LETTER *Earth Planets Space*, **52**, 873–876, 2000

A multi-antenna GPS system for local area deformation monitoring

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(Received January 11, 2000; Revised June 26, 2000; Accepted June 26, 2000)

A new method of using GPS for monitoring local area deformations such as landslides is presented. Unlike the standard method of using GPS for deformation monitoring where a GPS receiver is required for each point to be monitored, the new method allows multiple points to be monitored with one receiver. A system that implements the concept has been developed. It uses a specially designed electronic component that allows a number of GPS antennas to be linked to a single GPS receiver. The receiver takes data sequentially from each of the antennas attached to the receiver. A distinctive advantage of the approach is that one GPS receiver can be used to monitor more than one point. The cost per monitored point is therefore significantly reduced. The design of the system, as well as the data management and processing strategies will be introduced in detail. Results from some preliminary tests will also be given.

1. Introduction

GPS has proven to be a very useful tool for monitoring deformations of many man-made and natural structures such as dams, bridges, slopes and volcanoes. It offers many advantages over traditional surveying techniques that measure relative geometric quantities (i.e., distances, angles and height differences) between selected points. In general, GPS surveying is more accurate, more efficient, highly automated and not labour intensive. However, GPS also has its disadvantages when used for such applications. One limiting factor for large-scale use of GPS is its high cost. With standard approaches of using GPS, if permanent GPS receiver arrays are used for monitoring deformations, a receiver is required for each point that needs to be monitored. If there are a large number of points to be monitored, the cost of GPS hardware can be prohibitively expensive for most practical applications. For example, Hong Kong has tens of thousands of natural and cut slopes, and a large number of them are unstable and potentially dangerous. To determine the deformation and failure mechanism of a slope, a number of points on the slope often need to be monitored. GPS has not been used much at all for such applications mainly due to the high cost involved.

To reduce the hardware cost of GPS when used for deformation monitoring, a new concept of using GPS for local area deformation monitoring has been developed. It essentially uses a specially designed electronic component, namely a GPS multi-antenna switch (GMS), to connect a number of GPS antennas to one receiver. The GMS allocates time to each antenna sequentially to allow data to be acquired from them. After processing the data thus obtained, the deformations of all the points mounted with the antennas can be determined.

The design of a system that has been developed based on the above concept, as well as the data management and processing strategies associated with the system, will be described below.

2. System Design

2.1 System structure

The following are the major components of the multi-antenna GPS deformation monitoring system (Fig. 1):

- **GPS multi-antenna switch (GMS).** It is an electronic switch with multiple input and a single output channel. It is connected between the antennas and the receiver and allows GPS signals from each of the antennas to be logged sequentially into the receiver. The time allocated to each of the antennas can be specified by the user to suit different application requirements. With the help of the switch one GPS receiver works effectively as a number of receivers.

- **GPS antennas and receiver.** Any standard GPS receiver and antenna can be used with the system. The number of antennas that can be used with the system depends only on the design of the GMS. For the particular system that has been developed and tested, a maximum of 6 antennas can be used. (This number can be easily increased if necessary.) The antennas are connected to the receiver through the GMS using cables. For longer distances, fibre optic cables can be considered, or signal amplifiers can be used, to reduce the loss of signal strength through the cables.

- **Data link.** It is used to transmit data acquired on the monitored site to a data processing and analysis centre, which is basically a personal computer located in an office. A number of options are available for establishing the data link. For example, mobile phones, radios and dedicated communication networks can be considered

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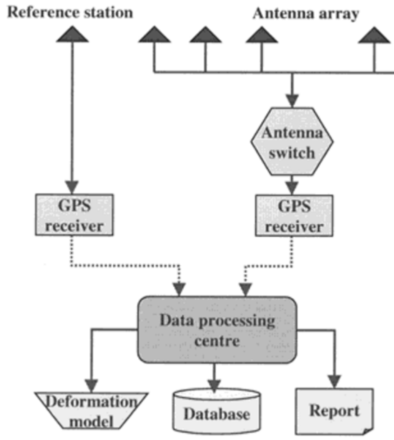

Fig. 1. System structure.

according to the site conditions (e.g., Ding *et al.*, 1996).

- **Data processing and analysis algorithms and software.** Standard or specialized algorithms and software can be used to process and analyze the data to determine the coordinates, and the deformations, of the monitored points with respect to the reference station(s).

2.2 Data stream and control

Two options are available when allocating the time for the antennas. First, the receiver can be connected to an antenna for a period of time to allow more than one epoch of data to be acquired from the antenna before switching to the next antenna. Second, the receiver stays at each antenna for one epoch of GPS measurements only and then goes to the next antenna or the next round of rotation. For the first option, the data can be separated for each of the antennas and processed using the standard methodology of baseline processing. The second option causes cycle slips whenever the GMS switches from one antenna to the next. The well-known methods of cycle slip detection and reconstruction do not work in this case. When the rate of deformation of the monitored objects is low, the integer ambiguities for each epoch may be initiated based on the prior known coordinates of the monitored points as to be discussed in more detail in the next section.

In deformation monitoring, depending on the type and nature of the monitored objects, sometimes the timing, i.e., rate of acquiring and processing the data, is important while in other cases, the accuracy of measurements is more important. Therefore, an appropriate option may be chosen for any particular situation.

3. Data Processing Strategies

3.1 Kalman filter and sequential adjustment

The Kalman filter is an algorithm applicable to all types of GPS positioning, especially for deformation surveying applications. The state vector X can be grouped as:

$$X = (XP_m, \Delta^2 I, \Delta^2 N_{rm}^{12}, \Delta^2 N_{rm}^{13}, \ldots, \Delta^2 N_{rm}^{1n})^T \tag{1}$$

where XP_m contains the coordinates, velocities and accelerations of the monitored points; $\Delta^2 I$ is the double-differenced ionospheric effects; $\Delta^2 N$ is the double-differenced phase integer ambiguities; n is the number of observed satellites; the superscripts are the numbers of the satellites; and subsripts r and m refer to the reference and monitored points respectively.

If the acceleration is treated as white noise, i.e., only the three-dimensional coordinates and velocities are included in XP_m, the transition matrix Φ and the system white noise ω become:

$$\Phi = \begin{bmatrix} \Phi_{XP} & 0 & 0 \\ 0 & \Phi_I & 0 \\ 0 & 0 & \Phi_N \end{bmatrix}; \qquad \omega = \begin{bmatrix} \omega_{XP} & 0 & 0 \\ 0 & \omega_I & 0 \\ 0 & 0 & \omega_N \end{bmatrix} \tag{2}$$

where

$$\Phi_{XP} = \begin{bmatrix} E_3 & \tau E_3 \\ 0 & E_3 \end{bmatrix}; \qquad E_3 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}; \qquad \omega_{XP} = \begin{bmatrix} \frac{1}{2}\tau^2 E_3 & 0 \\ 0 & \tau E_3 \end{bmatrix} \sigma_p \tag{3}$$

τ in the above equation is the data sampling interval and σ_p is the apriori variance factor. The phase integer ambiguities remain the same unless cycle slips (loss of lock) occurs. Therefore,

$$\mathrm{Diagonal}(\Phi_N) = (1, 1, \ldots, 1). \tag{4}$$

The ionospheric effects can also be treated as constant, i.e., $\Phi_I = 1$.

For most deformation surveying applications such as slope monitoring, the rate of deformation is low. Thus the system state can be treated as in a static mode. The transition matrix Φ_{XP} can be substituted by a unit matrix, i.e.,

$$\mathrm{Diagonal}(\Phi_{XP}) = (1, 1, 1, 1, 1, 1). \tag{5}$$

In this case, the Kalman filter algorithm becomes a sequential adjustment.

3.2 Fast ambiguity resolution

Many important contributions have been made in the area of GPS integer ambiguity resolution (e.g., Frei and Beutler, 1990; Teunissen, 1995; Teunissen *et al.*, 1997), and the standard methods can be readily used for data processing for the multi-antenna GPS systems. For example, a deformation surveying system can be treated as a slowly moving kinematic problem. In this case, the ambiguities can either be initiated at a known point or be solved using on-the-fly (OTF) techniques. However, if the coordinates of the monitored points are known with a few cm accuracy between two observation sessions, this information can be used to solve for the ambiguities instantaneously (or at least very quickly).

4. Preliminary Tests

4.1 Static and OTF tests

Two antennas were linked to a multi-antenna system in the tests (Fig. 2). Additionally, a second receiver was set up on a point with known position and about 1.5 km from the test site. The observation time for each antenna was set as

Table 1. Results of fast static solutions (m) (for simplicity, only the part of less than 1 m of the solutions are given).

	Channel 1			Channel 2		
Session	X	Y	Z	X	Y	Z
1	.684	.256	.244	.944	.159	.918
2	.682	.256	.244	.945	.160	.918
3	.683	.258	.246	.943	.161	.916
4	.681	.254	.245	.944	.155	.914

Fig. 2. The set up of the test site.

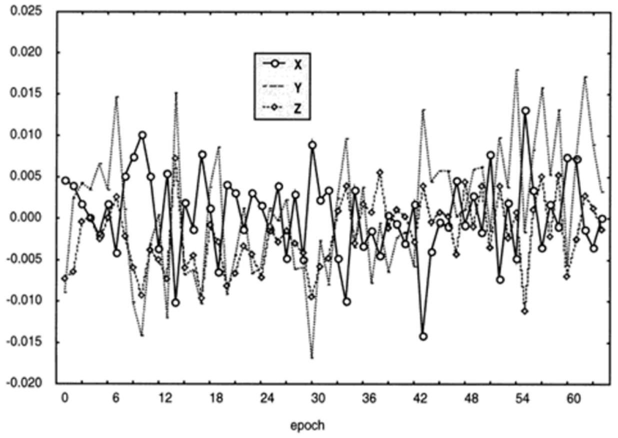

Fig. 4. Kinematic solutions (second antenna).

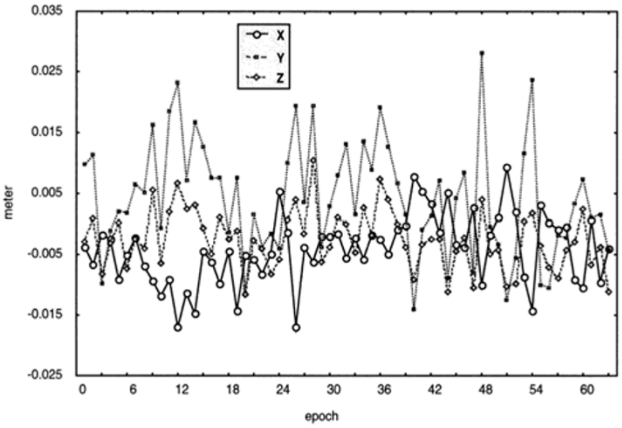

Fig. 3. Kinematic solutions (first antenna).

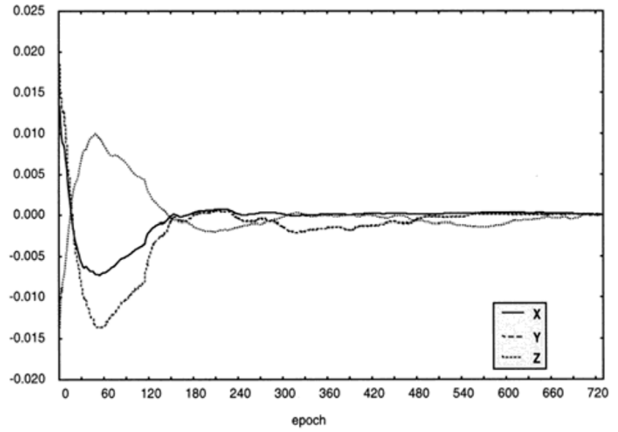

Fig. 5. Kalman filter solution (first antenna).

990 seconds (16.5 minutes) in each round of observations. This made it possible to carry out both the fast static and kinematic OTF positioning solutions. The results of the fast static solutions are shown in Table 1.

The kinematic solutions were based on single epochs of observations. The OTF technique was first used to solve for the integer ambiguities, which were then kept fixed for the subsequent kinematic solutions. The repeatability of the solved coordinates for the two points is shown in Figs. 3 and 4. It can be seen that the precision of the solutions is generally at the 1 ∼ 3 centimetre level.

Figure 5 gives the Kalman filter (sequential adjustment) solutions for the first antenna. It shows that the coordinates derived from the Kalman filter quickly converge to the static solution after a certain number of observation epochs.

5. Conclusions

A concept based on using multi-antenna GPS systems for monitoring local area deformations has been presented. The design of a prototype multi-antenna GPS system, the data processing strategies associated with the system, as well as some preliminary test results have been given. The concept has advantages over the standard method of using GPS receiver arrays in monitoring deformations because such a development significantly reduces the cost of GPS hardware for monitoring deformations.

Acknowledgments. The research was supported by a grant from the Research Grants Council of the Hong Kong Special Administrative Region (Project No. PolyU 5090/97E) and the National Natural Sciences Foundation of China (Project No. 49771062).

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