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TEST OF SIMULATED PSEUDOLITE MEASUREMENTS APPLIED TO GPS AND MULTI-PSEUDOLITE INTEGRATED POSITIONING

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ABSTRACT

The near-ground operation of a GPS-like signal transmitter, the pseudolite (PL), is expected to provide extra-measurements and improve the GPS positioning accuracy and availability. Based on the true measurements received from one PL instrument during the field trial, the multi-session combined technique and the self-session duplicated technique were proposed and tested for PL data simulation. The results demonstrate that the self-session duplicated technique can effectively provide the simulated PL measurements for any appropriate number and adequate configuration of so-called virtual PL (VPL) sites. The GPS+PL+3VPL observations were practically integrated to compute for a baseline solution. The results prove that baseline precision can be significantly improved by approximately 50% and 30% on the horizontal and vertical components, respectively, compared with those using only GPS data. When VPL sites are simulated to have the minus elevation angles, the vertical positioning errors can be further reduced to achieve a consistent precision in all three-dimensional coordinates. This preliminary study has shown good performance of using simulated PL measurements for integrated GPS and multi-pseudolite positioning.

KEYWORDS: Pseudolite. GPS integrated positioning. Accuracy. Data simulation.

INTRODUCTION

Centimetre-level positioning information has always been important for geodetic surveying and deformation monitoring. GPS positioning based on carrier phase observables is believed to effectively provide such precision of coordinate information. However, it is also well known that in practice, GPS positioning is affected by the geometric distribution of the satellites being tracked. In other words, when a sufficient number of 'visible' satellites can not be guaranteed under certain observation conditions, such as in a valley in mountainous terrain, or under dense foliage, GPS positioning may be deteriorated by the poor satellite geometry. Therefore, the feasibility of pseudolites (PLs) has created interest in using existing GPS positioning technology and equipment to combine those additional ranging signals transmitted from ground-based pseudolites to augment the satellite constellation and enhance the availability, reliability, integrity and accuracy of the GPS system [**3**].

To efficiently implement such ground-based pseudolite augmentation for high precision GPS applications, some technical issues need to be further investigated. For instance, the number and the geometric distribution of the pseudolites operating on the ground is believed to have a significant impact on the performance of the GPS/PL augmented systems [**4**]. Therefore, the effect of the pseudolite deployment as a network type must be practically tested and evaluated. Unfortunately, multi-site pseudolites installed for field trials are difficult to achieve because of logistics. However, this difficulty can be solved by using a software technique to generate simulated measurements for pseudolite-based positioning design studies [**8**].

Generally speaking, the simulation software developed for the generation of pseudolite measurements is based on the biases, errors and noises defined by the

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appropriate models which are then added to the geometric range computed by the coordinates of the receiver and pseudolite sites [**5**]. This paper, however, attempts to propose two types of data simulations, the multi-session combined technique and the self-session duplicated technique, based on using at least one set of real pseudolite data to generate simulated data for the so-called 'virtual' sites at any possible locations designed for the multi-pseudolite tests. The main objectives of this study are: (1) to develop the pseudolite data simulation techniques; (2) to investigate the biases of the simulated pseudolite measurements; and (3) to analyse the integrated GPS and multi-pseudolite positioning, in terms of geometry and precision, using real and simulated pseudolite data sets.

SIMULATION OF PSEUDOLITE MEASUREMENTS

Pseudolite Phase Observable

The pseudolite can be regarded as a near-ground operation of a GPS-like signal transmitter, which is expected to provide extra-measurements and improve the GPS positioning accuracy and availability. Based on the GPS positioning theory, the pseudolite carrier phase observable can be similarly defined as [**7**]

$$\phi_K^P = \frac{f}{c}\rho_K^P + f(dt^P - dt_k) + N_K^P + \frac{f}{c}T_K^P + \frac{f}{c}dr_K^P + \delta m_K^P + e_K^P \tag{1}$$

Where ϕ_K^P is the measured carrier phase in cycles from pseudolite P to receiver K; f is the signal frequency of the pseudolite signal; c is the velocity of light; ρ_K^P is the geometric distance between site K and pseudolite P; dt^P is the clock error of the pseudolite; dt_k is the clock error of the receiver; N_K^P is the integer ambiguity; T_K^P is the tropospheric delay; dr_K^P is the location error of the pseudolite; δm_K^P is the multipath signatures on the carrier phase; and e_K^P is the measuring errors of the carrier phase.

For simultaneous GPS/PL observations made at reference site *a* and rover site *b* (see Fig. 1), the GPS and pseudolite carrier phase observations ϕ^S, ϕ^P can be combined to form the double difference observations ϕ_{ab}^{SP} as

$$\phi_{ab}^{SP} = \frac{f}{c}\rho_{ab}^{SP} + N_{ab}^{SP} + \frac{f}{c}T_{ab}^{SP} + \frac{f}{c}dr_{ab}^{SP} + \delta m_{ab}^{SP} + e_{ab}^{SP} \tag{2}$$

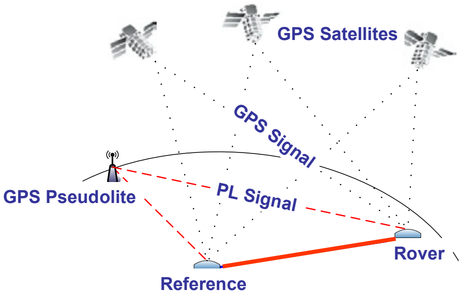


Fig.1. Double difference observation for GPS and PL signals

In general, the pseudolite transmitter clock is not designed as stable as the satellite clocks due to the prohibitively high cost involved [**6**]. In addition, the pseudolite signals synchronised to the GPS signals are specifically needed in single point positioning [**2**]. Therefore, the double difference observation is believed to have advantages in data processing since the receiver and GPS/PL clock errors have been eliminated in its equation. However, it must be noted that the multipath is one of the dominant errors for pseudolite signals received over short distances. Fortunately, when pseudolites are used in a static environment, multipath is theoretically constant and can be treated as a bias. It is suggested to determine any multipath biases associated with the pseudolite data before using them in baseline computations [**1**].

Raw Data Collection

The GPS and pseudolite data collection was carried out on the main campus of the University of Nottingham for three sessions (see Fig. 2). The test sites consist of three pseudolite stations (PL1, PL2 and PL3), occupied in turn with only one IntegriNautics IN200D pseudolite, and two baseline stations (Ref and Rov), both using a NovAtel DL-4 dual frequency receiver for the static observation. The distance between the two GPS/PL receivers was 70 m, and the three pseudolite sites were set up 22 m-128 m away from the rover.

An approximately two hour GPS and pseudolite data set was collected at a 1Hz rate for each session, and a total number of eight GPS satellites were tracked during the observation. Before the observation, four hours of GPS data was also collected at the pseudolite locations and at both ends of the baseline, in order to compute their precise three-dimensional coordinates for GPS/PL data processing.

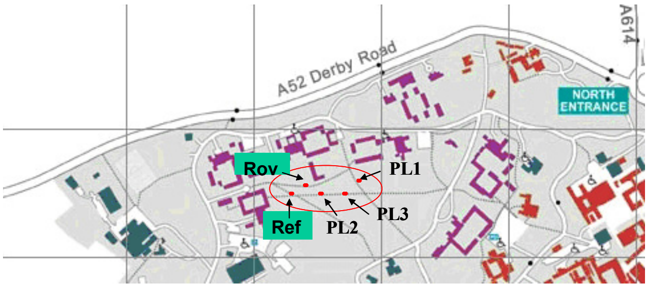


Fig.2. Configuration of the test sites set up at the University of Nottingham

Simulated Data Tests

The fact that only one pseudolite was in use during the field trials means that pseudolite data collected at PL1, PL2 and PL3 are observed by three different sessions and can not actually form a simultaneous multi-pseudolite observation. To achieve the goal of assessing the precision performance of using multi-pseudolite positioning, it is important to test any simulation technique that might be able to provide more sites of pseudolite data.

Based on using any set of ‘real’ pseudolite data collected at PL1, PL2 and PL3, two simulation techniques, a multi-session combined technique and a self-session duplicated technique, were proposed. Although the GPS/PL receivers installed at the two ends of the baseline remained fixed during the three observation sessions, the location of the pseudolite was moved session by session. This is considered to be the change of the constellation of the ground-satellite. When any two sessions of 'real' pseudolite data are combined, such as PL1+PL2, PL2+PL3 and PL3+PL1, the simulated pseudolite measurements, denoted by SPL-combined, can then be determined. Another simple way of simulating pseudolite data is to duplicate each epoch of 'real' pseudolite data into the same observation epoch for each session, played as the simulated pseudolite data and denoted by SPL-duplicated.

In order to realise the precision solved by the simulated pseudolite measurements, 600 epoch data with the most stable signal quality in a session were processed for three combined or duplicated data sets. The three-dimensional precisions, i.e. the mean of standard deviations obtained from three session of baseline solutions, are listed in Table 1 for the comparisons of the test results using GPS data, GPS+PL data or two simulated kinds of GPS+PL+SPL data.

Table 1. *Baseline precision based on GPS, GPS+PL or GPS+PL+SPL data sets*

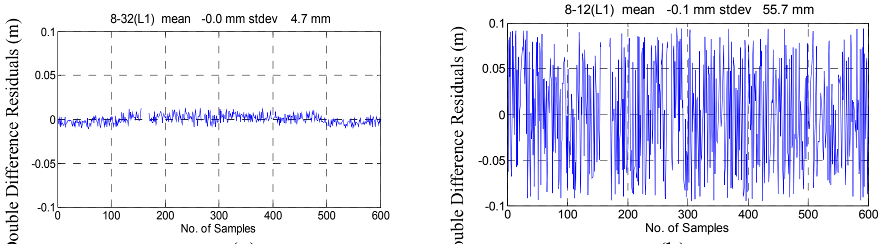
Components	GPS (mm)	GPS+PL (mm)	GPS+PL+SPL (mm)	
			SPL-combined	SPL-duplicated
N	3.6	3.5	11.7	3.5
E	3.0	2.7	13.4	2.7
H	5.9	4.2	27.4	4.2

As is evident in Table 1, less than 5 mm of positioning precisions in all three coordinate components have been demonstrated on those using GPS augmented pseudolite data. As expected, the vertical precision has been more obviously improved by using the additional low elevation pseudolite measurements. The test results also show that the simulated pseudolite data produced using the self-session duplicate technique allows for an effective application as a same level of precision is found. However, the precisions for the SPL-combined solution are relatively worse in the test results, which are probably caused by any constant biases.

Biased Data Tests

To investigate the worse performance of the SPL-combined data, the double difference residuals were computed for the real and multi-session combined pseudolite data using GPS as the reference satellite. The residual time series plots for the PL3 data and PL3+PL1 combined data are given in Fig. 3(a) and Fig. 3(b), respectively, as an example of showing their different patterns. For all three sessions, the average values of the mean and the standard deviation have both increased from 0.0 mm to 0.5 mm and ±4.0 mm to ±55.1 mm, respectively, when comparing between those of using PL data and SPL-combined data.

To further study any possible reasons causing such fluctuations in the SPL-combined data, as seen in Fig. 3(b), two tests were performed by conducting a 10 cm location shift or a 30 sec time shift into the SPL-duplicated data, which originally showed a well performance in the baseline solution, as listed in Table 1. For the tests results based on using the PL3 data set, the standard deviations of the baseline solution carried on with the biased data tests are listed in Table 2. The double difference residuals over 600 sample epochs are shown in Fig. 4(a) and Fig. 4(b) for SPL-duplicated data including a location bias or a time bias, respectively.

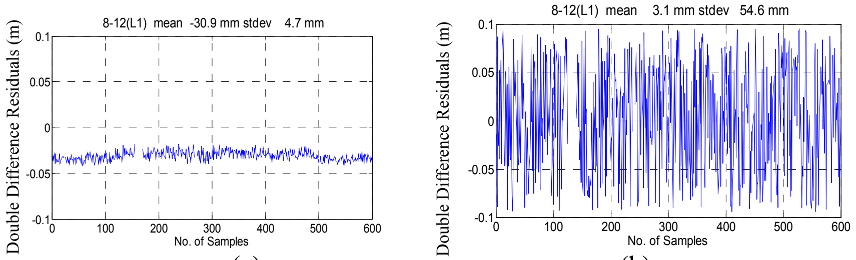


(a) (b)

Fig.3. Double difference carrier phase residuals for
(a) PL3 data and (b) SPL-combined data of PL3+PL1

Table 2. *Baseline precision based on location- or time-biased PL measurements*

Components	GPS (mm)	GPS+PL (mm)	GPS+PL+SPL-duplicated (mm)	
			SPL-location biased	SPL-time biased
N	3.2	3.1	3.0	5.9
E	2.5	2.3	2.4	8.6
H	4.3	3.9	4.3	20.3



(a) (b)

Fig.4. Double difference carrier phase residuals for SPL-duplicated data with
(a) location biases and (b) time biases

As expected, the fluctuation pattern of the double difference residuals plotted in Fig. 4(b) is visually identical to that shown in Fig. 3(b), whereas only a constant type of offset occurs in Fig. 4(a). This may confirm the presence of time biases, in the SPL-combined data, and the pseudolite clock error may not have been effectively eliminated by double differencing to a different session of the pseudolite data that was received but not synchronised.

MULTI-PSEUDOLITE MEASUREMENTS

Since the simulated pseudolite measurements based on using the self-session duplicate technique have been tested and found to be working normally, it is possible to use one set of 'real' pseudolite data to produce more sets of simulated data at the 'virtual' pseudolite site (VPL) for a multi-pseudolite type of observation. The computation procedure for creating such simulated pseudolite measurements at the VPLs designed for the tests is described as follows:

(1) The real pseudolite observation (ϕ_{rov}^{pl}) is made between a pseudolite site and a rover site, where the 3-D coordinates, i.e. (X^{pl}, Y^{pl}, Z^{pl}) and (X_{rov}, Y_{rov}, Z_{rov}), are actually known by using any precise positioning technique, such as GPS.
(2) The geometric range (R_{rov}^{pl}) between the two sites is then obtained from

$$R_{rov}^{pl} = \sqrt{\left(X^{pl} - X_{rov}\right)^2 + \left(Y^{pl} - Y_{rov}\right)^2 + \left(Z^{pl} - Z_{rov}\right)^2} \tag{3}$$

(3) The 3-D coordinate of the VPL site, i.e. (X^{vpl}, Y^{vpl}, Z^{vpl}), is now designed and given to compute the geometric range (R_{rov}^{vpl}) between the rover and the VPL site as

$$R_{rov}^{vpl} = \sqrt{\left(X^{vpl} - X_{rov}\right)^2 + \left(Y^{vpl} - Y_{rov}\right)^2 + \left(Z^{vpl} - Z_{rov}\right)^2} \tag{4}$$

(4) The range difference ($\Delta R_{rov}^{vpl,pl}$) between PL-rover and VPL-rover is also calculated by

$$\Delta R_{rov}^{vpl,pl} = R_{rov}^{vpl} - R_{rov}^{pl} \tag{5}$$

(5) This range difference is then converted to its phase observable ($\Delta\phi_{rov}^{vpl,pl}$) by using the signal wavelength, such as $\lambda_{L1} = 19.029636$ cm, and adding it into the real PL's phase observable as

$$\phi_{rov}^{vpl} = \phi_{rov}^{pl} + \Delta\phi_{rov}^{vpl,pl} = \phi_{rov}^{pl} + \frac{\Delta R_{rov}^{vpl,pl}}{\lambda_{L1}} \tag{6}$$

(6) The virtual type of phase observable (ϕ_{rov}^{vpl}) is then constructed with the considerations of a real PL-based range and the inherent observation errors, such as the clock errors and tropospheric delay etc.

TEST AND ANALYSIS

In a pseudolite-based positioning system, the installation of pseudolites in locations that ensure good geometry is one of the keys to good positional precision. In other words, if the pseudolites were placed in an optimum configuration, then a better level of positioning precision could be obtained. Like GPS positioning, a minimum of four satellites are required. This study was designed to adopt one PL site with real pseudolite measurements and create up to three VPL sites with simulated pseudolite measurements, as shown in Fig. 5, for the ground constellation of the pseudolites integrated with GPS measurements for the tests.

Number of Pseudolites

Based on the assumption that the GPS/PL positioning precision has a high likelihood to be related to the geometric locations of the multi-pseudolite stations, three plane configurations centred at the rover site and the setting-up of the VPL sites to form a straight line, a trilateral and a quadrilateral figure have been designed. For the test, it mainly used GPS integrated with pseudolite measurements, while the remainder included simulated pseudolite measurements from three additional locations. The same indications for precision are computed and listed in Table 3 for the four different data sets. To evaluate the effectiveness of using the simulated pseudolite measurements for different numbers of the pseudolites, the precision improvement rate with respect to the precision of the solution based on GPS data only is shown in Fig. 6.

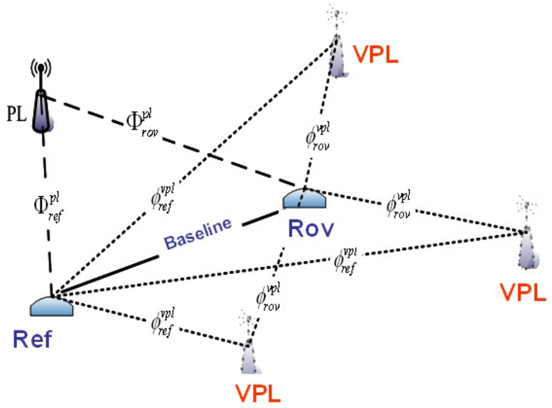


Fig.5. Constellation of pseudolite site (PL) and virtual pseudolite sites (VPLs)

Table 3. *Baseline precision based on the number of pseudolites applied (unit: mm)*

Components	GPS+PL	GPS+PL+1VPL	GPS+PL+2VPL	GPS+PL+3VPL
N	3.5	3.2	1.8	1.6
E	2.7	2.1	1.9	1.7
H	4.2	3.6	3.8	3.9

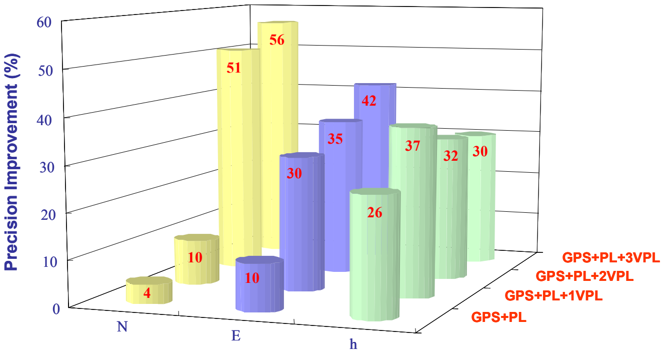


Fig.6. Precision improvement rate with respect to GPS solution

It is evident from the test results that the horizontal precision can be gradually improved by using more pseudolites in the configuration. However, it should also be noted that the most effective improvement on the two horizontal components is associated with different pseudolite configurations. For instance, the precision is significantly improved from 10% to 51% in the E component and from 10% to 30% in the N component with the configuration of GPS+PL+2VPL and GPS+PL+1VPL, respectively. This seems to indicate that there is a geometric effect with the multi-pseudolite constellation at the GPS/PL positioning.

In addition, the total range of the improvement for different pseudolite configurations can reach an obvious value of 52% in the N component and 32% in the E component, whereas a narrower range of 11% is found in the height when GPS+PL+1VPL is applied to augment the original constellation of GPS+PL. This could be attributed to the plane constellation of the pseudolites, which improves the horizontal coordinates and provides less variation to the vertical precision.

Elevation of the Pseudolite

It has been shown that the zero degree of elevation angle operated between pseudolites and receivers does not significantly impact on the vertical precision improvement, in conjunction with the multi-pseudolite configuration. To further evaluate the effect of elevation angle affecting the GPS/PL positioning solution, particularly with respect to the vertical component, the simulated pseudolite measurements were produced for different elevation angles, e.g. ±5°, ±10°, ±15°, ±30° and ±45°, at the two VPL sites to form a configuration of GPS+PL+2VPL for the test. After processing all the new generated GPS/PL data sets, the baseline precisions obtained are shown in Fig. 7.

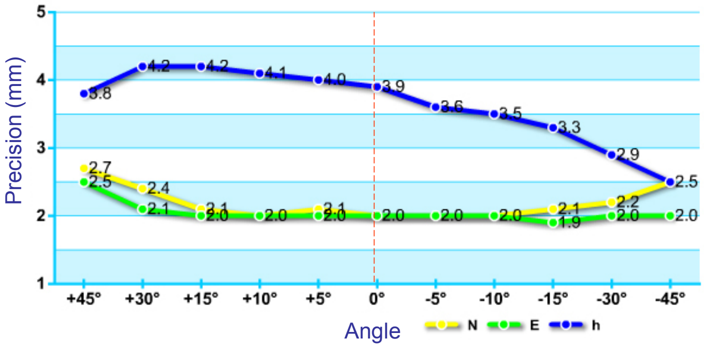


Fig.7. Baseline precision based on different elevations for GPS+PL+2VPL data

It is clearly evident from Fig. 7 that the pseudolite elevation angle plays an important role in the vertical precision. The significant variation range shown in height provides evidence to the pseudolite constellation that the lower elevation angle, the better vertical precision. It is well known that the vertical coordinate has always shown an intrinsic poor precision which might be three times worse than that of the horizontal coordinates, for satellite-based positioning systems, such as GPS. However, this drawback was tested to see if it could be possibly overcome using ground-based pseudolite augmentation. It has been found that the simulated pseudolite measurements made at the VPL sites for a minus elevation angle might be able to comprehensively reduce the vertical positioning error to achieve a consistent level of the precision in all three coordinate components. This leads to greater flexibility in the high precision geodetic applications using mainly GPS.

CONCLUDING REMARKS

Some of the technical issues involved in the integration of multi-pseudolites in the GPS positioning system, particularly those based on the simulated pseudolite measurements, have been discussed in this study. The data simulation using the method of multi-session data combination or self-session data duplication was proposed and tested for its error effects. It has been proved that the self-session duplicated pseudolite measurements can be effectively integrated into the GPS/PL raw data to provide a realistic precision of a baseline solution, and that it can be extensively applied to fabricate the virtual pseudolite site (VPL) for multi-pseudolite data tests.

A series of simulation tests were carried out to primarily investigate the geometric effect related to the pseudolite ground constellation. It was found that an appropriate number of pseudolites, e.g. one PL plus two VPL, is able to strengthen the GPS positioning precision by up to 50% and 30% on the horizontal and vertical components, respectively. A point of interest is that the pseudolite elevation has a significant effect on the vertical precision, in which a consistent level of the 3-D precision is obtained when an elevation angle of -45° is operated at two VPL sites as a part of the GPS+PL+2VPL observation.

Overall, the simulated pseudolite measurements based on a self-session duplicated technique have many benefits, such as: (1) providing more pseudolite data sets for GPS integrated positioning; (2) designing an optimal configuration for pseudolite-based auxiliary positioning; (3) simulating a test environment for pseudolite-based indoor positioning; and (4) improving the three-dimensional coordinate precision for GPS and multi-pseudolite integrated positioning.

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