ISRM Suggested Method for Monitoring Rock Displacements Using the Global Positioning System (GPS)

Norikazu Shimizu, Shinichiro Nakashima, and Tomohiro Masunari

1 Introduction

Monitoring rock displacements is important to understanding the behavior of a rock mass and to assessing its stability. The Global Positioning System (GPS) is a satellite-based positioning system developed in the USA; it was established as a navigation system and then as a method for long baseline surveys (e.g., Hoffman-Wellenhof et al. 2001; The Survey Advisory Board and the Public Land Survey Office for State of Washington Department of Natural Resources 2004; Misra and Enge 2006). GPS has the potential to monitor three-dimensional displacements over an extensive area with high accuracy. It began to be used for displacement monitoring in the mid-1980s in the fields of civil and mining engineering, and other related fields (e.g., Chrzanowski and Wells 1988; Burkholder 1988, 1989). Since then, practical applications have been performed by many researchers (e.g., Hudnut and Behr 1998; Gili et al. 2000; Malet et al. 2002; Kim et al. 2003; Taşçi 2008), and some guidelines have been published for displacement (deformation) monitoring (e.g., US Army Corps of Engineers 2002; Vermeer 2002; Bond 2004).

This Suggested Method describes a method for monitoring rock displacements using GPS, focusing on baselines which are <1 km in length. The devices, the procedure, and examples of applications are illustrated, together with methods of data correction for improving the measurement results. The terminology (glossary) about GPS used in this Suggested Method is listed in Appendix "Terminology".

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2 Scope

There are two methods for using GPS. One method is point positioning for navigation. The three-dimensional absolute coordinates of latitude, longitude, and height of a measurement point are obtained. The accuracy of the point positioning is approximately a few meters to ten meters or more.

The other method is relative positioning. Relative positioning using carrier phase measurements was established for precise surveying. It provides the three-dimensional relative coordinates between two points with an accuracy of millimeters to centimeters. Therefore, relative positioning is used for monitoring rock displacements. By continuously observing the coordinates of measurement points, the displacements are obtained as changes in the coordinates. The standard deviation of the measurement can be a few millimeters, when the baseline length is <1 km, and the installation and data corrections are conducted carefully.

The conventional geotechnical measurement devices, i.e., extensometers, inclinometers, etc., are usually available only for limited areas of several tens of meters at most. Besides, it is difficult to measure three-dimensional displacements with them. The advantage of GPS is that it can easily provide three-dimensional displacements with high accuracy over an extensive area.

3 Outline of GPS

GPS was firstly developed as a navigation system in the early 1970s. It was also established as a method for precise long baseline surveying in the late 1970s to early 1980s. The U.S. Department of Defense controls the system (Hoffman-Wellenhof et al. 2001; Misra and Enge 2006).

GPS is composed of three segments, namely, (1) the space segment, (2) the control segment, and (3) the user segment (Fig. 1). The space segment is composed of

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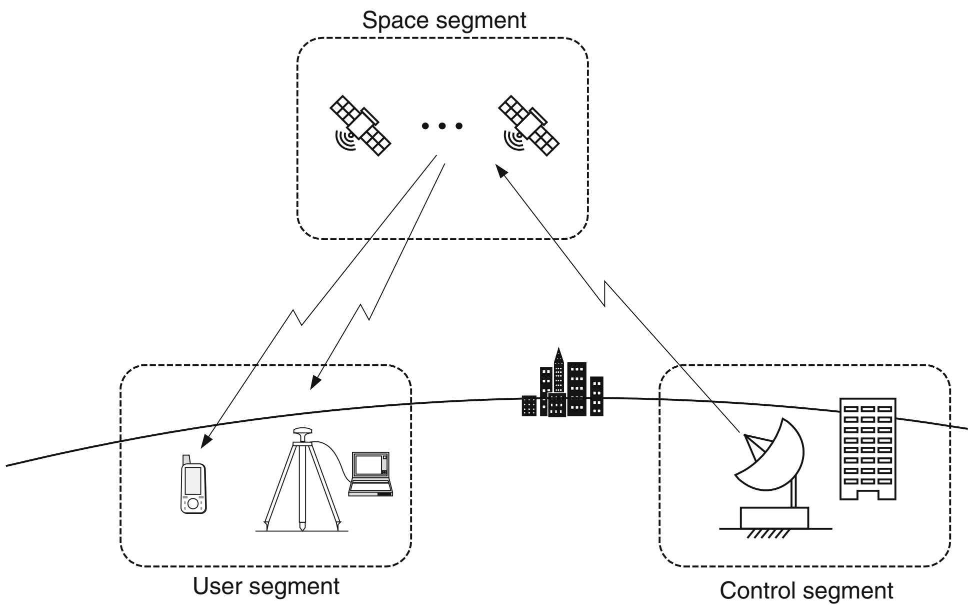


Fig. 1 System architecture of GPS

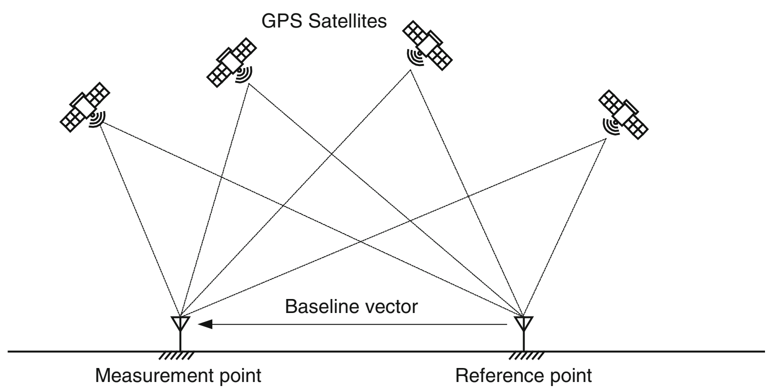


Fig. 2 Relative positioning of GPS

artificial satellites. Currently, 31 satellites are in operation. The satellites fly in nearly circular orbits for periods of sidereal hours (11 h and 58 min). Each satellite continuously transmits the signals for positioning. The control segment consists of a worldwide network of ground facilities. Its tasks are to track the satellites in orbit, to time the synchronization of the satellites, to upload the data messages from the satellites, etc. Both the space and the control segments are managed by the USA. The user segment consists of receiver equipment and a related system. Anyone who prepares the receiver can use GPS at any time.

When users conduct relative positioning for monitoring rock displacements, an antenna with its receiver is set on the reference point and a second antenna is set on the measurement point (Fig. 2). If users set antennas at a number of measurement points, the displacements are simultaneously obtained at each point.

The static method, which is one method of relative positioning, will yield the most reliable and precise results in GPS positioning, and, thus, is the method that is recommended for monitoring quasi-static (not dynamic) rock displacements.

4 Devices

4.1 General

In order to conduct displacement monitoring with the static method of relative positioning, which uses the carrier phase of the signal, at least two sets of antennas and receivers, data downloading software and baseline analysis (post-processing) software, and a computer are needed.

4.2 Antennas and Receivers

The antennas and receivers for the relative positioning, using the carrier phase, are commercially available (Fig. 3). Figure 3a shows an antenna set, consisting of an antenna, a

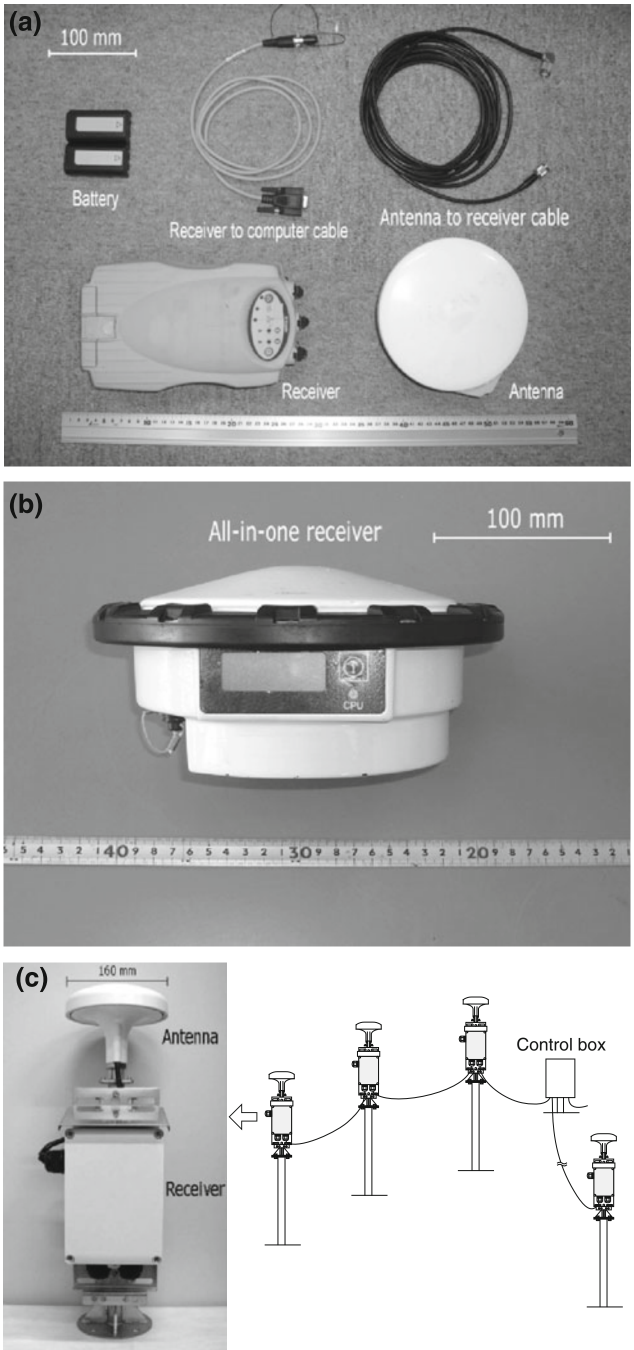


Fig. 3 Antenna and receiver: **a** separate type, **b** all-in one type, **c** system for displacement monitoring

receiver, and cables, which were originally developed for precise surveying or geodesy use, but they can also be applied for monitoring displacements. An all-in-one type of antenna and receiver is shown in Fig. 3b, while an automatic monitoring system is shown in Fig. 3c.

The L1 phase receiver is selected for monitoring displacements of short baseline length less than a few kilometers. It is desirable to use antennas designed to mitigate the multipath effect. The standard accuracy (root mean squares) of the positioning is at least 5 mm + 1 ppm $\times$ D and 10 mm + 1 ppm $\times$ D for horizontal and height directions, respectively. D is the distance of the baseline length in kilometers. Standard commercial receivers satisfy this accuracy. Better accuracy can be expected under good observation conditions.

The receiver continuously measures the carrier phase of the signal and receives the navigation data transmitted from the satellites and saves them in the memory. Stable electric power must be supplied to the receivers by an AC power supply and/or a 12 V DC battery.

4.3 Software and Computer

Software for downloading, logging, and processing the GPS data is needed for retrieving the data files from the receivers. Baseline analysis software is also required for determining the three-dimensional relative coordinates between two points. The software is provided by the manufacturer of the receiver. The software is generally not difficult to operate.

The format for the GPS data usually depends on the type of receivers or the manufacturers. GPS observation data can be converted to the Receiver INdependent Exchange (RINEX) format. If users are going to analyze data obtained from the receivers of different manufacturers during the same observing session, all the data should be converted to the RINEX format. Almost all GPS processing software provided by manufacturers can convert the received data to the RINEX format.

Computer equipment (standard personal computer) is used to run the software for data downloading and the baseline analysis.

4.4 Automatic Monitoring System

When standard receivers for surveys are used for monitoring displacements, the users are usually required to download the GPS data from the receivers, analyze the data to obtain the coordinates of the measurement points, and calculate the displacements for each session. If such a process is conducted manually, it is inconvenient and ineffective for continuous monitoring. In order to overcome this troublesome process, automatic monitoring systems can be designed and applied for monitoring displacements (e.g., Shimizu et al. 1996; Manetti and Glisic 2003; Masunari et al. 2003; Zhang et al. 2012).

5 Procedure

5.1 General

Before starting the fieldwork of the monitoring procedure, the number of visible satellites is predicted by the software provided by the manufacturer of the receiver. Each receiver must simultaneously observe at least four satellites.

The epoch interval (measurement interval or logging rate of the carrier phase) and the session length (the observing duration of the carrier phase measurements) are important user-defined parameters for precise monitoring (Table 1). The elevation mask (or mask angle) is another user-defined parameter (see Sect. 5.3).

The outline of the procedure for monitoring displacements by the static method is given as follows:

1. Set up the receiver(s) at the measurement point(s) and the reference point (Fig. 2).
2. Measure the carrier phase of the signal every epoch interval and receive the navigation data at every measurement point(s) and the reference point from the same satellites simultaneously. The measured carrier phase and data are saved automatically in the memory of the receivers. The receivers perform this process automatically.
3. Download data from all the receivers to a computer.
4. Select the downloaded data of the reference point and the measurement point(s) at which the user would like to know the displacements, and conduct a baseline analysis to obtain the relative coordinates of the measurement point(s) from the reference point.
5. Repeat Steps (3) and (4) for the succeeding observation session.
6. Calculate the changes in the coordinates at each measurement point between the two sessions, and then obtain the displacements.

5.2 Installation of Antennas and Receivers

The locations of the measurement points are determined according to the purpose of the monitoring project, i.e., monitoring the stability of slopes and structures, etc. The reference point should be selected on firm ground.

Antennas are set up above the measurement point(s) and the reference point by a tripod/pillar (Fig. 4). It is noted that GPS provides the coordinates of the antenna phase center. If an antenna is firmly fixed at a measurement point on the ground surface by a tripod/pillar and anchors, the displacement of the antenna can be supposed to coincide with one of the measurement points. It is recommended that the antennas be firmly fixed on the ground to mitigate errors due to the uncertainty of the antenna phase center. This is very important for precise monitoring with millimeter accuracy. When the height of the measurement point on the ground is needed, the antenna height must be measured in order to adjust the difference in height between the antenna phase center and the measurement point.

Multipath and signal disturbances can be significantly reduced by carefully selecting the site for each antenna in order to avoid reflective objects and signal obstructions, i.e., walls, fences, trees, etc.

Table 1 Typical values of user-defined parameters for displacement monitoring

Observation parameters	Value
Epoch interval	5–30 s
Session length	45 min to 3 h
Elevation mask (mask angle)	15°

5.3 Observation

The epoch interval and the session length affect the accuracy of the positioning. The epoch interval is typically 5–30 s, and the session length is normally 45 min to 3 h (The Survey Advisory Board and the Public Land Survey Office for State of Washington Department of Natural Resources 2004). If users take a 30-s epoch and a 1-h session under 5–6 observable satellites, the accuracy (the standard deviation) will be 2–3 and 3–4 mm or better in horizontal and height directions, respectively, for a short baseline of <1 km in length. Since a baseline analysis is conducted every session, displacements are obtained every session period. When the observation session is 1 h, the displacements are measured every hour.

The elevation mask (or mask angle) is another user-defined parameter. Signals transmitted from low-elevation satellites are strongly affected by tropospheric delays due to water vapor in the troposphere, multipath effects, and signal disturbances due to objects (walls, trees, mountains, etc.) near the earth's surface. In order to reduce such influences, the elevation mask is typically set to 15° from the horizontal plane so that the receiver cuts the signals from the low-elevation satellites.

Setting the user-defined parameters (Table 1), receivers continuously track the GPS signals and measure the carrier phase at every epoch. The data are saved in the memory of each receiver and downloaded into a computer for a baseline analysis.

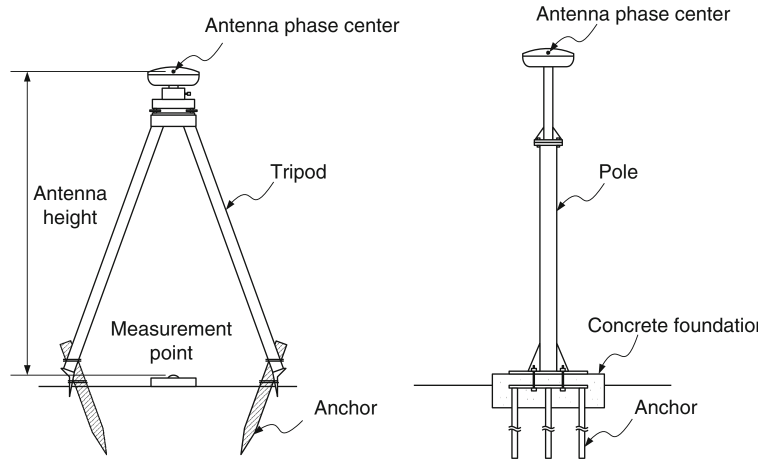


Fig. 4 Examples of the installation of an antenna at a measurement point by a tripod or pole

5.4 Analysis

The relative coordinates of the measurement point(s) from the reference point are determined by a baseline analysis using the GPS data collected from the receivers. The three-dimensional relative coordinates of a measurement point, i.e., latitude, longitude, and height, are provided in the 1984 World Geodetic System (WGS84), which is a coordinate system used in GPS. If users need to represent the coordinates in another system, they can convert them to the other coordinate system.

Repeating the baseline analysis for the succeeding observation session, displacements at a measurement point are obtained by taking the difference in the coordinates between the two sessions by supposing that the reference point does not move.

If users need to monitor displacements continuously, it is recommended that the data be downloaded and a baseline analysis conducted automatically.

In order to achieve precise monitoring, error-correction methods should be applied to improve the monitoring results.

5.5 Error Correction

Measurement results generally include random errors (noise) and bias errors. Random errors arise from random fluctuations in the measurements. On the other hand, typical bias errors in GPS monitoring are tropospheric delays, multipath effects, and other signal disturbances (Appendix "Sources of Error"). Since both random and bias errors affect the monitoring quality, it is recommended that appropriate error-correction methods be applied to reduce such errors.

5.5.1 Random Errors

Figure 5 shows the three-dimensional displacements originally obtained by the baseline analysis in the local coordinate system (the horizontal X and Y directions, and the height direction) as an example of GPS displacement monitoring results. The results denoted by the circles are scattered due to random errors. The standard deviations (denoted by σ in Fig. 5) are 2.4, 1.2, and 3.5 mm in the directions of X, Y, and height, respectively. The baseline length and the height difference between the two antennas were 142 and 13 m, respectively. The epoch interval and the session length were 30 s and 1 h, respectively.

The solid lines are drawn as smoothing results, which were obtained by applying the trend model (Kitagawa and Gersch 1984; Appendix "Fundamental Equations for Relative Positioning") to the original results. It is found that the trend model can yield good estimates from the original measurement results including random errors (Shimizu 1999; Shimizu and Matsuda 2002). It is recommended that users adopt an adequate method to reduce random errors.

5.5.2 Bias Errors

In the case of a short baseline length, tropospheric models using meteorological data (atmospheric pressure, temperature, and humidity), which are measured near the measurement points, are effective in reducing the bias due to tropospheric delays in the monitoring results. The tropospheric models, for example, the Saastamoinen model and the modified Hopfield model (Misra and Enge 2006; Hoffman-Wellenhof et al. 2001), are usually installed in the baseline analysis software. Users can select a model and input the measured meteorological data around the measurement area for this purpose.

Figure 6 shows the originally monitored three-dimensional displacements for a complete year. The baseline length and the height difference between the two antennas were 252 and 106 m, respectively. The epoch interval and the session length were 30 s and 1 h, respectively. The displacement in height increased from May to August and then decreased from August to October, although the monitoring area was stable and there must not have been any displacements during the monitoring period.

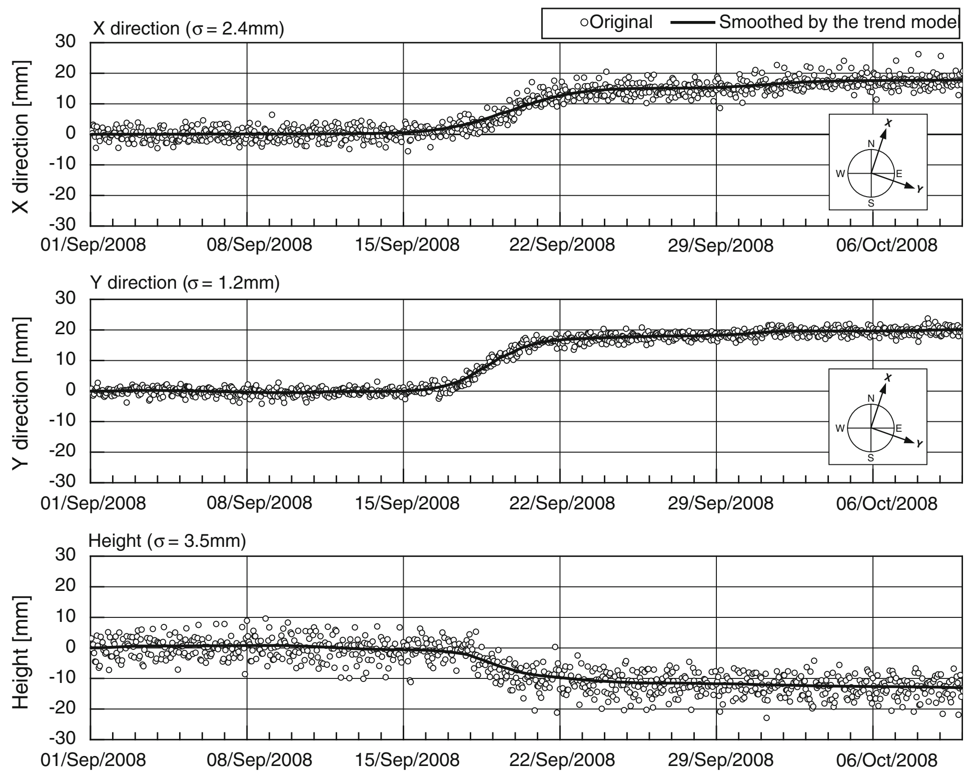


Fig. 5 Example of original monitoring results and estimated displacements using the trend model (baseline length: 142 m and height difference: 13 m) (Matsuda et al. 2012)

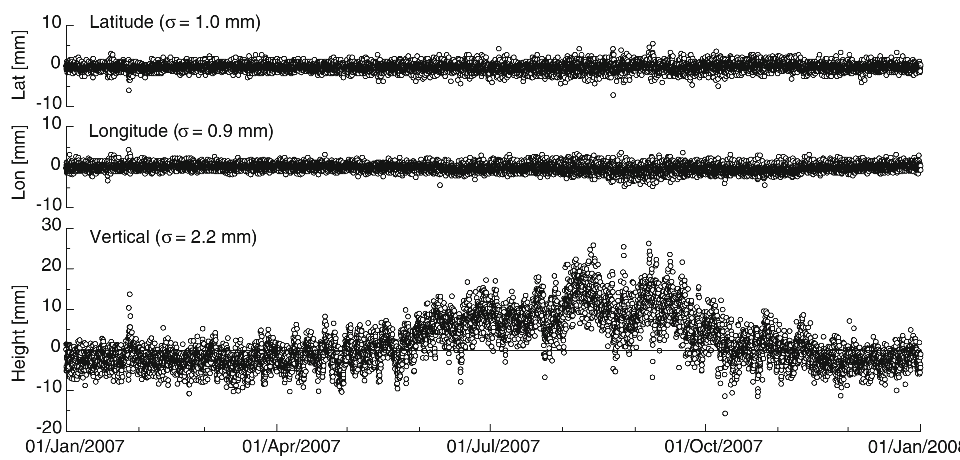


Fig. 6 Example of displacement monitoring results affected by tropospheric delay (baseline length: 252 m and height difference: 106 m) (Nakashima et al. 2012)

The above phenomenon is usually seen in cases where the height difference between the reference and the measurement points is large.

Figure 7 shows the measured temperature, the relative humidity, the atmospheric pressure, the estimated partial pressure of the water vapor, and the zenith tropospheric delay (per unit height difference) using the modified Hopfield model (Appendix "Tropospheric Model"). It is found that the transition in tropospheric delay over a year is quite similar to that of the displacements in height. This might indicate that the tropospheric delay affects the displacement in height.

In order to correct the tropospheric delay, the modified Hopfield model was adopted for the baseline analysis using the measured temperature, the relative humidity, and the atmospheric pressure. The corrected results are shown in Fig. 8. Figure 9 shows a comparison between the original and the corrected monitoring results, which are smoothed by the trend model. It is clear that the movement in the original displacements in height from May to November 2007, as well as daily scatters, have been almost eliminated (Nakashima et al. 2012). On the other hand, the horizontal displacements are hardly subjected to the influence of the tropospheric delay (see Figs. 7, 8). The bias caused by the tropospheric delay

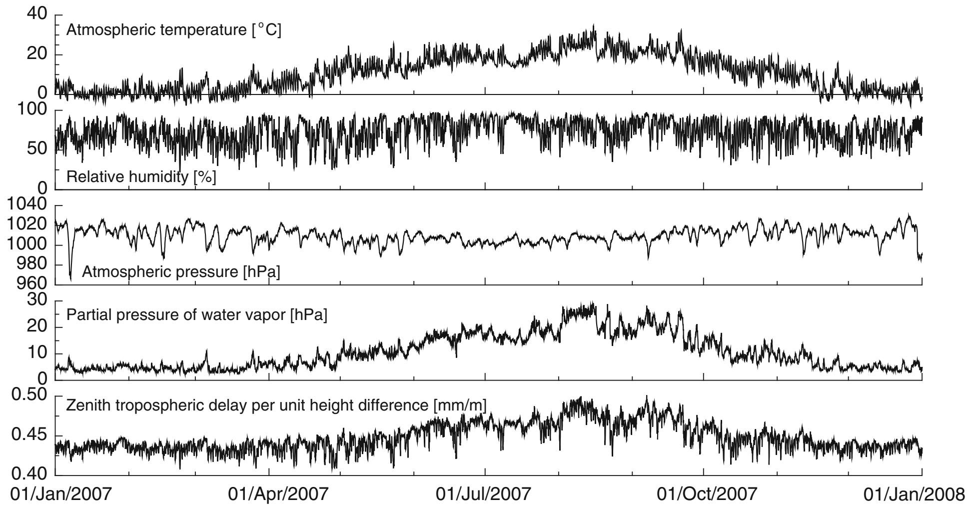


Fig. 7 Measured temperature, relative humidity and atmospheric pressure, and estimated partial pressure of water vapor and zenith tropospheric delays (Nakashima et al. 2012)

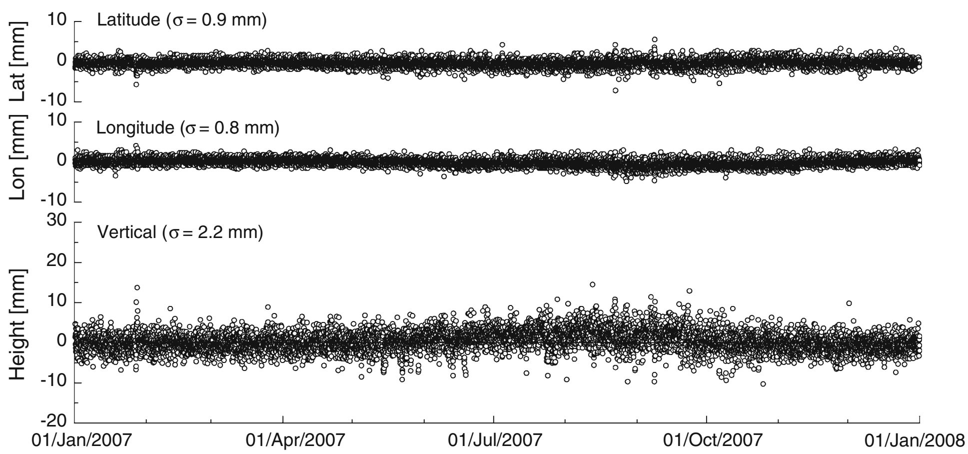


Fig. 8 Displacement monitoring results corrected by tropospheric delays using the modified Hopfield model (Nakashima et al. 2012)

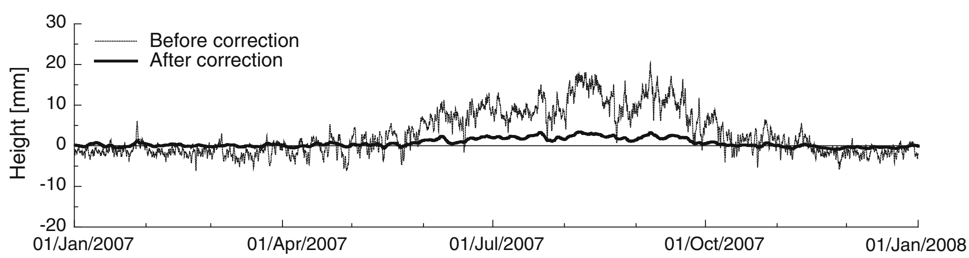


Fig. 9 Comparison between original and corrected monitoring results for tropospheric delay (Nakashima et al. 2012)

tends to be proportional to the height difference between the reference and the measurement points. The amount of bias is 10–20 mm for a height difference of about 100 m during a period of a year, as shown in Fig. 6. It is recommended that users correct the bias due to the tropospheric delays.

Another source of bias is the signal disturbance due to obstructions above antennas. When there are unavoidable obstructions (mainly trees) above the antennas, it is a good practice to analyze the data without the signals transmitted from the satellites behind the obstructions.

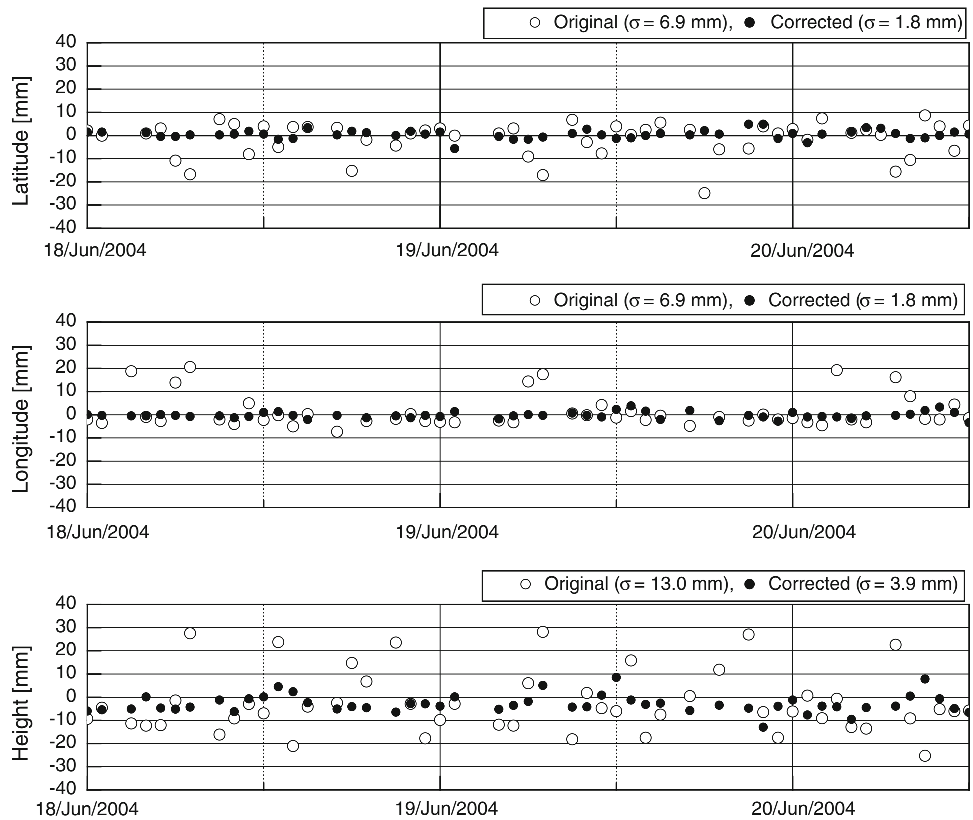


Fig. 10 Example of original and corrected monitoring results without using the data from the satellites moving behind the trees (baseline length: 266 m and height difference: 7 m) (Shimizu et al. 2011)

Figure 10 shows the monitoring results at a point on a slope where there were trees on the upper parts of the slope as obstructions. The baseline length and the height difference were 266 and 7 m, respectively. The epoch interval and the session length were 30 s and 1 h, respectively. The circles in Fig. 10 represent the original results obtained from the baseline analysis. They are seen to scatter periodically.

Figure 11 shows satellite paths, drawn in the sky photo above the antenna, for a session in which the monitoring results were largely scattered. The numerals represent the satellite numbers. The antenna received signals from all the satellites, except no. 24, which was moving behind the slope (its signal could not reach the antenna). The signals of satellite nos. 4 and 20 came through the trees and were disturbed. Therefore, the baseline analysis was conducted without using the data from satellite nos. 4, 20, and 24 moving behind the trees or the slope during the whole monitoring period.

The corrected results were obtained as the bullets shown in Fig. 10. The scattered results were significantly improved. The standard deviations in the horizontal and height displacements improved from 6.9 and 13.0 mm to 1.8 and 3.9 mm, respectively. It is clear that the analysis without the data from the satellites moving behind the obstructions is effective in reducing errors and in improving

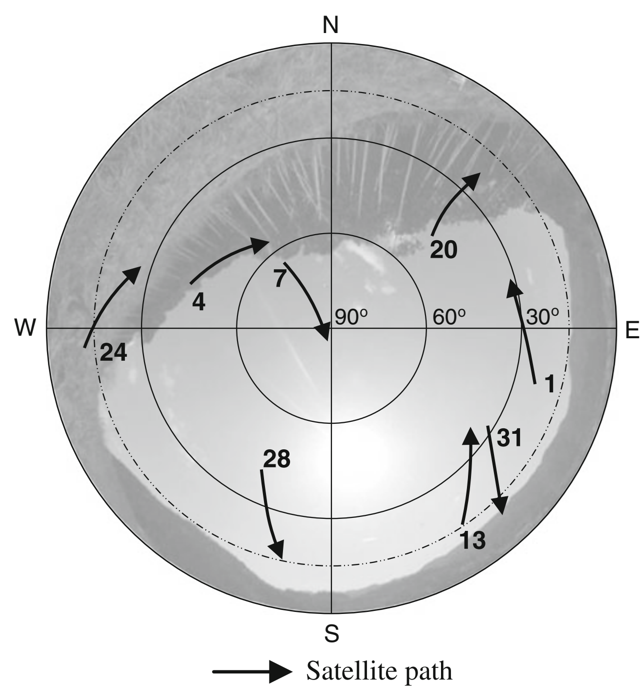


Fig. 11 Satellite paths on a sky photo above the antenna during a session (1 h) for scattered results (Shimizu et al. 2011)

the accuracy of the GPS displacement measurements (Shimizu et al. 2011). Users can conduct the process in a baseline analysis.

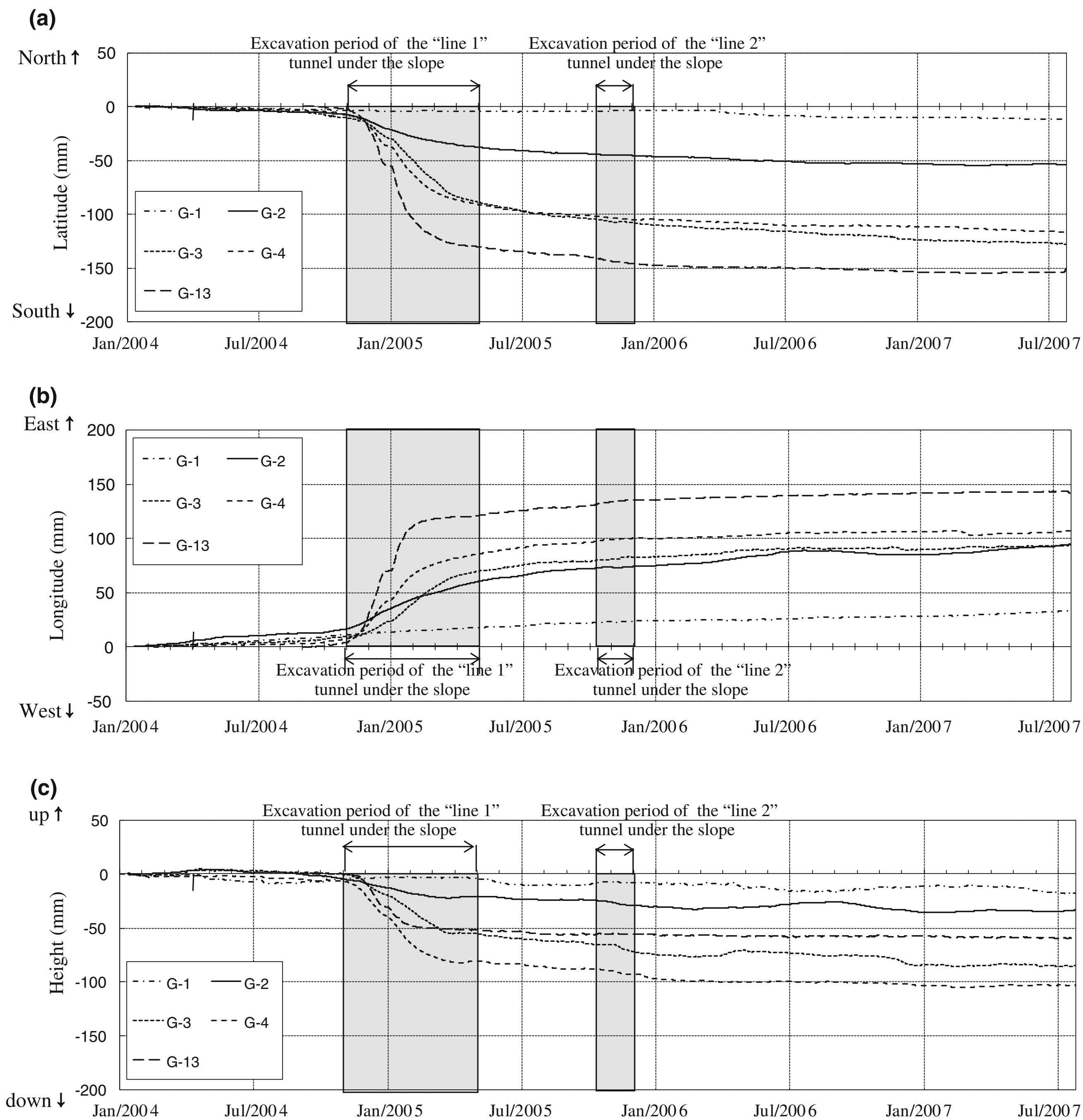


Fig. 12 Measurement results of displacements on a landslide slope due to tunnel excavations (Hirano et al. 2011)

5.6 Examples of Practical Application

Examples from practical applications of GPS to monitoring landslide displacements due to tunnel excavations are shown in Figs. 12 and 13. Two tunnels, "line 1" and "line 2", were constructed just beneath a landslide slope. Five measurement points, G-1 to G-4 and G-13, were installed on the slope. The reference point was located on stable ground about 400 m away from the slope. An automatic monitoring system was used in this case. The epoch interval and the session length were 30 s and 1 h, respectively. The mask angle was given as 15°.

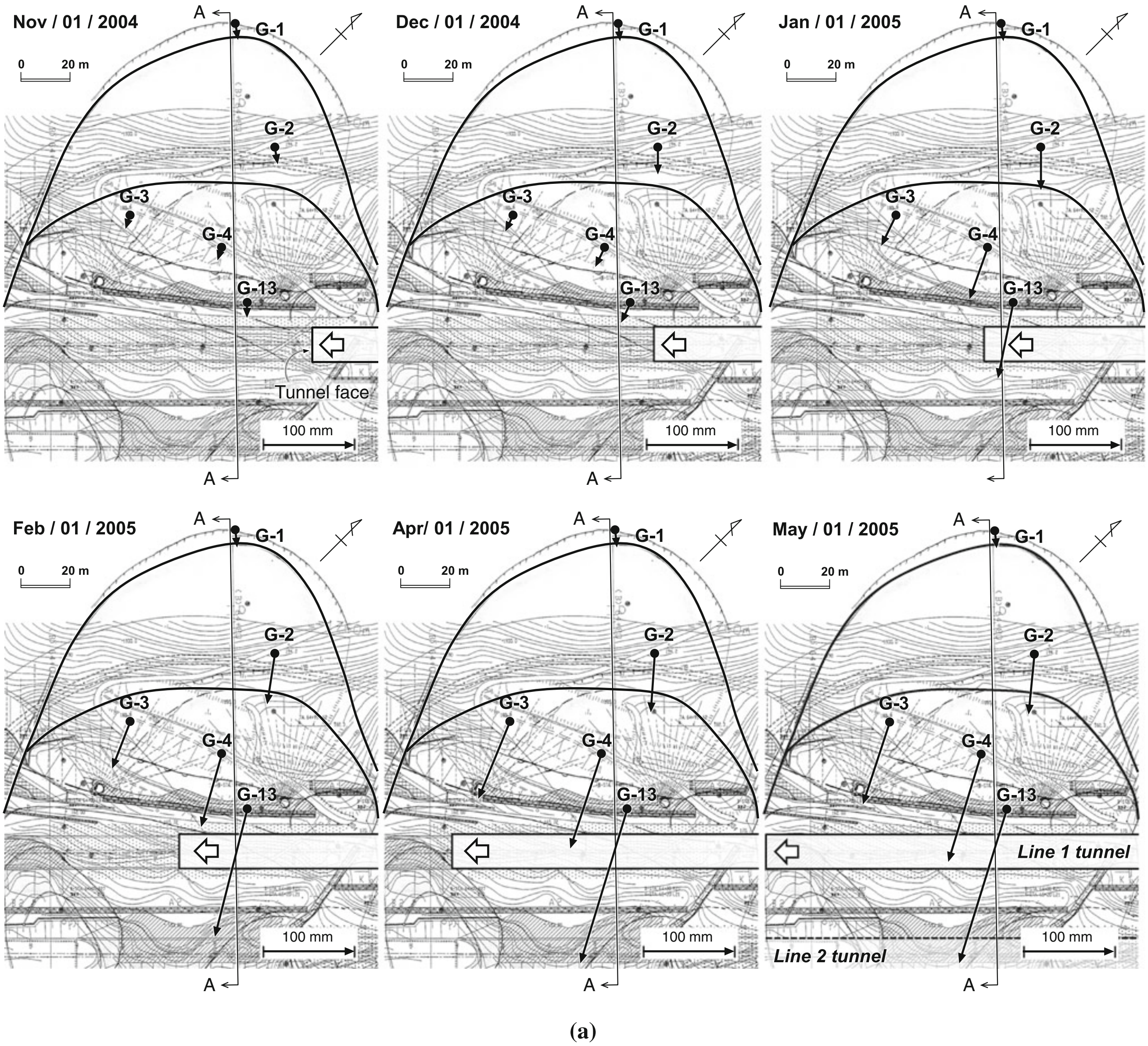


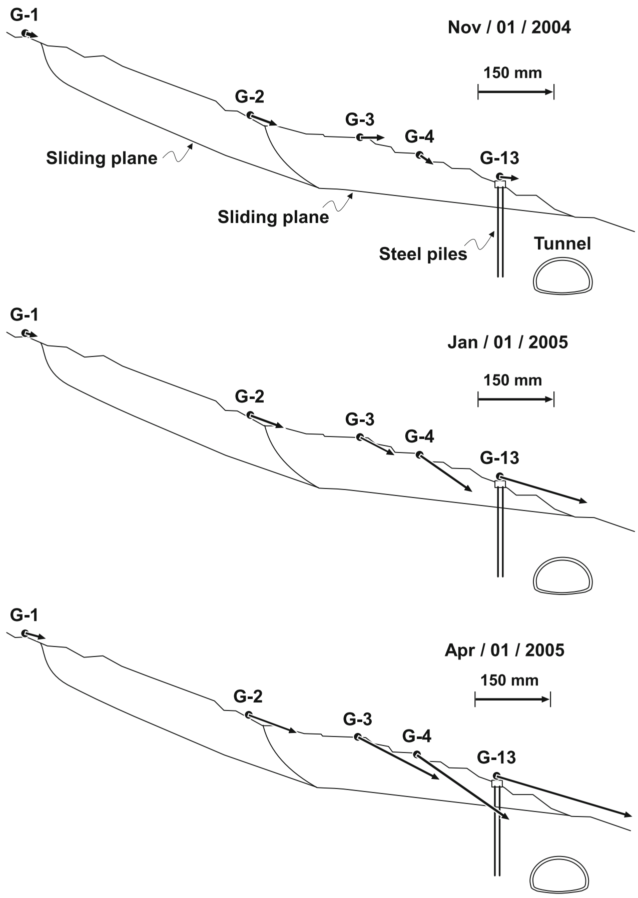
Fig. 13 Displacement vectors on a landslide slope due to tunnel excavations: **a** plane view and **b** vertical section (Hirano et al. 2011)

The three-dimensional displacements were automatically and continuously monitored for 4 years, as shown in Fig. 12. The displacements of all the measurement points, except G-1 located outside the landslide block, increased as the "line 1" tunnel was approaching. The "line 2" tunnel did not affect the displacement behavior of the slope much in comparison to the "line 1" tunnel. Figure 13 shows the transition in the displacement vectors in the plane view and in the vertical section. It is easy to recognize how the tunnel excavations influenced the landslide behavior and how the slope became stable after the tunnels passed through this area.

6 Report

6.1 General

Reports on GPS monitoring are important for evaluating the quality of the measurements, for interpreting the monitoring results, and for accumulating experience. Since the results of GPS monitoring depend on the equipment, the observation parameters, the software, and the error-correction methods, details of those items should be reported. Reports may be prepared in hard copy or by means of an electronic medium.



(b)

Fig. 13 continued

6.2 Installation Reports

Installation reports should contain the following items:

(a) Antennas and receivers (type and manufacturer)
(b) Method of mounting antenna(s) at measurement and reference point(s) (pole, tripod, foundations, etc.)
(c) Antenna heights (if needed)
(d) Environment (objects around antenna(s) and obstructions above antenna(s))
(e) Baseline analysis software (name and version and manufacturer or developer)
(f) Format of the GPS data
(g) Any additional comments.

6.3 Monitoring Reports

Monitoring reports should contain the following items:

(a) Location of measurement points
(b) Observation parameters: epoch interval (seconds), session duration (hours), and mask angle (degrees)
(c) Observing times (start and finish)
(d) Monitoring results (displacements represented in time series, vectors, etc.)
(e) Coordinate system (WGS84 and others)
(f) Error-correction methods (name of statistical methods, tropospheric models, and other methods)
(g) Meteorological measurement results (measurement place, atmospheric pressure, temperature, and humidity, if needed)
(h) GPS observational data files (save in DVD or other type of medium)
(i) Output files of baseline analysis (save in DVD or other type of medium)
(j) Any additional comments.

Acknowledgments The authors referred to several texts, guidelines, and home pages, in addition to those listed in the references here, for the fundamental and applied GPS, in order to prepare this Suggested Method. They wish to express their sincere appreciation to the authors of all the referenced publications.

Appendix

Sources of Error

For any measurement device, it is important to know the source of the errors and the corresponding correction methods. Sources of errors in positioning by GPS are summarized in Table 2. The errors can be classified into three groups, namely, errors related to satellites, errors associated with the propagation medium of the signal from the satellites to the receivers, and errors occurring in the vicinity of the antenna by receiver noise and signal disturbances.

Errors related to satellites are satellite ephemeris and clock parameters, which are broadcast by satellites in the navigation message. The control segment, managed by the USA, is responsible for correcting these errors.

The GPS signals are affected by the ionosphere and the troposphere through which they travel from the satellites to a receiver (Fig. 14). Ionospheric delays occur as a result of refractive effects, due to the total electron content, when signals propagate through the ionosphere extending from a height of about 50 to 1,000 km above the earth. These errors can be substantially removed by using a dual-frequency (L1/L2) receiver in the relative positioning. When a baseline length between two antennas is less than a few kilometers, it will be mitigated by taking the difference in carrier phases at two points to eliminate their common-mode errors (Appendix "Fundamental Equations for Relative Positioning"). A single-frequency (L1) receiver is enough, therefore, for use with a short baseline length, as described in this Suggested Method.

Table 2 Sources of errors

Sources
Satellite clock errors
Satellite ephemeris errors
Ionospheric propagation delays
Tropospheric propagation delays
Multipath
Receiver noise
Electrical phase center of antennas
Obstructions

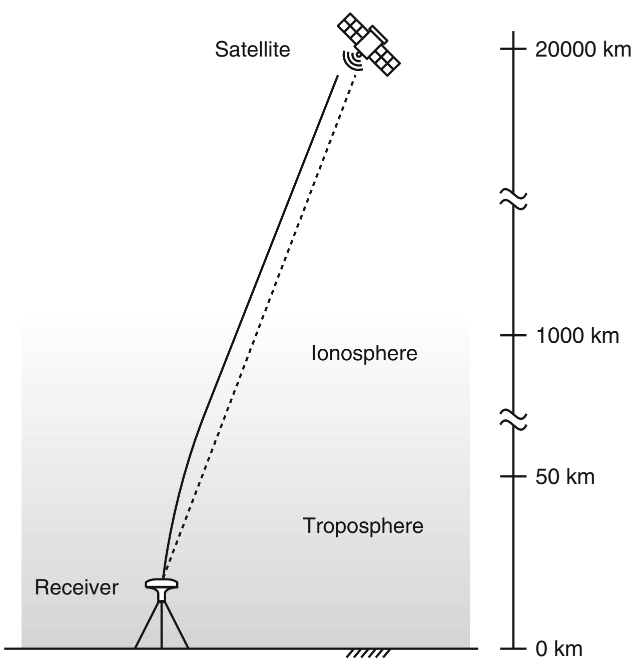


Fig. 14 Refraction of GPS signals in the atmosphere

Tropospheric delays occur as a result of refractive effects, due to the air density, when signals propagate through the troposphere extending from a height of about 0 to 11 km above the earth. The air density is a function of the pressure of dry gases and water vapor. This means that the measurement results are subject to the influence of the meteorological conditions along the signal propagation path. When the difference in height between antenna points is more than a few tens of meters, the bias of the tropospheric delays may not be able to be ignored in precise monitoring with an accuracy at the millimeter level, even for short baseline lengths. It is recommended that users employ an appropriate model (modified Hopfield model, Saastamoinen model, etc., Hoffman-Wellenhof et al. 2001; Misra and Enge 2006) to correct such tropospheric delays in order to realize precise monitoring. Tropospheric models are usually installed in the baseline analysis software. Users can select a model with the measured meteorological data for reducing these errors.

Multipath and signal disturbances, caused by the obstruction around antennas, and receiver noise affect the measurement results in the vicinity of the antenna.

Multipath is the phenomenon of a signal reaching an antenna via two or more paths; it is mainly caused by signal reflections from objects (buildings, walls, fences, etc.) and from the ground surface in the vicinity of the antennas. GPS antennas are designed to reduce the effect of multipath, and antenna/receiver manufacturers have developed and implemented proprietary techniques for dealing with it. Naturally, the primary defense against multipath is to position the antennas away from any reflective objects and to set a mask angle for cutting multipath signals.

Obstructions above an antenna (trees, slopes, etc.) may block the antenna signal reception or may cause a disturbance to the signals, and then overhead obstructions become error sources in GPS displacement monitoring. Antennas should be located in areas with a sufficiently open sky. When there are unavoidable obstructions (mainly trees) above the antennas, it is a good practice to analyze the data without the signals transmitted from the satellites behind the obstructions.

Carrier phase measurements are affected by random measurement errors due to receiver noise. Generally, receivers can measure the carrier phases of signals with a precision of 0.5–1 % of a cycle. Since the wavelength of L1 is about 19 cm, measurement errors due to receiver noise will be estimated at 1–2 mm. Users can adopt an adequate method (e.g., statistical model) to reduce this type of random error.

Fundamental Equations for Relative Positioning

The fundamental equation for relative positioning is described as follows (Misra and Enge 2006). The carrier phase of the signals transmitted from satellite k at measurement point mi is expressed as follows (Fig. 15):

$$\phi_{mi}^{k} = \frac{r_{mi}^{k} + I_{\phi} + T_{\phi}}{\lambda} + \frac{c\left(\delta t_{mi} + \delta t^{k}\right)}{\lambda} + N_{mi}^{k} + \varepsilon_{\phi_{mi}}^{k} \qquad (1)$$

where r_{mi}^{k} is the distance between measurement point mi and satellite k as follows:

$$r_{mi}^{k} = \sqrt{(x_{mi} - X_k)^2 + (y_{mi} - Y_k)^2 + (z_{mi} - Z_k)^2} \qquad (2)$$

(x_{mi}, y_{mi}, z_{mi}) and (X_k, Y_k, Z_k) are the coordinates of measurement point mi and satellite k, respectively. I_{ϕ} is the ionospheric delay, T_{ϕ} is the tropospheric delay, and λ is the wavelength of the signal. δt_{mi} and δt^{k} are the biases of

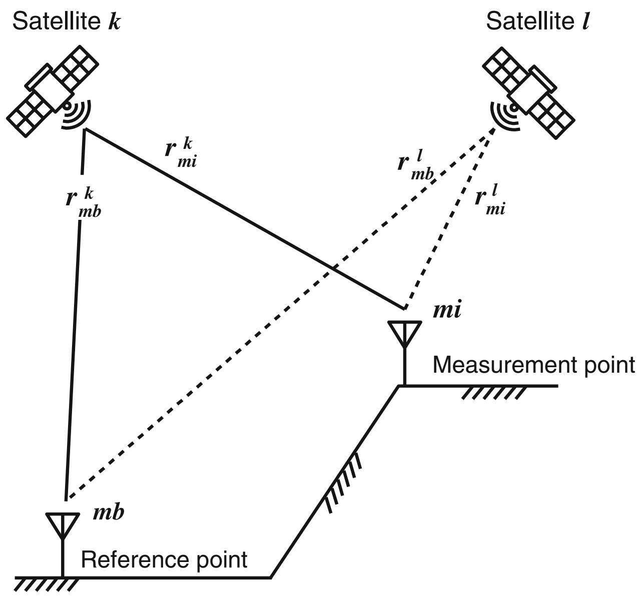


Fig. 15 Satellites, measurement point, and reference point

the receiver clock and the satellite clock, respectively. c is the velocity of light, N^k_{mi} is the unknown integer ambiguity of the carrier phase, and $\varepsilon^k_{\phi_{mi}}$ is an observation error.

The single-phase difference between measurement point mi and reference point mb for satellite $k, \phi^k_{mi} - \phi^k_{mb}$, is taken. In the same manner, another single-phase difference, $\phi^l_{mi} - \phi^l_{mb}$, is taken for satellite l. The double-phase difference, $\left(\phi^k_{mi} - \phi^k_{mb}\right) - \left(\phi^l_{mi} - \phi^l_{mb}\right)$, is obtained by using the above two single-phase differences as follows:

$$\phi^{k-l}_{mi-mb} = \frac{r^{k-l}_{mi-mb}}{\lambda} + N^{k-l}_{mi-mb} + \varepsilon^{k-l}_{mi-mb} + \frac{T^{k-l}_{\phi_{mi-mb}}}{\lambda} \tag{3}$$

Equation (3) is the fundamental equation for relative positioning. It is noted that the biases of the receiver clock and the satellite clock are eliminated as their common errors during the process of deriving the double-phase difference. In addition, the ionospheric delay is also eliminated when the baseline length between the measurement point and the reference point is short, as in the Suggested Method, less than a few km in length.

On the other hand, tropospheric delay $T^{k-l}_{\phi_{mi-mb}}$ remains when the difference in height between the measurement point and the reference point is more than a few tens of meters, even for such a short baseline length.

The observation equations for the relative positioning method are obtained from Eq. (3). The double-phase difference on the left side of Eq. (3) is observed by a GPS sensor. Then, the three-dimensional coordinates of the measurement point appearing in r^{k-l}_{mi-mb}, and integer ambiguity N^{k-l}_{mi-mb}, are determined by means of the least squares method for residual $\varepsilon^{k-l}_{mi-mb}$.

Trend Model: Model for Improving Measurement Results with Random Errors

The trend model is a smoothing technique for estimating the real values from scattered measurement data (Kitagawa and Gersch 1984). It is composed of a system equation and an observation equation, as follows:

$$\begin{aligned} \Delta^k u_n &= v_n \\ y_n &= u_n + w_n \end{aligned} \tag{4}$$

where u_n represents the estimates for the exact values of the displacements and y_n is the measured displacement. The measurement interval is Δt and subscript n denotes progressing time t ($t = n\Delta t$). Δ is the operator for the finite difference ($\Delta u_n = u_n - u_{n-1}$) and Δ^k means the rank "k" difference.

Equation (4) is a kind of probability finite difference equation for rank k. v_n and w_n are white noises with an average value of 0, a standard deviation of τ, and an observation error with a standard deviation of σ.

The trend model can yield good estimates for exact displacements from scattered data obtained from the GPS monitoring system. Through experiments and practical applications, it was proven that the system can detect displacements of 1–2 mm and displacement velocities of 0.1 mm/day (Shimizu and Matsuda 2002).

Tropospheric Model

Modified Hopfield model (Hoffman-Wellenhof et al. 2001)

Tropospheric delays are defined by the following equation:

$$\Delta R^{\text{Trop}} = 10^{-6} \int N^{\text{trop}} \mathrm{d}s \tag{5}$$

where N^{Trop} is the refractivity.

Hopfield showed the possibility of separating N^{Trop} into dry and wet components. The dry part results from the dry atmosphere, while the wet part results from water vapor. Equation (5) becomes:

$$\Delta R^{\text{Trop}} = 10^{-6} \int N_d^{\text{Trop}} \mathrm{d}s + 10^{-6} \int N_w^{\text{Trop}} \mathrm{d}s \tag{6}$$

Using real data covering the whole earth, Hopfield empirically found a presentation of the refractivity of the dry component as a function of height h above the surface:

$$N_d^{\text{Trop}} = N_{d,0}^{\text{Trop}} \left(\frac{h_d - h}{h_d}\right)^4 \tag{7}$$

where the height of dry component h_d is assumed to be the following equation:

$$h_d = 40136 + 148.72(T - 273.16)\ (\mathrm{m}) \quad (8)$$

where T is the absolute temperature (K). Similarly, the refractivity of the wet component is assumed to be:

$$N_w^{\mathrm{Trop}} = N_{w,0}^{\mathrm{Trop}} \left(\frac{h_w - h}{h_w} \right)^4 \quad (9)$$

where the average value, $h_w = 11,000$ (m), is used as the height of the wet component.

Models for dry and wet refractivity at the earth's surface have been used for some time. The corresponding dry and wet components are:

$$N_{d,0}^{\mathrm{Trop}} = c_1 \frac{p}{T} \quad c_1 = 77.64\ (\mathrm{K/hPa}) \quad (10)$$

$$N_{w,0}^{\mathrm{Trop}} = c_2 \frac{e}{T} + c_2 \frac{e}{T^2} \quad c_2 = -12.96\ (\mathrm{K/hPa}), \quad c_3 = 3.718 \times 10^5\ (\mathrm{K^2/hPa}) \quad (11)$$

where p is the atmospheric pressure and e is the partial pressure of the water vapor, namely:

$$e = 6.112 \cdot \left(\frac{RH}{100} \right) \cdot \exp \left(\frac{17.62T - 4813}{T - 30.03} \right) \quad (12)$$

where RH is the relative humidity (%).

Terminology

Antenna Phase Center

The electronic center of the antenna often does not correspond to the physical center of the antenna. The radio signal is measured at the antenna phase center. The phase center cannot be physically measured. The offset of the physical phase center from an external point on the antenna can be known commonly by referring to the base/bottom of antenna.

Baseline

It is the length of the three-dimensional vector between a reference point and a measurement point (or between a pair of measurement points) for which simultaneous GPS data are collected.

Baseline Analysis (Post-Processing)

The act of using a computer program to compute baseline solutions from measured data (i.e., carrier phase and navigation data) by receivers at both a reference point and a measurement point is a baseline analysis. The three-dimensional relative coordinates (latitude, longitude, and height) of a measurement point from the reference point are provided in the 1984 World Geodetic System (WGS84).

Carrier

It is the radio frequency sine wave signal. In the case of GPS, there are two transmitted carrier waves, namely, L1 and L2. The L1 carrier frequency is 1,575.42 MHz and the L2 carrier frequency is 1,227.60 MHz.

Dual-Frequency (L1/L2) Receiver

A type of receiver that uses both L1 and L2 signals from the GPS satellites is a dual-frequency receiver. A dual-frequency receiver can compute more precise position fixes over longer distances and under more adverse conditions by compensating for ionospheric delays.

Elevation Mask (Mask Angle)

Satellites are tracked from above this angle. Users can avoid interference and multipath errors from under this angle. It is normally set to 15°.

Epoch

It is a measurement interval used by a receiver when measuring and recording the carrier phase.

Ionospheric Delay

Ionospheric delays occur as a result of refractive effects due to the total electron content when signals propagate through the ionosphere. The errors can be substantially removed by using a dual-frequency receiver. When a baseline length is less than a few kilometers, it will be mitigated by taking the difference in carrier phases at two points (Appendix "Fundamental Equations for Relative Positioning").

L1/L2 Carriers

The frequencies of the L1 and the L2 carriers are transmitted by the GPS satellites.

Multipath

Interference, similar to ghosting on television, is called a multipath error. It occurs when the GPS signals traverse different paths before arriving at the antenna, typically as refracting from structures or other refractive surfaces (e.g., the ground, walls, fences, etc.) near the antenna.

Navigation Data

Data messages, containing the satellite's broadcast ephemeris, the satellite clock (bias) correction parameters, constellation almanac information, and satellite health constitute the navigation data. They are transmitted from satellites.

Observing Session

A period of time over which GPS data are collected simultaneously by two or more receivers is called the observing session (length).

Point Positioning

Point positioning is a method of obtaining the absolute coordinates (longitude, latitude, and height in WGS84) of a point in an instant by one receiver. The receiver measures the transit time of the signal from satellites to the receiver and receives the navigation data. The standard accuracy is around 30 m.

Relative Positioning

The determination of the relative positions between two or more receivers, simultaneously tracking the GPS signals, is the relative positioning. One receiver is set on the reference point, while the second receiver is set on a measurement point. Three-dimensional relative coordinates of the measurement point are provided in WGS84.

RINEX

RINEX is the Receiver INdependent Exchange format. It is a set of standard definitions and formats to promote the free exchange of GPS.

Single-Frequency (L1) Receiver

A single frequency receiver is a device that can receive signals (L1 wave) and navigation data; it can measure the L1 carrier phase during a specific time period. It is used for the relative positioning of short length baselines.

Static Method

This belongs to relative positioning. It is commonly used due to its reliability and ease of data collection. It is performed by setting up antennas at two or more points for a predetermined observing session length.

Tropospheric Delay

Tropospheric delays occur as a result of refractive effects due to the air density when signals propagate through the troposphere. These errors can be reduced by using an appropriate model to correct tropospheric delays for a short baseline length.

WGS84

WGS84 is the World Geodetic System 1984. It is a global geodetic datum defined and maintained by the U.S. Department of Defense. A mathematical model (or reference ellipsoid) of the earth, whose dimensions were chosen to provide a "best fit" with the earth as a whole, is used. Descriptions of the GPS satellite orbits in the navigation message are referenced in WGS84.

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