The Green Bank Telescope Active Surface System

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ABSTRACT

During the design phase of the Green Bank Telescope (GBT), various means of providing an accurate surface (0.220 mm) on a large aperture paraboloid (100 m), were considered. Automated jacks supporting the primary reflector were selected as the appropriate technology since they promised greater performance and potentially lower costs than a homologous or carbon fiber design, and had certain advantages over an active secondary.

The design of the Active Surface has presented many challenges. Since the actuators are mounted on a tipping structure, it was required that they support a significant side-load. Such devices were not readily available commercially so they had to be developed. Additional actuator requirements include low backlash, repeatable positioning, and an operational life of at least 20 years. Similarly, no control system capable of controlling the 2209 actuators was commercially available. Again a prime requirement was reliability. Maintainability was also a very important consideration.

The system architecture is tree-like. An active surface "master-computer" controls interaction with the telescope control system, and controls ancillary equipment such as power supplies and temperature monitors. Two slave computers interface with the master-computer, and each closes approximately 1100 position loops. For simplicity, the servo is an "on/off" type, yet achieves a positioning resolution of 25 microns. Each slave computer interfaces with 4 VME I/O cards, which in turn communicate with 140 control modules. The control modules read out the positions of the actuators every 0.1 sec and control the actuators' DC motors.

Initial control of the active surface will be based on an elevation dependant structural model. Later, the model will be improved by holographic observations. Surface accuracy will be improved further by using a laser ranging system which will actively measure the surface figure.

Several tests have been conducted to assure that the system will perform as desired when installed on the telescope. These include actuator life tests, motor life tests, position transducer accuracy tests, as well as positioning accuracy tests.

Keywords: surface accuracy, active surface, surface control, actuator.

1. INTRODUCTION

The Green Bank Telescope (GBT) is a100-meter, fully steerable, unblocked aperture radio telescope[1] presently under construction in Green Bank, WV, USA (Fig. 1). Challenging design requirements of large aperture, operating frequencies up to 86 GHz[2] and low cost have led to the implementation of an instrument with an active primary reflector. Following on the heels of adaptive primary optical telescopes[3] as well as radio telescopes which use actuators to make infrequent surface adjustments[4,5,6], the GBT is the first radio telescope to attempt to dynamically control a large primary.

An overview of the active surface system is presented in Section 2. This includes a general physical layout of the system and well as a basic description of how it operates. Detailed component descriptions and key design decisions are presented in Section 3. Although the system is not yet in use, much test time has been acquired on various subsystems. Since the testing has shaped several design decisions, several key tests are discussed in Section 4.

2. SYSTEM OVERVIEW

2.1 Dynamic Capabilities

The active surface system consists of 2209 electro-mechanical actuators and associated control electronics. With a positioning resolution of 25 microns and a speed of 250 microns/sec, the system is capable of correcting the 100-meter primary reflector for deformations due to gravity (even at the telescope's maximum slew rate), temperature, and steady wind. Expected gravitational deviations from a best fit parabola are expected to be less than 6 mm peak-to peak[7], well within the 51-mm travel range of the actuator. The system is operable in winds of up to 11 m/s at all telescope orientations.[8]

2.2 Control Model

Initially, commands to the system will be generated based on a structural model, which will later be refined by holographic measurements. Eventually, a laser ranging system[9] will be capable of measuring the surface in near-real-time. When interfaced with the active surface system, the laser ranging system will enable setting the surface to better than 220 microns.[2,10]

2.3 System Configuration

As shown in Figure 2, the actuators are
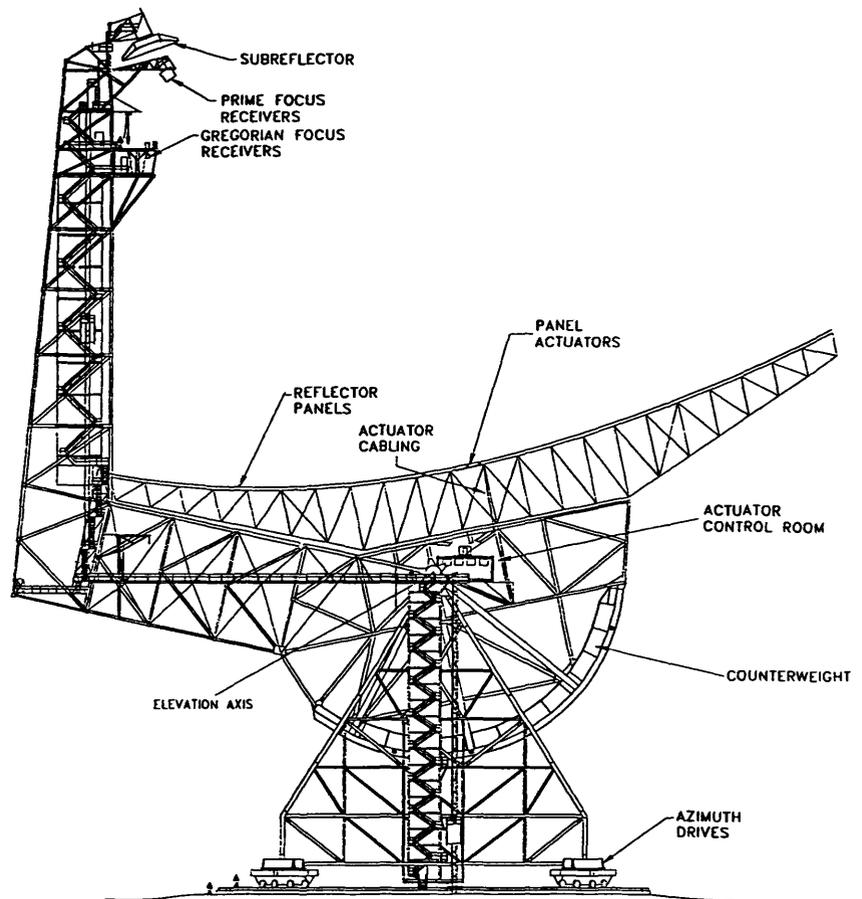
Figure 1: Drawing of the Green Bank Telescope (*Courtesy of COMSAT RSI*)
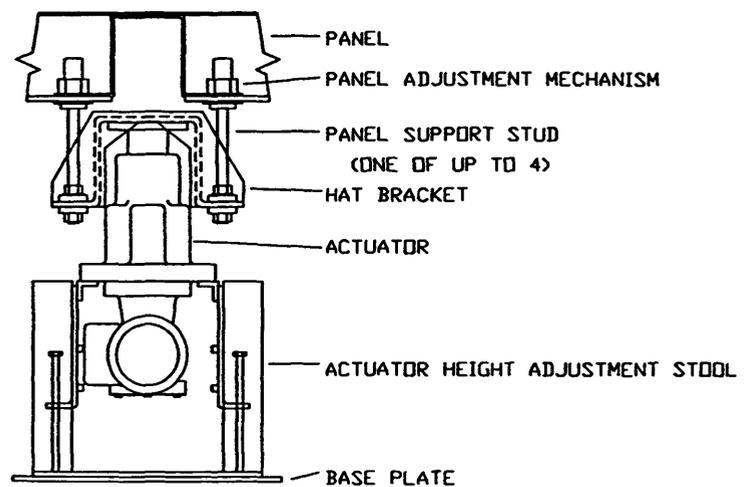
Figure 2: Mechanical configuration of the panel actuators.

configured to support up to 4 adjacent panel corners. For initial mechanical setting in three orthogonal directions, the actuators are mounted on a "stool" which is situated on a flat plate. The stool is adjustable, permitting vertical adjustment, and the flat plate permits adjustment in the horizontal plane. Once adjusted to within 3.2 mm of the design paraboloid, the vertical adjustment is pinned and the horizontal adjustment is welded.[11] The adjustment screws on the hat bracket provide for the relative adjustment of the panel corners as well as for the differential expansion of the aluminum panels and the steel backup structure. A network of cable trays in the backup structure routes cables from all actuators to a dedicated control room.[12] As shown in Figure 1 the control room is located near the elevation axis, on the tipping structure. With eight bulkheads, four each on opposite sides of the control room, this room accommodates all the actuator cables. All electronics required to control the actuators, and their associated power supplies, are housed in the control room.

2.4 System Block Diagram Description

A simplified block diagram of the system is shown in Figure 3. The main input to the system is a command vector of desired actuator lengths for each of the 2209 actuators. The main outputs are the lengths of the actuators. Commands are transmitted to the active surface system via an Ethernet connection, using a Remote Procedure Call (RPC) protocol. For convenience, the command vectors are ordered per the rib and hoop topology of the telescope backup structure, where the actuators are physically located.[13] The Active Surface Master Computer receives the commands and processes them in several ways. Initially the commands undergo a sanity check. Following this, the "ideal" commands are turned into "real" commands by compensating for the temperature, gain, and offset characteristics of the actuators. The commands are then permuted to account for the mapping of telescope ribs and hoops to control system addresses.
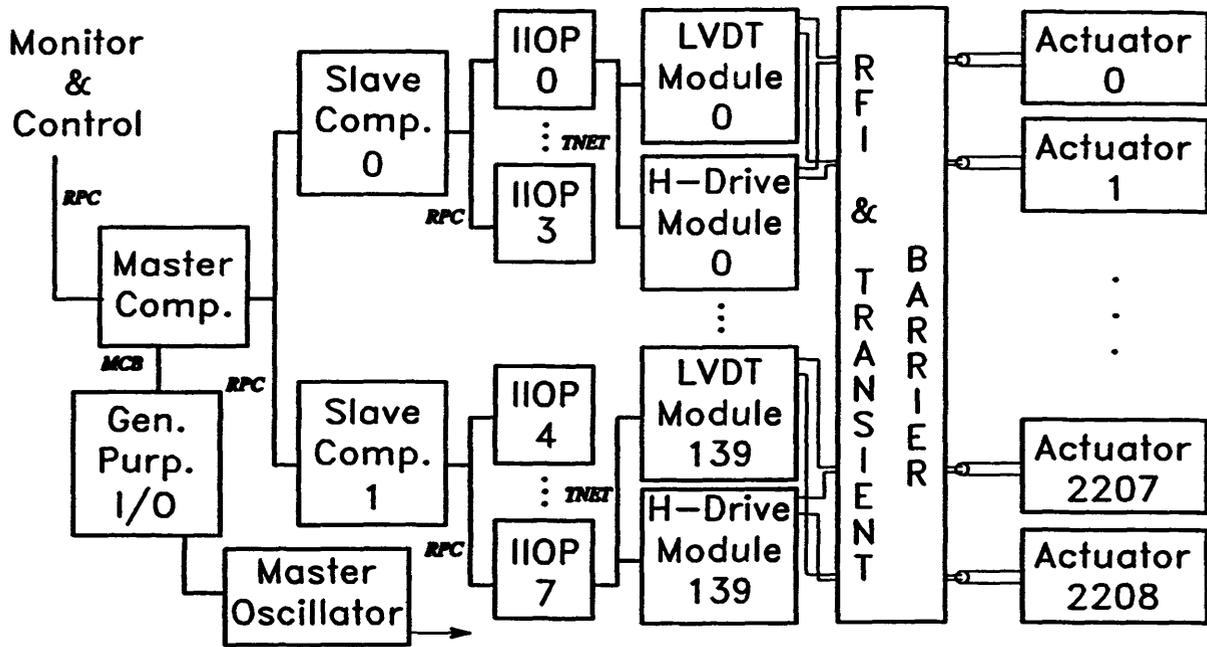
Figure 3. Active surface System block diagram.

Again using an RPC protocol, "real" position commands are transmitted to the Slave Computers, whose main task is to close the position loops. To control the actuators, the Slave Computers communicate with Intelligent I/O Processors

(IIOPs), which basically interface the VME computer bus to proprietary serial busses. In turn, the serial busses communicate with two types of control modules, the LVDT Module, and the H-drive Module. An LVDT module functions as a readout for 16 Linear Variable Differential Transformers, or LVDTs, (the actuator position transducers), while an H-Drive module functions as a motor driver for 16 DC Brush motors (the actuator motors). Thus, a pair of modules (one LVDT Module + one H-Drive module) contains the control electronics for 16 actuators. The system requires 139 pairs of modules to control the entire complement of actuators.[14]

Other modules shown on the block diagram include the Master Oscillator and General Purpose Input/Output (GPIO) modules. The Master Oscillator provides a common, stable reference frequency for all LVDT modules. The modules, in turn, excite the LVDTs at this frequency, providing optimum efficiency. Operating all LVDTs at the same frequency also obviates the possibility of crosstalk at beat frequencies of several independent references. The GPIO, as its name suggests, has many purposes. First it monitors and controls most power supplies in the system. This gives software the ability to monitor supply voltages and turn the supplies on or off, either to conserve power or to protect the system. Second, it monitors the room temperature, giving software the ability to send complaints to the telescope operator when the temperature reaches a "warning" or "fault" threshold. In the case of a temperature fault, software shuts down most of the system power, also through the GPIO. Third, hardware watchdogs in the GPIO guard against software crashes in each computer, shutting down affected hardware and in some instances, resetting parts of the system. Fourth, it interfaces to the telescope's emergency stop system, causing all actuators to stop by shutting down power supplies and signaling the master computer so that the software is aware of why the system has been shut down. Fifth, it provides a means for the software to read the status bits of the master oscillator. Finally, it provides a means of monitoring the temperature of 16 actuator position transducers. The software can then use these temperatures, and a temperature distribution model, to temperature compensate all transducers.

2.5 Actuator Control

Each actuator is controlled with a simple on/off method. Upon receipt of a valid position command, the actuator is driven at full speed in the direction that decreases the position error. Every 100 ms, the position error is measured. When the position crosses the edge of a pre-computed window around the desired position, the actuator is halted long enough to acquire an accurate position measurement. Based on the known velocity capability of the actuator, the time required to move the actuator from its present location to the desired location is computed. Finally, the actuator is powered on for the computed duration, quantized to the nearest 100 ms. Given the nominal actuator velocity of 250 microns per second, the 100-ms time quantization permits a positioning *resolution* comfortably within 25 microns peak.

The active surface system will have the benefit of the laser ranging system[9] soon after first light. The laser ranging system will provide the capability of calibrating all actuators in situ. Thus, the accuracy of the active surface system will be limited by the ability of the laser ranging system's ability to calibrate it, and the resources available to apply the calibration in real time. Early in the life of the active surface system, and probably periodically thereafter, the laser ranging system will be used to calibrate the gains and offset of all actuators. The positioning algorithm will use this calibration and the average nonlinear characteristic of the LVDTs (see Section 3.3.3) to position the actuators. Taking into account nonlinearity errors, calibration errors, temperature drifts, and positioning resolution, a system accuracy of 75 microns rms should be achievable. Greater accuracy can be achieved by embedding the actuators in position loops closed by the laser ranging system. Then the accuracy would be limited by the laser ranging system's accuracy, and the finite positioning resolution of the actuators.

3. SYSTEM DESCRIPTION

3.1 Design Environment

To gain a better appreciation for some of the design decisions, understanding the environment in which these decisions were made is useful. The initial construction schedule for the telescope called for completion in four years. Since the actuators are part of the structure, the schedule called for the delivery of actuators by NRAO to the antenna contractor in 26 months.[15] This put the development of the active surface on a fast track. Thus, some design decisions were made based on past designs that worked well rather than on lengthy evaluations. A second factor was a fixed budget, not indexed for inflation. Thus the

sooner money was spent, the more it was worth, so long as it was not wasted. Another constraint was the unknown mechanical performance of the telescope. How much would it deform? How much could panels be stressed before being permanently deformed? These uncertainties resulted in many safeguards and significant margin being designed into the system.

3.2 System Topology

In the earliest phases of the project, several means of achieving a 100-m radio telescope with a 220-micron surface[2] were considered. The first of these was the use of low expansion, high strength-to-weight ratio materials (e.g., carbon fiber). This approach was quickly discarded due to cost. The advantages of a deformable primary versus a deformable secondary were studied,[16,17] with no clear winner emerging. A deformable subreflector would require fewer actuators, resulting in a cost savings, and it would be more accessible. However, the weight of many actuators on the subreflector was deemed undesirable, and there would be no ability to correct small (panel sized) deformations of the primary, if this were required. Advantages of the active primary included the simplification of the precision setting of the primary, the ability to correct small scale deformations, and the possibility of using the prime focus for high frequency observations. Disadvantages included cost, and difficult access for maintenance purposes. When an active primary was selected, the debate turned to whether rafts of panels, adjacent panels, or individual panels should be controlled. Rafts were discounted by the structural engineers as being too complicated. Actuation of individual panels was too expensive, leaving the actuation of adjacent panel corners, as shown in Figure 2, as the only viable alternative.[18]
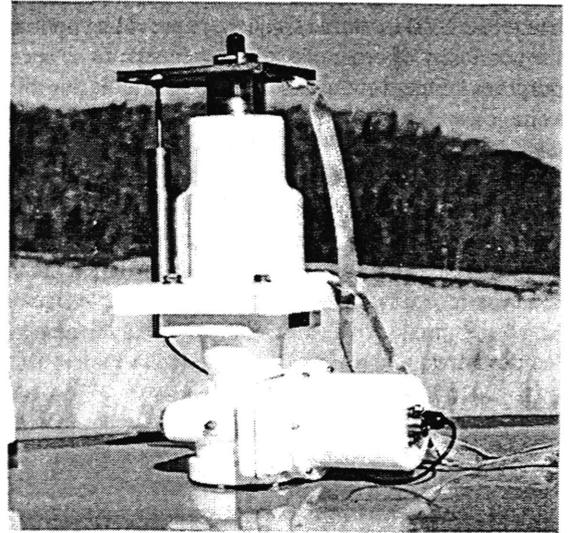
Figure 4: Photograph of a panel actuator.

3.3 Actuator Design

Since the actuators are critical to operation at frequencies above 15 GHz, and since access to them is quite difficult, reliability is a high concern. To this end, specifications[8] were generated and distributed to industry for bid. Prototype components were procured from several vendors and submitted to rigorous accelerated life testing. Based on the results of these tests and the vendor's final bid package, vendors were selected for all three main subsystems: the mechanical jack, the motor, and the LVDT position transducer. Each of these is discussed in the following sections. A photograph of the final product is shown in Figure 4.

3.3.1 Jack

To keep the panel interface simple, the antenna engineering group insisted that the jacks support both the axial and side loads of the panels. For many reasons it was also required that the actuators be self-locking with power removed. Such a design had been fielded on the Nobeyama 45-m radio telescope, but those jacks did not meet some of

Table I
Key Actuator Specifications

Stroke	51 cm
Speed	250 microns/sec
Static Load Axial Side	 481 kg 481 kg
Dynamic Load Axial Side	 186 kg 186 kg
Life	20 years at 1270 m/yr
Motor type	DC Brush
Position Sensor	LVDT

our requirements.[6] Thus specifications and a concept were distributed to the actuator industry. As described in Section 3.1, this tactic led to an acceptable design, and a vendor, Industrial Devices Inc., was selected.

A summary of the actuator specifications is shown in Table I. Featuring a ball-screw for low backlash and long life, and a large polished piston supported by a brass bushing to support the side-load, final version actuators have easily exceeded the 2000 hour (continuous operation) life requirement.[26]

3.3.2 Motor

A DC brush motor was selected to power the actuators for several reasons: it is a well-established technology, requires only two wires for control, and is relatively low cost and weight efficient. In addition, estimates of actuator run time showed that this technology would meet the 20-year life requirement of the actuator.[19,20] Despite the purported advantages, we experienced reliability problems with early production models, and delivery problems due to manufacturing problems. One known disadvantage, the generation of Radio Frequency Interference (RFI), was handled by several layers of filtering and shielding.

3.3.3 Position Transducer

The selection of the position transducer considered several potential technologies including linear potentiometers, LVDTs, rotary potentiometers, and incremental rotary and linear devices. Reliability considerations argued for measuring the controlled linear motion, and thus rotary devices were discounted. Incremental devices were discounted due to the need to periodically drive to a reference point to verify absolute position. This was deemed both wasteful operationally and risky due to the possibility of losing the initial panel setting during the telescope start-up phase. The only two real contenders were linear pots and LVDTs. Not having ample time to do long term reliability tests, LVDTs were selected based on past reliability experience.[21]
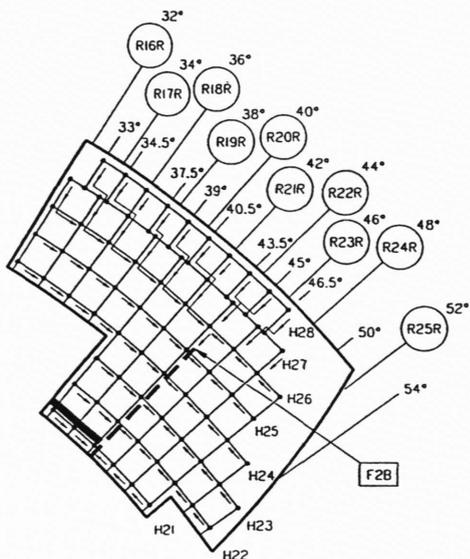
Figure 5: Cable routing plan for a section of the backup structure. Arrows show paths for each cable. Dotted and solid lines are 9 inch and 12 inch cable tray, respectively. (*Courtesy COMSAT RSI.*)
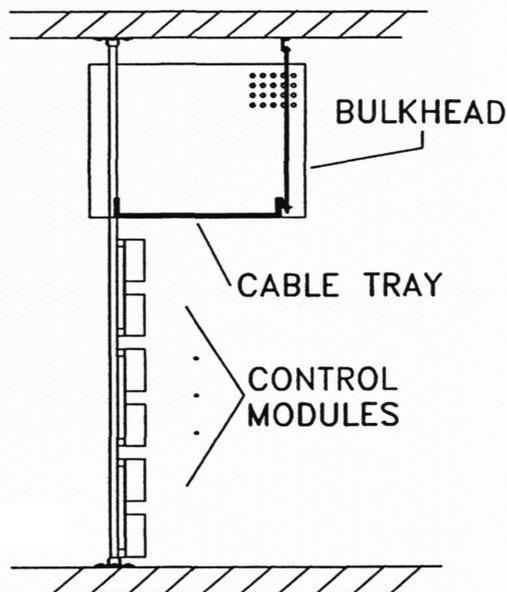
Figure 6: View from inside the actuator room, of the cable bulkhead, cable tray, and actuator control modules.

Two disadvantages of LVDTs are that they are somewhat nonlinear and temperature dependant. NRAO made detailed measurements of more than 1400 devices and analyzed the data from 500 of these.[22] Accurate indicated versus actual length measurements over the full stroke at five temperatures distributed over the operating range were performed. The analysis showed that the nonlinearity could be compensated using a model based on the *average* deviations of the 500 actuators, and that the resulting deviations from linearity would be approximately 40 microns. In addition it showed that deviations due to temperature variations were only about 16 microns rms, and therefore could be ignored for this application.

3.4 Cabling

For maintenance purposes, access to the actuators will probably be gained by removing a surface panel, and installing a special purpose platform in the resulting hole. One of the primary system design goals is to minimize the occurrence of this time consuming and hazardous process. To this end, all actuators are individually cabled to a control room located near the elevation axis, on the tipping structure. (Figure 1 shows the location of the "actuator control room.") Although this design uses a great deal of cable - over 160 km - it is considered the most reliable of several alternatives, since it minimizes the number of components required in the actuators and isolates faults to one actuator. One has direct electrical access to the actuator motor and LVDT from the actuator room and thus can, with high probability, isolate a fault before removing any panels. One obvious alternative, for instance, would be to use some type of daisy chained bus, which would drastically reduce the amount of cable, but this would require some electronics in each actuator and would double the number of outdoor connectors. A bus failure could disable a significant number of actuators and make it impossible to isolate a failure to a given actuator without removing a significant number of panels!

Each of the 2209 cables contains a 16 AWG twisted shielded pair for the motor and three 24 AWG low capacitance shielded twisted pairs for the LVDT. The routing of each cable and the termination of each wire requires careful planning and tedious bookkeeping. Each cable has been assigned a complete path from its actuator to its terminal board. Figure 5 shows the routing plan for a small part of the backup structure, while Figure 6 shows the arrangement of bulk heads, cable trays and control electronics in the actuator room.

3.5 Lightning Suppression

The cost of the system is well beyond the ability of NRAO to replace it out of operations money. Using construction money, safeguards against catastrophic damage due to lightning were built into the system. The first of these is a ground strap on the actuator to route high currents away from bearings. The second is a pair of transorb lightning suppressors on each wire, at the control room end. Tests at the Langmuir Lightning Institute[23] resulted in a recommendation of a 500-W rating on these devices. A low impedance ground system supports these devices. Thirdly, RFI filters are located between the transorbs and the control modules, further attenuating transient pulses. Finally, the control modules are isolated from their control and power inputs by transformers. They are electrically coupled only in small groups by heavily filtered motor power supply leads.

3.6 Radio Frequency Interference (RFI) Design

Both the DC brush motor and the control electronics are significant sources of RFI. On a radio telescope it is critical that this be suppressed. To suppress motor RFI, the motor is housed in a shielded enclosure within the actuator, and the motor leads are heavily filtered. The cable shield is connected to the actuator housing. RFI from the control modules is suppressed by housing the modules in a screened enclosure and filtering all leads in and out of the enclosure. Modules in the VME chassis and GPIO are housed in a shielded rack with all I/O filtered. In fact, the only items not shielded are the module and motor power supplies, which use ferroresonant technology, consequently emitting no RFI at frequencies of concern.

3.7 Control Modules

During the early actuator testing phase, and in previous projects, NRAO gained significant experience in the design of actuator control electronics. However, it lacked the manpower and manufacturing expertise to produce the quantity of

electronics required to control this large system. The method used to produce the required electronics combined the prototype and design experience at NRAO with the design and manufacturing expertise at Transition Technology Inc. The control modules are quite significant modifications of Transition Technology's standard products.[14]

Two types of modules were designed: the "LVDT Module" reads 16 LVDTs while the H-Drive module controls 16 motors. A total of 139 modules is required. Several features of the modules are of great benefit to the system. The first of these is the use of the AD598 chip to monitor LVDT position. Unlike most LVDT electronics, this chip basically senses the ratio of the input to the output of the system, rather than just the amplitude of the output. To first order it is thus cable length insensitive and insensitive to the phase of the LVDT signal. Another is that each module has local intelligence and so can be configured for fail-safe operation and can report a variety of information. Electrical isolation of the modules has been mentioned in Section 3.3. Finally, the modules are linked by a fast serial communication system which makes it possible for the control computers to query and command every actuator in 70 ms.

3.8 Computer system

3.8.1 Hardware

The control computers and associated interface cards are housed in a VME chassis. Most of the modules housed in this chassis are shown in Figure 1, and their functions are described in Section 2.4. The only exception is an IRIG board, which accepts an IRIG-B time signal and makes wall-clock time and timed interrupts available to other modules in the chassis.

3.8.2 Software

The basic functionality of the software system is described in Section 2.4. However, several useful details, not central to the operation of the surface, are omitted. These are described here. The system runs under the multitasking real-time operating system VxWorks which allows the use of remote consoles. The software includes several diagnostic functions which are callable from the consoles, permitting troubleshooting both at the master and slave levels. Heavily integrated into the telescope's monitor and control system, the software makes use of the Message System[24] to communicate warnings and faults to the operator, and of the logging system, to maintain a record of running time for each actuator. Several monitor tasks are included to measure the health of the system, both at start-up and during operation, and take appropriate action upon finding anomalies.

A graphical monitoring screen permits rapid evaluation of the status of the system. It shows which actuators are at their requested positions, which are in transition to their requested positions, and which are ignoring commands by using an array of color coded dots on a window. The dots are arranged to mimic the rib/hoop locations of the actuators on the physical structure. Additional capabilities can be gained by clicking on any of the dots. These include a detailed status and an ability to issue an individual position command. The rib/hoop to control-system address is dynamically displayed as the mouse is dragged across the array of dots.

The higher level software, which decides which actuators to move and by how much is not part of this system. It is described by Wells[25] elsewhere.
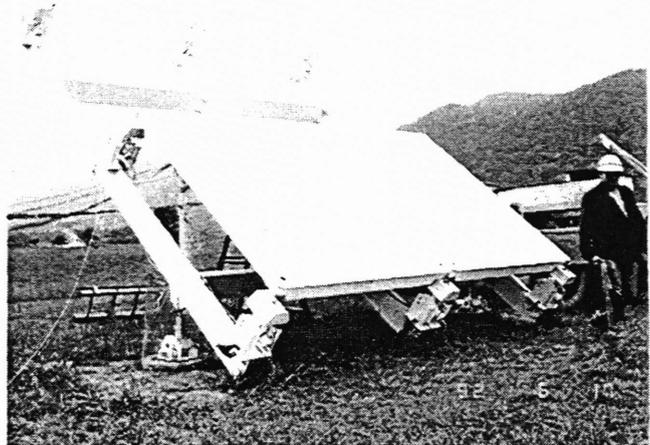
Figure 7: Four panel, nine actuator test jig used for testing production actuators.

4. COMPONENT TESTING

Throughout the design and manufacturing of the active surface system, a great deal of testing was performed - more than can be fruitfully reported here. Some tests proved particularly useful or interesting, however, and are mentioned below.

As soon as the first actuators were received, nine were placed in the test fixture shown in Figure 7. This fixture is essentially a four-panel subset of the telescope and was thus able to test for any mounting problems. Also, the loads and operating environment experienced by the actuators closely matched those of the final system. Two independent estimates of the required actuator running time in 20 years of telescope operation were roughly 2000 hours[19, 20]. All actuators on the jig were cycled continuously over most of their stroke. Approximately 1000 hours into the test, several motors experienced failures which were attributed to overzealous application of an adhesive to the brush screw. As a result, many motors had to be returned to the factory for repair.

Two other actuators were run on a separate fixture that applied varying loads to the actuator while it cycled over its full stroke. Approximately 1400 hours into this test, a defect was found in the actuators. As part of a manufacturing economy, a polished gear was replaced with a cut gear. In the failed actuator, it was found that the cut gear had completely worn the teeth of the gear with which it mated. The manufacturer promptly retrofitted many units.

Subsequent testing of the improved actuators and motors was quite satisfactory. These actuators had lifetimes of 5000 to 11000 hours, well beyond the 2000 hour requirement. In addition, the failure mode was the expected one: brush wear.[26]

Table II
Brush and Commutator Wear
in Short Step Tests

	Small Steps	Control
Brush Wear (microns)	192	163
Commutator Wear (microns)	84	17

One flaw in the above testing is that the accelerated testing did not test the effect of many start/stop cycles. The actuators were cycled at full speed from one end of the stroke to the other. To quantify the effect of many versus few start/stop cycles, a test was conducted in which control actuators were cycled from end to end as before, while other actuators were cycled the same *distance* but in many small steps.[27] The ratio of start/stop cycles in the small-step group versus the control group was 1000:1. An increase in brush and commutator wear was noted in the small-step group, as shown in Table II.

5. CONCLUSION

In summary, the design of the Active Surface System of the GBT has been presented. The system has demonstrated a 25-micron positioning resolution in the lab, and in outdoor tests. With the laser ranging system, a dynamic surface accuracy of better than 220 microns should be achievable in calm conditions. The system's tree-like architecture permits simple control via RPC's over an Ethernet connection. The modular architecture, individual cabling of actuators to a control room, and various software tools combine to make the system very maintainable. Several design features, both hardware and software, are included to safeguard the system. Many hours of testing have been logged in hopes of deploying a very reliable system.

6. ACKNOWLEDGMENTS

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