Geodesy and Geodynamics xxx (2017) 1–6

Contents lists available at ScienceDirect

Geodesy and Geodynamics

journal homepages: www.keaipublishing.com/en/journals/geog; http://www.jgg09.com/jweb_ddcl_en/EN/volumn/home.shtml

Ionospheric forecasting model using fuzzy logic-based gradient descent method

D. Venkata Ratnam*, G. Vindhya, J.R.K. Kumar Dabbakuti

KLEF, K L University, Department of ECE, Vaddeswaram, Guntur Dt, Andhra Pradesh, India

ARTICLE INFO

Article history:
Received 17 January 2017
Accepted 17 May 2017
Available online xxx

Keywords:
GPS
Gradient descent method
TEC

ABSTRACT

Space weather phenomena cause satellite to ground or satellite to aircraft transmission outages over the VHF to L-band frequency range, particularly in the low latitude region. Global Positioning System (GPS) is primarily susceptible to this form of space weather. Faulty GPS signals are attributed to ionospheric error, which is a function of Total Electron Content (TEC). Importantly, precise forecasts of space weather conditions and appropriate hazard observant cautions required for ionospheric space weather observations are limited. In this paper, a fuzzy logic-based gradient descent method has been proposed to forecast the ionospheric TEC values. In this technique, membership functions have been tuned based on the gradient descent estimated values. The proposed algorithm has been tested with the TEC data of two geomagnetic storms in the low latitude station of KL University, Guntur, India (16.44°N, 80.62°E). It has been found that the gradient descent method performs well and the predicted TEC values are close to the original TEC measurements.

1. Introduction

GPS provides accurate and continuous three-dimensional position, velocity and time data – anywhere on or above the surface of the Earth, anytime, and in all weather conditions [1,2]. However, the predominant ranging error source for GPS signals is an ionospheric error. The ionospheric error is directly proportional to the Total Electron Content (TEC). Sudden variations in TEC degrade the phase and amplitude of the Global Navigation Satellite System (GNSS) signals. Because of this, there will be an impediment to trans-ionospheric navigation and communication link disruptions. Ionospheric TEC variations over low latitude regions are dynamic and highly variable. The forecasting of the ionospheric TEC model provides additional support to GPS integrity requirements. The ionospheric prediction model is developed based on the autocovariance function method [3]. While Auto Regressing (AR) and ARMA (Auto-Regressive Multiple Average) models are developed using ionosonde foF2 data [4]. However, both these models are mostly linear, whereas ionospheric TEC values are non-linear in nature. Neural network-based ionospheric forecasting models have been developed based on GPS and ionosonde data [5]. NN is black box learning approach; it requires a large amount of data related to the input parameters to cover a wide range of possibilities to predict the output and cannot deal with uncertainties [6]. Meanwhile Fuzzy systems are successfully implemented non-linear, complex and ill-posed systems by producing rules. Takagi-Sugeno fuzzy inference technique has been used for predicting the ionospheric time delays. Akyilmaz and Arsalan [6] proposed an Artificial Neural Fuzzy Inference System (ANFIS) forecasting TEC model. This method combined the ANFIS method with the LDIVIDE optimization technique. However, proper structure optimization is of important significance for choose the variables, reducing the rule base and optimizing the number of fuzzy sets. In this paper, a gradient descent optimization technique based on searching a local minimum by updating the parameters using a local error gradient direction have been implemented [7,8].

* Corresponding author.
E-mail address: dvratnam@kluniversity.in (D. Venkata Ratnam).

Peer review under responsibility of Institute of Seismology, China Earthquake Administration.

ELSEVIER Production and Hosting by Elsevier on behalf of KeAi

http://dx.doi.org/10.1016/j.geog.2017.05.003

2. Forecasting ionospheric TEC values using fuzzy technique

Data obtained from the GPS station located at K L University (16.44°N, 80.62°E) were considered for the analysis. The GPS data parameters such as GPS week, seconds of week, PRN (Pseudo Random Noise) number, elevation angle, azimuth angle, C/N0, S4, Phase scintillation index and TEC values were extracted from the GPS data using the Novatel utility software. Modified planar fit ionospheric grid model was used to estimate nowcasting ionospheric TEC values [9]. One-day TEC time series contains 288 measurements, representing the 24-h TEC profile (with 5-min lag). Each day TEC profile was further divided into four segments of 6 h duration. 00:00–06:00 h morning TEC values were represented as the minimum while the maximum was represented by 00:00–12:00 h. 12:00–16:00 h represented the average state while 06:00–00:00 h again represented the minimum. The fuzzy logic was based on the identification of the fuzzy set that represents the possible values of the variables. A total of 2880 measurements were available in the dataset for 10 days with a sampling rate of 5 min. Of these, seven days' TEC data were considered as training TEC data while the last three days TEC were taken as the original. Original TEC data were compared with the forecasted TEC values. Crisp TEC values are fuzzified using membership functions (MFs) – in this paper; two trapezoidal MFs were used to represent the input TEC training series data. The GPS TEC crisp data represented in the range (0.0916, 9.59) was fuzzified to get membership values in the range (0, 1) [10].

$$U = \{(y, \mu_u(y))/y \in \mathrm{F}\} \tag{1}$$

where $\mu_{\mathrm{F}}(x)$ is the membership function. Trapezoidal membership function can be represented as follows

$$\mu_u(y, p, q, r, s) = \begin{cases} 0 & \text{if} \quad y < p \\ (y-p)/(q-p) & \text{if} \ p \le y \le q \\ 1 & \text{if} \quad q < y < r \\ (s-y)/(s-r) & \text{if} \ r \le y \le s \\ 0 & \text{if} \quad s < y \end{cases} \tag{2}$$

The output variable is represented by MFs that are linear functions of the input variables of the Takagi-Sugeno type FIS [10]. FIS rules were employed in the ionospheric forecasting model. The fuzzy modeling of the sequence similarity was considered as the Takagi-Sugeno fuzzy model design with four inputs, each being determined for four linguistic variables using ANFIS modeling with grid partition. These variables generated 16 numbers of conditional statements as "if-and-then" rules of the model. Optimization of FIS parameters was carried out by an iterative least-squares estimation and back-propagation using gradient descent algorithm that minimized the sum of the squares of the differences between the estimated TEC and the model (predicted by FIS) output $(U(y))$. Gradient descent techniques can be used to minimize a function $U(y)$ with respect to the input TEC vector y, when the gradient is available or estimated. Local minimum of an N-dimensional objective function in the direction of a negative gradient can be identified.

$$-g(y) = -\nabla f(y) = -\left[\frac{\partial f(y)}{\partial y_1} \frac{\partial f(y)}{\partial y_2} \cdots \frac{\partial f(y)}{\partial y_N}\right]^{\mathrm{T}} \tag{3}$$

The gradient can be represented as Ref. [8] with the step-size αk (at iteration k) adjusted so that the function value is minimized along the direction. In this technique, the initial step size is 0.01. The step increasing and decreasing rates are given as 1.1 and 0.9, respectively. The predicted TEC values were tuned according to the input vector and the error between the input and output TEC vector $(U(y))$. The fuzzified data were converted to crisp values or the output through the procedure of defuzzification. p, q parameters were calculated and updated [11]. Also, the TEC forecasting error was calculated.

3. Results and discussion

The forecasted TEC (output) values were obtained by varying the input parameters. FIS rules have been implemented in the MATLAB, with the Sugeno type of FIS in the fuzzy logic toolbox.

3.1. Geomagnetic storm 1 (March 16–18, 2013) TEC data

The geomagnetic storm started on March 17, 2013, morning. The Dst index is a measure of ring current around the Earth, from east to west, in the equatorial plane. Geomagnetic storm causes a sudden decrease in the Dst index values. Dst index on this day reached the minimum values of −131 nT, as represented in Fig. 1. The maximum VTEC variations reached 55 TECU on the pre-storm day, whereas VTEC values were enhanced to the maximum level of 67 TECU on the day of the storm; this was, hence, a positive geomagnetic storm. The enhancement of the ionospheric TEC occurs because of prompt penetration of the electric field, enhancement of EIA and

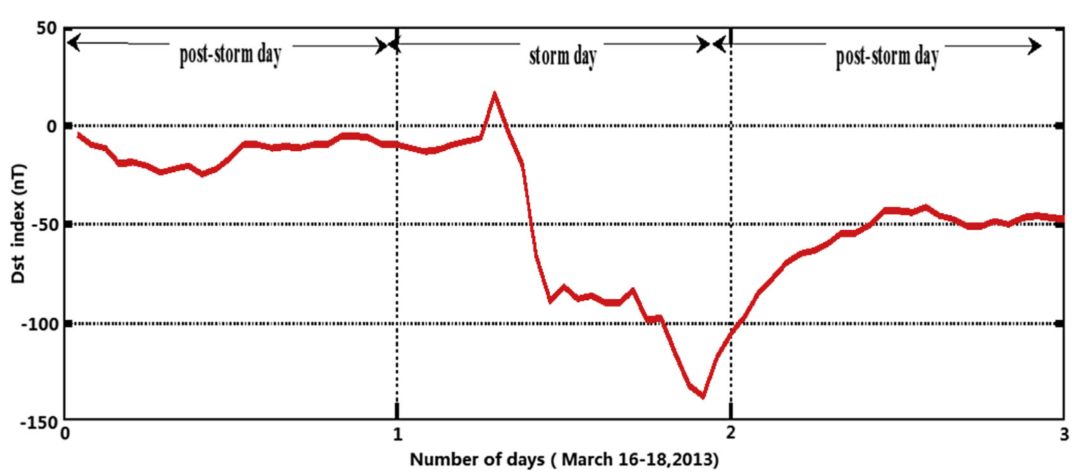

Fig. 1. Dst index values for geomagnetic storm (March 16–18, 2013).

Please cite this article in press as: D. Venkata Ratnam, et al., Ionospheric forecasting model using fuzzy logic-based gradient descent method, Geodesy and Geodynamics (2017), http://dx.doi.org/10.1016/j.geog.2017.05.003