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ScienceDirect

Advances in Space Research xxx (2017) xxx–xxx

ADVANCES IN SPACE RESEARCH
(a COSPAR publication)

www.elsevier.com/locate/asr

Advanced receiver autonomous integrity monitoring using triple frequency data with a focus on treatment of biases

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Received 5 April 2016; received in revised form 27 January 2017; accepted 28 January 2017

Abstract

Most current Advanced Receiver Autonomous Integrity Monitoring (ARAIM) methods are designed to use dual-frequency ionosphere-free observations. These methods assume that receiver bias is absorbed in the common receiver clock offset and bound satellite biases by nominal values. However, most multi-constellation Global Navigation Satellite Systems (GNSS) can offer triple frequency data that can be used for civilian applications in the future, which can improve observation redundancy, solution precision and detection of faults. In this contribution, we explore the use of this type of observations from GPS, Galileo and BeiDou in ARAIM. Nevertheless, the use of triple frequency data introduces receiver differential biases that have to be taken into consideration. To demonstrate the significance of these additional biases we first present a method to quantify them at stations of known coordinates and using available products from the International GNSS service (IGS). To deal with the additional receiver biases, we use a between-satellite single difference (BSSD) observation model that eliminates their effect. A pilot test was performed to evaluate ARAIM availability for Localizer Performance with Vertical guidance down to 200 feet (LPV-200) when using the triple-frequency observations. Real data were collected for one month at stations of known coordinates located in regions of different satellite coverage characteristics. The BSSD triple-frequency model was evaluated to give early indication about its feasibility, where the implementation phase still requires further comprehensive studies. The vertical position error was always found to be bounded by the protection level proven initial validity of the proposed integrity model.
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Keywords: ARAIM; GNSS; Integrity monitoring; Biases; LPV-200

1. Introduction

The presence of multiple GNSS constellations that provide a global coverage with multiple frequency observations led to the development of Advanced Receiver Autonomous Integrity Monitoring (ARAIM) methods for aircraft localizer performance with vertical guidance. For example, integration of GPS with Galileo in ARAIM has been shown in Rippl et al. (2011), and in Choi et al. (2012), Walter et al. (2013) using GPS and GLONASS. Integration of GPS with BeiDou in ARAIM has been demonstrated in Lijun et al. (2012), Liu and Zhu (2014); and El-Mowafy (2016).

The current proposed ARAIM methods use dual-frequency observations. Nevertheless, Galileo, BeiDou and GPS block III satellites provide triple-frequency observations. The additional use of a third frequency can improve positioning accuracy compared to the dual-frequency case (Elsobeiey, 2015; Duong et al., 2016) and can enhance the fault detection capability (Guo et al., 2011), which is a fundamental task in integrity monitoring. Another advantage of the use of a third frequency is that in case of unavailability of observation from one frequency, the remaining data of the satellite can still be used without excluding this satellite. Nevertheless, aviation requires the use of signals operating in designated safety-of-life aeronautical radionavigation service (ARNS) band. At present, the International Civil Aviation Organisation (ICAO) has

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http://dx.doi.org/10.1016/j.asr.2017.01.037
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Please cite this article in press as: El-Mowafy, A. Advanced receiver autonomous integrity monitoring using triple frequency data with a focus on treatment of biases. Adv. Space Res. (2017), http://dx.doi.org/10.1016/j.asr.2017.01.037

not published the required navigation standards for Galileo and BeiDou, and the standards for dual-frequency use. However, these standards are expected to be available in the near future. Naturally, the implementation phase of a third frequency still requires a long road until the three signals are operationally available and regulations and policies are developed.

Although the use of multi-constellation GNSS signals can enhance positioning accuracy and integrity monitoring (IM), such improvement requires proper handling and bounding of biases not only for satellite observations from each constellation but also among different constellations. The observation biases are dependent on the receiver and the individual satellite signal characteristics. They are mainly caused by signal distortion in the analogue and digital parts of the signal chain, which produces distortions in the chip shape that cause the receiver's correlation function to deviate from its ideal triangular shape leading to a shift in the tracking point, and thus causes a bias in the measured pseudorange (Hauschild and Montenbruck, 2016). Additional biases are attributed to satellite orbit and clock navigation message miss-modelling, antenna phase centre offsets, inter-frequency biases, code-carrier incoherence, in addition to signal path through the antenna, splitter, cabling and amplifier (Phelts, 2007). It is typically assumed that the signal characteristics of the satellites from the same GNSS constellation on the same spectral band are identical. Hence, in the current ARAIM dual-frequency methods, the receiver biases are assumed absorbed into the common receiver clock offset and the satellite biases are bounded by a nominal value. However, differential receiver biases will be introduced when a third civilian frequency is used due to the fact that receiver biases are frequency dependent, which then require a proper treatment.

In this paper, we explore the feasibility of using a third frequency in ARAIM by creating two dual frequencies ionosphere-free (*IF*) observations, expecting the presence of these signals for civilian use in the future. To this end, instead of making assumptions on the differential receiver biases between the two *IF* observations, or trying to estimate them, where both approaches have a degree of uncertainty, we use a between-satellite single difference (BSSD) observation model in place of the traditional undifferenced observation model. This approach eliminates receiver clock offset as well as receiver hardware biases and therefore solves the problem at hand.

In the following sections, integrity monitoring using the triple-frequency data is presented. A method for estimation of biases at stations of known coordinates is discussed to show the significance of the differential code biases and that they should be considered when using triple frequency observations. The implementation of the BSSD model in ARAIM using triple-frequency data to cancel these biases is next discussed. Then, results of experimental evaluation of ARAIM availability is presented and analysed at representative sites using data from multiple-constellations, including GPS, Galileo and BeiDou.

2. The triple-frequency observation model

In this study we use triple frequency data in the form of two ionosphere-free (*IF*) combinations. The *IF* observation equation of the pseudorange code measurements for satellite m from a GNSS constellation, such as Galileo, to receiver r for signals c_i and c_j on frequencies f_i and f_j in length units can be expressed as (El-Mowafy, 2014):

$$p(IF_{c_{i,j}})_r^m = \rho_r^m + C(d\check{t}_r - dt^m) + T^m + Cd^m(IF_{c_{i,j}}) + \varepsilon_{P(IF_{c_{i,j}})_r^m} \tag{1}$$

where

$$d\check{t}_r = dt_r + d_r(IF_{c_{i,j}}), \quad d_r(IF_{c_{i,j}}) = a_{i,j}d_r(c_i) - b_{i,j}d_r(c_j) \tag{2}$$

$$d^m(IF_{c_{i,j}}) = a_{i,j}d^m(c_i) - b_{i,j}d^m(c_j) \tag{3}$$

with

$$a_{i,j} = \frac{f_i^2}{f_i^2 - f_j^2}, \quad b_{i,j} = \frac{f_j^2}{f_i^2 - f_j^2} \tag{4}$$

$p(c_j)_r^m$ is the ionosphere-free combination code measurements, ρ_r^m is the satellite-to-receiver range, C is the speed of light in vacuum, dt_r and dt^m are the receiver and satellite clock offsets. T^m is the troposphere delay, $\varepsilon_{P(c_j)_r^m}$ comprises measurement noise and multipath of code measurements. $d_r(c_i)$ and $d^m(c_i)$ are the receiver and satellite hardware biases for c_i in time units, and similarly $d_r(c_j)$ and $d^m(c_j)$ for c_j. It is typically assumed that the signal characteristics of the satellites from the same GNSS constellation on the same spectral occupation are identical. Hence, it follows that the receiver-dependent biases are assumed the same for all observations modulated on the same frequency for all satellites from the same constellation. Thus, in the above model, the receiver hardware bias is combined with the common receiver clock offset, and the joint term $d\check{t}_r$ is determined as one of the unknowns per constellation.

In the case of using triple-frequency data, for instance using c_k in addition to c_i and c_j, a second *IF* observation is added to Eq. (1), such that:

$$\begin{aligned} p(IF_{c_{i,k}})_r^m = {} & \rho_r^m + C(d\check{t}_r - dt^m) + T^m + Cd^m(IF_{c_{i,k}}) \\ & + \Delta d_r(IF_{c_{i,j}}, IF_{c_{i,k}}) + \varepsilon_{P(IF_{c_i,c_k})_r^m} \end{aligned} \tag{5}$$

where

$$\Delta d_r(IF_{c_{i,j}}, IF_{c_{i,k}}) = d_r(IF_{c_{i,k}}) - d_r(IF_{c_{i,j}}) \tag{6}$$

is a receiver differential code bias (DCB). This term appears because a common receiver clock offset is used for all frequency combinations whereas it includes the bias of the ionosphere-free combination of the first pair of observations (i, j) as shown in (2). Hence, when the third frequency k is used; the additional differential receiver bias $\Delta d_r(IF_{c_{i,j}}, IF_{c_{i,k}})$ needs to be considered and bounded. Furthermore, when combining measurements from different constellations, as usually is the case in ARAIM, and when computing the vertical protection levels (PL), which

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