

Use of GPS Signals to Study Total Electron Content of the Ionosphere during the Geomagnetic Storm on 22 September 1999.

E. Yizengaw and E. A. Essex

*Cooperative Research Center for Satellite Systems
Department of Physics, La Trobe University, Victoria 3086, Australia*

Abstract--The ionospheric storm evolution process was monitored during the September 22-24, 1999 magnetic storm over the Australian region, through measurements of the ionospheric total electron content (TEC) from five GPS stations. The spatial and temporal variations of the ionosphere were analysed as a time series of TEC maps. All the maps presented in this paper are 15-minute averages of TEC. Storm positive and negative effects on temporal and latitudinal changes in TEC were investigated. Possible error sources in GPS measurements such as satellite and receiver biases were removed. A comparison of storm-time behaviour of experimental TEC GPS and values derived from ionosonde measured f_oF_2 at a range of latitudes was made. Comparison of the experimental TEC GPS data with the TEC values derived from the International Reference Ionosphere model (IRI2000) was also undertaken

Index Terms-- f_oF_2 , GPS, TEC

I. INTRODUCTION

THE ionosphere is the name given to a layer or layers of ionized air, formed by UV radiation from the sun, in the atmosphere extending from almost 60 km above the surface of the earth to altitudes of 1000 km and more. Different regions of the ionosphere are produced by the interaction between different chemical species and different wavelengths of radiation from the sun. Since the ionosphere is a weakly ionized plasma, or gas, it exerts a great influence on the propagation of radio signals, such as GPS signal [1].

The different layers of the ionosphere have different impacts on the propagation of radio signals, on GPS signals in our case. The D layer and E layer have negligible effect at GPS frequencies. The normal F1 layer, combined with the E layer, can account for up to 10% of the ionospheric time delay encountered by GPS. The F2 layer is the most dense, and also has the highest variability, causing most of the potential effects on GPS receiving systems [1].

Since the ionosphere is a dispersive region of the Earth's atmosphere, in order to quantify the propagation effects on a radio wave travelling through the ionosphere, the refractive

index of the ionosphere must be specified. Appleton and Hartree have derived the refractive index of the ionosphere, n , and it can be reduced, as a function of electron density, N , to an accuracy of better than 1%, to the following [2], [3]:

$$n = 1 - \frac{X}{2} = 1 - \frac{40.3N}{f^2} \quad (1)$$

Knowing the refractive index of the ionosphere, it is possible to derive the total number of electrons in the ionosphere, the parameter of the ionosphere, which produce most of the effects on GPS signal, along the GPS signal trajectory from each satellite to the observer. This integrated number of electrons is commonly called the Total Electron Content (TEC). TEC is expressed as the number of electrons in a vertical column having a one square meter cross section, and extending all the way from the GPS satellite to receiver, where $1\text{TECU} = 1 \times 10^{16} \text{el.m}^{-2}$

II. GPS DATA AND METHODS

The data used for this study were recorded during the period 18-27 September 1999 at four Australian Regional GPS Network (ARGN) stations, when the magnetometer data station recorded an intensive geomagnetic storm. The four stations are; Townsville (TOW) (19.6°S, 146.8°E), Tidbinbilla (TID) (35.4°S, 148.9°E), Hobart (HOB) (42.8°S, 147.4°E), Macquarie Island (MAC) (54.5°S, 158.9°E). Data from the International GPS Network (IGN) station, McMurdo (MCM) (77.8°S, 166.7°E) were also used in the study. Here after the abbreviated form of the stations is used.

ARGN is operated by the Australian Surveying and Land Information Group (AUSLIG). All the five stations are equipped with GPS dual frequency receivers recording GPS data with a sampling rate of 30 s. Both dual-frequency phase and code pseudorange observations have been used to derive the ionospheric TEC.

All ionospheric latitudes and longitudes quoted in the present study refer to the latitudes and longitudes of the ionospheric point, respectively. Ionospheric point is the point of intersection of the GPS ray path with the ionospheric shell [1], [2], [4], [5].

Corresponding Author. Tel.: +61 3 9479 2640; Fax: +61 3 9479 1552.
E-mail address: E.Yizengaw@latrobe.edu.au (E. Yizengaw)

A. Differential time delay (or range error) determination of TEC

GPS signal time delay means, that the signals traversing the ionosphere will arrive slightly later than they would have if they were travelling through a vacuum. By measuring the group path delay independently at the two, widely spaced GPS frequencies, namely $L_1 = f_1 = 1.57542 \text{ GHz}$, and, $L_2 = f_2 = 1.2276 \text{ GHz}$, the TEC along the path from satellite to receiver, Slant TEC (STEC), can be calculated using the following algorithm ([1], [4], [5]).

$$\begin{aligned} STEC &= \int_0^s N dr = \left(\frac{f_2^2}{f_1^2 - f_2^2} \right) \frac{2f_1^2}{K} \Delta P_{1,2} \\ &= 9.509E16 \Delta P_{1,2} = 2.852E25 \delta \Delta t \end{aligned} \quad (2)$$

where $\delta \Delta t$ is differential time delay in second, $\Delta P_{1,2} = P_1 - P_2$ is differential range error in meters. Therefore, one nanosecond of differential time delay tells us there is a $2.852 \times 10^{16} \text{ e/m}^2 = 2.852 \text{ TECU}$ along the signal trajectory.

B. Differential phase advance determination of TEC

GPS signal carrier phase advance means that signals traversing the ionosphere will arrive slightly earlier than they would have if they were travelling through a vacuum, which is exactly the same amount of time that the signals are delayed. Similarly the differential phase advance measurement related to STEC by [1], [4], [5]:

$$\begin{aligned} STEC &= \int_0^s N dr = \left(\frac{f_2^2}{f_1^2 - f_2^2} \right) \frac{2f_1^2}{K} \Delta L_{1,2} \\ &= 9.509E16 \Delta L_{1,2} \end{aligned} \quad (3)$$

where $\Delta L_{1,2} = L_1 - L_2$ is differential phase advance in cycles.

In both cases the STEC can be converted to vertical TEC as follow:

$$TEC = \text{slant TEC} \times \cos \chi_m \quad (4)$$

where χ_m is the angle of incidence at 400 km altitude of a GPS ray from satellite to ground receiver. $\cos \chi_m$, an obliquity factor, is defined as [5]:

$$\cos \chi_m = \sqrt{1 - \left(\frac{h_{sp} \cos \varepsilon}{h_{sp} + R_E} \right)^2} \quad (5)$$

where R_E is the radius of the Earth, ε is the elevation angle, h_{sp} is the height of the ionospheric point, which is usually assumed to be 400 km.

High precision TEC values can be obtained from the carrier phase data, but it contains an initial offset called the ambiguity term. To get absolute TEC values, the time delay measurements are used to determine the ambiguity term. By combining the GPS carrier phase with the code measurements for the same satellite pass, the absolute TEC value can be obtained with high precision [6], [1]. To eliminate the multipath effects on GPS data, we use only the TEC values for

satellites with an elevation angle greater than 20° . In addition to multipath effects, the accuracy of TEC measurements using GPS satellites is limited by two potential error sources. The measured time delay may contain "offsets" introduced by biases (instrumental time delay) in the satellite transmission system and/or the ground based receiver. The satellite biases are offsets between the time instants of transmission from each GPS satellite of similar signals at the two L-band frequencies. An offset is the time instant of the signal transmission at L_2 minus at L_1 . Receiver biases are offsets introduced by the receiving hardware or software [1], [7]. All the TEC values used for the present study have been corrected from biases using satellite and receiver bias values obtained from the data center of Bern University, Switzerland. The methods by which the instrument biases can be removed from the measured TEC values have been explained in detail in [1], [7].

III. TEC FLUCTUATION DURING THE STORM TIME

To investigate the ionospheric irregularities at mid and high latitudes, this paper presents result from the more intensively disturbed days, September 22nd - 24th or, according to day of the year, from day 265-267, data. The storm sudden commencement (SSC) time was 1222 UT or 2222 local time (LT) on September 22, 1999 (LT = UT + 10). Fig. 1 shows the Kp and Dst index for the period 20-26 September 1999. The maximum Kp index reaches 8 late on September 22. Fig. 2 shows the diurnal variation of TEC at all stations. In the first storm day the enhancement of TEC with respect to the background level or quiet days TEC (average of six quiet days) values (storm positive effect in TEC) took place in pre noon local time, September 23. The ionospheric TEC response for the SSC on September 22 was different for different latitude observations. Following the SSC on September 22, the TEC response was positive at high latitudes. About 80% and 130% increases relative to the quiet days TEC values have been recorded around 1000 LT on September 23 at MCM and MAC latitude region, respectively. The vertical broken line in fig. 2 & 3 depicts the SSC time. Note also that QDAY in fig. 2 stands for quiet days.

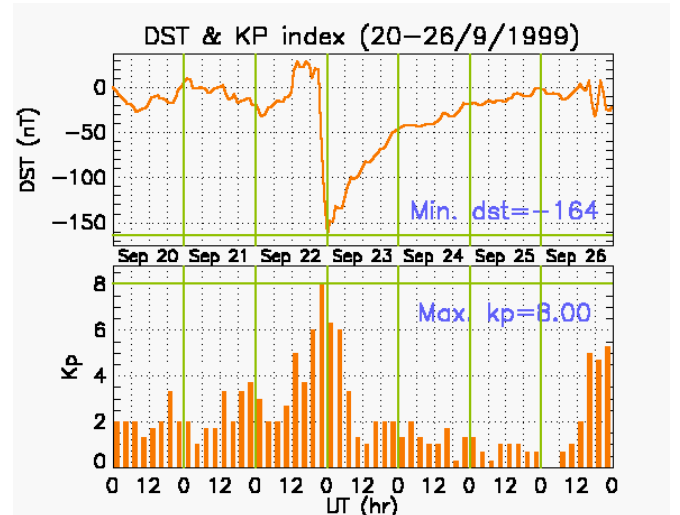


Fig 1. Dst and Kp changes during September 20 - 26, 1999. (LT = UT + 10)

Unlike the high latitudes situation, at the mid latitude region (HOB) a long time TEC depletion (negative response), about 50% decrease, started in the early morning (0800 LT) on September 23 and extended until noon local time (1400 LT). This mid latitude negative response, about 30% decrease, appeared at TID after 1-2 hr later from HOB negative response as shown in Fig. 3 & 4. Unlike the mid latitude regions, on September 23 in between 0800 and 1200 local time, the storm positive effect was more pronounced at high latitude regions as shown in fig 3 & 4. This may be due to the energetic auroral particle precipitation induced by the sudden solar wind collision with the Earth's atmosphere [8], [9]. Usually during quiet periods of time the daytime peak of TEC occurs around noon and post noon local time. However, on September 23 at MAC, the TEC maximum peak was observed during prenoon local time, which indicates about 2-3 hr time shift effect of the storm.

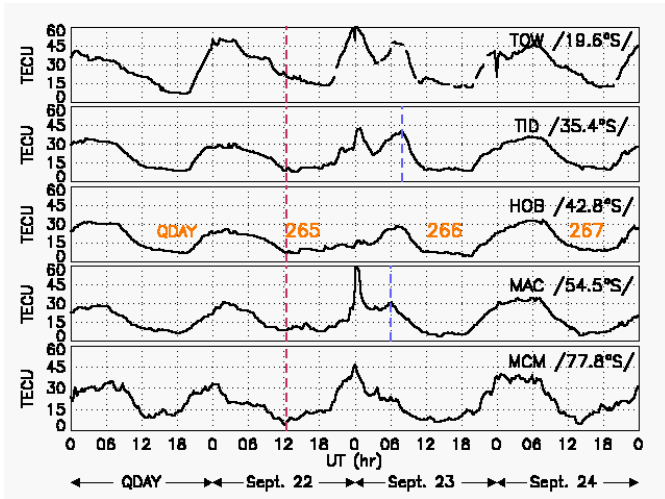


Fig. 2. Temporal variation of TEC at different latitudes during quiet days and September 22- 24, 1999. The dotted red line, which passes through all stations, indicates SSC. (LT = UT + 10)

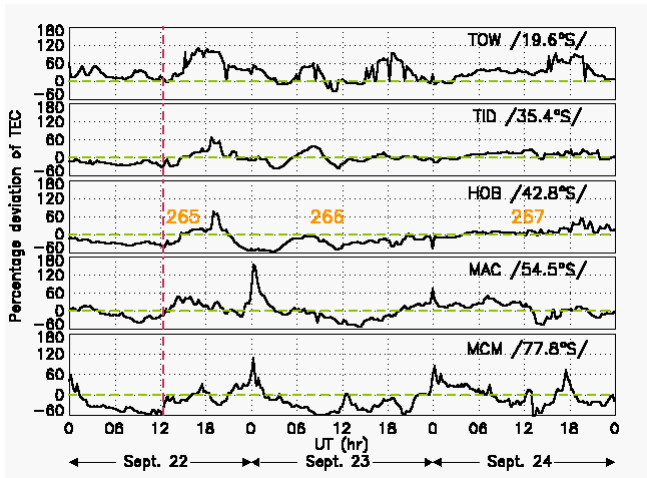


Fig. 3. Temporal profile of percentage deviation of storm time TEC relative to the quiet time, during September 22-24, 1999 at different latitude. Dotted red line indicates SSC.

The aforementioned mid-latitude TEC depletion was heading equatorward. Changes of the ionospheric composition due to heating of the ionosphere in high latitude regions during geomagnetic disturbances may cause this equatorward storm negative effect. Because the heating in high latitude regions induces its own circulation, which, at F₂ ionospheric layer heights, tends to bring the altered air composition equatorward, leading to depleted TEC at mid and low latitude regions [10].

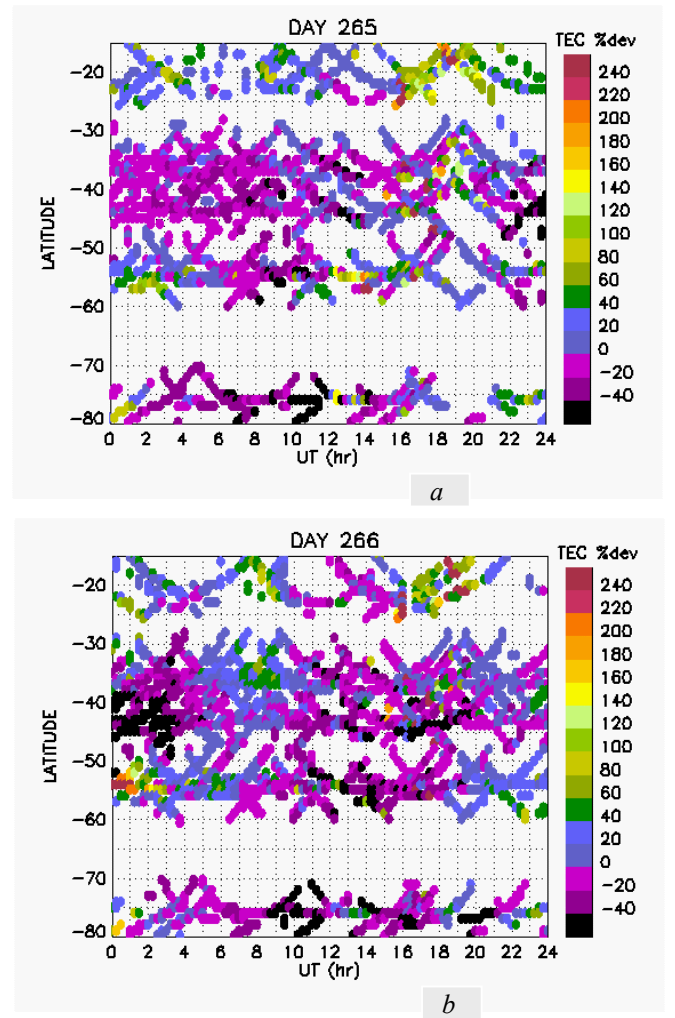


Fig. 4. Percentage deviation of TEC map of storm days relative to quiet days on (a) September 22 (day 265) and (b) September 23 (day 266), 1999

IV. DISCUSSION AND CONCLUSION

During the main phase of the storm, at 0700-1000 LT on September 23, its negative effect on TEC was more pronounced at HOB and lasted about 8-9 hours as shown in Fig. 3, 4, 5b & 5c. In addition to the negative effect, a daytime (0900-1400 LT) trough has been observed at HOB on

September 23 (see Fig. 5b, 5c & 6b). This depletion has been explained in the previous section. This equatorward travelling

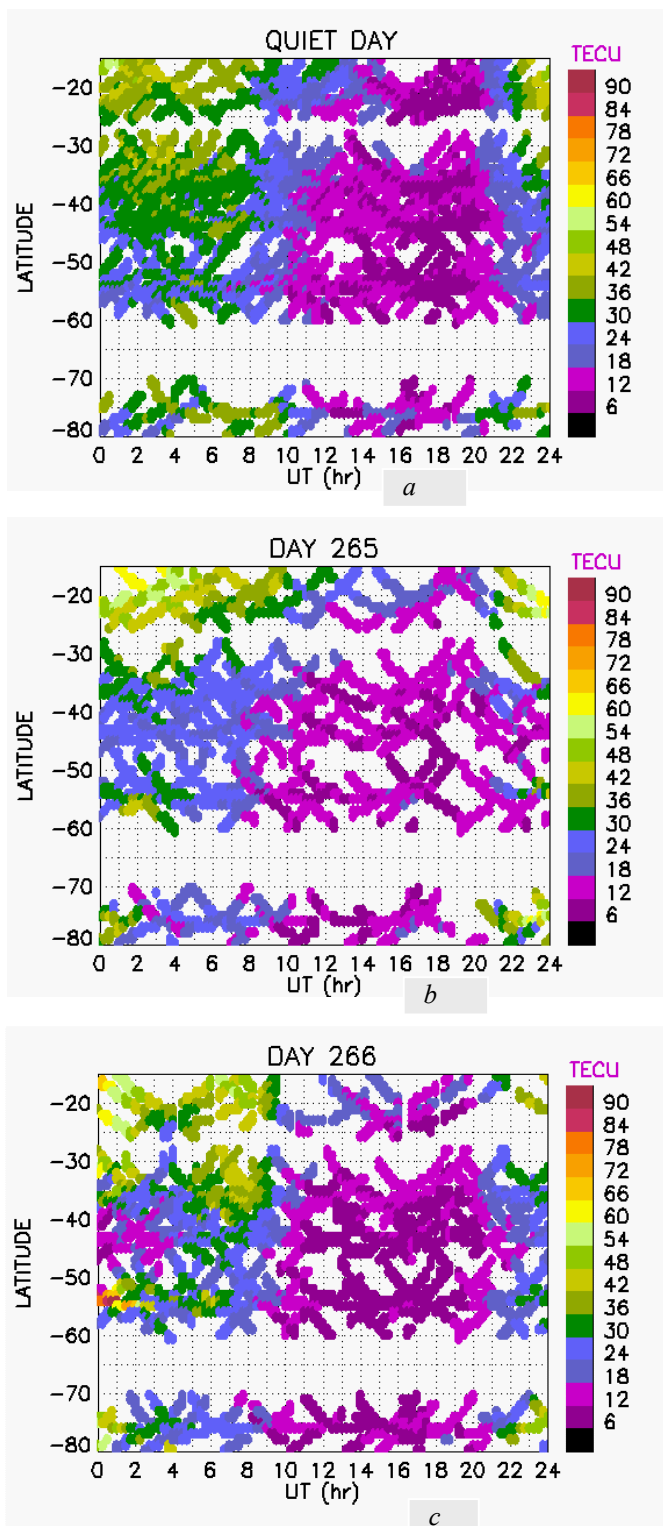


Fig. 5. Temporal TEC maps during (a) quiet days (six quiet days average TEC values), (b) the first day of storm (September 22, 1999) and (c) the second day of the storm (September 23, 1999). (LT = UT + 10).

trough is more clearly seen by observing the individual

satellite passes (see Fig. 7b). The passes of the four individual satellites' (PRN 4, 5, 6 and 24) clearly demonstrate that the ionospheric trough has been observed at HOB as compared with their quiet days individual passes (Fig. 7a).

Attention shall be paid to the time shift of daytime TEC maximum when going from high to lower latitude regions on September 23. Comparing the temporal TEC profiles at latitudes MAC and TID, it can be seen that the secondary peak TEC maximum at MAC appeared at 1600LT, whereas about 2 hours later, the TEC secondary peak appeared at TID as indicated by the blue broken line in Fig. 2. This may be due to the propagation delay of an atmospheric/ionospheric disturbance moving from high to low latitude [9], [10], [11].

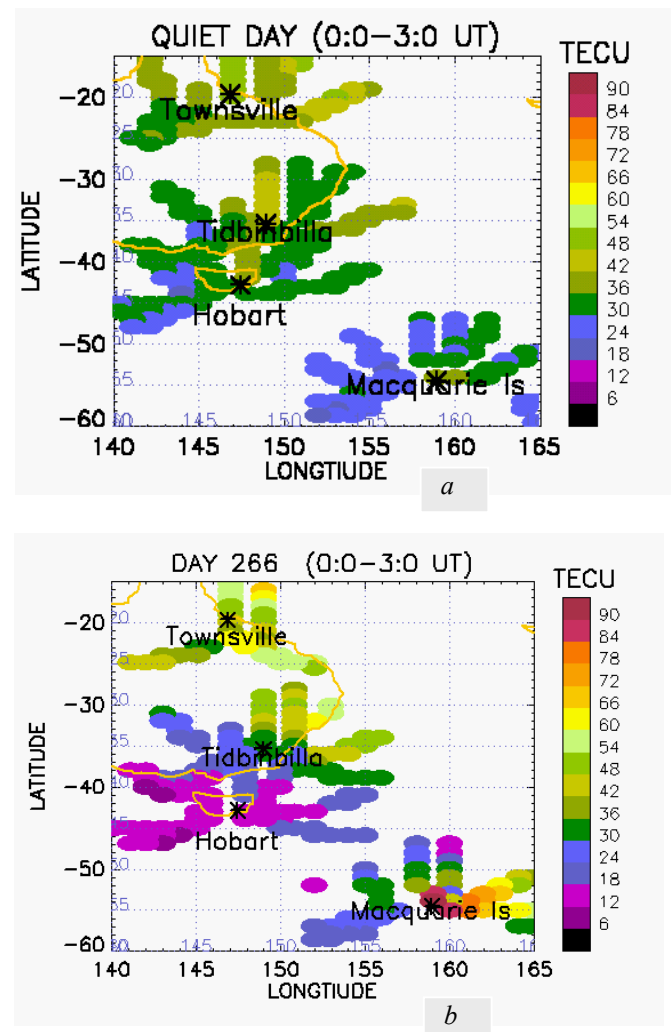


Fig. 6. TEC map in geographic coordinates for noon sector during (a) quiet days and (b) September 23, 1999. (LT = UT + 10)

On September 23 the temporal variation of TEC, Fig. 2, at TID and TOW, shows the simultaneous double peak TEC enhancement. These peaks may be correlated with a time varying electric field, which may penetrate to lower latitudes before the ring current has developed [8], [9]. The eastward or westward magnetospheric origin electric fields cause an upward or downward $\mathbf{E} \times \mathbf{B}$ plasma drift, respectively. The

$E \times B$ drift lifts up the equatorial plasma on the day side, which leads to an increase in TEC, and pushes the plasma down on the night side, which in turn causes the depletion of TEC [8], [9], [12]. The occurrence of the secondary peak observed at both latitudes may indicate the equatorial region role of magnetosphere origin electric field [9], [12]. Hence, during severe ionospheric disturbances, such as the September 22, 1999 storm, an increase of y-component electric field with the corresponding increase of the downward drift may occur, which causes TEC to be depleted [9]. This might be the case for the TEC depletion at 1300 LT on September 23 at low and mid-latitude regions (TOW and TID). Alternatively a decrease in the y-component and thus decrease in the downward drift may enhance the equatorial region TEC and lead to the creation of the secondary peak [9], [10]. All these, especially the double peak occurrence at TID, indicate the magnetosphere origin electric field can have an effect down to mid-latitude regions

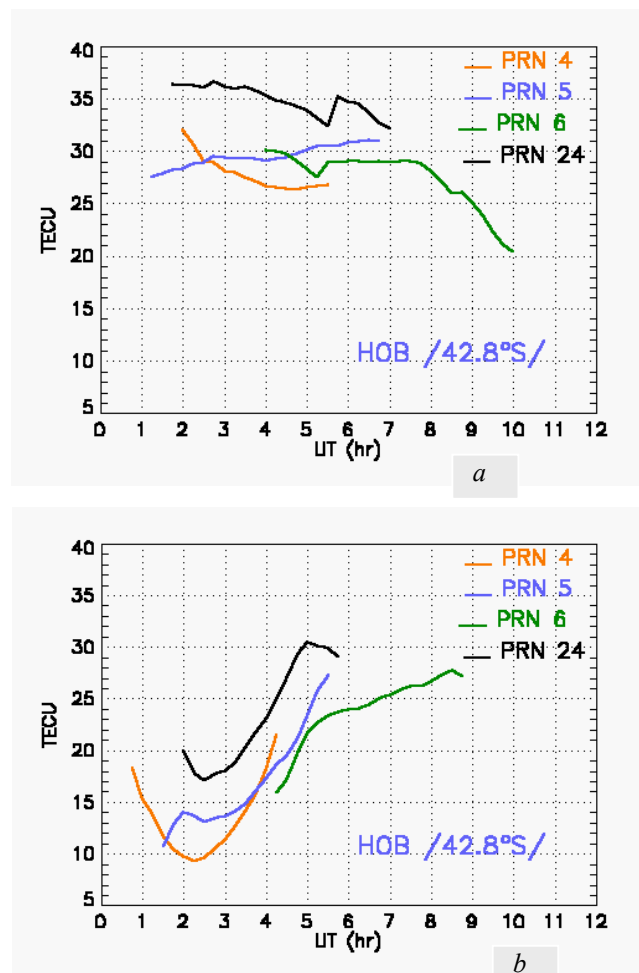


Fig. 7. Diurnal TEC change along individual satellite passes over Hobart during (a) quiet days and (b) September 23, 1999.

Fig. 8 shows a comparison of experimental GPS TEC data with TEC derived from ionosonde data and from one ionospheric model, namely the international reference

ionosphere model (IRI2000) [13]. The ionosonde data, used for this study, was recorded at the same region where GPS data have been recorded, i.e., HOB, TOW and MAC. Using a first approximate uniform slab thickness of 300km, the TEC was derived from ionosonde f_oF_2 data [7].

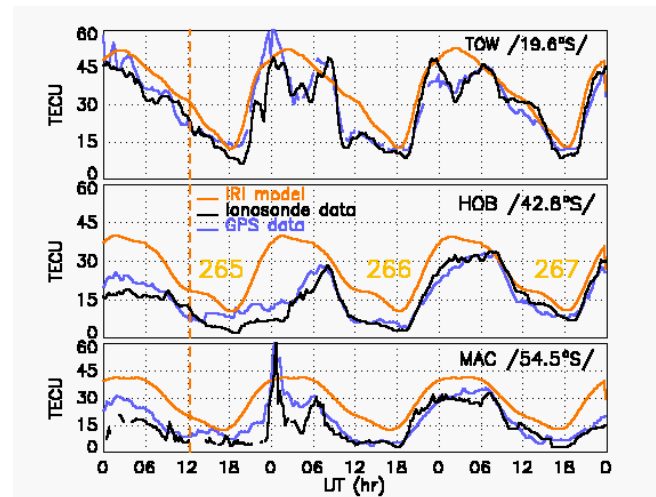


Fig. 8. Diurnal TEC values from experimental GPS measurements (blue) are compared with TEC derived from IRI2000 model (red) and ionosonde f_oF_2 data (black).

On the whole the reasonable correlation, with correlation coefficient 0.833 , 0.917 , and 0.773 at TOW, HOB and MAC, respectively, between the GPS and ionosonde data has been observed. The diurnal behaviour of the GPS, IRI2000 and ionosonde derived TEC were similar except at HOB, where maximum TEC value for IRI2000 occurred a few hours earlier than the GPS and ionosonde values, more significantly on the second day of the storm (September 23, 1999). This may be due to the IRI model gives the monthly average value of TEC

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