Site Specific Tropospheric Radio Atmospheres for Improved Accuracy through GPS

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ABSTRACT

Global positioning networks (GPS) which are used to study major crustal deformation through horizontal velocities are constrained for vertical velocities due to larger errors caused by tropospheric radio refractive index. Their variations in the Indian region are discussed in the light of synoptic and dynamical weather changes. Both the methods of using global models like ECMWF or NCAR to extrapolate weather parameters at the GPS site or Met pack at the site have limitations. In order to overcome these, various radio models for the Indian region are discussed from which site specific models can be evolved to improve the accuracy. It is suggested that local models of radio atmosphere (bi exponential model) can be initially taken with average scale heights of 9.01 km and 2.29 km for the dry and wet terms. A comparative study of the errors in velocity measurements from Indian navigation satellites, IRNSS with the other GPS networks is also called for to assess earthquake hazard in various sectors of Himalaya as well as within India.

Keywords: GPS accuracy, Refractive index, Site specific radio atmosphere

1. Introduction

Motions of the tectonic plates and crustal deformation in different parts of the world are now-a-days studied using Global Positioning networks (GPS) which make use of microwave signals transmitted by a network of satellites to a receiving station. Since microwaves pass through ionosphere and the troposphere, the presence of ionisation and the decrease of density of air with height in the respective layers cause bending of microwaves implying delay in their time of travel. NOAA's Space Weather Prediction Centre provides operational ionospheric delay estimates using a space weather model called USTEC. The accuracy of this model is about 2 TEC units. These frequency dependent delays in the ionosphere can also be eliminated by simultaneous measurements on two frequencies. In the troposphere, the presence of moisture causes additional delay in the travel time of microwaves. The density of dry and wet parts of the refractive index of air depends upon the atmospheric pressure, temperature and humidity. It is well known that errors in the horizontal velocity are much less than that in the vertical direction computed from GPS data. This is attributed to relatively lesser changes in the radio refractive index in the horizontal direction as compared to the vertical direction. Since the weather observations in the Indian regions have been used to compute different refractive index models, it is of interest to apply them for increased accuracy in the GPS results. The climatological values of radio refractive index have also been used for designing microwave communications network and prediction of transmission losses in the country, the objective of this paper is to present synthesized results of radio refractive models over India and adjoining coastal regions. An attempt has also been made to highlight the influence of synoptic and dynamical weather changes on the radio refractive index over the Indian region. Methodology is suggested to evolve site specific models from Met pack surface meteorological data or global models of ECMWF or NCAR.

2. Computation of Radio Refractive Index (RRI)

Radio refractive index, n is computed from meteorological observations by the following equations. However since it a very small quantity, it is computed by multiplying by 10^6 in the equation. The refractivity N is therefore computed by

$$N = (n-1)\,10^6 \quad \text{(i)}$$

$$N = 77.6/T \quad \{P + 4810\, e/T\} \quad \text{(ii)}$$

$$\text{or } N = 77.6\, P/T \;\{ 1 + 7.71\, m/T \} \quad \text{(iii)}$$

Here P is the atmospheric pressure in hPa, T is temperature in Kelvin scale related to temperatures in centigrade, t by well known relationship T = t + 273 and e is the vapour pressure in hPa. If mixing ratio m is taken in gm/ kg, m= 0.622 e/P. If dew point temperature is available as is generally the case from IMD data, it is converted to vapour pressure in hPa using the relation

$$e(T) = 6.105 \exp [\, 25.22 \{ Td- 273.0 / Td\} - 5.31 \ln \{ Td/273.0\}] \quad \text{(iv)}$$

The first term in the above relation, ii of radio refractive index is due to gases like oxygen, carbon dioxide, nitrogen and other inert gases in the atmosphere which are non polar in nature and non dispersive and thus they do not depend upon microwave frequencies. The second term arises due to water vapour which is polar and frequency dependent.

A formula for better accuracy in refractivity has been suggested (Roeger, 2002) as follows:

$$N = 77.6800\, Pd/T + 71.2052\, Pw/T + 375463\, Pw/ T^2 \quad \text{(v)}$$

Here Pd (= P tot – Pw) is the partial pressure of dry air (including 375 ppm carbon dioxide hPa), Pw is the partial water vapour pressure (in hPa), and T is the temperature (in K). The accuracy of the dry air refractivity component Nd (first term) is 0.02 % of Nd. A conservative value for the accuracy of the water vapour component Nw (sum of second and the third terms in above equation) is 0.2 % of Nw.

The weather observations at the ground surface and in the upper layers (radio sonde data) of the atmosphere are available from IMD and other meteorological services. Now-a-days weather observations are taken by meteorological instruments at the same place where GPS is located. This is called MET pack and generally provided by the manufacturers. However, this gives only surface weather observations. Where this is not available, global models like ECMWF and NCAR are used from which the observations need to be extrapolated at the GPS site since grid point values are given in the model. It may however be remembered that vapour pressure values become less accurate with altitude (height) due to humidity sensor response since the amount of vapour pressure decreases markedly with height.

Rao and Srivastava (1971) derived an equation for errors in the computation of radio refractive index and found that negligible errors occur whether computed from daily weather observation or mean monthly values. Srivastava and Pant (1968) using climatological normals showed the spatial distribution of refractivity over India during winter and southwest monsoon seasons. The largest effect of radio refractive index occurs near the ground surface while about 65% bending of microwaves occurs within a kilometre above the surface (Srivastava, 1968). A number of correlations between the surface value of refractivity with the gradient in the lowest 1 to 1.5 kilometers have been worked out for the Indian region (Srivastava and Chatterjee, 1967, Srivastava, 1968, Srivastava and Pathak, 1968). The high correlations except during southwest monsoon suggest that about 60 to 70% bending of GPS signals can only be accounted if we take surface values of refractive index but for precise measurements, the variation of refractive index with height needs to be considered. Climatological data of radio refractive index have also been used to compute radio ray refraction in the lowest 3Km (Srivastava and Maheshwari, 1970). This bending is more marked when the humidity or vapour pressure in the atmosphere increases.

The line of sight distance between the GPS station and the satellite becomes curved (and larger) due to complex radio refractive index. If a wave is propagating through atmosphere with n as its refractive index, the time taken by the wave to travel infinitesimal distance, ds is given by

$$dt = n\, ds/c \qquad \text{(vi)}$$

Here the velocity of electromagnetic waves is c in free space.

or $$c.dt = n.ds \qquad \text{(vii)}$$

The total time taken to cover the satellite to GPS station is

$$T^1 = \int dt = 1/c \int n\, ds \qquad \text{(viii)}$$

Thus the path length travelled by the microwaves

$$D = \int n\, ds \qquad \text{(ix)}$$

Due to the influence of troposphere, this path is larger than the line of sight or geometric distance, D. Thus the error in the range is given by

$$R = \int n\, ds - D \qquad \text{(x)}$$

$$R = \int (n-1)ds + \int ds - D$$

$$= \int (n-1)\, ds + \{S - D\} \qquad \text{(xi)}$$

$$= 10^{-6} \times \int N\, ds + [S-D] \qquad \text{(xii)}$$

The time delay, τ is represented in terms of radio refractive index by

$$\tau = \int (n - 1)\, ds + dg \qquad \text{(xiii)}$$

Here n is the refractive index of the atmosphere and dg is the difference between the curved and free space paths i.e.S-D (Herring, 1992). This delay consists of two parts; the dry air causes about 90 % delay and the wet component about 10 %. At normal incidence, the contribution of second (wet) term is zero since there is no bending of rays at nadir (zenith angle zero). The Zenith Tropospheric delay (ZTD) consists of two parts namely Zenith Hydrostatic Delay and Zenith Wet Delay. It is given by

$$ZHD = 10^{-6} \int Nd\,(h)\, dh \qquad \text{(xiv)}$$

$$ZWD = 10^{-6} \int Nw(h)\, dh$$

The integration in this equation extends from GPS antenna altitude to infinity h is the height at which Nd or Nw are computed. The measured delay can also be inverted to compute integrated water vapour in the atmosphere at the station and is widely used in numerical weather prediction models.

3. Diurnal, Seasonal and Vertical Variations of RRI

In general, radio refractive index near the ground surface is maximum in the morning during 00 to 03 hours GMT and minimum in the afternoon during 09 to 12 hours GMT. The diurnal changes are largest during pre-monsoon season (Johari and Srivastava, 1970). Largest values of radio refractive index occur during southwest monsoon over most parts of India (Srivastava and Pant, 1968). Due to the larger changes over north India and hill stations, refractivity errors may increase in these places (Srivastava, 1965). Also intra-seasonal oscillations may also cause marked changes in the refractivity (Srivastava et al, 1993). Radio refractive index variations in the upper troposphere show considerably lesser spatial variation over India due to absence of water vapour (Srivastava, 1967). These are generally modeled by harmonic functions whose coefficients are derived by least squares adjustment over a long period taking the data from global models like ECMWF or NCAR. This enables to interpolate meteorological parameters at the GPS site. This method has however, some limitation particularly for hill stations due to the need of higher resolution.

3.1 Weather phenomena affecting RRI

The following weather phenomenon may cause changes in the values of radio refractive index which may affect GPS results:

Subsidence: Subsidence or sinking of air such as in areas of high atmospheric pressure called anticyclones can modify the vertical temperature and humidity structure of the air. It frequently happens in the centre of stagnant anticyclones (high pressure areas) that large layers of air sink, or subside, towards the ground. This sinking is accompanied by an outflow of air from the area, horizontally near the surface since it is subjected to larger pressure in the lower levels close to earth's surface. It is compressed consequently, being confined in a small pocket where the air temperature rises. Under certain conditions, the decrease of temperature with height called the lapse rate decreases and may change to an inversion causing increase in temperature with height. It is also seen that subsidence or sinking of air will generally lead to a more rapid decrease of humidity with height. If air sinks in an anticyclone, the low value of the humidity corresponding to higher levels will be brought nearer to ground. This will result in increasing the vertical gradient of humidity.

Advection: On horizontal surface of the earth, the movement of air is caused by wind from one region to another region where the surface temperature or the vapour pressure is markedly different. For example, the air may be originally over a land surface, where it has been warmed and may then be carried across the coast and pass over a comparatively cold sea. The surface layers of the air are thus cooled and an inversion is formed.

Eddy diffusion: Small fluctuations in air gives rise to turbulence described by eddies. High eddy diffusion means almost uniform temperature and humidity and consequently normal propagation. Low eddy diffusion permits the existence of substantial atmospheric gradients and so makes super refraction possible. It may be mentioned that eddy diffusion is low in temperature inversion.

Sea breeze: Sea breeze occurs in the afternoon due to difference in the amount of sun's heat received over coastal regions and land. An effect of the sea breeze is to bring moisture inland in the lower layers for a short distance, creating conditions favourable for the formation of a duct. Although it is limited to an area of a few kilometers either side of coast line, it may be useful for coast line microwave transmission.

It may be mentioned that **s**ince microwaves travel in straight line, any obstruction in their path reduces signal. Therefore, nature of terrain is important particularly in Himalaya where valleys and ridges are abundant with large variations in vegetation and forest cover.

In addition, the predominant influence of southwest monsoon and the weather systems influence variations of refractive index over large area. The weather conditions in India rapidly change with the low pressure weather systems which move over northwest India or develop over oceanic areas in Bay of Bengal and Arabian sea. Due to marked change in temperature, humidity and rainfall, they affect microwave propagation.

3.2 Weather systems affecting RRI

Western Disturbances:

The change of the value of the radio refractive index during a western disturbance is of the order of +45 N_O units with the approach of the system which reduce to about 25 N_O units in the rear i.e. after its passage(

Maheshwari,1962) These values, however change depending upon the intensity of the system. After the passage of weather disturbances, cold air from northern latitudes decreases radio refractive index over northern India. .

Monsoon depressions:

The average value of the 24-hourly rise in surface refractivity based on several monsoon depressions at surface, 1.5 Km, 3 Km, and 6 Km mb levels was reported as 08, 16,08 and 05N units respectively (Srivastava, 1968). Since they form during southwest monsoon with moist or highly humid current, the changes in the refractive index due to depressions are relatively less. However, heavy rainfall may cause significant attenuation of microwaves.

Cyclonic storms:

The more destructive weather system called cyclonic storm occur during pre monsoon (March to May) or post monsoon (October, November). The values of radio refractive index rise markedly upto 800 mb level (Venkataraman et al, 1963).This rise is much larger than in the case of monsoon depressions.

4. Models of RRI over India and Adjoining Coastal Area

Tropospheric delay can be estimated by predictive refractivity models based on climatology

Analytical refractivity models based on surface weather observations of pressure, temperature and relative humidity or numerical weather prediction models e.g ECMWF or hybrid models like NOAA Trop. In this model, observations are taken or interpolated to the location of GNSS antenna at the station. The limitation arises because the relative humidity near the surface is poorly correlated with the upper air moisture as may occur in clouds. On the other hand NWP models which assimilate all available surface, upper air and satellite observations have problems with moisture. These are however more accurate in dense networks and high resolution models. The results are significantly affected during rains.

Exponential model of refractive index is given by

$$N = A \exp(-BhZ) \qquad (xv)$$

Where A and B are constants which are determined by least squares method. The value of A corresponds to radio refractive index at the surface.

Bi exponential model of refractive index is given by

$$N = N_d + N_w \qquad (xvi)$$

Where N_d and N_w are the dry (hydrostatic) and wet parts (terms) of radio refractive index. Both terms vary exponentially with height Z. In terms of surface values, they are expressed as

$$\log N_d = \log N_{do} - Z / H_d \log e \qquad (xvii)$$

$$\text{and } \log N_w = \log N_{wo} - Z / H_w \log e$$

where H_d and H_w are scale heights of the dry and wet terms respectively. Scale height is defined as the height where surface value of radio refractive index reduces to 1/e of surface value. This model is more representative for delay correction due to the wet term (Bean and Dutton, 1968).

For the Indian region, exponential and bi exponential models of radio refractivity have been studied in detail, (Srivastava and Pathak, 1969, Pathak and Srivastava, 1970, Srivastava and Pant, 1976, 1979), These models could be used to analyse GPS data by suitable change in the software. Meteorological data from 18 radio sonde stations for the period 1995-1999 were also used to develop the site specific monthly mean atmospheric models similar to Srivastava and Pathak (1970) for 12 stations in India . It has been found that the effect of water vapour pressure extends generally upto 4 km while the radiosonde ascents provide atmospheric pressure and temperature upto 25 to 30 km.. Srivastava (1967 a,b) also studied the radio characteristics in tropical atmosphere which could be used if data of larger number of stations in the tropical region are to be analysed. The COSPAR International Reference atmosphere (CIRA) Model provides many useful features. It may be mentioned that more recent climatological normals for the surface observatories (1960-1990) and upper air data from Indian radiosondes stations are available from India Meteorological Department at Pune. These have a distinct advantage of lesser errors due to modern radio sondes as compared to two types of mechanical radio sondes of C and F types used earlier.

5. National Programme of GPS

GPS networks can be local, regional and worldwide to monitor geophysical processes on different time and frequency scales. The GPS signals from satellites are received at the station and then amplified, down converted and digitised into samples. Their analysis enables to generate receiver position information. Daily vertical time series of GPS contains tectonic as well as non tectonic deformation signals, noise and atmospheric delay. Amiri-Simkooei (2007) assessed noise characteristics in time series for permanent GPS stations and confirmed the presence of annual and semi annual signals in the series. Peng et al (2016) used a modified approach of Principal Components analysis to separate atmospheric and soil moisture loading signal to explain the cause of seasonal variation of GNSS vertical time series in China. In the Indian region GAMIT/GLOBK MATLAB tools software is used to analyse the time series of signals and then converted to velocity field.. The Burnese GPS software is also used for post processing of GPS observations. In this software, station motions can be modelled for plate motions, solid earth tides and ocean tidal loading. Different tropospheric mapping functions are also provided.

The Indian National programme for GPS was launched more than 15 years back by the Department of Science and Technology. After its transfer to the Ministry of Earth Sciences it is constantly being expanded. As mentioned earlier, the expansion of the GPS network is to provide crustal deformation measurements to constrain the movement of Indian plate, locate the regions of strain accumulation and to estimate the convergence rates across some faults and plate boundaries. An overview of the co-seismic and post seismic deformation related to 2001 Bhuj, 2004 Sumatra Andaman, 2005 Muzaffarabad and Sikkim 2011 earthquakes has been discussed by Verma and Bansal (2012). The results obtained in some sectors of Himalaya, Indo Burmese region, Andaman Nicobar island region have also been synthesized by these authors. Mahesh et al (2012) brought out the constraints of Indian plate from detailed GPS data but better radio atmospheres may refine results.

Indian regional navigational satellite (IRNSS) launched by ISRO consists of seven satellites; three satellites in Geo stationary orbit and four satellites in Geosynchronous orbit with inclination of 29 degrees to the equatorial plane. It is designed to provide accurate real time positioning and timing services over India and neighbourhood extending to 1500 km around India. This is similar to GPS of USA (24 satellites), GLONAS of Russia (24 satellites), Galileo of Europe (27 satellites) and China s Beidou (35 satellites). The Indian network has reduced dependence on foreign navigation systems.

However its accuracy for precise GPS measurements as compared to other networks for plate movements is yet to be studied.

6. Discussion

Earthquake hazard in Himalaya is assessed using instrumental, historical and paleo seismic data on earthquakes and Indian plate velocitiy measurements through GPS. Some seismologists (Bilham and Wallace,2005, Ader et al, 2012) including those involved in paleo seismic studies (Kumar et al, 2006) suggested that earthquakes upto magnitude Mw 9 or more similar to subduction zones may occur in Himalaya. However Srivastava et al (2013) raised many questions about this inference and suggested a lower maximum magnitude along the Himalayas (around 8 to 8.5) due to fractured lithosphere caused by multiple collisions giving shorter faults lengths as compared to 500 to 600 km in subduction zones, lesser locked zone of about 100km as compared to 200 km in subduction zones and generally lower velocities of deformation caused by plate movements. This has also been corroborated by Gupta and Gahalaut, (2015). GPS data as well as seismological data also suggested that all the regions in Himalaya are not equally seismic. Srivastava et al (2013) identified discriminatory characteristics of two types of seismic gaps in Himalaya. The occurrence of recent Nepal earthquake, 2015 (Mw 7.8) in east central Nepal gap validated this classification (Prakash et al, 2016). It may be mentioned that in Himalayan region, the accumulated slip is too large to be explained with the largest magnitude of earthquakes in the past occurring from Kashmir to northeast India (2005,1555, 1905, 1803, 2015, 1934, 1947 and 1950). One of the theories suggested is that slow slip may be taking place but could not be detected with present GPS data. Another difficulty in the Himalayan region arises due to frequent cloudiness and rain which introduce errors in GPS results. However, the site specific radio atmosphere may improve the velocity measurements near the Indian plate boundary. Also high resolution models have been recommended for hilly regions. Thus large cluster of GPS in different sectors of Himalaya may increase the accuracy of plate velocity measurements .if proper radio atmosphere is worked out.

It has been found that bi exponential model of refractive index is more representative for the Indian region (Srivastava and Pathak, 1970). Since Met pack with GPS system if available gives only the surface values of meteorological parameters, a proper radio atmosphere should take into consideration its variation with height. The average value of scale heights for the dry and wet term of radio refractivity in the Indian region have been computed (Srivastava and Pathak,1969, Pathak and Srivastava, 1970). The measured value of surface refractive index can be initially used in bi exponential model with the scale heights as 9.09 km and 2.29 km respectively for the dry and wet terms over the Indian region (Table 1). It may however, be mentioned that there is much larger variation in scale height due to the wet term at different places and in different seasons over India (Pathak and Srivastava, 1970). For higher accuracy, the recent climatological radio sonde data available at the nearest station from India Meteorological Department may be used by extrapolation at the GPS site to develop site specific models.

It is well known that GPS signals are non linear. Using chaotic dynamics, Srivastava et al (1994) found that 6 to 9 parameters are needed for modelling radio refractivity which is of the same order as the weather elements like atmospheric pressure, temperature and humidity. .Byun and Bar- Server (2009) devised a new type of troposphere zenith path delay product of the international GNSS service. For this purpose, weather models of ECMWF or NCEP have been widely used. Chen et al (2012) analysed global models to find accuracy of topographic zenith delay. But site specific models of radio atmosphere are required to provide more accurate dry and wet term tropospheric corrections.

7. Problems to be Resolved

- A comparative study of the accuracy of IRNSS with GPS and other networks particularly near Himalayan foothills
- Application of site specific models of refractivity over Indian region for GPS studies
- Comparative study of GPS results (long term) by including and excluding southwest monsoon data

8. Conclusions

The above study has brought out that better accuracy in velocities deduced by GPS can be obtained if the surface values of refractivity computed from meteorological data (Met pack) can be fitted into bi exponential model with dry and wet tern scale heights to include their exponential variation with height. Mean values for the scale heights of dry and wet term may be initially taken as 9.09 km and 2.39 km over the country.The site specific radio atmospheres can then be worked out using recent radio sonde stations. If a radio sonde station is located near GPS station, suitable software changes are called for to insert this data.

Acknowledgements

The author is grateful to Dr V.K. Gahalaut, Head, National Centre for Seismology, Ministry of Earth Sciences for helpful clarifications.

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Table 1 Mean values of H_d and H_w over India (Srivastava and Pathak, 1969)

Month	**H_d (Km)**	**H_w (Km)**
February	9.06	1.67
May	9.20	2.80
August	9.03	2.71
November	9.05	1.98
Mean	**9.09**	**2.29**