Phase closure at 691 GHz using the Submillimeter Array

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ABSTRACT

Phase closure at 682 GHz and 691 GHz was first achieved using three antennas of the Submillimeter Array (SMA) interferometer located on Mauna Kea, Hawaii. Initially, phase closure was demonstrated at 682.5 GHz on Sept. 19, 2002 using an artificial ground-based “beacon” signal. Subsequently, astronomical detections of both Saturn and Uranus were made at the frequency of the $^{12}$CO(6-5) transition (691.473 GHz) on all three baselines on Sept. 22, 2002. While the larger planets such as Saturn are heavily resolved even on these short baselines (25.2m, 25.2m and 16.4m), phase closure was achieved on Uranus and Callisto. This was the first successful experiment to obtain phase closure in this frequency band. The $^{12}$CO(6-5) line was also detected towards Orion BN/KL and other Galactic sources, as was the vibrationally-excited 658 GHz H$_2$O maser line toward evolved stars. We present these historic detections, as well as the first arcsecond-scale images obtained in this frequency band.

1. Introduction

The Submillimeter Array (SMA) is a joint venture of the Smithsonian Astrophysical Observatory (SAO) and the Academia Sinica Institute of Astronomy and Astrophysics (ASIAA). The interferometer has been under construction since the early 1990s. First fringes at 230 GHz were initially obtained with a single baseline at Haystack Observatory in October 1998. This milestone was repeated on Mauna Kea in late September 1999. All eight 6-meter antennas will be commissioned by the fall of 2003. The surface of the primary reflector is composed of aluminum panels with a carbon fiber backup structure. There are 24 antenna pads arranged into four tangential rings approximating Reuleaux triangles with a maximum baseline of 508 m. The cryostat can accommodate up to eight SIS receiver inserts, which provides the capability to eventually cover the entire range from 175 to 950 GHz that is

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accessible from the ground. Further description of the SMA antennas, receivers, and IF/LO systems can now be found in Kubo et al. (2006), Rao & Marrone (2005), Blundell (2004), Hunter et al. (2002), Saito (2001), Patel (2000), and Moran (1998).

2. First Fringes at 650 GHz (July 2002)

Getting the array operating successfully in the 650 GHz band was a high initial priority for the SMA in order to enable observations at frequencies substantially higher than any of the existing millimeter interferometers. A theoretical plot of the opacity in this band in good conditions is shown in Figure 1. For some actual measurements with a Fourier Transform Spectrometer, see Paine et al. (2000).

![Figure 1](image_url)

**Fig. 1.**— The predicted opacity in the 600-700 GHz band as a function of frequency, at an airmass of 1.5, with a precipitable water vapor level of 0.8mm. The line frequencies for the spectra presented in this poster are marked.
On July 20, 2002, we saw first fringes on Venus with a single 16 m NE/SW baseline at 672/682 GHz. Although the data were acquired during the late afternoon and early evening (usually the worst part of the diurnal weather pattern on Mauna Kea) the RMS phase noise was only 16° after removing a fit to the residual error in the baseline length (Figs. 2 and 3).

Fig. 2.— These are the very first SMA fringes in the 650 GHz band. The baseline error has been fitted and removed, yielding a residual 16° RMS phase variation in 30 second integrations. This stability bodes well for future high-frequency work on Mauna Kea.

Several other strong dust continuum sources were detected during the night of July 20th, including IRAS 1629A, G10.62−0.38, and G34.26+0.14 (Fig 4).

3. 650 GHz Phase Closure (September 2002)

By late summer, we had three antennas (numbers 4, 5, and 6) working in the 650 GHz band, in a configuration with baseline lengths up to 25.2 m. A 682.5 GHz beacon for
In this plot, the raw correlator counts have been adjusted using a visibility model for Venus and an airmass correction. This amplitude calibration produces a fairly flat result, and has been applied to the four star-formation regions (shown in Fig. 4).

Holography had been installed on the exterior of the nearby Subaru telescope (Sridharan et al. 2004), and the first phase closure tests were performed on September 20th using this signal (Fig. 5).

The first convincing three baseline detections on a celestial source were obtained two days later, with the array re-tuned to place the $^{12}$CO(6-5) line in the USB. The zenith opacity in this frequency band was approximately 1.2 which causes a large elevation dependence in the system temperature (Fig. 6). The phase closure on Uranus was noisy, but the value averaged to the expected result of zero. Saturn was easily detected on all baselines, but since it was highly resolved, the closure phase was not constant. Strong $^{12}$CO(6-5) emission was detected strongly in the Orion BN/KL hot core (Fig. 7). A convincing closure phase was also seen in the continuum on Callisto (Fig. 8).
Fig. 4.— Single-baseline amplitude and phase for 4 star formation regions. Small dots show individual integrations; large dots are 5 minute averages. The red line is the single-dish JCMT flux density (Sandel 1994), and the green line is the SMA flux density.

4. First 650 GHz Image (December 2002)

One of the biggest problems for interferometric imaging in the 650 GHz band is the lack of strong point sources usable for the derivation of the complex gain as a function of time. Nearly all of the quasars used at millimeter wavelengths will be too weak for use as calibrators. Compact thermal sources such as small planets, planetary moons and asteroids will have to be used instead. As a star towards doing this, we took advantage of the close proximity of Jupiter to the evolved star IRC+10\(^{\circ}\)216 last year. While Jupiter itself was far too large, the Galilean moons were only slightly resolved. On December 8th, we were able to detect (Fig 9) make a calibrated image of CS(14-13) at 685 GHz in IRC+10\(^{\circ}\)216 using Mars for passband calibration and Callisto as a complex gain calibrator (Fig. 10). CS(14-13) has a high critical density (3.2 \times 10^8 \text{ cm}^{-1}) and was expected to be unresolved on our current
Fig. 5.— Shown are the phase of each of the three baselines, along with the closure phase, for the 682.5 GHz test beacon observations. These data were taken in rather poor weather (zenith opacity $\sim 3$) shortly after sunset. On this night, the response of the system stabilized as the atmosphere cooled.

On December 12th, we tuned down to 658 GHz, and made the first interferometric observations of the strong vibrationally-excited water line there (Menten & Young 1995). The line was detected in VY CMa, U Ori and W Hya (Fig. 11).

$^1$These data were later published by Young et al. (2004).
Fig. 6.— Due to the high opacity, the system temperature is a strong function of elevation and must be measured frequently, particularly for spectral line calibration.

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Fig. 7.— The $^{12}$CO(6-5) line in Orion spans 3/4 of the 328 MHz bandpass that was currently available at the time of the observation. The bandwidth will be increased sixfold during 2003.

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Fig. 8.— The phase closure result on Callisto is shown above. The plotted points are vector averages of 10 one minute scans which were interspersed with observations of IRC+10°216.

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Fig. 9.— The CS(14-13) spectrum of IRC+10°216 is shown after bandpass and complex gain calibration. The different colors show different, partially overlapping sections of the correlator.
Fig. 10.— A) The CS(14-13) data without any calibration. B) Image of CS(14-13) having used Callisto as the complex gain calibrator. C) Spectrum extracted from the central position of the calibrated image. D) Continuum image made using self-calibration table derived from the line channels. The continuum peak intensity is 5.5 Jy/beam (see [Young et al., 2004]).
Fig. 11.— The plot above shows the very strong water maser line at 658 GHz. This line has only been detected in evolved stars (Menten & Young 1995). This line is so strong that evolved stars may serve as gain calibrators or even pointing sources of future observations (Hunter et al. 2005).