Ionospheric studies for the implementation of GAGAN

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Satellite Based Augmentation System (SBAS), being developed by Indian Space Research Organization (ISRO) in collaboration with Airports Authority of India (AAI) is known as “GPS Aided GEO Augmented Navigation” (GAGAN). It is expected to offer better accuracy and integrity of navigation service than with GPS alone by providing correction terms to the GPS signals. This is achieved by modelling a Near Real Time Grid Based Ionospheric Delay Model for correcting propagation delay at 1575.42 MHz (L1) using measurements at 1575.42 and 1227.6 MHz (L2). Existing algorithms are replaced by Kriging based model to meet the requirement of correction with 0.5 m maximum residue over Indian region. Details of the data collection and pre-processing, including estimation of the Total Electron Content (TEC), which is a measure of ionospheric delay, has been described. Kriging algorithm and some preliminary results of studies are also presented in this paper. This includes the spatial decorrelation of the stochastic random field over the deterministic variation of ionospheric TEC. Its variation with time and locations are investigated and a temporal dependence found to exist. Large scale ionospheric irregularities and depletions that cause severe amplitude and phase scintillations are also studied. Their impacts on GAGAN are also shown. Some major scientific studies required to be carried out over Indian region to improve the GAGAN performance is discussed.

Keywords: GPS, Equatorial ionosphere, SBAS, GAGAN, Ionospheric Large scale model, Kriging, scintillation

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1 Introduction

Indian Space Research Organization (ISRO), in collaboration with Airports Authority of India (AAI), is planning to implement Satellite Based Navigation System (SBAS) over Indian airspace. This is popularly known as GAGAN (GPS Aided Geo Augmented Navigation). The basic architecture of GAGAN is similar to WAAS, as this need to be compatible with the international standards and recommendations.

International Civil Aviation Organization (ICAO) has suggested that a near-real time 5° × 5° grid based ionospheric large scale ionospheric model is required to be developed 1. So GAGAN has to retain the grid based structure. This puts the challenge, to retain the standards, on one hand and to make the system useful for the very dynamic equatorial region, on the other. Efforts have been undertaken by ISRO to alleviate all these impediments.

The Indian SBAS architecture of GAGAN is equipped with a network of eight dual frequency GPS receivers for operations. There are 18 additional receivers for Ionospheric studies. Data are collected at these receivers and archived. The present authors have developed in-house an end-to-end solution for pre-processing the raw data. It estimates Total Electron Content (TEC) up to the accuracy of 1 TEC unit. Raw measurements-code and carrier phase from GPS dual frequency receivers can be used to determine the slant TEC. The noisy but absolute code derived TEC measurements are carrier smoothed using a smooth but ambiguous carrier phase derived TEC. The inter-frequency bias (IFB) of satellite is estimated using the $T_{\text{gd}}$ values transmitted by GPS satellites while that of the receiver is estimated using Kalman filter.

The major source of error in GPS is the ionospheric propagation delay at $L_1$. This is typically of the order of 30-80 m over Indian airspace. Since Indian airspace lies in equatorial anomaly region, the daily, seasonal and yearly variation of ionospheric delay is large and unpredictable. As per the proposed error budget in GAGAN, suitable models are required to be developed over Indian region, to correct the ionospheric propagation delay to better than 0.5 m. None of the existing empirical models like Klobuchar,
IRI (International Reference Ionosphere), Bent, PIM (Parameterized Ionospheric Model), Andersen or Chan & Walker, can meet this requirement. So there is need to test and evaluate other models and compare with the existing models before implementing in the grid based scenario.

From the measured TEC it is possible to calculate the delay in $L_1$. These are converted to vertical delay at ionospheric pierce points, i.e. the points where the ray path cuts the effective ionospheric height of 350 km. From these estimations, vertical delay is calculated at the ionospheric grid points (IGP), of an internationally defined grid structure. The user, on interpolating these delays at his position from the surrounding IGPs, can estimate the delay in his receiver and can correct the same. Using the measured data, different models have been tested for reconstruction accuracy and their comparative results are shown in this paper.

Based on this observation, SAC/ISRO has developed a large scale ionospheric model for estimating the group delay and error bound using the Universal Kriging technique. This model gives the estimates, the iono-delay at the IGP and also gives an over bound of the possible error in delay estimation at the user point. In order to estimate the latter, a statistical spatial correlation estimate of the residues, i.e. deviation of the true measures from definite estimations, is required to be made. Universal Kriging assumed an underlying trend. A planar trend is taken for the purpose. The residues are obtained by detrending the data using a first order fit. The statistical spatial decorrelation of the residues is used to obtain the Kriging parameters.

In WAAS, which uses a Planar Model, this decorrelation is taken as a constant of 35 cm for the whole coverage area as well as with time. India lies within the region of equatorial anomaly and experience a large deviation in the ionospheric contents, temporally and spatially. This results in variation in fitting of the model both in space and time. Hence the assumption of a constant standard deviation in the residuals is not valid here.

As this forms an important component in the large scale estimation, the correlation variation has been studied. Study has been done on the variation in time segments of three hours each. To study the variations at different times of day, early morning, peak time and post peak time has been chosen. Out of these, some definite observations have been reached. Same exercise is done for three different locations over India to find its validity over different parts on India.

In addition, over Indian airspace, ionospheric irregularities and depletions are formed after sunset. They cause amplitude and phase scintillations in GPS signal resulting in frequent receiver unlocks, especially after sunset and up to midnight. They can cause degradation in availability and continuity of GPS and GAGAN service.

This paper presents the results of the statistical studies done on the above aspects.

2 Data collection and pre-processing
To carry out necessary ionospheric studies for GAGAN implementation, it is necessary to collect both TEC and Scintillation Index (both amplitude and phase scintillation) data over Indian region and suitable network of ionospheric stations. Use of GPS dual frequency receivers is required for this. Figure 1 show the selected locations over the grids in India where dual frequency GPS receivers are installed to collect the ionospheric data for GAGAN. The stations are selected nearly at the centres of the eighteen $5^\circ \times 5^\circ$ grids over India, including the islands. It is assumed that GPS data collected up to a lowest elevation angle of $15^\circ$ from each of the 18 stations in the network can be used to compute TEC accurate enough for implementation of the grid based model.

The receivers collect pseudorange and carrier phase data. It estimates in real time, TEC and amplitude and
phase scintillation parameters ($S_4$ and $\sigma_\phi$) from the data collected over one minute interval and record the data every minute on a PC. Simultaneously, the authors have developed in-house an end-to-end solution for pre-processing the raw data up to TEC estimation with adequate accuracy.

2.1 Data pre-processing

2.1.1 TEC estimation

TEC can be calculated from relative code delay and also from relative carrier phase measurement at $L_1$ and $L_2$ using dual frequency GPS receiver. The relation is as given below:

$$\text{TEC}_\varphi = 9.483 \times (\varphi_1 \lambda_1 - \varphi_2 \lambda_2)$$
$$\text{TEC}_\rho = 9.483 \times (\rho_2 - \rho_1) \quad \ldots (1)$$

where $\rho_1$ and $\rho_2$ are pseudo ranges in meters at $L_1$ and $L_2$ frequency. Also $\varphi_1$ and $\varphi_2$ are the carrier phases in cycles at $L_1$ and $L_2$ and $\lambda_1$ and $\lambda_2$ the respective wavelengths.

2.1.2 Carrier smoothing

Figure 2 shows that the TEC from pseudorange is noisy while the TEC from carrier phase is smooth but negative due to ambiguity factor. To get noise free and absolute TEC, an approach similar to Hatch filter is used for carrier smoothing. In this approach, moving average of the difference between TEC from code and carrier phase is calculated at each epoch and is added to the carrier phase TEC. It can be expressed as:

$$\text{TEC} = \text{TEC}_\varphi + \frac{1}{K} \sum_{k=0}^{K} \left( \frac{TEC^k}{\rho} - \text{TEC}_\varphi^k \right) \quad \ldots (2)$$

where, $k$ is the epoch time. As time progresses smoothing gets better by adding terms to moving average. It is observed that value of $K = 15$ chosen is enough for smoothing, as addition of more points doesn’t give any further conspicuous differences. The smoothed carrier phase TEC fitted to the level of code TEC is also shown in Fig. 2.

2.1.3 Bias removal

The total bias added to the signal is the sum of the satellite and the receiver bias. Satellite bias includes differential P1P2 code bias and differential P1C1 code bias, which are estimated and measured separately. Receiver IFB is caused by the difference between the frequency response of filtering the GPS $L_1$ and $L_2$ signals, resulting in a time-misalignment of the two pseudorange and can be treated as a systematic bias. The authors propose using Kalman filter for the IFB estimation of receiver. Combining all the biases one can write the true TEC as

$$\text{TEC}_{\text{true}} = \text{TEC} + P_1P_2'_{\text{bias}} - P_1C_1'_{\text{bias}} + R_{\text{bias}} \quad \ldots (3)$$

Differential P1P2 code bias can be determined from the GPS broadcasted $\tau_{GD}$ values by calculating GPS offset time and mean $\tau_{GD}$ values. Method of estimating P1-P2 bias has been studied and working algorithm developed. The P1C1 bias values are available on CODE website. These values are used and converting into TEC units, it is also applied to Eq. (3). The receiver bias ($R_{\text{bias}}$) is estimated using the Kalman filter (Ref 6). As the daily variation of the Receiver Bias is very small, it is estimated once in 24 h and applied for that day. Applying all these inter-frequency biases of satellite and receiver, the authors obtained the absolute true slant TEC from the receiver.

Figure 3 shows the effect of IFB for two different collocated receivers, viz. Rx-214 and Rx-215. The combined value of IFB of satellite and receiver for Rx-214 is $+6.6$, where as that of Rx-215 is $-5.45$. The close proximity of the two values after bias correction validates the method.

This validation of the method is further extended by using two collocated receivers for longer durations, which should give the same TEC value after removal of bias. Two dual frequency NovaTel OEM-4 receivers were placed at same location in Ahmedabad on 28 Feb. 2006. The GPS data were logged at the sampling rate of 1 s. The TEC is estimated at each epoch and averaged at one-minute
interval. The biases are estimated out of them. Figures 4 (a)-(c) show the values of slant TEC recorded by two receivers, viz. Rx-214 and Rx-215 after removal of bias on the said date and locations.

It can be observed that TEC from both the receivers follow the same trend and the difference between them is minimal and less than 1 TECU. On comparing the two receivers for two days it is observed that difference of slant TEC between two receivers is within 1 TEC unit. This validates the method to provide accuracy within 1 TECU.

Data have been collected since March 2004 from all the 18 stations and pre-processed and archived for analysis.

3 Studies and major results

ISRO and AAI have jointly carried out necessary data analysis for the following:

(a) Development of algorithm for implementation of 5° × 5° Grid Based Ionospheric Model, suitable for equatorial region
(b) Morphological studies of L-band scintillation and ionospheric bubbles

The algorithm should generate at the IGPs of the 5° × 5° grids over Indian region, Grid Ionospheric Vertical Delay (GIVD) and Grid Ionospheric Vertical Error (GIVE) at intervals of 300 s. The major assumptions in the Grid Based Model are as follows:

(i) The propagation delay effects due to higher orders of frequency (higher than second order) are negligible
(ii) Vertical TEC at any point within a grid of 5° × 5° can be determined with only four values at the corners of the 5° × 5° grid.
(iii) The ionosphere is assumed as a thin shell at a height of about 350 km and vertical TEC is assumed to be distributed at this height. Vertical gradients in electron density are neglected.
(iv) Mapping function to convert slant to vertical TEC and vice versa is a simple secant function. This assumes that the ionosphere is horizontally stratified.
(v) Ionospheric conditions do not change within 300 s and the GIVD and GIVE values need to be updated at intervals of 300 s.
3.1 Selection of model

There are many algorithms available and suggested for implementing real-time grid based ionospheric model. A list of the algorithms tried out by many scientists, working in WAAS implementations are as below.

Inverse Distance Weighted with Klobuchar Model (WAAS old Model)

(i) Planar Model (WAAS New Model)
(ii) Kriging Technique
(iii) Ionospheric Tomography
(iv) Two-layer Model
(v) Dual Shell Model
(iv) Junkin’s Model
(vii) Simple Bilinear Model
(viii) Minimum Least Squares Estimator

The first six algorithms are the most popular for GAGAN, the performance of these six algorithms are being tested with collected data for reconstruction at the measured point through estimation of GIVD.

In Fig. 5, the performance in terms of reconstruction accuracy of first three algorithms tested is shown. The

![Graph showing reconstruction errors using different algorithms in TEC for quiet and disturbed days.](image)

Fig. 5—Monthly mean of reconstruction errors using different algorithms in TEC for (a) quiet days and (b) disturbed days (From March 2004 to February 2006; Time – 0000 hrs UT; Grid size – 5° × 5°; Maximum and Minimum errors indicated by Error bars about mean error)
Figures show the monthly mean error in reconstructed TEC at the user IPP, with maximum and minimum errors obtained using Kriging. Inverse Distance weighted with Klobuchar model (US WAAS and modified US WAAS) and Planar technique for magnetically quiet for 0000 hrs UT (early morning hours when the ionospheric TEC values are minimum) and for magnetically disturbed days for 0800 hrs UT (afternoon hours when the ionospheric TEC values are maximum). The data used are for one year from March 2004 to February, 2005 from 16 stations (excluding the data from the two islands). The grid size used is 5° × 5°.

It can be seen that the performance of Kriging is the best. Still the Kriging technique does not provide the required accuracy for GAGAN at all times (accuracy better than 3 TECU), especially during very severe magnetically disturbed days.

On the basis of the performance, Kriging has been chosen as the best candidate among the selected ones for the large scale ionospheric model in this region. Algorithm has been developed, based on this technique, to generate the required GIVD and GIVE at the grids.

3.2 Kriging algorithm and correlation analysis

Ionospheric large scale model recreates the Ionospheric Vertical TEC in a broad scale over whole space from the knowledge of some measured values at known positions. Algorithm based on the Kriging Technique has been developed. The details of the same are given in Ref. 7. Universal Kriging is employed, which assumes a Planar underlying trend with a random field superimposed on the same.

If \( I(x) \) is the vertical ionospheric TEC at the IPP located at \( x_x \), then

\[
I(x) = a_0 + a_1 \times x_{\text{east}} + a_2 \times x_{\text{north}} + r(x) \quad \ldots (4)
\]

Here these coordinates \( (x_{\text{east}}, x_{\text{north}}) \) can be considered to be respectively the longitude and the latitude. The coefficients \( a_0, a_1 \) and \( a_2 \) describe the planar trend. The scalar field, \( r(x) \), includes the small features superposed on the planar trend and it determines the de-correlation between neighbouring measurements. This de-correlation data are used in Kriging model to obtain the relevant parameters, giving a refined optimal estimation above the assumed planar trend. It is the behaviour of this field, \( r(x) \) that determines the estimation accuracy at any unknown point by Kriging used in GAGAN. So it is needed to study the correlation between pairs of residuals \( r(x) \) over distance.

For this purpose, the concept of additive correlation is used. For the present requirements, this technique is more accurate. Here, first the planar trend is removed by fitting the measurement with the least square fit with data in the neighbourhood of a chosen location. Care has been taken to ensure that the outliers do not influence the fitting plane. The residues are thus obtained by differencing the measured values of the vertical TEC and the one estimated by the planar trend. From all these residues, all possible IPP pairs are made and their Vertical TEC residue difference is plotted against their distance. The differences of residuals for every possible pair of IPP are recorded against the distances between the IPPs in question. This is done for distance up to 2000 km in bins of 40 km each. For each distance, the counts of points are obtained for the residue differences in bins of 0.1 m of vertical delay (proportional to TEC). From these counts the \( \sigma \) for each distance is estimated with a resolution of 0.1 m using the technique described below. It is important to note that it is required to compute the distribution of residual differences, \( \Delta r(\Delta r) \), between the IPPs and not for the residues themselves.

From the obtained distribution of the residual difference, the required parameter is generated in the following manner. The standard deviation of the residual difference is determined for each distance, resolved by the bin size, considering the Gaussian distribution of errors. The idea is to assume normal distribution and compute the containment quantile line up, the distribution is close to Gaussian and the respective standard deviation is obtained. Such plots were analysed from data and inferences drawn from the observations.
4 Observations and discussion

4.1 Observation of correlation values

The days chosen for the purpose were 18 and 19 of Aug. 2006, with \( K_p \) indices 20.3 and 29.0, respectively (summed over all 8 measurements of the day). The neighbourhood selected were at three distant regions located at 25°N, 75°E in the west of India, 20°N, 85°E in the east and 15°N, 75°E down south.

Firstly, the trend of the residual difference is obtained with mean residual data derived from each 300 s snapshot and its variations are observed with time. The 2nd order polynomial trend lines of the same for 18 Aug. 2006 for three mentioned locations respectively, are shown in Figs 6(a), (b) and (c). The trend lines are observed to vary temporally peaking at the day time with much lower values at night. The same trend is observed for all three regions of interest and this is the motivation for the rest of the work.

The value of \( \sigma_{\text{decorrelation}} \) is obtained from the processed data for each segment over the whole day. Figures 7 (a), (b) and (c) represents spatial variation of \( \sigma_{\text{decorrelation}} \) at [15N°, 75 E°] for three segments of time, (a) 0300-0600 hrs UT, (b) 0600-0900 hrs UT and (c) 0900-1200 hrs UT, respectively. The general observation is that, the three quantile plots merge well around 1.0 m during the early morning times, viz. 0300-0600 hrs UT, when the ionosphere is very benign, revealing the Gaussian nature of the residuals. This feature continues to remain in the time segment of 0600-0900 hrs UT, but the value of \( \sigma \) increases to around 2.5 m. During the latter part of the day, say 9-12 hrs, they do not coincide well and the average value remains around 2.5 m. The distinct separation between the three quantile plots indicates that the tails of the distribution has extended beyond the normal distribution. The same nature exists for all regions considered. It is most important to note that, plots obtained at two different times have considerably

![Fig. 6](image1)

![Fig. 7](image2)
different values. Figures 8(a) and (b) show the temporal variations of the $\sigma_{\text{de-correlation}}$ for different locations for 18 and 19 Aug. 2006, respectively.

It is observed that conspicuous differences are obtained over the day. It remains low near the cold night and increases during the anomaly, although the maximum does not coincide with the anomaly peak time for the region. In both the days, it has been observed that the variation is highest in the southern regions compared to those in the anomaly belt. This is probably because the $\sigma_{\text{de-correlation}}$ values in the anomaly region, remains comparatively high throughout the day and hence do not show much variation. The highest value attained is more on the second day than the first. This may be due to the fact that the first day is magnetically quieter than the second.

### 4.2 Observation of scintillations

The aviation community in India, using GAGAN, is interested to know the impact of scintillation on the availability of GAGAN (and GPS in general) in the Indian region. For this, preliminary studies on spatial and temporal variation of $S_4$ index and their percentage occurrences are made at SAC/ISRO.

Figure 9 shows typical spatial and temporal variation of $S_4$ observed on 25 and 26 Mar. 2004 (equinoctial month) over Indian region. In Fig. 10, monthly plots of percentage occurrence of scintillation index $S_4$ exceeding 0.17, 0.3, 0.45 and 0.7 (causing signal fading of $> 3$ dB, $> 6$ dB, $> 10$ dB and $> 15$ dB, respectively at L-band) for 2004-05 for Trivandrum, Bangalore and Hyderabad are shown.

The main observations obtained for L-band scintillations over Indian region are:

(a) Scintillations are generally nighttime phenomena and normally occur after the sunset and lasts till 2 h after midnight.
(b) Highest levels of scintillations are observed between 20° and 25° latitudes, i.e. around the Equatorial anomaly peak.

(c) L-band scintillations do not occur every day even in equinoctial months.

(d) Daily variation of S4 index is large and is not related to the daily variation of magnetic activity. The scintillations do not predominantly occur either on magnetically quiet or disturbed days.

(e) Relatively maximum percentage of scintillation is observed over Hyderabad and Ahmedabad, near equatorial anomaly peak region, and minimum percentage of scintillation is observed over Shimla, which lie outside the equatorial anomaly.

One of the distinguishing features of the equatorial ionosphere is the occurrence of TEC depletions during night times. These TEC depletions known as Ionospheric Bubbles (IB), is a small confined region, with low electron density. These bubbles frequently form in equatorial regions just after sunset and rise into the F-region, where electron densities are otherwise high. The IBs cause (i) failure of convent-
ional grid based model, proposed to be used in GAGAN and (ii) strong scintillations, causing loss of lock of GPS signals. So it is very important to carry out a statistical study of occurrence of IBs in Indian region, in order to understand the extent of its effects on satellite navigation services. In Figs 11(a) and (b), simultaneous observations of TEC and S4 for a GPS satellite pass of PRN 20 on 2 Apr. 2004 over Trivandrum, Bangalore, Hyderabad, Visakhapatnam and Mumbai are shown. The stations (except Visakhapatnam) are along the same longitude in the increasing order of latitude. It can be seen clearly that simultaneous occurrence of bubbles and large L-band scintillations are observed at all stations but the levels are different at different places.

Development of suitable ionospheric depletion mitigation algorithm at the user receiver based on the statistical studies is planned for GAGAN. Efforts are also necessary, to develop L-band scintillation Prediction Models over Indian region, similar to WBMOD.14

5 Conclusions

Ionosphere specific studies are done over Indian airspace with pre-processed ionospheric data. Efforts are put mainly on, (i) development of suitable grid based ionospheric models and (ii) morphological studies on L-band scintillations. Heuristically, Kriging technique is found to be performing best among the many grid based algorithms. But during very severe magnetically disturbed days average Kriging reconstruction error remains large around 6.8 TECU. Efforts are on to study the performance of other approaches like Tomography and Multi-shell/layer Models.

It is observed that the $\sigma_{\text{decorrelation}}$ values of the residues over underlying planar trend of the vertical TEC are dependent on time in Indian equatorial anomaly regions, violating Gaussian assumption during certain periods. Hence it is concluded that a single decorrelation value is not recommendable for this region. The decorrelation values have been observed to vary largely by 1.5 - 2.5 m over a day. This is due to the reason that distribution of residues over the planar trend does not remain same over different periods of the day, expanding the most during the anomaly period of the day and reducing at quiet part of nights. This variation is feebly dependent on the locations where the decorrelation analyses are done. Any single flanked value of $\sigma$ may cause great deviations in GIVE values and may affect the availability of GAGAN. So this correlation values, used in Kriging for Indian equatorial region, should be updated with time of the day. An alternative way is to overbound the highest possible errors conservatively, sacrificing availability.

The L-band scintillations are severe over Indian region during equinoctial months, after sunset up to midnight and cause frequent loss of lock of GPS signals. Development of suitable L-band scintillation prediction models over Indian region will be useful. As IBs can cause failure of grid based models over Indian region, suitable mitigation techniques have to be developed over Indian region.

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