The Green Bank Telescope: current status and early results

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ABSTRACT

The National Radio Astronomy Observatory Green Bank Telescope (GBT), the world's largest fully steerable telescope, is now undergoing commissioning and early scientific operation. The GBT has many innovative design features that advance imaging quality, sensitivity, and versatility. These include an unblocked aperture, an active surface, and a six-degree of freedom Gregorian subreflector. The GBT has an advanced laser rangefinder metrology system, which will measure the position of the active surface panels, and also guide the precision pointing of the telescope. Early commissioning results have confirmed the performance of the telescope, and exciting scientific discoveries are already being made. This paper describes the various features of the telescope in more detail, and presents the latest results.

Keywords: radio telescope, astronomy, active surface, metrology systems

1. INTRODUCTION

The Green Bank Telescope[1,2,3], shown in Figure 1, is an advanced single dish radio telescope designed for a wide range of astronomical projects with special emphasis on precision imaging. The telescope was formally dedicated as the Robert C. Byrd Green Bank Telescope in August 2000, and has been undergoing scientific commissioning since February 2001. The first scientific observations took place in early April 2001, and scientific observations have continued to be interspersed with commissioning activities. Novel features of the GBT include its unblocked main aperture, its active surface, and its precision telescope control system that includes a laser metrology system, feedarm ranging system, and focus tracking system. Early scientific results have included bi-static radar imaging in collaboration with the Arecibo Observatory, continuum imaging of various objects with very high fidelity, the detection of several new millisecond pulsars, and the detection of the youngest-known radio pulsar in the supernova remnant 3C58.

Figure 1. The Green Bank Telescope

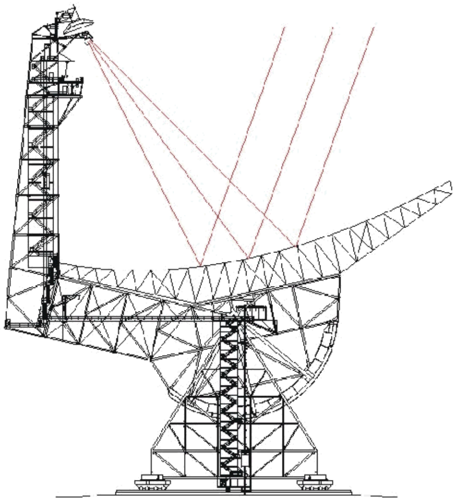

Figure 2. GBT offset optics

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1. TELESCOPE OVERVIEW

1.1 Structure and optics

The GBT is a massive structure weighing approximately 7700 metric tons, and is believed to be the largest moving structure on land. It is an azimuth-elevation telescope with a wheel and track design, and can be pointed to any elevation between 5 and 90 degrees, allowing access to 85% of the celestial sphere. One of the most significant features of the telescope, particularly given its large size, is the unblocked main aperture. The GBT reflecting surface is a 100 x 110 m section of a 208 m virtual parabola. A single, cantilevered feed support arm is attached from below the main reflector. With this offset design, incoming rays are not blocked before they reach the prime focus position or the secondary reflecting mirror, as shown in Figure 2.

The GBT can be used either as a prime focus system, or as secondary, Gregorian focus system. For prime focus operation, a retractable boom holding a receiver is placed in front of the Gregorian subreflector. The prime focus receiver mount can hold one receiver at a time and has a Sterling Mount with rotation and radial focus movement. The prime focus is used for the low frequency bands between 300 and 1200 MHz. The prime focus f/D is 0.29, relative to the 208 m parent parabola. The Gregorian subreflector is an 8 m mirror positioned by a Stewart Platform with 6 degrees of freedom. The Gregorian focus f/D is 1.9, referred to the 100 m effective aperture. The Gregorian receivers are mounted in a rotating turret and enclosed in a large receiver room. The turret can hold 8 different receivers that can be rotated into position under computer control within a few minutes. The Gregorian receivers include the higher frequency receivers, beginning with 1.2 GHz, and will ultimately include the 100 GHz systems.

1.2 Active Surface

The GBT's reflecting surface is composed of 2004 panels mounted in rings that are concentric to the vertex of the 208 m parent (virtual) parabola. The rms surface accuracy of individual panels is about 75 μm, on average. The panels are mounted at their corners on computer-controlled actuators such that the corners of four adjacent panels share one actuator. The actuators consist of electric motor driven, precision ball screws that can be positioned to within a tolerance of 25 μm. Each actuator assembly includes an LVDT position sensor for positive servo feedback.

The active surface can be used in at least three different modes; static correction, open-loop continuous active, and closed-loop continuous active. Given the results of photogrammetry or holography measurements of surface errors, the active surface can be commanded to remove those errors at the relevant elevation angle, as a one-time static improvement to surface accuracy. This has been done once on the basis of photogrammetry measurements, and the rms surface accuracy at the rigging angle of ~45 degrees elevation is now ~450 μm. The surface can also be adjusted continuously as a function of elevation angle based on a look-up table of positions. This lookup table can be generated from a finite element model (FEM) of the structure or, possibly, from a set of elevation-dependent holography maps produced by the phase-retrieval (out-of-focus) technique. As of late March 2002, the active surface is in use based on a FEM-generated look-up table. The improvement is quite dramatic in flattening the gain-elevation curve and in removing sidelobes from the beam at low elevation angles. (This is described in more detail in Section 2.) Ultimately, the active surface will be used in closed loop mode based on position feedback from the laser rangefinders and the Precision Telescope Control System described below.

1.3 Precision Telescope Control System

One of the most novel features of the GBT is the Precision Telescope Control System (PTCS) that should allow observations into the 100 GHz range. This system consists of several components, the most fundamental of which is a laser ranging system[4]. The transmit/receive system consists of a modulated laser, a two-axis, computer-controlled mirror system, and a phase detection system. The range-finders target retroreflecting mirrors, and can determine a position to 100 μm or less over a distance of 100 m or more. The measurement system consists of two sections: a system of twelve rangefinders on stable ground monuments that range to retro-spheres on the back of the GBT structure, and a system of 6 rangefinders mounted on the vertical feedarm that range to 2209 retro reflectors mounted above the actuators on the reflecting surface. The ground system is used to determine telescope position for pointing control. The feedarm system is used for measuring surface deformations and will ultimately be used in closed loop control of the active surface. At this writing, all twelve ground laser rangefinders are operational and undergoing tests and one of the feedarm rangefinders is mounted.

There are also several other critical components of the PTCS. A vertical feedarm ranging system measures the movement of the upper tip of the feedarm relative to a stable position below the surface of the dish. This will be used for focus-tracking refinements and, eventually, for measurement and possible removal of small oscillations in the feedarm induced by the wind or antenna drive motions. The focus-tracking system of the Gregorian subreflector is also an essential component of the PTCS, as is the active surface control. Finally, and equally importantly, this entire system must be integrated into the telescope monitor and control system. The PTCS is under active development and will be phased into normal operations over the next two years.

1.4 Receivers

The GBT has an excellent suite of heterodyne receivers, as listed in Table 1. The expected sensitivity that will be achieved with selected receivers after 60 seconds of observing time is given in Table 2.

Table 1. GBT Receiver Status

Receiver	Operating Range	Status
Prime Focus 1	290 – 920 MHz	Commissioned
Prime Focus 2	910 – 1230 MHz	Under Construction
L Band	1.15 - 1.73 GHz	Commissioned
S Band	1.73 - 2.60 GHz	Commissioned
C Band	3.95 - 5.85 GHz	Commissioned
X Band	8.2 – 10.0 GHz	Commissioned
Ku Band	12.4 – 15.4 GHz	Commissioned
K Band	18 – 26.5 GHz	Partially commissioned
Ka Band	26 – 40 GHz	Under construction
Q Band	40 – 50 GHz	Ready for commissioning
W Band	68 - 90 GHz / 90 – 115 GHz	Under construction

Table 2. GBT Sensitivity[*] in 60 seconds Total Integration Time

Spectral Line Sensitivity	**Bandwidth**	**RMS Noise**
1420 MHz (HI)	1 km/sec	0.06 K / 32 mJy
22 GHz (H_2O)	1 km/sec	0.03 K / 18 mJy
43 GHz (SiO, etc.)	1 km/sec	0.03 K / 15 mJy
89 GHz (HCN, etc.)	1 km/sec	0.04 K / 40 mJy
Continuum Sensitivity		
14 GHz	3 GHz	55 μJy
90 GHz	7 GHz (future heterodyne Rx)	270 μJy
90 GHz	20 GHz (future bolometer)	120 μJy

[*]with Closed loop Surface and Laser Metrology

1.5 Backends

The primary GBT backend is a 256k-lag autocorrelation spectrometer (the “GBT Spectrometer”), which provides a wide variety of spectral line observing modes. The spectrometer performs auto and cross correlations of the input signals. The input signals may be a) dual polarization IFs in a selected frequency range, b) a number of selected frequency ranges in a single polarization, c) IF inputs from different feeds of multi-feed receivers, or d) combinations of the preceding at different spectral resolutions. The maximum bandwidth is 6.4GHz (8 x 800MHz) at 391kHz resolution and maximum resolution is 49 Hz in a 12.5 MHz bandwidth. In addition to the spectral line modes, the spectrometer can be configured in a pulsar timing mode, producing 256 x 4096 samples of power as a function of frequency and time. This capability should be available by the end of 2002. Finally, we are in the process of developing a "pulsar spigot card", which will allow the raw correlation results to be streamed as fast as possible onto a recording medium, bypassing the main data rate limiting aspects of the spectrometer (the long term accumulators and the computer interface).

The Spectral Processor is an FFT spectrometer primarily designed for high time resolution pulsar observations. Because of its wide dynamic range it is also useful for spectral line observations at low frequencies where strong interference is a problem. It contains two FFT engines, each with 1024 channels over a maximum bandwidth of 40 MHz which may be divided into 1, 2, or 4 separate pass bands. The two FFT engines are synchronous and their outputs may be cross-multiplied to measure polarization. The most commonly used types of observing with the Spectral Processor are pulsar timing and either total power or frequency switched spectral line.

The primary pulsar backend currently in use is the Berkeley Caltech Pulsar Machine (BCPM). This is one of the family of Berkeley incoherent pulsar processors[5], and can be used in both search and timing modes. The BCPM is an analog/digital filter bank, which can split each of 2 IF input signals into 96 channels, with channel resolutions between 0.25 and 1.75MHz, and sampling times from 20 to 200 microseconds.

2. COMMISSIONING STATUS

Commissioning of the GBT Antenna itself has been divided into three phases. Phase I included operation up to 15GHz, using the passive surface (actuators fixed at the rigging angle). Phase II covers operation up to 50GHz, using the active surface in open loop mode. Phase III extends the antenna's capability up to 100GHz, using the active surface in closed loop mode with the laser metrology system. Each phase comes with successively more stringent specifications on the pointing accuracy, with a specification of 14", 3" and 1" respectively. Phase I commissioning was completed at the end of 2001. Conventional, blind pointing accuracy of ~7" has been achieved, and offset pointing accuracy of a few arcseconds is readily achievable. Close inspection of the pointing residuals from all-sky pointing and tracking individual sources through transit suggest that there are additional systematic terms over and above the six traditional geometric terms plus two gravity terms which we currently model. This implies that there are still some gains to be had even without the Precision Telescope Control System. Beam sidelobes at low frequency have been characterized and are ~30dB below the main beam. Focus tracking that is easily accurate enough for observations through 26 GHz has been achieved.

Phase II commissioning up to K-band (20GHz) was completed in the spring of 2002. The results are sufficiently impressive that we believe the completion of Phase II commissioning with the Q-band (40-50GHz) receiver should be relatively straightforward in the winter of 2002/03, once appropriate dry weather returns. Results of commissioning the open-loop active surface at 20GHz are shown in Figures 3 (measured aperture efficiencies) and 4 (beam shape), using the calibrator NGC 7027. The observations consist of on-the-fly cross scans and beam-switching using the dual beams of the 18-26.5GHz receiver. As the source rose, approximately every ten minutes the active surface was turned on and off. The significant improvements produced by the active surface are clearly apparent. The peak aperture efficiency with the active surface on is around 63%, slightly below the 70% expected for an ideal surface. Active surface efficiencies are more or less constant with elevation above 15 degrees. Sidelobes with the active surface on are almost undetectable, although they are quite significant with the active surface off.

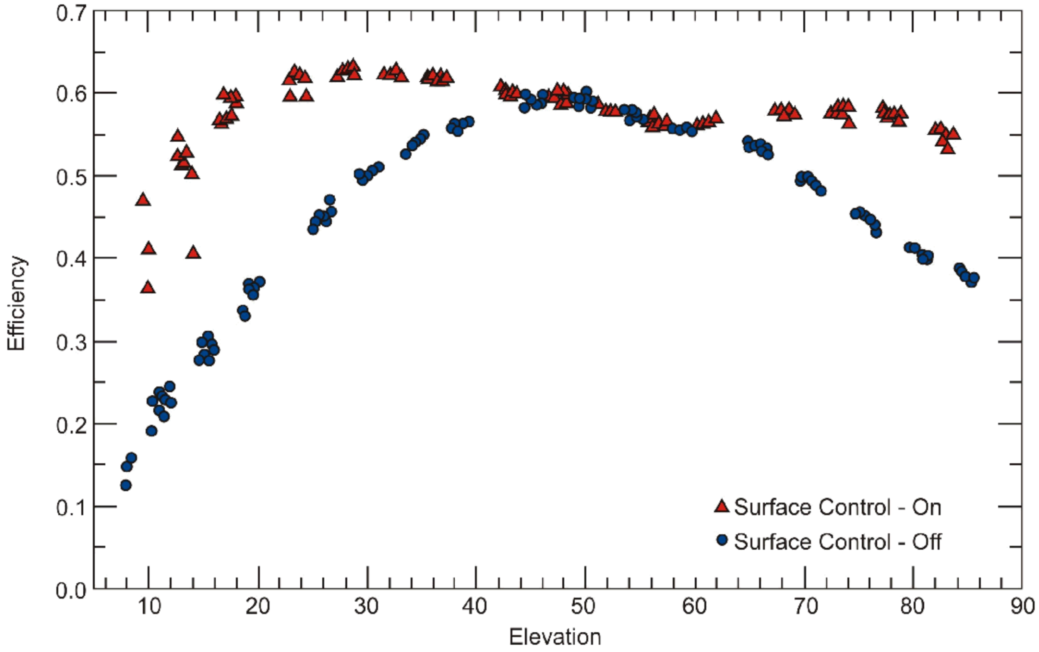

Figure 3. The aperture efficiency of the GBT at 20GHz with the active surface off (blue circles) and on (red triangles). The data have been corrected for the measured atmospheric attenuation.

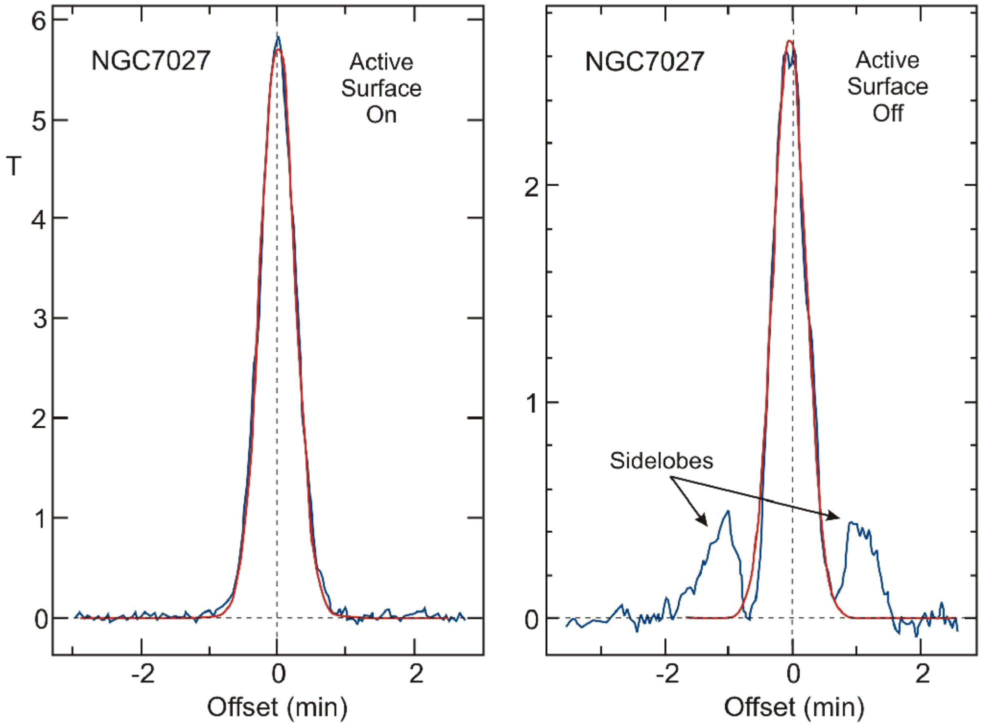

Figure 4. On-the-fly observations showing the beam shape with the active surface on and off. The observations were made back-to-back at an elevation of 12 degrees. The smooth curve is a Gaussian fit. Note the change of scale of the Y-axis between the two plots.

3. EARLY SCIENTIFIC RESULTS

As observing capabilities on the GBT have become available, scientific observations have been interspersed with commissioning. This has led to a number of exiting results covering a range of fields. Some highlights are included below.

3.1 Pulsars

Jacoby et al.[6] have discovered three new binary millisecond pulsars in the globular cluster M62 (NGC 6266). These have spin period between 2.3 and 3.4ms, and orbital periods between 4 and 27 hours. This brings the number of globular clusters known to contain six or more pulsars to three. Camilo et al.[7] have discovered 65ms radio pulsations from the X-ray pulsar J0205+6449 at the center of the supernova remnant 3C58, making this possibly the youngest radio pulsar known. The barycentric pulsar period and period derivative are consistent with the values previously measured from X-ray observations. The pulsar is an exceedingly weak radio source; its radio luminosity of ~ 0.5mJy kpc^2 is lower than that of ~ 99% of known pulsars, and is the lowest among known young pulsars. The data sets, de-dispersed at DM = 141cm^{-3}pc and folded at the best search periods, are shown in Figure 5.

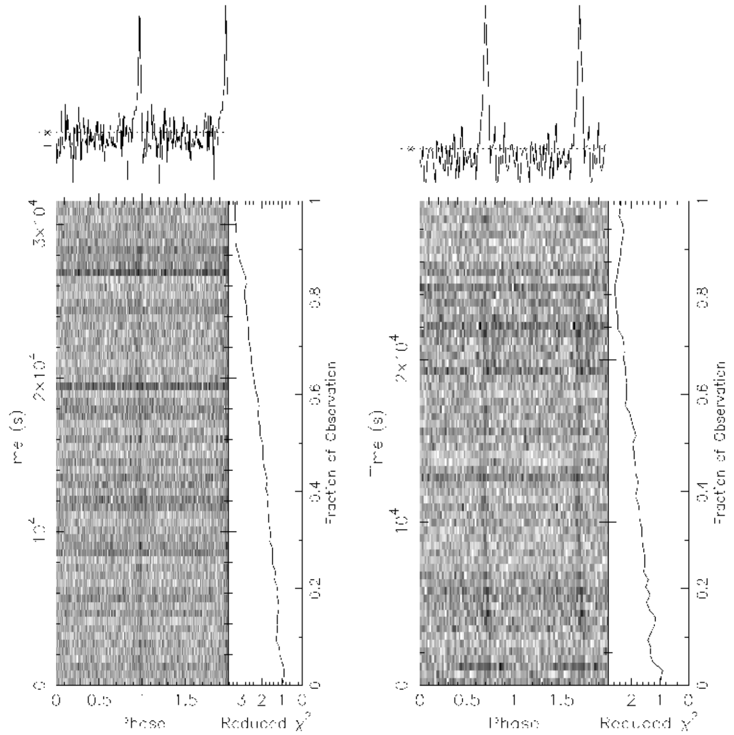

Figure 5. Pulse profiles of PSR J0205+6449 displayed as a function of time (bottom) and summed (top), at center frequencies of 1375MHz (left) and 820MHz (right). Two full periods are shown at each frequency. See Camilo et al[7] for more details.

3.2 Bi-static radar imaging

Some of the exciting early results from the GBT have come from the bi-static radar experiments performed in conjunction with Arecibo and Goldstone. Campbell et al. have used this technique to make images of the Maxwell Montes region of Venus. These images have a spatial resolution of < 2km, and altitude resolution of 100-200m. A novel radar technique used by Margot et al. has made use of observations of Mercury's speckle pattern at two different sites, the GBT and the DSN 70m antenna, to investigate the planet's obliquity and librations. These measurements can be used to place constraints on the size and state of the putative planet core, which in turn will enhance our understanding of how planets evolve thermally, and how they generate magnetic fields. Other radar work includes studies of near earth asteroids, and imaging of continent-sized regions of Titan.

3.3 Galactic Hydrogen

GBT observations of the Galactic HI halo in the inner galaxy by Lockman et al. show that in many directions the halo consists of previously-unresolved clouds, some of which are found more than 1kpc from the Galactic plane, co-rotating with the disk below. In previous, lower-resolution 21cm observations the cloud ensemble appeared nearly continuous, suggesting, incorrectly, that the HI halo was diffuse. It now appears that much if not all of the HI halo is concentrated into clouds with sizes of a few tens of parsecs.

3.4 Water mega-masers

Braatz et al.[8] are using the GBT to study H2O mega-masers in active galactic nuclei. The unsurpassed K-band sensitivity of the GBT and 800 MHz bandwidth spectrometer capable of observing at high spectral resolution make the GBT ideal for detecting high-velocity maser lines. Figure 6 shows a comparison of water vapor maser spectra taken with the GBT (top frame) and the NRAO 140-foot telescope (bottom). The 140-foot spectrum is the most sensitive ever taken of IC2560 with that telescope, and results from a 3-hour integration. The GBT spectrum represents a 1-hour (effective) integration taken during commissioning of the K-band receiver. Only the central 140 MHz of the full 800 MHz GBT spectrum is shown in this figure. The 140-foot spectrum covers 40 MHz. The GBT active surface was on. Not only is the difference in sensitivity evident, but so is the significance of the wider simultaneously observed bandwidth, which makes possible the detection of the weak, high velocity features. The maser can be used to trace dynamics of gas near the nucleus of this AGN.

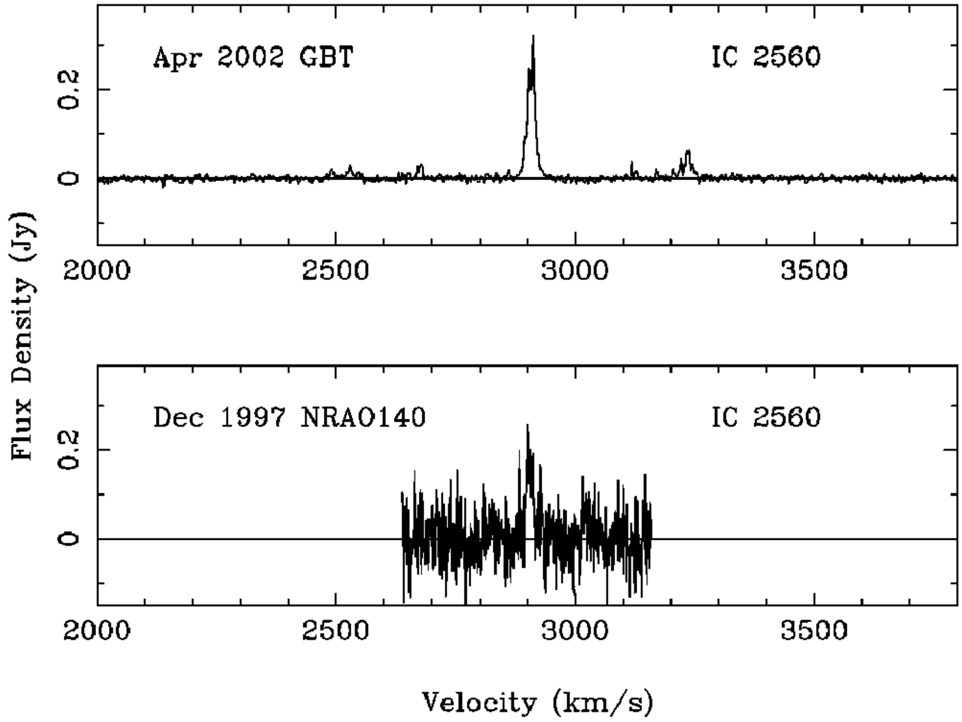

Figure 6. Spectra of the H20 mega-maser AGN IC 2560 taken with the GBT (top) and NRAO 140ft (bottom).

3.5 Continuum imaging

Early imaging results are also outstanding. As part of the commissioning process, GBT science staff have made continuum images of a number of well-known sources. As an example, Figure 7 shows an 8.4GHz image of the Omega Nebula (M17). These images have achieved dynamic ranges of over 10,000:1, and are believed to be the highest quality wide field images ever obtained with a filled aperture telescope.

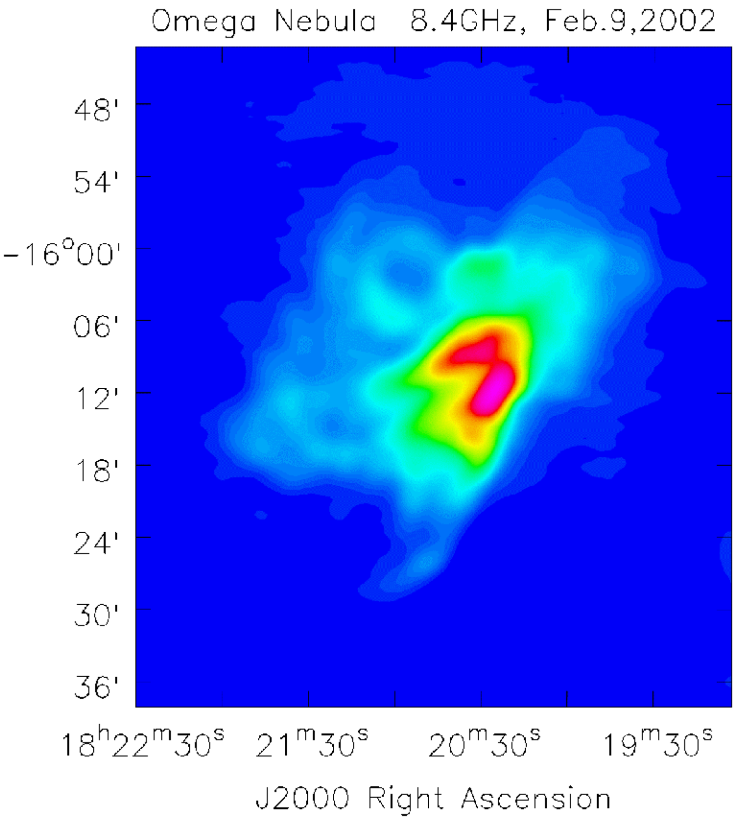

Figure 7. 8.4 GHz image of the Omega Nebula (M17) taken by the GBT commissioning team.

4. CURRENT OPERATIONS AND ENGINEERING WORK

The GBT currently has four scheduled eight-hour maintenance days per week, with the remainder of the time being devoted to a mixture of commissioning and scientific observations. All observations are now performed from the Jansky Laboratory, some 1.8km from the telescope. We expect the scheduled maintenance time to drop to three days per week by the Fall. Although excellent progress has been made to date, work is still required in a number of areas to allow routine scientific use of the telescope. Considerable system integration work is still required to bring all of the GBT Spectrometer modes on line. The spectrometer pulsar modes also have to be implemented and commissioned. Although the GBT has a rich and flexible engineering User's Interface, configuring the telescope for astronomical observations is still a complex process. We are in the process of re-engineering the Observer's Interface so that the telescope can be fully configured by simply specifying a small number of astronomical keywords. We are also working with the NRAO aips++ single dish group to streamline GBT data reduction procedures.

Perhaps our biggest problems to date have been associated with the antenna azimuth track. The track is made up of 48 segments of three steel plates on a concrete foundation. The wear strips are 2.25" thick plates of hardened 4140 steel.

Each wear plate is bolted to the base plate, which is a 9” thick by 27” wide A36 steel beam. The base plates are joined together at the bottom by splice plates made of a 5” thick A36 steel plate. The track is supported on a reinforced concrete foundation by a dry-pack cementitious grout. The total height of the foundation above the bedrock is 22 feet. The antenna rides on 16 conical wheels, 8 driven and 8 idler, in sets of four to a bogie. During the construction and testing of the GBT, a problem was noted with tangential motion of the wear strips with respect to the base plates, and the base plates with respect to the foundation. The latter was solved by welding the base plates to the splice plates (eight splice plates were not welded, to allow for thermal expansion). The wear-strip – base plate interface was improved by the addition of more and stronger bolts. Current problems include excessive tilt of the wheels while running over the joints in the track, and wear at the base plate – wear strip interface. The reason for the wheel tilt was originally suspected to be failure of the grout under the joint. In the course of testing this hypothesis, a section of grout was replaced. Replacing this grout did not affect the tilt, although it did reduce the vertical deflection at the joints. Further investigation revealed a peculiar wear pattern on the surfaces of the base plate that are in contact with each other. These wear patterns appear to be a textbook example of “fretting”. We now believe that the fretted areas on the ends of the base plates and wear strips are the cause of much of the tilting of the wheels as the joints are traversed. Potential solutions to these problems are under investigation.

5. FUTURE DEVELOPMENT PLANS

Owing to its offset optics and wide field of view at the Gregorian focus, the GBT is intrinsically a highly capable imaging telescope. Consequently, a major thrust of the instrumentation development program is to construct focal plane array imagers. Two such projects are underway. The NRAO is funding a project led by the University of Pennsylvania (Devlin, Dicker, et al.) and in collaboration with NASA-Goddard, to construct a 64-pixel bolometer camera for the 3 mm (~90 GHz) wavelength range. This will be a state of the art bolometer camera using TES bolometers and SQUID readouts. This project was initiated in the spring of 2002 and should be completed in three years. In addition, the NRAO is constructing a beam-forming array for the 1.5 GHz band (Bradley, Fisher, et al.). This will be a full-sampling array of 7-19 elements using digital beam-forming techniques. This program has an initial R&D period and should lead to a production array in about five years.

6. LESSONS LEARNED

Overall, the GBT is performing extremely well, with the basic antenna performing better than we had expected for the development stage we have currently reached. On the other hand, the system integration and commissioning process is proceeding far more slowly than had originally, perhaps optimistically, been hoped. In hindsight, most of our problems (apart from mechanical issues with the antenna track) have been rather mundane, and might have been predicted in advance; nevertheless it is perhaps worth noting the main issues here, in the hope that this might be of some use to future telescope developers.

- The GBT is a highly ambitious project. Although the offset geometry, active surface, and other advanced design features added a great deal of complexity to the project, the benefits of these features are already apparent and very significant, and have fully justified the design and construction effort required.

- The track problem itself may be of interest to other large telescope projects. The fact that there is some uncertainty about the physics and engineering of our problem suggests that there is scope for more R&D in this field.

- To get the desired performance, many parts of our 100m structure need to be aligned to ~ 100μm. Having a strong metrology group has been crucial to acceptance testing and diagnosing and resolving telescope problems.

- Have a robust, reliable workhorse scientific receiver/backend combination, which is available from before day one.

- Software won't just “take care of itself”. It can often be on the critical path. Sound project and technical management of the software systems is as important as for the mechanical and electrical/electronic components.

- Plan for in detail and budget sufficient time for system integration tests, and ensure that you have an adequate number of commissioning scientists, with the required skills and expertise.

7. AKNOWLEDGEMENTS

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