Study of Solar Radiation Variation over an Area using GNSS observations – Spatial Reference to KDU Southern Campus

WMHP Sandanayake[1#], KP Manuranga[1], AH Lakmal[1], and HMI Prasanna[2]

[1]*Faculty of Built Environment and Spatial Sciences, General Sir John Kotelawala Defence University, Ratmalana, Sri Lanka*
[2]*Department of Surveying and Geodesy, Faculty of Geomatics, Sabaragamuwa University, Sri Lanka*
[#] <36-sps-0002@kdu.ac.lk>

Abstract— *At present, Global Navigation Satellite Systems (GNSS) are used to study the behavior of the atmosphere including the ionosphere and the troposphere by calculating the time taken for a GNSS satellite signal to reach the Earth. The GNSS satellite signals get interrupted while traveling through the ionosphere due to free electrons produced from exposing the particles in the atmosphere to extreme Ultraviolet radiations. These amounts of free electrons are identified as the Total Electron Content (TEC) in the ionosphere. So due to these interruptions, a delay occurs when GNSS satellite signals reach the GNSS receivers on the Earth's surface. This effect is called the ionospheric delay. So, scientists use statistics related to ionospheric delay to study the behavior of the ionosphere. This study also describes a method to obtain the TEC in the ionosphere using the ionospheric delay and determine the solar radiation variation over an area using those calculated TEC values. Here single- frequency GNSS signals of the Global Positioning System (GPS) were used and thereafter TEC values along each signal path were calculated. Then variations of TEC values were obtained and thereby an equation was derived through nonlinear regression analysis to predict the solar radiation variation. After the analysis, the study is concluded by obtaining the TEC variations over an area and finding an ideal method to obtain solar radiation variation using those TEC values obtained with the help of the model created through nonlinear regression analysis.*

Keywords— **GNSS, TEC, Solar Radiation**

I. INTRODUCTION

The ionosphere is a layer of the Earth's atmosphere that is located within 80 – 600 km from the surface of the Earth. In the ionosphere, the atoms and molecules of the atmosphere are ionized by extreme ultraviolet rays and X-ray solar radiation to form a layer of electrons. Ionosphere charging is occurred due to different behaviors of the sun such as solar winds, solar flares, and geomagnetic storms. Therefore, when considering the behavior of the ionosphere the ionization in the nighttime and during the solar minimum period is less compared to the ionization in the daytime and solar maximum period. This layer of electrons or the ionosphere disrupts the radio waves used for communication and navigational purposes through reflection and modification (Swpc.noaa.gov, 2022). So, ionospheric behavior can be analyzed by using GNSS - based observations(Peng and Scales, 2021).

GNSS is a system of satellites that transmit data related to position and time to a GNSS receiver on the ground. By using these data transmissions, the GNSS receivers determine the location of points on the Earth's surface. There are a few functioning GNSS in the world such as GPS, Galileo, Global Navigation Satellite System (GLONASS), and Bei Dou. This GNSS technology can be used for navigational purposes, land surveying, and hydrographic surveying as well as for more advanced measurements such as weather predictions, seismic data collection, etc. other than ionospheric variation measurements (Novatel, 2022).

When considering the ionosphere and GNSS-based observations, the ionosphere acts as an error source for modern GNSS receivers due to the interferences occurring to the electromagnetic signals transmitted from a satellite to a receiver on the ground. This error is identified as the ionospheric delay (Subirana, Zornoza and Hernández-Pajares, 2011). This delay of the signal propagating through the ionosphere depends on the TEC along the path of the signal (Cooper et al., 2019). The TEC can be calculated by analyzing the path of the signal between the satellite and the ground-based receiver (Bust and Mitchell, 2008) of a GNSS system.

Solar radiation or in other words solar irradiance is the measuring of energy transferred by the sun to the surface of the Earth. The visible and infrared radiation from the sun controls the temperature of the Earth's surfaces so that it is ideal for sustaining life. Extreme ultraviolet radiation is mostly absorbed by the atmosphere (Garner, 2008). Hence, the TEC in the ionosphere mainly depends on the local time, latitude, longitude, seasons, and most importantly the effect of the sun's radiation or in other words the sun cycle (NOAA, 2022). The TEC level in the ionosphere increases due to exposure to a high amount of solar radiation and decreases when there is a low amount of solar radiation.

At present, there are various methods to obtain the TEC in the ionosphere such as the use of ionosondes and solar radiation measurements using instruments such as pyranometers or pyrheliometers (Hinckley, 2017). But GNSS based observations are not properly introduced for the determination of solar radiation variations.

Most of the researchers obtained the variation of the TEC in the ionosphere over a certain area for a considered period with the help of GNSS surveying techniques. But these findings were not used to provide an idea on the variation of the solar radiation on the Earth's atmosphere within a day, within a month, or within years when considering the effect of solar radiation on the TEC level in the ionosphere.

So, the primary objective of this study is to provide a method to determine the TEC variation using single-frequency GNSS observations and then use those TEC variations to obtain solar radiation variation over an area using GNSS observations by modeling the solar radiation variation using TEC.

This final output and the methods provided can be used to detect the solar flares and the intensity of those solar flares when they reach the Earth's surface. Detection of solar flares is necessary to assess the risks for satellites and spacecraft when a solar flare hits the Earth and it can be used to identify the time and areas that are affected by the solar flares through worldwide monitoring to provide necessary solutions to the negative impacts caused by the flares such as health risks, interferences to the communication networks and power grid failures. And also the final output can be used to study the solar radiation variation near Earth's atmosphere (Natras, Horozovic and Mulic, 2018). Further, the outputs can be used to determine suitable locations to establish solar power stations and further help to determine the effect of TEC and solar radiation on the GNSS readings.

II. METHODOLOGY AND EXPERIMENTAL DESIGN

The usage of GNSS observations to analyze the atmospheric conditions on the Earth has become an important research criterion in the present. The behavior of the ionosphere can be observed by determining the TEC in the ionosphere over a considered period by using the GNSS receiver data. The methodology of this study has been developed to calculate TEC values in the ionosphere using single-frequency GNSS observations and then use those TEC values to obtain the solar radiation variation over the study area.

Here, the TEC values were calculated based on the equation of the Nequick ionospheric model,

$$I_f = \frac{40.3 \times 10^6}{(f)^2} \times TEC$$

Here f is the frequency in hertz, TEC is the total electron content and then the equation gives I_f which is the Ionospheric correction (Segura, 2014).

So, equation (1) can be modified to calculate the TEC values using the ionospheric corrections obtained from the single frequency GNSS receiver data as follows,

$$TEC = \frac{I_f \times f^2}{40.3 \times 10^6} \quad (2)$$

The KDU Southern Campus premises was chosen to gather GNSS observation data because of the clear sky at most times and the lack of rain and cloud cover which will affect the satellite signals when traveling through the atmosphere. The multipath error can be reduced due to the lack of tall buildings and trees in the KDU - Southern Campus premises.

Then the single frequency (L1) GPS data was collected at 1-second intervals by using a TOPCON GR5 GNSS receiver 24 hrs. a day for 3 weeks as follows,

1. First week - 2022/02/14 - 2022/02/21
2. Second week - 2022/03/23 - 2022/03/28
3. Third week - 2022/05/05 - 2022/05/12

The collected GPS data were processed and the ionospheric corrections were obtained based on the Nequick ionospheric model using gLAB post-processing software.

Here only the GPS data were used because the gLAB software can only process the GPS data and the single-frequency GNSS observations were used because the Nequick model can only be applicable for single-frequency receivers and single-frequency receivers can't automatically correct the ionospheric delay during the data collection.

After obtaining the ionospheric correction for each observation using the gLAB software, the TEC values were calculated using equation (2) using only the observations given through L1P frequency. The frequency of the L1P band is 1575.42 MHz (Rodríguez, 2011) and it was substituted for the equation (2). Here only L1P frequency was used because the gLAB software provided ionospheric corrections for the L1P frequency and one frequency band was enough for the calculations using equation (2).

Then the obtained TEC values were plotted against time for each day to obtain the TEC variations for the 3 weeks.

The TEC variations obtained were validated using the Vertical Total Electron Content (VTEC) variations obtained from a research conducted by Jenan and the team (Jenan, Dammalage and Kealy, 2020).

After that, a model was prepared using nonlinear regression analysis to obtain solar radiation variations from TEC values calculated using the above method. The all-sky Ultraviolet A (UVA) irradiance data obtained from the National Aeronautics and Space Administration (NASA)'s Prediction of Worldwide Energy Resources (POWER) data access viewer within the period from 2022/03/24 - 2022/03/28 was used to prepare the model (NASA, 2022). With the help of the model, an equation was prepared to calculate the solar radiation using the TEC values obtained within the 3 weeks of data collection and for all future calculations of solar radiation from TEC values.

Then using the equation obtained, the solar radiation variations were plotted against the time for each day for the 3 weeks. Then weekly solar radiation variations were also plotted and obtained the final output of the research.

The solar radiation variations obtained were validated using all-sky UVA data obtained from NASA's POWER access viewer for the 3 weeks of data collection (NASA, 2022).

III. RESULTS

The TEC variations obtained for the 3 weeks are as follows.

A. TEC in Week 01 – 2022/02/16 – 2022/02/21

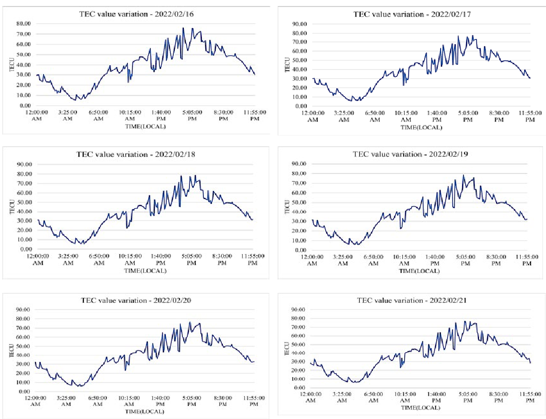

Figure 1. TEC variations from 2022/02/16 – 2022/02/21

Based on the above results of the 1st week in Figure 1, the minimum TEC values were shown between 4:15 AM – 5:10 AM and the highest TEC values were shown between 4:45 PM - 5:35 PM. The TEC values showed a continuous decrease from 5:35 PM onwards and then reached the minimum value around 4:15 AM. And after that, it showed a gradual increase until around 4:45 PM.

B. TEC in Week 02 – 2022/03/24 – 2022/03/28

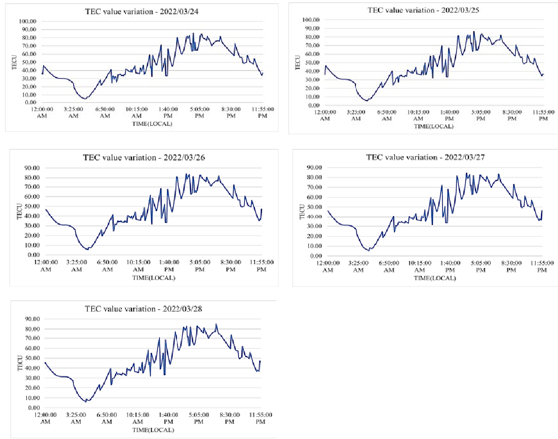

Figure 2. TEC variations from 2022/03/24 – 2022/03/28

Based on the above results of the 2nd week in Figure 2, the minimum TEC values were shown between 4:30 AM – 4:40 AM and the highest TEC values were shown between 3:30 PM - 4:25 PM. The TEC values showed a continuous decrease from 4:25 PM onwards and then reached the minimum value between 4:30 AM – 4:40 AM. After that, it showed a gradual increase until around 3:30 PM. Here the TEC value on 2022/03/28 showed a sudden spike at 7:00 PM hence the highest value was at 7:00 PM.

C. TEC in Week 03 – 2022/05/06 – 2022/05/12

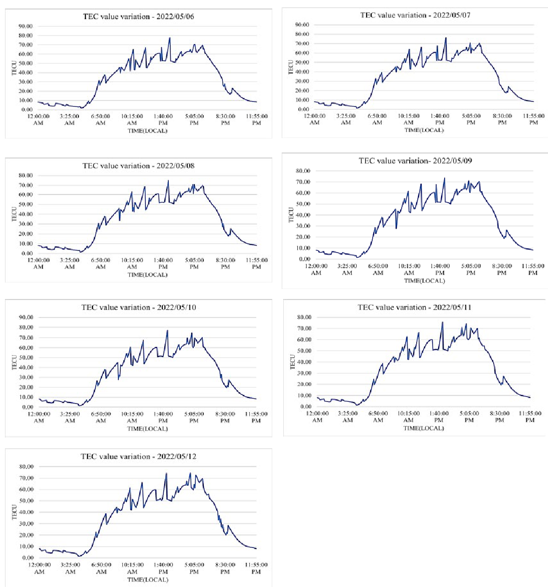

Figure 3. TEC variations from 2022/05/06 – 2022/05/12

Based on the above results of the 3rd week in Figure 3, the minimum TEC values were shown between 4:20 AM – 4:45 AM and the highest TEC values were shown between 2:05 PM - 2:25 PM. The TEC values showed a continuous decrease from 2:25 PM onwards and then reached the minimum value between 4:20 AM – 4:45 AM. And after that, it showed a gradual increase until around 2:00 PM. The TEC value at 4:40 PM on 2022/05/12 showed a sudden spike hence the highest TEC value of that day was at 4:40

PM. Therefore the 3rd week showed a variation slightly different from the other two weeks, but the variation pattern remained the same in all three weeks.

D. Daily Average TEC Value Variations in February, March, and May 2022

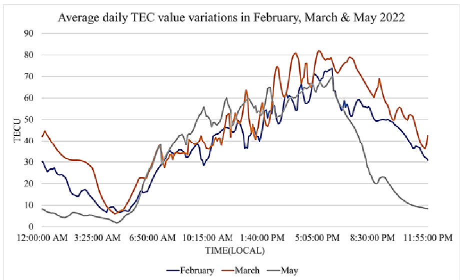

Figure 4. Daily average TEC variations in February, March, and May 2022

Based on the results of Figure 4, the month of February represents the winter solstices, March represents the equinox and May represents the summer Solstices in a year. Here, the daily TEC values of March were comparatively higher than the daily TEC values of February and May.

E. Validation of TEC

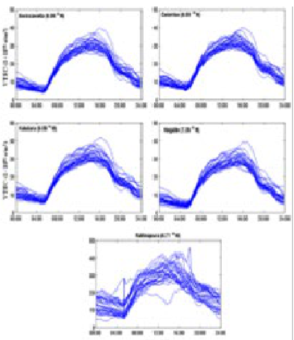

Figure 5. The VTEC Variations at 5 Stations during the Month of November 2017 Source: (Jenan, Dammalage and Kealy, 2020)

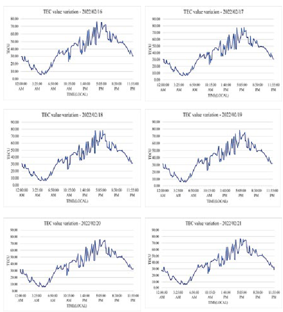

Figure 6. TEC variations from 2022/02/16 – 2022/02/21

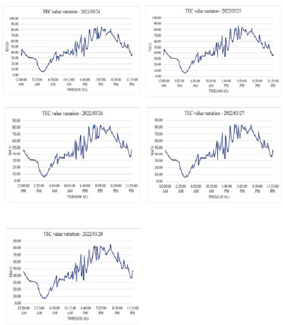

Figure 7. TEC variations from 2022/03/24 – 2022/03/28

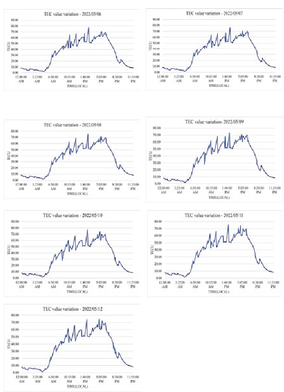

Figure 8. TEC variations from 2022/05/06 – 2022/05/12

Thus, the TEC variations obtained through this research provided similar variations when compared with the VTEC variations in Figure 5 obtained by Jenan and the team (Jenan, Dammalage and Kealy, 2020), and therefore TEC variations obtained in this research were validated.

The following equation was obtained from the prediction model prepared by conducting a nonlinear regression analysis between the UVA irradiance data from 2022/03/24 to 2022/03/28 and the TEC values obtained from 2022/03/24 to 2022/03/28 using the GNSS observations.

$$SIR = -4.02836 \times 10^{-8} \times TEC^{6} + 1.05753 \times 10^{-5} \times TEC^{5} - 0.001021325 \times TEC^{4} + 0.0421544 \times TEC^{3} - 0.565639602 \times TEC^{2} - 4.11814822 \times TEC + 106.8420508 \quad (3)$$

where SIR is the solar radiation and TEC is the Total Electron Content. The equation is with an $R^2 = 0.7696$ which indicates that 76.96% of the solar radiation values can be predicted by Equation (3) for a new set of data.

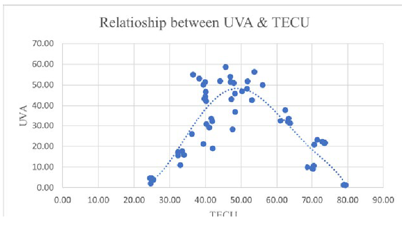

Figure 9. UVA vs TECU

Then, the solar radiations for the 3 weeks were obtained using Equation (3). Here the solar radiation variations from 6:00 AM to 6:00 PM of each day were obtained and the nighttime TEC variations were neglected because solar radiation can only be seen when sun rays fall on the Earth's surface.

F. Solar Radiation in Week 01 – 2022/02/16 - 2022/02/21

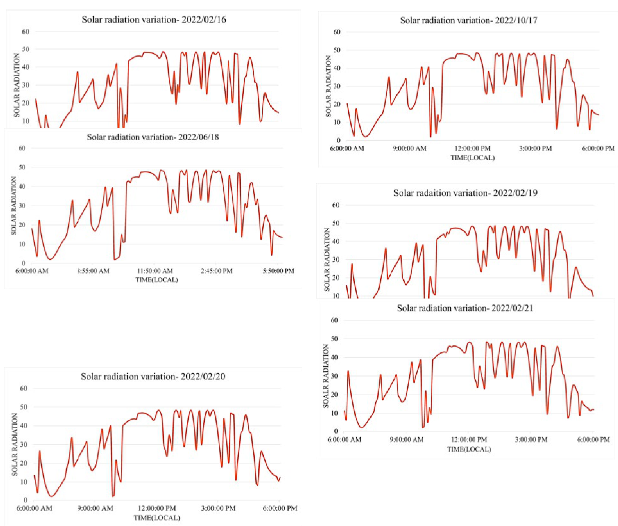

Figure 10. Solar radiation variation from 2022/02/16 – 2022/02/21

According to Figure 10, lower solar radiation values were shown in the morning and the evening while higher solar radiation values were shown at the noon from 12:05 PM to 2:45 PM. According to the variations provided, the solar radiation remained lowest in the morning and gradually increased until noon. After that, it decreased and became lower in the evening.

G. Solar Radiation in Week 2 – 2022/03/24 – 2022/03/28

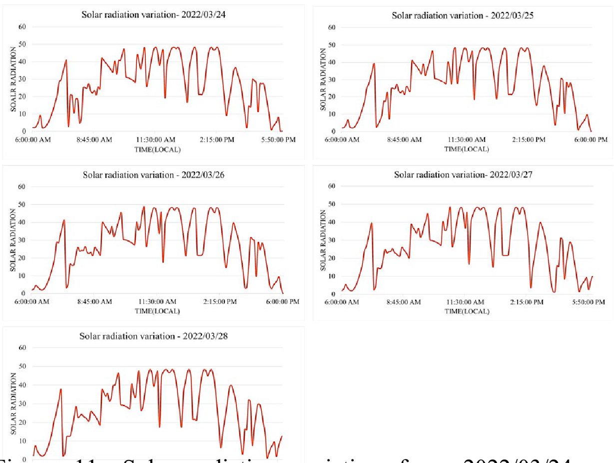

Figure 11. Solar radiation variation from 2022/03/24 – 2022/03/28

According to Figure 11, the highest solar radiation values were shown in the afternoon between 11:15 AM – 2:00 PM and the lowest solar radiation values were shown in the morning and the evening. Furthermore, the outputs provided a similar variation compared to the 1st week's solar radiation variation.

H. Solar Radiation in Week 3 – 2022/05/06 – 2022/05/12

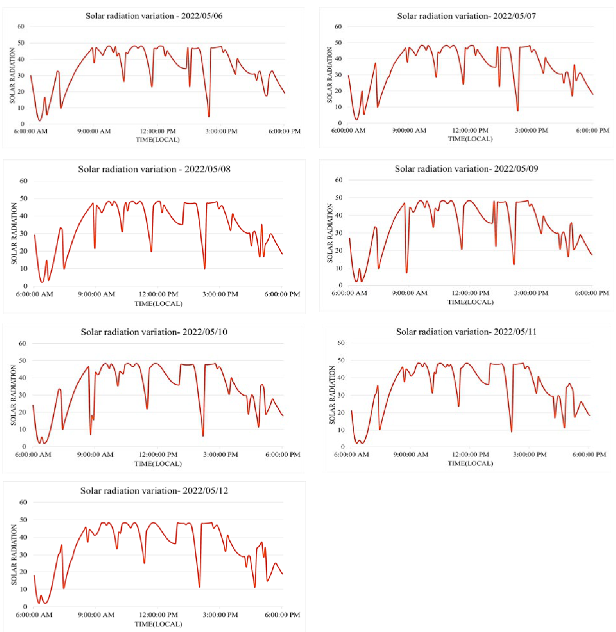

Figure 12. Solar radiaition variation from 2022/05/06 – 2022/05/12

According to Figure 12, a gradual increase in solar radiation was shown until 9:25 AM – 12:00 PM and it continued throughout the afternoon and then a gradual decrease was shown in the evening.

I. Validation of Solar Radiation

Those solar radiation variations were validated using all-sky UVA data obtained from NASA's POWER access viewer for the 3 weeks of data collection (NASA, 2022).

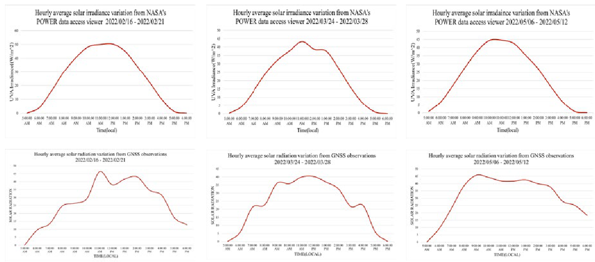

Figure 13. Comparison of hourly average of solar radiation variation between the data from NASA's POWER data access viewer & GNSS observations

IV. DISCUSSION AND CONCLUSION

A. TEC Variation in the Ionosphere

According to research conducted by Ya'acob and the team, the TEC values in the ionosphere get directly affected by the solar radiation falling on the Earth's surface (Ya'acob et al., 2011), and thereby it is evident that the TEC value variations as mentioned above were occurred due to the effect of the solar radiation falling on the Earth's atmosphere because it clearly showed an increase of TEC values in the daytime where solar radiation is abundant in the atmosphere and decrease of TEC values at the nighttime where no solar radiation falls on the atmosphere.

But according to Figure 1 to Figure 3, the highest TEC values were shown in the evening rather than in the afternoon. This gives the idea that there is a nonlinear relationship between TEC in the ionosphere and the amount of solar radiation falling into the atmosphere. The maximum TEC values in the evening rather than in the noon and other variations as given above were due to the variation of the sun's activity, the intensity of the sun's radiations, and the zenith angle at which the radiations interact with the Earth's upper atmosphere (Jenan, Dammalage and Kealy, 2020).

According to Figure 4, there is a monthly TEC value variation as well. The reason for these variations is due to the seasonal dependency of the TEC values (Jenan, Dammalage and Kealy, 2020). Here the month of March represents the seasonal period of the equinox, the month of May represents the summer solstice, and the month of February represents the winter solstice. So higher TEC values can be seen in the equinox period than in the winter and summer solstices. When comparing the summer and winter solstices higher TEC values can be seen in the summer solstice in the morning and early afternoon and higher TEC values can be seen in the evening and night during the winter solstice.

B. Solar Radiation Variation

The sudden drops and rises of solar radiation values within the general variation provided in the outputs in Figure 10 – 12 can be occurred due to errors such as tropospheric error, multipath error, and the cloud cover in the sky, and therefore those sudden changes should not be considered when providing a variation of solar radiation within a day, week, or a month.

So according to the data obtained for 18 days, the solar radiation variations obtained showed a similar pattern of variation where the solar radiation increases from morning to noon and decreases from noon to evening when compared with the all-sky UVA irradiance data released by NASA's POWER data access viewer.

Therefore, through this study, it is ideal to conclude that the TEC variations can be obtained from GNSS observations using the method provided in this study and those TEC variations can be used to determine the solar radiation variation over an area by using a prediction model. These variations can be used to detect sudden increases and decreases of solar radiation falling on the Earth's atmosphere and therefore it is suitable to detect solar flares when they reach the Earth and also to determine the areas with higher solar radiation which are ideal locations to establish solar power plants.

The main limitation is that only data collected within 5 days of the 2nd week was used to create the prediction model because the 2nd-week observations gave higher TEC values compared to the other two weeks.

Other than that, the study was conducted with the assumption that the variation of the TEC values is only affected by solar radiation falling into the atmosphere. But few other factors can be affected by the TEC variation such as local time, latitude, longitude, season, geomagnetic conditions, and troposphere conditions other than the solar radiation falling on the Earth's surface (NOAA, 2022).

This method can further be improved by using TEC values and all-sky UVA irradiance values for an extended period and by doing so the equation obtained from the model can be improved to give a very accurate solar radiation variation.

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REFERENCES

Bust GS & Mitchell CN (2008) History, current state, and future directions of ionospheric imaging, *Reviews of Geophysics,* 46.

Cooper C, Mitchell CN, Wright CJ, *et al.* (2019) Measurement of Ionospheric Total Electron Content Using Single-Frequency Geostationary Satellite Observations, *Radio Science,* 54**,** 10-19.

Garner R. (2008) *Solar Irradiance* [Online]. NASA. Available: https://www.nasa.gov/mission_pages/sdo/science/solar-irradiance.html [Accessed 2022/01/09].

Hinckley A. (2017) *Pyranometers: What You Need to Know* [Online]. Campbell Scientific. Available: https://www.campbellsci.com/blog/pyranometers-need-to-know#:~:text=A%20pyranometer%20is%20a%20sensor,signal%20that%20can%20be%20measured.&text=Instead%2C%20a%20pyrgeometer%20is%20used,to%20as%20the%20cosine%20response. [Accessed 2022/01/09].

Jenan R, Dammalage TL & Kealy A (2020) The Influences of Solar Activities on TEC Variations of Equatorial Ionosphere over Sri Lanka, *Sun and Geosphere,* 14**,** 131-137.

Nasa. (2022) *POWER Data Access Viewer* [Online]. Available: https://power.larc.nasa.gov/data-access-viewer/ [Accessed 10/20 2022].

Natras R, Horozovic D & Mulic M (2018) Strong solar flare detection and its impact on ionospheric layers and on coordinates accuracy in the Western Balkans in October 2014, *SN Applied Sciences,* 1.

Noaa. (2022) *Total Electron Content* [Online]. Space Weather Prediction Center National Oceanic and Atmospheric Administration. Available: https://www.swpc.noaa.gov/phenomena/total-electron-content [Accessed 11/09 2022].

Novatel. (2022) *Applications* [Online]. HEXAGON. Available: https://novatel.com/an-introduction-to-gnss/chapter-8-gnss-applications-and-equipment/applications [Accessed 2022/01/09 2022].

Peng Y & Scales WA (2021) Ionospheric Remote Sensing with GNSS, *Encyclopedia,* 1**,** 1246-1256.

Rodríguez JaÁ. (2011) *GPS Signal Plan* [Online]. eesa navipedia. Available: https://gssc.esa.int/navipedia/index.php/GPS_Signal_Plan#:~:text=The%20GPS%20L1%20band%20(1575.42,signals%20transmitted%20at%20this%20frequency. [Accessed 11/11 2022].

Segura DI. (2014). *Implementation of GNSS ionospheric models in gLAB.* Telecommunications engineering, Universitat Politecnica de Catalunya (UPC).

Subirana JS, Zornoza JMJ & Hernández-Pajares M. (2011) *Ionospheric Delay* [Online]. Available:

https://gssc.esa.int/navipedia/index.php/Ionospheric_Delay [Accessed 06/27 2022].

Swpc.Noaa.Gov. (2022) *Ionosphere | NOAA / NWS Space Weather Prediction Center* [Online]. Swpc.noaa.gov: Space Weather Prediction Center National Oceanic and Atmospheric Administration. Available: https://www.swpc.noaa.gov/phenomena/ionosphere [Accessed 2022/01/09].

Ya'acob N, Yusof AL, Ali MT*, et al.* (2011) Investigation of the Annual Solar Eclipse by Using TEC Measurements, *2011 IEEE Symposium on Wireless Technology and Applications (ISWTA),*.

AUTHOR BIOGRAPHY

WMHP Sandanayake is with a BSc (Hons) Surveying Sciences degree from General Sir John Kotelawala Defence University. He would like to do his future studies in the fields of Geodesy and Surveying including GNSS, Space Geodesy, and Earth Observation. Further he like to contribute to above mentioned research areas by solving the existing problems in them.