Atmospheric Phase Correction for Submillimeter Interferometry using Stratospheric Ozone Line Emission

Scott Paine

Smithsonian Astrophysical Observatory

60 Garden Street, MS 78

Cambridge, MA 02138 USA

spaine@cfa.harvard.edu

Summary

The non-uniformity and variability of water vapor in the troposphere often limit the performance of radio interferometers, by causing fluctuating path delay which differs for each antenna's line of sight. The problem becomes particularly severe at submillimeter wavelengths, where even in conditions of good atmospheric opacity, the fluctuating tropospheric delay can spoil the phase coherence of the interferometer.

Efforts to correct for atmospheric phase fluctuations caused by water vapor have been undertaken at several millimeter and submillimeter radio interferometers. The general approach has been to estimate the line-of-sight water column, from which the delay can be inferred, by radiometric measurement of the water vapor emission [1]. Water vapor radiometry has been implemented using both line emission, near the 22 GHz [2] and 183 GHz [3] water lines, and continuum emission near 90 GHz [4] and 230 GHz [5, 6]. The method has been demonstrated to work under favorable conditions, but has so far been difficult to put into routine operation for a variety of reasons. One source of difficulty is the radiometer gain stability which is required, typically better than one part per thousand between observations of a phase calibrator source.

At the Submillimeter Array, we are currently testing a new approach to estimating the line-of-sight water vapor column by monitoring stratospheric ozone emission lines. The proposed method depends on two basic attributes of the atmosphere. First, since ozone is concentrated in the stratosphere, and water vapor in the troposphere, the ozone line emission is viewed after traversing, and being attenuated by, nearly all of the the water vapor along an antenna's line of sight (Fig. 1). Second, the spatial scale for variations in ozone column density is large, and temporal variations are slow. The horizontal scales are typically several hundred km, and secular changes of order ten percent typically take days. The diurnal solar variation is averaged over photochemical time constants of several weeks, so that diurnal column density fluctuations are only a few percent. Consequently, for interferometer arrays as large as several km, the ozone column density along each antenna's line of sight is the same, and variations in ozone column density are common-mode over the array. Moreover, independent daily satellite measurements of ozone column density are available, and are assimilated into global models which enable forecasts several days into the future[8].

The proposed phase correction method uses the peak-to-wing contrast of an ozone emission line, as attenuated by foreground water vapor, to monitor fluctuations in the foreground water vapor column. Fig. 2 illustrates the principle using an ozone line at 700.9 GHz, which could, for example, be placed in the upper sideband of the astronomical receiver when observing the CO 6-5 rotational transition at 691.5 GHz in the lower sideband. Model brightness temperature spectra [9] are shown for 1.0 mm and 1.1 mm precipitable water vapor; this 0.1 mm change in water vapor column would correspond to a phase change of 500° at 690 GHz. As the water vapor column increases, the foreground continuum emission increases by approximately 8 K, whereas the contrast of the ozone emission line decreases by approximately 4 K. Averaged over an equivalent width of 100 MHz, and over both sidebands of a double-sideband receiver, the change in the line contrast is 1 K. Assuming a typical system temperature at this frequency of 750 K, and averaging for 2.5 s over the same bandwidth, gives a sensitivity of 50 mK, sufficient to for a 25° phase estimate.

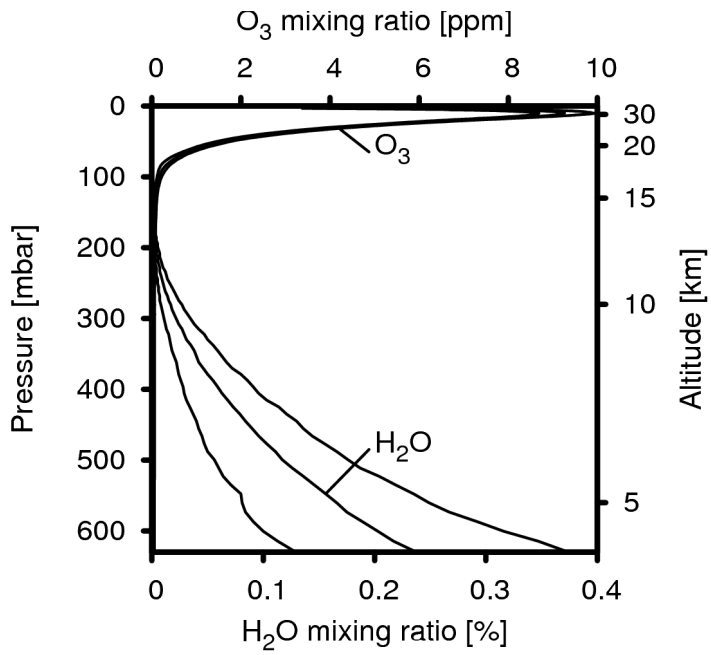

Fig. 1 - Quartile profiles of water vapor and ozone mixing ratio above the SMA site on Mauna Kea, Hawaii. Compiled from NOAA CMDL ozonesonde data for 1984-2004 [7].

For submillimeter interferometers, ozone radiometry offers potential advantages over water vapor emission radiometry. Sensitivity to radiometer gain fluctuations is reduced by the inherently differential nature of the line measurement. Being a transmission measurement, it is a more direct measure of the integrated water vapor column than an emission measurement. When a suitable ozone line can be located within the astronomical bandpass, the phase correction measurement and the astronomical observation sample the same propagation path through the atmosphere. A variation of the method is possible at the SMA, where pairs of receivers, operating in orthogonal polarizations, point along a common boresight axis. In this case, a second astronomical receiver can be used for the phase correction measurement. A disadvantage over direct water vapor radiometry is that the narrower pressure-broadened width of the ozone lines limits the bandwidth available for the measurement. Consequently, a low-noise cryogenic receiver is essential for obtaining sufficient sensitivity, and an approach such as the auxiliary room-temperature water vapor radiometers under development for ALMA [9] would not be feasible.

For tests on the SMA, we have developed stable IF spectrometers for two antennas, based on commercial FFT signal analyzers [10]. So far, one unit has been deployed for single-antenna tests. An example of an ozone line spectrum taken at the SMA, in parallel with routine astronomical observations, in 1 second of integration time is shown in Fig. 3. The line frequency is 231.3 GHz, in the upper sideband of the double-sideband astronomical receiver, with the antenna zenith angle at 64.8°. The RMS noise per 60 kHz channel was 0.4 K, corresponding to 10 mK in 100 MHz. For this spectrum, the receiver was calibrated using a single calibration load at ambient temperature. The model fit shown consequently has two fit parameters, which were the receiver noise temperature (45 K) and the water vapor column density (1.088 mm zenith pwv). In practice, as exemplified by this spectrum, the receiver noise is not necessarily constant across the IF band, and other artifacts such as baseline ripple affect the spectrum. These effects can be expected to vary slowly with time, for example with antenna elevation and focus tracking changes, so a suitable filtering scheme will need to be developed to prevent their affecting the water vapor estimate. The result of applying one simple method is shown in Fig. 4, in which the same spectrum as in Fig. 3 has been corrected by subtracting the trailing average residual from the atmospheric model fit for the prior 200 spectra. We anticipate further developments in this area, in connection with two-antenna phase correction tests on an astronomical phase calibrator, in the coming year.

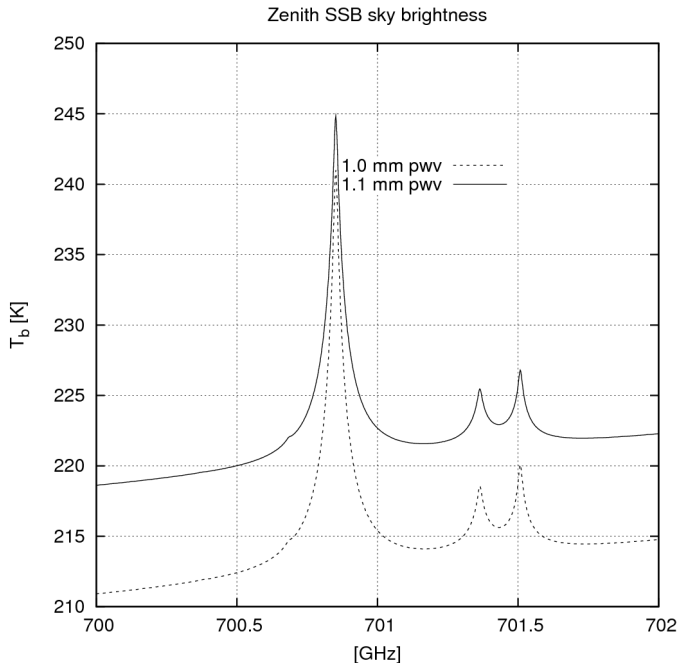

Fig. 2 - Model zenith brightness temperature spectra over Mauna Kea, computed for 1.0 mm and 1.1 mm precipitable water. As the water vapor column increases, the foreground continuum emission increases by ~8 K, while the contrast of the ozone emission line at 700.9 GHz decreases by ~4 K.

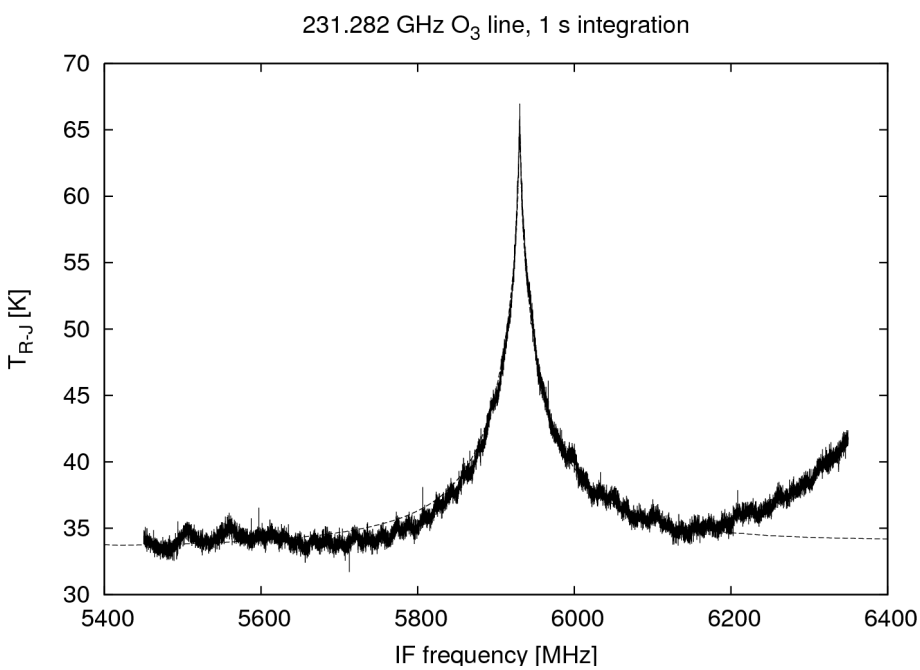

Fig. 3 - 1 s integration on an ozone line monitored at the SMA during an astronomical observation. The baseline ripple is caused by reflections in the antenna optics; the shortest period is caused by reflections from the antenna subreflector. The rising wing beyond 6200 MHz corresponds to the edge of the SMA IF band. The dashed line is a fit to an atmospheric model as described in the text.

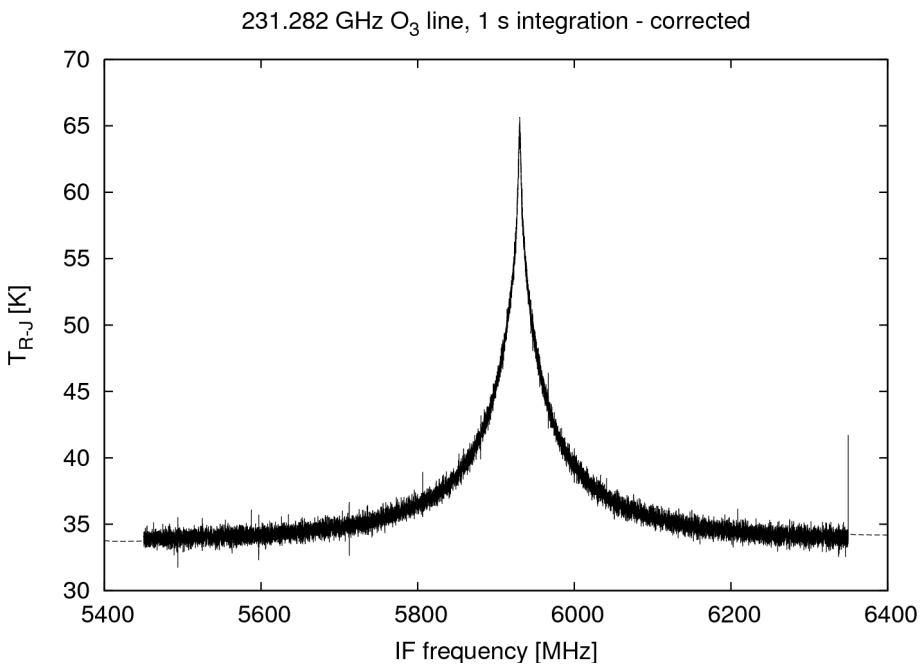

Fig. 4 - The same spectrum as in Fig. 3, after correction using the model fit residual, averaged over the trailing 200 1 second integrations.

References

1. Wm. J. Welch, "The Berkely-Illinois-Maryland-Association Millimeter Array," in M. Ishiguro and Wm. J. Welch (eds.), *Astronomy with Millimeter and Submillimeter Wave Interferometry*, ASP Conference Series, Vol. 59, 1994, pp. 1-9.

2. D. Woody, J. Carpenter, and Nick Scoville, "Phase correction at OVRO using 22 GHz Water Line Monitors," in J.G. Magnum and S.J.E. Radford (eds.) Imaging at Radio through Submillimeter Wavelengths, ASP Conference Series, Vol. 217, 2000, pp 317-326.

3. M. C. Wiedner, R. E. Hills, J. E. Carlstrom, and O. P. Lay, "Interferometric Phase Correction Using 183 GHz Water Vapor Monitors," *Ap. J.* **533**, June 1 2001, pp. 1036-1041.

4. S. S. Zivanovic, J. R. Forster, and W. J. Welch, "A new method for improving the interferometric resolution by compensating for the atmospherically induced phase shift," *Radio Science* **30**, July-August 1995, pp 877-884.

5. M. Bremer, S. Guilloteau, and R. Lucas, "Atmospheric Phase Correction Based on Sky Emission in the 210-248 GHz Band," in P.A. Shaver, ed., *Science with Large Millimetre Arrays*, Springer 1995, pp. 371-374.

6. J.B. Battat, R. Blundell, J.M. Moran, and S. Paine, "Atmospheric Phase Correction Using Total Power Radiometry at the Submillimeter Array," Ap. J. Letters **616**, November 20 2004, pp L71-74.

6. The CMDL data archive can be accessed through ftp://ftp.cmdl.noaa.gov/ozwv/. See also J. Harris, et al., NOAA CMDL Summary Report #27, http://www.cmdl.noaa.gov/publications/annrpt27/ozonewater4.pdf, pp 97-114.

7. See, for example http://www.temis.nl/protocols/O3global.html

8. S. Paine, "*The am Atmospheric Model*," SMA Technical Memo 152. The SMA memo series is available online at http://sma-www.cfa.harvard.edu/memos/tech_no.html.

9. R. Hills, H. Gibson, J. Richer, H. Smith, V. Belitsky, R. Booth, and D. Urbain, "Design and Development of 183 GHz Water Vapour Radiometers," ALMA Memo 352, March 2001. The ALMA memo series is available at http://www.alma.nrao.edu/memos/.

10. Acqiris (Agilent) model AC240, http://www.acqiris.com/