

The Green Bank Telescope Laser Metrology R&D Project

A Review and Bibliography

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Abstract

This ongoing collection of notes, calculations, procedures, and references is intended to be an internal reference source for the GBT Antenna Metrology group as the instrumentation, architecture, and control systems are developed. Due to the large number of people who contributed to the project on a part-time basis, as consultants, as transient students, who retired, or who moved on to other things—and the fact that a number of areas remain to be finalized—there is a problem with the documentation of all aspects of the project. It is hoped that this first in a series of notes will serve as a basis for more formal documents as various aspects of the project come to completion, and as a pointer to various references that have influenced the design of the GBT Laser Metrology System.

1 Historical Development

Following the collapse of the NRAO Green Bank, WV 300 Foot Telescope on November 15, 1988, and the rapid approval of a \$74,501,500 appropriation for its replacement on June 23, 1989, NRAO was thrust into the situation of writing specifications for the new 100 meter Green Bank Telescope (GBT) on a fast-track basis. The request for proposals went out on June 1, 1990 [1] with a target completion date of December 1994, and operation starting January 1995. The contract was awarded to Radiation Systems Incorporated on December 19, 1990, and groundbreaking took place May 1, 1991 [2].

The merit of a 100 GHz antenna [3,4,5] and the fact that an active surface would be necessary in order to build a 100 meter telescope at this frequency was recognized early in the project [6,7,8]. Of the four operational scenarios outlined [8], the closed-loop laser ranging feedback was considered the most ambitious. John Payne outlined an alternate method for the surface correction at the subreflector, instead of the primary reflector, in GBT Memo 12 [9], but the decision was made to make the correction at the main reflector [10].

The evolution of the laser metrology design is documented in a number of early GBT Memos [3,4,5,8,11,12,13,14,15,16,17]. Building on earlier work he and von Hoerner did on the 65 Meter Telescope [18], work John Payne had done in this area [19], and a long interest in the subject [20,21], John Findlay outlined the general idea of what was to become the basis of the GBT laser measurement system in GBT Memo 24 [15].

This memo describes “floodlight” and “beam” methods for measuring the surface. It also points out the merits of using distances and avoiding angle measurements, as well as a ground-based laser system. John Payne and Fred Schwab followed up in GBT Memos 36 [16] and 37 [17] with a more detailed architecture and error analysis of the “beam” laser metrology system.

It was tacitly understood that the laser system would be a relative measurement—with little precision in the mounting of the retroreflectors with respect to the surface panels, and little precision in the zero point offset of the instrument. The surface measurements would be relative measurements to bring the surface back into agreement with a calibration measurement derived from holography measurements [22], and

the structural information would be used to correct the differential motions due to thermal drift and to improve the finite element analysis model.

Due to the tough pointing requirements of the GBT and uncertainties in the yet to be designed "beam" laser system (e.g., the impact of weather and vibration of the feed arm), it was felt that a number of redundant systems should be investigated [23]. John Payne researched available hardware to implement the "floodlight" method [24].

In GBT Memo 38 [25], Chuck Brockway expanded on a system of autocollimator measurements to correct up to the elevation axis. A quadrant detector system, patterned after a system used on the 12 meter telescope in Tucson, was later proposed by John Payne [26,27] to be used as a closed-loop correction system for the position and vibration of the feed arm [28,29,30,31,32].

While it was felt that these systems were technically sound, they were all beyond the state-of-the-art in antenna design, and it would have been very hard to obtain reasonable bids from a contractor [33]. It was decided to bring each level of complexity into the GBT in phases, as later outlined by Bob Hall in GBT Memo 113 [34].

The Request for Proposals [1] called for the contractor to deliver a basic telescope using more conventional construction techniques, but with the provisions to incorporate the more unconventional technologies—which NRAO would provide.

Based on these proposals, \$3,866,555 was allocated to the surface actuator system, \$3,138,496 was allocated to the laser and quadrant detector systems development, and \$500,073 was allocated to the autocollimator system development as internal NRAO projects to provide these features [35,36,37,38].

With the confidence gained from field experiments [39,40,41,42,43,44,45,46,47,48], the need to easily interchange laser instruments, and a better understanding of the trilateration calculation errors, it was decided to make the laser system an absolute, rather than relative, measurement in 1992 [49,50,51].

Due to manpower limitations, the floodlight method was set aside in favor of the slower but more conventional serial mirror scan method [52]. However, the floodlight method was later patented by Ulich and Pfibsen [53,54]. After

the retirement of Chuck Brockway in December 1993, manpower limitations, and budget pressure, it was decided to abandon the autocollimator [42,55,56,57,58] development and reallocate the money; and rely on the laser system alone to measure the elevation shaft tilt and rotation.

From the outset of the GBT project, John Payne headed the metrology group and the Tucson electronics group while shuttling between Charlottesville, Green Bank, Tucson, and Australia. With the fundamentals of the laser system out of the way, and increased activity on the millimeter array, he backed out of the daily activities of the metrology group in April 1995. David Parker was assigned responsibility for the project [59].

2 Related Technologies

The concept of a near real-time closed-loop active surface and a ground-referenced pointing system is being pioneered with the GBT. There have been a number of steps taken in telescope surface setting, but to our knowledge there has not been a previous design using ground-based instrumentation to correct telescope pointing.

In the late 50's, the Navy started a 600 foot telescope at Sugar Grove, WV [60]. This telescope was to include 108 panels mounted on hydraulic actuators, with mechanical dollies that traveled over the surface, sending back data on the shape of the reflector. Due to technical difficulties with the telescope structure, this project was never completed.

The closest previous demonstration of the GBT metrology architecture is the Nobeyama 45 Meter telescope. As reported in GBT Memo 23 [14], Fred Crews and Rich Lacasse visited the Nobeyama telescope at the start of the GBT project. This telescope has 700 actuators, but they are not designed for closed-loop control.

As described in *Sky & Telescope* [61] and NRO Technical Report 3 [62] the telescope also includes a single laser ranging theodolite with an accuracy of 0.1 mm and 2 arc seconds. The measurements are reported to be accomplished in a single night. The IRAM 15 Meter and SEST 15 Meter telescopes also incorporate motor-driven panel adjustments [63] but again, not for closed-loop control.

In L0024 [64] John Payne reported on discussions he had with Greve, Isagura, and Hills at the 1990 URSI conference and the status of the IRAM 30 Meter and Nobeyama 45 Meter metrology systems. The general conclusion was that the system should use trilateration only and not try to use angle measurements, due to turbulence.

Greve and Harth [65,66,67] developed a laser ranging theodolite for the IRAM 30 meter telescope. The theodolite measurements had to be made through a tube to reduce beam jitter. It is interesting to note that in a 1994 paper by Greve et al. [63], they stated

Despite considerable progress in optomechanical equipment, viz. laser interferometer, laser distance ranger, infrared imaging instruments, electrical transducers etc., the implementation of these devices into accurate surface measurement systems has only been of limited success.

NASA and JPL have developed a Spatial, High-Accuracy, Position-Encoding Sensor (SHAPES) for tracking retroreflective targets on a structure [68]. This system also uses distance and angles, but the angles are sensed on a CCD camera and do not require pointing the instrument like a theodolite. The Russians have done laser ranging work for radio telescopes [69,70,71,72].

The GBT metrology system is being followed by a number of other interested parties [73,74,75,76]. NASA Goddard Space Flight Center, Experimental Instrumentation Branch, began developing a laser ranging system for the Gravity Magnetism Experiment Satellite (GAMES) Project. Kent Christian and his group visited Green Bank in February 1993 to get some ideas [77,78,79].

The high energy physics community [80,81,82,83,84], The National Institute of Standards and Technology (formerly The National Bureau of Standards) [85,86] and The National Geodetic Survey [87,88,89,90,91,92,93,94] also have dimensional metrology requirements in the same regime as radio astronomy.

In February 1993, John Payne was invited to visit the Superconducting Super Collider project [95]. A group from the Harvard High Energy Physics Lab visited Green Bank in April 1993, in

conjunction with an experimental package being developed for the SSC. The Harvard group duplicated a number of features of the GBT system as reported by Hashemi [82].

Unfortunately, with the cancellation of the SSC and reduced government spending at NASA, none of these projects were funded beyond the initial phases.

It is interesting to note that a plot of the accuracy of length measurements at NIST shows calibration standards better than 1 ppm only go up to 5 meters, and the maximum length of the surveying tape facility is 50 meters with an accuracy of 2 ppm [85]. The best U.S. calibration baselines for the 100 meter range are maintained by the Stanford Linear Accelerator. This baseline is used for world wide round-robin calibration of the highest accuracy EDM instruments.

3 Why Now?

With the lackluster history of applying EDM to radio telescope surface setting, much less a closed-loop system, it behooves one to ask why try it on the GBT. The answer is that there are a number of converging technologies that were not available even a few years ago that make it practical at this time.

The most obvious is the availability of cost effective computer hardware and software. The entire control package is built from catalog items, with a minor modification to the A/D board to generate a clock signal. Each instrument has its own embedded PC/AT bus control computer. The servo system board has two dedicated computer chips for complete servo mirror control. Analog-to-digital converters at 100 kHz sample rates with 16 bit resolution are now available at modest prices—thanks to digital audio consumer electronics.

IRIG time distribution and ethernet make interlocking remote embedded instruments very cost effective. Network boards and software are commonplace. The availability of laser diodes with built in GRIN lenses that can be directly modulated at 1500 MHz for less than \$150 is a result of consumer electronics CD players.

Electronic total station surveying instruments are a mature technology. While not up to the requirements of the GBT system, the allied technologies contribute to economies of scale. The

2400 retroreflectors purchased for the GBT surface represents about 2 weeks of world production. It is interesting to note that with the introduction of GPS, the production of retroreflectors has already passed its peak.

With the availability of this modestly priced technology and the networking ability of embedded computers, the GBT will be the first known demonstration of 18 automated instruments working in concert to produce redundant trilateration measurements. Moreover, 12 of the instruments will be mounted on very stable ground monuments which will be used to transform all coordinates to a fixed coordinate system.

Of course the most important reason for the laser metrology development at this time is the necessity! Due to the offset reflector design and asymmetric structure, deformation of the reflector and feed arm will be very large. While the Finite Element Analysis model will give first order gravity corrections, the as-built structure will not match the model exactly and no attempt is being made to model thermal deformations.

Without new metrology systems, the GBT would be severely limited at all but the lowest frequencies. With the direct allocation of \$7,000,000, and a significant commitment of the Green Bank electronics department resources to the active surface and metrology systems, and the additional expense in the contract to make the panels, subreflector, and structure up to specifications to go to 100 GHz, NRAO made a major commitment that the metrology system *has* to be made to work. Instead of incremental improvements, the metrology system is deeply embedded in the design and success of the telescope.

4 Design Criteria for the GBT

The basic design requirements were stated in John Findlay's GBT Memo 24 [15]. At this time, the standard high-end commercially available instrument is the Kern (Now Leica) Mekometer ME5000, with an accuracy of $0.2 \text{ mm} + 0.2 \text{ ppm}$ with a 2 minute measurement time and operator target sighting. The industry standard for length measurement is the Hewlett-Packard laser interferometer, but this instrument requires that the retroreflector be carefully translated along a lin-

ear track in order to avoid a loss of sight.

For applications where a target can be physically moved from one location to another, without a break in the interferometer path, the Leica SMART310 tracking laser interferometer is available [96]. Trackers incorporate a closed-loop servo-controlled mirror and a quadrant detector to keep the beam on the target. The accuracy on this instrument is 10 ppm. Leica later introduced the LT500, and in July 1996 they introduced the LTD500 laser tracker which incorporated an electronic distance measurement feature in addition to the interferometer. Chesapeake Laser Systems also makes a tracking laser interferometer. The CMS-3000 accuracy is 20 ppm. Later, SpatialMatriX Corporation (SMX) entered the laser tracker market.

A number of two-color instruments have been built over the years [97,98,99,100,101]. These instruments can correct for the speed of light dependence on temperature by using the difference in the group refractive index at two wavelengths, but no commercial instruments are now on the market. John Payne and Chris Salter did the calculations in 1990 and found that the dispersion was not great enough to measure the temperature over 100 meter path lengths.

While the accuracy of differential GPS is improving at a rapid pace, it still does not meet the accuracy and speed requirements to locate the feedarm, and of course it could not be used to set the surface [102,103].

Given that no known instruments met the requirements for the GBT, John Payne decided to custom design a system for the application.

The basic metrology architecture is composed of two systems—instruments mounted on the arm which measure 2209 points on the surface, and instruments on the ground that tie cardinal points on the structure (including the instruments on the arm) to the ground—and thus a fixed earth-based coordinate system [42]. The instruments on the arm can be thought of as providing measurements of the optical element (focal length, optical axis, surface accuracy, etc.), while the instruments on the ground provide information about the mounting (pointing) of the optical element. Approximate coordinates of the retroreflectors are obtained from a combination of conventional survey coordinates, design coordinates, a rigid telescope model as a function of azimuth,

and an elevation model corrected for gravity by the finite element analysis model [104,105,106].

The surface measurements will be used as feedback to adjust the surface, and to perform a best fit to a paraboloid [107]. The ground instruments will be used to locate cardinal points on the antenna, which will be used to orient the axis of the best fit paraboloid with respect to the earth and to locate the focal point. Cardinal points near the subreflector [108] will be used in conjunction with the subreflector actuator instrumentation to position the subreflector in the proper position. Points attached in close proximity to the elevation bearings [109] and other cardinal points on the structure will be used to refine the finite element model and thus improve the traditional pointing model of the telescope for those times when the laser system is unavailable due to weather conditions.

Measurement accuracy of 100 μm (the thickness of a sheet of paper) is required. Nominal measurement speed for adjacent panel retroreflectors is 5 points per second. All of the software features that were found to be useful in the experimental phase of the instrument design are included in the embedded control system.

After some debate about the merits of using several modulation frequencies in order to avoid the $n\lambda/2$ ambiguity in distance [110], it was decided to optimize the design to the GBT requirements and to measure modulo $\lambda/2$, with a modulation frequency of 1500.000 MHz, i.e., the distances must be known within ≈ 50 mm *a priori*.

In order to account for moving targets, all measurements must be time tagged using a common clock, and a central computer must have a running model of the structure to calculate retroreflector coordinates as a function of azimuth and elevation. An index of refraction model based on a combination of weather data, refractometer measurements, atmospheric model as a function of elevation, and possibly acoustic thermometry is required.

Due to the large number of instruments to be built (20), manufacturing costs were a major consideration in the design. Due to the complex application specific software that is required, the effort has been leveraged by using as much commercial software as practical in order to concentrate efforts on the unique software.

5 Documentation

A number of reports, articles and papers have been written in the open literature on the metrology system [41,111,112,113,114,115,116,117]. Some information is also available on-line via the internet at <http://freya.gb.nrao.edu/GBTMetrology/index.html>.

After the creation of the GBT archive file (with copies in Green Bank and Charlottesville) system in October 1994 [58,118,119,120,121], copies of a number of documents have been entered into the system primarily under the "L" (Laser), "P" (Pointing), and "AS" (Active Surface) number series.

Since this file system was created after the fact, some relevant documents may not have made it into the system. Documents are being added as they are found, but, of course, this makes searching difficult for the unfamiliar, since subject titles tend to be nondiscript, e.g., many documents are simply titled "laser ranging".

Experimental results and notes were recorded in a series of bound record books [122,123,124,125,126,127,128] and John Payne's lab notebooks. Data is archived in a collection of sequentially numbered disks, and plotted data is kept in chronological order in a series of binders and referenced to the source disk. An extensive photo collection has been maintained by Ron Monk, and the development has been filmed by Photosynthesis at regular intervals.

The signed mylar plots of the engineering drawings are filed under the D35420 series, and the AUTOCAD versions are maintained by the draftsman in the project directory—although some of the early drawings were not numbered and the originals are now lost. Drawing control sheets and CNC program listings are kept under the D35420D drawing series. The early (unnumbered) drawings are collected in a D size folder in the D35420 file drawers.

Earlier software documentation was insured by off site archival of source code, and written documentation [129]. This has now been automated [130].

All purchase orders are collected in two binders, with production instruments in a segregated section of the second binder. Transmittal forms are also kept in binders.

The project schedule documentation has undergone a number of software discontinuities with the transitions of responsibility from Bill Porter to Lou Macknik to Roger Norrod. The metrology has kept a separate Time Line program over the years, but the updates have not been at regular intervals.

6 Development Path

The laser metrology development was considered a reasonably high risk R&D project from the outset. It was felt that the highest priority should be put on getting experimental results as quickly as possible in order to evaluate the feasibility of implementing the system on the GBT. With this in mind, a rapidly conducted series of experiments was performed, starting in the spring of 1990 [131,132,133,134]. When issues arose about the most elegant way of doing something vs the most expedient way to gain the answer to a particular question, expedience was given the priority—as the early photographs show.

It was recognized early in the project that a potential fundamental limitation for the laser system could be atmospheric turbulence [98,99,135]. This would show up in the measurement data as noise and could require averaging over a long period of time in order to filter out the actual distance. In order to quantify this limitation, the first instrument was built and tested in the spring of 1990. This instrument was modulated at 400 MHz [136], but with the availability of directly modulated laser diodes, attention turned to a 1500 MHz instrument.

The choice of 1500 MHz was checked with the astronomers in the October 1990 NRAO Newsletter [137], and again with the Green Bank Director in January 1991 [138]. Wes Sizemore checked the system in January 1991 [139]. Sizemore and Lou Macknik checked the first article oscillators a few years later (no report can be found on this test), but results were very inconclusive due to the lack of equipment to conduct calibrated testing. This is expected to be rectified with the addition of an anechoic test chamber in the new Navy building.

After almost continuous operation since 1990, only 1 documented case of 1500 MHz interference has been reported [140]—but it is expected that Project Phoenix will require closer coordination with the metrology experiments [141]. It is also

assumed that the laser system will be turned off when observing at 1500 MHz harmonics, so provisions have been made to switch the RF power on and off under software control.

Working from John Payne's specifications [142,143,144], Richard Bradley designed and built the 1500 MHz laser modulator [145]. Borrowing a 1 kHz digital phase lock design from Dick Thompson, John Payne designed the first 1500.000 MHz modulation and 1500.001 MHz phased locked LO system, which Tom Dunbrack put together in a few days. Andy Dowd put together a 1 kHz generator and high speed counter, along with comparators to trigger the counter on a zero crossing. Dwayne Schiebel interfaced the counter to a PC to measure the phase of the return signal [146].

David Parker was hired and Ralph Becker transferred back to Green Bank, from Tucson, in July 1990. John Payne moved from Charlottesville to Green Bank in September 1990, for a year.

For the first 1500 MHz experiments, conducted in July 1990, a general purpose Clark-Hess phase meter was connected to a strip chart recorder, i.e., no computer was required. The Green Bank machine shop built the prototype instrument which looked much like an underwater camera [147]. It worked on a single line of sight and was pointed mechanically, and thus it was only practical to measure a single retroreflector. The strip chart was calibrated by translating the instrument on a machine shop stage.

The experiments were conducted in an abandoned antenna test building west of the GBT site, where many late evenings were spent. A shack was placed over an existing monument 120 meters away to house the retroreflector target, and electricity was run out to the building in order to provide lights for night work. The instrument was placed on a heavy surface plate table looking out a hole in a plexiglas window that was built by knocking out some of the concrete blocks.

Armed with only a phosphor infrared sensor card detector, attempts to align the infrared (780 nm) beam on the retroreflector at night were very difficult, since the phosphor card faded out for distances greater than 10-20 meters. This was compounded by walking in an unmowed field with groundhog holes while trying to watch the card.

A system was improvised to use an oscilloscope to watch the return 1 kHz IF signal and "walk" the path holding a retroreflector in the beam, based on shouted instructions from someone watching the oscilloscope. This allowed alignments to be done during the daytime. This procedure was later simplified by attaching the retroreflector to a Simpson meter with 120 meters of cable and watching the meter while keeping the retroreflector in the beam as it was carried down range.

Later the procedure was modified to use an audio amplifier and speaker to broadcast the 1 kHz tone when a signal was being returned. One could then simply go to the approximate location and "fish around" with a retroreflector until the tone was detected. Of course, an infrared viewer quickly became a high priority item, an intercom was added at the shack 120 meters down range, and the field was mowed.

From this humble beginning, the experimental work yielded valuable data almost immediately. This work showed that even next to the ground (which should be the worst case) and using a commercial phase measuring instrument, with no special filtering, turbulence was not a major problem [39,148,149].

In the fall, when a heater was installed in the building, it was discovered that better results were obtained when the window was opened, instead of looking through a hole in the window, due to turbulence created by the temperature difference between the room and the ambient [150]. In addition to seeing this on the oscilloscope, the turbulence was visible with the IR viewer when looking at the return beam projection on the wall of the building. With the first snow, it was discovered that minimum turbulence was seen in a light snow with the ground covered.

One particularly eventful experiment was conducted to simulate heat shimmer introduced by the surface panels. The suggestion was made to simply build a fire under the path. Due to EPA restrictions, the suggestion of pouring gas on the ground was nixed—but the works group built a long trough which was filled with water and gasoline was floated on the water. With a fire truck and crew standing by and the strip chart rolling, the signal was given to ignite the gasoline. The results were somewhat inconclusive, but not repeated, due to the huge fireball and thick smoke.

The second step was to build a servo-controlled mirror in order to direct the beam to multiple targets and study the characteristics of slower thermal drifts as a function of distance and paths, i.e., to study the homogeneity of the atmosphere and measure the time constant of thermal drift [151]. This version followed the "camera" style, but was mounted vertically inside a framework mounted on top of a block of concrete poured on top of the floor slab. An azimuth/elevation style mirror was attached above the "camera" lens and the beam was directed through the open window. This rather strange device looked like a flying saucer hovering over the "camera", or something from *War of the Worlds*. The spider holding the outgoing laser mirror in the center of the lens was later replaced by a much smaller mirror glued directly to the lens.

This instrument was built and tested in October 1990 [43]. The servo loop used 16 bit absolute angle encoders and tachometer velocity feedback. Dwayne Schiebel built the electronics to output an analog error between a computer set point and the encoders. This was input to an analog servo control board. At this point, the computer became an integral part of the instrument.

Three phase measurement techniques were evaluated. The phase meter was interfaced through the IEEE 488 interface, a zero crossing and counter circuit was implemented, and the presently used digital method [41,152,153] was prototyped. In December 1990, Andy Dowd spent a week in Green Bank. He wrote a "search" algorithm to spiral out around a starting coordinate until a retroreflector was detected—which greatly reduced the problem of locating a new retroreflector. He also wrote some strip chart plotting software to plot the data in real time.

A reference retroreflector, mounted on the instrument, was introduced in order to correct for electronic phase drift of the instrumentation by subtracting the common mode phase shifts. Monuments were constructed at 25, 47, 117, 196, 320 and 515 meters. These results showed that drift, due to changes in index of refraction, were linear functions of distance over adjacent paths [40,41,44,45,154].

The third step was to build three instruments and control the experiments from a central computer over serial interfaces. This step incorporated a number of improvements in the mechani-

cal and optical design. The architecture of the instrument changed from the "camera" design with enclosed optical paths to an open optical breadboard design in order to facilitate access to the optics and detector.

A modular detector enclosure was incorporated. The lens specification was changed from "the largest single element plano-convex in the Edmund Scientific catalog" to a 300 mm focal length achromat chosen to minimize the spot size on the detector. This made the optical train significantly longer.

The first mirror servo control board required manual tuning with a screwdriver. This proved to be a significant problem due to changes in the mechanical system as the temperature changed, e.g., the viscosity of the bearing grease. A review of vendor literature prompted a change to smaller and less expensive incremental encoders in order to use digital servo control chips. This design also eliminated the need for tachometer velocity feedback. The reduced size allowed the encoders to be directly coupled to the servo motors and thus reduced servo stability problems.

In January 1991, Mike Hedrick was transferred to the laser budget to provide machine shop support and Ray Creager was hired to provide software and hardware interface support for the experimental work. This control system required much more software development, but it was not yet a full-time job, so one of Ray's first jobs was to build the first control panel. Embedded computers for each instrument, commercial PID (Proportional/Integral/Derivative) [155,156,157] servo control boards, and digital phase detection was incorporated, as well as a central computer to direct each instrument.

Significant development time was required to master the PID servo control system, which made the mirror head resemble a paint shaker at first. Another problem that consumed several weeks was an undocumented read recovery time for the servo control chip (LM628), which resulted in lost encoder counts and thus major pointing errors.

After this problem surfaced, questions were raised about the reliability of incremental encoders, but the problem was solved by adding delays in the read cycle to compensate for faster computers. The clue to solving the problem was that a test program written in Basic worked fine, but a program written in C++ resulted in accu-

mulated errors over time. After this experience and testing, great confidence was gained in the incremental encoder software and LM628 chip.

One of the objectives was to subject the instruments to realistic environmental conditions. It had already been discovered that the instrument performed best when operating in ambient conditions—much like an optical telescope. Fortunately, the building also has a tall shelter area open to the existing retroreflector target paths.

Three concrete monuments were built under the shelter area. A Kelvin mount was introduced in order to make the instrument location on the monument reproducible. Each instrument's control electronics, including the computer, was enclosed in a NEMA 12 cabinet and mounted out in the environment next to the instrument. A 100 MHz reference was run from the MASER in the interferometer building to replace the crystal oscillator. Later experiments showed significant phase noise on the MASER at 30 Hz. This came as a surprise at first, but is now well understood and will be the subject of another report. No environmental problems were encountered with the control system, except possibly a floppy disk drive failure. The oscillator systems failed to lock in cold weather however, until they were wrapped with a heating pad and blanket.

John Shelton was hired and the first article was tested in November 1991. A full demonstration of the three instruments under a central computer control took place in February 1992. Software development for the first article was a stand-alone program which was known as the "CAMERA" program. For the three-instrument system, the program was broken up into the "ZY" [158,159] and "ZIY" programs. Even though the "ZY" and "ZIY" software has changed greatly, the "CAMERA" program is still used for stand-alone trouble shooting in the field and operation of the calibration lab laser. Shortly after that time, remote operation capability was added using commercially available pcANYWHERE software and a modem [160].

Using a HeNe laser in the shack, a technique was developed to align the instrument laser along the optical axis, and thus insured that the mirror and laser were in sync and the return beam hit the detector. We were somewhat surprised at first to see a clear image of the detector chip reflected back onto the wall of the shack when the HeNe

was properly pointed into the mirror and detector! Of course, we quickly realized that this was a cat's eye retroreflector and a potential problem for multiple reflections, but this showed that the technique could also be used to set the detector at the focal point of the lens. Now this technique is used in the calibration lab, but a 780 nm laser and CCD camera have been added.

A weather station was interfaced into the computer to monitor temperature, humidity, and pressure. Plots of apparent distance vs temperature consistently showed a hysteresis loop, i.e., the phase was not the same for the same temperature in the morning and afternoon. An appreciation for the complexity of measuring the group index of refraction was rapidly developed.

Atmospheric effects were investigated through a path from the ground to a 150 foot tower in April 1992 with very good results. This experiment also demonstrated the ability of the instrument to track vibrations when the tower was excited by pulling on a guy wire and tracking the classic damped sinusoidal displacement of the retroreflector.

Experiments were conducted to measure cross talk between lasers. First, one laser was pointed at a retroreflector and continuous measurements were taken. Then the other lasers were pointed at the retroreflector, and no change was seen in the first lasers measurements. Various permutations of the experiment were conducted—all showed no problems with cross talk.

The trilateration software was written and tested in May 1992. Demonstration of the trilateration software and receiving the first production actuators was celebrated by a dinner with the Metrology and Active Surface groups [161].

The fourth step was to close the loop with the surface actuator control system [162,163,164]. The three-laser demonstration was moved in July 1992 to include a 2×2 panel array (9 retroreflectors) located 80 meters from a simulation of the feedarm configuration, using two lasers on the ground and a third instrument mounted 100 feet up on a weather tower [46]. Report L0090 [165] contains interesting data from August 1992—including vibrations of the framework. Four fixed ground monuments were also used to continue the index of refraction model work.

The control computer operation was moved to the interferometer basement at that time, and

changes were made to incorporate ethernet communication with the monitor and control group. The central computer was changed from DOS to Windows in order to take advantage of ethernet software available for the Borland C++ compiler being used.

Ray Creager and Tim Weadon demonstrated the full closed-loop control of three lasers and the active surface actuator control systems in September 1992. This required interfacing 3 ZY (DOS) computers, the ZIY (Windows) computer, a Sun computer, a VXWorks computer, and Transition Technology Incorporated embedded control modules for the motor control and LVDT transducers. A demonstration was given to the GBT Advisory Committee at the December 1992 meeting.

With activities expanding, Bill Radcliff transferred to the metrology group in January 1993.

The need to develop a pointing model for the lasers became an immediate problem. Trying to keep 3 lasers pointing to 13 targets by searching for the coordinates at night was very time consuming. A surveyor was hired to produce coordinates for each cube. A regression of the coordinates and experimentally determined encoder readings was produced for each instrument on its monument. This worked well enough for adding new retroreflectors, but any change in the instrument optics or moving the instrument to another monument required starting over. A total station surveying instrument was purchased at this point, but the problem was not to be fully resolved until the calibration lab was built.

A bench mark retroreflector was calibrated and used as a refractometer to correct the distances to the other fixed retroreflectors. Small systematic residual pointing errors indicated possible monument deflections—probably due to the sun shining on them and a lack of symmetry in the monument mounting point. This would influence the later monument design in order to avoid these problems.

In the summer of 1992, experiments were conducted on the use of acoustic thermometry [166]. Further experiments were conducted in 1993. These experiments used an arbitrary function generator, audio amplifier, and loudspeaker to generate an audio pulse on a trigger command from a computer. The function generator also output a programmable delayed trigger, to trig-

ger an A/D board, which digitized the audio signal received by a parabolic reflector and microphone. The received signal was cross-correlated with a typical signature waveform, and the delay time was calculated as the sum of the trigger delay and peak of the cross-correlation function. The proof of concept showed that it could be used, but an array of transducers would be required to correct for wind. Work was halted due to manpower limitations and uncertainty about the need for the additional data.

While thinking about the effects of temperature on the speed of light, questions came up about the effects on the radio waves, i.e., could it be that the mechanical surface needs to be corrected from a parabola if there is a temperature gradient in the dish? John Payne hired Leonid Kogan to calculate the effect in August 1992 [167]. The calculations reported in GBT Memo 97 [168] showed that the effect on the radio waves was a secondary correction.

The serial interface to the ZY instruments was replaced by ethernet, which allowed the central ZIY computer to be moved from the interferometer basement to the new laser lab which was set up in the old 300 Foot Telescope building in April 1993.

Software development was then at a point to branch out into what was viewed as two components. With the release of production instrument purchase orders, a commitment was made to the embedded PC architecture that had been developed in just over 2 years. While the PC to Sun interface that had been demonstrated with the panel experiment showed that the systems were compatible, the monitor and control group felt strongly that their interface (the ZIY computer) should be through a Sun or VXWorks computer. With this in mind, Ed Meinfelder transferred to the laser group in April 1993. The software development was to be divided, with Ray Creager responsible for the hardware and metrology intensive embedded system side, and Ed Meinfelder responsible for the buffer between the instrument and the monitor and control system.

The first objective was to reproduce the closed-loop panel demonstration, with a Sun replacing the PC as the ZIY computer. An extensive software documentation of the ZY instrument was reported in GBT Memo 111 [129]. After the predictable glitches, the Sun computer replaced the

PC.

Ray Creager, Tim Weadon, and Ed Meinfelder prepared a second closed-loop demonstration for the October 1993 GBT Advisory Committee Meeting. Unfortunately, time constraints limited the demonstration to a small number of the committee members after the meeting. For one reason or another, the closed-loop panel experiment was not given a priority and it was never operated again.

For the 1992 demonstration, the backup structure was moved and the lasers output an error which was corrected by the actuators [165]. For the 1993 demonstration, a novel experiment which illustrated two concepts was demonstrated. By placing a 3 mm thick optical window in front of the retroreflector, the phase of the signal was delayed due to the increase in the group index of refraction of the glass. The servo motor drove the actuator toward the laser to correct for the apparent distance increase. When the window was removed, the actuator returned to the original position. Everyone seemed to enjoy this hands-on demonstration—where they could insert the window and hear the motor move as a result—more than watching data being plotted on the computer screen.

A second objective of the Sun ZIY program was to incorporate real-time plotting of data as it was being taken. Attempts were made to use the GBT UNIX standard PVWave software package. This turned out to be a misapplication and custom UNIX plotting software was written at a great time expense. The PVWave license was later dropped [169].

A third objective was to incorporate data from the GBT weather station into the group refractive index calculation. This was the first attempt to interface to production monitor and control software by anyone outside the monitor and control group and a number of communication problems surfaced. The net result was that it was not successful by the time Meinfelder left the project in December 1994 and was not attempted again until 1996.

While the block diagram of the instrument has not changed since 1992, practically every subsystem has been refined in the present instrument. Jeff Kingsley took on the job of refining the mirror head mechanical design, in his spare time, in November 1992 [170,171,172,173,174]. Prior to

this point, John Payne did all of the mechanical engineering work.

From the previous mirror systems, it had been learned that the elevation mirror bearing housing stiffness was critical to good servo performance. The new design incorporated single piece construction for the elevation bearing housing, and thus was much stiffer. It could also be made to a much higher orthogonality accuracy—which is critical to good pointing. An internal cable wrap, as well as a mechanical stop on the azimuth was included to avoid tangle problems with the elevation cables. A replicated mirror greatly reduced mounting and calibration problems. A fourth axis was purchased for the machine shop CNC milling machine [175,176] in order to improve the accuracy of the mirror and speed up production. Inspection techniques were developed in the lab to measure the more critical dimensions and orthogonal axis specifications.

Between October 1992 and March 1994, 3 prototype mirror heads were built and tested (see drawing control sheet D35420D001B). The initial cable wrap design had to be modified to prevent the cables from pinching and breaking. With the tighter tolerances required to improve the servo and pointing performance, the azimuth bearings became sensitive to temperature changes. This was resolved by removing metal in the center of the azimuth axis, which increased the heat radiation and provided some compliance between the two parts. A series of experiments was conducted to tighten the clamping between the outer race of the bearing and the housing, and thus adjust the critical preloading of the bearing and reduce end-play in the azimuth.

The single most time consuming problem turned out to be the incorporation of modular encoder components [177]. Two styles of encoders were tested, and Dynamics Research custom designed an encoder for the application. After fighting problems with critical alignment of the rotor and stator, and shielding to eliminate motor electrical noise problems, the final blow was discovered at the 140 Foot experiment. After careful calibration of the instruments in the lab and field calibration of the laser monuments and ground target points, it was discovered that the encoders were not linear. This was later confirmed using an optical polygon and autocollimator. After that discovery, the modular units were

replaced with the slightly larger Heidenhain incremental encoders originally used for the three-mirror experiment.

With the proof of principles out of the way, attention turned to refining and manufacturing 20 instruments, software development [105,129,178], and developing calibration techniques [48,179,180,181]. Major purchase orders began being released in March 1993. The machine shop started production work in June 1994 [182,183,184], with a major commitment of time by Mike Hedrick, Dwayne Barker, and Windell Monk. The first article of the critical forks is dated September 1994, and the last unit is dated August 1995.

The first 6 units were assembled in June 1995. Problems were found with the elevation axis on these first units, which required that the parts for an elevation axis be built in matched sets. Additional problems were traced to a simple bearing retainer ring component, which required rework on these units, but it was replaced before assembly of the remaining units. In July 1994, Jeff Kingsley took a supervisors job, and his time to devote to engineering and the project was mostly limited to evenings at home—which he did a lot. John Shelton and Mike Hedrick were forced to pick up most of the troubleshooting and refinements in technique. This included the encoder mounting and cover design, and an improvement in the mirror cell adjustment.

John Shelton produced a step-by-step assembly procedure reported in L0100 [185]. After 4 hard years of development and manufacturing, a major landmark (memorialized by a metrology group party) was the completion of assembly and testing of 20 mirror heads in December 1996 [179,180,181,186]. By that time, the drawing control sheet (D35420D001) showed 4 major revisions of the mirror head.

Richard Bradley refined the laser modulator design and greatly reduced the package size [187]. With increased pointing precision of the mirrors, tighter divergence laser diodes were evaluated and used in the production modulators. Ironically, these diodes would probably not have worked with the earlier prototype instruments, due to blockage by the spider and less accurate pointing capability—not to mention the problem of finding the beams. Bill Radcliff made some refinements and completed the assembly and test-

ing in April 1995. Step-by-step assembly instructions were included with the drawing package.

In August 1992, John Payne developed specifications for the oscillator system, and a large number of companies were solicited to submit proposals to supply the oscillator systems [188,189]. Contracts were awarded to two companies [190] to develop prototype oscillator systems. One of the vendors dropped out early in the testing phase. After extensive testing and working with the vendors, Tony Ersepke, at Magnum Microwave, perfected an excellent (and less expensive) design for the oscillator [191,192]. The purchase order was placed for 25 units in July 1993. Complete vendor drawings and parts list were included in the D35420 series laser drawing system.

Based on the success of the experimental work, the novelty of the instrument capabilities, and interest in the instrument expressed by a number of parties, John Payne, David Parker, and Richard Bradley filed a patent application on May 27, 1993. After an initial rejection and some responses to the examiner, the patent was granted and assigned to Associated Universities on October 3, 1995 [193,194,195,196].

Outdoor retroreflectors are highly subject to frost and dew formation. Contamination on any one of the surfaces scatters the light and power drops dramatically. This power loss is compounded by the optical path passing through the front surface, 3 rear surfaces, and back through the front surface. Due to the environmental conditions on the telescope surface, hollow retroreflectors were ruled out.

The question came down to using total internal reflection, or aluminum coated back surfaces. Three test stands were built and located behind the Jansky lab [126]. A modulated LED was used to measure the return power on an aluminum coated cube, a total internal reflection cube mounted in a protective housing, and an open total internal reflection cube. The return power was measured every 15 minutes from September 1991 to February 1993, using a programmable multiplexed DVM, with the data downloaded into a PC every week.

Shorter tests were conducted using eyeglass antifog wipes, and a new type windshield glass, being developed by PPG [197,198]. Additional experiments were conducted using windshield deicer heater strips bonded to the glass. Some pro-

totype retroreflectors with silver back surfaces degraded in a period of a few weeks, probably due to moisture penetration of the epoxy back surface overcoat. Some aluminum coated retroreflectors turned orange and became poor reflectors.

All things considered, it was decided to use 1 inch solid glass total internal reflection retroreflectors in open air mountings with no coatings for the surface retroreflectors [199]. The contract to supply 2400 retroreflectors was bid by 9 companies [200], and the three low bidders were visited by John Payne, David Parker, and Frank Serna to audit the quality control programs and see the manufacturing process. In the course of the visit, each manufacturer was asked to inspect a sample retroreflector which had previously been tested by The University of Arizona. Each vendor promptly cleaned the retroreflector and tested it, with the same results. All three vendors were judged to be well qualified to supply the retroreflectors, so the contract was awarded to PLX, the lowest bidder, in July 1993. Delivery was completed in February 1994.

In March 1993, the Navy removed asbestos from the old 300 Foot Telescope building in order to use the building for temporary housing of the clocks scheduled to be placed in Green Bank. The laser group had been looking for a controlled access basement location for a calibration lab [50]. So, with the asbestos out of the way, it was built in the basement of the old 300 Foot Telescope building. Sections of the concrete floor were broken out and isolated stable monuments were poured with an 18 meter optical path. The Navy was only scheduled to use the south end of the building, so the metrology group was given use of the north end for a computer lab. The Navy clock project was later cancelled, so the metrology group expanded into the south end, where the control panels and mirror heads were assembled.

The availability of this facility turned out to be a real windfall for the project. Besides being remote from traffic and vibrations (the HVAC system is switched off when calibrating inclinometers), the work environment is probably the best location on the site—a sidewalk superintendent's dream. When the group moved in, the first level of the alidade was going up. From the picture windows, and driving by the construction site several times per day, everyone has witnessed the

construction process. A scanner radio was also brought in, which allows the lab to listen in on the activities at the site and draws attention to interesting activities.

A significant capital investment was made in calibration standards and instrumentation, including: a Hewlett-Packard laser interferometer, Topcon total station surveying instrument [201], autocollimator, surface plates, optical flat, flat and parallel Croblox mirrors, surface plate dual-sided mirror, optical polygon, angle gage blocks, 21 inch granite sine bar, granite squares, 8 inch granite cube finished and square on 6 sides, sets of 3 foot and 10 inch granite straight edge parallels, steel and granite V blocks, mercury barometer, certified thermometers, cathetometer, set of gage blocks, set of gage balls, 4.2000 inch and 7.00012 inch diameter hole gage calibration standards, digital micrometers, digital calipers, digital height gage, digital depth gage, digital comparator stand, telescope gages, invar wire, optics breadboards and mounting hardware, calibrated hollow retroreflectors, CCD camera, etc.

In addition, most existing NRAO metrology instruments and standards were collected from Sid Smith and the machine shop for use in the lab, e.g., the 50 foot hydrostatic level (purchased by the antenna group to level the GBT track [202]), N3 level, automatic level, invar and wood level rods, T2 theodolite (on loan from the VLA), clineometer, machinist level, microscope, alignment telescope with an optical square (originally purchased for the 140 Foot Telescope construction), instrument stands, automatic autocollimator (from the GBT autocollimator project), 100 foot invar tape, 34 (17 × 2) foot set of Starrett length rods, 8 ft steel straight edge, 39" × 21" Starrett steel square, chilled mirror dew point sensor, aneroid barometer, and more.

John Payne and Dale Webb acquired two military surplus 8 × 2 foot 10 inch thick granite surface plates and had them shipped to Green Bank. They also attempted to acquire instruments from the SSC project [203], but the high energy physics community had a higher priority on this equipment.

In addition to supporting the GBT metrology project, this equipment has been used in support of the panel setting tool [204] (to be described later in this section), the machine shop, the measurement of the GBT wheel ta-

pers [205] (which resulted in sending several out of specification wheels back for rework), calibration of the linearity of the subreflector actuators [206,207,208,209,210], calibration of the GBT weather station [211,212], site maps, establishing the GBT centerline and track elevation with respect to established NGS bench marks, and locating the Navy and OVLBI [213] antennas.

Mark Leach joined the project, on a temporary basis from CSIRO (Australia), in July 1993. Among other things, he took on responsibility for building the control panels. Purchase orders for the control panel components were placed in August 1993 and construction was completed by the time Mark returned to Australia in February 1995.

Alternate servo power systems were evaluated; however, in the end, the pulse width modulated systems previously used were judged to be best for the application. Problems were encountered with the production A/D converter boards, which were traced to a revision in the manufacturer's board design between the prototype and production units. Solid state relays were added in order to switch the power supplies on and off through the computer and thus kill the laser, mirror, or RF power supplies from the ZIY computer.

Leakage of 1500 MHz into the detector was traced to power supplies. The oscillator was discovered to be sensitive to power supply voltage, so critical RF components were placed on individual power supplies. The sensitivity to power supply voltage was traced by John Payne to a correlation between phase jumps and the heater on a 100 MHz crystal oscillator using the trusty strip chart recorder.

Bill Radcliff did extensive testing on the prototype detector analog circuitry. Modifications were made to increase the gain of the IF section and circuit board art work was generated. The laser detector mechanical design was modified and 25 units were built. Later testing revealed significant grounding and RF leakage problems with the mechanical design, which introduced a small 1 kHz signal and thus linearity residuals in the IF signal. After some evaluation, Bill Radcliff redesigned the housings and new units are being built. Bill Radcliff and Mark Leach also did extensive testing of the laser modulator modulation

depth [214].

In May 1992 an optics engineer, Marty Valente, transferred to the project on a 1 year appointment in Tucson. He designed, and the Green Bank machine shop built, a prototype quadrant detector. This unit was tested in an elevator shaft at The University of Arizona with excellent results [26]. Some initial field testing was done in Green Bank on the 150 foot tower, and a control panel (VY computer) was built and installed at the base of the tower.

Valente went on to design a larger aperture unit. Production of the larger instrument was handled in Green Bank by the machine shop and Mark Leach. Some field testing was done, but this project fell by the wayside for several years due to manpower limitations. Later, this project was picked up by Dwayne Schiebel and John Payne [215].

In July 1992, John Payne did some calculations on the problem of setting the four corners of the surface panels [216,217]. The specifications required the contractor to set the surface to 0.040 inches, but it did not set a specification on the corner-to-corner setting, which would require NRAO to come back and set the surface for high frequency work. John Payne proposed that NRAO provide the contractor with an instrument that would facilitate setting the corner-to-corner relationship to 0.001 inch in order to make all future adjustments with the actuators and thus avoid a major job in the future. Dave Seaman and the metrology group designed this instrument, which will be provided to the contractor [218,219,204].

After looking at the surface retroreflector mounting in detail, and taking into consideration the panel setting tool design, as well as the implications (ice, RF, visibility, access, dissimilar metal corrosion) of having a small ridge protruding above the surface, it was decided to mount the retroreflectors on the panels instead of the actuator, as originally designed [220,221,222].

This allowed the retroreflectors to be calibrated to the panel surface [223,224] and tied to the coordinate measurement machine data on each panel via the panel setting tool. The opening at the panel corners was also reduced from 2×2 to 1×1 inches [218,219].

Dave Seaman designed a zinc casting and found a vendor to supply the mountings. The

purchase order for the mountings was placed in December 1994 and most of the retroreflectors were mounted [225] by October 1996, with the remaining retroreflectors being held in order to make small adjustments in the tilt angles for some panels.

While John Payne had raised questions about holography in May 1991 [27,226], the full ramifications of the fortunate decision to calibrate the retroreflectors to the surface were not realized until the fall of 1996, when the possible limitations of holography became better understood [227,228,229,230,231,232,233]. When questions were raised about the ramifications of thickness variations of the powder paint around the retroreflector mounting holes [234], it became apparent that previous assumptions that the laser system would ultimately be calibrated against holography [235] were questionable. This put a new emphasis on the calibration of the surface retroreflectors, i.e., the laser system, in conjunction with the coordinate measurement machine data on each panel, and the panel setting tool, will probably be better than the holography measurements.

Starting with informal talks between John Payne and Roland Shack while on the plane to visit the SSC project, a proposal was made by The University of Arizona to design and build 2 prototype wide angle spherical retroreflectors in August 1993 [236,237,238]. While evaluating the first article in the calibration lab, in October 1993, a significant discrepancy in the optical offset (phase delay due to the index of refraction of glass) was measured. After repeating the measurements several times and getting the same results, John Payne called John Findlay for some advice. Findlay immediately straightened out the lads with a lecture on group index of refraction.

Based on the prototype evaluation [239,240,241], a contract was awarded in August 1995 to build 18 production retroreflectors to be used at cardinal points on the GBT structure. This purchase order was completed in November 1996 and engineering work on the mountings is underway [242].

The design was later verified by Michael Goldman [236], a physicist that joined the metrology group in January 1996 to help with the GBT metrology architecture. Goldman came to

NRAO from Brookhaven, where he did metrology work for the Relativistic Heavy Ion Collider project—which has many similarities to the accuracy requirements for the GBT.

An HP laser interferometer was rented, and later purchased, to check linearity of the instrument over a long path. In April 1994, a translation rail system was built between the monuments in the calibration lab basement which allowed simultaneous measurements with the laser and interferometer in a “push-pull” configuration [124]. The repeatability of the first experiments was not as good as expected. This turned out to be due to minor errors in the level of the fixture that held the target in place on the monument. This was corrected, and the repeatability was on the order of 5 μm over 18 meters!

After tedious lab measurements, small residuals were detected in the linearity of the instrument which were traced to multiple path reflections from the detector back to the retroreflector. This was corrected by the addition of an isolator in the detector path.

Calibration lab experiments were conducted using reflective tape targets. These results showed that at close range, reflective tape can not be used, due to the fact that the tape acts like tiny retroreflectors. Due to the small blockage in the center of the lens for the outgoing beam, the instrument depends on the divergence of the beam and the lateral translation of the retroreflector for the energy to get to the detector. The retroreflectors in tape do not return a beam translated far enough off axis to get to the detector.

An even more elusive problem, which was first seen in March 1992 [44], was tackled in late 1994. What was thought to be phase inhomogeneity [70] in the beam resulted in a slight change in the distance measurement as a function of where the retroreflector was in the beam. Experiments were done using spatial filtering in the Fourier transform plane by sending the laser beam through a microscope objective, with a pinhole at the focus, and recollimating with a second lens. While this cleaned up the beam, it did not help the problem and alignment was very tedious. Experiments were conducted by placing various size apertures in the laser path to expand the beam, with mixed results.

The conclusive experiment was conducted by

adding a beam splitter and a second detector. A portion of the outgoing beam was picked off and directed into the second detector. It was discovered that the phase of the outgoing beam jumped by several mm when a retroreflector was inserted into the beam! So, the symptoms turned out to be only a small ripple on top of a much larger phase shift in the laser modulator when power reflected back into the laser. The larger phase shift had gone undetected due to the fact that the previous experiments had been differential measurements, i.e., the “zero point” correction had not yet been addressed.

This was isolated in the lab after a long series of experiments reported in the GBT archive file L0070 [243] and the lab notebooks. This problem was corrected by the addition of an isolator on the outgoing laser beam. The focal length of the lens was reduced from 300 mm to 150 mm in order to reduce travel of the focal point on the detector, and thus a phase shift, when the retroreflector catches the beam off the centerline. This design was also verified by Michael Goldman using ray tracing software [244,245,246,247,248]. He also worked out the pointing corrections for non-perpendicular mirror heads [249] and angle corrections for glass retroreflectors [250].

At Bob Hall’s request, a plan was initiated to modify the 50 foot hydrostatic level to 50 meters in order to expedite a check of the as-built GBT track elevations with respect to a point in the center [251,252]. A contract was awarded to do the job but, unfortunately, the inventor of the instrument became ill and died before he could make the modifications. The metrology group began plans to modify the instrument, but manpower constraints limited work to reworking the instrument to improve reliability and producing documentation on the design. As a result, the GBT track has not been given a final check.

Due to the delay in the GBT construction project, it was decided to perform the final round of tests at the 140 Foot Telescope [253]. In anticipation of this experiment, and the fact that the telescope position was not available over the network from the existing software, Dwayne Schiebel built and tested an interface board. Ray Creaiger wrote the software (program named HA) to allow a PC to eavesdrop on the signal going to the operator’s console over the network in December 1993. Four monuments were poured in

July 1994, and the control panels were started up in September 1995.

A calibration procedure was developed to point the instruments and calibrate monument Kelvin mounts [249]. The detailed calibration procedure will be the subject of another paper. This allowed any instrument to be placed on any monument and point to retroreflectors which had been located by conventional surveying techniques. In December 1995, problems were discovered with the mirror encoders which required a major redesign of the mirror system. This problem had gone undetected in the lab due to the limited ranges and angles available in the basement.

After Ed Meinfelder left the project in December 1994, the ZIY program running on the Sun computer became dated for the 140 Foot experiments, e.g., it only handled 3 instruments, and had no tracking or weather capability. A new ZIY program was written to operate on a PC running Microsoft NT. The PC fully replaced the Sun computer in February 1996 [254], and the first successful demonstration of the program and a laser tracking a spherical retroreflector mounted on the 140 Foot Telescope took place in May 1996. Subsequently, a number of bizarre hardware problems at the ZYs (which were ultimately traced to a combination of CPU boards and terminating resistors on the computer backplanes) were resolved in the summer of 1996.

This ZIY program was written as an "engineering control mode" with the objective of continuing the experimental work and serving as an operating example to be rewritten when a UNIX programmer joined the group. Based on the successful demonstration of the compatibility of NT with the monitor and control system, it has been decided to keep this software on the PC—with a few modifications.

With a complete working system in hand, operational logistics became an area of concentration during the summer and fall of 1996. An area of the laser lab was set aside for the exclusive use of the experimental operation. This was included in the October 1996 GBT Advisory Committee tour of the computer and calibration labs. At the same time the PC took over operations, a status panel reflecting the state of a number of parameters for each instrument was added on an auxiliary computer in order for this information to remain on display at all times without competing

with the operator for screen real estate. Later, this was upgraded to a dual-monitor display card in order to include a frame grabber display of the site.

The frame grabber feature was developed in early 1995 in order to equip an instrument with a CCD camera at the detector and test the pointing capability of instruments in the field [178]. While color CCD cameras are not sensitive at 780 nm, inexpensive monochrome CCD cameras (without IR blocking filters) see the lasers quite well. It is also anticipated that a CCD will be useful to observe the surface of the GBT.

For example, a camera with a light directed at the surface will yield a snapshot of the retroreflector conditions. Clear retroreflectors will show up as bright spots, while retroreflectors covered with dew and frost will not return a spot. This may be useful information for the operator to make a decision to turn the antenna into the sun to clear sections of the reflector. The CCD could be used with a beam splitter to do bore sighting, or it could be mounted off the optical axis (like a receiver array) and alternate mirror pointing coordinates could be computed for this detector.

The wealth of data available from only 4 instruments is overwhelming! In order to expedite the analysis of this data, the OLE interface available with the Microsoft NT 4.0 operating system was exploited in order to send the data directly into a Microsoft Excel spreadsheet. This made all of the Excel resources available to the ZIY program.

Starting in August 1996, the program was modified to graph data in real time for each laser and each retroreflector, as well as GBT weather station data which Joe Brandt and Ray Creager successfully made available from monitor and control through RPCs in August 1996. It is noteworthy that this was the first demonstration of a software connection between the metrology group and actual GBT monitor and control software.

A co-op student developed Excel macros which produce a printed report of all data on demand. All of the statistical, graphical, and data manipulation of Excel are also available on other NT computers which allows the operator to look at data and process it in the background on another machine while data is being taken. More details of the experiments are contained in GBT Memo 157 [255] and an example of the typical data is

reported in L0125 [256].

As operation was being handed off from software development to the co-op student, a number of logistical procedures were developed. A safety training session was held with the 140 Foot Telescope personnel, electronics, maintenance, safety committee, and other interested personnel. The status panel screen and frame grabber software was added to a computer at the 140 Foot Telescope in order for the operator to see what the lasers are doing and get user feedback. A formal operating policy was established between the metrology and 140 Foot Telescope groups [257]. A formal procedure was developed for archiving source code and program releases [130] using commercial Source Safe software. The co-op student successfully compiled versions of programs as an independent test of the system. A procedure was written and tested for bringing the computer systems up from a power failure [258]. The standard data processing procedure was also documented [259].

In order to get some long range (1000 meters) data for index of refraction studies, a retroreflector was mounted on a rigid microwave reflector tower on a nearby mountain in the spring of 1996. After cutting a few trees, a clear path was obtained for 2 (ZY10 and ZY13) of the 140 Foot Telescope lasers. Excellent results were obtained, with short term atmospheric noise around 0.1 parts per million, under ideal conditions [256,116]. By removing one tree top, one of the 140 Foot instruments (ZY10) gained a clear line of sight to a retroreflector mounted on the GBT construction derrick 800 meters away. An interesting demonstration of the instrument measuring the deflection of the derrick was reported in GBT Memo 160 [260].

Over the years, the GBT architecture has been formulated. Fred Schwab did a number of simulations on the number and locations of the ground monuments. While there is not a single "best" number and location, due to the tradeoffs as the telescope changes elevation, it looked like a good plan to locate 12 equally-spaced instruments at a radius of 120 meters.

It was desirable to locate these instruments on a level plane above the top of the GBT track elevation in order to facilitate hydrostatic leveling and provide as many lines of sight between instruments as practical. In order to avoid future

interferences in the lines of sight, it was agreed that nothing would be built above the track elevation within a 120 meter radius without notification to the metrology group [261]. In order to avoid hydraulic subsidence problems with the monuments, it was agreed to avoid pumping water or locating a septic tank near the laser monuments. A well was later drilled about 100 meters from the telescope, but it was agreed not to use it if it resulted in perturbations in the ground water level [262]. A study was initiated to log the well water levels [263].

Preliminary locations which minimized interferences with the RSI warehouse (which was assumed to remain after construction was finished) were staked out and marked in June 1995 [264]. At the same time, the centerline of the pintle bearing and the centerline of level 1 of the alidade was surveyed to monuments "King" and "RSIEAST". These monuments, and thus the telescope centerline, were later tied into surveys of all other monuments on the Green Bank property—including an A order NGS monument (T007). The track elevation was also transferred to "King".

This decision also had additional safety and security implications [265,266,257] for the site and local control room. Compounded by concerns expressed by the site safety officer in August 1996 about the proposed local control building proximity to the telescope and the danger of falling objects [267], an agreement was reached in the fall of 1996 to build a fence around the telescope, and to locate the local control room outside the laser monument ring, as well as diverting the normal traffic flow around the lasers. The 12 monuments were then rotated counterclockwise, slightly, as shown on drawing D35420C004B [268].

With the site problems resolved and the confidence gained from the experiences with the 140 Foot monuments [255], the 9 monument locations available to NRAO were poured in November 1996 [269,270]. In January, 1997, conduit was run to the 7 monuments located north of the road and the earthwork was done in April 1997. The 2 monuments south of the road will require minimal earthwork, so the decision was made to delay cutting the road at this time.

The plans are to move the equipment trailer from the 140 Foot Telescope experiment to the

east side of the monument ring in the spring. Power is available from the contractor on the west end of the ring, but ethernet is not expected to be available until the local control room is built. So, control will be on a local ethernet, with communication to the lab via modem (telephone service is available nearby). It is expected that these 7 monuments will be operational in the summer of 1997, and testing will shift from the 140 Foot telescope to the GBT.

In support of an effort to verify the finite element analysis model of the telescope [106] as it is being built, as well as resolving some unanswered questions about the dynamics of the telescope [271], plans are being developed to use these 7 lasers to measure deflections and vibrations of cardinal points on the structure [272,273,274,275,109,276].

7 Acknowledgements

Due to the broad scope of expertise required for this project, and the extended period of time required to bring it to fruition, a large number of people have made direct contributions to the success of the project.

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