Analysis of 1-Hz GPS data for the estimation of long-period surface motion of Tohoku-Oki Mw9.0 2011 earthquake

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Abstract. The GPS displacement time series are today mostly used for the estimation of the transient (period <2sec) and coseismic (static) displacement of an earthquake, while the estimation of the velocity and acceleration is based only seismic networks. In this study, we examine whether the GPS records can be used to capture the spectral characteristics of the long-period signal and their consistency with the corresponding seismic motion sensors, for the displacement, velocity and acceleration. For this purpose, we use the 1-Hz GPS network records of the Tohoku-Oki 2011 earthquake processed in Precise Point Positioning (PPP). The derived GPS and strong-motion waveforms were analysed resulting into displacement, velocity and acceleration for periods ranging from 3 to 100s. The derived GPS and strong-motion time series were compared and it was found that these are of similar pattern and amplitude. However, there is a non-constant phase shift between the corresponding GPS and strong-motion time series, resulting in significant difference between the time series in the time domain. On the contrary in the frequency domain, the GPS and strong-motion time series are consistent for periods larger than 3-4s. Finally the GPS and the strong-motion records were compared in the time-frequency domain based on wavelet analysis, revealing that both GPS and seismic records express consistently the variation of the long-period of the seismic signal. Thus, it is proved that the GPS records can be used for the estimation of the long-period ground motion and contribute to the reliable estimation of the corresponding characteristics (displacement, velocity, acceleration).

Keywords. GPS, PPP, strong-motion, waveforms, filtering, Tohoku-Oki 2011, wavelet, spectral analysis

1 Introduction

The GPS is being used for the monitoring of the slow and dynamic motion of structures and bridges (Meng et al., 2007; Moschas and Stiros, 2014) and it has been proved its ability to detect the frequency of the motion (Celebi and Sanli, 2002) even though if the motion amplitude is close or in the noise level of the measurements (i.e. a few mm; Psimoulis and Stiros, 2008) or the frequency varies with time (Psimoulis et al., 2008).

However, the last decade the GPS is an essential tool in the field of earthquakes, not only for the estimation of the coseismic displacement (Larson et al., 2003) and the correction of the seismic data (Wang et al., 2003), but also for the estimation of the transient motion of the seismic waves (Ohta et al., 2012; Guo et al., 2013; Houlié et al., 2014, Psimoulis et al., 2014) and the estimation of earthquake characteristics (i.e. magniture, source, etc.; Wright et al., 2012; Koketsu et al., 2012). Furthermore, the high-rate GPS has been proved very useful for the monitoring of structures and the estimation of the structural characteristics (displacement, frequencies, etc.; Meo et al., 2006;

Psimoulis et al., 2008; Psimoulis and Stiros, 2012; Moschas et al., 2013; Moschas and Stiros, 2014), which agrees with the recent trend of using the desired displacement for the design of the structure (Panagiotakos and Fardis, 1999).

In this study, we explore whether GPS can be used for the estimation of the spectral characteristics of the long-period seismic signal, by comparing with seismic records, what are the inconsistencies between the GPS and seismic records for the estimation of displacement, velocity, acceleration for frequency below 0.5Hz of an earthquake event, which cannot be covered sufficiently by the seismic data. The latter would be beneficial for covering the gap of the seismic data, at the long-periods (>2s) and would also improve the characterisation of the seismic source.

We selected for this study the seismic event of Tohoku-Oki Mw9.0 2011, as this is one of the strongest and well-recorded earthquakes, recorded in a broad area from the fault rupture (ranging from 75 to 800km from the epicentre) by the GEONET continuous GPS network, the KiK-net and K-NET seismic networks. Furthermore, the extreme ground motion makes this case representative for the assessment of reliable use of GPS for the estimation of long-period velocity and acceleration.

For the processing of GPS records, the Precise Point Positionig (PPP) mode was used, which can produce the displacement waveform of cm-accuracy level based on standalone GPS station (Ge et al., 2008; Geng et al., 2011). This processing mode is broadly used the recent years, mainly for the large GPS networks and for near real-time applications. We used PPP processing mode, in order to assess the reliability of GPS records for estimating velocity, acceleration in near real-time applications.

2 Data

2.1 GPS data

GPS records from 847 GEONET stations of 15-hour duration and 1 Hz sampling rate were available, fully covering the earthquake period. The data were processed with the Bernese GPS Software (Dach et al., 2007) in PPP mode, using a-priori information (precise orbit, precise clock, etc.) of highest quality from CODE (Dach et al., 2009).

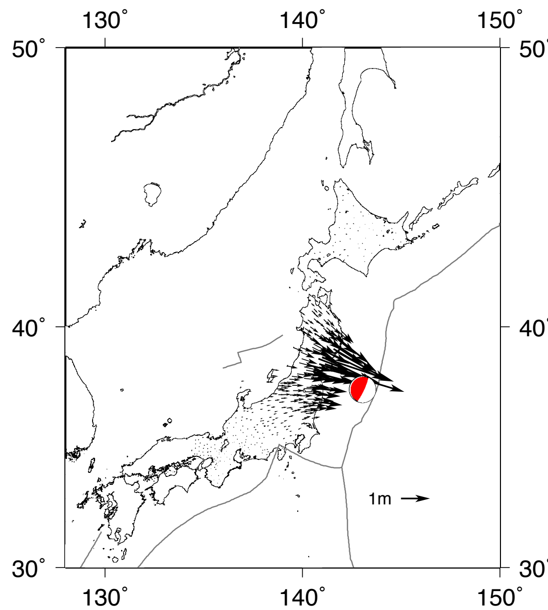


Fig. 1 The coseismic horizontal displacement field derived from the PPP processing of the available GPS records, at the time 300 seconds after the earthquake.

The PPP GPS process resulted in displacement time series in North, East, vertical component (Fig. 1) of 1 Hz sampling rate of a posteriori formal accuracy of about 1 and 2 cm in the horizontal and vertical component, respectively (Psimoulis et al., 2014).

2.2 Strong motion data

The largest strong-motion networks of Japan called K-NET and KiK-net consist of 1034 and 660 stations, respectively. Their main difference is that the K-NET stations are located mainly on thick sedimentary sites, while the KiK-net stations are deployed on rock or thin sedimentary sites. Consequently, the K-NET and KiK-net triggering thresholds are different (2 and 0.2 cm/s^{-2}, Aoi et al., 2004).

The Tohoku-Oki 2011 earthquake was recorded by the two strong-motion networks, having available raw data from 700 K-NET sites and 525 KiK-net sites. The raw data of three components, corresponding to north, east and vertical directions, were sampled at 100Hz and up to 300s duration. The acceleration of each site derived from correcting the raw data for the gain and converting the record time from UTC to GPS time.

3 Data analysis

The analysis of the GPS and strong motion data followed two main approaches. Initially, the very closely spaced GPS and strong-motion sites, whose their in-between distance was less than 100m, were used for the evaluation of their consistency (Fig. 2). Spectral analysis was applied and the data consistency was checked in the frequency domain. The second approach was to compare the estimated displacement, velocity and acceleration, derived from the closely located GPS and strong-motion sites, for different long-period bands, and assess their consistency in the time domain.

3.1 Spectral analysis of the GPS and strong-motion data

For the spectral analysis of the GPS and the strong-motion data, the GPS time series were differentiated twice for the acceleration time series, in order to avoid the double integration of the strong-motion data, which would lead to significant accumulated error, characterised by drift (Stiros, 2008). Potential attempt to correct the drift would not make reliable the long-period motion due to the significant coseismic displacement (Wang et al, 2003). In Fig. 3 are presented the EW component of two representative closely located GPS and strong-motion sites; one close to the epicentre (179km) and one far from the epicentre (771km). From these spectra is clear the consistency between the spectra of the GPS and the strong-motion acceleration time series for periods larger than 3-4 seconds. For lower periods (<3-4 sec) and mainly far from the epicentre, the GPS time series seem to be more noisy, as the motion signal is weaker and it appears similar spectral characteristics with the GPS signal (black line) of the period before the earthquake, which expresses noise. Also for period below 3-4s the GPS and the strong-motion spectra do not match. Probably, the observed noise in the GPS spectra for the short-period is a combination of the GPS noise from the PPP processing mode, amplified partly during the differentiation procedure for the estimation of the acceleration. However this GPS noise is significantly lower than the error of the double integration of the strong-motion data in order to estimate the displacement.

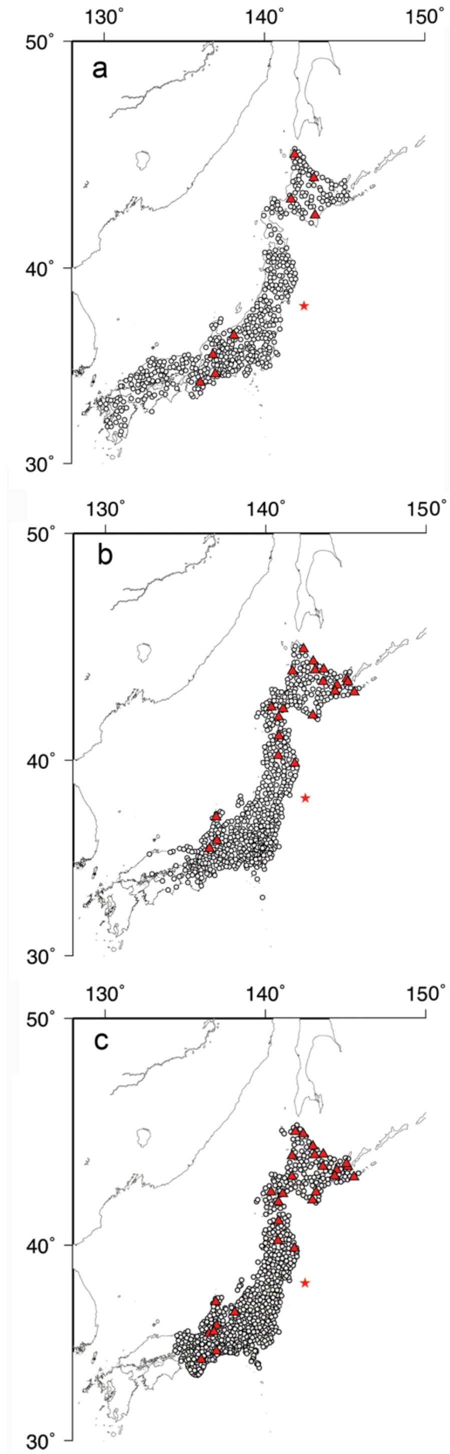


Fig. 2 The available sites of the a) KiK-net, b) K-NET and c) GPS network. The very closely located sites are indicated with red triangles. The red star indicates the earthquake epicentre.

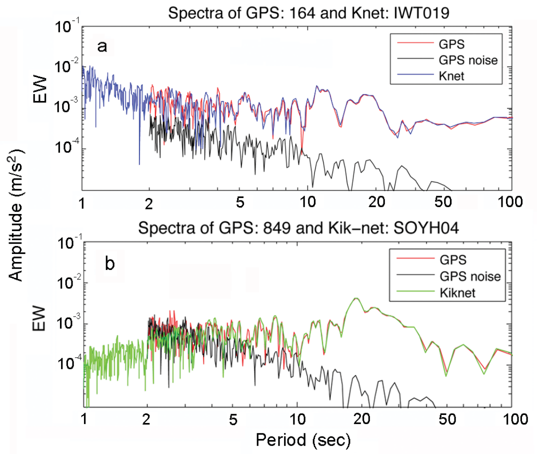
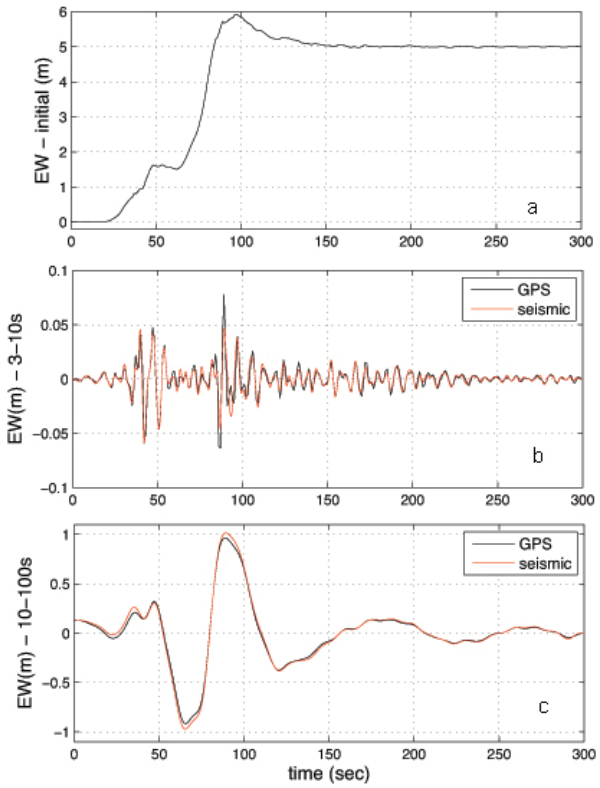


Fig. 3 The spectra of derived acceleration time series for closely located GPS and strong-motion sites, a) close (179km) and b) far (771km) from the epicentre. The solid black line corresponds to GPS time series before the earthquake occurrence, expressing noise.

3.2 Estimation of GPS and strong-motion displacement, velocity and acceleration time series

For the estimation of the velocity and acceleration, the GPS displacement time series were differentiated once and twice, respectively, while the strong-motion acceleration time series were integrated once and twice for the velocity and displacement time-series, respectively. The derived displacement, velocity and acceleration time series were analysed for the relative short- (3-10s) and long-period (10-100s) domains. More specifically the derived time series were filtered using Chebyshev filter for these two period-bands. The period >100s were not examined in order to avoid the drift effect of the strong-motion time series in the displacement time series. Finally due to the different sampling rate of the strong-motion time series (100Hz) from that of GPS (1Hz), the strong-motion time series were decimated to 1Hz, in order to assess completely compatible time series.

The filtered GPS and strong-motion time series were correlated to limit potential time lag between the two data sets, which could be due to the distance between the two sensors or potential clock drift of the strong-motion sensors, which is not regularly corrected (Moschas and Stiros, 2012).



direction of the GPS 0550 site, b) the short- (3-10s) and c) the long-period (10-100s) component of the EW direction for the closely located sites GPS 0550 and K-NET MYG011.

From the cross correlation it was revealed time lag, ranging between -2 and 3s, which was not depended on the in-between sensors distance (Psimoulis et al., 2015).

Finally, the GPS and strong-motion time series were shifted according to the time lag and the time series were compared. In figure 4 are presented the displacement time series of the short- and long-period components of the EW direction for the closely located GPS 0550 and K-NET MYG011, showing clearly an identical pattern, with small differences in the amplitude. However, the estimated difference of the two time series appears maximum amplitude significantly larger than the difference between the maximum amplitude of the two time series. The latter is due to the phase shift between the two time series, which is not constant, making not possible its correction and resulting in the relative difference of the two time series in the time domain (Psimoulis et al., 2015).

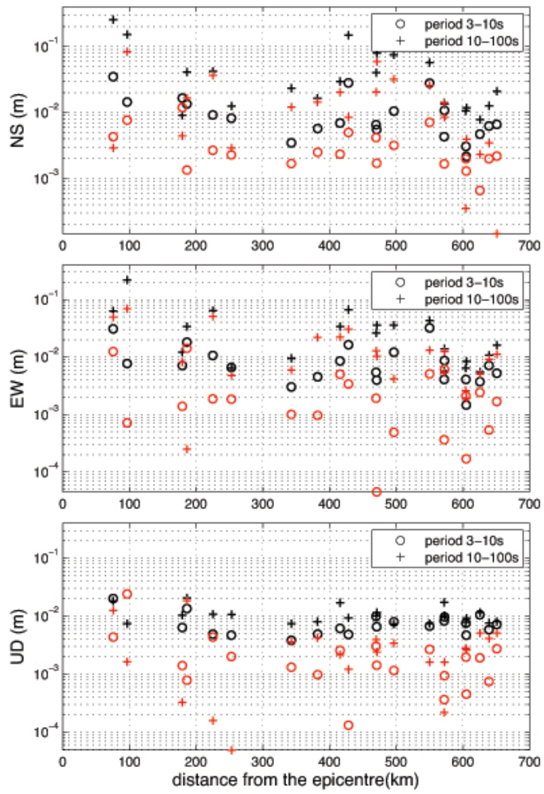


Fig. 5 The maximum differences between the displacement time series of the GPS and the strong-motion (black symbols) and the difference between the maximum values of the displacement time series of GPS and the strong-motion (red symbols). The differences were estimated for the North-South (top), East-West (middle) and Up-Down (bottom) direction and the two period-bands.

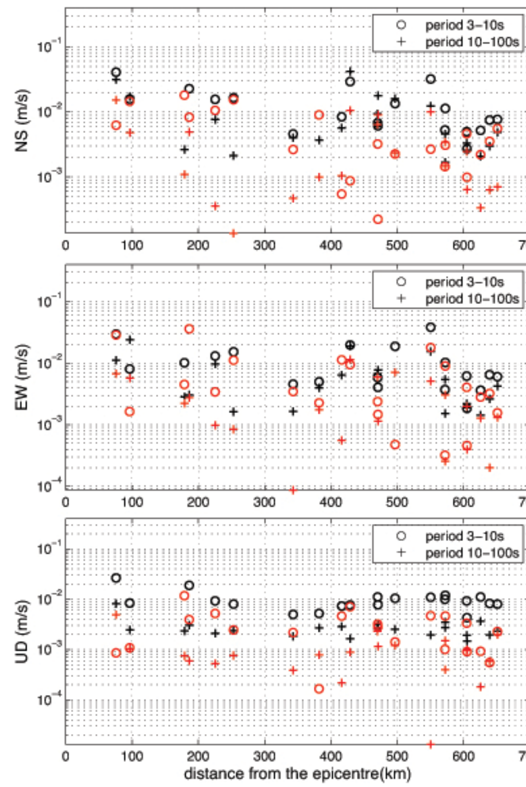


Fig. 6 The corresponding plots as in Figure 5 for the velocity time series.

The latter is clearly shown in Figure 5, where we show the maximum difference between the time series of the GPS and the strong-motion sites for the two period-bands and the difference between the maximum values of the corresponding time series of the GPS and the strong-motion sensor. It is clear that the difference between the maximum values of the GPS and the strong-motion time series are smaller than the corresponding maximum difference of the time series. The latter is observed for every period-band and every direction.

Likewise the velocity and the acceleration time series of the GPS and the strong-motion sites were computed and the corresponding differences were estimated. In Figure 6 are presented the maximum difference of the velocity time series and the difference of the maximum velocities. Similar to the displacement, the difference of the maximum velocities of GPS and strong-motion is smaller than the maximum difference between the corresponding velocity time series, indicating consistency of the velocity time series is also affected in the time domain, due to the phase shift. However, the differences of the GPS and strong-motion velocity time series are generally smaller than in the displacement time series, which probably is the result of the combination of the lower amplitude of the velocity time series, relatively to that of the displacement and the reduction of the noise in the strong-motion records analysis by having one integration step less.

Furthermore, the difference of the estimated displacement and velocity is smaller for sites of 250-400km distance from the epicentre than the sites closer or further from the epicentre; the latter could be the result of inconsistency of the GPS and the strong-motion signal due to the severe motion close to the epicentre and the attenuation of the signal far from the epicentre (Psimoulis et al., 2015).

Similarly, for the acceleration time series the differences of the maximum acceleration was smaller than the maximum difference of the two acceleration time series. However, the differences proportionally were more significant than the velocity due to the two-differentiation step of the GPS time series, which increases the noise level of GPS acceleration time series mainly for the short-period component.

4. Evaluation of the wavelet transform analysis of GPS waveform

Finally, we evaluated the performance of GPS records to detect variations of the seismic motion frequencies by using wavelet transform analysis and comparing it with the corresponding strong-motion record, for the common frequency-band (i.e. 0-0.5Hz). Following similar methodology as in the spectral analysis, we compared only the GPS and strong-motion sites, which are very closely-located (<100m in-between distance), by double-differentiating the GPS displacement timeseries to acceleration, in order to avoid the double-integration of the strong-motion sites. The strong-motion site was low-pass filtered at 0.5Hz to be consistent with the GPS acceleration timeseries. Finally we had the GPS and strong-motion acceleration timeseries of the 0-0.5Hz frequency band, which were analysed by using the wavelet transform technique, based on the coiflet wavelet.

In Figure 5 are presented the spectrograms of a representative case of acceleration timeseries of GPS0164 and the strong-motion IWT019 site, which have in-between distance 39m. The two spectrograms have the same peak-pattern, of roughly the same amplitude, occurring for the same frequency-bands at the same time. Some small inconsistencies in the revealed frequencies between the two spectrograms are mainly in low-frequencies (<0.05Hz), where the GPS spectrogram has some peaks of weak signal though, and the high-frequencies (>0.4Hz), where the GPS spectrogram has some random peaks with respect that of the strong-motion spectrogram. The inconsistencies in low-frequency are due to the weakness of the strong-motion sensor to recover the low-frequency motion, while in the relative high-frequencies (>0.4Hz), the GPS noise level is increased due to the double-differentiation,

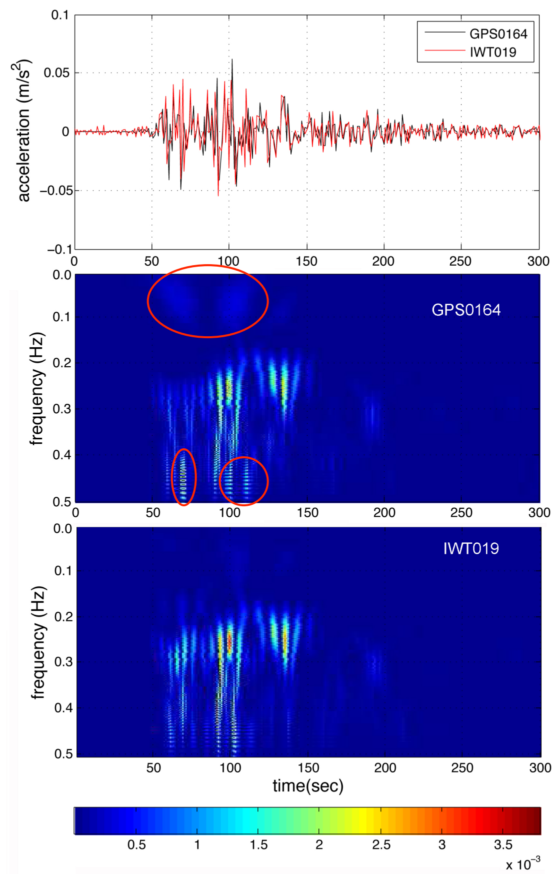


Figure 5: (top) The acceleration time series of the GPS0164 and the strong-motion IWT019 site for the common frequency-band 0-0.5Hz. (middle and top) The wavelet spectrograms of the GPS and the strong-motion acceleration time series. The scale of the spectrogram is common.

increasing the amplitude of the corresponding peaks.

4. Conclusions

The current study proved that the GPS displacement and the integrated accelerograms are consistent for period-bands between 3 and 100s, as the GPS records describe accurately the oscillatory long-period ground motions, while the double integration the of the accelerograms affects in the phase shifting of the time series, but not on the amplitude.

Thus, the PPP GPS data, which will be possible to be processed in near real-time or even real time, allow the accurate characterization of the spectral characteristics of the long-period seismic signal and supplement the current seismic monitoring systems (Liu et al., 2014).

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