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Development of TEC Map over Equatorial Anomaly using GPS Data

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Abstract

Total Electron Content (TEC) is a parameter of the ionosphere that originates multiple effects, in many radio applications such as the Earth-space radio communication, satellite navigations and space weather. As one-third of the total global ionization in this narrow belt around the magnetic equator, it acts as a perturbing medium on satellite-based navigational systems like GPS.

A systematic variation in the maximum ionization, Equatorial Anomaly, extends in the topside ionosphere resulting TEC exhibiting similarity in the features of maximum ionization. In this paper, results are presented from a study of seasonal and geomagnetic effects on Equatorial Ionospheric Anomaly (EIA) during solar cycle by considering four different epochs. Project aims to develop a regional GPS-based, bias free ionospheric TEC map over equatorial anomaly using Leica GNSS QC, Matlab and GPS data from Center for Orbit Determination in Europe (CODE). The study will help in determining position of the Sun with respect to the Earth, seismo-ionospheric anomaly behavior, and space weather prediction, satellite positioning and ionospheric impacts on radio wave propagation.

Keywords: Equatorial Anomaly, Ionosphere, Total electron content, GPS data

1. Introduction

Solar ionizing radiations are responsible for ionospheric theory. Molecules of the atmosphere, ranging in between 50 km to 500 km, are ionized by the radiation of the Sun thus forming ionosphere [4]. In actual interaction between extreme ultra violet and X-ray radiation yields free electrons and ions [1]. TEC is one important parameter of ionosphere, has an impact on satellite navigation system and earth-space radio communication and enables us for space weather prediction. TEC values facilitate to retrieve the electron density of the ionosphere (Nava et al., 2006) and can provide accurate specification of ionosphere (Wang et al., 2004) [5, 8].

Rise and fall activity observed in the Sun is known as solar cycle with the quasi period of around 11 years (Smith and Marsden, 2003) [10]. Number of sunspots makes the solar maximum and solar minimum. Around solar maximum there is a greater likelihood of large solar flares occurrence. The ionosphere varies with the solar cycle and this phenomenon is more prominent over equatorial anomaly.]. The region around the geomagnetic equator, located between ± 20° of geomagnetic latitude is characterized by an anomaly on the ionospheric behavior, called the Ionospheric Equatorial Anomaly (IEA) [11]. The cause of equatorial ionospheric anomaly (EIA) is often attributed to the so-called fountain effect. At the geomagnetic equator where the magnetic field is horizontal, the plasma movement is vertically upward during the day, resulting from an eastward ionospheric electric field [12]. In equatorial region, spatial gradients and absolute slant TEC are known be to highest in the world (Komjathy et al., 2003b) [3].

The ionosphere is a dispersive medium, and electromagnetic waves such as GPS signals, experience time delays when traversing the ionosphere (Ratcliffe et al., 1959), which is directly proportional to TEC along the signal path from broadcasting position [2]. The ionosphere affects earth-space radio communication and high frequency waves propagating through it are attenuated. F_2 layer exists for 24 hours however D and E layers disappear at night and E region is greater in summer than winter. Density of free electrons decreases with the increasing latitude as the solar radiations striking the atmosphere are oblique. Sometimes the Earth's magnetic field gets disturbed due to events on the Sun. For the improvement of radio communication links, it is necessary to know the actual behavior of ionospheric characteristics with high temporal and spatial resolution with the best possible accuracy. This paper presents an attempt to study the behavior of solar cycle variations and TEC observed over equatorial anomaly.

2. Methodology

The GPS is composed of a constellation of satellites, usually 24–28 operational at any given time distributed in six orbital planes. It is designed for precise navigation, unencumbered by range errors imposed by the retardation of radio signals as they pass through the ionosphere [7]. Center for Orbit Determination in Europe (CODE), Astronomical Institute; University of Berne, Switzerland contributes with ionosphere products [6]. GPS data is obtained from CODE and is processed using Leica GNSS QC. Matlab is used to obtain regional TEC maps i.e. across equatorial anomaly, which is the subject of interest. TEC maps were plotted for different epochs of the solar cycle. Monthly averaged sunspot number was used as a proxy for solar activity cycle 23 which begins in 1996 and ends in Jan 2009.

Four epoch selections were made and they are

1. Solar maximum peaked in 2000-2002 with many furious solar storms;

2. Solar minimum which was in year 2007-2008;

3. Moderate solar activity condition which is taken for the year 2005 and

4. During Tsunami incident which hit severely those countries which fall on equatorial anomaly (Thailand, Indonesia, Malaysia etc.) on 26th December 2004.

Figure 1 shows the solar cycle 23 and a graph is plotted against the number of sunspots and years. For these four different epochs, TEC maps have been drawn and observations have been made which are discussed in the next sections.

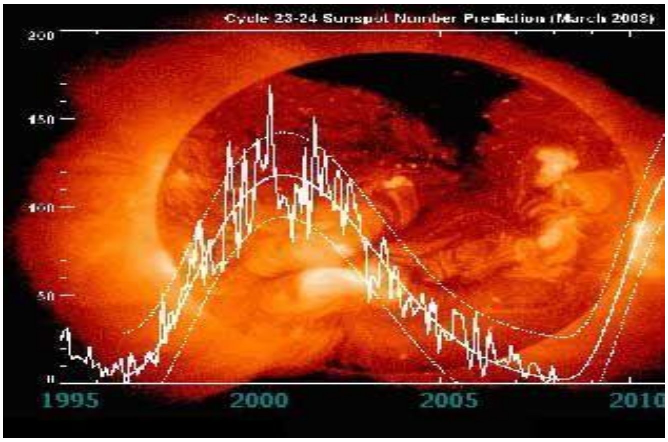

Figure 1. Solar Cycle 23, monthly averaged sunspot Vs years. Courtesy by NASA

3. Observations

As discussed in the preceding section those four different periods of solar cycle have been chosen for analysis. Figure 3 shows TEC map for solar maximum of solar cycle 23 which occurred in 2000 to 2002. 198th (July 16) day of year 2000 was selected at 01:00 UT, 07:00 UT, 13:00 UT, 19:00 UT for analysis keeping Kp and Ap index in mind. It can be seen that the dense intensity of TEC is following a sinosidal path and travelling from east to west as the Sun moves. Depending on the colors based on intensity, days and nights can be differentiated in different parts of the world. Major anomalies started appearing in year 1999 and the peak was in 2001 with many solar flares. In between 1996 to 1999, solar conditions were normal and nearly no major anomaly appeared. Years from 2000 to 2002 can be considered as highly instable and unpredictable. The geomagnetic field and the ionosphere are linked in complex ways and a disturbance in the geomagnetic field can often cause a disturbance in the ionosphere. These disturbances are called ionospheric storms. We can see from the Figure 3 that at 01:00 UT, that the heavy concentration of electrons is at extreme the East and West part of the Earth. The region which is in these regions includes Fiji, Marshall Island, Solo-man Island, equatorial part of Pacific ocean, Kiribati, Hawaian Island and the regions nearby. If TEC map is observed at 07:00 UT, then the most affected region are partial Australia, Indonesia, Malaysia, Philippines, Thailand, Vietnam, Sri Lanka, South China Sea, Singapore Papua New Guinea and other regions nearby the mentioned countries. When TEC is plotted for at 13:00 UT peak concentration of electrons is found in the regions surrounding Sri Lanka, Bay of Bengal, Southern India, Arabian

Sea, Democratic republic of Congo, Angola, Kenya, Somalia and Tanzania. For the plot of 21:00 UT the path of dense electrons are around the region of Brazil Bolivia, Peru, Venezuela, Colombia, Caribbean Sea, Chille and the western part of the equator.

Figure 2 shows the Dst index for July 16, 2000. We can see that the Dst index is touching -300 value shows the extreme solar storm and the TEC map for the same day has been shown in Figure 3.

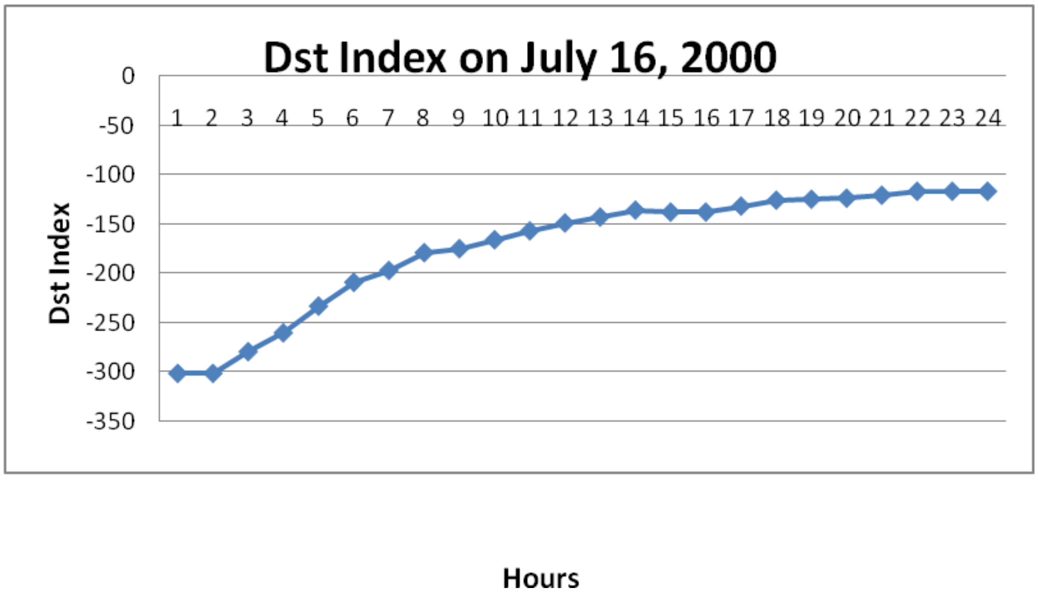

Figure 2. Dst Index against hours for July 2000

Tsunami incident creates seismo waves resulting in some disturbance in the equatorial ionospheric anomaly. The seismo-ionospheric anomaly is quite interesting to observe as concentration of electrons was increased in F region implying some geo-magnetic disturbance. Impulsive input of energy into the atmosphere can activate various kinds of waves. Chimonas and Hines (1970) predicted that gravity waves could be generated by a total solar eclipse. These waves travel upwards to reach F-region. This phenomenon is shown in Figure 4. Equatorial Anomaly TEC maps were computed using Leica GNSS for day 361 (Sunday, December 26) at 00:00 UT, 06:00 UT, 12:00 UT, 18:00 UT for Tsunami incident observations. Location for the earth quake was 3.316 N, 95.854 E. It was proposed (Namgaladze et al. 2007) that the principle cause of the appearance of the local anomalies in the form of the increased (decreased) total electron content of the ionosphere, observed on the base of GPS signals measurements, is the vertical drift of F2-region ionospheric plasma upward (downward) under the influence of the zonal electric field of seismogenic origin directed to the east (west) [14].

When TEC was plotted for moderate condition of solar cycle 23 in year 2005, it showed intermediate behavior when compared with solar maximum and solar minimum. Equatorial anomaly TEC maps were computed for day 182 (Thursday, 7 July, 2005) at 00:00 UT, 06:00 UT, 12:00 UT, 18:00 UT for moderate solar condition. Comparison between figure 3, 5 and 6 will reveal this fact. During moderate conditions, the most effected regions at 00:00 UT is the area of covered by equatorial region of Pacific Ocean on the west side. As the day moves, when TEC is plotted at 06:00 UT the concentrated patch of electrons is covering Asia Pacific region, South China Sea and Philippines Sea. When TEC is plotted at 12:00 UT, the most concentrated parts are India, Bay of Bengal and Arabian Sea and the least concentration can be found at the extreme east and west side of the equator. For 18:00 UT, the least concentration is on the East side of the equator which implies that there is no direct Sun facing the Earth at 18:00 UT. In other words we can say that East part of the world has night at this time. However, in the upper atmosphere, the concentration has moved to the areas of Yemen, Sudan, Ethiopia, Kenya and Somalia. This is the pattern of TEC showed during moderate solar conditions over equator region.

When GPS data were plotted for year 2008 for solar minimum, the red area was nearly absent as compared with solar maximum drawing on the same scale representing the lack of concentration of electrons across equatorial anomaly. Figure 6 shows the equatorial anomaly TEC maps computed for day 182 (Monday, June 30, 2008) at 00:00 UT, 06:00 UT, 12:00 UT, 18:00 UT for solar minimum. Currently we are in the 24th solar cycle and solar minimum of solar cycle 23 was in year 2008. Solar cycle 24 started from January 2009 as reported by NASA. During this time, sunspot and solar flare activity diminishes, and often does not occur for days at a time. Generally, this is the safest time for astronauts to do their missions due to an associated decrease in solar radiation.

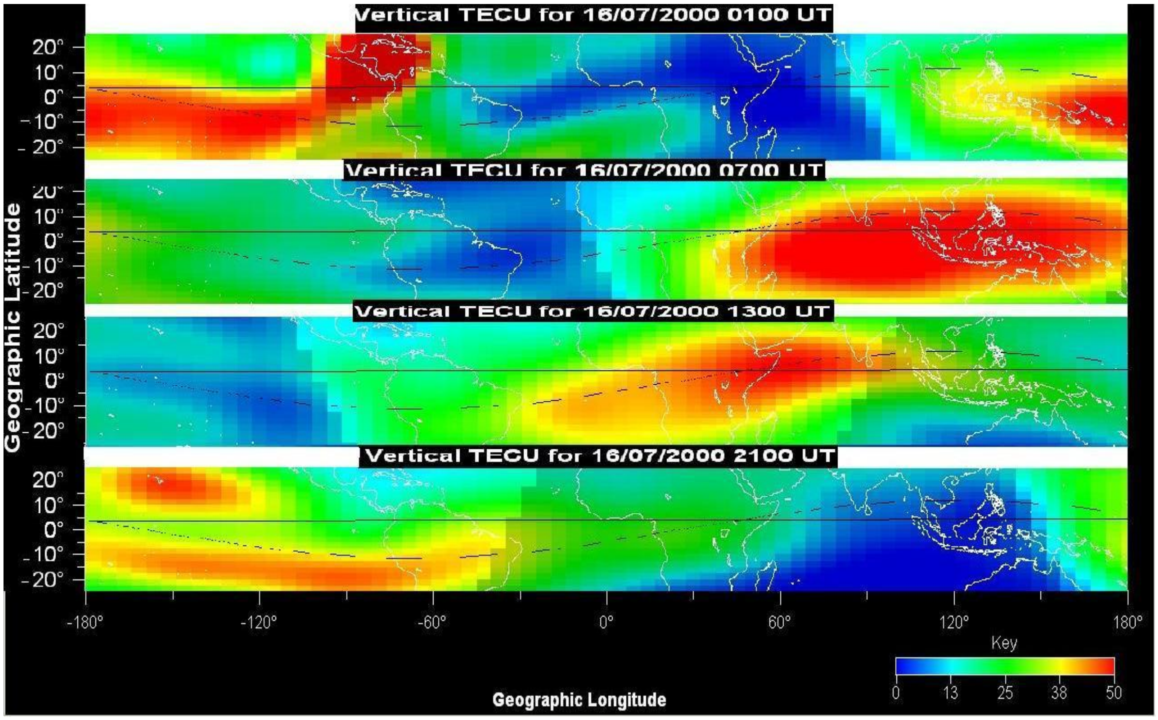

Figure 3. Equatorial Anomaly TEC maps computed using Leica GNSS for day 198, 2000

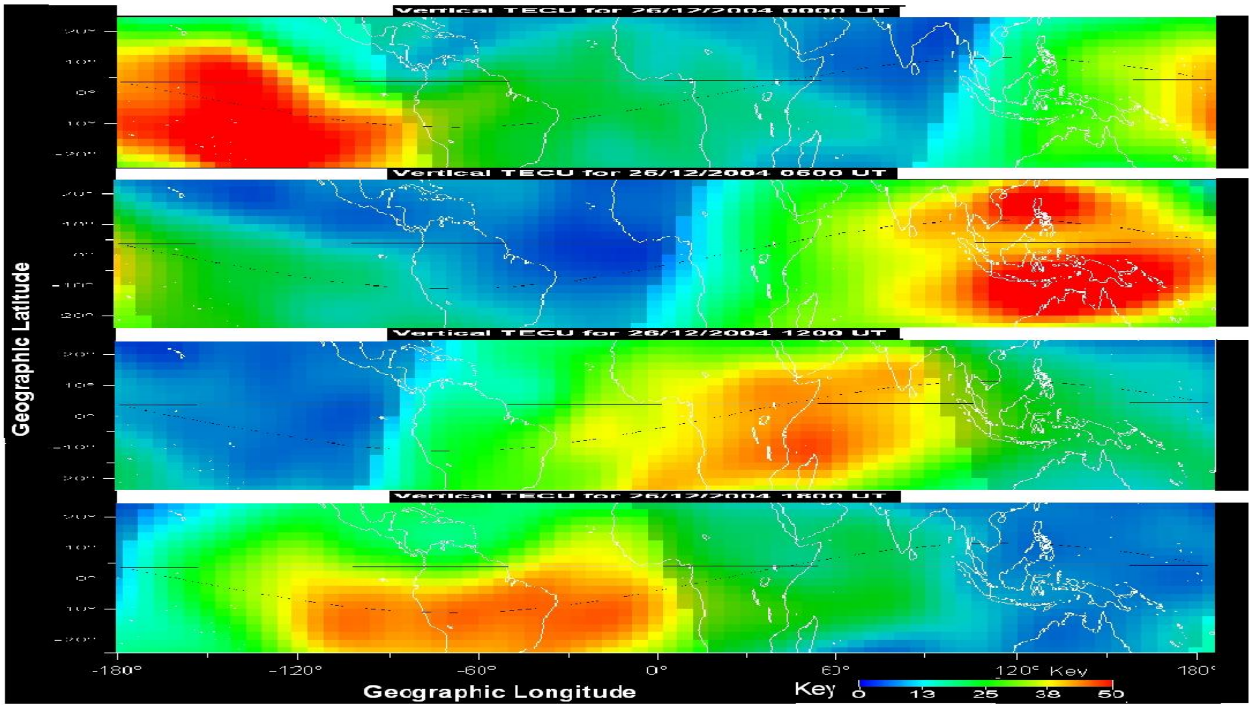

Figure 4. Equatorial Anomaly TEC maps for day 361 for Tsunami

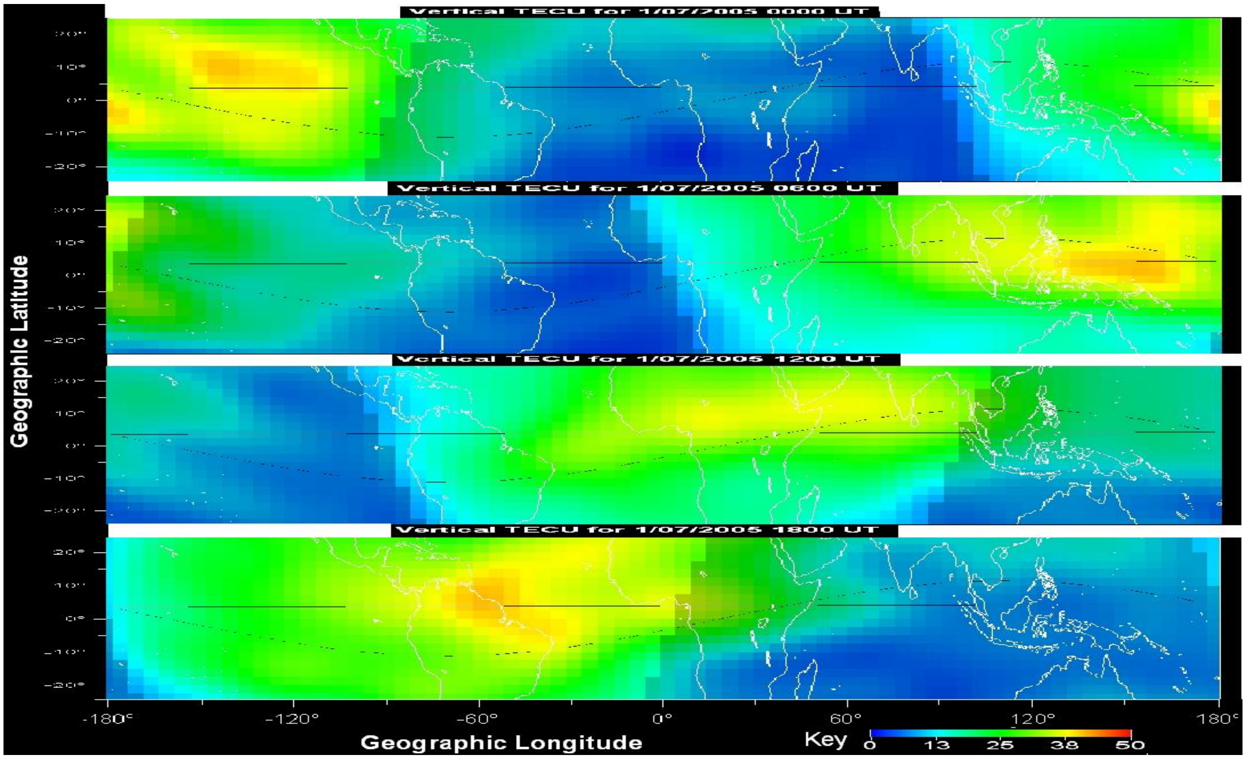

Figure 5. Equatorial Anomaly TEC maps for day 182 for moderate solar condition

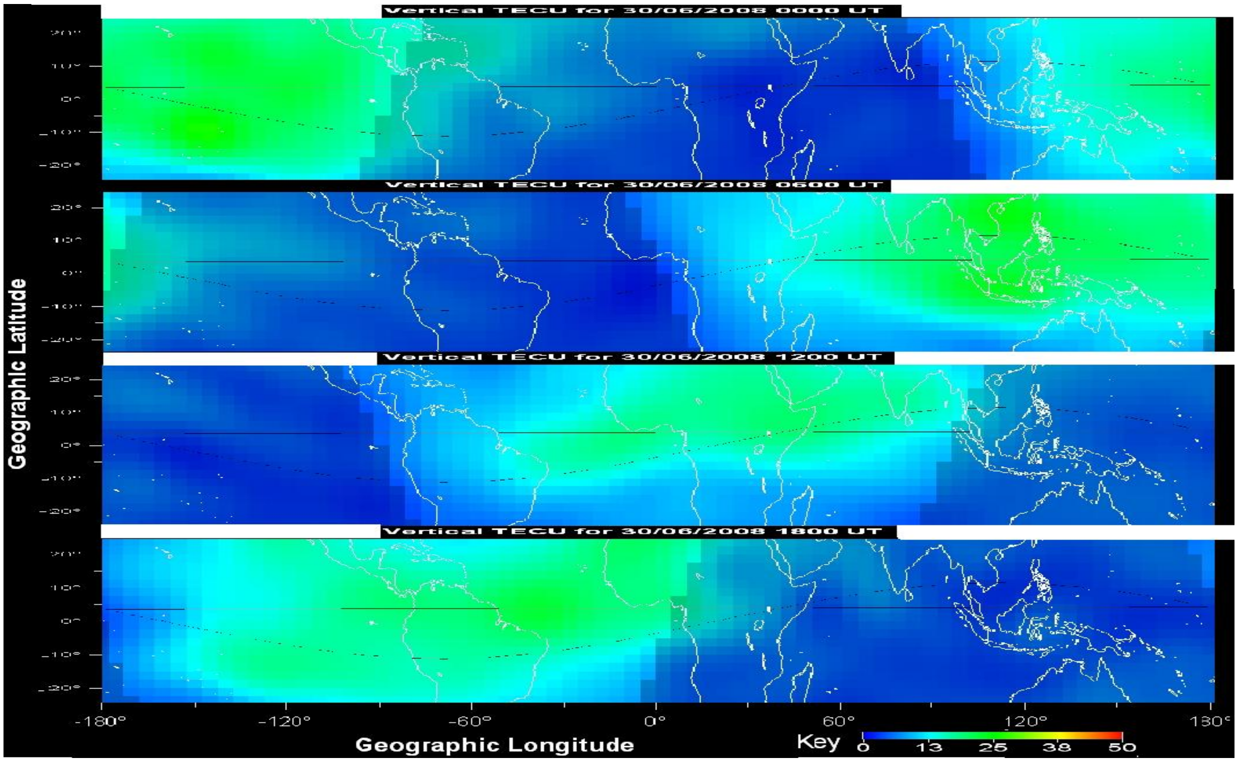

Figure 6. Equatorial Anomaly TEC maps for day 182 for solar minimum

4. Discussion and Results

Electron density in the upper atmosphere is the maximum on the region surrounding the equator within ±25° of geographic latitude. As we move away from the equatorial anomaly the concentration of electrons becomes less dense and minimum along the North and South poles. So as we move away from 0° geographic latitude on either side, the concentration of the electrons in the upper atmosphere will reduce. Therefore equatorial anomaly region is the most affected region because of the presence of thick TEC around the world. During solar maximum the dense patch of charged ions moves in a sinosidal fashion on the Earth from East to West and the peak concentration is observed within ±25° from the equator. As the Sun moves around the Earth, dense path of ionized ions also moves along with the Sun and thus follows its virtual footprints. So observing the TEC, we can estimate that which part of the Earth has day and which part of the Earth has night time. An interesting thing to note is, in 23rd solar cycle, the numbers of sunspots during year 2001 were found to be maximum in all the preceding solar cycles. It makes the ionized particles in the upper atmosphere dense as ever found before in any solar cycle.

During solar minimum, when the numbers of sunspots on the Sun were very few, TEC is not very prominent. Behavior of TEC during solar minimum day timings is nearly the same as its behavior during solar maximum at night. So during solar minimum, the earth space radio communication is not very much affected by the presence of electrons and signals are not reflected back heavily. During moderate solar activity condition, the behavior of TEC along the equatorial anomaly is intermediate between solar maximum and solar minimum.

As the activities on the Sun influence the pattern of TEC, similarly disturbance in the Earth's geo-magnetic field yields traces of disturbances on TEC as well. For instance, when boundary plates of the Earth move abruptly, releasing energy and creating seismic waves can cause geomagnetic disturbance. . Tsunami impact was such that even the earth's rotation axis has been shifted by a few cm. It may have initiated waves in the troposphere which could then propagate to ionospheric heights. The increase of the atmospheric radioactivity level during the earthquake preparation leads to the enlargement of the ionization and electric conductivity of the near-ground atmosphere. The joint action of these processes leads to the intensification of the electric field in the ionosphere up to the value of units-tens mV/m (Chmyrev et al. 1989). When TEC is mapped along the Tsunami affected regions on 26th December 2004, it shows some difference i.e. increases of electron concentration from the preceding and proceedings days which can be area of active research for further investigations.

5. Conclusion

Above mentioned discussion shows that it is quite necessary to have better spatial and time resolution ionospheric information as it has an influence on a number of applications like space weather prediction, earth-space radio communication and satellite navigation systems. TEC can also be used to predict the happenings on the Sun. In addition TEC values can be used in determination of the position of the Sun with respect to the Earth at a given time. Seismo-ionospheric anomalies are also an active area of research which can be observed through TEC.

The mutual interaction between the Sun and the Earth which makes ionosphere to effect gives a beautiful illustration that the Earth and the Sun are the part of same solar system. When solar cycle 23 is compared with preceding cycles, it was found to be more instable and extreme in its nature. Same extreme phenomenon can be observed on the Earth in the form of earth quakes, volcanoes etc. during the same era. As far as communication is concerned, it is highly recommended to use low frequencies for earth-space radio communication along equatorial anomaly favoring less attenuation and more reliable communication. Discussion can be summarized as follows in Table 1

Table 1: Summary of Solar Cycle 23

Solar Condition/Parameter	Solar Flares	Space Mission	Sunspots (Monthly)	Dst Peak
Solar Maximum	Maximum	Not Recommended	>150	-301
Solar Minimum	Minimum	Highly Recommended	<10	-14
Moderate Condition	Moderate	Recommended	~ 50	-4
Tsunami	Abnormal	N/A	N/A	-22

6. Recommendations for Further Studies

TEC mapping using GPS data is relatively new technique to know more about ionosphere and there is a lack of research on ionospheric studies especially using new techniques. It is quite necessary to have better spatial and time resolution ionospheric information as it has an influence on number of applications like space weather prediction, earth-space radio communication and satellite navigation system. Rigorous amplitude fading and strong scintillation influence the trustworthiness of GPS navigational system and satellite communications. Therefore, it is enviable to obtain more and more understanding of ionospheric scintillation and its effects on GPS by means of a receiver able of performing in such conditions.

Many studies reported results from hourly or median values. Much of the everyday changeability of the equatorial anomaly is engrossed by these statistical results. As a result the physics of the triggering mechanisms for instabilities and overall dynamics for the east/Asian pacific ionospheric region is still unknown. Higher time resolution observations and analysis is needed. The anomaly regions in the Southeast Asia sector would be unique due to stronger trapping of higher energy particles at a given altitude. No measurement of the variation of the E_xB drift for the Pacific/Asian region exists. As far as prediction of earthquake from TEC in the ionosphere is concerned, further studies need to be conducted as this is influenced by a number of complex parameters and Travelling Ionospheric Disturbances (TID) must be carefully monitored [13].

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