

The Rate of Ionospheric Total Electron Content Index (ROTI) as a Proxy for Nighttime Ionospheric Irregularity Using Ethiopian Low-Latitude GPS Data

T. K. Gogie*

Physics Department, College of Science Bahir Dar University, Bahir Dar, Ethiopia

**e-mail: tsegaye8684@gmail.com*

Received April 16, 2020; revised September 17, 2020; accepted January 28, 2021

Abstract—The correlation between the rate of TEC index (ROTI) and amplitude scintillation index S_4 for low-latitude region is analyzed using data collected from a Global Positioning System (GPS) scintillation monitoring receiver installed at Bahir Dar Ethiopia for the periods of 2012 and 2013. The analysis was done for selected quiet and disturbed days based on Kp and Dst values. Generally speaking, the ROTI and S_4 are nicely correlated almost in all cases we considered. It is also found that there is a good consistency between the temporal variations of ROTI with scintillation activity under different ionospheric conditions. ROTI has a high correlation with scintillation index on geomagnetically disturbed days. These results demonstrated the feasibility of using ROTI derived from GPS observations recorded by common non-scintillation GPS receivers to characterize ionospheric scintillation. Based on the correlation results, we have mapped the spatial variations of ionospheric scintillation over Ethiopia from a chain of ten non-scintillation GPS receivers. The mapped ROT index has clearly illustrated the spatial propagation of ionospheric scintillation over the considered area.

DOI: 10.1134/S0016793221030051

1. INTRODUCTION

Ionospheric irregularities, as one of the earliest known effects of space weather, have a great impact on the Global Navigation Satellite System (GNSS) and satellite communication because they can result in rapid random fluctuations or degradation of the signal amplitude, phase and delay. Moreover, ionospheric scintillation can simultaneously accompany the occurrence of cycle slips or the complete loss on GNSS signals. Similarly affected by irregular ionospheric activities, GNSS has become a powerful tool for investigating the total electron content (TEC) and TEC fluctuations associated with irregular ionospheric activities along signal paths, which have become essential to the way we live and work (Aggarwal et al., 2012; Balan et al., 1993; Bilitza, 2000; Chen et al., 2008; Gorney, 1990; Kassa et al., 2015; Kassa et al., 2017; Zhao et al., 2005).

The amplitude/phase scintillation index S_4 and ROT I are typically used to quantitatively describe the intensity of ionospheric scintillation or TEC fluctuations. Measurements of both S_4 and can be derived from GNSS scintillation monitoring receivers sampled at high frequencies, but the number and regional/global distribution of scintillation monitoring receivers are limited due to high costs. This sparsity of scintillation monitoring receivers restricts the

extensive use of S_4 and indices (Afraimovich et al., 2006; Bilitza, 2000; Gorney, 1990; Judge et al., 1998; Zhao et al., 2005).

The Total Electron Content fluctuation index ROTI, which is derived from ordinary non-scintillation GNSS receivers sampled at low frequencies, was first proposed in 1997. Since then, it has been widely used to detect irregular ionospheric activities, which are defined as the standard deviation of the rate of TEC (ROT) in a given 5 min interval. Previous studies have demonstrated close correlations between ROTI and scintillation indices. Over the past two decades, ROTI has been widely used to detect regional and global TEC fluctuations, especially with the growing number of GNSS tracking sites (Balan, 1993; Bilitza, 2000; Chen et al., 2008; Chen et al., 2015; Guo et al., 2007; Hedin, 1984; Lean et al., 2011; Li et al., 2013).

There exist thousands of dual-frequency geodetic GNSS receivers that have been deployed at globally and regionally distributed permanent stations. The networks of such receiver stations include the global GNSS network managed by the International GNSS receiver (IGS), the Continuously Operating Reference Stations (CORS) network managed by the U.S. National Geodetic Survey, the GPS Earth Observation Network (GEONET) developed by the Geographical Survey Institute of Japan, etc. The standard

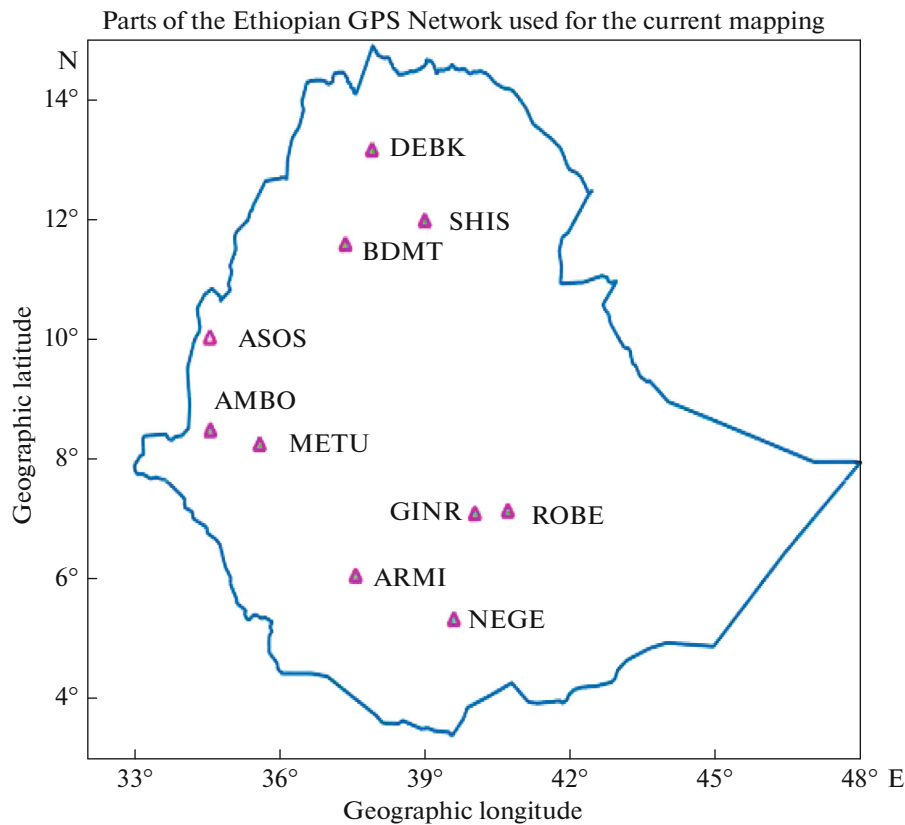


Fig. 1. Parts of Ethiopian GPS Network used for the current ν TEC and ROTI mapping.

GNSS data collected from these networks have been used for many scientific and technological applications, including geodetic survey, precise GNSS orbit determination, global differential GPS System, global

total electron content (TEC) mapping, ionospheric irregularity and scintillation measurements, etc (Afraimovich et al., 2006; Akala et al., 2013; Kelly 2009; Klobuchar et al., 1996; Li et al., 2013).

Table 1. Geographic Coordinates of GPS receivers used for the study

Station	Code	Lat. (N)	Long. (E)
Arbaminch	ARMI	6.06	37.55
Ambo	ABOO	8.50	34.56
Debark	DEBK	13.15	37.89
Asosa	ASOS	10.05	34.55
Ginir	GINR	7.15	40.7
Metu	METU	8.27	35.58
Robe	ROBE	7.11	40.02
Shis	SHIS	11.99	38.99
Negele	NEGE	5.33	39.59
Bahir Dar	BDMT	11.60	37.38

In this paper, we further introduce the rate of TEC index (ROTI) maps that measure regional ionospheric irregularity and scintillation activities using the standard dual-frequency GNSS phase data. The measurement technique was originally proposed in 1997. The coverage of GNSS-inferred ROTI maps has significantly improved since then as the GNSS networks continuously expand. The map has performed from a chain of 10 ground-based GPS receivers in East African region. Details about the receiver stations are illustrated by Table I and Fig. 1. Furthermore, a correlation analysis has presented in order to verify that ROTI is a good indicator of ionospheric scintillation occurrence traditionally measured by S_4 and indices.

2. MOTIVATION

Specialized receivers that can generate the ionospheric scintillation indices, namely the amplitude scintillation index (S_4) and phase scintillation index are not available worldwide, which limits the application of these approaches. In order to overcome this problem, it is proposed to investigate the relationship

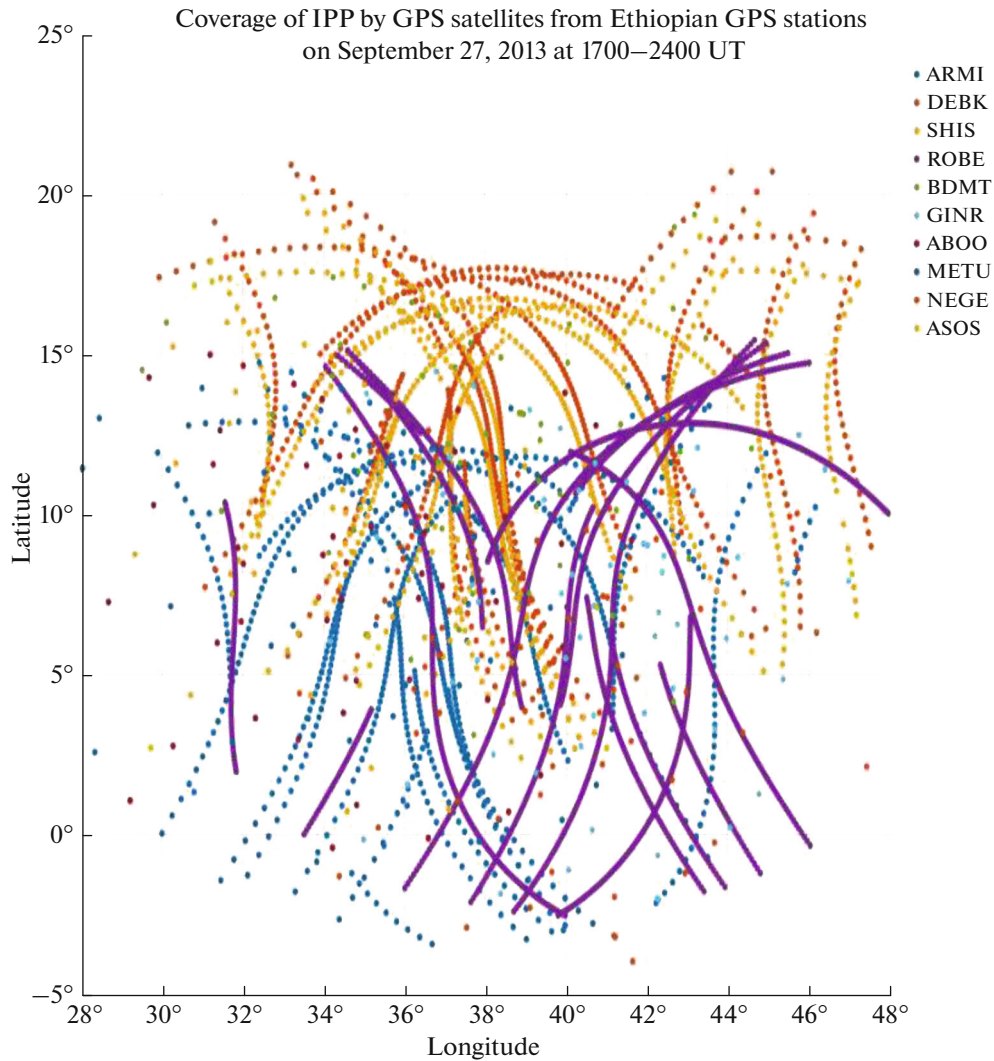


Fig. 2. Coverage of Ionospheric Pierce Point (IPP) by GPS satellite from Ethiopian stations on September 27, 2013 at 1700–2400 UT (nighttime depression).

of rate of change of total electron content index (ROTI) that can be obtained from standard generic receivers to represent scintillation indices.

Pi et al., 1997 proposed the ROT index ROTI as indicator of ionospheric irregularities. Being ionospheric scintillation of radio signals an important phenomenon under focus, the relationship between ROTI and scintillation indices has been widely studied. Basu et al., 1999 noted that ROTI/S₄ varies in correspondence to the zonal velocity of ionospheric irregularities. Yang and Liu, 2016 considered each satellite-receiver propagation path, and found larger correlation between ROTI and S₄ can be achieved under stronger scintillation circumstances. The study also found that more often poor correlations between them exist.

Liu et al., 2019 further addressed the impacts of receivers and sampling rates on the behaviors of

ROTI. Carrano et al., 2019 showed evidences that only under certain geometry ROTI and S₄ are highly correlated. The same study clarifies the differences between ROTI and S₄ considering that S₄ is more

Table 2. Quiet time correlation between S₄ and ROTI indices

Date	Max R	Elevation (Max R)
01 January 2012	0.5	53.11
01 February 2012	0.496	56.87
01 March 2012	0.625	56.6
01 April 2012	0.57	51.87

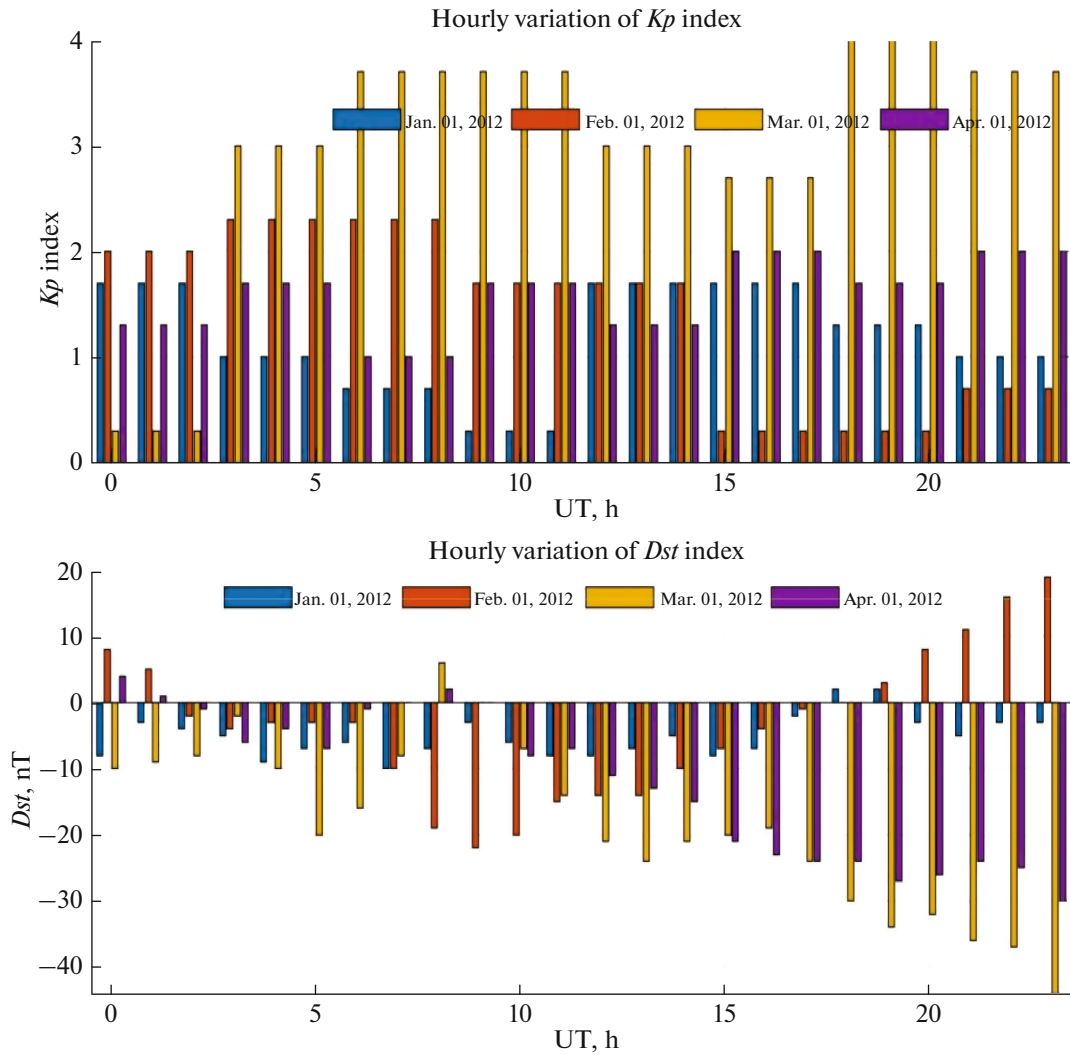


Fig. 3. Hourly variations of *Kp* and *Dst* quiet time indices.

influenced by the scintillation spectrum and Fresnel scale. From the above-mentioned reports, we came to infer that there is no conclusive and homogenous rela-

tionship between ROTI and *S*₄ index. Thus, further investigation in their relation should be carried out in both temporal and spatial domains and even in differ-

Table 3. Effect of storm on nighttime scintillation inferred from *S*₄ and ROTI indices

Date	<i>Dst</i> , nT	Effect	Max R	Elevation (Max R)
12 June 2012	-82	Suppression	0.653	53.50
17 June 2012	-82	Suppression	0.656	56.81
05 April 2012	-80	Enhancement	0.577	57.22
01 June 2013	-120	Suppression	0.55	58.19
06 July 2013	-83	Enhancement	0.528	76.90
14 July 2013	-83	Enhancement	0.773	65.80

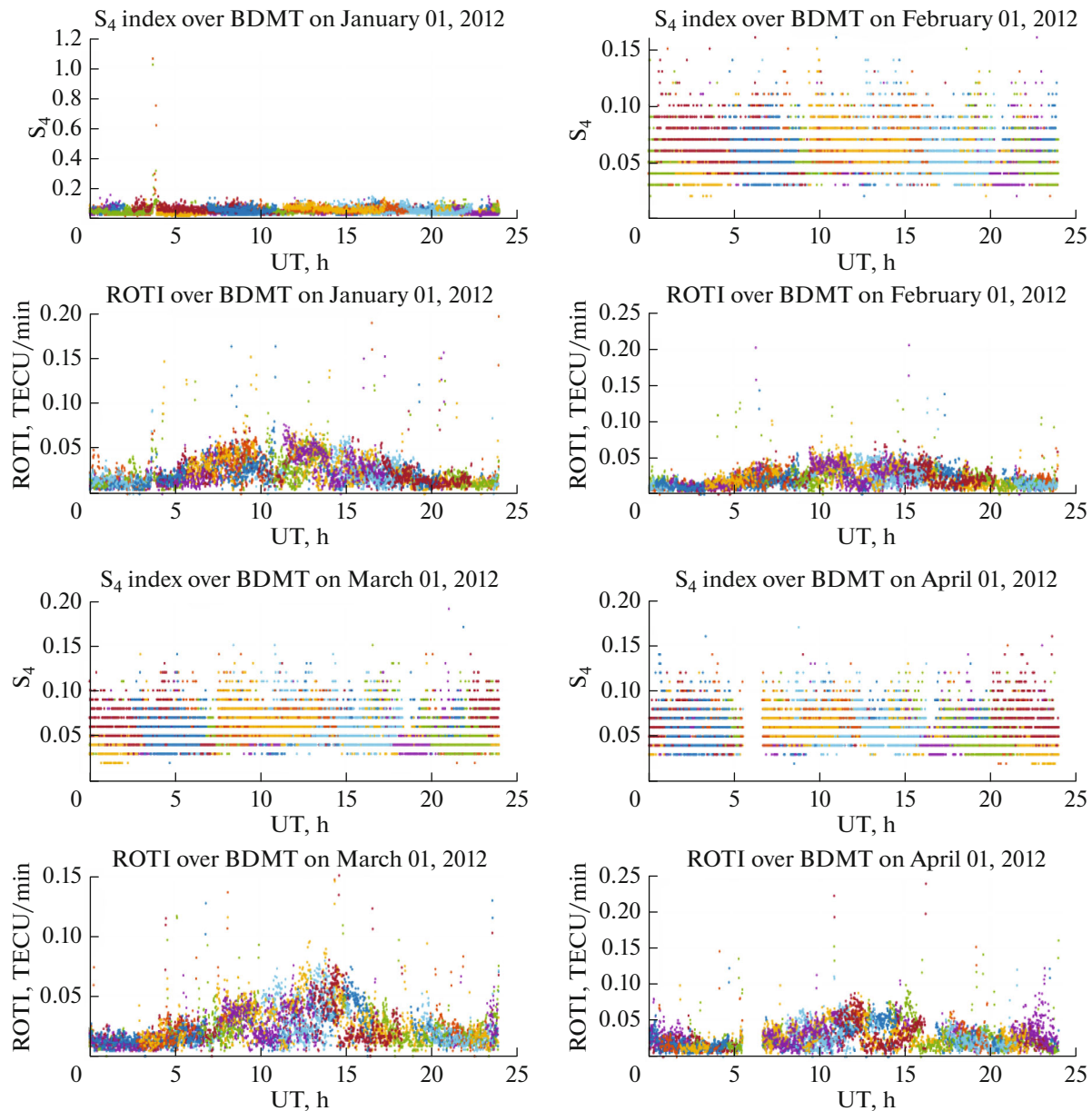


Fig. 4. Hourly variations of S_4 and ROTI indices during January 1, February 1, March 1 and April 1, 2012 over Bahir Dar, Ethiopia.

ent circumstances. In this paper, the relationship between ROTI with S_4 in both the spatial and temporal domains is investigated.

3. DATA AND METHODS

According to Akala et al., 2013, Kumar et al., 2012, Okoh et al., 2014, Sharma et al., 2012 and Tariku, 2015, the rate of TEC index (ROTI, in TECU/min) was proposed for the first time in 1997 to describe the measurements of ionospheric irregularity and scintillation activity. The rate of TEC (ROT, in TECU/min) is

measured by utilizing dual-frequency GPS observation phase data, and computing the relative TEC changes, epoch by epoch, along the signal paths from each individual to the receiver, as shown in Equation (1). The ROTI is defined as the standard deviation of ROT over 5 min time intervals, as shown in Equation (2).

$$\sqrt{\text{ROT}} = \frac{\Delta \text{STEC}}{\Delta t}, \quad (1)$$

$$\sqrt{\text{ROTI}} = \sqrt{\langle \text{ROT}^2 \rangle - \langle \text{ROT} \rangle^2}. \quad (2)$$

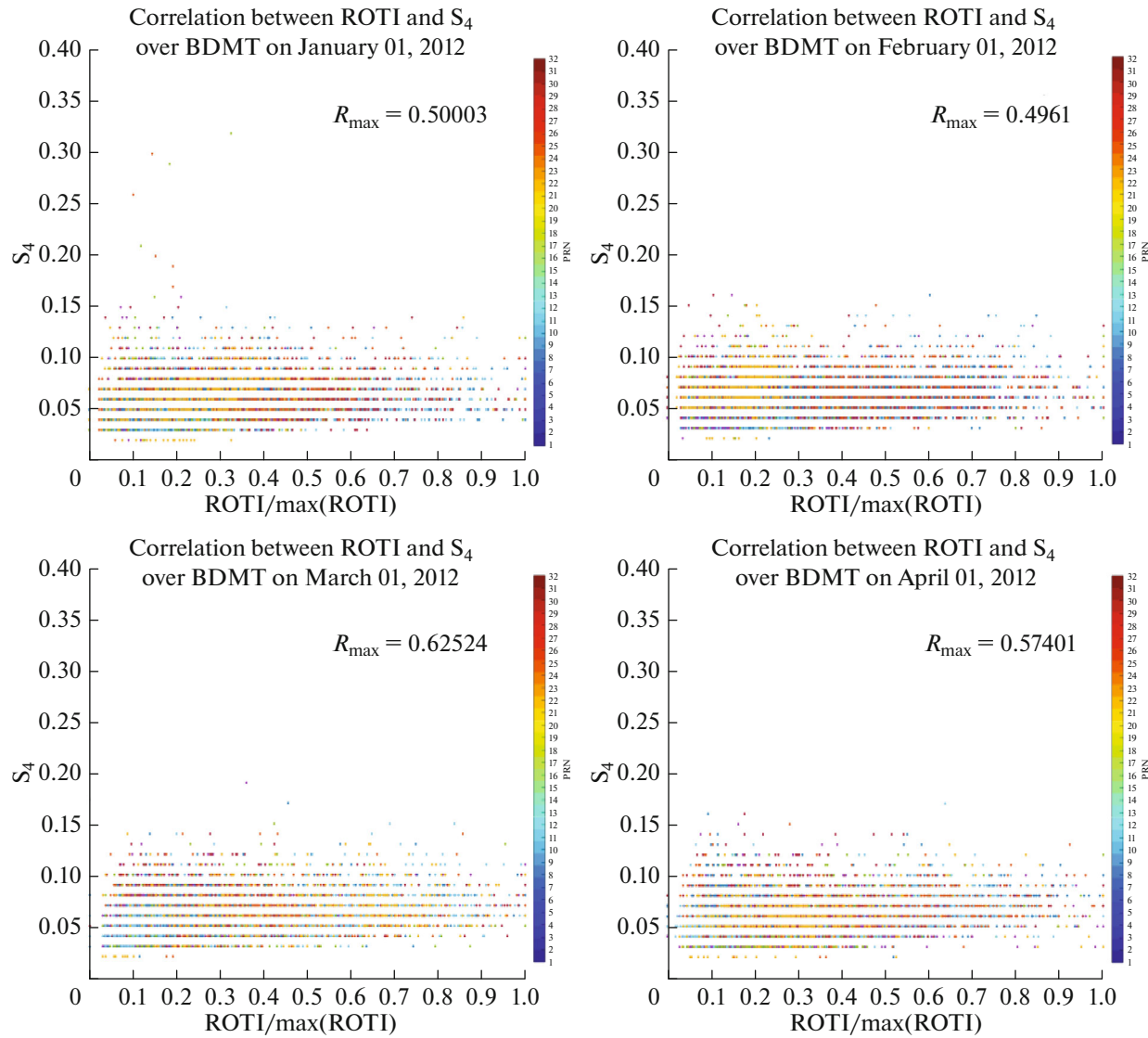


Fig. 5. Scatter plot of S_4 and ROTI indices during January 1, February 1, March 1 and April 1, 2012 over Bahir Dar, Ethiopia.

In this paper, dual-frequency GPS data has been obtained from IGS in Ethiopian GPS network and about 10 continuously operating GNSS tracking stations have been selected to detect TEC fluctuations associated with ionospheric disturbances over East Africa (See Table 1 and Fig. 1). The recorded GPS-TEC data at these stations are obtained from (<http://sopac.ucsd.edu>). Dual-frequency GPS observations have sampled at 30 s intervals; the cut-o elevation angle has set at 30° ; and the selected time period is from 2012 to 2013, although some data are missing. Figure 2 illustrates the coverage of ionospheric pierce point (IPP) by GPS from 10 Ethiopian ground-based stations on 27 September 2013 at 1700–2400 UT. The IPP trace shows that the mapping is from real observations.

4. RESULTS AND DISCUSSIONS

We studied the correlations between ROTI and S_4 using data from each individual satellite as well as the amalgamated data from all the satellites. Both pattern and person statistical correlations have employed to clearly show the relation between S_4 and ROT indices. The analysis was done for the period of 2012 and 2013 in both quiet and disturbed conditions.

4.1. Quiet-time Correlation Analysis between S_4 Index and ROTI

The hourly variations of K_p and Dst indices of the selected quiet days (01 January, 01 February, 01 March and 01 April 2012) are depicted by the top and bottom panels of Fig. 3 respectively. As one can see from this figure, relatively small positive K_p and small negative

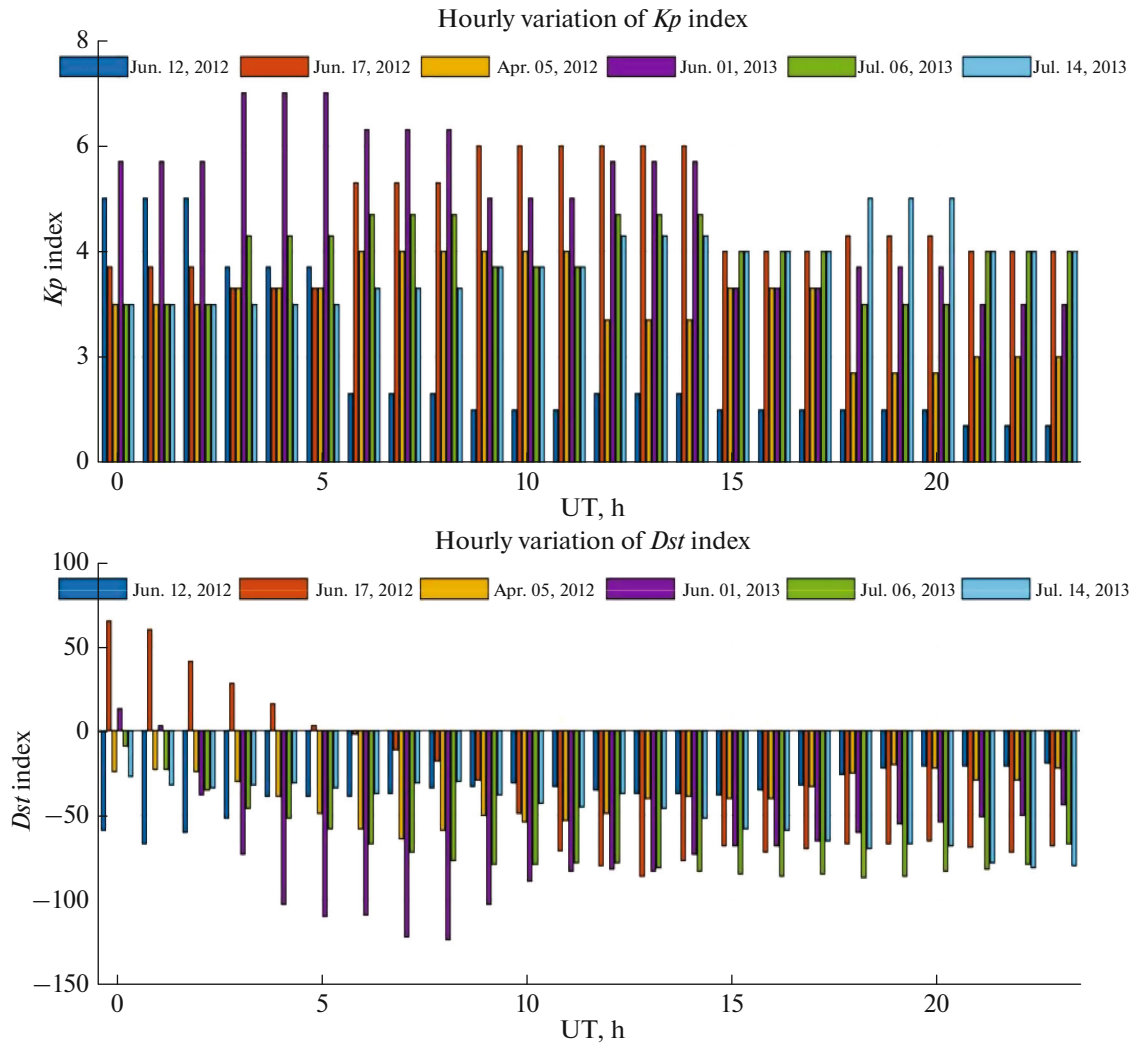


Fig. 6. Hourly variations of K_p and Dst disturbed time indices.

Dst values were recorded during these days. The blue bar stands for the K_p and Dst values for 01 January, red for 01 February, orange for 01 March and purple for 01 April 2012 respectively.

The quiet-time correlation between S_4 index and ROTI in the year 2012 during the first day of January, February, March and April months of 2012 are displayed by Figs. 4 and 5.

From Figure 4 one can easily infer the pattern correlation between S_4 and ROTI whereas from the scatter plot of Fig. 5 we could see the one to one statistical correlation obtained from each satellite coded by their respective PRN. The maximum correlation and their respective satellite elevation at which the maximum correlation was observed are displayed by Table 2.

Figures 1–4 and Table 1 clearly demonstrate in most cases a positive correlation between S_4 index and ROTI. However, minimum correlation coefficient was also observed and this might be due to the

fact that these satellites have very low elevation angle. Compared with other satellites, the relatively higher noise in their measurements may lead to weaker correlation between ROTI and scintillation indices (Zhe and Zhizhao, 2015).

This quiet time correlation has revealed that between the mapped as well as the time series ROTI values can be used as a proxy for the presence of ionospheric irregularity. Thus, in the absence of SCINDA receivers, one can use ROTI as a proxy for the occurrence of ionospheric scintillation.

4.2. Disturbed-time Correlation Analysis between S_4 Index and ROTI

The hourly variations of K_p and Dst values for the selected disturbed days in the year 2012 and 2013 are demonstrated by the top and bottom panel of Fig. 6 respectively. Dst was depressed to its minimum value (see the bottom panel of Fig. 6 and the second column

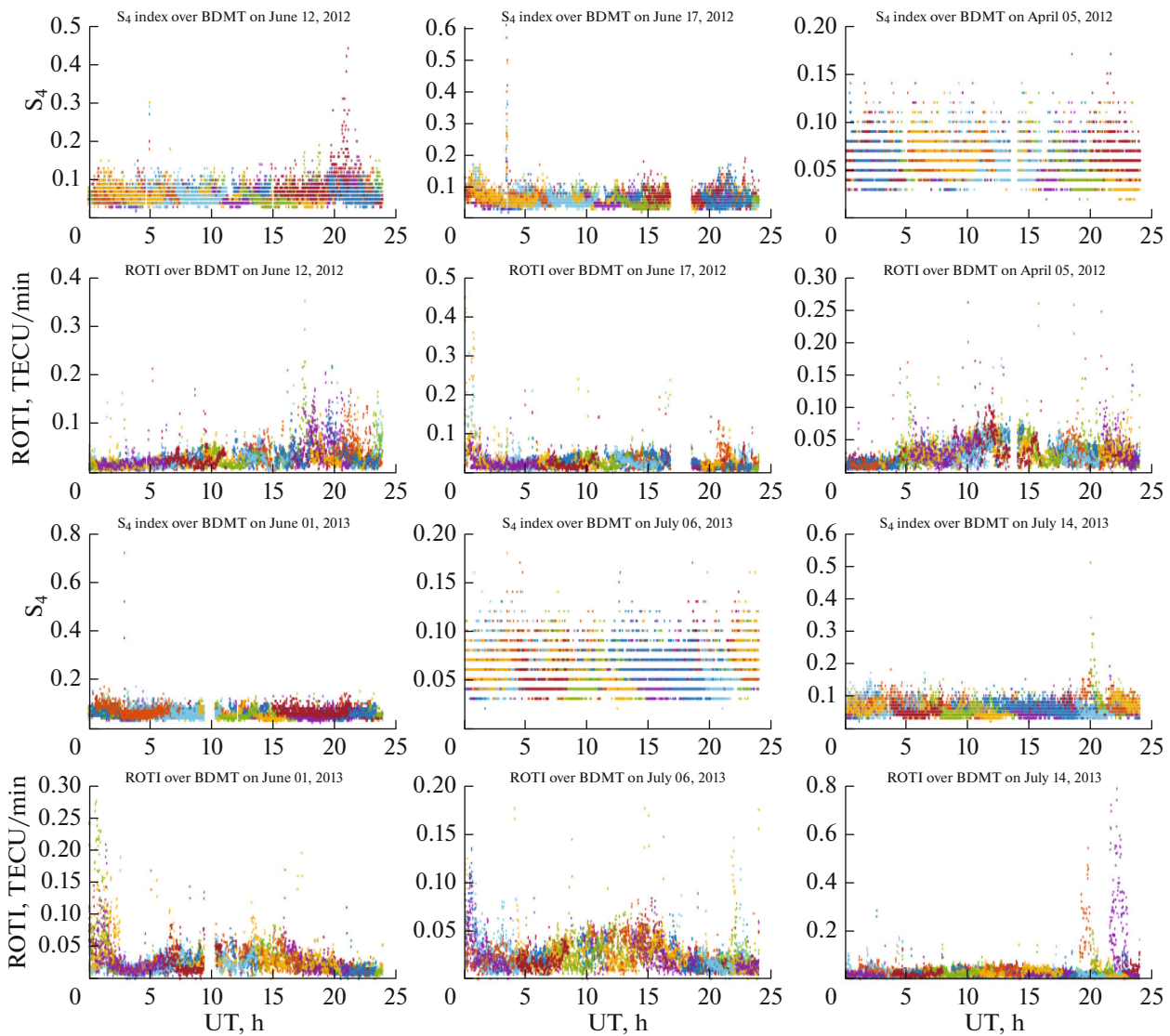


Fig. 7. Hourly variations of S_4 and ROTI indices during June 12, 2012, Jun 17, 2012, April 5, 2012, June 1, 2013, July 6, 2013 and July 14, 2013 over Bahir Dar, Ethiopia.

of Table III) -80 nT on 05 April 2012; -82 nT on 12 and 17 June 2012; -120 nT on 01 June 2013; -83 nT on 06 and 14 July 2013.

The disturbed-time correlation analysis of S_4 and ROT indices is done based on the strength of Dst and Kp indices observed during the year 2012 and 2013.

The corresponding storm-time patterns of ROTI in the above-mentioned days are demonstrated by Figs. 7, and 8 respectively. In all cases, the patterns illustrated by S_4 index due to geomagnetic storm are nicely captured by ROTI images. The suppression (negative effect) as well as enhancement (positive effect) of ionospheric scintillation are clearly illustrated by the time series as well as ROTI images. The summarized effect of the above-mentioned storm cases and maximum correlation coefficients are depicted by Table 3.

Such variations on storm-time effect on ionospheric scintillation might be seen the categories reported by (Aarons et al., 1980). According to this report, the effect of storm on scintillation depends on the time of occurrence of storm i.e. the time at which the Dst gets its minimum value. Both S_4 and ROTI indices have clearly responded to the geomagnetic storm effect and they are somehow in line with a report by (Aarons et al., 1980).

Besides, we have computed the ROTI values for the 2012 and 2013 and observed a little bit different correlation between S_4 and ROTI. Such yearly variations on the correlation between S_4 and ROTI might be due to year to year variations in solar and geomagnetic activities (Todd et al., 2010; Yu et al., 2009).

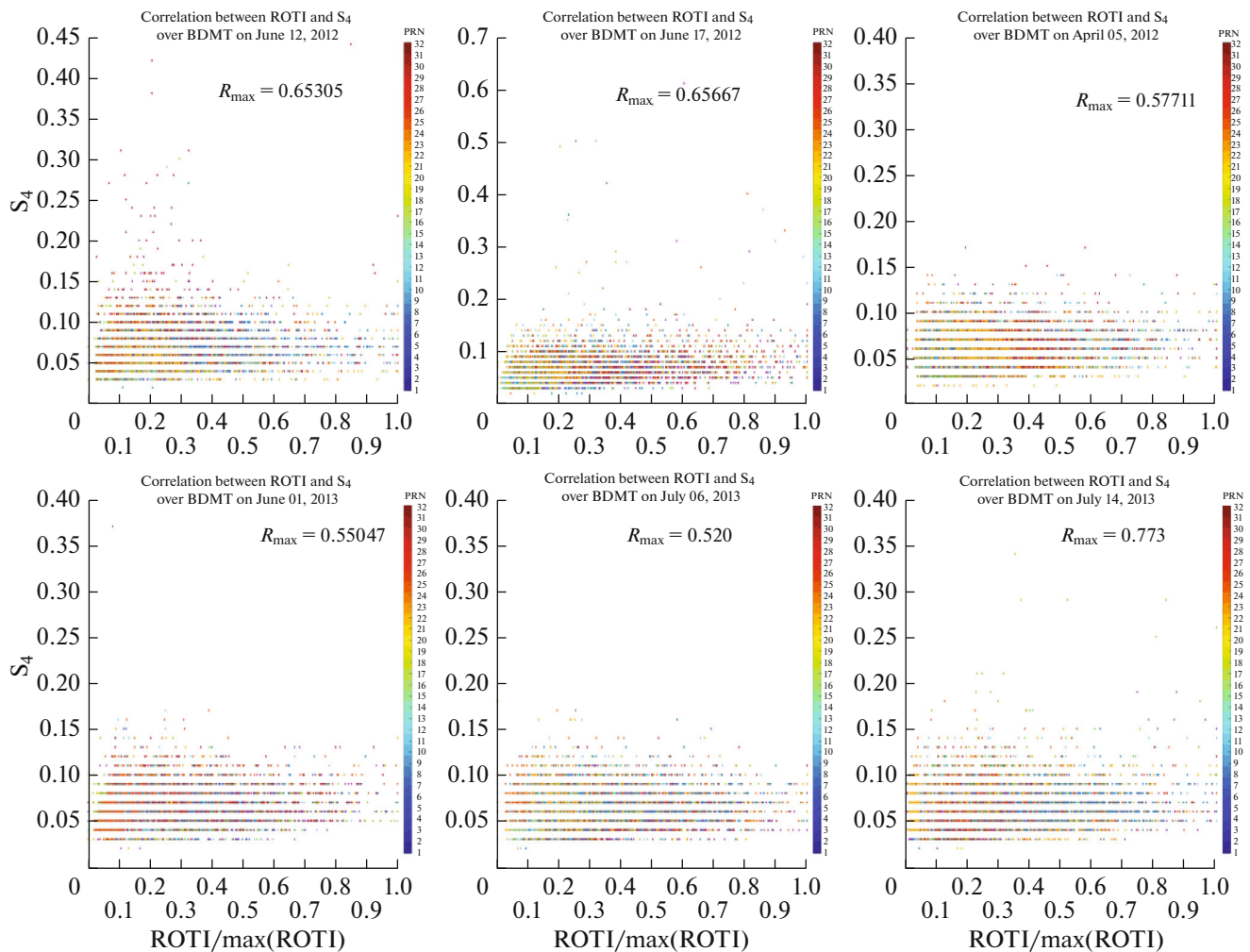


Fig. 8. Scatter plot of S_4 and ROTI indices during June 12, 2012, Jun 17, 2012, April 5, 2012, June 1, 2013, July 6, 2013 and July 14, 2013 over Bahir Dar, Ethiopia.

4.3. Temporal and Spatial Variations of Ionospheric Observables Inferred from Maps

The maps of ionospheric $\sqrt{\text{TEC}}$ and rate of TEC index are displayed by Fig. 9. The top and bottom panels of Fig. 9 illustrate the hourly variations of the mapped $\sqrt{\text{TEC}}$ and ROTI (1800–2000 UT) on 27 September 2013 respectively. The pronounced ROTI is observed during depleted $\sqrt{\text{TEC}}$ that could be considered as a proxy for nighttime ionospheric scintillation.

According to the above figure, significant fluctuations and maximized values of ROTI were observed after sunset (1800–2000UT). Maximum value of S_4 during sunset time indicates that there are ionospheric irregularities during sunset time. This implies that ionospheric scintillation occurred during nighttime or post set time between 1800 to 2000 UT. The reason for this, during sunset period, the eastward electric field is enhanced (pre-reversal enhancement (PRE) electric field), which is coupled with the earth's geomagnetic field to produce an upward vertical force derived from

E B. The upward vertical force results in steep gradient of ion and electron densities between upper and lower layer, thereby producing plasma bubble irregularities arising from Rayleigh-Taylor instability process (Todd et al., 2010), which is the cause for ionospheric scintillation in equatorial region.

5. CONCLUDING REMARKS

In this paper, we have analyzed the capability of ROTI time series data as well as ROTI maps (images) in using as a proxy for the expected pattern of nighttime ionospheric irregularities. Both the spatial and temporal maps/patterns of ionospheric scintillation are analyzed. From the analysis, we came to conclude the following points.

1. The temporal and spatial values of ROTI could explain the expected ionospheric irregularity patterns and magnitude during both quiet and storm-times events.

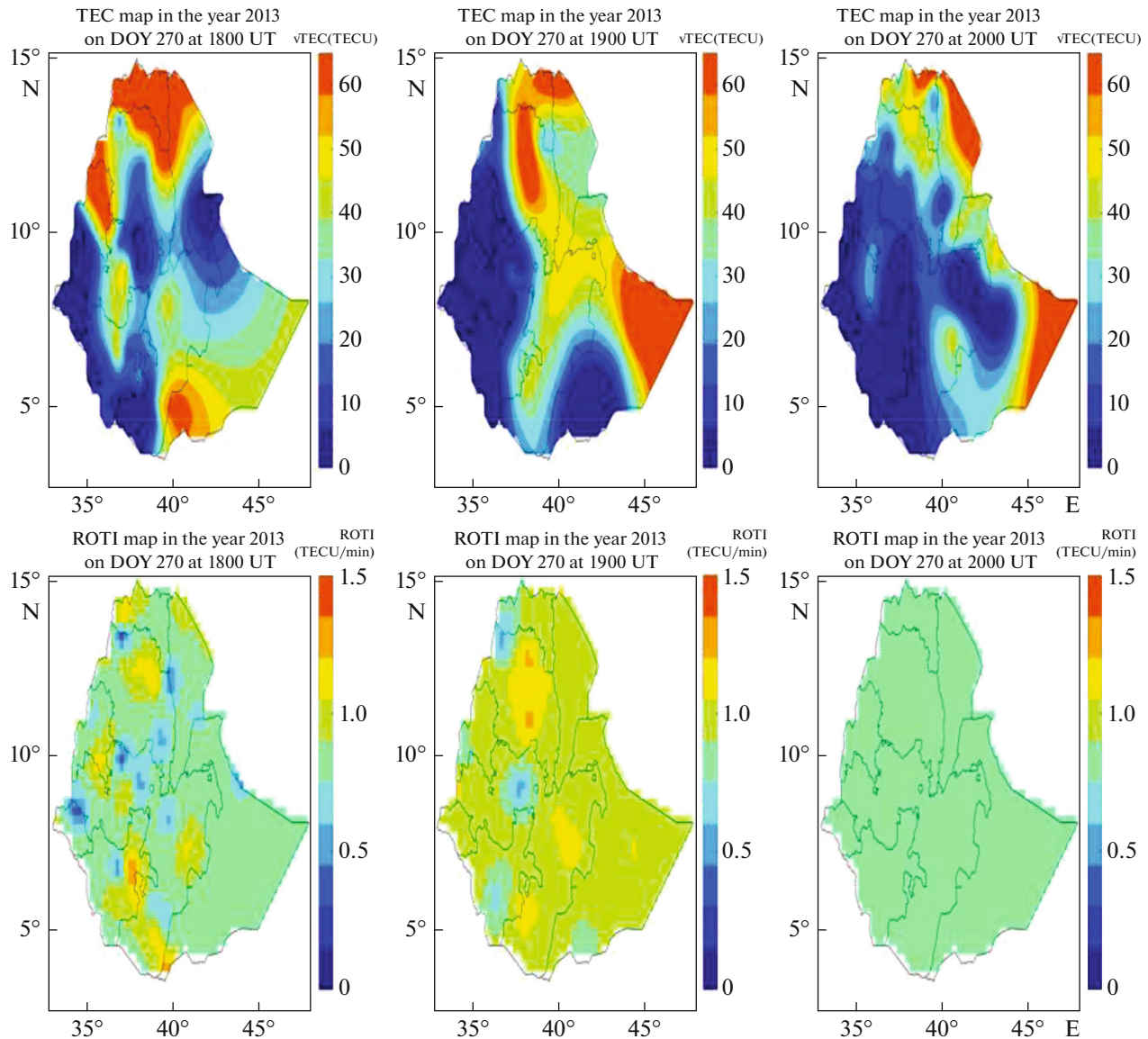


Fig. 9. Map of ionospheric TEC (top) and ROTI (bottom) at 18–20 UT on September 27, 2013 (DOY = 270) over Ethiopia.

2. In the absence of SCINDA receivers, we could use ROTI time-series values as well as maps to characterize at least the regional variations of ionospheric irregularities.

ACKNOWLEDGMENTS

We are grateful to Bahir Dar University, Ethiopia for partly supported the current work. We also appreciate all data providers for realizing the current work.

REFERENCES

- Afraimovich, E., Astafyeva, E., and Zhivetiev, I., Solar activity and global electron content, *Dokl. Earth Sci.*, 2006, vol. 409A, no. 6, pp. 921–924.
- Aggarwal, M., Joshi, H.P., Lyer, K.N., Kwak, Y.-S., Lee, J.J., Chandra, H., and Cho, K.S., Day-to-day variability of equatorial anomaly in GPS-TEC during low solar activity period, *Adv. Space Res.*, 2012, vol. 49, pp. 1709–1720. <http://dx.doi/10.1016/j.asr.2012.03.005>.
- Akala, A., Somoye, E., Adewale, A., Ojitalayo, E., Karia, S., Idolor, R., Okoh, D., and Doherty, P., Comparison of GPS-TEC observations over Addis Ababa with IRI2012 model predictions during 2010–2013, *Adv. Space Res.*, 2013, vol. 56, pp. 1686–1698.
- Araujo-Pradere, E., Fuller-Rowell, T., Codrescu, M., and Bilitza, D., Characteristics of ionospheric variability as a function of season, latitude, local time, and geomagnetic activity, *Radio Sci.*, 2005, vol. 40, RS5009.
- Aarons, J., Mullen, J.P., Koster, J.P., DaSilva, R.F., Medeiros, J.R., Medeiros, R.T., and Paulson, M.R., Sea-

- sonal and geomagnetic control of equatorial scintillations in two longitudinal sectors, *J. Atmos. Terr. Phys.*, 1980, vol. 42, nos. 9–10, pp. 861–866.
- Balan, N., Bailey, J., Jenkins, B., Rao, B., and Moett, J., Variations of ionospheric ionization and related solar fluxes during an intense solar cycle, *J. Geophys. Res.*, 1993, vol. 99, no. A2, pp. 2243–2253.
<https://doi.org/10.1029/93JA020995>
- Bagiya, M.S., Joshi, H., Lyer, K., Aggarwal, M., Ravindran, S., and Pathan, B., TEC variations during low solar activity period (2005–2007) near the equatorial ionospheric anomaly crest region in India, *Ann. Geophys.*, 2009, vol. 27, pp. 1047–1057.
- Basu, S., Groves, K.M., Quinn, J.M., and Doherty, P., A comparison of TEC fluctuations and scintillations at Ascension Island, *J. Atmos. Sol.-Terr. Phys.*, 1999, vol. 61, no. 16, pp. 1219–1226.
- Bilitza, D., The importance of EUV indices for the International Reference Ionosphere, *Phys. Chem. Earth*, 2000, vol. 25, nos. 5–6, pp. 515–521.
- Carrano, C.S., Groves, K.M., and Rino, C.L., On the relationship between the rate of change of total electron content index (ROTI), irregularity strength (CkL), and the scintillation index (S4), *J. Geophys. Res.: Space Phys.*, 2019, vol. 124, no. 3, pp. 2099–2112.
- Chen, Y., Liu, L., and Le, H., Solar activity variations of nighttime ionospheric peak electron density, *J. Geophys. Res.*, 2008, vol. 113, A11306.
<https://doi.org/10.1029/2008JA013114>
- Chen, Y., Liu, L., Le, H., and Zhang, H., Discrepant responses of the global electron content to the solar cycle and solar rotation variations of EUV irradiance, *Earth Planets Space*, 2015, vol. 67, id 80.
<https://doi.org/10.1186/s40623-015-0251-x>
- Ferbes, J.M., Palo, S.E., and Zhang, X., Variability of ionosphere, *J. Atmos. Sol. Terr. Phys.*, 2000, vol. 62, pp. 685–693.
- Gao, Y. and Liu, Z. Precise ionospheric modeling using regional GPS network data, *J. Global Positioning Syst.*, 2002, vol. 1, no. 1, id 18.
- Gorney, D., Solar cycle effects on the near-Earth space environment, *Rev. Geophys.*, 1990, pp. 315–336.
<https://doi.org/10.1029/RG028i003p00315>
- Guo, Y., Wan, W., Forbes, M., Sutton, E., Nerem, S., Woods, N., Bruinsma, S., and Liu, L., Effects of solar variability on thermosphere density from CHAMP accelerometer data, *J. Geophys. Res.*, 2007, vol. 112, A10308.
<https://doi.org/10.1029/2007JA012409>
- Hedin, A., Correlations between thermospheric density and temperature, solar EUV flux, and 10.7-cm flux variations, *J. Geophys. Res.*, 1984, pp. 9828–9834.
<https://doi.org/10.1029/JA089iA11p09828>
- Huang, Y. and K. Cheng, Solar cycle variation of the total electron content around equatorial anomaly crest region in East Asia, *J. Atmos. Terr. Phys.*, 1995, vol. 57, no. 12, pp. 1503–1511.
[https://doi.org/10.1016/0021-9169\(94\)00147-G](https://doi.org/10.1016/0021-9169(94)00147-G)
- Humphreys, T.E., Psiaki, M.L., and Kintner, P.M., Modeling the effects of ionospheric scintillation on GPS carrier phase tracking, *IEEE Trans. Aerospace Electron. Syst.*, 2010, vol. 46, no. 4, pp. 1624–1637.
- Judge, D., McMullin, D.R., Ogawa, H.S., et al., First solar EUV irradiances obtained from SOHO by the SEM, *Sol. Phys.*, 1998, vol. 177, pp. 161–173.
<https://doi.org/10.1023/A:1004929011427>
- Kassa, T. and Damtie, B., Ionospheric irregularities over Bahir Dar, Ethiopia, during selected geomagnetic storms, *Adv. Space Res.*, 2017, vol. 60, no. 1, pp. 121–129.
<https://doi.org/10.1016/j.asr.2017.03.036>
- Kassa, T., Damtie, B., Bires, A., Yizengaw, E., and Cilliers, P., Storm-time characteristics of the equatorial ionization anomaly in the East African sector, *Adv. Space Res.*, 2015, vol. 56, pp. 57–70.
<https://doi.org/10.1016/j.asr.2015.04.002>
- Kelly, M.C., *The Earth's Ionosphere: Plasma Physics and Electrodynamics*, San Diego, Calif.: Academic, 2009.
- Klobuchar, J.A., Parkinson, B.W., and Spilker, J.J., Ionospheric effects on GPS, in *Global Positioning System: Theory and Applications*, Washington, DC: American Institute of Aeronautics and Astronautics, 1996.
- Kumar, S., Priyadarshi, S., Krishna, S.G., and Singh, A., GPS-TEC variations during low solar activity period (2007–2009) at Indian low latitude stations, *Astrophys. Space Sci.*, 2012, vol. 339, pp. 165–178.
- Lean, J., Meier, R., and Emmert, J., Ionospheric TEC: Global and hemispheric climatology, *J. Geophys. Res.: Space Phys.*, 2012, vol. 116, A10318.
- Li, S., Peng, J., Xu, W., and Qin, K., Time series modeling and analysis of trends of daily averaged ionospheric total electron content, *Adv. Space Res.*, 2013, vol. 52, pp. 801–809.
- Liu, Z., Yang, Z., Xu, D., and Morton, Y.J., On inconsistent ROTI derived from multiconstellation GNSS measurements of globally distributed GNSS receivers for ionospheric irregularities characterization, *Radio Sci.*, 2019, vol. 54, no. 3, pp. 215–232.
- Okoh, D., McKinnell, L., Cillers, P., Okere, P., Okonkwo, C., and Rabiun, B., IRI-vTEC versus GPS-vTEC for Nigerian SCINDA GPS stations, *Adv. Space Res.*, 2014, vol. 55, no. 8, pp. 1941–1947.
- Pi, X., Mannucci, A.J., Lindqwister, U.J., and Ho, C.M., Monitoring of global ionospheric irregularities using the worldwide GPS network, *Geophys. Res. Lett.*, 1997, vol. 24, no. 18, pp. 2283–2286.
- Rishbeth, H., Day-to-day ionospheric variations in a period of high solar activity, *J. Atmos. Terr. Phys.*, 1993, vol. 55, no. 2, pp. 165–171.
[https://doi.org/10.1016/0021-9169\(93\)90121-E](https://doi.org/10.1016/0021-9169(93)90121-E)
- Sharma, K., Dabas, R., and Ravindran, S., Study of total electron content variations over equatorial and low latitude ionosphere during extreme solar minimum, *Astrophys. Space Sci.*, 2012, vol. 341, pp. 277–286.

- She, C., Wan, W., and Xu, G., Climatological analysis and modeling of the ionospheric global electron content, *Chin. Sci. Bull.*, 2008, vol. 53, pp. 282–288.
- Tariku, Y., Patterns of GPS-TEC variation over low latitude regions (African sector) during the deep solar minimum (2008–2009) and solar maximum (2012–2013) phases, *Earth Planets Space*, 2015, vol. 67, no. 35, pp. 1–9.
- Yang, Z. and Liu, Z., Correlation between ROTI and ionospheric scintillation indices using Hong Kong low-latitude GPS data, *GPS Solutions*, 2016, vol. 20, no. 4, pp. 815–824.
- Yu, Y., Wan, W., and Liu, L., A global ionospheric TEC perturbation index, *Chin. J. Geophys.*, 2009, vol. 52, pp. 907–912.
- Zhao, B., Wan, W., Liu, L., and Venkatraman, S., Statistical characteristics of the total ion density in the topside ionosphere during the period 1996–2004 using empirical orthogonal function (EOF) analysis, *Ann. Geophys.*, 2005, vol. 23, no. 12, pp. 3615–3631.
- Zhe, Y. and Zhizhao, L., Correlation between ROTI and ionospheric scintillation indices using Hong Kong low-latitude GPS data, *GPS Solutions*, 2015.
<https://doi.org/10.1007/s10291-015-0492-y>