ARTICLE IN PRESS

Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research xxx (2016) xxx–xxx

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

www.elsevier.com/locate/asr

Azimuth-dependent elevation threshold (ADET) masks to reduce multipath errors in ionospheric studies using GNSS

Tsige Y. Atilaw [a,b,*], Pierre Cilliers [a,b], Peter Martinez [b]

[a] South African National Space Agency, P.O. Box 32, Hermanus 7200, South Africa
[b] SpaceLab, Department of Electrical Engineering, University of Cape Town, Rondebosch 7700, South Africa

Received 25 November 2015; received in revised form 12 October 2016; accepted 20 October 2016

Abstract

Physical structures found in the vicinity of GNSS receivers can introduce multipath interference effects when a signal arrives at the receiver by different routes. Multipath effects are well recognized as one of the most significant sources of error that degrade the accuracy of GNSS signals for navigation and positioning applications. These effects also reduce the quality of GNSS data used for ionospheric studies. The principal cause of multipath effects is proximity of the antenna to reflecting structures and it is more pronounced when the signal comes from a satellite with low elevation. Typically, conservative fixed-elevation thresholds of 20–40° are used to filter out signals from low elevation angles, but this leads to the exclusion of a significant quantity of useable data. In this paper we present a series of azimuth-dependent elevation thresholds that were developed by characterizing the multipath environment of the GPS Ionospheric Scintillation and TEC (Total Electron Content) Monitor (GISTM) receivers installed by SANSA (South African National Space Agency) at Mauritius (20.14°S and 57°E), Marion Island (46.87°S and 37.86°E) and SANAE IV in Antarctica (71.73°S and 2.2°W). The threshold masks were developed from azimuth-elevation maps of the S_4 index, σ_ϕ index, the Code-Carrier Divergence Standard Deviation (CC-STDDEV) and the L1 Carrier-to-Noise Density (L1 CNo) from 1-min scintillation data taken over a period of 10–12 months at each location to identify signals that are distorted by multipath effects. Using the azimuth-dependent elevation threshold (ADET) mask typically gives 22–28% more useful data than using a fixed-elevation threshold at the sites studied in this paper.

Keyword: GNSS; Multipath errors; Scintillation; GISTM

1. Introduction

Ionospheric scintillation studies provide useful insights regarding the formation and evolution of ionospheric irregularities (Alfonsi et al., 2011; Romano et al., 2013). The proliferation of Global Navigation Satellite System (GNSS) constellations provides an extremely useful tool for carrying out ionospheric scintillation studies. However, the environment surrounding GNSS antennas has a great impact on the quality of the data that can be used for scintillation studies. Therefore, characterizing the antenna environment should be the first step to improving the quality of GNSS data used in such studies.

Multipath effects are location dependent, which means that each receiver environment has to be characterized individually in order to reduce errors that are caused by multipath effects without losing valuable data. Characterizing the multipath environment of a GNSS antenna can help to identify in azimuth-elevation space areas affected by stationary multipath sources. A location-specific elevation mask can be developed from the characteristics of the environment. Such a mask can filter out signals that

* Corresponding author at: South African National Space Agency, P.O. Box 32, Hermanus 7200, South Africa.
E-mail addresses: atltsi001@myuct.ac.za, tsigeyared11@gmail.com (T.Y. Atilaw).

http://dx.doi.org/10.1016/j.asr.2016.10.021
0273-1177/© 2016 COSPAR. Published by Elsevier Ltd. All rights reserved.

are distorted by multipath effects and thus reduce the multipath errors.

Typically, conservative fixed-elevation thresholds of 20–40° are used to filter out signals from low elevation angles. However, such fixed-elevation masks do not take into consideration the surrounding environment of a specific receiver antenna. Applying a fixed-elevation cut-off angle leads to the loss of valuable data associated with non-multipath signals and may not remove all of the multipath errors due to structures that have elevation angles above the fixed cut-off angle.

Various methods have been developed to reduce the effect of multipath errors on GPS position estimation and ionospheric studies. One of the approaches developed to improve high-rate GPS positioning uses the ground track repeat period of GPS satellites, it was first suggested by Genrich and Bock (1992) and has been modified by Choi et al. (2004) and Larson et al. (2007) at different times to improve the precision of high rate GPS positioning. This method takes advantage of the daily repeated multipath effects as the GPS orbital period and the geometry of a GPS satellite with respect to an antenna repeat daily (Choi et al., 2004; Larson et al., 2007). It has been suggested by Choi et al. (2004) that this method can also be useful for ionosphere and troposphere studies with more accurate assessment of the orbit repeat period.

Characterizing the antenna environment is proven to be very essential in order to improve the quality of GNSS data for ionospheric scintillation studies and to develop multipath mitigation techniques (Romano et al., 2013; Spogli et al., 2014). The study done by Romano et al. (2013) shows how to characterize the multipath environment of GISTM stations to find the areas from where, around the receiver, multipath signals are coming. In the characterization azimuth-elevation maps of scintillation indices, that were averaged over a long period, and panoramic pictures that show the surrounding (360° view) of the receiver has been used (Romano et al., 2013). This type of plots, which are known as Ground-Based Scintillation Climatology (GBSC), were also used by Spogli et al. (2014) to develop a multipath signal filtering method. The multipath filtering method developed by Spogli et al. (2014) uses the inter quartile range (IQR) of the standard deviation of the CCSTDDEV (Code-Carrier Divergence Standard Deviation) to find the mild outlier and extreme outlier data. Which in this case bins in the azimuth-elevation maps that correspond to mild outlier values are considered as multipath and they were filtered out (Spogli et al., 2014). It has been proved that, this method can reduce the amount of the data loss that will be introduced by using a fixed elevation threshold for filtering out multipath errors (Spogli et al., 2014).

This project aims to characterize the multipath environment of ionospheric scintillation receivers in order to identify areas in azimuth-elevation space, which might be linked to stationary physical structures in the vicinity of the antenna that give rise to multipath errors. An azimuth-dependent elevation threshold (ADET) mask, which can be used to filter out these multipath errors is developed. The use of this mask will improve the quality of the scintillation data used for ionospheric studies.

2. Scintillation indices

2.1. Amplitude scintillation (S_4 index)

Amplitude scintillations are observed as fading and enhancement of signal intensity. Such scintillation can cause errors in decoding the GNSS data message and also in estimating the range (Wanninger, 1993; Carrano et al., 2005). When signals fade below the receiver's lock threshold, which depends on the bandwidth of the GNSS receiver system and on the type of the tracking channel, it will cause loss of lock on signals coming from the satellite (Wanninger, 1993; Aquino et al., 2005). In the worst case of amplitude scintillation, for deep and long-duration signal fading, it will be difficult to acquire the satellite in the first place (Beach, 1998; Shanmugam et al., 2012). The S_4 index is the standard deviation of the signal intensity normalized to the mean value of the intensity, namely (Beach, 1998; Datta-Barua et al., 2003; Kintner et al., 2004)

$$S_4 = \sqrt{\frac{<I^2> - <I>^2}{<I>^2}}, \tag{1}$$

where I is signal intensity and $<>$ indicates the mean value, usually taken over a period of 1 min.

2.2. Phase scintillation (σ_ϕ index)

Phase scintillations are observed as rapid fluctuations on the phase of the received signal. Phase scintillation stresses the ability of the phase-lock loops of the receiver to maintain lock, which might lead to a loss of phase lock and frequent cycle slips (Wanninger, 1993; Groves et al., 1997; Carrano et al., 2005; Shanmugam et al., 2012). The phase scintillation index is calculated by taking the standard devi-

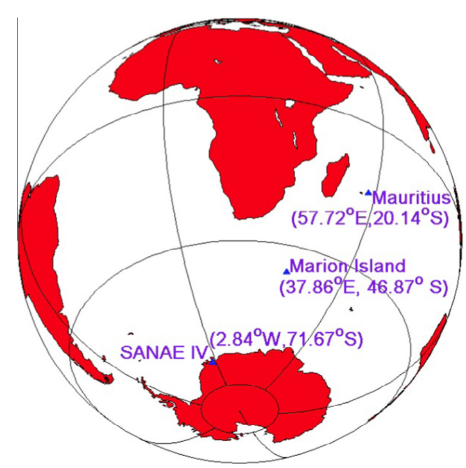

Fig. 1. Geographic locations of the GISTM receivers at Mauritius, Marion Island and SANAE IV.

Please cite this article in press as: Atilaw, T.Y., et al. Azimuth-dependent elevation threshold (ADET) masks to reduce multipath errors in ionospheric studies using GNSS. Adv. Space Res. (2016), http://dx.doi.org/10.1016/j.asr.2016.10.021