Neutral Atmosphere Delay Mitigation Techniques

Richard B. Langley

Geodetic Research Laboratory
Dept. of Geodesy and Geomatics Engineering
University of New Brunswick
Fredericton, N.B., Canada

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1. No mitigation technique
2. Discard low-elevation-angle observations
3. Predict neutral atmosphere delay (NAD) using models
4. Reduce NAD using between-receiver single differencing
5. Estimate NAD from GPS observations
6. Measure NAD using external techniques
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No Mitigation

- In standalone GNSS positioning, suffer the full effect of the neutral atmosphere propagation delay

- Many metres of horizontal and vertical position error.

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Discard Low-Elevation-Angle Observations

• Reduces the effect of neutral atmosphere delay but position error in standalone positioning can still be at the metre level.

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Predict Neutral Atmosphere Delay (NAD) Using Models

• Many profiles and mapping functions have been developed over the years. Let's take a look at one particular set.

UNB Neutral Atmosphere Prediction Models

- A sequence of predictive, climatology-based, hybrid models
- Based on Saastamoinen zenith delays, Niell mapping functions, look-up tables of sea-level pressure, temperature, water vapour pressure or relative humidity, and lapse rate annual means and amplitudes, and height propagators
- UNB3 widely used; basis for SBAS in-receiver model (Niell mapping functions replaced by simpler Black & Eisner model); application details in RTCA Minimum Operational Performance Standards document

UNB Neutral Atmosphere Prediction Model Zenith Delays

$$d_h^z = \frac{10^{-6} K_1 R_d}{g_m} \cdot P_0 \cdot \left(1 - \frac{\beta H}{T_0}\right)^{\frac{g}{R_d \beta}}$$

← Height propagators

$$d_{nh}^z = \frac{10^{-6}\left(T_m K_2' + K_3\right) R_d}{g_m \lambda' - \beta R_d} \cdot \frac{e_0}{T_0} \cdot \left(1 - \frac{\beta H}{T_0}\right)^{\frac{\lambda' g}{R_d \beta} - 1}$$

Definitions-1

- d_h^z and d_{nh}^z are the hydrostatic and non-hydrostatic zenith delays (m)
- T_0, P_0, and e_0 are MSL temperature (K), barometric pressure (mbar), and water vapour pressure (mbar) – e_0 can be related to relative humidity
- β and λ' are the temperature lapse rate (K m^{-1}) and water vapour pressure height factor (unitless)

Definitions-2

- H is orthometric height of site (m)
- R_d is the gas constant for dry air (287.054 J kg^{-1} K^{-1})
- g_m is acceleration of gravity at atmospheric column centroid (m s^{-2})

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

- g is standard acceleration of gravity (9.80665 m s^{-2})

Definitions-3

- T_m is the mean temperature of water vapour (K)

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

- $\lambda = \lambda' + 1$ (unitless)
- $K_1 = 77.60$ K mbar^{-1}
- $K_2' = 16.6$ K mbar^{-1}
- $K_3 = 377600$ K2 mbar^{-1}

UNB3

- UNB3 look-up table has 5 latitude sets of mean (average) and annual MSL values
- Values are interpolated for latitude of station
- Day-of-year values computed from

$$X_{\phi,doy} = Avg_{\varphi} - Amp_{\phi} \cdot \cos\left(\left(doy - 28\right)\frac{2\pi}{365.25}\right)$$

- UNB3 is capable of predicting total zenith delays with average uncertainties of 5 cm under normal atmospheric conditions.
- Corresponding SBAS model error is significantly overbounded for safety reasons

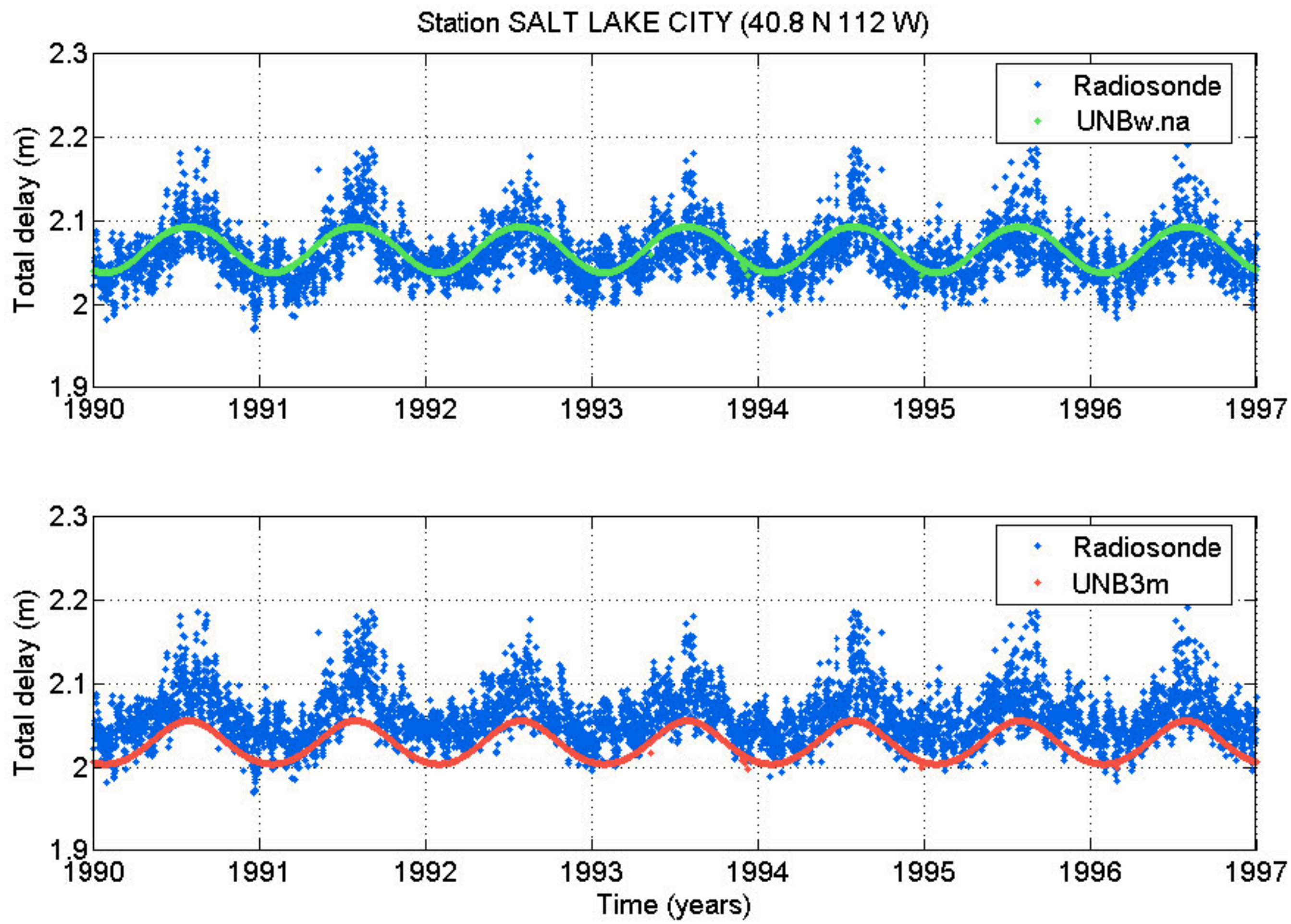
UNB3m

- In UNB3m, water vapour pressure lookup values are replaced with relative humidity values
- Standard deviation of UNB3m prediction error is similar to that of UNB3 but absolute mean error reduced by almost 75%
- Package with source code in Fortran and MatLab, UNB3m_pack, has been made publicly available

UNBw.na-1

- More reliable model for wide area augmentation systems users with some homogeneity in accuracy performance over area of interest
- Based on actual surface meteorological values over many years rather than standard models
- Look-up table is a grid of values in both latitiude and longitude with spacing of 5°
- Initially developed for North America (0° to 90° in latitude and -180° to -40° in longitude)

UNBw.na-2


Station SALT LAKE CITY (40.8 N 112 W)
Radiosonde
UNBw.na
Total delay (m)
2.3
2.2
2.1
2
1.9
1990
1991
1992
1993
1994
1995
1996
1997
Radiosonde
UNB3m
Total delay (m)
2.3
2.2
2.1
2
1.9
1990
1991
1992
1993
1994
1995
1996
1997
Time (years)

UNB3w.na-3

- UNB3w.na is consistently better than UNB3m with average bias reduced by about 30% and significant predictive performance for the south-western part of the U.S. (dryer, hotter, and higher)
- Further details in a paper in Navigation, the journal of The Institute of Navigation (Leandro, Rodrigo F., Santos, Marcelo C., Langley, Richard B., “A North America Wide Area Neutral Atmosphere Model for GNSS Applications”, NAVIGATION, Vol. 56, No. 1, Spring 2009, pp. 57-71.)

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Reduce NAD Using Between-Receiver Single Differencing

- This approach is used in differential GNSS positioning.

- Delay along nearby ray paths is similar, so when measurements collected at a pair of nearby receivers are differenced, the NAD remaining in the differenced observations is quite small.

- Residual delay still needs to be modelled for high-accuracy applications.

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Estimate NAD From GNSS Observations

- The zenith delay can be estimated by including it as a parameter (deterministic or stochastic) in the data processing software (parametric least squares or Kalman filter).

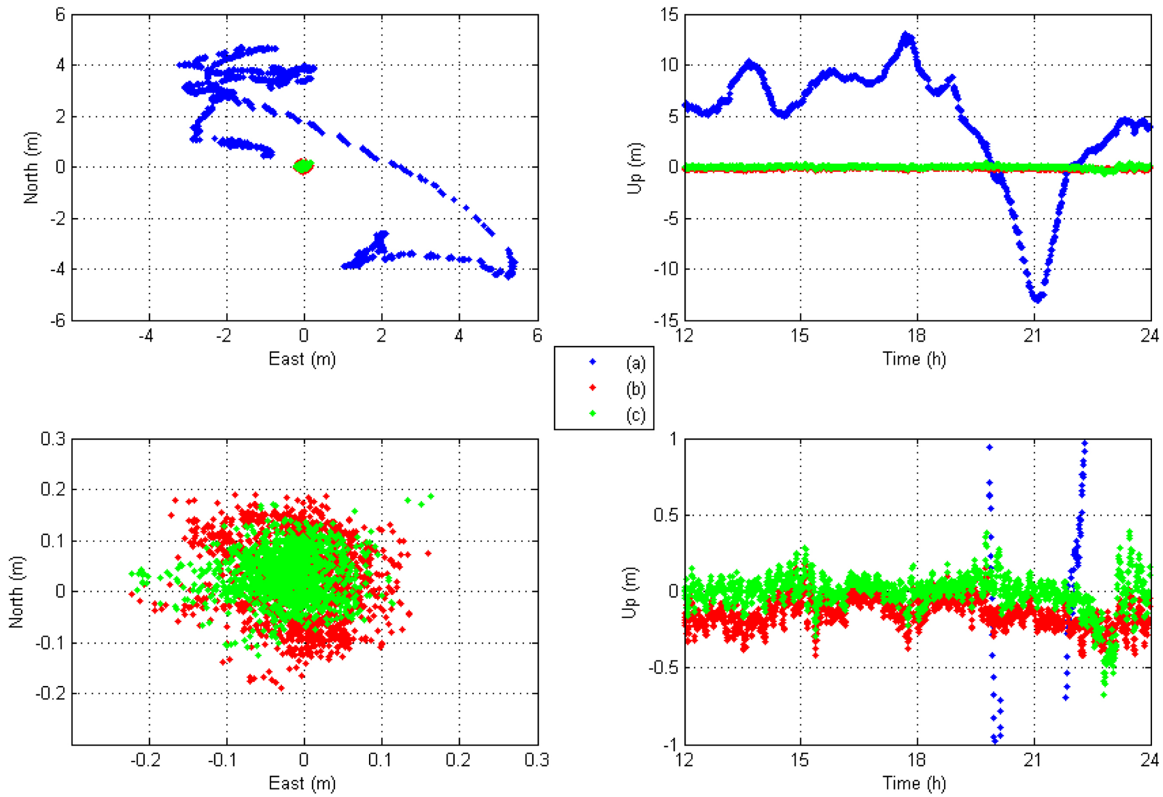
- Partial derivative of an observation with respect to the zenith delay is simply the mapping function.

A Test of Options 1, 3, and 5

Three modelling options were used to process 12 hours of GPS data from IGS station UNBJ in kinematic mode with GAPS (UNB's precise point positioning package) and the results compared with the known coordinates of the station:

(a) Not accounting for the neutral atmosphere – no corrections were applied;
(b) Accounting for the neutral atmosphere using the UNB3m prediction model (see http://gge.unb.ca/Resources/unb3m/unb3m.html);
(c) Accounting for the neutral atmosphere estimating the delay as a random walk parameter.

Precise Point Positioning Error for Different Modelling Strategies



Positioning Error Statistics

	RMS			BIAS		
	East	North	Up	East	North	Up
(a)	2.23	3.22	7.29	-0.41	1.32	4.39
(b)	0.06	0.08	0.17	-0.01	0.03	-0.15
(c)	0.05	0.06	0.12	-0.02	0.03	-0.01

(all units are metres)

Gradient Models

• Many neutral atmosphere delay models assume azimuthal symmetry; i.e., the atmosphere is assumed to be the same all around a site.

• Clearly this doesn't match reality particularly during the passage of weather fronts.

• Models have been enhanced by including gradient terms that can be estimated from the GNSS data.

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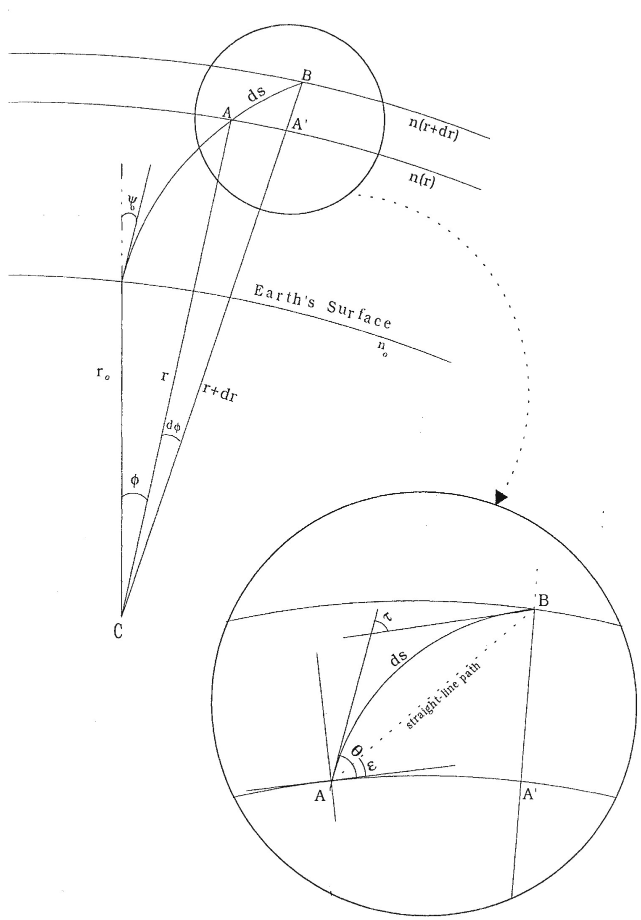
Ray Tracing Through Radiosonde Profiles or Numerical Weather Models



• Radiosondes (also known as weather balloons) are launched from many locations around the world twice a day.

• Pressure, temperature, and relative humidity measurements are send by radio to the ground.

• The profiles can be used to determine refractivity at points along a path entering or leaving the atmosphere at a particular elevation angle.

• The same procedure can be used with numerical weather models.

Water Vapour Radiometer

- Measures brightness temperature at two or more frequencies near and adjacent to the water vapour line
- Radiometrics WVR-1100 uses 23.8 and 31.4 GHz
- Measurements converted to wet tropospheric delay along direction of measurement using calibration constants

- Accuracies typically better than 1 centimetre

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Interpolate NAD From Estimates at Nearby Stations

- This approach is used in real-time differential GNSS, such as DGPS and real-time kinematic (RTK) positioning.

- In pseudorange-based DGPS, the transmitted correction includes the effect of NAD as experienced at the reference station.

- In network RTK, an interpolated zenith NAD can be sent to the user.