Real-Time GPS Landslide Monitoring Under Poor Satellite Visibility

Mami Ueno [1], Kenji Itani [2] and Richard B. Langley [3]
(1) CNRS I3S Laboratory, Sophia Antipolis, France
(2) FURUNO Electric Co., Ltd., Nishinomiya, Japan
(3) University of New Brunswick, Fredericton, Canada
mueno@i3s.unice.fr, kenji.itani@furuno.co.jp, lang@unb.ca

BIOGRAPHY

Mami Ueno obtained her Ph.D. in Geomatic Sciences from Laval University, Canada and her B.Sc. and M.Sc. in Marine Systems Engineering from Tokyo University of Mercantile Marine, Japan. She has been working on the development of GPS data processing algorithms and software. Mami is currently working on underwater robot navigation as a research fellow at CNRS I3S signal processing laboratory, Sophia Antipolis, France.

Kenji Itani is a chief engineer in the Research Division of Furuno Electoric Co., Ltd., Nishinomiya, Japan. He received his B.S.E.E. and M.S.E.E. from Kobe University in 1971 and 1973, respectively. He has been involved in the development of GPS receivers since 1991 as a software engineer. He is currently developing carrier-phase applications with low-cost GPS receivers.

Richard Langley is a professor in the Department of Geodesy and Geomatics Engineering at the University of New Brunswick, where he has been teaching and conducting research since 1981. He has a B.Sc. in applied physics from the University of Waterloo and a Ph.D. in experimental space science from York University, Toronto. Prof. Langley has been active in the development of GPS error models since the early 1980s and is a contributing editor and columnist for GPS World magazine.

ABSTRACT

Among the available technologies such as cables and lasers, the Global Positioning System (GPS) is being increasingly used for automated continuous monitoring of landslides and avalanches. The timely identification of precursory movements of landslides could save lives and minimise collateral damage.

Carrier-phase observations from four or more GPS satellites allow relative displacements to be measured with centimetre accuracy. However, signals from four satellites with good geometry are not always guaranteed, as the landslide sites are often located along mountain slopes, which are subject to poor satellite visibility. Such landslide locations may, therefore, experience several minutes to hours of positioning discontinuity for some periods of the day. The effect of the availability of satellite signals is greater for sites located on north-facing slopes due to GPS orbit characteristics.

We have investigated a method for detecting a displacement of the order of millimetres under poor satellite visibility. We estimate the displacement without differencing the positioning results, supposing that a landslide occurs along the slope in the direction of maximum inclination (this assumption could be later replaced with a landslide outbreak model for a particular site). First, we investigated the method to detect a landslide with only 2 satellites (1 misclosure vector) and then, the improvement of the positioning results when more satellites are available.

In this paper, we discuss our algorithms permitting continuous landslide monitoring for low visibility observations and some results of field tests. We discuss specific aspects of our investigations using field data simulating landslides: 1) multipath elimination, 2) estimation of displacement supposing a priori knowledge of the antenna location at the monitoring site, and 3) the necessary time span of observations for detecting landslides.

INTRODUCTION

Carrier-phase observations from four or more GPS satellites allow relative displacements to be measured with centimetre accuracy. GPS has been widely used for measuring crustal motion, river level and ground subsidence, and for monitoring deformation of man-made structures such as bridges, dams, buildings, *etc.* (Ashkenazi *et al*., 1998; Duffy & Whitaker, 1999; Moore *et al.*, 2000). GPS is being increasingly used also for automated continuous monitoring of landslides and avalanches.

For such GPS-based deformation monitoring systems, the accuracy, availability, reliability and integrity of the positioning solutions heavily depend on the number and geometric distribution of satellites being tracked. However, signals from four satellites with good geometry are not always guaranteed, as the landslide sites are often located on mountain slopes, which are subject to poor satellite visibility. Such landslide locations may, therefore, experience several minutes to hours of positioning discontinuity for some periods of the day. The problem of satellite-signal availability is greater for sites located on north-facing slopes due to GPS orbit characteristics.

In order to use GPS in such situations for monitoring hill-side stability, we investigated a method for detecting a displacement of the order of millimetres under poor satellite visibility using the principle of hyperbolic navigation. We discuss in the following our algorithms permitting continuous landslide monitoring for low visibility observations and present some results of field tests.

GPS OBSERVATION EQUATIONS

The observation equation for GPS carrier phase measurements is given by (Leick 1995):

$$\Phi = \rho + c \cdot (dt - dT) + \lambda N - d_{ion} + d_{trop} + \varepsilon_\Phi \quad (1)$$

For a pair of stations simultaneously observing the same satellite, the mathematical model for the between-receiver single differenced observable is obtained as follows:

$$\Delta\Phi = \Delta\rho + c \cdot \Delta dT + \lambda \Delta N - \Delta d_{ion} + \Delta d_{trop} + \Delta\varepsilon_\Phi \quad (2)$$

Between-receiver single differences remove the satellite clock errors and greatly reduce the effects of errors associated with satellites and the signal path such as orbit errors and atmospheric delays for short baselines.

The double difference observations are obtained by subtracting the single difference observation of a reference satellite from that of another satellite. The receiver-satellite double differences are expressed by the following equation and we note that double differencing also removes the effects of errors associated with the misalignment of clocks between the two receivers:

$$\nabla\Delta\Phi = \nabla\Delta\rho + \lambda \nabla\Delta N - \nabla\Delta d_{ion} + \nabla\Delta d_{trop} + \nabla\Delta\varepsilon_\Phi \quad (3)$$

In Equations (1) to (3), ρ is the distance between satellite and receiver (m); c is the light speed in vacuum (m/s); Φ is the carrier-phase measurement (m); λ is the carrier wavelength (m); N is the integer carrier-phase ambiguity; d_{ion} is the bias of the ionospheric delay (m); d_{trop} is the bias of the tropospheric delay (m); dt is the bias of the satellite clock (s); dT is the bias of the receiver clock (s); ε_Φ is the measurement noise and the errors which cannot be modeled. The symbols $\Delta(*)$ and $\nabla\Delta(*)$, are the single and double difference operators, respectively.

The observation equation is written as:

$$\boldsymbol{l} = f(\boldsymbol{X}) + \boldsymbol{V} \quad (4)$$

where $\boldsymbol{l}$ is the observation vector, $\boldsymbol{X}$ is the vector of unknown parameters; $f(*)$ is the vector of known non-linear functions mapping $\boldsymbol{X}$ to $\boldsymbol{l}$; and $\boldsymbol{V}$ is the vector of residuals.

To use a Kalman filter or least-squares algorithm, the equations must be linearised with respect to the unknowns. Equation (4) is linearised by replacing the non-linear functions with their Taylor series approximations expanded about an approximate position of the observer, $\boldsymbol{X}^0$ and taking only the first order terms:

$$\boldsymbol{l} - f(\boldsymbol{X}^0) = \left.\frac{\partial f}{\partial \boldsymbol{X}}\right|_{\boldsymbol{X}^0} d\boldsymbol{X} + \boldsymbol{V} \quad (5)$$

HYPERBOLIC METHOD FOR POOR SATELLITE VISIBILITY

For the use of least-square algorithms, signals from at least four satellites with good geometry are needed. However, landslide sites are often located on mountain slopes, which are subject to poor satellite visibility, and the minimum needed number of satellites is not guaranteed.

We investigated a method for detecting a displacement of the order of millimetres under poor satellite visibility using the principle of hyperbolic navigation (Fig. 1). The geometrical distances from the receiver M to two satellites A and B are denoted D_A and D_B. We compute the difference of the distances (D_A-D_B). The locus of the points that have the same value for $D_A - D_B$, is a hyperboloid which includes the receiver point (Strang & Borre, 1997). In the vicinity of the receiving point M, we assume that the surface of the hyperboloid is a plane (P_1). Plane P_1 is oriented to the direction that divides the angle made by the two satellites viewed from the receiving point M. Plane P_1 is perpendicular to the plane that includes the positions of two satellites A and B, and the receiver position M. The coordinates of the three points

A, B, and M establish the equation of this plane. The vector of direction cosines for P_1 can be specified from the geometrical relationship of the three points.

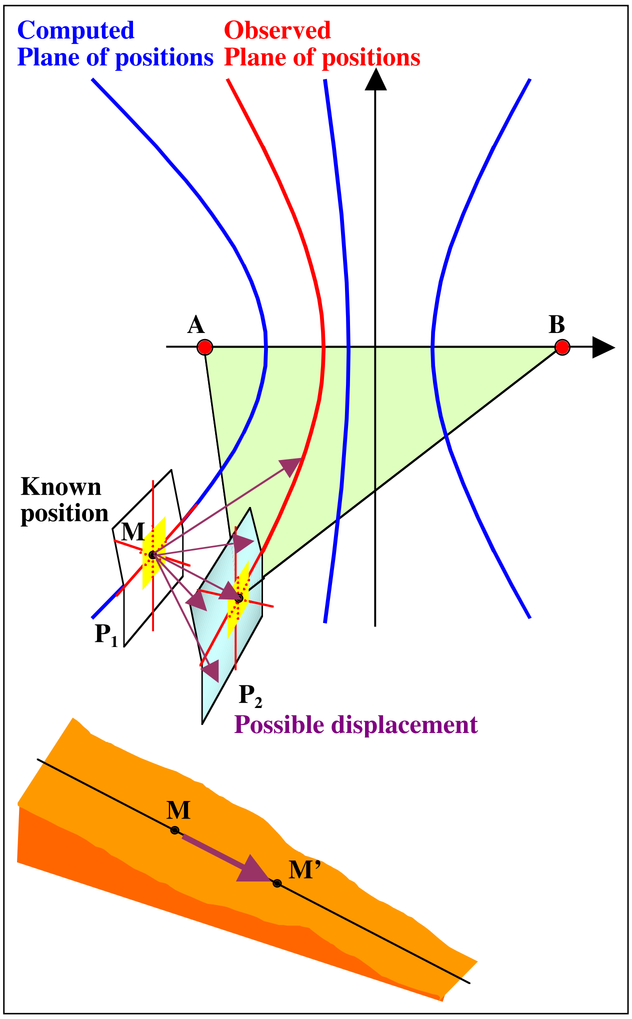

Figure 1. Hyperbola and schematic presentation of landslides

When plane P_1 includes the point M (x_0, y_0, z_0) and the components of the normal vector to P_1 $\boldsymbol{N}$ are a, b and c, the equation of the plane is expressed as follows:

$$a \cdot (x - x_0) + b \cdot (y - y_0) + c \cdot (z - z_0) = 0 \qquad (6)$$

This equation can be rewritten as:

$$a \cdot x + b \cdot y + c \cdot z - d = 0 \qquad (7)$$

with $d = a \cdot x_0 + b \cdot y_0 + c \cdot z_0$.

We define a local coordinate system that has the x-axis pointing towards the east, y-axis towards the north, and z-axis perpendicular to the both axes pointing up towards the zenith. The origin is the point M.

We assume that the monitoring receiver is located on the slope and the slide occurs along the slope that has a maximum inclination. The shape of the slope is approximated by a plane. A unit displacement along the slope is a vector of direction cosines, defined by the azimuth ψ that is measured from the north, and the elevation angle θ. Then the vector of direction cosines of the slope $\boldsymbol{V}$ is expressed as follows:

$$V = \begin{pmatrix} i \\ j \\ k \end{pmatrix} = \begin{pmatrix} \cos\psi \sin\theta \\ \cos\psi \cos\theta \\ \sin\psi \end{pmatrix} \qquad (8)$$

Now we consider that the receiver moves a distance D from the point M to M' along the slope. The movement caused by the landslide is usually downwards. A unit displacement along the slope can be expressed with a vector of direction cosines $\boldsymbol{V}$ (i, j, k) as follows:

$$\frac{x - x_0}{i} = \frac{y - y_0}{j} = \frac{z - z_0}{k} \qquad (9)$$

The line given by Equation (9) represents the maximum gradient of the slope and gives the direction in which movement is expected.

We consider two planes of positions: P_1 and P_2 as shown in Figure 2. Plane P_1 includes the initial position (M) and Plane P_2 includes the position after the slide (M'). Plane P_1 is the theoretical (computed) plane of positions and Plane P_2 is obtained from the observation. $\boldsymbol{W}$ is the misclosure vector.

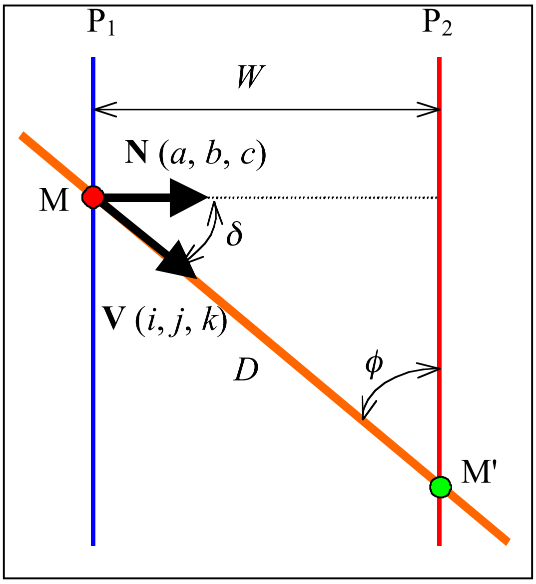

Figure 2. Geometry of planes of positions and displacement along the slope of maximum inclination

The inner product of the normal vector and the vector of direction cosines is expressed as:s

$$N{\cdot}V=|N||V|\cos\delta \tag{10}$$

As the vector of direction cosines is a unit vector $|V| = 1$, we can rewrite the relationship as:

$$\cos\delta=\frac{N{\cdot}V}{|N|} \tag{11}$$

From the geometrical relationship shown in Figure 2, we obtain the following equation:

$$D\cos\delta=|W| \tag{12}$$

The angle between the slope of maximum inclination and the observed plane of positions P_2 is ϕ. From the complementary relationship of trigonometry, the cosine of the angle δ equals the sine of the angle ϕ. The sine of this angle is expressed in the following equation:

$$\sin\phi=\cos\delta=\frac{a{\cdot}i+b{\cdot}j+c{\cdot}k}{\sqrt{a^2+b^2+c^2}} \tag{13}$$

The position after the landslide has occurred is estimated from the displacement ***D*** (M-M'). The magnitude of ***D*** is a function of the angle ϕ and the separation between the two planes of positions which includes both points, the initial point M and the point M' after the slide. The separation can be obtained as the misclosure ***W*** (observed - computed). The relationship in Equation (12) can be rewritten as:

$$D\sin\phi=|W| \tag{14}$$

Thus we obtain:

$$D=\frac{|W|}{\sin\phi} \tag{15}$$

WEIGHTING STERATEGY IN CASE OF BETTER SATELLITE VISIBILITY

When the inverse of the least-squares normal equations matrix is not available due to poor geometry (either too few satellites or very high position dilution of precision (PDOP) with four or more satellites), the standard least-squares method cannot provide a solution. However, our method provides a solution with data from only 2 satellites. When 2 or more misclosures (with 3 or more satellites) are available, it is better to consider the use of observation weighting for finding the distance between the positions a priori and after the displacement. We compute the displacement for *n* combinations of 2 satellites. The weighing scheme is expressed as follows:

$$D=\frac{p_1{\cdot}D_1+p_2{\cdot}D_2+\cdots+p_n{\cdot}D_n}{p_1+p_2+\cdots+p_n} \tag{16}$$

For appropriate weighting, the variance of displacement ***D*** must be correctly calculated. The weight can be obtained from the inverse of the variance resulting from the least-squares adjustment or Kalman filtering. When all the weights are equal to 1, the results obtained are equivalent to those obtained by a standard least-squares method.

The variance of displacement ***D*** is computed from the variance of the misclosure ***W*** scaled with the separation of the planes of positions *dv* and the cosecant of the angle of maximum inclination of the slope *dd*.

Weights are therefore expressed as:

$$p=\frac{1}{(dv)^2{\cdot}(dd)^2} \tag{17}$$

The variance of the distance can be defined by the variance of the misclosure scaled by the squares of *dv* and *dd*.

$$\sigma_D^2=\sigma_W^2{\cdot}\left(dv\right)^2{\cdot}\left(dd\right)^2 \tag{18}$$

The normal distance to the plane of positions from the origin, is expressed as follows:

$$dv=\frac{|d|}{\sqrt{a^2+b^2+c^2}} \tag{19}$$

where $|d|=a{\cdot}x_0+b{\cdot}y_0+c{\cdot}z_0$.

We consider the point M' as origin and then we compute each normal distance to the plane of positions which includes the point M.

The cosecant of the angle ϕ between the slope of maximum inclination and a plane of positions is expressed as:

$$dd=\mathrm{cosec}\,\phi=\frac{\sqrt{a^2+b^2+c^2}}{a{\cdot}i+b{\cdot}j+c{\cdot}k} \tag{20}$$

In our algorithms, all the computations are done in double difference mode to eliminate common errors.

FIELD TESTS

In order to verify the algorithms developed for landslide monitoring under poor satellite visibility, we conducted realistic field tests by selecting a period of unfavourable geometry. The following describes the testing methodology and results and analysis of the field tests.

We simulated landslides by installing two GPS antennas on the roof of Furuno's research centre building. The roof faces north, and is inclined by 30°. The area was surrounded by reflective objects and therefore it was considered to be a high multipath environment. We collected data at 1 Hz for a period of an hour on each of two days – 24 and 25 December 2002. Two single frequency receivers were used. The GPS receivers used for the tests were a variation of the GN-77, Furuno's 12-channel GPS receiver for car navigation. The receiver's firmware was modified to obtain the output of carrier-phase measurements at a rate of up to 5 Hz. One of the antennas was slid along the slope by 1 cm during the observations.

Figure 3 shows the installation for our experiments. Two GPS antennas were placed on the roof of the building with a separation about 20 m. Figures 4 and 5 show the antennas of the reference and mobile stations, respectively. Figure 6 shows our set-up for simulating the slides. When the protruding wooden bar was removed, the antenna slid downwards by 1 cm.

Figure 3. Antenna installation on the roof

Figure 4. Reference antenna

Figure 5. Monitoring antenna

Figure 6. Set-up for simulating slides

Observations were made with an elevation mask angle of 15°. Figure 7 shows the satellite constellation for a whole day on the 25th of December. The roof faces north, but the sky plot clearly shows there were no satellites available in that direction. Figure 8 shows the satellite constellation during the test on that day. Four satellites (PRN 14, 30, 25, 6) were visible during the test. For our analyses, we used data spanning a period of about 40 min. (0:20-0:56 UTC for the 24th and 0:16-0:56 UTC for the 25th of December).

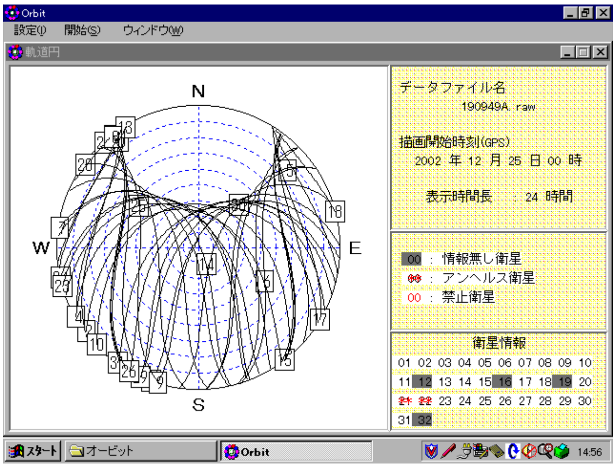

Figure 7. Satellite constellation for a whole day (25 December)

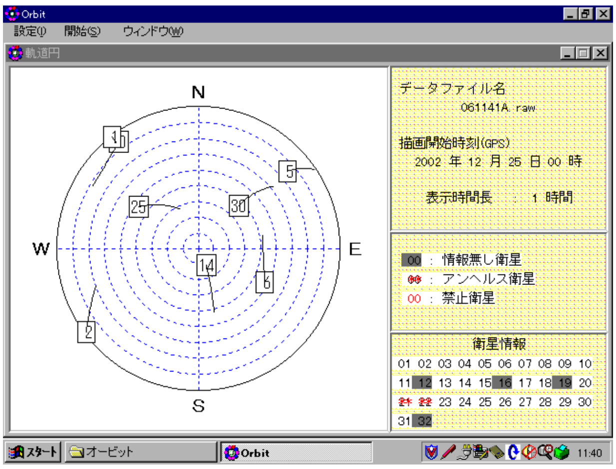

Figure 8. Satellite constellation during the test (25 December)

Figure 9 shows the results of conventional positioning using standard least-squares algorithms. We used all 4 satellites available during the test. We experienced large errors when the PDOP value surged to more than 20 for 13 minutes.

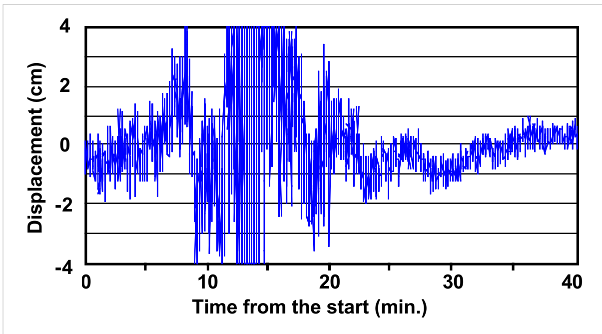

Figure 9. Results using a standard least-squares method

We estimated the displacement without differencing the positioning results, supposing that a landslide occurred along the slope in the direction of maximum inclination. Figure 10 shows the results of our new approach estimating the displacement (relative movement) instead of absolute movement. We used only two satellites (PRN 14 and 30) to obtain this result. This method allowed us to estimate the movement even for the period of unfavourable geometry. As the antennas were located in an area surrounded by reflective objects such as buildings, the results showed the presence of high multipath.

We used the data from the previous day to remove the multipath by correlating the multipath signature in the solutions. The results after removing the multipath are shown in Figure 11. Figure 12 shows the results of landslide detection using weighted data from 4 satellites. The results shown in Figures 9 and 12 are from the same data but using different processing methods.

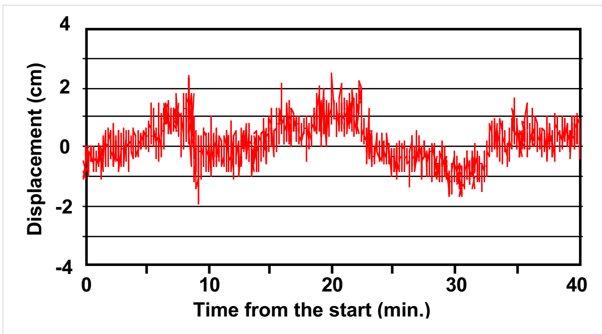

Figure 10. Results using the new approach with 2 satellites

In order to investigate the necessary time span of observations for detection of landslide precursory motion, we used moving averages of different window-width to determine the optimum smoothing for detecting the motion of an antenna. Using a window of 30 seconds (shown in blue in Figures 11 and 12), the maximum values of variation became less than 5 mm. A 30-second window allowed the detection of the slide. When 4 satellites are available, we can obtain even better results.

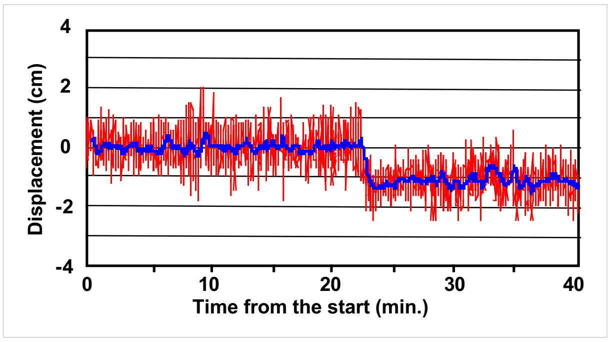

Figure 11. Results using the new approach with 2 satellites after multipath removal

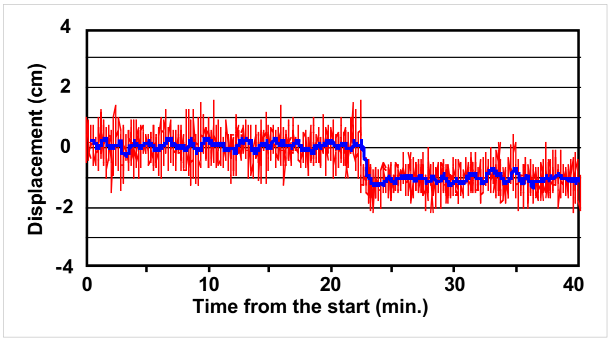

Figure 12. Results using the new approach with 4 satellites after multipath removal

Table 1 shows a summary of the results obtained using 2 satellites. Table 2 shows the same but using 4 satellites. The values in the tables are in cm. The results obtained using a 15-second window-width seems to be sufficient for this data. The symbols μ and σ represent the mean and RMS value (1 sigma), respectively

Table 1. Summary of the displacement estimate after removing the multipath using 2 satellites

	Before the slide			After the slide		
	Raw	15 s	30 s	Raw	15 s	30 s
Min	-1.80	-0.43	-0.26	-2.30	-1.61	-1.52
Max	2.00	0.71	0.50	0.60	0.42	0.29
μ	0.03	0.03	0.02	-1.12	-1.11	-1.10
σ	0.53	0.19	0.13	0.48	0.25	0.23

Table 2. Summary of the displacement estimate after removing the multipath using all 4 visible satellites

	Before the slide			After the slide		
	Raw	15 s	30 s	Raw	15 s	30 s
Min	-1.50	-0.51	-0.26	-2.20	-1.47	-1.34
Max	1.60	0.52	0.33	0.40	0.33	0.21
μ	0.06	0.06	0.06	-1.06	-1.05	-1.04
σ	0.46	0.18	0.12	0.39	0.18	0.17

We have shown that we can estimate the displacement (the actual change in position along the slope due to the "landslide") from observations of just two satellites when the direction of the movement is known. In this case, the slope is another line of position. This assumption could be later replaced with a landslide outbreak model for a particular site.

CONCLUSIONS

We have developed and investigated a new method for detecting landslides under low satellite visibility – a common occurrence as landslide sites are often located along mountain slopes with obscured views of the whole sky. We estimated the displacement without differencing the positioning results, supposing that a landslide occurs along the slope in the direction of maximum inclination.

Field tests were carried out by simulating precursory landslide displacements of 1 cm. Multipath was removed using the data from the previous day. We used moving averages of different window-widths. Using a window of 30 seconds, the variation became less than 5 mm and allowed the detection of the slide.

The algorithms we developed allowed continuous landslide monitoring for low visibility observations with only 2 satellites. The positioning results can be improved with a weighted mean technique when more satellites are available.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the help and cooperation of Mr. Watanabe and Ms. Kamo for the development of the system prototype and conducting the field experiments.

REFERENCES

Ashkenazi, V., R. Bingley, A. Dodson, N. Pena & T. Baker (1998). GPS monitoring of vertical land movements in the UK, The 11th International Technical Meeting of the Satellite Division of the U.S. Institute of Navigation, Nashville, Tennessee, U.S.A., September, pp. 99-107.

Duffy, M.A. & C. Whitaker (1999). Deformation monitoring scheme using static GPS and Continuous Operating Reference Stations (CORS) in California, The 12th International Technical Meeting of the Satellite Division of the U.S. Institute of Navigation, Nashville, Tennessee, U.S.A., September, pp. 63-70.

Moore, T., G. Close & R. Moore (2000). RiGHt: River level monitoring using GPS heighting, The 13th International Technical Meeting of the Satellite Division of the U.S. Institute of Navigation, Salt Lake City, Utah, U.S.A., September, pp. 1840-1844.

Leick, A. (1995); GPS Satellite Surveying - Second Edition, John Wiley & Sons, Inc., New York, NY, 560 pp.

Strang, G. & K. Borre (1997). Linear Algebra, Geodesy, and GPS, Wellesley-Cambridge Press, Wellesley, MA, 624 pp.