First Science Observations with MUSTANG

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Abstract

The Multiplexed SQUID TES Array for Ninety Gigahertz (MUSTANG) is a 64-pixel bolometer array, constructed for the 100-meter Green Bank Telescope by a collaboration comprising the University of Pennsylvania, NRAO, NASA-GSFC, NIST, and the University of Wales. MUSTANG achived first light on the GBT in engineering observations in Fall of 2006 and has subsequently been substantially upgraded. We present an overview of the instrument and commissioning observations, and present results from early science observations collected in February and March of 2008.

1. The Instrument

The Multiplexed SQUID TES Array for Ninety Gigahertz (MUSTANG) is a bolometer array which has been constructed for use on the 100-meter Green Bank Telescope (GBT – see [1]). A unique feature of the GBT is its active surface, comprising 2004 individual, remotely actuated reflector panels. A semi-empirical model of the surface keeps the shape of the mirror constant to within 390 microns (RMS), with an eventual target of 240 microns. With a blind pointing accuracy of 3 arcseconds (2-dimensional RMS) and excellent focus tracking provided by a real-time suite of temperature monitors, the GBT is an ideal platform for developing long-millimeter wave instrumentation, and in the near future will be a world-class facility for millimeter astronomy.

MUSTANG operates at the Gregorian focus of the GBT. Two high density polyethylene lenses reimage the Gregorian focus onto the 8x8 detector array, providing half-f-lambda sampling and an 8" beam. Between the lenses a Lyot stop controls the illumination of the telescope, with the 80-100 GHz bandpass defined by capacitative mesh filters, made at Cardiff University, over the array. A comprehensive ray-tracing analysis was performed to minimize ghosting and ensure good image quality over the entire array [2]. The near-field beam pattern of the receiver was measured using a chopped nitrogen load and found to be in good agreement with the design prediction.

The detectors are cooled to below 300 mK by a helium-3 sorption refrigerator, backed up by a helium-4 sorption refrigerator and a two-stage pulse-tube cooler [3]. The pulse tube obviates the need for liquid cryogens, greatly simplifying operations on the GBT where access to receivers is limited. The pulse tube will also produce far weaker vibrations than a conventional GM fridge, but carries the penalty of reduced cooling power at low elevations, limiting effective operations to zenith angles less than 70 degrees or so. Following a cycle of the sorption fridge, the Helium-4 lasts 8-12 hours and the Helium-3 lasts 17-19 hours; when the Helium-4 runs out observing is possible, but rebiasing the detectors may be required. Cycling the Helium refrigerators takes 1.5 hours with the telescope above 40 degrees elevation. Full recovery from extreme tips (< 10 degrees for several hours) requires 3 hours with the telescope above 30 degrees.

The pixels, fabricated at NASA-GSFC, are 3mm square membranes of silicon coated with Bismuth absorber suspended by legs 10 microns wide [4]. A TES on each pixel provides a sensitive temperature measurement and is read out with SQUID multiplexing electronics developed at NIST [5]. The TES detectors have superconducting transitions at temperatures ranging from 477 to 500 mK, with a typical value of 490 mK. The pulse tube cooler was found to introduce significant noise to the system. Replacing solid copper heat straps with braided copper rope significantly reduced the vibrational noise. Further mitigation was accomplished by softening the 300 K pulse tube mount point.

2. First Observations

First light was achieved in engineering observations taken in the fall of 2006; these observations verified the basic functionality of the instrument. The sensitivity of the instrument was greatly improved following first light by vibrationally isolating the focal plane, as described above. MUSTANG was reinstalled on the GBT for a run lasting from December 2007 through March of 2008, during which further commissioning and early science observations were collected.

Maps are made by scanning the telescope continuously in azimuth and elevation while reading out the detector array. A variety of scan patterns were tested on the telescope in advance of first light observations in order to optimize the scan speed and coverage subject to constraints of the GBT servo performance and structural limitations. A key consideration is avoiding the excitation of feedarm vibrations which can introduce significant pointing errors. Typically it is possible to execute motions of a few arcminutes with periods of 20 seconds or so. Unfortunately, it is not possible to use the subreflector to modulate the sky faster than this due to significant aberrations which arise when the subreflector is tilted. It is necessary to check the telescope pointing and focus after each half-hour of observing. This is accomplished by making a series of quick maps of a nearby calibrator source at a range of focus positions. At present effective 3mm operations of the GBT are restricted to calm winds (< 10 mph), and to the night to avoid excessive temperature gradients in the structure.

NASA's Instrument Remote Control (IRC--- see [6]) software is used to read out and control the receiver. IRC is an extensible Java framework. Components capable of basic readout and control of generic Mark III electronics were developed at NASA. MUSTANG-specific components--- principally a GUI and a detector bias routine--- were developed at UPenn, and the system was interfaced with the GBT monitor and control system. Commissioning data were analyzed in IDL using a set of tools developed by the project team, and written (using simulations and lab data) well in advance of observations. A more sophisticated iterative pipeline, capable of producing publication-quality images, has been implemented in OBIT [7].

Initial observations have focused on fairly bright objects and are chosen to exploit the excellent angular resolution and surface brightness sensitivity of the GBT at 3 millimeters. With the current on-telescope sensitivity it is possible to map 3'x3' to an RMS of 2.5 mJy in an hour. The prime target for early science observations was the integral shaped filament in Orion. This portion of the Orion A molecular cloud is one of the most active sites of star formation near the Sun. MUSTANG maps of Orion will be used to search for sites of early star formation. In conjunction with sub-millimeter images [8], HCN data cubes [9], and the wealth of data available at other wavelengths these data will provide valuable constraints on the size, temperature, and emissivity of dust grains, and on the interaction of the ionized medium with the surrounding environment. A map of Orion made with MUSTANG on the GBT is shown in Figure 1.

A range of other bright objects have also been targeted. As an example, a map of the Crab Supernova Remnant made with MUSTANG on the GBT is shown in Figure 2.

3. Plans and Further Development

Current work is focused on migrating the data acquisition and control software to YGOR, NRAO-GB's hardware control framework [10] and developing and implementing interfaces and automated tuning and biasing algorithms to make the instrument routinely usable by non-expert users. Additional work underway at the Green Bank Observatory will also benefit near-future users of MUSTANG. The Precision Telescope Control System project (PTCS--- see [11]) is aiming to improve the surface efficiency of the telescope with tradiational and out-of-focus holography measurements [12], as well as to improve the servo system for better scanning performance and to develop instrumentation to measure telescope structure dynamics due, for instance, to wind and thermal effects. In addition to increasing the telescope's raw sensitivity this work holds the promise of expanding the useful operational envelope of the telescope, thus making more observing time available; for instance, windier conditions and potentially daytime. The summer of 2008 will see the first tests of fully dynamic scheduling on the GBT, which will be necessary to make the best use of prime conditions.

MUSTANG is one of the first instruments to use TES arrays to make astronomical arrays. It is the first 90 GHz instrument on the GBT, and the first focal plane array on the GBT. The technologies employed lend themselves to larger-scale focal plane arrays. As a modest step in this direction it would be possible fairly straightforwardly to quadruple the number of pixels in the MUSTANG focal plane using the existing dewar and multiplexing electronics. The lessons learned through the MUSTANG project, and the instrument itself as a testbed, will be valuable in moving the state of the art yet further. The instrument will begin to be available to the user community in October 2008.

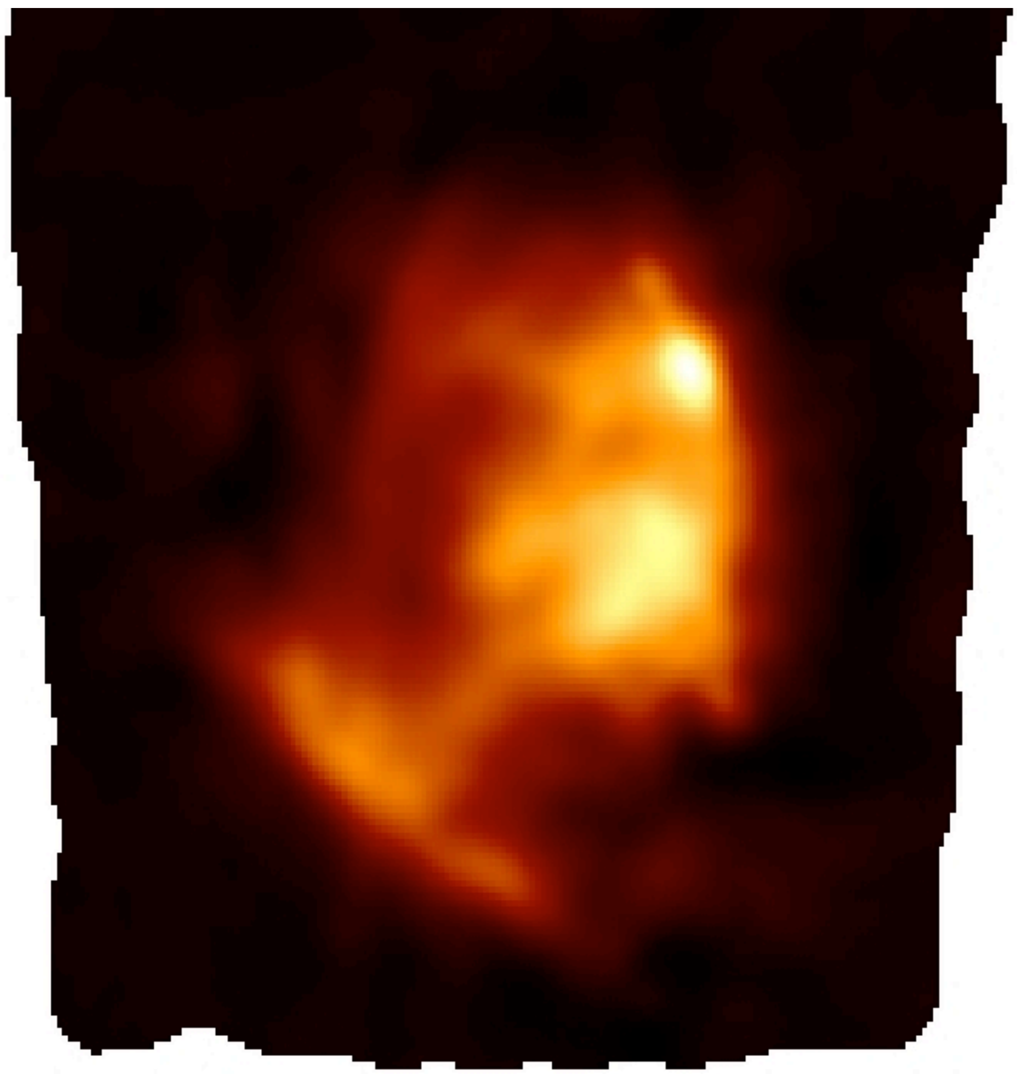

Figure 1: 3mm Image of the area around Orion KL made with MUSTANG on the GBT. The region shown is ~5'x5', and is a fraction of the total area covered.

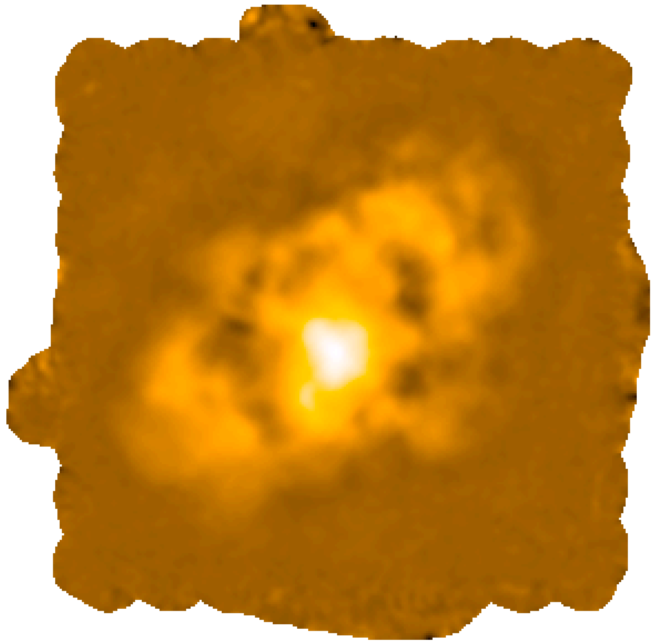

Figure 2: A 90 GHz map of the Crab SNR made with MUSTANG on the GBT. The image size is 8'x8'

REFERENCES

1. P. Jewell & R. Prestage 2004, *SPIE* 5489, 312
2. S. Dicker & M. Devlin 2005, *Applied Optics* 44, 5855
3. M. Devlin, S. Dicker, J. Klein, & M. Supanich 2004, *Cryogenics* 44, 611
4. D. Benford, S. Dicker, E. Wollack, M. Supanich, J. Staguhn, S.H. Moseley, K. Irwin, M. Devlin, J. Chervenak, & T.C. Chen 2004, in *Millimeter and Submillimeter Detectors for Astronomy II* Proc. SPIE, W.S. Holland and S. Withington, Eds., vol. 5498.
5. C. Reintsema et al. 2003, *Review of Scientific Instruments* 74, 4500
6. T.J. Ames & L. Case 2003, *SPIE* 4857, 73
7. W. Cotton 2008, *PASP in press*
8. D. Johnstone & J. Bally 1999, ApJ 510, L49
9. N. Ikeda, K. Sunada, & Y. Kitamura 2007, ApJ 665, 1194
10. M. Clark 1998, *SPIE* 3351, 287
11. R. Prestage, K. Constantikes, D. Balser, & J. Condon 2004, *SPIE* 5489, 1029
12. B. Nikolic, R. Prestage, D. Balser, C. Chandler, & R. Hills 2007, *A&A* 465, 685