Neutral Atmospheric Refraction on Microwave Propagation and Its Implication on GPS Based Ranging System

Korak Saha, **Suresh Raju and K. Parameswaran**

Space Physics Laboratory, Vikram Sarabhai Space Centre, Thiruvananthapuram 695 022, Kerala.

ABSTRACT

Tropospheric refraction affects microwave propagation by retarding and bending, causes an error in microwave ranging. This limits the accuracy in satellite-based GPS navigation. This paper attempts to model tropospheric range error (ΔR_T) over Indian subcontinent (8^oN-32^oN) using mean model of atmosphere derived from Radiosonde data. A set of empirical relationships connecting surface atmospheric parameters with ΔR_T (rather its zenith component, TZD) was established for different stations over the Indian subcontinent. The accuracy of these models in predicting the range errors are established by comparing the model estimates, with true ΔR_T estimated through ray tracing. The models agree well with GPS measured TZD for all seasons within ±5cm.

INTRODUCTION

The refractive characteristics of the neutral atmosphere (mainly troposphere) are governed by its composition. The water vapor molecules in atmosphere are polar in nature possessing of permanent dipole moment. All the other gases are non-polar molecules and the dipole moment is induced among these gases when microwave propagates through atmosphere. These molecules reorient themselves according to the polarity of propagating wave causing a change in the refractive index of the atmosphere. The refractive index is a function of pressure, temperature and water vapor pressure. The tropospheric refraction affects the microwave propagation by retarding and bending, thus causing an error in microwave ranging. This limits the accuracy in many applications like terrain elevation mapping by Interferometric SAR and satellite based GPS navigation. The neutral atmosphere is being non-dispersive, the tropospheric range error correction is possible only by using models based on easily available atmospheric parameters (pressure, temperature and humidity). This paper deals with development of tropospheric range correction models and their validation with GPS measured tropospheric range error.

Atmospheric Refractive Index

The refractive property of the neutral atmosphere is related to pressure, temperature and water vapor partial pressure. Troposphere is a non-dispersive medium and its refraction effect estimation is possible only by modeling the tropospheric medium. The atmospheric parameters like pressure, temperature and water vapor undergoes variations based on the geographical locations and seasons. The first step is to estimate the refractivity of the atmosphere. The refractive Index of the neutral atmosphere is related to atmospheric parameters as [6]

$$N = (n-1)x10^6 = K_1 \frac{P}{T} + K_2 \frac{e}{T} + K_3 \frac{e}{T^2} \qquad (1)$$

where N is termed as refractivity and $P = P_d + e$, is the hydrostatic atmospheric pressure. The values of the constants as reported by Hartmann (Proc. Satellite Beacon Symposium, Warsaw, Poland, 1980) K_1 = 77.67, K_2 = 99.3 and K_3 = 37,42,32.96 are found to be valid for the estimation of N for frequency up to 30 GHz and for normally encountered ranges of pressure, temperature and humidity. The tropospheric refractivity given by (1) consists of two parts [5], one the hydrostatic component or dry component (N_D) represented by first term in the right side of (1) and the other non-hydrostatic component or wet component (N_w) represented by second and third terms in the right side of (1). The dry gases like N_2, O_2, *etc*., contributes for N_D while water vapor (which is essentially non-hydrostatic) causes wet component (see details [1]). The water vapor though is mostly confined to lower part of troposphere shows significant temporal and spatial variability. This makes the prediction of N_W rather complex. On the other hand the variability of P and T are well defined and hence it is much easier to predict N_D. Integrating N_D and N_W at layer by layer in the atmosphere respectively accounts for the dry and wet component of TZD [5].

ESTIMATION OF DRY AND WET RANGE ERROR

The region like Indian sub-continent has large variability in its climatic conditions. In order to model the atmosphere the meteorological data for different stations that are located over wide geographical locations between 8^oN to 32^oN is considered in this study. Using three years (1995-1997) of daily Radiosonde data, procured from IMD for eight stations the monthly mean atmospheric models were developed. The refractivity profiles are developed for these atmospheric models using (1). The ray-tracing technique is employed to these atmospheric models to compute the accurate total tropospheric zenith delay (TZD). The implication of day-to-day variability of atmospheric parameters, such as Pressure (P), Temperature (T) and water vapor pressure (e) on Tropospheric range error was studied based on error propagation technique [3]. The tropospheric delay is computed for all stations by applying the ray-trace techniques to monthly mean atmospheric model. The Fig. 1 shows the monthly mean dry and wet error for Bangalore. The vertical lines in the graphs show the deviation of range error due to day-to-day deviation in atmospheric parameters. The maximum deviation in dry range error is about ~5 cm for all station. The deviation in wet range error due to daily water vapor changes is significant which is more than 40% of the monthly mean wet range error for all stations. Though wet range error contributes only about 10% of the total range error, its day-to-day variability is very significant for the GPS ranging application like aircraft navigation. The seasonal variation of dry range error is 2.097 (0.0039) m and wet range error is 0.244 (0.0469) m. The values given in the bracket is the deviation month-to-month or seasonal variation of the range error values. The dry component shows very less variation within year but latitude dependent is also seen, though it is small.

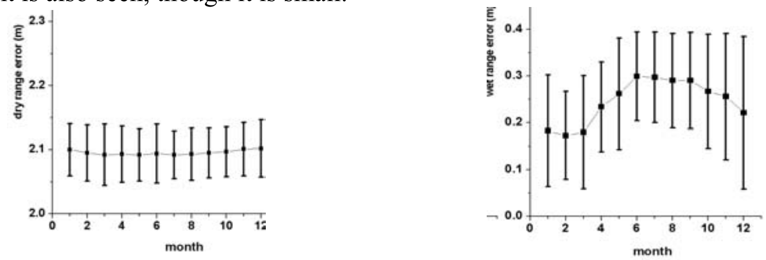

Fig. 1. Seasonal variation of dry and wet tropospheric range error for Bangalore

When altitude profiles for ray-tracing is not available, development of various models with easily available surface weather parameters is required. Radiosonde data of eight stations in Indian subcontinent is used to develop these models.

Unified Surface Model

Though, the contribution to dry component of tropospheric refractivity comes from an altitude region extending from surface to lower stratosphere its spatial and temporal variability is rather well defined making the prediction relatively easier than that of wet components of atmospheric refractivity which shows significant temporal and spatial variability due to the variation in atmospheric water vapor. As the variability of dry refractivity is somewhat regular, the simple linear relationship between surface pressure (P_s) and Hydrostatic (dry) zenith delay (HZD) is sought for prediction purposes. The regression analysis shows a simple linear relationship with zero Y-intercept (2). As in the case of wet range error, the simple models to estimate wet zenith delay (WZD) using surface water vapor pressure (e_s) and integrated water vapor content (I_W) are also sought based on the monthly mean atmospheric models for these two stations (3). These studies showed that most accurate prediction of ΔR_W comes form the integrated water content vapor while the prediction from e_s is relatively inferior. As such they could be used only in the absence of integrated water vapor measurements. The large spatial and temporal variability of water vapor profile makes the prediction of wet range error from surface weather parameters more difficult, though its contribution is only less than 10% of tropospheric range error.

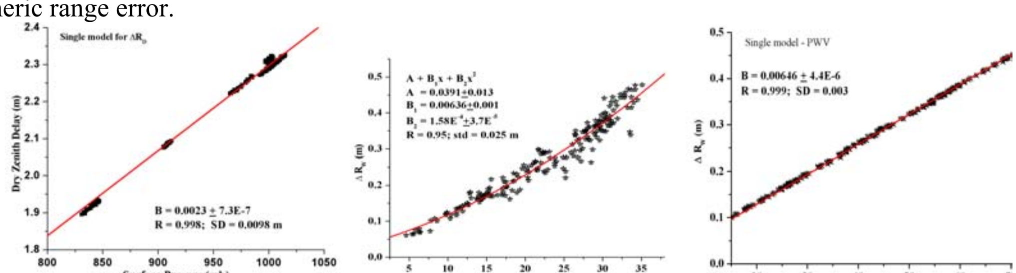

Fig. 2 HZD and WZD estimation from surface weather parameters (UNIFIED SURFACE MODEL)

$$\text{HZD} = 2.3 \times 10^{-3} \times P_s \quad (2)$$

$$\text{WZD} = 0.0391 + 0.00636 \times e_s + 0.00015 \times e_s^2 \quad (3)$$

$$\text{WZD} = 0.00646 \times I_s$$

Unified Hopfield model

Hopfield [2] developed an analytical model for the altitude profile of refractive index based on surface refractive index (N_0) and the "characteristic height" which is based on modeling. Once the monthly pattern of characteristic height is modeled for a station, it will be possible to estimate the range error from surface refractive index. In this study we are also examining the possibility of developing an atmospheric range correction for Bangalore, based on Hopfield's approach. It is assumed that effects of N_D and N_W above the respective characteristic heights (h_D and h_W (in km)) are negligible for HZD or WZD. If N_{0D} and N_{0W}, respectively, surface values for dry and wet components of atmospheric refractivity, are estimated using equations (1) and

$$\mu = [g/(R\alpha)]-1 \quad (4)$$

where g is the acceleration due to gravity of earth, R is the dry universal gas constant and α is the temperature lapse rate. The temperature lapse rate vary with geographic latitude as well as to certain extend with altitude also. Considering the temperature lapse rate is about 6.7 ^{o}K/km, g = 9.78066 m/s^2 and R = 287.054 j/kg/^{o}K in expression (3), value of μ can be approximated to 4.0. Then the expressions for zenith range errors HZD and WZD can be written as

$$HZD = \int_0^{h_D} N_D dh = N_{0D}\frac{h_D}{(\mu+1)} \quad (5a)$$

$$WZD = \int_0^{h_W} N_W dh = N_{0W}\frac{h_W}{(\mu+1)} \quad (5b)$$

The above equations are strictly valid only when the integrals are taken up to the respective characteristics height. But, in the present case the value of N_D is available only upto 26 km and N_w upto 12 km. As will be seen later the value of h_D will be larger than 26 km and N_w will be larger than 12 km. This limits the accuracy of models derived from the available data.

The applicability of Hopfield model was explored by seeking regression analysis between easily available atmospheric parameters and the wet and dry 'characteristic height' (h_D and h_W) of refractivity profiles. The regression analysis to relate characteristic heights and surface temperature (Ts) (6a) and (6b) is shown in Fig. (3).

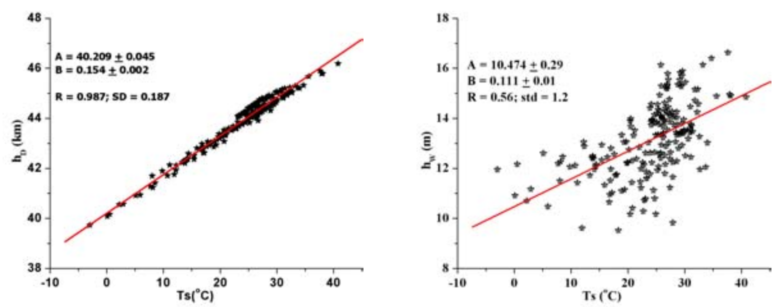

Fig. 3 Regression analysis to relate characteristic heights and surface temperature

$$h_D = 40.209 + 0.154 \times T_s \quad \text{(km)} \quad (6a)$$

$$h_D = 10.474 + 0.111 \times T_s \quad \text{(km)} \quad (6b)$$

VALIDATION OF MODELS USING GPS DATA

A set of surface models (2), (3) and (6) applicable for all stations to estimate dry and wet tropospheric range error was developed. These models are also validated based on daily radiosonde data and GPS measurement from Bangalore. For this the data from Bangalore International GPS Service (IGS) station is used. The dual frequency GPS receiver was installed at IISC - campus, Bangalore, India, as a part of International GPS station network since 1994. The dual channel GPS receiver collects the data continuously at 30 seconds. This data in a system (GPS receiver) independent format (RINEX) is also available from IGS website, http://www.ngs.noaa.gov/CORS/Data.html. The daily GPS data for one year (1997) along with other IGS stations around Bangalore (required for data processing) was downloaded for this study. These data were processed with GAMIT version 10.07, developed jointly by MIT and SIO [4], for estimating TZD. The precise GPS orbits were obtained from IGS sites. The tight constraints (0.005 m) were given to the IGS station Coordinates in this analysis. The final output is the TZD. The TZD derived from the GPS data showed a seasonal variation, which is mainly due to the variability of the atmospheric parameters. The model values are in good agreement with that of GPS measurements for all seasons, however, there is a small disagreement within 4 -5cm.

The GAMIT analysis at both the end of the given eight base line cases provided the estimate TZD for respective station. One year (1997) of daily TZD value for every 2-hour interval was derived for Bangalore using GAMIT processing. The TZD values at 0000 and 1200 UTC were filtered out for the comparison of GPS measurements with model estimates of TZD. The Unified surface models based on pressure and water vapor partial pressure are used based on daily surface met data (procured from IMD). Hopfield model is implemented based on surface temperature. The comparison of these TZD values with GAMIT derived TZD is shown in Fig. 4, which shows the day-to-day variations as well as the seasonal variation of TZD in a year. The large day-to-day variability of TZD is mainly attributed to the variability of wet range error, caused by the water vapor variation. Winter season (December-February) shows low values of TZD and higher values in the monsoon period (June-October). This large day-to-day variation in TZD demands the tropospheric correction in many GPS applications like, navigation, Plate tectonics, surveying, sea surface studies, etc.

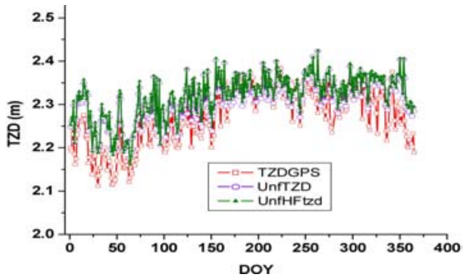

Fig. 4 Comparison of day to day TZD estimates from unified surface model and Hopfield models with GPS derived TZD for 1997 Bangalore

Overall, the model predicted TZD is slightly higher than the GPS derived TZD. The most important factor to be noticed is the same trend of the TZD variation obtained from GPS analysis and models.

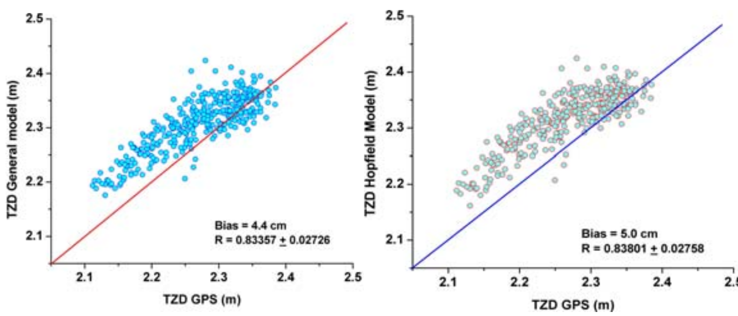

Fig. 5. Regression analysis between GPS derived TZD and that of model derived TZD

RESULTS

A more quantitative assessment of models and GPS measurements was carried out based on the regression analysis. The Fig. 5 shows the plot between TZD derived from GPS and models. There is a good correlation (~ 0.83) with a bias of ~ 5 cm. This clearly validates surface models developed for the hydrostatic and non-hydrostatic components of zenith delays based on, respectively, surface pressure and water vapor pressure. Thus unified models to estimate TZD with ~ 5 cm accuracy are proposed for the Indian subcontinent depending on the availability of surface parameters.

Reference

[1] Davis, J. L., Herring, T. A., Sharipo, I. I., Rogers, A. E. E., and Elgered, G. (1985). Geodesy by radio interferometry: Effects of atmospheric modeling errors on estimates of baseline length, *Radio Sci.,* 20(6)**,** 1593-1607.

[2] Hopfield, H. S. (1971). Tropospheric effect on electromagnetically measured range: Prediction from surface weather data, *Radio Sci.*, 6(3), 357-367.

[3] Ku, H. H. (1966). Notes on the use of propagation of error formulas, *J. Research Engineering and Instrumentation,* NBS-C, 70C(4), 263-273.

[4] MIT and SIO (2000). ***Documentation for the GAMIT GPS analysis software,*** Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, and Scripts Institute of Oceanography, University of California at San Diego.

[5] Saastamoinen, J. (1972). Atmospheric correction for the troposphere and stratosphere in radio ranging of satellites, in *The Use of Artificial Satellites for Geodesy, Geophys. Monogr. Ser.,* 15, edited by S. W. Henrisksen, et al., AGU, Washington, D. C., 247-251.

[6] Thayer, D. (1974). An improved equation for the radio refractive index of air, *Radio Sci.,* 9, 803-807.