Abstract

In recent years, the development of high-frequency observations of the Global Navigation Satellite System (HR-GNSS) is undoubtedly impressive: starting from the first attempts to describe earthquakes using GPS observations with a sampling frequency of 1 Hz at the turn of the 20th and 21st centuries, through the increase in the frequency of observations (10 Hz and more), as well as the development of processing techniques dedicated to HR-GNSS, and the combination of various GNSS constellations, to the integration of HR-GNSS with seismic techniques and the earthquake parameters estimation. This vast amount of research focused mainly on medium to large natural earthquakes, also using various vibration simulators. However, earthquakes are not limited only to those of natural origin, but can also be induced, including anthropogenic, caused, for example, by mining activity, which so far has yet to be given much attention in GNSS-seismology. Thus, this thesis covers the description of vibrations caused by shallow anthropogenic earthquakes of relatively low amplitude, recorded with the HR-GNSS technique.

This PhD dissertation aims to propose the procedures for retrieving the HR-GNSS time series of displacements and velocities adopted for earthquakes resulting in small-amplitude vibrations. Particular attention was paid to events of anthropogenic origin, mainly caused by mining activity. Various leading approaches to HR-GNSS processing were validated, including the differential approach, Precise Point Positioning and variometric approach. Also, the influence of a combination of GPS and Galileo observations was investigated. The analyses of the HR-GNSS time series were performed in comparison to the seismic data of co-located seismometers, if available. The agreement was validated in terms of peak displacements or velocities and the correlation.

One of the main parts of this research concerned the HR-GNSS time series accuracy and its improvement by noise reduction procedures with Butterworth filter and wavelet analysis. The Butterworth filtering confirmed the possibility of reducing the HR-GNSS time series noise, improving accuracy. However, this approach requires using the reference data from the co-located seismic station to assess the dominant frequency, not to cut off the signal containing vibrations. To overcome the necessity of the co-located seismic sensor, an improved denoising procedure was developed based on a combination of wavelet analysis and the interquartile range test, named MRA-IQR. With the presented procedure, the HR-GNSS time series noise can be reduced by several dozen percent to 1-2 millimetres, sufficient to reliably describe the short-term vibrations caused by the anthropogenic tremor.

An experimental determination of the seismic moment tensor for mining tremors was also carried out, including the standard seismic data and data from the HR-GNSS station for the calculations. It was demonstrated that it is possible to retrieve reliable source parameters for such small and local tremors by combining the data of various sensors. In addition, the analysis revealed that when the seismic network does not provide adequate spatial distribution around the earthquake source, HR-GNSS data may become crucial for correctly estimating event parameters.

During the research, the possibility of detecting short-term vibrations of mining tremors in the HR-GNSS time series was verified by analysing the time variability of the standard deviation and median absolute deviation, as well as the developed procedure for detecting the first motion with the Fisher statistical test. The procedure facilitates determining the first epoch of vibrations with accuracy at the level of 1-second agreement between the seismic data and HR-GNSS, which confirms the effectiveness of both the noise reduction and the detection procedure.

To sum up, the research presented in this PhD dissertation extends the current field of interest of GNSS-seismology to anthropogenic tremors, i.e., mining tremors. The developed procedures for obtaining the high-rate GNSS time series make it possible to retrieve the vibrations of 3.4-4.0 magnitude tremors consistent with seismic waveforms – the agreement within 1-2 mm for displacements and 5-10 mm/s for velocities .

Keywords: high-rate GNSS; GNSS-seismology; small-magnitude earthquakes; mining tremors