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The Ionospheric Response to the Annular Solar Eclipse on 26th January 2009

Riri Darwanisari Didong,
Electrical, Electronics and Systems Engineering,
Faculty of Engineering and Builds Environment,
Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor.

Mohammad Awad Momani
Institute of Space Science (ANGKASA),
Engineering Building,
Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor
Email: momani@ukm.my

Abstract—**The paper examines the ionspheric responses to the annular solar eclipse on 26th January 2009 over Southern Atlantic, Australia and Indian Ocean. The solar eclipse event took place during quiet solar and magnetic activities with maximum Kp and Dst indices are 3 and -32 nT. The external contacts of penumbra U1 and U4 occurred at 06:02:39 UT in the South Atlantic and 09:54:44 UT in the Celebes Sea. The GPS Total Electron Content (TEC) measurements obtained from 5 GPS stations belonging to International GNSS Service (IGS) network over India, Australia, and Antarctica have been employed in the analysis. 5 stations had been selected to conduct this study. They are Syowa in Antarctica, Windhoek in Namibia, Indian Institute of Science in India, Ceduna and Kerguelen Islands in Australia. The observations showed clear depletion in the TEC level from about 0.4 to 20% during the eclipse period.**

Keywords- Solar Eclips;, GPS; Ionosphere; TEC

I. INTRODUCTION

Solar eclipses provide unique opportunity to study the behavior of the ionosphere. During a solar eclipse, the Moon's shadow decreases the ionizing radiation from the sun, causing changes in electron concentrations and temperature [16]. During the past decades, the responses of the ionosphere to solar eclipses have been studied extensively with various methods, such as the Faraday rotation measurement, ionosonde network, incoherent scatter radar (ISR), Global Positioning System (GPS) and satellite measurements [1][2][5][10]. These studies have shown that there is almost a consistent behavior in the low altitudes where electron density drops by a large percentage during a solar eclipse, whereas the F2-region behavior may be quite complicated during different eclipse events, showing either an increase or decrease in electron density. In addition, responses of the low-latitude and equatorial ionosphere may be quite different from those in the mid-latitude ionosphere [16]. A low-latitude ionospheric tomography network (LITN) is used to observe the ionospheric response during the solar eclipse on 24th October 1995 where an enhancement and depression is found in Total Electron Content (TEC) during the solar eclipse [13]. During the same eclipse event, there might be different ionospheric responses at different locations because of the differences in background parameters. The ionospheric effects during a solar eclipse depend on several factors such as the solar activity level, geomagnetic disturbances, geophysical latitude and longitude and local time [4][18]. Depending on those factor, the increase in the reflection heights, reduction in the concentration of the F-layer maximum and the decrease in TEC can take place during solar eclipse [6][3].

II. SOLAR ECLIPSE CONDITION / SOLAR ACTIVITY

The annular solar eclipse of 26th January 2009 was visible across Indian Ocean and western Indonesia. The path of the eclipse was shown in Figure 1. The annular path runs from 06:02:39 UT, begins in the South Atlantic when the Moon's antumbral shadow meets Earth and forms a 363 kilometers wide corridor. Traveling eastward, the shadow quickly sweeps south of the African continent, missing it by approximately 900 kilometers. Slowly curving to the northeast the path crosses the southern Indian Ocean. The point of greatest eclipse, with 7 minutes and 54 seconds of annularity, occurs where the Indian Ocean is about halfway between Madagascar and Australia. It takes place at 07:58:39 UT when the eclipse magnitude will reach 0.9282. At this instant, the path width is 280 kilometers and the Sun is 73° above the flat horizon formed by the open ocean. The central track continues northeast where it finally encounters land in the form of the Cocos Islands and onward to southern Sumatra and western Java. At 09:04 UT, the central line duration is 6 minutes 18 seconds and the Sun's altitude at 25°. In its final minutes, the antumbral shadow cuts across central Borneo and clips the northwestern edge of Celebes before ending just short of Mindanao, Philippines at 09:54:44 UT. During 3 hour 52 minute 5 second, the Moon's antumbra travels approximately 14,500 kilometers and covers 0.9% of Earth's surface area. In addition, a partial eclipse was seen within the much larger path of the Moon's penumbral shadow, which includes the southern third of Africa, Madagascar, and Australia except Tasmania, southeast India, Southeast Asia and Indonesia between 04:56:38 UT and 11:00:41 UT. An eclipse was seen in Southern Sumatra and Borneo around 09:42 UT and 09:48 UT respectively.

III. DATA PROCESSING

All GPS data is obtained from SOPAC data center website with all stations that are used in the analysis belong to

Ministry of Science, Technology and Innovation Malaysia (MOSTI)

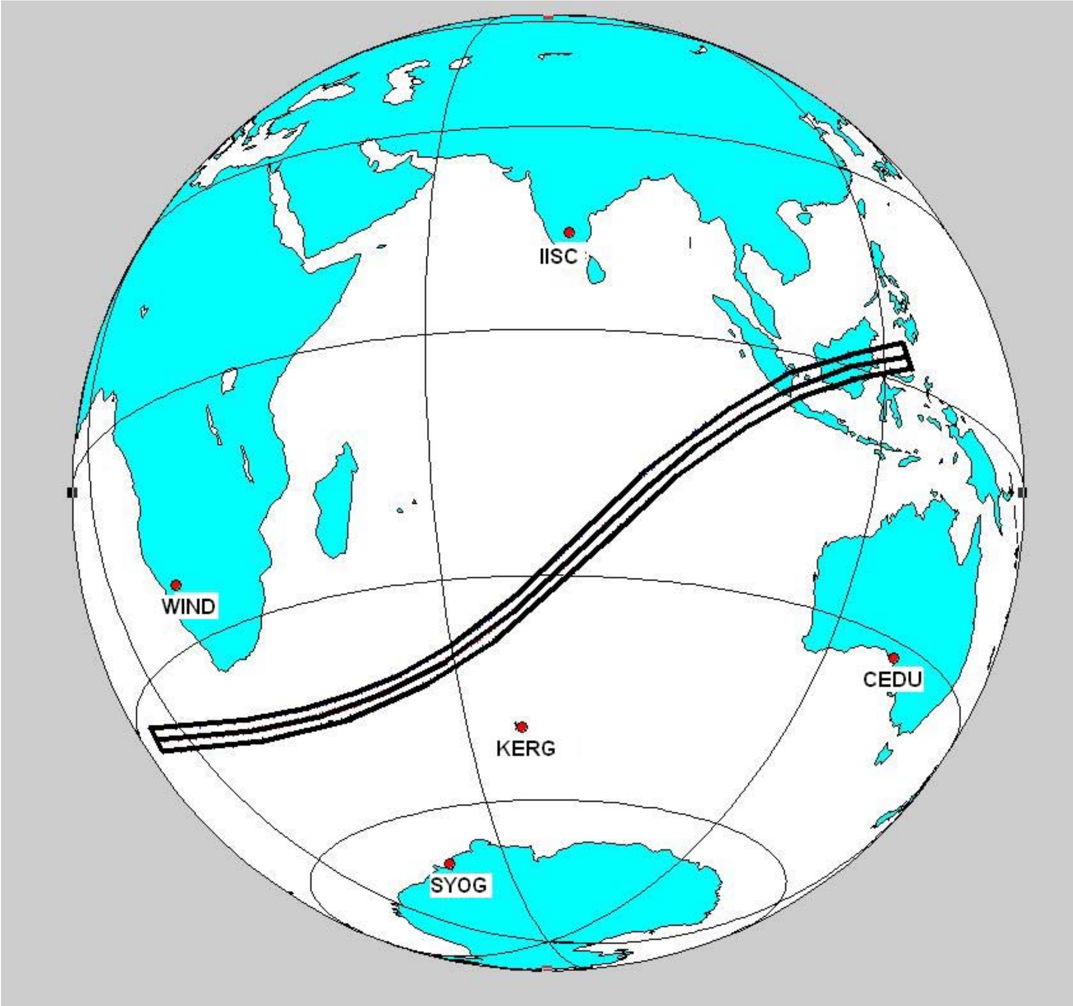


Figure 1. Orthogonal projection map during the annular solar eclipse of 26th January 2009
[http://www.hermit.org/Eclipse/2009-01-26/path.html].

TABLE 1. The geophysical condition of the solar eclipse at 5 stations
[http://eclipse.gsfc.nasa.gov/SEgoogle/SEgoogle2001/SE2009Jan26Agoogle.html]

Name of Stations	Abbr.	Country	Geo. Coordinate		Eclipse Mag.	1st Cont (UT)	Max. Ecl. (UT)	4th Cont (UT)
			Lat (deg)	*Lon (deg)*				
Syowa	SYOG	Antarctica	-69.01	39.58	0.314	06:04:15.8	07:01:00.3	07:59:07.2
Ceduna AU019	CEDU	Australia	-31.87	133.81	0.170	08:26:25.2	09:05:17.9	09:42:02.0
Kerguelen Islands	KERG	Australia	-49.35	70.26	0.624	06:05:50.1	07:35:10.1	09:02:11.2
Windhoek	WIND	Namibia	-22.57	17.09	0.413	05:01:42.5	06:04:03.5	07:16:45.2
Indian Institute of Science	IISC	India	13.02	77.57	0.107	09:03:25.7	09:46:35.4	10:26:25.1

international GNSS service (IGS) stations [http://sopac.ucsd.edu/]. The GPS observables are biased on instrumental delays; therefore it is necessary to remove the differential instrumental biases for accurate estimation of TEC [23]. The absolute TEC using observables may be obtained from differential time delay (P_1-P_2) or from differential phase advance (Φ_1- Φ_2). The TEC obtained from differential time delay gives the level of absolute TEC, but it is highly exposed to multipath effect, while the TEC attained from differential phase advances gives high precision TEC, but the level is unknown due to the initial offset called the ambiguity. Therefore, the level of TEC is adjusted to the TEC derived from the corresponding code difference for each satellite-receiver pair [20][25].

In this work, the TEC values were corrected from the receiver and satellite bias using data obtained from AIUB Data Center of Bern University in Switzerland (AIUB, 2009). The following details the method for calculating the ionospheric TEC using method described by [24].

A. *Ionospheric GPS TEC Calculation*

The following steps are used to calculate the absolute GPS TEC at the conjugate points:

(i) Calculation of the geometry-free combination (GFC) of dual frequency code and phase measurements of the dual frequency GPS receiver by using Equation 1 [12][24]:

$$P^s_r = P^s_{r,1} - P^s_{r,2}$$

$$\Phi^s_r = \Phi^s_{r,1} - \frac{f_1}{f_2}\Phi^s_{r,2} \qquad (1)$$

where $P^s_{r,1}$ and $P^s_{r,2}$ are the GPS pseudorange observables (in meter).

(ii) Calculation of the geometry-free linear combination of code and phase measurements as a function of TEC from Equation 2 [7][24]:

$$P^s_r = -0.105\,TEC^s_r + (Dg_r - Dg^s)$$
$$\Phi^s_r = -0.552\,TEC^s_r + N^s_r \qquad (2)$$

Where Dg^s and Dg_r are the satellite and receiver differential group delay and N^s_r is the ambiguity term in cycle.

(iii) Resolving of the ambiguity term by combining the geometry-free code with phase measurements for each satellite path using Equation 3 [24]:

$$P^s_r - \lambda_1\,\Phi^s_r = (Dg_r - Dg^s) - \lambda_1 N^s_r \qquad (3)$$

where λ_1 is the wavelength.

(iv) Determination of the equivalent VTEC for each satellite receiver path using Equation 4 :

$$VTEC^s_r = TEC^s_r \cos\chi \qquad (4)$$

where χ is the zenith angle of the line of sight at the sub-ionospheric point.

(v) The zenith angle of the line of sight at the sub-ionospheric point is calculated by using Equation [15]:

$$\chi = \arcsin\left(\frac{R}{R + h_m}\cos\theta\right) \qquad (5)$$

where Θ is the elevation angle, R is the mean radius of the earth (6371.137 km) and h_m is the height of subionospheric point which is assumed at 400 km above the earth's surface. In calculation the diurnal TEC curve, the GPS signals obtained from all satellites at maximum elevation angle is only extracted at a particular time.

IV. RESULT AND DISCUSSION

The ionospheric response during the annual solar eclipse on 26th January 2009 was investigate at 5 GPS stations locate under the solar eclipse shadow as shown in Figure 1. In the analysis, the GPS TEC measurements during the solar eclipse time at each IGS station were compared with the TEC measurements during same time on the day before and day after which are 25th and 27th January 2009 respectively. The GPS TEC measurements during the solar eclipse time were also compared with average four days quiet day TEC (QDTEC) on 21st, 22nd, 23rd and 24th January 2009 where during these days the planetary magnetic Kp index was ≤ 2. Figure 2 shows the GPS TEC variations during the solar eclipse period at 5 stations namely Syowa, Ceduna AU019, Kerguelen Islands, Windhoek and Indian Institute of Science station which is labeled as SYOG, CEDU, KERG, WIND and IISC respectively.

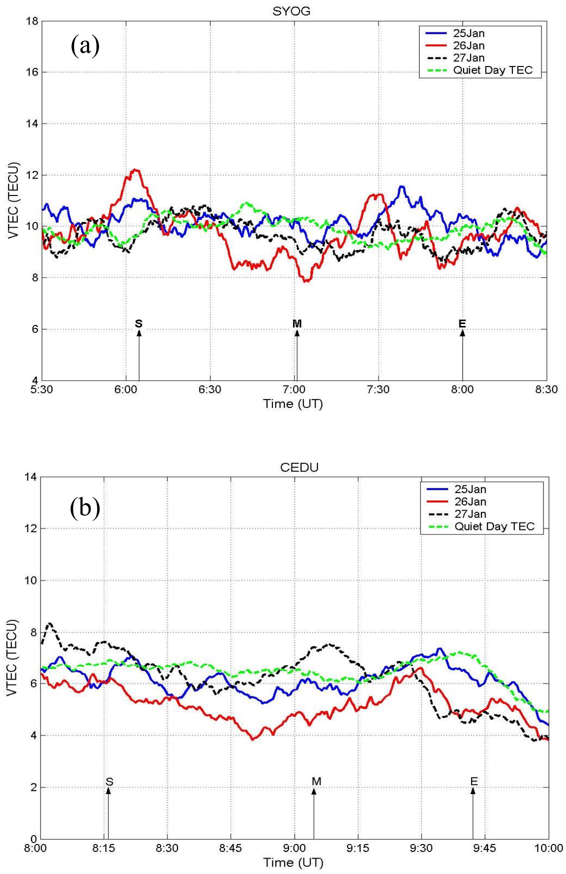
Fig. 2(a) show the TEC measurements at Syowa station (Eclipse magnitude is 0.314) during the solar eclipse on 26th January 2009, day before, day after and during quiet day TEC. The TEC measurements on 26th Jan 2009 were compared with the TEC measurements on 25th, 27th Jan 2009 and QDTEC to observe effects of the solar eclipse to the TEC variations at that particular station. A sharp TEC depletion was observed starting about 30 minutes before the maximum solar eclipse time particularly at 06:31 UT and continued until the end of solar eclipse at 08:00 UT. The maximum TEC depletion was seen at few minutes following the maximum solar eclipse time particularly at 07:05 UT. Comparison of TEC level during the eclipse time shows that the total TEC level during eclipse period decreased by about 6% and 0.49% with respect to TEC level on the days before and after eclipse. Meanwhile comparison between eclipse time on 26th January 2009 and during QDTEC show a decreased of about 3%. These values were calculated by comparing the total intensity ratio of TEC ($\sum$TEC) obtained during the observation window of the annual solar eclipse on 25th, 26th and 27th January 2009.After the end of eclipse period, the TEC gradually increase to the normal level.

Fig. 2(b) illustrates the TEC measurements at Ceduna AU019 station (Eclipse magnitude is 0.170). The comparison of the TEC variation shows that the TEC level at this station gradually decreased right after the started of eclipse and became more pronounced during the whole period of solar eclipse. Maximum TEC depletion was observed at 8:50 UT. Comparisons of TEC level during eclipse time show that the total TEC during the eclipse period decreased by about 16% and 17% with respect to TEC level on the days before and after eclipse. Meanwhile comparison between eclipse time on 26th January 2009 and during QDTEC show a decreased of about 19%.

The TEC observation at Kerguelen Islands station (Eclipse magnitude is 0.624) show TEC depletion of 0.8 and 1.0 TECU occurs at around 06:50 UT and 07:33 UT respectively. Maximum TEC depletion was observed at around 08:42 UT. Analysis of the total TEC measurements during three days (25th, 26th and 27th January 2009) at this station show that the total TEC during the eclipse period decreased by about 14% and 16% with respect to TEC level on the days before and after eclipse. But comparison of the TEC level during eclipse period show that the TEC level is 1% higher than TEC level during QDTEC.

At Windhoek station (Eclipse magnitude is 0.413), clear TEC depletion was seen during the whole solar eclipse period comparing with the TEC response on the day before and day after. At this station, the TEC depletion started following the solar eclipse onset and continued until after the end of the eclipse. The TEC depletion started at about 05:03 UT and reached its maximum values at 05:12 UT. After the end of eclipse, the TEC started to recover to the normal level. The TEC level during the eclipse day is lower than the days before and after the eclipse by 16.69% and 12.82% respectively. Comparison also shows that the TEC level during eclipse period is 11.71% lower than the TEC level during QDTEC.

The GPS TEC observations at Indian Institute of Science station (Eclipse magnitude is 0.107) show that the TEC level start to decreased right after the eclipse onset at about 09:05 UT before it reached its maximum value at 09:58 UT followed by sudden increased and decreased of the TEC level. Comparison of total TEC level during the eclipse period with the day before, day after and during QDTEC show that the TEC level on the day of eclipse was 18.58%, 10.2% and 11.96% lower than the day before, the day after and QDTEC respectively.



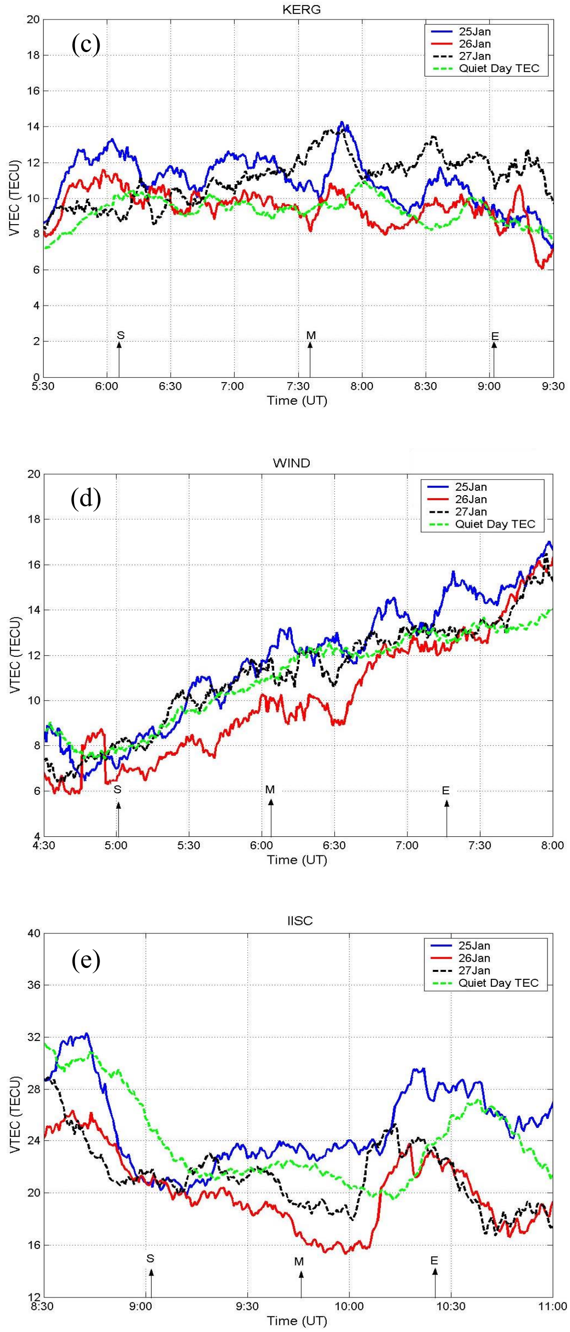


Figure 2. The GPS TEC measurements during 26th January 2009 solar eclipse at Syowa, Ceduna AU019, Kerguelen Islands, Windhoek and Indian Institute of Science stations (a) SYOG (EM:31.4%) (b) CEDU (EM:17.0%) (c) KERG (EM:62.4%) (d) WIND (EM:41.3%) (e) IISC (EM:10.7%).

Table 2 illustrates the TEC level during the period of eclipse. The comparison between the TEC level (as shown in Table 2) on the days 25th, 26th, 27th January 2009 and QDTEC show obvious TEC decreases occurrence on the day of eclipse compared with the day before, day after and QDTEC. The TEC level on the day of eclipse decreased in range between 0.4-20% with respect to the day before, day after and QDTEC.

TABLE 2. The total TEC level during the solar eclipse period at 5 stations

Station	∑ TEC (TECU)				Percentage of TEC depletion (%)		
	25th Jan	*26th Jan*	*27th Jan*	*QDTEC*	*With respect to 25th Jan*	*With respect to 27th Jan*	*With respect to QDTEC*
SYOG	2462.7	2319.4	2330.9	2394.7	5.82	0.49	3.15
CEDU	1483.7	1251.2	1504.2	1547.7	15.67	16.82	19.16
KERG	4349.5	3742.8	4444.0	3715.7	13.95	15.78	-0.73
WIND	3545.1	2953.6	3387.8	3345.2	16.67	12.82	11.71
IISC	4265.3	3473.0	3867.5	3944.6	18.58	10.20	11.96

Figure 3 illustrate the average TEC for the five selected station during eclipse on 26th January 2009 and QDTEC. The figure show that depletion in the TEC level occurs during the eclipse period on 26th January 2009 compared with the TEC level during QDTEC.

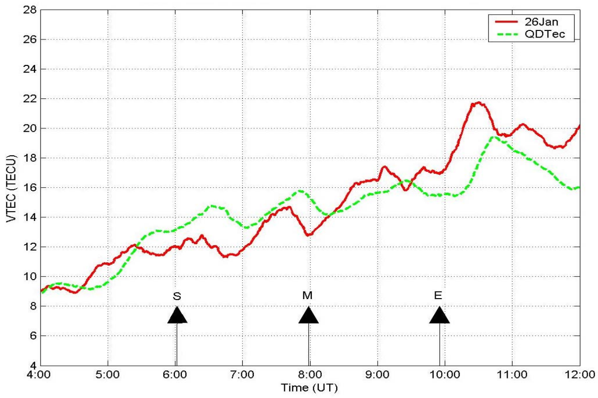


Figure 3. Comparison of the TEC level during eclipse period between 26th January 2009 and QDTEC

V. CONCLUSION

This paper examines the ionospheric behavior during the annular solar eclipse on 26th January 2009 over South Antarctica, India Ocean and Australia. The analysis was done by comparing the TEC level during the eclipse with respect the day before and day after the eclipse. The comparison also had been done by comparing the TEC level during the eclipse with the quiet day TEC (QDTEC) where the QDTEC is the average TEC value during 21st, 22nd, 23rd and 24th January 2009 where the value of the Dst index is ≤ 2. From the analysis, it can be shown that there is depletion in the TEC values from about 0.4 to 20% during the solar eclipse in the 26th January 2009.

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