Tropospheric Delay Models Analysis for NavIC

Presented By:
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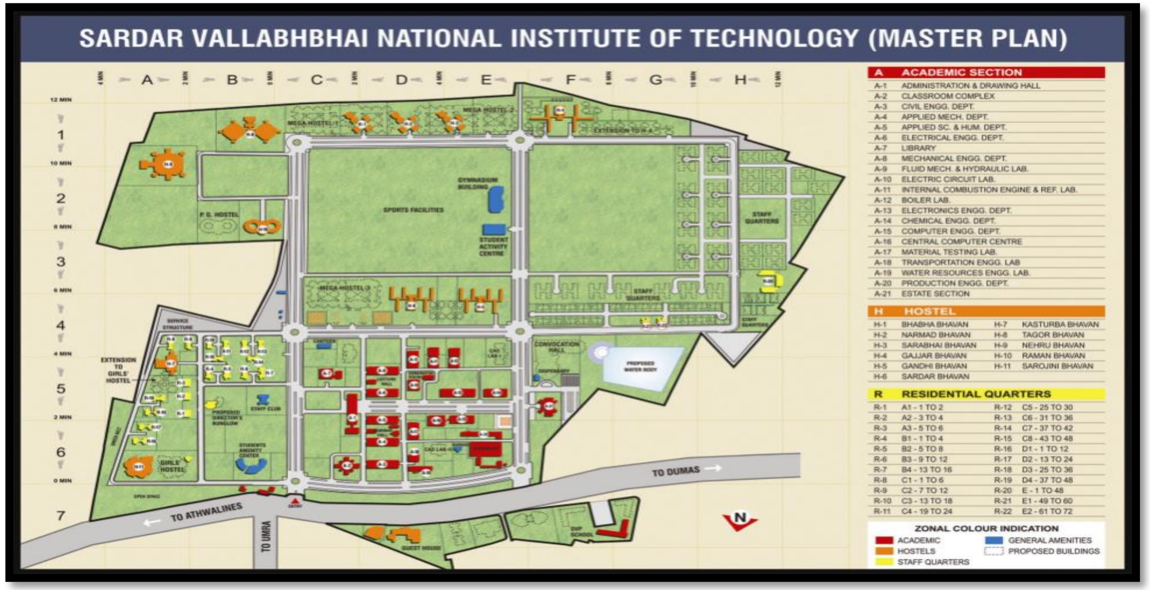

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CONTENTS

INTRODUCTION

- The services provided by Global Navigation Satellite Systems (GNSS) are used in a massive number of applications, both civilian and military.
- All GNSS systems comprise many satellites orbiting the Earth at very high elevations.
- At a single point in time, there will be several satellites from which a receiver may have a clear line of sight to receive signals and build its own navigation solution.
- However, these signals are prone to several sources of disturbance, causing errors in the measurements that are generated inside the receiver, which in turn degrades positioning accuracy.
- GNSS can provide standard positioning and precise point positioning service
- This presentation will focus on:
- GNSS signal delays caused by the Earth's atmosphere, concentrating on the neutral (non-dispersive) region called the troposphere.
- Here the comparative study of various tropospheric delay models and Mapping functions are presented to identify which one is most suitable.

OBJECTIVES of NavIC

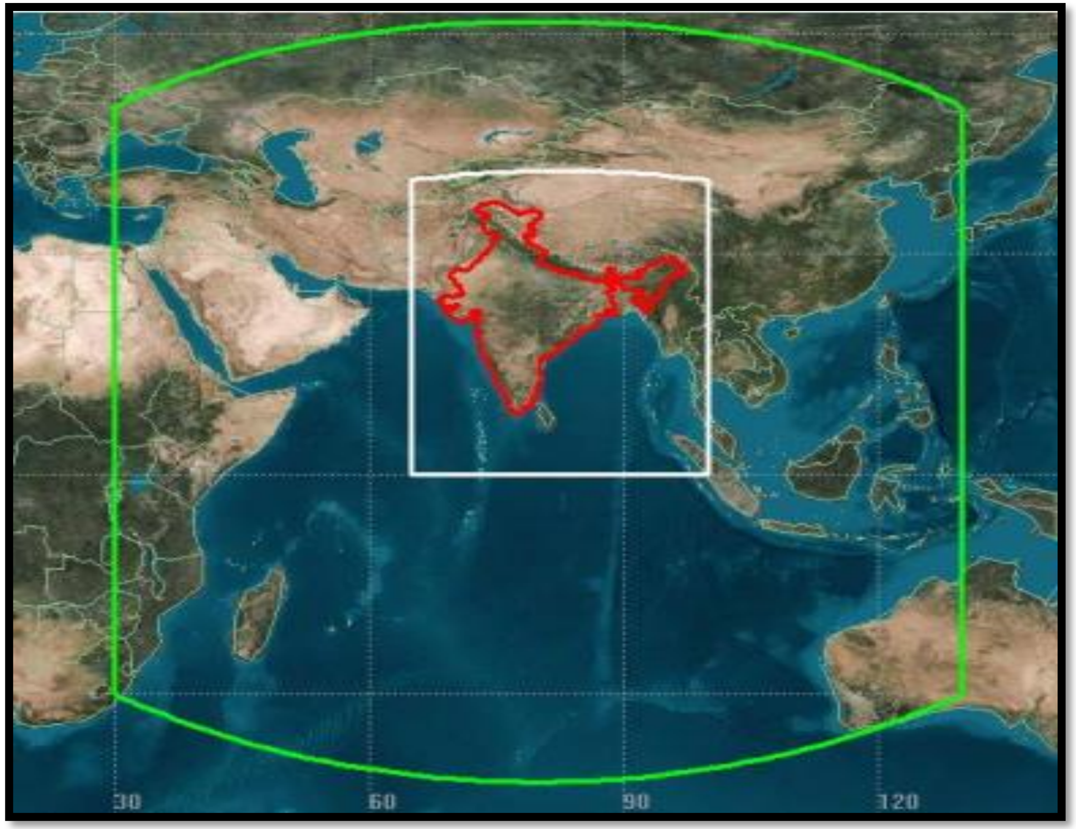


Fig. 1 : Extended Service Area: Area between primary service area and area enclosed by the rectangle of Lat. 30˚S to 50˚ N, Long. 30˚ E to 130˚E [1]

http://www.unoosa.org/documents/pdf/copuos/2016/copuos2016tech24E.pdf

CONSTELLATION of NavIC

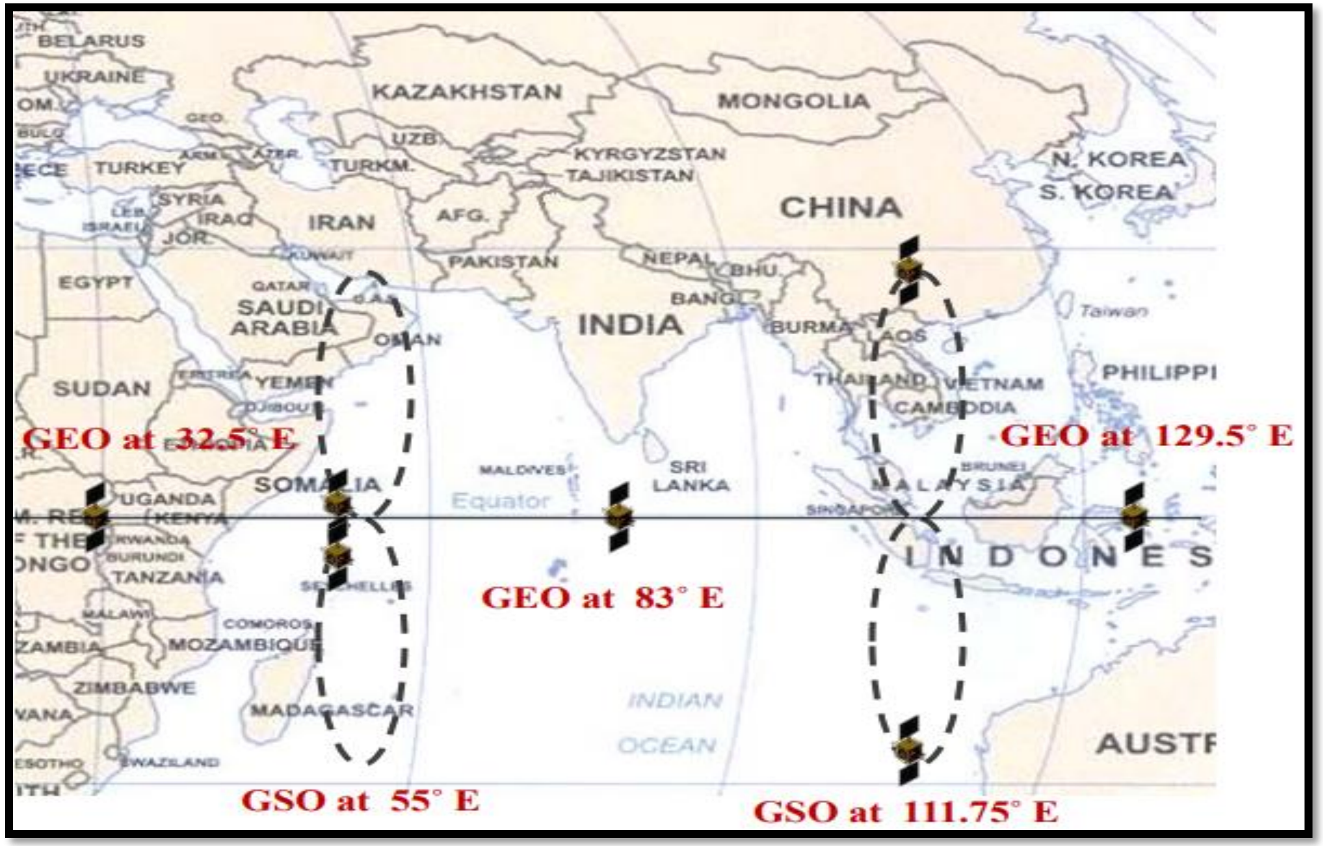
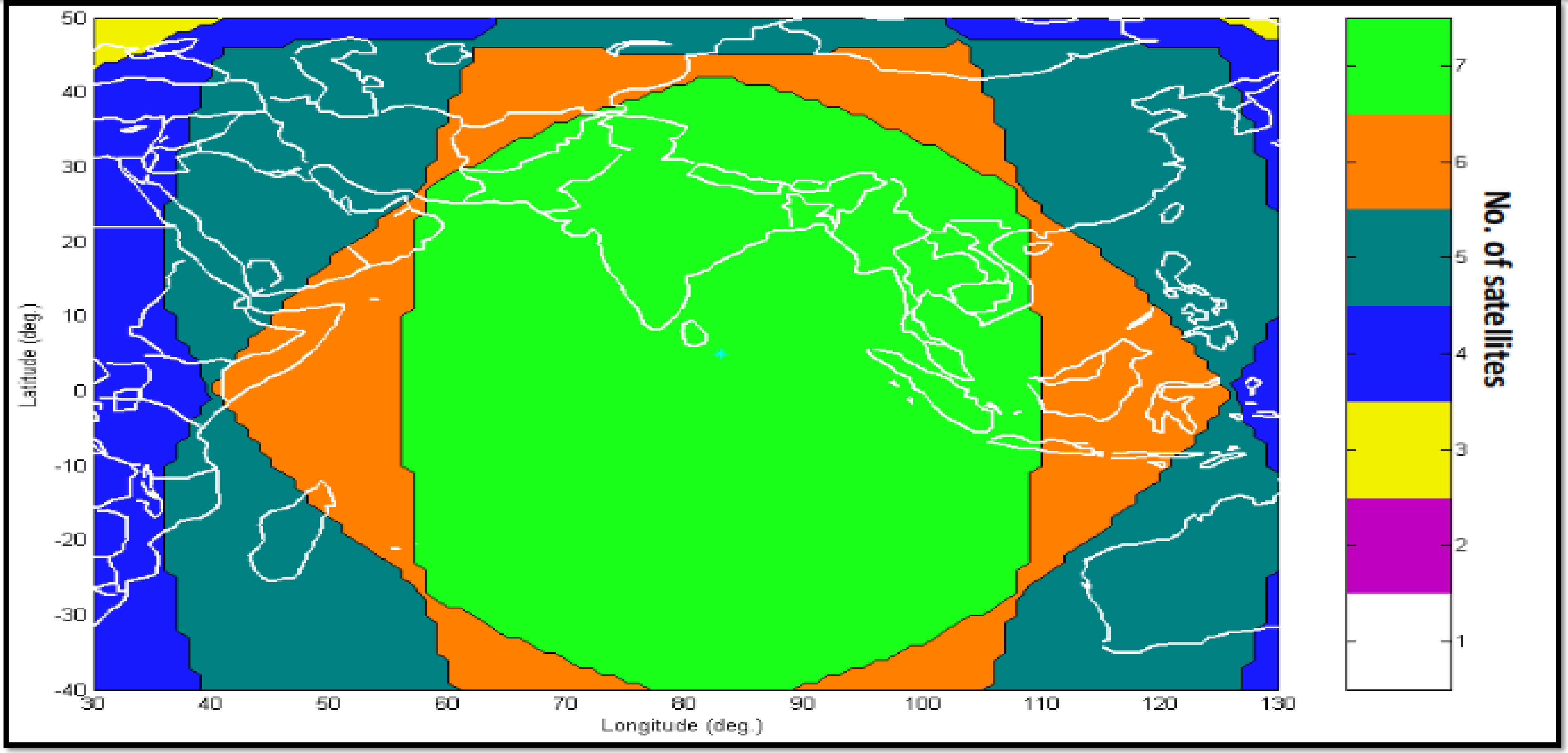


Fig. 2 : NAVIC Constellation Footprint [1]

http://www.unoosa.org/documents/pdf/copuos/2016/copuos2016tech24E.pdf

SPACECRAFT VISIBILITY



[2] http://www.unoosa.org/documents/pdf/copuos/2016/copuos2016tech24E.pdf

ARCHITECTURE of NavIC

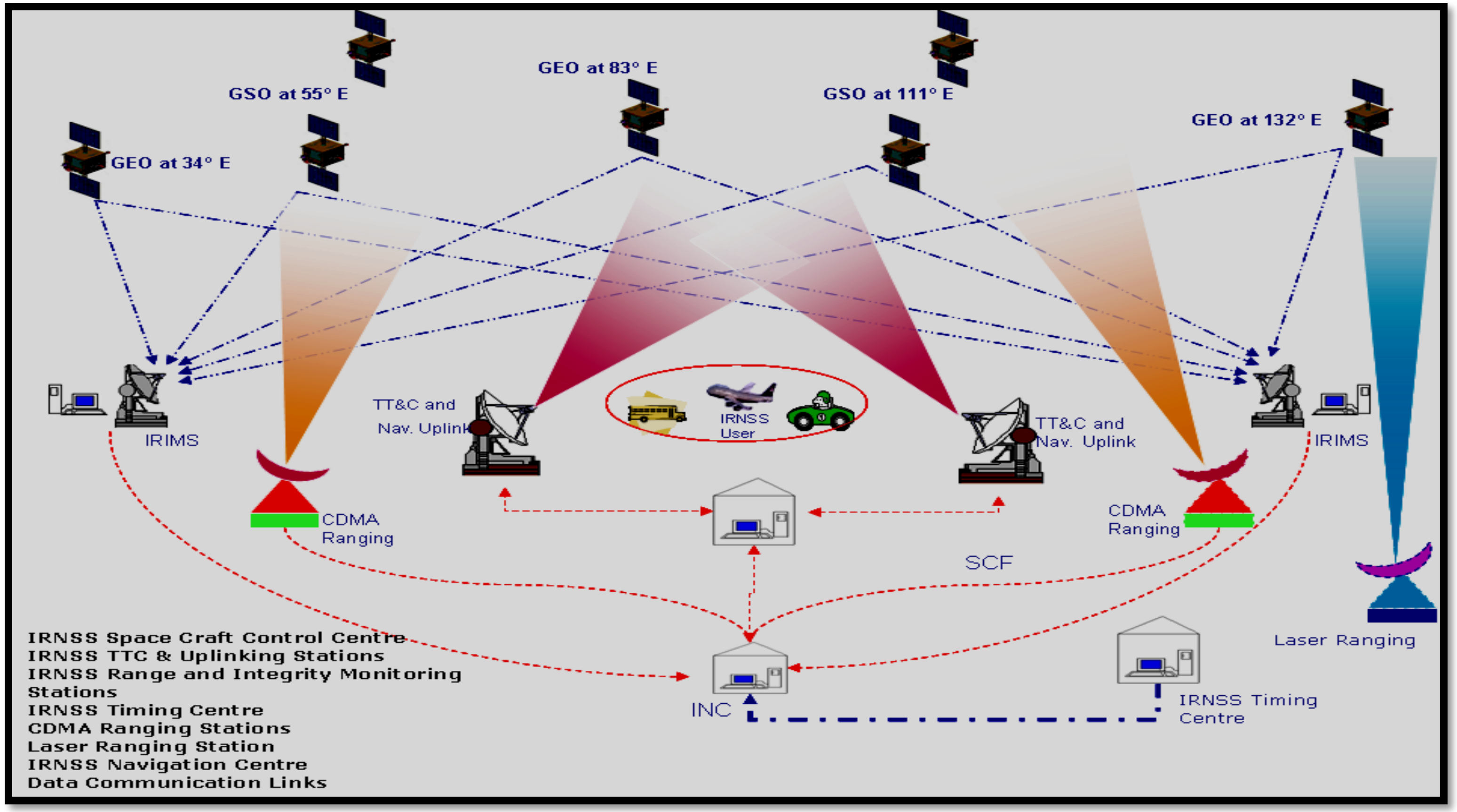


Fig. 3 : NavIC/IRNSS Architecture [1]

IRNSS signal in space ICD August 2017, ISRO-ISAC V 1.1; http://www.isro.gov.in/irnss-programme/.

SPECTRUM of IRNSS

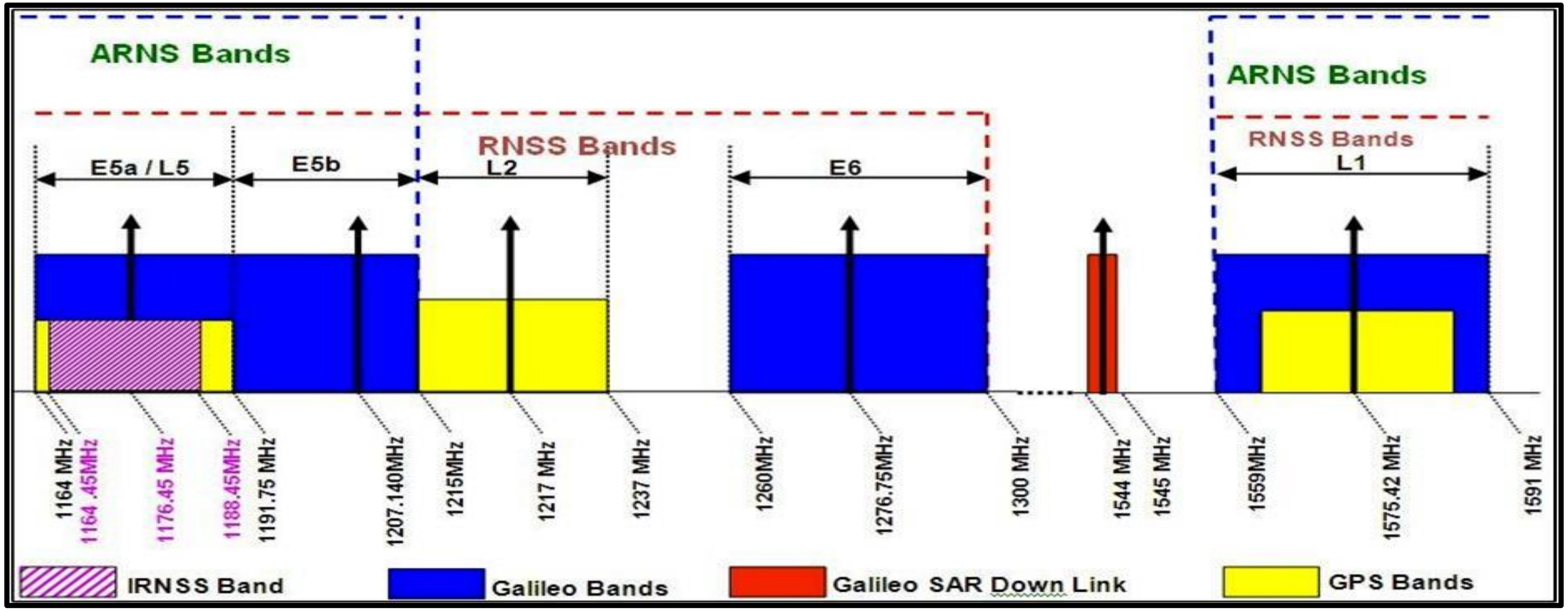


Fig. 4 : Spectrum for RNSS in L Band [1]

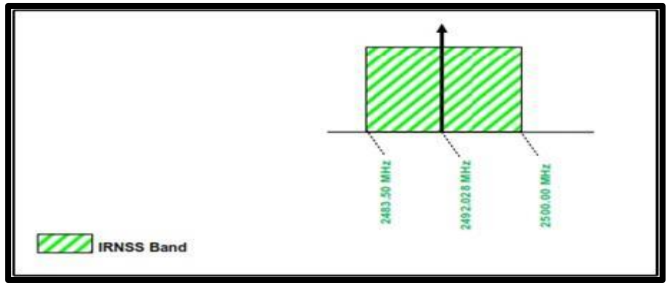


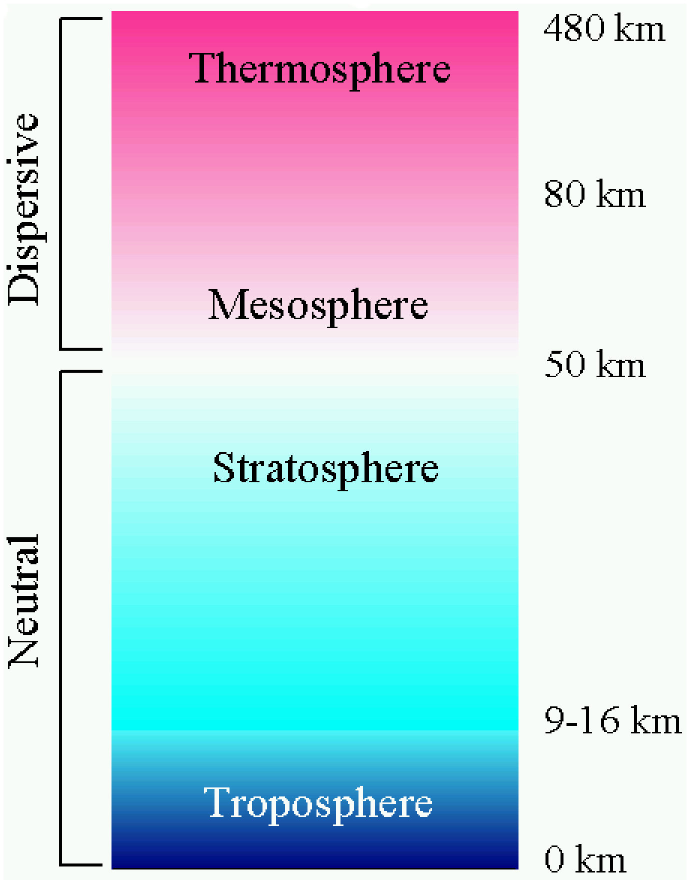
Fig. 5 : Spectrum for NavIC Signal in S Band [2]

Band of NavIC	Carrier Frequency	Bandwidth
L5 Band	1176.45 MHz	24 MHz (1164.45 -1188.45)
S Band	2492.028 MHz	16.5MHz (2483.50 – 2500.00)

IRNSS signal in space ICD August 2017, ISRO-ISAC V 1.1; http://www.isro.gov.in/irnss-programme/.

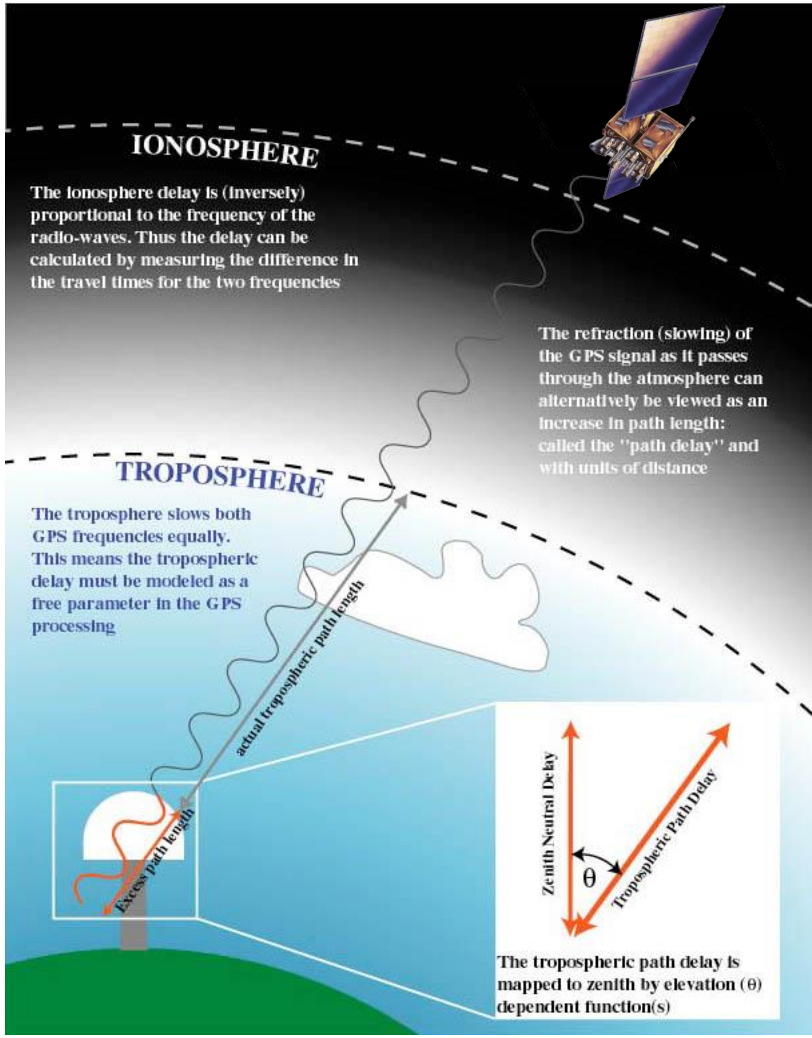
GNSS Atmospheric Signal

- There are two major contributions of the atmosphere:
  - Neutral atmospheric delay composed of hydrostatic component (N_2, O_2, CO_2, trace gases and part of the water vapor contribution) and water vapor component.
  - Ionospheric delay component due to free electrons. This component is frequency dependent and can be estimated from dual frequency measurements (ex. L1 and L2 frequencies).
- The lower atmosphere is non-dispersive, below 30 GHz, so all GNSS signals regardless of frequency are slowed equally [3,6].



Atmospheric Signal Delay

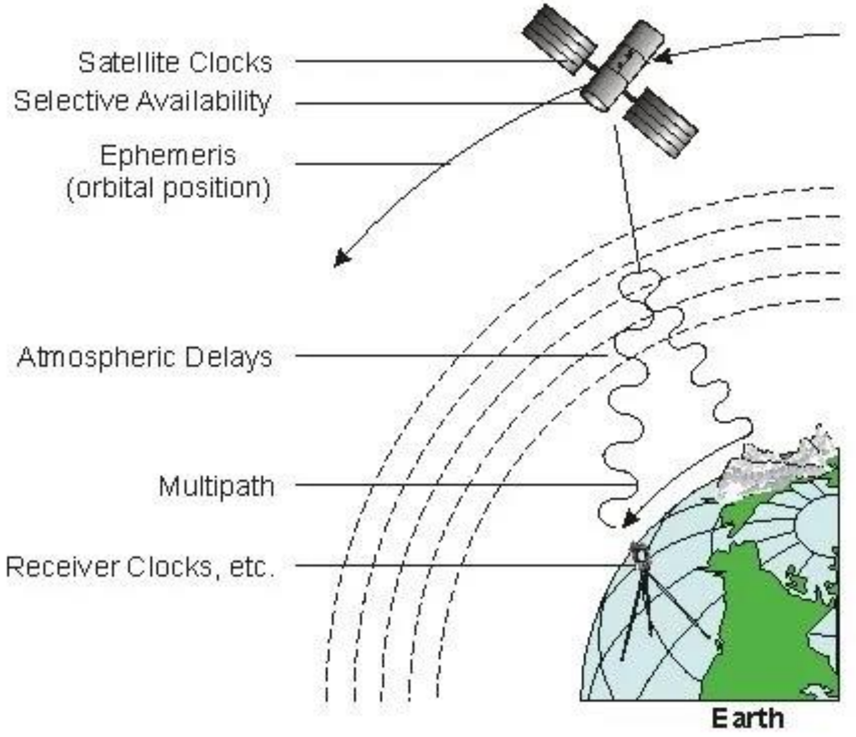
- Refractivity associated with T, P, and WV in the troposphere which ranges from 9-16 km.
- It causes the radio signals broadcast by the GNSS satellites to refract (slow and bend) as they travel from space to receivers at or near the surface of the Earth.
- Since tropo delays are not frequency dependent, they cannot be estimated directly like ionospheric delays but must be modeled [9].



GNSS Error Budget

- There are fundamental limitations on positioning accuracy using any GNSS technique.
- These limitations are defined by the error budget for the GNSS pseudorange observable:

$$P = R + c \cdot (\Delta T - \Delta t) + \Delta_{ion} + \Delta_{trop} + \Delta_{mult} + \varepsilon$$



Where:

P = measured pseudorange;

R = the geometric range to the satellite;

c = speed of light in a vacuum;

ΔT and Δt = errors in the satellite and receiver clocks;

Δ_{ion} and Δ_{trop} = ionospheric and tropospheric signal delays;

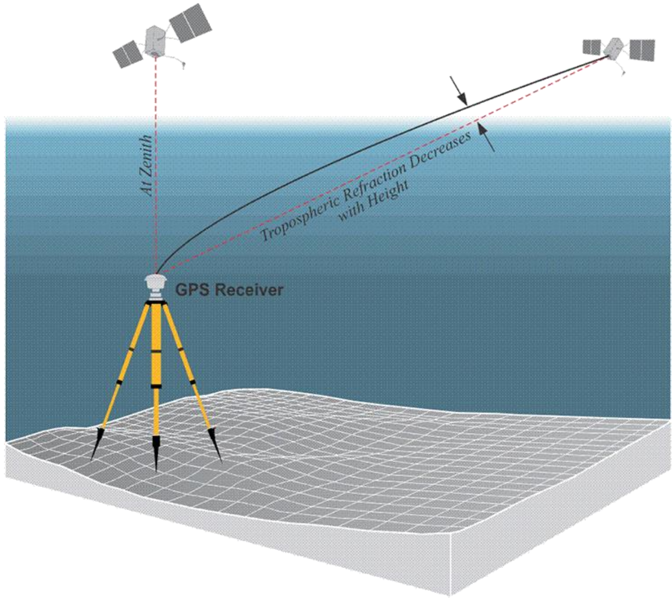
Δ_{mult} = errors introduced by multipath; and

ε = receiver noise.

PPP Error Budget [7]

Effect	Magnitude	Domain	Mitigation method	Residual error
Ionosphere	10s m	range	linear combination	mm
Troposphere	few m	range	modelling; estimation	dm - mm
Relativistic	10 m	range	modelling	mm
Sat phase centre; variation	m - cm	pos; range	modelling	mm
Code multipath; noise	1 m	range	filtering	dm - mm
Solid Earth tide	20 cm	position	modelling	mm
Phase wind-up (iono-free)	10 cm	range	modelling	mm
Ocean loading	5 cm	position	modelling	mm
Satellite orbits; clocks	few cm	pos; range	filtering	cm - mm
Phase multipath; noise	1 cm	range	filtering	cm - mm
Rcv phase centre; variation	cm - mm	pos; range	modelling	mm

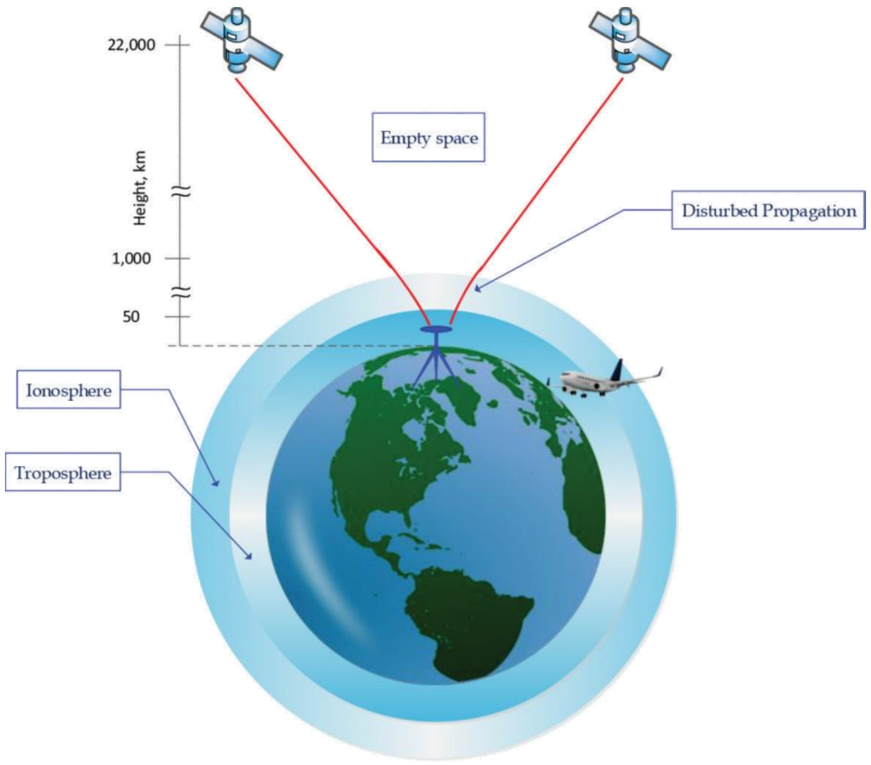
- Under active space and tropospheric weather conditions, the refractivity of the ionosphere and troposphere can change radically in time and space.
- GNSS accuracy usually degrades significantly under these conditions.
- The ultimate utility of GNSS depends on our ability to describe and correct for atmospheric signal delays under virtually all conditions.
- We have focus on the troposphere and studied the different models especially for NavIC and GPS signals [9].



Tropospheric Delay [8]

- **Total delay**
  - ~2.3m at zenith, greater at horizon
  - Elevation angle dependency may be relatively well modelled with a mapping function (M) for each of two tropospheric components
- **Two components**
  - Hydrostatic – could be well modelled with accurate pressure
  - Wet – not well modelled and must be parameterise

$$T_{Slant} = T_{hydro}.M_{hydro}(El) + T_{wet}.M_{wet}(El)$$



- **General approach**

  Model hydrostatic with standard pressure or (more accurate) use station met data Parameterise zenith wet delay (T_{wet}), which also absorbs any residual T_{hydro}, once per 1-2 h (static) or every epoch (kinematic)

GNSS Tropospheric Parameters

- **Tropospheric delay effects in GNSS model is composed from**:
- a) signal delay (major) + delay due to signal trajectory bending (minor)
- b) hydrostatic delay (major) + wet delay (minor)

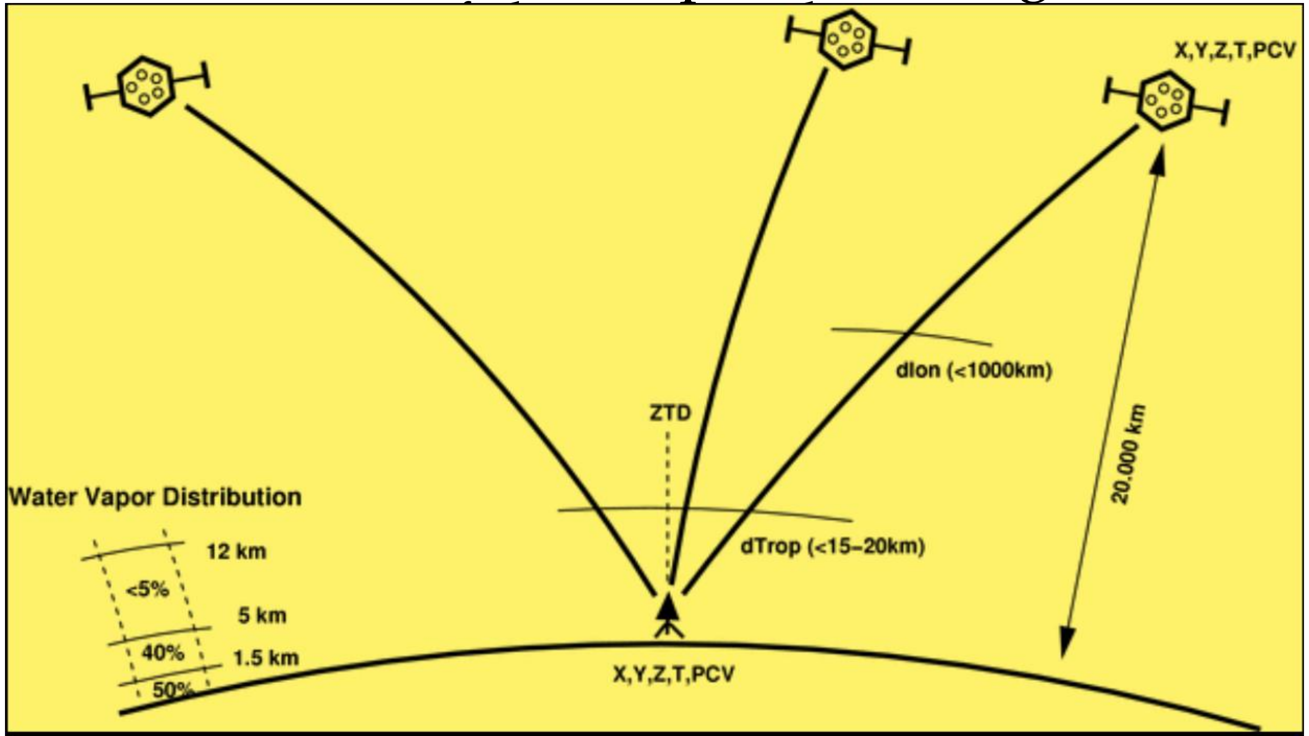
- **Standard parameters**:
- **ZTD** – zenith total path delay
- **ZHD/ZWD** – zenith hydrostatic/wet path delay
- (ZTD = ZHD + ZWD)
- **STD** – slant total path delay
- **SHD/SWD** – slant hydrostatic/wet path delay
- (STD = SHD + SWD)
- $\mathbf{G_N}$ – North-South horizontal tropospheric gradients
- $\mathbf{G_E}$ – East-West horizontal tropospheric gradients

Zenith Total Delay – ZTD [7]

The basic tropospheric parameter in present GNSS is the Zenith Total Delay (ZTD) that describes the signal delay in zenith direction above the receiver.

It results from the mapping of the delays to each individual satellite into the zenith direction with appropriate mapping functions.

- The zenith delay is the combination of all these mapped delays into one parameter. It is therefore an average over all elevation angles and azimuths of the satellites in view and as such a spatial average over a



Zenith Total Delay – ZTD [7]

- The ZTD is traditionally either separated into a dry and wet part, called the Zenith Dry Delay (ZDD)and the Zenith Wet Delay (ZWD), or into a hydrostatic and non-hydrostatic (also termed: wet) part.

- The hydrostatic and dry part are much larger in amplitude but less varying in time. They are of the order of 2.30 m at sea level.

- The non-hydrostatic or wet part is more variable but smaller in amplitude, typically 0.0–0.40 m.

Modelling Troposphere Delays [9]

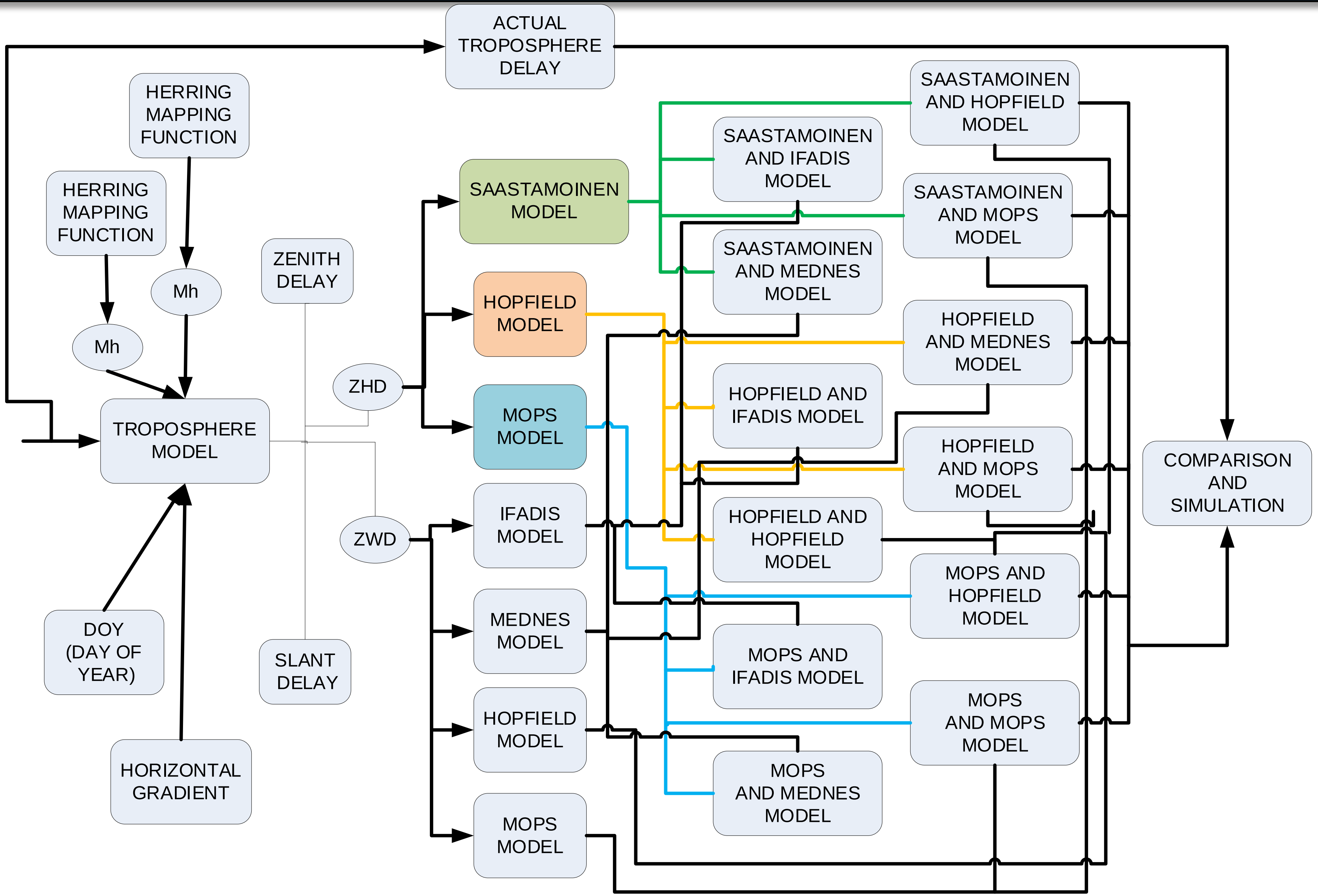
$$T_{Slant} = T_{hydro} . M_{hydro}(El) + T_{wet} . M_{wet}(El)$$

- T_{slant}: total delay dependent on elevation
- T_{hydro} : hydrostatic delay in zenith direction; can be modeled a priori
- T_{wet} : wet delay in zenith direction; approximated or estimated in data analysis
- $M(El)$: mapping function ($M_{hydro}(El) > M_{wet}(El)$)

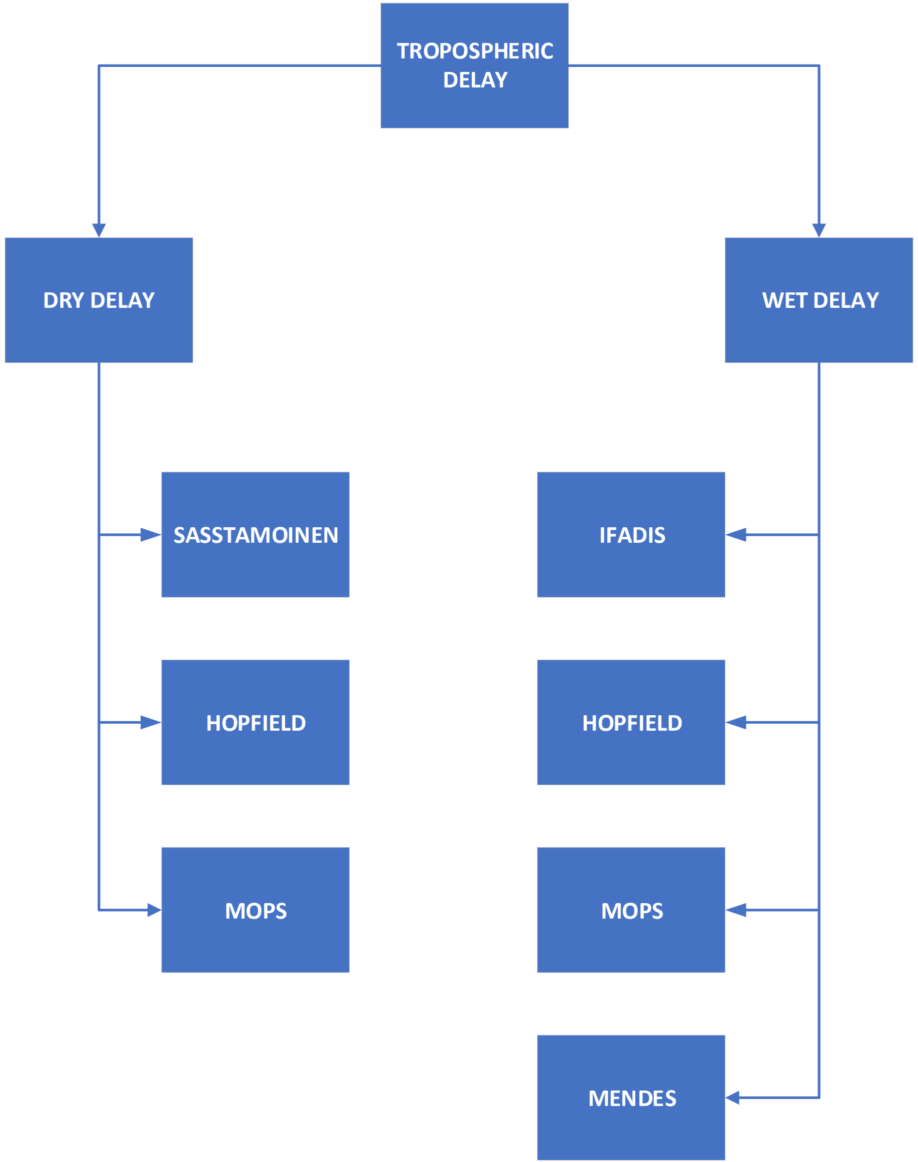
Mapping functions [10]

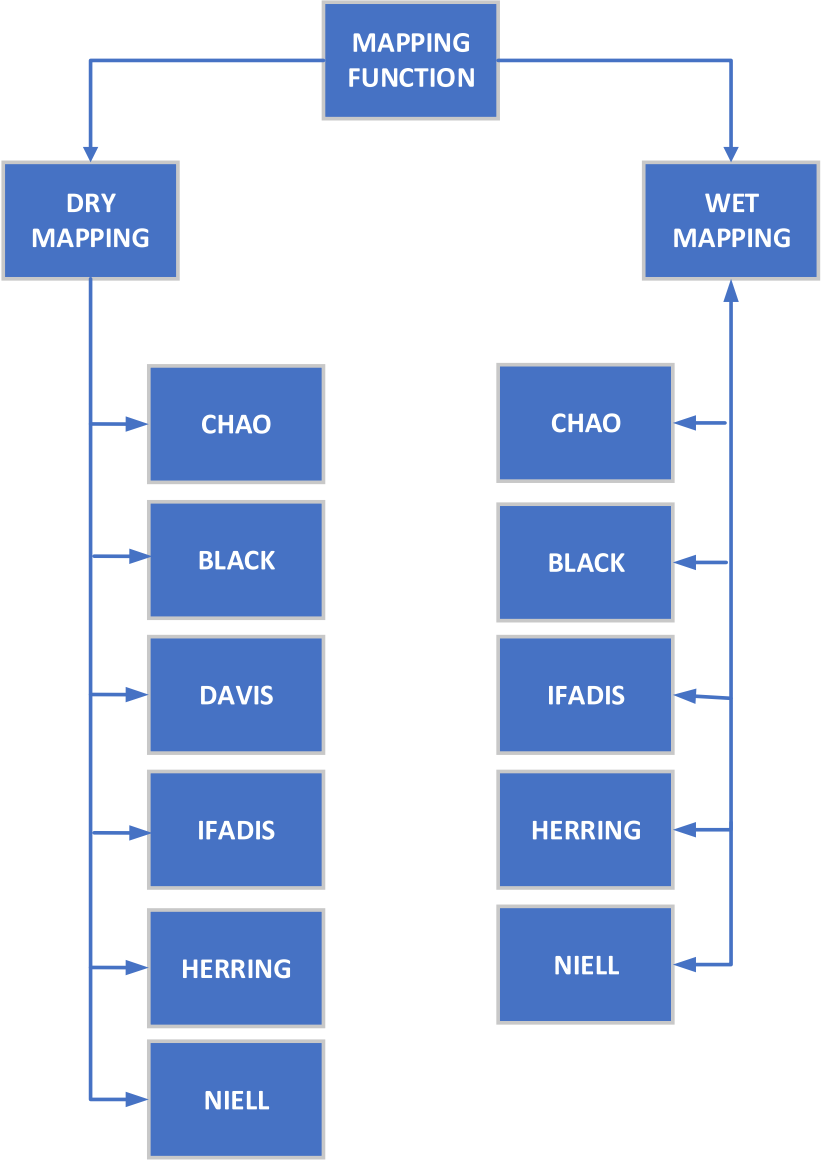
- Mapping function not perfectly known
  - May be different for different regions and receivers used
- Errors via correlations also in station heights
  - Ex., In kinematic measurement, the heights of two receivers/antenna plays important role in tropo delay calculations
- Low elevations necessary to de-correlate heights, clocks, and zenith delays
- ***Rule of thumb: the station height error is about 1/5 of the delay error at 5°elevation***

Tropospheric Delay Classification



Tropospheric Modelling and Mapping Function





Tropospheric Delay Models

Hopfield Hydrostatic Delay Model

$$ZHD = \left(0.62291\left[\frac{m.K}{hPa}\right].\frac{1}{T_0} + 0.0023081\left[\frac{m}{hPa}\right]\right).P_0$$

Sasstamoinen Hydrostatic Delay Model

$$ZHD = \frac{0.022767\left[\frac{m}{hPa}\right].p_0}{\left(1 - 0.00266.cos\emptyset - 0.00028\left[\frac{1}{km}\right].h\right)}$$

MOPS Hydrostatic Delay Model

$$ZHD = ZHD_0\left(1 - \frac{\beta.H}{T}\right)^{\frac{g}{R_d.\beta}}$$

Hopfield Wet Delay Model

$$ZWD = \left(555.7\left[\frac{m.K^2}{hPa}\right] + 1.792.10^{-4}\left[\frac{m.K^2}{hPa}\right].exp\left(\frac{t_0}{22.90[°C]}\right)\right).\frac{e_0}{T_0^2}$$

Ifadis Wet Delay Model

$$ZWD = 0.554 * 10^{-2}[m] - 0.880 * 10^{-4}\left[\frac{m}{hPa}\right] * (\rho - 1000) + 0.272 * 10^{-4}\left[\frac{m}{hPa}\right] * e + 2.771\left[\frac{m°C}{hPa}\right] * \frac{e}{T}$$

Mendes Wet Delay Model

$$ZWD = 0.122[m] + 0.00943\left[\frac{m}{hPa}\right] * e$$

MOPS Wet Delay Model

$$ZWD = \frac{10^{-6} * k_3 * R_d}{g_m * (\lambda + 1) - \beta * R_d} \cdot \frac{e}{T}$$

Tropo Mapping Functions [3,4,5]

Sasstamoinen Hydrostatic Mapping Function

$$\delta S_{[NEU]} = \frac{0.002277\left[\frac{m}{hPa}\right]\cdot(1+D)}{\cos Z^*}\cdot \left(\rho_0 + \left(\frac{1255[K]}{T_0} + 0.005\right)\cdot e_0 - B\cdot tan^2 z^*\right) + \delta_R$$

Chao Hydrostatic Mapping Function

$$m(\varepsilon)_{[HYD]} = \frac{1}{sin\varepsilon + \frac{0.00143}{tan\varepsilon + 0.00035}}$$

Black Hydrostatic Mapping Function

$$\delta S_{[HYD]} = \frac{1.552\cdot 10^{-5}\left[\frac{K}{hPa}\right]\cdot\frac{\rho_0}{T_0}\cdot H_d}{\sqrt{1-\left(\frac{\cos\varepsilon}{1+I_C}\cdot\frac{H_d}{r}\right)^2}} - \frac{1.92\left[\frac{m}{\circ}\right]}{\varepsilon^2 + 0.6^\circ}$$

Davis Hydrostatic Mapping Function

$$m(\epsilon)_{[HYD]} = \frac{1}{sin\varepsilon + \frac{a}{sin\varepsilon + \frac{b}{sin\varepsilon + c}}}$$

Ifadis Hydrostatic Mapping Function

$$m(\epsilon)_{[HYD]} = \frac{1}{sin\varepsilon + \frac{a}{sin\varepsilon + \frac{b}{sin\varepsilon + c}}}$$

Herring Hydrostatic Mapping Function

$$m(z) = \frac{1 + \frac{a}{1 + \frac{b}{1 + c}}}{sin\varepsilon + \frac{a}{sin\varepsilon + \frac{b}{sin\varepsilon + c}}}$$

Niell Hydrostatic Mapping Function

$$m(z) = \frac{1 + \frac{a}{1 + \frac{b}{1 + c}}}{sin\varepsilon + \frac{a}{sin\varepsilon + \frac{b}{sin\varepsilon + c}}}$$

Chao Mapping Function

$$m(\varepsilon)_{[WET]} = \frac{1}{sin\varepsilon + \frac{0.00035}{tan\varepsilon + 0.0017}}$$

Black Mapping Function

$$\delta s_{[WET]} = \frac{0.07465\left[\frac{K^2}{hPa}\right] \cdot \frac{e_0}{T_0^2} . H_T}{\sqrt{1 - \left(\left(\frac{cos\varepsilon}{1 + I_c\frac{H_T}{r}}\right)^2\right)}} - \frac{1.92\left[\frac{m}{o}\right]}{\varepsilon^2 + 0.6^{\circ}}$$

Davis Mapping Function

$$m(\epsilon)_{[HYD]} = \frac{1}{sin\varepsilon + \frac{a}{sin\varepsilon + \frac{b}{sin\varepsilon + c}}}$$

Elgered Et Al Mapping Function

$$ZHD = [0.0022779\, m/mbar] * P_o/f(\Phi, h)$$

Askne and Nordius Mapping Function

$$ZWD = 10^{-6}\left(k_2{}' + \frac{k_3}{T_m}\right)\frac{R_d}{(\lambda + 1)g_m}e_o$$

Baby Et Al Mapping Function

$$ZWD = v\, 10^{\gamma(T_o - 273.16)}\tau h_o$$

Where,

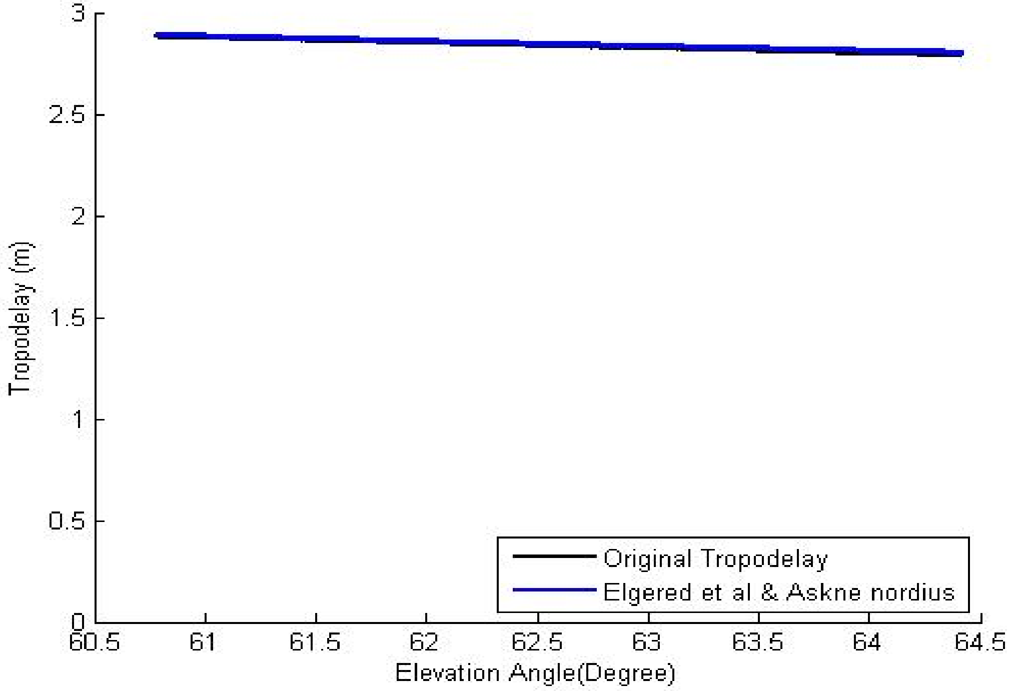
T_m: Surface mean temperature
e_o: Surface pressure
k_2': 22.7 K $mbar^{-1}$: empirical constant
k_1: 77.604 K $mbar^{-1}$: empirical constant
k_3: 382000 K^2 $mbar^{-1}$: empirical constant
R_d: 287054 J mol^{-1} K^{-1}: gas constant
g_m: 9.784 m s^{-2}: acceleration due to gravity at the center
T_0: Temperature[k]
ϕ = geodetic latitude
h = 0.02: height above msl
P_0 = air pressure
r_{ho} = 48 %: relative humidity
T_0 = 31 °C: Temperature[°C]
v = 73.27 mm: empirical coefficient
g = 0.0236[K^{-1}]: empirical coefficient

Tropospheric Correcting Errors [12]

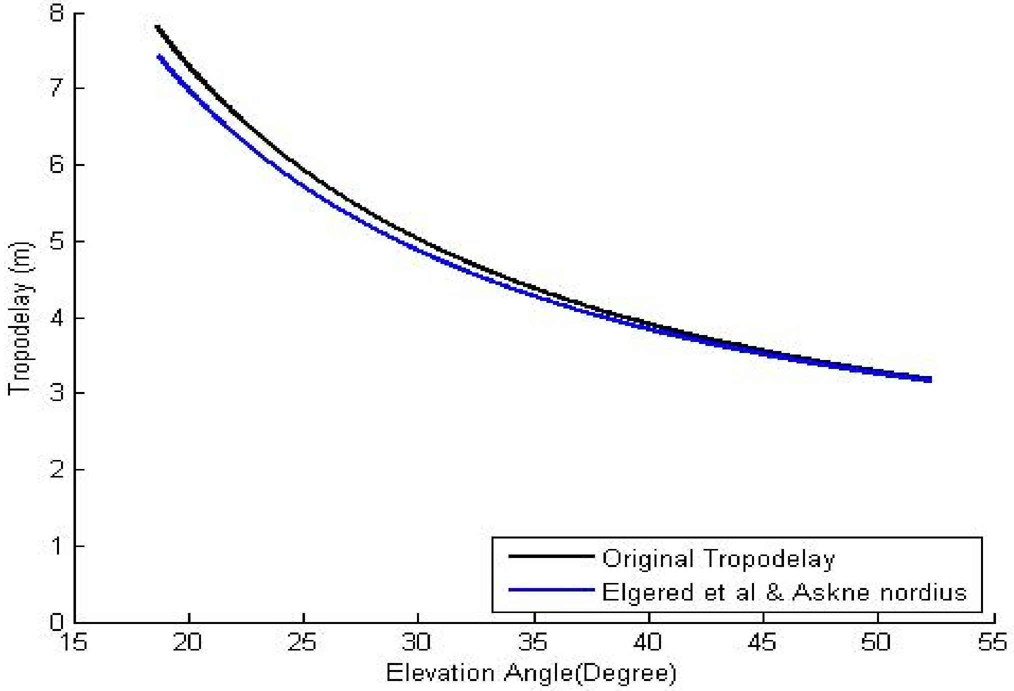
- Commonly Used Strategies
  - Ignore the tropospheric delay
  - Estimate the tropospheric delay from surface meteorological observations
  - Predict the tropospheric delay from empirically-derived signal delay climatology
  - Use additional information provided by ground and space-based augmentations
  - Estimate directly from carrier phase observables.
- Different strategies are appropriate for different applications.
- Positioning accuracy is not the only criterion for selecting a error mitigation strategy.

Commonly Used Strategies [11]

STRATEGY	ADVANTAGES	DISADVANTAGES
Ignore it	• Nothing to do	• ZTD errors range from 2.5-0.5 m
Estimate it from surface met observations e.g. Hopfield & Saastamoinen models	• Autonomous • Easily implemented	• Requires T, P, RH sensors. • Surface moisture observations are poorly correlated with trop delay • ZTD errors range from 0.5-0.2 m
Predict it from empirically-derived signal delay climatology e.g. UNB3/3m	• Autonomous • Easily implemented	• Difficult to build • Static • Provides expected vs actual values • ZTD errors range from 0.2-0.07 m
Use augmentations e.g. N/MDGPS, RTK, WAAS, EGNOS, GAGAN, MSAS, StarFire	• Local-regional implementation • Global implementation	• Baseline-length dependent, especially for ground-only DGPS • Accuracy of correctors depends on proximity to base stations • ZTD errors range from 0.5-0.1 m
Estimate it directly from carrier phase observables e.g. Carrier phase-ionospheric free double-differencing; Precise Point Positioning	• ZTD estimated as a free parameter in the calculation of antenna position • High accuracy	• Computationally intensive • Long observations needed to resolve ambiguities • ZTD errors range from 0.025-0.01 m



Comparison Troposphere Delay Verses Elevation for PRN 3

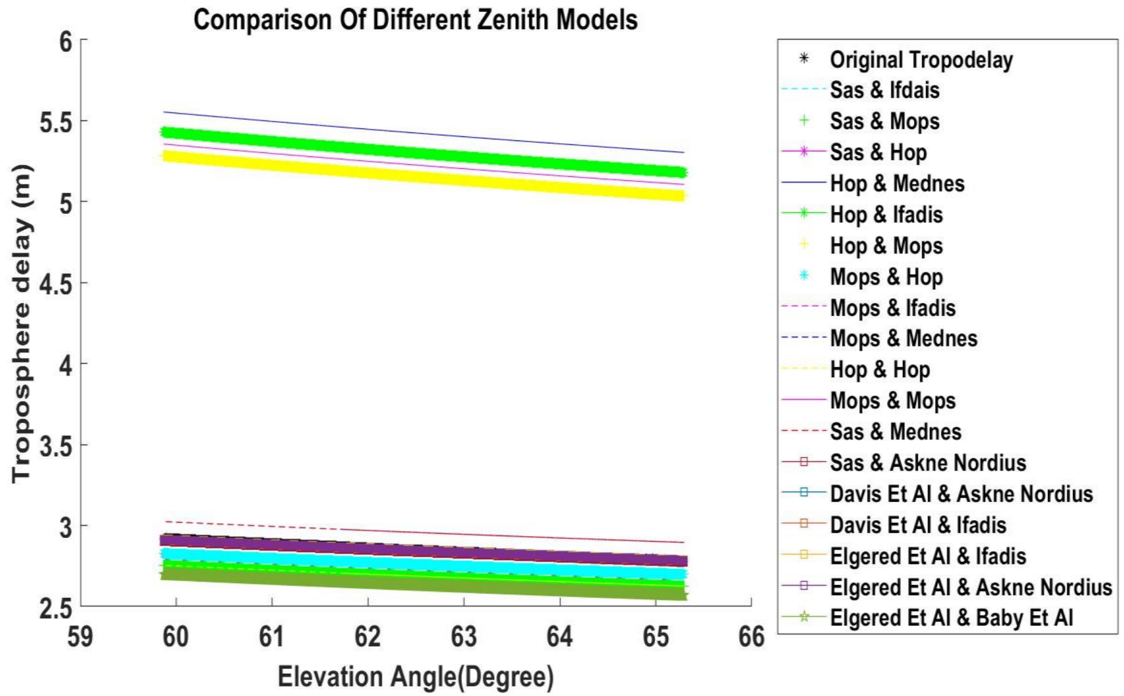


Comparison Troposphere Delay Verses Elevation for PRN 5

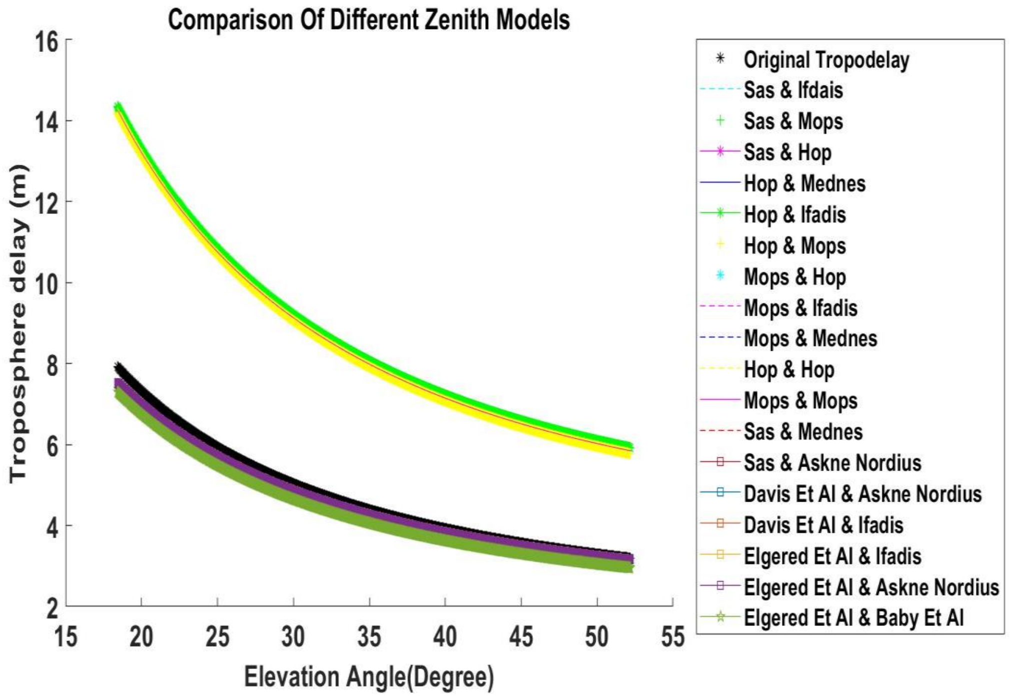
Here the graphs for PRN3 (Geostationary) & PRN5 (Geosynchronous) are shown for the comparison of Original tropospheric delay received from the receiver compared with Elgered Et Al & Askne Nordius Model verses Elevation Angle. The results highlight that the Elgered Et Al & Askne Nordius Model is nearest in comparison to original troposphere delay which is received from NavIC receiver.

SVNIT Station Data (Accord Receiver)

Comparative Analysis of Different Zenith (Tropo) Models Verses Elevation Angle



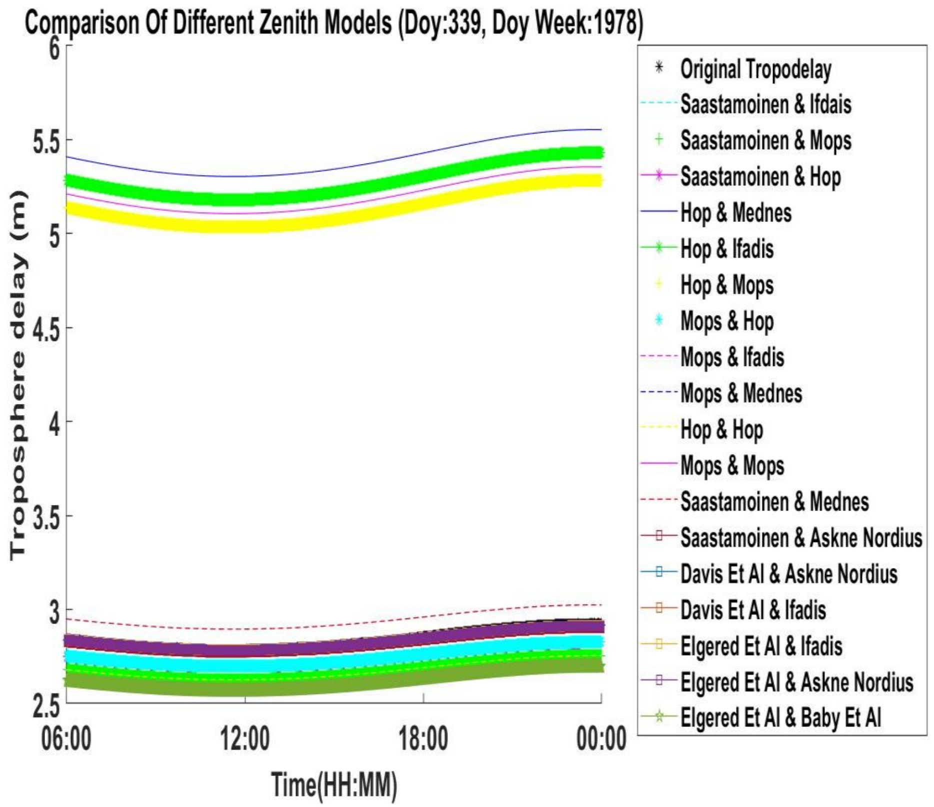
Comparison Troposphere Delay Verses Elevation for PRN 3



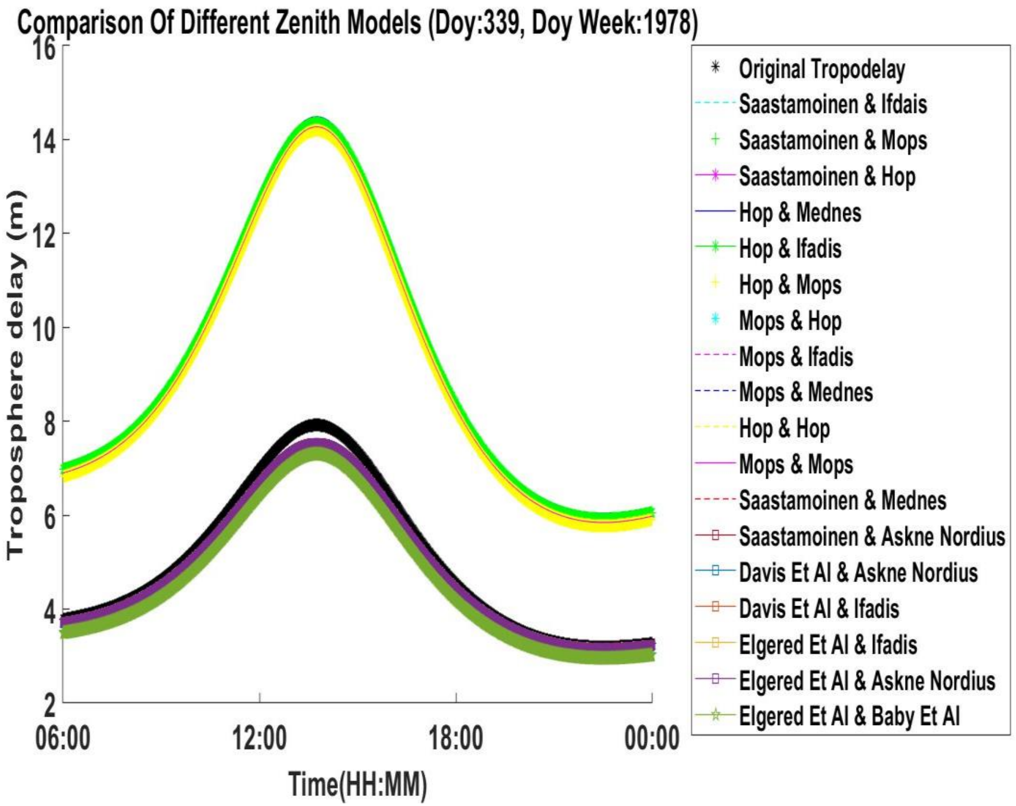
Comparison Troposphere Delay Verses Elevation for PRN 5

Here the graphs for PRN3 (Geostationary) & PRN5 (Geosynchronous) are shown for the comparison of 18 different combinations of zenith delay models verses Elevation Angle. The results highlight that the Elgered Et Al & Askne Nordius Model is nearest in comparison of all other models to original troposphere delay which is received from NavIC receiver.

Comparative Analysis of Different Zenith (Tropo) Models Verses Time (HH)



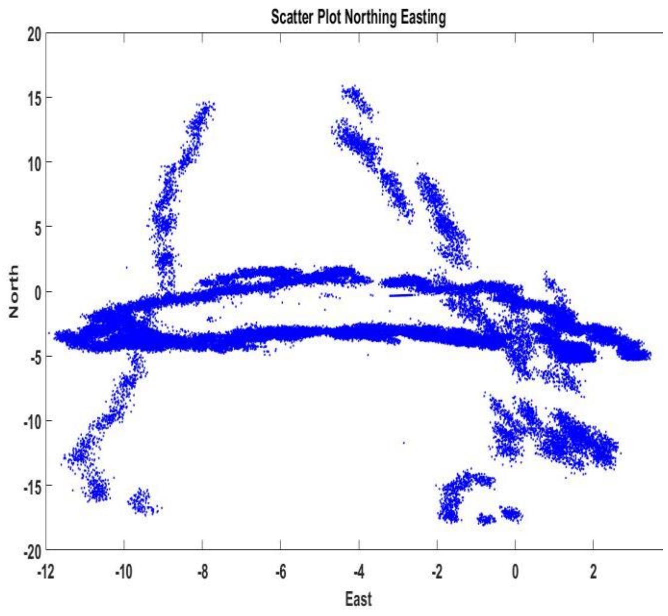
Comparison Troposphere Delay Verses Time for PRN 3



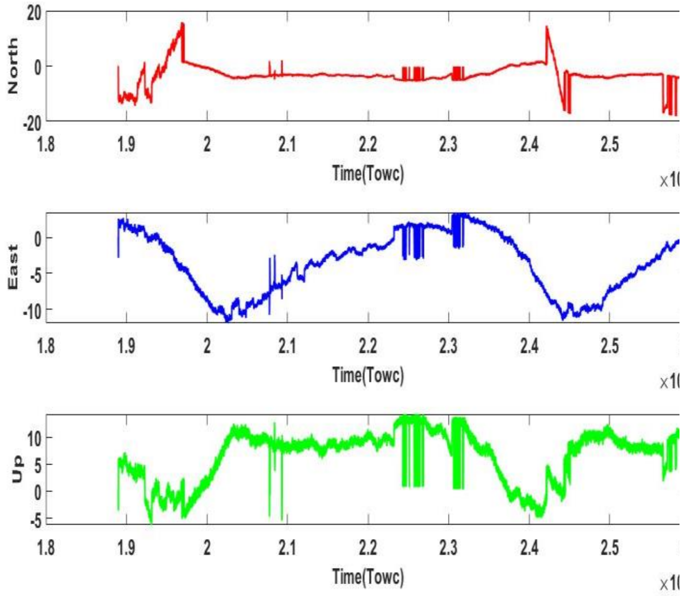
Comparison Troposphere Delay Verses Time for PRN 5

The presented results are for PRN 3 and PRN 5 displaying characteristics of various combination of tropo models vs time.

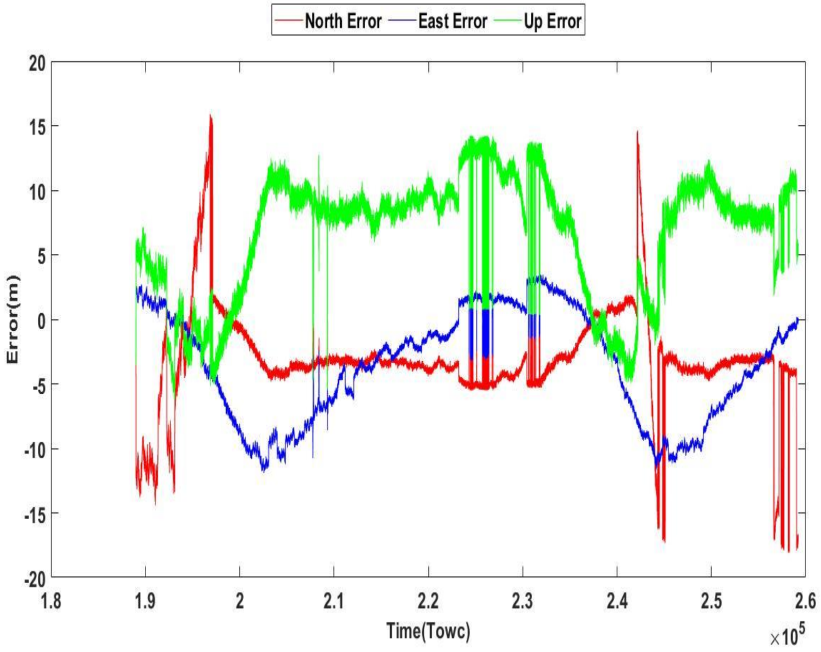
North East Up positioning Error by applying Least Square Solution For Code



2D Graph North East Error Using Least Square Solution for Code



North East Error Using Least Square Solution for Code



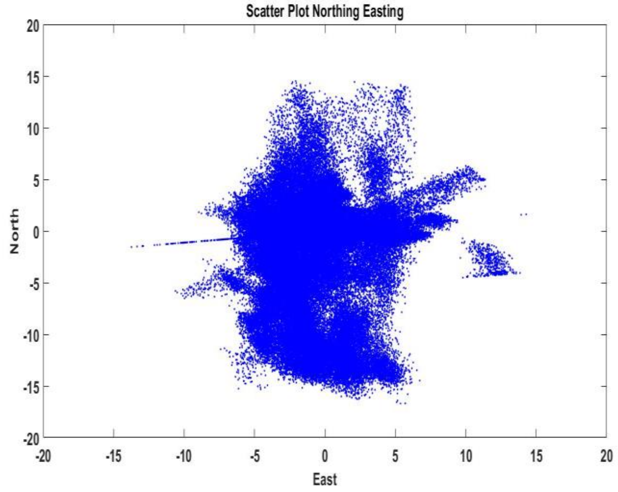
Single Plot North East Error Using Least Square Solution for Code

Positioning Error North East Up based on code (Least square)

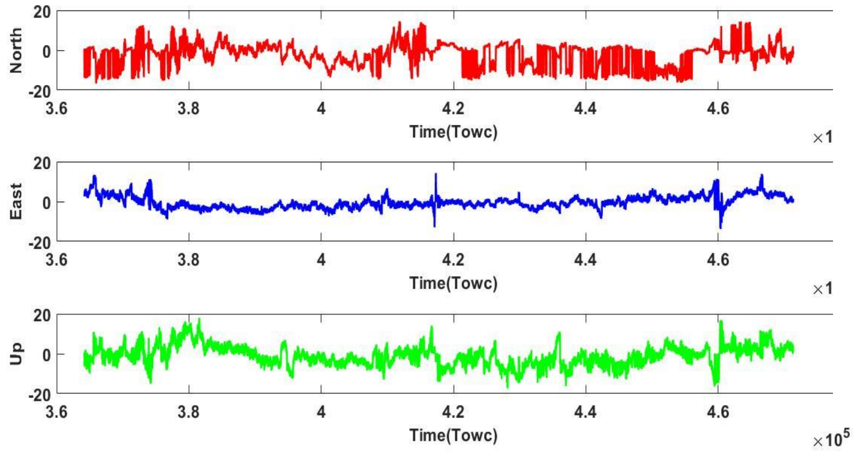
Positioning Error	North Error	East Error	Up Error
Min	-18.0736	-11.9152	-6.2139
Max	15.87821	3.466596	14.23955
Mean	-3.15838	-3.58256	6.628282

Here fig is Showing position error north east up using least square algorithm and code based PPP.

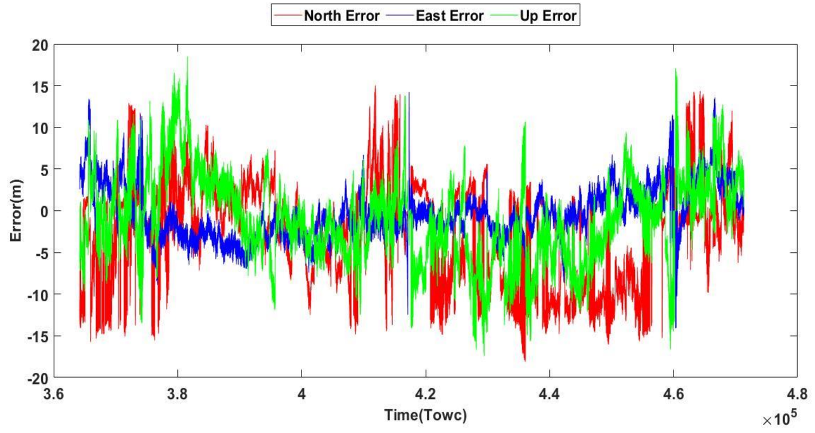
North East Up positioning Error by applying Iterative Least Square Solution For Code



2D Graph North East Error Using Iterative Least Square Solution for Code



North East Error Using Iterative Least Square Solution for Code



Single Plot North East Error Using Iterative Least Square Solution for Code

Positioning Error	North Error	East Error	Up Error
Min	-14.2731	-17.6102	-16.4025
Max	20.3504	14.07892	18.41453
Mean	3.906704	-1.27069	-1.59667

Positioning Error North East Up based on code (Iterative Least square)

Here fig is Showing position error north east up using Iterative least square algorithm and code based PPP.

PRECISE POINT POSITION ALGORITHM				Iterative Least Square Method			Least Square Method		
User position (Accord receiver)				Code-based positioning			Code-based positioning		
Sr no.	Latitude	Longitude	Altitude	Latitude	Longitude	Altitude	Latitude	Longitude	Altitude
1.	23.02508321	72.51894777	4.9114	23.02504405	72.51896348	5.850857214	23.02504953	72.51899927	7.850995755
2.	23.02508043	72.51894664	5.2143	23.0250414	72.51896227	6.241870402	23.02505167	72.51899937	8.40891496
3.	23.02508167	72.51894709	4.858	23.02504271	72.51896264	5.790932786	23.02504822	72.51899607	7.803748694
4.	23.0250804	72.51894929	4.9706	23.02504164	72.51896468	5.881959814	23.02504632	72.51899532	7.876661428
5.	23.02507687	72.51894927	4.8951	23.02503799	72.51896478	5.949334702	23.02504983	72.51900113	8.175379762
6.	23.02508156	72.51894885	4.3948	23.02504256	72.51896445	5.351370703	23.02504915	72.51899915	7.396963075
7.	23.02508215	72.51894933	4.5185	23.02504331	72.51896479	5.471038285	23.02504995	72.5189975	7.525881288
8.	23.0250792	72.51894917	4.9355	23.02504073	72.51896436	5.937154531	23.02505047	72.51899459	8.113588176
9.	23.0250776	72.51894949	4.8112	23.02503863	72.51896506	5.777175977	23.02504573	72.51899971	7.840809868
10.	23.02507771	72.51894981	4.1793	23.02503977	72.5189646	5.293994959	23.02505617	72.51899255	7.718525069

Sr no.	ZHD	ZWD	ZTD=ZHD+ZWD	Mapping Function ZHD	Mapping Function ZWD
1.	Saastamoinen	Asken Nordius	Saastamoinen & Asken Nordius	Herring Mapping Function	Herring Mapping Function
2.	Davis et al	Asken Nordius	Davis et al & Asken Nordius	Herring Mapping Function	Herring Mapping Function
3.	Davis et al	Ifadis	Davis et al & Ifadis	Herring Mapping Function	Herring Mapping Function
4.	Elgered et al	Asken Nordius	Elgered et al & Asken Nordius	Herring Mapping Function	Herring Mapping Function
5.	Elgered et al	Ifadis	Elgered et al & Ifadis	Herring Mapping Function	Herring Mapping Function
6.	Elgered et al	Baby et al	Elgered et al & Baby et al	Herring Mapping Function	Herring Mapping Function

Troposphere Delay for Three Different Station for Elgered et al (Dry) & Askne Nordius (Wet) & Herring Mapping Function

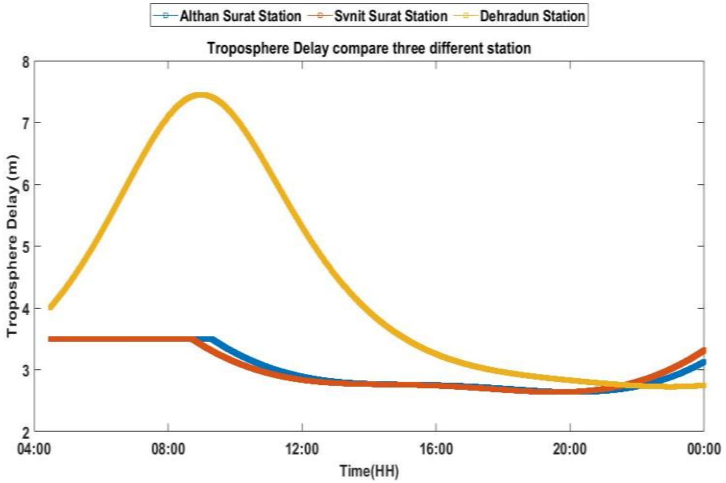


Figure 38 Troposphere Delay for Elgered et al (Dry) & Askne Nordius (Wet) & Herring Mapping Function for PRN2.

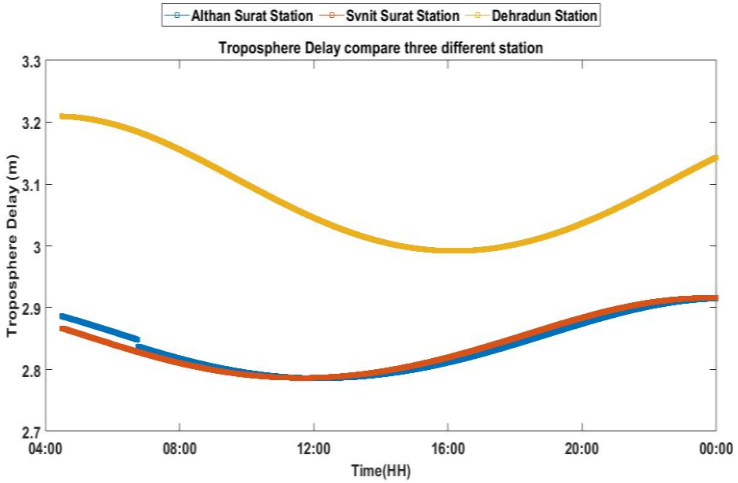


Figure 39 Troposphere Delay for Elgered et al (Dry) & Askne Nordius (Wet) & Herring Mapping Function for PRN3.

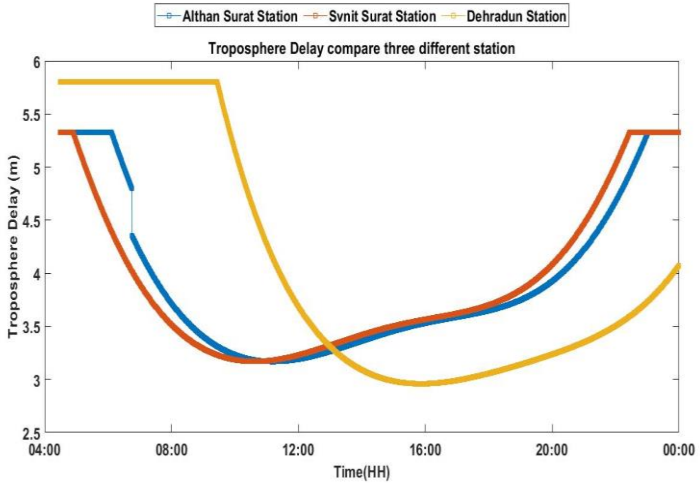


Figure 40 Troposphere Delay for Elgered et al (Dry) & Askne Nordius (Wet) & Herring Mapping Function for PRN4.

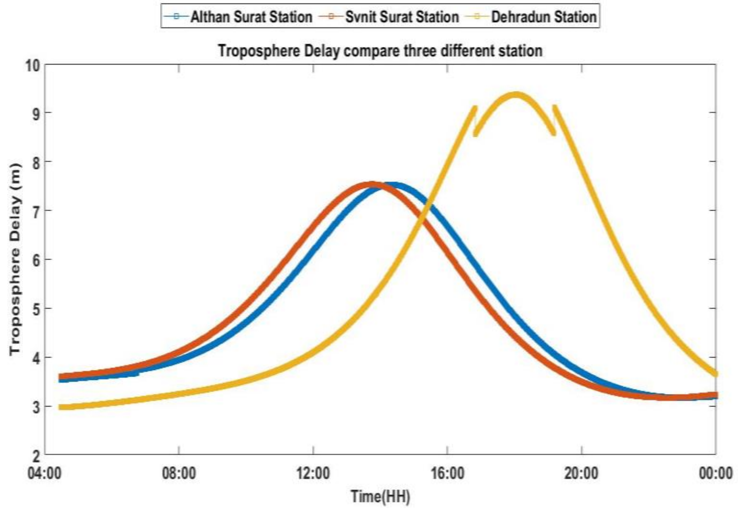


Figure 41 Troposphere Delay for Elgered et al (Dry) & Askne Nordius (Wet) & Herring Mapping Function for PRN5.

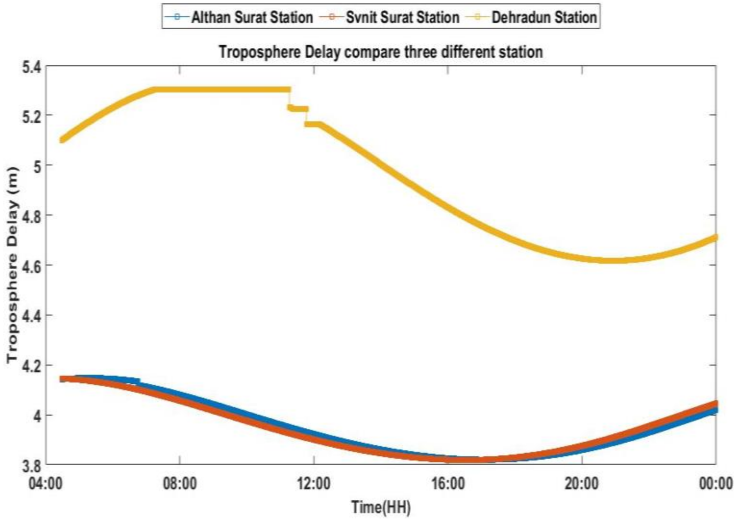


Figure 42 Troposphere Delay for Elgered et al (Dry) & Askne Nordius (Wet) & Herring Mapping Function for PRN6.

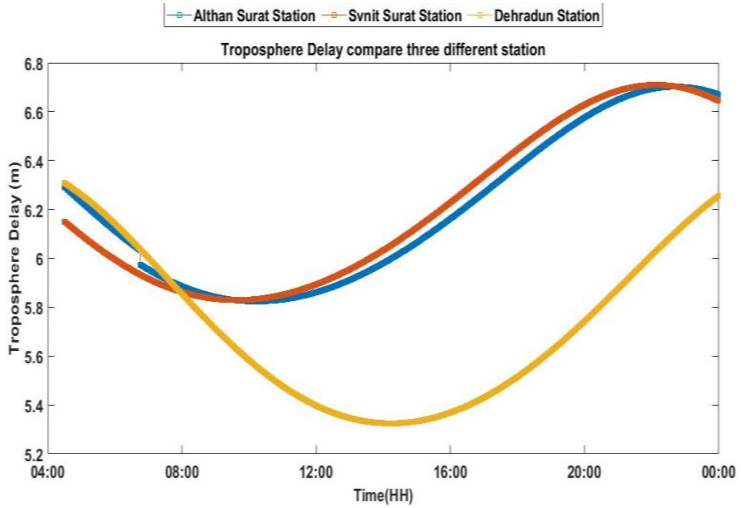
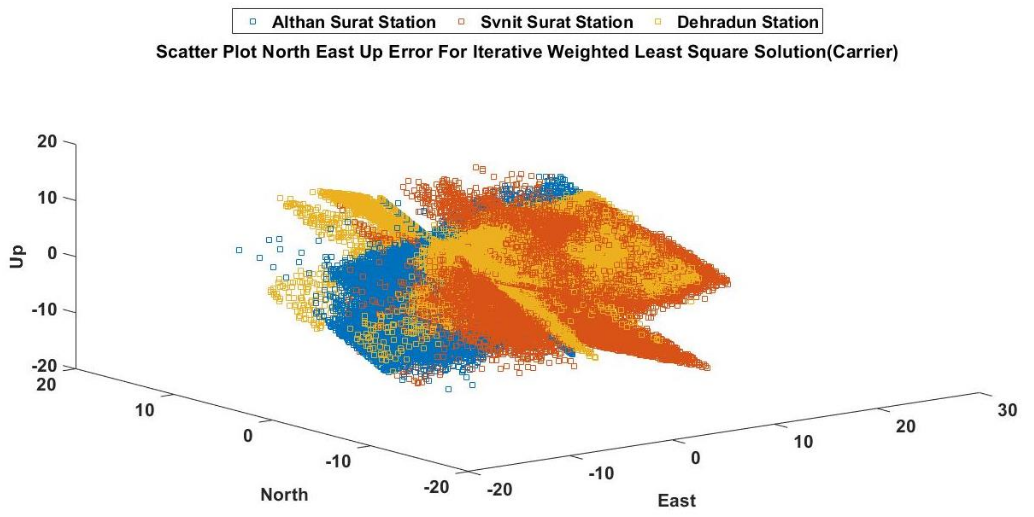
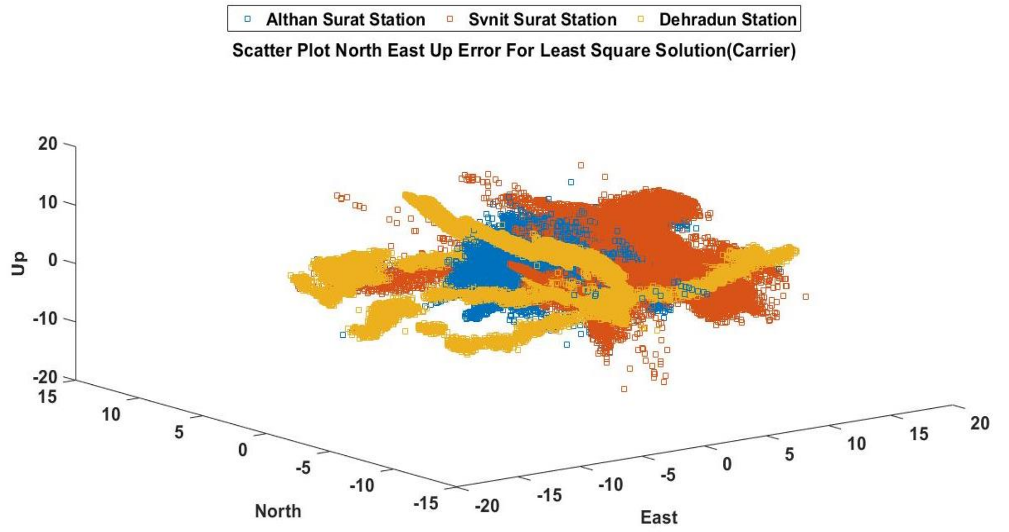


Figure 43 Troposphere Delay for Elgered et al (Dry) & Askne Nordius (Wet) & Herring Mapping Function for PRN9.

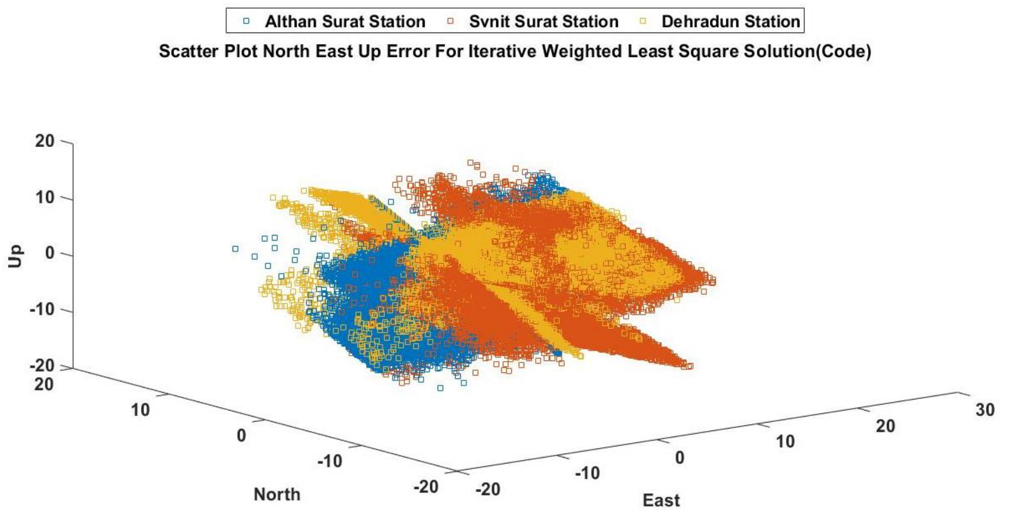
Comparison & Analysis Three Station Data (Position Error)



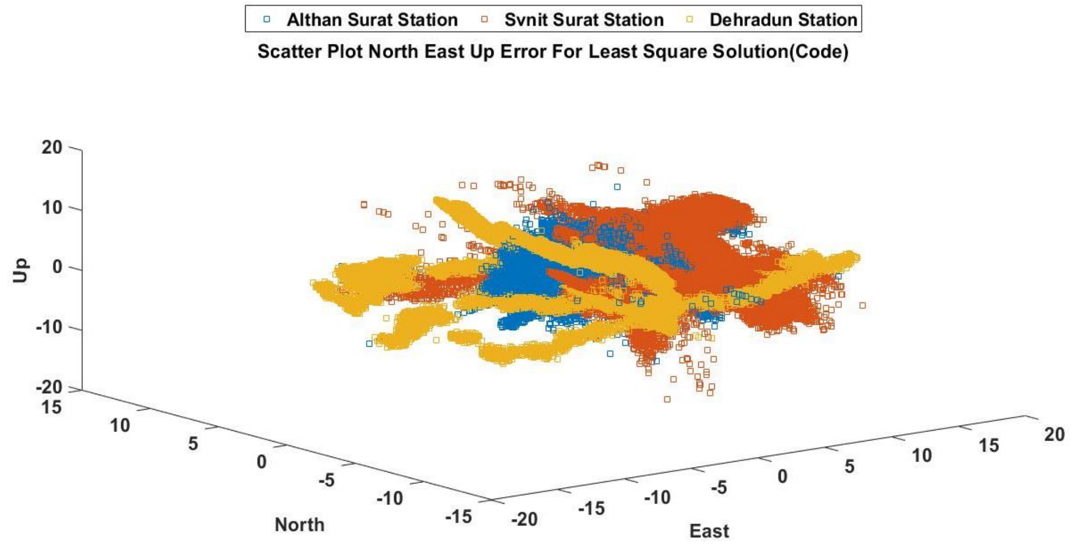
North East Up Error Iterative Least Square (Carrier).



North East Up Error Least Square (Carrier).



North East Up Error Iterative Least Square (Code).



North East Up Error Least Square (Code).

Key Observations

- Here we have concluded that Elgered et al. and Askne Nordius gives the nearest actual troposphere estimation with the real data from the accord receiver at SVNIT station.
- Based on calculated ZTD the user position is estimated using code and better positioning is seen iterative least square method compared to least square estimation method.
- The Iterative least square algorithm gives variation in Altitude compared to the Least square algorithm.
- The future work would be to carried out the analysis based on the carrier.

ALTERNATIVE APPROACH

- Assimilate meteorological data into Numerical Weather Prediction (NWP) models.
- Invert analyses and short-term predictions to provide real-time tropospheric signal delay estimates.
- For all end users, NWP-derived signal delay information is independent of their GNSS range or carrier phase observations.
- It is now possible to provide the following signal delay estimates at any point in the model domain:
  - Zenith hydrostatic delay (ZHD)
  - Zenith wet delay (ZWD)
  - Horizontal gradients in ZHD and ZWD.
- **Largest errors in NWP come from:**
  - **Limitations in our ability to describe water vapor variability in time and space**
  - **Mismodeling 4-d moisture structure.**
- Largest errors in GNSS height measurements come from tropospheric delay errors caused by water vapor variability.

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THANK YOU…

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