Christopher S. Jacobs et al.: Improving Astrometric VLBI by Using Water Vapor Radiometer Calibrations, IVS 2006 General Meeting Proceedings, p.336–340
http://ivscc.gsfc.nasa.gov/publications/gm2006/jacobs2

Improving Astrometric VLBI by Using Water Vapor Radiometer Calibrations

Christopher S. Jacobs, Stephen J. Keihm, Gabor E. Lanyi, Charles J. Naudet, Lance Riley, Alan B. Tanner

Jet Propulsion Laboratory

Contact author: Christopher S. Jacobs, *e-mail:* `Christopher.S.Jacobs@jpl.nasa.gov`

Abstract

Astrometric observations of distant active galactic nuclei (AGN) using the VLBI technique have been used to construct quasi-inertial global reference frames, most notably the International Celestial Reference Frame (ICRF) which now forms the basis for all astrometry including deep space navigation.

The accuracy of VLBI global astrometry has long been limited by systematic errors–notably path delay variations induced by stochastic spatial and temporal fluctuations in the distribution of atmospheric water vapor. In order to calibrate the water vapor induced path delay fluctuations, a pair of advanced design water vapor radiometers (A-WVR) have been built and deployed. We present intercontinental VLBI results calibrated with the A-WVRs showing a factor of 2.5 to 3 decrease in phase delay residuals over time scales of 10 to 1000 seconds. These results suggest that it may be possible to develop the next generation ICRF (at X/Ka-band) much more rapidly than previously estimated and that spacecraft navigation may be possible at sub-nanoradian levels of accuracy.

1. Introduction

Many studies have shown that astrometric applications of Very Long Baseline Interferometry (VLBI) often have their accuracy limited by systematic errors arising from tropospheric water vapor (e.g. Truehaft & Lanyi, 1987). One approach to this problem that has been pursued over the last several decades has been to calibrate the spatial and temporal fluctuations of atmospheric water vapor by measuring emissions from the 22 GHz rotational line of water.

2. The VLBI Observations

The results presented here are from two observing sessions done during the summer of 2004 using NASA's Deep Space Station (DSS) 26 in Goldstone, California and DSS 55 near Madrid, Spain to form an 8400 km interferometer baseline.

The first session was on Day-of-Year (DOY) 200 (18 July 2004) and the second session was on DOY 217 (4 August 2004). We recorded VLBI data simultaneously at X (8.4 GHz) and Ka-band (32 GHz) sampling each band at a rate of 64 Mbps. The data were sampled, digitally filtered and recorded to hard disk using the JPL designed VLBI Science Receivers (VSRs). The data were then played back over a network connection and correlated with the SOFTC software correlator (Lowe, 2006). Fringe fitting was done with the FIT fringe fitting software (Lowe, 1992). This procedure resulted in a phase delay measurement for each second of an hour-long scan. The observed elevations were moderate ranging from roughly 30 to 50 degrees. The table below indicates elevations at the start and stop of the scan on each of the two days for each of the two stations.

Table 1. Observations

Time	DSS 26	DSS 55
DOY/hh:mm	El (deg)	El (deg)
200/10:00	31.7	53.5
200/11:00	43.7	41.9
217/09:00	33.0	52.0
217/10:00	45.1	40.6

3. The Advanced WVR

The Advanced Water Vapor Radiometer (A-WVR), as shown in Figure 1, is a JPL designed and built microwave radiometer with observing bands at 22.2 GHz, 23.8 GHz and 31.4 GHz. Design highlights include a 1.5-meter offset parabolic antenna which provides a highly efficient 1 degree beam, and very high radiometric stability. Drifts in the radiometric calibrations are well below 0.01 Kelvin of brightness temperature on time scales of 10,000 seconds. Key to this stability is the non-cryogenic instrument enclosure which uses thermo-electric coolers to maintain an internal temperature of 35 ± 0.005 Celsius in all weather. In addition to the A-WVR, our atmospheric measurement suite also includes a Microwave Temperature Profiler (MTP) and surface metrology package which are used to better constrain the water vapor retrievals of the A-WVR. These are to the left of the A-WVR in Figure 1. A detailed description of the A-WVR system is given in Tanner & Riley (2003).

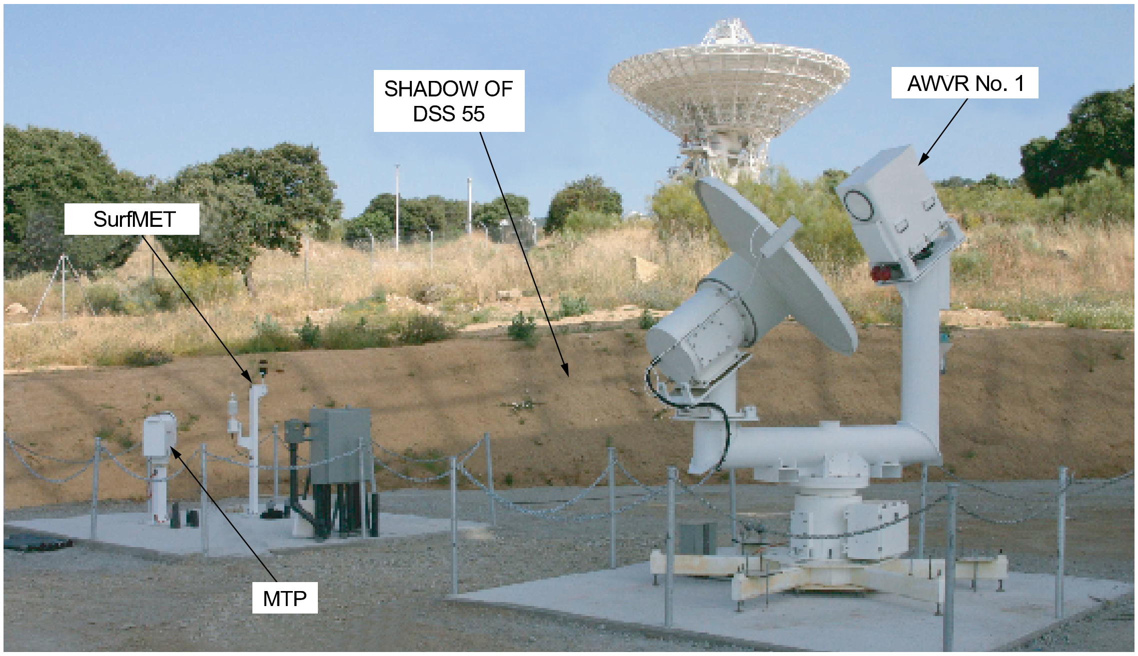

Figure 1. The Advanced Water Vapor Radiometer (A-WVR) instrument package deployed in Spain.

The Advanced WVR design improves several items relative to our previous generation of WVRs.

First, previous designs simple feedhorn was improved upon by adding the 1.5 meter clear aperture dish antenna. This narrowed the beam to about 1 degree from the feedhorns 7 deg beam. In parallel, the radiometer pointing knowledge was improved by an order of magnitude to +-0.05 deg. This resulted in an instrument that more nearly sampled the same spatial scales and direction as the VLBI antenna. Also, one may now observe much closer to the horizon before ground pickup through sidelobes becomes a problem. Second, as previously mentioned, the gain stability of the radiometer was improved. Third, the addition of a Microwave Temperature Profiler (MTP) allows empirical determination of the atmospheric temperature vs. altitude above the site during the measurements.

4. Results

The plots in Figure 2 show the VLBI phase residuals in black and the A-WVR wet troposphere delay in blue (dark gray). A quadratic term was estimated from the VLBI-AWVR differences in order to remove slowly changing systematic effects such as station location and nutation mis-modeling. These plots clearly show a high correlation between the VLBI phase and the A-WVR troposphere calibrations. The improvement in residuals is a bit less than a factor of three. For example, the DOY 200 VLBI phase residuals improved from 3.4 mm down to 1.2 mm—a factor of 2.8 improvement. For scale, an 8.4 mm rotation of our 8400 km long interferometer represents 1 nano-radian or about 200 μasec.

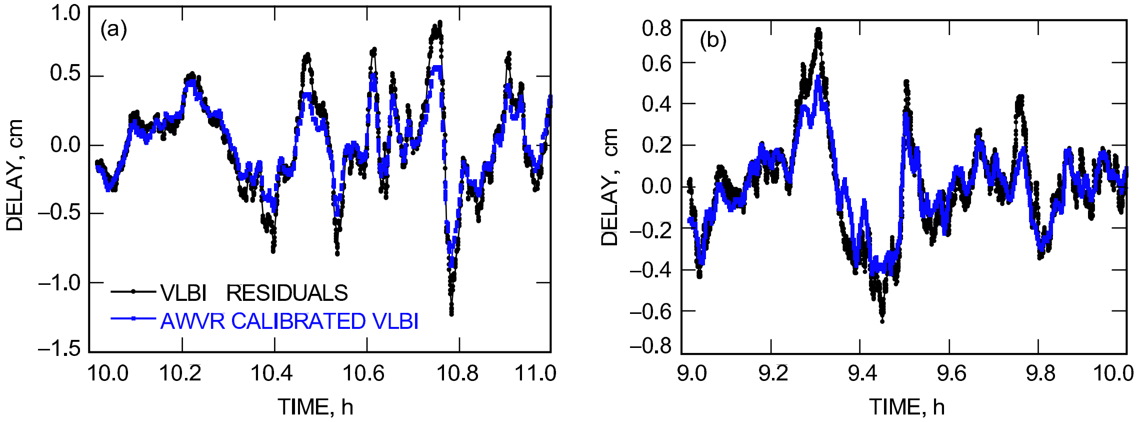

Figure 2. VLBI phase delay residuals (black) vs. A-WVR Calibrations (blue, dark gray).

In order to examine the range of time scales over which the VLBI residuals are being improved, we calculated the Allan standard deviation of the VLBI phases. Figure 3 shows the VLBI data before (red) and after the A-WVR calibration (green). The result shows a strong improvement on time scales of 10 to 1000 seconds. For times scales shorter than 10 seconds, we note that SNR considerations for the A-WVR measurement forced its shortest measurement integrations to be 10 seconds—thus the lack of significant improvement on times scales less than 10 seconds. The DOY 200 and 217 experiments only lasted 3600 seconds thus limiting our ability to examine the quality of calibrations on time scales much longer than 1000 seconds. Longer data arcs will have to be acquired before we can evaluate the quality of calibrations on time scales of 10,000 seconds to a day which are also of interest to global VLBI astrometry.

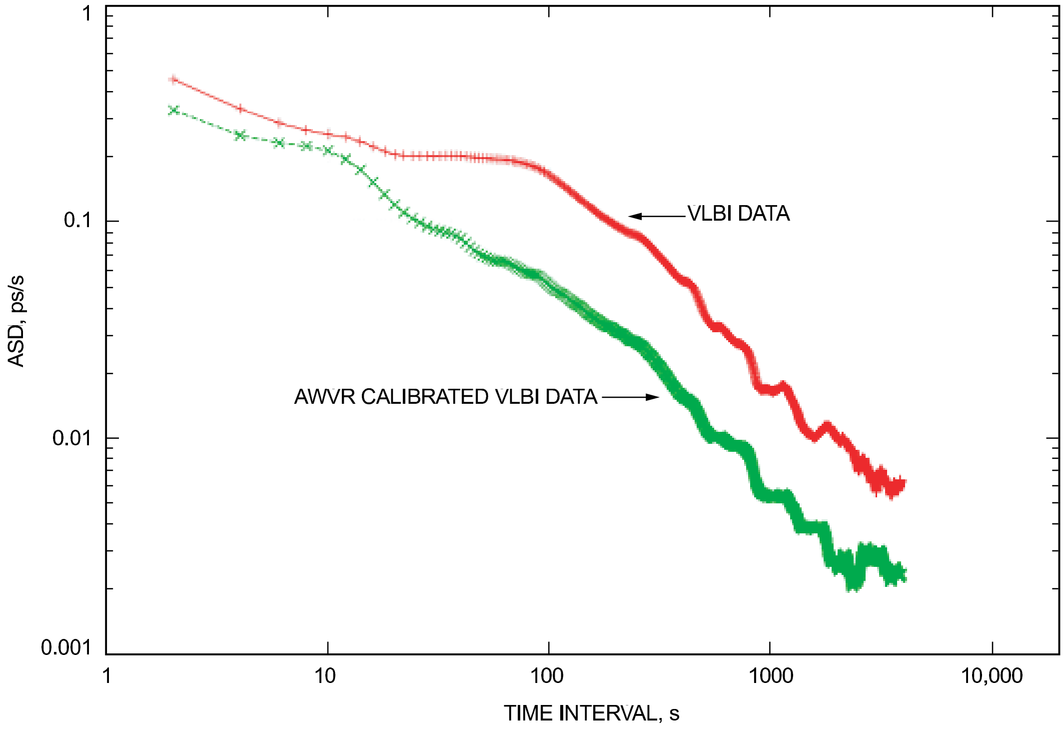

Figure 3. Allan Deviation of VLBI phase with and without A-WVR calibrations.

5. Areas for Further Study and Conclusions

The results shown represent a work in progress. There is a suggestion in the data that the A-WVR does not track some sharp peaks in the VLBI phase. This has not yet been carefully studied. The wider beam of the A-WVR (1 deg) relative to the VLBI antenna (0.02 deg at Ka-band, 32 GHz) and the spatial offset of the two instruments (of order 100 meters) are potential contributors to this effect.

We also note that these tests probed only time scales on the order of 10 to 1000 seconds. Because global VLBI experiments often last for 24 hours, one would like to demonstrate that the A-WVR calibrations reduce VLBI residuals on time scales as long as a day (~100,000 sec). Furthermore, these measurements represent one continuous track of a single natural radio source as it moves slowly across the sky. We have not yet demonstrated that the dramatic improvements seen in our data can be sustained in a typical global astrometry scenario in which the target radio source is changed every few minutes to a different part of the sky.

However, if the improvements that our limited data show can be sustained in more challenging global astrometry scenarios then the benefit would be dramatic. A threefold improvement in residuals would mean that A-WVR calibrated data would carry almost ten times the weight of un-calibrated data in a least squares fit. This could dramatically reduce the amount of time needed to develop an X/Ka-band (8.4/32 GHz) celestial reference frame for applications such as spacecraft tracking. For actual spacecraft tracking sessions, the application of A-WVR calibrations has the potential to help enable a factor of 2-3 improvement in spacecraft tracking accuracy.

Acknowledgements

The research described in this paper was performed at the Jet Propulsion Laboratory of the California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

References

[1] Lowe, S. T., 'Theory of Post-BlockII VLBI Observable Extraction', JPL Publication 92-7, JPL, Pasadena, CA, 15 Jul 1992.

[2] Lowe, S. T., 'SOFTC: A Software VLBI Correlator', JPL, Pasadena, CA, in preparation, 2006.

[3] Tanner, A. B., and A. L. Riley (2003), 'Design and performance of a high-stability water vapor radiometer', Radio Science, 38(3), 8050, doi:10.1029/2002RS002673.

[4] Treuhaft, R. N., and G. E. Lanyi, 'The Effect of the Dynamic Wet Troposphere on Radio Interferometer Measurements', Radio Science, vol 22, pp. 251-265, March-April 1987.