

PSEUDOLITE-AUGMENTED GPS SURVEY TECHNIQUE FOR DEFORMATION MONITORING: ANALYSIS AND EXPERIMENTAL STUDY

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Abstract: Although GPS has been widely used for precision surveys, many survey environments, like in urban areas, deep open-pit mines and valleys, limit the number of visible GPS satellites, deteriorating the survey accuracy. Pseudolite-augmented GPS survey technique can strengthen the positioning geometry. Although the concept of pseudolite (PL) was initiated in 1970s, its applications have been limited in aviation for precision approach and landing. A great attention was not given until recently to its potential applications in precision surveys. This paper concentrates on the study of its application in deformation monitoring. The methodology for integration of GPS and PL measurements has been developed, in particular the method/strategy to estimate PL multipath effect, one of the server sources of errors in PL measurements. An analysis and test were conducted to illustrate how PL measurements can improve positioning geometric strength and accuracy. A set of real GPS/PL observations were processed to demonstrate the usefulness of the developed methodology.

1. INTRODUCTION

GPS has been widely used for precision surveys, e.g., deformation surveys, precise geodetic control, setting out of engineering structures, and machine guidance. The accuracy, availability, and reliability of GPS surveys, however, are much dependent on the number and distribution of GPS satellites being tracked. Because the visible satellites are distributed above the horizon, the accuracy of GPS-derived height component is known to be 2-3 times lower than that of the horizontal ones. In addition, many survey conditions (like in urban areas, deep open-pit mines, valleys) limit the number of visible satellites and therefore deteriorate the survey accuracy. Moreover, some projects require higher positioning accuracy in a particular direction, which GPS survey may not be able to satisfy. To overcome the limitation and meet special requirement, ground-based “pseudo satellites”, hereafter called pseudolites (PLs), can be added into a GPS survey system to strengthen positioning geometry, which is referred as the PL-augmented GPS technique. A pseudolite is a signal generator, broadcasting GPS-like signals. A modified GPS receiver can then receive both GPS and PL signals.

PS measurements, however, suffer from various sources of errors different from GPS observations. In comparison with GPS much smaller separation between PLs and users causes,

among others, a “near-far” problem in signal tracking. To solve the problem various methods were proposed, which are broadly divided into: the frequency offset, the use of different PN code and the signal pulsing [7]. Only the third one does not require modification of GPS receivers. The multipath is of major concern in PL applications, for low elevation angle of signal reception at user sites generates much severer multipath effect than GPS measurements. For the last decade it has been a continuing interest to mitigate the effect of multipath in GPS measurements, from the simplest approach like optimal antenna selection to most sophisticated receiver technology. A number of methods for the mitigation of GPS multipath effects have been proposed, which can be categorized into mathematical modeling of multipath and the reduction of its effect with stochastic means. The former can be done by identifying effective reflector using the signal to noise ratio, e.g., [1], [9], or a multiple closely-spaced antennas system [10]; or by filtering out the common model effects of signal multipath using its character of sidereal repetition, e.g., [6]. The stochastic approach includes the adaptive Kalman filtering, e.g., [5], and self-calibrating weighting scheme [11]. Some of these methods are applicable to PL measurements. PL synchronization is another source of error. Because PLs are usually equipped with low cost clocks, which are not accurate enough to synchronize time between the reference and user receivers in a differential positioning mode. [12] proposed some techniques to deal with the problem. Tropospheric delay is another major source of error, which can not be cancelled out through differencing like GPS. The delays can be modeled when precise meteorological data are available or estimated as unknown parameters in the position solution [2]. A thorough review on the current developments of pseudolite is given in [13].

During the last decade the most notable pseudolite application was in aviation for precision approach and landing. A great attention was not given until recently to PL potential applications in precision surveys. Some experiments were conducted in monitoring of dynamic motions of bridges [8], monitoring of deformations [4], and in deep open-pit mines [3]. This paper studies some of the issues in the application of PLs in monitoring of deformations. In deformation surveys because of the static relative positions of monitoring points with respect to PLs, the multipath effect of PL signal at a monitoring site is more or less constant, which can be estimated in data processing. The paper first presents the methodology for integration of GPS and PL measurements. In particular the strategy to estimate multipath effects of PLs is discussed. An analysis on how PSLs can improve the strength of positioning geometry is then performed. Experiment studies are then conducted to show how PLs can improve positioning accuracy and to demonstrate the usefulness of the developed methodology for mitigating multipath effect of PL signals.

2. METHODOLOGY FOR INTEGRATION OF GPS AND PL MEASUREMENTS

2.1. Mathematic model for integration of GPS and PL measurements

In similar to GPS, PL carrier phase observable can be expressed as:

$$\varphi_r^{PL} = \rho_r^{PL} + N_r^{PL} \lambda + c \delta t^{PL} - c \delta t_r + \delta_{pos} + \delta_{trop}^{PL} + \delta_{mp}^{PL} + \delta_n^{PL} \quad (1)$$

where ρ_r^{PL} is the geometric distance between a pseudolite and receiver r, δt^{PL} , δt_r , δ_{pos} , δ_{trop}^{PL} , δ_{mp}^{PL} , and δ_n^{PL} are PL clock error, receiver clock error, PL location error, tropospheric delay, PL signal multipath, and observation noise, respectively, λ and N_r^{PL} are the wavelength and

zero-differenced integer ambiguity, and c is the speed of light.

The linearized observation equation for PL single-differenced carrier-phase between the reference station and a monitoring station r reads:

$$\Delta\varphi^{PL} = -u_r^{PL} \delta X_r + \Delta N^{PL} \lambda - c\Delta\delta t + \Delta\delta_{pos} + \Delta\delta_{trop}^{PL} + \Delta\delta_{mp}^{PL} \quad (2)$$

where u_r^{PL} is the unit vector from station r to a PL, δX_r the corrections to the approximate coordinates of station r , and Δ stands for differential operator. Unlike GPS surveys the position error of a PL and troposphere delay can not be cancelled out in single-differencing process because the baseline length between reference station and monitoring station is not longer negligibly small compared with their distance to a PL. The position error of a PL can be corrected for and troposphere delay can be modelled with air temperature and pressure like EDM measurements. In equation (2) the observation noise is omitted.

Let n be number of GPS satellites and m the number of PLs being tracked. Selecting a referenced satellite j , we write the following double-differenced carrier-phase observation equations:

$$\Delta^2\varphi^{ji} = -\Delta u_r^{ji} \delta X_r + \Delta^2 N^{ji} \lambda \quad , \quad i=1, 2, \dots, n \text{ for GPS} \quad (3a)$$

$$\Delta^2\varphi^{jk} = -\Delta u_r^{jk} \delta X_r + \Delta^2 N^{jk} \lambda + \Delta\delta_{mp}^k \quad , \quad k=1, 2, \dots, m \text{ for PL} \quad (3b)$$

The integrated observation equations take the following form:

$$l + v = A\delta X_r + By + Cz \quad (4)$$

where l is the vector of observations (misclosures), v vector of residuals, y vector of ambiguities, z vector of the PL multipath effects, and A, B, C are the corresponding matrices. The above observation equations are similar to those for GPS baseline solution except additional parameters z , multipath errors for all PLs. The parametric least squares technique can be used to estimate the unknown parameters. In static applications, like deformation monitoring the quantities z will be regarded as constant. However, they, if treated as unknowns in the least squares solution, can not be separated from the unknown ambiguities in equation (3b), causing singularity problem in the solution. Therefore a strategy needs developing.

2.2. Solution strategy

The PL multipath is less than a quarter of the cycle (5cm), it is possible to solve the single-differenced pseudolite multipath bias with the following strategy.

- (1) Use GPS/PL data of long observation period for the ambiguity-float solution. In the solution (refer to equation (4)) the multipath effects z are neglected. Long observation period is necessary to mitigate the effects of other error sources and increase the reliability of the solutions. Then the ambiguities can be fixed to integers.
- (2) Given the estimated integer ambiguities, one can solve for the multipath biases z with equation:

$$(l - B \hat{y}) + v = A\delta X_r + Cz$$

where \hat{y} is the estimated integer ambiguities.

- (3) Since the above-estimated ambiguities may be affected by neglecting the multipath biases, an

iteration process is proposed, i.e., use of the estimated multipath biases \hat{z} from (2) as known quantities and solve for the ambiguities again:

$$(I - C \hat{z}) + v = A\delta X_r + By$$

The process stops until the estimated integer ambiguities remain unchanged.

- (4) The estimated multipath biases will be used for subsequent solutions. In this step there are two alternatives: one is to treat the estimated multipath biases obtained from the above as known values to correct PL carrier phase observations. Then the model for GPS/PL integrated solution will not include $\Delta\delta_{mp}^k$ in equation (3b) and z in equation (4); the other alternative is to treat the multipath biases as unknown parameters in equation (4) with the estimated ones with proper variances being their prior information. The parametric adjustment with prior information on some parameters applies and the singularity problem will not exist.

3. OPTIMUM DEPLOYMENT OF PLs

To evaluate how pseudolites can improve the positioning geometric strength (the positioning accuracy) we conducted an evaluation at a hydropower dam located in a valley. GPS signals from southeast sector are blocked by mountains (see Figure 1). The analysis was done in various scenarios (see Figures 2 and 3). The visible satellites on a day at the site were used in this study.

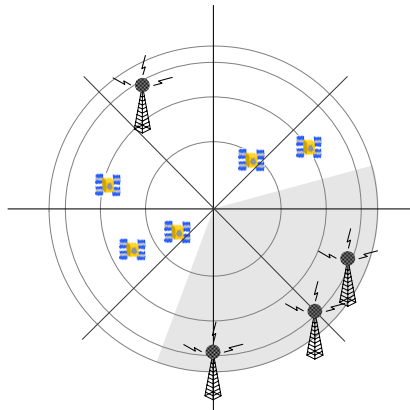


Figure 1 Integration of GPS and PL for monitoring of a dam site

In the first simulation 3 pseudolites are placed at elevation angle of 5° and different azimuth of 110° , 180° , and 230° respectively (see Figure 1). To study the effect of pseudolite placement, PL1 is also re-allocated to 1° . Figure 2 and 3 shows the value of GDOP and VDOP, respectively, with respect to time and the number of pseudolites. In the second simulation the pseudolites are placed at different elevation angles, the results are not given here due to space limitation. The conclusions are (1) it significantly affects the VDOP, but not much the HDOP; (2) the lower the elevation angle, the smaller the VDOP.

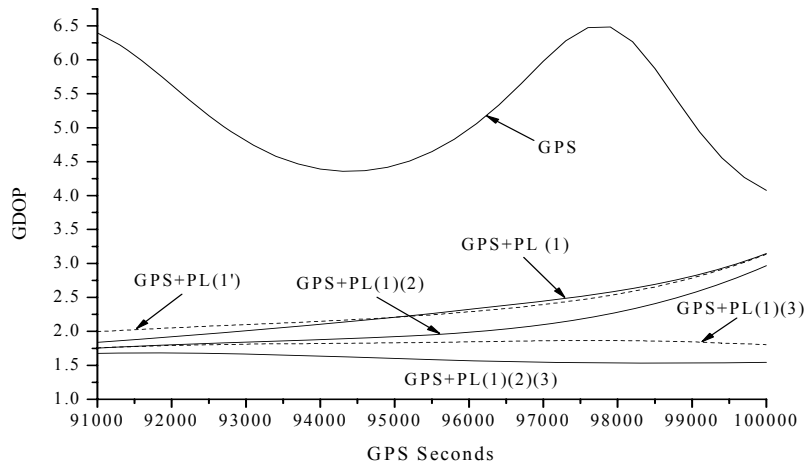


Figure 2 GDOP value

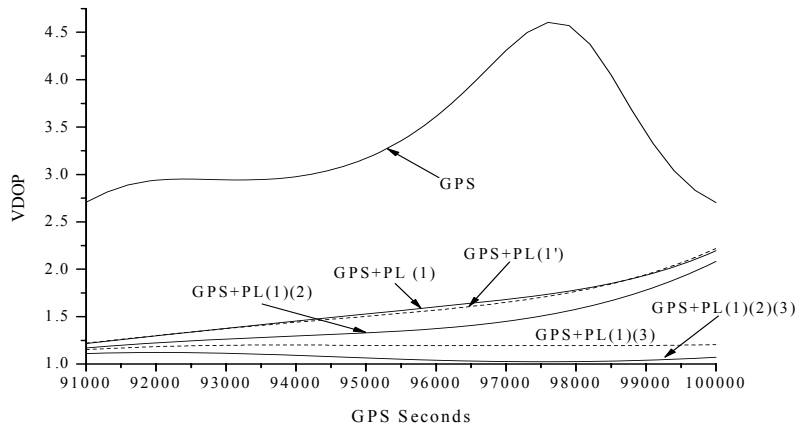


Figure 3 VDOP values

From the above one can conclude that

- (1) The positioning geometry (DOPs value) is greatly strengthened with placement of PSL #1;
- (2) The more PLs, the greater improvement it will be. But the improvement by additional PSL #2 and 3 is less significant;
- (3) Re-allocation of PL #1 from 1 to 1' does not change positioning geometry much, and addition of PL #1 and 3 is better than PL#1 and 2;
- (4) The lower the PL elevation angle, the smaller the VDOP values will be.

Placement of more PLs will, of course, give higher positioning accuracy and reliability, but increases in the cost. Therefore, one must optimally design the number and distribution of PLS. Given the required accuracy and topographic conditions at a survey site we can determine the

number and locations of PLs to satisfy the accuracy requirement as well as with less cost.

4. EXPERIMENTAL STUDIES

4.1 Test on the performance of a PL-augmented system

To test the performance of a PL-augmented GPS system and multipath effect an experiment was conducted with 1 IN200 pseudolite and 2 Novatel DL 4 receivers with Pinwheel 600 antennas (see Figure 4). To create PL signal multipath effect a sheet of aluminum foil (approximately 1.5m by 1m) was located near the rover antenna (see Figure 5). During the observations this reflector was moved to four locations (marked as 1, 2, 3, and 4) around the antenna in a boxed-in fashion. Each scenario was observed for about 20 minutes.

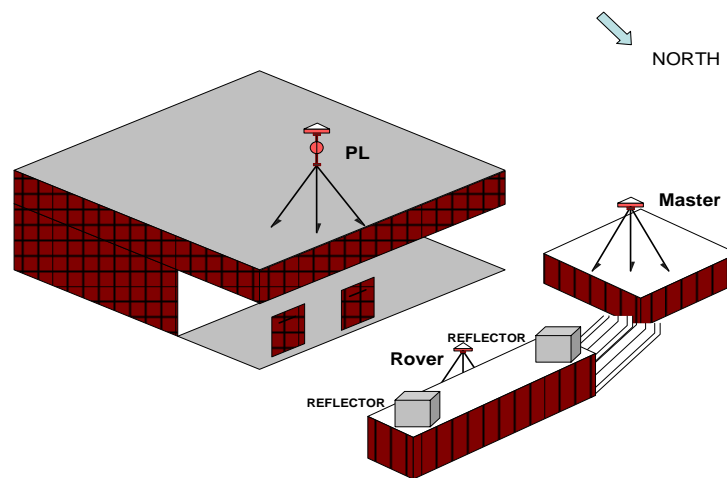


Figure 4 The set-up of the test

Figure 6 shows a plot of position fixing in east component without and with PL signal. Table 1 gives the standard deviation of coordinate component (i.e., east, north and up) for each epoch fixing. As can be seen, introduction of PL significantly improve positioning accuracy, in particular in the north-south direction, which is expectable because the PL is located in the south direction with respect to rover receiver. The tests on the multipath effect were shown in table 2. The table provides the differences between the baseline results with a reflector at different location and those without the reflector. The baseline results were computed from 20 minute observations. The reflector at location 1, 2, 3 and 4 is about 2-3 m away from the rover receiver, while at 2a only 1m. The table tells that the multipath effect in most of testing cases is insignificant, within the positioning errors, but significant at 2a. The effect depends on the relative position among PL, rover receiver and reflector, and also number of GPS satellites being tracked.

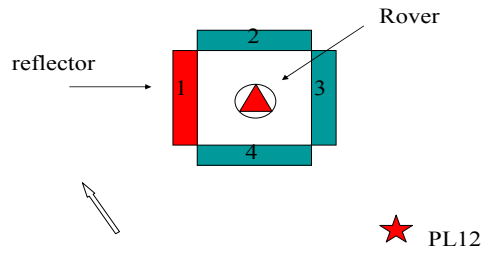


Figure 5 Location of a reflector

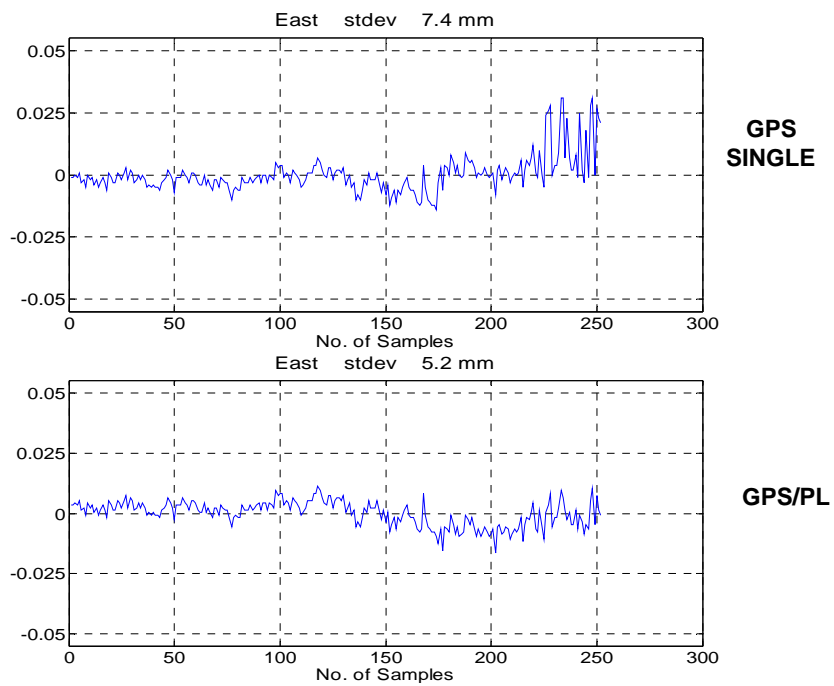


Figure 6 A plot of position fixing in east component

	E-component	N-component	U-component
without PL	7.4	15.9	17.3
with PL	5.2	3.5	11.7

Table 1 Standard deviation of coordinate component (mm)

	E-component	N-component	U-component
At location 1	2.3	2.3	3.0
At location 2	2.9	3.1	5.0
At location 3	2.5	0.3	-2.7
At location 4	2.2	-0.7	-2.2
At location 2a	-0.8	-12.8	-0.2

Table 2 the multipath effects (mm)

4.2 The test on the methodology to mitigate multipath effect

The data for this test were obtained from Dr. JL Wang. Two NovAtel Millennium GPS receivers separated by 11.4m and one IntegriNautics IN200C PL were used. The distance from base station and rover station to the PL is 22.9m and 19.2m, respectively. The PL transmitted L1 signals in PRN 32 and was operated in a pulsed mode. Two receivers collected the GPS and PL data at rate of 1Hz. During the test five satellites (PRN4, 5, 9, 24, 30) and one PL (PRN32) were tracked. Total 5400 epoch data were collected.

To estimate the PL multipath effect, a set of 2000 epoch observations (epoch 562680 - 564680) were selected. GPS satellite PRN24 with the highest elevation angle was selected as the reference satellite. The estimation was done by following the strategy developed above. The ambiguities of all GPS satellites and the PL were fixed and the single-differenced PL multipath bias of 18.3mm was estimated. The estimated multipath bias will be used to correct PL carrier phase observations in the following test. In this test, 2000 epoch data (epoch 565880-567880) were used with 3 GPS satellites (PRN5, 9, 30) (see Figure 7). PRN 5 was selected as the reference in data processing because of highest elevation angle. The data processing was conducted in three scenarios: (1) GPS observations only; (2) GPS and PL observations without correcting for the multipath bias; (3) GPS and PL observations with correcting for the multipath bias. The results are given in Table 3. The error values in the table are the differences between the calculated and the reference coordinates.

From the results, it can be seen that the positioning accuracy with GPS alone is low in particular for short observation time, and hardly reaches millimeter accuracy due to poor geometry of visible satellites (GPS signals from east part of sky are blocked). The integration of GPS and PL data can not improve the accuracy significantly because of the serious multipath bias. But if the multipath bias is calibrated, the PL-augmented GPS can improve the accuracy dramatically. The baseline solution can converge to the reference values in about 1000 epochs in this test, and the errors are millimeter even with 600 epoch observations.

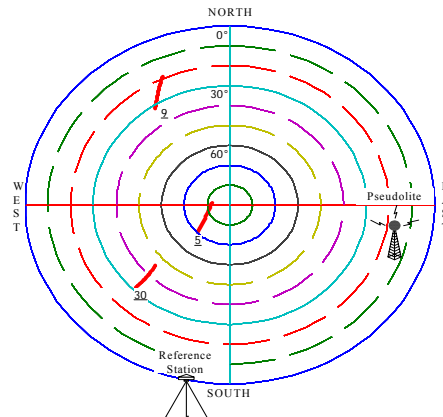


Figure 7 Sky-plot for epoch 565880 - 567880

Processing scenarios	Baseline coordinate	600 epochs		1000 epochs		2000 epochs	
		results (m)	error (mm)	results (m)	error (mm)	results (m)	error (mm)
GPS only	X	-6.4531	-4.6	-6.4557	-7.2	-6.4494	-0.9
	Y	0.8772	38.1	0.8923	53.2	0.8466	7.5
	Z	9.3626	-9.6	9.3581	-14.1	9.3703	-1.9
GPS+PL without MP corrected	X	-6.4466	1.9	-6.4467	1.8	-6.4462	2.3
	Y	0.8246	-14.5	0.8245	-14.6	0.8246	-14.5
	Z	9.3770	4.8	9.3757	3.5	9.3751	2.9
GPS+PL with MP corrected	X	-6.4483	0.2	-6.4485	0.0	-6.4482	0.3
	Y	0.8380	-1.1	0.8379	-1.2	0.8382	-0.9
	Z	9.3733	1.1	9.3722	0.0	9.3721	-0.1

Table 3 Baseline solution results of different scenarios

5. CONCLUDING REMARKS

PL-augmented GPS technique can overcome the limitations of GPS-only surveys in some unfavorable environments. However, several problems need to be solved before PLs can be employed in precise surveys. This paper addressed three issues: mathematical model for integration of GPS and PL measurements; PL multipath effects; and impact of number and distribution of PLs. Due to low elevation angle of PL signal reception at user site, PL multipath effect will be severe. This study takes full advantage of the static relative position of the user receiver with respect to a PL in deformation monitoring, which suggests the multipath bias remains unchanged, and can be estimated in data processing. Based on the above reasoning a strategy has been developed to estimate the multipath biases. Processing of real observations supports the development. Both simulation analysis and experiment test show the significance of addition of PLs into a GPS survey scheme. DOP analysis conducted in this paper indicates that different number and location of PLs are of different contribution to the strength of positioning

