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A Low-Cost Water Vapor Radiometer for Deep Space Network Media Calibration

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ABSTRACT. — A water vapor radiometer system based on a commercial off-the-shelf radiometer was constructed and tested as a potential alternative to the JPL advanced water vapor radiometer (AWVR). The system is simple and lends itself to installation on the antenna to allow sampling the same air mass of the antenna main beam. The system was tested in a side-by-side comparison to the AWVR. The system is capable of measuring the effect of atmospheric water vapor on the fractional frequency stability of a microwave link to 1 part in 10^{-14} at 1000 s. The system delivered performance within an order of magnitude of the AWVR for timescales of 100 to 10,000 s.

I. Introduction

NASA Deep Space Network (DSN) radio science missions require precise measurement of the radio signal path delay introduced by the water vapor in the atmosphere. The primary instrument for this measurement is the water vapor radiometer (WVR). The change in the apparent noise temperature of the atmosphere measured near the water vapor emission line at 22 GHz is proportional to the concentration of water vapor present.

The JPL advanced water vapor radiometer (AWVR) was developed to support the Cassini radio science mission and is the prime instrument for all current and future missions requiring accurate estimate of path delay over timescales from 1000 to 10,000 s [1]. It represents the state of the art in WVR stability, resolution, and accuracy. The AWVR is shown in Figure 1.

The instrument was built in the mid 1990s. Two are in operation, one at the Deep Space Station (DSS)–25 antenna site at Goldstone, California, and the other at DSS-55 at the Madrid, Spain, complex. Both are operating and supporting missions such as the Cassini radio science mission and other tasks. They are slated for use for Juno radio science experiments starting in 2016.

The DSN would like to provide WVR capability at other antenna sites and have an alternative to replicating the AWVR, primarily due to cost. The AWVR is a JPL-built device that is

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Figure 1. The AWVR installed at DSS-55.

both complex and relatively expensive. It requires support from JPL engineering for troubleshooting and repair. There is also evidence that providing a WVR that measured the water vapor in the actual antenna beam by mounting it coaxially with the main antenna would provide improved accuracy for some applications [2].

This article describes a demonstration of a low-cost commercial WVR that could be mounted on an antenna to provide an alternative to the AWVR. It is a relatively low-cost system that is well suited to this application. It is a lightweight, easy-to-implement system that outputs sky brightness measurements directly over a serial link.

II. Description of the Radiometer

The instrument is built by Radiometrics Corporation in Boulder, Colorado.[1] The PR- 2230 is a self-contained radiometer that measures and outputs the apparent sky brightness measured in kelvins from 20 to 30 GHz in 21 discrete steps. The system uses a single power supply and outputs the sky brightness over a serial link. A single RS-232 serial cable is the only required interface from the radiometer to the end user. The basic radiometer weighs only 9 kg. It is a robust, semi-hermetic system designed for harsh environments. A picture of the basic radiometer is shown in Figure 2.

The radiometer system consists of an antenna that is a linearly polarized corrugated horn behind a dielectric lens. The output of the antenna and a synchronous gain correction

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[1] The company website is http://radiometrics.com.

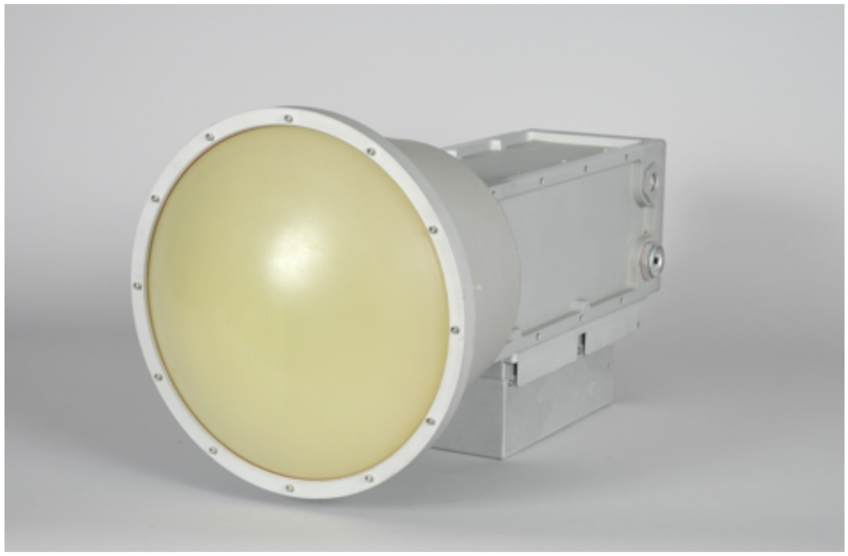

Figure 2. The PR-2230 water vapor radiometer.

noise source is fed to a downconverter with a digitally synthesized local oscillator (LO) source. The intermediate frequency (IF) from the downconverter is connected to a baseband controller that measures the IF power and controls the LO frequency and noise source switching. The measured sky brightness is transmitted to the user using a serial link. The key radiometer specifications from the manufacturer are shown in Table 1.

Table 1. Key radiometer specifications.

Parameter	Specification
Operating Frequency	22 to 30 GHz selectable in 21 steps
IF Bandwidth	150 MHz double sideband
Antenna Beamwidth	3 deg
Antenna Sidelobe Level	< –30 dB
Calibrated Brightness Temperature Accuracy	0.2 + 0.002*|Tref-Tsky| K
Measurement Resolution	0.05 K @ 1 s integration time (measured)
Power Requirements	22–30 VDC; 100 W max
Data Interface	ASCII over RS232/RS422/485
Operating Temperature Range	–55 to 55 deg C
Mass	9 kg

One limitation of this radiometer as compared to the AWVR is that it sequentially samples individual frequencies where the AWVR simultaneously measures the three separate frequencies required to derive the water vapor path length delay. This results in three times less data for a given integration period. This results in an inherent disadvantage of a factor of 1.7 in resolution and stability for the PR-2230 compared to the AWVR.

III. Temperature Control and Radiometer Stability

One of the most critical factors in high-stability radiometers is temperature control. The PR-2230 uses a thermoelectric temperature controller to maintain the radiometer internal components at 40 deg C. The most critical temperature is that of the noise temperature reference in the radiometer. The typical temperature stability of the noise source is ±0.01 deg C.

The PR-2230 is very stable and has the potential to be useful for many applications as delivered; however, it does not match the stability of the AWVR when subjected to typical ambient temperature changes and is therefore not acceptable for use in demanding radio science applications that require AWVR-level performance.

The largest contribution to instability of the radiometer was related to the temperature of the external dielectric lens, which cannot be controlled with the PR-2230 controller. The estimated insertion loss of the window is approximately 0.5 dB, which results in a 0.1 K change in the measured sky brightness per degree of physical temperature change.

To mitigate this effect and improve the stability of the radiometer, the system was installed in a temperature-controlled enclosure. The enclosure consists of a box constructed of 50-mm-thick polystyrene foam. A commercial-off-the-shelf (COTS) 160-W thermoelectric cooler is used to maintain the temperature of the PR-2230 to 35 ±2 deg C. Four fans are used to reduce the temperature gradient inside the enclosure. The radiometer antenna beam enters the enclosure through a 25-mm-thick window constructed of Propazote PPA-30 foam. This foam is one of the lowest-loss solid materials measured at JPL. A 25-mm-thick window contributes less than 0.03 K when measured at 32 GHz [3]. A heat lamp is installed on the outside of the enclosure to prevent condensation of water vapor on the window. The radiometer enclosure is shown in Figures 3 and 4.

IV. Radiometer Absolute Accuracy

The absolute accuracy was measured over the 22- to 30-GHz range using a calibrated liquid-nitrogen-cooled target supplied by Radiometrics. The target was placed over the window of the radiometer enclosure. The average error was –0.9 K. This error and the difference across the band are believed to be due to interaction and scattering between the radiometer lens and the Propazote window. The error is systematic and can be calibrated out by periodically using the cooled target. A plot of radiometer error vs. frequency is shown in Figure 5.

V. COTS Radiometer Stability Tests

In order to evaluate the stability of the COTS radiometer in an operating environment, it was fielded at DSS-25, and was located in close proximity to the existing AWVR (Figure 6). The goal of the testing described in the following paragraphs was to essentially use the high-stability AWVR zenith sky temperature data as "truth measurements" of the atmosphere. Thus, the AWVR data was subtracted from the COTS data and any residual variation

Figure 3. Enclosure internal view.

Figure 4. Radiometer in enclosure installed at DSS-25.

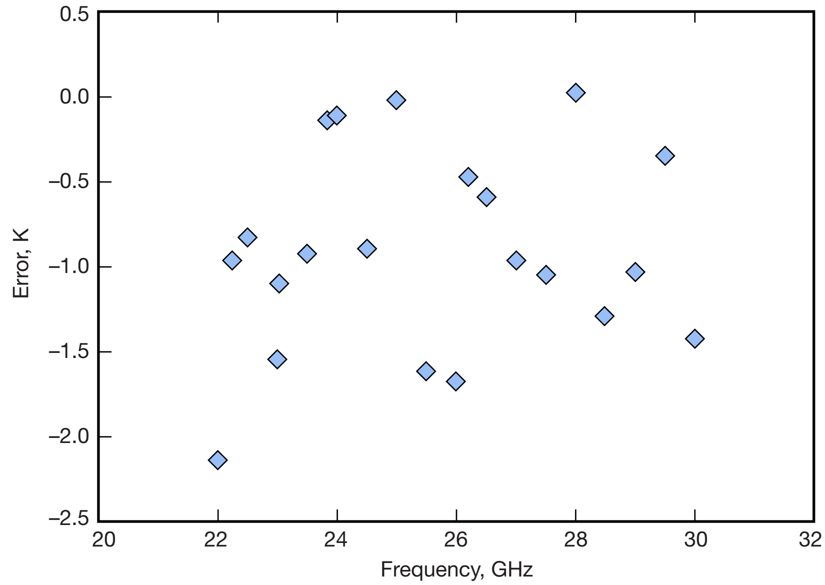

Figure 5. Sky brightness measurement error.

Figure 6. COTS and AWVR instruments installed at DSS-25.

in the temperature measurements was attributed completely to instability in the COTS unit. Three frequencies were used: 22.2 GHz and 23.8 GHz on both radiometers, and a set near 30 GHz, 30.0 GHz on the COTS unit and 31.4 GHz on the AWVR. Any errors caused by the difference in sky temperature at 30.0 and 31.4 GHz will thus appear as additional instability in the COTS unit.

Figure 7 shows the instantaneous zenith sky temperature measured by the AWVR and the COTS unit at 22.2 GHz. Also shown are the COTS data averaged to a sample interval of 6 s, slightly shorter than the AWVR data interval of 8.25 s. A high degree of correlation between

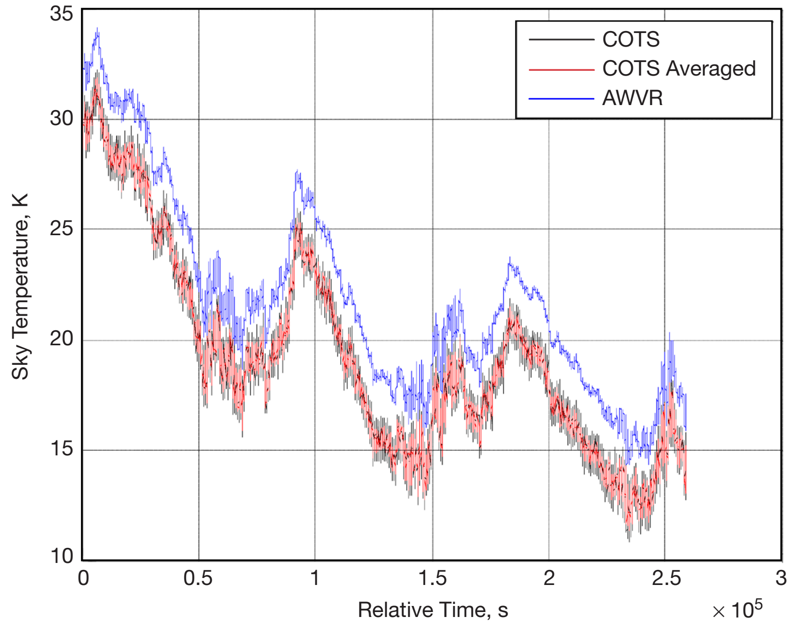

Figure 7. Instantaneous sky temperature, 22.2 GHz.

the AWVR and COTS data is evident, as is a constant offset of approximately 2.6 K over the experiment time span. When used for calibration of atmospheric effects, the bias is unimportant, but can be removed from the COTS unit through side-by-side comparison with the AWVR or other reference radiometer. Similar results were observed in the other two frequency bands.

Figure 8 shows the relative instantaneous zenith sky temperature difference measured by the AWVR and the COTS unit at 22.2 GHz. Also shown are the COTS data averaged to a sample interval of 6 s, slightly shorter than the AWVR data interval of 8.25 s. This relative measurement removes the bias in Figure 7. Excellent agreement between the two instruments is observed.

Figure 9 shows the difference in instantaneous zenith sky temperature (COTS–AWVR) at 22.2 GHz. Aside from the constant offset mentioned earlier, we observe a drift related to the daily variation in temperature over the three-day experiment, as well as rapid temperature fluctuations on a sample-to-sample interval. These fluctuations are related to the white-noise characteristics of the radiometer.

Next, we difference the adjacent values of sky temperature shown in Figure 9 and divide by the time interval. This results in the instantaneous stability of the COTS radiometer in K/s at 22.2 GHz, plotted in Figure 10. We observe a rapid variation in this quantity between ±50 mK/s.

Allan deviation is typically used to evaluate frequency stability of clocks and frequency sources. It is also the figure of merit for pathlength stability in DSN radio science applications. It is also useful as a figure of merit for radiometer stability as expressed in units of

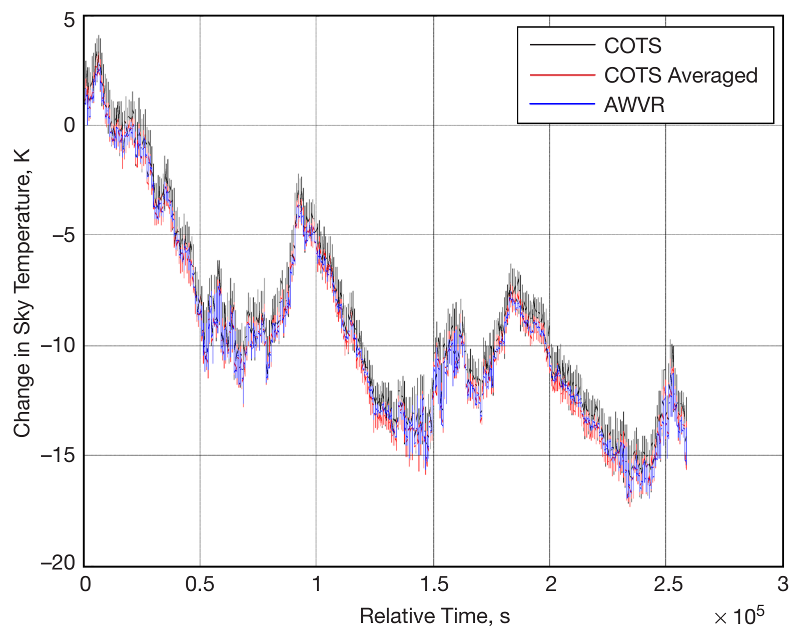

Figure 8. Relative sky temperature, 22.2 GHz.

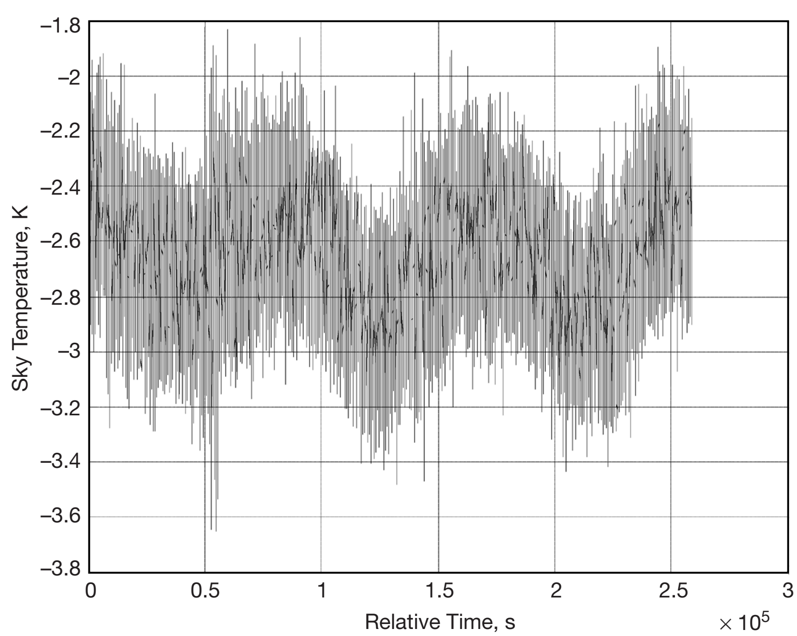

Figure 9. COTS–AWVR sky temperature, 22.2 GHz.

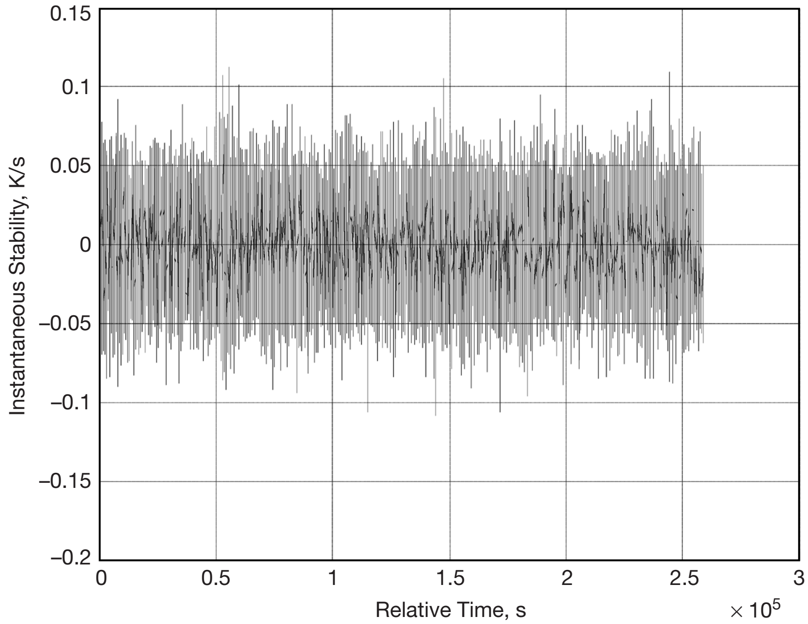

Figure 10. COTS instantaneous temperature stability, 22.2 GHz.

K/s [4]. An ideal radiometer will exhibit a linear response with a slope of –0.5. Figure 11 shows the Allan standard deviation of the COTS radiometer temperature stability for averaging times between a few tens of seconds and 100,000 s. Also plotted is an approximate value for the AWVR stability, which is approximately 10 times better than that of the commercial unit. Typical radio science path stability requirements (Cassini) have been translated to the required radiometer stability and those are plotted on the figure as well.

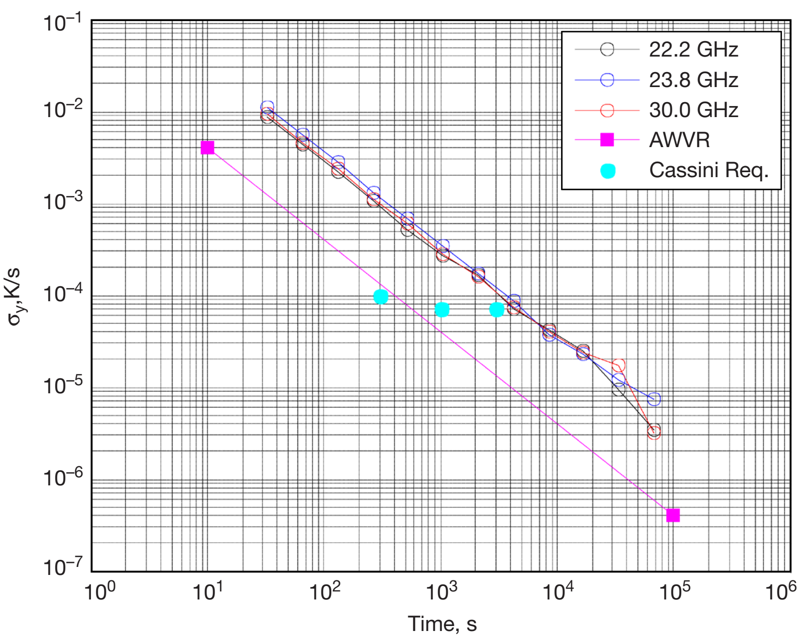

Figure 11. Allan standard deviation of the COTS temperature stability, 22.2 GHz.

Finally, in Figure 12 we convert the radiometer stability of Figure 11 into fractional frequency stability. The approximate fractional frequency stability or Allan standard deviation in units of s/s can be obtained by multiplying the radiometer Allan standard deviation by the conversion factor from K to path delay (approximately 0.01 m/K), and dividing by the speed of light. The factor of 10 in radiometer stability translates to exactly a factor of 10 in frequency stability due to the linear scaling factor involved.

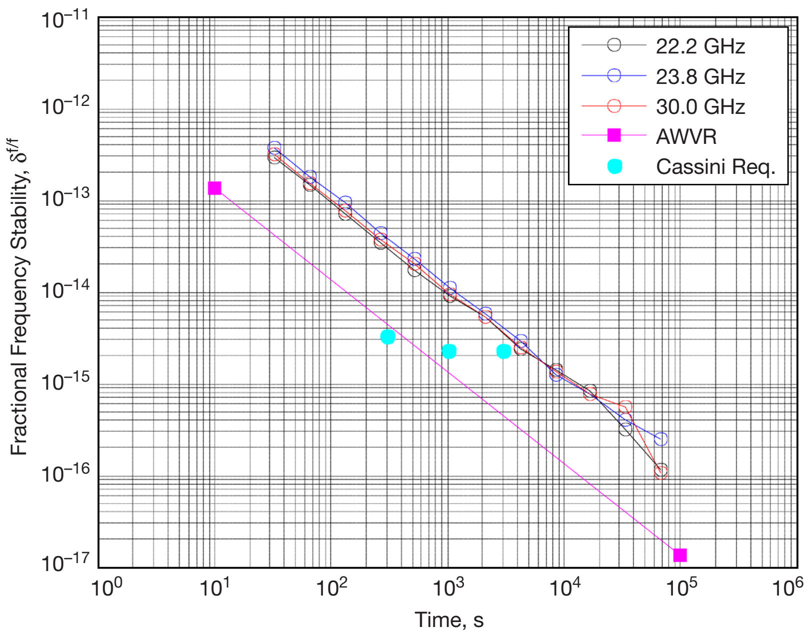

Figure 12. COTS stability at 22.2 GHz, converted to frequency stability (δf/f).

Figure 13 plots the measured ambient temperature throughout the test and shows a peak-to-peak variation of 16 deg C. Figure 14 shows the temperature of the antenna lens inside the COTS unit throughout the same time period. The opposite side of this lens is exposed to the environment of the secondary enclosure and this measurement demonstrates the excellent environmental control achieved by the thermoelectric cooler, which reduces the antenna temperature variation to approximately 0.1 deg C.

VI. Mounting the Radiometer Coaxially with the Main Antenna

The small footprint and simplicity of the PR-2230 would allow it to be mounted coaxially with the main antenna on the subreflector support structure. This has two advantages. Mounting the radiometer on the antenna eliminates the need for a separate positioner; this reduces the implementation cost and eliminates the need for separate pointing predicts for the radiometer. The other advantage is that the radiometer samples the same air mass as the main antenna with no offset, which can be advantageous [2]. The mounting enclosure developed for the radiometer was designed to use the same mounting used by the X-band acquisition aid used on beam-waveguide (BWG) antennas. The single power supply and single interface cable make implementation on an antenna straightforward. A photo of the X-band acquisition aid location is shown in Figure 15.

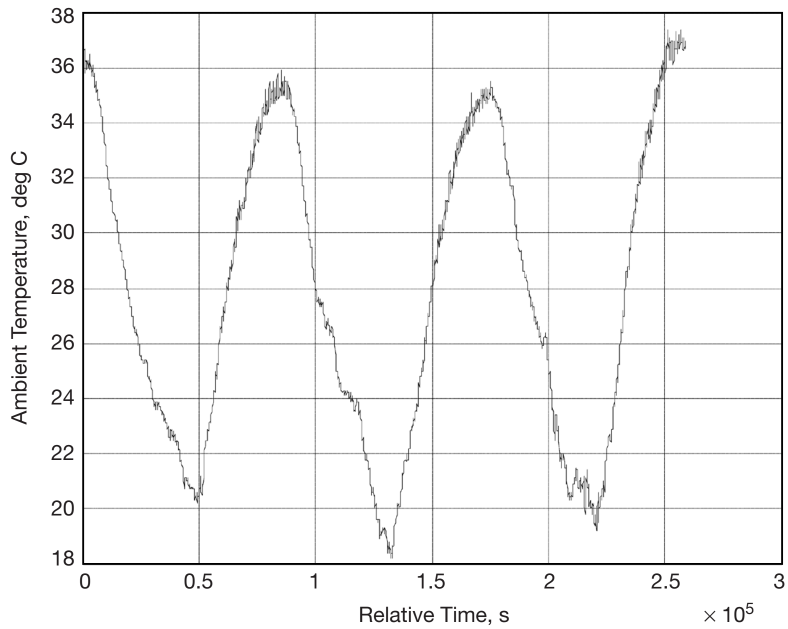

Figure 13. Ambient temperature during the stability test.

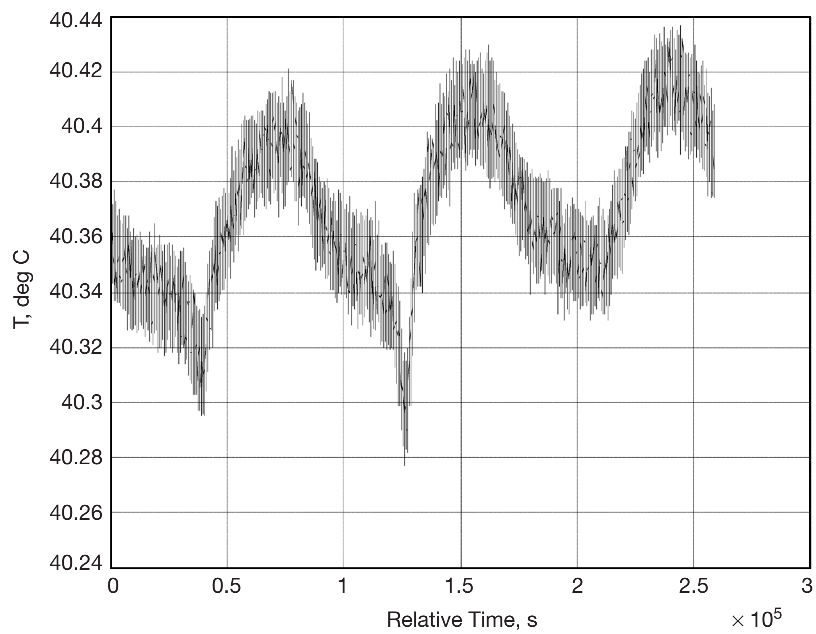

Figure 14. COTS antenna temperature during the stability test.

Figure 15. Acquisition aid mounting on 34-m BWG antenna subreflector.

VI. Conclusion and Recommendations

The WVR system based on a commercial radiometer was designed and tested. The system is capable of measuring the effect of atmospheric water vapor on the fractional frequency stability of a microwave link to 1 part in 10^{-14} at 1000 s. The system delivered performance within an order of magnitude of the AWVR for timescales of 100 to 10,000 s. One disadvantage of the PR-2230 is that it uses a tunable receiver to measure the three frequencies required for pathlength measurement, while the AWVR uses three separate receivers. This results in an integration time that is effectively three times shorter and results in a $\sqrt{3}$ reduction in the radiometer resolution, which decreases the resulting stability by the same factor. Although the system does not deliver AWVR performance, it may be useful for applications where an AWVR is unavailable. It also has the advantage that it can be mounted to sample the same air mass of the main antenna. The system as demonstrated is relatively low cost and results in a system that would be easy to implement and maintain. The system operated continuously for hundreds of hours with no problems. Due to its commercial availability and service, absence of required maintenance, and simple interface, it is ideal for implementation in the DSN. The actual advantage of the coaxial mounting is yet to be verified and should be investigated by installing the system on a DSN antenna.

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