Early high-resolution millimeter-wave maps from TolTEC

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Abstract.
TolTEC is a polarization-sensitive camera at millimeter wavelengths with unprecedented sensitivity and 5-10 arcsecond resolution in three photometric bands. TolTEC achieved first light on the 50-meter Large Millimeter Telescope in July 2022, just prior to a planned summer telescope maintenance shutdown, and began commissioning observations when the telescope resumed observations in December 2022. The commissioning program consisted of observations of targeted nebulae, molecular clouds, polarized quasars, galaxies, and clusters of galaxies. The goals of these observations include demonstrating the science capabilities of the camera and characterizing the performance and instrumental properties, including noise, beams, and polarization sensitivity in its three bands centered at 1.1, 1.4, and 2.0 mm with angular resolutions of 5, 6, and 10 arcseconds, respectively.

We present early results from the commissioning observations of the Crab Nebula. Upcoming observations will include selected proposals from the broader astronomy community in Mexico and the United States, as well as legacy surveys focused on mapping galactic molecular clouds, cold dust emission in local galaxies, polarized dust emission in filaments around star-forming regions, massive galaxy clusters, and distant obscured star-forming galaxies.

1 Introduction

High-resolution photometric observations at millimeter wavelengths provide a window to observe astrophysical processes, ranging from the interactions of electrons with magnetic fields in nebulae to the pressure profile of the hot ionized gas that makes up the intercluster medium. Current state-of-the-art instruments like MUSTANG2 on the GBT \cite{1}, SCUBA-2 on the JCMT \cite{2}, and NIKA2 on the IRAM 30-meter telescope \cite{3} probe from roughly 90 GHz up to the near terahertz with angular resolutions ranging from several to tens of arcseconds. While these current instruments represent a monumental achievement in imaging at millimeter wavelengths with incredible science results, pushing higher angular resolution measurements and observing in multiple millimeter bands simultaneously with greater sensitivities can open doors toward large surveys of astronomical objects. There is much to discover in the millimeter sky, covering topics ranging from galactic astronomy to cosmology, and building an instrument that can resolve smaller features from 2.0 to 1.1 mm wavelengths can be key to uncovering more about the universe.

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TolTEC is a polarimeter on the 50-meter Large Millimeter Telescope (LMT) [4] in Mexico. It images simultaneously in three bands at 2.0, 1.4, and 1.1 mm with respective angular resolutions of 10, 6, and 5 arcseconds. The instrument achieved first light in Summer 2022, with commissioning observations beginning in December 2022. This proceedings reports on the status of commissioning of the instrument and presents preliminary results from those observations. The instrument is briefly described in Section 2, and its commissioning status is described in Section 3. Preliminary images of the Crab Nebula taken with TolTEC in both intensity and polarization are presented in Section 4, with conclusions discussing the next steps of commissioning and science observations to follow.

2 The TolTEC instrument

TolTEC is a three-band polarimeter observing at 2.0, 1.4, and 1.1 mm. Light from the sky is focused by the primary and secondary mirrors of the LMT and is directed to the TolTEC warm optical system by a tertiary mirror inside the LMT receiver cabin. A series of mirrors that make up the TolTEC warm optical system redirects the light to the camera’s window, where it passes through a series of IR blocking filters [5]. Inside the cryostat, the incoming light is split and focused onto the detector arrays using a system of dichroic filters and silicon lenses. Before reaching the detector arrays, the light passes through a low-pass filter to limit the pass-bands. The three detector arrays are feedhorn-coupled Microwave Kinetic Inductance Detectors (MKIDs) [6, 7]. In Figure 1, you can see the open TolTEC cryostat and its cold optical system, with the path of the light incident on the three detector arrays indicated by colored arrows. For a detailed description of the instrument, refer to [8], and for information about the fielded instrument, consult [9]. The TolTEC camera was shipped to and installed at the LMT in late 2021, and it achieved first light in June 2022.

3 Instrument commissioning

The TolTEC team began commissioning of the instrument in December of 2022. Effectively, about 2 nights were spent observing unresolved and extended sources, as well as some initial scans on blank fields.

The primary goals of the first few nights were to confirm the alignment of the warm mirrors and to observe bright radio sources for mapping MKID resonators across the detector array. Alignment observations consisted of Lissajous scans that were approximately 30 seconds in duration. Fast data processing provided by the CItlali reduction pipeline [10] enabled a quick turnaround on images of the point sources, allowing for the diagnosis of beam quality and necessary mirror adjustments. Observations of bright sources were made using raster scans. The data from these observations are used by CItlali to populate an array properties table containing resonator information, such as location on the detector array, the calibration from raw timestream units to flux density, and the beam’s full width at half maximum (FWHM) of a detector. Details on the detector properties resulting from those observations will be presented in a future work.

While several science targets were observed as part of instrument commissioning, the majority of our analysis has focused on the brightest source, the Crab Nebula. Observations of the Crab Nebula demonstrate the resolution, frequency coverage, and polarization capabilities of TolTEC. These results are presented in Section 4. After the observing season, improvements were made to the readout chain in Summer 2023, and we expect to confirm that these changes will bring TolTEC’s sensitivity in line with expectations when the LMT resumes observations in the Fall 2023. Subsequently, we will finish instrument commissioning and carry out our full science program.
4 Preliminary images of the Crab Nebula

The Crab Nebula (also known as M1, Taurus A, or NGC 1952) is a supernova remnant that has been well studied across the electromagnetic spectrum [11–13]. It is of particular interest to the millimeter-wave community as the polarized synchrotron emission from electrons in the pulsar’s magnetic field are particularly bright at those wavelengths. This makes the Crab Nebula a valuable astrophysical polarization calibrator, with applications in CMB experiments seeking to detect a faint polarization signal in the relic radiation, which could indicate the presence of gravitational waves — a "smoking gun" signature of cosmic inflation [14].

There have been numerous observations of the Crab Nebula in Stokes I, Q, and U at wavelengths spanning most of the millimeter-wave window. These observations range from relatively large angular resolutions of several arcminutes, as seen with Planck, to finer resolutions between 10 and 20 arcseconds, such as those from NIKA/NIKA2 [15, 16]. Keeping these observations in mind, TolTEC included the Crab Nebula in its commissioning campaign in December 2022, with the goal of demonstrating the polarimeter’s ability to observe linearly polarized emission at its 5-10 arcsecond angular resolution.

During commissioning, TolTEC observed the Crab Nebula for a total of 22 minutes, spread across six different observations. A raster scan strategy measuring 12’ by 10.5’ was employed, with a scan rate of 2 arcminutes per second. The scan strategy was rotated relative to the celestial equator a couple of times. As a result, two observations were made with a raster scan along lines of declination, two were performed with the raster pattern angled at 45° to the previous frame, and two were conducted with the raster orthogonal to the original frame. Although TolTEC has the capability to observe with a warm half-wave plate to mod-
Figure 2. Preliminary maps of the Crab Nebula made with TolTEC. From the top row to bottom correspond to maps of 2.0, 1.4, and 1.1 mm respectively. Left to right corresponds to flux from Stokes I, Q, and U respectively. Further calibration work is still to be performed hence the lack of a colorbar. The linear polarization intensities presented here may still be subject to a rotation calibration. All of the plots are smoothed with a common 5 arcsecond FWHM Gaussian kernel to smooth out pixel-scale noise.

To simulate the incident radiation on the camera, this half-wave plate was not utilized during the commissioning observations of the Crab Nebula.

We present the resulting coadded maximum-likelihood maps of the Crab Nebula in Stokes I, Q, and U in Figure 2. These maps were created using raw, unfiltered timestreams generated by the Citlali software and processed by the maximum-likelihood mapmaker, Minkasi, developed by the MUSTANG2 collaboration \(^1\). Maximum-likelihood mapmaking provides an unbiased representation of the sky, allowing the recovery of signals on angular scales that would otherwise be filtered out by "filter-and-bin" style mapmakers.

The overall flux calibration of the TolTEC instrument in intensity and polarization remains uncertain, which is why we have not included color bars in the figure. However, the color scale is consistent across the three different wavelengths in intensity, and the color scale

\(^1\)https://github.com/sievers/minkasi
remains the same for all of the Stokes $Q$ and $U$ maps. The intensity, which decreases inversely with wavelength, is indicative of synchrotron emission, as expected for this source.

The intensity maps from the three arrays can be combined to create an RGB color image, as shown in Figure 3, with red, green, and blue colors corresponding to 2.0, 1.4, and 1.1 mm wavelengths, respectively. The predominantly reddish-orange color of this image indicates a higher intensity at longer wavelengths, which is consistent with synchrotron emission characteristics.

Additional work reporting the calibrated flux of the Crab Nebula, as well as its polarized intensity and angle, will be presented in a future publication following the completion of the TolTEC instrument’s commissioning. The images presented here showcase TolTEC’s resolution, polarization sensitivity, and its three-color imaging capabilities.

5 Conclusion

The commissioning of the TolTEC instrument is ongoing, with a focus on optimizing and calibrating the instrument. The early images resulting from the first commissioning observations demonstrate TolTEC’s remarkable ability to measure intensity and linear polarization over scales ranging from five to ten arcseconds to several arcminutes. Additionally, the commissioning observations have highlighted TolTEC’s polarization sensitivity, a crucial feature for various science observations, such as the study of magnetic fields in nebulae.
TolTEC will resume its commissioning campaign in late 2023 when the LMT is back in operation. Improvements to the readout chain were implemented in the summer of 2023, which will enhance the instrument’s sensitivity. Moreover, the LMT project has been utilizing TolTEC beammaps and point source observations to understand and constrain wavefront errors in the primary mirror. This information can be used in the future to create a more accurate model of the mirror surface and improve TolTEC’s mapping speed. The plan is to complete TolTEC’s commissioning by early 2024, with science observations commencing thereafter.

After commissioning, TolTEC will embark on its first four public legacy surveys: the Clouds-to-Cores Legacy Survey, the Fields in Filaments Legacy Survey, the Large-Scale Structure Survey, and the Ultra-Deep Survey of Star-Forming Galaxies. These legacy surveys have various scientific goals, including probing the magnetic fields around galactic filaments, mapping the cosmological distribution of matter, and imaging galaxy clusters via the Sunyaev-Zeldovich effect. In conjunction with these legacy observations, TolTEC will also be involved in observing community PI-led projects.

Acknowledgements

TolTEC is supported in-part by the National Science Foundation, grants #1636621 and #2034318. JG is supported by a NASA Space Technology Research Fellowship (80NSSC21K0411).

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