Geomagnetic Storm Effects on GPS Aided Navigation over Low Latitude South Indian Region

N. Venkateswara Rao†, T.Madhu† †, K. Lal Kishore†††

†Bapatla Engineering college, Bapatla-522 101, A.P., India, Phone: 90-94 41 81 83 16
†† ASR College of Engineering,Tetali, TANUKU-534211, A.P., India, Phone: 08819- 229100
† † †J N T U H, Kukatpalli, Hyderabad-500 072, A.P., India, Phone: 90-96 18 02 34 78,

Summary
The Indian Navigation System, GPS Aided GEO Augmented Navigation, 'GAGAN', being designed and developed as a Global Navigation Satellite System, is expected to become operational by 2010. Ionospheric time delay, a function of Total Electron Content (TEC), is the major error source in GNSS. The ionosphere exhibits a peculiar behavior corresponding to large TEC fluctuations in low latitude regions. Further, geomagnetic storms will also produce severe enhancements in the TEC. The TEC values estimated from the SOPAC data archive of the International GNSS Service (IGS) for the low latitude stations, Hyderabad (78.45oE, 17.35oN) and Bangalore (77.51oE, 13.03oN) in the southern region of India during the severe geomagnetic storm period in October 2003 are compared with the TEC values obtained from International Reference Ionosphere 2007 (IRI) empirical model. Such findings would help in developing a region-specific ionospheric empirical prediction model for the GAGAN.

Key words:
GNSS, GPS, GAGAN, IRI, GEOMAGNETIC STORM, TEC

1. Introduction

The satellite based Global Positioning System (GPS) is widely used for navigation, relative positioning and time transfer. GPS operates by transmitting radio waves (L1-1575.42 M Hz and L2-1227.60 M Hz) from satellites to receivers on the ground, aircraft or other satellites. When GPS signals propagate through the ionosphere, the carrier experiences a phase advance and the code experiences a group delay due to the total number of free electrons along the path of the signals from the satellite to receiver [1]. Therefore, the key parameter for navigation is the Total Electron Content (TEC), which is an integral of the total electron content in a column of 1 m2 from the observation point to the satellite. A value of TEC equal to 1x1016 electrons / m2 is called one TEC Unit (TECU).

TEC depends on a number of factors, such as; the time of day; the time of year; the 11-year solar cycle; and the geographic location. In the equatorial region, TEC is often quite large with large horizontal gradients. Also, the day-to-day variability is the highest in low latitudes [2-3]. Therefore the ionosphere above the Indian subcontinent, which is located near the equatorial region, is highly volatile. Further, space weather disturbances such as solar flares, coronal holes and coronal mass ejections (CME's) result in geomagnetic storms on earth. In such situations there may be some rapid fluctuations in TEC values [4-5]. The ionospheric time delay which is a function of TEC along the signal path is the main error source in navigation systems and can reach up to 150 meters under extreme solar activities, at mid day, and near the horizon [1]. High resolution applications of GPS technology will hence require better space weather support to compensate for these ionosphere – induced errors. Accurate specification and prediction of ionospheric conditions for both quiet and disturbed periods will aid in the design and operation of Global Navigation Satellite Systems (GNSS). Further, in India also, Indian Space Research Organization (ISRO) and Airport authority of India (AAI) are jointly developing a navigation system popularly known as GAGAN (GPS Aided GEO Augmented Navigation) over the Indian Air Space and is expected to become operational by 2010 [6]. Therefore the electron content models for low latitudes have to take care of large extents of day-to-day variation in electron content.

Severe space weather disturbance was observed on 29th and 30th October 2003. This event has occurred in the decreasing part of the 11-year solar activity cycle that reached its maximum in 2001. In this paper, the TEC values estimated using GPS data for two low latitude stations in southern region of India (Hyderabad and Bangalore) during the severe geomagnetic storm of October 2003 are presented and compared with the TEC values obtained from the International Reference Ionosphere (IRI) 2007 empirical model [7] results.

2. Geo Magnetic storms

Areas of instability in the sun can release high speed plasma, with great amounts of matter and energy, the so called coronal mass ejections (CME's) throughout the whole 11-year solar cycle. Although, more frequent during

Manuscript received March 5, 2010
Manuscript revised March 20, 2010

maximum phase, these CME's are also present during low activity periods of the solar cycle. Eventually these solar CME's, which take around 20 hours to travel from sun to reach earth, enter into the earth's magnetosphere and cause great disturbances in the earth's magnetic field. These disturbances are observed by the ground magnetic observatories and are denominated as geomagnetic storms. These storms are usually associated with increased electron densities in the lower ionosphere and simultaneous increase in absorption of radio waves [8]. The delay is greater for lower frequencies than for higher frequencies. Thus, for GPS signals, the ionosphere delay is greater at the L2 carrier frequency than that at L1 carrier frequency. Generally ionosphere delay is of the order of 0.5 meters to 15 meters, but can reach over 150 meters under extreme solar activities, at mid day, and near the horizon [1]. Magnetic storms usually last 24 to 48 h ours, but some may last for several days.

The severity of geomagnetic storms is usually explained with the help of Dst (Disturbance storm time) index as well as Kp index (weighted average of K-indices from a network of geomagnetic observatories i.e. planetary K indices). The Dst index is a measure of geomagnetic activity used to assess the severity of magnetic storms. It is expressed in nano teslas and is based on the average value of the horizontal component of the earth's magnetic field measured hourly at four near equatorial geo magnetic observatories. Use of the Dst as an index of storm strength is possible because the strength of the surface magnetic field at low latitudes is inversely proportional to the energy content of the ring current, which increases during geomagnetic storms. These geomagnetic storms can be classified according to different Dst index levels: weak; -50 nT ≤ Dst ≤ -30nT; moderate; -100 nT ≤ Dst ≤ -50 nT and intense Dst<-100 nT. The kp index, a quasi-logarithmic index, is computed on a three-hour basis and represents the overall level of planetary geomagnetic field disturbance. It is derived from ground based magnetic field measurements and ranges from 0-9, with each scale step being ten times more disturbed than the previous step at the higher end of the scale. A typical quiet day will have Kp values of 0-2. According to the NOAA scale, storms are classified into strong (G3: kp = 7), severe (G4: kp = 8) and extreme (G5: kp = 9).

An extreme geomagnetic storm was observed between 27-31, October 2003. A major solar flare developed at approximately 11.00 UT on October 28. A severe geomagnetic storm commenced in the earth's environment at 6.00 UT on October 29. Activity continued for several days, with further coronal mass ejections at approximately 21.00 UT October 29 and 16.00 UT October 30.The Dst index is less than -100 nT during the October 2003 storm days and peaked to -410 nT on October 29 [9]. The Kp values of 9 were observed on October 28 and 29, 2003 [5, 10]. From Dst and Kp indices, it is evident that the October 2003 storm is very severe and is considered as the 6th most severe geomagnetic storm since 1932 and is called the Halloween storm. Such a severe geomagnetic storm is known to have an adverse impact on the navigation systems in use.

3. TEC Estimation from GPS

The signals from the GPS satellites travel through the ionosphere on their way to receivers on or near the earth's surface. The electrically charged particles mainly free electrons in the ionosphere introduce the propagation error (Ionospheric time delay) to the observations of GPS measurements. A first order expression for the ionospheric time delay 'τ' is given by [11] as

$$\tau = \left\{ \frac{40.3 \times TEC}{c \times f^2} \right\} \quad (1)$$

Where, c is the velocity of light in m/sec, f is the frequency in Hz.

Since the ionosphere is a dispersive medium it allows correction of the first order ionospheric range delay errors. Ionospheric time delay can be estimated using a single frequency approach, but it can remove only 60% of the error [1]. A dual frequency GPS receiver can minimize Ionospheric time delay through a linear combination of L_1 (f_1 =1575.42 MHz) and L_2 (f_2 =1227.60 MHz) observables. If range measurements (p_1 and p_2) are available on two separate frequencies (f_1 and f_2), then the *TEC* can be estimated using the following formula.

$$TEC = \frac{1}{40.3} \times \left\{ \frac{f_1^2 f_2^2}{\left(f_1^2 - f_2^2\right)} \right\} \times \left(p_2 - p_1\right) \quad (2)$$

Where, p_1 and p_2 are pseudo range observables on L_1 and L_2 signals respectively.

As the *TEC* between the satellite and receiver depends on the satellite elevation angle, this measurement is called as slant *TEC* (*STEC*).As slant *TEC* is a quantity which is dependent on the ray path geometry through the ionosphere, it is desirable to calculate an equivalent vertical value of *TEC* (*VTEC*) which is independent of the elevation of the ray path. The slant *TEC* can be converted into *VTEC* using the following formula.

$$VTEC = STEC \times \sqrt{\left[1 - \left\{ \frac{R_e \cos\theta}{R_e + h_i} \right\}^2 \right]} \quad (3)$$

Where, R_e is radius of earth (6378 Km), θ is the elevation angle and h_i is the height of the ionosphere shell (350 Km).

In this paper, the GPS data obtained from the Scripps Orbits and Permanent Array Center (SOPAC) data archive networks [12] is used to investigate the response of the ionosphere for two low latitude stations, Hyderabad (78.45° E, 17.35° N) and Bangalore (77.51°E, 13.03°N) in southern region of India during the severe geomagnetic storm period in October 2003.

4. International Reference Ionosphere (IRI)

The International Reference Ionosphere is a joint project of the Committee on Space Research (COSPAR) and the International Union of Radio science (URSI)**.**This is an standard empirical model of the ionosphere, which provides the monthly averages of the Total Electron Content (*TEC*; a user can select the starting and ending height of the integral), electron density, electron temperature, ion temperature, ion composition, the occurrence probability for Spread-F and also the F1-region and the equatorial vertical ion drift in the altitude range from 50 km to 2000 km for any given location, time and date. Several steadily improved editions of the model have been released with IRI2007 being the latest [7].

5. Results and Discussion

The required data for the measurement of *TEC* during the 27th-31st October 2003 storm period, for both Hyderabad and Bangalore stations, were obtained from observation data files of SOPAC data in Receiver Independent Exchange (RINEX) data format. The data is available for every 30 seconds. From the data, using pseudo range observables on L_1 and L_2 signals (p_1 and p_2), the slant *TEC* is computed using equation (2). The data is resampled every 60 seconds and the required *TEC* is stored in a file. The slant *TEC*'s are then converted into vertical *TEC*'s using equation (3) and stored in a file. However, the individual GPS satellite group delay offsets are not taken into account in this analysis. In the next step the *VTEC* values obtained for all satellite vehicles (SV's) are averaged for every two hours. The measured *VTEC* values from GPS data (ESTD) are then compared with the *VTEC* values predicted by IRI-07 model and are presented in Figs.1-5.

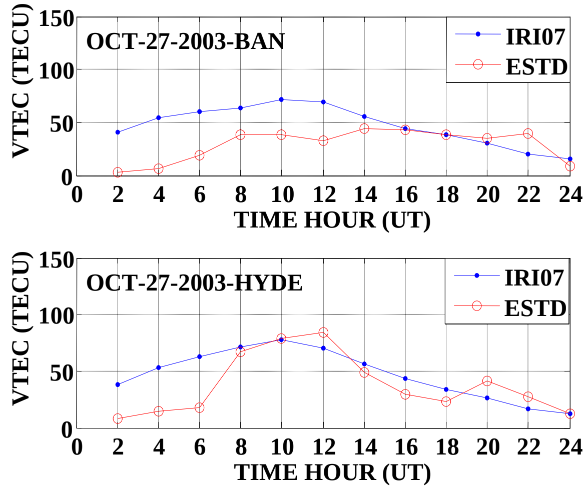

Fig.1: Comparison of *VTEC* with IRI 2007 model on October 27, 2003

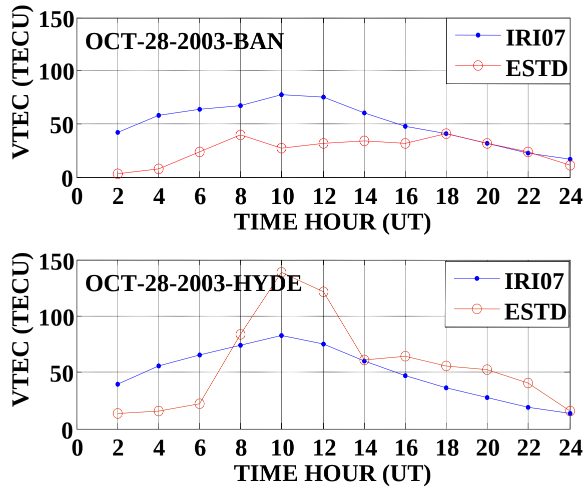

Fig.2: Comparison of *VTEC* with IRI 2007 model on October 28, 2003

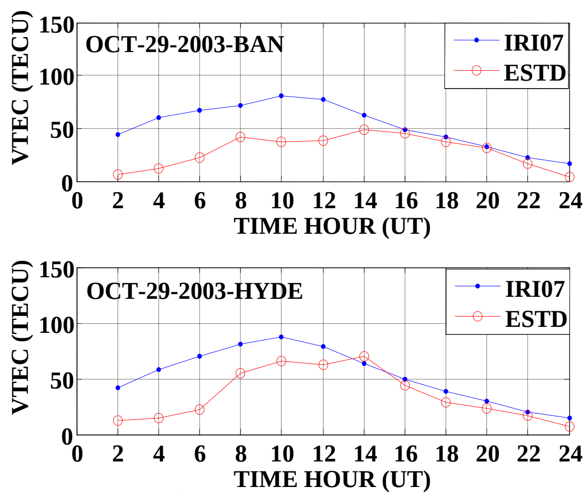

Fig.3:Comparison of VTEC with IRI 2007 model on ctober29,2003

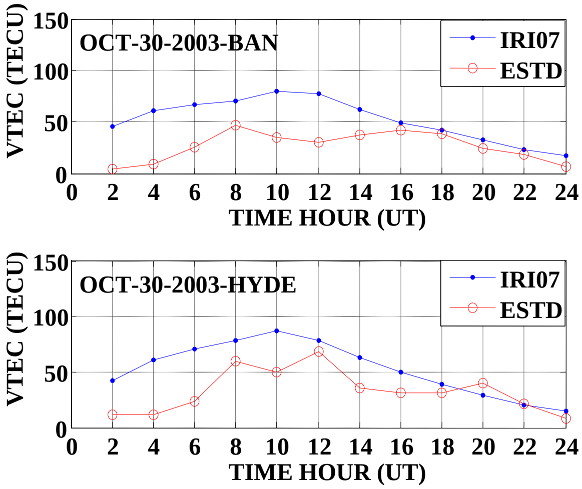

Fig.4: Comparison of VTEC with IRI 2007 model on October 30, 2003

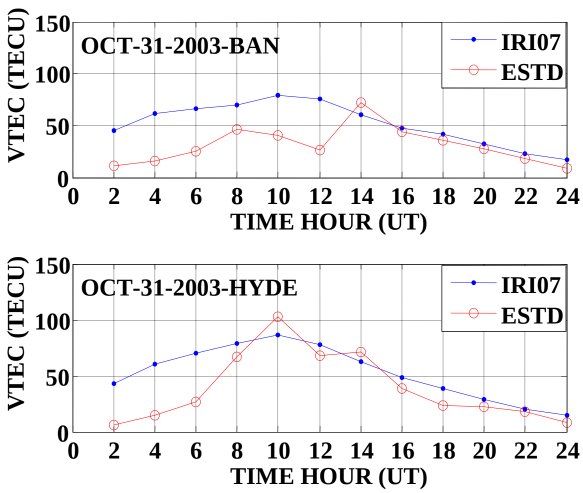

Fig.5: Comparison of VTEC with IRI 2007 model on October 31, 2003

The maximum VTEC values measured from GPS data and predicted by IRI-07 model and their corresponding occurrence time are tabulated in table 1.

Table 1.Comparison of Maximum measured VTEC values and its occurrence time for October 2003 storm period for Hyderabad and Bangalore stations with IRI-07 model values.

Method/Station		ESTD /BAN	IRI-07/ BAN	ESTD/HYD	IRI-07/ HYD
27-10-2003	Max TECU	43.81	71.9	84.2	77.5
	Occ. Time (UT)	14.00	10.00	12.00	10.00
28-10-2003	Max TECU	40.40	77.3	139.2	82.1
	Occ. Time (UT)	18.00	10.00	10.00	10.00
29-10-2003	Max TECU	48.43	80.8	70.58	87.2
	Occ. Time (UT)	14.00	10.00	14.00	10.00
30-10-2003	Max TECU	46.5	79.8	68.6	86.7
	Occ. Time (UT)	08.00	10.00	12.00	10.00
31-10-2003	Max TECU	72.33	78.9	102.9	86.0
	Occ. Time (UT)	14.00	10.00	10.00	10.00

The maximum measured VTEC values (ESTD) are varying between 40 TECU to 72 TECU for Bangalore station and between 68 TECU to 139 TECU for Hyderabad station during the storm period. There is a variation in the occurrence time of maximum VTEC value for both the stations. The maximum measured VTEC value for Hyderabad station is 139.2 TEC units on 28th October 2003 corresponding to a range error of 22meters for Hyderabad station and 72.33 TEC units on 31st October 2003 for Bangalore station corresponding to a range error of 11.57 meters. From the results it is observed that the magnitude of TEC and its variation is large for Hyderabad station compared with Bangalore station. Further, when compared with measured TEC values, IRI-07 model is overestimating the TEC values for Bangalore station during day time. From the results (Fig.1 to Fig.5), it is evident that, IRI estimates are almost consistent over the storm period for both the stations. Though one of the major geomagnetic storms is taking place between the provided dates, IRI estimates do not catch any of the variability taking place in the ionosphere. The difference in VTECU value for a quiet day and a storm day is only 8 TEC units. More over IRI-07 model predicted maximum VTEC value occurrence time is 10.00UT for both the stations and for all the days i.e. for quiet and disturbed days.

Actually IRI is an empirical deterministic program that inputs sunspot number as its major indicator. The sunspot numbers for the period from 27th October 2003 to 31st October 2003 are tabulated in Table 2.

Table 2 . Solar Sunspot Number (SSN) values during October 2003 storm period.

DATE	27-OCT-03	28-OCT-03	29-OCT-03	30-OCT-03	31-OCT-03
SSN	133	165	167	167	160

The SSN is small (133) on 27th October 2003 compared with remaining storm days. Correspondingly the IRI-07 estimation of VTEC is also less compared with remaining storm days. Further the VTEC estimations are almost approximately same for the remaining storm days since the SSN values are also approximately same. IRI estimations for Hyderabad and Bangalore stations are compared over the storm period considered in this paper and presented in Fig.6.

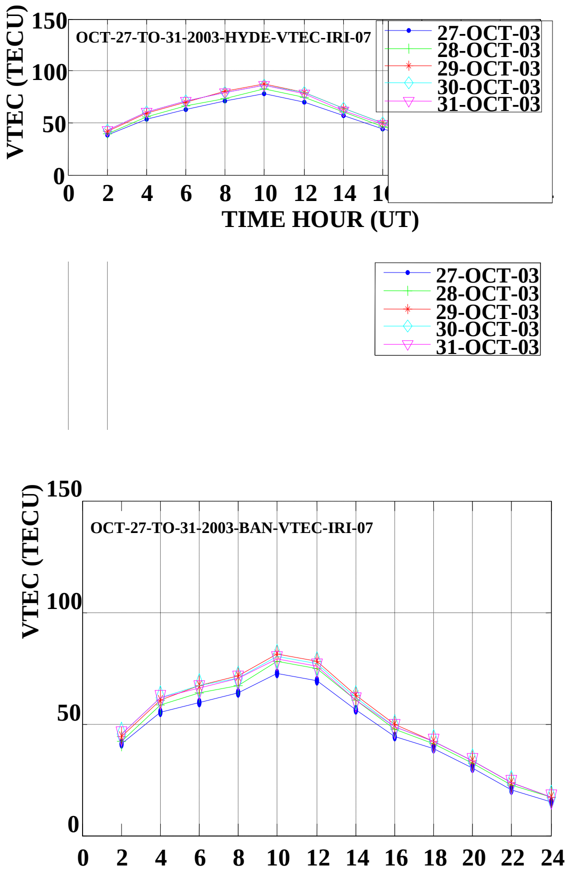

Fig.6: Comparison of IRI 2007 VTEC for HYDE and BAN stations from October 27 to October 31, 2003

It is evident that although during the evening and night hours IRI is providing a reasonable estimate of VTEC in comparison with the measured (ESTD) values, IRI is not able to predict the VTEC variations during a severe storm period for the Indian conditions.

Further, the measured VTEC values using GPS data (ESTD) and IRI-07 predicted VTEC values are compared using normalized root mean square expression (NRMSE) and are tabulated in Table 3.

Table 3.NRMSE values for Hyderabad and Bangalore stations during October 2003 storm period.

STATION	27/10	28/10	29/10	30/10	31/10
HYDERABAD	0.41	0.57	0.41	0.47	0.40
BANGALORE	0.55	0.59	0.53	0.56	0.51

The expression used to determine NRMSE is given below.

$$NRMSE = \sqrt{\frac{\sum_{n=1}^{N}\left[ESTD(n) - IRI(n)\right]^2}{\sum_{n=1}^{N}\left[IRI(n)\right]^2}} \qquad (4)$$

From the Table it is observed that the $NRMSE$ is small for Hyderabad station compared with Bangalore station on all the storm days. As the Bangalore station is nearer to equator by 4.320 compared with Hyderabad station, it is observed that the IRI is over estimating the VTEC (as the location is moving towards equator). Moreover, the accuracy requirement of the ionospheric model for GAGAN is better than 3 TEC units (corresponding to a delay of 0.5m). It has been observed in general that the worst performance of the models is around 08.00 UT (corresponding to 13.30 IST), when the TEC values are high and equatorial anomaly gradients are a maximum over Indian Region [13-14]. This clearly demonstrates the necessity of developing a region specific ionospheric model for the Indian conditions, by analyzing GPS data from more number of locations, so as to obtain a more accurate prediction model.

6. Conclusions

Magnetic storms affect the *TEC* of the ionosphere in turn affecting the performance of GNSS systems. It is found that the empirical IRI model is also not able to accurately predict the *TEC* values for low latitude Indian stations (Bangalore and Hyderabad) during the storm conditions. IRI is over estimating the *VTEC* as the location is moving towards equator during day time**.** Though, IRI model presents a reasonable estimate of the *VTEC* during night time, its suitability to the Indian conditions, particularly during day time is to be further investigated. Hence, a region specific ionospheric prediction model for GAGAN is necessary for better estimation of *TEC*.

Acknowledgements

The data used in this analysis is obtained from SOPAC data archives of the IGS network.

References

[1] Ahmed El-Rabbany, "Introduction to GPS: The Global Positioning System", Artech House Publishers, Boston, USA, 2001.

[2] A.D.Sarma and T.Madhu, "Modeling of F2 using Neural Networks at an Equatorial Anomaly Station", Current Science, PP: 1245-1247, Vol.89, No.7,10th October, 2005.

[3] P.K. Bhuyan and Rashmi Rekha Borah, "TEC derived from GPS network in India and Comparison with models", Advances in Space Research, Volume 39, pp. 830-840 issue 5, 2007.

[4] P. V. S. Rama Rao, S.Gopi Krishna, J. Vara Prasad, S.N.V.S. Prasad, D.S.V.V.D. Prasad and K. Niranjan, "Geomagnetic storm effects on GPS based navigation" Ann. Geophys., 27, 2101–2110, 2009

[5] B.T.Tsurutani, A.J.Mannucci, B.Iijima, F.L.Guarnieri, W.D.Gonzalez,D.L.Judge,P.Gangopadhyay, J.Pap, " The extreme Halloween 2003 solar flares (and Bastille Day, 2000 Flare), ICMEs, and resultant extreme ionospheric effects: A review", Advances in Space Research 37 (2006) 1583–1588.

[6] A.D.Sarma, N. Prasad and T.Madhu, "Investigation of suitability of grid-based ionospheric models for GAGAN", Electronics Letters, Vol.42, No.8, 13th April 2006.

[7] D. Bilitza and Reinisch, B., International Reference Ionosphere 2007: Improvements and new parameters, J. Adv. Space Res., 42, #4, 599-609, doi:10.1016/j.asr.2007.07.048, 2008.

[8] R.Cop, S.Mihajlovic and LJ.R.Cander, "Magnetic Storms and their influence on Navigation", Pomorstvo (Journal of Martimes Studies), Croatia, god.22.br.1 (2008), str 89-99.

[9] E.Correiaa, R.V. de Souzaa ,"Identification of solar sources of major geomagnetic storms", Journal of Atmospheric and Solar-Terrestrial Physics 67 (2005) 1702–1705.

[10] Ruiguang Wang, "Large geomagnetic storms of extreme solar event periods in solar cycle 23", Advances in Space Research 40 (2007) 1835–1841.

[11] Pratap Misra and Per Enge, "Global Positioning System'',Ganga-Jamuna Press, NY, 2001.

[12] http://sopac.ucsd.edu/dataArchive

[13] Orhan Ugurlu, Umut sezen and Ali Ziya Alkar, "Web Based Automated Total Electron Content computation", 3rd international conference on Recent Advances in Space Technology, 2007 (RAST'07), Istambul, Turkey, pp 35-38,14-16 June 2007.

[14] Rajat acharya, P.D.Yadav, Vipin Chandra Pant, M.R.Sivaraman, "Development of Grid Based Model for GAGAN", URSI GA Poster Presentations, Tuesday, October 25, 2005, GP1.54(01182).

N.Venkateswara Rao received his B.Tech. degree in Electronics and Communication Engg from Jawaharlal Nehru Technological University, Hyderabad, India in 1990, the M.E. degree in microwave and Radar Engg. From Osmania university, Hyderabad, India in 1997, and now working towards his PhD from Jawaharlal Nehru Technological University. He is currently a Professor with the Department of Electronics and Communication engineering, Bapatla Engineering College, Bapatla, A.P, India. His research interests include satellite Navigation, mobile communication.

T.MadhuDr. T.Madhu received his B.E. degree in Electronics and Communication Engg from University of Madras, Chennai, India in 1992, the M.Tech degree in E.C.E from R.E.C., Kurukshetra, India in 1994, and his PhD from Osmania university, Hyderabad, India in 2004. He is currently working as Principal, ASR College of Engineering, Tanuku, A.P., India. His research interests include satellite Navigation, mobile communication.

Dr. Lal Kishore the Rector of the now autonomous Jawaharlal Nehru Technological University is an expert in the academic front. He has good administrative skills having handled various positions in the university itself. Dr.Kishore has membership in many honourable professional societies. The awards and honours received by him indicate that he is an able administrator and an academician too. He has the credit of writing many textbooks on complex subjects like Electronic Devices and Circuits, Linear I.C. Applications and Electronic Measurements. Along with this he is the recipient of many awards and honours both nationally and internationally. A few of his awards are from the Defence Engineering College, Ethiopia for distinguished service, another award from International Compendium for distinction in Academics.