

## UNB3m\_pack: a neutral atmosphere delay package for radiometric space techniques

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Published online: 15 August 2007  
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**Abstract** Several hybrid neutral atmosphere delay models have been developed at the University of New Brunswick. In this paper we are presenting UNB3m\_pack, a package with subroutines in FORTRAN and corresponding functions in MatLab which provides neutral atmospheric information estimated using the UNB3m model. The main goal of UNB3m is to provide reliable predicted neutral atmosphere delays for users of global navigation satellite systems (GNSS) and other transatmospheric radiometric techniques. Slant neutral atmosphere delays are the main output of the package, however, it can be used to estimate zenith delays, Niell mapping functions values, delay rates, mapping function rates, station pressure, temperature, relative humidity and the mean temperature of water vapor in the atmospheric column. The subroutines work using day of year, latitude, height and

elevation angle as input values. The files of the package have a commented section at the beginning, explaining how the subroutines work and what the input and output parameters are. The subroutines are self-contained, i.e., they do not need any auxiliary files. The user has simply to add to his/her software one or more of the available files and call them in the appropriate way.

**Keywords** GNSS · Neutral atmosphere · UNB3m

### Introduction

For any radiometric space technique, such as those utilizing global navigation satellite systems (GNSS), it is necessary to account for the propagation delay caused by the neutral atmosphere. Because of the nature of the neutral atmosphere, which is composed mainly of gases including water vapor, a radio signal is refracted when passing through the atmosphere, which means its speed changes (the signal travels more slowly than the vacuum speed of light) as does its path (the signal doesn't travel in a straight line between the signal source and the receiver). Due to these changes in speed and direction, it takes longer for the signal to reach the receiver's antenna than if it was traveling through a vacuum. This difference in time, which can also be represented in units of length, is the neutral atmosphere propagation delay. The magnitude of this delay depends on the profile of the refractive index along the signal's path, which is determined by the values of total atmospheric pressure, temperature, and the partial pressure of water vapor. The variation of these quantities at a particular location drives the variation of the delay from one day to another, over the different climate seasons. In the zenith direction, the neutral atmosphere delay at a relatively dry

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location at sea level is around 7.7 ns, or 2.3 m, and it increases to more than 10 m for elevation angles of about 10°, and to more than 20 m at 5°.

Typically, one does not know the actual refractive index profile at a particular location, so prediction models are often used to account for neutral atmosphere delay, particularly in real-time positioning and navigation applications. Several hybrid neutral atmosphere delay models have been developed by UNB researchers over the past decade or so. The most recent version in use is UNB3m, which uses the Saastamoinen zenith delays (as modified by Davis et al. 1985), Niell (1996) mapping functions, and a look-up table with annual mean and amplitude for temperature, pressure, and relative humidity varying with respect to latitude and propagated to station 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. UNB3m's performance has been validated using radiosonde data, and based on ray-tracing analyses the prediction errors of UNB3m derived zenith delays have shown a mean bias of −0.5 cm and SD of 4.9 cm. Leandro et al. (2006) have provided a comprehensive explanation of how UNB3m works and an analysis of its performance.

In this paper we are introducing UNB3m\_pack, a package with subroutines in FORTRAN and corresponding functions in MatLab that can be used to access UNB3m (from now on we will mostly refer to subroutines in FORTRAN and to functions in MatLab as simply subroutines).

## How UNB3m works

In this section we briefly describe how the UNB3m model works, including the usage of the look-up table and the delay (or delay rate) computation algorithm. The procedure described in this section is similar to the one already

reported by Leandro et al. (2006). Typographical errors in that paper have been corrected here.

UNB3m's algorithm is based on the prediction of meteorological parameter values for a particular location (latitude and height) and day of year, which are used to compute hydrostatic and non-hydrostatic zenith delays using the Saastamoinen models. The slant delays (and/or delay rates) are determined using the Niell mapping functions (or mapping function rates in case of delay rates).

In order to account for the latitudinal and seasonal variation of the neutral atmosphere behavior, a look-up table for meteorological parameters is used. The parameters are barometric pressure ( $P$ ), temperature ( $T$ ), relative humidity (RH), temperature lapse rate ( $\beta$ ) and water vapor pressure height factor ( $\lambda$ ). 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 UNB3m. 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 UNB3m 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 table latitudes is done with a linear function.

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

$$\text{Avg}_\phi = \begin{cases} \text{Avg}_{15}, & \text{if } \phi \leq 15 \\ \text{Avg}_{75}, & \text{if } \phi \geq 75 \\ \text{Avg}_i + \frac{(\text{Avg}_{i+1} - \text{Avg}_i)}{15}(\phi - \text{Lat}_i), & \text{if } 15 < \phi < 75 \end{cases} \quad (1)$$

where  $\phi$  stands for the latitude of interest, in degrees,  $\text{Avg}_\phi$  is the computed average,  $i$  is the index of the nearest lower

**Table 1** Look-up table of UNB3m model

Latitude (deg.)	Pressure (mbar)	Temperature (K)	RH (%)	$\beta$ (K m <sup>-1</sup> )	$\lambda$ (unit less)
Average					
15	1013.25	299.65	75.0	6.30e−3	2.77
30	1017.25	294.15	80.0	6.05e−3	3.15
45	1015.75	283.15	76.0	5.58e−3	2.57
60	1011.75	272.15	77.5	5.39e−3	1.81
75	1013.00	263.65	82.5	4.53e−3	1.55
Amplitude					
15	0.00	0.00	0.0	0.00	0.00
30	−3.75	7.00	0.0	0.25e−3	0.33
45	−2.25	11.00	−1.0	0.32e−3	0.46
60	−1.75	15.00	−2.5	0.81e−3	0.74
75	−0.50	14.50	2.5	0.62e−3	0.30

tabled latitude and Lat stands for latitude (from the table). The annual amplitude can be computed in a similar manner:

$$\text{Amp}_\phi = \begin{cases} \text{Amp}_{15}, & \text{if } \phi \leq 15 \\ \text{Amp}_{75}, & \text{if } \phi \geq 75 \\ \text{Amp}_i + \frac{(\text{Amp}_{i+1} - \text{Amp}_i)}{15}(\phi - \text{Lat}_i), & \text{if } 15 < \phi < 75 \end{cases} \quad (2)$$

where  $\text{Amp}_\phi$  stands for the computed amplitude. After the average and amplitude are computed for a given latitude, the parameter values can be estimated for the desired day of year according to:

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

where  $X_{\phi, \text{doy}}$  represents the computed parameter value for latitude  $\phi$  and day of year (doy). This procedure is followed for each one of the five parameters. In case the latitude of interest is negative (southern hemisphere) the amplitude is used with inverted sign.

Because UNB3m uses only a cosine function with a 1-year period for the time variation of meteorological parameters, their values have a very smooth variation over any given day, or even between consecutive days. This smooth variation causes UNB3m delay predictions to be practically the same for any time of the day, because UNB3m does not account for daily variation of the parameters, such as the diurnal variation of temperature.

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

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

and

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

where

- $d_h^z$  and  $d_{nh}^z$  are the hydrostatic and non-hydrostatic zenith delays, respectively;
- $T_0$ ,  $P_0$ ,  $e_0$ ,  $\beta$ , and  $\lambda$  are the meteorological parameters computed according to (1)–(3), water vapor pressure  $e_0$  can be computed using the equations in Leandro et al. (2006), or those in UNB3mm.f;
- $H$  is the orthometric height in m. (Even though the use of orthometric height is recommended, other heights, such as ellipsoidal height, can be used. The difference

of results caused by using different height types will be typically smaller than the uncertainty of the model.);

- $R$  is the gas constant for dry air ( $287.054 \text{ J kg}^{-1} \text{ K}^{-1}$ );
- $g_m$  is the acceleration of gravity at the atmospheric column centroid in  $\text{m s}^{-2}$  and can be computed from:

$$g_m = 9.784(1 - 2.66 \times 10^{-3} \cos(2\phi) - 2.8 \times 10^{-7} H) \quad (6)$$

- $g$  is the standard acceleration of gravity ( $9.80665 \text{ m s}^{-2}$ );
- $T_m$  is the mean temperature of water vapor in K and can be computed from

$$T_m = (T_0 - \beta H) \left(1 - \frac{\beta R}{g_m \lambda'}\right) \quad (7)$$

- $\lambda' = \lambda + 1$  (unitless);
- $k_1$ ,  $k_2'$  and  $k_3$  are refractivity constants with values  $77.60 \text{ K mbar}^{-1}$ ,  $16.6 \text{ K mbar}^{-1}$  and  $377,600 \text{ K}^2 \text{ mbar}^{-1}$ , respectively.

The total slant delay is computed according to

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

where  $m_h$  and  $m_{nh}$  stand for the hydrostatic and non-hydrostatic Niell mapping functions, respectively.

Total slant delay rates are computed as:

$$dr_t = mr_h d_h^z + mr_{nh} d_{nh}^z, \quad (9)$$

where  $mr_h$  and  $mr_{nh}$  stand for the hydrostatic and non-hydrostatic Niell mapping function rates in  $\text{rad}^{-1}$ , respectively. Mapping function rates are the partial derivatives of the respective mapping functions with respect to elevation angle. After the mapping function rates are combined with the two components of the zenith delay (as in Eq. 9), the result is a total delay rate in  $\text{m rad}^{-1}$ . This means the user has to multiply this value by the elevation angle rate of the satellite or other object (computed in  $\text{rad s}^{-1}$ ) to obtain the delay rate in metric units ( $\text{m s}^{-1}$ ).

### UNB3m\_pack

Although slant neutral atmosphere delays are the main output of the UNB3m package, it can also be used to estimate zenith delays (hydrostatic, non-hydrostatic and total), Niell mapping function values (hydrostatic and non-hydrostatic), delay rates, mapping function rates, station barometric pressure, temperature, relative humidity, and mean temperature of water vapor. These values are a function of day of year, latitude and height and (for some parameters) elevation angle, as shown in the previous section.

The package is made available as a zip-compressed file (UNB3m\_pack.zip) which contains the following files:

- UNB3m.f: FORTRAN code for delays subroutine;
- UNB3mr.f: FORTRAN code for delay rates subroutine;
- UNB3mm.f: FORTRAN code for meteorological values subroutine;
- UNB3m.m: MatLab code for delays function;
- UNB3mr.m: MatLab code for delay rates function;
- UNB3mm.m: MatLab code for meteorological values function;
- Readme.txt: description of package contents;
- Leandroetal2006.pdf: Reference paper for UNB3m (PDF).

Each one of the source code files has a commented section at its beginning, explaining how the subroutine works and what the inputs and outputs (with format and units) are. The subroutines are self-contained; i.e., they do not need any auxiliary files. The user has simply to add to his/her software one or more of the available files listed above and call them in the appropriate way.

### Using UNB3m subroutines

This section explains how to use the UNB3m subroutines, both the FORTRAN and MatLab versions (in this case, functions). There is one subsection for each type of subroutine: delays, delay rates, and meteorological values, respectively. All input and output variables are of type DOUBLE. The subroutines were implemented in FORTRAN 77 and MatLab 7.2, however, because they are based on basic mathematical operations, only minor changes (if any) would be necessary to run them using other versions of either FORTRAN or MatLab.

#### UNB3m: delays subroutine

This is the primary subroutine of the package. It uses the UNB3m model to calculate the slant neutral atmospheric delay for a given latitude, height, day of year (doy), and elevation angle.

How this subroutine works

- (1) A look-up table is used to calculate mean sea level (MSL) values for pressure, temperature, relative humidity, temperature lapse rate, and water vapor pressure (WVP) height factor (for given latitude and doy).
- (2) MSL water vapor pressure is computed according to IERS Conventions 2003 (IERS 2004).

- (3) Pressure, temperature, and WVP values are computed for the station height.
- (4) Zenith hydrostatic and non-hydrostatic delays are computed using modified Saastamoinen formulas.
- (5) Computation of hydrostatic and non-hydrostatic Niell mapping function values.
- (6) Total slant delay is determined using Eqs. (4), (5) and (8).

Input and output parameters of the subroutine

The parameters are listed in Table 2.

**Table 2** UNB3m input and output

Variable	Description	Units
INPUT		
LATRAD	Station geodetic latitude	rad
HEIGHTM	Station orthometric height	m
DAYOYEAR	Day of year	days
ELEVRAD	Elevation angle	rad
OUTPUT		
RTROP	Total slant delay	m
HZD	Hydrostatic zenith delay	m
HMF	Hydrostatic Niell mapping function	unit less
WZD	Non-hydrostatic zenith delay	m
WMF	Non-hydrostatic Niell mapping function	unit less

Syntax in FORTRAN (UNB3m.f file)

Call UNB3m(LATRAD,HEIGHTM,DAYOYEAR, ELEVRAD,HZD,HMF,WZD,WMF,RTROP)

Syntax in MatLab (UNB3m.m file)

[RTROP HZD HMF WZD WMF] = UNB3m(LATRAD, HEIGHTM,DAYOYEAR,ELEVRAD)

#### UNB3mr: delay rates subroutine

This subroutine uses UNB3m to calculate the slant neutral atmospheric delay rate for given latitude, height, doy, and elevation angle.

How this subroutine works

Steps 1–4 are the same as for the UNB3m subroutine.

- (5) Computation of hydrostatic and non-hydrostatic Niell mapping function rates.
- (6) Total slant delay rate is determined using Eqs. (4), (5) and (9).

Input and output parameters of the subroutine

The parameters are listed in Table 3.

**Table 3** UNB3mr input and output

Variable	Description	Units
INPUT		
LATRAD	Station geodetic latitude	rad
HEIGHTM	Station orthometric height	m
DAYOYEAR	Day of year	days
ELEVRAD	Elevation angle	rad
OUTPUT		
HZD	Hydrostatic zenith delay	m
DHMFDEL	Hydrostatic Niell mapping function rate	rad <sup>-1</sup>
WZD	Non-hydrostatic zenith delay	m
DWMFDEL	Non-hydrostatic Niell mapping function rate	rad <sup>-1</sup>
DRATE	Total slant delay rate	m rad <sup>-1</sup>

Syntax in FORTRAN (UNB3mr.f file)

Call UNB3mr(LATRAD,HEIGHTM,DAYOYEAR, ELEVRAD,HZD,DHMFDEL,WZD,DWMFDEL,DRATE)

Syntax in MatLab (UNB3mr.m file)

[DRATE HZD DHMFDEL WZD DWMFDEL] = UNB3mr(LATRAD,HEIGHTM,DAYOYEAR, ELEVRAD)

### UNB3mm: meteorological values subroutine

This subroutine uses UNB3m to calculate the estimated station temperature, station pressure, station water vapor pressure, and mean temperature of water vapor for given latitude, height, and doy.

The goal of this subroutine is to allow the user to access meteorological values computed from the UNB3m look-up table to be used with delay computation algorithms different from Saastamoinen, which is used in the UNB3m delay and delay rates subroutines. A value for the mean temperature of water vapor is provided, which is useful for

deriving water vapor quantities from zenith delays determined with GNSS, for example.

How this subroutine works

Steps 1–3 are the same as for the UNB3m subroutine.

- (4) Mean temperature of water vapor is computed.

Input and output parameters of the subroutine

The parameters are listed in Table 4.

**Table 4** UNB3mm input and output

Variable	Description	Units
INPUT		
LATRAD	Station geodetic latitude	rad
HEIGHTM	Station orthometric height	m
DAYOYEAR	Day of year	days
OUTPUT		
T	Station temperature	kelvins
P	Station pressure	millibars
E	Station water vapor pressure	millibars
TM	Mean temperature of water vapor	kelvins

Syntax in FORTRAN (UNB3mm.f file)

Call UNB3mm(LATRAD,HEIGHTM,DAYOYEAR, T,P, E,TM)

Syntax in MatLab (UNB3mm.m file)

[T P E TM] = UNB3mm(LATRAD,HEIGHTM,DAYOYEAR)

### UNB3m\_pack retrieval

UNB3m\_pack can be downloaded from the website of the Department of Geodesy and Geomatics Engineering of the University of New Brunswick:

<http://gge.unb.ca/Resources/unb3m/unb3m.html>

In order to decompress the file the user can use one of the many compression/decompression applications available on the Internet, such as Filzip (<http://www.filzip.com/>) or Winzip (<http://www.winzip.com/>) for Windows OS with comparable applications for Macintosh, UNIX, and Linux

OS. The uncompressed text files have DOS end-of-line delimiters.

**Acknowledgments** This work was funded by the GEOIDE (Geomatics for Informed Decisions) Network of Centres of Excellence and the Natural Sciences and Engineering Research Council of Canada. The authors also acknowledge financial support provided by the Canadian International Development Agency.

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