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Multipath extraction and mitigation for bridge deformation monitoring using a single-difference model

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Abstract

Multipath is one of the primary error sources in high precision GNSS applications. Since it is highly correlated with observation environments, the multipath effect is difficult to be parameterized with an empirical model or eliminated by current differencing techniques. A sophisticated multipath extraction and mitigation technique is proposed. The technique uses the spectrum density of the time series of single-difference (SD) phase residuals to identify which portions of the observation environments contribute the various multipath constituents. Wavelet analysis is used to extract the time-varying frequency and magnitude contents of multipath. Multipath templates are built to assess the performance of ambiguity resolution before and after multipath mitigation. Using GPS data measured at the Forth Road Bridge in Scotland, we identify that there are two types of multipath with different affecting characteristics on the bridge. The initial analysis reveals that the correlations between adjacent days remain higher than 80% for both carrier phase and pseudorange multipath. Further comparisons indicate that the standard deviations of the residuals are reduced roughly by 30% for most of the satellites when multipath templates are applied, whereas the reductions of the mean standard deviations of the coordinate components, from 13 consecutive days, maintain stable at about 30% for a 1.5 km baseline and 45% for a 36 m baseline. It is also evident that ambiguity resolution has significant improvement with applying multipath mitigation, contributing to more accurate and reliable ambiguity results in high-precision deformation monitoring.

Keywords: GNSS; Multipath; Single-difference model; Ambiguity resolution; Spatiotemporal repeatability

1. Introduction

The demands for high accuracy positioning requires us to address each individual error present in GNSS data carefully. As one of the primary error sources, multipath is difficult to address via empirical models or/with differencing techniques due to its site-dependent nature. Generally, the multipath effects could be classified into three types (Tranquilla and Carr, 1990): (1) diffuse multipath scattering from a widely distributed area with a repetition period ranging from less than one minute to 2–3 min; (2) specular multipath from smooth reflective surfaces with periods ranging between 5 and 10 min; and (3) very low-frequency multipath associated with reflection from water surface, with a very long repetition period of the order of 25–60 min. The presence of multipath effects in the GPS observables would lead to range errors on the order of

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meters for pseudorange and several centimeters for carrier phase measurements. Multipath on carrier phase shows a direct and significant effect on high-precision positioning as compared to that on pseudorange. The phase multipath at a certain level may always remain undetectable, leading to errors in phase measurements, since the design of the phase lock loops (PLLs) must be able to distinguish clock dynamics from user motion in order to prevent cycle slips (Lau and Cross, 2007). Theoretically, the maximum phase multipath error can reach a quarter of the signal wavelength, approximately 4.76 cm for the GPS L1 carrier phase. This means that the maximum multipath-induced error could reach 1/2 of the wavelength if the phase errors at both ends of a baseline reach their maximum but in the opposite signs for the baseline phase differencing (Dong et al., 2015). If the geometry of the satellites with respect to the reflector and antenna changes smoothly, the carrier-phase multipath error typically displays sinusoidal characteristics and is difficult to be separated from the coordinate results.

In general, multipath errors are not easy to be extracted and mitigated among other systematic errors (e.g., receiver clock and atmospheric delay) and the observation noise of satellites. Current multipath mitigation techniques can be classified into three types. Firstly, the straightforward method is to select a favorable environment and reduce the reflections surrounding the antenna. Nevertheless, this method is not feasible for some applications such as structural monitoring, since the reflection is inevitable due to the nature of the environment. Secondly, the hardware-dependent approaches are used to improve the antenna gain patterns. For example, polarization-related antenna gain pattern, choke rings or ground planes can be used in different observation environments. Depending on the signal type, bandwidth, chipping rate, etc., the receiver-internal correlation techniques are also used to improve the quality of signals within the code and frequency tracking loops (Irsigler and Eissfeller, 2003), such as the narrow correlator (Dierendonck et al., 1992), and the double-delta correlation variants (McGraw and Braasch, 1999). Current hardware-dependent methods can minimize code and/or carrier phase multipath, but they are difficult to fully mitigate multipath whilst still recording the required signals. Therefore, the third method which is based on data post-processing algorithms should also be considered for high precision applications.

The post-processing algorithms can be categorized with regards to the use of un-differenced, single- and double-difference residuals. Wanninger and May (2001) used double-difference (DD) residuals of short and long baselines to extract the carrier phase multipath errors in a static environment and proved the successful multipath calibration and correction. Using the spectral content of signal to noise ratio (SNR), Lau and Mok (1999) improved the accuracy by using the SNR weighted least squares processing algorithm. Bilich and Larson (2007) exploited the relationship between the SNR data and the phase multipath to image the multipath environment. In order to realize the real-time multipath reduction, the sidereal filtering approach (Genrich and Bock, 1992) was proposed using repeatable GPS orbits for static antennas. Using adaptive filtering, Dodson et al. (2001) separate the real bridge movement from multipath signal and individual receiver random noise in the coordinate domain. By adopting an actual mean orbit repeating period for satellites, Choi et al. (2004) improved the efficiency of sidereal filtering in the coordinate domain. Ragheb et al. (2007) compared the measurement and coordinate domain multipath filtering techniques and confirmed that the coordinate domain method gave slightly better precision, whereas the phase residual domain approach is computationally efficient for the ambiguity resolution. It is important to note that the conventional phase multipath analysis is mainly based on the DD phase residuals, therefore the relationship between multipath, elevation and azimuth is difficult to analyze. In order to attain the spatial characteristic of the multipath, the assumption that the sum of observed satellites' single-difference (SD) residuals will be zero was implemented through a transfer matrix (Alber et al., 2000; Ye et al., 2015), so that DD residuals could be transformed to the SD residuals. However, the reference satellite also needs to be selected at every epoch. Making use of the arithmetic mean of the Precise Point Positioning (PPP) residuals, Fuhrmann et al. (2015) proposed an advanced approach to perform residual-based multipath stacking maps in the space domain. Using PPP, the un-differenced phase residuals can be obtained, but unstable uncalibrated phase delays (UPD) of both satellites and receivers are absorbed in the float-ambiguity PPP carrier phase residuals and cannot be distinguished from the phase multipath. Dong et al. (2015) compared the multipath stacking maps and sidereal filtering approaches utilizing the between-receiver (BR) SD ambiguity resolution under static environment, but the between-receiver UPD should firstly be separated and certain convergence time is needed. Although for the static environment, multipath can be significantly reduced through carefully arranged data processing, such options are not feasible or effective, especially for monitoring dynamic structural deformation. A new method to evaluate the multipath effects is therefore of a great value.

This paper is concerned with the pseudorange and carrier-phase multipath, particularly in relation to high accuracy deformation monitoring applications. Section 2 introduces the BR SD integer ambiguity resolution for the generation of SD residuals. In the subsequent section, the characteristics of the multipath and the mitigation method are described in detail. In Section 4 the results using data gathered from the Forth Road Bridge are presented. In the study the Fast Fourier transform is used to distinguish the specular and diffuse multipath. The multipath time series is further investigated using correlation analysis to assess the day-to-day signature and estimate the time shift of the day-to-day residual time series. The results with the above-mentioned methods are shown, including the comparison of ratio-test and coordinate vari-