Performace of High-Rate Kinematic GPS During Strong Shaking: Observations from Shake Table Tests and the 2010 Chile Earthquake

Research Article

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Abstract:
Over the last decade, the 1-sample-per-second kinematic Global Positioning System (GPS) has been used as a displacement sensor in earthquake observations and for structural health monitoring. Many researchers in both seismology and engineering have expressed the desire for higher-sample-rate (10-sample-per-second or higher) GPS data to acquire high-frequency displacement information. We performed several shake table tests of GPS observation on 29 April, 2009 for the purpose of evaluating the performance of high-rate kinematic GPS. We found that the accuracy of high-rate kinematic GPS depended on antenna movement, but was independent of receiver sampling rate. The errors in kinematic GPS measurements during the periods of strong shaking were systematically larger than those during the static periods. Furthermore, we found that these large errors were coincident with large accelerations and jerks in the motions experienced by the GPS receivers and antennas. Observations from the 2010 earthquake in Maule, Chile (M 8.8) indicated that strong ground motions can degrade the accuracy of high-rate kinematic GPS measurements. Significant jerks and/or accelerations can cause GPS units to temporarily lose tracking on satellite signals and lead to gaps in GPS-recorded seismograms.

Keywords:
high-rate GPS • accuracy • strong ground motion • shake table

1. Introduction

During the last decade, 1-sample-per-second (sps) continuous GPS data have been used to measure strong earthquake ground motions and the vibrations of high-rise buildings and long-span bridges. A number of previous studies have found good agreement between 1-sps kinematic GPS positions and medium- and long-period (e.g., > 4 s) earthquake ground motions recorded by nearby or collocated accelerographs or by broadband velocity sensors. This has been shown for various earthquakes: 2002 Denali, Alaska (M 7.9), (e.g., Larson et al., 2003; Bock et al., 2004; Bilich et al., 2008); 2003 Tokachi-Oki, Japan (M 8.0), (e.g., Clinton, 2004; Irwan et al., 2004; Miyazaki et al., 2004; Emore et al., 2007); 2003 San Simeon, California (M 6.5), (e.g., Ji et al., 2004; Wang et al., 2007); and 2004 Sumatra, Indonesia (M 9.1), (e.g., Davis and Smalley, 2009). High-rate GPS has been recognized as a technology useful for measuring large earthquake displacements. The potential for GPS seismology has been discussed by many researchers (e.g., Ge, 1999; Ge et al., 2000b; Nikolaidis et al., 2001; Larson et al., 2003; Wang et al., 2007; Bilich et al., 2008; Larson, 2009; Smalley, 2009). In the engineering community, high-rate GPS has been used frequently as a displacement sensor to study the dynamics of tall
buildings, towers, and bridges during earthquakes, high winds and traffic loading (e.g., Celebi, 2000; Celebi and Sanli, 2002; Oğaja et al., 2007). Many researchers have pointed out the need for 10-sps GPS (or even higher sampling rate) data in both seismology and engineering studies (e.g., Celebi and Sanli, 2002; Genrich and Bock, 2006; Wang et al., 2007; Oğaja et al., 2007; Larson, 2009; Smalley, 2009). Several 10-sps GPS seismograms from the 2009 earthquake in L’Aquila, Italy, (M 6.3) have been used to study strong ground motions and earthquake source mechanisms (e.g., Avallone et al., 2011). A few researchers in civil engineering have used 10-sps GPS as a new displacement sensor in structural health monitoring of bridges, dams, high-rise buildings, and other structures (e.g., Celebi and Sanli, 2002; Liet al., 2006).

Accuracy studies of high-rate GPS have become an active area of research. The majority of results, however, have been obtained from comparisons with limited seismograms recorded during several medium and large earthquakes. Ji et al. (2004) reported standard deviations of 0.3, 0.7, and 1.1 cm for the east-west, north-south, and vertical displacements for the 1-sps GPS data from the 2003 San Simeon, California earthquake (M 6.5). Bock et al. (2004) demonstrated single sample accuracy of 0.2 to 0.3 cm in the horizontal directions for teleseismic waves derived from 1-sps GPS data recorded by the Southern California Integrated GPS Network (SCIGN) during the 2002 Denali earthquake (M 7.9). Elosegui et al. (2006) reported errors generally less than 0.5 cm from their positioning table studies, which were based on single-axis (north-south) movements and 1-sps GPS data. To evaluate the performance of high-rate kinematic GPS in a dynamic environment, we performed tests with an outdoor shake table in Boulder, Colorado, on 29 April, 2009. The shake table, supplied by ANCO Engineers Inc. (http://www.ancengineers.com), was a six-degree-of-freedom (6-DOF) servo hydraulic table (Figure 1a). The table was available for these tests for a short interval prior to being shipped to an ANCO client. We installed a reference GPS station (STRF) on the roof of ANCO’s offices (Figure 1b) and three rover GPS stations on three corners of the table. We refer to these rover GPS units as STNE, STNW, and STSW according to their locations on the table (Figure 1c). Throughout the study, we used Trimble NetRS GPS receivers and choke ring antennas (IGS Model: TRM29659.00), which represent the majority of GPS units used at current Plate Boundary Observatory (PBO, http://pbo.unavco.org) GPS stations. Our motivation for choosing this particular GPS unit is to study the performance of PBO GPS stations during large earthquakes. Most PBO stations have a high-rate (5-sps) data buffer to record seismic waves during large earthquakes. The motions of the shake table were described by three translational motions (X, Y, Z) and three rotational motions (pitch, roll, and yaw), as defined in Figure 2. Pitch and roll are tilts of the platform about the horizontal axes. Yaw is rotation of the platform about the vertical axis. In order to record high-frequency shake table motions, we also installed a triaxial strong-motion accelerometer manufactured by Kinematics Inc. (model Ena, http://www.kinemetrics.com/p-76-Etna.aspx) at
The definition of the 6 degrees of freedom (6-DOF) measurements of satellites was set to 15° used TRACK version 1.21, released with the GAMIT/GLOBK version processing program TRACK developed at MIT (Chen, 1998). We of these GPS antennas were calculated using the kinematic data Checking) (Estey and Meertens, 1999). The kinematic positions were converted to Receiver Independent Exchange (RINEX) format by using the program "TEQC" (Translating, Editing, Quality Checking) (Estey and Meertens, 1999). The kinematic positions of these GPS antennas were calculated using the kinematic data processing program TRACK developed at MIT (Chen, 1998). We used TRACK version 1.21, released with the GAMIT/GLOBK version 10.35 (Herring et al, 2009), as well as IGS final orbits. The mask elevation of satellites was set to 15°. The GPS unit on the office roof was used as a reference station in the kinematic data processing. The accelerograph raw data were in binary format. We converted them to the standard Seismic Analysis Code (SAC) format and then conducted basic processing, including removing pre-event means, high-pass or bandpass filtering, double integration, and Fourier transformations. The final displacement time series from both the GPS and accelerograph were translational motions in three components: the north to south (NS), east to west (EW), and vertical (Z) directions.

3. Accuracy vs. Sampling Rate

The Trimble NetRS receivers were set up to log data simultaneously at 10 sps, 5 sps, 1 sps, and 1 sample per 15 seconds. According to the manufacturer, no internal averaging or filtering was applied to the raw data. The maximum sampling rate of Net RS receivers is 10 sps. The 5-sps, 1-sps, and 1-sample-per-15-second raw data streams can be regarded as decimated streams from the 10-sps raw data stream, so the raw data at the same instant (epoch) should be identical. We confirmed this for carrier phase observations.

However, we wondered if kinematic positions obtained by the TRACK processing still retain this characteristic. TRACK is a time-dependent form of data analysis that applies a Kalman filter, that estimates past, present, and future states. Kalman filtering consists of three parts: initialization, prediction, and update. The prediction step provides a best guess of the position at the next sample time and its associated variance, based on the available information up to that time. The update step takes the incoming observations and predictions to estimate a new position (Chen, 1998). TRACK defaults were used in this study, and we did not tailor any parameters of the Kalman filter to match the positions obtained from different data sets. Figure 3 is an example of a kinematic GPS position time series calculated by TRACK from each of these four raw-data streams (10 sps, 5 sps, 1 sps, and 1 sample per 15 second). These plots show identical positions (baseline lengths) at common epochs, so the accuracy of these kinematic measurements will be the same. Thus, we only investigated the accuracy of 1-Gsp s kinematic GPS measurements in the following study.

4. Comparisons of GPS and Accelerograph Data

Figure 4 illustrates a portion of the three-component translational motions measured by the accelerograph and one GPS unit (STNE). The signals sent to the shake table control system were 2-Hz sinusoidal waves with amplitudes of ±5 cm for all three translational components. No rotational motions were commanded. The accelerograph and GPS data were aligned according to GPS time, which was 15 s ahead of Coordinated Universal Time (UTC) at the time we performed these tests. GPS time was used throughout this study. The original accelerograph data were, of course, acceleration. So the displacement time series were calculated by double integration. A band-pass filter (1−3 Hz) was applied to both accelerograph and GPS data to make sure that the comparisons were in a similar frequency range. This comparison indicates that the two displacement traces compare well in phase but show some differences in amplitude. In the NS component, for example, displacements estimated by GPS were about 2 cm larger than those derived from the accelerograph. The differences in EW and vertical components were smaller.

The mismatch between the two kinds of data is explained as follows. First, the accelerograph and GPS antenna (STNE) were not in the same place (see Figure 1c). Translational motions were different at different locations on the table because of rotations and tilts of the shake table. Complete characterization of motions of a rigid body requires measurements of all six-degrees-of-freedom (DOF), as shown in Figure 2, including three translational and three rotational motions. A single GPS or strong motion accelerograph can only measure three translational motions. Figure 5 illustrates a session of the 6-DOF shake table motions including three translational motions and three rotations (pitch, roll, and yaw). The rotational motions of the rigid table were inferred from three translational motions of the GPS array. The maximum pitch and roll were
The center of the accelerograph was about 10 cm away from the center of the table (the table is approximately 1 m by 1 m). The horizontal distances between centers of the accelerograph and the GPS antenna were about 50 cm in both NS and EW components. One degree of rotation around the EW axis (pitch) or NS axis (roll) could cause about 0.6 cm difference in the vertical translational displacements between the accelerograph and the GPS antennas, while one degree of rotation around vertical axis (yaw) would cause about 0.6 cm difference in the two horizontal components. Thus a 3° rotation would cause a 2 cm difference in translational motions between the accelerograph and GPS antennas.

The second reason for the mismatch between the two types of data is that the displacements inferred from accelerograph data do not represent the true translational motions at the site of the accelerograph. Seismometers are sensitive to not only translational motions, but also to rotational motion induced by rotations and tilts. Measurements from an accelerograph represent the combined effects of translational motions and the tilts within the Earth’s gravitational field, and possibly other effects (Boore 2001; Wang et al., 2003; Graizer 2006; Graizer 2009; Graizer 2010). For example, a 3° tilt will cause a horizontal acceleration error of 5% of $g$. These previous studies suggest that rotations and tilts mainly affect long-period motions, particularly residual displacements. Graizer (2005) reports that ignoring the presence of tilts does not significantly affect the calculation of the oscillatory (high-frequency) component of a displacement time series. A high-pass filter is often applied to minimize the effect of tilts on seismograms. The displacements illustrated in Figure 4 were subjected to a band-pass filter ($1$–$3$ Hz). We believe that tilts and rotations of the shake table may have caused certain errors on the accelerograph, though this effect has been reduced to low levels by the filter. Errors inherent to both the accelerograph and GPS devices would also have contributed to the mismatch between the accelerograph and GPS data. This study focused on investigating...
the possible errors related to the high-rate GPS device.

5. The True Inter-Antenna Distance

The shake table was being tested when we performed our experiment and was not fully calibrated. Figure 5 shows significant rotational motions even though only translational motions were sent to the device. We did not install other kinds of sensors to independently record the table motions; as a result, it is difficult to get the true movements of the shake table. We did not attempt to study the accuracy of kinematic GPS component by component here because of the difficulty in getting true values of the displacements. Instead, we analyzed the distances between each pair of GPS antennas on the shake table, which should be constant. We used these distances as a length standard to evaluate the accuracy of high-rate kinematic GPS. We call this distance the inter-antenna distance.

The commercial GPS software package Topcon Tools (Version 7.1) (Topcon Inc., http://www.topconpositioning.com) was used to calculate the “true” inter-antenna distance with a rapid-static method using static data collected during a 25-minute window. The distances so derived are listed in Table 1. The measurements were accurate to 1 mm horizontally and 2 mm vertically, according to the Topcon software reports. We also measured the inter-antenna distances on the table with a steel tape. The rapid-static GPS results are comparable with our direct measurements, as expected, but show higher precision. The rapid-static measurements were regarded as the “true” inter-antenna distances in evaluating the accuracy of kinematic GPS in this study. The TRACK program outputs three-component positions relative to the reference GPS station on the office roof at each epoch. The inter-antenna distance at each epoch was therefore the vector difference between the two antenna positions. The error time series was defined as the difference between the static and kinematic GPS estimates:

$$\text{Error}(i) = \text{TRUTH} - K(i)$$

where \(\text{TRUTH}\) is a constant distance calculated by the rapid static GPS method, and \(K(i)\) represents the inter-antenna kinematic distance at epoch \(i\). We analyzed the error time series over
Figure 5. Plots showing the effects of shake table motions on the accuracy of 10-sps GPS kinematic positions. (a) The error time series of inter-antenna distance (see Equation (1)). (b) Three-component rotational motions of the table inferred from the GPS array. (c) Three-component translational motions at the GPS antenna STNE. The right column is 30-s period shaded in the left column.

6. Errors vs. Shake Table Motions

In this section, we discuss the error time series of kinematic GPS measurements within a 700-s window started at 19:45:40 (29 April, 2009). Figure 5 illustrates the translational and rotational shake table motions and the corresponding error time series of the kinematic GPS measurements. It is clear that the magnitude of the error depends on the status of the table (moving or stationary). The right-hand column is an expanded view of the 10-s window.
Figure 6. Distribution of errors of 10-sps kinematic GPS displacements in both time (left column) and frequency (right column) domains. The top plots illustrate the error time series of the GPS measured inter-antenna-distance and their corresponding Fourier spectra while the table was moving. The bottom plots illustrate the error time series and spectra while the table was stationary.

Table 1. Comparisons of Inter-Antenna Distances Calculated With Two Different GPS Methods: Rapid Static and Kinematic

<table>
<thead>
<tr>
<th>GPS-to-GPS</th>
<th>Rapid Static $^a$ (cm)</th>
<th>Kinematic-Stationary $^b$ (cm)</th>
<th>Kinematic-Moving $^c$ (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>STSW-to-STNW</td>
<td>99.42</td>
<td>100.00</td>
<td>0.23</td>
</tr>
<tr>
<td>STSW-to-STNE</td>
<td>141.68</td>
<td>141.96</td>
<td>0.26</td>
</tr>
<tr>
<td>STNW-to-STNE</td>
<td>100.18</td>
<td>99.66</td>
<td>0.28</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>0.26</strong></td>
<td><strong>0.66</strong></td>
<td></td>
</tr>
</tbody>
</table>

$^a$ Data collected during a 25-minute window from 18:00 to 18:25, 29 April, 2009 (GPS time) was used for the rapid static processing.

$^b$ Kinematic positions during the 1-minute stationary window (600 samples) from the 5th second to 65th second (Figure 6) were used in the statistical study.

$^c$ Kinematic positions during the 1-minute moving window (600 samples) from the 280th second to 340th second (Figure 6) were used in the statistical study.

shaded in the left-hand column. The errors during moving intervals are systematically larger than those during static intervals. Figure 6 further illustrates the distribution of the errors in both time and frequency domains. The bottom plots illustrate the errors in a static time window. The Fourier spectra of the static session indicate that the high-frequency (e.g., 0.2 Hz to 5 Hz) response is flat ("white noise"), which implies that the errors are equally distributed across the whole frequency range. However, the distribution of the errors during the moving window is not a simple white noise process but instead contains significant periodic components. In order to highlight the long-period components, the spectra were replotted on a log-log scale (Figure 7). The spectra are a combination of white noise (for the static window) or near-white noise (for the moving window), flicker noise, harmonic, and subharmonic components. This result is consistent with the findings from earlier studies of both daily and single-epoch GPS solutions (Zhang et al., 1997; Mao et al., 1999; Caporali, 2003; Williams et al., 2004; Elosegui et al., 2006; Genrich and Bock, 2006). Mao et al. (1999) report that a combination of white noise and flicker noise appears to be the best model for noise characteristics in daily time series of GPS data. Our results indicate that the error distribution of 10-sps kinematic GPS measurements with motionless position can also be modeled effectively by combining white noise and flicker noise. The corner frequency of the flicker noise where it rises above the white noise floor is about 0.2 Hz. This value may vary, depending on the specific data set. Genrich and Bock (2006) report that the corner frequency is about 0.5 Hz for the 50-sps data they studied. Flicker noise occurs in all electronic devices at low frequencies. This behavior is common in complex systems, and represents the combined effects of noise in the GPS receiver and antenna electronics.
Figure 7. The log-log plots of the Fourier displacement spectra from Figures 6(a) and (b). The top-plot shows the spectra of errors while the table is moving, and the bottom-plot shows the spectra while the table is stationary.

The white noise signature at high frequencies (higher than the corner frequency 0.2 Hz) suggests that kinematic GPS positions are essentially uncorrelated or independent over short time intervals. This result implies that the sampling rate can be increased without loss of accuracy, which is consistent with our comparisons of kinematic measurements from several raw-data streams with different sampling rate streams (Figure 3). The white noise distribution of kinematic GPS errors at high frequencies supports the goal of developing high-rate GPS seismometers, because it implies that the receiver sampling rate can be increased without loss of precision.

Figure 8 shows the jerk and acceleration time series and the Fourier spectra of the shake table motions derived from accelerograph data; jerk is the derivative of acceleration with respect to time. A high-pass filtering at 0.2 Hz was applied to the accelerograph data to minimize the effect of instrument tilt. While these data were distorted by uncommanded rotations of the shake table, their high-frequency contents reflected at least the general spectral and temporal behavior of the table motion. The peak jerks and accelerations during the 2-Hz sinusoidal motions were over 50 g/s and 1 g, respectively, which are comparable to the peak jerks and accelerations that were observed in the near-fault area of the 1999 Chi-Chi, Taiwan earthquake (M 7.6) (Wang et al., 2002; Tong et al., 2005). It is clear that the table motions are not pure sinusoidal motions, and likely contain sharp signals caused by backlash in the shake table mechanism. The spectra are rich in superimposed harmonic waves, in addition to the 2-Hz fundamental. Sudden or discrete movements of the shake table would create these harmonics. Figure 6 shows that the GPS errors are dominated by a fundamental frequency at 2 Hz and its associated harmonic frequency (4 Hz), as well as subharmonics (1 Hz and 3 Hz). The agreement between the dominant frequencies of the GPS errors and of the shake table motions indicates that these two are related.

We also sent 1-Hz and 0.5-Hz sinusoidal motions to the shake table and studied their error time series. We found that GPS error time series corresponding to 1-Hz and 0.5-Hz sinusoidal shake table motions were also dominated by a fundamental frequency (1 Hz or 0.5 Hz) and its associated harmonics, but there were no considerable subharmonics. The Fourier spectra of the accelerograph data also did not show any considerable subharmonic frequencies (Figure 8). We believe that the subharmonic components within the GPS errors were inherent to the GPS system rather than the shake table system. Subharmonic noises have been well studied in electronic engineering. They are often related to the nonlinear response of a system to oscillator signals (Reik et al., 1969; Dykman et al., 1996). The subharmonic components within the kinematic GPS errors may correlate to the nonlinear response of the GPS system to direct or reflected satellite signals, which act as oscillator signals relative to the GPS antenna during periods of strong shaking.

7. Sources of Errors

Figure 9 is a detailed comparison of the GPS errors to the accelerations and jerks of the shake table as inferred from the accelerograph data within a 5-s window. It shows that the large errors are synchronous with large accelerations and jerks, while keeping a phase lag with respect to velocities. This implies that the issue causing these large errors is the rate of the change of the force or the force itself. The synchronism suggests a causal relationship between the strong motions (as shown by the large accelerations and jerks) and the large errors in kinematic GPS measurements. Slight relative movements between the GPS antennas and shake table, and/or slight flexure of the table could also affect GPS measurements. However, we do not think the contribution from these effects would be large. We mounted GPS antennas on the table very firmly using custom-welded 15-mm-diameter steel bolts that held the base of the antenna 10 cm above the table. We did not observe any loss of connection or relative motions of the antennas at any point during the test. The table top is 4-cm-thick aluminum with additional welded stiffening braces. Its resonant frequency is above 30 Hz. We are certain that the table did not flex considerably during the tests.

To further investigate the correlations between the strong shaking and the errors of kinematic GPS, we diagnosed the raw GPS data with UNAVCO’s quality check program TEQC (Estey and Meertens,
Figure 8. Plots showing jerks, accelerations, and Fourier acceleration spectra inferred from original accelerograph data. A high-pass filter at 0.2 Hz was applied to the accelerograph data to limit the effects of instrument tilts. The bottom plots show the Fourier spectra of accelerations, indicating that table motions were not pure 2-Hz sine waves but contain harmonics at 4 Hz, 6 Hz, and 8 Hz.

1999). The main output of the TEQC program is eight parameters: satellite elevation angle, satellite azimuth, L1 signal-to-noise ratio (SNR), L2 SNR, L1 pseudorange multipath (MP1), L2 pseudorange multipath (MP2), the normalized L2-L1 ionospheric delay, and the time rate of change of the ionospheric delay. TEQC does the calculations on an epoch-by-epoch basis. We evaluated the time series of elevation, azimuth, carrier SNR, and pseudorange multipaths, as described below.

There were eight visible satellites at this site during the 700-s window. The elevations of three satellites were below 15°, and were not used in the TRACK program for calculating baseline lengths, leaving only five for use by the TRACK program during this time period. The elevations of three high-elevation satellites (G31-60°, G14-56°, G22-39°) changed no more than 5° during this same period. The elevation changes of the other two satellites (G11-30°, G30-21°) were even less than 2°. The changes of the satellite azimuths during the 700-s window were also small (less than 5°). We believe that the changes of satellite elevation and azimuth during our experiment (less than 15 minutes) did not impact the multipath significantly.

Multipaths are the dominant error source in high-precision positioning applications. If the antenna is stationary, the multipath errors will be characterized as a very slow frequency fluctuation, with amplitudes and periods dependent on nearby reflective surfaces (Ogaja and Satirapod, 2007). A GPS receiver can readily resolve the multipath if the multipath delay is large, but multipath values normally indicate large tracking errors. It is clear that both SNRs degraded systematically during shaking periods, particularly for L1. The decreasing of SNR might result from the decreasing of signal, increasing of noise, or both. Several authors have used SNR to assess carrier phase multipath conditions (e.g., Bilich and Larson, 2007). Figure 11 illustrates the evolution of multipath during the same time window. In general, MP1 and MP2 were larger during rapid-motion sessions than during static sessions. According to the TEQC documentation, “MP1” is a linear combination of P1, L1, and L2, while “MP2” is a linear combination of P2, L1, and L2. L1 and L2 refer to the phase measurements of the two GPS frequencies, and P1 and P2 refer to pseudorange measurements. Thus, the effect of strong motions on MP1 and MP2 (combination of phase and code observations) is not as clear as the effect to on SNA (only phase observations) shown in Figure 10. However, the larger MP1 and MP2 values during strong shaking periods still indicate the change of multipath environments, particularly for lower-elevation satellites.
Figure 9. Plots indicate that significant GPS errors were synchronous with jerks and accelerations while kept a phase lag with velocities of shake table motions derived from the accelerograph data. A high-pass filter at 0.2 Hz had been applied to the accelerograph data.

reflections from nearby objects (trees, buildings, ground, and vehicles), or even grazing multipath reflected from distant objects, can arrive with short delays (tens or hundreds of nanoseconds) relative to the direct signal (Kaplan and Hegarty, 2006). These short-lag multipaths can distort the composite phase of the received signal and thus will introduce errors in pseudorange and carrier phase measurements. Numerous studies of the mitigation of GPS multipath errors have been performed (e.g. Elosegui et al., 1995; Ge et al., 2000a; Choi et al., 2004; Larson et al., 2007). Most of these studies focused on middle and long period (e.g. larger than 10 s) multipaths generated in stationary environments; multipaths generated in a dynamic environment and those relevant to high-rate GPS data have not been widely studied. The multipath errors induced by rapid, periodic relative movements between an antenna and its nearby reflectors may be much more complex. A high-cut (low-pass) filter can be applied to remove certain errors caused by the rapidly changing multipaths (Figure 12). However, ground motion information at frequencies higher than the corner frequency of the filter will also be removed. A reasonable corner frequency should be applied depending on the ground-motion frequency range of interest.

Figure 10. Plots showing signal to noise ratios (SNRs) for various GPS satellites. SN1 and SN2 represent the signal to noise ratio for GPS satellite signal L1 and L2, respectively. The top plot illustrates the corresponding shake table motions at GPS antenna STNW (EW component) and the errors of the kinematic GPS measurements (distance between STNW and STNE).

The TEQC program resets MP1 and MP2 to zero whenever a cycle slip is detected. Figure 11 indicates frequent cycle slips within the low-elevation GPS satellite G12 during shaking periods. A cycle slip is caused by temporary loss-of-lock in the carrier tracking loop of a GPS receiver, which can corrupt the carrier phase measurement. A low SNR due to multipath and high receiver dynamics can cause cycle slips, and a failure in the GPS receiver can also cause incorrect signal processing and cycle slips (Hofmann-Wellenhof et al., 2001). Data from satellite G12 were not used in calculating the baselines since its elevation was lower than 15° during the time period. Thus, its cycle slips did not contribute to these errors that were observed in Figure 6 but they do indicate that high dynamics can...
Figure 11. Plots showing pseudorange multipath estimates (MP1 and MP2) for each GPS satellite. The top plot illustrates the corresponding shake table motions at GPS antenna STNE (EW component) and the errors of the kinematic GPS measurements (distance between STNW and STNE).

degrade the tracking capabilities of GPS units. High dynamics can even cause loss-of-lock on satellite signals and corrupt phase measurements. This was observed from a few near-source 1-sps GPS seismograms recorded during the 2010 Chile earthquake (M 8.8).

8. Performance of the High-Rate GPS During the 2010 Chile Earthquake (M 8.8)

The large 2010 Maule, Chile earthquake (M 8.8) provided a significant number of near-fault high-rate (1-sps) GPS seismograms. We found that a few high-rate GPS seismograms were “clipped” during this earthquake. Three-component 1-sps GPS seismic data recorded by the International GNSS Service (IGS) station CONZ in the Transportable Integrated Geodetic Observatory (TIGO) in Concepción are analyzed in this section. CONZ was about 107 km south of the epicenter of this earthquake.

The CONZ GNSS station was equipped with a Leica GRX1200 GPGPRO receiver and TPSCR3_GGD antenna with a radome, which recorded the strong motions at both 30- and 1-sps sampling rates. Seismic data recorded by a nearby strong motion station CCSP were used to estimate the high-frequency strong ground motions at the GPS site. The strong motion station is in San Pedro de Concepción, 7 km west to the CONZ GPS station. The accelerograph (ENTA) used at CCSP was manufactured by Kinemetrics Inc. (http://www.kinemetrics.com), and is a similar model to the accelerograph that we used for the shake table tests. Uncorrected data were available via the USGS website (http://nsmp.wr.usgs.gov/data_sets/20100227_0634.html). Both stations were about 107 km south of the epicenter, and thus the P and S arrivals of seismic waves at the two sites should have
Figure 12. Comparisons of un-filtered and high-cut (low-pass) filtered error time series from 10-sps kinematic GPS measurements. A high-cut (low-pass) fourth-order Butterworth filter was applied. A high-cut filter removes some high-frequency multipath errors, but sacrifices any true ground motion information at frequencies higher than the corner frequency of the filter.

been similar. The peak ground accelerations (PGAs) recorded at the CCSP site were 638 cm/s$^2$ NS, 594 cm/s$^2$ EW, and 571 cm/s$^2$ vertical. The peak velocities inferred from the acceleration data were 39 cm/s NS, 45 cm/s EW, and 25 cm/s vertical. The permanent displacements inferred from the 1-sps GPS data were 0.7 meters to the south, 3 m to the west, and 0.2 m to the down direction.

Figure 13 shows the seismic waves recorded by the CCSP and the availability of phase observations recorded by the CONZ GPS station. There were two observation gaps (missing data) within the GPS phase observations, indicating the GPS receiver lost its lock on satellite signals. The receiver was tracking 8 GPS satellites and 6 GLONASS satellites at the time this earthquake happened. It lost lock on both L1 and L2 of five GPS satellites and three GLONASS satellites at the time this earthquake happened. The average elevation of each satellite within this 100-s window is marked at the right side of each plot. It is surprising to see that the receiver lost lock on two GPS satellites with higher elevation degrees (G20-68° and G23-70°) while maintaining lock on two GPS satellites and one GLONASS satellite with lower elevation degrees (G17-30°, G3-40°, R18-20°). The GPS receiver recovered lock on L2 of these three GLONASS satellites in one second, but it took five seconds to recover lock on L1 of these same three GLONASS and L1 and L2 of the five GPS satellites. The receiver maintained continuous lock on both L1 and L2 of these 14 satellites until 6:35:39, 44 s after the recovering of the first break. The receiver lost lock on all signals of all satellites at this epoch, then recovered lock on L2 of all GLONASS satellites in one second, and recovered lock on L1 of all GLONASS satellites except R11 and L1 and L2 of all GPS satellites after four seconds. The L2 of GLONASS satellite R11 was recovered after a five-second break. The first data gap was coincidental with the large jerks.
Figure 14. Plots showing effects of strong ground motions on satellite signal to noise ratios (SNRs) at CONZ during the 2010 Chile earthquake (M 8.8). The top plots illustrate jerk and acceleration time series (NS component) at CCSP (over 20 g/s) and accelerations (over 0.6 g) occurring shortly after the arrival of the earthquake's shear wave. The second gap is more difficult to explain, however. It appears that the lock-break also followed a significant horizontal jerk pulse as shaded in Figure 13, but stronger jerks and accelerations had occurred before this pulse, and the GPS receiver maintained lock on all satellite signals. Further investigations indicate that the satellite signal to noise ratio (SNR) was significantly degraded during the period of strong shaking (Figure 14). Low SNRs tend to cause phase tracking problems and lead to large errors in GPS measurements. Senior engineers at Leica analyzed the 1-sps raw data from the Leica GRX1200GGPRO receiver at CONZ station and a brief report (Neil Brown of Leica, personal comm.) indicated confidence that the first data gap during the initial impact of the earthquake was related to the sudden movement (large acceleration and/or jerk) that exceeded the limits of the carrier tracking loop, causing loss of lock on most of the satellites. If the instantaneous jerk on the system is high enough, it can push the tracking loops outside their capture range. The loss-of-lock could have occurred by a combination of movement of the antenna, internal receiver clock, and external master clock.

The permanent GPS station, CONT, in the Transportable Integrated Geodetic Observatory also recorded the strong earthquake ground motions induced by the Chile earthquake with a 1-sps sampling rate. CONT had a SEPT POLARX2 receiver and an ASHT700936E antenna with a SNOW radome. The distance between CONZ and CONT was about 100 m. We also found the loss-of-lock problem in the raw data. Another IGS station SANT in Santiago (about 400 km away from the epicenter) also suffered from the data loss problem during this earthquake. This GPS station had an ASHTECH UZ-12 receiver and AOAD/M_T antenna with a JPLA radome. There was a 32-s data gap during the 1-sps GPS seismogram coinciding with the strongest earthquake ground motions at this site. The large gap may be caused by a combination of the receiver loss-of-lock and a temporary failure of power supply. Figure 15 illustrates earthquake displacement time series derived from 1-sps GPS raw data recorded by the three GPS receivers. The GPS seismograms were precise point-positioning solutions processed by the GIPSY software using the JPL final orbits and clocks. The top plots illustrate the acceleration time series recorded by nearby strong-motion stations. The distance between strong-motion station CCSP and GPS stations CONZ and CONT was about 7 km. The distance between strong motion station STL and SANT was about 30 km. Figure 15 clearly indicates that these 1-sps GPS seismograms were “clipped” by significant strong-earthquake ground motions. As a result, GPS seismograms missed the most meaningful strong earthquake ground motion information.

9. Discussion and Conclusions

We have shown that the accuracy of high-rate kinematic GPS depends on the motions of GPS antennas. The errors that occur while the antennas are moving are larger than those when they are at rest. Large errors correlate with large motions of the antenna, particularly with large jerks and accelerations. The causes of large errors during motion are likely complex. Weak performance of the GPS units (receiver and antenna) in a dynamic environment and rapidly changing multipaths are two possibilities. Though our tests used sinusoidal shake table motions, Trimble NetRS GPS receivers and choke ring antennas (TRM29659.00), and TRACK kinematic software, we believe that the negative impacts of strong motions on the performance of other GPS units are likely to be similar during strong shaking. Robust carrier-phase tracking remains challenging for GPS systems when the antennas and receivers undergo significant dynamics.

The accuracy of traditional seismographs mostly depends on the intrinsic design of the instruments. The accuracy of high-rate kinematic GPS, however, depends on both the instrument and its environment. For typical geodetic GPS antenna installations, such as Plate Boundary Observation (PBO, http://pboweb.unavco.org) stations, the most likely multipath reflectors are the ground, close-by structures, and trees. A GPS antenna installed directly on the ground through a stable monument will move in largely the same manner as these proximal reflectors do. As a result, high-frequency multipaths induced by rapid relative movements of a GPS antenna and its surrounding reflectors would be smaller than those in our
Figure 15. Strong motion displacement time series (kinematic PPP solutions) derived from 1-sps GPS data recorded by three GPS units during the 2010 Chile earthquake (M 8.8). The GPS data were processed by the GIPSY software using the final JPL orbits and clocks. The top plots illustrate acceleration time series recorded by nearby strong motion stations. The distance between strong motion station CCSP and GPS station CONZ (also CONT) was about 7 km. The distance between strong motion station STL and GPS station SANT was about 30 km.

Experiment. The rapidly changing multipaths experienced in our shake table tests may be stronger than in free-field GPS seismometers. However, high-frequency multipaths can be significant if GPS units are installed on high-rise buildings or long-span bridges. These structures could amplify earthquake ground motions and lead to considerable rapid relative movements of the GPS units and their nearby reflectors, inducing high-frequency variations in multipathing and degrading the accuracy of high-rate kinematic GPS.

This study reminds us that the accuracy of high-rate GPS seismograms from areas near the epicenter of a large earthquake should be evaluated with caution. In particular, there should be no assumption of uniform accuracy for a group of high-rate GPS seismograms obtained from one earthquake. Instead, accuracy can vary even within a single GPS seismogram. The errors during strong-motion periods are likely larger than those during periods of weak-motion or repose. The effects of strong shaking on GPS receivers may be partially minimized by installing GPS receivers on seismic isolation devices. Since the positions were decided by the location of an antenna, specifically the phase center of an antenna, which is connected to a receiver by a soft cable, mounting the receiver on an isolation device will not change the final GPS position. We are developing an outdoor shake table facility to further study the accuracy of high-rate kinematic GPS measurements.

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