Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research 59 (2017) 2794–2808

ADVANCES IN SPACE RESEARCH
(a COSPAR publication)

www.elsevier.com/locate/asr

The use of PSD analysis on BeiDou and GPS 10 Hz dynamic data for change detection

Gethin Wyn Roberts*, Xu Tang

The University of Nottingham Ningbo, China, 199 Taikang Road East, Ningbo 315100, China

Received 16 January 2016; received in revised form 19 October 2016; accepted 20 October 2016
Available online 27 October 2016

Abstract

This paper examines the use of GPS and BeiDou data to measure the movements of two oscillating platforms in a series of field experiments. Data were gathered from a variety of GNSS receivers at a rate of 10 Hz, and processed in an on the fly manner, resulting in 3D coordinates at a 10 Hz rate with the corresponding precise time. These data were then analysed using a Power Spectral Density (PSD) function to derive the frequency of the movements. The positional data were also compared by matching a 500 epoch section of the data from the start with 190 successive 500 epoch long sections in order to demonstrate whether the movement measured was constant throughout, or whether there were any changes. The results show that the correlation of the positional data over a 30,737 epoch period deviates between 99.8% and 76.7% correlation with RMS values of 89.2%, 87.9% and 77.5% in the Eastings, Northings and Vertical directions respectively when using GPS. The RMS of the Eastings and Northings remain the same when BeiDou is introduced, but the height component improves slightly to 78.9%. The frequency analysis of the same 500 epoch long sections is constantly measured at 0.1172 Hz in all three positional components, illustrating less deviation when analysing the frequencies. The main conclusion is that analysis of the resulting PSD output from GNSS data gathered on an oscillating platform is more constant and precise than analysing the results of the coordinates alone. This suggests that such analysis would be well suited for a Structural Health Monitoring system. The introduction of BeiDou also improves the results slightly, even in its current incomplete constellation. The novelty of this work is the analysis of the movements in such a controlled environment, and the correlation approach of the resulting positional output as well as the frequency derivation from the positions using both GPS and BeiDou.

Keywords: GPS; BeiDou; Kinematic

1. Introduction

The use of Global Navigation Satellite Systems (GNSS) for deflection monitoring of structures (Rizos et al., 2010; Çelebi, 1998; Teague et al., 1995; Lovse et al., 1995), and in particular long span bridges (Roberts et al., 2014) has been an area of ongoing research for over 20 years. The work initially focussed on using carrier phase Global Positioning System (GPS) observations, gathered from a reference GPS receiver located adjacent to the bridge, as well as one or more GPS receivers attached to the bridge. Typically, on the handrail at deck level or on top of the support towers. The bridge data was initially gathered at a 1 Hz rate, but over successive pieces of work, this soon increased to 10 Hz, 20 Hz and even 100 Hz in some instances. The data were processed in an on the fly manner (Hofmann-Wellenhof et al., 2008) relative to the reference receiver data, either in a post processed or real time manner. Movements at decimetre level on long span bridges were calculated, as well as synchronised movements

---

* Corresponding author.
E-mail addresses: Gethin.roberts@nottingham.edu.cn (G.W. Roberts), xu.tang@nottingham.edu.cn (X. Tang).

http://dx.doi.org/10.1016/j.asr.2016.10.020

between multiple GPS receivers located on a bridge (Roberts et al., 2014). More recently, combined GNSS data have been used to determine the movements, including data gathered directly on the suspension cables (Roberts et al., 2014).

GNSS data gathered using survey grade receivers typically consist of pseudorange and carrier phase data, on one, two or even three frequencies. Such data can be gathered at 10 Hz, 20 Hz or even 100 Hz when using specific GNSS receivers. These data can also consist of GPS, GLONASS, BDS (BeiDou System), Galileo and even Regional Navigation Satellite Systems (RNSS) such as the Japanese Quazi Zenith Satellite System (QZSS). This all depends on the specific GNSS receiver used. The resolution of the carrier phase measurement is of the order of sub-millimetre (Roberts et al., 2012).

Due to the GNSS data consisting of a precise time with the corresponding range related data; the frequency of the movements can also be derived (Psimoulis and Stiros, 2008; Psimoulis et al., 2008; Ogundipe et al., 2014; Çelebi et al., 1999; Roberts et al., 2012). Such movements have been used to detect the vibration frequencies of tall buildings (Xu and Wu, 2014). The use of frequency analysis using Fast Fourier Transformations (FFT) and Power Spectral Density (PSD) analysis looks like a promising method to analyse the data, and also to detect changes in the characteristics of the movements, and hence to possibly use such frequency analysis as part of a Structural Health Monitoring (SHM) scheme. Such a SHM could be created using GNSS data from a bridge or structure to create and validate a realistic structural analyses model, such as a Finite Element Model (FEM). Periodically, more GNSS data gathered from the structure could be used to continuously compare the real data (GNSS) with the model in order to look at the deviations. GNSS data have been shown again and again to be very precise. Xu et al. (2013) illustrate that it is possible to obtain accuracies of the order of 2–4 mm in plan and vertical accuracies at the sub-centimetre level when using Precise Point Positioning. Other work have shown that precise millimetre level positioning is possible (Chen et al., 2015; Vaclavovic and Dousa, 2015). BDS is currently under development, but already has good satellite coverage over China and the surrounding area, due to the addition of Geostationary Earth Orbit (GEO) and Inclined Geosynchronous Orbit (IGSO), in addition to the Mid Earth Orbit (MEO) satellites, and constantly improving (Jin, 2013; Xiao et al., 2016). Various pieces of research have been undertaken, including combining GPS and BDS signals for better ambiguity resolution and positioning. Specific research, for example, has been carried out on improving attitude determination through integrating GPS and BDS (Nadarajah et al., 2014), and improving ambiguity resolution for Low Earth Orbiting satellite formation flying (Verhagen and Teunissen, 2014). Research has also been ongoing, integrating GPS and GNSS with accelerometers (Roberts et al., 2004) as well as rapidly developing MEMS based accelerometers (Tu et al., 2013, 2014). Such integration can result in a complimentary system, where the advantages of GPS/GNSS and the accelerometers are combined. Such advantages include the rapid data available from the accelerometers, the lack of drift in the GNSS data and the higher precision of the MEMS sensors.

This paper investigates the use of PSD analyses and a cross correlation function in order to analyse datasets from two experiments. The first experiment consists of a rig using three tripods that support three bungee cords which in turn support a wooden platform, with a GNSS antenna attached to it. The platform can be excited and will move in an oscillating manner. The second rig consists of a 3 m long rotating arm, with a GNSS antenna located at the end. Both experiments included the use of multi-GNSS receivers connected to the same antenna using a cable splitter. These data were then post processed relative to the GNSS receivers attached to the reference station pillar. All the experiments were carried out on the roof of the Science and Engineering Building (SEB) at the University of Nottingham Ningbo China (UNNC) campus.

This paper concentrates on data from specific receivers, and also through analysing the BDS and GPS data processing, either as individual solutions or as a combined multi-GNSS solution. The analysis of the results using PSD and the correlation function attempts to illustrate that analysis of the frequency of the oscillating data derived from GNSS, and any changes in the frequency, is a strong method to compare any changes in the movement charac-

Fig. 1. The bungee experiment located on the roof of the Science and Engineering Building, UNNC (left), and a close up view of the Leica AR25 choke ring GNSS antenna (right).