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Development of Six-Degree-of-Freedom GNSS Seismometer[1]

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1 THE DEFICIENCY OF OBSERVATION TECHNIQUES ON STRONG NEAR-FIELD EARTHQUAKES

Catastrophic earthquakes often result in huge loss on people's lives and property. Therefore, techniques concerning earthquake prevention and disaster reduction are closely related to citizens' livelihood. It requires that seismologists master the mechanisms of seismic hazards, and perform timely warning for earthquakes. Unfortunately, the current observation technology on strong near-field earthquakes is still defective and cannot capture deformations accurately. At present, the instruments on seismic monitoring include seismometers, macroseismographs, GNSS receivers, etc. In detail, translational deformations can be directly obtained by processing the high-precision carrier phase observations from GNSS (Larson K. M., 2009). The major approaches include Precise Point Positioning (PPP) and Relative Positioning (RP). RP requires relatively dense continuously operating reference stations, among which the stations adjacent to the epicenter will experience the shock. Thus, researchers usually use PPP that collects absolute ground positions from each individual stations (Geng Jianghui. et al., 2017). However, limitations also exist in the GNSS technology. Firstly, GNSS has noisier observations than traditional seismometers in the entire frequency band, especially under the condition that the dynamic stress exceeds an acceleration of 2g. Meanwhile, when the signal-to-noise ratio is low, it is challenging for GNSS to independently identify small-amplitude phases such as P-wave. The possible reasons include the errors induced by satellite orbit, refractive delay, multipath effect, etc. (Geng Jianghui. et al., 2018). Secondly, under the high dynamic environment, carrier signals may generate massive amplitude error and phase distortion, leading to a result that the GNSS precision for seismic deformation measuring is limited in a centimeter scale (Ebinuma T. et al., 2012; Clare A. et al., 2017). Thirdly, the sampling rate of the GNSS seismometer is generally no more than 10 Hz. Frequency aliasing may occur when measuring strong earthquakes, contaminating the seismic low-frequency displacement observation (Liu Gang. et al., 2017). Seismometers and macroseismographs can limit the noise to as low as 0.6 ($\mu m/s^2/\sqrt{Hz}$), and have the similar ability to measure the "zero frequency" displacement signals. However, they can only obtain the ground deformations after conducting the numerical integration singly or doubly. Errors may accumulate in the

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integration process and, more importantly, the base-line is likely to be shifted if the corresponding instruments rotate in the vibration process. The current base-line correction algorithm is highly dependent on empiricism, making it hard to recover the missed coseismic displacement signals at low frequency (Tu Rui et al., 2014). High-pass filter is used for this situation and thus, the permanent ground deformation signals are missed. In addition, the combination of the multi-source data obtained by both GNSS technology and macroseismographs is also a well-known application method. However, the base-line shift phenomenon may decrease the contribution of macroseismograph data during the process of data combination (Bock Y. et al., 2011). Another typical approach for seismic deformation monitoring is to obtain the deformations with six-degree-of-freedom, through modifying macroseismograph data using gyroscope (Nigbor R., 1994). Nonetheless, gyroscope is a kind of inertial sensor as well that may be influenced by multiple error sources, such as acceleration sensitivity (Lindner F. et al., 2016). These errors may lead to large angle drift after data integration, impeding the extraction of rotation amount from low frequency band and further affecting the data correction. Therefore, recovering the shifted base-line using gyroscope is far from enough in that large discrepancies still exist in the recovered ground deformation. In conclusion, the most obvious limitation at present is the low precision, especially in the low frequency band.

2 SIX-DEGREE-OF-FREEDOM BROADBAND SEISMOGEODESY (Geng Jianghui et al., 2019)

We systematically analyze the current limitations on collecting seismic deformation information through contrast experiments. After high-pass filtering and integration, the seismic deformation displacements are able to be recovered from macroseismometer data. However, the missing low-frequency information during the high-pass filtering process cannot reflect the static permanent displacement generated by the earthquake. Furthermore, strong distortion may exist in the recovered displacement if instruments rotate in the vibration process. The combination of two inertial instrument, accelerometer and gyroscope, can provide us with information regarding six-degree-of-freedom. Due to the inherent systematic errors of gyroscope itself, the further correction using accelerometer will also result in cumulative errors and cannot reflect the actual situation. Theoretically, high-rate GNSS technology can capture the static displacement generated after the earthquake, but the actual seismic signals may be drowned by the noise because of the fact that the entire frequency band is characterized by the intrinsically loud measuring noise. Additionally, the combination of high-rate GNSS displacement and acceleration data can accurately recover the seismic deformation in the broadband. However, the weighting factor of the accelerometer should be decreased in the actual situation, weakening the contribution of accelerometer in the combination process. Thus, there is no reliable method to accurately recover seismic deformation at present. For this reason, our research group indicate a method, whereby the three allocated instruments (high-rate GNSS, accelerometer, and gyroscope) are combined together for the purpose of utilizing the advantage of each instrument, and further enhancing the information precision. The experiment results show that this method can not only recover the integrated six-degrees-of-freedom information, but also improve the precision of low-frequency information, reaching 68%. Such method is significant for the investigation of focal mechanism.

3 STRONG MOTION SEISMOGEODESY: A COMBINATION OF GNSS RECEIVER AND INERTIAL MEASUREMENT UNITS (Geng Jianghui et al., 2020)

According to the mechanism of phase-locked loop in GNSS receiver, the temperature noise of carrier waves and dynamic stress error are in a opposite state, suggesting that the dynamic stress error may increase if the temperature noise is inhibited and vice versa. Thus, under the situations with strong near-field earthquakes, we usually enlarge the temperature noise to ensure that the receiver runs steadily, tracing satellite signal continuously. However, the experiment under the strong earthquake environment shows that the position error can reach up to 4cm when the receiver is under ~$2g$ vibration. Meanwhile, we also observed the phase delay. Under the environment of strong near-field earthquakes, it is common to see vibration greater than $2g$, leading to intense observational distortion and inaccurate seismic deformation when using traditional receivers. In view of this, we propose the combination of deeply coupling GNSS receivers and inertial measurement units, in which inertial units are used to observe data and improve the precision of carrier wave phase value output by GNSS receivers. The experiment shows that the seismic deformation can be accurate to millimeter and is not influenced by the phase delay. Further, combining the recovered deformation with gyroscope in a six-degree-of-freedom way may enhance the observation precision, marking a huge breakthrough for the observation of strong near-field earthquakes.

In the 21^{st} century, destructive earthquakes have caused massive casualties and economic loss in a global scale. This research achievement successfully covers the shortage of traditional techniques for strong near-field earthquake observation. Ensuring the observational stability, it highly increase the deformation precision to a millimeter scale. Such precision is extremely important for the focal mechanism of strong earthquakes and earthquake early warning. Currently, the achievement has been successfully granted as national patent (ZL201810580041.0, ZL201410027100.3), which is the result obtained by the research team of Jianghui Geng. The team has delved into the GNSS and the combination of multiple sensor analysis, and has supported by National Natural Science Foundation of China and National key research and development projects.

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