UNB Neutral Atmosphere Models: Development and Performance

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BIOGRAPHIES

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Richard B. Langley is a professor in the Department of Geodesy and Geomatics Engineering at UNB, where he has been teaching since 1981. He has a B.Sc. in applied physics from the University of Waterloo and a Ph.D. in experimental space science from York University, Toronto. Prof. Langley has been active in the development of GPS error models since the early 1980s and is a contributing editor and columnist for GPS World magazine. He is an ION fellow and shared the ION Burka Award for 2004.

ABSTRACT

Several hybrid neutral atmosphere delay models have been developed by UNB researchers over the past decade or so. The most widely applicable current version is UNB3, which uses the Saastamoinen zenith delays, Niell mapping functions, and a look-up table with annual mean and amplitude for temperature, pressure, and water vapour pressure varying with respect to latitude and height. These parameters are computed for a particular latitude and day of year using a cosine function for the annual variation and a linear interpolation for latitude. The UNB3 model has been extensively used in several regions of the world, being capable of predicting total zenith delays with average uncertainties of 5 cm under normal atmospheric conditions. A modified version of UNB3 has been used in GPS receivers utilizing the Wide Area Augmentation System and other space-based augmentation systems. Other versions of the UNB neutral atmosphere model have been developed aiming at getting better predictions for the non-hydrostatic delay component. One of the new versions is UNB3m, whose performance has been investigated using radiosonde data and compared to that of UNB3. Based on ray-tracing analyses of 703,711 profiles from 223 stations in North America and surrounding territory from 1990 to 1996, the prediction errors of UNB3m have a mean value -0.5 cm and standard deviation of 4.9 cm. Although the standard deviation of the prediction error of UNB3m is similar to that of UNB3, the absolute mean error has been reduced by almost 75%.

INTRODUCTION

UNB3m was created by modifying parameter values in the UNB3 look-up table and the associated UNB3 algorithms. These changes were made in order to carry out the predictions using relative humidity rather than water vapour pressure. The part of the table that was related to water vapour pressure was replaced with values related to relative humidity. In UNB3m, all the computations for the point of interest are done initially using relative humidity, which is subsequently converted to water vapour pressure for use in the zenith delay computation.

In this paper, we present a brief review of the development of the UNB3m neutral atmosphere model. We provide a comprehensive description of the model's algorithm and assess its performance using radiosonde measurements. In this analysis, we compare the estimated zenith delays as well as those of UNB3 with ray-traced values computed using radiosonde measurements from across North America and neighbouring territories.

The motivation of this work is the need for optimal neutral atmosphere models to be used as input for GPS positioning software where the adjustment of residual delay is not easily performed, or not performed at all. The goal of UNB neutral atmosphere model research is improving our models as much as possible, and, in the specific case of UNB3m, this improvement is related to the non-hydrostatic component of the delay. The goal of this paper is to present our latest model development as well as a validation of its performance with a trustworthy reference.

UNB NEUTRAL ATMOSPHERE MODEL DEVELOPMENT

In 1997, Collins and Langley [1997] proposed a hybrid neutral atmosphere model designed for Wide Area Augmentation System (WAAS) users. This model, called UNB3, has its algorithm based on the prediction of meteorological parameter values, which are then used to compute hydrostatic and non-hydrostatic zenith delays using the Saastamoinen models. The slant delays are determined using the Niell mapping functions. A modified version of UNB3 was actually adopted for WAAS with the Niell mapping functions being replaced by the single Black and Eisner mapping function and with some other minor simplifications [RTCA, 2001]. The WAAS version of UNB3 has been favourably assessed for use with the European Geostationary Navigation Overlay Service [Dodson et al., 1999; Penna et al., 2001] and the Japanese Multi-functional Transport Satellite-based Satellite Augmentation System [Ueno et al., 2001].

In order to account for the seasonal variation of the neutral atmosphere behaviour, a look-up table of meteorological parameters is used. The parameters are barometric pressure, temperature, water vapour pressure (WVP), temperature lapse rate (β) and water vapour pressure height factor (λ). This look-up table was derived from the U.S. Standard Atmosphere Supplements, 1966 [COESA, 1966]. Table 1 shows the look-up table values for UNB3. The data is divided into two groups, to account for the annual average (mean) and amplitude of a cosine function for each parameter. Both amplitudes and averages vary with respect to latitude, for all parameters.

The first step in the UNB3 algorithm is to obtain the meteorological parameter values for a particular latitude and day of year using the look-up table. By definition, the origin of the yearly variation is day of year (doy) 28. This procedure is similar to the one used in the Niell mapping functions computation. The interpolation between latitudes is done with a linear function.

The annual average of a given parameter can be computed as:

Table 1. Look-up table of UNB3 model.

Average					
Latitude (degrees)	**Pressure (mbar)**	**Temperature (K)**	**WVP* (mbar)**	**β ($K\ m^{-1}$)**	**λ (-)**
15	1013.25	299.65	26.31	6.30e-3	2.77
30	1017.25	294.15	21.79	6.05e-3	3.15
45	1015.75	283.15	11.66	5.58e-3	2.57
60	1011.75	272.15	6.78	5.39e-3	1.81
75	1013.00	263.65	4.11	4.53e-3	1.55
Amplitude					
Latitude (degrees)	**Pressure (mbar)**	**Temperature (K)**	**WVP* (mbar)**	**β ($K\ m^{-1}$)**	**λ (-)**
15	0.00	0.00	0.00	0.00	0.00
30	-3.75	7.00	8.85	0.25e-3	0.33
45	-2.25	11.00	7.24	0.32e-3	0.46
60	-1.75	15.00	5.36	0.81e-3	0.74
75	-0.50	14.50	3.39	0.62e-3	0.30

$$\mathrm{Avg}_\phi = \begin{cases} \mathrm{Avg}_{15}, \text{ if } \phi \le 15 \\ \mathrm{Avg}_{75}, \text{ if } \phi \ge 75 \\ \mathrm{Avg}_i + \frac{(\mathrm{Avg}_{i+1} - \mathrm{Avg}_i)}{15} \cdot (\phi - \mathrm{Lat}_i), \\ \qquad \text{if } 15 < \phi < 75 \end{cases} \quad (1)$$

where ϕ stands for the latitude of interest, in degrees, Avg_ϕ is the computed average, i is the index of the nearest lower tabled latitude and Lat stands for latitude (from the table). The annual amplitude can be computed in a similar manner:

$$\mathrm{Amp}_\phi = \begin{cases} \mathrm{Amp}_{15}, \text{ if } \phi \le 15 \\ \mathrm{Amp}_{75}, \text{ if } \phi \ge 75 \\ \mathrm{Amp}_i + \frac{(\mathrm{Amp}_{i+1} - \mathrm{Amp}_i)}{15} \cdot (\phi - \mathrm{Lat}_i), \\ \qquad \text{if } 15 < \phi < 75 \end{cases} \quad (2)$$

where Amp_ϕ stands for the computed amplitude. After average and amplitude are computed for given latitude, the parameter values can be estimated for the desired day of year according to:

$$X_{\phi,doy} = \mathrm{Avg}_\phi - \mathrm{Amp}_\phi \cdot \cos\left((doy - 28) \frac{2\pi}{365.25} \right), \quad (3)$$

where $X_{\phi,doy}$ represents the computed parameter value for latitude ϕ and day of year doy. This procedure is followed for each one of the five parameters. Figure 1 shows an illustration of the variation of temperature, pressure, and water vapour pressure provided by the UNB3 model, for several latitudes and days of year. All values were computed for mean sea level. The other two parameters, β and λ, drive the changes with respect to height of the temperature (β) and water vapour pressure (λ).

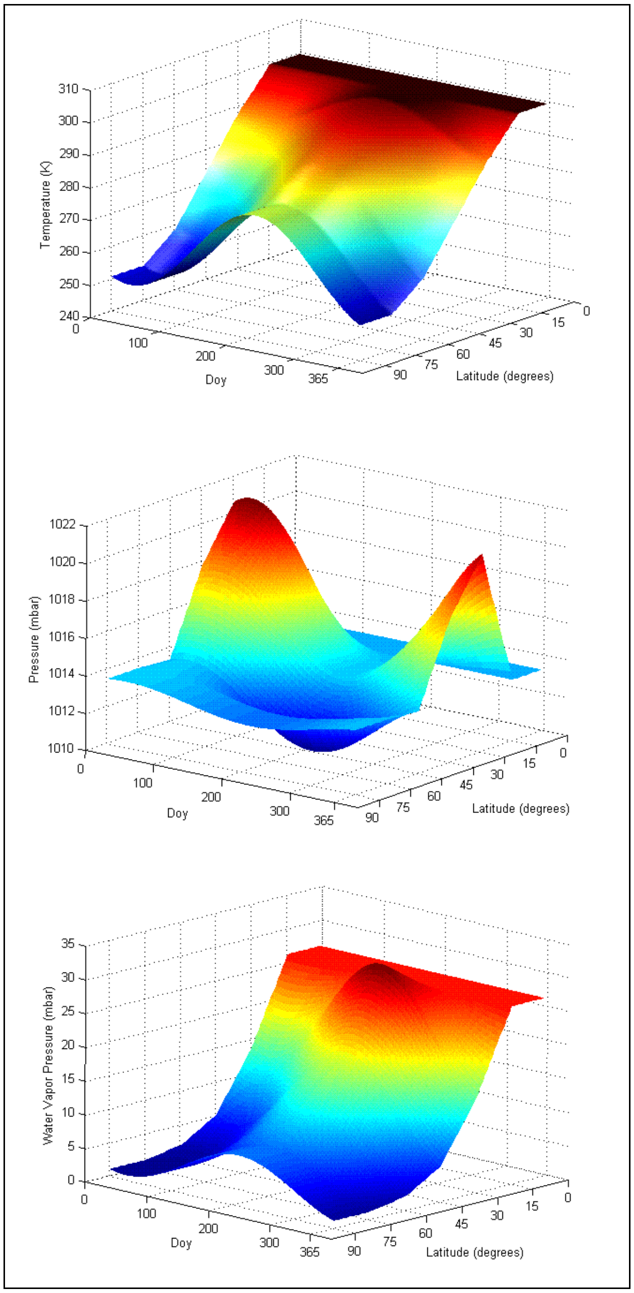

Figure 1. Variation of meteorological parameters provided by UNB3.

Once all five parameters are determined for given latitude and day of year, the zenith delays can be computed according to:

$$d_h^z = \frac{10^{-6} k_1 R}{g_m} \cdot P_0 \cdot \left(1 - \frac{\beta H}{T_0}\right)^{\frac{g}{R\beta}}, \qquad (4)$$

and

$$d_{nh}^z = \frac{10^{-6}\left(T_m k_2' + k_3\right)R}{g_m \lambda' - \beta R} \cdot \frac{e_0}{T_0} \cdot \left(1 - \frac{\beta H}{T_0}\right)^{\frac{\lambda' g}{R\beta} - 1}, \qquad (5)$$

where

- T_0, P_0, e_0, β, and λ are the meteorological parameters computed according to (1) to (3);
- H is the orthometric height in m;
- R is the gas constant for dry air (287.054 J kg^{-1} K^{-1});
- g_m is the acceleration of gravity at the atmospheric column centroid in m s^{-2} and can be computed from

$$g_m = 9.784\left(1 - 2.66 \text{x} 10^{-3} \cos(2\phi) - 2.8 \text{x} 10^{-7} H\right) \qquad (6)$$

- g is the surface acceleration of gravity in m s^{-2};
- T_m is the mean temperature of water vapour in K and can be computed from

$$T_m = T\left(1 - \frac{\beta R}{g_m \lambda'}\right) \qquad (7)$$

- $\lambda' = \lambda + 1$ (unitless)
- k_1, k_2', and k_3 are refractivity constants with values 77.60 K $mbar^{-1}$, 16.6 K $mbar^{-1}$ and 377600 K^2 $mbar^{-1}$, respectively.

The total slant delay can be finally computed according to

$$d_t = m_h d_h^z + m_{nh} d_{nh}^z, \qquad (8)$$

where m_h and m_{nh} stand for hydrostatic and non-hydrostatic Niell [1996] mapping functions, respectively.

Further details about UNB3 development and performance can be found in Collins and Langley [1997]. An extensive discussion of neutral atmosphere propagation delay modelling and testing can be found in Mendes [1999].

According to Collins and Langley [1998], the UNB3 model is capable of predicting zenith neutral atmosphere delays with an uncertainty (1-sigma) of 5 cm under normal (non-extreme) atmospheric conditions.

In further analyses of the UNB3 model, it was found that the relative humidity computed from water vapour pressure values were, in some cases, not realistic. For some intervals during the year in certain regions, the predictions resulted in relative humidity values greater than 100%. Figure 2 illustrates this problem.

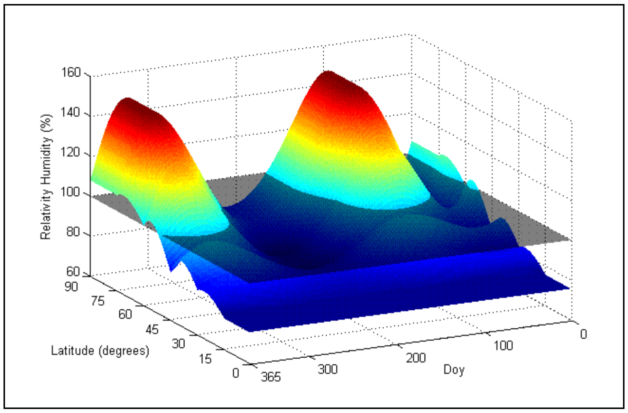

Figure 2. Relative humidity values computed from UNB3.

In Figure 2, the gray horizontal plane shows the limit of 100%. In worst cases, the values reach almost 150%. For latitudes greater than 45°, relative humidity values are greater than 100% for roughly half a year. This problem stems from the fact that the annual variation in water vapour pressure is not well represented by a cosine function due to the non-linear relationship between relative humidity, temperature and water vapour pressure. In order to overcome the problem of humidity overestimation of UNB3, a new version of the model called UNB3m (where *m* stands for "modified") was developed.

THE NEW VERSION: UNB3m

The version UNB3m was developed to avoid the problematic values of relative humidity. Following the same method of computation as for the pressure and the temperature, average and amplitude for relative humidity were derived from the U.S. Standard Atmosphere Supplements, 1966 [Orliac, 2002]. These values are shown in Table 2.

Table 2. Average and amplitude values for relative humidity used in UNB3m.

	Relative Humidity (%)	
Latitude	**Average**	**Amplitude**
15	75.0	0.0
30	80.0	0.0
45	76.0	-1.0
60	77.5	-2.5
75	82.5	2.5

It can be noticed that this look-up table provides more realistic values for relative humidity, with average values varying between 75% and 82.5%. Figure 3 shows an illustration of the relative humidity values provided by UNB3m, compared to the ones derived with UNB3.

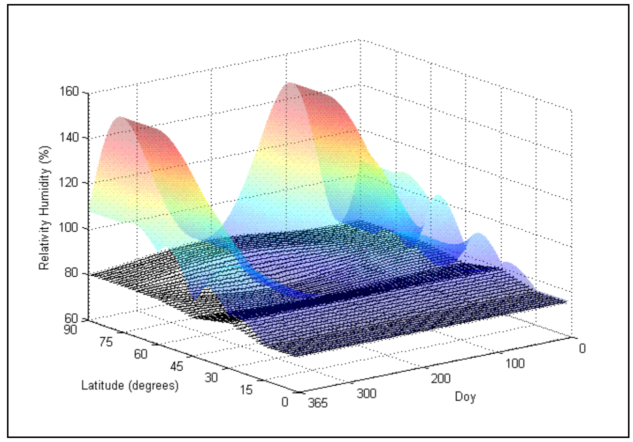

Figure 3. Relative humidity provided by UNB3m (black-lined surface) and UNB3 (semitransparent colour surface).

Table 2 should replace the columns for water vapour pressure in the UNB3 look-up table. In this case, the computations according to (1) to (3) are carried out for the relative humidity for given latitude and day of year. The final value is then transformed to water vapour pressure. This conversion between relative humidity and water vapour pressure can be carried out following the International Earth Rotation and Reference Frame Services (IERS) conventions [McCarthy and Petit, 2003] as follows:

$$e_0 = \frac{RH}{100} \cdot e_s \cdot f_w , \quad (9)$$

where the saturation vapour pressure, e_s, can be computed as:

$$\begin{aligned} e_s = 0.01 \cdot \exp(&1.2378847x10^{-5} T_0^2 \\ &-1.9121316x10^{-2} T_0 + 33.93711047 \\ &-6.3431645x10^3 T_0^{-1}) \end{aligned} , \quad (10)$$

and the enhancement factor, f_w, can be determined as follows:

$$f_w = 1.00062 + 3.14x10^{-6} P_0 + 5.6x10^{-7} \left(T_0 - 273.15\right)^2 . \quad (11)$$

Once the water vapour pressure is computed, the delays are estimated according to (4) to (8) in the same manner as for UNB3. One can notice that the hydrostatic delay will not be affected by this modification in the model, since it does not depend on the vapour pressure. Therefore the difference between UNB3 and UNB3m estimations will be only in the non-hydrostatic delay. Figure 4 shows the differences for the non-hydrostatic delay estimation for sites at sea level using the two models for different latitudes.

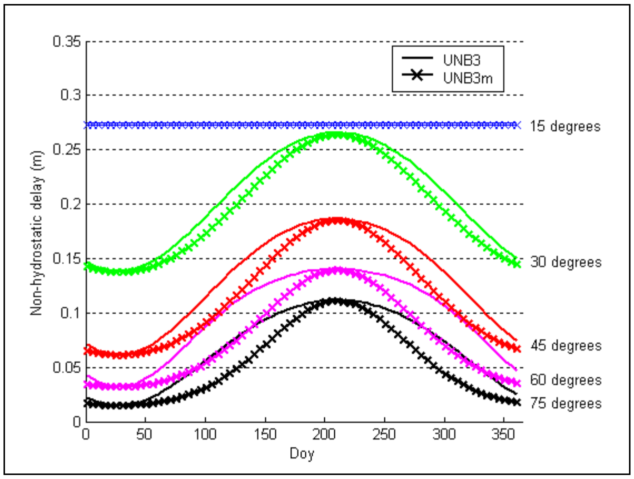

Figure 4. Hon-hydrostatic delay estimations with UNB3 and UNB3m.

We can see that the differences in the estimations are almost zero near 15° and below, varying up to approximately 4 cm near 60° latitude, around day of year 100 or 300. Differences vary through the year with the size of the difference depending on latitude.

VALIDATION: DATA PROCESSING AND RESULTS

In order to verify if the UNB3m implementation is truly more realistic than UNB3, a validation process was realized. In this approach we have used radiosonde-derived delays as reference ("truth"). The radiosonde profiles of temperature, pressure, and relative humidity were used to compute zenith delays using a ray-tracing technique. We used radiosonde soundings taken throughout North America and some neighbouring territories through the years from 1990 to 1996 inclusive. A total of 223 stations were used, distributed as shown in Figure 5.

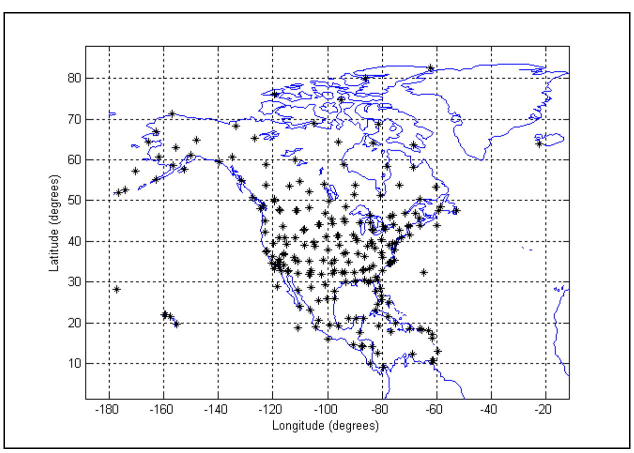

Figure 5. Distribution of radiosonde stations in North America and some nearby territories used in analyses.

Soundings are carried out typically twice daily at each of the stations. The complete data set used in this investigation has a total of 703,711 soundings, after filtering in a quality-control process. Quality control is performed in order to avoid biases and/or outliers in the radiosonde measurements. Details about the quality control of the radiosonde data can be found in Collins and Langley [1999]. The comparison of UNB3 predicted delays with zenith ray-traced delays has previously also been made by Collins and Langley [1999].

Figure 6 shows the estimation errors of the non-hydrostatic delay for the two models in the sense UNB3/UNB3m minus ray trace.

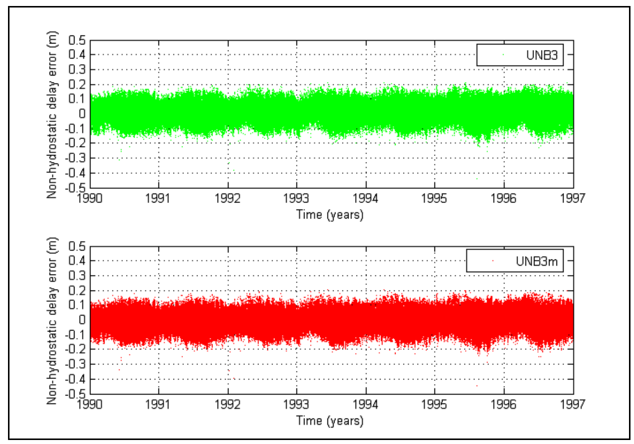

Figure 6. Non-hydrostatic delay estimation errors.

Although Figure 6 is a good illustration of the behaviour of the estimation errors, it is difficult to notice any difference in the performance of the two different versions of the model. It can be noticed that, for both models, larger errors are experienced at times closer to the middle of the year, when humidity is higher (in the northern hemisphere). It can be noticed also that the errors are almost never higher than 20 cm. Table 3 summarizes the results obtained year by year (UNB3/UNB3m minus ray trace).

Table 3. Results for non-hydrostatic delay estimations per year (all values in cm).

	UNB3			UNB3m		
Year	**Mean**	**Std. Dev.**	**RMS**	**Mean**	**Std. Dev.**	**RMS**
1990	1.9	4.7	5.1	-0.5	4.7	4.8
1991	1.7	4.8	5.1	-0.8	4.8	4.9
1992	2.0	4.6	5.0	-0.5	4.6	4.6
1993	1.9	4.7	5.1	-0.5	4.7	4.8
1994	2.0	4.7	5.1	-0.4	4.7	4.8
1995	2.0	5.1	5.5	-0.4	5.1	5.1
1996	2.3	4.9	5.4	-0.1	4.9	5.0
Total	2.0	4.8	5.2	-0.5	4.8	4.8

According to our results, UNB3 has a consistent bias of around 2 cm and standard deviation and RMS close to 5 cm. The results are consistent between years, and agree with those reported by Collins and Langley [1998]. UNB3m shows a significant improvement in bias with respect to UNB3, providing estimations with a mean error of around -0.5 cm. One can say that, on average, while UNB3 overestimates non-hydrostatic delays, UNB3m underestimates them, however with a much smaller bias. In terms of standard deviation the two models are equivalent, with a mean spread of 4.8 cm. With the same spread and less bias, UNB3m shows also an improvement in RMS (4.8 cm versus 5.2 cm provided by UNB3). Figure 7 shows a histogram for the estimation errors (UNB3/UNB3m minus ray trace) of the non-hydrostatic component of the two models.

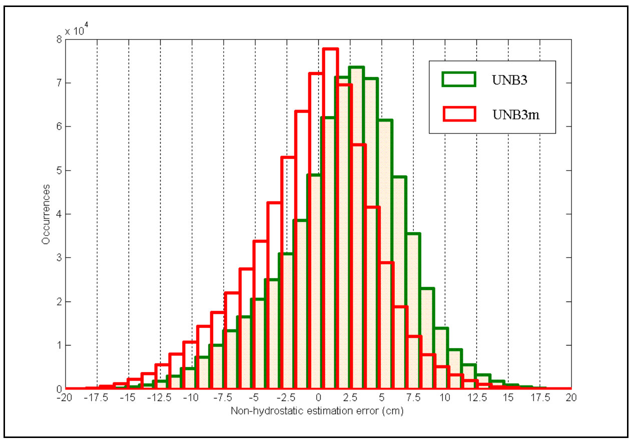

Figure 7. Histogram of non-hydrostatic delay estimation errors for UNB3 and UNB3m.

In Figure 7 we can see that the histogram of UNB3m errors is more centred on zero than the one for UNB3. It can also be noticed that the two tails of UNB3m are not quite similar (the tail to the left is slightly more elongated than the one to the right). This difference could be explained by a systematic underestimation of UNB3m for this data set. The UNB3 histogram has a clear positive offset, which is caused by its abnormal humidity overestimation.

In next figures, three stations were isolated in order to visualize their non-hydrostatic delay estimation time series. The selection was made in order to have a sample with average, low, and high latitudes. Stations Albany (New York State), Balboa (Panama), and Alert (Ellesmere Island, Canada) at latitudes 42.7° N, 9.0° N, and 82.5° N, respectively were chosen. The plots below show the radiosonde ray-traced delays and estimations from UNB3 and UNB3m through the seven years, for each station.

In the case of station Albany (average latitude), we can see that UNB3m provides a better fit to the ray-traced delays than UNB3. As expected, UNB3 overestimates the delays while UNB3m tends to be near the middle of the spread of the ray-traced delays. UNB3 performs better during the summer than the winter, while UNB3m seems to be consistent for both seasons.

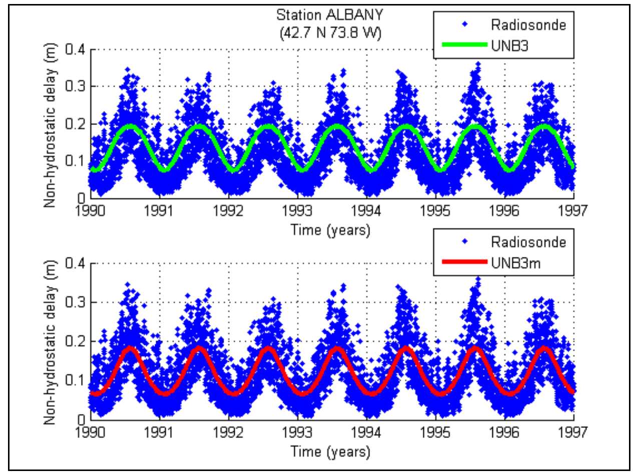

Figure 8. Non-hydrostatic delays for station Albany.

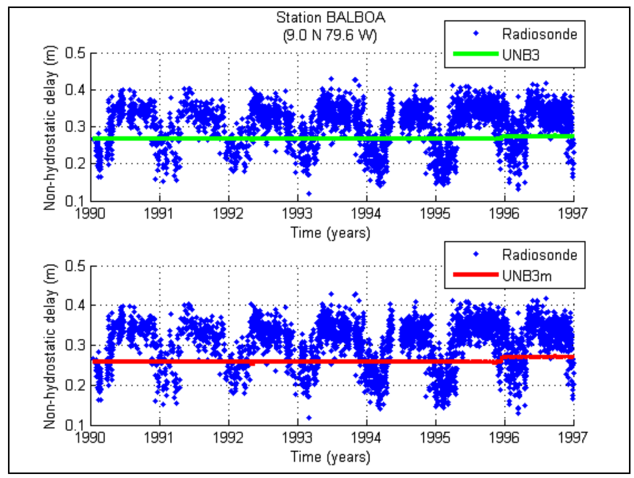

Figure 9. Non-hydrostatic delays for station Balboa.

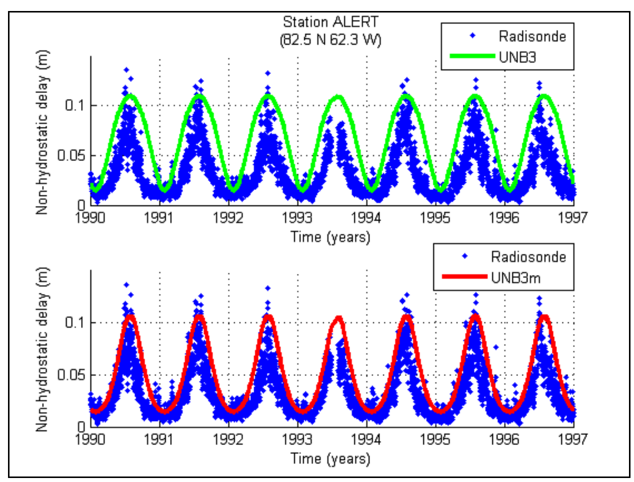

Figure 10. Non-hydrostatic delays for station Alert.

For low latitudes (case of station Balboa) the two models do not account for seasonal variations, resulting in an unrealistic modeling of the delays. Although the mean values match the ray-traced values relatively well, the absence of an amplitude term in the model is an assumption which is not realistic, according to this analysis. The lack of an amplitude term for low latitudes in both UNB3 and UNB3m is due to the lack of a seasonal variation in the Standard Atmosphere Supplements for 15° latitude.

The results for the third analyzed station (Alert – high latitude) show an overestimation of the delays from the two models. Although both of them are biased with respect to the ray-traced values, UNB3m shows a better fit than UNB3. The mean delay provided by UNB3m is slightly high, but the general behaviour including the annual amplitude matches the ray-traced values quite well.

Although the plots above are a good illustration of the performance for the three sample stations, it is impossible to tell if the behaviour is systematic. In order to verify if the errors vary systematically, we computed UNB3m mean errors (UNB3m minus ray trace) for each station and plotted them with respect to latitude, longitude and height. These plots are shown in Figure 11. Each point was evaluated by considering all estimation errors for one station over the seven years (hence 223 points). The error bars represent the standard deviation (1-sigma) of the station bias.

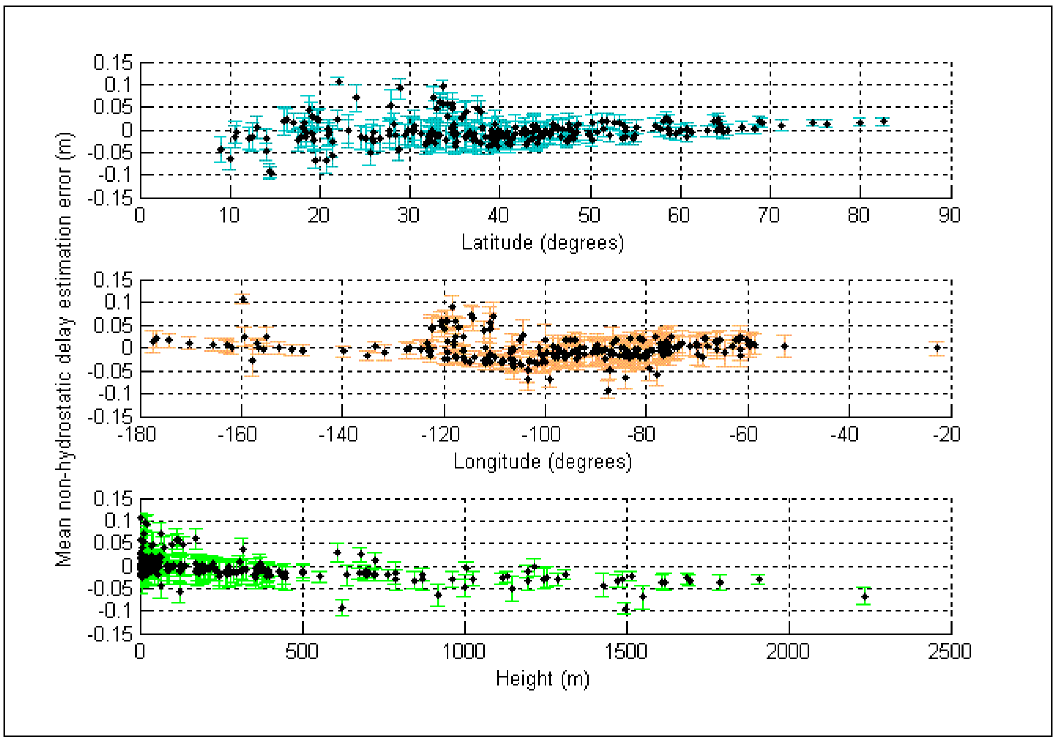

Figure 11. UNB3m mean estimation errors with respect to latitude, longitude and height.

In the first of the plots of Figure 11 we can see that for the lower latitudes UNB3m underestimates the non-hydrostatic delay. As the latitude increases, the mean estimation errors get larger, crossing the zero line for middle latitudes and presenting a slight overestimation for the higher latitudes. In terms of variation with respect to longitude, it is hard to see a clear pattern in the error behaviour. The variation with respect to height, however, shows a clear trend where a bias tends to increase negatively with height. In order to identify the problem for latitude and height variations, Tables 4 and 5 show the results divided into intervals of latitude and height, respectively. In Table 4, we can clearly see that for latitudes below 15° and above 75° the bias is considerably higher than for the other bands. In Table 5 the variation of the bias with height is evident, with a trend of larger (negative) biases for higher altitudes.

Table 4. Non-hydrostatic delay estimation error for different latitude bands.

Latitude (°)	Mean (cm)	Std. Dev. (cm)	Sample size
$\phi \le 15$	-2.3	5.4	16506
$15 < \phi \le 30$	-0.5	5.9	100247
$30 < \phi \le 45$	-0.8	5.4	318322
$45 < \phi \le 60$	-0.1	3.7	168071
$60 < \phi \le 75$	0.6	2.6	86008
$\phi > 75$	1.6	1.7	14557

Table 5. Non-hydrostatic delay estimation error for different height bands.

Height (m)	Mean (cm)	Std. Dev. (cm)	Sample size
h≤500	0.1	4.9	553861
500<h≤1000	-1.8	3.7	75276
1000<h≤1500	-2.8	3.6	44196
1500<h≤2000	-3.5	3.3	25506
h>2000	-6.1	3.8	4872

In terms of latitude, the biases for high and low latitudes might be due to the unrealistic assumption that over 75° and below 15° the meteorological parameters do not vary with latitude. For latitudes below 15° there is an additional problem, which is the assumption that there is no annual variation in meteorological parameters (amplitudes equal zero). This problem can be clearly seen in Figure 9. Degraded performance in estimating low latitude delays using other models has been previously reported by Mendes and Langley [1999].

The variation of the non-hydrostatic delay with respect to height is function of the lapse rate parameters (β and λ), incorrect values of which could cause a systematic error with respect to height. In order to determine if one or both of these parameters need to be recalibrated, we evaluated Table 6 in the same way as Table 5, but for the hydrostatic delay estimation errors. Because the hydrostatic delays depend only on β and the non-hydrostatic delays depend on β and λ, depending on the behaviour for each component, it might be possible to identify the source of errors.

Table 6. Hydrostatic delay estimation error for different height bands.

Height (m)	Mean (cm)	Std. Dev. (cm)	Sample size
h≤500	0.0	1.9	553861
500<h≤1000	-0.1	1.6	75276
1000<h≤1500	0.0	1.3	44196
1500<h≤2000	-0.2	1.2	25506
h>2000	-0.1	1.6	4872

The errors shown in Table 6 do not show a pattern of bias trend with height, therefore we can conclude that parameter β is adequately calibrated. Based on this, we can assume that the source of errors in Table 5 is the parameter λ, which should be somehow readjusted.

We focused the analysis of the results presented in this paper on the non-hydrostatic delays, which was the object of improvement in the development of UNB3m. The hydrostatic delay model component of UNB3m is identical to that of UNB3. Nevertheless, we have also assessed the total neutral atmosphere delay predictions of the two models. The results are presented in Table 7 (UNB3/UNB3m minus ray trace).

Table 7. Results for neutral atmospheric (total) delay estimations per year (all values in cm).

	UNB3			UNB3m		
Year	**Mean**	**Std. Dev.**	**RMS**	**Mean**	**Std. Dev.**	**RMS**
1990	1.9	4.8	5.1	-0.6	4.8	4.8
1991	1.6	4.9	5.1	-0.8	4.9	5.0
1992	2.0	4.7	5.1	-0.5	4.7	4.7
1993	1.8	4.8	5.2	-0.7	4.8	4.9
1994	1.9	4.8	5.2	-0.5	4.8	4.9
1995	2.0	5.1	5.5	-0.4	5.1	5.1
1996	2.2	5.0	5.4	-0.2	5.0	5.0
Total	1.9	4.9	5.2	-0.5	4.9	4.9

The results for total delays are quite similar to the ones obtained for non-hydrostatic delays, because the hydrostatic delays can be very well modeled so the uncertainties related to the total delays are mostly driven by the non-hydrostatic part.

CONCLUSIONS AND FUTURE WORK

The new version of the UNB neutral atmosphere model, namely UNB3m, provides an improvement in water vapour pressure estimations. The implementation of the new model was motivated by the unrealistic humidity overestimation provided by UNB3. Different from the previous model, UNB3m predictions of relative humidity yield realistic values, lying between 75% and 82.5%.

The modification in relative humidity causes changes in the non-hydrostatic delay estimations. The estimation differences between the two model versions vary from zero up to around 4 cm depending on latitude and day of year.

The delays were compared against ray-traced delays using radiosonde atmospheric profiles to verify if the estimations from the new version of our model were truly more realistic. Data from 1990 to 1996 was processed for stations across North America and surrounding territory. The results are consistent for the different years, with a mean bias in non-hydrostatic delay error of around -0.5 cm for UNB3m, which is better than the +2 cm provided by UNB3. In terms of standard deviation, the two versions are similar, with spreads of around 4.8 cm for both. The decreased bias results in a small improvement of 0.4 cm in RMS for UNB3m. In general, UNB3m underestimates non-hydrostatic delays, while UNB3 overestimates them, however the mean bias of UNB3m is much smaller than that of UNB3.

An analysis for specific stations was also made. Three stations with low, average, and high latitude were chosen. In the case of the station with low latitude (Balboa), it was clear that the assumption of zero amplitude for the meteorological parameters is not valid. The estimations were well performed for the average latitude station (Albany). For this site, the fit of UNB3m predicted delays was generally better than the ones provided by UNB3. The curve of UNB3m estimations was always closer to the average of the ray-traced delays. The results for station Alert (high latitude) showed that both model versions overestimate non-hydrostatic delays for this case. Although there is a positive bias for both of them, the fit of UNB3m to the ray-traced delays was slightly better than that of UNB3.

While the site dependent results provided a good close view of what happens at those specific sites, we needed to verify if these characteristics were systematic. In order to do so we computed the UNB3m mean error for each station and plotted the results with respect to latitude, longitude and height. In this analysis it was possible to see that UNB3m errors have a systematic behaviour with respect to height, with a negatively increasing bias from 0.1 cm up to -6.1 cm. This effect could be caused by an unrealistic calibration of one or both of the lapse rate parameters (β and λ). Based on the hydrostatic delay estimation errors we could conclude that the parameter β is adequately calibrated and that therefore the parameter λ is the source of the height-related errors in the non-hydrostatic delays. A recalibration process for this parameter should improve UNB3m estimations.

Regarding variation with respect to longitude, we could not identify a clear trend in the mean errors. This means that for a mean atmosphere, the assumption that meteorological parameters do not vary systematically in longitude is valid. A small dependence on latitude could be noticed for the higher and lower latitudes. One possible cause for that is the assumption made in the model in which meteorological parameters are constant for latitudes below 15° and above 75°. An expansion of the look-up table values towards the equator and the poles and a recalibration for latitude variation might account for those biases. In the case of latitudes below 15°, there is one additional problem which is the assumption that the annual amplitude of meteorological parameters is equal to zero.

In the analysis of total delays, the results are similar to the ones for non-hydrostatic delay. This is due mainly to the fact that the errors are mostly caused by the non-hydrostatic delay rather than by hydrostatic delay that can be very well predicted.

Further developments are underway at UNB, aiming at still more realistic models for the neutral atmosphere. Among future investigation options, we will consider possible functional modifications to the model. Recalibration of the look-up tables with more realistic data than that derived from the U.S. Standard Atmosphere Supplements, 1966 will also be considered. We intend to investigate the benefits of regionally dependent look-up tables as well as validate our models for the Southern Hemisphere.

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REFERENCES

COESA (1966). *U.S. Standard Atmosphere Supplements, 1966*. U.S. Committee on Extension to the Standard Atmosphere. Sponsored by Environmental Science Services Administration, National Aeronautics and Space Administration, United States Air Force and published by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C.

Collins, J.P. and R.B. Langley (1997). *A Tropospheric Delay Model for the User of the Wide Area Augmentation System*. Final contract report for Nav Canada, Department of Geodesy and Geomatics Engineering Technical Report No. 187, University of New Brunswick, Fredericton, N.B., Canada.

Collins J.P. and R.B. Langley (1998). "The Residual Tropospheric Propagation Delay: How Bad Can It Get?" *Proceedings of ION GPS-98, 11th International Technical Meeting of the Satellite Division of The Institute of Navigation*, Nashville, TN, 15-18 September 1998, pp. 729-738.

Collins J.P. and R.B. Langley (1999). *Nominal and Extreme Error Performance of the UNB3 Tropospheric Delay Model*. Final contract report for Nav Canada, Department of Geodesy and Geomatics Engineering Technical Report No. 204, University of New Brunswick, Fredericton, N.B., Canada.

Dodson, A.H., W. Chen, H.C. Baker, N.T. Penna, G.W. Roberts, J. Westbrook, and R. Jeans (1999). "Assessment of EGNOS Tropospheric Correction Model." *Proceedings of ION GPS-99, 12th International Technical Meeting of the Satellite Division of The Institute of Navigation*, Nashville, TN, 14-17 September 1999, pp. 1401-1407.

McCarthy D.D. and G. Petit (2004). *IERS Conventions (2003)*. IERS Technical Note 32, Verlag des Bundesamts für Kartographie und Geodäsie, Frankfurt am Main.

Mendes, V. B. (1999). *Modeling the Neutral-Atmosphere Propagation Delay in Radiometric Space Techniques*. Ph.D. dissertation, Department of Geodesy and

Geomatics Engineering Technical Report No. 199, University of New Brunswick, Fredericton, New Brunswick, Canada, 353 pp.

Mendes, V.B. and R.B. Langley (1999). "Tropospheric Zenith Delay Prediction Accuracy for High-Precision GPS Positioning and Navigation." *Navigation: Journal of The Institute of Navigation*, Vol. 46, No. 1, pp. 25-34..

Niell, A.E. (1996). "Global Mapping Functions for the Atmosphere Delay at Radio Wavelengths." *Journal of Geophysical Research*, Vol. 101, No. B2, pp. 3227- 3246.

Orliac E. (2002). *Troposphere Delay Models for Satellite Navigation Applications*. Diploma thesis, École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland.

Penna, N., A. Dodson, and W. Chen, (2001). "Assessment of EGNOS Tropospheric Correction Model." *Journal of Navigation,* Vol. 54, No. 1, pp. 37-55.

RTCA, Inc. (2001) *DO-229C, Minimum Operational Performance Standards for Global Positioning System/Wide Area Augmentation System Airborne Equipment*, SC-169, RTCA, Inc., Washington, D.C.

Ueno, M., K. Hoshinoo, K. Matsunaga, M. Kawai, H. Nakao, and R.B. Langley, (2001). "Assessment of Atmospheric Delay Correction Models for the Japanese MSAS." *Proceedings of ION GPS 2001, 14th International Technical Meeting of the Satellite Division of The Institute of Navigation*, Salt Lake City, UT, 11-14 September 2001, pp. 2341-2350.