The Astrophysical Journal Supplement Series, 153:363–367, 2004 July

SIDE-BY-SIDE COMPARISON OF FOURIER TRANSFORM SPECTROSCOPY AND WATER VAPOR RADIOMETRY AS TOOLS FOR THE CALIBRATION OF MILLIMETER/SUBMILLIMETER GROUND-BASED OBSERVATORIES

J. R. Pardo[1]
Departamento de Astrofísica Molecular e Infrarroja, Instituto de Estructura de la Materia, CSIC, Serrano 121, E-28006 Madrid, Spain; pardo@damir.iem.csic.es

M. C. Wiedner[2]
Harward-Smithsonian Center for Astrophysics, 60 Garden Street, MS 78 Cambridge, MA 02138

E. Serabyn
Division of Physics, Mathematics and Astronomy, California Institute of Technology, MS 320-47, Pasadena, CA 91125

C. D. Wilson
Department of Physics and Astronomy, McMaster University, Hamilton, ON L8S 4M1, Canada

C. Cunningham
Herzberg Institute of Astrophysics, National Research Council of Canada, 5071 West Saanich Road, Victoria, BC V9E 2E7, Canada

R. E. Hills
Mullard Radio Astronomy Observatory, Cavendish Laboratory, Madingley Road, Cambridge CB3 0HE, UK

and

J. Cernicharo[1]
Departamento de Astrofísica Molecular e Infrarroja, Instituto de Estructura de la Materia, CSIC, Serrano 121, E-28006 Madrid, Spain
Received 2003 November 27; accepted 2004 February 23

ABSTRACT

Measurement techniques to monitor the atmospheric transmission at millimeter and submillimeter wavelengths are necessary for the operation of instruments such as the Atacama Large Millimeter Array (ALMA). Our previous Fourier transform spectroscopy (FTS) work at the Caltech Submillimeter Observatory (CSO) has shown that the atmospheric transmission spectrum can be accurately measured by this technique up to ~1100 GHz with a time resolution of a few minutes. An alternative technique is water vapor radiometry, generally using a few channels around the 183 GHz H_2O line that can provide much finer time resolution but relies upon models to translate the derived water vapor columns into spectrum predictions over the required frequency ranges. Time resolutions of the order of 1 s are necessary to carry out phase correction in ground-based mm/submm interferometry that can easily be reached by water vapor radiometers but not by FTS. Water vapor radiometry has the added advantages of being easier to operate and having lower costs than an FTS.

In this context, we initiated a comparison campaign between the CSO FTS on Mauna Kea and a three-channel 183 GHz water vapor monitor (WVM) mounted on one of the antennas of the Sub-Millimeter Array (SMA), some 250 m away. The data presented here were taken on 2002 March 3 under very dry conditions (total precipitable water vapor zenith column, PWV, below 0.35 mm). The atmospheric transmission at microwaves (ATM) model described in a previous paper has been used to analyze the data. The primary conclusion is that for weather conditions allowing ground-based submillimeter interferometry to be carried out, the PWV can be measured with an agreement of about 0.01 mm between both instruments in timescales of several minutes, and therefore a combination of WVM plus an accurate mm/submm atmospheric model (based on extensive FTS work) provides a suitable tool for ALMA calibration in those conditions.

Subject headings: atmospheric effects — instrumentation: miscellaneous — radiative transfer — submillimeter

1. INTRODUCTION

The most ambitious ground-based instrument for future mm/submm astronomy will be the Atacama Large Millimeter Array (ALMA) in the Atacama desert (Chile). It should eventually be able to perform astronomical observations in all millimeter and submillimeter regions of the electromagnetic spectrum that are partially transparent at 5000 m above sea level. Ground-based radioastronomy has been extending its observing capabilities to increasingly higher frequencies, with the first astronomical lines above 1 THz detected from the ground by Pardo et al. (2001a, hereafter PAR01) and Kawamura et al. (2001). The need of suitable atmospheric monitoring techniques and detailed modeling for calibration tasks at these frequencies is nowadays obvious. For millimeter and submillimeter interferometry it is not only necessary to have an estimate of the transmission of the atmosphere as accurate as possible, but also to measure, and correct for, the phase delay, as it degrades the spatial resolution of ground-based instruments.

Ground-based atmospheric transmission Fourier transform spectroscopy (FTS) measurements have been performed in the past at frequencies up to 1600 GHz (Matsuo et al. 1998) or even up to 3000 GHz (Paine et al. 2000). Based on measurements

[1] Visiting scientist at Division of Physics, Mathematics and Astronomy, California Institute of Technology, MS 320-47, Pasadena, CA 91125.
[2] Present address: Physikalisches Institut, Universität zu Köln, Zülpicherstrasse 77, 50937 Köln, Germany.

up to 1080 GHz calibrated to the 1% level, PAR01 have derived or confirmed models for the different opacity terms up to 1 THz. The resulting model (Pardo et al. 2001a, hereafter the ATM model) is proposed as a retrieval and prediction tool for ALMA calibration, to be used in combination with FTS or other types of in situ measurements. Although FTS transmission measurements covering the full frequency range of ALMA should be planned, water vapor radiometry is probably the cheaper and more efficient technique to monitor atmospheric phase fluctuations caused by spatial and temporal variations of the water vapor distribution. The aim of the present study is therefore to check consistency between the costly but very accurate FTS technique and the 183 GHz radiometry one. The availability of 183 GHz radiometers installed at the Sub-Millimeter Array (SMA; Moran 1998) and an FTS installed at the Caltech Submillimeter Observatory, which are both located on Mauna Kea, 250 m or so apart, has made possible the side-by-side comparison that we present in this paper.

We devote § 2 to a description of the instruments used. Section 3 describes data acquisition, reduction, and comparisons of the results from the two instruments, along with the conclusions. Finally, a summary of this work can be found in § 4.

2. INSTRUMENTAL SETUP

Our measurements were carried out on Mauna Kea, Hawai'i, at an altitude of 4100 m above sea level. We measured the atmospheric emission on 2002 March 3 with two different instruments.

2.1. *Water Vapor Monitor (WVM)*

The WVM was mounted on one of the SMA antennas about 250 m to the west of the Caltech Submillimeter Observatory (CSO). The radiometer, as well as two other such instruments, were originally designed to continuously monitor the atmospheric emission with integration times of about 1 s in order to perform real-time phase correction of millimeter and submillimeter wave interferometers (Wiedner et al. 2001). The WVM measures the atmospheric emission in three double-sideband channels in the wings of the 183.3 GHz water vapor line. The innermost channel is centered at 1.2 GHz on both sides of the water line and covers the frequency range of 181.9–182.3 and 184.3–184.7 GHz; the second channel is centered 4.2 GHz away from the water line covering 178.6–179.6 and 187.0–188.0 GHz; and the third channel is centered 7.8 GHz away from the line center covering 175.0–176.0 and 190.6–191.6 GHz. The radiometer employs an uncooled subharmonic Schottky mixer and therefore has receiver temperatures of ~2000 K. It contains two calibration loads at about 30°C and 100°C, which are observed once every second to calibrate the gain of the instrument.

2.2. *Fourier Transform Spectrometer (FTS)*

The Fourier transform spectrometer used in this work is installed at the CSO 2–3 times a year for dedicated atmospheric and planetary measurements. The basic instrumental setup was described in Serabyn & Weisstein (1996), the atmospheric calibration technique can be found in Serabyn et al. (1998), and some updates of this technique were described in PAR01. The main difference introduced in the instrument for the present work has been a new 1600 GHz low-pass filter that was acquired after success with the 1100 GHz low-pass filter used in the study published in PAR01. The filter allows measurements of the whole 300–1600 GHz frequency range (the lower limit is imposed by the 20″ light concentrator at the bolometer entrance). The beam-splitter in this configuration is a 2 mil thick mylar sheet. Unfortunately, in this case the beam-splitter passband cannot match the broad filter passband, yielding lower instrumental transmission at the highest frequencies, resulting in higher noise, ~3 times more in the region 1400–1600 GHz than in the rest of the band.

Prior to the observations presented here, a few checks were carried out with known FTS configurations, and then we proceeded with measurements using the 1600 GHz low-pass filter. Owing to the presence of very strong, saturated lines in the large frequency band (300–1600 GHz), the noise was larger than in previous FTS observations. We thus decided to use a 1 GHz spectral resolution, lower than in previous scans, which provides a good compromise between scan time, noise, and spectral resolution needed to correctly measure the broad features of the atmospheric spectrum due to water vapor and oxygen. Narrow features (mainly O_3) are then diluted, but the continuum between the lines is largely unaffected. The calibration of the data was performed after each sky measurement using two different loads (ambient temperature and liquid N_2 temperature) and using the second-order corrections to the measured flux ratios described in Serabyn et al. (1998).

3. WVM AND FTS OBSERVATIONS, DATA REDUCTION, COMPARISON AND DISCUSSION

The observations presented in this paper were performed on 2002 March 3 7:00–9:30 and 14:30–17:00 UT (with special focus on 8:00–8:10 UT). Over the course of the night, the weather conditions were excellent, but not very stable, with the derived amounts of PWV varying between ~0.25–0.45 mm (see Fig. 1).

3.1. *WVM Observations and Data Reduction*

During the observations, the SMA antennas were pointing to the north at an elevation of 45°. Data from the WVM were recorded every second, integrating 0.4 s on the sky and 0.2 s on each of the two calibration loads. The measurements on the loads were used to determine the gain and receiver temperature of the radiometer in order to convert the measured voltages into brightness temperatures. The load temperatures were in turn calibrated with a measurement of liquid nitrogen and an ambient load prior to the observations. The output was averaged over 10 s intervals.

The coupling of the radiometer to the sky was determined by adding an offset (spill-over) term to the simulated atmospheric emission and adjusting this offset such that the simulated profile best fits the WVM data in all three frequency channels (see Fig. 2). The actual fit is performed based on the ATM model. In order to perform the WVM data fit, we first initialize an atmospheric profile and the corresponding absorption coefficients in ATM using the following input information:

1. *Average ground pressure in the time interval considered* ($P_{\rm ground}$).—Known to an accuracy better than 1 mb. The profile is reinitialized if the pressure has changed by more than 0.3% (≈2 mb).
2. *Average ground temperature in the same interval* ($T_{\rm ground}$).—Known to an accuracy better than 1 K. The profile

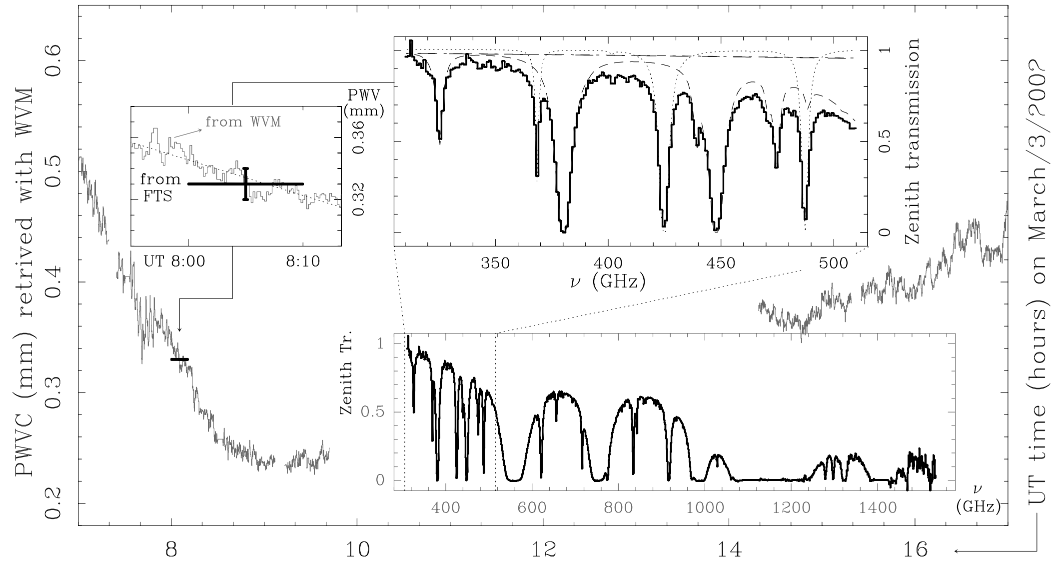

Fig. 1.—Precipitable water vapor zenith column (PWV) obtained from fitting the WVM data obtained on 2002 March 3. At 8:00–8:10 UT we recorded an FTS spectrum (*lower right inset*). The 310–510 GHz data (*upper right inset*) was used to determine the PWV independent of the continuum-like absorption. The dotted line in the upper inset marks oxygen lines, the dashed line marks water lines. The third contribution plotted is associated with continuum-like absorption according to PAR01. The detailed comparison of PWV retrieved from both instruments is shown in the left inset.

is reinitialized if the temperature has changed by more than 0.5% (about ≈1.5 K).

3. *Average ground relative humidity, as measured with a calibrated thermo/hygrometer.*—This parameter is used by the fitting routine just to initialize a water vapor profile but, in fact, the water vapor column is the output from the fit.

4. *Spill-over temperature (for the WVM).*—Known to an accuracy better than 1 K. In our case a polarization splitter and half-wave plate for rotation of the polarization are responsible for most of the loss in the coupling, as well as the finite size and imperfections in the mirrors close to the radiometer. All these devices are inside the SMA antenna, and it is reasonable to chose a spill-over temperature equal to the cabin temperature, which is continuously monitored.

5. *Water vapor scale height* (h_{H_2O}).—With measurements of the water vapor line at only three frequencies we cannot retrieve the vertical distribution of water vapor, therefore the water vapor is assumed to exponentially decrease with a scale height typical for the latitude of the site (around 2 km). This value is most probably true to within 0.5 km based on radiosonde data from the nearby Hilo International Airport.

6. *Tropospheric temperature lapse rate* $\Delta T_{\rm trop}$.—A value of -5.6 K km^{-1} is typical for a tropical atmosphere. It agrees well with radiosonde data from the nearby Hilo International Airport. The uncertainty can be at most 2.0 K km^{-1}.

7. *Altitude of the site above sea level* (4.1 km).

8. *Primary pressure step* (mb).—In the model the atmosphere is approximated by layers each having a constant set of parameters. For the pressure we use a logarithmic average across the layer. The pressure of the lowest boundary varies from the one above by the primary pressure step. The pressure of the $(n+1)$th boundary is smaller than the one of the nth by the primary pressure step times the nth power of the pressure step factor (see below).

9. *Pressure step factor (no units).*—The thickness in pressure from one layer to another is multiplied by this factor as we move upward (also see no. [8]).

The above input parameters are fixed based either on measurements by other devices and/or on numerical considerations. The free parameters for the fit are in principle the coupling to the sky and the PWV. The iterating retrieval procedure then gives the sky coupling and PWV that minimize the residual between measurements and model (see Fig. 2). In fact, we noticed that the sky coupling was basically constant during the few hours of measurements presented here. Therefore, the fitting procedure had only one free parameter: the PWV.

A typical fit of the data for the three WVM channels with the ATM model is shown in Figure 2. For this particular measurement the fixed input information is (1) 623.0 mb; (2) 268.15 K; (3) 11.30%; (4) 285.15 K; (5) 2.2 km; (6) -5.6 K km^{-1}; (7) 4.1 km; (8) 10 mb; (9) 1.5. The sky coupling of the WVM was found to be 0.63, and this value remained stable during this experiment. This strategy has been designed and is currently used to reduce WVM data for phase corrections at the SMA (M. C. Wiedner et al. 2004, in preparation). The error in measuring the brightness temperature of the atmosphere with the WVM is estimated to be ∼1 K in the 10 s integration time (including errors due to calibration inaccuracy, gain variations, and thermal noise).

We have calculated the sensitivity of the zenith sky brightness temperature $T_{\rm EBB,sky}$ in the innermost channel of the WVM (183.3 ± 1.2 GHz) with respect to parameters 1, 2, 5, and 6 when they have the values given above and the PWV is 0.3 mm. Of all frequencies used for our retrievals, this WVM channel is the one that should see the greatest changes in sky brightness with respect to changes in the cited parameters. The results are as follows: $\partial T_{\rm EBB,sky}/\partial P_{\rm ground} = 0.02$ K mb^{-1}, $\partial T_{\rm EBB,sky}/\partial T_{\rm ground} = 0.1$ K K^{-1}, $\partial T_{\rm EBB,sky}/\partial h_{H_2O} = 0.06$ K km^{-1}, $\partial T_{\rm EBB,sky}/\partial \Delta T_{\rm trop} = 0.32$ K K^{-1} km. The value of $T_{\rm EBB,sky}$ in those conditions should be about 80 K. Therefore, we can conclude that parameters 1, 2, 5, and 6 have a very small effect on the retrievals compared with the measurement errors, coupling terms, and continuum-like terms in

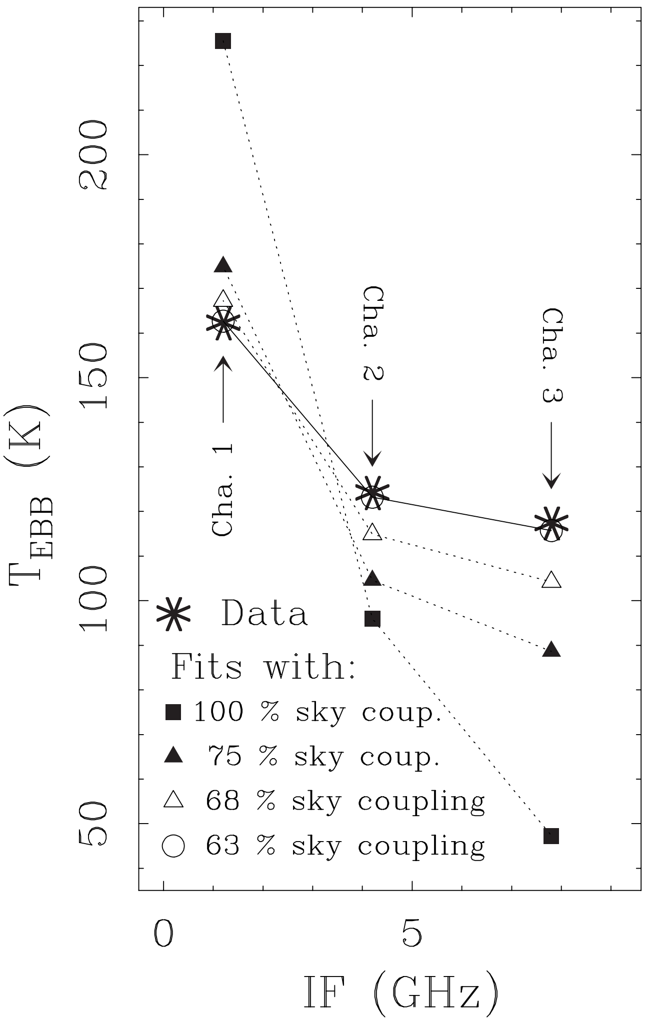

FIG. 2.—Fit of a set of WVM measurements from which the sky coupling of the instrument can be directly deduced. The signal is given in equivalent blackbody temperature ($T_{\rm EBB}$).

the absorption model, which we will discuss below. Moreover, any given error in those parameters should affect in the same way both the FTS and WVM retrievals.

3.2. *FTS Data Reduction*

Our main long-term goal is the separation of the continuum-like absorption from the line absorption in order to elucidate its true physical nature. The CSO-FTS provided in this run its first atmospheric transmission measurements in the two windows centered at approximately 1350 and 1500 GHz with peaks at 18% transmission. The extension of our previous results (see PAR01) to frequencies above 1 THz based on the FTS spectrum presented here and others acquired later under different weather conditions will be discussed in a separate paper.

After acquiring the FTS spectra to the zenith and calibrating them as described in Serabyn et al. (1998; we assume $\eta_{\rm sky} = 1$ based on our earlier measurements), the same set of a priori parameters described in the previous section is also used for the FTS data. However, we have to keep in mind that the determination of the PWV has to be as independent as possible of the continuum-like terms. In order to do so we have to keep a frequency range of the FTS data in which the continuum-like terms are either small compared with the line opacity and/or well known. To meet the above criteria we have selected the 310–510 GHz frequency range. The lower frequency limit is imposed by the Winston cone (light concentrator) used at the bolometer's entrance. The upper limit has been set to avoid the center of the very strong 557 GHz water line. As we have previously shown in PAR01 the continuum-like opacity in this region is small compared with the line opacity, and furthermore it is accurately determined in that work. The PWV during the new measurements presented here lies between those of the spectra presented in PAR01, so we are confident of the accuracy of the continuum terms used here. There are also several water lines of moderate opacity under the conditions of the observation (centered around 380, 390, 437, 439, 443, 448, 471, 475, and 488 GHz).

3.3. *Discussion*

The retrieved PWV from the WVM data as a function of time is shown on Figure 1. The atmosphere over the site was experiencing a smooth humidity change, but overall the night was excellent for submillimeter astronomy. The comparison with the FTS was performed at 8:00–8:30 UT (8:00–8:10 on the sky) using for the measurement the 1600 GHz low-pass filter but keeping only the 310–510 GHz frequency range for the analysis as explained above. In some cases, especially for low frequencies, no continuum terms are taken into account for PWV retrievals. Here the fit to the FTS data in the proposed range would then yield a PWV of 0.36 mm. However, as stated in PAR01, these continuum terms are important for an accurate determination of the PWV especially at frequencies above 200 GHz. Therefore, a more accurate value of 0.33 mm is obtained if the continuum-like terms found in PAR01 are taken into account, resulting also on smaller fit residuals. Neglecting the continuum-like terms therefore results in an error of 9% in the PWV estimate for this particular case. Therefore, assuming a generous uncertainty of 30% in the continuum-like terms of PAR01 results in a derived PWV from the FTS of 0.33 ± 0.01 mm. The WVM-based retrievals also use the proper continuum-like terms. The simultaneous FTS and WVM measurements show very good agreement to within experimental errors and temporal variation levels (the PWV retrieved from the WVM measurements between 8:00 and 8:10 UT fits to a straight line from 0.345 to 0.320 mm with an rms of 0.005 mm, see Fig. 1).

It might seem surprising that two instruments that are sampling different paths through the atmosphere, because they are 250 m apart, agree in the retrieved PWV to within 10 μm. It seems that over a 10 minute period both instruments had seen the same basic atmospheric PWV gradient (linear decreasing) passing over them (see Fig. 1, *inset*). On top of this, there are shorter timescale fluctuations (possibly also acting on spatial scales well below 250 m) that only the WVM can see. The rms of these fluctuations is 5 μm (estimated from the fit of the WVM retrievals to a straight line, see Fig. 1, *inset*), well below our claimed agreement of 10 μm over a 10 minute average.

The comparison of both instruments was not continued after the 8:00–8:10 UT FTS measurement because under these excellent atmospheric conditions we proceeded to carry out astronomical observations with other detectors. However, the comparison is consistent enough to reach the conclusion that the used 183 GHz water vapor monitor, in conjunction with an accurate atmospheric model, can yield water vapor columns probably to a precision of 0.01 mm under observing conditions where PWV is ∼0.5 mm or less, in timescales of the order of 1 s. For predictions of the absolute transmission at submillimeter wavelengths, a 3% error in PWV (0.01 mm/0.33 mm) would translate into 5% in uncertainties in the submillimeter transmission according to the ATM model.

The estimates on the performance of the WVM for phase correction are different because systematic errors are not an issue as they do not change at the timescales of water fluctuations. We will consider in this analysis a timescale of 1 s for phase correction. The noise reached for all three channels of the radiometer in 1 s is about 0.4 K. The sensitivities of the three channels to changes in PWV when the reference PWV value is 0.5 mm are 173, 60, and 23 K mm^{-1}, which would translate, using the above figure for the noise in 1 s, into 2.3 μm uncertainty in PWV. According to the ATM model the path length changes because of atmospheric water vapor at 490, 650, and 850 GHz are, respectively, 8.47, 6.65, and 7.51 μm per μm of PWV, and therefore, using the above estimation for the PWV uncertainty, we are quite close to the 15 μm of path length accuracy specified for ALMA. This limit should easily be reached with an improved new generation of radiometers.

4. CONCLUSIONS

We have shown in this work that to correctly determine the PWV using broadband FTS data it is necessary to eliminate the impact of the continuum-like terms. This can be accomplished by selecting either a partially transparent frequency range where the water vapor line opacity is dominant, or a frequency range where the continuum-like opacity is correctly known. With our present knowledge, both of these conditions are best met below 500 GHz for dry, high-altitude conditions. On the other hand, when determining the PWV using WVM data it is critical to correctly determine the sky coupling of the WVM first. This does not require a sky dip, since it is a multifrequency instrument and the coupling can be retrieved by fitting models to the measured signal in the different channels. Both FTS and WVM measurements of PWV have been obtained as described with instruments running side by side at Mauna Kea with a consistency in the results of about 0.01 mm in conditions suitable for ground-based submillimeter astronomy. This is a very good result, especially taking into account that we expect the final ALMA WVM to have even higher sensitivity than the instruments used in these tests. Since the FTS-based retrievals are expected to be very accurate owing to the large frequency range involved and our past experience, our results are very encouraging to favor water vapor radiometry as a suitable technique for phase correction within the ALMA requirements, based on ATM estimates and the sensitivity improvements of the new WVM prototypes currently under development for ALMA. WVMs combined with ATM should also provide atmospheric transmission curves accurate to at least 3%–5% levels in the submillimeter (with the WVM used here) or better.

The authors are grateful to the CSO and SMA Hawai'i staff for providing assistance during the observations. This work has been supported by NSF grant ATM-9616766, and by Spanish DGES and PNIE grants ESP2002-01627, AYA2002-10113-E, and AYA2003-02785-E. Construction of one WVM on the SMA was made possible by funding from the Natural Sciences and Research Council of Canada. CSO operations were supported by NSF grant AST-9980846.

REFERENCES

Kawamura, J., et al. 2001, AAS Meeting, 198, 59.18
Matsuo, H., Sakamoto, A., & Matsushita, S. 1998, PASJ, 50, 359
Moran, J. 1998, Proc. SPIE, 3357, 208
Paine, S., Blundell, R., Papa, D. C., Barrett, J. W., & Radford, S. J. E. 2000, PASP, 112, 108
Pardo, J. R., Cernicharo, J., & Serabyn, E. 2001a, IEEE Trans. Ant. Prop., 49, 1683
Pardo, J. R., Serabyn, E., & Cernicharo, J. 2001b, J. Quant. Spectrosc. Radiat. Transfer, 68, 419 (PAR01)
Serabyn, E., & Weisstein, E. W. 1996, Appl. Opt., 35, 2752
Serabyn, E., Weisstein, E. W., Lis, D. C., & Pardo, J. R. 1998, Appl. Opt., 37, 2185
Wiedner, M. C., Hills, R. E., Carlstrom, J. E., & Lay, O. P. 2001, ApJ, 553, 1036