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ScienceDirect

Advances in Space Research 57 (2016) 245–256

ADVANCES IN SPACE RESEARCH
(a COSPAR publication)

www.elsevier.com/locate/asr

Ionospheric tomography over South Africa: Comparison of MIDAS and ionosondes measurements

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Received 14 May 2015; received in revised form 19 August 2015; accepted 21 August 2015
Available online 4 September 2015

Abstract

This paper aims to show the results of an ionospheric tomography algorithm called Multi-Instrument Data Analysis System (MIDAS) over the South African region. Recorded data from a network of 49–53 Global Positioning System (GPS) receivers over the South African region was used as input for the inversion. The inversion was made for April, July, October and December representing the four distinct seasons (Autumn, Winter, Spring and Summer respectively) of the year 2012. MIDAS reconstructions were validated by comparing maximum electron density of the F2 layer (NmF2) and peak height (hmF2) values predicted by MIDAS to those derived from three South African ionosonde measurements. The diurnal and seasonal trends of the MIDAS NmF2 values were in good agreement with the respective NmF2 values derived from the ionosondes. In addition, good agreement was found between the two measurements with minimum and maximum coefficients of determination (r^2) between 0.84 and 0.96 in all the stations and validation days. The seasonal trend of the NmF2 values over the South Africa region has been reproduced using this inversion which was in good agreement with the ionosonde measurements. Moreover, a comparison of the International Reference Ionosphere (IRI-2012) model NmF2 values with the respective ionosonde derived NmF2 values showed to have higher deviation than a similar comparison between the MIDAS reconstruction and the ionosonde measurements. However, the monthly averaged hmF2 values derived from IRI 2012 model showed better agreement than the respective MIDAS reconstructed hmF2 values compared with the ionosonde derived hmF2 values.The performance of the MIDAS reconstruction was observed to deteriorate with increased geomagnetic conditions. MIDAS reconstructed electron density were slightly elevated during three storm periods studied (24 April, 15 July and 8 October) which was in good agreement with the ionosonde measurements.

Keywords: GPS; Ionosonde; MIDAS; IRI; Tomography; Ionosphere

1. Introduction

The ionosphere is a complex and dynamic medium whose refractive nature affects radio waves in such a way that their magnitude becomes frequency dependent. This effect makes high frequency (HF) communication beyond the horizon possible since oblique signals can be refracted and returned to the ground (Mitchell and Spencer, 2003). While the ionosphere is a dynamic medium whereby the ionospheric parameters change with time of the day, season and solar cycle, it is still a cost effective and efficient tool for radio communication, although not as reliable as radio propagation by satellites. Moreover, the ionosphere affects the accuracy of Global Navigation Satellite System (GNSS) positioning and timing. Hence, it is important to study the characteristic features and dynamics of the ionosphere so that a near real-time variation of the

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http://dx.doi.org/10.1016/j.asr.2015.08.017
0273-1177/

ionosphere can be traced and mapped using ionospheric measurement tools. An organized near real-time 3D global map of electron density that is updated regularly allows the radio frequency system user to apply corrections both where and when needed (Bust and Mitchell, 2008).

Ionospheric tomography techniques reconstruct three-dimensional, time-dependent images of electron density from observations of relative or calibrated slant total electron content (TEC) recorded via dual-frequency Global Positioning System (GPS) receivers. Ionospheric tomography has been used to probe the ionosphere for quite some time using different techniques both on a global scale and regional scale (Zhao et al. (2013), Austen et al. (1988), Fridman et al. (2009), Fremouw et al. (1992) and the references therein).

The quality of ionospheric tomographic inversions depends mainly on the density of the ray paths which in turn depends on the number of intersecting ray paths between transmitters and receivers over a wide range of angles (Kunitsyn and Tereshchenko, 2003). Studies also show that data collected from an uneven distribution of ground receivers impacts the quality of the reconstructed images as is the case when sparse data is used; for example see Zapfe et al. (2006) and Materassi and Mitchell (2005). Yao et al. (2013) has also implemented a computerized ionospheric tomography (CIT) technique to analyze the effect of a severe geomagnetic storm on 15 May 2005 on the ionosphere over the South African region using the South African network of GPS receivers, and they reported that there was a significant enhancement in the electron density at 10:00 UT (local noon) on the storm day compared with the same period on the day before.

The tomographic technique used here is the latest Multi-Instrument Data Analysis System (MIDAS) algorithm developed by Spencer and Mitchell (2007) from the work of Mitchell and Spencer (2003). MIDAS has been used for studying the ionosphere in several parts of the world. For example, it has been used by Chartier et al. (2012a), Kinrade et al. (2012) and Mitchell and Spencer (2003) to study the mid-latitudes and polar regions; Muella et al. (2011) and Materassi and Mitchell (2005) used it to image the equatorial and low latitude ionosphere over Brazil, and the equatorial anomaly respectively; Katamzi (2008) and Cilliers et al. (2004) used MIDAS to produce electron density profiles over the South African region. The objective of this study is to optimize ionospheric tomography imaging over South Africa using the extensive South African GPS network so as to derive a reasonable electron density profile and verify it with profiles determined from independent measurements, such as those from the three South African ionosondes.

2. Method and data

As shown in most of the publications by Chartier et al. (2012a), Spencer and Mitchell (2007), Materassi and Mitchell (2005) and Mitchell and Spencer (2003), the normal MIDAS inversion procedure is followed. First, the inversion problem is mapped from electron density space to basis function space using a mapping function. Once a regularization condition is applied to penalize solutions that give rise to nonzero second order derivatives of the electron density in horizontal space and time, the problem is then converted into a set of normal equations from which the final inverted solution is obtained (Chartier et al., 2014).

Since the inversion problem is underdetermined, a model or mathematical based orthogonal functions is/are used to compensate for the missing information to allow for the reconstruction of a spatially continuous electron density field (Bust and Mitchell, 2008). To address this issue, MIDAS inversion requires orthogonal functions to define the vertical profile of electron density. The profile is assumed to be a linear combination of a given set of three-dimensional empirical orthogonal functions (EOFs) (Materassi and Mitchell, 2005). The EOFs describe the shape of the altitude profile of ionospheric electron density thus providing a level of prior information to the inversion whilst constraining the inversion problem vertically.

In MIDAS, the electron densities are generally assumed to change linearly in each voxel over the time-window of inversion (Mitchell and Spencer, 2003). The right tuning of the number of EOFs brings about improved optimization of electron density profiles. MIDAS uses either the Chapman functions or the International Reference Ionosphere 1995 version (IRI95) to create the empirical orthogonal functions from a set of radial profiles of the ionospheric electron density (Spencer, 2008). By varying the number of EOFs, better results can be obtained from the inversion process. Therefore in the optimization process it was found that using IRI95 and 2 EOFs yields better results over the other possibilities hence the results presented in this paper are based on these choices.

The paucity of input data is another major problem that all tomographic inversion techniques experience. The best solution to alleviate this problem is to incorporate *a priori* information about ionospheric parameters of interest from for example empirical models (such as the IRI model) or physics based functions (e.g. Chapman function) so that the inversion solutions are reasonable. In MIDAS there is a provision to use electron densities from the IRI95 model as *a priori* information to start the inversion process. However, for this study, the IRI model (IRI95) was used only to create the basis functions and no initial guess of the ionosphere was provided during the inversion process since for our chosen grid setup there was ample data coverage over the South African region as shown in Fig. 1(a).

The GPS data used in this study were obtained from a network of continuously operating Global Navigation Satellite System (GNSS) base stations distributed throughout South Africa at approximately 100–300 km spacing as shown in Fig. 1(b) (red dots). This network called Trignet is installed, maintained and operated by Chief Directorate: National Geospatial Information in South Africa (http://