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 psuedolites (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:

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

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:

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

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

The integrated observation equations take the following form:

$$l + \mathrm{v} = \mathrm{A}\delta X_\mathrm{r} + \mathrm{By} + \mathrm{Cz} \quad (4)$$

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:

$$(l - \mathrm{B}\,\hat{y}) + \mathrm{v} = \mathrm{A}\delta X_\mathrm{r} + \mathrm{Cz}$$

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:

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

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 pseudolits 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.

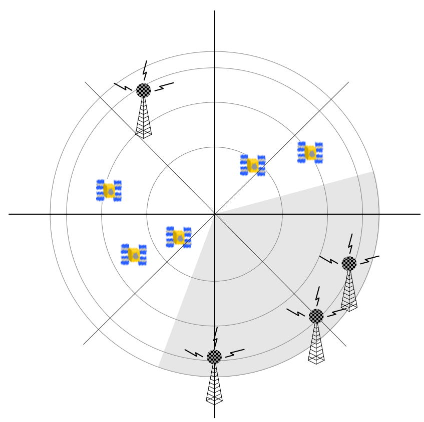

Figure 1 Integration of GPS and PL for monitoring of a dam site

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.