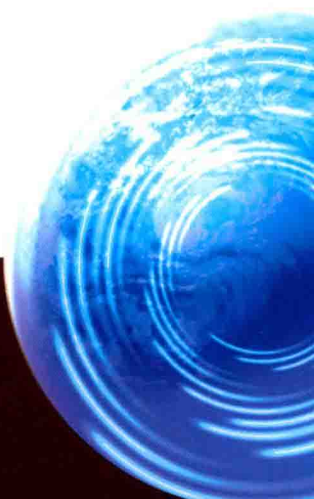
实时高频GNSS地震监测与预警



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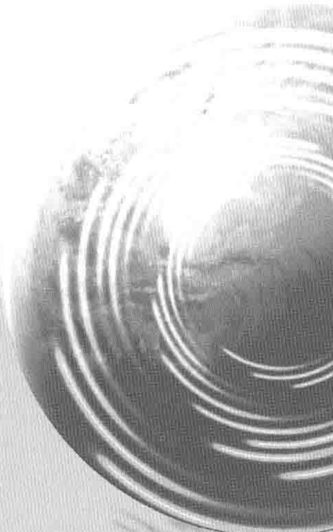

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Preface

In recent times increasing numbers of high-rate GNSS stations have been installed around the world and set-up to provide data in real-time. These networks provide a great opportunity to quickly capture surface displacements, which makes them important as potential constituents of earthquake/tsunami monitoring and warning systems. The appropriate GPS real-time data analysis with sufficient accuracy for this purpose is a main focus of the current GNSS research. The objective of this book is to develop high-precision GNSS algorithms for better seismological applications. The core research and the contributions of this book are summarized as following:

With the availability of real-time high-rate GNSS observations and precise satellite orbit and clock products, the interest in the real-time Precise Point Positioning (PPP) technique has greatly increased to construct displacement waveforms and to invert for source parameters of earthquakes in real time. Furthermore, PPP ambiguity resolution approaches, developed in the recent years, overcome the accuracy limitation of the standard PPP float solution and achieve comparable accuracy with relative positioning. In this book, we introduce the real-time PPP service system and the key techniques for real-time PPP ambiguity resolution. We assess the performance of the ambiguity-fixed PPP in real-time scenarios and confirm that positioning accuracy in terms of root mean square (RMS) of 1.0 cm-1.5 cm can be achieved in horizontal components. For the 2011 Tohoku-Oki (Japan) and the 2010 El Mayor-Cucapah (Mexico) earthquakes, the displacement waveforms, estimated from ambiguity-fixed PPP and those provided by the accelerometer instrumentation are consistent in the dynamic component within few centimeters. The PPP fixed solution not only can improve the accuracy of coseismic displacements, but also provides a reliable recovery of earthquake magnitude and of the fault slip distribution in real time.

We propose an augmented point positioning method for GPS based hazard monitoring, which can achieve fast or even instantaneous precise positioning without relying on data of a specific reference station. The proposed method overcomes the limitations of the currently mostly used GPS processing approaches of relative positioning and global precise point positioning. The advantages of the proposed approach are demonstrated by using GPS data, which was recorded during the 2011 Tohoku-Oki earthquake in Japan.

We propose a new approach to quickly capture coseismic displacements with a single GNSS receiver in real-time. The new approach can overcome the convergence problem of precise point positioning (PPP), and also avoids the integration process of the variometric approach. Using the results of the 2011 Tohoku-Oki earthquake, it is demonstrated that the proposed method can provide accurate displacement waveforms and permanent coseismic offsets at an accuracy of few centimeters, and can also reliably recover the moment magnitude and fault slip distribution. We investigate three current existing single-receiver approaches for real-time GNSS seismology, comparing their observation models for equivalence and assessing the impact of main error components. We propose some refinements to the variometric approach and especially consider compensating the geometry error component by using the accurate initial coordinates before the earthquake to eliminate the drift trend in the integrated coseismic displacements.

We propose an approach for tightly integrating GPS and strong motion data at raw observation level to increase the quality of the derived displacements. The performance of the proposed approach is demonstrated using 5 Hz high-rate GPS and 200 Hz strong motion data collected during the El Mayor-Cucapah earthquake (Mw 7.2, 4 April, 2010) in Baja California, Mexico. The new approach not only takes advantages of both GPS and strong motion sensors, but also improves the reliability of the displacement by enhancing GPS integer-cycle phase ambiguity resolution, which is very critical for deriving displacements with highest quality. We also explore the use of collocated GPS and seismic sensors for earthquake monitoring and early warning. The GPS and seismic data collected during the 2011 Tohoku-Oki (Japan) and the 2010 El Mayor-Cucapah (Mexico) earthquakes are analyzed by using a tightly-coupled integration. The performance of the integrated results are validated by both time and frequency domain analysis. We detect the P-wave arrival and observe small-scale features of the movement from the integrated results and locate the epicenter. Meanwhile, permanent offsets are extracted from the integrated displacements highly accurately and used for reliable fault slip inversion and magnitude estimation.

List of Abbreviations

AC	Analysis Center
ARP	Antenna Reference Point
BDS	the Chinese BeiDou Navigation Satellite System
BKG	Federal Agency for Cartography and Geodesy, Germany
C/A	Coarse/Acquisition Code
CDDIS	Crustal Dynamics Data Information System
CODE	Centre of Orbit Determination in Europe
CORS	Continuously Operating Reference Stations
DCB	Differential Code Biases
DD	Double Difference
DF	Dual-Frequency
DFG	Deutsche Forschungs Gemeinchaft (i.e. German Research Foundation)
DOD	the U.S. Department of Defense
ECMWF	European Centre for Medium-Range Weather Forecasts
ESA	European Space Agency
EU	European Union
EEW	Earthquake Early Warning
Galileo	the European Union Satellite Navigation System
GEO	Satellites in Geostationary Orbit
GFZ	Helmholtz-Centre Potsdam-GFZ German Research Centre for Geosciences

GIM	Global Ionospheric Map
GLONASS	the Russian GLOBAL Navigation Satellite System
GLOT	GLONASS Time
GMF	Global Mapping Function
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GPST	GPS Time
GSI	Geospatial Information Authority
IAR	Integer Ambiguity Resolution
IGR	IGS Rapid Orbit
IGS	International GNSS Service
IGSO	Inclined Geosynchronous Orbit
IGU	IGS Ultra-Rapid Orbit
IOV	In-Orbit Validation
IPP	Ionospheric Pierce Point
ITRF	International Terrestrial Reference Frame
LC	Ionosphere-Free Linear Combination
LEO	Low Earth Orbit
MEO	Medium Altitude Earth Orbit
MET	Meteorology
MW_WL	MW Widelane Linear Combination
NASA	National Aeronautics and Space Administration
NRTK	Network-Based Real-Time Kinematic Positioning
OMC	Observation Minus Computation
PCO	Phase Centre Offsets
PCV	Phase Centre Variation
PNT	Positioning, Navigation and Timing
PPP	Precise Point Positioning
PPP-RA	Precise Point Positioning Regional Augmentation
RMS	Root Mean Square
RTK	Real-Time Kinematics

SAPOS	Satellite Positioning Service of the German State Survey
SD	Single Difference
SP3	IGS Standard Product 3
SPS	Standard Positioning Service
STD	Slant Total Delay
UD	Un-Differenced
UPD	Un-Calibrated Phase Delays
UTC	Coordinated Universal Time
WL	Widelane Combination
WGS-84	Word Geodetic System 1984
ZHD	Zenith Hydrostatic Delay
ZTD	Zenith Total Delay
ZWD	Zenith Wet Delay

List of Related Publications

1. Li, X., M. Ge, X. Zhang, Y. Zhang, B. Guo, R. Wang, J. Klotz, and J. Wickert (2013). Real-time high-rate coseismic displacement from ambiguity-fixed precise point positioning: Application to earthquake early warning. Geophys. Res. Lett., 40(2), 295-300, doi:10.1002/grl.50138.

2. Li, X., M. Ge, Y. Zhang, R. Wang, P. Xu, J. Wickert, and H. Schuh (2013). New approach for earthquake/tsunami monitoring using dense GPS networks. Sci. Rep., 3, 2682, doi:10.1038/srep02682.

3. Li, X., M. Ge, B. Guo, J. Wickert, and H. Schuh (2013). Temporal point positioning approach for real-time GNSS seismology using a single receiver. Geophys. Res. Lett., 40(21), 5677-5682, doi:10.1002/2013GL057818.

4. Li, X., M. Ge, Y. Zhang, R. Wang, B. Guo, J. Klotz, J. Wickert, and H. Schuh (2013). High-rate coseismic displacements from tightly integrated processing of raw GPS and accelerometer data. Geophys. J. Int.

5. Li, X., X. Zhang, and B. Guo (2013). Application of collocated GPS and seismic sensors to earthquake monitoring and early warning. Sensors, 13:14261-14276.

6. Li, X., M. Ge, C. Lu, Y. Zhang, R. Wang, J. Wickert, and H. Schuh (2014). High-rate GPS seismology using real-time precise point positioning with ambiguity resolution. IEEE transactions on geoscience and remote sensing, pp.1-15.

7. Li, X., B. Guo, C. Lu, M. Ge, J. Wickert, and H. Schuh (2014). Real-time GNSS seismology using a single receiver. Geophys. J. Int. doi: 10.1093/gji/ggu113.

Contents

Chapter 1 Introduction

Recent destructive earthquakes that struck Sumatra, Indonesia (Mw 9.2) in 2004, Wenchuan, China (Mw 7.9) in 2008, Maule, Chile (Mw 8.8) in 2010 and Tohoku, Japan (Mw 9.0) in 2011 have once again brought us to focus the urgent need for earthquake monitoring and early warning. Rapid source and rupture inversion for large earthquakes is critical for seismic and tsunamigenic hazard mitigation (Allen and Ziv, 2011; Ohta et al., 2012), and earthquake-induced site displacement is key information for such source and rupture inversions. For earthquake early warning (EEW) systems, the estimation of accurate coseismic displacements and waveforms is needed in real-time. Traditionally, displacements are obtained by double integration of observed accelerometer signals or single integration of velocities observed with broadband seismometers (Kanamori, 2007; Espinosa-Aranda et al., 1995; Allen and Kanamori, 2003). The broadband seismometers are likely to clip the signal in case of large earthquakes. Although strong-motion accelerometer instruments do not clip, the displacement converted from acceleration could be degraded significantly by drifts caused by tilts and the non-linear behavior of the accelerometer (Trifunac and Todorovska, 2001; Boore, 2001).

Since Remondi (1985) first demonstrated cm-level accuracy of kinematic GPS, Hirahara et al. (1994) labeled kinematic GPS as GPS seismology, which has since attracted more and more attention and applications in seismology (see, e.g., Ge et al. 2000; Larson et al., 2003). High-rate GNSS (e.g., 1 Hz or higher frequency) measures displacements directly and can provide reliable estimates of broadband displacements, including static offsets and dynamic motions of arbitrarily large magnitude (Larson et al., 2003; Bock et al., 2004). GPS-based seismic source characterization has been demonstrated in near-and far-field with remarkable results (Nikolaidis et al., 2001; Larson et al., 2003; Bock et al., 2004; Ohta et al., 2008; Yokota et al., 2009; Avallone et al., 2011; Melgar et al., 2012; Crowell et al., 2012). GNSS-derived displacements can be used to quickly estimate earthquake magnitude, model finite fault slip, and also play an important role in earthquake/tsunami early warning (Blewitt et al., 2006; Wright et al., 2012; Hoechner et al., 2013). Consequently in the recent years, dense GPS monitoring networks have been built in seismically active regions, e.g., Japan's GEONET (the GPS Earth Observation Network System, http://www.gsi.go.jp/) and UNAVCO's Plate Boundary Observatory (PBO, http://pbo.unavco.org/). These networks are complementary to seismic monitoring networks and contribute significantly to earthquake/tsunami early warning and hazard risk mitigation (Blewitt et al., 2006; Crowell et al., 2009).

Currently, two processing strategies are mainly used in most of the studies related to GPS seismology and tsunami warning: relative baseline/network positioning (e.g., Nikolaidis et al., 2001; Larson et al., 2003; Bock et al., 2004, Blewitt et al., 2006) and precise point positioning (PPP) (Zumberge et al., 1997). For relative kinematic positioning, at least one nearby reference station should be used for removing most of biases and recovering integer feature of ambiguity parameters by forming double-differenced ambiguities. Consequently, ambiguities can always be fixed to integers even instantaneously for achieving high positioning accuracy of few cm (Bock et al., 2011; Ohta et al., 2012). Therefore, it is already applied in real-time displacement monitoring (e. g., Crowell et al., 2009). The technique of instantaneous positioning (Bock et al., 2000) is one typical real-time relative positioning method and is integrated into EEW system (Crowell et al., 2009) and is demonstrated by applying the result for centroid moment tensors (CMT) computation (Melgar et al., 2012), finite fault slip inversion (Crowell et al., 2012) and P-wave detection by combining collocated accelerometer data and the GPS displacements using a Kalman filter (Bock et al., 2011; Tu et al., 2014). The real-time kinematic (RTK) technique is also utilized by Ohta et al. (2012) to analyze the displacement of the 2011 Tohoku-Oki earthquake. All of the previously mentioned studies used the relative positioning technique, which is able to guarantee a high accuracy at 1 cm level. However, for the relative positioning technique, GPS data from a network is analyzed simultaneously to estimate station positions. It is complicated by the need to assign baselines, overlapping Delaunay triangles, or overlapping sub-networks. This is a significant limitation for the challenging simultaneous and precise real-time analysis of GPS data from hundreds or thousands of ground stations. Furthermore, intermittent station dropouts complicate the network-based relative positioning. Relative positioning also requires a local reference station, which might itself be displaced during a large seismic event, resulting in misleading GPS analysis results. In the case of large earthquakes, such as the Mw 9.0 Tohoku-Oki event in Japan, the reference station may also be significantly displaced, even when it is several hundred kilometers away from the event. The reference station should be sufficiently far from the focal region, but must also be