SMA Memo 164

Systematic shift in 225 GHz optical depth measurements on Maunakea

Simon J. E. Radford
Submillimeter Array, Hilo

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Abstract

Since 1989, a 225 GHz tipper has monitored the atmospheric transparency on Maunakea. In the aftermath of a blizzard on 2015 January 2, a block of ice fell on the tipper's scanning mirror and damaged its alignment. Although the instrument was repaired, realigned, and returned to service on January 4, comparison with measurements by other, unchanged instruments indicates this incident affected subsequent data. The measured 225 GHz optical depths are systematically smaller than before. An empirical correction will place newer ($\geq$ 2015) and older ($\leq$ 2014) data together on a common scale.

1 Introduction

On Maunakea, three independent instruments monitor the submillimeter atmospheric transparency: a 225 GHz narrowband tipping radiometer since 1989 August at the CSO and relocated to the SMA in 2015 October; a 350 μm broadband tipper since 1997 December at the CSO; and a 183 GHz heterodyne spectrometer since 2007 May at the JCMT.

Strictly speaking, the atmospheric transparency depends on the line of sight profiles of water vapor, temperature, and pressure (altitude). Water vapor, however, is the strongest influence and is more variable than the temperature. Hence the transparency is often taken as a proxy for the precipitable water vapor (PWV) column density, and vice versa, especially for monitoring variations in observing conditions at a particular observatory.

In the aftermath of a blizzard on 2015 January 2, a block of ice fell on the 225 GHz tipper's scanning mirror and damaged its alignment. The instrument was repaired, realigned, reinstalled, and returned to service on January 4. Because of natural variations in the atmospheric transparency, the effect of this incident on subsequent data cannot be easily assessed from the 225 GHz measurements alone. Comparison with data from other instruments undamaged by the blizzard, however, indicates subsequent 225 GHz measurements were affected. The measured 225 GHz optical depths are systematically smaller than before.

2 Instruments and measurements

The 225 GHz tipper is one of a series constructed at NRAO for comparative measurements of potential sites for the MMA (Liu 1987; McKinnon 1987; Hogg et al. 1988). It uses a DSB heterodyne receiver with a 500 MHz bandwidth and makes a measurement every 10 min throughout the day. In 1989 August, it was installed on the roof of the CSO outbuilding, tipping to the northwest. Around 1997, it was rebuilt. After the closure of the CSO, this tipper was relocated on 2015 October 21 to the SMA hangar roof, where the tipping direction is approximately the same, northwest, but the horizon is lower. In the aftermath of a blizzard on 2015 January 2, a block of ice fell on the tipper's scanning mirror and damaged its alignment. The instrument was repaired, realigned, reinstalled, and returned to service on January 4. Data are available on the CSO and SMA web pages.

The 350 μm tipper is also one of a series constructed at NRAO for comparing sites for submillimeter astronomy (Radford & Peterson 2016). It uses a pyroelectric detector with a broadband filter matched to the atmospheric window and makes a measurement about every 13 min throughout the day. In 1997 December, it was installed on the CSO outbuilding near the 225 GHz tipper, also tipping to the northwest. In due course, it will also be relocated to the SMA hangar roof. Data are available from the author.

Both tippers use the standard technique of tipping radiometry (Dicke et al. 1946). They measure the sky brightness $T_{\rm sky}(z)$ at different zenith angles, z, then determine the zenith optical depth, τ, by fitting the data to $T_{\rm sky}(A) = T_{\rm atm}(1 - e^{-\tau A})$, where the airmass $A = \sec z$ and $T_{\rm atm}$ is the effective atmospheric brightness.

At 225 GHz, the optical depth is small, $\tau \ll 1$, so the response is almost linear, $T_{\rm sky}(A) \approx (T_{\rm atm}\tau)\, A$. To determine the optical depth, τ, requires, therefore, independent knowledge of the atmospheric brightness, $T_{\rm atm}$.

At 350 μm, on the other hand, the optical depth is much larger so there is significant curvature in the brightness curve. Hence both the optical depth and the atmospheric brightness, τ and $T_{\rm atm}$, may be determined independently. This non linearity limits, however, the dynamic range so the results are heteroscedastic: the uncertainty in the optical depth depends on the magnitude of the optical depth. The fitting procedure is robust over the range $0.5 < \tau < 4$. Under poor conditions, when $\tau > 4$, the brightness difference between the zenith and the horizon vanishes. The 350 μm data presented here are corrected for the effect of the instrument's window (Calisse 2004; Radford & Peterson 2016).

The 183 GHz spectrometer mounted on the JCMT employs a different technique than the tippers (Wiedner et al. 2001). It measures the sky brightness in several channels to gauge the strength of the water vapor emission line and, hence, the precipitable water vapor (PWV) column density along the line of sight. Measurements are made once per second but only while the telescope is observing, mostly at night. The results are presented, for historical reasons, as the equivalent 225 GHz zenith optical depth (Dempsey et al. 2013). Around 2015 March 25, the *silver* instrument in use up until then was replaced by a *black* instrument

(Berke private communication). Data from these instruments are available since 2007 May on the EAO web page.

3 Comparisons

3.1 Tipper measurements

For comparison, simultaneous 225 GHz and 350 μm tipper measurements were paired within a synchronization window of 15 min. Although there is considerable scatter, attributable to both instruments, the paired data for 1997–2014 are strongly correlated (Fig. 1, left). To suppress the undue influence of outliers, which are more numerous than expected for a normal distribution, data on the outskirts of the measurement distribution were rejected and the data range considered for linear regression was restricted to the best half of conditions, $\tau(350\,\mu\mathrm{m}) \leq 2.55$ and $\tau(225\,\mathrm{GHz}) \leq 0.105$. This permits a robust characterization of the range of most interest, good observing conditions. Comparing the quantiles of the paired measurements provides a clear view of the underlying correlation (QQ plot; Fig. 1, right). The quantiles trace the ridge of maximum density in the data distribution and closely follow the linear regression line.

In 2015, the correlation between paired measurements remains strong but the data no longer follow the best fit linear regression determined for the earlier data (Fig. 2). Either the measured 225 GHz optical depths are systematically smaller or the measured 350 μm optical depths are larger than earlier data. Because the 350 μm tipper remained unchanged while the 225 GHz tipper was damaged, and repaired, at the start of 2015, the shift in the data is attributable to the 225 GHz tipper.

For 1997–2014, individual yearly quantiles of the paired measurements are consistent with each other and closely follow the best fit linear regression for the ensemble (Fig. 3, left),

$$\tau(350\,\mu\mathrm{m}) = 26\,\tau(225\,\mathrm{GHz}) - 0.2 \qquad [\leq 2014], \tag{1}$$

demonstrating the relative calibration of the two tippers did not change significantly during this period. For 2015–2016, on the other hand, the quantiles and best fit linear regression are clearly distinct from the earlier data (Fig. 3, right),

$$\tau(350\,\mu\mathrm{m}) = 28\,\tau(225\,\mathrm{GHz}) - 0.03 \qquad [\geq 2015]. \tag{2}$$

The difference between the best fit linear regressions for the two periods indicates a shift in the measured 225 GHz optical depth,

$$\tau(\geq 2015) - \tau(\leq 2014) = \Delta\,\tau(225\,\mathrm{GHz}) \approx -0.07\tau - 0.006, \tag{3}$$

where more recent measurements are systematically smaller than earlier data (Table 1). This empirical difference may be used to place newer and older data together on a common scale.

3.2 JCMT measurements

Because the JCMT measurements are more frequent, the data were paired within a synchronization window of 1 min. The paired data from all instruments are strongly correlated. For simplicity, only the yearly quantile comparisons are shown.

The yearly quantiles of the 225 GHz tipper measurements and the JCMT data separate into three groups (Fig. 4, left). For 2012–2014, the 225 GHz tipper measurements and the JCMT data agree well, with the quantiles closely following the diagonal, $\tau(\mathrm{JCMT}) = \tau(225\,\mathrm{GHz})$. For 2007–2011 and also for 2015–2016, the quantiles indicate $\tau(\mathrm{JCMT}) > \tau(225\,\mathrm{GHz})$. Either the tipper measurements were systematically smaller or the JCMT data were systematically larger during these two periods. Absent other information, these possibilities cannot be distinguished.

The quantiles of the 350 μm tipper measurements and the JCMT data exhibit two groupings (Fig. 4, right). For 2013–2016, the yearly quantiles cluster together close to the best fit linear regression determined for the tipper data (Fig. 1). For 2007–2010, the quantiles are systematically offset so the JCMT data appear relatively larger. For 2011–2012, the quantiles fall between the other two groups, suggesting a transition period.

Considering these comparisons together indicates: During 2013–2014, the data from the three instruments agreed. For 2007–2010, the JCMT data is shifted compared with both the 225 GHz and the 350 μm tipper measurements, indicating the JCMT spectrometer measurements were systematically larger then. For 2015–2016, on the other hand, the shift between 225 GHz tipper and JCMT data was not matched by any corresponding shift in the 350 μm measurements. Hence the 225 GHz tipper measurements were systematically smaller during this period.

4 Discussion

Comparison between 225 GHz and 350 μm tipper measurements indicates significant shift in 225 GHz measurements after 2015 January 2. The measured 225 GHz optical depths are smaller than before the incident, $\Delta\,\tau(225\,\mathrm{GHz}) \approx -0.07\tau - 0.006$. Comparison with the JCMT measurements confirms this 2015 shift in the 225 GHz tipper data but also indicates the calibration of the JCMT measurements relative to the tipper data was different before 2011–2012. (Possible causes of this apparent shift in the JCMT measurements are beyond the scope of this memo.)

What caused the shift in the 225 GHz measurements? After the physical damage caused by the icefall was repaired, the instrument was reinstalled in the same location. On previous occasions, the instrument had been removed for service and replaced without affecting the measurements. There was no apparent shift in the data after the instrument was relocated from the CSO outbuilding to the SMA hangar roof (Fig. 3, right). This suggests installation is not to blame for the measurement shift. Residual misalignment of the scanning mirror is certainly possible and will be investigated. For now, however, the reason for the measurement shift is unknown.

What mitigation is possible? To avoid confusion, the 225 GHz tipper data will be reported without adjustment. In the long term, the instrument may be repaired when (if) the underlying cause of the measurement shift is identified. In the meantime, to put newer (≥ 2015) measurements on the same scale as older (≤ 2014) data, *subtract* the the empirical difference (Table 1) from the new measurements, $\tau(\geq\ 2015) - \Delta\,\tau(225\,\mathrm{GHz})$. This procedure should be sufficient for planning observations and for monitoring observing conditions.

	1997–2014	≥ 2015
	$\tau(225\,\mathrm{GHz})$	$\Delta\tau$
75%	0.175	−0.018
50%	0.105	−0.013
25%	0.065	−0.011
10%	0.045	−0.009

Table 1: Historical quantiles of 225 GHz optical depths on Maunakea and empirical magnitude of the 2015 measurement shift, $\Delta\,\tau(225\,\mathrm{GHz}) = \tau(\geq\ 2015) - \tau(\leq\ 2014)$.

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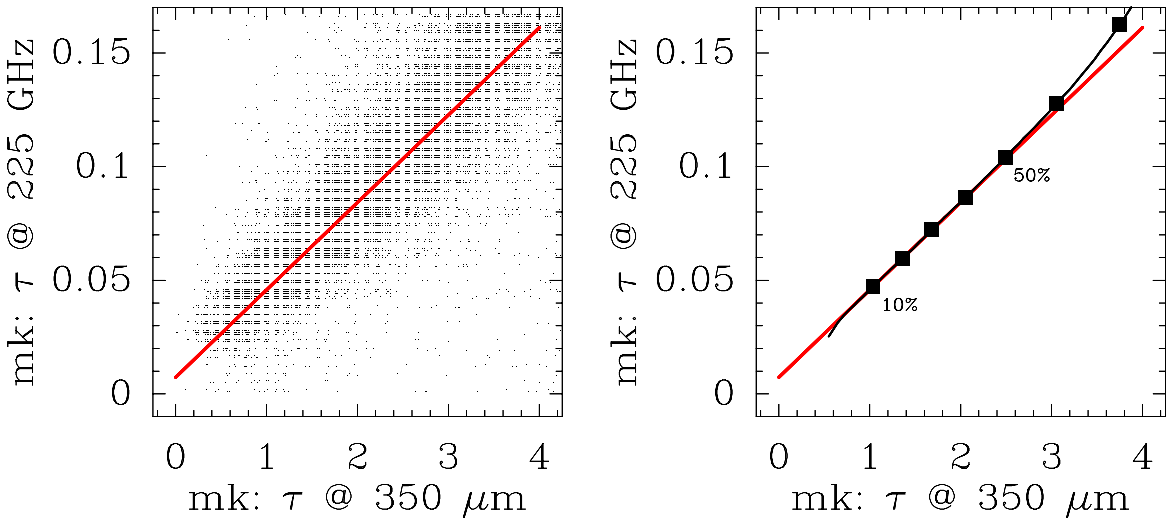

Figure 1: *Left:* Correlation between simultaneous, paired measurements of the broad band 350 μm and the narrow band 225 GHz zenith optical depths on Maunakea during 1997–2014. *Right:* Quantiles of the paired measurements (*QQ* plot). Deciles are marked. The guide lines (*red*) illustrate $\tau(350\,\mu\mathrm{m}) = 26\,\tau(225\,\mathrm{GHz}) - 0.2$, the best fit linear regression.

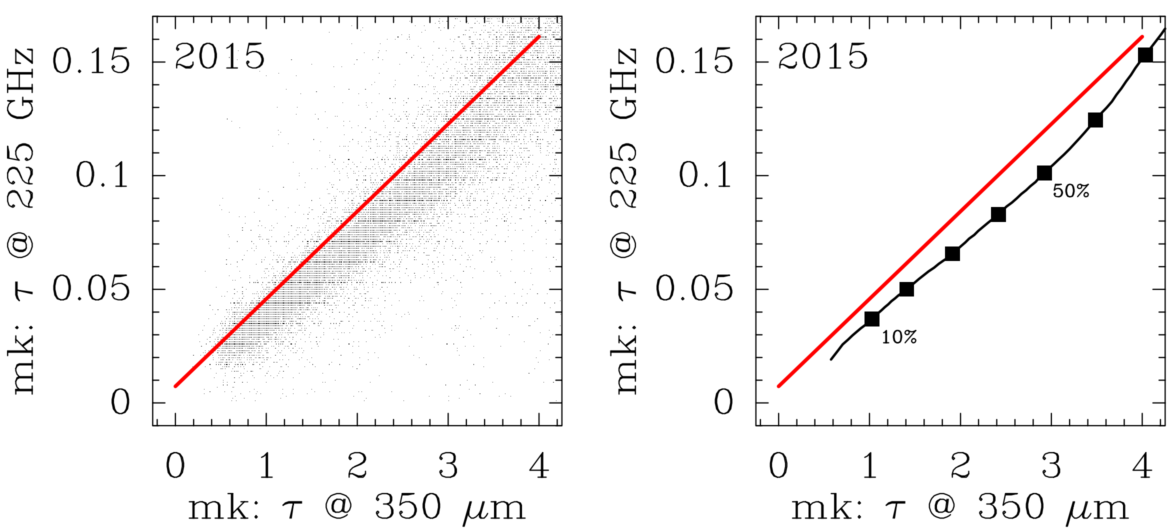

Figure 2: *Left:* Correlation between simultaneous, paired measurements of the broad band 350 μm and the narrow band 225 GHz zenith optical depths on Maunakea during 2015. *Right:* Quantiles of the paired measurements (*QQ* plot). Deciles are marked. The guide lines (*red*) illustrate $\tau(350\,\mu\mathrm{m}) = 26\,\tau(225\,\mathrm{GHz}) - 0.2$, the best fit linear regression for 1997–2014.

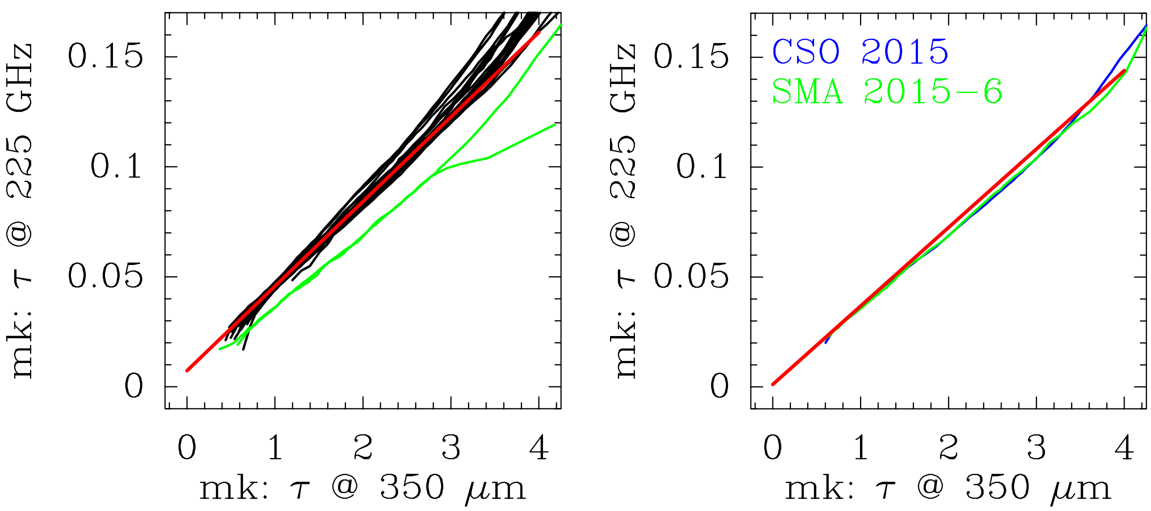

Figure 3: *Left:* Quantiles of simultaneous, paired measurements of the broad band 350 μm and the narrow band 225 GHz zenith optical depths on Maunakea during 1997–2014 (*black lines*) and 2015–2016 (*green lines*) (*QQ* plot). The guide line (*red*) illustrates $\tau(350\,\mu\mathrm{m}) = 26\,\tau(225\,\mathrm{GHz}) - 0.2$, the best fit linear regression for 1997–2014. *Right:* Quantiles of the measurements during at the CSO during 2015 January–October (*blue*) and at the SMA during 2105 October–2016 March (*green*). The guide line (*red*) illustrates $\tau(350\,\mu\mathrm{m}) = 28\,\tau(225\,\mathrm{GHz}) - 0.03$, the best fit linear regression for 2015–2016.

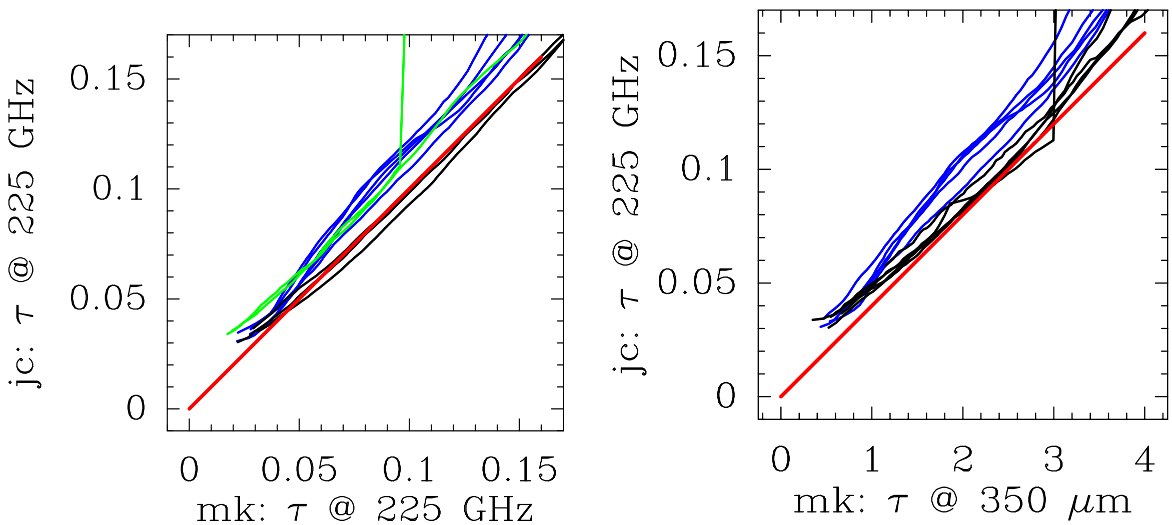

Figure 4: *Left:* Quantiles of simultaneous, paired measurements of the narrow band 225 GHz and the JCMT equivalent 225 GHz zenith optical depths on Maunakea during 2007–2011 (*blue lines*), 2012–2014 (*black lines*), and 2015–2016 (*green lines*) The guide line (*red*) illustrates $\tau(\mathrm{JCMT}) = \tau(225\,\mathrm{GHz})$. *Right:* Quantiles of simultaneous, paired measurements of the broad band $350\,\mu$m and the JCMT equivalent 225 GHz zenith optical depths on Maunakea during 2007–2011 (*blue lines*) and 2012–2016 (*black lines*) (*QQ* plot). The guide line (*red*) illustrates $\tau(350\,\mu\mathrm{m}) = 26\,\tau(225\,\mathrm{GHz}) - 0.2$, the best fit linear regression for the tipper measurements during 1997–2014.