The Green Bank Telescope: A Status Update

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***Abstract*—This paper provides a brief overview of the current Green Bank Telescope science program, and an update on technical developments performed since 2010.**

***Keywords*—Astronomy, Radio Astronomy Antennas, Microwave Technology, Spectroscopy.**

I. INTRODUCTION

The Robert C. Byrd Green Bank Telescope (GBT) of the Green Bank Observatory (GBO) is a 100-m-diameter dual offset Gregorian reflector radio telescope operating in the frequency range 230 MHz to 115 GHz (wavelength 1.3 m to 2.6 mm). Located in the US National Radio Quiet Zone, the GBT features a large, unblocked aperture; an active surface comprising 2004 panels and 2209 actuators; a sophisticated system for real-time measurement and optimization of surface deformations, and an advanced telescope control system that provides excellent pointing and tracking.

The GBT had first light in August 2000, and the telescope started routine operation up to 20 GHz in the fall of 2003. Using modest resources, the Observatory has continued to improve telescope performance, with 43 GHz operation commencing in 2005, and operation up to 90 GHz in 2010. This summary paper provides a brief overview of the GBT science program, and technical developments since 2010.

II. THE CURRENT GBT SCIENCE PROGRAM

The GBT is in high demand for investigations in many fields including planetary science, chemistry, and fundamental physics. Nearly 1000 individual scientists and their students used the telescope in 2013-2105.

The GBT is the world's premier pulsar observatory and has discovered the most massive pulsar known [1]. It has made precise measurements of general relativistic effects in the strong field approximation [2], and placed strict limits on violations of the equivalence principle [3] and variations in the gravitational constant [4]. The GBT has discovered and monitored H_2O megamasers in accretion disks around galactic nuclear black holes, yielding masses of the supermassive black holes with just a few percent error, and a determination of the Hubble constant that depends only on geometry [5]. It has produced strict limits on the background of gravitational radiation [6].

Star formation in a key area of GBT science. The telescope has been used to study the evolution of dense cores in filamentary clouds [7], and determined their evolutionary state through abundance changes in long carbon-chain molecules [8]. Wide-area mapping in transitions of NH_3 has measured the gas dynamics, temperature, and chemistry in star-forming regions [9], and identified areas where turbulence dissipates prior to star formation [10]. The GBT has detected mm-size interstellar dust through 3mm continuum measurements of the filaments of OMC 2/3 [11], and has discovered more than 1,000 new Galactic HII regions through their recombination line emission [12].

The GBT has made extremely sensitive observations of HI in dwarf galaxies [13], measured very faint neutral circumgalactic gas [14], and through surveys of HI in galaxies revealed the structure of the local Universe [15]. It has discovered hitherto unknown structures in the hot gas of galaxy clusters through the Sunyaev-Zel'dovitch effect [16].

III. ANTENNA

The GBT azimuth track began experiencing functional loss and increased maintenance during construction, and the track was replaced in 2007 following extensive analysis [17]. By 2010 some cracks had begun to form on the ends and bottoms of some of the wear plates, and these continue to propagate. In 2014, we implemented a strategy to reduce the effect of fretting by shifting the position of the wear plates. This year, some of the original cracks reached the top surface of the plates. The new track was designed with replaceable wear plates, and to date we have replaced 13 out of 48. This was done with minimal effort, and negligible additional effect on telescope pointing over the normal impact of routine track inspections.

In 2010 a new turret rotator was designed, fabricated and installed on the GBT. The original turret rotator required the feed arm to be in a vertical position to be operated, increasing observing overhead. The new rotator has four times the torque of the original rotator, occupies the same envelope, and can be rotated at any elevation.

The GBT main drive control system has recently been upgraded to replace the control computer with modern hardware and software. The upgrade will allow further development of advance servo control to minimize tracking error, and increase disturbance rejection. Initially the analog rate loop will remain in hardware, but the replacement system is designed to allow the implementation of both position and velocity control loops in software.

IV. INSTRUMENTATION

The GBT has now fully entered the era of multi-pixel instrumentation, with three major new instruments. MUSTANG2 is a bolometer camera built by a collaboration including the University of Pennsylvania, NIST, NRAO, GBO, the University of Michigan, and Cardiff University. It consists of 200 single-polarization, feedhorn coupled bolometers with an instantaneous $\sim$ 2'.5 field of view. Due to the feedhorn coupling and detector upgrades, the expected sensitivity is significantly better than the former MUSTANG camera, and should achieve a $50\mu Jy$ RMS point source sensitivity over a 4' × 4' area in one hour. MUSTANG2 underwent initial tests in 2016, and will be fully commissioned in 2017.

Argus, a collaboration between Stanford U., Caltech, JPL, Univ. Maryland, Univ. Miami, and GBO, is a 16-pixel W-band (85-116 GHz) focal plane array for millimeter spectroscopy. Argus uses fully integrated miniature heterodyne receiver modules based on monolithic millimeter-wave integrated circuit technology. Argus has a minimum receiver noise temperature of 27 K, and less than 40 K in the range of 75-107 GHz. Routing of the local oscillator, and in-phase and quadrature intermediate frequency signals is accomplished using multilayered printed circuit boards with high-frequency laminates and flexible low-loss cables between temperature stages. The Argus array on the GBT will vastly improve mapping speeds and allow rapid surveys of substantial areas of the sky with high spectral resolution. Argus achieved first light in March 2016, and the instrument will be fully commissioned in 2017.

The new GBT multi-beam spectrometer, VEGAS, was developed and built by a partnership between the GBO and the University of California at Berkeley. VEGAS is based on a Field Programmable Gate Array (FPGA) frontend and a heterogeneous computing backend comprised of Graphical Processing Units (GPUs) and CPUs. Its hardware platform consists of 8 ROACH II boards, 16 high-speed (5GSPS) ADCs, and 8 High Performance Computers equipped with GPUs. This system can analyze up to 8 dual-polarization or 16 single-polarization inputs at bandwidths of up to 1.25GHz per input, or 10GHz when configured to process one dual polarization beam. VEGAS was released for shared-risk observing in March 2014 and it became the default GBT spectral line backend in August 2014. It is anticipated that all pulsar observing modes will be available for VEGAS by early 2017.

V. Software

The original software specifications for the GBT software required support for a variety of backends which produced data at rates on the order 10 MB/s. At the time, only single or dual beam receivers were available. The new, FPGA-based backends produce data rates of 10s of GB/s. At the same time, the new receivers utilize multiple pixels. These instruments generate many more samples per scan than the original software system was required to support. Moreover, the flexibility offered by FPGA-based devices and the emergence of rapid hardware development utilizing re-usable hardware results in more frequent system updates, which in turn drive new requirements for monitor and control software.

The GBT software system uses C++ object-oriented features to model the instruments and their interactions, and this approach continues to serve extremely well, but the original implementation had some limitations in the areas of interprocess communication and data handling. To address these, the monitor and control software has been extended to use the ZeroMQ messaging library. This was achieved by extending the existing C++ object hierarchies using inheritance. The modifications allow for flexible data processing architectures which do not rely on writing and reading potentially large data sets to and from disk. Most importantly, these changes position the system to support even higher data rate instruments and to create a more efficient interface to the data processing system. The resulting software also allows us to remove a direct dependency on output formats, which in turn allows us to easily extend the system in the future to support any output data format. Finally, the changes allow us to unify data publishing into one interface.

VI. Conclusions

With its new instrumentation the GBT now has unrivaled capabilities for astronomical research in the 3mm atmospheric window. The NSF has announced their intention of reducing support for the GBT to 30% of operational needs by 2019, beginning with a reduction to 60% in 2017. Whether the GBT will be able to achieve its potential for scientific discovery thus remains to be seen.

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