RANGEFINDER METROLOGY FOR THE GREEN BANK TELESCOPE

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ABSTRACT

A scanning laser rangefinder metrology system for the 100-meter Green Bank Telescope is described. Use of this system for correction of the primary reflector's shape and pointing of the telescope is described.

1 INTRODUCTION

The GBT is a fully steerable radiotelescope nearing completion at Green Bank, West Virginia (Fig. 1). Designed to operate between VHF and millimeter wave frequencies, it has a gregorian configuration with a 60 meter focal length, 100×110 meter offset paraboloid primary surface, and an 11 meter focal spacing, 8 meter dia. ellipsoidal secondary. The primary is an active surface of 2209 panels, accurate to 100 μm, joined at each corner by an actuator drive piston. The GBT moving mass is 8,000 tons. As the main reflector moves in elevation it deforms due to varying weight load. Its surface must be re-shaped to a paraboloid appropriate to its elevation. The secondary reflector, located on an offset feed arm, is driven to bring the gregorian focus to the receiver feed, located on a turret house on this arm.

A laser rangefinder metrology system was developed to measure primary surface shape and location, telescope structure cardinal reference locations, and subreflector location. Each rangefinder can make fast multiple range measurements. The general system, electronics, and laser modulation circuits are described in [1] and [6]. Six rangefinders are sited on the offset feed arm. A cube corner retroreflector mounts into one corner of each primary surface panel, and at locations on the subreflector. Laser beams from the rangefinders, amplitude modulated at 1.5 GHz frequency, scan the reflector targets. Optical path is measured from a scan mirror's center point (the intersection point of its scan axes, which lies in the plane of the mirror) to the optical center of a target prism retroreflector, modulo the modulation frequency half wavelength. Approximate ranges accurate to $\lambda_{\mathrm{mod}}/2$ are known *a priori* for each range to be precisely measured. Ranges from scan mirror center to retroreflector center are measured for a subset of the target prisms on the primary surface. Measured distances are first corrected for atmospheric refraction and then corrected to give distances from the scan center point to a point on the telescope's primary surface, the foot of the $\perp$ from the target optical center to the nearby panel surface [2]. The effective back reflection point from a cube corner prism target (optical center point) was calculated by Peck [3] and Rüeger [4]. Ranges will also be measured along stationary comparison paths of accurately known length to provide mean atmospheric refractive index corrections.

Twelve rangefinders will sit on piers around the base of the GBT on a 120 meter radius circle. They range to retroreflectors located on the rim of the telescope primary and on the feed arm and alidade structures. Those retroreflectors, designed by R. Schack and M. Valenti of the Univ. of Arizona Optical Sciences Center, are of cat's eye type, and have a wide acceptance angle for reflection, 130°. Rangefinders can also range to target prisms mounted on the rear of other rangefinder scan mirrors, to measure between one another. Using ground-based rangefinders, structure fiducial reference points on the telescope are related to a ground coordinate frame, tied to a survey control network. Ground-based coordinates of fiducial reference points on the telescope can thereby be measured by multiple laser range trilateration to a target. Fig. 2 shows an operating rangefinder.

Each rangefinder can measure up to five different ranges per second, with precision of 50 μm at 200 m, the greatest required system range. The system will have capability of measuring 2000 points on the antenna surface to this precision in about 7 minutes. The GBT is a steel structure; dynamic heating effects and temperature gradients would normally limit operation to 8 mm wavelength. It is desired that the GBT eventually operate at 3mm. To do this a requirement exists for real time measurement and correction. The rangefinder system is expected to fulfill this requirement.

2 RANGEFINDER OPTICS

A rangefinder is shown schematically in Fig. 3. The laser diode (Melles-Griot, 07HF033) has 10 mw output,

0.4×0.4 mrad far-field divergence, $0.78\,\mu$m wavelength; output is modulated at 1.5 GHz by varying diode drive current. A faraday rotation isolator (Isowave, 1-80T-4) follows the laser. The outgoing beam is deflected by a sequence of mirrors to a 5 mm right angle prism, cemented to the vertex of an 85 mm dia. lens used to focus target return signal onto a photodiode detector. The diagonal surface of this small prism is mirrored and reflects the outgoing laser beam to a plane scan mirror. The scan mirror is yoke-mounted and can rotate about an axis lying in the mirror plane (local elevation scan axis). A servo motor rotates the scan mirror in elevation; an optical angle encoder with 10^5 output positions per revolution monitors scan elevation angle.

The yoke mount couples to an azimuth scan shaft with azimuth servo motor and azimuth scan angle encoder. The azimuth scan axis is accurately perpendicular to the elevation scan axis, and intersects it at a point lying in the plane of the scan mirror. This "scan center point" remains stationary relative to the rangefinder's support platform. It is a fiducial point for instrument range measurements. The rangefinder is calibrated so that distances to retroreflector targets are measured from this scan point.

The beam reflected from the 5 mm prism is aligned to propagate accurately along the azimuth axis to the scan mirror center. The beam then reflects from the scan mirror either to a distant ranging target, or to a nearby comparison cube corner retroreflector, whose optical-center-to-scan-center distance is accurately known.

After reflection from a target prism, the return beam is focused onto a fast photodiode detector (Antel Optronics, AR-S1), through a circular polarization isolator (Meadowlark Optics, CPM-0.5-0780).

The return signal from the photodiode is amplified and mixed with an rf signal offset 1 kHz from the laser modulating signal. The phase of the resulting 1 kHz intermediate frequency is directly related to the phase of the 1.5 GHz modulation envelope of the returned signal, and is a measure of the optical path length to the retroreflector. The detailed mixing scheme is described in [1]. The stable 1.5 GHz modulating frequency is generated from the 15'th harmonic of a 100 MHz output of a Rubidium atomic clock.

3 CALIBRATION

3.1 Common Mode Distance Compensation

A comparison cube corner reflector mounts on each rangefinder, beneath the scan mirror. Distance between the scan mirror surface and the cube prism optical entrance face is measured, using gauge blocks, when the scan mirror is set parallel to the prism entrance face. Prism depth is measured. The prism depth, divided by the group refractive index of the prism glass, plus the measured distance between the two parallel surfaces is the distance of the comparison prism's optical center from the scan center. After each laser range measurement to a distant target, common mode distances from the laser diode face to the scan mirror center (outgoing beam) and scan mirror center to photodetector diode surface (return beam) are removed, by subtracting the comparison range and adding the mechanically measured distance from comparison prism center to scan mirror center.

Two details concerning the compensation are important. If the return laser beam along the short comparison path is not attenuated, phase detection circuitry will saturate. To prevent this, a zero thickness attenuator is provided, by making one of the cube faces partially absorbing. Also, the corner of the comparison prism is offset laterally from the incoming beam's center, to allow the return comparison beam to enter the focusing lens without hitting the mirror prism cemented onto it.

3.2 Refraction Compensation

Instrument ranging accuracy inside the laboratory is near $25\,\mu$m but outside ranges must be corrected for atmospheric variation.

Temperature, pressure and dew point data are sent to the range system computer from weather stations near the GBT, to allow refractive index correction. Also, ranges are measured along paths of accurately known length (refractometer paths) to independently get refraction corrections.

Atmospheric turbulence effects are discussed in [1]. Range tests indicate that they will not limit rangefinder operation, at ranges of interest for GBT.

3.3 Surface Reflector Calibration

For each cube corner prism, prism depth (i.e. the $\perp$ height of the corner above the optical entry face) is measured mechanically to $8\,\mu$m. This is done by placing the prism in a vee block inclined at angle $\arccos(\sqrt{\frac{2}{3}})$ on a sine plate resting on a granite surface plate. The prism's entry face is then parallel to the surface plate. One of the cube faces rests on an end plate, bolted to the lower end of the vee block. The entry face height above the surface plate is measured, using gauge blocks and a dial indicator gauge. The other two cube corner faces are in turn placed against the end plate, and distance is re-measured, and the measurements averaged. Distance of the entry face above the surface plate is equal to a constant plus the prism depth. The calibration constant is found by substituting a ball bearing for the prism. This measurement gives prism depth independent of any chamfer of the cube edges or truncation of the corner. That is, height of the intersection point of the cube face planes above the entry face is measured, independent of any chamfer or flaw in the prism corner. Prism depth is needed to find the position of the prism's optical center, and to correct measured laser ranges to the telescope surface panels.

The prisms are cemented into castings (Fig. 4) that bolt into holes in the telescope surface panels. Each casting has an annular plane rim that sits flush with the panel and defines the position of the prism with respect to the panel surface. Three casting configurations are used. The prism optical entry face is inclined at either 25°, 35° or 45° to the casting rim and panel surface, depending upon the panel's position on the telescope primary, to permit an incident laser beam to enter the prism close to normal incidence. For each prism-casting assembly the $\perp$ distance of the prism optical center to the casting rim surface is determined. A subset of the assemblies is measured on a coordinate measuring machine to determine positions of the prism faces and corner with respect to the casting's rim surface. The remaining assemblies are calibrated by a substitution method.

4 CONTROL INTERFACES

The ranging system is controlled by computer boards at each of the ranging stations and by a system command and monitor computer. The system computer has a television screen data monitor with graphic user interface windows for command, control, and monitoring of ranging operations. The following status windows are provided, among others:

A "Telescope Status" window displays current GBT telescope parameters: Azimuth, elevation, error, rate, local and universal time.

A "Server Select" window chooses a rangefinder for command or query.

A subwindow "Az/El Pointing Status" allows one to select a set of target retroreflectors for this rangefinder and enter nominal laser target scan angle coordinates. (The actual scan coordinates assigned during measurement will be modified in the individual rangefinder's computer to compensate for telescope elevation).

A subwindow "Servo Status" reports on status, fault, interrupt, operating mode, scan direction, and other operating parameters of the rangefinder.

A subwindow "Phase Status" allows one to select the number of range scanning cycles, the number of range data samples per cycle, and the frequency of range sampling.

Atmospheric data from the weather stations is provided to the range system command computer. The GBT monitor and control system provides telescope position and status data, current surface shape data, and laser range scan requests.

5 DISTANCE OBSERVATIONS

Rangefinder monitoring of small amplitude structural deflections was tested by mounting a retroreflector atop a large derrick used for construction of the GBT [5]. The rangefinder was approximately 725 meters from the reflector. Range was measured before and during hoisting of a 45 ton telescope section load. Deflections of 50 μm amplitude were easily measured (Fig.5).

Differential ranging observations were also made to two target retroreflectors 1 km away on a nearby mountain. One target prism was mounted on an optical bench with micrometer distance drive. Measured range of the stationary reflector, at fixed position, was used to normalize each range measurement of the moving reflector for refraction along the common path. Ten range scans were taken for each distance. Measured range of the moving prism versus its translation indicated by the micrometer is shown in Fig. 6.

ACKNOWLEDGMENT

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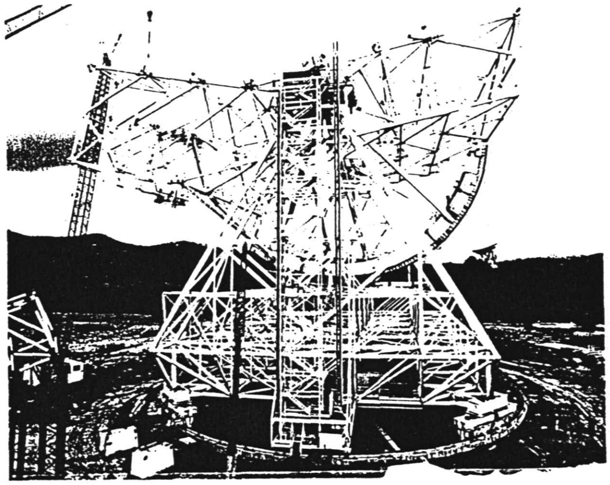

Fig. 1. Green Bank Telescope Construction. January 1997

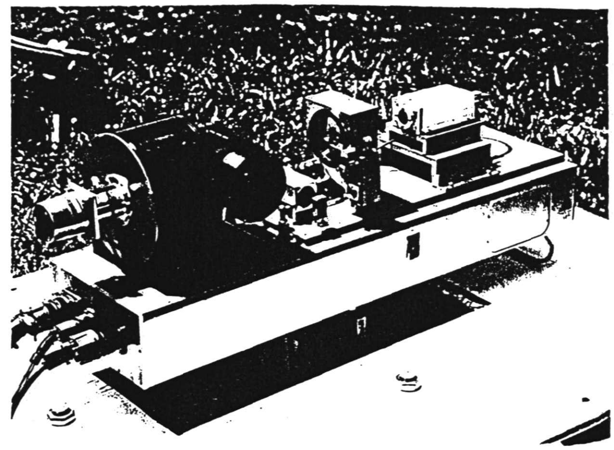

Fig. 2. An Operating Rangefinder.

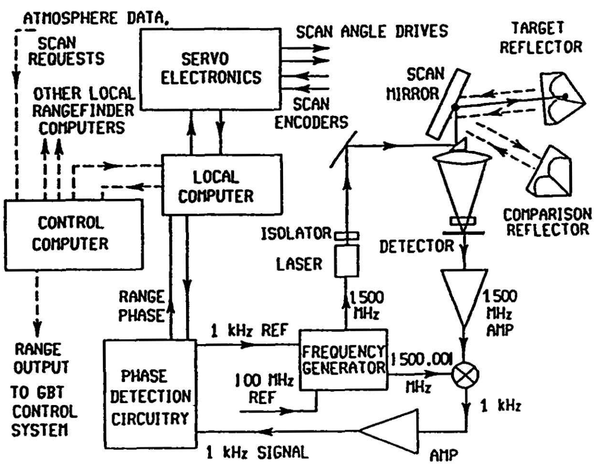

Fig. 3. Block Diagram of Rangefinder

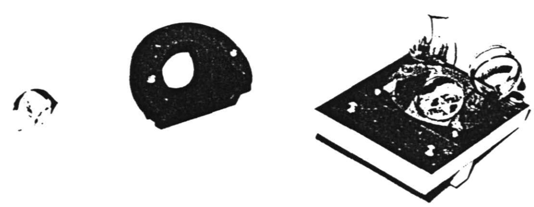

Fig. 4. Retroprism-Casting Assembly Which Mounts Onto GBT Surface Panels.

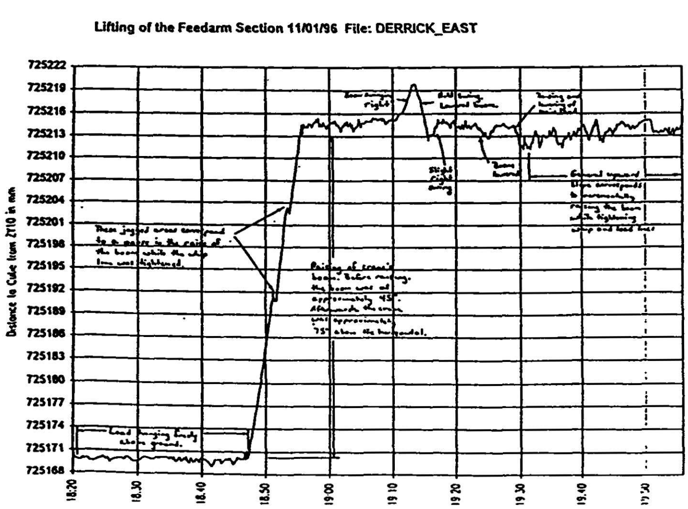

Fig. 5. Range To Derrick Retroreflector During Hoist Of 45 Ton Antenna Section

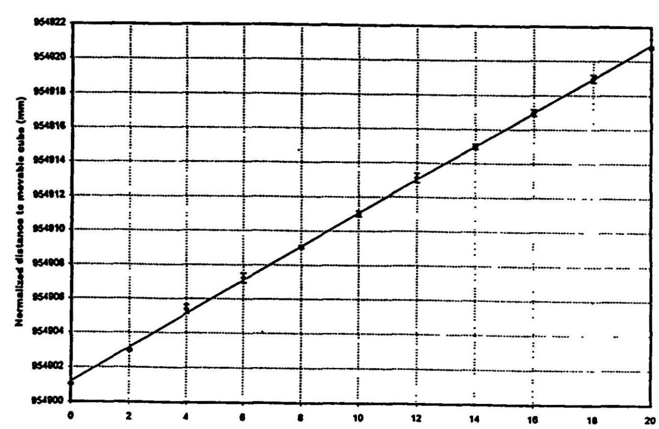

Fig. 6. Ranges To Retroreflectors At 1 km As One Reflector Is Displaced.