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# Media Calibration in The Deep Space Network - A Status Report

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**Abstract**

A new media calibration system (MCS) has been implemented at the Goldstone complex of the DSN. It is intended to calibrate the delay of radio signals imposed by the neutral atmosphere. The system provides periodic measurements of both the static dry and fluctuating wet components of this delay. In particular, the system will calibrate the fluctuations in line of sight path delay due to atmospheric water vapor that we believe will dominate the error budget for several radio science and radio astronomy experiments. We have compared two of these media calibration systems with a connected element interferometer on a 21 km baseline. In this report we describe a total of 30 observations in which a radio source was tracked for an hour or more and the delay residuals then calibrated using the MCS. The accuracy of the comparison appears to be limited by systematic errors in the interferometer, which are under investigation. However, our results do indicate that the MCS can meet or exceed the two-way Allan standard deviation specification of $1.5 \times 10^{-15}$ on time scales of 2,000 - 10,000 sec, as required by the Cassini GWE for two way Doppler tracking.

## 1. Introduction

Over the last few years we have been developing a troposphere calibration system, in support of the Cassini radio science experiments. The Cassini spacecraft was launched in 1997, will arrive at Saturn in 2004, and started radio science experiments during its cruise phase (late 2001). The Cassini gravitational wave experiment (GWE) has been described in detail by Armstrong, [1] and Tinto and Armstrong [2]. Detailed studies of the GWE error budget [3] [4] point to atmospheric delay fluctuations as the dominant error component on time scales greater than 100 seconds. Thus the sensitivity of the GWE is limited, unless these atmospheric delays are calibrated. Since almost all the power in the atmospheric delay fluctuations at frequencies less than 0.01 Hz is due to the wet troposphere, the principle instrumentation used for calibration is a water vapor radiometer.

An advanced water vapor radiometer (UV), shown in Figure 1, was developed at JPL and is described in detail by Tanner [5]. The WVR has an off-axis reflector, giving a one degree beamwidth with very low sidelobes The pointing accuracy is 0.1 degree. The WVR measures the brightness temperature at 22.2, 23.8, and 31.4 GHz, with long term stability of 10 mK on time scales of 10,000 seconds. The path delay along the line-of-sight depends on the integrated columnar density of water vapor, and may be estimated by measuring the strength of the 22.2 GHz spectral line of water. In order to reduce the sensitivity to the variable height distribution of the water vapor, and to the presence of clouds, we use two additional frequency channels at 23.8 and 31.4 GHz [4]. The WVR acquires data in subsecond intervals and produces a time-series of line-of-sight brightness temperatures. Off to the right in the background of the picture one can see the microwave temperature profiler (MTP). The microwave temperature profiler retrieves the vertical distribution of atmospheric temperature. The data from the WVR, MTP, and surface meteorological stations are then post-processed with two retrieval algorithms [8] [9] to extract the line-of-sight delay

Figure 1. A photo of the Cassini calibration subsytem taken at DSS-13 in Goldstone CA. The new advanced WVR is seen in the center and the MTP and J-series WVR are shown in the background to the right.

## 2. Performance Testing

The objective of the Cassini media calibration system is to measure the atmospheric path delay fluctuation of signals transmitted between the Cassini spacecraft and the Goldstone DSS-25 antenna. Two advanced WVRs have been built to support Cassini radio science experiments. Dual WVRs allows for operational reliability and robustness in the case of equipment failure, and allow cross-checks between the units. A detailed inter-comparison between the two units has been made [9], and the Allan standard deviation (ASD) [10] was shown to be significantly better than the GWE requirements for all interval times greater than 100 seconds. However, this side-by-side comparison reflects only the stability of the WVR. In order to demonstrate a WVR's accuracy it is necessary to compare it to results from another measurement technique. Following earlier successful comparison experiments utilizing older model WVRs [6] [7] a connected element interferometer (CEI) was used to independently measure the line-of-sight path delay fluctuations. Additional details of the experimental setup can be found in reference 10.

From Aug, 1999 until May, 2001 we conducted a series of dual frequency (2.3 and 8.4 GHz) CEI observations on the 21 km baseline between the Deep Space Network's (DSN) high efficiency 34 m diameter antenna at DSS15 and a 34 m diameter beam waveguide antenna at DSS13. Since the effective wind speed is typically between 5 and 10 m/s, the tropospheric fluctuations at each site will be nearly independent for time scales less than $\sim$ 4000 seconds making this baseline well-suited for a WVR comparison experiment. Strong, point-like radio quasar sources (flux density $\geq$ 1Jy) with accurately known positions were chosen to minimize CEI errors. The data from each antenna were cross-correlated and the interferometric delay (difference in arrival times at the two antennas) was extracted. After subtraction of an apriori model, the residual phase delay (phase divided by the observing frequency) and delay rate (time rate of change of phase delay) were obtained. In addition, a linear clock model was fitted to the data and removed.

Each WVR was positioned ~50 meters from the base of the 34 m antenna. This offset was chosen to maximize the sky coverage, while minimizing the magnitude of beam-offset errors. The WVR was co-pointed with the DSN antennas during sidereal tracking of distant natural radio sources. The WVRs were monitored in real time and derived path-delay time series were produced during post-processing at JPL. After the WVR path delay time series were smoothed over 6 seconds, the WVR data from each site (DSS15, DSS13) were subtracted to create a site-differenced delay time-series. Finally, the data was fitted for clock-like effects, resulting in a differenced WVR data type which could be directly compared with the CEI residual phase delays.

The comparison experiments conducted in 1999 were limited in scan duration to less than 26 minutes (the duration of a single pass on the CEI tape recorder). Several experiments produced little data, due to an assortment of instrumental problems and operator errors. In addition, instrumental problems at DSS13 caused uncalibrated delay errors on long ($\geq$ 1000s) time scales [11]. By May, 2000 we were able to correct long-term CEI instrumental stability problems enabling WVR-CEI comparison over very long time scales ($\geq$ 1000 seconds). A detailed discussion of the entire data set may be found in references 11 and 12. In this report we will discuss two representative experiments, DOY137 and DOY138, that were conducted after these long term stability problems were corrected. The CEI and WVR delay time-series data from DOY138 is shown in Figure 2. For ease of comparison between data sets at different elevations, both the CEI and WVR data sets have been converted (mapped) to the equivalent delays in the zenith direction. It is clear that the correlation between the two data sets is strong. The CEI data can be corrected for phase delay fluctuations by subtracting the corresponding WVR data. The CEI data has a RMS of ~4.3 mm. After WVR calibration this is reduced to ~1 mm, a factor of four improvement. On DOY137 an improvement factor of 1.7 was measured, however the surface winds were measured to be greater than 40 km/hour. For a full discussion of all the experimental results see references 11, 12 and 13. Figure 3 shows a histogram of CEI residuals both before and after the WVR calibration for the entire data set acquired after May 2000. The CEI residual RMS is seen to improve (decrease) by almost a factor of four after calibration by the WVR data.

Figure 4 plots the Allan standard deviation (ASD) of the site-differenced delays as a function of the sampling time for DOY138. The CEI data and WVR data have ASD values that track one another very closely over almost the entire range of sampling times. After the WVR data is used to calibrate the CEI data, the ASD decreases by a factor of six at time intervals greater than 1000 seconds. The calibrated CEI data shows improvement for all sampling times down to ~15 seconds, below which the 50 m WVR-DSN offset precludes useful calibration.

## 3. Discussion

We have described an atmospheric media calibration system which was shown to calibrate out the atmospheric delay fluctuations down to a Allan standard deviation level of $1.5 \times 10^{-15}$ for sampling times greater than 2000 seconds. This system meets the GWE requirements for time

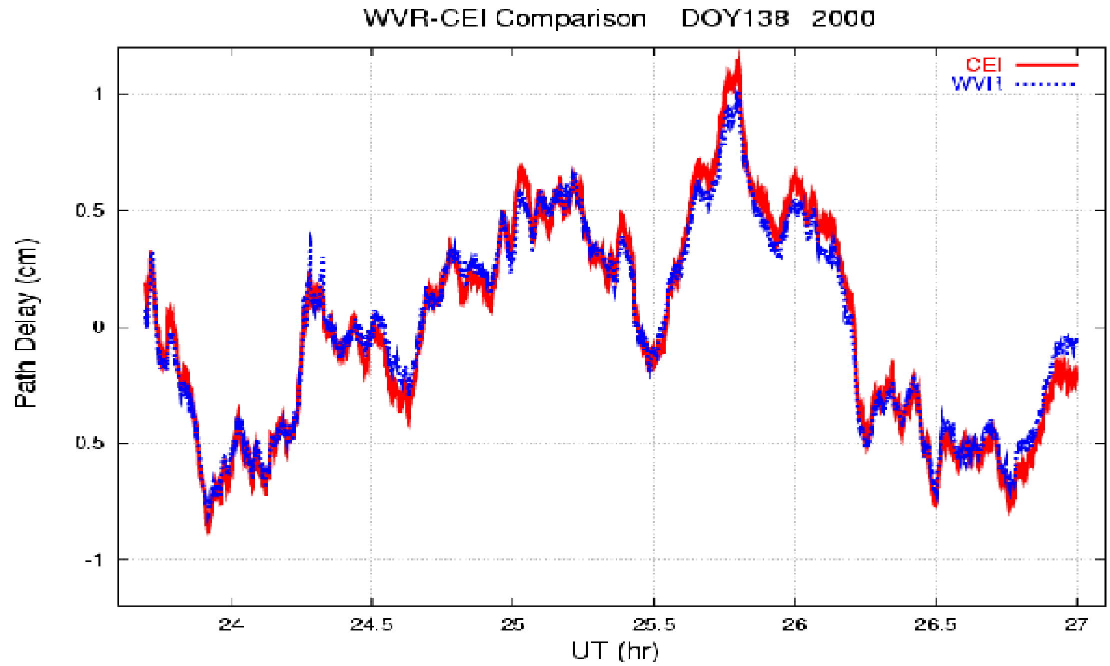


Figure 2. The site differenced, zenith mapped residual delay data from the CEI and WVR for DOY 138, 2000.

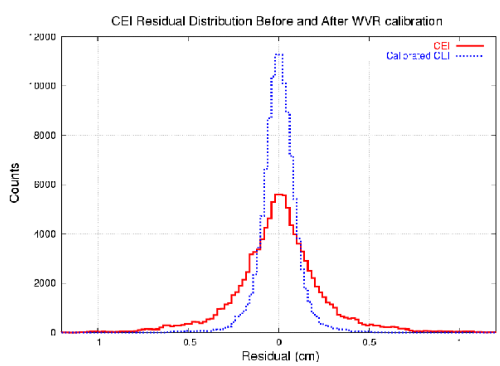


Figure 3. The Histograms of the residual CEI before and after WVR calibration

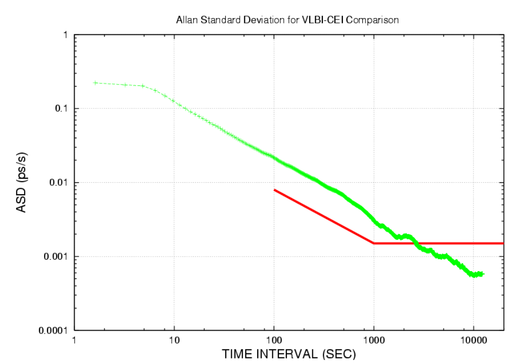


Figure 4. The Allan standard deviation plotted for DOY 138, 2000. The figure shows the calibrated CEI residual data and the requirements for the Cassini GWE.

scales greater than 2000 seconds. Calibration of the CEI data reduced the measured delay residuals by a factor of ∼4.

The level of the CEI residual delay error is composed of the quadrature sum of the CEI errors and the WVR errors. Hence, the Allan standard deviation values in Figure 4 really are an upper estimate of the WVR residual delay errors. To improve upon our assessment of the WVR performance, the error budget of each measurement technique must be independently examined in greater detail. Work is now under way to critically reevaluate the WVR error budget (precision, stability, beam size, beam offset, beam mismatch, retrieval accuracy) and the CEI error budget (electronic stability, instrumental delay mis-modelling, baseline accuracy).

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## References

[1] Armstrong, J.W., and R.A. Sramek, Observations of tropospheric phase scintillations at 5 GHz on vertical paths, Radio Science, 17, pp. 1579 - 1586, Nov. 1982.

[2] Tinto, M., and J.W. Armstrong, Spacecraft Doppler tracking as a narrow-band detector of Gravitational Radiation, Phys. Rev. D, 58, 042002, 1998.

[3] Armstrong, J.W, B. Bertotti, F.B. Estabrook, L. Iess, and H.D. Wahlquist, The Galileo/Mars Observer/Ulysses Coincidence Experiment, Proc. of the Second Edoardo Amaldi Conf. on Gravitational Waves, Ed., E. Coccia, G. Pizzella, and G. Veneziano, Edoardo Amaldi Foundation Series, Vol. 4, World Scientific, 1998.

[4] Keihm, S.J. Water Vapor Radiometer Measurements of the Tropospheric Delay Fluctuations at Goldstone Over a Full Year, TDA Prog. Report, 42-122, p 1-11, 1995.

[5] Tanner, A.B., Development of a high-stability water vapor radiometer, Radio Sci., 33, pp. 449-462, Mar. 1998.

[6] Resch, G.M., D.E. Hogg, and P.J. Napier, Radiometric correction of atmospheric path length fluctuations in interferometric experiments, Radio Sci., 19, pp. 411-422, Jan. 1984

[7] Teitelbaum, L.P, R.P. Linfield, G.M. Resch, S.J. Keihm, and M.J. Mahoney, A Demonstration of Precise Calibration of Tropospheric Delay Fluctuations With Water Vapor Radiometers, TDA Prog. Report 42-126, pp. 1-8, 1996.

[8] Resch, G.M., Inversion Algorithms for Water Vapor Radiometers Operating at 20.7 and 31.4 GHz, TDA Prog. Report 42-76, pp. 12-26, Oct. 1983.

[9] Keihm, S.J. and S. Marsh, Advanced algorithm and system development for Cassini radio science tropospheric calibration, TDA Prog. Report 42-127, pp. 1-19, 1996.

[10] Allan, D.W., Statistics of Atomic Frequency Standards, Proc. IEEE, 54.

[11] C. Naudet, C. Jacobs, S. Keihm, G. Lanyi, R. Linfield, G. Resch, L. Riley, H. Rosenberger, and A. Tanner, The Media Calibration System for Cassini Radio Science: Part I, TMO Progress Report 42-143, pp 1-8, 2000.

[12] G. Resch, J.E. Clark, S. Keihm, G. Lanyi, C. Naudet, L. Riley, H. Rosenberger, and A. Tanner, The Media Calibration System for Cassini Radio Science: Part II, TMO Progress Report 42-145, pp 1-21, 2001.