22. GPS AND TOPEX MID-LATITUDE TROUGH OBSERVATIONS IN THE SOUTHERN HEMISPHERE AT LOW SUNSPOT NUMBERS

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Abstract

For the low sunspot number period of February 1995 to February 1996, the southern hemisphere mid-latitude trough has been studied using the Global Positioning System (GPS) and TOPEX satellite data. A complete procedure was developed for each technique to reduce the raw satellite data to ionospheric Total Electron Content (TEC) values. The GPS data from the ground stations at Tidbinbilla (35.38°S; 148.97°E), Hobart (42.80°S; 147.43°E) and Macquarie Island (54.50°S; 158.94°E) were plotted in various ways to observe variations in trough characteristics that were related to the current magnetic activity, including magnetic storms. The GPS results were supplemented with the TOPEX data, which were also used to establish diurnal and seasonal trends in the Australian region. The feature of initial build-up of ionisation associated with the development of the trough was also investigated. This feature was compared to observations made previously by other researchers utilising different satellite techniques at Macquarie Island. The effects of auroral activity and magnetic storms on GPS recordings and trough occurrence, respectively, were also investigated. The theoretical TEC generated by PIM 1.4, a complex Parameterised Ionospheric Model (Daniell *et al.*, 1995), was compared directly to the GPS TEC.

22.1 Introduction

22.1.1 The mid-latitude trough

The 'main trough' or 'mid-latitude trough' was first reported by Muldrew (1965) and Sharp (1966). It designates an electron depletion zone aligned in the magnetic east-west direction in the nighttime F_2 region of both hemispheres. The trough is located at the magnetic shell parameter L of 4 along the equatorward side of the auroral oval, at an invariant latitude L range of 60°–65° (Taylor, 1973). The trough is associated with two gradients, one equatorward and the other poleward, which define its basic shape. Its average width is around 5°, but the trough can be

up to 10° wide and the factor of electron reduction is between 5 and 10, depending upon the magnetic activity (Schunk *et al.*, 1976). The trough itself terminates the mid-latitude ionosphere and is regarded as a boundary between the mid- and high-latitude regions (Thomas and Dufour, 1965) and as a marker of the plasmapause (Rycroft and Burnell, 1970). The trough is produced by normal F-region processes such as plasma convection, ion production and ion loss. The larger offset between the southern geographic and geomagnetic poles creates hemispherical differences in the Earth's polar environment and therefore there is a marked difference between the northern and southern hemisphere troughs (Fuller-Rowell *et al.*, 1987). Mallis (1989) and Mallis and Essex (1993) investigated the unique characteristics of the southern mid-latitude trough and established diurnal and seasonal trends, at high sunspot numbers. Accordingly, the trough is a persistent feature of the southern ionosphere, appearing in both the daytime and night-time sectors. It is more clearly defined at daytime, regardless of seasons. The narrower and deeper night-time trough lasts for longer periods of time, even after midnight. The night-time trough was observed more frequently and better developed in the seasons of summer and vernal equinox, than in any other season of the year, making up the highest frequency of occurrence and greatest prominence. These features became increasingly moderate through the autumnal equinox toward winter.

22.1.2 Aim

The principal aim of this project was to study the main characteristics of the southern hemisphere mid-latitude trough and the structure of the ionisation at the time of trough occurrence at low sunspot numbers, by utilising two independent satellite techniques, namely GPS and TOPEX. The total electron content values obtained from raw satellite data were used to identify the location, the time and rate of development and the spatial configuration of the trough. The information collected was used to establish diurnal, seasonal and magnetic activity related trends.

22.1.3 Study area

This study makes use of GPS measurements recorded from a small number of receiver stations forming a longitudinal chain across the mid-latitude Australian continent to the high-latitude sub-Antarctic region, in order to derive land-based total electron content values (see Figure 1(a)). The receiver stations are situated at the locations of Tidbinbilla, Hobart and Macquarie Island. For the comparison of results of the different techniques, long and continuous TOPEX passes were selected from the Australian sector of the Pacific Ocean, situated close to the east coast section of the Australian GPS receiver network (see Figure 1(b)).

22.1.4 Database

The GPS database was established by collecting RINEX observational and TEC data files through the Internet for up to seven days, centred on the Priority Regular World Day of each month, for a 13-month period extending between February 1995 and February 1996 inclusive. The GPS database was augmented with the extensive collection of TOPEX data,

stored on CD-ROM's and each containing two complete repeating cycles, covering the same period of time.
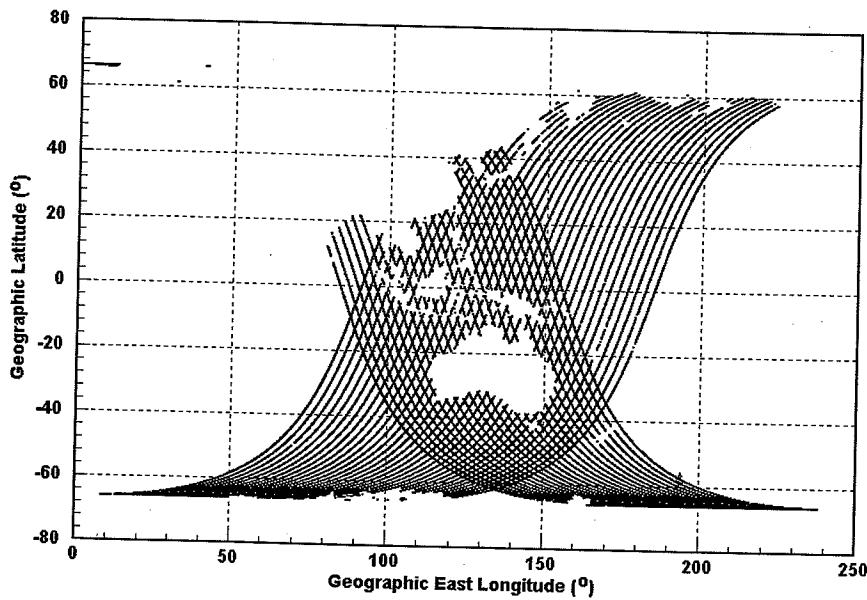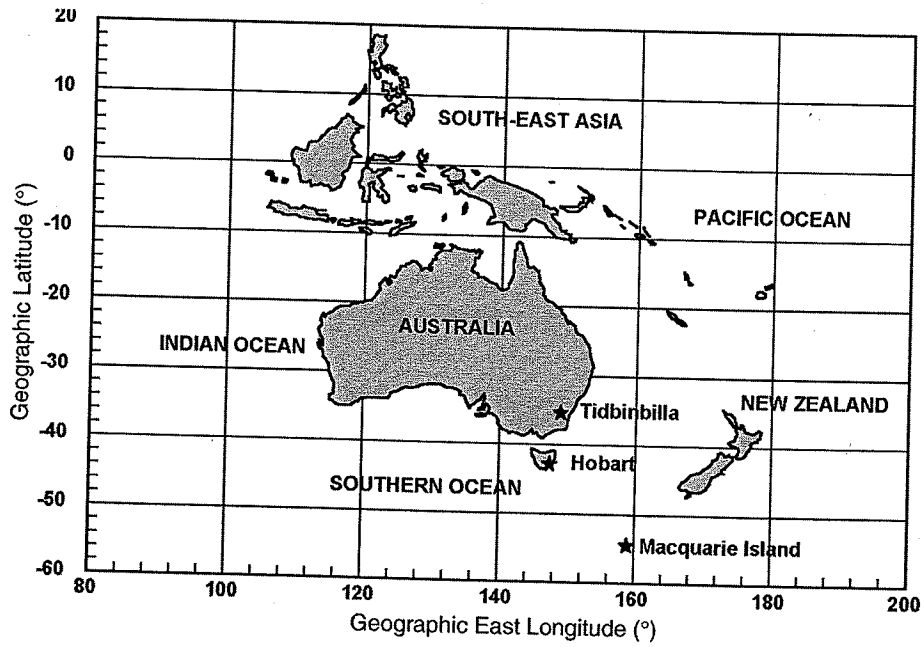

Figure 1. (a) The map of the GPS study area illustrates the location of the dual-frequency receiver sites in the grid of geographic co-ordinates. (b) The ground tracks of the TOPEX/Poseidon satellite define the TOPEX study area over the oceans in the Australian region.

22.2 Experimental and theoretical considerations

The dual-frequency GPS users take advantage of two of the ionospheric effects occurring on modulated L-band radio signals propagating to Earth. One is the absolute differential time delay ($\delta\Delta T$) measured between the two carriers (in nanoseconds), which allows one to compute the value of differential group path delay ($\delta\Delta P'$ in meters). The other is the relative differential carrier phase advance ($\delta\Delta f$), recorded with respect to the lower frequency (in cycles). The combination of $\delta\Delta P'$ and $\delta\Delta f$ gives the slant GPS TEC (see Equation 1()) after the magnitude of the baseline, i.e. the offset between the two data curves (see Figure 2), was established (Klobuchar, 1996).

$$\text{slant GPS TEC} = \int_0^S N\,ds = \frac{2cf_2}{K}\left(\frac{f_1^2}{f_1^2 - f_2^2}\right)\delta\Delta\phi + \text{baseline} \qquad (1)$$

where: $c = 2.997 \times 10^8$ m s^{-1}, $K = 80.62$ m^3 s^{-2}, $f_1 = 1.57542$ GHz and $f_2 = 1.22760$ GHz.

A vertical content can be computed if the orbital elements of the satellite are known. Since the orbital height of the satellite (20 183 km) is in the range of the plasmasphere, the vertical content obtained is the sum of ionospheric (ITEC) and protonospheric (PTEC) components:

$$\text{vertical GPS TEC} = \text{slant GPS TEC} * \overline{\cos\chi} = \text{ITEC} + \text{PTEC} \qquad (2)$$

where: $\overline{\cos\chi}$ = mean value of $\cos\chi$ at the median height of the ionosphere along the integration path.
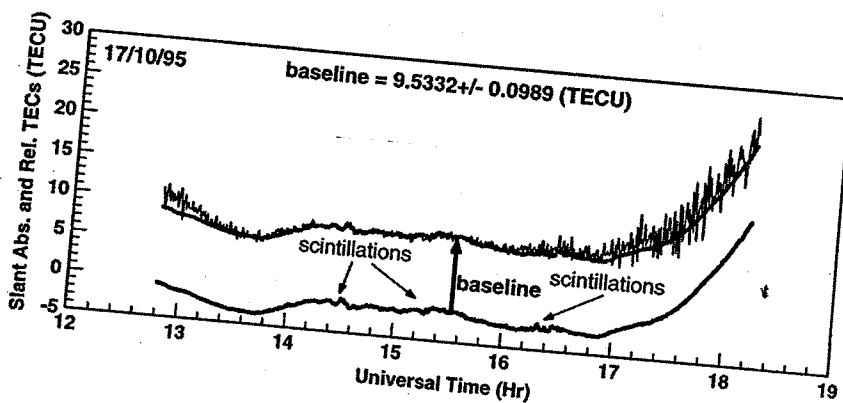
χ = zenith angle of the ray.

Figure 2. The Macquarie Island GPS plot shows that the group path and carrier phase measurements give TEC values, which represent a less accurate absolute scale (top curve) and a more accurate relative scale (bottom curve), respectively. The concept of baseline is also shown. The scintillations of the carrier phase signal, as a response to auroral disturbances, are also indicated.

310

The ionospheric height correction ($\Delta R_{ionosphere}$) (see Equation (3)), made by the on-board radar of the TOPEX/Poseidon satellite taking vertical sea height measurements at Ku-band and C-band frequencies, gives unambiguous TEC measurements (Imel, 1994).

$$\Delta R_{ionosphere} = -\frac{1}{2}\frac{K}{f^2} \int_0^{hs} N dh \tag{3}$$

where: f = 13.65 GHz.

Since the altimeter operates in the nadir direction and the orbital height (1336 km) of the satellite is in the topside F_2 region, a vertical ionospheric TEC can be obtained directly:

$$TOPEX\ TEC = \frac{\Delta R_{ionosphere} f^2}{-403.1} = ITEC \tag{4}$$

where: TOPEX TEC is in TECU, $\Delta R_{ionosphere}$ is in mm and f is in GHz.

22.3 Experimental results and discussion

As the trough is a structure not only in space but time, as well, its main characteristics will be discussed and illustrated by vernal equinox GPS data, plotted in time and geographic co-ordinates. The GPS findings will be compared with the TOPEX results. As Figure 3(a) shows, on 20 September 1995 the trough was detected from Macquarie Island at around 1500 LT and remained visible for several hours. The main features of the trough such as the initial build-up of ionisation and the equatorward wall are shown in Figures 3(a) and (b). Here the satellite PRN 7 detected the equatorward wall twice, since the satellite turned back to lower latitudes after reaching its maximum position at the station. The equatorward and poleward walls and the trough minimum are clearly visible in Figures 3(a) and (c). Here the satellite PRN 6 travelled straight through the trough minimum and later turned south of Macquarie Island. Therefore it detected the equatorward and poleward walls, and a small section of the auroral oval, indicated by the fine-scale TEC fluctuations. The signatures of auroral activity appear as scintillations on the carrier phase data (see Figure 2) and indicate that the satellite beam travelled through the auroral oval. Observations from the low sunspot number GPS data revealed that the initial build-up of ionisation is a distinctive and regular feature developing on the equatorward wall of the trough. It can be defined as a sudden increase in TEC from normal to anomalously high values that peak and drop back at the edge of the electron depletion. According to Foster (1993), fresh co-rotating ionospheric plasma along the equatorward edge of the two-cell convection pattern produces such increases. The TOPEX trough observations indicated also the initial build-up of ionisation and therefore confirmed the GPS observations. Two of those TOPEX observations are shown in Figures 4(a) and (b). The TOPEX TEC is plotted against the geographic latitude and shows a vernal equinox trough on 28 September 1995 and 4 October 1995, at around 15.7 LT.
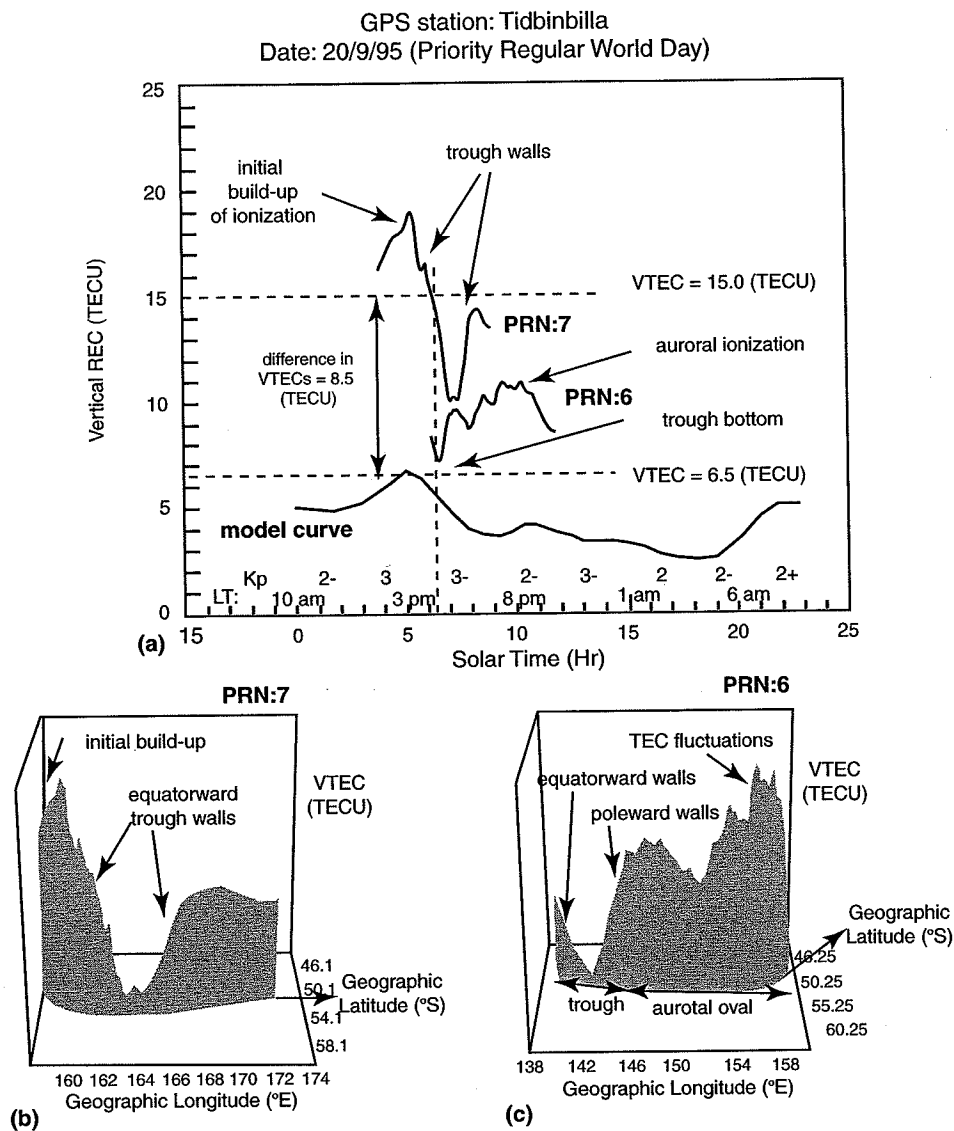
GPS station: Tidbinbilla
Date: 20/9/95 (Priority Regular World Day)

Figure 3. *(a) The 2-dimensional daily and (b and c) 3-dimensional spatial GPS TEC plots depict the major characteristics of a daytime vernal equinox trough. The direction of the satellite pass is also shown (–>). (a) A PIM generated model TEC curve is displayed for comparing theoretical and experimental results. (a, b and c) The satellites are designated by their PRN (Pseudo Random Noise) numbers.*
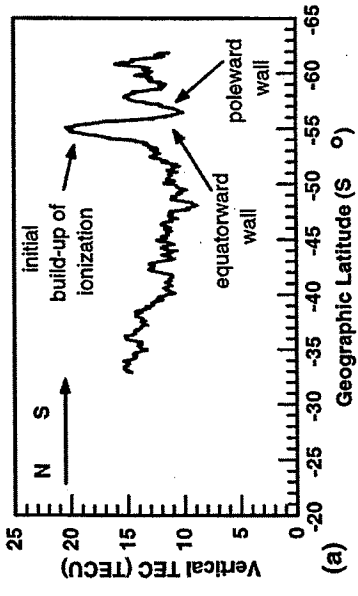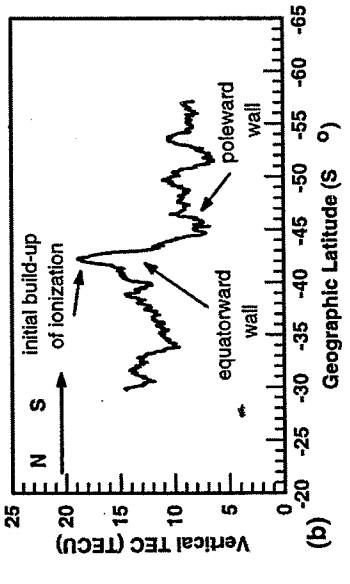
312
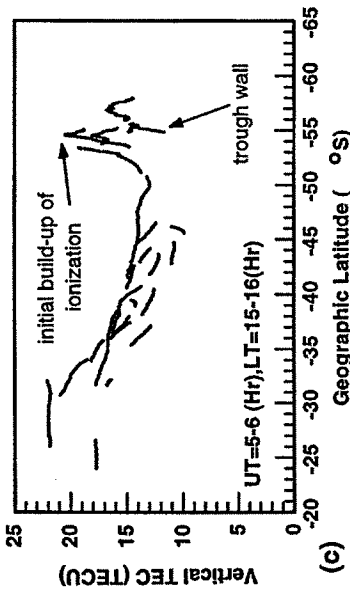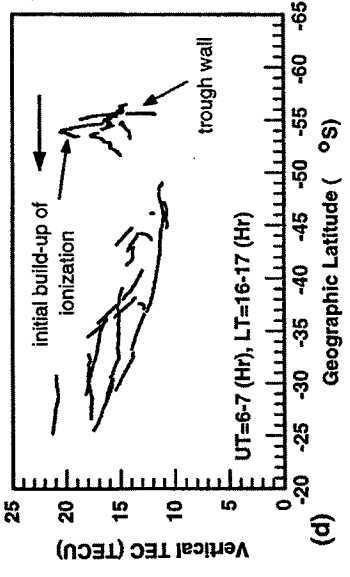
Figure 4. (*a and b*) *The TOPEX maps depict a daytime vernal equinox trough. The direction of the satellite pass is also shown (→). (c and d) The hourly GPS maps show the diurnal latitudinal movement of a daytime vernal equinox trough.*
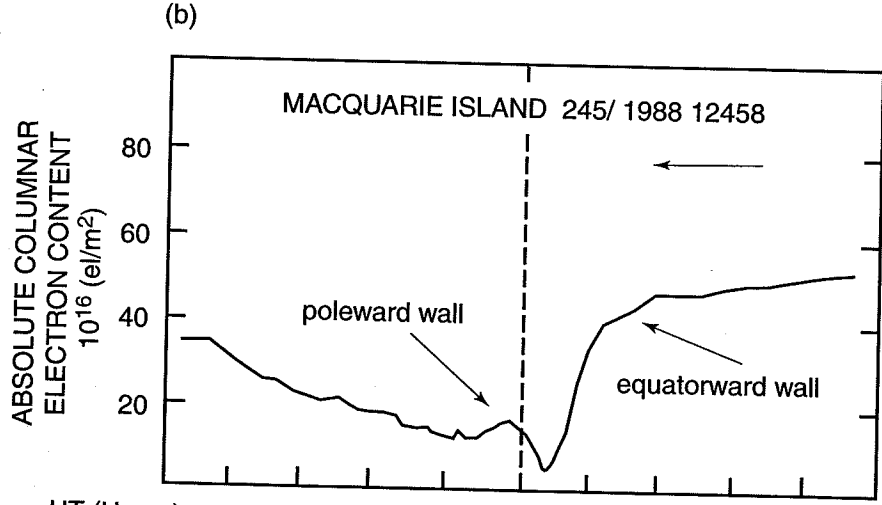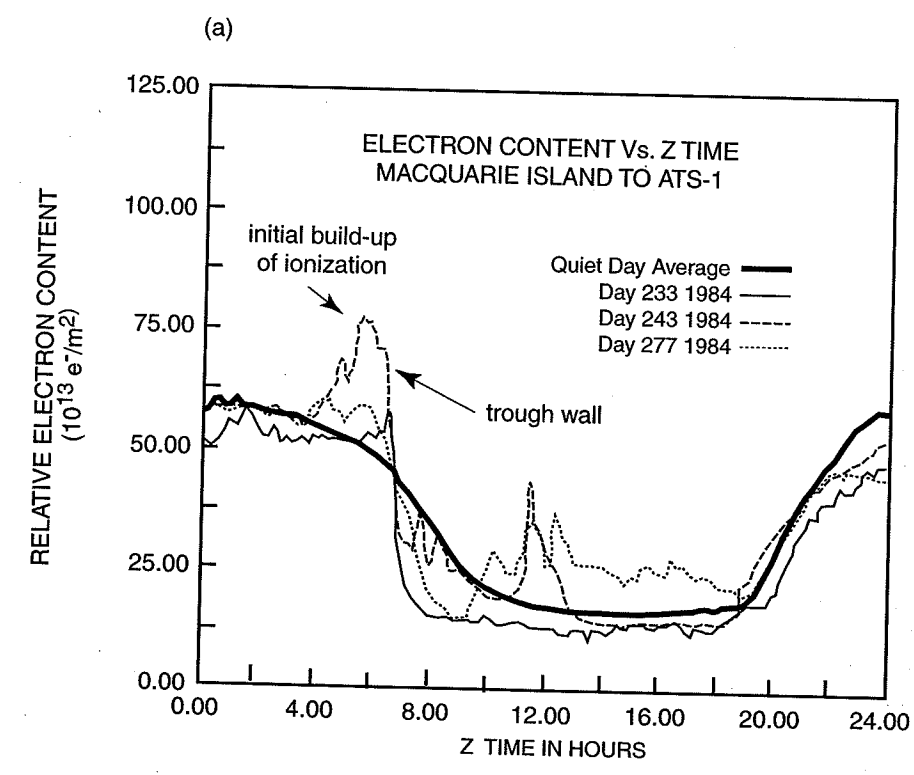
313

For the period investigated, the diurnal variation of the trough shows a higher number of daytime and a smaller number of night-time trough occurrence. The trough develops into a more well-defined formation in the daytime sector. The location of the trough was studied with hourly latitudinal maps. The GPS plots on 17 October 1995 at 1500–1600 LT and 1600–1700 LT show that the peak of the initial build-up moves towards the equator at 160°E longitude, after the trough appeared in the daytime sector (see Figures 4(c) and (d)). These latitudinal maps also show the gradual and linearly increasing electron content toward the equator, from ordinary low values at higher mid-latitudes. The peak TEC related to the initial build-up of ionisation is almost as high as the maximum values observed at the low-latitude region.

It is interesting to compare trough observations obtained by different techniques operating at the same recording station, during different periods of the solar cycle. The TEC data from the Faraday technique at Macquarie Island (Lambert and Cohen, 1986; Lambert and Essex, 1987), in a low sunspot number period, show the trough for vernal equinox in 1984 at 0600 UT with the initial build-up of ionisation on the equatorward side (see Figure 5(a)). Contrary to this, the differential phase technique, employed in a high sunspot number period (Mallis, 1989; Mallis and Essex, 1993), detected the trough without this distinctive characteristic on vernal equinox 1988 at around 4.7 UT (see Figure 5(b)).

The most significant seasonal trend observed is, that the daytime trough develops best during equinoctial times, less in summer and least in winter. During the summer season the night-time trough develops better, which is narrower and deeper than its shallow and wide daytime counterpart.

The trough is a structure in space and time, and has a substantial movement during the course of the year. This is called annual latitudinal movement and was studied with TOPEX passes (see Figure 6) of similar equator crossings related to different seasons. Figure 6(a) shows a summer trough on 15 February 1995 at 1459 LT with the equatorial anomaly centered on the geomagnetic equator. Figure 6(b) depicts a winter trough on the 20 July 1995 at 1411 LT and shows the equatorial anomaly in a not so well developed form at 0918 LT. During those moderately disturbed magnetic periods, the daytime trough was observed at higher latitudes ($\approx 60°S$, $\Lambda = -73.8°$) in summer than in winter ($\approx 52°S$, $\Lambda = -62.4°$). In agreement with the results of Mallis (1989) and Mallis and Essex (1993), this indicates a movement away from the equator and then back towards lower latitudes, during the course of the year. Figure 6 also illustrates that in winter, the daytime trough is shallower than in summer, because of the less ionisation available.
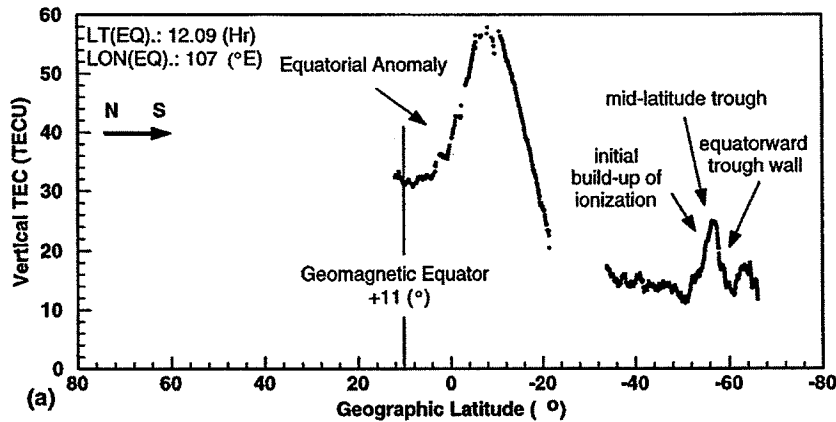
The effects of magnetic disturbance on trough occurrence and GPS recordings were studied with GPS TEC data. The magnetic storm studied, identified from geomagnetic data, commenced on 18 October 1995 at 1400 UT. On that day the minimum D_{st} index was -122 nT and the maximum K_p was 7-. During the storm, the trough was detected from

314

(a)

ELECTRON CONTENT Vs. Z TIME
MACQUARIE ISLAND TO ATS-1

RELATIVE ELECTRON CONTENT (10^{13} e⁻/m²)

125.00

100.00

initial build-up
of ionization

Quiet Day Average ▬▬▬
Day 233 1984 ───────
Day 243 1984 ─ ─ ─ ─
Day 277 1984 ··········

75.00

trough wall

50.00

25.00

0.00

0.00   4.00   8.00   12.00   16.00   20.00   24.00

Z TIME IN HOURS

(b)

ABSOLUTE COLUMNAR ELECTRON CONTENT 10^{16} (el/m²)

MACQUARIE ISLAND 245/ 1988 12458

80

←─────

60

poleward wall

40

equatorward wall

20

UT (Hours)	4.892	4.825	4.758	4.692	4.625
INV Lat (°)	-78.6	-70.8	-65.3	-59.7	-50.6
GG Lat (°)	-69.1	-60.2	-54.6	-48.9	-39.7
GG Lon (°)	158.3	157.8	157.6	157.3	156.9

Figure 5. The plots of TEC from (a) the Faraday technique (modified after Lambert and Essex, 1987) and (b) the differential phase technique (modified after Mallis, 1989) show the mid-latitude trough at Macquarie Island in a low and a high sunspot number period, respectively. (b) The direction of the satellite pass is also shown (←).

date: 15/2/95, UT: 4.89 – 5.42 (Hr), LT: 11.74 – 17.91 pm, kp:3+
trough: -60 (°);140 (°E), Λ=-67 (°)

LT(EQ).: 12.09 (Hr)
LON(EQ).: 107 (°E)   Equatorial Anomaly

Vertical TEC (TECU)

N   S

mid-latitude trough

initial
build-up of
ionization

equatorward
trough wall

Geomagnetic Equator
+11 (°)

80   60   40   20   0   -20   -40   -60   -80
(a)   Geographic Latitude (°)

date: 20/7/95, UT: 8.8 – 9.65 (Hr), LT: 12.88 – 22.36 (Hr), kp = 2- and 4-
trough: -52 (°);79 (°E), Λ=-62 (°)

LT(EQ).: 9.18 (Hr)
LON(EQ).: 108 (°E)

Vertical TEC (TECU)

N   S

mid-latitude trough

initial
build-up of
ionization

equatorward
trough wall

Geomagnetic Equator
+11 (°)

80   60   40   20   0   -20   -40   -60   -80
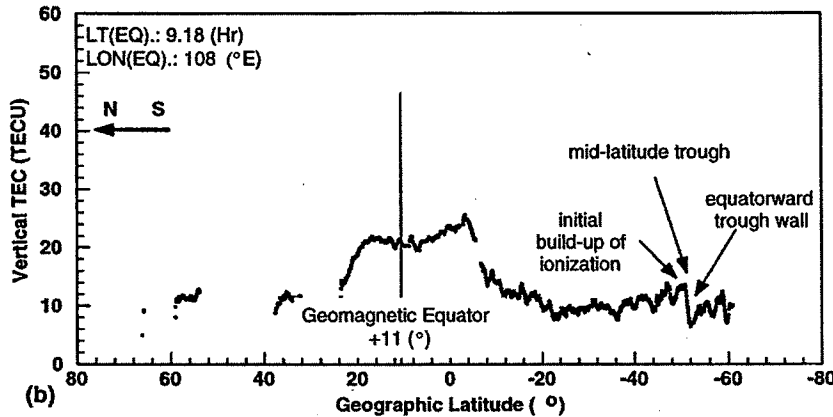**(b)**   Geographic Latitude (°)

Figure 6. The TOPEX passes depict a daytime southern mid-latitude trough in the seasons of (a) summer with the southern half of the equatorial anomaly, and (b) winter, and indicate the annual movement of the trough. (a and b) The equator crossing local time (LT(EQ)), the equator crossing longitude (LON(EQ)) and the direction of the passes ((a) → and (b) ← are also shown.

Hobart, situated at lower geographic latitude than Macquarie Island, indicating that the trough follows the movement of the expanding auroral oval. At that time fine- and larger-scale TEC fluctuations and large-scale wave like formations were also detected. Figure 7 shows these ionospheric formations on a GPS TEC latitude plot constructed for a one-hour period (LT = 1800–1900) on 19 October 1995. Since the different segments of the trough are detected by different satellites, its complete image is highlighted, in order to obtain a clearer presentation. Opposite

GPS stations: Tidbinbilla, Hobart and Macquarie Island
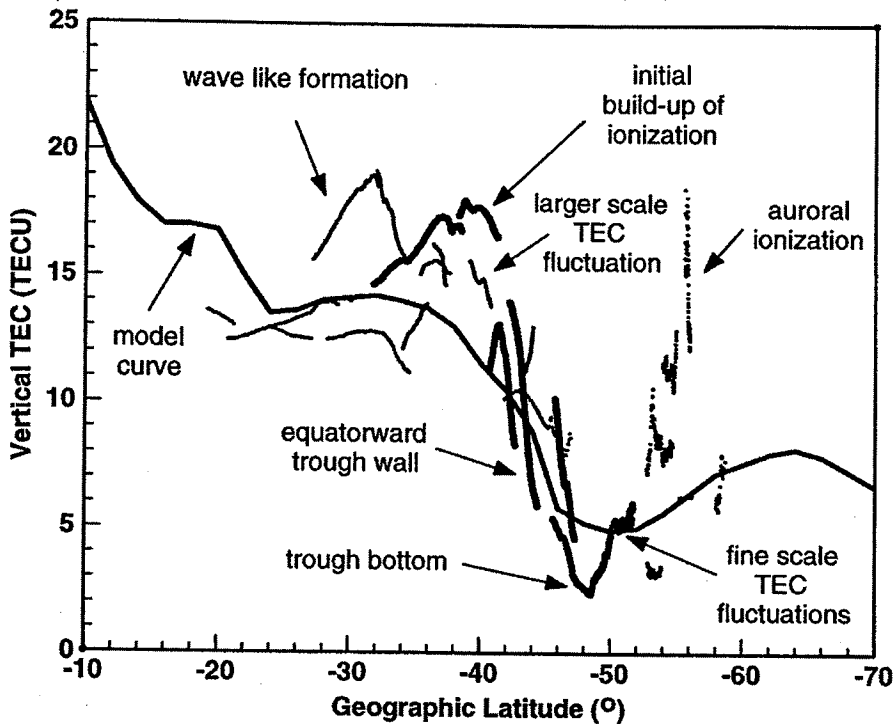Date: 19/10/95 (Regular World Day), kp = 4+
UT = 8 - 9 (Hr), LT = 18 - 19 (Hr)

Figure 7. *The latitudinal GPS plot depicts a vernal equinox daytime trough detected from Hobart during the 19 October 1995 magnetic storm. The PIM generated model TEC is also shown.*

to storm times, during less disturbed magnetic periods, the auroral oval is situated at higher latitudes and the trough is observed from the location of Macquarie Island in the Southern Ocean.

The theoretical TEC values generated by PIM were directly compared to the GPS results, for different magnetic conditions. In Figure 3(a) during a moderate magnetic disturbance, the model values are significantly lower than the experimental values and the phenomenon of mid-latitude trough is not indicated at all. Figure 7 shows that the agreement is better for higher K_p, but PIM is still not able to model the trough.

22.4 Conclusion

The overall results obtained in this project indicate that the combination of dual-frequency GPS and TOPEX techniques provide a comprehensive way to study the ionosphere. Approximately one year of GPS data was analysed to study the major characteristics of the mid-latitude trough of the southern hemisphere, during low sunspot numbers. The GPS findings were confirmed with TOPEX observations, which provided additional information on the structure of the ionisation at the time of the trough occurrence. The initial build-up of ionization was found to be a unique feature that was also detected by the Faraday method at low sunspot numbers, but was not detected by the differential-phase technique during high sunspot number periods. The high number of daytime observations indicates that the trough develops better in the daytime sector. The trough was found to be better defined in the equinoctial seasons, while the degree of development and the frequency of occurrence were observed to be decreasing through the summer towards winter. The daily and annual movements of the trough were also defined. The established diurnal and seasonal trends are in good agreement with the findings of Mallis (1989) and Mallis and Essex (1993). The magnetic activity related trends were also investigated and the findings supported the well-known mechanism of the polar environment. The experimental data were compared with the PIM generated theoretical TEC. For the low sunspot number period, the theoretical TEC is generally below the measured values and PIM is not able to model the structure of the ionisation at the time of trough occurrence.

22.5 Acknowledgements

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