The Doppler Tracking Accuracy of the NRAO 12 Meter Telescope

Jeff Mangum (jmangum@nrao.edu)

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1 Introduction

The Millimeter Autocorrelator (MAC) at the 12 Meter Telescope has a minimum spectral resolution of 6.1 kHz. This very high resolution mode requires a very accurate calculation of the sky frequency so that the assignment of local standard of rest (LSR) velocities in the data is correct. To check the accuracy of the 12 Meter Telescope's doppler tracking system, we made a series of measurements of the mesospheric CO $2 \rightarrow 1$ emission in December of 1998.

2 Doppler Tracking Measurements

Atmospheric features can be used as external frequency standards since they are nearly at rest with respect to an observatory. In these tests, the telescope was pointed to the zenith and held there while the control system was commanded to doppler track a fixed astronomical position on the sky. We tuned the facility 1mm receiver to the CO $2 \rightarrow 1$ transition and made a series of frequency switched measurements using a frequency switch throw of ± 5 MHz. In this observing setup, the mesospheric CO emission should be centered at the negative velocity offset (doppler plus LSR) of the source. With these measurements, we can determine the overall precision of the doppler tracking system to an accuracy with which the center velocity of the mesospheric CO emission can be determined. The accuracy of the determination of the center velocity of the mesospheric CO emission is about 2 m/s, which is comparable to the vertical motions of the atmosphere.

3 Sources of Uncertainty

3.1 The Local Oscillator System

The oscillators that compose the LO chain have an uncertainty given by the following:

$$\delta\nu_{sky} = \Delta\nu_{fluke} \times N_{flukeharm} \times N_{LOharm} \times N_{mult} \tag{1}$$

where

$$\begin{aligned}
\delta\nu_{sky} &\equiv \text{Sky frequency uncertainty} && (2)\\
\Delta\nu_{fluke} &\equiv \text{Frequency resolution of the Fluke synthesizer} && (3)\\
&= 1.0 Hz && (4)\\
N_{flukeharm} &\equiv \text{Fluke synthesizer harmonic} && (5)
\end{aligned}$$

$$
\begin{aligned}
&= 20 && (6)\\
N_{LOharm} &\equiv \text{LO harmonic} && (7)\\
&= 30 \text{ to } 50 && (8)\\
N_{mult} &\equiv \text{LO multiplier} && (9)\\
&= 3 \text{ for the 1mm receiver} && (10)\\
&= 2 \text{ for the 2mm receiver} && (11)\\
&= 1 \text{ for the 3mm receiver} && (12)
\end{aligned}
$$

N_{LOharm} is determined by the following:

$$
N_{LOharm} = \frac{\frac{\nu_{sky} \pm \nu_{IF}}{N_{mult} - \nu_{lock}}}{1900 \text{ to } 2000 \text{ MHz}} \tag{13}
$$

where

$$
\begin{aligned}
\nu_{sky} &\equiv \text{Sky frequency in MHz} && (14)\\
\nu_{IF} &\equiv \text{IF frequency in MHz} && (15)\\
&= 1500 MHz && (16)\\
\nu_{lock} &\equiv \text{Phase lock LO} && (17)\\
&= 100 MHz (\text{negative since the lock IF is USB} && (18)
\end{aligned}
$$

and the division by 1900 to 2000 MHz is to keep the LO in the 2 GHz band.

For our mesospheric CO $2 \rightarrow 1$ measurements, $N_{LOharm} = 39$, so that $\delta\nu_{sky} = 2.34$ kHz.

3.2 Doppler Correction Calculation

The doppler correction calculation currently in use at the telescope follows the algorithm originally developed by Ball (1969, MIT Lincoln Lab. Tech. Note TN 1969-42). A more accurate calculation of the Earth's barycentric velocity term in the doppler correction has been developed by Stumpf (1979, A&A, 78, 229), which significantly improves the accuracy of the doppler correction. Uncertainties for both the traditional doppler correction and the correction which includes the Stumpf barycentric velocity calculation are given in Table 1.

Table 1: Doppler Tracking Uncertainties

Source	Value (m/s)
LO	2.34
Calculation (Ball)	5.00–20.00
Calculation (Stumpf)	4.20
Measured (Average)	3.09

4 The Measurements

Figures 1, 2, 3, 4, and 5 show the results of our measurements. Initially when these data were analyzed we noticed a systematic shift of about 10 m/s between our measured CO central velocities and the calculated doppler velocity for each measurement. Further investigation revealed that the standard rest frequency for the CO 2 $\rightarrow$ 1 transition, 230537.990 MHz, dates from the 1970's and is inaccurate by about 10 kHz when compared to recent laboratory measurements (230538.0000(1) MHz; Belov *et. al.* 1992, ApJ, 393, 848). Once we corrected our data using this more accurate rest frequency, the difference between the observed and calculated doppler velocity was very small. Figures 4 and 5 show the difference between the measured and calculated doppler velocity for each measurement, where we have averaged the two individual channel measurements before differencing.

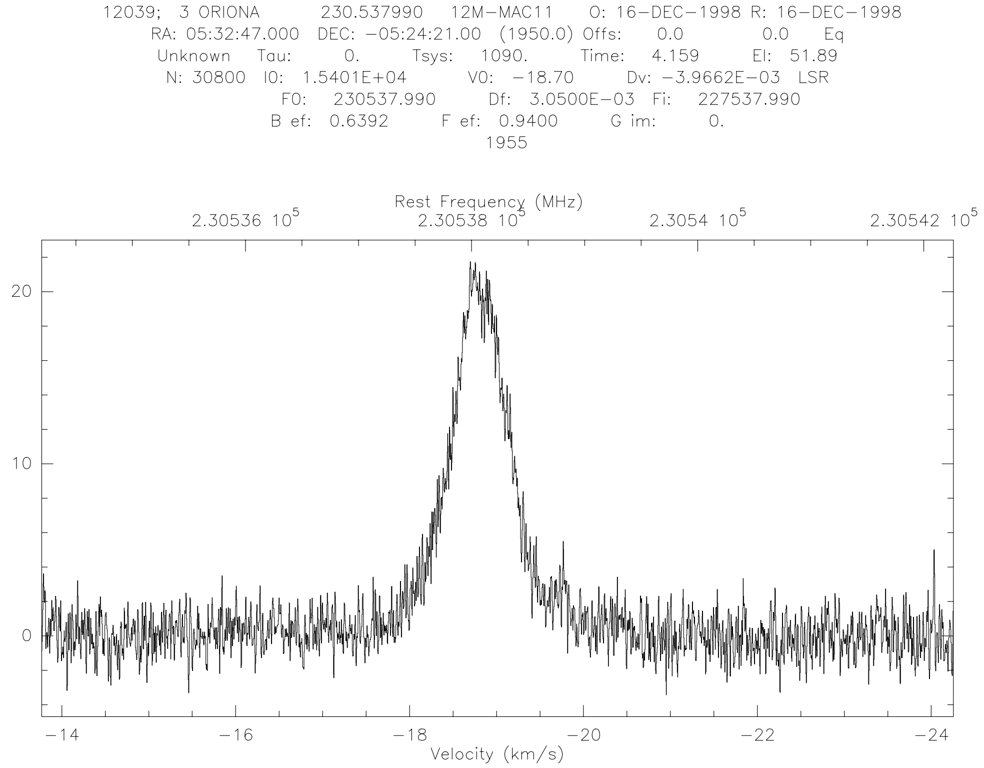

Figure 1: Sample CO 2 $\rightarrow$ 1 spectrum from our December 16, 1998 observations.

5 Results

- The difference between the traditional (Ball) doppler correction and that which includes the Stumpf calculation for the barycentric velocity of the Earth is about 7 m/s for these measurements. Since the smallest channel spacing possible with the MAC is about 6 m/s at 300 GHz, this difference is significant. The Stumpf barycentric velocity calculation will be incorporated into the telescope system in the coming months to remedy this problem.

- The RMS of the residuals shown in Figures 4 and 5 are about half of the smallest channel spacing possible with the MAC. This 3 m/s jitter is probably caused by vertical motions of the troposphere.

- With an improvement to the doppler correction calculation algorithm at the 12 Meter Telescope the doppler tracking accuracy will be sufficient to properly determine the velocity scale for all possible spectroscopic measurements.

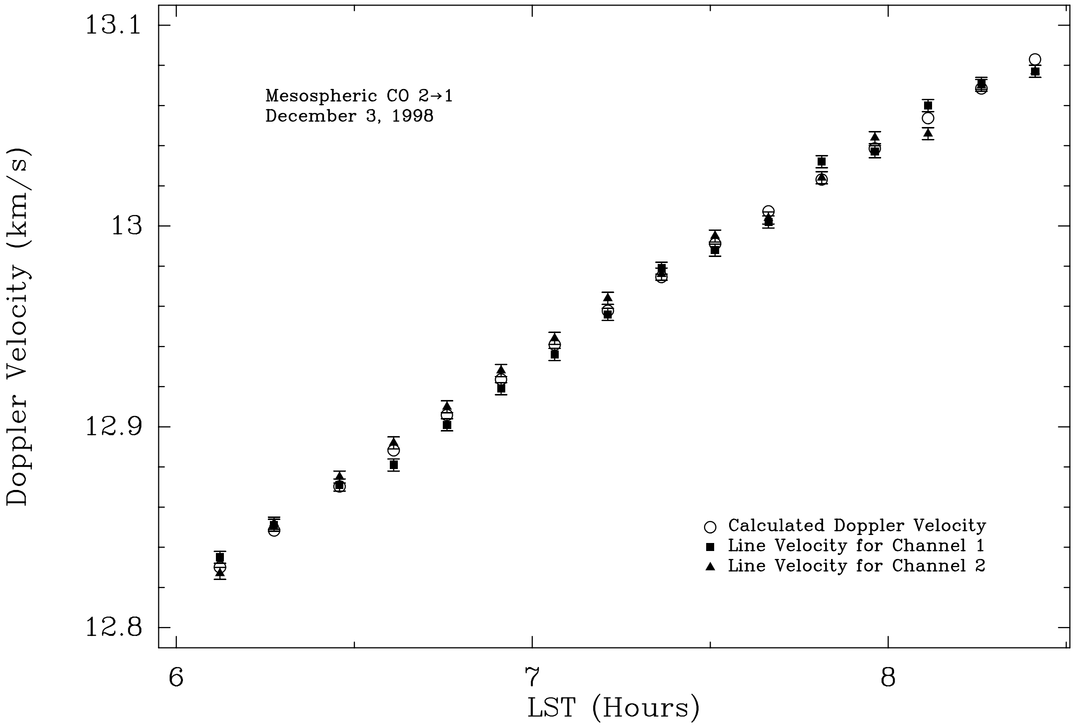

Figure 2: Results from our measurements of December 3, 1998.

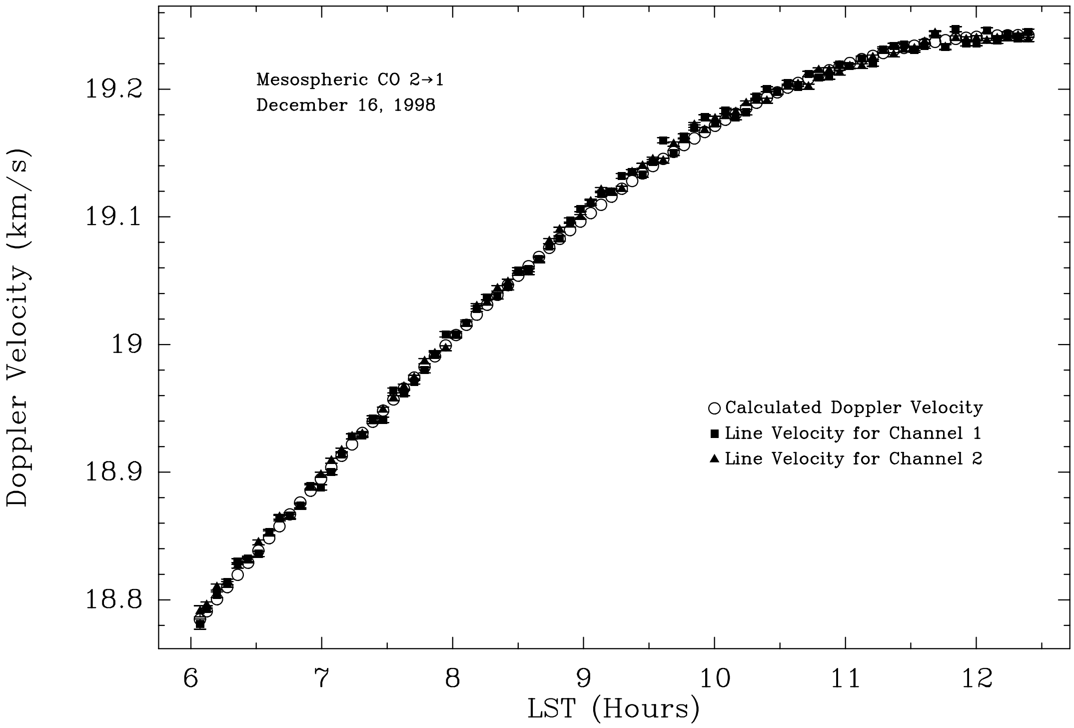

Figure 3: Results from our measurements of December 16, 1998.

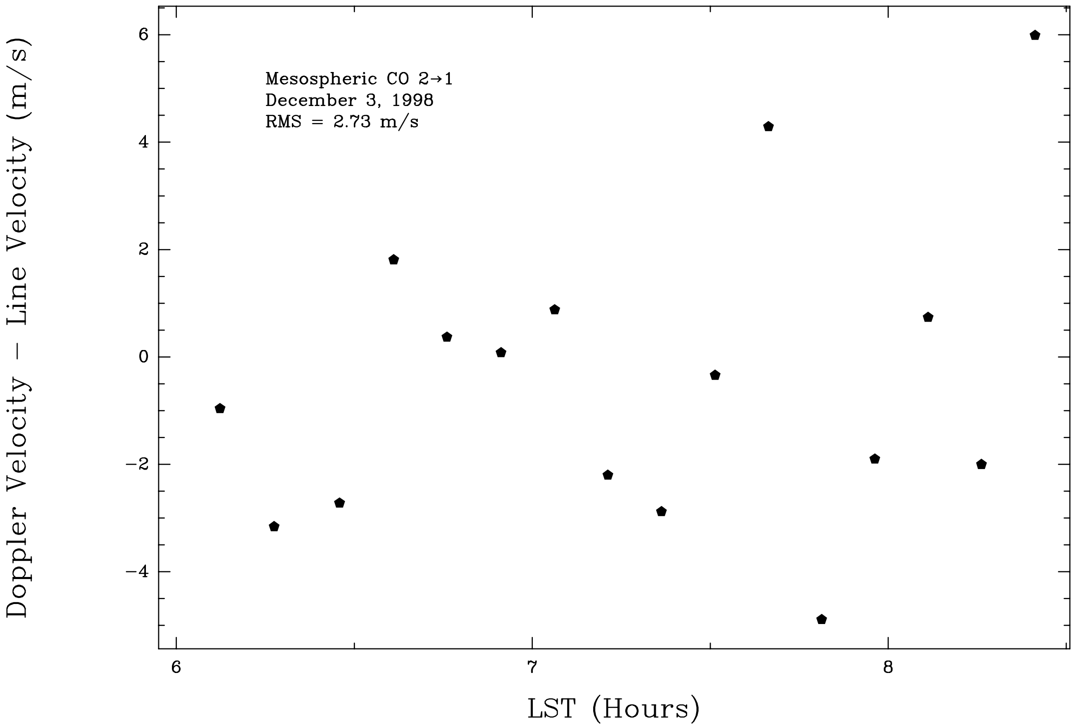

Figure 4: Residuals from our measurements of December 3, 1998.

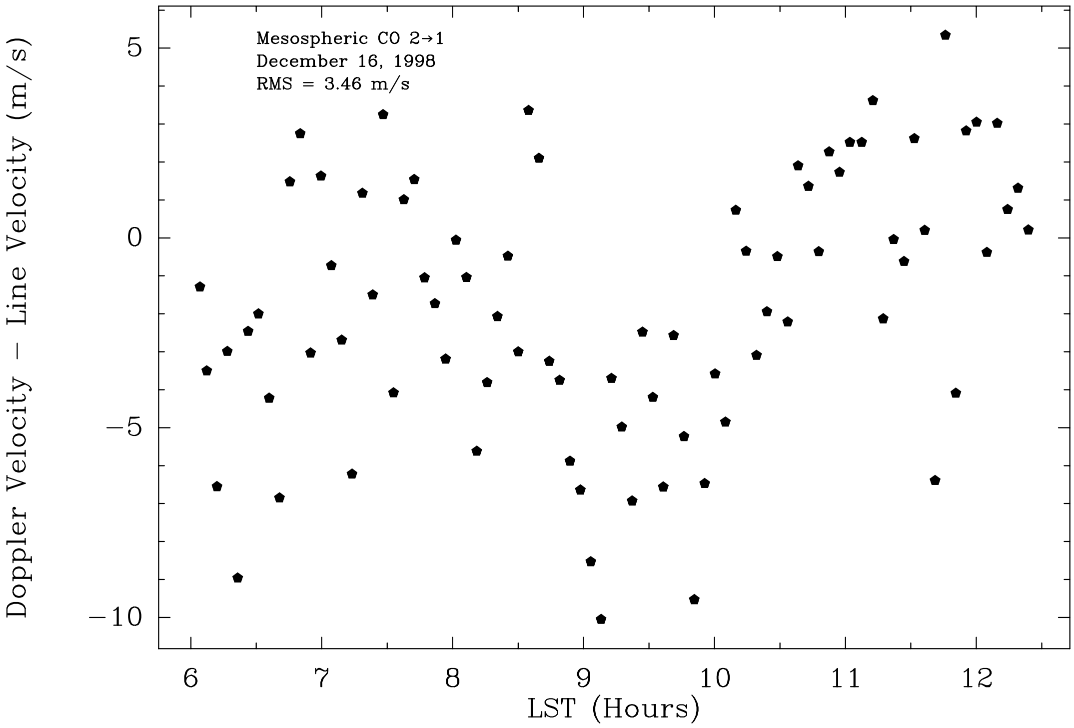

Figure 5: Residuals from our measurements of December 16, 1998.