Journal of Geodetic Science

• 1(3) • 2011 • 191-203 DOI: 10.2478/v10156-010-0022-3 •

GPS Landslide Monitoring: Single Base vs. Network Solutions – A case study based on the Puerto Rico and Virgin Islands Permanent GPS Network

Research article

Guoquan Wang*

Puerto Rico Seismic Network, Department of Geology, University of Puerto Rico, P.O. Box 9000, Mayaguez, PR 00681, U.S.

Abstract:

This study demonstrated an approach to using permanent GPS stations from a local continuous GPS network as no-cost references in conducting long-term millimeter-level landslide monitoring. Accuracy and outliers from a series of single-base and network GPS measurements of a creeping landslide were studied. The criterion for accuracy was the weighted root-mean-square (RMS) of residuals of GPS measurements with respect to true landslide displacements over a period of 14 months. This investigation indicated that the current Puerto Rico and Virgin Islands GPS network, as a reference frame, can provide accuracy of 1 to 2 mm horizontally and 6 mm vertically for local 24-hour continuous landslide monitoring with few outliers (<1%). The accuracy degraded by a factor of two for 6-hour sessions, and more for shorter sessions. This study indicated that adding a few reference stations to GPS data processing can reduce the number of outliers and increase the accuracy and robustness of landslide surveying, even if these references are far from the study site. This improvement was particularly significant for short sessions and vertical components. The accuracy of network solutions depended slightly on the number of reference stations, but the dependence on the distance and geometric distribution of the references was weak. For long-term landslide monitoring, accuracy under 5 mm horizontally and 15 mm vertically are often expected. Accuracy at this level can be stably achieved in the Puerto Rico and Virgin Islands region by performing field observations for 4 hours or longer, and applying 3 or more reference stations for solving a network solution. This study also indicated that rainfall events can play a crucial rule in high-precision GPS measurements. GPS data collected during heavy rainfall events should be cautiously analyzed in landslide studies.

Keywords:

GPS accuracy • landslide monitoring • Puerto Rico • single base • network • outlier • rainfall

Received 19 February 2011; accepted 04 April 2011

1. Introduction

In recent years, Global Positioning System (GPS) technologies have been frequently applied to the monitoring of landslide movements, both as a complement, and as an alternative to conventional surveying methods (e.g., Gili et al., 2000; Malet et al., 2002; Coe et al., 2003; Sato et al., 2003; Mora et al., 2003; Squarzoni et al., 2005; Br¸ckl et al., 2006; Tagliavini et al., 2007; Psimoulis et al., 2007; Peyret et al., 2008; Wang et al. 2011). One or more reference GPS stations are often installed at the outside of a studied landslide area to achieve high-precision measurements (relative position or displacement) at the landslide site by using a carrier-phase measurement double-difference technique. There are many disadvantages to a field GPS surveying project that depends on one or two temporarily installed reference stations. Poor performance or failure of a reference station can ruin the

---

*E-mail: guoquan.wang@upr.edu

entire field effort. It is often difficult, in practice, to precisely reoccupy a reference station, though it is crucial to a repeated campaign landslide surveying project. The error occurring in the reference GPS will propagate to all the surveying points. It is also not cost effective for a survey project to operate extra GPS stations outside the target area. Permanent GPS reference stations are being increasingly established all over the world and a great number of regional-scale GPS networks have been established for multi-functional users. Continuous data from these permanent GPS stations are often freely available through public data archives. This study demonstrates the application of permanent GPS stations as references to monitor an active landslide in Ponce, Puerto Rico.

The current Puerto Rico and Virgin Islands Permanent GPS network includes seven stations operated by the Puerto Rico Seismic Network and a few stations operated by other agencies (Figure 1). One of the major missions of this GPS network is to provide a platform for local multi-hazard study and mitigation, such as large earthquake monitoring, tsunami early-warning, hurricane intensity forecasting, and landslide monitoring. This study aims to demonstrate its applications in local landslide monitoring. Continuous GPS data from a 14-month period were used to study the accuracy of both single-base and network GPS solutions. Data from MAYZ were not used since this station only collected five months of data within the study period. All of these GPS stations are equipped with Trimble NetRS GPS receivers and choke ring antennas (model: TRM41249.00). Raw data are available through public data archives at UNAVCO (http://www.unavco.org) and Continuously Operating Reference Stations (CORS) (http://www.ngs.noaa.gov/CORS/) operated by the National Geodetic Survey.

The GAMIT/GLOBK software developed at MIT (Herring et al., 2009) and final orbits from the International GNSS Service (IGS) (Dow et al., 2009) were applied to the GPS data processing. Standard models for solid-Earth and ocean tides, satellite attitude, antenna offsets and phase center variation were used. The a priori hydrostatic delay and mapping function were used to model the atmospheric delays (http://igscb.jpl.nasa.gov/igscb/center/analysis/MIT`acn.html). To account for unmodeled variations in atmospheric water vapor, a zenith delay was estimated using a linear spline with knots every two hours. An elevation-angle cutoff of 10 degrees and assigned elevation-dependent weights were applied to phase observations based on the noise for each station on each day. For a single-base solution, the reference frame was defined by fixing the coordinates of the reference station. In a network solution, generalized constraints (Dong et al., 1998) were applied in order to estimate three translation parameters while minimizing the adjustments from a priori coordinates of all network stations, with the exception of the landslide GPS. Only three translation parameters, rather than a full 7-parameter Helmert transformation, were estimated in generalizing the network constraints. Although the use of the simple transformation allows the occurrence of possible errors due to variable rotation and scale, it is more robust for a small network. Prior to this study, the a priori positions and velocities of these permanent GPS stations (Figure 1) with respect to the 2005 International Terrestrial Reference Frame (ITRF 2005) (Altamimi et al., 2007) were determined by combining 24-hour sessions spanning two years from June 2008 to August 2010. Although the accuracy of the estimated positions and velocities from the 2-year solution are less than that of the ITRF05 itself, they are self-consistent for the time span of this study and hence provide a reliable reference frame for evaluating the accuracy of displacement measurements. The accuracy of GPS measured landslide displacements inferred from different observation sessions and reference configurations were evaluated in this study. The criterion for evaluating the accuracy was the daily scatter (weighted root-mean-square, WRMS) of the residuals of estimated landslide displacements with respect to ``true'' landslide displacements. The true landslide displacements were obtained from 24-hour continuous observations by single-base processing using a reference GPS 130 meters away.

2. Cerca del Cielo Landslide and Continuous GPS Monitoring

Puerto Rico is located in the northeastern Caribbean Sea, east of the Dominican Republic and west of the Virgin Islands. Mountainous terrain and tropical climate make this island one of the most landslide-prone areas in the United States (Jibson, 1986, 1989). This study used continuous GPS data from an active landslide located in the Cerca del Cielo community in the municipality of Ponce. The landslide began to creep in the summer of 2007, and over time, the sliding mass cut through the sole access road to the whole community and 10 houses were completely destroyed. A further 15 houses close to the margins of the sliding mass had to be abandoned. A continuous GPS monitoring system was installed at the head of the landslide in May of 2009. The monitoring system includes a rover GPS station installed on the roof of a two-story building and a reference GPS outside the sliding mass as shown in Figure 2. The reference GPS was installed on the roof of a one-story residential building. The distance between the reference and rover GPS station is 130 meters. Both of the reference and rover GPS stations were equipped with Trimble NetRS receivers and Choke Ring antennas.

Figure 3 illustrates local rainfall and landslide displacements during a period of fourteen months spanning from June 1, 2009 to July 31, 2010. The top plot illustrates the accumulated precipitation recorded by a U.S. Geological Survey (USGS) weather station (USGS50115230) in the vicinity. The distance between the weather station and the landslide site is 4.5 km. The red dots represent the positions of the landslide GPS related to the reference GPS, which were derived from a single-base processing using 24-hour continuous data. The stability of the reference GPS was further investigated by using a local GPS network with ten permanent GPS stations under the International Reference Frame (ITRF05). The velocities of these references were fixed at zero during the

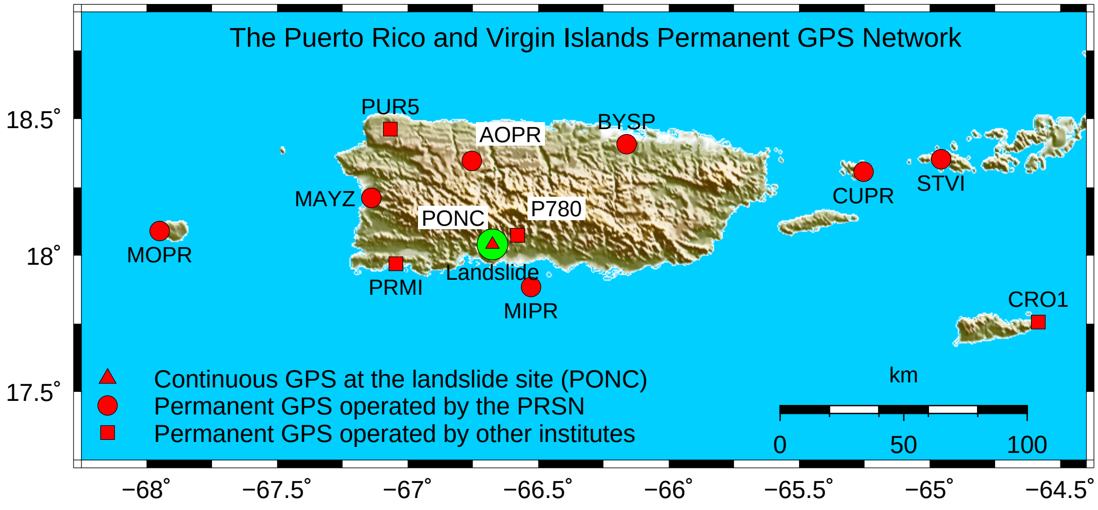

Figure 1. Map showing the geometry of the Puerto Rico and Virgin Islands Permanent GPS Network. PONC represents the landslide GPS installed at the head of the sliding mass.

study period. The dark points represent the daily positions of the reference GPS. The horizontal trend of the reference position time series indicates the stableness of the reference site during the studied period. Thus, the measurements of the landslide GPS truly represent the landslide movements at the GPS site. There is a linear relationship between the landslide displacement and time during the first two-month time window. However, during a longer time period, the relationship tends to be nonlinear. The daily positions during the first two months were used to calculate the precision (or repeatability) of the landslide GPS by removing a linear trend. The root-mean-square (RMS) of the detrended position time series was calculated, then used as an index to evaluate the precision of the GPS measurements in this study. The precision of the landslide GPS (PONC) were 0.5 mm (NS), 0.5 mm (EW), and 1.3 mm (vertical). The precision of the reference GPS was also calculated by using the measurements within the first two month. They were 2.4 mm (NS), 1.6 mm (EW), and 6.1 mm (vertical). It should be noted that the positions of the landslide GPS and reference GPS were solved with two different GPS approaches using different reference frames. The positions of the landslide GPS were calculated with a single-base GPS solution with an extremely short baseline (130 m), while the positions of the reference GPS were calculated with a network solution using ten local permanent GPS stations. In this study, the displacements derived from the single-base solution were used as the ``true'' displacements of the creeping landslide because they attained sub-millimeter precision horizontally and millimeter precision vertically. The differences (also called residuals) between GPS measurements at the landslide site and the ``true'' landslide displacements were studied statistically. Thus, the term ``accuracy'' rather than ``precision'' is used in the following discussions. Continuous data with different session lengths (24-hour, 6-hour, and 4-hour) were studied. The windows of time for 6-hour and 4-hour sessions range from 10:00 AM to 4:00 PM and from 10:00 AM to 2:00 PM (local time), respectively. The windows of observations were chosen to cover the most likely working period for a campaign-style landslide survey, assuming a technician starts working at local time 8:00 AM, then spends two hours traveling to a landslide site and setting up the GPS equipment.

3. Criteria for Removing Outliers

In generating statistics for evaluating the accuracy of GPS measurements at the landslide site, the two-criterion approach proposed by Firuzabadi and King (2011) was applied to remove outliers. Figure 4 demonstrates the two-step process of removing outliers by using measurements from a single-base solution (BYSP, 6-hour session). These dark dots represent 6-hour single-base measurements, and the red dots represent the true landslide displacements. The following steps were taken to remove outliers.

First, the days for which the uncertainty was greater than 2.0 times of the average uncertainty of the entire measurement (422 days) were removed. The uncertainty of each measurement was directly outputted by the GAMIT/GLOBK program. This criterion serves to exclude poor measurements due to loss of data (for example, due to short-term power failure, sky masking, receiver malfunction, and/or onsite maintenance), significant multipath effects, large wet tropospheric delay, or failure to resolve of the integer-cycle phase ambiguities. This criterion is referred to as criterion-1. The outliers removed in this process are referred to as outlier-1s. Second, the displacement time series from which the outlier-1s had been removed and the true displacement time series were overlapped by applying a least-squares adjustment approach, which lead to minimal RMS of the residual time series. The residual time series between the measurements and true displacements

Figure 2. Photos showing the head of the Cerca del Cielo landslide and the continuous GPS monitoring system. The landslide GPS was installed on the roof a two-story residential building at the head of the landslide. The reference GPS was installed on a one-story resident building outside of the landslide mass. The distance between the landslide GPS and the reference GPS is about 130 meters. Both of the reference and landslide GPS sites are equipped with a Trimble NetRS GPS receiver and a Choke Ring antenna. A weather sensor was also installed at this site in the summer of 2010. Rainfall data from the weather sensor were not used in this study since they only cover a small section of the study period.

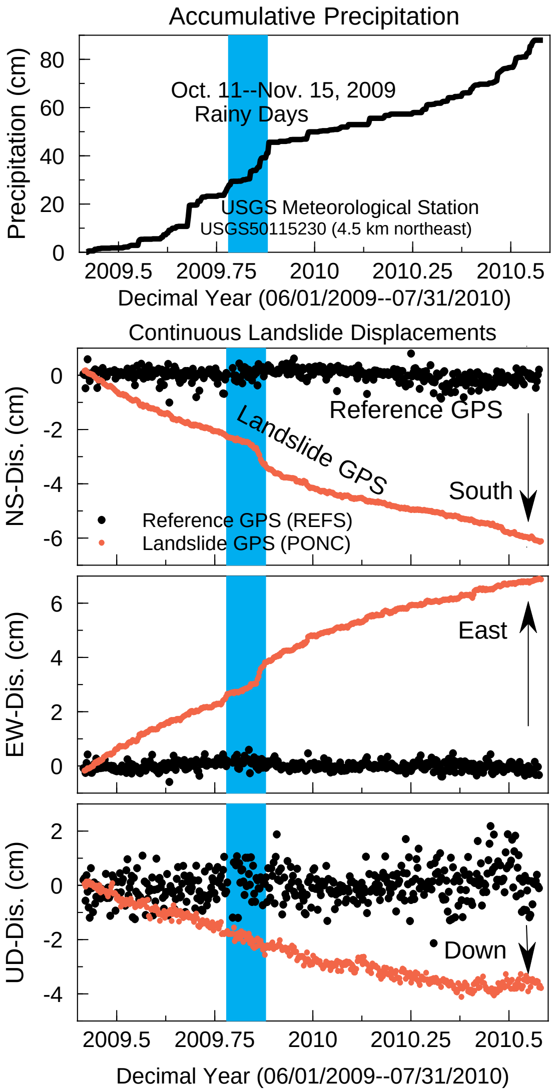

Figure 3. Plots showing local precipitation and landslide movements during the 14-month period from June, 2009 to July, 2010. The top plot illustrates accumulative precipitation at a vicinity USGS weather station. The bottom plots illustrate three-component daily positions of the landslide (red) and reference GPS (dark) inferred from 24-hour continuous observations. The positions of the landslide GPS were derived from single-base processing using the reference GPS as a fixed base station. The baseline length is 130 meters. The positions of the reference GPS were derived from network processing using 10 references (Figure 1) within the International Terrestrial Reference Frame (ITRF2005) by fixing the velocity of each reference at zero.

were then calculated to scale the original uncertainties of the GPS measurements. The uncertainty was scaled by a coefficient (k) calculated with the following formula:

$$k = \sqrt{\frac{\sum_{1}^{n}\left(\frac{r(i)}{e(i)}\right)^2}{n-1}} \tag{1}$$

where $r(i)$represents the residue time series, and $e(i)$ represents the original uncertainty time series of the GPS measurement time series. The scaling process sets the RMS scatter of the normalized residue time series $\left(\frac{r(i)}{k \cdot e(i)}\right)$ equals 1.0. Third, the days for which the residual is three times larger than its scaled uncertainty were removed. The residual cutoff serves to avoid biasing the statistical results with the presence of a small number of outliers. This criterion is referred to as criterion-2, and the outliers removed by this process are referred to as outlier-2s. Finally, after removing all

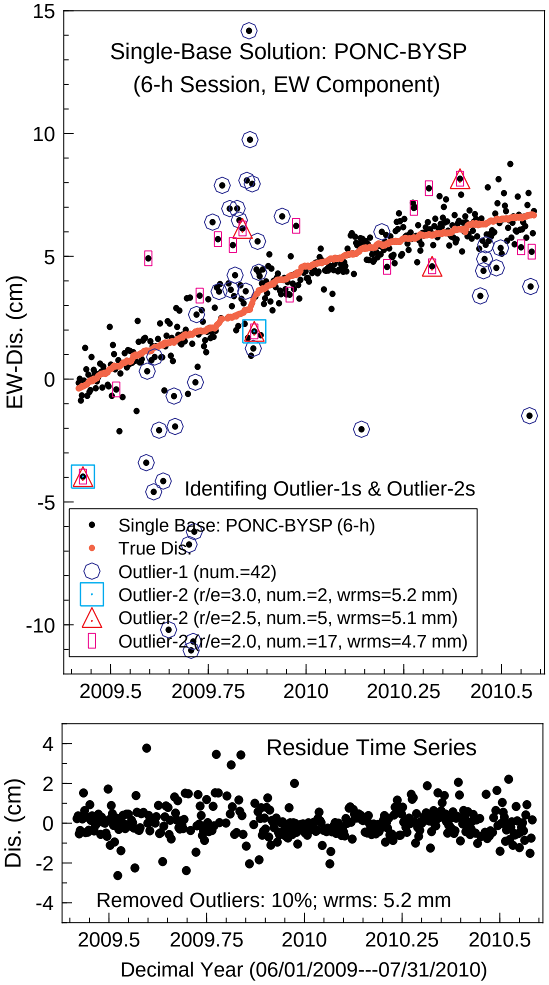

Figure 4. Plots illustrating two criteria for removing outliers. Outlier-1 represents a measurement whose uncertainty is larger than the average uncertainty of the whole samples by a factor of two. Outlier-2 represents a measurement whose residual is greater than its scaled uncertainty by a factor of three. The original uncertainty was scaled by a coefficient calculated through Formula (1).

outliers, the measurement time series and the true displacement time series were re-overlapped. The final accuracy, the weighted RMS (WRMS) of their residuals, was calculated with the following formula:

$$WRMS = \sqrt{\sum_{1}^{n}\left(\frac{r(i)}{e'(i)}\right)^{2} \Bigg/ \sum_{1}^{n}\left(\frac{1}{e'(i)}\right)^{2}} \qquad (2)$$

where $r(i)$ is the residual time series, and $e'(i)$ is the scaled uncertainty time series. In the practice of GPS monitoring on suspected creeping landslides, the measurements are often updated daily. Cost and/or logistics may allow for each position to be measured only once. True position on the working day and the future position are unknown. Thus, an outlier can be easily misinterpreted as a sign of a rapid slide. Criterion-1 for identifying outliers is very useful in practice, as it does not require knowing the true and future displacements of the landslide. It requires only an average uncertainty of GPS measurements at the GPS site, which can be inferred from previous observations under similar environmental conditions and references. Criterion-2 is used to further remove measurements that majorly drift away from their corresponding true displacements. The ratio of the residual to the scaled uncertainty of a measurement was used as an index to identify outlier-2s. Different ratios were tested in order to evaluate the sensitivity of the final accuracy and number of outliers to the selection of the ratio. Figure 4 shows that while the number of outlier-2s increased from 2 to 17 if the ratio changes from 3 to 2, the change of final weighted RMS was very small (0.5 mm). It is clear that the choice of the residual to uncertainty ratio can considerably affect the number of outlier-2s. Since the reasons causing outlier-2s are not clear, a loose criterion was used in removing outlier-2s in order to avoid rejecting too much data from the original measurements.

4. Single Base Solutions

Figure 5 illustrates accumulative precipitation within six 4-hour windows during a day-long period and the accuracy of single-base GPS measurements using 4-hour sessions. The number of outliers and the weighted RMS of these single-base (BYSP) measurements are listed in Table 1. There were higher accuracy and fewer outliers at night (local time 8:00 PM-8:00 AM) than during the day time (local time 8:00 AM-8:00 PM). The highest accuracy was achieved during the early morning window (local time 4:00-8:00AM), while the lowest accuracy was achieved during the early afternoon window (local time 12:00-4:00 PM). The accuracy and number of outliers of the two windows differed by a factor of 2. The 4-hour window with the lowest accuracy also experienced the largest amount of rain among these six 4-hour windows. There are frequent thunderstorms and heavy rainfall activities in early afternoon all year round in the tropical region, particularly in the summer months. These extreme weather activities can exert a large impact on the troposphere and affect the propagation of GPS signals, which will in turn degrade the accuracy of GPS measurements. It should be noted that the dynamics of local GPS satellite geometry could also contribute to the variations of GPS accuracy.

Figure 6 shows the displacement time series derived from single-base solutions using three 4-hour sessions: local time 4:00 AM-8:00 AM, 12:00 PM-4:00 PM, and 10:00 AM-2:00 PM. The accumulative 4-hour (12:00PM-4:00PM) precipitations at both the reference and landslide GPS sites were plotted at the top, which indicated that from December to March were relative ``dry'' days, and from April to November were relative ``wet'' days. The rainfall data at the reference GPS site (BYSP) were recorded by a co-located weather

Table 1. Outliers and Accuracy (WRMS) of Daily Measurements at the Landslide Site (PONC) Inferred From Different 4-Hour Sessions (Single-Base Solution: PONC-BYSP).

Session	Outlier-1s			Outlier-2s			Total Outliers			WRMS (mm)			
(Local Time)	NS	EW	V	NS	EW	V	NS	EW	V	NS	EW	V	V/H
8:00PM-12:00AM	22	20	20	3	4	4	6%	6%	6%	3.7	3.6	15.9	3.1
12:00AM-4:00AM	11	11	11	2	4	3	3%	4%	3%	3.4	3.5	14.2	2.9
4:00AM-8:00AM	13	15	14	4	3	3	4%	4%	4%	3.0	3.2	14.0	3.2
8:00AM-12:00PM	12	19	7	0	0	3	3%	5%	2%	4.0	4.0	18.6	3.3
12:00PM-4:00PM	26	59	19	4	0	3	7%	14%	5%	7.8	6.6	27.1	2.7
4:00PM-8:00PM	32	53	27	1	0	3	8%	13%	7%	5.1	5.1	22.1	3.1
10:00AM-2:00PM	23	49	17	4	1	3	6%	12%	5%	5.7	5.1	23.1	3.0
Average	20	32	16	3	2	3	5%	8%	5%	4.67	4.44	19.3	3.0

Table 2. Outliers and Accuracy (WRMS) of Single-Base Solutions.

Base	BL (km)	Days	Outlier-1s (NS, EW, V)									Outlier-2s (NS, EW, V)									Total Outliers			WRMS: NS, EW, V (mm)											
			24-H			6-H			4-H			24-H			6-H			4-H			24-H	6-H	4-H	24-H			V/H	6-H			V/H	4-H			V/H
P780	11	422	0	0	0	13	24	8	21	27	11	1	3	0	3	5	2	4	5	3	<1%	2%	4%	1.9	1.7	6.6	2.6	42	3	17	3.3	4.3	3.4	19	3.4
MIPR	16	422	1	2	1	9	23	7	10	25	9	1	0	1	2	4	1	3	3	1	<1%	1%	3%	2	1.9	7.5	2.7	4.3	3.2	17	3.2	4.3	3.5	20	3.5
BYSP	68	422	4	7	5	15	42	16	23	49	17	3	2	2	3	2	2	4	1	3	2%	3%	5%	2.9	2.7	9.5	2.4	6.7	5.2	22	2.6	5.7	5.1	23	3.0
MOPR	133	422	2	1	2	12	35	8	11	41	7	1	1	2	5	3	1	2	2	1	1%	2%	5%	3.3	3.7	9.3	1.9	6	6.1	24	2.8	6.6	8.4	30	2.8
CUPR	150	422	0	0	0	6	24	5	15	40	10	1	2	1	2	2	4	2	0	3	<1%	1%	3%	3.4	3.1	10	2.2	3.9	4.6	17	2.8	4.8	7.1	23	2.7
CRO1*	225	350	1	1	1	11	21	12	11	24	11	2	1	1	5	0	3	4	3	2	1%	2%	4%	3.4	2.4	10	2.4	6.1	5.5	20	2.4	5.7	5.8	24	2.9
Ave.			1	2	2	11	28	9	15	34	11	2	2	1	3	3	2	3	2	2	1%	2%	4%	2.8	2.6	8.8	2.4	5.2	4.6	19	2.9	5.2	5.6	23	3.1

*CRO1 missed three-week of data after the middle of May 2010. Continuous data from June 1, 2009 to May 15, 2010 were used in this study.

sensor. It is clear that the errors in GPS measurements, on wet days were, on average, larger than those on dry days.

Table 2 lists statistical results, including outliers and weighted RMS, from six single-base solutions with different baseline and session lengths. The statistical results indicated that all single-base solutions (baseline $<$ 250 km) using 24-hour sessions could provide 2-3 mm horizontal accuracy and sub-centimeter vertical accuracy. The accuracy degraded by a factor of two for 6-hour sessions, and even more for shorter sessions. The number of outliers did not seem to depend on the baseline length, at least not within the studied baseline length range ($<$ 250 km). However, the number of outliers did seem to depend on the session length. The average percent of the number of outliers from 24-hour, 6-hour, and 4-hour sessions were 1%, 2%, and 4%, respectively. These outliers were dominated by outlier-1s, which constituted 85% of the total outliers. The statistics listed in Table 2 also indicated the degradation of accuracy with the increase of baseline length, particularly for 6-hour and 4-hour sessions. This result differed slightly from the results of Eckl et al. (2001), and Firuzabadi and King (2011). Eckl et al. found little baseline-length dependence up to 300 km, for sessions as short as four hours. Firuzabadi and King found little systematic degradation with baseline length for sessions of 6 hours or longer within approximately 300 km. It is believed that the high spatial variability of weather conditions in the tropical region could make the accuracy of GPS measurement more sensitive to the distance between rover and reference GPS stations.

5. Effects of Rainfall Events

Figure 7 shows the landslide displacement time series derived from single-base solutions using three references with baseline lengths of 11 km (P780), 133 km (MOPR), and 224 km (CRO1) for 24-hour, 6-hour, and 4-hour sessions, respectively. It is clear that a great number of outliers were concentrated within a one-month window from the middle of October, 2009, to the middle of November, 2009, which experienced continuous moderate rainfalls as shaded in Figure 3. The accumulated rainfall during the one-month period was about 25 cm. The continuous rainfall eventually caused a rapid slide of the landslide as indicated by a small step

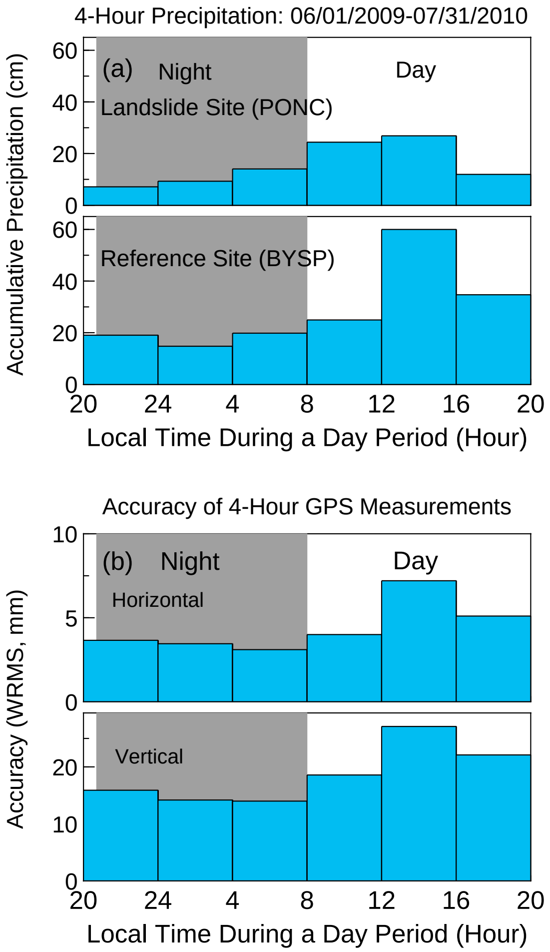

Figure 5. Plots showing a strong correlation between rainfall and the accuracy of GPS measurements. (a) 4-hour accumulative precipitation during a 14-month period (06/01/2009-07/31/2010) at the landslide and reference GPS sites; (b) The accuracy (weighted RMS) of 4-hour static GPS measurements derived from the 14-month GPS observations.

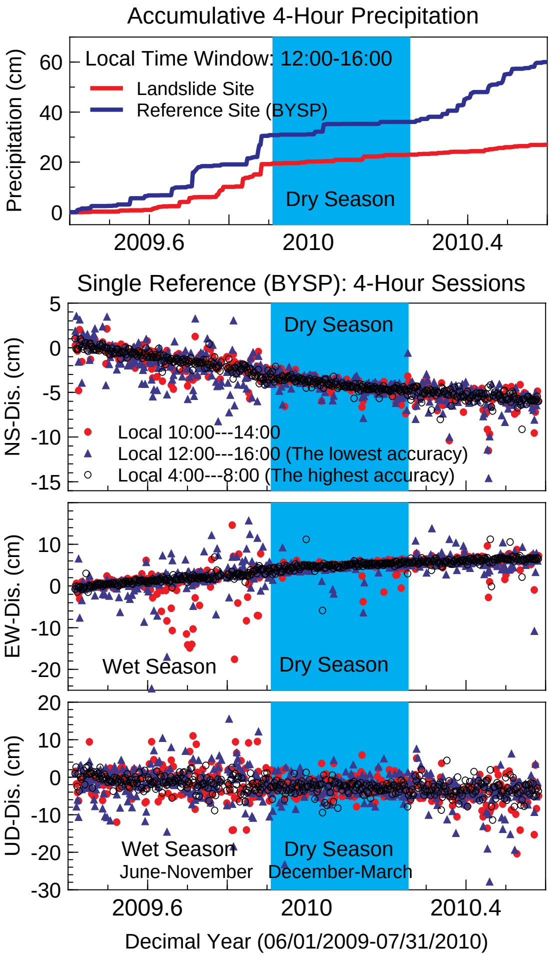

Figure 6. Rainfall vs. landslide displacements derived from single-base GPS measurements using 4-hour sessions. (a) The accumulative precipitation at the reference (BYSP) and landslide GPS sites during the 4-hour window (local time 12:00-16:00) with the largest amount of rainfall; (b) The daily landslide displacement time series derived from three 4-hour sessions: 4:00-8:00, 12:00-16:00, and 10:00-14:00 (local time). The number of outliers and accuracy are listed in Table 1. The shaded period represents dry days ranging from December to March.

in the true landslide displacement time series (Figure 3). This coincidence suggested a causal relationship between the rainfall and the significant outliers within GPS measurements. The effects of extreme weather conditions on high precision GPS positioning, especially for the vertical measurements, had been addressed by several previous studies (e.g., Davis et al., 1993; Bevis et al., 1995; Dodson et al., 1996; Gregorius and Blewitt, 1998; Soler et al., 2006). It is believed that heavy rainfalls can impact GPS measurements through at least the following three mechanisms.

First, heavy rainfalls, usually accompanied by high atmospheric activities, such as thunderstorms and the passage of weather fronts, can cause significant temporal and spatial variations of atmospheric water vapor and impact the propagation of GPS signals (Rocken et al., 1995; Dodson et al., 1996; Gregorius and Blewitt, 1998; Iwabuchi et al., 2003). The effect of water vapor is also known as wet delay. Although the wet component of the delay constitutes less than 10% of the total atmospheric delay (Janes et al., 1989), the errors in the models for the wet delay are larger than the errors in the models for the dry delay. Local storms and heavy rainfalls are very frequent in most parts of the Puerto Rico and Virgin Islands region, particularly during the summer time. These frequent spatial and temporal variations of atmospheric conditions cannot be modeled by a standard atmospheric model. The GAMIT/GLOBK software uses the Saastamoinen model (1972) and the ``global mapping functions'' (GMF) of Boehm et al. (2006) as

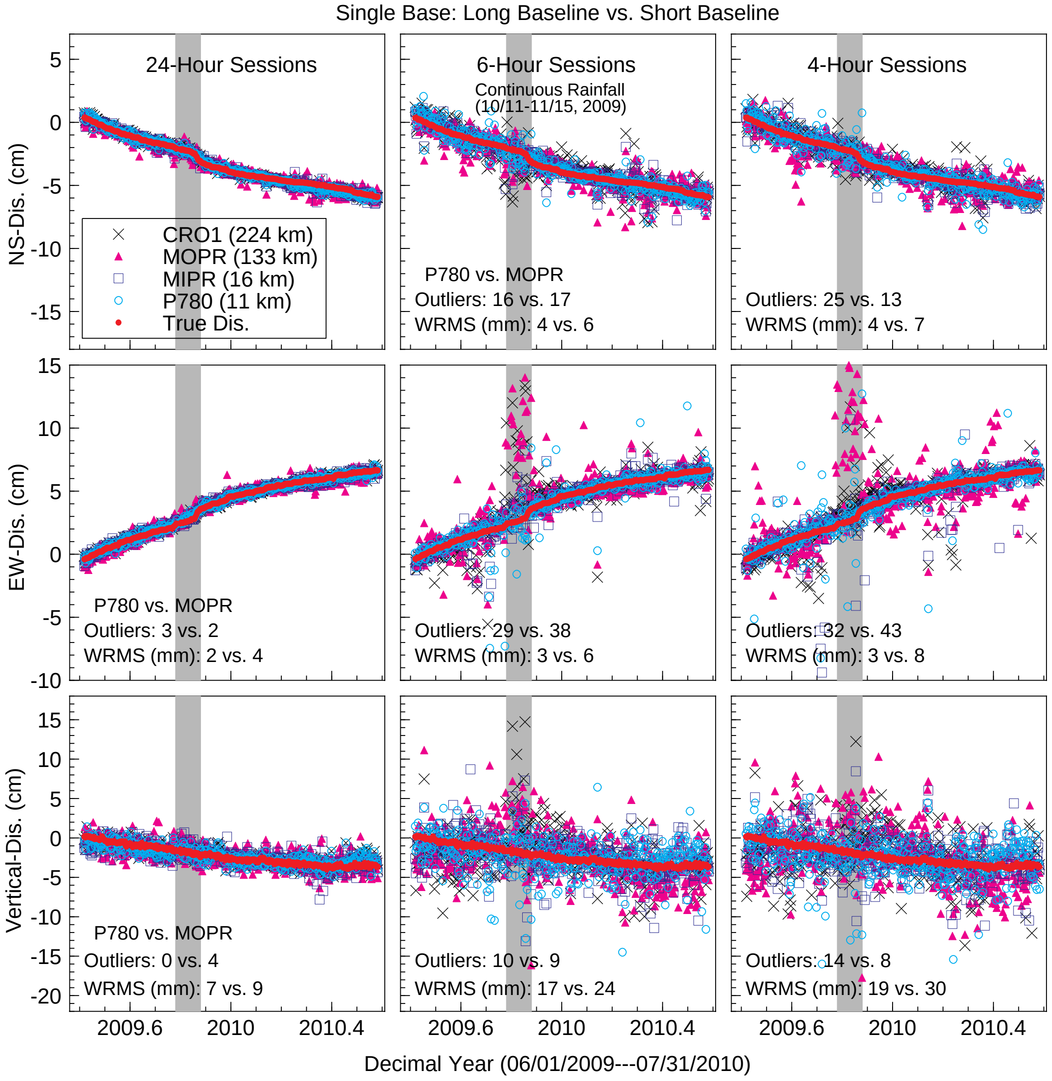

Figure 7. Landslide displacement time series derived from single-base solutions. Locations of these base stations are illustrated in Figure 1. These three columns illustrate the measurements from 24-hour, 6-hour, and 4-hour sessions. The 6-hour and 4-hour sessions cover local time windows from 10:00 to 16:00 and from 10:00 to 14:00, respectively. The true displacement was derived from a single-base solution (baseline 130 m) illustrated in Figure 3.

defaults to estimate satellite signal path delays and thus to correct for the positioning error caused by the troposphere. According to Brunner and Welsch (1993), a residual tropospheric delay error of 1 cm between the baseline stations will cause a 3-cm error in the height difference. Most summer storms and heavy rainfalls in the Puerto Rico and Virgin Islands regions are limited to a small area, such as a few square kilometers. The residual troposphere delay error between a rover GPS and a reference GPS could be significant. Figure 4 indicates that rainfalls, at both the reference and rover GPS sites, can affect the GPS measurements.

Second, a short period of concentrated, extremely high-intensity rain drops (liquid water) can attenuate the strength of GPS signals through a combination of absorption and scattering. The effects of rain on microwave propagation have been under study for more than 100 years, starting with Mie (1908), in the atmospheric research community. Rain droplets may have insignificant effects on the wet tropospheric delay, but can temporarily attenuate the strength of satellite signals (Ray, 1972; Olsen et al., 1978; Wu, 1979). Weak signals often cause large errors in final measurements. It is even possible for dense droplets to form a continuous layer of liquid water over the GPS antenna during a heavy rainfall, which can temporarily block all GPS signals. GPS signals are at the frequencies of 1.575 GHz (L1) and 1.227 GHz (L2). Water absorbs microwaves at this frequency range fairly well. A few millimeters of water will severely attenuate GPS signals. Modeling the temporary variations of atmosphere and the influence of liquid water is difficult and requires external information such as the location, intensity, droplet size, and duration of the rain events.

Third, rainfall events can temporarily change multipath environments at both rover and reference GPS sites, and induce significant multipaths. The landslide GPS was installed on the corner of a roof. Water can remain on the roof for several days following a rainfall event. The water's surface can induce multipaths. Increased soil moisture at these free-field reference GPS sites will also induce multipaths. The effects of soil moisture on multipaths have been studied by Larson et al. (2008a, 2008b, and 2010). A perusal of Table 2 reveals that the EW component had more outliers, by a factor of two or more, than NS and vertical components. Figure 6 indicates that most outliers in the EW component occurred during these ``wet'' days. Notable azimuthal asymmetries of water vapor distributions can cause different tropospheric delays on GPS signals at different azimuthal directions and affect the precision of three-component GPS measurements differently. The azimuthal asymmetry effects of tropospheric delay had been observed by previous studies (e.g., MacMillan, 1995; Chen and Herring, 1997; Iwabuchi et al., 2003). Multipaths from a certain direction induced by water surface can also exert different effects among the three-component measurements.

6. Network Solutions

Network solutions with 10 references, 6 references, and 3 references were tested in this section. The 10-reference network includes all GPS stations (except MAYZ) plotted in Figure 1. The 6-reference network includes six permanent stations more than 65 km away from the landslide site: BYSP (68 km), PUR5 (65 km), MOPR (133 km), CUPR (150 km), STVI (180 km), and CRO1 (225 km). To study the sensitivity of accuracy to the geometry of a reference network, two 3-reference networks were tested. One reference network included three references (MOPR, CUPR, and CRO1) with a good geometric coverage, which were symmetrically distributed with respect to the landslide GPS. Another reference network included three references (CUPR, STVI, and CRO1) with poor geometric coverage, which were asymmetrically distributed with respect to the landslide GPS (see Figure 1). The statistical results of these network solutions are listed in Table 3.

There was a systematic trend showing that the accuracy degraded slightly with the decrease of the number of references and the duration of the observation. The 10-reference network processing attained the highest accuracy, 1-2 mm horizontal and 6 mm vertical for 24-hour sessions. The accuracy decreased by a factor of 2 for 6-hour sessions. The statistics listed in Tables 2 and 3 indicated that network solutions improved both horizontal and vertical accuracy as compared to single-base solutions. The improvement was particularly significant for short sessions and for the vertical component. The average ratios of vertical to horizontal accuracy were 2.4, 2.9, and 3.1 for single-base processing using 24-hour, 6-hour, and 4-hour sessions, respectively. They were reduced to 2.1, 2.3, and 2.7, respectively, by network solutions.

Figure 8 illustrates the comparison of landslide displacement time series derived from the 6-reference-network processing and a single-base processing. The single-base solution used BYSP as a reference station, which was the closest reference to the landslide site among these six references. It is clear that the network solution provided higher accuracy than the single-base solution. The improvements in the horizontal components were 1 mm for 24-hour session and 1 mm to 2 mm for 6-hour and 4-hour sessions, while the improvements in the vertical component were 3 mm for the 24-hour session, and 8 mm to 9 mm for 6-hour and 4-hour sessions. The network solution also reduced the number of outliers of 6-hour and 4-hour sessions. The reduction of outliers during the shaded rainy-window was particularly significant. The comparison of single-base and network solutions suggested that adding a few references to the GPS data processing, even if they are far away from the study site, can reduce outliers and increase accuracy, particularly for the vertical component and for short sessions.

The statistics listed in Table 3 also indicate that there was little systematic difference between the displacements derived from the two 3-reference-network solutions with good or poor geometric distributions. This result coincides with the findings of Firuzabadi and King (2011). The current Puerto Rico and Virgin Islands GPS network provides at least 3-GPS coverage within 100 km for any place in the Puerto Rico and Virgin Islands region. Thus, the statistic results obtained from this case study can be extrapolated to the whole Puerto Rico and Virgin Islands region. The results obtained from this study could also be applied to other regions covered by regional GPS networks.

7. Discussion and Conclusions

This study provides a useful guide for optimizing the practice of landslide monitoring with respect to selection of references, duration of field observations, and windows of observation time. The results from this study indicate that the current permanent GPS stations in the Puerto Rico and Virgin Islands region can provide a precise and robust reference frame for local landslide monitoring. The choice of references depends primarily on the expected accuracy. For long-term landslide monitoring, accuracy under 5 mm horizontally and 15 mm vertically are often expected. If continuous 24-hour observation is to be conducted in the field, a single-base solution with a baseline length of less than about 250 km, or a network solution with three or more references can achieve this level of accuracy. However, if campaign-style observations (i.e. a few hours) are to be conducted in the field, then the choice of references, session lengths, and observation windows are critical to achieving the expected accuracy with minimum outliers. Based on

Table 3. Outliers and Accuracy (WRMS) of Network Solutions.

Network*	Days	Outlier-1s (NS, EW, V)									Outlier-2s (NS, EW, V)									Total Outliers			WRMS: NS, EW, V (mm)											
		24-H			6-H			4-H			24-H			6-H			4-H			24-H	6-H	4-H	24-H			V/H	6-H			V/H	4-H			V/H
10-Ref.	422	0	0	1	12	21	12	8	18	8	1	3	1	3	5	3	2	4	3	<1%	4%	3%	2.1	1.4	5.8	2.3	4.2	2.3	11.0	2.3	4.0	2.5	14.0	3.0
6-Ref.	422	0	1	1	15	27	13	10	26	10	1	2	4	2	4	1	3	2	3	<1%	5%	4%	2.5	1.7	6.3	2.1	5.1	2.8	13.0	2.2	4.6	3.0	15.0	2.7
3-Ref.-Good	350	1	1	1	11	8	4	6	7	6	0	3	3	3	5	2	3	3	2	1%	3%	3%	2.5	1.7	6.4	2.1	5.1	3.1	14.3	2.4	5.1	3.5	17.0	2.7
3-Ref.-Poor	350	1	1	1	11	15	10	6	8	3	1	0	5	2	2	3	3	2	3	1%	4%	2%	2.6	2.1	6.4	1.9	5.3	3.9	14.1	2.1	5.2	4.2	16.4	2.5
Average		1	1	1	12	18	10	8	15	7	1	2	3	3	4	2	3	3	3	1%	4%	3%	2	2	6	2.1	5	3	13.1	2.3	5	3	16	3

*The 10-reference network used all permanent GPS stations plotted in Figure 1 except MAYZ.

*The 6-reference network used six permanent GPS stations: MOPR, PRMI, BYSP, CUPR, STVI, and CRO1.

*The 3-reference network with good geometric distribution used three permanent GPS stations: MOPR, CUPR, and CRO1.

*The 3-reference network with poor geometric distribution used three permanent GPS stations: CUPR, STVI, and CRO1.

the experience of this study, a network solution using three or more references and 4-hour, or longer, observations is recommended in order to achieve the desired level of accuracy. Evening to early morning is often a good time window for campaign GPS surveying. It is necessary to avoid storms and rainy periods for field landslide monitoring projects. The number of permanent GPS stations is rapidly growing. A great number of regional networks are being developed around the world. These public infrastructures will be significant to the improvement of landslide, subsidence, and large structural monitoring.

GPS does not directly measure the displacements of landslide movements while measuring the distances between the antenna and different satellites. Carrier phase double differences are primarily used for calculating precise positions, or changes of positions. Most commercial software packages only provide single-base processing (e.g., Topcon Tools, http://www.topconpositioning.com), which is often thought to be simpler than network processing. In fact, this is not always true. The results of single-base processing depend on the quality of the reference. A references GPS can occasionally miss data or have certain poor data. It is even possible for a reference GPS to be creeping, particularly if it is close to an active landslide area. Thus, it is necessary to check the data quality, and study the stability of the reference GPS by using a global reference frame as demonstrated in Figure 3, which makes single-base processing complex and time consuming in practice. However, it is generally not necessary to check data availability, nor the quality and stability of each reference if a group of local permanent GPS stations are used as a reference frame. The GAMIT/GLOBK program will automatically download reference data from public data archives and perform quality control, as well as optimize the final resolutions. Thus, network processing can, in practice, be simpler and more robust than single-base processing.

The statistical accuracy of static GPS measurements achieved in this study (Tables 2 and 3) are smaller in general than the precision obtained by Eckl et al. (2001) in North America and Firuzabadi and King (2011) in Europe for sessions of 4 to 24 hours. Eckl et al. used single-base processing, specifically the average of three single-base solutions. Firuzabadi and King used both single-base and network solutions. Eckl et al. reported average precision (RMS) of 2 mm horizontal and 8 mm vertical for 24-hour session with baseline less than 300 km, 3.7 mm horizontal and 14.2 mm vertical for 6-hour sessions, and 4.8 mm horizontal and 18 mm vertical for 4-hour sessions. Firuzabadi and King reported precision of 3 mm horizontal and 10 mm vertical of single-base solutions for baseline length within 200 km, and session duration longer than 3 hours; the precision of 1mm to 2 mm horizontal and 3 mm to 5 mm vertical of network solutions for four or more references and 6-hour or longer sessions. The larger errors in the measurements obtained from this study may be due to differences in meteorological conditions, station quality, outlier removal, and data processing. This study applied data collected over a 14-month period that experienced large atmospheric variability among different seasons. Eckl et al. (2001) used 10 days of data observed in May 1998. Firuzabadi and King (2011) applied 31 days of data collected in March, 2006. The average accuracy during a longer time period covering different seasons could be different from the accuracy attained during a short time period. The tropical weather of the Puerto Rico and Virgin Islands region, which is marked by numerous weather fronts, and accompanied thunderstorms and heavy rainfalls, as well as high temperatures and humidity throughout the year, may have contributed largely to the overall lower accuracy of GPS measurements. It should be noticed that the 4-hour session used in this study (local time 10:00 AM-2:00 PM) was slightly better than the accuracy in the worst time window (local time 12:00-16:00), but much worse than the accuracy in the best time window (local time 4:00AM-8:00AM) (Figure 6). The 6-hour window (local time 10:00 AM-4:00 PM) used in this study encompasses the entire worst

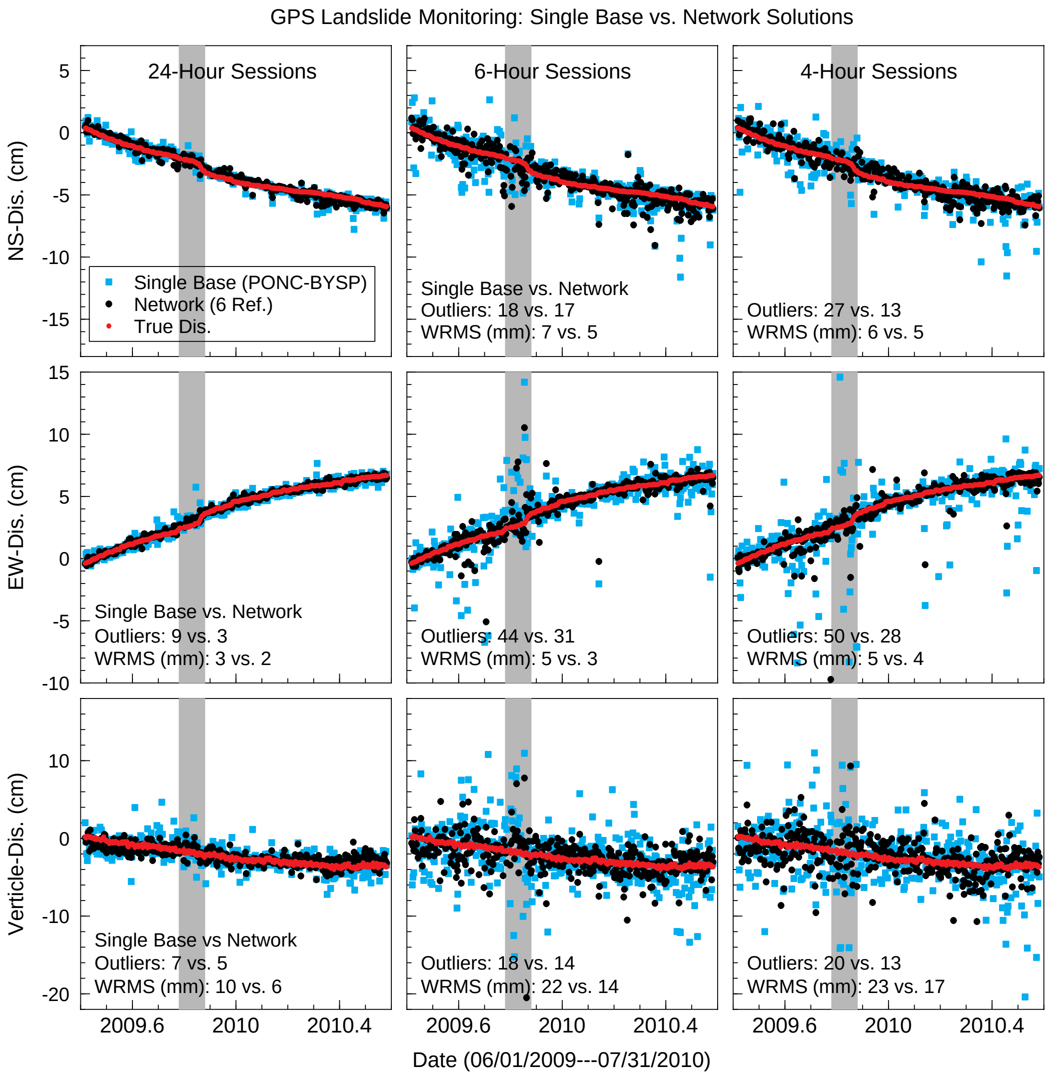

Figure 8. Plots illustrating the comparison of landslide displacements derived from a single-base solution and a network solution. The network solution utilized six reference stations (MOPR, PUR5, BYSP, CUPR, STVI, CRO1) 65 km away from the landslide site. The single-base solution used the closest reference (BYSP) among these six references. The true displacement was derived from a single-base solution (baseline 130 m) illustrated in Figure 3.

4-hour window. Thus, the statistical results presented in this study will tend to be conservative if campaign GPS surveys are performed at night or in the morning.

Standard tropospheric models are empirically derived from available radiosonde data, which were mostly observed in North America and Europe. A standard atmospheric model often fails to describe the actual meteorological conditions at a GPS site during a particular observation session. A site (spatial) and season (temporal) dependent database of weather condition statistics may provide a practical way to improve the estimation of wet tropospheric delay. Most permanent GPS stations of the Puerto Rico and Virgin Islands network are equipped with a weather sensor (Vaisala WXT-510, http://www.vaisala.com), which measures the six most essential weather parameters: wind speed, wind direction, precipitation, air temperature, air pressure, and humidity. Meteorological data is directly logged into GPS receivers. Continuous GPS data and meteorological data from about 10 stations covering 3 years are now available. Future research will be the determination of a site and season dependent statistical wet tropospheric model for the Puerto Rico and Virgin Islands region.

Acknowledgment

This study was initiated through discussion with Dr. Robert W. King at MIT. I thank him for his thoughtful suggestions regarding this study. Many people have contributed to the continuous landslide monitoring project. I particularly acknowledge Dr. James Joyce (University of Puerto Rico at Mayaguez) for many thoughtful discussions about the geological aspects of this landslide. I appreciate Ms. Ana Vicky Sanchez at USGS for providing rainfall data at USGS weather station 50115230. Graduate student Felix O. Rivera, and many geology and civil engineering undergraduates assisted in maintaining the continuous GPS monitoring. I appreciate their hard work in the field. This study was funded by a NSF project (EAR-0842314). The two continuous GPS at the landslide area were provided by UNAVCO (http://www.unavco.org) through its Equipment Loan Program. I appreciate Jim Normandeau, Frederick Blume, and Charles Meertens (UNAVCO) for their technical support.

References

Altamimi Z., Collilieux X., Legrand J., Garayt B., Boucher C., 2007, ITRF2005: A new release of the International Terrestrial Reference Frame based on time series of station positions and Earth Orientation Parameters , J. Geophys. Res., 112, B09401, doi:10.1029/2007JB004949.

Bevis M. M., Chiswell S., Businger S., 1995, GPS/STORM--GPS sensing of atmospheric water vapor for meteorology, Journal of Atmospheric and Oceanic Technology, 12: 468-478.

Boehm J., Niell A., Tregoning P., Schuh H., 2006, Global Mapping Function (GMF): A new empirical mapping function based on numerical weather model data, Geopgys. Res. Lett., 33, L07304, doi:10.1029/2005/GL025546.

Brückl E., Brunner F. K., Kraus K., 2006, Kinematics of a deep-seated landslide derived from photogrammetric, GPS and geophysical data, Engineering Geology, 88: 149-159.

Brunner F., Welsch W. M., 1993, Effect of the troposphere on GPS measurements, GPS World, 4(1): 42-51.

Chen G., Herring T. A., 1997, Effects of atmospheric azimuthal asymmetry of the analysis of space geodetic data, J. Geophys. Res., 102: 20,489--20,502.

Coe J. A., Ellis W. L., Godt J. W., Savage W. Z., Savage J. E., Michael J. A., Kibler J. D., Powers P. S., Lidke D. J., Debray S., 2003, Seasonal movement of the Slumgullion landslide determined from Global Positioning System surveys and field instrumentation, July 1998--March 2002, Engineering Geology, 68: 67-101.

Davis J. L., Elgered G., Niell A. E., Kuehn C. E., 1993, Ground-based measurement of gradients in the ``wet'' radio refractive index of air, Radio Sci., 28: 1003-1018.

Dodson A. H., Shardlow P. J., Hubbard L. C. M., Elgered G., Jarlemark P. O. J., 1996, Wet tropospheric effects on precise relative GPS height determination, Journal of Geodesy, 70: 188-202.

Dong D., Herring T. A., King R. W., 1998, Estimating regional deformation from a combination of space and terrestrial geodetic data, J. Geod., 72: 200-214.

Dow J. M., Neilan R. E., Rizos C., 2009, The international GNSS Service in a changing landscape of Global Navigation Satellite Systems, J. Geod., 83: 191-198.

Eckl M. C., Snay R. A., Soler T., Cline M. W., Mader G. L., 2001, Accuracy of GPS-derived relative positions as a function of interstation distance and observing-session duration, J. Geod., 75: 633-640.

Firuzabadi D., King R. W., 2011, GPS precision as a function of session duration and reference frame using multi-point software, GPS Solutions (doi: 10.1007/s10291-011-0218-8).

Gili J. A., Corominas J., Rius J., 2000, Using Global Positioning System techniques in landslide monitoring, Engineering Geology, 55: 167-192.

Gregorius T., Blewitt G., 1998, The effect of weather fronts on GPS measurements, GPS World, 1998-May, 52-60.

Herring T. A., King R. W., McCluskey S. M., 2009, Introduction to GAMIT/GLOBK, Release 10.35, mass. Instit. of Tech., Cambridge.

Iwabuchi T., Miyazaki S., Heki K., Naito I., Hatanaka Y., 2003, An Impact of estimating tropospheric delay gradients on tropospheric delay estimations in the summer using the Japanese nationwide GPS array, Journal of Geophysical Research, 108 (D10), 4315, doi:10.1029/2002JD002214.

Janes H. W., Langley R. B., Newby S. P., 1989, A comparison of several models for the prediction of tropospheric propagation delay, Proceedings of the Fifth International Geodetic Symposium on Satellite Positioning, Las Cruces, New Mexico, March 13-17, vol. 1, 28-52.

Jibson R. W., 1986, Evaluation of landslide hazards resulting from the 5-8 October 1985 storm in Puerto Rico, U.S. Geological Survey Open-File Report, 86-26.

Jibson R. W., 1989, Debris flows in southern Puerto Rico. Geol. Soc. Am., Special paper 236: 29-55.

Larson K. M, Small E. E., Gutmann E. D., Bilich A., Axelrad P., Braun J. J., 2008a, Using GPS multipath to measure soil moisture fluctuations: Initial results, GPS Solut., 12(3): 173-177, doi:10.1007/s10291-007-0076-6.

Larson K. M., Small E. E., Gutmann E. D., Bilich A. L., Braun J. J., Zavorotny V. U., 2008b, Use of GPS receivers as a soil moisture network for water cycle studies, Geophys. Res. Let., 35, L24405, doi:10.1029/2008GL036013.

Larson K. M., Braun J. J., Small E. E., Zavorotny V. U., Gutmann E. D., Bilich A. L., 2010, GPS multipath and its relation to near-surface soil moisture content, IEEE J-STARS, 3: 91-99, doi: 10.1109/JSTARS.2009.2033612.

MacMillan D. S., 1995, Atmospheric gradients from very long baseline interferometry observations, Geophys. Res. Let., 22(9): 1041-1044.

Malet J. P., Maquaire O., Calais E., 2002, The use of Global Positioning System techniques for the continuous monitoring of landslides---application to the Super-Sauze earthflow (Alpesde Haute-Province, France), Geomorphology, 43: 33-54.

Mie G., 1908, Beiträge zur Optik trüber Medien, speziell kolloidaler Metallˆ sungen, Annals of Physics, Vol. 25: 377-445.

Mora P., Baldi P., Casula G., Fabris M., Ghirotti M., Mazzini E., Pesci A., 2003, Global Positioning Systems and digital photogrammetry for the monitoring of mass movements: application to the Ca di Malta landslide (northern Apennines, Italy), Engineering Geology, 68: 103-121.

Olsen R.L., Rogers D.V., Hodge D.B., 1978, The aRb relation in the calculation of rain attenuation, IEEE Trans. Ant. Prop., Vol. AP-26: 318-329.

Peyret M., Djamour Y., Rizza M., Ritz J. F., Hurtrez J. E., Goudarzi M. A., Nankali H., Chery J., Le Dortz K., Uri F., 2008, Monitoring of the large slow Kahrod landslide in Alboz mountain range (Iran) by GPS and SAR interferometry, Engineering Geology, 100: 131-141.

Psimoulis P., Ghilardi M., Fouache E., Stiros S., 2007, Subsidence and evolution of the Thessaloniki plain, Greece, based on historical leveling and GPS data, Engineering Geology, 90: 55-70.

Ray P. S., 1972, Broadband complex refractive indices of ice and water, Applied Optics, 11 (8): 1836-1844.

Rocken C., Hove T. V., Johnson J., Solheim F., Ware R., 1995, GPS/STORM---GPS sensing of atmospheric water vapor for meteorology, Journal of Atmospheric and Oceanic Technology, 12: 468-478.

Saastamoinen J., 1972, Atmospheric correction for the troposphere and stratosphere in radio ranging of satellites, The use artificial satellites for geodesy. Edited by S. W. Henricksen, A. Mancini, B. H. Chovitz, Geophysical Monograph 15, American Geophysical Union, Washington D. C., pp. 247-251.

Sato H. P., Abe K., Ootaki O., 2003, GPS-measured land subsidence in Ojiya City, Niigata Prefecture, Japan, Engineering Geology, 67: 379-390.

Soler T., Michalak P., Weston N. D., Snay R. A., Foote R. H., 2006, Accuracy of OPUS solution for 1- to 4-h observing sessions, GPS Solution, 10: 45-55, doi:10.1007/s10291-005-00087-3.

Squarzoni C., Delacourt C., Allemand P., 2005, Differential single-frequency GPS monitoring of the La Valette landslide (French Apls), Engineering Geology, 79: 215-229.

Tagliavini F., Mantovani M., Marcato G., Pasuto A., Silvano S., 2007, Validation of landslide hazard assessment by means of GPS monitoring technique--- a case study in the Dolomites (Eastern Alps, Italy), Natural Hazards and Earth System Sciences, 7: 185-193.

Wang G., Phillips D., Joyce J., Rivera F. O., 2011, The Integration of TLS and Continuous GPS to Study Landslide Deformation: A Case Study in Puerto Rico, Journal of Geodetic Science, 1(1): 25-34, doi: 10.2478/v10156-010-0004-5.

Wu S. C., 1979, Optimum frequencies of a passive microwave radiowave radiometer for tropospheric path-length correction, IEEE Transactions on antennas and propagation, 27(2): 233-239.