Human migration-induced impacts on noise in GNSS position time series

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ABSTRACT
The accuracy of (Global Navigation Satellite System) GNSS site coordinates is known to have been impacted by human activities, especially for sites located in or near populated or urban areas. A better understanding of these human-originated noise sources would benefit GNSS research and applications. However, much less such studies have elucidated the error sources originated by human-induced environmental and mobility or migration effects, and their respective adverse impacts on GNSS positioning accuracy. Here we investigate the level of human originated noise reduction of GNSS site coordinate time series over mainland China during the ongoing coronavirus (COVID-19) pandemic from two main sources: the reductions of human-generated migration ground vibrations, and electromagnetic signal delays from the orbiting GNSS satellites to ground stations. We processed the GNSS height time series at selected 154 sites located in 110 cities in mainland China from 1 January 2017 to 25 March 2020, including the COVID-19 pandemic time period, to quantify the improved noise levels of GNSS displacement time series, and identified their correlations with the human migrations. We concluded the human-induced signal in continuous GNSS coordinate time series can be used as a real-time metric of regional human activity or migration intensity during COVID-19 episodes.

1. Introduction
Global Navigation Satellite System (GNSS) is now a well-established technological and operational infrastructure for positioning, navigation, and timing. In addition, new and unexpected applications of GNSS in geoscience research have also been developed, such as applications to hazard monitoring and hydrology (Bock & Melgar, 2016; Larson, 2019). Variations in GNSS site coordinates, particularly for the highest variability of the vertical component, arise primarily from crustal deformation induced by mass transportation within the climate system: the land, the atmospheres and the oceans (Figure 1). Therefore, precise GNSS vertical position time series contain important geophysical information concerning to mass changes regionally and over time (e.g. Blewitt et al., 2001; Dong et al., 2002; Jiang et al., 2021; Li et al., 2020; Samrat et al., 2020). Long-term trends in the time series are expected for purely tectonic motions, which are considered fairly well-known (Ray et al., 2008). Periodic signals on GNSS height estimates (Figure 2a) are dominated by surface loading due to hydrology and atmospheric pressure (Van Dam et al., 2001) as well as related to the anomalous GNSS position harmonics (Ray et al., 2008), large-scale spurious signals caused by unmodeled periodic land displacements (Penna et al., 2007), and other signals due to unknown reasons (Amiri-Simkooei et al., 2017). After removing the secular trend and the periodic signal, GNSS height residuals (Figure 2b) are related to anomalous of climate and weather such as heavy rainfall (King et al., 2007; Yao et al., 2020b), temperature (Yan et al., 2009), droughts (Borsa et al., 2014; Chew & Small, 2014; Yao et al., 2020c), reservoir water impoundment (Tangdamrongsub et al., 2019), and large transient motions induced by such as earthquake (Avallone et al., 2016; Ji & Herring, 2013) as well as observation noise in a level of about 3 ~ 5 mm (Ji and Herring, 2013; Milliner et al., 2018) related to the environment surrounding the sites and human activities (Figure 1).

2. Noise in GNSS position time series
Understanding noise characteristics and respective adverse impacts to the accuracy of GNSS time series are crucial for geodetic and other applications. The former is important for estimating the uncertainties of parameters derived from the time series (Mao et al., 1999; Tehranchi et al., 2021; Wang et al., 2018; Williams, 2003; Zhang et al., 1997), but it does not offer ways to reduce that noise (Williams et al., 2004). The later can help to detect and interpret the noise sources and the signals of interest, and as a result help to increase the accuracy and precision of the time series (Dong et al., 2002; Langbein & Johnson, 1997). Among the possible noise sources, geodetic monument
instability induced by changes in the anchoring media (e.g. soil, bedrock, buildings) is an important noise source (Johnson & Agnew, 1995; Klos et al., 2015). This noise can largely be reduced by carefully designed monuments (Williams et al., 2004). Some noise sources that are common to all sites spatially or temporally, such as orbit errors and reference system orientation, can be reduced by applying a filtering method (Bock et al., 1997; Zheng et al., 2021), such as stacking, principal component analysis and independent component analysis (Dong et al., 2006; Liu et al., 2015; Milliner et al., 2018; Wdowinski et al., 1997). Other important site-specific error sources from multipath, signal scattering, and antenna-phase centre variations, can be reduced by repeating observations, and thus they may not be as critical for long-term continuous measurements (Genrich & Bock, 1992).

It is essential to identify and mitigate source of noise to obtain mm-level site coordinates and submillimeter per year level secular velocities (Blewitt et al., 2009). In addition to the error sources mentioned above, with the rapid development of urbanisation, human activity is becoming a considerable noise source for geodetic measurements, especially for those sites located in or near populated areas. For seismic noise, human activity is regarded as a third source of seismic signal (Lecocq et al., 2020). Compared to seismometers, which are generally installed in a quiet environment and are highly sensitive detectors, GNSS sites are more influenced by human activities since they are installed in exposed areas to have a full view for receiving signals from satellites. As a result, GNSS site position time series are more impacted by anthropogenic noise.

3. Progress in quantifying human impacts on accuracy of GNSS time series

Human activity-related signals are recorded on GNSS sites from two main sources in a dynamic environment. One is the ground vibration induced by heavy or light transportations. The other is the atmosphere effects due to frequent or sporadic human activities, which influences delaying range distance of electromagnetic signals between the GNSS satellites and the GNSS receivers on Earth’s surface. Similar to seismometers (Diaz et al., 2017; Gibney, 2020; Green et al., 2017; Lecocq et al., 2020; Riahi & Gerstoft, 2015), variations in the evolutions of GNSS sites.
are inevitably impacted by traffic and public transportation-generated vibrations (Figure 1). To quantify human-induced vibrations in GNSS height time series effectively, we must separate the natural from the anthropogenic contributions as clean as possible. Otherwise, the stronger natural signal could mask out the human-induced signal. For instance, temperature shows a strong impact on the total GNSS height noise anomalies after mid-March 2020, with an obvious increase of temperature (Figure 3a) corresponding to an increase of noise (Figure 3b).

In late 2019, the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) virus caused coronavirus diseases (COVID-19) has created an unprecedented global pandemic. With the restriction of human mobility worldwide, improvements on the environment have been identified during the pandemic (Arora et al., 2020; Hodges & Jackson, 2020), such as dramatic reductions in air and water pollution, seismic, underwater and aircraft annoyance noise as well as soundscape in urban areas (Figure 1). Many cities in China were under quarantine by the end of January 2020, resulting in dramatic falls in inter-city population mobility (Figure 3a). However, long-term lockdown in a wide area provides a unique opportunity to study the nonstationary environmental noise in GNSS position time series. By further removing the temperature-attributed noise changes from the GNSS height noise anomalies (Figure 2b), good consistencies are found between the human mobility-induced height noise anomaly and the migration index during the COVID-19 pandemic from 1 January to 25 March 2020 in China (Figures 3 and 4). Compared to the total GNSS height noise anomalies, a significant improvement in the correlation from 0.16 to 0.64 was found between human mobility-induced noise anomaly and migration index (Figure 3). Noise anomalies reduced with a mean of ~145% before and after the pandemic in the 107 cities, which coincides with the decline of migration index (Figure 4c). Even the magnitude of human mobility-induced GNSS site vibrations is particularly small (generally less than 0.5 mm), if not mitigated, it would bias the acquisition of trends and other signals from GNSS time series.

From the perspective of the receiving electromagnetic signals from GNSS satellites orbiting 20,000 km from the Earth's surface, two types of human-originated impacts occur 1) those which impact the receiver, such as the number of cars parked surrounding the station (Karegar & Kusche, 2020), and 2) those which impact the signals path to the receiver, such as propagation delays from pollutants (Guo et al., 2019; Solheim et al., 1999). Compared to ground vibrations, changes in the reflector roughness resulted in more significant noise anomalies. The uncertainty of retrieved GNSS antenna height drops from average of 4 cm to about 2 cm due to the reduction of parked vehicles surrounding a GNSS site during the COVID-19 pandemic (Karegar & Kusche, 2020). Environmental pollutants (mainly particulate matter) in the air from human activities (Figure 1) will change water vapour content and humidity, resulting in changes in GNSS tropospheric delay (Solheim et al., 1999; Liu et al., 2014; Guo et al., 2019), and the effect is comparable with the noise level of GNSS observations (Lau & He, 2017). Although this proportion can be mostly eliminated by estimating tropospheric delay as an unknown parameter (Wei et al., 2017), the residual tropospheric delay could impact the accuracy of GNSS coordinate time series.

4. Application prospects

Urbanisation around the world leads to accelerated migration, which is notable in the fast-growing emerging countries. For instance, since the 1990s, urbanisation rate in China increased by 10% per decade with
the implementation of the reform and opening up policy (Li, 2020). By 2050, about 66% of the world population (7, 875 million in 2021) will be living in cities (https://www.un.org/en/observances/world-population-day). The sustained economic and social development provides a favourable condition for population migration and mobility. Such environments generate vibrations (e.g. Diaz et al., 2017; Lecocq et al., 2020; Riahi & Gerstoft, 2015) and affect GNSS signal propagation (e.g. Solheim et al., 1999; Liu et al., 2014; Guo et al., 2019; Karegar & Kusche, 2020) given the dense transportation networks and machinery. There are now nearly a third (~5000) of global GNSS sites located within urban areas and the number is increasing (Karegar & Kusche, 2020), which are being affected by human activity more and more severely. Therefore, investigating the associated human impacts would promote the accuracy of GNSS time series and the monitoring of natural hazards triggered by weak natural processes, such as slow earthquake and slow-moving landslide.

Filtering methods could be effective to reduce the impact of large, coherent changes in human activity on noise in GNSS time series since they are common to all sites, such as strict lockdown measurement in a country. However, there is also asynchronous human-generated noise in specific GNSS sites which is difficult to model or separate. For instance, anthropogenic impacts at two adjacent GNSS sites, e.g. tens of kilometres, located in two different administrative regions, may be significantly different since different strategies to curb the spread of COVID-19 are adopted. In this case, filtering methods may be ineffective. In order to quantify anthropogenic effects more precisely, more noise-related data around the sites are needed for comprehensive analysis, such as population mobility, air quality and hydrometeors. The ever-increasing massive human activity-related data will provide a better understanding of the noise floor of GNSS observations.

An apparent improvement in the correlation (Figure 3) and a good consistency (Figure 4) between noise anomaly and migration index at regional and city scales after

Figure 3. Mean variations in (a) migration index and number of confirmed cases in 110 cities in China belonging to 24 provinces, and temperature at 154 sites, in the midst of the COVID-19 pandemic time period, 1 January to 25 March 2020; (b) mean time series of total and human mobility-induced GNSS height anomalies at 154 sites. The shaded regions show the corresponding standard deviations of selected cities, provinces and GNSS sites. The human migration index data set is based on the daily number of inbound and outbound events by rail, air and road traffic, were sourced from a web-based programme (https://qianxi.baidu.com). The temperature data set is provided by the China Meteorological Data Service Center (http://cdc.cma.gov.cn). The daily number of infected people is obtained from the internet (https://www.zq-ai.com/#/fe/xgfybigdata).
separating natural contributions during the COVID pandemic indicate the efficacy of our method to extract anthropogenic noise from the original GNSS height time series. This approach could be applied outside of COVID lockdown in regions where human activity and meteorological data are available around the GNSS sites. However, it should be noted that since human activities and the natural environment interact with each other, this complicated interaction needs to be considered for a more precise separation of human and natural-induced impacts. The challenges of GNSS coordinate time series applications also include (1) the accurate extraction of the target signal due to the time series contain multiple signals and the uncertainties in modelling load deformations; (2) the construction of theoretical models to estimate various human activities induced impacts. These could be the subjects for the future research.

In addition, understanding and quantifying correlations between GNSS noise and human mobility (Figure 4) suggest that geodesy provides a real-time cross-disciplinary metric of human activities. This metric can be used to reflect the development of human activity associated public events such as the COVID-19 pandemic, since a good consistency between the number of confirmed cases and human mobility-induced GNSS height noise anomalies is detected (Figure 3). With better quantification of the sources of human-induced noise, GNSS could potentially be used to monitor changes in human activity outside of COVID lockdown. This finding is perceived to be invaluable for both the identification of GNSS coordinate time series noise floors, as well as cross-disciplinary applications such as decision-making in response to human migrations during severe global pandemic.

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Disclosure statement

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