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Evaluation of GPS/BDS indoor positioning performance and enhancement ☆

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Abstract

This paper assesses the potential of using BDS and GPS signals to position in challenged environments such as indoors. Traditional assisted GNSS approaches that use code phase as measurements (i.e., coarse-time solutions) are shown to be prone to multipath and noise. An enhanced approach that has superior sensitivity and positioning performance—the so-called direct positioning receiver architecture—has been implemented and evaluated using live indoor BDS and/or GPS signals. Real indoor experiments have been conducted in Shanghai and significant improvement has been observed with enhanced approaches: results with BDS constellation show better horizontal positioning performance (biases are less than 10 m) than using GPS alone, but are slightly worse in the vertical axis; when using the enhanced approach with BDS and GPS, both horizontal and vertical axes show promising results for the environments considered herein; the coarse-time state converges faster and is more reliable compared to other solutions.

Keywords: Assisted GNSS; Indoor positioning; Indoor BDS

1. Introduction

In the past, the concept of assisted-GPS significantly broadened the applications for mass market GPS receivers. Typically, the signal reception sensitivity is enhanced for each individual satellite channel with long non-coherent integration Van Diggelen (2009). Few results have been found (to the best of authors' knowledge) in the literature evaluating or comparing the positioning performance using assisted BeiDou (BDS), assisted GPS or both, in real indoor environments. This could be due to the fact that BDS MEO satellites are not fully established globally. However, in eastern China, the coverage of BDS is good enough to evaluate such performance. In the past, the benefits of five GEO satellites in China area for positioning indoors have not been mentioned or discussed either. Moreover, current literature lacks discussing of the methods to further enhance the receiver's performance using single or multiple constellations based on live indoor data.

To improve signal tracking performance, standard approaches include increase integration, such as using high quality oscillator and increasing long coherent integration are reported in Pany et al. (2009) and Gaggero and Borio

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(2008); or use advanced receiver architectures such as vector tracking, ultra-tight integration with sensors as discussed in Lashley et al. (2009) and Pany and Eissfeller (2006) to name a few. In the meantime, some researchers also suggest to use all-in-view satellite to enhance the acquisition performance in GNSS receivers known as 'collective detection' as reported in Axelrad et al. (2011), Cheong et al. (2012), and Esteves et al. (2014). One interesting by-product for this direct approach is that the positioning or navigation solution can also be determined during the acquisition or detection process. For these collective detection oriented algorithms, a chip spacing of 0.5 are often used which gives the worst case and average correlation losses about 2.5 dB and 1.16 dB respectively as shown in De Wilde et al. (2006). To the contrary, others have focused on improving estimation performance of this direct approach as a maximum likelihood positioning method (evaluate the likelihood function in some region) or maximum a posterior method (making use of a prior information recursively), such as reported in Closas et al. (2007), He and Petovello (2014), and He (2013). Multiple correlator is often used by evaluating multiple correlator output within interested region van Graas et al. (2005). The multiple correlator approach for code phase estimation turns out to be a straight forward ML code phase estimator. Analogously, the direct positioning approach also can be used for the Doppler and velocity determination with multiple constellations, and the corresponding results in different indoor environments have been discussed in He et al. (2012). By using above-mentioned approaches, weak GPS signals can be more reliably tracked, which also have other potentials such as reflectometry reported in Jin and Najibi (2014) or indoor navigation He et al. (2013) and Zhuang et al. (2015).

The first objective of paper is to evaluate the performance of assisted GPS/BDS (A-GPS/BDS) traditional architecture in real harsh environments. Blockage, fading or multipath can all occur simultaneously resulting in signals having a carrier to noise-density ratio (C/N_0) lower than 15 dB-Hz. The paper also implements a direct positioning receiver architecture similar to that in He (2013) and He and Petovello (2014) which is an enhanced assisted receiver. The performance of enhanced A-GPS, A-BDS and A-GPS/BDS are also assessed and compared to the traditional approach in real harsh environments.

Section 2 briefly discusses the traditional assisted GPS/BDS technology and also outlines the enhanced approach. Section 3 shows the experiments conducted in Shanghai and illustrates indoor environments used. In Section 4, data processing results are presented and the corresponding positioning statistics are summarized for comparison. Finally, Section 5 concludes the paper.

2. Traditional and enhanced assisted-GNSS

The traditional A-GPS technology has been discussed in Van Diggelen (2009) and typically uses code phase measurements instead of pseudorange. Code phase observations have millisecond ambiguities since accurate time of transmission information is not required when constructing the measurements. The A-GPS will use network information to get fine time assistance in sub-second level, and ephemeris or satellite positions/velocities. Using this information, the receiver only needs to evaluate the correlation between incoming signal and local replica within a much smaller region. Long non-coherent integration is commonly used to improve the reception sensitivity and quality of the observations.

It is also known that using standard delay-lock loops with strong signals will tend to yield a good approximation of maximum likelihood code phase estimators as reported in Parkinson (1996). For the indoor scenarios considered herein, multiple correlators are used to track the code phase errors over observation intervals whose duration, T_I, depends on both the coherent integration time (T_{CI}) and number of noncoherent combinations, P. In Hurd et al. (1987), it has shown that the maximum likelihood code phase estimate, $\hat{\tau}_{ML}$, can be expressed as:

$$\hat{\tau}_{ML} = \underset{\tau}{\operatorname{argmax}} \left| \int_0^{T_{CI}} \tilde{r}(t)c(t-\tau)dt \right|^2 \tag{1}$$

where $c(t)$ is the local code sequence, τ is the code phase and $\tilde{r}(t)$ is the complex envelope that is obtained by performing quadrature decomposition Proakis (2001). In this equation, the Doppler is assumed to be accurately compensated for in order to simplify the following analysis. The in-phase and quadrature correlator outputs for a coherent integration of T_{CI} can be defined as:

$$y_{I,p}(\tau) = Re\left(\int_{(p-1)T_{CI}}^{pT_{CI}} \tilde{r}(t)c(t-\tau)dt \right) \tag{2a}$$

$$y_{Q,p}(\tau) = Im\left(\int_{(p-1)T_{CI}}^{pT_{CI}} \tilde{r}(t)c(t-\tau)dt \right) \tag{2b}$$

With correlator outputs defined above, the correlator power at code phase τ for the pth coherent integration interval of T_{CI} can be defined as

$$z_p(\tau) = y_{I,p}^2(\tau) + y_{Q,p}^2(\tau) \tag{3}$$

Then the maximum likelihood estimate of code phase for a total integration time of $T_I = PT_{CI}$ can be expressed as:

$$\hat{\tau}_{ML} = \underset{\tau}{\operatorname{argmax}} \sum_{p=1}^{P} z_p(\tau) \tag{4}$$

The standard single point positioning navigation solution takes pseudorange measurements as inputs, and thus only four states are estimated: three user position terms and the unknown clock bias between the satellite and receiver. If decoding of navigation message is not possible in weak signal environments such as indoors, a coarse-time

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