-based deformation monitoring systems, the accuracy, availability, reliability and integrity of the positioning solutions is heavily dependent on the number and geometric distribution of satellites being tracked. However, in some situations, such as in urban canyons, dam monitoring 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 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 deformation monitoring applications in areas where the number of visible satellites is limited or satellite geometry is poor, especially where real-time high accuracy height component monitoring is needed, as in such applications as ground subsidence or deformation monitoring of man-made structures. Therefore, in order to improve the performance of GPS-only deformation monitoring systems, the integration of GPS with other technologies needs to be investigated.

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 situations. The pseudolites mostly transmit signals at the GPS frequency bands (L_1: 1575.42MHz or / and L_2: 1227.6MHz). 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 & Dolloff, 1976), where the pseudolites in fact were used to validate the GPS concept before launch of the first GPS 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 be used to enhance the availability, reliability, integrity and accuracy in many applications, such as aircraft landing (Holden & Morley, 1997; Hein et al, 1997), deformation monitoring applications (Dai et al, 2000), Mars exploration (Lemaster & Rock, 1999), precision approach applications, and others (Boris, 1994; Barltrop et al, 1996; Weiser, 1998; Choi et al, 2000; Wang et al, 2000; Stone & Powell, 1999; O'Keefe et al, 1999).

In this paper, the potential pseudolite potential applications in deformation monitoring are discussed. They include GPS and pseudolite integration for deformation monitoring applications, an indoors pseudolite-only deformation monitoring system, and the pseudolite-based 'inverted' deformation monitoring system concept. Some additional effects, including the near-far problem, signal interference, multipath, atmospheric delay effects, and location-dependent errors such as 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. In order to ascertain whether the application of pseudolites for deformation monitoring systems is feasible, some experiments have been carried out using NovAtel GPS receivers and IntegriNautics IN200CXL pseudolite instruments.

2. Pseudolite Potential Applications in Deformation Monitoring

There are three general classes of potential pseudolite applications for deformation monitoring applications.

2.1 GPS deformation monitoring augmented by pseudolite(s)

The augmented GPS deformation monitoring 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 monitoring is needed. 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 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 indicated in Figure 1.

The geometry of the 'satellite constellation' can be improved by the 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. Therefore, high quality pseudolite measurements with low elevation angles, when included in the 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 provides an additional ranging source to augment the GPS constellation. More measurements make it easier to isolate outliers in the carrier phase measurements, and hence enhance the result reliability.

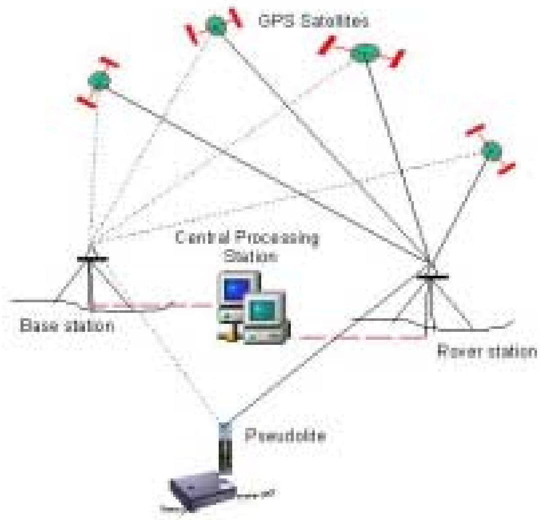

Figure 1. Configuration of a GPS deformation monitoring system augmented by pseudolite(s).

2.2 Pseudolite-based deformation monitoring

As is well known, GPS techniques cannot be used when the signals are completely blocked by obstacles, natural and man-made. However, the monitoring requirements of man-made structures may be needed in areas such as canyons, or underground and in tunnels. In these situations, GPS-based deformation monitoring is impossible. However, pseudolite arrays can, in principle, replace completely the GPS satellite constellation, as shown in Figure 2. This can extend the concept of ‘satellite-based’ deformation monitoring indoors, for such applications as in tunnels and underground, where GPS satellite signals cannot be tracked.

In the case of an indoor pseudolite-based deformation monitoring system, the pseudolite transmitters can be placed at arbitrary locations on the ground. Therefore, the pseudolite geometry can be designed in advance with maximum optimisation so that the best results can be obtained. According to the different requirements of the monitoring applications, different design scenarios can be considered. For example, in order to monitor ground subsidence, the one monitoring system scenario 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 deformation if the constraint of no horizontal deformation is applied. Furthermore, due to the potentially low cost of pseudolite products, many more pseudolites can be used in the system design. The transmitted frequency can also be selected for the particular situation. In the pseudolite-based system, all the instruments including receivers and pseudolites are under the user control, unlike the case with GPS. Hence users have more flexible choices.

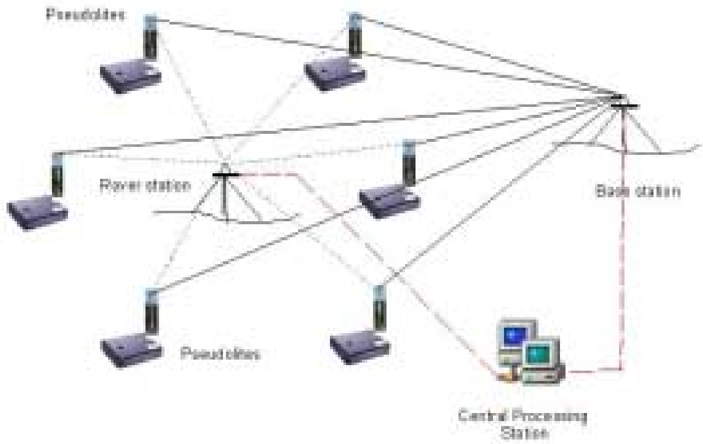

Figure 2. Configuration of pseudolite-based deformation monitoring system.

2.3 Pseudolite-based 'inverted' deformation monitoring

The last case involves a pseudolite-based inverted deformation monitoring system, where a 'constellation' of GPS receivers with precisely known 'orbit' tracks a mobile pseudolite. The system consists of an array of GPS receivers, the base reference pseudolite and the mobile pseudolite (Figure 3). The concept of inverted pseudolite positioning was first introduced by Raquet et al (1995). In their experiment, a ground-based test was conducted to investigate the feasibility of using the mobile pseudolites for precise positioning of military aircraft. O'Keefe et al (1999) also discussed the pseudolite-based inverted GPS concept for local area positioning and presented their experimental results. In this system, more 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 be able to operate in the presence of jamming at GPS frequencies.

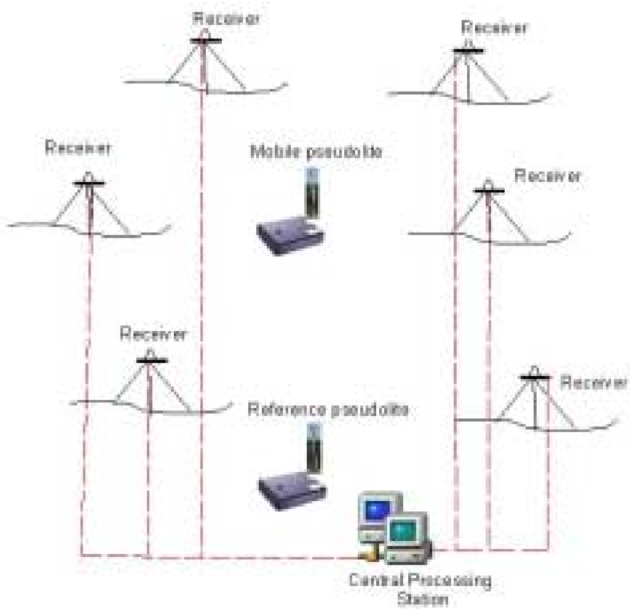

Figure 3. Pseudolite-based 'inverted' deformation monitoring system concept.

3. Practical Considerations on Pseudolite Applications

In the case of such pseudolite-only or hybrid pseudolite-GPS deformation monitoring systems, there are many additional issues that need to be addressed in comparison to GPS-only systems because of the proximity of the receivers to the stationary pseudolites. These include the near-far problem, multipath, atmospheric delay effects, and location-dependent errors such as receiver and pseudolite location biases.

3.1 Near-far problem

GPS receivers are designed to track the GPS satellite signals transmitted at an altitude of about 20100km, and at a large and relatively constant distance from all the user receivers. The power level of these signals received by GPS antennas on the surface of the Earth is very weak (around –130db), but relatively constant. This is the 'far-field' situation. The situation with pseudolites is, of course, quite different. Normally, the distance between pseudolites and receivers may be highly variable, of the order of tens, hundreds or thousands of metres. The strong pseudolite signals cause interference with the GPS satellite signals and can jam the receivers if they are situated inside the 'near-field' region. Beyond the far-field boundary, the pseudolite signals will be too weak to be tracked by the GPS receivers. Between these near-field and far-field regions is the 'dynamic range' (Cobb & O'Connor, 1998) within which the pseudolite and GPS satellite signals are balanced, and they can both be tracked by a GPS receiver. It is this so-called 'near-far problem' which must be resolved before many pseudolite applications can be satisfied. The Near-Far Problem limits the coverage area. To overcome this problem, a couple of methods have been developed. The first method is signal 'pulsing'. 'The RTCM SC-104 has a recommendation on tackling this 'near-far' problem involving the use of the Time Division Multiple Access (TDMA) approach (Stansell, 1986). It recommended that pseudolites transmit pulsed signals at the 10% duty cycle with selected Gold Codes (i.e. 93 code chips), and varying every signal pulse position from millisecond to millisecond such that each of the 11 portions of the Gold Code will be transmitted within a 10 millisecond interval. The second method would be to use a best-fit antenna diagram (Martin, 1999). The type of antenna used would depend on the application and environment. Martin (1999) suggests that microstrip patch antennas, which provide a uniform spherical pattern, are optimal for small areas, e.g. indoor usage, and high-gain parabolic or helix antennas are suitable for long-range coverage. Possible reflectors could be exclude by notches in the antenna pattern, or by beam sharpening using different kinds of ground planes.

3.2 Pseudolite location bias

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 GPS orbit bias. The effects of the pseudolite location biases have been analyzed in detail (Dai et al, 2000; Wang et al, 2000). Due to the pseudolite being stationary (unlike the moving GPS satellites) the pseudolite-location bias 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 bias 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 centimeters in magnitude. It clearly shows that good design of pseudolite location can mitigate the effect of the bias. It also should be empasized that the pseudolite location should be precisely determined.

3.3 Pseudolite multipath characteristics

Pseudolite multipath has some different characteristics compared to GPS signals. Firstly, the multipath from pseudolites is not only from reflected signals from the 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 and reduced to the same extent over time as in the case of GPS. Finally, the multipath will significantly increase the noise level of the measurement in a dynamic environment, because it is very hard to eliminate. Therefore, indirect pseudolite signal reception is very difficult to avoid even though careful 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. The constant (or very near invariant) bias can be predicted and removed during data processing, and pseudolite signals can, in principle, make a contribution to improving the performance of the deformation monitoring system.

3.4 Pseudolite atmospheric delay

The atmospheric delay of GPS signals comprises the ionospheric delay and the tropospheric delay. It should be emphasised that no terms need to be introduced to account for ionospheric delay for the 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 apply a model to estimate the delay, such as the Saastamoinen, Hopfield, or Black models. The delay derived from all of these models is highly dependent on the satellite elevation angle. For the pseudolite case it is possible that a small difference in height can lead to a few degrees difference in the elevation angle. Obviously the standard tropospheric models cannot be used to compensate for pseudolite tropospheric delay. This is because the model parameters are designed for signals from GPS satellites more than 20000km space. One simple troposphere model for pseudolite signals has been derived (Dai et al., 2000). From that model, 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 mitigated.

Another issue is the effect of additional 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. If the observation takes place in a static environment, pseudolite ambiguities can only be resolved with the help of GPS observations, or other external sensor observations, because the geometry does not change. However, pseudolites can make a significant contribution to solution accuracy because of the high accuracy observable and the low elevation angle.

4. Experiments

Two static experiments were carried out to investigate the potential applications of pseudolites for deformation monitoring. The NovAtel Millennium™ GPS receivers and the IntegriNautics IN200CXL pseudolite instruments were used in these experiments. The pseudolites transmitted only GPS L1 signals. In order to avoid signal interference, the RTCM pulsing signals at a 1/11 cycles were used, and 32 db attenuation was applied to the signal power.

The first experiment was conducted using two NovAtel receivers and three IntegriNautics IN200CXL pseudolite instruments at a factory site on 3 January 2001. Heavy industry, such as steelworks, are very challenging environments for precise positioning because 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 and labour intensive. 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. These three pseudolites were set up to transmit PRN codes 12, 16 and 18. Two sets of NovAtel Millennium GPS receivers were used to collect the GPS and pseudolite data. The distance between the GPS receivers was about 7m. Figure 4 indicates the locations of the three pseudolites and the two GPS receivers.

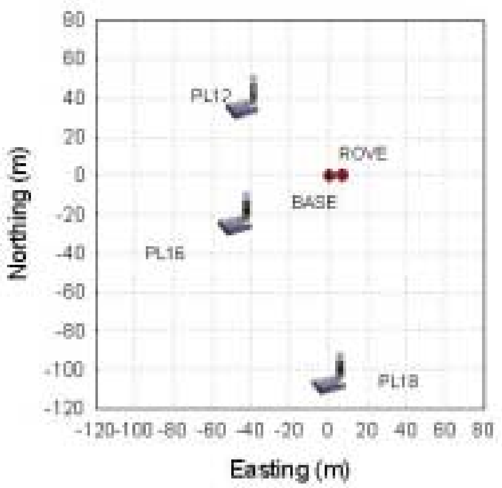

Figure 4. Location of instruments for the multiple pseudolite experiment, 3 January 2001.

The distances from the reference GPS receiver to pseudolites PL12, PL16 and PL18 were 54m, 55m and 109m respectively, and the corresponding elevation angles are 0.02°, 0.39° and 0.26°. During this experiment six 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 has been processed together, in static mode, using the baseline software developed at The University of New South Wales (UNSW) for this purpose.

It should be pointed out that no significant bias exists in the carrier phase residuals for this experiment. The evaluation of the constant bias may not be just based on the ambiguity-fixed solutions of the integrated pseudolite-GPS case or in case of GPS-only. The reason is that the pseudolite constant biases can be absorbed by the solutions and contribute to the baseline components, especially to the height component. 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 5, 6 and 7 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 respectively. It can be clearly seen that the accuracy of the horizontal and vertical components from an integrated GPS-pseudolite solution can also 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 deformation monitoring system, especially where high accuracy height component monitoring is needed, as in such applications as ground subsidence or for deformation monitoring of man-made structures.

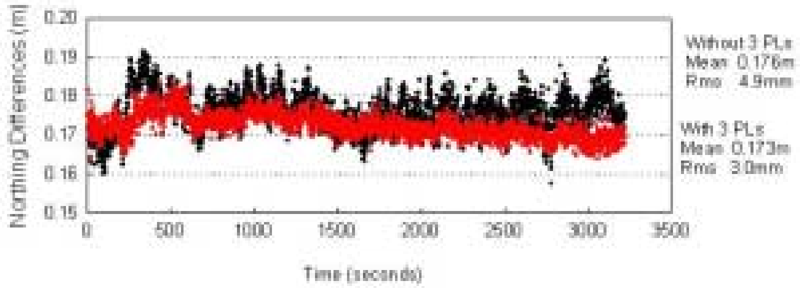

Figure 5. North component residuals of the carrier phase solutions with GPS-pseudolite integration (red plot) and without pseudolites (black plot).

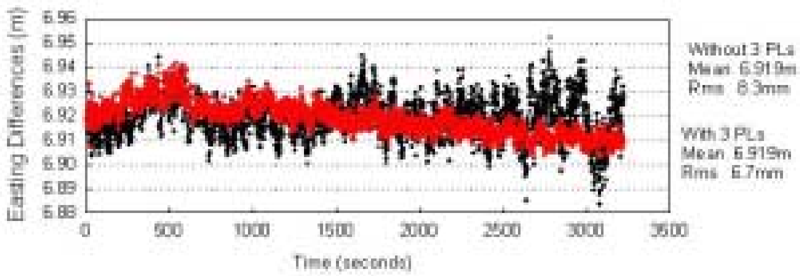

Figure 6. East component residuals of the carrier phase solutions with GPS-pseudolite integration (red plot) and without pseudolites (black plot).

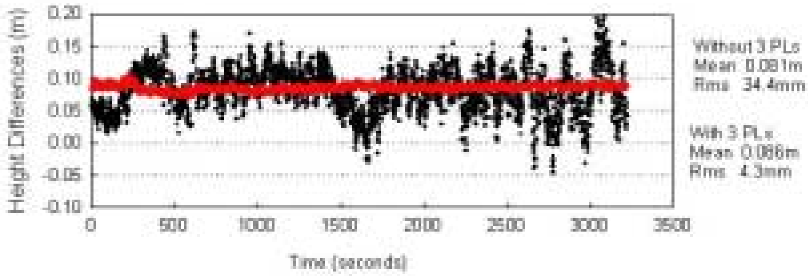

Figure 7. Height component residuals of the carrier phase solutions with GPS-pseudolite integration (red plot) without pseudolites (black plot).

A further experiment was conducted using six Novatel receivers (four Millennium™ and two Beeline™) 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 for deformation monitoring applications. The two pseudolites were configured as PRN codes 12 and 18. The six receivers were sited on the UNSW cricket ground.

In the case of the NovAtel receivers, channels can be easily assigned to the specified PRNs to track pseudolite signals. The left channels were used to track GPS satellite signals. At the beginning of this experiment, one receiver failed to record data. The other five receivers tracked the GPS satellites and the two pseudolites. About an hour of GPS and pseudolite measurements were collected with one second sampling rate. The coordinates of the six receivers and pseudolite sites were precisely determined using the GPS techniques in advance. Figure 8 shows the XDOP value (North-direction dilution of precision) and YDOP (East-direction dilution of precision) of the mobile pseudolite PL18 during the experiment. The small difference in the heights of the six receivers (the biggest difference is only 15cm) leads to bad geometry, especially in HDOP. As a result, three-dimensional positioning was not conducted with the data from this experiment, and a height constraint was applied during data processing to obtain two-dimensional results. From Figure 8, it can be seen that XDOP and YDOP values are 5.5 and 11.2 respectively. Compared to typical GPS situations, the DOP values are quite large. However, the geometry can be optimised for a particular application through careful selection of antennas.

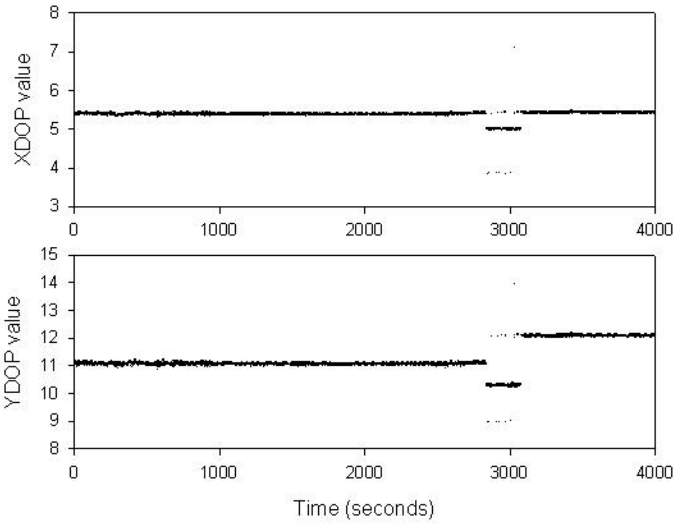

Figure 8. The XDOP and YDOP values (number of receivers tracking is 5, except around time epoch 3000 when 6 receivers were tracking).

Carrier phase ambiguity resolution could not be attempted in the normal manner because the receivers and pseudolites are stationary. The carrier phase processing was conducted by fixing the double-differenced ambiguity using the first epoch of carrier phase measurements and the known initial position of the mobile pseudolite. During the data processing, it was found that significant constant biases existed in the pseudolite carrier phase measurements. The constant biases may come from the invariant multipath because the elevation angles from receivers to the pseudolites are quite low (about 2-3 degrees, see Table 1). The carrier phase multipath for the one-way signal does not exceed about one-quarter of the wavelength (5-6cm for L1 or L2). However, the double-differenced measurements, involving four one-way signals, could be seriously contaminated by multipath. It is necessary to calibrate the constant biases before the data processing. In this experiment, each receiver not only tracks the two pseudolite signals but also GPS signals. Therefore, GPS measurements can be used to calibrate the constant biases in the pseudolite measurements. Table 1 lists the values of the constant biases, and the RMS, in the double-differenced observables between receivers and pseudolites. It can been seen that 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 of these bias values are about 5mm (0.025 cycle).

Table 1. Calibration of the constant biases in the double-differenced carrier phase between receivers and pseudolites.

Receiver No.	Constant Bias (cycle)	RMS of Bias	Elevation
1	Ref. Receiver	-	2.3348°
2	0.477	0.0265	2.0649°
3	-0.251	0.0246	2.0158°
4	-0.341	0.0265	2.5356°
5	0.157	0.0255	2.3221°
6	0.476	0.0253	2.1473°

The data set was divided into 400 sessions. One solution can be made for each session with the 10-second data span. The residuals from the pseudolite-based inverted positioning solutions are shown in Figure 9. The RMS of the North and East components are 1.3cm and 2.2cm respectively. After the correction calibration of the constant biases in the carrier phase, 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 geometry).

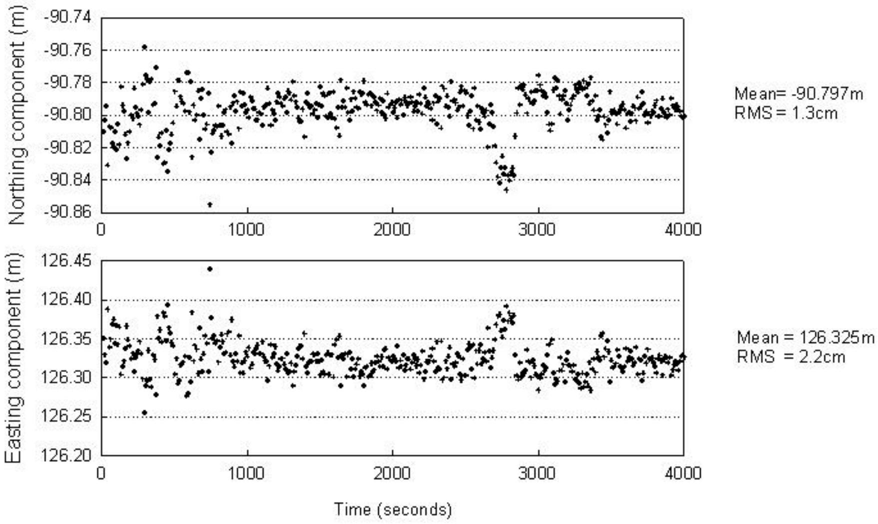

Figure 9. The North and East solution based on pseudolite-based inverted carrier phase positioning.

5. Concluding Remarks

In this paper, the feasibility of three different pseudolite applications for deformation monitoring systems (integrated GPS and pseudolite, pseudolite-only, and pseudolite-based ‘inverted’ positioning) has been investigated. Some practical considerations concerning issues such as the ‘Near-Far’ problem, pseudolite location bias, multipath, and atmosphere delay from pseudolites, have been implemented in order to determine whether the use of pseudolite signals can improve the performance of deformation monitoring systems.

A few experiments have been carried out using NovAtel GPS receivers and up to three IntegriNautics IN200CXL pseudolites. The first experimental results indicate that the accuracy of the height component can indeed be 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 significantly improved. The second experiment, with severe conditions such as very poor geometry and high multipath environment, shows that the carrier phase positioning results in the pseudolite-based inverted mode have RMS errors of the order of 1-2cm in the horizontal components. These are expected to decrease with better-designed geometry.

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