ESTIMATING THE TROPOSPHERIC CORRECTION FOR ΔT DATA FROM WEATHER STATION MEASUREMENTS

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ABSTRACT

We present the algorithm which will be used to estimate the tropospheric delay along a given line of sight in the calculation of the tropospheric delay correction due to non-reciprocity for the DELTAT file data. The NRAO OVLBI earth station weather station periodically measures the atmospheric temperature, dewpoint and pressure at the antenna. This data is then smoothed to remove any effects of tropospheric turbulence in the data. Using the Smith-Weintraub equation and a model for the zenith angle dependence of the troposphere, the tropospheric delay for a given line of sight can be estimated.

Introduction

At the NRAO OVLBI earth station the TWT subsystem will measure the residual phase in the two way signal from the NRAO OVLBI earth station to the space VLBI satellite and back to the NRAO OVLBI earth station. These residual phases arise mainly due to three factors: 1) tropospheric propagation effects 2) ionospheric propagation effects and 3) errors in the predicted orbit. The timing errors that need to be corrected for at the spacecraft are the result of the phase residuals on the uplink signal path, which to first order is half of the total round trip phase residual. Since the ionosphere and troposphere create different phase residuals for the uplink and downlink signal we must correct for these non-reciprocities in order to determine the true timing corrections at the spacecraft. In this document we present the method for determining the tropospheric corrections to the DELTAT file.

Measurement Period and Smoothing of the Weather Data

The troposphere is a turbulent medium. This results in the tropospheric phase delay having a rapidly fluctuating component due to the turbulence and a slowly varying, smooth component due to the "mean troposphere". The tropospheric corrections to be applied to the DELTAT data will be derived from periodic measurements of the temperature, dew point and pressure at a single location. Thus we are not capable of modeling the turbulent fluctuations in the troposphere and we can only correct for the mean troposphere. Hence, in estimating the tropospheric corrections to the DELTAT data, we want the temperature, dewpoint and pressure to represent the mean tropospheric quantities with the effects of the tropospheric turbulence removed from the measurements. The effects of the turbulence in the troposphere on the spacecraft timing have been investigated by R. Linfield [1] and have been found to be negligible.

Interferometric observations of the phase fluctuations induced by the tropospheric turbulence show that the largest size scale of the tropospheric turbulence is of the order of 3 km [2]. The average wind speed measured at the NRAO OVLBI earth station is $\sim$ 3 m/s. This gives the estimate that the largest cell of turbulence in the troposphere will take about 17 minutes to pass by the NRAO OVLBI earth station. In Figure 1 we plot the structure function of the NRAO OVLBI earth station weather station temperature measurements for May 1, 1996. The structure function is defined as follows:

$$D(\delta t) = \left\langle [T(t) - T(t + \delta t)]^2 \right\rangle \qquad 1$$

where T is the temperature and t is the time. In Figure 1 we show a line with the predicted power law index of 5/3 for Kolmogorov turbulence in the troposphere for comparison. It can be seen that the temperature measurements are affected by tropospheric turbulence. We would expect the diurnal variations in the temperature to be sinusoidal to first order. For small angles, which corresponds to values of $\delta t < 2$ hours, we expect the structure function to be described by a power law with an index of 2 when the diurnal variations in the weather dominate. Hence, a power law with an index of 2 is also shown in Figure 1 for comparison. It is easily seen from Figure 1 that the largest turbulent cells in the troposphere take $\sim$ 20 minutes to pass by the NRAO OVLBI earth station and that turbulent fluctuations in the troposphere dominate changes in the mean troposphere for periods up to $\sim$ 20 minutes in duration.

In order to remove the effects of the tropospheric turbulence on the weather measurements, we need to smooth the weather data. The interval over which the smoothing function operates should be larger than the time it takes for the largest turbulent cell to pass by the weather station. Also, the interval at which the weather data are recorded must be much less than the time it takes the largest turbulent cell to pass by the weather station so that a good statistical sample of weather data is obtained. We also must be carefull that we do not remove any variations in the mean troposphere when we smooth the data. We have evaluated the power spectrum of the weather data and have found that greater than 90% of the power in the mean tropospheric changes occurrs for periods greater than 40 minutes. The weather data, therefore, should be smoothed with a window smaller than 40 minutes in duration. We have thus chosen to sample the temperature, dewpoint and pressure at the NRAO OVLBI earth station once every two minutes and to smooth the data with a 20 minute wide boxcar function. The resulting smoothed weather data will therefore represent the temperature, dewpoint and pressure of the mean atmosphere without removing features due to changes in the mean troposphere.

Interpolation of Weather Data

Since the weather data will be sampled at two minute intervals and the Δt values will be calculated every 0.1 seconds, the weather data will have to be interpolated in calculating the tropospheric delay correction due to non-reciprocity to the Δt data. The simplest method of interpolation is to use the set of weather measurements closest in time to the desired time. This method, however, will produce unrealistic jumps in the non-reciprocity tropospheric correction to the DELTAT file once every two minutes. These jumps will on average only create less than 2×10^{-3} psec discontinuities in the DELTAT data. For situations when the satellite will pass overhead and reaches perigee near the horizon while a thunderstorm begins

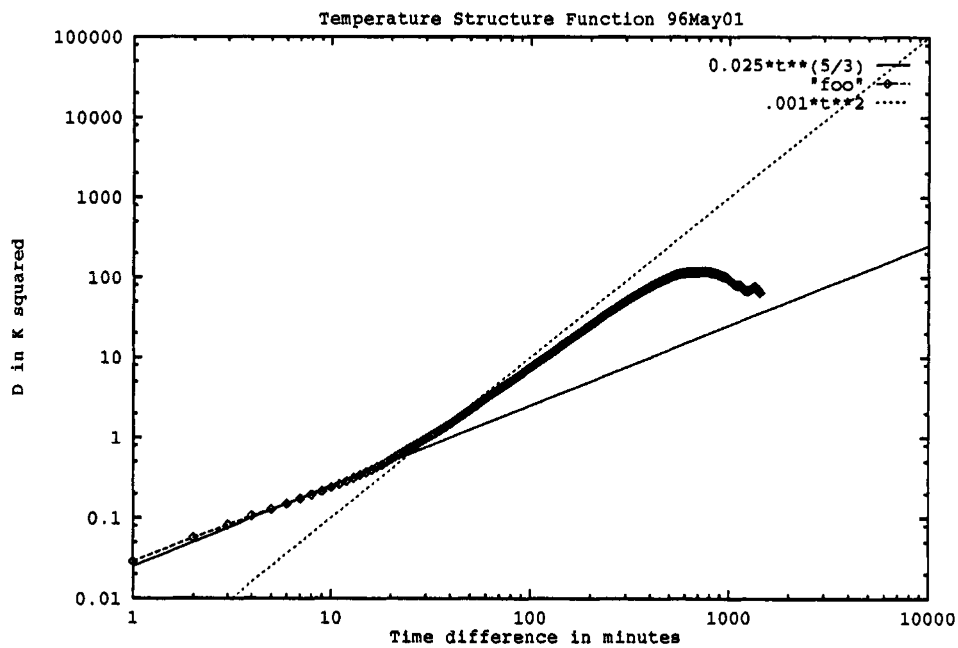

Figure 1: Plot showing the structure function of the measured temperature at the NRAO OVLBI earth station weather station on May 1, 1996. A line with the predicted power law index of 5/3 for Kolmogorov turbulence in the troposphere is shown for comparison. A power law with an index of 2, indicative of sinusoidal fluctuations over small angles, is also shown for comparison. It is easily seen that the largest size scale turbulent cells in the troposphere take $\sim$ 20 minutes to pass by the NRAO OVLBI earth station.

at the tracking station (worst case senerio), the jump in the tropospheric case is limited to be less than 0.4 psec. A less than 2×10^{-3} psec error in the spacecraft timing will have no effect on the coherence of the orbiting VLBI spacecraft's observations and under even the most extreme conditions the coherence factor will be greater than 0.998. Therefore, we find that this interpolation method will be sufficient and will not result in a significant loss of coherence of the spacecraft observations.

Tropospheric Model

From the interpolated temperature, dewpoint and pressure data, we can estimate the tropospheric delay along a given line of sight by using a model of the troposphere. In the model to be used at the NRAO OVLBI earth station the troposphere is assumed to be composed of a dry and wet component, each of which has its vertical structure described by an exponential. The scale height for the wet component is taken to be 2 km while the scale height of the dry component is taken to be 8 km. The dry component is mainly composed of N_2, O_2, Ar and CO_2 and consitutes more than 90% of the tropospheric delay. The variation the the dry tropospheric delay is small and seasonal in nature [4]. The wet component is comprised of water vapor in the troposphere and is highly variable. The turbulence in the troposphere discussed above is a result of the highly variable wet component [4]. The Smith-Weintraub equation is used to estimate the zenith refractivity of the atmosphere for a given pressure, temperature and water vapor partial pressure [2]. The water vapor partial pressure P_w is determined from the dewpoint via the following formula:

$$P_w = \exp\left[\frac{17.27\ D}{237.3 + D} + 1.81\right]\ \text{mb} \qquad 2$$

where D is the dewpoint in centigrade. The Smith-Weintraub equation gives the tropospheric path length towards the zenith as being

$$L_t^{dry}(z = 0^\circ) = 0.228P\ \text{cm} \qquad 3a$$

$$L_t^{wet}(z = 0^\circ) = \frac{75000P_w}{T^2}\ \text{cm} \qquad 3n$$

$$L_t(z = 0^\circ) = L_t^{dry}(z = 0^\circ) + L_t^{wet}(z = 0^\circ) \qquad 3c$$

where P is the pressure in millibars and T is the temperature in Kelvin. A more detailed discussion of this model can be found in Thompson, Moran and Swenson [2]. Once the wet and dry tropospheric delays at the zenith are known they must be mapped to the line of sight. The mapping function which we have chosen to use is given by the following function

$$R_i(z) = \frac{1}{\cos z + \frac{A_i}{\tan(90^\circ - z) + B_i}} \qquad 4$$

where, for $i = dry$:

$$A_{dry} = 0.00143$$

$$B_{dry} = 0.0445$$

and, for $i = wet$:

$$A_{dry} = 0.00035$$

$$B_{dry} = 0.017$$

where the values of A and B were determined empirically [4]. This mapping function has been found to be good to within less than 1% for $z > 89°$ when compared to direct integrations of the tropospheric model [4]. The tropospheric delay at a given zenith angle is thus given by

$$L_t(z) = L_t^{dry}(z = 0°)R_{dry}(z) + L_t^{wet}(z = 0°)R_{wet}(z) \qquad 5$$

and will be accurate to 1% compared to direct integrations of the tropospheric model [2][4].

Determination of the Tropospheric Correction to the DELTAT File

The tropospheric correction to the DELTAT data is half the difference between the tropospheric delay on the uplink signal path and the downlink signal path. Since the distance to the orbiting VLBI spacecraft from the tracking station will be much greater than the signal's pathlength through the troposphere, we can make the simplifying assumption that the tropospheric delay for a round trip signal occurrs instantaneously at the the transmission time of the uplink signal and at the reception time of the downlink signal. Thus knowing the elevation angle of the spacecraft at the transmission and reception times allows us to determine the tropospheric correction to the DELTAT data (ϵ_t) using equation (5) as follows:

$$\epsilon_t = \frac{L_t(z_{up}, t_{up}) - L_t(z_{down}, t_{down})}{2}. \qquad 6$$

Procedure for Determining the Tropospheric Correction to the DELTAT File

Consider a tracking pass observed by the NRAO OVLBI earth station that lasts from time t_0 until t_1 for which a DELTAT file will be created. The following procedure outlines how the NRAO OVLBI earth station weather station data will be used to estimate the tropospheric delay along a given line of sight at any given time during the tracking pass.

- Weather data will be collected at two minute intervals in the time range $t_0 - 12$ minutes to $t_1 + 12$ minutes.
- The weather data will be smoothed with a boxcar function whose width is 20 minutes resulting in smoothed weather data in the time interval $t_0 - 2$ minutes to $t_1 + 2$ minutes.
- The smoothed data will be "interpolated" by taking the smoothed weather data measurement nearest in time to the desired time.
- The "interpolated" values of the temperature, dewpoint and pressure will be used in conjunction with the tropospheric model described in equations (2) thru (5) in order to estimate the tropospheric delay for the uplink and downlink signals at time $t_0 < t < t_1$.
- The tropospheric correction to the DELTAT file at time $t_0 < t < t_1$ is then found to be half the difference in the tropospheric delay of the uplink and downlink signals (equation 6).

References

[1] R. Linfield, 1995, "Tropospheric Coherence in the Space VLBI Phase Transfer Process", JPL memo 335.1-95-004.

[2] Thompson, Moran and Swenson, 1986, Interferometry and Synthesis in Radio Astronomy, (Krieger).

[3] OVLBI-ES memo 38, "Post-Pass Processing of Two-Way Timing Measurements" by Larry D'Addario.

[4] "A Comparative Survey of Current and Proposed Tropospheric Refrection-Delay Models for DSN Radio Metric Data Calibration", by J.A. Estefan and O.J. Sovers, October 1994, JPL Publication 94-24.