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An improved method for tight integration of GPS and strong-motion records: Complementary advantages

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Abstract

The complementary nature of GPS and seismic sensors for station ground motion estimation is well recognized and many studies have proposed the integrated processing of the two datasets for obtaining more accurate and reliable seismic waves (displacement, velocity and acceleration). There are two critical issues in the integrated processing; one is the precise correction of the strong-motion's baseline shifts which are caused by tilting and/or rotation of the seismic sensors, the other is the suitable constraint of the high resolution accelerations to get more reliable seismic waves. In this contribution, we present an improved approach for the integration estimation in two steps. First, proper introduction of the baseline-corrected acceleration into the Precise Point Positioning (PPP)'s state equation and treatment of the baseline shifts as unknown parameters to be estimated for each epoch. Second, after correction of these baseline shifts, use of the high resolution acceleration for constraint of the GPS solution and ambiguity resolution. The efficiency of the improved approach was validated using an experimental dataset which was recorded by a pair of collocated GPS antenna and an accelerometer, and it shows that the advantages of each sensor are complementary.
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1. Introduction

High-rate GPS is widely used for effective displacement monitoring associated with earthquake hazards (Weber et al., 2007; Zollo et al., 1997; Crowell et al., 2009; Wang et al., 2011; Bock et al., 2011; Houlié et al., 2011, 2014). However, high-rate GPS has the limitation of a low signal to noise ratio (Bock et al., 2011; Wang et al., 2013), such as the displacement, velocity and acceleration waveforms usually involve large uncertainties which are mainly caused by environmental and instrumental noise (Elósegui et al., 2006; Genrich and Bock, 2006; Larson et al., 2007). In comparison, digital accelerometers can measure the strong ground motion with a much higher sampling rate than GPS, but their records usually include baseline shifts (small steps or distortions of the acceleration in the reference level of motion), which are mainly caused by the tilting and/or rotation of the strong-motion sensor (Iwan et al., 1985). These small baseline shifts in the acceleration will translate into larger offsets for the integrated velocity and displacement (Boore, 2003). In previous studies, the baseline shifts of strong-motion records are usually corrected by different empirical methods (Iwan et al., 1985; Boore, 2001; Zhu, 2003; Graizer, 2006; Wu and Wu, 2007; Wang et al., 2011). However, most of these methods involve large and unquantifiable uncertainties compared with the geodetic results, and they are also inappropriate for real-time

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implementation. Recently, GPS-based baseline correction has been proposed in the literature (Xu et al., 2013; Bock et al., 2011; Wang et al., 2013; Tu and Chen, 2014). The optimum method to combine the two sensors for integrated processing in order to retain the advantages of each is a hot topic in GPS seismology (Bock et al., 2011; Melgar et al., 2012, 2013; Psimoulis et al., 2015).

Many researchers have studied integrated processing of high-rate GPS and strong-motion records, and their methods can be classified into two categories. The first is by a loose integration process, such as Bock et al. (2011), who applied a multi-rate Kalman filter to estimate broadband displacements by combining 1 Hz GPS displacement and 100 Hz strong-motion acceleration, and applied it to the 2010 Mw 7.2 E1 Mayor–Cucapah earthquake. Xu et al. (2013) used 50 Hz GPS displacements to correct an inertial measurement units (IMU) derived 200 Hz displacements. This included correlation, baseline and scaling corrections. Wang et al. (2013) used 1 Hz GPS displacement as a reference to solve the empirical baseline shift correction parameters and recover the seismic waveforms, and applied this method to the 2011 Mw 9.0 Tohoku-Oki earthquake. Tu et al. (2013a) presented a cost-effective approach to retrieve high precision and broadband ground motion waves by joint use of a single-frequency GPS and a MEMS accelerometer, and validated it by analysis of an experimental dataset.

The second category of methods is the use of tight integration. An example of this approach is that used by Geng et al. (2013), who added the acceleration's observation into the Precise Point Positioning (PPP) solution, and modeled the transient baseline error as a random walk process to be estimated together with displacement. In another example, Tu et al. (2013b) presented an integration approach in which the baseline shifts are estimated by introducing the seismic acceleration corrected by baseline errors into the state equation system, then quickly recovering the seismic waveforms accurately within only 5 min of data. Li et al. (2013) used data from seismic sensors after applying an empirical baseline shifts correction to strengthen the GPS solutions for better integer ambiguity resolution and consequently better accuracy. These integration methods fall into two groups. In the first group, the high-precision GPS was used to recognize and correct the strong-motion's baseline shifts, and recover the seismic waveforms more accurately. In the second group, the high resolution acceleration record was used to constrain the GPS, and improve the strength and reliability of the solution.

Based on this background, this paper describes an improved method for tight integration of GPS and strong-motion records. This method comprises two steps. The first step uses PPP technology to estimate and correct acceleration baseline shifts of the strong-motion sensor (Xu et al., 2013; Tu and Chen, 2014). In the second step, the baseline shift corrected acceleration is constrained for integration solution and ambiguity resolution. This not only effectively reduced the GPS noise but also improved the reliability of the GPS solution, and high precision seismic waveforms can consequently be provided.

2. Methodology

In this paper, the dynamic PPP was used for the improved tight integration process. First, the strong-motion sensor's baseline shifts were estimated by introducing the acceleration and baseline shifts's observation and state equations into the PPP model. Second, the accelerations which after corrected baseline shifts are constrained for integration solution and ambiguity-resolution, then high precision seismic waveforms were retrieved.

2.1. Using GPS to estimate baseline shifts for the strong-motion sensor

The GPS carrier phase observation only contains a small random error with a precision of a few millimeter to a centimeter after consideration of all of the observation errors (Zumberge et al., 1997). This is much smaller than the baseline shifts caused by large system errors, so combining the GPS observation and strong-motion sensor acceleration in the integration process, can allow recognition of the baseline shifts and their effective correction (Xu et al., 2013).

While the ionosphere-free observation is used for PPP, the baseline shifts of the strong-motion are treated as a random walk process, so the observation equations of the tight integration model can be written as follows.

$$\begin{bmatrix} L_p^g \\ L_l^g \end{bmatrix}_k = \begin{bmatrix} A^g & B^g & 1 & 0 \\ A^g & B^g & 1 & 1 \end{bmatrix}_k \begin{bmatrix} s \\ z \\ dt^g \\ N^g \end{bmatrix}_k + \begin{bmatrix} \varepsilon_p^g \\ \varepsilon_l^g \end{bmatrix}_k, \quad \begin{matrix} \varepsilon_p^g \sim N\left(0, \delta_{p,g}^2\right) \\ \varepsilon_l^g \sim N\left(0, \delta_{l,g}^2\right) \end{matrix} \tag{1}$$

$$[L_a^{sm}]_k = [a]_k + [u]_k + [\varepsilon_a^{sm}]_k, \varepsilon_a^{sm} \sim N\left(0, \delta_{a,sm}^2\right) \tag{2}$$

where, L is the observed minus computed observations from satellite to receiver; g, sm represent the GPS and strong-motion sensor respectively; A is the unit direction vector from satellite to receiver; B is the wet part of the global tropospheric mapping function (Boehm et al., 2006; Jin et al., 2010); s, a denote the vector of the receiver position and acceleration; u denotes the vector of the acceleration's baseline shifts; z, dt, N are the tropospheric zenith delay, and receiver clock and phase ambiguities; ε is the measurement noise, and its variance is δ^2; and k is the epoch number. Error components such as the antenna center offsets and variations, the relativistic effect, tide loading and phase wind-up can be corrected with existing methods (Kouba and Héroux, 2001; Dach et al., 2007).

The state equations for the station movement and baseline shifts are expressed as follows.

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