Ionospheric Effects on SBAS Performance – Indian perspective

By

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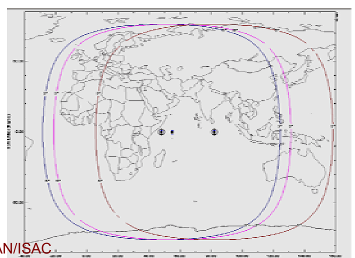
Overview

- Current status on GAGAN Development activities
- Features of Ionosphere over Equatorial region
- TEC Data Network
- Temporal and Spatial Study of TEC
- Morphological study of Scintillation
  - Annual, seasonal, diurnal & Latitudinal variation of S4 index during 2004-2009
  - Study of plasma Bubbles
- Space Weather Effects
- Ionospheric Models
  - Empirical Models
  - Grid Based Models

GAGAN Objective

- To realize:
  - RNP 0.1 en route navigation within Indian FIR
  - APV-1/1.5 precision approach over the landmass of Indian FIR

- GAGAN SIS to meet the
  - Integrity
  - Availability
  - Continuity
  - Accuracy



Common coverage of GAGAN GEO satellites (55, 82 and 83 deg) is beyond the Indian FIR (GSAT-8, GSAT-10 & GSAT-9)

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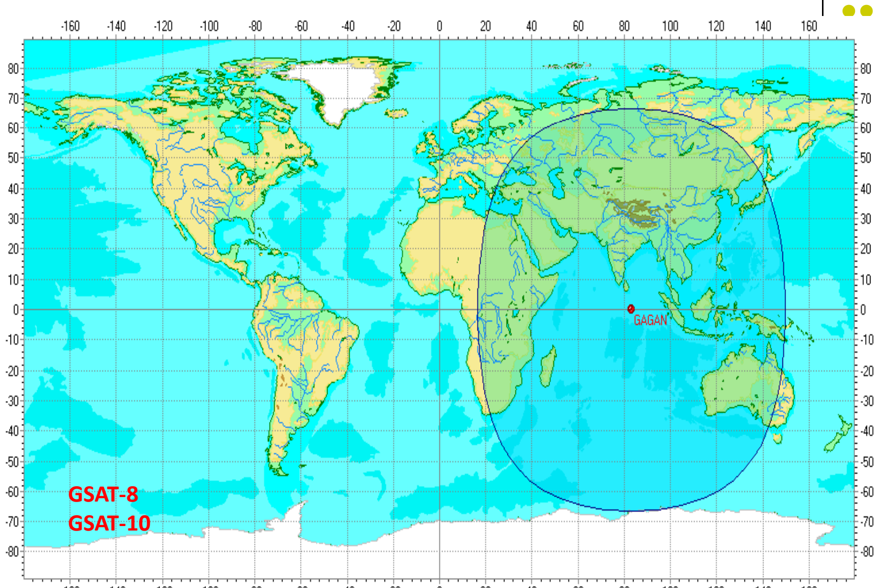
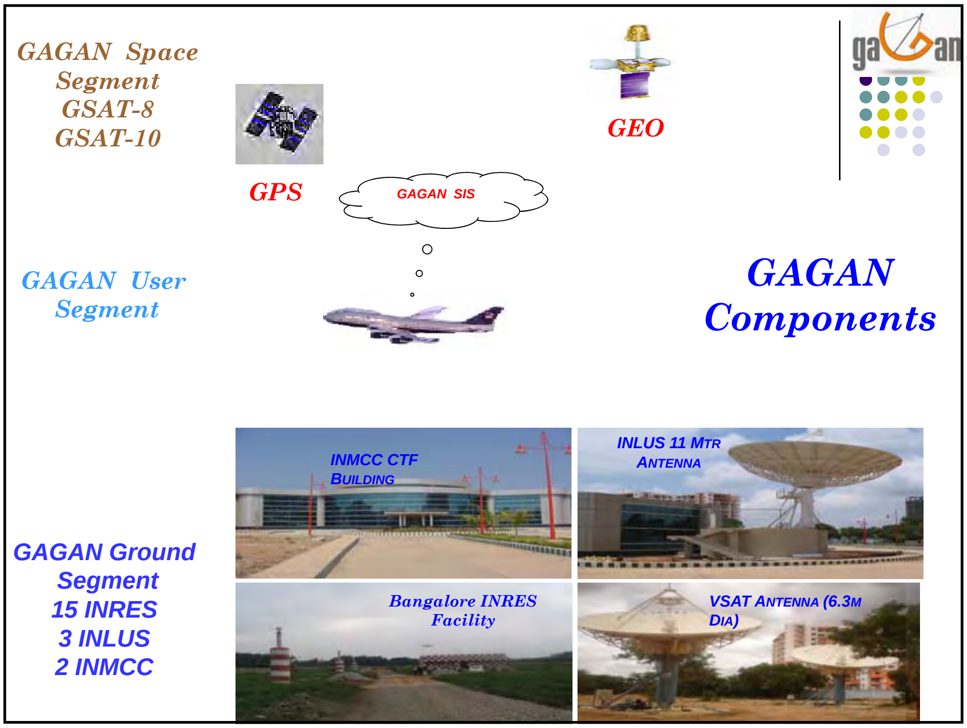
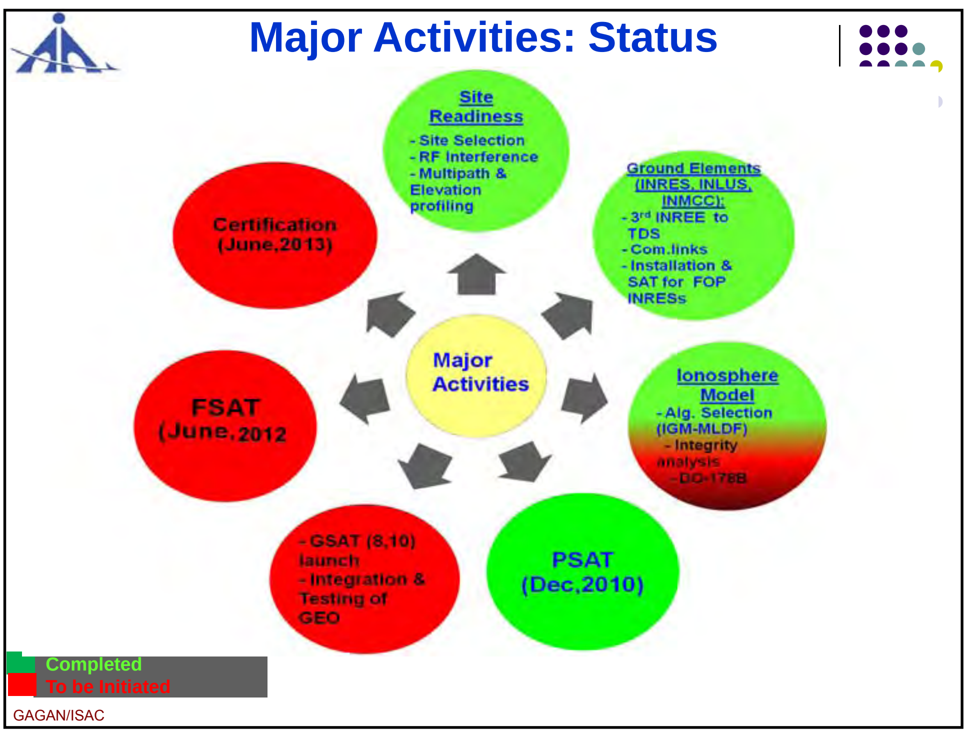
GAGAN Coverage




GAGAN Space Segment
GSAT-8
GSAT-10
GPS
GEO
GAGAN SIS
GAGAN User Segment
GAGAN Components
GAGAN Ground Segment
15 INRES
3 INLUS
2 INMCC
INMCC CTF BUILDING
INLUS 11 MTR ANTENNA
Bangalore INRES Facility
VSAT ANTENNA (6.3M DIA)


Major Activities: Status
Site Readiness
- Site Selection
- RF Interference
- Multipath & Elevation profiling
Ground Elements (INRES, INLUS, INMCC):
- 3rd INREE to TDS
- Com.links
- Installation & SAT for FOP INRESs
Ionosphere Model
- Alg. Selection (IGM-MLDF)
- Integrity analysis
- DO-178B
PSAT (Dec,2010)
- GSAT (8,10) launch
- Integration & Testing of GEO
FSAT (June,2012
Certification (June,2013)
Major Activities
Completed
To be Initiated
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Path Forward

Jun' 13

- Data analysis for HMI
- Certification Process
- Procedures for GAGAN approaches
- Final Certification

Jun' 12

- Data collection for IGM-MLDF validation
- S/w Build updates
- Open service to users
- Study and Analysis of SIS
- Launch of GSAT-10
- INLUS Integration with GEO
- Final System Acceptance Test

May' 11

- Certification: TRT Activities
- Launch of GSAT-8 & INLUS Integration with GEO
- OJT & other trainings
- Establish second chain communication links
- Iono model Integration and Testing
- Technical Consensus for System Performance

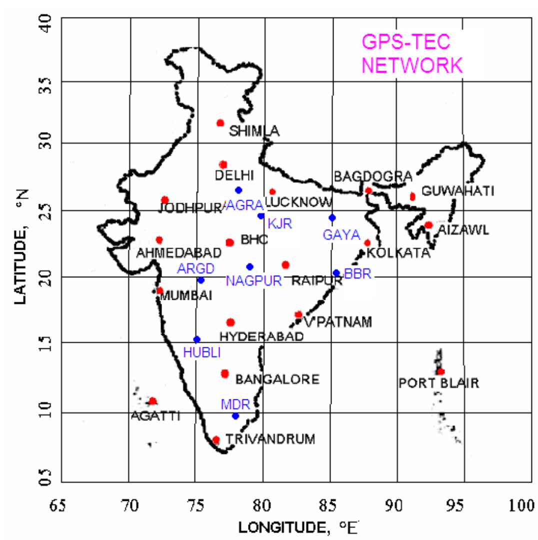
Critical Path

- Study of Ionospheric effects
- Mitigation process for GAGAN
  - India wide data collection & analysis
  - Studying suitable model for GAGAN
  - Carrying out threat model analysis
  - Study by Algorithm Working Group
  - Technical consensus
  - Integration with APV 1.0 applications

Features of Ionosphere over India

- India lies in Equatorial Ionization Anomaly (EIA) region
- Ionospheric delay at L band are very high
- It is highly variable with time and latitude (Dynamic)
- High Occurrence of L band scintillation
- Ionospheric Bubbles (depletions) occur more frequently over the region
- **Equatorial ionosphere is extremely complex to model where as Mid-latitude ionosphere is well behaved and successfully modeled.**
- Large number of interdependent parameters
  - Electric field
  - Neutral wind (zonal, meridional, vertical)
  - Solar parameters (F10.7, sunspot no., IMF)

GPS- TEC data Stations



GPS-TEC data Network

- Installation of TEC data loggers - 18 dual frequency GPS receivers - 2003-2004. Later by 2008 increased to 26.
- GSV4004 for ionospheric data collection providing-
  - time tagged TEC and Scintillation data
  - elevation angle
  - azimuth angle
  - Carrier to Noise Ratio C/N_0
  - Lock time, etc.

GPS-TEC data Network

- Raw data logging rate – 10 second interval
- The file size at this interval is approx 10 MB for 24 hours.
- The receiver and satellite bias is a major issue in getting absolute and accurate TEC.
- Satellite bias is corrected by downloading the DCB values from internet and Receiver bias is estimated using the Kalman filter.

Effect of Ionosphere on Satellite-Based Navigation

- Range error due to the group delay of the signal traveling through the ionosphere

  Δ_g iono = (40.3 / f^2) * TEC

  Range error due to 1 TECU = 0.16m at L_1

- Carrier phase advance

  $$\Delta\phi = \frac{1.34\times10^{-7}}{f}\times TEC \text{ (cycles)}$$

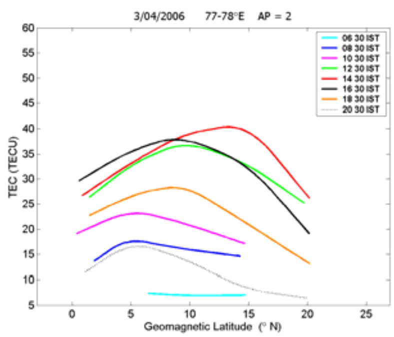
- Phase and amplitude scintillations caused by irregularities in the electron density distribution
- Effect:
  - Loss of Lock of satellite
  - Degradation of position accuracy
  - Affects the service availability

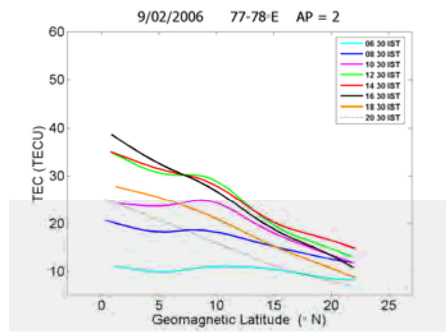
Equatorial Ionization Anomaly (EIA) Region

- The electron density is expected to be maximum over magnetic equator and monotonically decreasing on both sides (North and South)
- Appleton observed the peak electron density forming the 'trough' at the magnetic equator and crests at 15^0 to 20^0 North and South. This anomalous behavior is known as EIA or Appleton Anomaly region.
- EIA is strongly influenced by
  - solar flux and Earth's magnetic field
  - Diurnal, seasonal, & 11 year (solar cycle) variations
  - Storms, disturbances, irregularities

EIA development

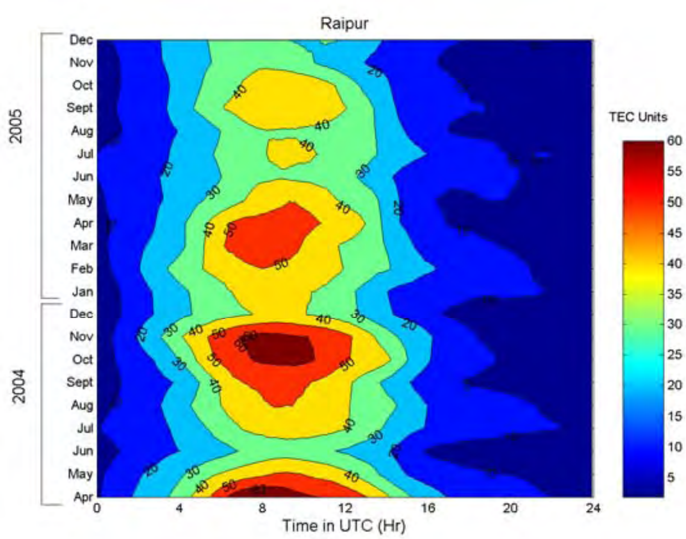
Typical EIA development | **Weak EIA development**



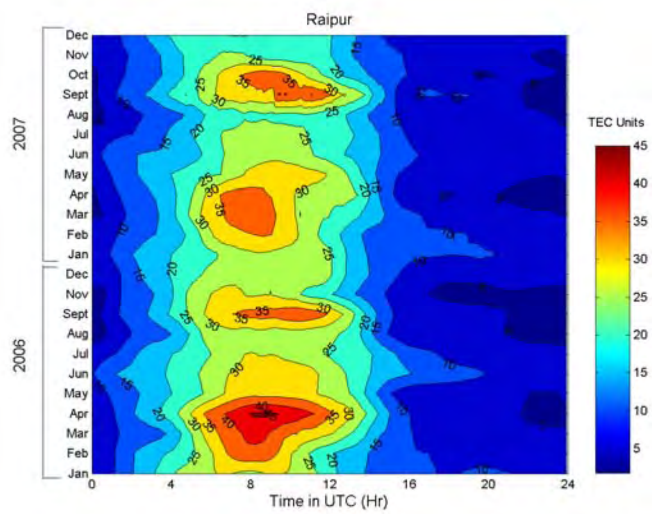


courtesy Dr. Sudha Ravindran , VSSC

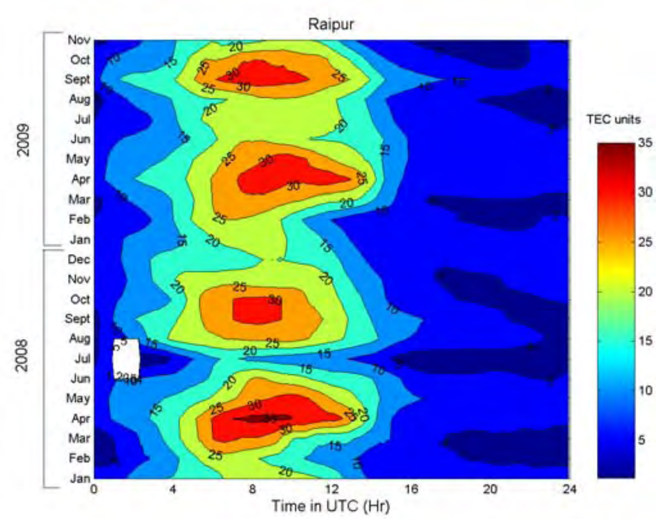
Annual and Seasonal Variations of TEC



Annual and Seasonal Variations of TEC



Annual and Seasonal Variations of TEC



Summary of TEC Studies

- The crest of Equatorial Ionization Anomaly (EIA) passes through 20^0 to 25^0 geographic latitude in Medium solar activity and 15^0 to 20^0 in solar minima.
- Large Day to day variations in TEC/range delays can be seen over the equatorial anomaly stations mainly during peak time of 1200 to 1600 hours.
- Maximum TEC at peak was around 60 TEC in 2004, 50 TEC in 2005, 45 TEC in 2006, 40 TEC in 2007, 35 TEC in 2008, 30 TEC in 2009 and 45 TEC in 2010 at crest of EIA (Raipur), which shows the direct dependency on solar activity.
- These values will go up in High Sun Spot Activity periods.
- The Equatorial Ionization Anomaly (EIA) maximizes during equinoxes (March, April and September, October) followed by winter and then summer months.
- Impact of Solar cycle on strength of EIA can be observed using the continuous study for one full solar cycle.

Scintillation

- Scintillation is defined as the rapid change in amplitude and phase of the GPS signal as it passes through the small scale irregularities in electron density in the ionosphere.
- It mainly depends on Solar cycle (Year), Season, Location (Latitude), Local time and Elevation angle.
- Amplitude scintillation is measured by the S_4 index, which is essentially a normalized standard deviation in the signal intensity over 60 seconds.

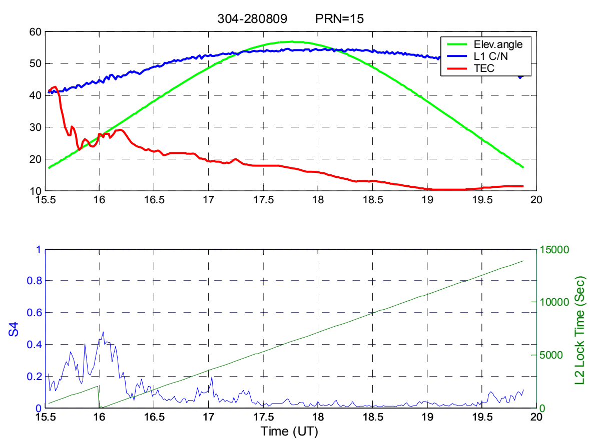
$$S_4 = \sqrt{\frac{\langle SI^2\rangle - \langle SI\rangle^2}{\langle SI\rangle^2} - \frac{100}{\overline{S/N_0}}\left[1 + \frac{500}{19\,\overline{S/N_0}}\right]}$$

- Phase scintillation is monitored by the standard deviation, $\sigma_{\Delta\varphi}$, of detrended carrier phase from signals received from satellites.

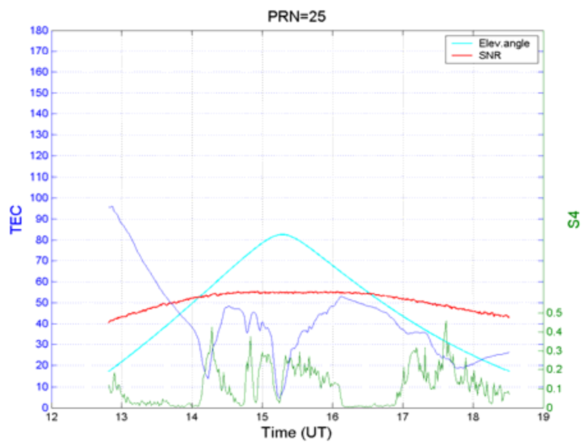
Scintillation

- Normally amplitude scintillation is divided into 3 categories- weak (S_4 <0.3), medium (0.3> S_4 <0.7) and strong ($S_4 \geq 0.7$)
- Scintillation Index S_4 > 0.4 could cause a receiver to lose lock on the ranging signals broadcast by the Geostationary SBAS satellites or GPS satellites depending upon the receiver tracking capability.
- It potentially can cause a short service outage for one or more aircraft.
- Statistics have been generated for scintillation epochs of S4 >= 0.4 for 2004- 2009 using the data from all the TEC stations.
- They have been segregated in terms of its dependent variables i.e. Year, Season (Month of year), Geographic Latitude, Time and Elevation Angle.

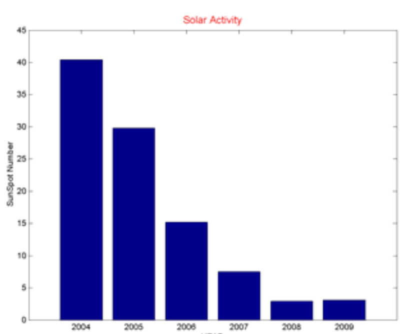
Scintillation – Loss of Lock

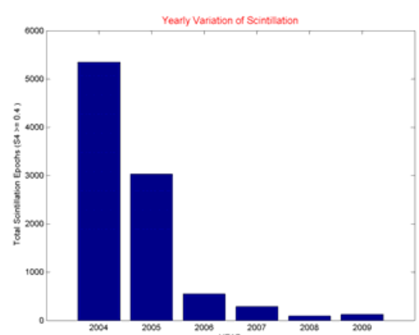


Depletion associated with Scintillation



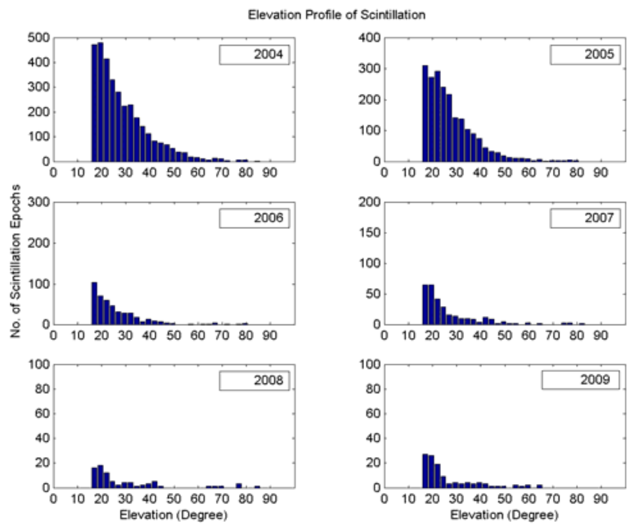
Scintillation
Annual variation with solar activity





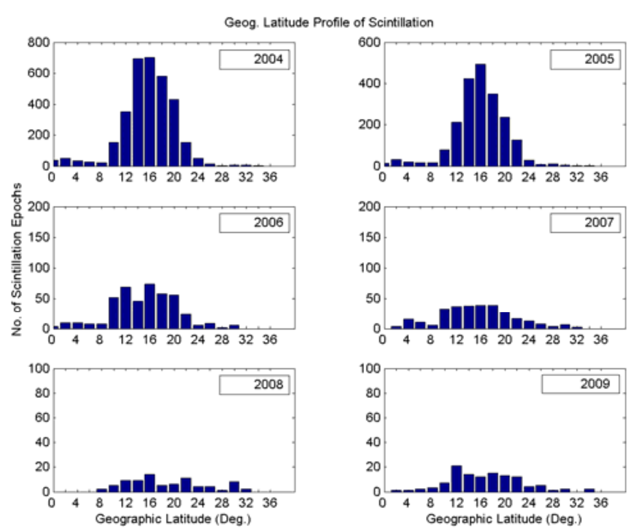
Scintillation

Variation with Elevation angle



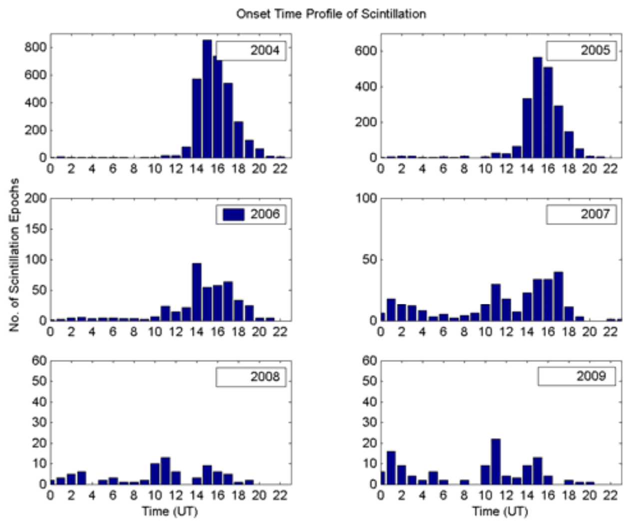
Scintillation

Variation with Geog. Latitude



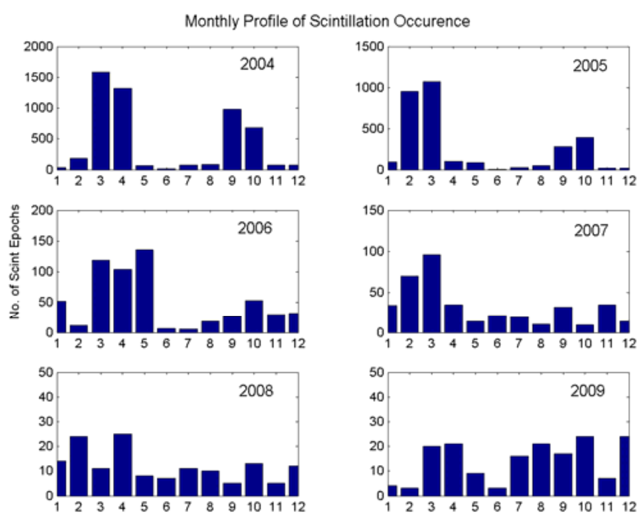
Scillation

Variation with Time



Scintillation

Seasonal Variation



Scintillation

- Scintillation mainly occurs between 1400 hour UT (19:30 IST) to 1900 hour UT (00:30 IST) i.e. after sunset till midnight.
- Most of the scintillation activity lies between geographic latitude of 10 to 22 Degree and occurs in equinoctial months- Mar, Apr, Sept, Oct.
- Large scintillation events are observed in high solar active period and very few events in solar minima.
- Low elevation satellites are more prone to scintillation activity as GPS signal has to traverse through more irregularity compared to high elevation.

Space weather effects

- Sun is major energy source to drive magnetosphere, thermosphere and ionosphere
- Coronal Mass Ejections (CME) from sun interact with solar wind and Interplanetary Magnetic Field (IMF) lines during their propagation.
- Fast CMEs eventually drive the shock hitting the magnetosphere and compressing the magnetic field and trigger the geomagnetic storms.
- It takes about 1 to 4 days to reach the ejected particles, whereas radiation from solar flares hits the earth's surface within 8 minutes from sun.
- Intense geomagnetic storms can cause electrical power outages, failure of communication satellites, loss of HF comm link etc.

Geomagnetic Storm

- K_p Index is used to classify the geomagnetic storms on the scale of 0 (quite) to 9 (Severe). K_p =5 indicates moderate storm.
- Most of the severe magnetic storms occur during the high solar activity period and only moderate storms occur during low solar activity period.
- Storm begins either gradually or with an abrupt change called a Sudden Storm Commencement (SSC), followed by initial positive phase, Main negative phase, and recovery phase according to the Disturb storm time (D_{st}) index.
- 5 moderate storms were recorded during the low solar activity period of 2007-2009.
  - March 24, 2007
  - Nov 20, 2007
  - March 9, 2008
  - October 11, 2008
  - July 22, 2009

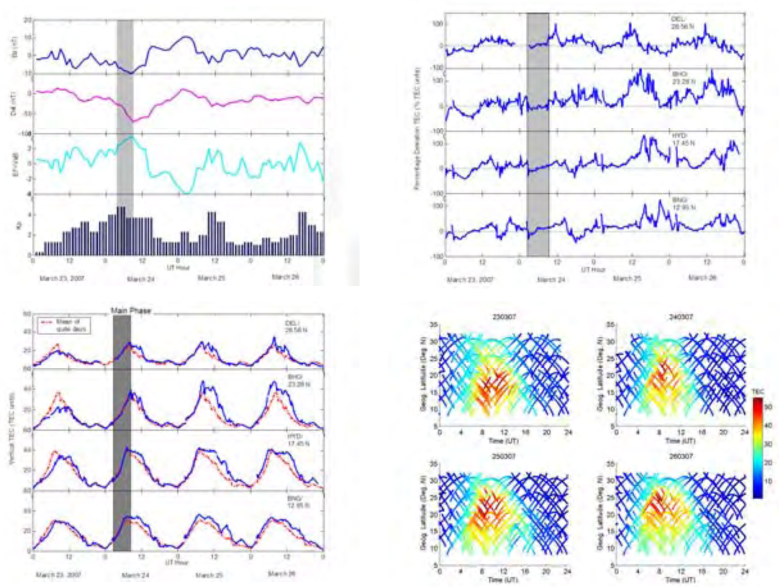
Geomagnetic Storm

- Each magnetic storm has unique character and varying effects on ionosphere at different latitudes and longitudes
- The electric field, plasma drifts and the onset of plasma instabilities in the equatorial ionosphere exhibit complex variations as compared to their quiet day patterns
- Forecasting the response of ionosphere during magnetic storm becomes difficult especially over equatorial region and therefore major concern for satellite navigation.
- Investigating the behavior of ionosphere during all sorts of geomagnetic storm will be helpful in developing the threat model for GAGAN.

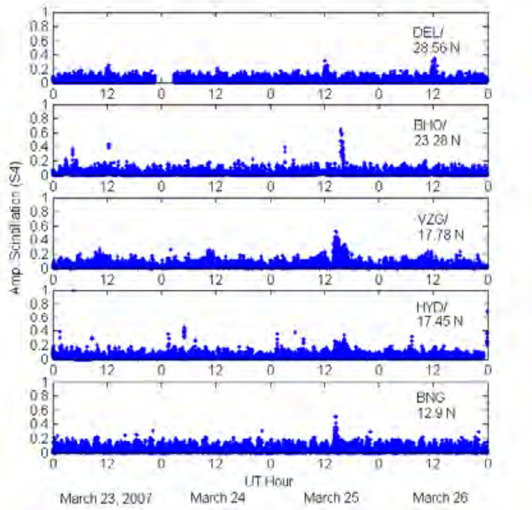
Iono response during Magnetic Storms

- Diurnal variation of TEC during storm days (SSC day, Main phase and next 2 days)
  - Vertical TEC is computed at 5 stations- Bangalore, Hyderabad, Bhopal/Raipur, Delhi and Shimla
  - Comparison of TEC with mean of 6 previous quite days
- Percentage Deviation of TEC
  $\%\delta = (TEC_s - TEC_{avgQ}) / TEC_{avgQ} \times 100$
- Latitudinal Variation of TEC
  - IPPs calculated from stations lying in the 77^0 E longitude and latitudes in the range of 5^o to 35^0 N
  - Vertical TEC is computed at each IPP to show the latitudinal behavior
- Investigation of Scintillation
  - Phase and Amplitude Scintillation
  - Loss of lock
  - Depletion (Bubble) or enhancement of TEC

Mag. Storm of March 24, 2007

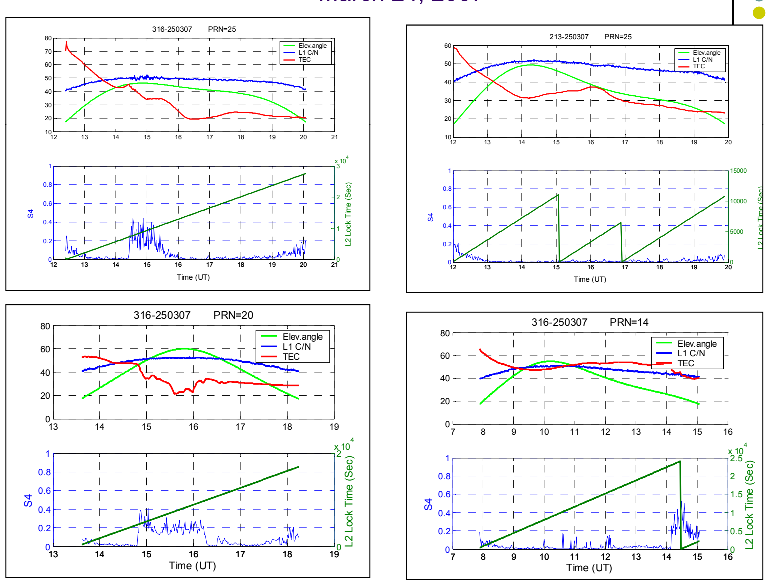


Scintillation during Mag. Storm of March 24. 2007



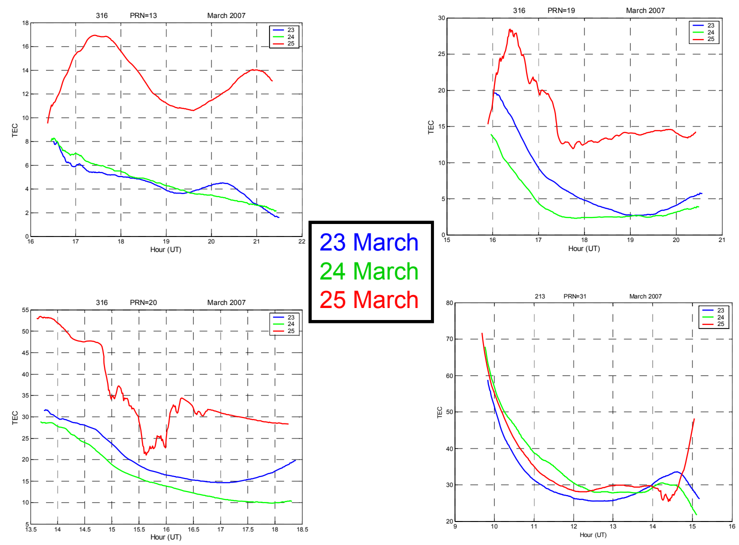
Scintillation and Loss of Lock

March 24, 2007



Depletion and Enhancement of TEC

March 24, 2007



Iono response during Magnetic Storms

- Storm positive phase during main phase is observed in 2 magnetic storms in local day time due to prompt penetration of electric field from high latitude to low latitude and equatorial region.
- This happens if there is sharp and sudden decrease in Dst. If decrease in Dst is gradual (Main phase duration ~ 5-6 hours), Negative effect (-ve deviation) is observed before main phase and no effect during main phase at Low Lat station but quick positive effect at high latitudes is observed.
- It is also observed that crest of equatorial anomaly shift towards higher latitudes if negative excursion of Dst is during local noon.
- Maximum positive deviation of 100% to 150 % is observed during all the storms in different phases.
- About 150 % deviation is recorded at the crest of equatorial anomaly BHO (23.28^0 N) during recovery phase of March 24, 2007 and Oct 11, 2008 storms in local night time.

Iono response during Magnetic Storms

- Scintillation is observed at many low latitude stations- Hyderabad, Bangalore, Vizag, Mumbai and Bhopal in between 1400 to 1800 UT for mag storm of March 24, 2007.
- Scintillation leading to loss of lock is also observed at Vizag and Bangalore for PNR 14 and 25.
- Depletion (bubbles) are observed accompanied with scintillation over Vizag for PNR 20.
- Enhancement of TEC is also observed during Night (1600-1700 hours) at Vizag for PNR 13 and 19 and at Bangalore for PRN-31 after 1430 UT
- No significant Scintillation is observed during other four moderate storms

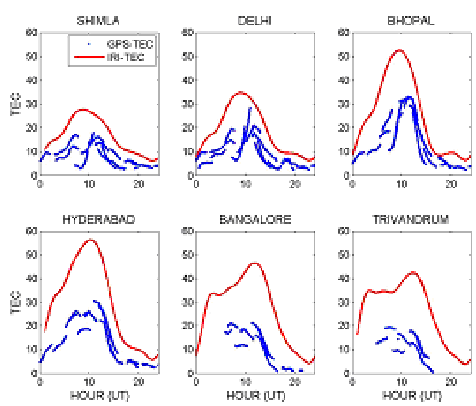
Types of Iono Models

- Empirical Models
  Used for generating the 'Supertruth' data for verification and validation of Grid based model.
  - Klobuchar model
  - IRI Model
  - PIM Model
  - ISRO-TEC model
- Grid Based Models
  Used for generating the GIVE and GIVD to be transmitted to GEO for error correction at User end (Aircraft)
  - US WAAS (Inverse Distance Weighted)
  - Modified US WAAS Model
  - Planar Model
  - Kriging Technique
  - Dual Shell Model
  - MLDF planar Model

Comparison of IRI Model

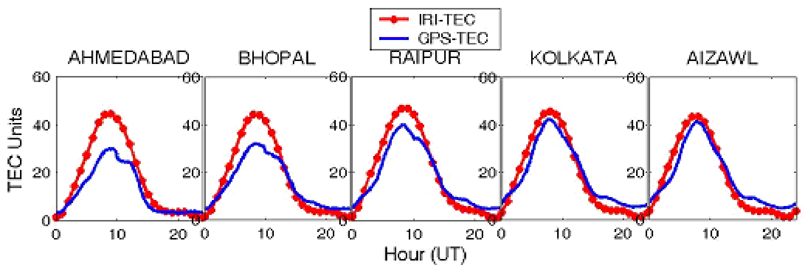
- International Reference Ionosphere (IRI) is empirical model which is developed and updated by a joint working group of URSI and COSPAR.
- For given location, time and date, IRI gives the electron density with altitude (50-2000 km) & also TEC.
- Measured TEC from GPS receivers has been compared with IRI model for all the stations.
- It is observed that in general IRI overestimates TEC over many of the locations in India.
- The IRI model is found to be more close to the observations at mid latitude than over low latitude stations of India.
- Newly launched model IRI-2007 gives better results as per the study so far.

Comparison with IRI-2001



August 2006

Comparison with IRI-2007 Model

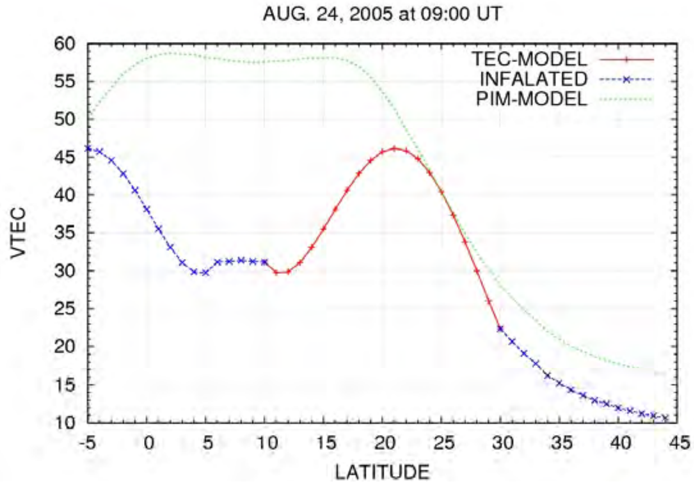


March 2007

ISRO-TEC Model

- Consider 77 deg longitude section as reference (because it constitute longest chain of receivers)
- Changes in TEC over other longitudes due to changes in solar zenith angle/ other physical processes (neutral wind, electric field)
- Ionosphere not to behave erratically in next half an hr/one hour (Solar flare/ Spread-F cases excluding)
- Project all the data only at 77 Deg. Longitude bin.
- Interpolate TEC at 1 deg latitude bins in the 77 deg longitude sector using best polynomial fit.
- Initialize the first principle models (like PIM) using the interpolated latitudinal profile.
- Generate TEC at corresponding latitude bins for different longitudes (1 deg. resolution)

ISRO-TEC model

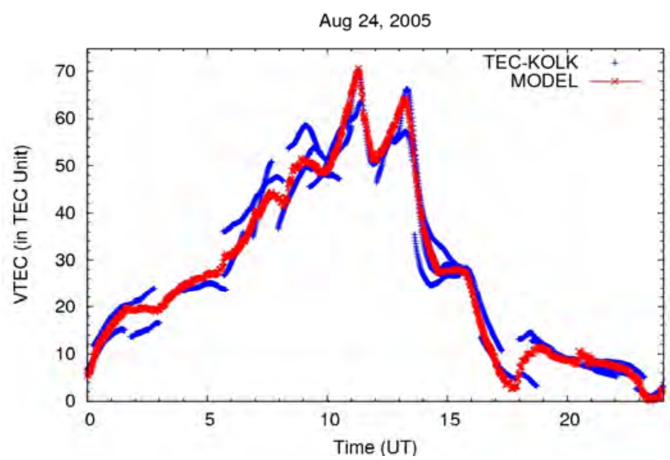


The line shown in Red shows the ISRO-TEC output (where measurements from TEC Stations are available). The blue line between 30 and 45 Deg Latitude represents data Inflated by PIM model.

Courtesy Dr. Rajkumar Choudhary

ISRO-TEC model

Results



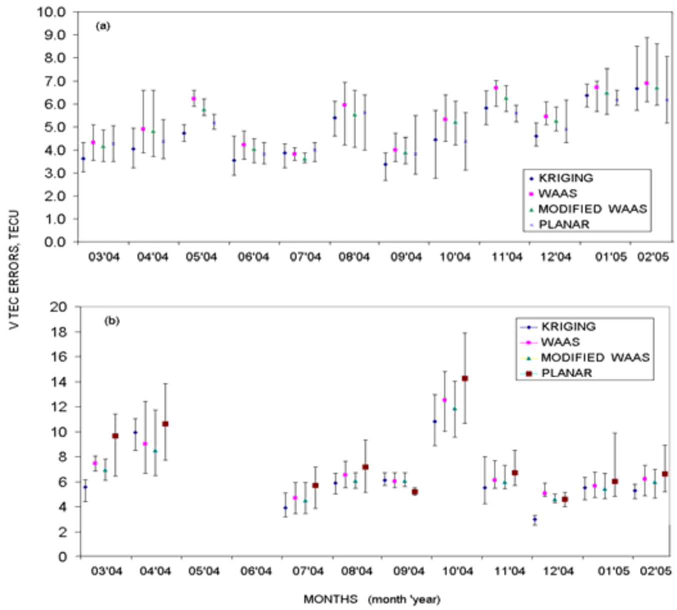
ISRO-TEC Model

- ISRO TEC model provides a reasonably accurate estimate for TEC at Indian latitude sector (even during highly disturbed days).
- Some difference in model output and measurements are noted, but no model can accurately duplicate the measurements.

Comparison of Grid Based Models

- Statistical comparison and validation of Inverse Distance Weighted, Planar and Kriging has been done for both quiet days and disturbed days.
- **Inverse Distance Weighted**
  - IPPs around an IGP contribute the iono delay through the weights proportional to the square of its inverse distance from the IGP.
- **Planar Model**
  - IPP delays assumes a 1^{st} order linear (planar) variation in the neighbourhood of an IGP from which the delay at the IGP is estimated.
- **Kriging Technique**
  - IPPs around an IGP contribute the iono delay through weights obtained from variation of correlations of detrended delay values with distance. It minimizes the mean-square estimation error.

Comparison plots



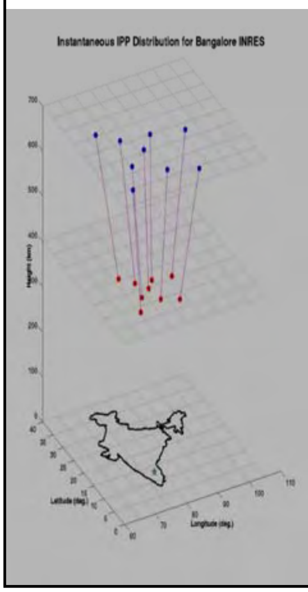
Quite Days

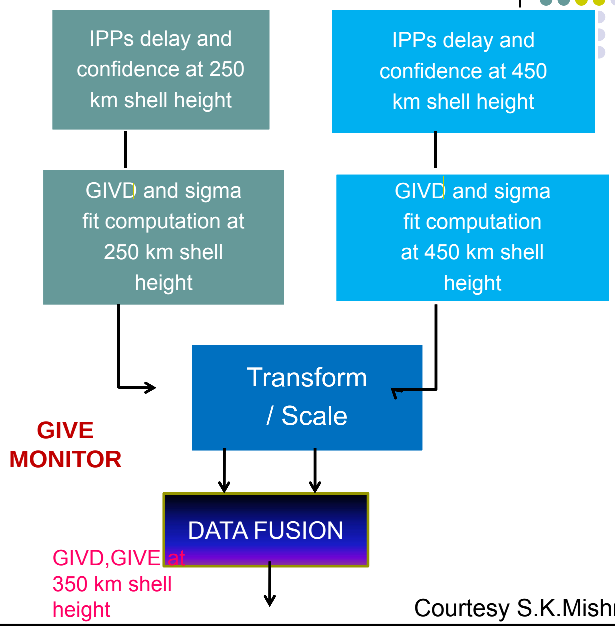
Disturbed Days

Comparison of Grid Based Models

- Kriging technique was the best candidate for the grid based model as per the comparison results.
- It is found to be giving minimum RMS error of Vertical TEC.
- But still it is not fit as per the requirements of GAGAN as it gives error of more than 3 TEC (0.5 meter) during high solar activity period (2004-05).
- Above models suggested changes to MOPS.
- IGM-MLDF model is down selected for GAGAN due no MOPS change approach

Multi Layer Data Fusion





Courtesy S.K.Mishra

MLDF Results (Preliminary)

Nominal Days

Selection Criteria Parameters	Ref. Value	MLDF (NO MOPS)
Land coverage @99% availability	90	51.41
Land coverage @95% availability	100	95.22
Continuity risk per PA	8 e-6 /15 sec	5.37E-03
Integrity plausibility	HPE<HPL, VPE<VPL	√
User position accuracy – VPE/HPE	16m, 20m	7.40/10.60
GIVD accuracy – RMS	1m	0.37
GIVD accuracy – Max	10m	3.80
GIVD error bounding Gaussian sigma	1	0.45

Stormy Days (To check ruggedness of algorithm)

Selection Criteria Parameters	Ref. Value	MLDF (NO MOPS)
Land coverage @99% availability	90	43.41
Land coverage @95% availability	100	53.85
Continuity risk per PA	8 e-6 /15 sec	1.77E-02
Integrity plausibility	HPE<HPL VPE<VPL	√
User position accuracy – VPE/HPE	16m, 20m	10.92/18.5
GIVD accuracy – RMS	1m	0.46
GIVD accuracy – Max	10m	6.93
GIVD error bounding Gaussian sigma	1	0.75

Questions

MOPS changes approach

Dual Shell Model:

- **Delay is computed as a parametric fit (12 coefficients)**
- **12 parameters are fit at each shell**
- **(2 x 12) parameters are up linked to users**
- **Requires changes in SBAS message structure & user processing algorithm**
- **New messages (4)**

Message 29 – Equatorial Ionosphere Parameters

Message 30 – Ionospheric correction region configuration

Message 31 – Dual shell ionospheric corrections

Message 32 – Equatorial GIVE I

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