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Phase Correction using 183 GHz Radiometers during the Fall 1998 CSO-JCMT Interferometer Run

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Abstract

We report the performance of the 183 GHz radiometer system for the CSO-JCMT interferometer during the October 1998 run. The phase correction using the radiometers produced the rms phase fluctuations by a factor (a factor of five less in signal loss due to decorrelation) and achieved a corrected rms path length fluctuation of 60 μm under a moderately good atmospheric condition (2.2 mm of PWV). We also offer several suggestions for the future MMA radiometer system that should result in significant improvements.

1 Introduction

Water vapor in the atmosphere affects the index of refraction of the troposphere. The variation in the precipitable water vapor (PWV) causes phase variations for a electromagnetic wave propagating through it and results in "phase noise". An excellent review of the topic and the techniques of using radiometers to reduce this phase fluctuations is given in Wiedner (1998) and the MMA Memo 210 by Carilli, Lay, & Sutton (1998) and references therein. The water line opacity at the Chajnantor site is very low (median $\tau_{225GHz} = 0.065$ and median PWV ~ 1 mm, see http://www.tuc.nrao.edu/mma/sites/Chajnantor/data.c.html), and it is likely that an array of radiometers monitoring the 183 GHz water line is going to be used for the tropospheric phase correction for the MMA. The beam of the 183 GHz radiometer should also overlap the astronomical beams more closely than a low frequency system. The only currently operating 183 GHz phase correction radiometer system is the one for the CSO-JCMT interferometer described in the PhD thesis of M. Wiedner (1998, also available at http://www.mma.nrao.edu/workinggroups/cal_imaging/183GHz.html).

M. Yun attended the first week of the 10 days long CSO-JCMT Interferometer run in October 1998 and participated in the setup and calibration of the radiometers. Here we report the performance of the 183 GHz radiometer system and compare its performance with the existing 22 GHz radiometer systems. We also discuss concerns and improvements desirable for the future MMA radiometer system.

2 The 183 GHz Radiometers

The 183 GHz radiometers for the CSO-JCMT interferometer are double sideband heterodyne systems with uncooled Shottky mixers. The IF signal is mixed down to three frequencies of 1.2, 4.2, and 7.8 GHz away from the water line center at 183.31 GHz, and the three radiometer channels have individual bandwidths of 0.4, 1.0, and 1.0 GHz, respectively (see Figure 1). All the electronics are temperature regulated, and a phase lock loop is used to stabilize the LO frequency.

The calibration of the radiometers is performed using two temperature loads at 35°C ("warm") and 100°C ("hot") and a flip mirror that cycles through these calibration loads and the sky at 1 Hz frequency. The temperatures of the hot and warm load are calibrated daily using liquid nitrogen. Knowing the absolute temperature of each load is not critical since the phase correction utilizes differential measurements. On the other hand, the short term stability of the load temperature is crucial as it directly limits the ability to track the radiometer gain. The load temperatures are measured to be stable to about 10 mK on time scales of minutes. The overall system temperature of the each radiometer is about 2500 K.

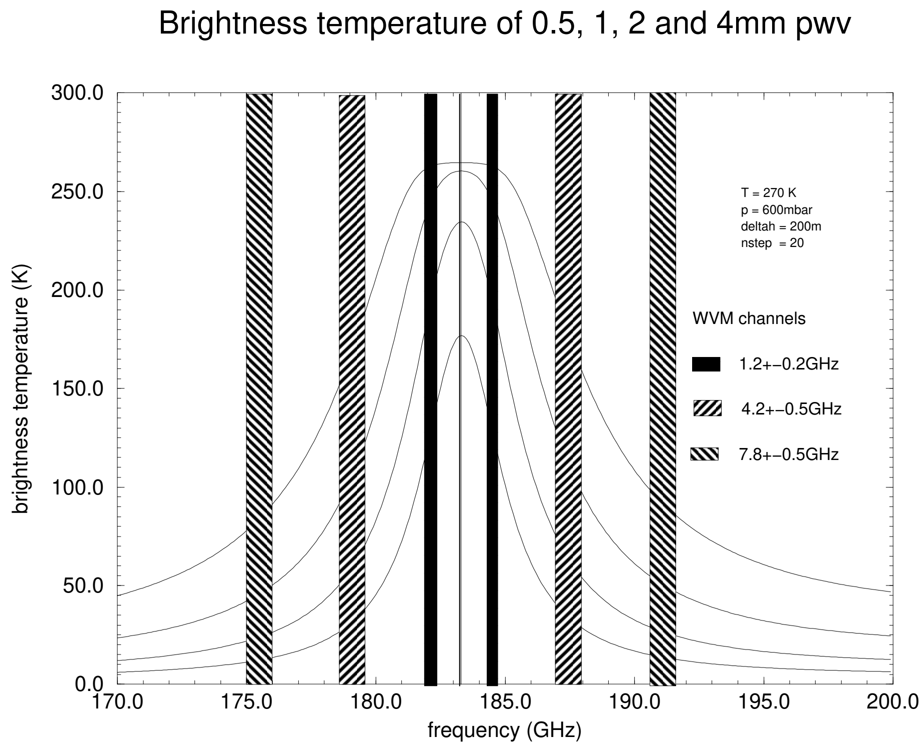

Figure 1: The three double-sideband frequency channels of the water vapor radiometer are shown superposed on the spectrum of the 183.31 GHz water line for 0.5, 1, 2, and 4 mm of PWV.

3 Results from the Fall 1998 Run

The 183 GHz radiometer data were recorded simultaneously with the astronomical interferometer observations whenever possible. The data discussed below were taken between 05:00 UT and 06:00 UT on October 24, 1998 under a good but not exceptional atmospheric condition. The PWV estimated from the atmospheric data was 2.2 mm, and the CSO 225 GHz opacity was 0.11. The astronomical phase data shown are those of the hydrogen recombination line maser at 353.6 GHz in MWC 349 measured by the CSO-JCMT interferometer.

The astronomical phase data and the corresponding 183 GHz radiometer phases for all three radiometer channels are compared in Figures 2 & 3. In each panel, green solid line is the raw interferometer phase, blue dashed line is the phase correction predicted from the radiometer measurements, and the red solid line is the corrected interferometer phase. The rms phase fluctuations are measured after subtracting a linear phase drift that is most likely due to interferometer baseline error. A detailed comparison of the pre- and post-correction results for the Channel 2 data is also shown in Figure 4. The predicted phase from the radiometer data track the astronomical phase extremely well, and the improvement in the corrected phase is obvious.

The radiometric phase correction has achieved more than a factor of two reduction in the rms phase fluctuation. The raw rms phase fluctuation in the astronomical data at 353.6 GHz is 60.1 degrees, which corresponds to the raw path length fluctuation of 143 μm. The corrected phase using the radiometric data from the Channels 1, 2, and 3 has reduced rms phase fluctuations of 38.4, 26.3, and 39.7 degrees, respectively. These reductions correspond to path length fluctuations of 92, 61, and 95 μm ($\sigma_L = 833\ \sigma_\phi / \nu_{GHz}$). For the phase correction, we can use the most sensitive channel or any combination of the channels. The best result achieved in Channel 2 is within a factor three of the target value for the MMA (15 μm *per antenna*). The relatively poor performance of the Channel 1, which is located closest to the line center, is due to the line saturation, which occurs with ≥ 1 mm of PWV. The radiometer sensitivity of the Channel 2 is about 50% better than the Channel 3, which covers only the outer line wings. We note that the reduced phase noise from $\sigma_\phi = 60^\circ$ to 26° corresponds to nearly a factor five improvement in signal loss due to decorrelation – i.e., the signal coherence improves from 50% to 90%.

The radiometer measurement (ΔT) to the phase correction ($\Delta\phi$) conversion factor for this and other radiometer systems is usually chosen *ad hoc* to minimize the rms phase in the calibration data. As discussed in Wiedner (1998), the conversion factor from ΔT to $\Delta\phi$ depends primarily on the PWV with secondary dependences on the vertical temperature and pressure profile in the atmosphere. By modeling the water line emission using an atmospheric model and ground meteorological measurements, the conversion factor can also be computed explicitly. The theoretical conversion factor based on the meteorological data is 20% larger (4.8 K/turn) than the "best" conversion factor that minimizes the residual rms phase (3.9 K/turn), but the phase correction using this theoretical conversion factor is only slightly worse, 27.9 degrees versus 26.3 degrees. This success of the theoretically derived conversion factor suggests that the 183 GHz water line is reasonably well understood and modeled.

The results presented here are representative of the radiometer performance under good (but not exceptional) weather conditions. The corrected rms phase was generally higher under poorer weather conditions because of reduced radiometer sensitivity (see Wiedner 1998). In an earlier run under a somewhat worse condition, a corrected phase fluctuation of 38 degrees (90 μm) was achieved (from uncorrected rms phase of 127 degrees) with 3.5 mm of PWV – still a significant improvement, from complete decorrelation to only 20% loss in amplitude.

4 Comparison with the 22 GHz System

We now compare the performance of the 183 GHz radiometer with that of the 22 GHz water line monitor system operating at the Owens Valley Radio Observatory (OVRO). The OVRO 22 GHz radiometer system is also a 3 channel system with channel widths of 2 GHz each. The two outer channels are used to determine the continuum level for the middle channel, which covers the 2 GHz band centered on the 22 GHz water line itself. A detailed description of the OVRO 22 GHz system is found in Marvel & Woody (1998).

Despite the very low electronic noise, the radiometric phase correction using the 22 GHz system is still challenging because the 22 GHz water line is significantly weaker than the 183 GHz line. As summarized in Table 1, the system temperature of the 22 GHz system is 10 times smaller than the 183 GHz system, but the sensitivity, $\Delta T/\Delta L$, is also at least 10 times lower. The best phase correction achieved with the OVRO 22 GHz system is about 100 μm in "good" conditions (4 mm of PWV). In comparison, the phase correction achieved with the 183 GHz system discussed in the previous section range between 60 and 90 μm with 2-4 mm of PWV. Both systems work significantly better under more favorable conditions (smaller PWV), and the data taken under similar conditions suggest that the 183 GHz system may perform slightly better phase correction than the 22 GHz system.

At the Chajnantor site where the median PWV is only about 1 mm, the weakness of the 22 GHz water line may pose a challenge for the 22 GHz system. On the other hand, the sensitivity of the 183 GHz system should improve dramatically (by factors > 2 for PWV ≤ 1 mm) under the excellent conditions expected because the line center is no longer saturated and the center channel provides the best overall sensitivity. Further, the strength of the 183 GHz line also makes the effects of ground pick-up or clouds less problematic than the 22 GHz line systems.

Table 1: Comparison of Current Water Line Radiometers

	183 GHz (SBI)	22 GHz (OVRO)
T_{sys}	2500 K	200 K
$\Delta\nu$	0.4-1.0 GHz	2 GHz
$\Delta T/\Delta L$	4-20 K/mm	0.4 K/mm
Corrected rms ΔL	60–90 μm	100–300 μm

5 Suggested Improvements

There are several obvious improvements that will make the 183 GHz radiometer system significantly more sensitive. We suggest following improvements for the future 183 GHz radiometer system for the MMA:

- Cooled system. The current radiometer system is still limited largely by detector noise. A 3-5 folds improvement in sensitivity should be achievable when the detector noise is reduced by using cooled mixers and amplifiers.
- Wideband spectrometer backend. By fully sampling the water line, a more accurate determination of the continuum contribution, line profile, and the conversion factor can be derived. The shape of the line wings depends strongly on the vertical temperature and pressure profile, from which an accurate conversion factor can be determined.
- Improved data interpretation. The data from the individual channels are analyzed independently at the moment. Using the most sensitive channel alone seems to do a good job, but a new analysis method incorporating all the data simultaneously may produce a better phase correction. A future improvement incorporating an accurate model of the vertical temperature and pressure distribution, in concert with a full sampling of the water line profile, is highly desirable.

6 Summary

Phase correction using the 183 GHz water line radiometer data has reduced the rms phase fluctuations in the astronomical data taken with the CSO-JCMT interferometer by a factor of two or more. The path length fluctuation was reduced to about 60 μm in good weather conditions (2 mm PWV) and to about 90 μm under poor weather conditions (4 mm PWV). The corresponding reduction in amplitude loss due to decorrelation is even larger. The radiometric measurement to path length delay conversion factor derived theoretically using an atmospheric model and meteorological data was highly effective, giving some confidence that the 183 GHz water line is well understood and modeled.

The performance of the 183 GHz radiometer system is comparable or better than the existing 22 GHz radiometer system and should offer a superior performance at the very dry Chajnantor site. Significantly better results are expected from future improvements such as cooled systems, widband spectrometer backends, and refined data reduction method.

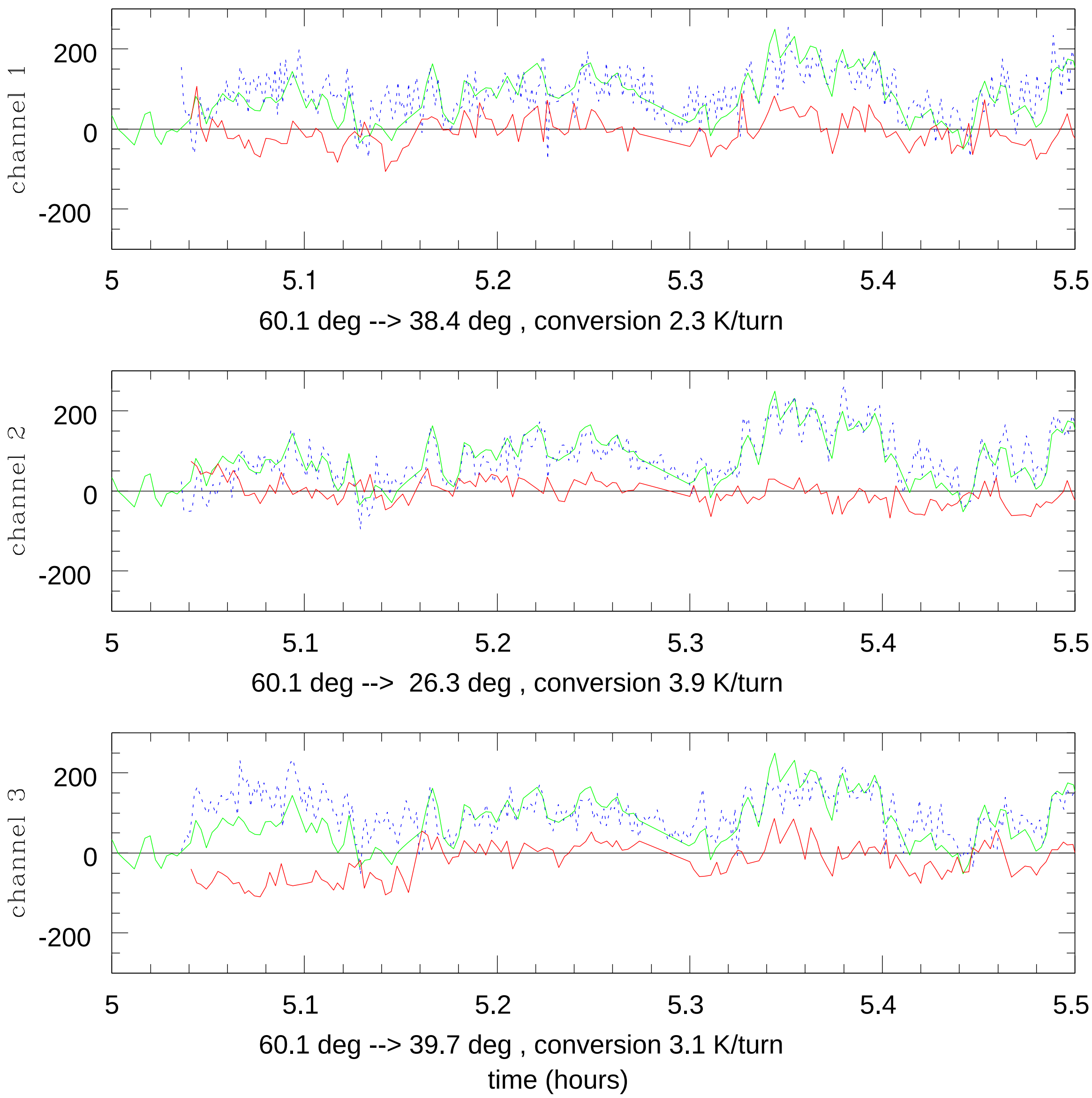

Figure 2: The raw astronomical interferometer phase (green solid line), the phase correction predicted from the radiometer measurement (blue dashed line), and the corrected interferometer phase (red solid line) are shown for each of the three radiometer channels. After subtracting a linear phase drift due to the interferometer baseline error, the rms phase fluctuations are computed as listed above.

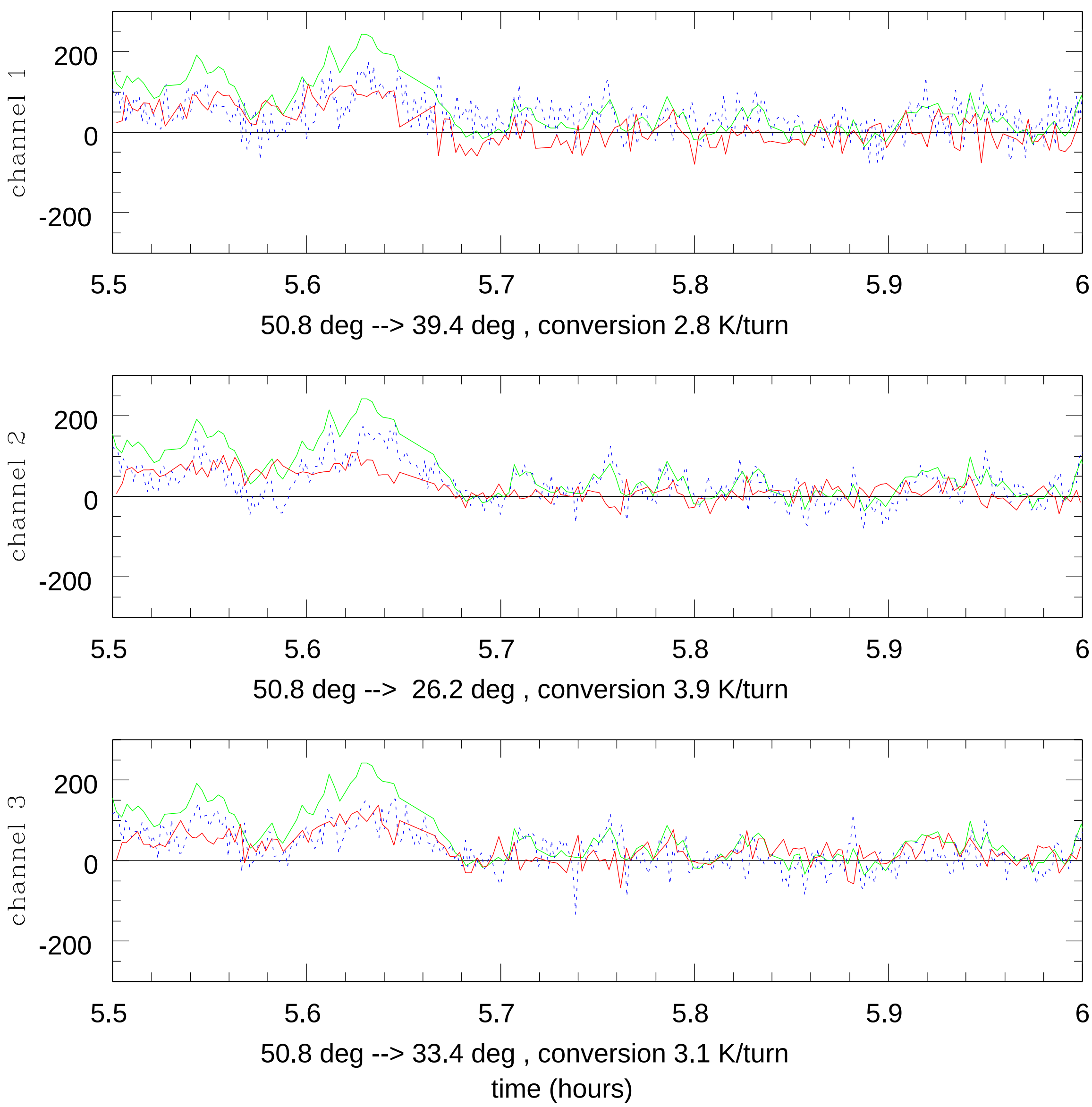

Figure 3: Same as Figure 2 but for 05:30 - 06:00 UT on October 24, 1998.

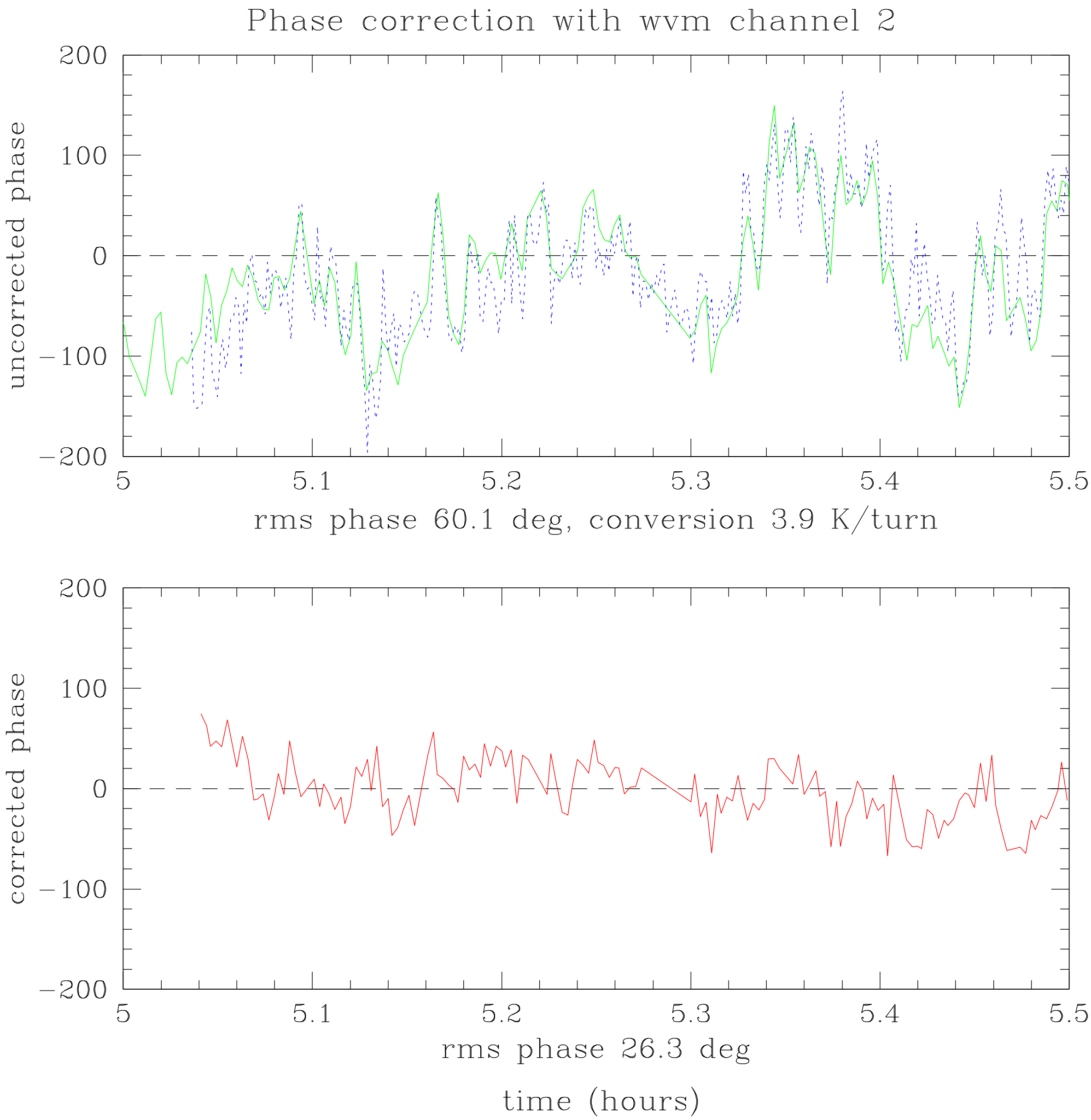

Figure 4: The radiometric phase correction for the Channel 2 is shown in detail. The lines shown are the same as in Figure 2. The radiometric phase correction closely track the astronomical data, and the significant improvement is obvious in the lower panel.

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