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Pseudolite-augmented GPS for Deformation Monitoring: Analysis and Experimental Study

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伪卫星增强 GPS 方法在变形监测中的应用研究

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摘　要: 应用 GPS 对深开采的露天矿以及深山峡谷中的水库大坝进行变形监测, 由于接收到的 GPS 卫星数目减少, 导致 GPS 定位精度大大降低。采用伪卫星增强 GPS 的定位技术是解决这个问题的有效途径之一。提出 GPS 伪卫星组合测量新方法, 建立组合观测量模型, 开发减小伪卫星多路径效应的方法。基于实际的水电站观测数据分析伪卫星增强 GPS 提高定位精度的效果, 给出 GPS 伪卫星组合定位的试验结果并验证所开发方法的有效性。

关键词: 全球定位系统; 伪卫星; 变形监测; 精密定位

Abstract: Although GPS has been widely used for deformation monitoring, many survey environments, like in deep open-pit mines and valleys, limit the number of visible GPS satellites, deteriorating the survey accuracy. Pseudolite-augmented GPS survey system can strengthen the positioning geometry. This study concentrates on pseudolite (PSL) application in deformation monitoring. The methodology for integration of GPS and PSL measurements is developed, in particular the method/strategy to estimate PSL multipath effect, one of the server sources of errors in PSL measurements. An analysis is conducted to illustrate how PSL measurements can improve the strength of positioning geometry at a hydro-power dam. A set of real GPS/PSL observations are processed to demonstrate the usefulness of the developed methodology.

Key words: GPS; pseudolite; deformation monitoring; precision positioning

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 spe-

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cial requirement, ground-based "pseudo satellites", hereafter called psuedolites (PSLs), can be added into a GPS survey system to strengthen positioning geometry, which is referred as the PSL-augmented GPS technique. A pseudolite is a signal generator, broadcasting GPS-like signals. A GPS receiver can then receive both GPS and PSL signals.

The concept of pseudolite was proposed in the 1970s to validate GPS user equipment. The first low cost pseudolite with GPS L1 C/A code was developed in early 1990s for testing a category III aircraft automatic landing system. PSL measurements, however, suffer from various sources of errors different from GPS observations. In comparison with GPS much smaller separation between PSLs and users causes, among others, a "near-far" problem in signal tracking. The near-far problem is due to large distance variation between a PSL and receiver when the two are in relatively close proximity. The received power level of PSL signals can be over a large range, and the discrepancy in power level between PSL and GPS signals will jam the receiver. The multipath is of major concern in PSL applications, for low elevation angle of signal reception at user sites generates much severer multipath effect than GPS measurements. A number of methods/strategies for the mitigation of GPS multipath effects have been proposed[1~3], which can be categorized into mathematical modeling of multipath and the reduction of its effect with stochastic means. Tropospheric delay is another major source of error, which can not be cancelled out through differencing like GPS. It has been estimated that the tropospheric delays in the PSL measurements may reach up to 320×10^{-6} with standard meteorological parameters, and even 600×10^{-6} under extreme weather conditions[4]. The delays can be modeled when precise meteorological data are available or estimated as unknown parameters in the position solution[5].

Applications of pseudolite can basically categorized into three classes: the pseudolite-only approach[6], the pseudolite-augmented GPS approach, and the integration of PSL with GPS and other sensors[7,8]. During the last decade the most notable pseudolite application was in aviation for precision approach and landing[9,10]. A great attention was not given until recently to PSL potential applications in precision surveys. Some preliminary experiments were conducted in monitoring of dynamic motions of bridges[11], monitoring of deformations[12], and in deep open-pit mines.

From the above discussion one can see that a number of problems need to be solved before PSLs can be employed in precise surveys. This paper studies some of the issues in the application of PSLs in monitoring of dam deformations. Hydro-power dams are usually located in valleys where visible GPS satellites are limited due to the topographic conditions, and therefore PSLs can have a great help in improving the strength of positioning geometry. In deformation surveys because of the static relative positions of monitoring points with respect to PSLs, the multipath effect of a PSL at a monitoring site is constant, which can be estimated in data processing. The paper first presents the methodology for integration of GPS and PSL measurements. In particular the strategy to estimate multipath effects of PSLs is discussed. An analysis of how PSLs can improve the strength of positioning geometry is then performed. A set of the real GPS/PSL observations are processed as an experimental study to demonstrate the usefulness of the developed methodology.

2 Methodology for integration of GPS and PSL measurements

2.1 Mathematic model for integration of GPS and PSL measurements

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

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

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 PSL clock error, receiver clock error, PSL location error, tropospheric delay, PSL 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 PSL single-differenced carrier-phase between the reference station and a coordinating station r reads:

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

where u_r^{PL} is the unit vector from station r to a PSL, 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 PSL and troposphere delay can not be cancelled out in single-differencing process because the baseline length between reference station and coordinating station is not longer negligibly small compared with their distance to a PSL. The position error of a PSL 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 PSL being tracked. Selecting a referenced satellite j, we write the following double-differenced carrier-phase observation equations:

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

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

The integrated observation equations take the following form:

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

where $\boldsymbol{l}$ is the vector of observations (misclosures), $\boldsymbol{v}$ vector of residuals, $\boldsymbol{y}$ vector of ambiguities, z vector of PSL multipath effects, and $\boldsymbol{A}$, $\boldsymbol{B}$, $\boldsymbol{C}$ are the corresponding matrices. The above observation equations are similar to those for GPS baseline solution except additional parameters z, multipath errors for all PSLs. The parametric least squares technique can be used to estimate the unknown parameters. However, the qualities z, if treated as an unknown in the solution, can not be separated from the ambiguities in equation (3b) and causes singularity problem in the solution. A strategy needs developing.

2.2 Estimation of multipath effect of pseudolites

Considering that the pseudolite multipath is a constant for static observation environment, and the bias is less than a quarter of the cycle, it is possible to solve the single-differenced pseudolite multipath bias with the following strategy.

1. Use GPS/PSL 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 using the FARA (Fast Ambiguity Resolution Approach) method.

2. Given the estimated integer ambiguities, one can solve for the multipath biases z with equation

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

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:

$$(\boldsymbol{l} - \boldsymbol{C}\hat{z}) + \boldsymbol{v} = \boldsymbol{A}\delta Xr + \boldsymbol{By}$$

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 PSL carrier phase observations. Then the model for GPS/PSL 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 being their prior information. The parametric adjustment with prior information on some parameters applies and the singularity problem will not exist.

3 DOP analysis of a pseudolite-augmemted GPS system

To evaluate how pseudolits can improve the positioning geometric strength (the positioning accuracy) we conducted evaluation at Xiaodongjiang dam located in a valley. GPS signals from southeast sector are blocked by mountains (Fig. 1). The analysis was done in various scenarios (Fig. 2 and 3). The visible satellites in January 14, 2002 at the site were used in this study.

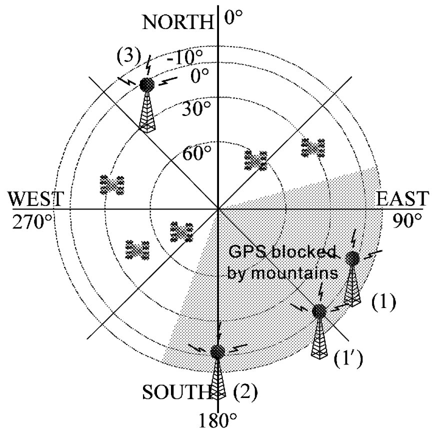

Fig. 1　Integration of GPS and PSL for monitoring of Xiaodongjiang Dam

In simulation 3 pseudolites are placed at elevation angle of 5° and different azimuth of 110°, 180°, and 230° respectively (Fig. 1). To study the effect of pseudolite placement, PL1 is also re-allocated to 1′. Fig. 2 and 3 show the values of GDOP and VDOP, respectively, with respect to time and the number of pseudolites.

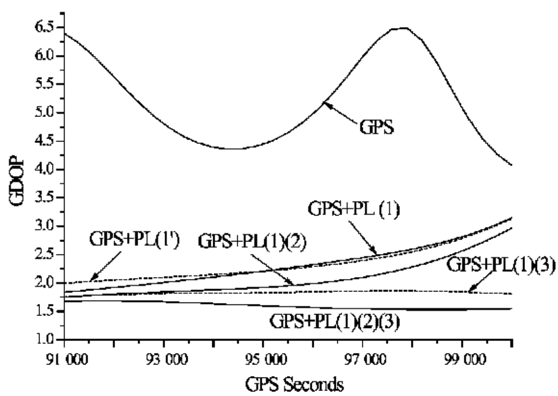

Fig. 2　GDOP value

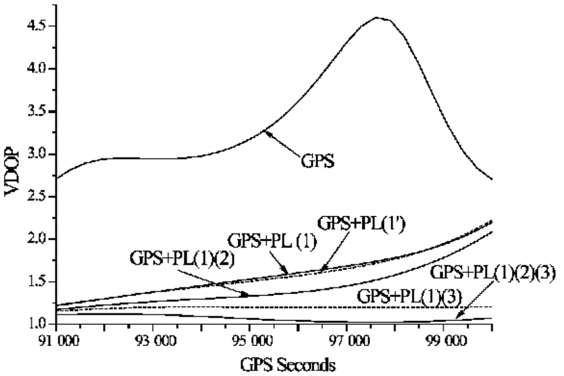

Fig. 3 VDOP values

From the above one can conclude that:

1. The positioning geometry (DOPs value) is greatly strengthened with placement of PSL # 1;

2. The more PSLs, 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;

Of course placement of more PSLs will give higher positioning accuracy and reliability, but increases in the cost. Therefore, there is question how to optimally design the number and distribution of PSLs. Given the required accuracy and topographic conditions at a survey site we should be able to design the number and locations of PSLs to satisfy the accuracy requirement as well as with less cost. This question will be addressed in another paper.

4 An experimental study

4.1 The data description

Fig. 4 is the field test set-up. Two NovAtel Millennium GPS receivers separated by 11.4 m and one IntegriNautics IN200C pseudolite were used. The distance from base station and rover station to the pseudolite is 22.9 m and 19.2 m, respectively. The pseudolite transmitted only GPS L1 signals in PRN 32 and was operated in a pulsed mode with a 10% duty cycle to reduce interference and the near-far problems. Two receivers collected the GPS and pseudolite data at rate of 1 Hz. During the test five satellites (PRN4, 5, 9, 24, 30) and one pseudolite (PRN32) were tracked. Total 5 400 epoch data were collected.

4.2 Estimation of pseudolite multipath effect

To estimate the pseudolite multipath effect, a set of 2 000 epoch observations (epoch 562 680 – 564 680) 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 fixed ambiguities of all GPS satellites and the pseudolite are $[86, 43, 80, 88, -150]^T$ and the single-differenced pseudolite multipath bias is 0.096 4 cycles (18.3 mm). The estimated multipath bias will be used to correct pseudolite carrier phase observations in the next calculation. Adaptive filtering[13] can be also used to estimate multipath bias. This method will be discussed in another paper.

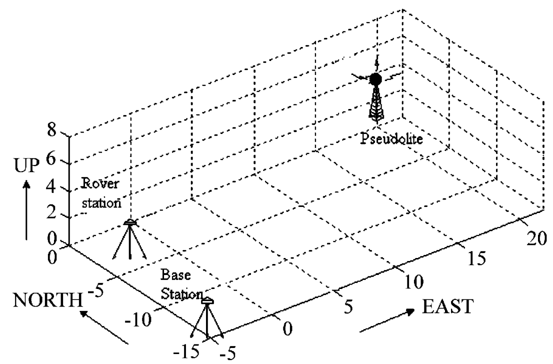

Fig. 4 A field test set-up

4.3 Baseline calculation results

In this experiment, 2 000 epoch data (epoch 565 880-567 880) were used with 3 GPS satellites (PRN5, 9, 30) and 1 pseudolite tracked (Fig. 5). 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 (PRN4, 5, 9, 24, 30); ② GPS (PRN5, 9, 30) and pseudolite (PRN32) observations without correcting for the multipath bias; ③ GPS and pseudolite observations with correcting for the multipath bias. The results are given in Tab. 1. The error values in the table are the differences between the calculated and the reference coordinates. The reference coordinates were given by the data provider.

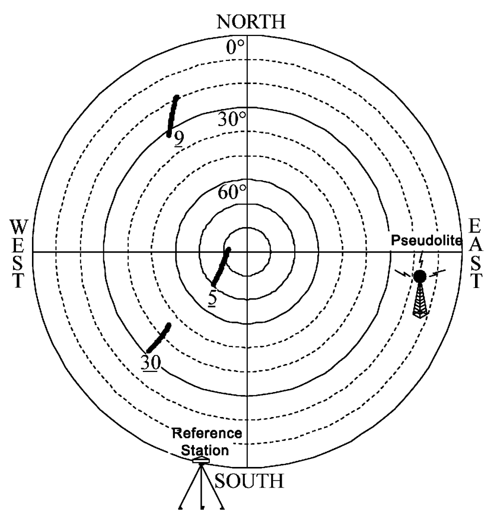

Fig. 5 Sky-plot for epoch 565 880 – 567 880

Tab. 1　Baseline solution results of different scenarios

Processing scenarios	Baseline coordinate	600 epochs		1 000 epochs		2 000 epochs	
		results/ m	error/ mm	results/ m	error/ mm	results/ m	error/ mm
GPS only	*X*	− 6.453 1	− 4.6	− 6.455 7	− 7.2	− 6.449 4	− 0.9
	Y	0.877 2	38.1	0.892 3	53.2	0.846 6	7.5
	Z	9.362 6	− 9.6	9.358 1	− 14.1	9.370 3	− 1.9
GPS+ PL without MP corrected	*X*	− 6.446 6	1.9	− 6.446 7	1.8	− 6.446 2	2.3
	Y	0.824 6	− 14.5	0.824 5	− 14.6	0.824 6	− 14.5
	Z	9.377 0	4.8	9.375 7	3.5	9.375 1	2.9
GPS+ PL with MP corrected	*X*	− 6.448 3	0.2	− 6.448 5	0.0	− 6.448 2	0.3
	Y	0.838 0	− 1.1	0.837 9	− 1.2	0.838 2	− 0.9
	Z	9.373 3	1.1	9.372 2	0.0	9.372 1	− 0.1

From the above table, 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 GPS and pseudolite data can not improve the accuracy significantly because of the serious multipath bias. But if the multipath bias is calibrated, the augmented-pseudolite GPS can improve the accuracy dramatically. The baseline solution can converge to the reference values in about 1 000 epochs in this experiment, and the errors are millimeter even with 600 epoch observations.

5　Concluding remarks

Pseudolite-augmented GPS technique can overcome the limitations of GPS-only surveys in some unfavorable environments, like in urban area, deep open-pit mines, and valleys. It can also improve the accuracy of GPS-derived heights. However, several problems need to be solved before pseudolites can be employed in precise surveys. This paper addressed three issues: mathematical model for integration of GPS and PSL measurements; multipath effects of pseudolites; and impact of number and distribution of pseudolites. Due to low elevation angle of PSL signal reception at user site, PSL multipath effect will be severe. This study takes full advantage of the static relative position of the user receiver with respect to a pseudolite in deformation monitoring, which suggests the multipath bias remains unchanged, and can be estimated in data processing. Based on the above reasoning a method/ strategy has been developed to estimate the multipath biases. Processing of real observations supports the development. Hydro-power dams are usually located in valleys, where the number and distribution of visible GPS satellites are unfavorable. PSLs will have a great help in overcoming the problem. DOP analysis conducted in this paper demonstrates how importance of addition of PSLs into a survey scheme. The analysis also indicates different number and location of PSLs are of different contribution to the strength of positioning geometry, and optimum design in terms of the cost needs conducting regarding the number and locations of PSLs, given accuracy requirement.

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