The Green Bank Telescope

The largest fully steerable single-dish radio telescope in the world is located in Green Bank, West Virginia; its history, construction, and features are described.


ABSTRACT | The Robert C. Byrd Green Bank Telescope of the National Radio Astronomy Observatory is the world’s premiere single-dish radio telescope operating at centimeter to long millimeter wavelengths. This paper describes the history, construction, and main technical features of the telescope.

KEYWORDS | Antennas; pointing systems; radio astronomy

I. INTRODUCTION

The Robert C. Byrd Green Bank Telescope (GBT) of the National Radio Astronomy Observatory (NRAO) Fig. 1 is a 100-m-diameter dual offset Gregorian reflector radio telescope operating in the frequency range 100 MHz to 115 GHz (wavelength = 3 m to 3 mm). Its key technical features include a large, unblocked aperture; a fully active surface of 2004 panels; a sophisticated system for real-time measurement and optimization of the wave front, and a highly advanced telescope control system that provides excellent pointing and tracking. These characteristics represent significant technical advances over previous large single-dish radio telescopes.

The GBT offset optics enable perhaps the best imaging capability of any single-dish radio facility; its superior spectral baseline performance and polarization properties are unparalleled among large single-dish radio telescopes.

The large diameter (in wavelengths) of the GBT filled aperture results in a unique combination of high sensitivity and resolution for point sources plus high surface-brightness sensitivity for faint extended sources. This, together with the wide field of view, makes the GBT ideally complimentary to the next generation of interferometers [the Expanded Very Large Array at centimeter wavelengths, and the Atacama Large Millimeter Array (ALMA) at millimeter wavelengths] currently under construction.

The GBT’s location in the U.S. National Radio Quiet Zone, with its relatively low levels of radio frequency interference, allows access to frequencies that might not otherwise be usable, giving greater sensitivity for continuum and pulsar observations and greater opportunity to observe spectral lines both at rest and red-shifted throughout the spectrum. The GBT has a powerful and flexible observing control system, and supports remote and queue-based observing. A dynamic scheduling system is currently under development.

A broad overview of the GBT, including details on operations, instrumentation, and software, is given by

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This paper focuses primarily on the history, design, and construction of the antenna, including the surface control and pointing models. A summary of the basic parameters of the GBT is given in Table 1.

II. HISTORY AND CONSTRUCTION

For an antenna of its size, the GBT design is unique, and a discussion of its development is in order. In 1987, the NRAO scientific staff and several outside scientists began informal discussions about the possibility of building a new, large, filled-aperture radio telescope. In February 1988, Dr. K. Kellermann issued a memorandum to the NRAO Scientific and Engineering Staff announcing an effort to investigate the possible characteristics of a modern large steerable filled aperture antenna, and prepare a report for the [NRAO] Director discussing the options. There followed over the next several months a series of memoranda from interested parties discussing the scientific application and technical requirements for such a telescope. This process was given real urgency when the NRAO 300-ft telescope collapsed due to structural failure on the evening of November 15, 1988. Fifty-six astronomers from around the country came together for a workshop [2] on December 2–3 to discuss the impact of this loss to radio astronomy and to begin planning for the future. Shortly thereafter, a group of NRAO scientific and engineering staff were assigned to a Technical Study Group chaired by Dr. L. D’Addario, charged “to estimate quantitatively the performance achievable with various designs, along with their costs,” starting with instrument characteristics derived from the December meeting. Working to a remarkably short schedule, this group produced a 23-page report [3] on April 18, 1989, containing design concepts for both axisymmetric and offset 100-m class antennas. The report discussed pros and cons of each antenna type, performance and cost estimates, physical limits on reflector accuracy, and rules-of-thumb on how the construction costs would scale with size. While recognizing the risks associated with an offset design (then, as now, the next largest offset antenna is thought to be 11.5 m), the report recommended further study of the offset concept because of its potentially superior electromagnetic performance. The NRAO then assigned staff to perform these studies, and the results were presented in a workshop held in December 1989, a little under two years from the start of formal discussions.

The GBT was proposed to the National Science Foundation in June 1989, and funding of $75 million for construction was approved in December 1990. The contract was awarded to Radiation Systems, Inc. (RSI), and work began in 1991. The GBT had first light on August 22, 2000, although construction was not completed until the early fall of 2001. Basic astronomical commissioning of all telescope systems and instruments, together with a great deal of early science observations, were performed over the next two years, and the telescope started routine operation up to 20 GHz in the fall of 2003.

III. GBT STRUCTURE AND OPTICS

The GBT is an azimuth-elevation telescope with a wheel and track design. It can be pointed to any elevation between 5° and 90°, which, given its latitude, allows access to 85% of the entire celestial sphere. When operating at full azimuth rate (36°/min), the elevation limit for sidereal tracking is 89.7°. The resulting zone of avoidance is only about 50% larger than the area subtended by the full Moon. When operating at half rate, the elevation limit is 89.4°.

The GBT has a moving weight of 7856 metric tons distributed over 16 wheels; it is one of the heaviest moving structures on land and has the largest known rolling loads. In azimuth, the moving structure runs on four trucks, with four wheels per truck, two of which are not driven while the other two each have two DC brush drive motors. In elevation, the GBT has eight drive motors with a bull gear/pinion arrangement.

A. Azimuth Track

The GBT’s azimuth track is a layered structure consisting of a hardened steel wear plate, a mild steel base
The track is divided into 48 circumferential sections with an additional steel splice plate below each base plate joint. In the original design, the wear plate joint was directly above the base plate joint. Starting from the early operation of the telescope, it became apparent that the track was underengineered. Symptoms included the development of fretting wear cavities between the wear and base plates near the joints, breakage of wear plate hold-down bolts, and fatigue cracks near the ends of the wear plates. These symptoms were controlled via extensive preventative maintenance, and little actual observing time was lost. During a three-month outage in summer 2007, the entire track was replaced from the grout upwards [4].

The new track design includes higher grade materials for the base and wear plates, and thicker wear plates. Epoxy grout was used in place of dry-pack grout; the thickness of the grout was reduced to keep the telescope at the same height. Teflon shims were inserted between the base and wear plates, and tensioned through-bolting was used to replace the existing bolts. Finally, all base plate joints were welded and the wear plates staggered with respect to the base plates.

B. Optics

The GBT main reflector is a 100-m section of a 208-m parent paraboloid (Figs. 2 and 3). The ratio of the paraboloid focal length to reflector projected diameter is 0.6, chosen as the minimum at which the offset reflector cross-polarization (beam squint in circular polarization) was judged satisfactory when fed from the prime focus [5]. A Gregorian secondary focus is used for frequencies above 1.2 GHz. The offset ellipsoidal 7.6 by 8.0 m subreflector (Fig. 3) and the feedhorn axes are tilted at precise angles in order to cancel cross-polarization due to asymmetry of the primary reflector [6], [7]. The GBT subreflector is more than 25 wavelengths across at 1.2 GHz, and analysis has shown that the reflector cross-polarization throughout the Gregorian frequency range should be less than $-40$ dB [8]. From the secondary focus, the GBT is equivalent to an axisymmetric reflector of 190 m focal length. No special feeds are required; all the GBT Gregorian feeds are linear taper or compact corrugated horns. The receiver room located at the secondary focus includes a feed turret used to bring one of eight feed positions to the focus. A jack-screw actuated boom is used to deploy a receiver and feed to the prime focus position, in front of the subreflector, when desired.

The relatively low magnification of the GBT was a compromise between field-of-view and feed size, as well as
the desire to operate at the secondary focus for HI observations at 1.42 GHz. Use of shaped reflectors for high efficiency was studied but eventually rejected because of higher sidelobes (due to nearly uniform illumination) and greatly reduced field-of-view. Finally, the Gregorian rather than Cassegrain configuration was selected since a Gregorian configuration gives the minimum ground noise for an offset reflector with the arm at the top and also allows easy access to the prime focus.

Two major advantages of the dual-offset reflector in comparison with axisymmetric designs are lower sidelobe levels (because of the absence of feed strut or central blockage) and greatly reduced internal reflections—important for precise spectroscopic measurements. To further improve performance, there is a fairly tight specification on the gap between surface panels, and the total gap area is less than 0.1% of the total reflector area. Feed radiation spillover past the subreflector edge toward the feed arm structure is deflected by a flat trapezoidal shield, reflected back to the main reflector, and then to the sky.

C. GBT Structural Design

The GBT was designed to operate to 15 GHz without use of the active surface but with the requirement that the surface panels, active surface, and maximum structural deflections would allow eventual operation up to 115 GHz. For a 100-m offset dish to operate with a fixed surface at 15 GHz requires a quasi-homologous design. Two independent conceptual designs were studied: one developed by engineers at the Jet Propulsion Laboratory (JPL) and the other by NRAO engineers. The final design was accomplished by the construction contractor but contains features from both of these concepts. The elevation structure consists of the reflector backup structure with 44 tiers of surface panels, the “feed arm” (secondary optics support structure), the elevation wheel, gear and bearings, and counterweights. All elements of the elevation structure are connected to, and supported by, a strong box structure. The elevation structure rotates on a 64-m-diameter track whose foundation extends down to bedrock.

The construction contractor, RSI, made numerous improvements to the design to simplify the construction and installations. One significant change was to assemble the elevation shaft. Other problems with excessive stress on certain members were resolved by making a structural optimization.

For the GBT, the structural optimization sought to minimize the weight, surface error, pointing error, and member stresses. Optimizations were carried out by D. Strain of JPL using the IDEAS Finite Element Analysis and Design Optimization program there.

Even after successful optimization, the final calculations indicated that there were a few overstressed members. These were fabricated with high-strength steel. At times, design, fabrication of members, and construction were under way in parallel.

D. Active Surface

The GBT’s reflecting surface is composed of 2004 relatively small (average of 3.9 m²/panel) trapezoidal panels mounted in rings that are concentric to the vertex of the 208 m parent (virtual) parabola. The panels have a 3.2 mm aluminum surface supported on “x” shaped aluminum members. The root mean square (rms) surface accuracy of individual panels is about 68 μm. The panels are mounted at their corners on 2209 computer-controlled actuators [9] such that the corners of four adjacent panels share one actuator. The requirement that the actuators support significant side-loads when the GBT is at low elevation eliminated all off-the-shelf actuators from consideration. Accordingly, a custom actuator design was implemented, which features a large piston for supporting side-loads, a ball-screw for low backlash, and a worm gear for self-braking. The actuator assembly also includes an ac linear variable differential transformer (LVDT) for position sensing, a dc motor for driving, and a VME bus interface for control. This system provides the ability to close all 2209 position loops every 0.1 s. With the nominal speed of 250 μm/s, this results in a positioning resolution of 25 μm.

The actuators are controlled from a room on the GBT behind the surface. During the design phase of the actuator system, there was concern that a command error might cause the actuators to deform a surface panel permanently. Though later tests showed that this fear was unfounded, the control software contains numerous interlocks and sanity checks. The actuator system has proven to be extremely reliable, and the surface is continually adjusted as a function of elevation for all observations performed at frequencies higher than 5 GHz. At any given time about 20–40 actuators (1–2%) show faults due to a variety of causes, but the failed actuators are usually distributed over the surface and have a minimal effect on the GBT’s performance.

E. Surface Accuracy and Optimization

Most of the GBT receivers illuminate the subreflector with a 14 dB edge taper resulting in about 1% rear spillover
and a total efficiency of about 71% times the surface efficiency. Thus at frequencies below 5 GHz, where the Ruze surface efficiency loss is less than 1%, the aperture efficiency is typically 70% and the effective area is 5500 m². At higher frequencies, the telescope efficiency begins to be limited by surface errors. Measuring and removing these errors is necessary for the GBT to reach its potential performance at high frequency.

1) Initial Surface Measurement and Panel Setting: During construction, the contractor aligned the optics (surface panel settings and subreflector and receiver room locations and orientations) to the design values, within specified tolerances, for the “rigging angle” elevation (50.3°). A surface set to have minimum error at this angle is expected to have equal gravitational errors at the extremes of antenna elevation. All surface panels for the primary mirror were measured at the manufacturer on a coordinate measuring machine with an uncertainty of ±10 µm. The mean panel rms was 68 µm, with nearly every panel meeting the specification of < 75 µm. For cost savings, the 44 tiers of panels were cut from only 16 molds, which adds an extra 18 µm to the surface rms due to designed-in errors. During fall 1999–spring 2000, the panels were attached to the actuators and aligned using a custom-built device incorporating four digital indicators along with a dual-axis inclinometer to obtain a gravity reference vector [10]. The relative corner heights were set in accordance with the designed-in errors to an estimated accuracy of 50 µm. With the telescope positioned at the rigging angle, photogrammetry of the surface was then performed from a crane in order to verify that all actuators had been placed within 6.35 mm of the best fit paraboloidal surface. Only 3% of the actuators exceeded that tolerance, and the worst 23 were adjusted mechanically. The photogrammetry results were used to derive a table of zero-offset positions for the actuators, which has been in use for high-frequency observations since the commissioning of the active surface control system in spring 2002. In summer 2006, a sample of panel corners was remeasured with a mechanical tool, and the error in the relative corner heights was found to have an rms of 78 µm, indicating that the surface has held its intended shape well [11].

The current measured efficiencies of the GBT (62% at 22 GHz, 44% at 43 GHz, and 10% at 90 GHz) along with analysis of lunar scan profiles imply that the small-scale surface error (including primary and subreflector) is approximately 390 µm rms [12], [13]. This performance indicates that the initial photogrammetry reached an accuracy of four parts in 10⁶ (in terms of wavefront to aperture diameter), comparable to results on smaller telescopes (e.g. ALMA, South Pole Telescope). In order to reach the surface rms goal for the GBT (210 µm), a campaign of traditional holography is under way. The goal is to generate surface maps with a noise level of 100 µm at a linear resolution of 0.5–1.0 m. Such data should allow us to measure and remove much of the residual actuator zero-point error. If the small scale error can be reduced to 210 µm rms, and the large scale error is actively kept below 100–150 µm rms, then the aperture efficiency at 115 GHz can reach 15–20%.

2) Large-Scale Surface Measurement and Control: Much of the large-scale gravitational deformation of the surface can be predicted by the antenna finite-element model, which was incorporated into the active surface control software in 2002. However, a significant residual gravitational deformation is not well modeled. The member properties and joint locations are accurate in the model, but some other details such as joint sizes and joint stiffness are only estimates. In addition, the weight and location of some equipment deviates from the model assumptions. These result in model errors, which are usually small compared with the overall deformations, but the resultant large-scale errors are significant at high observing frequencies. In recent years, the elevation-dependence of this residual deformation has been rigorously measured during benign nighttime conditions using out-of-focus (OOF) holography [14]. The OOF model correction, parameterized by a set of Zernike polynomials, has been applied during all high-frequency observations since fall 2006, and the nighttime gain curve at 50 GHz now has no dependence on elevation. Large-scale thermal deformation of the surface remains a potential problem for daytime high-frequency observations. OOF holography maps taken during clear sky days indicate that surface deformations become significant when the Sun is above 10° elevation but that they change slowly while tracking a single source (Fig. 4). An automated observing procedure has been developed to measure and correct thermal deformations in near real time using the OOF technique. This will largely control daytime large-scale thermal errors.

IV. TELESCOPE POINTING AND TRACKING

The design and scale of the GBT, along with a lack of protection from environmental influences and the objective of high-frequency operations, presents unique challenges for pointing and tracking [15], [16]. The ability to point the telescope main beam at a source is perturbed by a variety of effects [17], including deviations from the ideal telescope alignment; alignment changes as the telescope varies in elevation angle; distortions due to temperature gradients and the resultant internal stresses; distortions due to the overconstrained track-alidade interface and errors due to truck wheel out-of-round; changes in material properties such as the change in structural modulus of elasticity with respect to temperature; angle encoder non-linearity, cyclic errors, alignment, and windup; wind-induced distortions; refractive effect of the atmosphere leading to changes in the apparent elevation of the source...
The prediction of static pointing and focus errors (i.e., neglecting vibrational and servo error) is formulated as a weighted least squares problem given the linearized model of effects and a database of careful observations of astronomical calibrator positions [19]. Bootstrapped fitting of astronomical observations to a main beam and baseline model provides estimates of observational errors and is used for weighting the fit of the linear pointing error model. The resulting model is inverted to determine the corrections to servo commands that result in the desired main beam angular position on the sky. These corrections will change in time, even for fixed source azimuth and elevation, due to the dynamical nature of some of the corrections, e.g., wind and thermal distortions that are functions of the telescope’s environment.

The model is quite stable in time. Occasional (approximately monthly) pointing observations are performed to check model performance and can be used to update the model parameters, but in practice a single pointing model has provided excellent results over several years (Table 2).

If all possible sources of pointing error are included in the model, the estimation of model parameters becomes ill-conditioned. For now, we identify model effects that contribute to the ill-conditioning by bootstrapping the model fit and removing terms that are unstable. Alternatives that could reintroduce these terms include regularization methods (ridge regression), but this has not become necessary yet.

Dynamical errors in pointing lead to loss of aperture efficiency and uncertainty in radiometric calibration of observations. These effects have been investigated using system identification methods [16] and reduced-order dynamical models with the objective of predicting the errors given perturbing inputs, e.g., azimuth and elevation angular acceleration and wind velocity. Optimal control methods have been proposed to replace the classical servo controls in order to mitigate vibration as well as improve observing efficiency and general control robustness. These methods have not to date been implemented, as the relevant dynamics of the structure have yet to be modeled.

At wind speeds below 2.5 m/s, the tracking error of the GBT is approximately 1.5″ rms and is dominated by servo effects. At wind speeds > 3 m/s, the contribution of wind effects begins to dominate the tracking error and can influence the determination of local pointing corrections. Observations at ν > 40 GHz will be affected, especially those obtained with single-pixel receivers. Half-power tracking experiments confirm that the contribution of wind-induced tracking error scales with the square of the wind speed. At wind speeds above 5 m/s, observations at ν > 20 GHz will be affected. All observing is stopped if sustained winds exceed 11 m/s, or gusts exceed 16 m/s.

Motion of the feed arm with respect to the primary surface can be detected by the quadrant detector instrument and by the accelerometers in the receiver cabin. The magnitude can be up to several millimeters. Experiments have shown that as a result of this motion, the radio beam on the sky deflects and oscillates primarily in the cross-elevation direction. An area of promising research is the

![Fig. 4. Observed wavefront errors at 43 GHz (using up to fifth-order Zernike polynomials) in chronological order (left to right, top to bottom) obtained by making repeated OOF measurements on a single source as it rose and set during a clear sunny day. The saturated grayscale runs from -1.5 rad (white) to -1.5 rad (black). The numeric labels are as follows: top left is elevation of the Sun (degrees), top right is ambient temperature (Celsius), bottom left is large scale wavefront error (°m), bottom right is total wavefront error (°m) assuming 350 °m rms in an unresolved small-scale component.](Image)

Table 2: Pointing and Focus Errors After Application of the Pointing Model. Errors are Sixty-Eighth Percentiles in Arcseconds (Cross-Elevation and Elevation) and Millimeters (Focus) Over a Sampling of Azimuths, Elevations, and Wind Speeds Less Than 3 m/s
application of the quadrant detector data to provide a calibrated, dynamic pointing correction to the data in the analysis stage. This technique has already been demonstrated in the (post-facto) construction of 90 GHz images from MUSTANG bolometer array data.

At very low temperatures ($< -8 \, ^\circ C$), the azimuth slew speed is reduced due to concerns about the performance of the grease in the wheel bearings. This results in an extremely small loss of observing efficiency.

V. INSTRUMENTATION

The GBT has an extremely flexible suite of heterodyne instrumentation covering 290 MHz–50 GHz ($\lambda = 1 \, m$ to 6 mm) currently, with plans to extend up to 115 GHz ($\lambda = 2.6 \, m$) in the future (Table 3). Heterodyne array receivers are under development. In addition, the GBT provides a very flexible and accessible platform for a wide range of university and other visitor instrumentation. The MUSTANG 64-pixel bolometer array [20] provides continuum imaging capability at 90 GHz. As the anchor of the High Sensitivity Array (HSA), the GBT enables sensitive very long baseline interferometry observations between 300 MHz and 50 GHz; the HSA has over three times the sensitivity of the NRAO Very Long Baseline Array alone.

VI. GBT SCIENCE PROGRAM

The GBT is operated as a general-purpose user facility, and telescope time is assigned by open competition. Its scientific program is constantly evolving as science progresses and new instrumentation opens up new parts of discovery space. Because of its large collecting area, excellent instrumentation, wide frequency and sky coverage, and excellent sensitivity to faint spectral lines, the GBT is making significant advances in a number of fields.

A. Pulsars

The first paper published using GBT data reported the discovery of the youngest radio pulsar known. Subsequently, the GBT has been used to discover several dozen new pulsars in the globular cluster Terzan 5. One of these is the fastest known pulsar whose rotation rate constrains the equation of state of matter at nuclear densities. In another experiment, precise observations of a pulsar–pulsar binary system have led to a measurement of relativistic precession arising from spin-orbit coupling. This is a new test of the theory of general relativity in extremely strong gravity [21]–[23].

B. Chemistry

The GBT has sparked a renaissance in the study of chemical processes in interstellar space. More than a dozen new molecular species have been discovered, including the first interstellar anions C$_6$H$^-$ and C$_8$H$^-$; cyclopropenone, an interstellar ring molecule; and acetamide, the largest interstellar molecule with a peptide bond. These discoveries are driving theoretical chemistry in new directions [24]–[26].

C. Star Formation

Molecules are efficient tracers of conditions in star-forming regions. The GBT has been used to detect H$_2$O maser and methanol lines from the molecular ring around the black hole at the galactic center, showing that star formation is occurring within a few parsec of the center. GBT studies of infrared dark clouds give the distance, kinematics, and internal physical conditions in these objects, which are the likely precursors to stellar clusters. The physical conditions in protostellar cores within

Table 3 Information on the Receivers Available for Use With the GBT. Unless Noted, All Receivers are Dual-Polarization and Are Used at the Gregorian Focus. All Except for MUSTANG Use HFET Low-Noise Amplifiers Cooled to 15 Kelvin. One Prime Focus and Up to Eight Gregorian Receivers Can Be Installed Simultaneously and Selected Remotely. Additional Information About the GBT Receivers, Data Acquisition Systems, and Other Instrumentation Can Be Found in the GBT Observing Guide.

<table>
<thead>
<tr>
<th>Receiver</th>
<th>Freq. Range (GHz)</th>
<th>BW (GHz)</th>
<th>Tsys (K)</th>
<th>No. Beams</th>
<th>Notes</th>
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<td>PF1</td>
<td>0.34–0.92</td>
<td>0.1–0.24</td>
<td>30–45</td>
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<tr>
<td>PF2</td>
<td>0.91–1.23</td>
<td>0.32</td>
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<td>1</td>
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<td>S-Band</td>
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<td>0.87</td>
<td>22</td>
<td>1</td>
<td></td>
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<td>1.90</td>
<td>18</td>
<td>1</td>
<td></td>
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<tr>
<td>X-Band</td>
<td>8–10</td>
<td>2</td>
<td>27</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Ku-Band</td>
<td>12–15.4</td>
<td>3.4</td>
<td>30</td>
<td>2</td>
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<tr>
<td>K-Band</td>
<td>18–22</td>
<td>4</td>
<td>30–40</td>
<td>2</td>
<td></td>
</tr>
<tr>
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<td>30–40</td>
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<tr>
<td>Ka-Band</td>
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<td>TES bolometer planar array; commissioning</td>
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<td>18–26.5</td>
<td>1.8</td>
<td>25–35 est.</td>
<td>7</td>
<td>Under construction</td>
</tr>
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</table>
molecular clouds are probed by observations of NH$_3$, CS, and other molecules, while measurement of the OH Zeeman effect in molecular clouds determines the role of magnetic fields in star formation [27]–[29].

D. Galaxy Formation

The GBT was used to study highly red-shifted hydrogen and molecular lines from young galaxies. From comparison of GBT HI absorption lines with lines in the optical and ultraviolet from species like Fe and Zn, it is possible to study the abundance and dust content within damped Lyman-alpha systems. A detection of the Zeeman splitting of the HI line from one of these systems shows that the magnetic field is quite strong even at $z = 0.7$. Measurement of CO lines at high $z$ give the molecular content of galaxies at their time of their assembly. By comparing different spectral lines from a single object, it is possible to study the change in values of fundamental physical constants with time [30], [31].

E. Galaxy Evolution

The GBT has been used for numerous studies of the formation and evolution of nearby galaxies and galaxy groups. It has discovered a population of hydrogen clouds around the Andromeda galaxy, new remnants of galaxy interactions in the M18 group, and a massive cloud merging with the Milky Way [32]–[34].

F. Cosmology

Many galaxies harbor central black holes that are surrounded by an accretion disk of cold gas. These disks may contain H$_2$O masers, which can be detected by the GBT and used to determine the physical size of the disk and thus the distance to the galaxy. The GBT is being used to discover and monitor nuclear H$_2$O masers in a project to determine the Hubble constant to an uncertainty of only a few percent. This will provide significant limits on cosmological models. So far the GBT has discovered more nuclear H$_2$O masers than all known previously. Measurement of the Zeeman effect in these masers has provided a limit on the magnetic field in an accretion disk less than a parsec from the central black hole [35]–[37].

Acknowledgment

The excellent engineering of the GBT was the cooperative effort of many people involved from RSI, JPL, and NRAO. Although the authors are privileged to report on the excellent performance and exciting science being produced by the telescope, these accomplishments were achieved through the dedication and innovation of a large group of engineers and scientists at the NRAO. The authors congratulate this team on their truly outstanding work.

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