Investigation of the Severe Geomagnetic Storm Effects on Ionosphere at Nighttime through ROTI

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ABSTRACT
In this study, the effect of the intense geomagnetic storm on the Earth's ionosphere during the period 07-08 September 2017 with the early arrival of coronal mass discharges associated with X-9 flares on the 6 September 2017 was investigated through ROTI, an index of Total Electron Content (TEC) ratio (ROT). The study was conducted with TEC values obtained from ten stations connected to the IGS-GPS network for five different latitude regions. As a result, it was observed that during the storm, the disturbances that occurred in the high latitude region of the southern hemisphere were more disturbed than the high latitude region of the northern hemisphere at nighttime. In addition, ROTI values were found to be higher than other days on disturbed days (07-08 September 2017).
Keywords: Ionospheric TEC, ROTI, geomagnetic storm

Şiddetli Jeomanyetik Fırtınanın Gece Yarısı İyonosfer Üzerindeki Etkisinin ROTI Aracılığıyla İncelenmesi

ÖZ
Bu çalışmada, 6 Eylül 2017'deki X-9 ışımaları ile ilişkili koronal kütle boşalmalarının erken ulaşması ile 07-08 Eylül 2017 tarihlerinde Dünya'nın iyonosferindeki yoğun jeomanyetik fırtınanın etkisi ROTI, Toplam Elektron İçerik (TEC) indeksinin oranı (Rate of TEC Index-ROTI) aracılığıyla incelendi. Çalışma beş farklı enlem bölgesi için IGS-GPS ağına bağlı on istasyondan elde edilen TEC değerleri ile gerçekleştirilmiştir. Sonuç olarak, fırtına sırasında gece yarısı güney yarımkürenin yüksek enlem bölgesinde meydana gelen rahatsızlıkların kuzey yarımkürenin yüksek enlem bölgesinden daha büyük olduğu gözlenmiştir. Ayrıca, tedirgin günlerdeki ROTI değerlerinin (07-08 Eylül 2017) diğer günlerden daha yüksek olduğu belirlendi.
Anahtar Kelimeler: İyonosferik TEC, ROTI, jeomanyetik fırtına

INTRODUCTION

A geomagnetic storm expresses a great perturbation of the Earth's magnetosphere, which occurs when there is a very effective energy exchange from the solar wind to the space environment around the Earth. These storms are caused by changes in the solar winds that bring about major changes in the currents, plasmas and fields in Earth's magnetosphere. Polar, auroral and equatorial regions, especially in high geomagnetic activity, are areas where plasma distribution is disturbance. Compared to high and low latitudes, mid-latitude ionosphere is generally regarded as less irregular environment [1]. The effects of geomagnetic storms at different altitudes and latitudes reflect different features of geomagnetic storms as their development varies in time and intensity, and their mechanics are different. This makes it difficult to determine the effect of storms and to establish responsible mechanisms for these effects [2]. In the high-latitude ionosphere, phase fluctuations of GPS signals are primarily caused by vertical ionospheric density gradients and disturbances associated with auroral and Cusp precipitation and polar head patches [3-7]. However, during strong geomagnetic storms, the auroral region moves towards the equator and the equatorial ionization anomaly (EIA) expands towards the mid-latitudes, so that the mid-latitude ionosphere becomes very disturbed and irregular [1]. The ionospheric irregularities in the equatorial region are produced on the magnetic equator due to plasma instabilities after sunset and the most important parameter for their development is vertical plasma drift at night ($\mathbf{E} \times \mathbf{B} / B^2$) [8, 9].

The ionospheric response to the geomagnetic storm is known as the ionospheric storm and causes a variety of effects not yet fully understood [1]. Ionospheric storms lead to various disturbances, such as large and small-scale travel disturbances. Estimating and modeling of the formation of ionospheric distributions is difficult because the ionosphere and solar energy change with time and location [10]. It has been found that the formation of these disturbances depends on the season, geographical region, solar activity and geomagnetic activities. Ionospheric disturbances generally affect the amplitude and phase fluctuations of trans-ionospheric radio waves passing through the ionosphere. These can cause significant effects on GPS positioning accuracy [11].

In this study, the effect of the severe geomagnetic storm on 07-08 September 2017 on the Earth's ionosphere was investigated through the Rate of TEC Index (ROTI). Ionospheric disturbances on the globe were identified on 05-09 September 2017 and the causes were discussed by calculating ROTI values at ten stations from five different latitudes (Northern Hemisphere High and Middle Latitude, Equatorial Latitude, Southern Hemisphere High and Middle Latitude).

MATERIAL and METHOD

In this study, we used raw GPS measurements provided by GPS receivers on the Earth's networks. We considered the high and mid-latitudes of the northern and southern hemispheres and the equatorial region in the study. TEC values were calculated by obtaining raw GPS data for each station (total of five regions, i.e. 50 stations) for the station. These stations and their coordinates are given in Table 1.

Obtaining GPS TEC Data

Raw data is available in RINEX format with a resolution of 30 s. The processing of raw data to obtain TEC data was done by means of the ionolabtecv1.26 software provided by the IONOLAB group. IONOLAB-TEC provides accurate, reliable and robust GPS-TEC estimation at high latitude, mid-latitude or equatorial GPS stations with the same reliability and accuracy for both quit and active days (www.ionolab.org) [12-14] . The current version of IONOLAB-TEC, which can be used online or downloaded as *.exe from www.ionolab.org, can estimate the GPS-TEC at the temporal resolution of any RINEX file. Therefore, if the data in the RINEX file is 1 s or 30 s, IONOLAB-TEC can produce the same temporal resolution.

Rate of TEC Index (ROTI)

The ROTI is defined as the standard deviation of the ROT (Rate of TEC) over certain time intervals. This index calculation is used by many researchers to detect ionospheric disturbances, as it is fairly simple to calculate based on the data obtained from normal Global Navigation Satellite System (GNSS) receivers and can also eliminate the variances and uncertainties that often complicate the analysis of GNSS data [15]. In this study, ROTI as a GPS-based index was used to detect the presence of GPS ionospheric irregularities and to measure irregular structures of TEC spatial gradients [16].

To calculate the ROTI from the vertical TEC (VTEC) values, the ROT value was first calculated using the following formula;

$$ROT = \frac{VTEC_k^i - VTEC_{k-1}^i}{\left(t_k - t_{k-1}\right)} \qquad (1)$$

where i is a GPS receiver and t_k is a period of time. The ROT is calculated as the total electron content unit (TECU) per minute for each GPS station. A TECU equals 10^{16} electrons/m^2. Then, ROT values were used to obtain ROTI values as standard deviation at 5-minute intervals.

$$ROTI = \sqrt{\left\langle ROT^2 \right\rangle - \left\langle ROT \right\rangle^2} \qquad (2)$$

Additional sources of ionospheric error include amplitude and phase scintillations and a straight-line deviation of the signal paths due to break in the ionosphere. In general, these effects can be fully reproduced during periods of high ionospheric activity resulting from the interaction between the solar wind and the Earth system. Except for amplitude scintillation, the ROTI is expected to be affected by such disorders. ROTI is more closely related to phase scintillation [15].

RESULT and DISCUSSION

In order to investigate the global response of the ionospheric TEC to the geomagnetic storm at G4 level, which was formed on 07-08 September 2017 in the study, IGS stations shown in Table 1 were selected from the northern and southern hemisphere (30^o S-30^o N, 30^o S-60^o S, 60^o S-90^o S, 30^o N-60^o N, 60^o N-90^o N) have selected ten stations for each latency interval. The formation of ionospheric disturbances according to latitudes is handled separately at 24:00 universal time (UT).

In this study, Dst index was used for the detection of geomagnetic storm. The change in the Dst index from 05-09 September 2017 is shown in Figure 1. At 00:00 UT on 07 September 2017, the Dst value increased suddenly in the north direction and reached 32 nT at 1:00 UT. The geomagnetic Dst index used to describe the storm displays an increase in the positive direction before heading south. This indicates the sudden start of the storm.

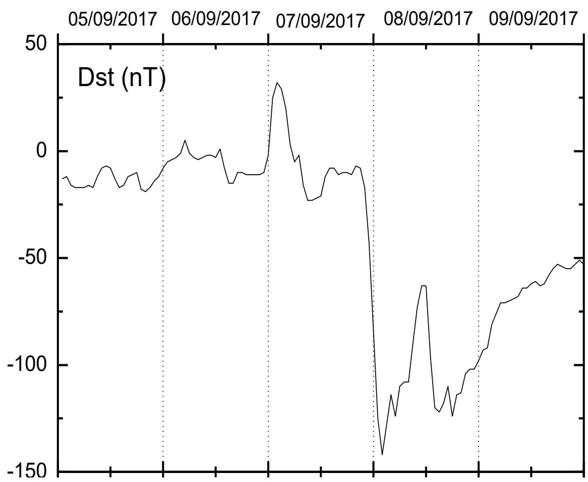

Figure 1. Change of geomagnetic indices Dst over time from 05-09 September 2017.

Table 1. Information on the stations used in the study.

No	Station's Name	Country	Latitude	Longitude	Magnetic Latitude	Magnetic Longitude
1	FAIR	ABD	64.97	-147.49	66.20	-96.44
2	HOLM	CANADA	70.73	-117.76	76.10	-73.87
3	RESO	CANADA	74.69	-94.89	82.89	-53.33
4	ALRT	CANADA	82.49	-62.34	87.22	152.41
5	SCOR	GREELAND	70.48	-21.95	74.96	78.55
6	NYAL	NORWAY	78.93	11.87	76.41	129.28
7	NYA1	NORWAY	78.93	11.86	76.41	129.27
8	TRO1	NORWAY	69.66	18.93	67.53	116.48
9	NRIL	RUSSIAN	69.36	88.35	60.25	166.99
10	YAKT	RUSSIAN	62.03	129.68	52.90	-162.25
1	QUIN	ABD	39.97	-120.94	46.30	-55.91
2	NLIB	ABD	41.77	-91.57	50.55	-22.66
3	STJO	CANADA	47.59	-52.67	56.68	24.38
4	BRST	FRANCE	48.38	-4.49	51.19	78.94
5	MEDI	ITALY	44.51	11.64	44.72	94.41
6	ISTA	TURKEY	41.10	29.01	38.38	109.53
7	TASH	UZBEKISTAN	41.32	69.29	33.54	146.60
8	URUM	CHINA	43.80	87.60	35.02	163.29
9	BJFS	CHINA	39.61	115.89	30.36	-171.71
10	MIZU	JAPAN	39.13	141.13	30.92	-149.53
1	ASPA	UNITED STATES	-14.32	-170.72	-15.62	-95.80
2	FAA1	FRENCH	-17.55	-149.61	-15.45	-74.40
3	MANA	NICARAGUA	12.15	-86.25	21.47	-14.27
4	KOUG	FRENCH GULANA	5.09	-52.64	14.12	20.33
5	ASCG	SAINT HELENA	-7.92	-14.33	-3.37	57.45
6	NKLG	GABON	0.35	9.67	1.74	83.15
7	SEY2	SEYCHELLES	-4.67	55.45	-11.00	127.52
8	BAKO	INDONESIA	-6.49	106.85	-16.35	-179.73
9	PNGM	PAPU	-2.043	147.36	-9.96	-138.86
10	KIRI	KIRIBATI	1.35	172.92	-2.27	-113.57
1	ANTC	CHILE	-37.33	-71.53	-27.79	0.86
2	COYQ	CHILE	-45.51	-71.89	-36.08	0.31
3	LPGS	ARGENTINA	-34.91	-57.93	-26.03	12.95
4	SUTM	SOUTH AFRICA	-32.38	20.81	-32.65	88.06
5	CZTG	FRENCH SOUTHERN	-46.43	51.85	-51.41	115.74
6	KERG	FRENCH	-49.35	70.25	-56.66	134.90
7	PERT	AUSTRALIA	-31.80	115.88	-41.60	-169.45
8	MOBS	AUSTRALIA	-37.83	144.97	-45.41	-135.87
9	AUCK	NEW ZELAND	-36.60	174.83	-39.82	-104.56
10	WGTN	NEW ZELAND	-41.32	174.80	-44.25	-103.34
1	ROTH	ANTARCTICA	-67.57	-68.12	-58.26	3.33
2	PALM	ANTARCTICA	-64.77	-64.05	-55.64	6.51
3	OHI3	ANTARCTICA	-63.32	-57.90	-54.03	10.89
4	SYOG	ANTARCTICA	-69.00	39.58	-70.57	87.00
5	MAW1	ANTARCTICA	-67.60	62.87	-73.48	113.72
6	CAS1	ANTARCTICA	-66.28	110.52	-75.87	-173.89
7	MAC1	AUSTRALIA	-54.49	158.94	-59.64	-114.86
8	COTE	ANTARCTICA	-77.80	161.99	-79.93	-73.64
9	MCM4	ANTARCTICA	-77.83	166.66	-79.26	-70.29
10	SCTB	ANTARCTICA	-77.84	166.75	-79.25	-70.11

The Dst value, which varies from -15 / -20 nT after the initial phase reaches -84 nT at 23:00 UT, -125 nT at 00:00 UT and -142 nT at 1:00 UT. Thus, it can be said that the main phase of the severe storm has begun. Geomagnetic parameters decreased to Dst = -63 nT in the first twelve hours of the main phase. From at 11:00 UT on 8 September 2017, by decreasing in negative direction to Dst value reach to -122 nT. In the main phase of this severe storm, again a severe storm has appeared. After about 14:00 UT on 8 September 2017, both Dst value have begun to damp and return to its ground-state values. This stage represents the recovery phase of the storm.

In the literature, if the ROTI values are greater than 0.08 TECU/min, then there is an ionospheric event in this region [17-19]. The results obtained are shown in Figure2-6.

ROTI changes calculated from TEC values obtained from fifty stations from different latitudes of the Earth at 5 and 6 September 2017 are shown in Figures 2 and 3.

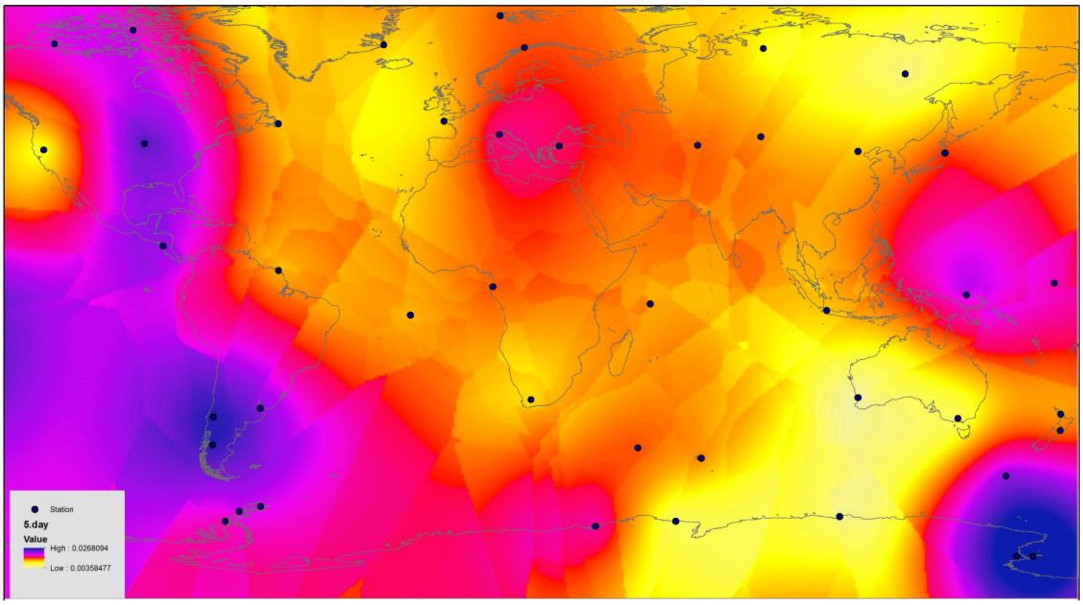

Figure 2. The determination of the irregularities occurred in Earth's ionosphere at 24:00 UT on 5 September 2017. The dots indicate the stations used in this study.

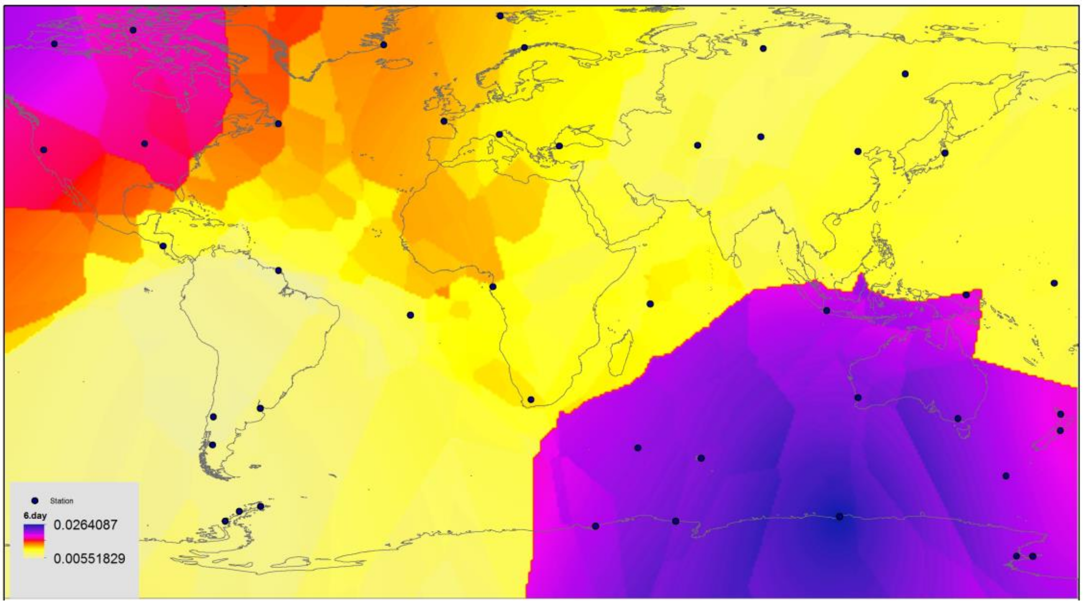

Figure 3. The determination of the irregularities occurred in Earth's ionosphere at 24:00 UT on 6 September 2017. The dots indicate the stations used in this study.

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The highest ROTI values are 0.026 TECU/min. These values were obtained on the American continent. These values mean that there is no ionospheric disturbance because the ROTI values are lower than the threshold values of 0.08 TECU/min.

On September 7, 2017, the largest ROTI values increased to 0.16 TECU/min. Since these values are greater than the threshold (0.08 TECU/min), this indicates that ionospheric disturbances have occurred. Ionospheric perturbations are particularly concentrated in the upper latitudes of the southern hemisphere. During the geomagnetic storms, ionospheric perturbations occurring in the upper latitudes of the Earth are associated with auroral particle precipitation [10]. Ionospheric perturbations occurring during this geomagnetic storm may also be related to auroral particle precipitation.

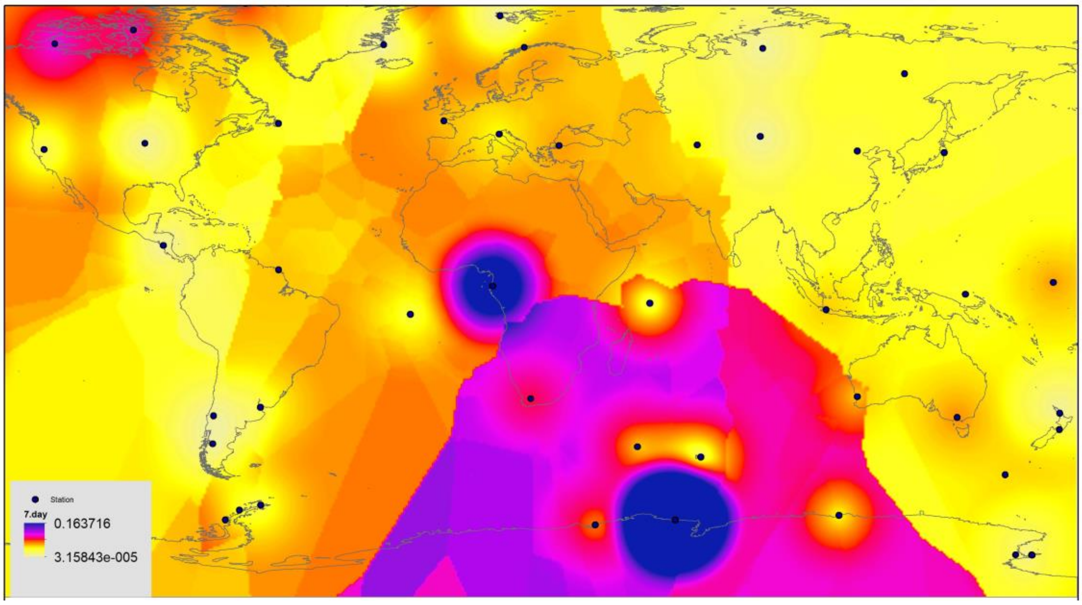

Figure 4. The determination of the irregularities occurred in Earth's ionosphere at 24:00 UT on 7 September 2017. The dots indicate the stations used in this study.

Figure 5 shows that ionospheric disturbances occurred on September 8, 2017. These ionospheric perturbations have lower ROTI values than those occurring on the previous day. However, these perturbations occurred again in the upper latitudes of the southern hemisphere.

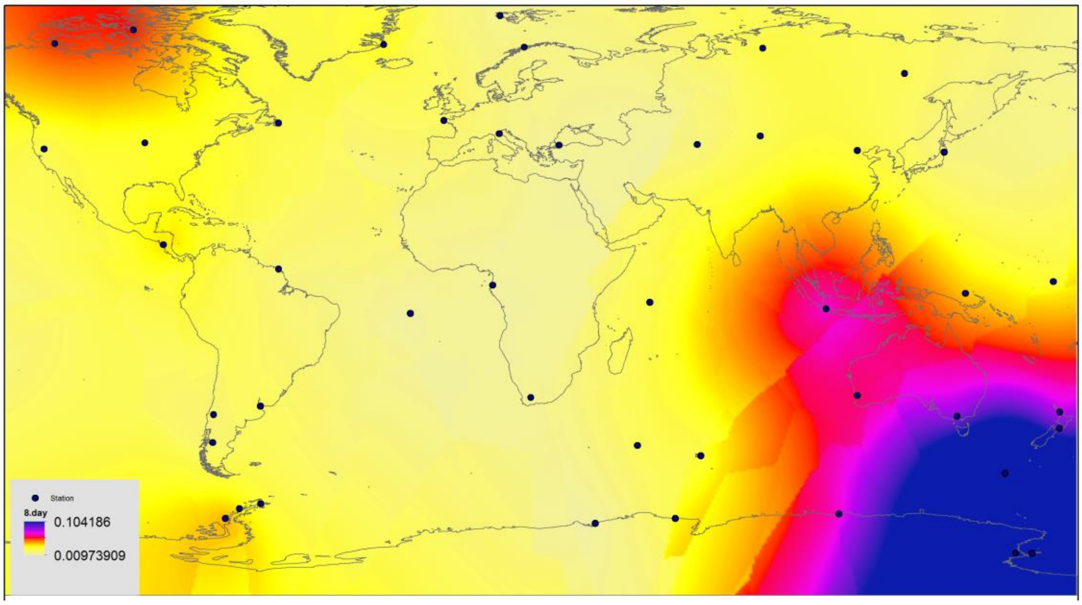

Figure 5. The determination of the irregularities occurred in Earth's ionosphere at 24:00 UT on 8 September 2017. The dots indicate the stations used in this study.

The change of ROTI values on September 09, 2017 is shown in Figure 6. In the return phase of the geomagnetic storm (September 09, 2017), it can be stated that the ionospheric disturbances disappeared because ROTI values fall below the threshold value.

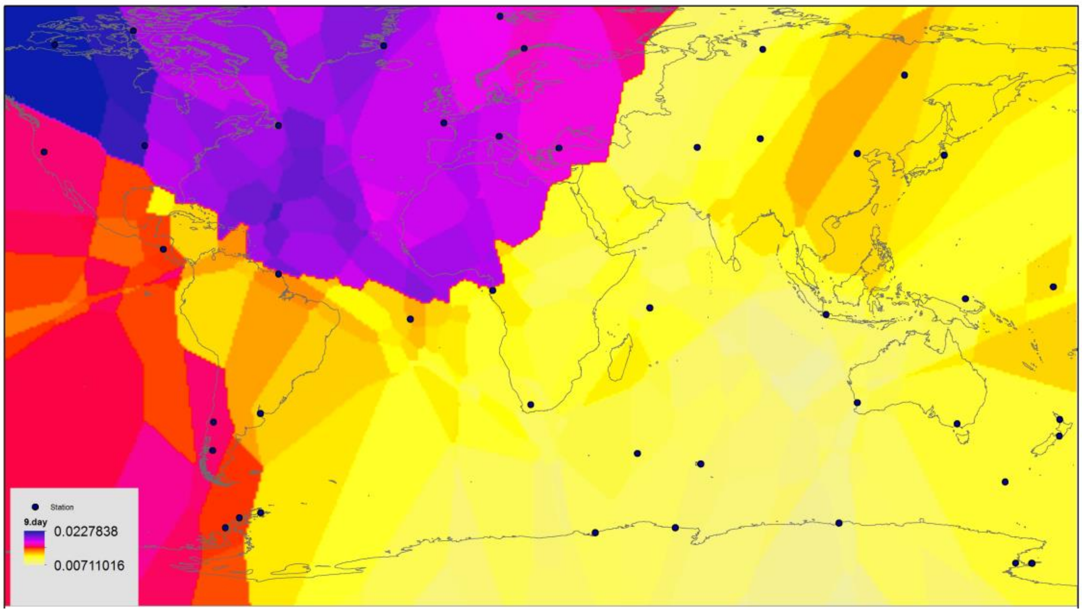

Figure 6. The determination of the irregularities occurred in Earth's ionosphere at 24:00 UT on 9 September 2017. The dots indicate the stations used in this study.

CONCLUSION

Using the TEC data obtained from at fifty stations around the earth provided from the IGS GPS network, the occurrence of density perturbations of the ionospheric plasma spherically during the geomagnetic storm of 07-08 September 2017 was investigated. During the days of the storm (07-08 September), many ionospheric disturbances have occurred in the signals obtained at GPS stations in the southern hemisphere high latitude at nighttime.

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