

Measurement program for the Green Bank Telescope

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ABSTRACT

The development of metrology instrumentation needed for realization of the active surface and precision pointing for the Green Bank Telescope (GBT) presents the opportunity for a complete characterization of this complex structure prior to the first astronomical observations. It is our intention to use the metrology program to evaluate the completed telescope and to point the way to improvements in performances. We also anticipate using the instrumentation for early detection of possible developing faults in the structure and the foundation.

For the first time, it should be possible to derive parameters that determine the repeatable pointing variations as a function of elevation and azimuth position prior to astronomical observations. The measurement program will also give an estimate of the non-repeatable pointing errors resulting from thermal gradients within the structure.

Laser rangefinders surrounding the telescope permit the non-invasive measurement of thermal and gravitationally-induced deformations within the structure at the 100 micron accuracy level. These measurements, and others, will be used to confirm the finite element analysis of the structure and to predict the performance of the completed telescope.

This paper outlines the instrumentation used in the measurement program and gives the results obtained to date. These include dominant modal resonances in the structure, along with the damping coefficients associated with these resonances.

Key Words: antenna, metrology, radio telescope, electronic distance measurement

1. INTRODUCTION

The Green Bank Telescope (GBT) will be the largest, most accurate, fully-steerable radio telescope in the world. It is unique in the variety of features it provides. These include an unblocked aperture, an active surface to compensate for deformations due to external loads of the primary reflector support structure, a six-degree of freedom Gregorian subreflector, a three-degree of freedom primary focus, and a receiver turret which moves to the secondary focus any one of eight receivers on command. Some turret positions provide a feed rotator which compensates for parallactic angle rotation. This feature can also be used with multi-horn feeds. The GBT has a metrology system using laser rangefinders to measure the position of the 2004 active surface panels accurately.^{1,2,3,4,5,6,7,8,9} The rangefinder system will also guide the precision pointing of the telescope.^{10,11,12,13}

Figure 1 shows the GBT from two perspectives. The left view shows the relationship between the feedarm, reflector backup structure, and box girder and elevation wheel. This entire tipping structure is supported by the elevation axis positioned atop the alidade towers. The right view illustrates the two vertical feedarm legs, elevation axis, alidade, azimuth pintle bearing and the four azimuth trucks.

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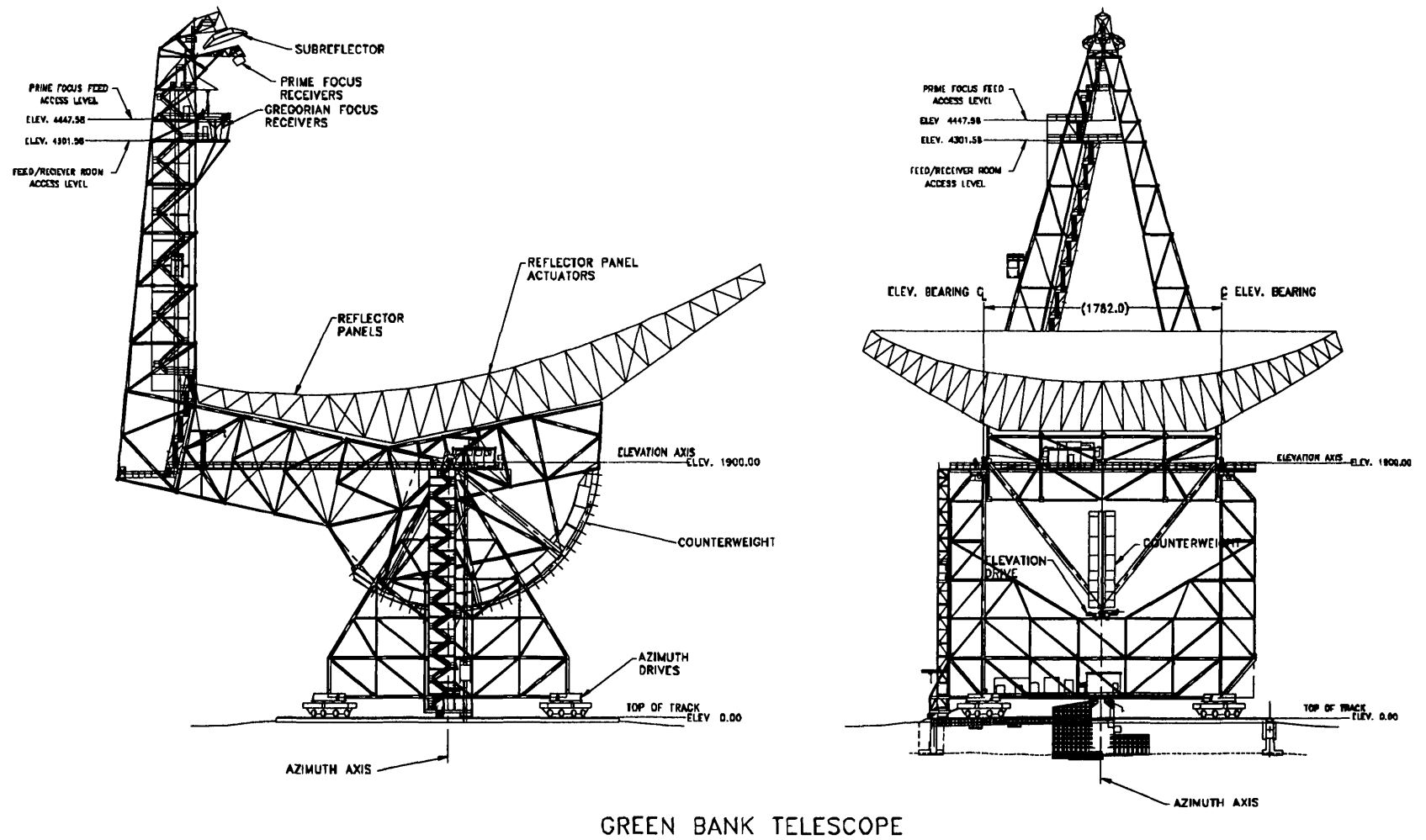


Figure 1: The Green Bank Telescope

2. OBJECTIVES OF THE METROLOGY SYSTEM

The laser rangefinder metrology system will be used to measure locations of both surface reference points and structural reference points. In conjunction with the total metrology system new capabilities are provided: to check critical alignments;^{14,15,16} to test finite element models of the structure;^{17,18,19} to identify structural anomalies and fault conditions; to provide useful data for optimization of servo algorithms;^{20,21,22,23,24,25} to allow independent measurements of acceptance criteria; to aid in expediting outfitting and commissioning operations; to improve surface setting accuracy,²⁶ servo performance and pointing accuracy;^{27,28,29} to provide a basis for on-going trend analysis and to be of service in development of a GBT maintenance program.

The twelve ground-based rangefinders surrounding the telescope allow non-invasive measurement of alignment, thermal, and gravitationally-induced deformations of the structure, at the 100 micron accuracy level.^{30,31} The rangefinders are the core of the measurement program. (See Figures 2 and 3³².) They will be used in conjunction with standard metrology instruments (accelerometers, strain gauges, theodolites, quadrant detectors, EDM's and tilt meters) which will be strategically located on the telescope structure. The metrology system (including a calibration lab) is regarded as a unique feature of the GBT Project and was contemplated since the inception of the design, with a major commitment of money and engineering.

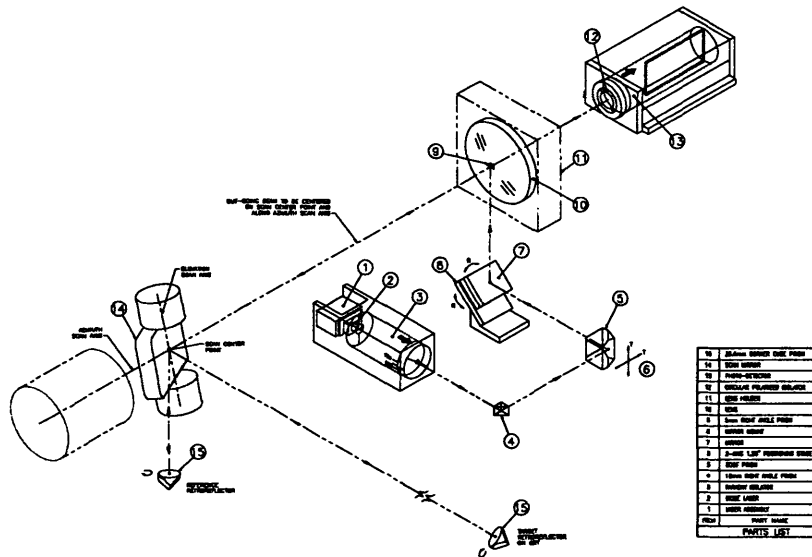


Figure 2: A laser (1) is amplitude modulated at 1500 MHz, transmitted through an isolator (3) and beam steering optics (4,5,7,9) to a dual-axis servo controlled mirror (14) which directs the beam to the selected retroreflector (15). The retroreflector returns an expanded beam to the mirror (14) which directs the beam to a lens (10), which focuses the beam on the detector (13). This phase of the return signal is measured, corrected for the group index of refraction, converted to distance, and transmitted to a central computer. Data from three or more instruments are converted to a 3-D coordinate by a trilateration algorithm.

3. MEASUREMENTS TAKEN DURING CONSTRUCTION

Measurements taken as construction of the antenna progresses are used to check structural, mechanical and optical alignments. Important structural alignments include: leveling of the azimuth track,³³ alignment of the elevation shaft, and setting the primary reflector and subreflector surface panels. Mechanical alignments include: the conical azimuth truck wheels,³⁴ the azimuth pintle bearing, elevation bearings, bull gear and drives, and azimuth and elevation encoders. The telescope optical alignments are:

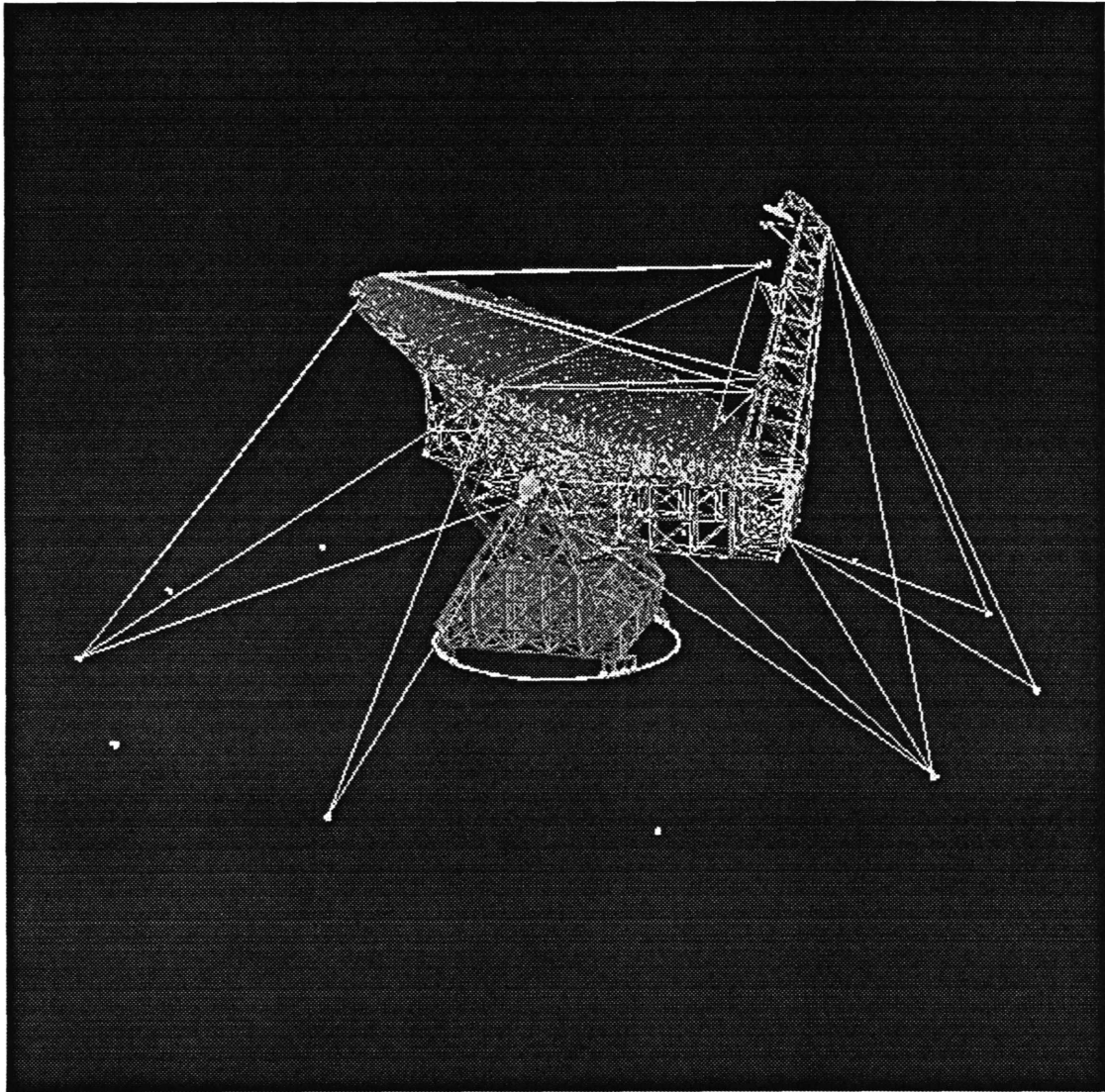


Figure 3: The electronic distance measurement instrumentation which has been custom designed by the GBT Antenna Metrology group for the GBT application. It includes 12 ground based instruments on stable monuments to provide an absolute earth based coordinate system, and 6 antenna mounted instruments to measure 2209 points on the main reflector every eight minutes. Together, the instruments will measure the shape of the reflector and cardinal points on the structure, and translate the coordinates into the absolute coordinate system for surface shape correction (by actuators on the surface panels) with an accuracy of around 0.1 mm, and provide a dynamic model of the structure to provide pointing accuracy of around 1 arcsecond.

primary and secondary foci, the primary focus adjustment mechanism, the subreflector position and orientation, and the secondary focus turret position. All alignments will be checked under both static and dynamic conditions. The care with which the antenna has been assembled, erected and aligned has already allowed us to detect and correct fabrication errors and has facilitated the total construction process.

Specific examples of measurements being taken during construction of the GBT include: use of P. Pellissier's Hydrostatic Level System to set the azimuth track; monitoring of structural frequencies of major components and subsystems as erection proceeds coupled with a measurement analysis giving the mode damping coefficients; photogrammetry to set the subreflector surface and calibrate the adjustment mechanism; tests of alidade track level effects on pointing; and telescope thermal and wind stability. As construction progresses the metrology system will be used to verify the shape of the main reflector surface at the

rigging angle; ascertain subreflector orientation versus elevation; evaluate vertical feedarm stability under gravitational, thermal, and wind effects; and continue overall characterization of the telescope. Figure 4, as an example, shows vibrational amplitude measurements made by accelerometers placed on the alidade structure during construction. This provided a vibrational spectrum, Figure 5, from which a definitive value of damping associated with the dominant modal resonance may be calculated, in this case, 0.4 percent. This value is consistent with a very high quality welded steel structure.

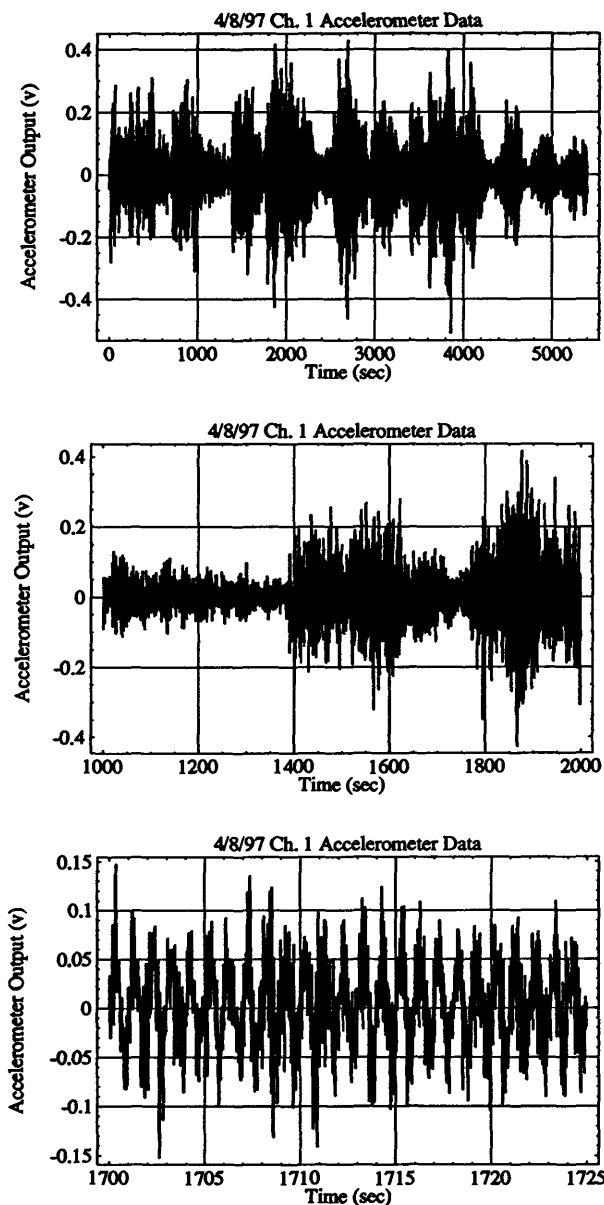


Figure 4: A 1 ½-hour time series of accelerometer data, recorded on April 8, 1997, showing the vibration response of the GBT alidade structure to random excitation forces (due to wind gusts and construction activity). (*Top*) The entire recording; (*Middle*) A 1000 second segment of the recording; (*Bottom*) A 25 second segment; here the ~ 1 Hz modal resonance is evident.

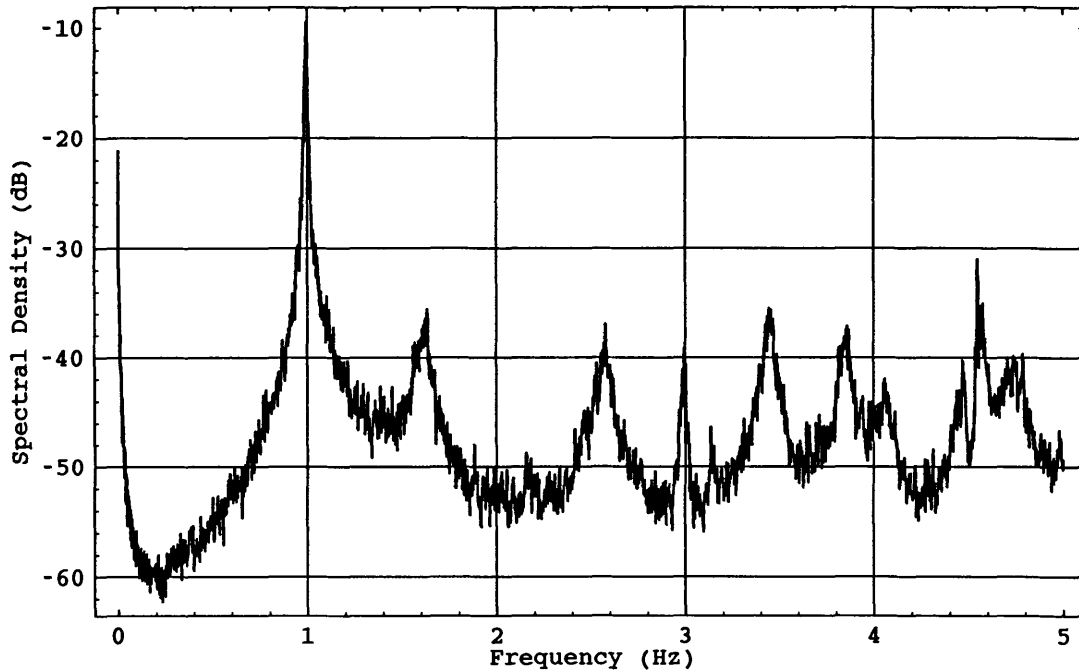


Figure 5: Power spectrum of vibrations of the GBT alidade structure, derived from the data of the previous figure, plotted over the range 0-5 Hz. The dominant modal resonance is at ~1 Hz. The spectrum was computed from 90 minutes of data using a 32,768 point sliding data window, 50% overlap, and no tapering.

4. VALIDATION AND AMENDMENT OF THE FINITE ELEMENT ANALYSIS

Because the GBT is the first large telescope to be built with an offset feed (unblocked aperture), dictating the use of an asymmetrical and highly indeterminate configuration, care is taken to validate and amend the structural finite element model so that it correctly predicts telescope performance. The finite element model of the tipping structure has 5790 joints, 18,200 elements and 33,600 degrees of freedom. Refinement of the FEM is a continuing task as the telescope evolves. Early design assumptions regarding the degree of fixity of the joints, offsets at the joints and density and stiffness of the members are modified to fit actual measured performance. Note that the design itself is not changed, i.e., member sizes, areas, connections, or configuration—only the assumptions are modified. Using the laser system to observe the telescope response to thermal gradients and wind loads provides data to check the finite element model, and also to characterize and predict future performance. Observation of vibrational excitation effects is allowing the preparation of various plans to deal with the induced vibration. Throughout this time, the structure is being carefully examined for faults or potential design errors. Marginal performance areas or subsystems will be earmarked for possible upgrades as part of concerted efforts of the GBT team to achieve telescope operation at higher frequencies.

5. CONFIRMATION OF ACCEPTANCE CRITERIA

The contractor is responsible for making proper tests to verify the operation of both the azimuth-elevation and the feedarm servo systems using traditional proportional servo controllers. As an adjunct to these tests, NRAO will further characterize the actual structural modes, using the metrology system, and develop optimized servo control algorithms to minimize excitation of these modes. Use of these high performance algorithms should also allow operation at higher wind velocities due to their inherent disturbance rejection property.

In the past, large antennas with symmetrical designs were accepted based upon a combination of physical measurements which could be conveniently made and performance as predicted purely by calculation. Concrete measurements included static locked rotor frequencies (normally the first few modes), surface panel settings, feedarm deflection due to gravity, etc. Structural

response to wind, thermals and determination of vibrational behavior fell in the category of calculated performance, which at best had an uncertainty factor of about 15 to 25 percent consistent with the quality of the available Finite Element Model. Today however, with sophisticated measurement programs, nearly all acceptance criteria can be physically measured with a high degree of certainty.

As an example of the capabilities of the ground based rangefinders, Figure 6 shows a rangefinder measurement of the relative motion of a reference retroreflector target mounted atop the contractor's tower derrick during the hoisting of the 68 ton (7R) module of the backup structure to its position in the tipping structure. The rangefinder was located $\frac{3}{4}$ of a kilometer from the derrick during the hoist. As a comparison the rangefinder also monitored a secondary stationary target reflector located 1 kilometer away on a nearby mountain to observe the effect of atmospheric fluctuations and change during the lift.

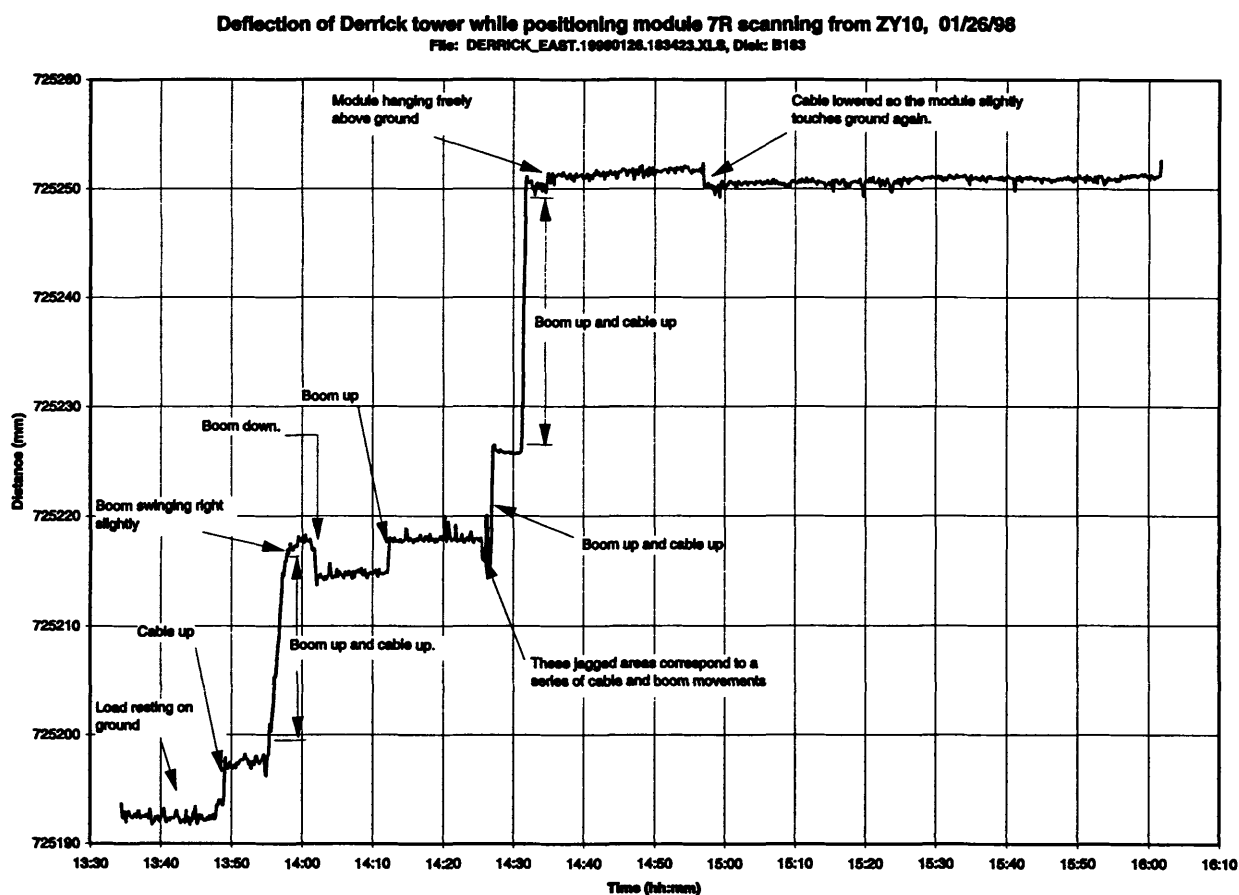


Figure 6

6. OUTFITTING AND COMMISSIONING THE GBT

Following NRAO's acceptance of the antenna from the contractor, the measurement program will provide data to aid the rapid outfitting and commissioning of the GBT. The program will provide a means to validate and verify the construction and proper erection of the structure, leading to efficient and timely integration of NRAO furnished equipment. Without a careful calibration plan to isolate variables and deal with them one, or at most a few at a time, gain and pointing optimization will converge much too slowly, if at all. Also, the program can identify design, fabrication and installation deficiencies while the antenna is still under warranty. Time spent to achieve successful operation at higher observing frequencies will be shortened, due to the knowledge base developed in the early part of the project. The program management intends to overlap the outfitting of the

telescope with the final completion phase of the structure. If this can be achieved it will shorten the time to fully commission the telescope, while providing valuable on-the-job training for NRAO operation and maintenance personnel.

7. GBT PHASES

The GBT is designed for versatility. It will be capable of continuous improvement throughout its lifetime. In line with this viewpoint, the GBT program has been classified into four phases.³⁵ Phase 0 is acceptance of the “as built” structure. Phase 1 (operation at 15 GHz) deals with outfitting and commissioning the telescope. In Phase 2, (operation at 43 GHz) the active surface will become operational on an open-loop basis. In phase 3 (operation at mm wavelengths) closed-loop operation of the active surface system and establishment of the closed-loop precision pointing system will be achieved. The expected setting and performance accuracies are listed below:

Phase	Measurement and Setting	Surface Accuracy	Pointing Accuracy
0	1.00 mm (0.040 in)		
I	0.450 mm (0.018 in)	1.25 mm rms (0.049 in)	7 arcsecond
II	0.100 mm (0.004 in)	0.42 mm rms (0.017 in)	3 arcsecond
III		0.22 mm rms (0.009 in)	1 to 2 arcsecond

As previously noted, during construction the measurement program will be instrumental in monitoring critical alignments; flagging design deficiencies; initially characterizing structural, mechanical and servo performance; starting the amendment of the finite element model (FEM); confirming acceptance criteria and isolating areas of performance which might be improved later. At this point the program will be structured to provide data which will assist in the effort to achieve telescope operation at millimeter frequencies. As indicated in the table above, this involves improving the surface accuracy of the 100 meter primary reflector, refining servo control algorithms and upgrading telescope pointing accuracy.

8. IMPROVEMENT OF SURFACE ACCURACY

By the specification, the Contractor is required:

“not to exceed an overall root mean square (RMS) surface error of 1.25 mm (0.049”). This total error budget includes contributions from both the primary reflector and the subreflector. Causes of surface errors include manufacturing, setting, measuring, gravity, and wind or temperature. This error budget was designed to permit operation at frequencies of 15 GHz and below.”

The Contractor is also responsible for measuring and setting the GBT surface to an accuracy of 0.040" rms. This will be accomplished using a Leica TDM 5000 Total Station together with photogrammetric measurements and independently verified by feedarm laser metrology, when available. Since four (4) surface panel corners are supported from a single active surface actuator, and the corners must meet in a smooth fashion, the metrology group has developed and is furnishing a panel corner setting tool, which provides relative measurements allowing the adjustment of each individual panel to its “best fitted” manufacturing accuracy.

In Phase 0, the Contractor is only required to set the GBT surface to an accuracy of 0.040" rms. NRAO needs to improve this measuring/setting accuracy to 0.018" rms. We presently plan to achieve this, during the Phase I outfitting and commissioning operations, through the use of photogrammetry or holography. When the laser metrology system becomes fully operational, a data base of telescope surface data will be collected allowing good surface accuracy to be achieved over the full range of antenna elevations. When the open-loop active surface becomes operational, hopefully toward the end of Phase I, the surface accuracy will be optimized by recalibrating the zero point on the actuators in accordance with the surface accuracy data base.

In addition to providing measurements which will allow the measuring/setting tolerances to be reduced, the metrology system will provide a complete definition of the paraboloidal surface performance under a wide range of weather, wind and environmental conditions.

9. IMPROVEMENT OF SERVO SYSTEM

The GBT servo systems specification states:

“The specifications given in this section are for a servo system that will give performance adequate for operation at 15 GHz. Of critical importance, however, is that the performance of the servo system not be a limiting factor in the implementation of high frequency operation, in which the pointing of the instrument will be upgraded by NRAO to the 2 arcsecond level.”

Analysis of the GBT pointing error allocations shows that the AL-EL servo and drive, the subreflector servo and drive and the mechanical system contribute approximately 50 percent of the total pointing error. To assist in the minimization of these errors, individual error contributors will be carefully measured and analyzed with the objective of minimizing or eliminating it.

A series of servo tests will be made to investigate the control algorithms' performance and dynamical excitation of the structure, feedarm, and the subreflector caused by external disturbances.

These include:

- a) Position error as a function of axes orientation (angles) and rate.
- b) Position switching at various axes orientations.
- c) Servo performance as a function of counter torque variations.
- d) Servo performance as a function of rate loop gain variations.
- e) Servo performance as a function of position loop control algorithm optimization to minimize structural excitation.
- f) Servo performance as a function of wind induced disturbances.

The measurement system (i.e., laser rangefinders, accelerometers, . etc.) will be used during these tests to observe the vibrational properties of the structure, feedarm, and subreflector. These measurements will be analyzed to characterize the vibrational modes of the telescope under various conditions. The measurement system, and the information it provides, will be invaluable toward development of control algorithms essential to successful operation at higher frequencies of Phase II and III.

10. IMPROVEMENT OF POINTING ACCURACY

In the GBT specifications:

“pointing error is defined as the difference between the commanded position of the antenna and the actual sky position of the main beam of the antenna. Contributions to pointing error caused by gravitational deformation, axis misalignment, encoder offset, bearing run out, bearing misalignment, track deviations and the like, are repeatable. Nonrepeatable pointing errors are due to wind, acceleration forces, temperature differences and changes, encoder resolution, encoder error, data converter error, servo and drive errors, position update rate, bearing nonrepeatability, and all other random errors.”

It is a requirement of the Contractor that: The nonrepeatable pointing error under normal operating conditions shall not exceed 7 arcsecond RSS without wind and thermal effects, and shall be less than 14 arcsecond RSS when wind or thermal effects are included.

NRAO plans to achieve high frequency operation of the GBT in two phases: Phase II - precision operation (43 GHz) and Phase III - high frequency operation (mm wave). As shown in Table 1, the associated telescope pointing accuracies required

are 3 arcseconds and 1 to 2 arcseconds, respectively. In Phase II the active surface becomes operational, in Phase III the precision pointing system will be actuated. Although the active surface will improve the gain and efficiency of the telescope, it will contribute little to improving the pointing. Thus, the real challenge lies in improving the pointing accuracy during Phase II, since Phase III operation will benefit from the precision pointing system. We believe that the improvements in pointing made to accommodate Phase II will be of help in implementing the high frequency operation in Phase III.

11. SUMMARY

It is obvious that sophisticated instrumentation and methodology are needed to realize the performance improvements required to operate the GBT at higher frequencies. The measurement system has already been used to minimize alignment errors during the construction of the GBT. If major elements of the telescope were poorly aligned, pointing coefficients would be significantly larger than for a well aligned telescope. The larger the pointing coefficients, the harder it is to determine them accurately enough, using astronomical methods, for mm-wavelength observing.

For the first time, a measurement program will be used for the accurate determination of systematic errors and the total characterization of a telescope. In the case of the GBT, these data will be used for the early development of pointing coefficients. The metrology system will provide an accurate characterization of the telescope allowing the precise determination of some of the pointing coefficients. The resulting precision of the pointing algorithms will decrease the amount of observing time required to recalibrate the pointing. The metrology system should be helpful in identifying pointing residuals and their possible causes for further evaluation and possible elimination. The early determination of pointing coefficients will assist astronomers in the efficient commissioning of the telescope. It should be possible to generate a complete set of pointing coefficients in just a few hours of measurement.

A continuing goal of the GBT Metrology Group will be to develop historical data for a trend analysis program. Range and other performance measurements are made on a routine basis to various points and equipment on the structure to give advance warning of changes in performance. These changes will be analyzed to determine the need or methodology for correction. When coupled with an effective maintenance program, it will increase the availability of the GBT for basic science research.

12. ACKNOWLEDGEMENT

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