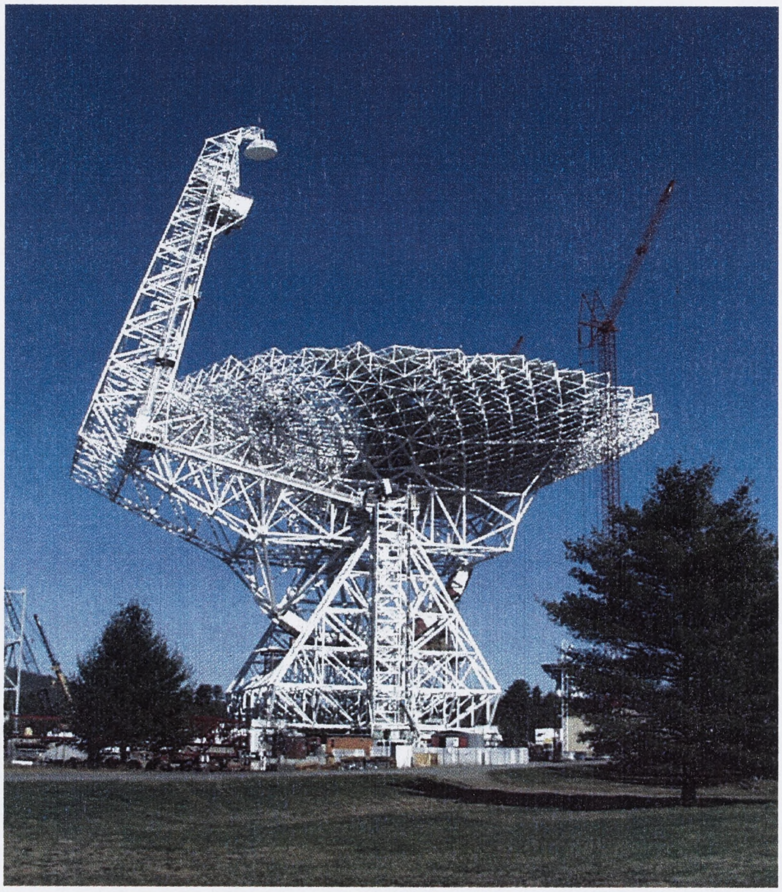
# A Program for Developing the 3 mm Observing Capability of the Green Bank Telescope

P. R. Jewell and M. M. McKinnon
December 2, 1999



## Summary

This paper outlines a program to establish a powerful and efficient observing capability for the GBT in the 3 mm wavelength band within the next four years. The program has several components, including site atmospheric measurement and evaluation, continued development of the metrology program for closed loop settings of the surface and antenna positioning, measurement and compensation, if necessary, for movements in the vertical feedarm, development of a suite of advanced observing instruments, and development and implementation of tools for dynamic (flexible) scheduling of observations. The targets for full implementation of the metrology system, the first two observing instruments, and dynamic scheduling are two years from funding; the additional advanced instruments would follow in two more years. Staffing and budget estimates are provided.

## 1. Introduction

The GBT is a versatile and innovative telescope that will bring major advances throughout its operating range from 3 meters to 3 millimeters. The GBT's potential in the 3 mm wavelength window is particularly exciting. By a large factor, the GBT will have the largest collecting area of any telescope in the world operating at 3 mm wavelengths. The 3 mm sensitivity of the GBT should allow breakthrough science in a number of important areas, including studies of the early universe and star formation. The GBT may be the first radio telescope with enough sensitivity to observe unlensed, high redshift galaxies in the earliest stages of formation (z ~ 5-15). Combes, Maoli & Omont (1999) have calculated that an extragalactic observation requiring 86 hours with the Plateau de Bure Interferometer, the most sensitive existing instrument for such studies, can be done in 13 minutes with the GBT.

The GBT will bring major, new capabilities in both the 3 mm spectroscopic and continuum modes. The GBT will be used to observe high redshift CO and CI lines, which have their maximum observability in the 3 mm window. The GBT will also be used for molecular spectroscopy of star forming regions and molecular clouds in the rich, 3 mm window. The possibilities for using the GBT for 3 mm continuum observations of dust and other emission mechanisms are very exciting and match well with the enormous advances in bolometer camera technology that are currently occurring. Calculations show that a state-of-the-art bolometer system could have sensitivities well less that 1 mJy per root second, per pixel. The GBT would be able to detect local dust, and would be particularly sensitive to very high redshift dust emission from the early universe. Bolometer cameras with >10,000 pixels are currently being proposed. A camera of this format coupled with the sensitivity of the GBT would be an impressive leap forward.

The potential of the GBT for 3 mm operation has been recognized since the inception of the telescope project. If anything, this potential has grown with time owing to discoveries of detectable high redshift emission and to the rapid development of bolometer and heterodyne receiver technology for this window. Much effort has already been expended to make the GBT work at 3 mm; this includes the active surface, the metrology system, and the specification of individual surface panels to have an average RMS accuracy of 75 μm. Bringing the GBT into routine operation in the 3 mm band, and developing a complete suite of instrumentation for 3 mm that maximizes the potential of the telescope will require considerably more effort. This proposal outlines the program required to achieve this.

## 2. Overview of the Program

The scientific potential of the GBT at 3 mm is enormous, but it will not be trivial to achieve effective operation in this band. The GBT is a 100-m diameter, open-air telescope, standing 146 m high, with a moving weight of 7700 metric tons. As such, it is one of the largest, precision moving structures on Earth. The half-power beamwidth of the GBT is about 7 arcseconds at 3 mm, which requires an RMS pointing accuracy of 1 arcsecond or less. As described below, the Green Bank site is very good for 3 mm observing for a significant fraction of the time, but not all the time; efficient use of the telescope that does not waste observing time in inappropriate weather conditions will require a sophisticated scheduling system.

The 3 mm development program is made up of several components:

- *Atmospheric evaluation and monitoring.* This program is to determine the statistical properties of the site as regards atmospheric transparency and anomalous refraction, which is closely related to phase stability. The information obtained will help us optimize the use of the telescope.
- *Metrology System Development.* This program will continue the extensive efforts in developing, testing, and implementing the systems that measure the surface panel and structural positions and feed that information back into the active surface control and pointing control systems, respectively.
- *Vertical Feed Arm measurement and compensation.* This program will measure the positional stability of the cantilevered feed arm and, if necessary, actively compensate for its movement.
- *3 mm Instrumentation Development.* A suite of advanced instrumentation is necessary to exploit the scientific potential. Instruments will include dual-beam heterodyne systems for optimum point source sensitivity, heterodyne focal plane arrays and bolometer cameras for wide field imaging.
- *Dynamic scheduling development.* To make the most efficient use of telescope observing time, a flexible scheduling system is required that matches observing programs with the most appropriate observing conditions. This requires the development of an extensive set of software and hardware tools.

The sections that follow discuss these program components in more detail. The proposal concludes with discussion of the staffing and budget estimates and the project plan.

## 3. Site Characteristics

Three atmospheric and weather effects could limit 3 mm observations with the GBT: signal attenuation by water vapor, water vapor instabilities that cause anomalous refraction, and high winds that could degrade pointing and surface accuracy.

Atmospheric water vapor and molecular oxygen absorb cosmic signals, and for this reason, most millimeter-wave observatories are situated on high, dry sites. Lower elevation sites with clear, cold winter months can also have excellent 3 mm transparency during these times, and Green Bank is such a site. Since December 1997, an 86 GHz tipping radiometer has been in operation on the Green Bank site. Statistics are available on the NRAO Green Bank web page. The results show that on a year-round basis, the zenith opacity ($\tau$) is below 0.1 for about 30% of the time. During the 6-month period from October through March, $\tau$ is <0.1 for ~50% of the time. In fact, reasonably efficient observations could be undertaken for $\tau < 0.2$, which exists for as much as 60-70 % of the time during the year. A cumulative distribution for 1999 January through November is shown in Figure 1.

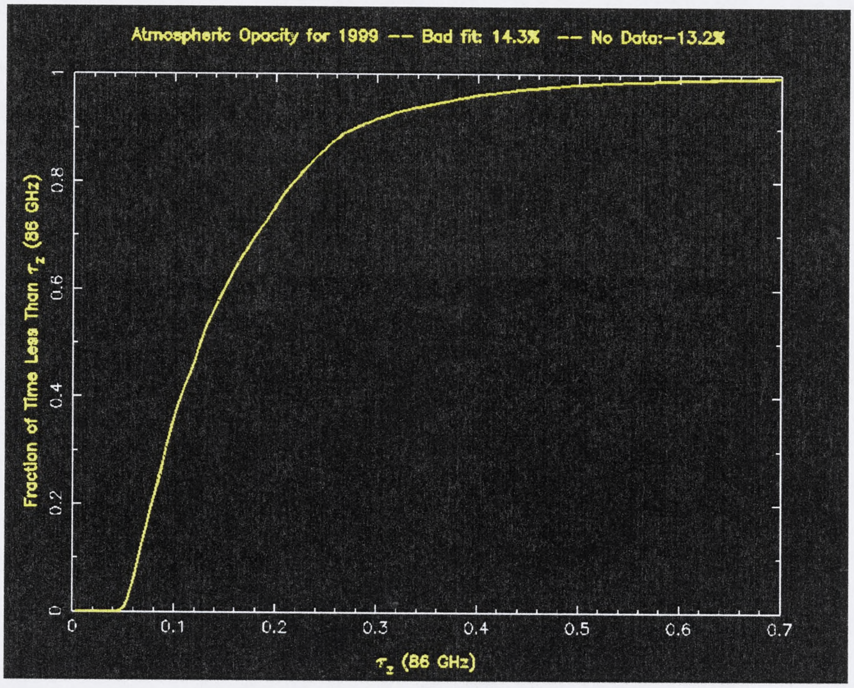


*Figure 1 – Distribution curve for 86 GHz zenith opacity at Green Bank from 1999 January through November.*

Wind can cause the surface figure to deform from its optimal shape, can induce pointing errors in the structure as a whole, and could potentially cause oscillations in the vertical feed arm. Calculations show that wind speeds of 6-7 m/s (~15 mph) could cause surface deviations of up to 200 μm (Norrod 1995), which would be comparable to or greater than the rss of all other surface errors. Site statistics show that Green Bank has wind speeds that are generally low (McKinnon 1995). For the period from 1991 to 1994, the mean wind speed was 2.8 ± 1.9 m/s (6.3 ± 4.3 mph). The wind speed was below 4.5 m/s (10 mph) for about 90% of the time. Since the wind could be higher on a given day, monitoring and flexible scheduling will be necessary. Wind speeds are highest in the spring months, although the peak-to-peak excursions about the mean as a function of time of year are only about 1.1 m/s.

Non-uniform water vapor distributions can also distort the phase front of incoming radiation. This results in phase fluctuations in an interferometer array and can cause anomalous refraction for single dish observations (Altenhoff et al. 1987; Church & Hills, 1990; Holdaway & Woody 1998). An effective method of measuring water vapor fluctuations is to use a site-testing interferometer, such as that used for ALMA site testing (Radford 1999). A copy of the ALMA system is being built for Green Bank and will be installed near the 300 Foot building in January 2000. The system will allow the site to be evaluated for anomalous refraction in a statistical sense and will be useful as a real-time site diagnostic, which will become a parameter in flexible scheduling decisions. When 3 mm observing commences on the GBT, the first order approach will be to actively measure phase stability at the site, and when conditions are poor, flexibly schedule around them. Methods have been suggested whereby anomalous refraction can measured and its resulting pointing effects corrected in real time (e.g., Lamb and Woody 1998). If anomalous refraction conditions prove troublesome for a significant fraction of the time, correction methods such as these could be implemented.

## 4 Laser Metrology and Active Surface

The active surface and laser metrology systems that will be installed on the GBT are essential to successful observations at 3 mm. The initial surface and pointing accuracies of the GBT are expected to be 1.2 mm rms and 14 arcsecond, respectively. Our stated goal is to improve the surface accuracy to 0.24 mm and the pointing accuracy to one arcsecond with the active surface and laser metrology systems. We will work to improve the surface accuracy beyond this figure, which may be possible. At an observing wavelength of 3 mm, the pointing accuracy is about one eighth of a GBT beamwidth.

### 4.1 System Description

The active surface system (Lacasse 1998) consists of 2209 electro-mechanical actuators and associated control electronics. A single actuator is configured to support up to four adjacent panel corners. The total number of panels on the telescope primary surface is 2004. The expected peak-to-peak surface deviations from the best fit parabola due to gravity are less than 6 mm, well within the actuator's total range of travel of 51 mm. The actuators can position the panel corners to an accuracy of 25 μm. In open loop active surface mode, the actuators will be positioned to predetermined locations to remove the predictable, repeatable, and elevation dependent gravitational deformations of the surface. In closed loop mode, the actuators will be commanded to remove the non-repeatable, time-variable, and primarily thermal, surface deformations that are measured with the laser rangefinders.

The laser metrology system consists of six laser rangefinders mounted on the telescope feedarm and 12 ground-based rangefinders equally spaced on a 120 meter radius around the telescope perimeter (Payne, Parker, & Bradley 1992; Goldman 1997). The feedarm rangefinders will survey the telescope primary reflector by measuring the locations of 2209 retroreflectors on the reflector surface. The entire surface measurement can be completed in approximately 8 minutes. The ground rangefinders will track retroreflectors mounted on the telescope structure for pointing error corrections. The instruments use a laser diode modulated at 1.5 GHz and a phase measurement technique to determine retroreflector distance modulo 10 cm. The accuracy of the rangefinders is approximately 100 μm at 100 m.

### 4.2 System Status

As of November 29, 1999, 1830 of the 2209 actuators have been installed and 1714 of these have been welded in place. A total of 1210 panels have been laid, and the setting of panel corners with the NRAO-designed corner setting tool has begun. Actuator cables have been run to the actuator control room, cut to length, and secured. All software for the master and slave computers that position the actuators has been written and tested. The higher level software (Wells 1995), that decides which actuator to move and by how much, has also been written and incorporated into the telescope monitor and control system. The operation of the active surface system under closed loop control was verified experimentally in 1992 with a subsystem made of four panels, nine actuators, and a laser rangefinder. The major tasks remaining for the active surface include the testing and termination of the actuator cables and the outfitting of the actuator control room.

The highest priority for the metrology group is the development and installation of metrology hardware and software. Nine of the 12 ground laser rangefinders have been installed, and the three remaining ground lasers should be installed before the end of this year. Access platforms for the feedarm lasers have been installed on the telescope, but no feedarm lasers have been installed to date. Retroreflectors have been installed on the elevation weldments and feedarm. The surface retroreflectors have been fabricated and will be installed as part of telescope outfitting after the contractor delivers the telescope. The metrology group has devoted significant effort to predicting retroreflector visibility at different telescope orientations, understanding the effects of telescope motion on rangefinder measurements (Goldman 1998), and establishing trajectory protocols with the telescope monitor and control system (Brandt 1999).

Tests of metrology hardware and software are made with field measurements. Recent measurements of the ground rangefinders and the vertical feedarm are particularly notable. With the urging of the GBT Advisory Committee, point-to-point measurements of nine ground rangefinders were made on June 23, 1999. The rangefinders measured distances to one another, and the resulting data were analyzed in a fashion similar to the phase closure technique that is used in radio interferometry. The data matched the physical model of the rangefinder locations to within the measurement error of about 100 μm, thereby proving "phase closure" in the experiment (Wells 1999b). The experiment also demonstrated for the first time laser-target scheduling, automatic laser pointing optimization, and online analysis of laser servo performance.

The first differential measurement of motions of the GBT feed arm with multiple ground rangefinders was made on October 15, 1999 (Parker 1999). The raw rangefinder data reveal two modes of telescope oscillation and indicate that the rms error of the measurements was approximately 10 μm. The improved measurement error is attributed to the absence of thermally-induced turbulence in the air that occurs when laser measurements are made near and parallel to the ground. The frequency of the telescope oscillations (0.7 Hz and 0.9 Hz) agreed with values determined from accelerometer data recorded during the experiment as well as values predicted from simulations of the telescope structure (Gawronski & Parvin 1995a). The raw rangefinder data were converted to an x,y,z coordinate system. The maximum drift in feedarm motion over a four minute observation was 2.7 mm and occurred in feedarm cross-elevation (the x coordinate). The feedarm motion does not appear to be correlated with wind velocity. This type of feed arm motion was expected (Payne 1992; Gawronski & Parvin 1995a) and can be accounted for by measuring it with a quadrant detector system and repositioning the telescope subreflector (see section 5).

### 4.3 Implementation

Operating the GBT under closed loop, active surface control is our ultimate goal. However, our highest priority now is to outfit and commission the GBT so that it can be rapidly placed into routine operations in its open loop, active surface mode. The major outfitting tasks to complete for the active surface and metrology systems include outfitting the actuator control room and installing feed arm lasers and surface retroreflectors.

Once outfitting is complete, the rangefinders will figure prominently in determining telescope performance. Rangefinder measurements of the surface and structure can be used to update the structural model of the telescope. An accurate structural model can then be used to predict deflections that are important for RF performance and structural integrity. Although 12 GHz holography will be used to measure the GBT surface, the technique is limited to a narrow range of telescope elevation angles because of the locations of geostationary satellites in the sky. The rangefinders can confirm the holography results and make more accurate measurements of the surface over the entire range of elevation angles. We have also documented the measurements and calculations required to determine telescope pointing coefficients from rangefinder data (Goldman, Balser & Wells 1999). A favorable comparison between these coefficients and those determined from traditional telescope pointing will give us confidence in our understanding of the structure.

The properties of the telescope we discover in acquiring initial sets of rangefinder measurements will help us optimize data acquisition techniques for closed loop, active surface control. Data acquired in this mode of operation will likely be analyzed in a manner similar to the method used for the recent point-to-point measurements of the ground-rangefinders; the redundancy available in the data should allow the determination of the telescope pointing vector. The details of how the real time acquisition and analysis of the metrology data is to be integrated within the telescope monitor and control system is yet to be decided.

Laser safety is an important consideration when acquiring rangefinder data. Access to the telescope must be restricted to avoid eye injuries that can be incurred in the vicinity of the ground rangefinders. We will restrict access to the GBT by installing a fence around the perimeter of rangefinders and relocating the existing road. Rangefinder enclosures also need to be designed, purchased, and installed to allow their remote operation.

## 5. Compensation of Feedarm Motions

The offset feed arm on the GBT is not as rigid as the more conventional feed support systems on symmetric telescopes with blocked apertures. Therefore, the feedarm of the GBT is comparatively floppy, and one must compensate for feedarm motions to optimize the performance of the GBT at 3mm. In this section, we discuss how we will compensate for the feedarm motions we expect to encounter on the GBT.

As the telescope is tipped in elevation, gravity causes the feedarm to sag, moving the prime focus receiver or subreflector away from the focal point of the primary reflector by about 25 cm (Wells & King 1995; Wells 1998a and 1998b). Since this effect is caused by gravity, it is repeatable. It can be measured with radio source observations or with the laser rangefinders. The measurements can be used to compensate for feed arm sag by adding elevation-dependent offsets to the positions of the actuators on the prime focus receiver and subreflector.

Differential heating and steady winds can move the feedarm over timescales of minutes. In these cases, the magnitude of the feedarm motion is largest in cross-elevation. A quadrant detector system (Payne 1992), consisting of a laser on the feedarm and a quadrant detector near the reflector surface, will be used to measure feedarm motion. The output of the quadrant detector will be used as a servo input to the subreflector actuators to compensate for these feedarm motions.

A sudden change in telescope azimuth or gusting wind along the elevation axis can excite a structural resonance corresponding to a 0.7 Hz motion of the feedarm in cross-elevation. Simulations indicate that a one degree step in azimuth excites the resonance with an initial amplitude of 36 arcseconds peak-to-peak (Gawronski & Parvin 1995a). The settling time of the resonance is fairly long (15 seconds). To suppress the oscillations induced by changes in azimuth, we will implement servo shaping techniques such as CPP-B (Gawronski & Parvin 1995b), LQG (Gawronski & Parvin 1995c), or Posicast (Wells 1999a). We will try to avoid the feedarm vibrations induced by gusting winds by scheduling high frequency observations during the calmest times of day and year (McKinnon 1995). An active damping system has also been proposed to minimize feedarm vibrations (Payne & Emerson 1998). Although this system can reduce the vibrations independent of the mechanism that excites them, it has the disadvantage of adding unwanted weight to the telescope tipping structure.

## 6. 3 mm Instrumentation

Since early 1999, a group of scientists and engineers from the NRAO and from external sites has been working to define a 3 mm instrumentation program for the GBT. The working group has recommended that a family of instruments be built that would cover the major scientific areas. The first instrument to be built would exploit the point-source sensitivity of the GBT, which is regarded as the single most powerful capability of the GBT at 3 mm. The next instruments would be aimed at sensitive, wide-field imaging of both continuum and spectral line emission. These instruments are described in more detail below.

### 6.1 Dual-beam Spectroscopic and Continuum Receiver

The GBT's large collecting area provides a major advance in sensitivity in the 3 mm band. Many of the most important projects in current astrophysical research involve objects of small angular scale such as nascent galaxies and compact, pre-stellar nebulae. The point-source sensitivity of the GBT will allow observations of these objects that simply cannot be undertaken with existing instruments. Consequently, the first 3 mm instrument to be built for the GBT should exploit the point source sensitivity of the telescope for both spectroscopic and continuum observations, if possible.

The 3 mm Working Group for the GBT has recommended that this first instrument be a dual-beam, dual-polarization receiver of the pseudo-correlation (continuous comparison) type, similar in design to those built for the Microwave Anisotropy Probe (MAP). This will be a heterodyne instrument using 3 mm HFET amplifiers. The pseudo-correlation design was chosen to overcome 1/f noise and give the receiver excellent continuum, as well as spectroscopic performance. The dual-beam, dual-polarization system will provide optimum point-source sensitivity and will fully exploit the antenna gain. In spectroscopic mode, the system temperature per channel is expected to be in the vicinity of 100 K. A chopping tertiary will be built that will allow one dual-polarization beam to be on source at all times in spectroscopic mode. In continuum mode, the receiver will chop between source and sky at kHz rates using its two feed horn sets. Continuum sensitivity of the system should be about 2 mJy per root second of integration time.

The pseudo-correlation module will cover the lower waveguide band from approximately 68 to 95 GHz. A second module, to be housed in the same cryostat, will cover the upper band from ~90-115 GHz. The second module will be of a simpler, total power design, since the excellent continuum performance afforded by the correlation design is needed in only one of the two bands.

The cost of this project will be about $300k including both modules and will require about 1.75 years to build.

### 6.2 Mark I Bolometer Camera

It is now possible to build large-format bolometer focal plane arrays (cameras). When coupled with the sensitivity of the GBT, the scientific potential is enormous. Calculations show that per pixel NEFD sensitivity of modern bolometer cameras should be <1mJy/Hz$^{-1/2}$ on the GBT in the 3 mm window. As shown in Figure 2, the GBT will have considerable sensitivity to local dust emission in the 3 mm band. Even though cool dust peaks at submillimeter and far-infrared wavelengths, the GBT's collecting area will give it about the same sensitivity for the detection of local dust as current, large submillimeter telescopes. The GBT will sample optically thin dust, which will be an advantage for some projects. For observations of highly redshifted dust, the GBT will have unparalleled sensitivity.

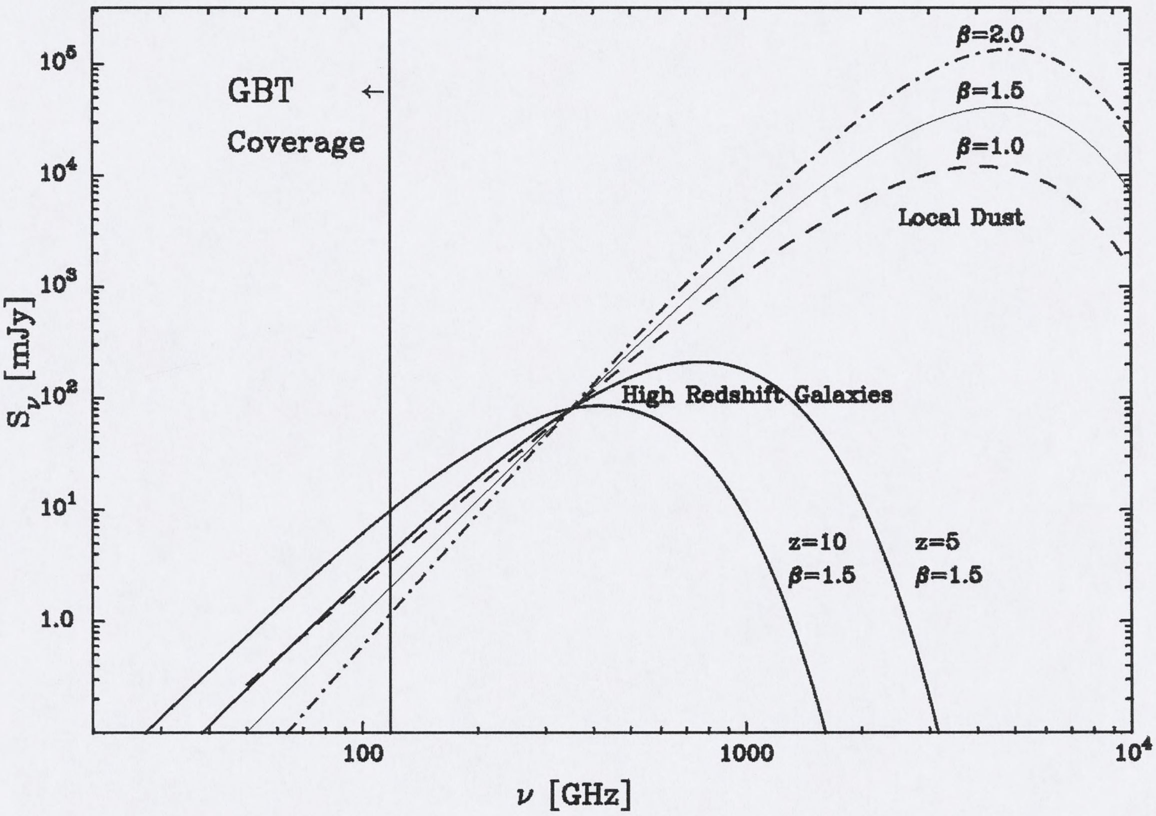


*Figure 2 – Emission curves for local and redshifted dust. β is the dust spectral index parameter.*

The NRAO does not have in-house bolometer expertise at present and it will be most effective to collaborate with university or other observatory groups in constructing a bolometer camera. Following the major success of the SCUBA bolometer camera on the JCMT, other groups are building next generation bolometer cameras. An example of this is Bolocam, a joint project of UMass and CalTech. Bolocam will have 144 pixels optimized for 1.3 mm and will have excellent sensitivity. Bolocam could be adapted for operation in the 3 mm window with a smaller format array (37 pixels) on a relatively short time-scale. We are discussing the possibilities of a collaboration with the Bolocam project team to bring a version of the instrument to the GBT. Members of the Bolocam consortium may cover the costs of adapting the instrument itself to 3 mm operation. NRAO would be responsible for mounts, external optics, and interfaces to GBT systems. The cost to NRAO should be $50k or less. This would appear to be the most cost-effective and rapid method of acquiring bolometer camera capability for the GBT. If an agreement is reached, it is possible that a 3 mm Bolocam could be available in 2001, when high frequency observing at the GBT begins. The camera might be available for 1-2 years, and then could be moved to the LMT or elsewhere.

## 6.3 Spectroscopic Focal Plane Array

The GBT has great potential for wide-field, spectroscopic imaging at 3 mm. Many astrophysical phenomena occur on angular scales of arcminutes (or more) and often involve extended, low surface-brightness emission. Examples include star-formation and outflow regions, supernova remnants, and the structure of nearby galaxies. The information provided by spectroscopic instruments such as velocities, gas temperatures, and chemical abundances are invaluable for analysis and interpretation of these regions. The point-source sensitivity of the GBT coupled with its large field of view make it ideal for such observations and will allow it to complement future high-resolution observations with ALMA. Clearly, a 3 mm focal plane array system for spectroscopy work would be very fruitful for GBT observers.

A 3 mm focal plane array of 16 beams (to be expanded to 32) has already been built by the group at UMass (the SEQUOIA array). This array covers 85-115 GHz with very competitive noise temperatures in each pixel. An array such as this would be excellent for the GBT. The new GBT Spectrometer can accommodate 32 IF inputs with 50 MHz bandwidth each (150 km/s velocity bandwidth at 3 mm). This will serve nicely for virtually all Galactic spectral line imaging projects. The Spectrometer also supports an 8 x 800 MHz bandwidth mode (8 x 2400 km/s) which can be used for wideband extragalactic imaging. A 32-beam array will cost on the order of $1M and will require about 2 years to build if we follow an existing design. Either discrete or MMIC HFET amplifiers could be used.

## 6.4 Mark II Bolometer Camera

Integrated bolometer array technology is advancing at an amazing rate. One observatory group is currently proposing to build a submillimeter camera with 30,000 pixels using folded, transition-edge superconducting bolometers with SQUID-multiplexed readouts, which alleviates the wiring problem that would otherwise be prohibitive. The technology for such an instrument appears to be available already and the time-scale for development of a practical camera of this size is thought to be ~3-4 years from now. A bolometer camera of this format begins to approach the millimeter-wave analog of an optical CCD camera. The ability to make completely sampled, wide-field millimeter-wave "photographs" with a single pointing of the telescope would be a revolutionary capability. We should have such a camera for GBT continuum observations in the 3 mm band.

The NRAO should pursue membership in a consortium for the development of such a camera. This is a longer-term project and would be a follow-on to Bolocam, assuming a collaborative agreement for its use is reached. Bolocam will allow important science to be done in the near-term and will help us refine the operation of the GBT for this type of observation. However, the instrument will probably not be available for use on the GBT for more than ~2 years. Given the likely arrangements for Bolocam, the rapid advance in camera technology, and the lead time for acquiring a next-generation camera, we should pursue membership in a consortium now. Furthermore, there may be a narrow window of opportunity for joining a consortium for development of a Mark II camera on an appropriate time scale. A camera of >10,000 pixels will likely cost at least $2.5M for materials and outside contract effort, and will probably also require a significant collaborative contribution by NRAO engineering staff toward the construction of the instrument.

## 7. Dynamic Scheduling

Dynamic (flexible) scheduling is a desirable goal for GBT operations in general, and will be essential for efficient operation at 3 mm. The level of atmospheric water vapor can affect observations above 15 GHz and are particularly important in the 3 mm band. Short-term variables such as wind, snow, anomalous refraction and RFI conditions can also affect observations.

Flexible scheduling is a significant departure from the traditional observing method in which the schedule is drawn up months in advance and the observing team travels to the site to conduct the observations in person. In the flexible mode, the schedule could change on an hourly basis. It will not be practical for the PI to be on site in this mode; the observations must be serviced by others or with the PI logged in remotely, or by some combination of the two. For the many programs that require real-time supervision and interactive decisions by the PI, an effective remote observing capability must be present. Facilities for accessing and predicting weather and RFI conditions, and presenting the information in an effective way to the telescope operator and the observers will be essential. Proposal submission must be automated and the information entered automatically into a queue management system. This system must also keep track of the progress of the program, as parts of it may be done at different times. Since the program may be initiated without the presence of the PI, a scripting facility for configuring the telescope system and executing the observations will be necessary.

The facilities listed above will require a substantial amount of software, and some hardware development. One applications programmer and supervising scientist working for 2 years will be required to develop the flexible scheduling system. Additional scientific staff will be needed to run the system when it is in operation.

## References

Altenhoff, W. J., Baars, J. W. M., Wink, J. E., Downes, D. 1987, Observations of anomalous refraction at radio wavelengths, A&A 184, 381.

Brandt, J. J. 1999, A Protocol for Pointing Synchronzation Messages, GBT Memo 197

Church, S., and Hills, R. 1990, Measurements of daytime atmospheric "seeing" on Mauna Kea made with the James Clerk Maxwell Telescope, URSI/IAU Symposium on Radio Astronomical Seeing, J. Baldwin, ed., p. 75.

Combes, F., Maoli, R., and Omont, A. 1999, CO lines in high redshift galaxies: perspective for future mm instruments, A&A, 345, 369.

Gawronski, W. & Parvin, B. 1995a, Modeling and Analysis of the GBT Control System, GBT Memo 129

Gawronski, W. & Parvin, B. 1995b, Simulations of the GBT Antenna with the Command Preprocessor, GBT Memo 134

Gawronski, W. & Parvin, B. 1995c, Simulations of the GBT Antenna with the LQG Controller, GBT Memo 136

Goldman, M. et al. 1997, Rangefinder Metrology for the Green Bank Telescope, GBT Memo 162

Goldman, M. 1998, Dynamical Rangefinder Measurements, GBT Memo 188

Goldman, M., Balser, D., & Wells, D. 1999, GBT Pointing Coefficient Estimates for Phase I from Metrology, GBT Memo 195

Holdaway, M. and Woody, D. 1998, Yet another look at anomalous refraction, MMA Memo 223.

Lacasse, R. 1998, The Green Bank Telescope Active Surface System, GBT Memo 184

Lamb, J., and Woody, D. 1998, Radiometric Correction of Anomalous Refraction, MMA Memo 224.

McKinnon, M. 1995, The Statistics of Wind Speed near the GBT, GBT Memo 126

Norrod, R. 1995, GBT Surface Accuracy, GBT Memo 119

Parker, D. 1999, First Differential Measurements of the GBT Feedarm and Future Plans, GBT Archive Document L055

Payne, J. M. 1992, Pointing the GBT, GBT Memo 84

Payne, J. M., Parker, D. H., & Bradley, R.F. 1992, Rangefinder with Fast Multiple Range Capability, Review of Scientific Instruments 63(6).

Payne, J. M. & Emerson, D. 1995, Active Damping for the GBT Feedarm, GBT Memo 133

Radford, S. J. E. 1999, private communication.

Wells, D. & King, L. 1995, GBT Best-Fitting Paraboloid in C, GBT Memo 131

Wells, D. 1998a, GBT Subreflector Motions and Servo Properties, GBT Memo 176

Wells, D. 1998b, GBT Gregorian Focus Tracking in C, GBT Memo 183

Wells, D. 1999a, Jerk-Minimizing Trajectory Generator in C, GBT Memo in prep.

Wells, D. 1999b, Results of the June 23, 1999 Point-to-Point Experiment, GBT Memo in preparation.

## 8. Staffing Requirements

The table below provides an estimate of the staffing levels required to undertake the program described above. The staff positions listed are additional staff needed beyond the resident Green Bank staff. There are currently 5.5 FTEs working in the Metrology Group not shown in this table who would continue on the project. At least two engineers and two technicians from the resident staff would also be available for work on the instrumentation development program. The final year of the chart represents the steady state in which the staff is refining and maintaining the hardware and software already developed.

**GBT 3 mm Development Program**
**Staffing Requirements**

| | Staff in FTEs | | | | |
|---|---|---|---|---|---|
| **Task Position** | **CY2000** | **CY2001** | **CY2002** | **CY2003** | **CY2004** |
| *Metrology Program (additional positions)* | | | | | |
| Engineers | 0 | 1 | 0.5 | 0.5 | 0.5 |
| Scientists | 1 | 1 | 1 | 0.5 | 0.5 |
| Technicians | 1 | 1 | 1 | 1 | 1 |
| *Atmospheric monitoring* | | | | | |
| Engineers | 0.35 | 0.1 | 0.1 | 0.1 | 0.1 |
| Scientists | 0.25 | 0.25 | 0.1 | 0.1 | 0.1 |
| *Instrumentation Development (additional positions)* | | | | | |
| Engineers | 1 | 2 | 3 | 3 | 1 |
| Technicians | 1 | 2 | 2 | 2 | 1 |
| Scientists | 1 | 1 | 1 | 1 | 1 |
| *Dynamic Scheduling* | | | | | |
| Scientists | 1 | 0.5 | 0.5 | 0.5 | 0.5 |
| Programmers | 1 | 1 | 0.5 | 0.25 | 0.25 |
| **Totals** | 7.6 | 9.85 | 9.7 | 8.95 | 5.95 |

## 9. Budget Requirements

An estimate of the budget required for the 3 mm development program is given below. Only the 68-115 GHz dual-beam receiver and a possible Bolocam adaptation to 3 mm have had engineering studies performed; the remaining costs are rough guesses. In particular, the Mark II bolometer costs are unknown at this time, although they might be refined soon, based on work at other observatories. Staffing costs are based on the previous table.

**GBT 3 mm Development Program**
**Budget**

| | | | **Cost in k$** | | | |
|---|---|---|---|---|---|---|
| **Task** | **CY2000** | **CY2001** | **CY2002** | **CY2003** | **CY2004** | **Project Sum** |
| *Metrology System* | | | | | | |
| Staff | 111 | 189 | 150 | 117 | 117 | **683** |
| Materials | 25 | 25 | 10 | 10 | 10 | **80** |
| *Atmospheric Monitoring* | | | | | | |
| Staff | 44 | 24 | 14 | 14 | 14 | **111** |
| Materials | 25 | 10 | 10 | 5 | 5 | **55** |
| *Dynamic Scheduling* | | | | | | |
| Staff | 124 | 91 | 62 | 62 | 47 | **385** |
| Materials | 20 | 10 | 5 | 5 | 5 | **45** |
| *Instrumentation Development* | | | | | | |
| Staff | 189 | 312 | 390 | 390 | 189 | **1469** |
| 68-115 GHz Dual Beam Rx | 200 | 100 | | | | **300** |
| Mark I Bolometer Camera | 30 | 20 | | | | **50** |
| 85--15 GHz Focal Plane Array | | 600 | 300 | 100 | | **1000** |
| Mark II Bolometer Camera | | 1000 | 1000 | 500 | | **2500** |
| **Totals** | 766 | 2381 | 1941 | 1203 | 387 | **6677** |

## 10. Project Plan

The following chart gives a first-order work breakdown structure and Gantt Chart for the 3 mm development project. Most of the time estimates are not yet based on detailed engineering analyses and should be regarded as more conceptual than precise.

| ID | Task Name |
|---|---|
| 1 | **ATMOSPHERIC MONITORING** |
| 2 | **12 GHz Interferometer** |
| 3 | Install dishes, cable |
| 4 | Install, test electronics |
| 5 | Install acquisition software |
| 6 | Develop analysis software |
| 7 | Acquire baseline data set |
| 8 | **On-line monitoring tools** |
| 9 | Tipper, phase monitor, wind, etc. |
| 10 | **METROLOGY / ACTIVE SURFACE** |
| 11 | Telescope outfitting |
| 12 | Telescope commissioning |
| 13 | Initial structural measurement |
| 14 | Initial surface measurement |
| 15 | Gravitational surface errors determinec |
| 16 | Implement / test open loop |
| 17 | Implement / test quadrant detector |
| 18 | Open loop operational |
| 19 | |
| 20 | Data analysis for M&C integration |
| 21 | Refine M&C integration concept |
| 22 | Detailed M&C integration |
| 23 | Implement / test closed loop |
| 24 | Closed loop operational |
| 25 | **Ready for 3 mm observations** |
| 26 | **INSTRUMENT DEVELOPMENT** |
| 27 | **68-115 GHz Dual-beam system** |
| 28 | 68-95 GHz correlation module |
| 29 | 90-115 GHz total power module |
| 30 | **Mark I Bolometer Camera** |
| 31 | Outside contract / collaboration |
| 32 | External mount & optics (NRAO) |
| 33 | System interface (NRAO) |
| 34 | **85-115 GHz Spectral Line Array** |
| 35 | Amplifier construction |
| 36 | Cryostat / System Electronics |
| 37 | IF distribution system |
| 38 | **Mark II Bolometer Camera** |
| 39 | Outsidel contract / collaboration |
| 40 | External mount & optics (NRAO) |
| 41 | System interfaces (NRAO) |
| 42 | **DYNAMIC SCHEDULING** |
| 43 | **Queue Management** |
| 44 | System design |
| 45 | Proposal processing software |
| 46 | Scripting system development |
| 47 | Verification / simulation software |
| 48 | Queue management software |
| 49 | **Remote Observing Package** |
| 50 | A/V/White-Board system |
| 51 | Quick Look Data Display System |
| 52 | Site monitoring, strip charts, etc. |