J Geod (2009) 83:227–233
DOI 10.1007/s00190-008-0233-x

ORIGINAL ARTICLE

GPS seismology

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Received: 31 December 2007 / Accepted: 29 April 2008

Abstract GPS seismology uses convential geodetic models to analyze GPS data at high sampling rates, such as 1 Hz. GPS seismology results are shown for the Denali, San Simeon, Tokachi-oki, and Chuetsu earthquakes. Records for these earthquakes indicate that GPS is an excellent instrument for measuring large displacements near earthquake ruptures. GPS systems can be improved for seismic applications if their sampling rates are increased from 1 to 10 Hz.

Keywords GPS · Seismology · Multipath

1 Introduction

As will be discussed by other authors in this volume, the development of the IGS has had a profound impact on the geosciences. Early efforts to use GPS to measure plate boundary deformation required individual scientists to estimate orbits (e.g. Feigl et al. 1993, Freymueller et al. 1993). Since these results were based on "campaign style" measurements, where only a few days of data were collected each year, the computational burden for also estimating orbits was fairly minimal. This was particularly the case when the Block I constellation consisted of only seven satellites and there were three global tracking sites. As more and more continuously operating GPS sites were installed to facilitate precise orbit determination and the Block II constellation began to be built, the computational burden for geophysicists increased markedly. By providing high-precision GPS orbits in a well-defined terrestrial reference frame (e.g. Altamimi et al. 2007) for geoscientists, the IGS has nurtured the development of new GPS applications such as the one discussed here: GPS seismology. In addition to orbits, the IGS has contributed to the development of GPS seismology with their unrestricted data policy. This has meant that data collected by the IGS and their partner agencies for other purposes (e.g. precise orbit determination for low-Earth orbiters), provided the unintentional dataset used to observe seismic waves in GPS data.

The potential for GPS seismology was first discussed by Hirahara et al. (1994), Ge (1999), and Ge et al. (2000). While focused on very short baselines, they were the first to show that GPS should be able to measure large displacements over short time intervals. In this review, I will focus on measurements made during earthquakes rather than on feasibility studies. First I will review how GPS data are analyzed for seismic studies, followed by descriptions of seismic results from a few recent earthquakes. I will conclude with some recommendations for how currently existing GPS receivers could be operated to improve their value to seismologists.

2 Data analysis

Data used for GPS seismology (also called high-rate GPS data) can typically be analyzed using the same models that were created to analyze daily average positions. In the studies from my research group, this has meant that IGS orbits (Beutler et al. 1994) were used to define the spacecraft positions, carrier phase ambiguities are estimated, and receiver/satellite clocks are estimated with respect to a reference oscillator using the GIPSY software (Lichten and Borders 1987). Ionosphere delays were removed with the dual-frequency combination. Because seismic displacements occur over very short periods of time (up to several hundred seconds), a single zenith delay parameter can be estimated

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for each site. Typically we used the Niell mapping function (Niell 1996), and ambiguity resolution was attempted (Blewitt 1989). Although only a small time interval of GPS data is of interest to seismologists, I have traditionally analyzed several hours of GPS data in order to increase the success of ambiguity resolution. A more computationally efficient analysis scheme would use the 30-s IGS satellite clock products, although a network approach would still preferred for ambiguity resolution.

The main difference between traditional GPS analysis and high-rate analysis is how positions are estimated. For most geophysical applications, a position is estimated once per day; for seismic applications, a position is estimated at every data epoch. In the examples highlighted here, that means a position was estimated every second. In general, the sampling interval can be much higher (e.g. Genrich and Bock 2006). From the perspective of the GPS analysis softwares, sampling rates higher than 1 Hz mean that dimensions will most certainly need to be expanded. If the community begins to operate GPS receivers at higher rates such as 10 Hz, it will be necessary to determine exactly which sampling interval is being used. For example, are GPS measurements reported each 0.1 s an average over 0.1 s, or were they averaged over a smaller interval and decimated each 0.1 s? These issues are generally of little interest to GPS geodesists, but are extremely important to seismologists who study earthquakes that have energy at high frequencies.

3 Results

3.1 Denali: 2002 November 3

Dynamic seismic displacements were first observed for the M7.9 Denali Fault earthquake (Larson et al. 2003). As shown in Fig. 1, this earthquake ruptured 300 km to the southeast, about 150 km from IGS site Fairbanks (FAIR). All broadband seismometers within thousands of km of the rupture "clipped," meaning that they saturated in the presence of the very large displacements. For example, even the very small ground velocities (1 cm/s) caused the broadband seismometer at Yellowknife (YELL) to clip. Also shown on Fig. 1 is the extension of the fault rupture; in other words, the direction of directivity (i.e. direction of maximum seismic displacement amplitudes). It is easily seen that IGS sites (WHIT, DRA2, BREW) and sites operated by Natural Resources Canada were well situated with respect to the maximum earthquake directivity. If the GPS sites had been situated at the same distances but perpendicular to the direction of maximum directivity, only very small displacements would have been observed by GPS, as was the case for IGS site YELL. The largest displacements (peak-to-peak signal of nearly 50 cm) were observed in Skagway (Fig. 2) and at WHIT. The geodetic signature of the Denali event was further studied by Kouba (2003) and Bock et al. (2004). Because so many broadband seismometers clipped, the Denali GPS seismograms were

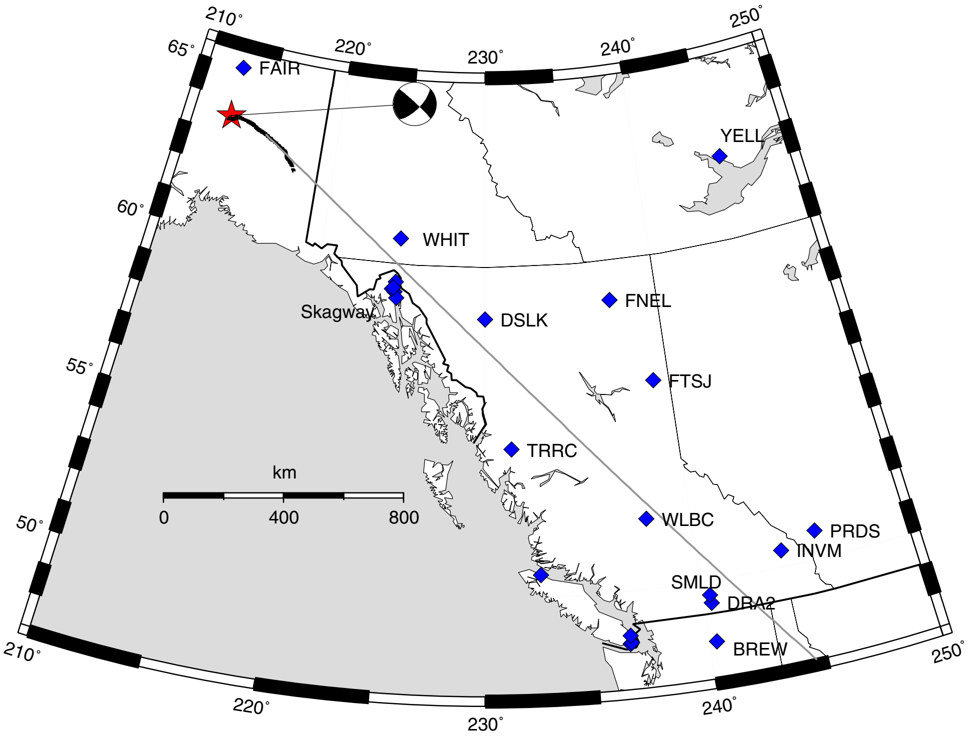

Fig. 1 1-Hz GPS stations that observed displacements during the 2002 Denali earthquake are shown as *blue diamonds*. The epicenter is shown as a *red star*, the rupture is shown in *black*, and rupture direction is extended in *gray*. Focal mechanism for the earthquake is also given

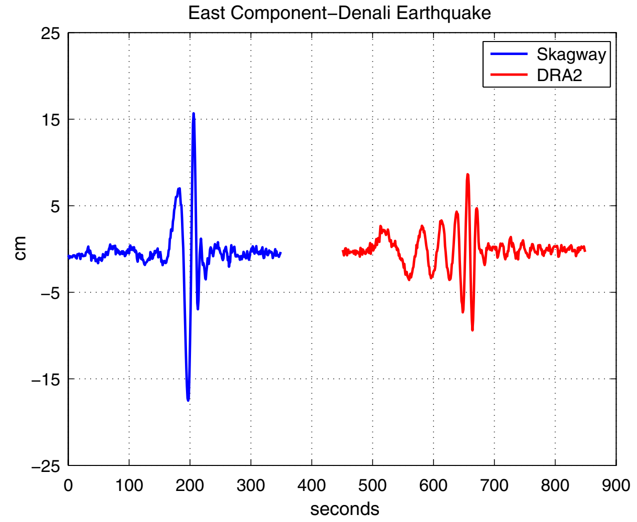

Fig. 2 East component GPS displacement records for a Skagway site and DRA2. These GPS receivers were located over 700 and 2,200 km, respectively, from the Denali epicenter. The difference in arrival times for the seismic displacements reflects the additional time it took the surface waves to travel the 1,500 km between Skagway and DRA2

used by Gomberg et al. (2004) to study earthquake triggering. Bilich et al. (2008) compared GPS seismograms from the Denali event with both clipped and unclipped seismic records in western Canada in order to assess the noise and validity of the GPS seismograms.

3.2 San Simeon: 22 December 2003

Another earthquake which produced seismic displacements that was observed by GPS was much smaller: the M6.5 San Simeon earthquake (Hardebeck et al. 2004). For an earthquake of this size, the GPS sites must be much closer than for the Denali event. In this case, we were fortunate that GPS sites had been installed by SCIGN in anticipation of the next Parkfield earthquake. This resulted in very large displacements as shown in Fig. 3, although there is clearly an indication that a higher sampling rate than 1 Hz was needed. The San Simeon dataset resulted in the first demonstration that GPS seismic data could be used in a rupture inversion (Ji et al. 2004).

While the use of the San Simeon GPS displacements by seismologists was notable, this dataset were also used in making improvements to what has become known as "sidereal filtering." First proposed by Genrich and Bock (1992), an empirical multipath model is derived from apparent displacements from days before or after the day of interest. In order to apply the multipath correction, the analyst must know how much time to use in shifting the correction profile. If the GPS orbital period is exactly half of a sidereal day, the shift will be 23 h, 56 min, 4 s. Choi et al. (2004) subsequently reported that each satellite has a distinct repeat period, which was

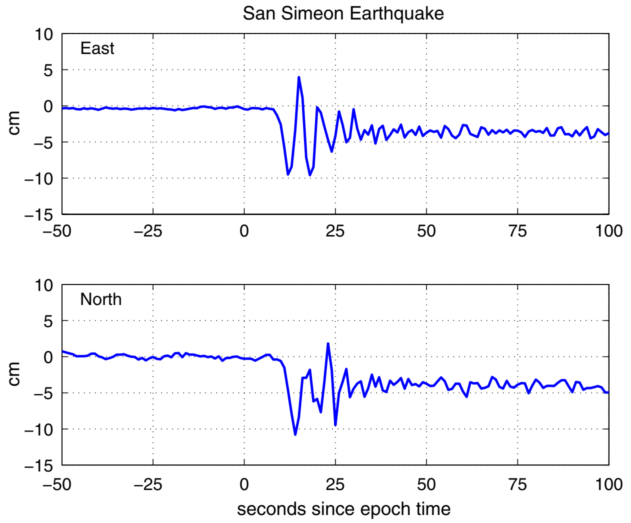

Fig. 3 GPS seismograms from the 2003 San Simeon earthquake recorded for station CRBT (35 km from the epicenter)

9 s less than sidereal for the San Simeon event. This paper also demonstrated that satellite orbital periods change slowly over time due to $J2$, lunar and solar perturbations, and maneuvers by the constellation operators. Larson et al. (2007) and Agnew and Larson (2007) subsequently showed that more exact shift times can be derived based on the aspect repeat time, which is how long it takes a satellite to return to the repeating geometry for a given station location. Software to calculate both orbit and aspect repeat times are available online Agnew and Larson (2007). Other methods for modeling multipath have been developed using adaptive filtering techniques (Ge et al. 2000).

3.3 Tokachi-oki: 25 September 2003

The largest displacements recorded to date by a GPS seismology system were observed during the 2003 M8 Tokachi-oki earthquake. Recordings were made by GEONET, the Japanese national GPS network. Tokachi-oki was the largest earthquake in 2003; its epicenter was located 80 km offshore the northernmost Japanese island of Hokkaido. GEONET operates at both 1 and 30-s sampling intervals, with the 30-s data archived onsite. The 1-s data are primarily used for navigation applications and are telemetered in real-time. The sites closest to the epicenter show peak displacements of well over 1 meter horizontally. Figure 4 shows displacements in all three components for a site that is 170 km from the epicenter. This example clearly shows that GPS seismology is sensitive to *both* horizontal and vertical ground displacements. Our group used displacements from 35 GPS sites to compute a finite-fault rupture model (Miyazaki et al. 2004). This study demonstrated that high-rate GPS data alone can be used to study the rupture characteristics of great

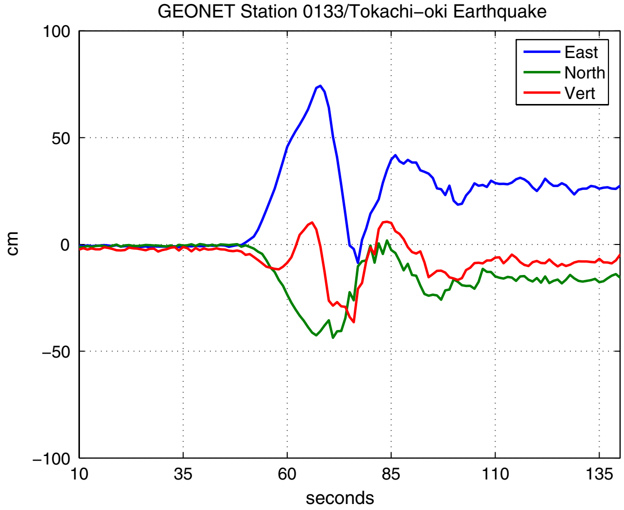

Fig. 4 GPS seismograms for GEONET station 0133 and the 2003 Tokachi-oki earthquake. Station 0133 is located 170 km from the earthquake epicenter

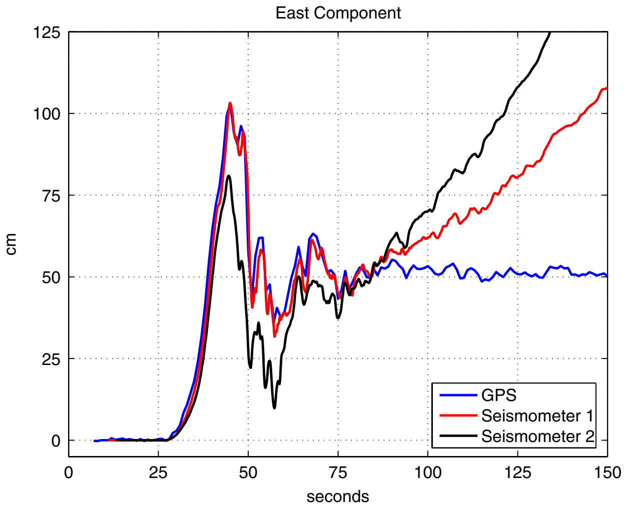

Fig. 5 Integrated strong motion records for Knet and KiKnet seismic sites compared with collocated GPS GEONET site, Tokachi-oki earthquake. Note that the seismic records do not agree with each other, nor does either produce a physically realistic postseimic record. Observations taken from Miyazaki et al. (2004)

earthquakes, although I expect that such studies will typically combine strong-motion, GPS, and teleseismic data. Each of these datatypes has different strengths, and thus all contribute something when properly weighted in an inversion.

4 Applications of GPS seismology

The ability of GPS to detect seismic displacements is certainly far beyond what community expectations were 10 years ago. Now that the GPS constellation has matured and analysis techniques exist to optimally measure GPS seismic displacements, an outstanding question remains: when are the data useful? Perhaps the most utilitarian definition is that GPS seismic data are useful when seismologists use them. Using that perspective, the seismic waveforms from San Simeon were valuable because they were used in an inversion for seismic rupture. Seismologists were willing to include them because of the dearth of traditional seismic instruments near the San Simeon epicenter. The GPS waveforms for Japanese earthquakes have been the most notable, but Japan also has the most extensive seismic network in the world. There is less of a need for the GPS seismic waveforms in Japan, although the high-rate GPS data are invaluable for resolving cumulative slip for great earthquakes and differentiating between coseismic and postseismic deformation (Miyazaki and Larson 2008). This was also shown for the Parkfield earthquake (Langbein et al. 2006, Johnson et al. 2006). How can the geodetic community increase the likelihood that seismologists will use high-rate GPS observations in their earthquake studies? One way is to archive the GPS waveforms where seismologists can find them. For example, my group's Denali and Tokachi-oki waveforms have been archived at IRIS (http://www.iris.edu/mda/GD). Simply archiving the RINEX files for large earthquakes will not be helpful to seismologists.

In some senses, it was unfortunate that the first demonstration of GPS seismology came with the Denali earthquake, where displacements was observed at distances over 3,000 km. This was due to the mechanism of the earthquake (shallow and strike-slip), which produced large Love waves in the rupture direction (Love waves are horizontally polarized shear waves guided by an elastic layer). Not all earthquakes ruptures will be shallow, and we cannot expect GPS receivers to be located along the rupture direction. For example, the similar magnitude Tokachi-oki earthquake produced no measurable displacements in China which is at a similar distance as the sites that showed such remarkable signals for Denali. Significant displacements at great distances were shown by Ohta et al. (2006) for the Sumatra–Andaman Island event, but they were not nearly as large as seen for Tokachi-oki.

I believe the future of GPS seismology should focus on using GPS as a *strong motion* instrument. This term strong motion is generally used by seismologists who study large-amplitude ground motions and the response of engineered structures to these motions. Since strong motion seismometers measure acceleration, one way that GPS seismology can contribute to this field is by providing accurate measurements of displacement. Typically after integrating strong motion accelerations to displacement, large drifts are visible (see, e.g., Fig. 5). While GPS seismology is a much less precise accelerometer than a strong motion instrument, it has been shown that it more accurately measures displacement for very large earthquakes (Emore et al. 2007). Strong motion

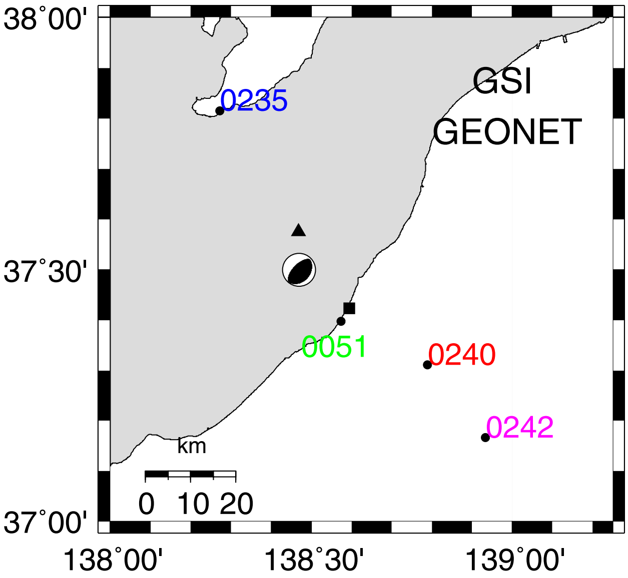

Fig. 6 GEONET station locations for the 2007 Chuetsu–Niigata earthquake. Epicenter is shown by the *triangle*, seismic site KKZ1R2 shown by a *square*, and the Harvard focal mechanism is shown

records are also important for finite-fault rupture models, and thus GPS seismology can also provide important constraints on the temporal-spatial distribution of slip during an earthquake.

5 Data collection strategies

One-Hz GPS data continue to be routinely collected by thousands of GPS receivers around the world. In the global IGS network, over 110 receivers are currently contributing to the high-rate archive at CDDIS. Thousands more are available from individual geodetic agencies, with particularly large concentrations of 1-Hz receivers in Canada, Europe, Japan, and the US. The data are particularly valuable for surveyors and many of the receivers are operated with the assumption that they will service multiple communities. While this is adequate to study some earthquakes, data from these receivers would be far more valuable for studying earthquakes if the receivers sampled at 10 Hz or higher. Operating at this sampling rate would be a burden if the data were to be telemetered and archived, but fortunately this is not necessary. For earthquake studies, 10-Hz data could be telemetered only if a seismic event occurred. Modern receivers allow the user to define multiple sampling intervals, and can segregate the data streams so that the geodetic data (30-s samples) are kept in memory for many weeks, whereas the higher-rate (10 Hz) data are overwritten more frequently. Finally, while it can be very advantageous to have high-rate GPS data from the day before an earthquake to facilitate multipath corrections (Choi et al. 2004, Larson et al. 2007), it is *not* necessary to download them at the 10-Hz rate, as 1-Hz GPS data are more than adequate for removing multipath effects.

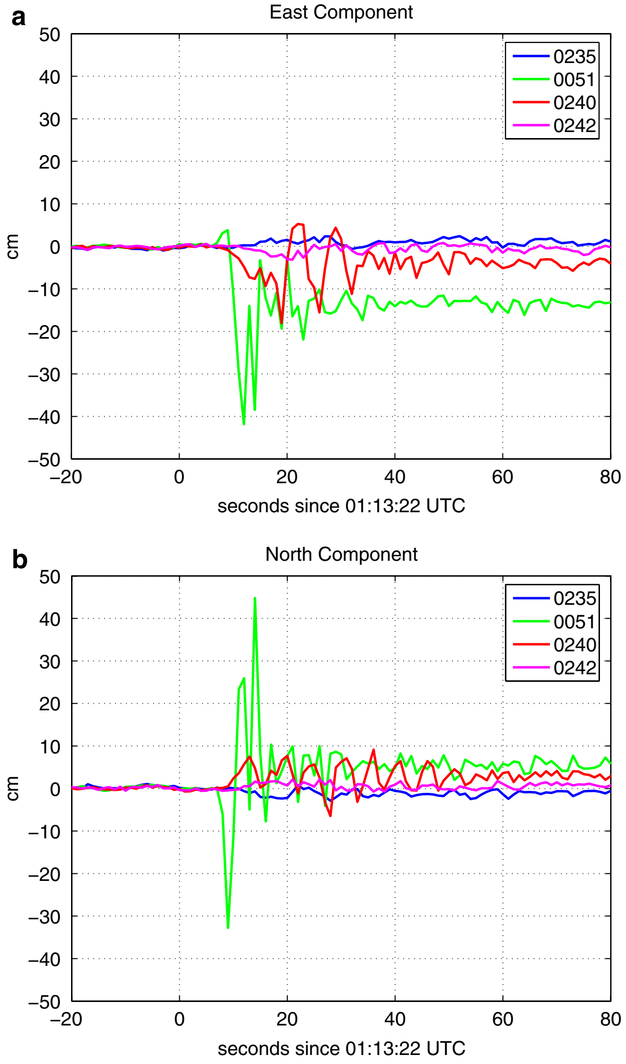

Fig. 7 GPS displacement records for the 2007 Chuetsu–Niigata earthquake

If such a multi-mode model of network operation is used, network operators must know when it is appropriate to download the 10-Hz GPS data. Unfortunately, current download "rules" only take into account the magnitude of an earthquake and its distance from the GPS network without taking into account the azimuth of the GPS sites with respect to the rupture direction. These rules also ignore the existence of seismic networks that are far better able to measure seismic displacements at far distances. Data from the 2007 July 16 Chuetsu–Niigata earthquake are used to illustrate some of these concerns. The epicenter and station locations are shown in Fig. 6. Although a fairly small earthquake (magnitude 6.5), very large peak-to-peak dynamic displacements (>80 and 20 cm) are seen at GPS stations 0051 and 0240

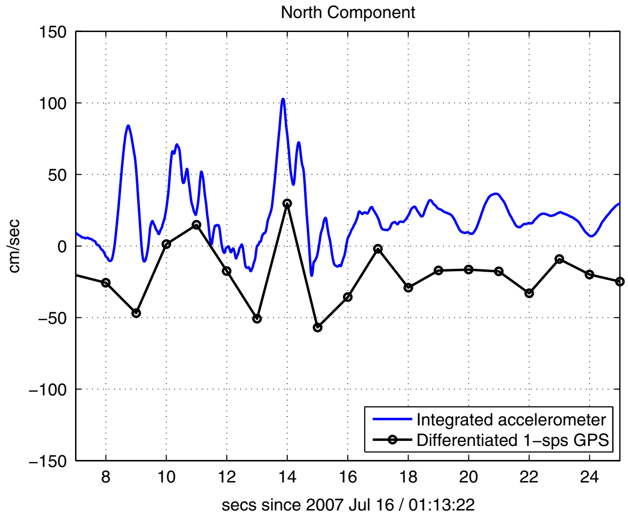

Fig. 8 Differentiated GPS displacement records for GEONET site 0051 compare with velocity records from the Kashiwazaki–Kariwa power plant site KKZ1R2. The seismic records were originally acceleration measurements sampled at 100 Hz. The records are offset along the y-axis for clarity

(Fig. 7). These GPS receivers are approximately 25 and 40 km away from the epicenter. Station 0235 is at a similar distance (30 km), but no meaningful seismic displacements can be observed because it is *behind* the rupture direction. If a simple distance–magnitude relationship had been used to download a much larger GPS network, archivists would be overwhelmed with large quantities of useless data. Much larger earthquakes will of course produce much larger displacements, as was seen for Tokachi-oki, but the size of the signal observed by GPS will still depend on the direction (and depth) of the rupture. Another concern illustrated in the Chuetsu GPS seismograms is aliasing. One-Hertz sampling is simply not sufficient if GPS is going to be a valuable tool for measuring dynamic seismic displacements. I further emphasize this by showing seismic velocity records in Fig. 8 for the Chuetsu earthquake. The seismometer closest to GPS station 0051 is operated by the Kashiwazaki–Kariwa nuclear power plant, emphasizing the societal importance of having accurate measurements of ground motion during earthquakes. In this record only 18 s of ground motion are shown. There is clearly energy at high-frequencies in the seismic data. This information can never be faithfully recorded by a GPS instrument operating at 1 Hz (records for station 0051 are also shown). While not shown here, the 1-Hz GPS records made before the earthquake are consistent with an error of 0.3 cm/s, which is over two orders of magnitude smaller than the signal during the earthquake, indicating that high-rate GPS can certainly contribute meaningful results to the field of strong-motion seismology. But if GPS is to augment seismic recordings of strong ground motion, they must be operated at higher sampling rates. I urge GPS station operators that have sites that are near fault zones to consider operating their sites at 10 Hz or higher, telemetering the data only upon request.

6 Conclusions

The field of GPS seismology is an unexpected outcome of geodetic networks that were primarily installed to measure plate boundary deformation and plate tectonics. The fact that a GPS receiver can accurately measure motions on both geologic (1 mm/year) and seismic time scales (500 mm/s) is a testament both to the GPS system (receivers and satellites) and the IGS community. GPS seismology relies on the availability of IGS orbits, and was also positively impacted by the open IGS data policy that allows individual geodesists to innovate. GPS seismology also owes a great debt to all geodesists that have developed models to improve our analysis softwares.

Acknowledgments I acknowledge support from NSF (EAR 0337549, 0337206, and 0538116), NEHRP (20050036), NASA-SENH, and a travel fellowship from JSPS. I also gratefully acknowledge valuable conversations with D. Agnew, A. Bilich, K. Choi, J. Clinton, T. Heaton, S. Miyazaki. I am particularly grateful to K. Koketsu and Y. Yokota of the Earthquake Research Institute, University of Japan, for providing the seismogram in Fig. 8. Organizations that have provided important geodetic data used in this study include IGS, GSI-GEONET, NRCAN, SCIGN, JPL, NGS, CDDIS, ITRF, CORS, and the IERS.

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