GPS and Pseudolite Integration for Deformation Monitoring Applications

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BIOGRAPHY

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Chris Rizos, B.Surv. (UNSW) Ph.D. (UNSW), has been an academic staff member of the School of Surveying (renamed the School of Geomatic Engineering in 1994), at UNSW, since 1987, where he is now an Associate Professor. Chris is leader of the SNAP group, the premier academic GPS R&D group in Australia, specialising in the development of software and techniques that address precise static and kinematic applications of GPS. He has published over 150 papers, as well as authored and co-authored several books relating to GPS and positioning technologies.

Shaowei Han is a Senior Lecturer in the School of Geomatic Engineering, UNSW, having received his Ph.D. from UNSW in 1997. His research interests are GPS/GLONASS ambiguity resolution and error mitigation methods for carrier phase-based kinematic positioning over short-, medium-, and long-range, GPS attitude determination and the integration of GPS, INS and pseudolites. Shaowei is Chairman of the International Association of Geodesy (IAG) Special Study Group (SSG) 1.179 "Wide (regional) area modelling for precise satellite positioning", and has authored over 100 journal and conference publications.

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ABSTRACT

Due to the millimeter-level resolution of the carrier phase observable, the Global Positioning System (GPS) technology has been widely used for monitoring crustal motion and ground subsidence, and more recently for deformation monitoring of man-made structures such as bridges, dams, buildings, etc. However, due to the limitations of satellite geometry, the accuracy of the height component is generally 2 or 3 times worse than the horizontal components. Pseudolites, which are ground-based instruments that transmit GPS-like signals, can improve the satellite-receiver geometry. Hence, in principle, they can be used as additional range observations to improve the performance of a GPS-based deformation monitoring system.

There are many additional effects that need to be considered in hybrid GPS-pseudolite systems compared to GPS-only systems. These include pseudolite location-dependent errors, multipath, and troposphere delay effects, and must be modeled in a different way to the GPS signals. In this paper some theoretical analyses of these factors will be presented in order to determine whether the use of pseudolite signals can indeed improve GPS performance. In particular, the effects of additional pseudolite signal(s) on ambiguity resolution and positioning accuracy have been investigated.

A few experiments have been carried out using NovAtel receivers with three IntegriNautics IN200CXL pseudolite instruments. The results indicate that the accuracy of the height component can indeed be improved to the almost 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.

INTRODUCTION

Because of the high precision of the carrier phase observable, the Global Positioning System (GPS) technology has been widely used in real time monitoring crustal motion and ground subsidence, and more recently for deformation monitoring 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). It is well known that, for such satellite-based deformation monitoring systems, the accuracy, availability and reliability of the GPS-derived position solution is highly dependent on the number of tracked satellites. 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. Furthermore, due to the limitations of satellite geometry, the accuracy of the height component is generally 2 or 3 times worse than the horizontal components. These factors constrain precise GPS applications, making it difficult to address positioning applications in areas where the number of visible satellites is limited or satellite geometry is very poor.

Pseudolites, which are ground-based instruments that transmit GPS-like signals, can improve the satellite geometry. Pseudolites in fact were used to validate the GPS concept before launch of the first satellites. With the development of the pseudolite techniques and GPS user equipment, the pseudolites can be used to enhance the availability, reliability, integrity and accuracy in some applications such as aircraft landing, land vehicle and robot guidance and tracking (Holden & Morley, 1997; Cobb & O'Connor, 1998; Hein et al., 1997; Boris, 1994), precision approach applications (Barltrop et al, 1996; Weiser, 1998), open pit mining applications (Stone & Powell, 1999), inversed posiioning (O'Keefe et al., 1999), and Mars exploration (Lemaster & Rock, 1999). Hence, in principle, they can also be used as additional range source information to improve the performance of a GPS-based deformation monitoring system.

Because stationary pseudolites are unlike GPS, such as the comparatively short distances between GPS receivers and pseudolites, there are many additional effects that need to be considered in comparison to GPS-only systems. Normally GPS orbit error can be mitigated significantly after the application of the double-difference operator on data. However, for pseudolites, the influence of location-specific biases on the solution will probably be greater in some cases more than others. Hence, small errors can not be ignored. Due to the low elevation angle from receivers to the pseudolite transmitter(s), pseudolite observables maybe are contaminated by serious multipath. Other error source such as troposphere delay and pseudolite clock synchronization must also be modeled in a different way to the GPS signals. In this paper some theoretical analyses of these factors will be presented in order to ascertain whether the use of pseudolite signals can improve GPS performance. In particular, the effects of additional pseudolite signal(s) on ambiguity resolution and positioning accuracy have been investigated. Theoretical analysis and experimental results of the integration of GPS and pseudolites for deformation monitoring applications will also be discussed.

THE USE OF ADDITIONAL PSEUDOLITE SIGNALS

The pseudolite observables can be expressed similar to GPS satelite observations as:

Pseudo-range:

$$R_r^s = r + c \cdot d^s - c \cdot d_r + d_{orb} + d_{trop} + d_{m_R} + e_R \tag{1}$$

carrier phase:

$$\varphi_r^s \cdot \lambda = \rho + N + c\cdot\delta^s - c\cdot\delta_r + \delta_{orb} + \delta_{trop} + \delta_{m\varphi} + \varepsilon_\varphi \qquad (2)$$

Where R_r^s and φ_r^s are code and carrier phase observables respectively; ρ is the geometric range between pseudolite s and receiver r; δ^s, δ_r, δ_{orb} and δ_{trop} are pseudolite clock bias, receiver clock bias, pseudolite-location error and tropospheric delay respectively; $\delta_{m\varphi}$ and δ_{mR} are multipath error for pseudo range and carrier phase respectively; λ and N are the wavelength and zero-differenced integer ambiguity; c is the speed of light; and ε_R and ε_φ are the pseudo-range and carrier phase observation noise respectively.

It should be emphasized 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). Though the pseudolite equations for carrier phase and pseudo-range are similar to the GPS observation equations, errors such as the pseudolite-location bias, multipath, tropospheric delay and pseudolite clock synchronization have to be considered carefully in a different way to the GPS observables.

Error of Pseudolite-Location $\Delta\delta_{orb}$

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. It is necessary to derive the effect of pseudolite-location error on the single-differenced observations. Assume that the pseudolite-location bias in the plane (O) consisting of the reference station, the rover station and the pseudolite location is η. The other component that is perpendicular to the plane (O) is ε. Figure1-a illustrates their geometric relations. The range from the pseudolite to the reference station can be represented by ρ_1 without orbit bias and ρ_1' with orbit bias respectively, and similarly for ρ_2 ρ_2', the range from the pseudolite to the rover station. α and β represent the angles between the direction of the pseudolite bias in the plane (O) and the direction from the pseudolite to the reference and rover stations respectively. The influence of the pseudolite-location bias on the single-differenced observation $\Delta\delta_{orb}$ then can be represented as in Figure 1-a.

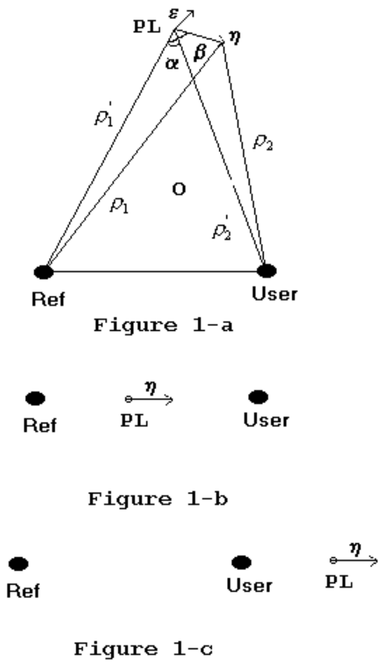

Figure 1 Geometric representation of pseudolite-location error.

$$\begin{aligned}\Delta\delta_{orb} &= \rho_2' - \rho_2 - \rho_1' + \rho_1 \\ &= \eta\cos(\beta-\alpha) - \eta\cos(\beta) \qquad (3) \\ &= 2\eta\sin(\frac{\alpha}{2})\sin(\frac{2\beta-\alpha}{2})\end{aligned}$$

In the worst case ($\sin(\frac{2\beta-\alpha}{2}) = 1$), $\Delta\delta_{orb}$ can be written as:

$$\Delta\delta_{orb} \le 2\eta\sin(\frac{\alpha}{2}) \qquad (4)$$

For GPS satellites, α is so small that it can be written as:

$$\sin(\frac{\alpha}{2}) = \frac{\Delta B}{2\rho} \qquad (5)$$

From the Equations (4, 5), the influence of the orbit bias can be simplified to:

$$\Delta\delta_{orb} \le \frac{\eta\Delta B}{\rho} \qquad (6)$$

The component ε has no influence on the differenced-observable. From Equation (6), it can be seen that a 5m orbit bias in η will result in less than a 5mm bias in the single-differenced range between receivers separated less than 20km. Hence, for short baselines, GPS orbit errors can be ignored because they are scaled by the ratio of the baseline length to the satellite-receiver range. However, for the pseudolite-location bias, it will have a significant effect because the α value can reach any value from 0 to 180. From Equation (4), a 5cm pseudolite-location error in η will result in about a 5cm error in the single-differenced range if α is equal to 60°. In general, it can easily be seen that the larger the value of α, the worse becomes $D\, d_{\text{orb}}$. This means that if the pseudolite site can be located far away from the receivers on the same side, the pseudolite-location bias can be mitigated after differencing. In the worst case, such as in Figure 1-b (α=180), the influence of the pseudolite-location bias on the differenced range becomes doubled. The best configuration, shown in Figure 1-c (α=0), can cancel completely the pseudolite-location bias. It can be clearly seen from Equation (4) that 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. 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.

Pseudolite Multipath Characteristics

If one or more reflected signals arrive at the receiver antenna in addition to the direct signal, multipath will be present in both the code and carrier measurements. The effect of multipath on code observations is two orders of magnitude larger than on the carrier phase observations. The theoretical maximum multipath bias that can occur in pseudo-range data is approximately half a chip length of the code, that is, 150m for C/A code ranges and 15m for the P(Y) code ranges. Typical errors are much lower (generally <10m). The carrier phase multipath does not exceed about one-quarter of the wavelength (*5-6cm* for L1 or L2). However, 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 minimize 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 can not 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 be 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.

Pseudolite Tropospheric Delay

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. Figure 2 shows the single-differenced tropospheric delay between the receivers if the difference between the satellite elevation angles from both stations to the satellite is one degree.

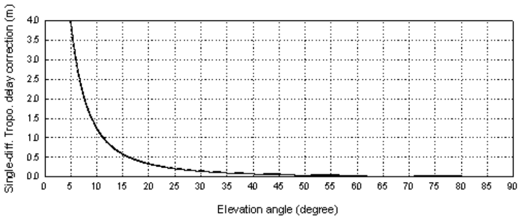

Figure 2 single-differenced tropospheric delay with 1° elevation angle difference between a pair of GPS receivers.

It can be clearly seen that the tropospheric correction can reach a magnitude of a few meters after between-receiver data differencing. For the pseudolite case it is possible for a small difference in height can lead to a few degrees difference in the elevation angle. Obviously, the standard tropospheric models can not 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. The refractivity n at the base of the atmosphere can be described as a function of the meteorological parameters (Hartmann & Leitinger, 1984):

$$N = (n-1) * 10^6 = 77.6\frac{P}{T} + 3.73 \cdot 10^5 \frac{e}{T^2}$$

(7)

Where P is the air pressure in hectopascals, e is partial pressure of the water vapor in hectopascals, T is the absolute temperature in degrees Kelvin. The partial pressure of the water vapor can be calculated via the relative humidity RH:

$$e = RH \cdot exp(-37.2465 + 0.2133T - 2.569e^{-4}T^2)$$

(8)

If the meteorological parameters can be assumed the same, the tropospheric delay after between-receivers single-differencing can be represented by:

$$\Delta\, d_{trop} = (77.6\frac{P}{T} + 3.73 \cdot 10^5 \frac{e}{T^2}) \cdot 10^{-6}\, \Delta r$$

(9)

Where *Dr* is the difference in geometric ranges between the pseudolite transmitter and the two receivers. For the standard meteorological parameters (P=1013mPa, T=20°, RH=50%), from Equation (9) the tropospheric delay correction can reach 32.05ppm (32.05cm per km). It is obvious that local weather conditions have a significant effect on the correction. Barltrop et al. (1996) suggest 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 *Dr* as small as possible, the tropospheric error can be significantly mitigated.

Pseudolite Clock Synchronization

In the IntegriNautics IN200CXL pseudolite an inexpensive crystal oscillator clock is used as the time base, unlike GPS satellites which use a an atomic (Rubidium or Cesium) clock. It is therefore not synchronized to the GPS time system. As a result, the magnitudes of the pseudolite measurements are totally unpredictable after power is applied to the instrument. The pseudolite measurements can be either very large or very small, and positive or negative in magnitude. This affects all the receiver measurements instantaneously. If the measurement values are too large, they can not be accommodated when converted from binary to the RINEX data format. The constant value that can be obtained from the starting epoch has been deducted from all the pseudolite pseudo-range data so that the data processing software is capable of processing and analysing both the GPS data and pseudolite observations.

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 changes. However, pseudolites can make a significant contribution to solution accuracy because of the high accuracy observable and the low elevation angle.

EXPERIMENTS

In order to determine whether the use of pseudolite signals can improve GPS performance for deformation monitoring applications, three experiments have been carried out using NovAtel receivers with the IntegriNautics IN200CXL pseudolite instruments. They included a zero-baseline test, a multipath test and a static experiment with multiple pseudolites.

Zero-Baseline Test

A zero-baseline test was carried out on 14 March 2000 to evaluate the quality of the pseudolite carrier phase and pseudo-range measurements under ideal conditions. The influence of multipath, pseudolite-location bias and atmospheric errors on the differenced observable is canceled completely. A total of 30 minutes of data were collected using two NovAtel receivers and one IN200CXL pseudolite, with a 1Hz sampling rate. Satellite PRN29, with the highest elevation angle, was selected as the reference satellite. The double-differenced carrier phase and pseudo-range residuals for pseudolite PL32 and satellite PRN31 have been plotted in Figures 3 and 4. From Figure 3, the standard deviations of the pseudo-range residuals for the transmitter pairs PL32-PRN29 and PRN31-PRN29 are 0.11m and 0.08m respectively. It can be seen that only small biases (0.02m and 0.01m) exist in the residual errors. Figure 3 also shows that the quality of the pseudolite pseudo-range data is almost the same as for one of the GPS satellites.

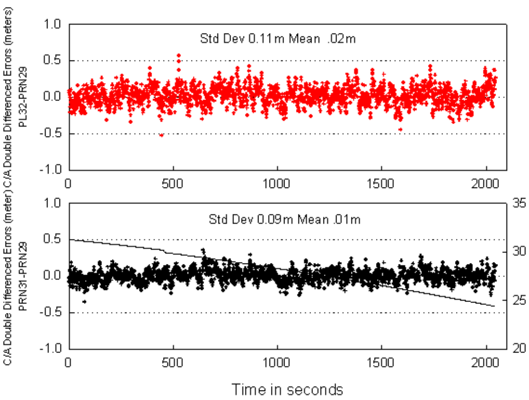

Figure 3 Noise level of the double-differenced pseudo-range residuals.

From Figure 4, the standard deviations of the carrier phase residuals for the transmitter pairs PL32-PRN29 and PRN31-PRN29 are 1.3mm and 0.8mm respectively. It can be seen that only small biases (-0.03mm and -0.01mm) exist in the residual errors. Figure 3 also shows that the quality of the pseudolite carrier phase data is as almost the same as for the GPS satellites.

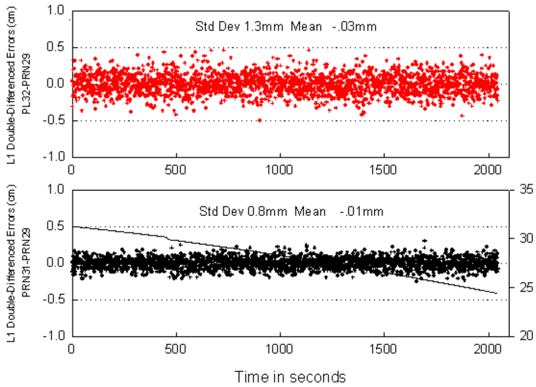

Figure 4 Noise level of the double-differenced carrier phase residuals.

The zero-baseline experiment shows that the pseudolite, as a satellite-on-the-ground, can provide similar high quality observations as a GPS satellite. Hence it is, in principle, possible to improve the performance of a GPS-based deformation monitoring system using pseudolite data.

Multipath Experiment

To study the characteristics of the multipath disturbance associated with pseudolites, an experiment was carried out. Two sets of NovAtel GPS receivers were located on pillars close to a wall while a pseudolite transmitter was sited on the roof of the Geography & Surveying (GAS) building, UNSW. Successive three day data sets, with a 1 Hz sampling rate, were collected. During the three day period, power to the receivers and the pseudolite transmitter was switched off and on several times. Double-differenced residuals of the pseudo-range and the carrier phase observables have been plotted in Figures 5 and 6 respectively. GPS satellites with the highest elevation angles were selected as reference satellites, and it was assumed that no multipath affected their signals. The mean value and standard deviation for the pseudo-range data are -1.25m and 0.21m, and for the carrier phase are -0.105 cycles and 0.008 cycles respectively. It can be clearly seen that the influence of multipath remains at significant levels even though power has been switched off and on. It also shows that it is possible, and essential, in the case of for a deformation monitoring system to calibrate these biases in advance.

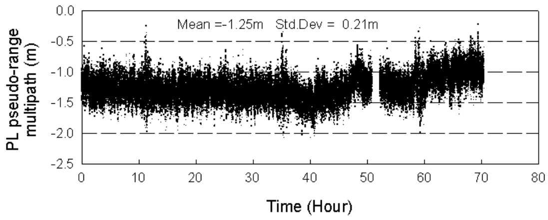

Figure 5 Multipath influence on the double-differenced pseudo-range.

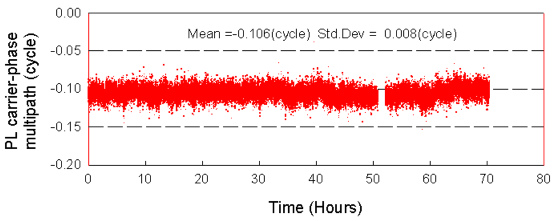

Figure 6 Multipath influence on the double-differenced carrier phase.

The pseudolite multipath experiment shows that due to low elevation angles from receivers to the pseudolite transmitter, a significant almost constant multipath influence on the carrier phase and pseudo-range observations is present. Its effect can be removed through careful calibration.

Static Experiment

Further experiments have been carried out using NovAtel receivers and three IntegriNautics IN200CXL pseudolite instruments on the UNSW campus in January 2000. The objective was to study the feasibility of integrating GPS and pseudolites for positioning. The pseudolites were set up on the roofs of three high buildings, namely the GAS building, the Applied Science (AS) building, and the Warrane College (WAR), building both of which are sited near the UNSW cricket ground. 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 7 indicates the locations of the three pseudolites and two receivers.

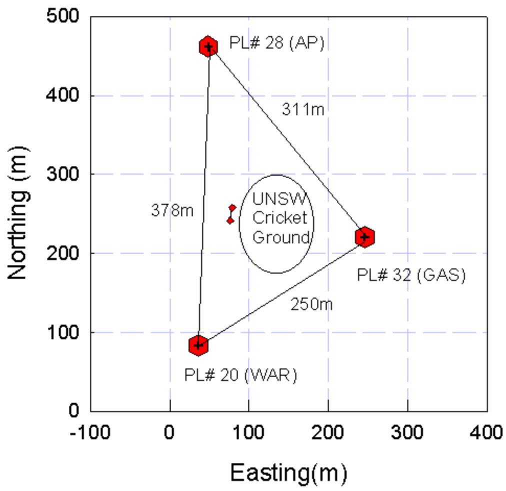

Figure 7 Location of instruments for the multiple pseudolite experiment.

The distances from the reference station to pseudolites PL32, PL28 and PL20 are 206m, 171m and 180m respectively, and the corresponding elevation angles are 9.1°, 16.7° and 8°. During this experiment six GPS satellites were tracked and half an hour of GPS and pseudolite measurements were collected with a one second sampling rate. The pseudolite and GPS data has been processed together, in static mode, using the baseline software developed at UNSW for this purpose. The double-differenced carrier phase residuals from the combined GPS and pseudolite positioning solutions are plotted in Figure 8.

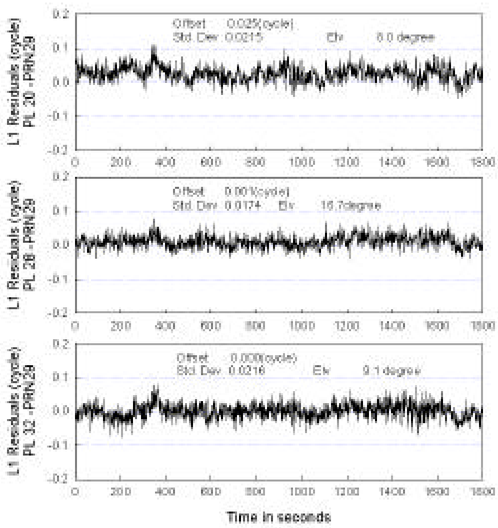

Figure 8 Double-differenced carrier phase residuals from the multiple pseudolite experiment.

It should be pointed out that no bias exists in the carrier phase residuals for this experiment. The difference in the baseline vector (E, N, U) and length between the static GPS-only fixed solution and the static integrated solution are 1.0mm, 2.3mm, 4.3mm and 1.8mm respectively. Figures 9, 10 and 11 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 3.0mm, 2.3mm and 4.5mm for the integrated GPS-pseudolite solutions, and 7.0mm, 3.0mm, 14.3mm for the GPS-only solutions respectively. It can be clearly seen that the accuracy of the solutions from an integrated GPS-pseudolite system can also be significantly improved. The results 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 real-time high accuracy height component monitoring is needed, as in such applications as ground subsidence or for deformation monitoring of man-made structures.

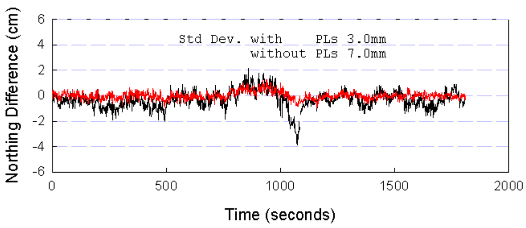

Figure 9 Northing component accuracy of the carrier phase solutions with GPS-pseudolite integration.

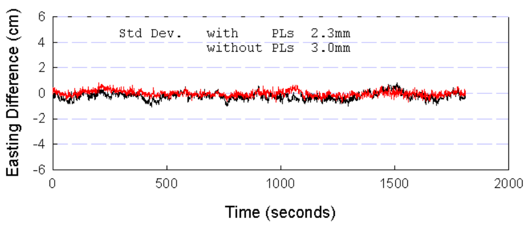

Figure 10 Easting component accuracy of the carrier phase solutions with GPS-pseudolite integration.

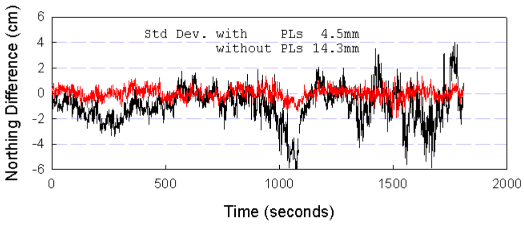

Figure 11 Height component accuracy of the carrier phase solutions with GPS-pseudolite integration.

CONCLUDING REMARKS

In this paper, the feasibility of integrating GPS and pseudolites for deformation monitoring applications has been investigated. Some theoretical analyses concerning effects such as location bias, multipath, and tropospheric delay from pseudolites have been undertaken in order to determine whether the use of pseudolite signals can improve GPS performance.

A few experiments have been carried out using NovAtel GPS receivers and up to three IntegriNautics IN200CXL pseudolites. The 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.

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