

The Green Bank Telescope: an Overview

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ABSTRACT

The Green Bank Telescope, now under construction at the National Radio Astronomy Observatory in Green Bank, WV, will be the world's largest fully-steerable telescope upon its completion in 1999. This article describes the general features of the telescope including its site, optics, surface, expected performance, and some of the areas of astronomy to which it will contribute.

Keywords: Radio Telescope, astronomy, receivers

1. INTRODUCTION

The Green Bank Telescope (GBT) of the National Radio Astronomy Observatory in Green Bank, WV, is the successor to the 300 Foot telescope, which collapsed catastrophically in 1988 during routine observations on a calm autumn evening, 26 years after it was first put into operation. The GBT has been designed to replace the 300 Foot and to match or exceed all of its capabilities. The new telescope is a 100 meter diameter, clear aperture, solid surface paraboloid with an operational frequency range from 25 MHz to ≥ 52 GHz. It will outperform the 300 Foot in every respect including sky coverage, frequency coverage, and sensitivity. Figure 1 shows an artist's conception of the completed telescope, Figure 2 gives a more accurate schematic drawing, and Table 1 compares it to its predecessor.

In this article I will describe some of the more interesting and innovative features of the GBT and discuss some astronomical projects that it will most likely undertake. Extensive documentation and many technical memos from the GBT project are available via the NRAO Web site: <http://info.gb.nrao.edu>. A discussion of the GBT with emphasis on spectroscopic applications is given by Vanden Bout and Haynes¹. An extensive description of the measurement and metrology program for the GBT is given by Hall, Goldman, Parker and Payne elsewhere in this volume.

2. SITE

The telescope is located at the National Radio Astronomy Observatory in Green Bank, WV. The Observatory is at a latitude of 38.4° and an elevation of 800 meters in a valley surrounded by mountains that reach 1400 meters. A 13000 square-mile area around the Observatory enjoys special legal protection from any new fixed transmitters. This, together with shielding afforded by the mountains, makes Green Bank an especially suitable site for radio astronomy. Information about the atmospheric quality of the site at mm-wave bands is only now being acquired, but preliminary indications are that $\tau \leq 0.1$ at 86 GHz on a significant number of days during the autumn and winter months. Thus the site may be suitable for observations to frequencies of 115 GHz some fraction of the time.

Table 1. The 300 Foot Telescope and the GBT

	300 Foot	GBT
Diameter:	91 m	100 m
Mount:	Transit	Az-el
Declination Coverage:	$> -19^\circ$	$\geq -46^\circ$
Surface:	3/8 inch mesh	solid, active
Highest Frequency:	5 GHz	≥ 52 GHz
Optics:	Symmetric	Offset

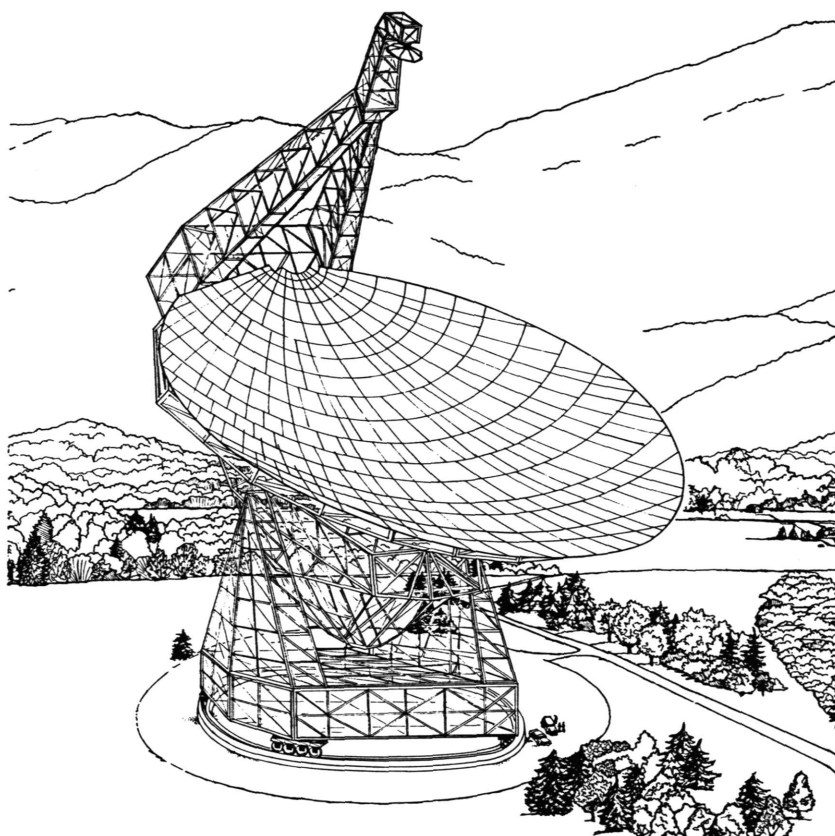


Figure 1. Artists conception of the Green Bank Telescope (GBT). Since this sketch was done the upper part of the feed arm has been redesigned as shown in Figure 2. Hall et al in this volume give additional schematic drawings of the telescope.

3. MOUNT

The most conventional aspect of the telescope is its mount. In azimuth, 16 wheels ride on a 64 meter diameter rail allowing tracking over $\pm 270^\circ$ from due South at a maximum azimuth rate of 40° per minute. The azimuth drive consists of 16 motors, each 30 horsepower. The upper part of the structure which moves in elevation has a 46 meter long elevation axle connected to a 30 meter radius bull gear driven by eight 40 horsepower motors. The telescope can move between elevations 5° and 95° at a rate of up to 20° per minute. The lower elevation limit is well-matched to the local horizon.

4. THE OFFSET GEOMETRY

He was a bold man that first eat an oyster. – Jonathan Swift

Most radio telescopes are symmetric paraboloids with the focal point in the center of the aperture and resultant blockage from feed support legs, the subreflector and the Cassegrain house. The blockage not only reduces the telescope gain, but more important, creates sidelobes which increase system noise and make the telescope more susceptible to interference and stray radiation^{2,3}. Reflections from blockage in the aperture can also cause standing waves which are often the limiting factor for sensitive spectroscopy⁴.

The GBT is an offset paraboloid: a 100×110 meter section of a parent 208 meter diameter symmetric paraboloid. The GBT has a completely unblocked aperture and therefore no scattering sidelobes, a small component of scattered ground radiation resulting in a low antenna temperature, and few locations for standing waves to develop. In place of feed support legs, the receivers and secondary reflector are mounted on a large arm which has an overall extent

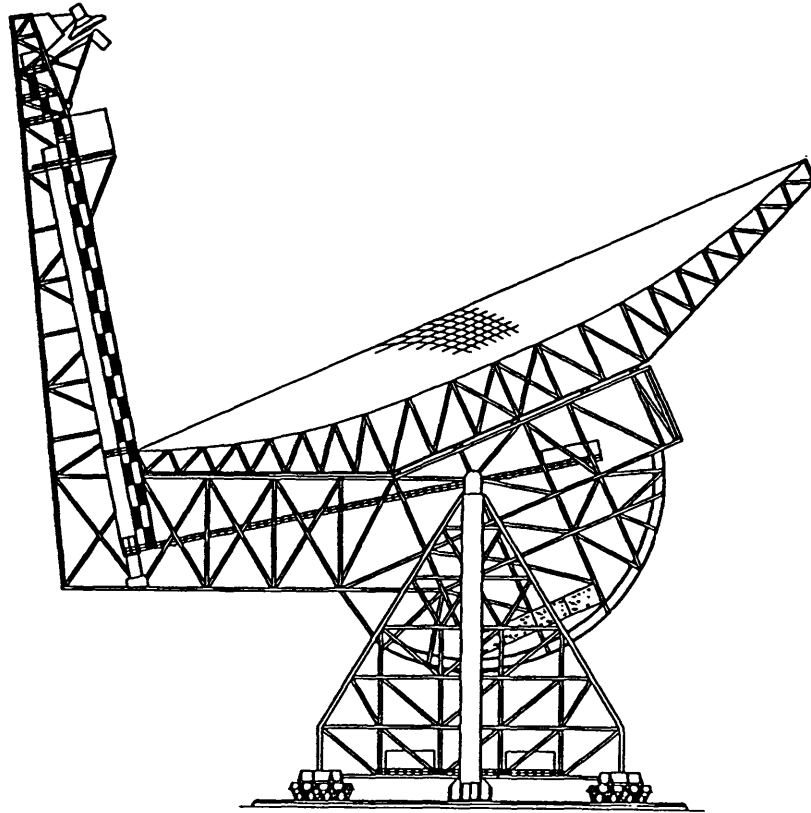


Figure 2. Schematic drawing of the Green Bank Telescope. At the top of the arm the prime focus boom can be seen in front of the 8 meter Gregorian subreflector. The boom is retracted in order to use the receivers located in the receiver room on the inner side of the arm.

of about 90 meters from its origin below the surface to its termination almost 10 meters above the focal point. The prime focus is 60 meters above the vertex point of the parent paraboloid. Receivers for frequencies ≤ 1.2 GHz are located at the end of a boom which can be extended to the prime focus or retracted in a few minutes. At the Gregorian focus a room holds receivers for frequencies ≥ 1.1 GHz. A more detailed description of the optics and receivers is given below.

5. THE PASSIVE SURFACE

The primary reflector is composed of more than 2000 panels, each with a solid aluminum surface. The individual panels are specified to have an rms error of no more than 125μ due to manufacturing and gravity. The total error of the reflecting surface is calculated with respect to the "best fit" paraboloid at each telescope elevation. The design goal is for an overall surface error of no more than 1.2 mm rms at the nominal rigging angle, an elevation of 44° . At higher and lower elevations gravitational bending distorts the surface; performance is worst at the zenith and horizon, where the rms deviation from the best fit paraboloid is 1.5 mm. The maximum deviation of any point from the best fit paraboloid will be < 5 mm at any elevation.

6. THE ACTIVE SURFACE

The large-scale gravitational distortions that limit the overall surface accuracy of the passive GBT are believed to be repeatable and predictable from detailed models of the telescope structure. To remove these distortions and substantially improve the performance of the telescope at high frequencies, each surface panel corner will be mounted

on a motor-driven actuator which can be positioned in increments of 25μ over a total travel range of 5 cm. Since four panel corners move together, the effect is to create a “rubber surface” which can be adjusted to compensate for gravitational deformations of the support structure below it. When the telescope first begins operation, the active surface will use a look-up table of expected deflections calculated from the structural model to derive corrections which are sent to the actuators. Holographic measurements of the telescope will be used to refine this technique and to determine any offsets of the actuator zero-points. The active surface in these open-loop operations should have an overall rms error of 0.36 mm on calm nights when thermal distortions are not severe. When the active surface is in operation, the telescope gain should have no significant elevation dependence.

7. TELESCOPE METROLOGY

After correction for the expected gravitational deformations, the major residual source of surface error will be the result of thermal distortions. Unlike the effects of gravity, temperature differentials across the structure cannot be predicted, so a “closed-loop” adjustment procedure is required, in which the surface is measured and moved to the desired position in real time. There is currently no commercial system available which can measure the requisite locations (the panel corners) to the required accuracy, so a laser ranging system has been developed at NRAO^{5,6,7,8,9}. The goal of this system is to measure distances to an accuracy of $\sim 50\mu$ over ~ 200 meter paths through the open air.

Several laser ranging units mounted on the telescope arm will measure the distance to laser retroreflectors mounted on the surface panel corners near each actuator, and thus trilaterate a three-dimensional location for each panel edge. The laser ranging system can measure the distance to five different retroreflectors each second, so the entire antenna surface can be scanned in a few minutes. Because the dominant surface errors are expected to be large-scale deformations, measurement of only a representative sample of the surface should be needed under typical operating conditions. The surface metrology should also allow improvement of the accuracy of the structural model for gravitational deformations, which will lead to improved surface accuracy for the “open loop” mode of operation.

The metrology system will also be crucial in achieving the necessary accuracy in telescope pointing. At a frequency of 50 GHz the telescope’s half-power beam-width will be $\sim 14''$, so pointing errors must be $\leq 1''$. This is an exceptionally strict pointing requirement which requires that the servo system have more information than is provided by the azimuth and elevation encoders alone. For example, a temperature difference of 1° C between the two alidade towers will shift the antenna beam by about $2''$ on the sky, yet not appear as a large error at the elevation or azimuth axes. At the GBT, a set of 12 laser ranging units will be mounted on the ground in a ring of radius 120 meters around the telescope. The lasers will measure the distance to a number of reflectors mounted at fiducial points on the dish, backup structure and arm, and thus tie the telescope’s electrical axis to a terrestrial reference frame. This system is now being tested on the 140 Foot telescope in Green Bank. Additional metrology systems are under development that can monitor the motion of critical parts of the structure while observations are being made. Of particular concern is possible oscillations of the telescope arm excited by telescope motion or wind¹⁰.

8. PERFORMANCE

The half-power beam-width of the GBT will be $\approx 12\nu^{-1}$ arc-min where the frequency is in GHz. The aperture efficiency is expected to be about 70% between 1 GHz and 20 GHz when the active surface is in use. With the laser ranging metrology and the active surface, the aperture efficiency should reach 60% at 50 GHz¹¹, for an antenna gain of 2 K Jy^{-1} over most of the operational range of the telescope. The absence of blockage eliminates many of the far sidelobes and reduces the near sidelobes by more than 10 dB relative to a conventional 100 meter telescope.

The expected sensitivity of the telescope is a function of its mode of operation: passive surface; active surface in look-up mode; active surface operating closed-loop with aid of the laser metrology. Table 2 summarizes the expected performance in each of these modes. Figure 2 shows the dependence of the aperture efficiency at 50 GHz on elevation and operational mode.

There will be times when the full metrology system will be unavailable because of dew on the retroreflectors, fog which obscures the laser rangefinders and so on. To use the telescope most efficiently requires that we be able to switch between observing programs and frequency bands with little delay. The optics and electronics of the GBT have been designed with this capability in mind.

Table 2. Estimates of GBT Surface and Pointing Errors

Mode	Surface rms	Pointing rms	Notes
Passive	1.2 mm	< 14"	
Active	0.36 mm	3"	Modest winds
Active with Metrology	0.24 mm	1"	Benign weather conditions

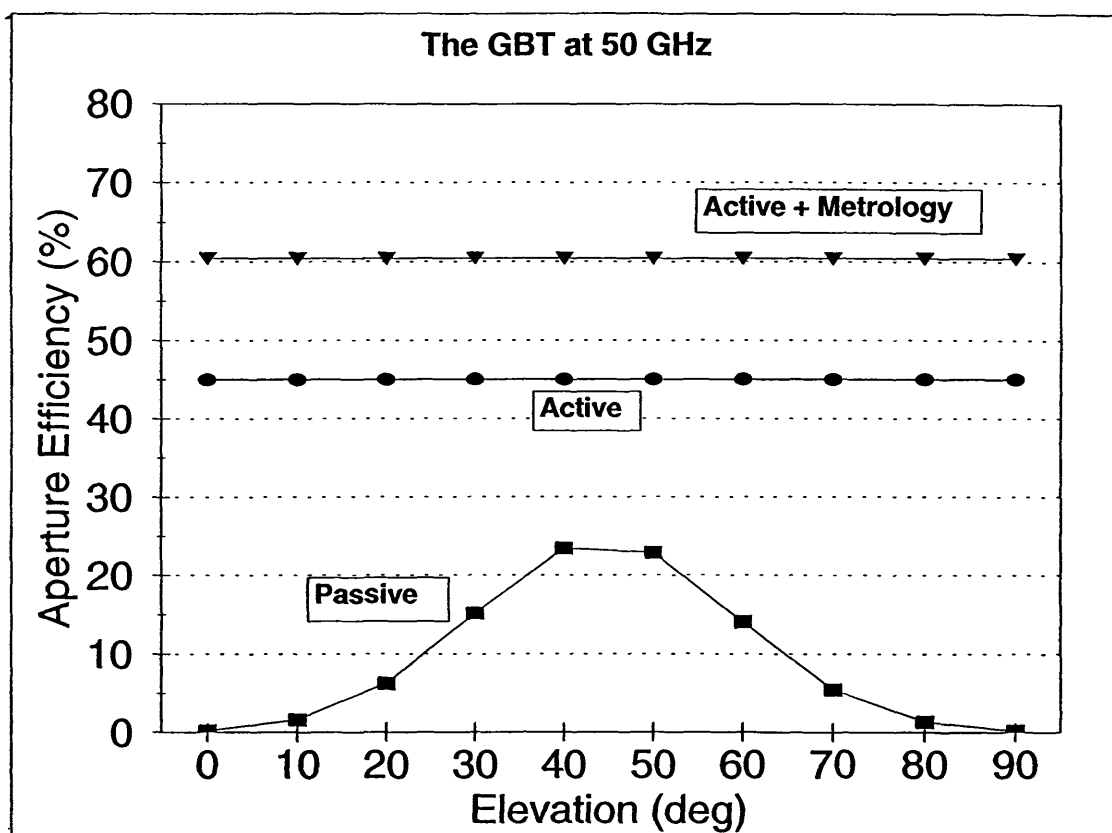


Figure 3. Expected aperture efficiency of the GBT at 50 GHz as a function of elevation for the passive structure, with the active surface enabled to correct for predicted gravitational distortions, and with the laser ranging system providing real-time measurements of the telescope surface¹¹.

Table 3. GBT Receivers

Frequency	T_{sys}	Notes
230–395 MHz	70 K	Prime Focus
385–520 MHz	60 K	Prime Focus
510–610 MHz	50 K	Prime Focus
620–910 MHz	30 K	Prime Focus
910–1230 MHz	25 K	Prime Focus
1.15–1.73 GHz	20 K	
1.73–2.60 GHz	20 K	
3.95–5.85 GHz	20 K	
8.0–10.0 GHz	25 K	
12.0–15.4 GHz	30 K	dual beam
18.0–26.5 GHz	35–50 K	dual beam
40.0–50.0 GHz	40–80 K	4 beam

9. OPTICS

The GBT is a 100×110 meter section of a 208 meter diameter $f/D = 0.29$ symmetric paraboloid. The focal point lies along the vertex of the “parent” paraboloid, but out of the optical path. Prime focus receivers are mounted on the end of a boom 9 meters long which can be retracted into the arm uncovering the Gregorian secondary. The prime focus will generally be used only for observations below about 1.2 GHz, though the boom appears to be stable enough to allow its use at much higher frequencies.

For general observations at > 1.2 GHz the 8 meter Gregorian secondary will redirect the radiation to a secondary focus atop the receiver room. The general design of the receiver room is illustrated in Figure 4. A 14 foot diameter turret in the ceiling of the receiver room can be rotated to bring any one of more than 10 receiving systems into the secondary focal plane. The highest frequency receivers will have additional small mirrors to allow for rapid beam switching and possibly for adding fine pointing corrections. The secondary focus lies 11 meters below the primary focus at an angle of 5.6 degrees with respect to the vertex line. This geometry, which includes a predetermined tilt of the subreflector, removes beam squint between the two orthogonally circularly polarizations that is otherwise a feature of offset paraboloids^{13,14,15}. All receivers operating at the secondary (Gregorian) focus should thus have excellent polarization properties¹⁶. At the prime focus special feeds will be constructed as necessary to remove the beam squint for measurement of circularly polarized sources.

10. RECEIVERS

There are detailed plans for receivers that cover the entire spectrum between 230 MHz and 52 GHz and also the 25–125 MHz band^{17,18,19}. Table 3 summarizes the performance of some of the receivers currently built or under construction. A simple feed change will be necessary to move from one prime-focus band to another. All other receivers will be mounted permanently and available for use at any time. The mechanical, electrical, and IF system can support an array of more than 50 feeds at 50 GHz, although such an instrument is not currently under construction. The IF signals will be carried on optical fibers giving an instantaneous bandwidth of > 5 GHz.

11. DETECTORS

A new set of detectors and data processing equipment has been built as part of the GBT project. A 256K-channel spectrometer can be configured in a variety of modes with bandwidths of 800 MHz to 12.5 MHz, 3-level or 9-level sampling, and either 8 or 32 independent IF inputs depending on the bandwidth. The spectrometer can generate polarization cross-products and also produce an array of 256×4096 samples of power as a function of frequency and time for pulsar observations. A digital continuum receiver will allow fast sampling at a variety of bandwidths and will be used for pointing and continuum mapping. The telescope will have several backends for support of Very Long Baseline Interferometry, including one that is identical to those used on the Very Long Baseline Array.

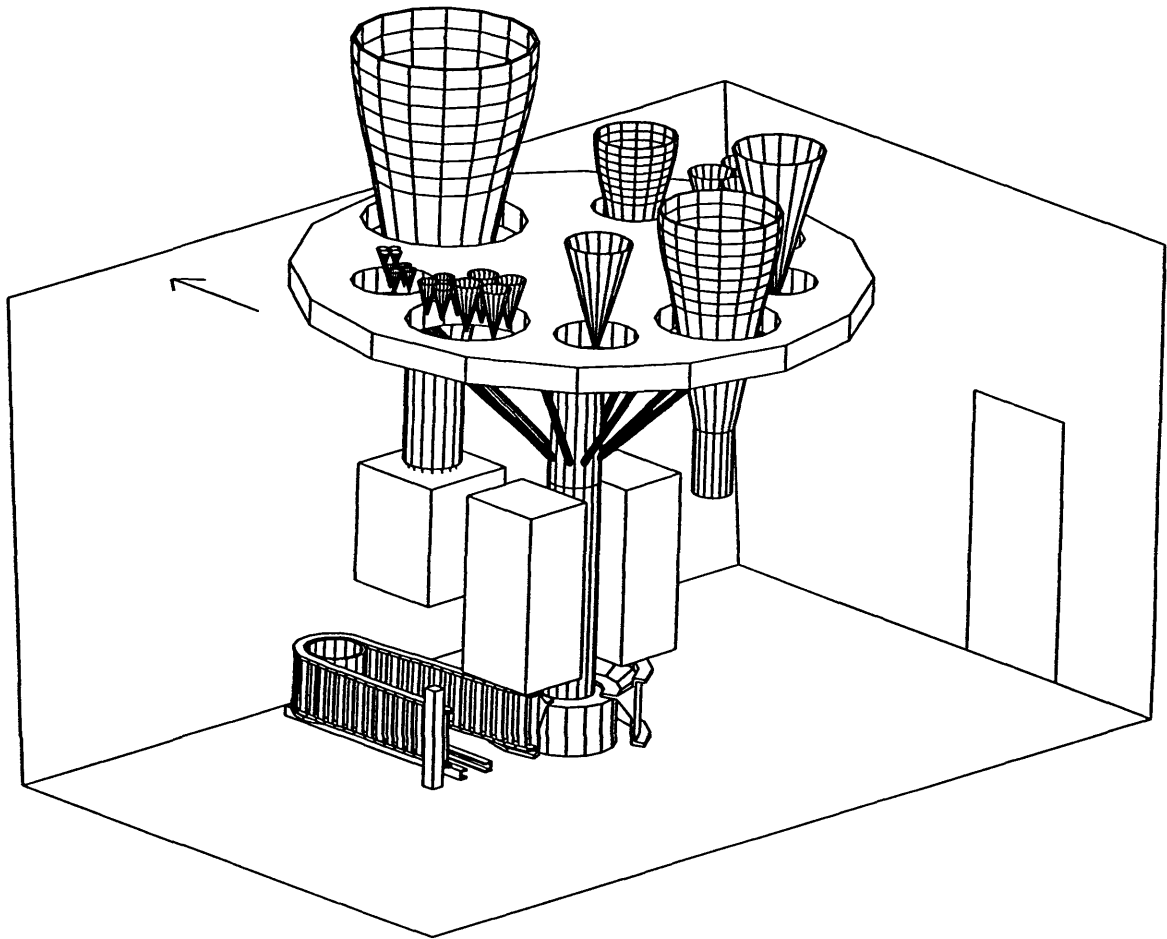


Figure 4. Schematic of the Gregorian receiver room. Receivers for frequencies ≥ 1.2 GHz are mounted in a turret that forms part of the ceiling of the room. Feeds protrude through the turret while the amplifiers and associated electronics hang below. The turret will be rotated to bring a specific receiver to the focal point.

12. SOFTWARE

There has been substantial development of new software for monitoring and control of devices and systems on the GBT, and for data reduction²⁰. A description of the software architecture of the telescope is given by M.H. Clark in the proceedings of SPIE Conference 3351. As of this date, more than 200,000 lines of object-oriented C++ have been written and are running on the nearly 30 computers that control various systems on the telescope. Most of the computers are single-boards running VxWorks; the remainder are workstations with the Solaris operating system. The laser metrology system relies on a number of PCs running the Windows NT operating system. The software effort takes advantage of the extensive amount of astronomical software now available through the STARLINK library. Early in the project it was decided that communication between various computers at the GBT should use standard network protocols, thus ensuring that remote observing capability would be built in from the start. A goal is to have a unified look and feel for all user interfaces whether they control the telescope, a receiver, or an observing setup. Data reduction needs, both for astronomical and engineering data, will be met by the AIPS++ system.

13. OPERATIONAL STYLE

The very large range in frequency coverage and the diversity of experiments expected to be performed on the telescope, make it likely that the GBT will be operated in a substantially different style than large telescopes have been in the past. With the ability to switch rapidly between receivers, and the modern software which will support remote observing, we are likely to see increased numbers of very short programs, during which a particular radio source (or pulsar) is observed for just a few minutes every day for a year, or during which a single quick spectrum is obtained by observers who are communicating with the telescope from their home institution. Likewise, there will be experiments that require clear, dry weather, and others that can be performed in the pouring rain. The ability to switch between receivers and detectors rapidly will make it possible to tailor the observing program to the specific quality of the weather on any particular day.

The increased development of scientific programs which involve coordinated observations with radio and optical telescopes, space observatories, or on phenomena where a rapid response is required such as a passing asteroid or supernova, places new requirements of flexibility and dependability, and will certainly mean that the focus of future developments in the GBT will be as much on software as on hardware.

14. ASTRONOMICAL PROGRAMS

The GBT will be a facility of the US National Science Foundation and observing time will be assigned on the basis of scientific merit. Because of this, the specific scientific programs that it will undertake will be determined competitively and cannot be predicted. But one can predict with some confidence that the following several areas of research will certainly be among the most active at the telescope:

14.1. Pulsars

With its large collecting area, good sky coverage ($> 85\%$ of the entire celestial sphere will be accessible to the GBT), sensitive receivers, and relatively interference-free site, the GBT will be ideal for observations of pulsars. Among the studies likely to be done will be deep searches for pulsars in directions like the galactic center and toward many globular clusters that are not easily observed from more northern observatories. The high electron column through the interstellar medium in the direction of the galactic center produces significant smearing of the pulsar signals at frequencies below 1 GHz, where the pulsars are strongest. The large collecting area of the GBT will give it the sensitivity to observe pulsars at frequencies of ≥ 5 GHz, where the pulse smearing is considerably diminished.

14.2. Spectroscopy

The continuous frequency coverage and freedom from standing waves makes the GBT very well suited for observations of spectral lines. In the frequency range from about 22 GHz to 52 GHz, the GBT will have a sensitivity that is unmatched by any other telescope. This is the spectral regime where highly redshifted CO and other species are just now beginning to be detected with existing instruments. Study of these lines is crucial in determining chemical evolution and galaxy formation in the early universe, and it is expected that the GBT will become the dominant instrument in this field.

At frequencies below 1.4 GHz, the GBT will be used for studies of highly redshifted HI, an area of research that is plagued by considerable radiofrequency interference. The relatively shielded site, the low sidelobes of the telescope, and the good spectral response of the telescope (few standing waves) should make it quite useful for this work.

There will also be substantial use of the GBT to study interstellar chemistry, and for this purpose its broad-band receivers will be well-matched to observation of many species simultaneously, or to searches over a wide band with high velocity resolution. Many of the largest molecules have transitions in the cm-range accessible to the GBT, and these can be used to study chemical abundances and evolution in dark clouds in the Milky Way and other galaxies.

14.3. VLBI

The GBT will have an effective area equivalent to approximately 16 25-meter class telescopes, and nearly as much sensitivity as the Very Large Array. As such it will be a valuable addition to the Very Long Baseline Array for the most sensitive measurements at extremely high angular resolution, and for experiments with orbiting telescopes such as VSOP and Radioastron. With its location on the East coast of the US, it is well positioned for trans-Atlantic as well as North American baselines. A variety of objects can be studied to advantage with these merged arrays, from maser emission of OH, H₂O and SiO in the atmospheres of evolved stars, to the nonthermal radiation from the "central engines" of radio galaxies and quasars.

15. SUMMARY COMMENTS

Current photographs of the state of telescope construction are available on the NRAO Web site. At this time all the structural steel has been manufactured and is on site, most of the surface panels have been made, and more than half of the telescope backup structure is in place. By the summer of 1998 the telescope surface should be installed, and first test operations of the telescope should be possible in early 1999.

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