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GBT Active Optics Systems and Techniques

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Abstract. The GBT is a 100-meter radio telescope whose parabolic primary mirror is composed of 2004 rectangular panels, with 2209 actuators at their corners. Retroreflector prisms are installed on the panels. Six laser rangefinders are used to trilaterate to these prisms so that departures from paraboloidal shape due to wind pressure and thermal gradients in the backup structure can be measured. The actuators can adjust the panels to correct these wavefront errors. Deflections of the secondary optics from their design positions (focus tracking errors) will also be measured by the six rangefinders, and will be corrected by moving the ellipsoidal subreflector. Twelve rangefinders on ground monuments will measure to retroreflector spheres and prisms attached to the elevation bearings and to the backup structure so that pointing errors due to wind pressure and thermal gradients can be measured; pointing corrections will be supplied to the telescope control system.

1. About the Green Bank Telescope [GBT] Project

NRAO's 300-Foot telescope was completed in 1962, having been designed to last ten years. After operating for 26 years, it collapsed in November 1988, due to a structural failure. The US Congress appropriated US$74.5M for a replacement antenna in June 1989. NRAO decided to build a 100-meter unblocked (off-axis) millimeter-wave active surface antenna, with laser rangefinders to control both mirror shape and pointing, and to call it the "Green Bank Telescope" [GBT]. The construction contract was signed with Radiation Systems, Inc., in December 1990, groundbreaking was May 1991 and the initial completion target was December 1994. There have been many delays due to various causes. Steel erection was finished in July 1999. At the time of writing this paper (November 1999), about half of the 2004 aluminum panels had been installed. Figure 1 shows the GBT as it looked in the Fall of 1999. Acceptance testing should occur during the first half of 2000.

The GBT[1] has a 100-meter circular *clear aperture* (i.e., *no* secondary obscuration or support legs to scatter radiation) which is centered 54 meters from

[1] The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

[1] `http://info.gb.nrao.edu/GBT/GBT.html`

Figure 1. The GBT on 1999-09-17, from its control room ($\approx 2\,\mathrm{km}$).

the axis of a 208 meter diameter paraboloid with 60 meter focal length; the actual dimensions of the primary mirror are 100×110 meters. The collecting area is $\approx 7850\,\mathrm{m}^2$. The mirror is composed of 2004 rectangular panels, each about two meters on side, with 2209 actuators at their corners. The surface accuracy goal for panel manufacturing was $\pm 75\,\mu$m; almost all of the panels meet this goal, and many are better. The backup truss structure for the primary mirror has been designed to produce a "homologous" paraboloid: in the absence of wind and thermal gradient perturbations it will maintain its paraboloid shape to about 1 mm RMS (10 ppm!) over the range $5° < E < 90°$.

Except for its off-axis optics, the GBT is a conventional wheel-and-track, fully steerable, radio antenna which can observe $E > 5°$. The azimuth track has a diameter of 64 m; at its completion some years ago it was measured to be level to ≈ 2 arcsec. The moving structure has a mass of nearly 8000 metric tons, of which the tipping structure is about 5000 tons. The elevation axle collimation error was ≈ 2 arcsec in the absence of thermal gradients when the two bearings were set several years ago.

NRAO wants to operate the GBT at $\nu \approx 100\,\mathrm{GHz}$. We must maintain pointing to about $\frac{1}{10}$ of $\theta_{\mathrm{beam}} \approx 10\,\mathrm{arcsec}$ and surface shape to about $\frac{1}{20}$ of $\lambda \approx 3\,\mathrm{mm}$. Distortions of the structure and optics caused by wind pressure variations and thermal gradients are likely to exceed these limits. Therefore, early in the GBT project NRAO began to develop several types of sensors (rangefinder, autocollimator, quadrant detector) to enable measurement of the distortions so that they can be compensated. The laser rangefinders are the key technology in the GBT project for achieving closed-loop active optics control. The GBT control strategy is to compensate all predictable wavefront errors with open-loop algorithms, so that the closed-loop active optics servo will operate in a nearly-null condition. One motivation for this strategy is the desire that the telescope should degrade gracefully when the rangefinders become unavailable for some reason.

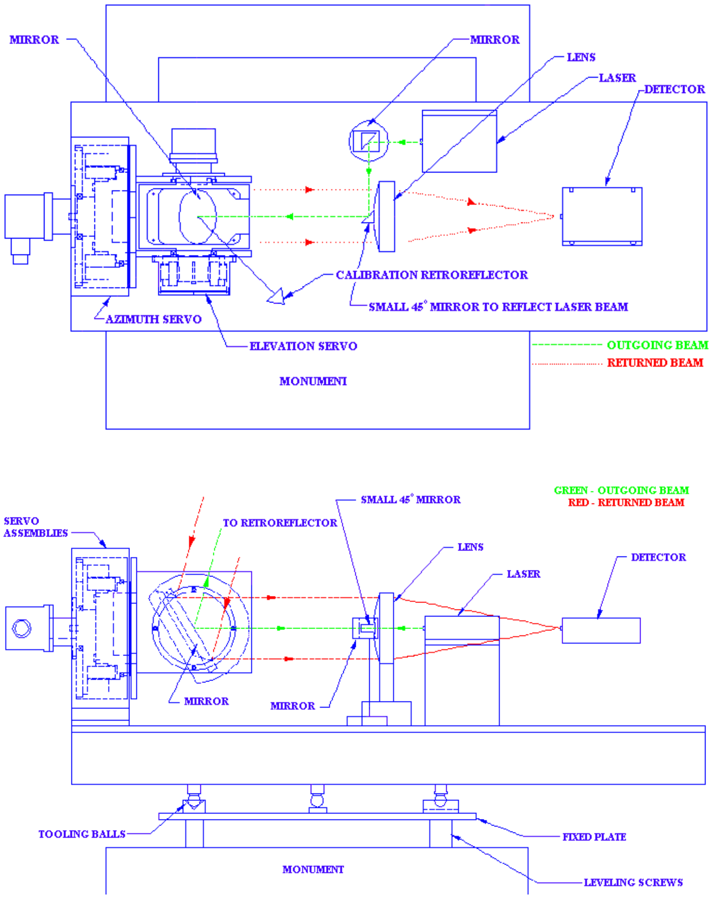

Figure 2. Features of the GBT rangefinders (≈ 1 m length).

2. The GBT Laser Rangefinders

The GBT rangefinders (Figure 2) use 780 nm semiconductor lasers modulated at 1.5 GHz. Light returned by target retroreflectors is detected and the signal is mixed with the transmitted signal to detect the phase difference. The cycle length is $\approx$ 100 mm, so distances to targets must be known within ± 50 mm a priori. The prototype instruments had typical typical range RMS $\approx 50\,\mu$m at 50 m with integration time 128 ms,[2] but recently several of the production instruments have demonstrated range RMS less than $10\,\mu$m at ranges greater

[2]Note that 100 μm is approximately the thickness of a typical sheet of paper!

than 150 m. The measurement rate capability is up to 5 ranges/s for angular motions of order 1°, ≈ 2 ranges/s on random targets with motion of order a radian. Slow drifts of the phase zero points are removed by measuring internal reference prisms; one measurement per minute is sufficient to maintain zero point error $< 15\,\mu$m. The index of refraction of air varies ≈ 1 ppm/°C, and so air temperature sensors and/or targets at known distances must be used to adjust the index when reducing range measurements to true distance. At ranges of order 100 m the beam diverges to several times the diameter of a retroreflector prism, so the rangefinder angular positional precision of 20 arcseconds is more than adequate. Approximate coordinates of target retroreflectors on the GBT can be obtained from surveying, telescope design geometry and the finite-element gravity model (which will be improved with rangefinder data). The rangefinders can range on each other, using prisms mounted on the back sides of their scan mirrors. The rangefinder hardware has been described by Payne, Parker and Bradley (1992, 1995); the real-time software[3] was described at ADASS VIII (Creager 1999).

3. Open- and Closed-Loop Control of the Primary Mirror

The corners of the 2004 primary mirror panels are supported by 2209 ball-screw actuators driven by DC motors with travel range ±25 mm and LVDT position encoders. The active surface control system[4] contains five VME-based real-time computers, which position their actuators to within ±0.001 inch (±25 μm). The *number of components* in this system poses a major challenge for the GBT project: 2209 actuators, *kilometers* of wire, more than 20,000 connections. The homologous backup structure will depart from paraboloidal shape by ≈ 1 mm RMS over $5° < E < 90°$, so that gravity compensation using the GBT finite-element structural model will use only a few millimeters of the full actuator travel range. The goal of the software servo will be to move to the "best-fitting paraboloid" [BFP] at each elevation. Actuator target positions will be computed as the zero point determined from holography, plus the actuator structural model displacements minus the BFP projected normal to surface, plus a subreflector astigmatic aberration term, plus the closed-loop surface correction function when available. About every 20 s the servo will send new computed positions for the 2209 actuators to the active surface control system.

Each of the 2004 primary mirror panels will have a retroreflector prism mounted in one corner, adjacent to an actuator. Six rangefinders on the feedarm will trilaterate to these prisms (Figure 3[5]). Measuring all of the prisms will take many minutes and so, in practice, we expect that the surface servo algorithm will measure only 94 of the prisms (≈ 15 m spacing), taking less than one minute. Wind variations will move the feedarm during the measurements, and so repeated observations of a small set of reference retroreflectors must be interleaved to enable adjustment to a consistent coordinate system. Structural

[3] `http://freya.gb.nrao.edu/GBTMetrology/index.html`

[4] `http://www.gb.nrao.edu/GBT/ActiveSurface/`

[5] Figures 3 & 4 were produced using visualization techniques described previously (Wells 1995).

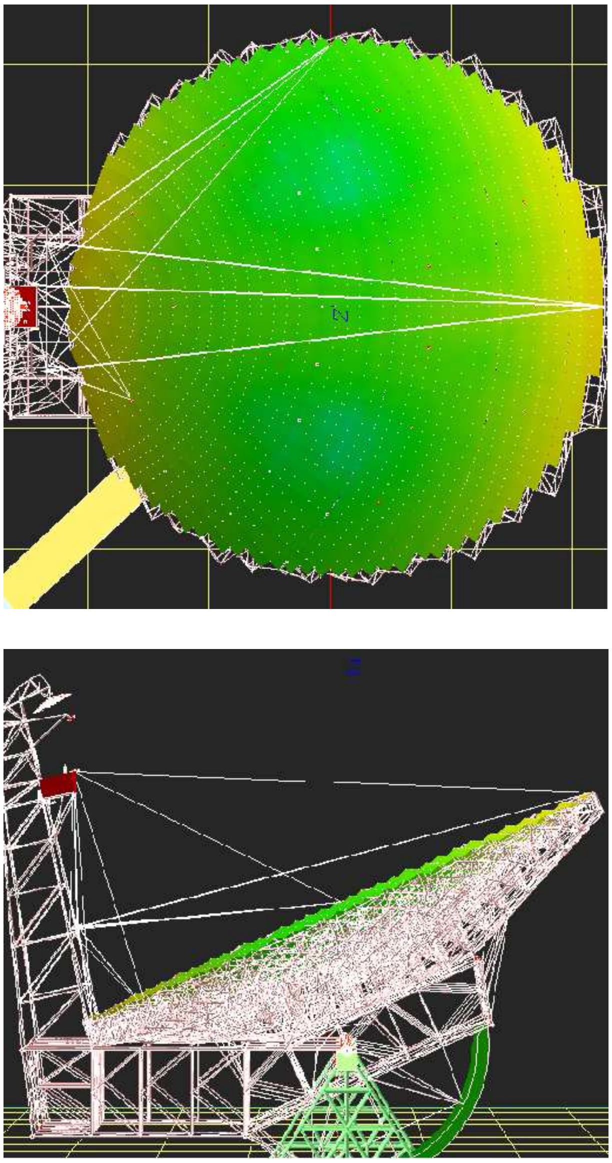

Figure 3. Surface servo trilateration, top and side views.

vibrations at modal frequencies due to wind turbulence will be corrected by using the structural model eigenvectors scaled by amplitude and phase values determined from accelerometer and quadrant detector data. Corrected ranges will be used to solve for a time-varying Zernike polynomial expansion of the wavefront error. The coefficients of the Zernike expansion will be passed to the open-loop surface servo. This will create a closed-loop surface servo operating in a measure-compute-actuate cycle with period less than a minute, synchronized with the $\approx 20\,\mathrm{s}$ period of the open-loop surface servo. The goal is to track and correct large-scale, slowly-changing thermal- and wind-induced distortions of the backup structure. Note that ranges across the 100 m steel backup structure will be quite sensitive to thermal expansion: $10^8\,\mu\text{m} \times 10^{-5}\,^\circ\text{C}^{-1} \times 0.1^\circ\text{C} = 100\,\mu\text{m}$, so $\Delta T < 0.1^\circ\text{C}$ will be easily detectable in a single rangefinder measurement.

The relative heights of the corners of the panels supported by each actuator will be adjusted to better than $50\,\mu\text{m}$ using a special tool developed by NRAO, and the retroreflector prism heights relative to the panels are predictable to $\approx 60\,\mu\text{m}$ RMS. Therefore, in principle, trilateration by the rangefinders can determine proper zero points for the actuators with high precision, and holographic calibration may turn out to be used only as a sanity check.

4. Open- and Closed-Loop Control of the Gregorian Secondary Mirror

The Gregorian subreflector is an $\approx 8\,\text{m}$ diameter portion of an ellipsoid with $f = 11\,\text{m}$, with ≈ 50 panels set to $\approx 100\,\mu\text{m}$ RMS by photogrammetry. The subreflector will be adjusted so that its two foci will coincide with the primary mirror prime focal point [PFP] and the feedhorn phase center when $E = 50.8^\circ$. Gravity deflection moves the feedarm relative to the PFP $\approx 23\,\text{cm}$; the focus tracking algorithm compensates this by moving the subreflector. Ray tracing analysis shows that the optimum focus tracking algorithm can compensate the 3^{rd}-order aberrations curvature (focus), coma and spherical aberration *exactly*, leaving only 0.4 mm of residual astigmatism at the extremes of elevation:

		Wavefront Errors					
		$2\rho^2-1$	$6\rho^4-6\rho^2+1$	$\rho\cos\theta$	$(3\rho^3-2\rho)\cos\theta$	$\rho^2\cos 2\theta$	
E	ΔP	*Curv*	*SphAb*	*Tilt*	*Coma*	*Astm*	σ
d	mm	mm	mm	μr	mm	mm	μm
0	-19.6	-0.0	0.0	-2	-0.0	-0.4	12
20	-16.0	-0.0	0.0	-1	-0.0	-0.2	7
44	-0.0	-0.0	0.0	-0	-0.0	-0.0	0
70	28.8	0.0	-0.0	-0	0.0	0.3	7
90	56.0	0.0	-0.0	-1	0.1	0.4	12

This astigmatism will be corrected by adding a $\rho^2\cos 2\theta$ term to the open-loop surface servo. In the above table ΔP is the change of total pathlength through the GBT and σ is the residual (5^{th}-order) wavefront error.

There are six retroreflector prisms attached to the subreflector panels; their positions relative to the ellipsoid foci were determined by analysis of photogrammetric data. The feedarm rangefinders will observe these prisms to locate the subreflector in the primary mirror closed-loop servo coordinate system. Slow changes in the feedarm position relative to the open-loop gravity model prediction will be determined as a part of the closed-loop surface servo, and these will be added to the open-loop focus-tracking algorithm, thereby making it closed-loop too.

5. Open- and Closed-Loop (Ground-Referenced) Pointing Corrections

The GBT will use a "traditional" pointing model with about 10 terms. The rangefinders will be used to calibrate many, and perhaps all, of the pointing

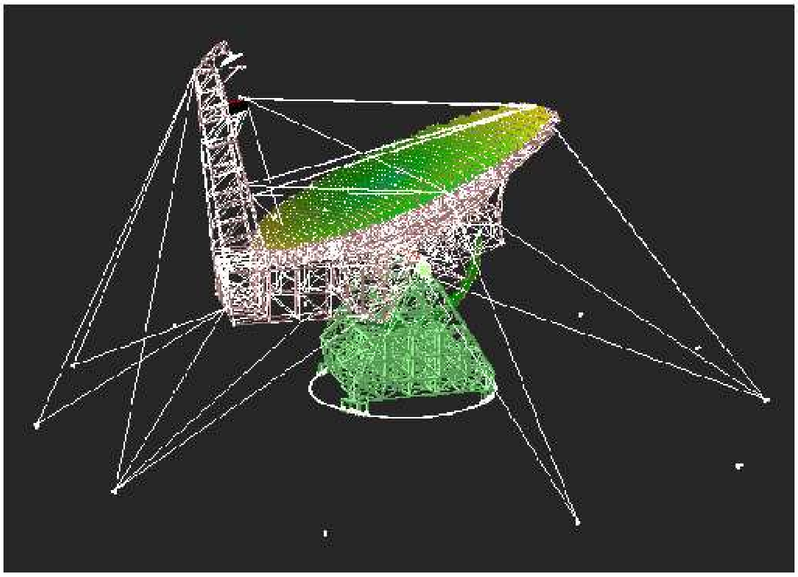

Figure 4. Trilateration of alidade, tipping structure and surface.

coefficients because the metrological determination is expected to be more accurate than the traditional technique of fitting to radio source observations, but this model will still be used as an open-loop pointing servo.

Wind forces and thermal gradients will cause the beam to deviate from the position indicated by encoders after the traditional model corrections have been applied. The GBT has 12 of its rangefinders mounted on stable ground monuments at 120 m radius from the pintle bearing (Figure 4). These will be used to range on retroreflectors attached to the alidade and tipping structure so that these unpredictable changes of orientation can be measured. This process has been simulated by generating fake data for 12 ground rangefinders measuring 6 retroreflectors at 2 ranges/s during 3 s to produce 72 ranges with $\pm 100\,\mu$m noise added. The simulation assumed the tipping structure is moving with constant velocity in Az and El. The Gaussfit least-squares program (Jefferys et al. 1988) was used to fit the data, using the model shown in Figure 5. The simulated orientation was $A = 23°, E = 54.5°$, and angular velocities were 1 mr/s (200 arcsec/s, $\approx 10\times$ sidereal) in both axes. The simulated GBT tipping structure differed from nominal geometry due to an assumed $\Delta T = 0.2°$C. The simulated solutions have $\sigma_{\mathrm{Az,El}} \approx 1\,\mu$r (0.2 arcsec), $\sigma_{\mathrm{translation}} \approx 30\,\mu$m and $\sigma_{\Delta T} \approx 0.03°$C. It is interesting to note that Gaussfit, even spawned by a Perl script and with various other inefficiencies, proved to be faster than real-time on the author's 450 MHz P-II. Therefore, it is possible that this simulation program will be adapted for production use! In practice the model-fitting technique will be slightly different from the one used in this simulation: we will solve for the difference between the observed orientation and the commanded trajectory. This is because this offset is independent of the trajectory shape.

There are retroreflectors attached to the elevation bearing housings. Ranges to them from the ground rangefinders (see Figure 4) will be analyzed to infer

```
/* Gaussfit model which fits translation, orientation & temperature
   parameters to observations of range to retroreflector prisms
   which are attached to a moving truss structure, assuming that the
   truss is rigid and that the angular velocities and the rangefinder
   and prism coordinates are known. */

constant        pr[ranger,axisr];     /* XYZ_ground of rangefinder   */
constant        pc[cube,axisc];       /* XYZ_truss of retroreflector */
constant        coefficient;          /* per degC (1.2e-5 for steel) */
constant        eulervelocity[axisp]; /* known angular velocities    */

parameter       translate[axisp];     /* Delta_XYZ of truss          */
parameter       euler[axisp];         /* Az=euler[0],El=euler[1],t=0 */
parameter       temperature;          /* Delta_T of truss [degC]     */

data            time, r, c;
observation     range;     /* rangefinder 'r' to prism 'c' at 'time' */

main() {
        variable i, cp[3], sum, computed, naxes=3;

        while (import()) {
            for (i = 0; i < naxes; i = i + 1)
                cp[i] = pc[c,i] * expansion(temperature,coefficient);
            about_z(cp, (euler[2]+eulervelocity[2]*time));
            about_x(cp, (euler[1]+eulervelocity[1]*time));
            about_z(cp, (euler[0]+eulervelocity[0]*time));
            sum = 0.0; for (i = 0; i < naxes; i = i + 1) {
                cp[i] = cp[i] + translate[i];
                sum = sum + (cp[i] - pr[r,i])^2;
            }
            computed = sqrt(sum);
            export(range - computed);
        }
}
about_z(v, a) { variable temp;
    temp = +v[0]*cos(a) +v[1]*sin(a);
    v[1] = -v[0]*sin(a) +v[1]*cos(a);
    v[0] = temp;
}
about_x(v, a) { variable temp;
    temp = +v[1]*cos(a) +v[2]*sin(a);
    v[2] = -v[1]*sin(a) +v[2]*cos(a);
    v[1] = temp;
}
expansion(temp, tempcoeff) {
    return (1 + temp * tempcoeff);
}
```

Figure 5. Fitting translation, tilt and temperature to a moving truss.

changes in the elevation axis collimation angle and the azimuth zero point. It is likely that these corrections will be applied directly to the corresponding coefficients of the traditional pointing model. If so, the model fitting technique discussed above will be determining pointing corrections due to distortions of the tipping structure, independent of the distortions of the alidade structure determined by measuring the elevation bearings. Anecdotal evidence for other large radio antennas suggests that typically about half of the total pointing error occurs in the alidade structures.

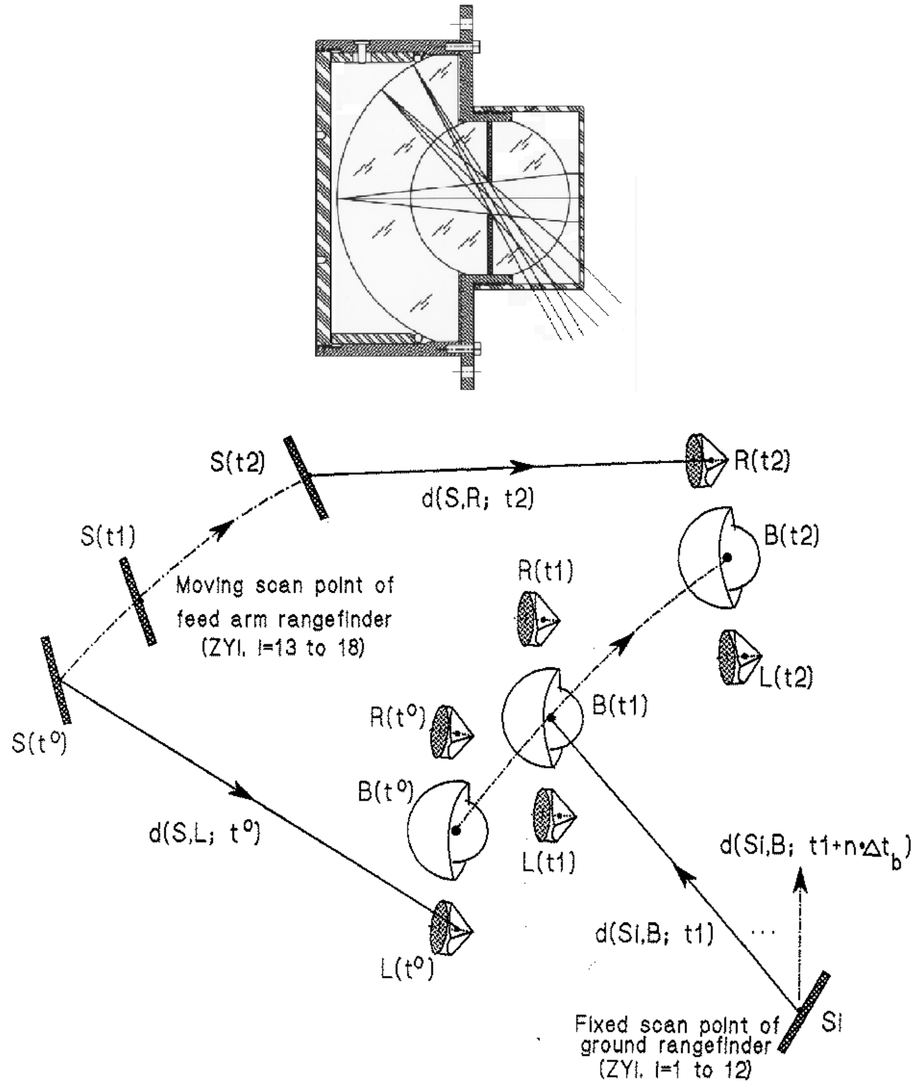

Figure 6. "Triplet" retroreflectors (observable from front and rear).

NRAO hopes that eventually this ground-referenced pointing technique will be able to point the beam absolutely (of course, until we are confident about absolute pointing we intend to use radio sources for local zero point pointing corrections in the usual fashion). A key requirement for absolute pointing of the wavefront produced by the primary mirror is to be able to determine the locations of the feedarm rangefinders relative to the ground. The enormous primary mirror blocks many of the lines-of-sight needed for such determination. We wish that we could "bend" the lines-of-sight around the obstruction; this idea led to a concept which we call "triplet" retroreflectors: one retro faces in one direction and two other retros face in the opposite direction, with the reflection point of the first retro coincident with the bisector of the line connecting the other two retros. Conventional corner-cube prisms operate to $\pm 25^\circ$ off-axis, covering only $\approx 0.6\pi$ steradian $= 2\pi(1 - \cos 25^\circ)$. The desire for increased solid angle coverage caused NRAO to contract with the Optical Sciences Center in Tucson to produce a set of spherical retroreflectors (Goldman 1996) which can be deployed to critical points on the structure where wider-angle capability is needed; the $\pm 65^\circ$ off-axis capability (see Figure 6) of the retrospheres covers 1.15π steradian.[6] Six triplet retros will be installed around the rim of the primary mirror. Measurements of these triplets from the ground will yield pointing corrections and measurements from the feedarm by the surface servo (note the laser beams intersecting at the rim of the primary in Figure 4, and compare the schematic in Figure 6) will refer the surface prism measurements to the triplet prism pairs (using the geometric mean of the ranges), thereby determining the wavefront orientation referred to the ground monuments. The schematic in Figure 6 reminds us that we will be ranging on the moving triplets from a moving feedarm as well as from the ground, without the simplification of simultaneity.

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[6] If a sphere could be made of material with index $n = 2$, it would act as a retroreflector covering up to 4π steradian. In the past this was only a theoretical possibility, because such material was not available. Recently the GBT metrology group learned of the development of retrospheres made of a lanthanide material which does have $n = 2$; the group expects to test these devices when they become available. If they prove satisfactory, the bulky and expensive "triplet" assemblies covering 1.15π could be replaced by compact single spheres covering almost 4π.

[7] `http://clyde.as.utexas.edu/Software.html`

[8] `http://www.patents.ibm.com/cgi-bin/viewpat.cmd/US05455670__`