Prediction of GPS TEC during the X9.3 Solar Flare for DGAR low latitude station by using OKSM

S Kiruthiga¹, S Mythili², R Mukesh³, V Karthikeyan⁴, M Vijay⁵
¹Department of ECE, SRM TRP Engineering College, Trichy, India.
²Department of ECE, PSNA College of Engineering and Technology, Dindigul, India.
³Department of Aerospace Engineering, ACS College of Engineering, Bangalore, India.
⁴Department of ECE, Dr. MGR Educational and Research Institute, Chennai, India.
⁵Department of Aerospace Engineering, ACS College of Engineering, Bangalore, India.

Abstract. The effect of solar flares on the ionospheric regions of earth, which in turn affects signals of the various Global Navigation Satellite Systems, is a very important criterion to be considered in satellite communication. In this paper, we are investigating the prediction capability of the Kriging based Model and its effect on calculating the signal delay of GPS system on 6.9.2017 during which NASA have observed a solar flare which have recorded X9.3 on solar storm scale. The GPS data used in this paper for prediction of TEC is taken from the DGAR Island station. The Vertical Total Electron Content data for GPS is predicted from 3rd September 2017 to 7th September 2017 by using the previous collected 6 days of TEC data of the low latitude DGAR station from IONOLAB and also by using the input parameters like Kp index, SSN, Ap index and Dst index. The predicted results are validated by comparing them with IRI 2016 and IRI PLAS 2017 model collected during the same date.

1. Introduction

Satellite transmissions have become an integral part of the communication infrastructures used by humans around the world. One of the major concerns for satellite-based positioning applications is the delay experienced in receiving the signal. Most of the delays are caused due to erratic space weather conditions such as solar storms, solar flares, coronal mass ejections, etc. These conditions cause variations in the ionospheric layer which in turn affects performance of all the Global Navigation Satellite Systems (GNSS). Even Global Positioning System (GPS) which is one of the key players in the GNSS network experiences less strong signal at the user receiver due to multiple error sources as it travels through various atmospheric layers causing range error in the system [1]. This signal degradation depends upon the factors such as Total Electron Content (TEC), elevation, azimuth angle, frequency of the satellite transmission, etc [2]. Based on the literature review, it is observed that TEC values can be predicted and used for correcting the errors which further increases accuracy of the signal received. The effects of solar flare and storm on the navigational satellite systems have been analyzed by various researchers [3-7]. In this paper, we have tried to examine the capability of TEC prediction model during one of the strongest solar flare event. On 6th September of 2017, earth has observed a very strong solar
flare named as X9.3 based on the solar storm scale. In this time period we have collected GPS data from the IGS network for Diego Garcia Island (U.K. Territory) [DGAR] station located in -7.22°N Latitude and 72.37°E Longitude. The objective of this paper is to perform prediction of TEC by means of Ordinary Kriging based Surrogate Model (OKSM) for calculating ionospheric delay during the strongest solar flare event. It is essential to know that this prediction model is based on various solar parameter inputs such as Sun Spot Number (SSN), Kp index, Ap index and Dst index.

2. Methodology

The methodology utilized in this work is clearly outlined in the figure 1. This prediction model flow chat is followed step-by-step in order to forecast the Total Electron Content during the event of the solar flare.

Figure 1: Methodology for Total Electron Content Prediction during X 9.3 Solar Flare

3. Ordinary kriging Technique:

The ordinary kriging technique is implemented in this paper for predicting the TEC during the solar flare days by using the previous six days input parameters and TEC values. The equation of the OKSM to forecast the TEC is given in Equation (1) [8].
\[ \hat{f}(x_p) = \sum_{i=1}^{N} \gamma_i(x_i)f(x_i) \]  

(1)

4. Results and Discussion:

The Prediction model evaluates the data parameters in sets of hourly averaged TEC values recorded on previous dates and produces one primary TEC prediction result and four subroutine parameters listed in Table 1, such as RMSE, Mean Absolute Error, Correlation Coefficient, and Mean Absolute Percentage Error. The prediction program is developed by using MATLAB and plots are generated using the same. The comparison between original TEC value and predicted TEC value from 3.9.2017 to 7.9.2017 is shown in figure 2. The individual plots for prediction on the observation dates are given between figures 3. From the results it is observed that the developed model for TEC prediction gives good results. From the obtained results Range error is calculated to increase the accuracy of GPS signals during high energy solar flare.

| DATE     | MAX TEC | RMSE  | Corr_Coeff | MAE   | MAPE (%) | Range Error (m) |
|----------|---------|-------|------------|-------|----------|-----------------|
| 03-09-2017 | 31.8456 | 2.8731 | 0.97613    | 2.423461 | 23.17635 | 3.344106        |
| 04-09-2017 | 51.7215 | 7.6991 | 0.97872    | 4.881248 | 31.55341 | 5.431275        |
| 05-09-2017 | 47.3856 | 3.6502 | 0.9707     | 2.613774 | 22.48474 | 4.975962        |
| 06-09-2017 | 41.4426 | 3.0261 | 0.98184    | 2.038251 | 14.71162 | 4.351887        |
| 07-09-2017 | 47.4017 | 5.785  | 0.98691    | 4.393289 | 22.87390 | 4.977653        |

Figure 2. Comparison of True and Predicted TEC plot for DGAR station from 3-7. 9. 2017
Figure 3. Predicted vs. Actual TEC for DGAR station using OKSM from 3-9-2017 to 7-9-2017

Figure 3 a. Predicted vs. True on 3-9-2017

Figure 3 b. Predicted vs. True on 4-9-2017

Figure 3 c. Predicted vs. True on 5-9-2017

Figure 3 d. Predicted vs. True on 6-9-2017

Figure 3 e. Predicted vs. True on 7-9-2017
5. Validation

Once the results are finalized, we have attempted to validate the results by comparing them with globally recognized prediction models namely IRI 2016 and IRI PLAS 2017 [9, 10]. It is found that OKSM prediction model give a consistently good prediction results than the other two models as shown in figure 4. For further analysis RMSE, Max TEC and Corr_Coeff are calculated for two models and the results are tabulated in Table 2 & 3. It is also shown through comparative bar graphs in figures 5 and 6.

![Figure 4. Comparison of True & Predicted TEC plot for DGAR with IRI 2016 and IRI PLAS 2017](image)

Table 2. Maximum TEC, RMSE and Correlation coefficient of DGAR Low Latitude from IRI 2016

| DATE       | Max TEC | RMSE     | Corr_Coeff |
|------------|---------|----------|------------|
| 03-09-2017 | 29.7    | 6.202625 | 0.949172   |
| 04-09-2017 | 29.9    | 6.506839 | 0.881202   |
| 05-09-2017 | 30.6    | 7.534431 | 0.89655    |
| 06-09-2017 | 29.3    | 7.036783 | 0.900383   |
| 07-09-2017 | 29.5    | 10.10836 | 0.902604   |

Table 3. Maximum TEC, Resend Correlation coefficient of DGAR Low Latitude from IRI PLAS 2017

| DATE       | Max TEC | RMSE     | Corr_Coeff |
|------------|---------|----------|------------|
| 03-09-2017 | 38.6    | 5.214562 | 0.976135   |
| 04-09-2017 | 38.41   | 6.506839 | 0.953609   |
6. Conclusion

In this research work, Kriging based model is constructed for forecasting the VTEC values during the X 9.3 solar flare. The GPS TEC is taken from IGS, DGAR low latitude station. Based on the model, TEC values are predicted from 3/9/2017 to 7/9/2017 by using six days of previous input parameters and TEC values belongs to that station. The forecasting performance of the model was assessed with the actual GPS TEC values. The maximum RMSE value was 5.7 TECU recorded during the next day of the solar flare and the developed model gives better results during the solar flare day. Apart from that we

| DATE       | OKSM | IRI PLAS 2017 | IRI 2016 | IRI 2016 |
|------------|------|---------------|----------|----------|
| 05-09-2017 | 39.87| 5.947443      | 0.944485 |
| 06-09-2017 | 39.35| 4.732552      | 0.956495 |
| 07-09-2017 | 39.83| 5.78228       | 0.96232  |
have compared our model with IRI 2016 and PLAS 2017 and found that the kriging-based model gives accurate results when compared to the other models.

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