GBT Memo No. 38

NATIONAL RADIO ASTRONOMY OBSERVATORY
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MEMORANDUM

To: GBT Memo Series

From: C. Brockway

Subj: GBT Fine Pointing

An approach for fine positioning of the GBT is described. A summary of the ideas is:

1. There does seem to be at least one way to define the elevation axis position in space to a precision of about one arc second with respect to a ground based frame of reference. The method uses signal collimators, mirrors or prisms, and shielded light beams that are not affected by atmospheric conditions.

2. It does seem possible that high frequency components of the pointing error spectrum can be measured and compensated even for frequencies outside the bandwidth of the telescope servo drive system. This is important because otherwise "ideal" observing conditions at the shorter wavelengths may often be accompanied by substantial pointing uncertainties from structural responses to wind turbulence.

3. The method calls for the availability of a stable foundation at the telescope pintle bearing. Stabilized reference tables on the telescope turntable rotate with azimuth so as to always remain under the ends of the elevation axle. Rotation and tilt of the elevation axle are measured using reference platforms mounted near the tops of the tower structures. All connecting light beams are contained in tubes for stability.

4. Pointing information is derived from distance and angle measurements. Two measurement systems are used together; the one described here for the structure between ground and elevation axis and another for the active surface/optics measurement. (At the same time the surface is adjusted for optimum profile, the beam steering component is measured from which pointing corrections can be computed). In between, is the surface to elevation axis region that is expected to contribute a smaller part of pointing uncertainty than elevation axis orientation or surface/optics geometry.

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The enclosed sketch shows a possible method for fine positioning of the GBT. Light beams are used to couple rotating reference tables to the telescope elevation axis. The tables are stabilized normal to the gravity vector and are compensated to correct for azimuth velocity and acceleration. Optically coupled servo loops detect rotation about all three axes of the instrumental (telescope) coordinate system with respect to a stable frame of reference; thus, the pointing errors arising from changes in the instrumental system are determined. Since the light beams move with the telescope they can be contained in tubes thereby minimizing the limiting effects of weather and air currents on pointing accuracy. Broad bandwidth servo loops retain higher frequency (up to 5 Hz or so) components of the positioning error spectrum. These higher frequencies are expected to be mostly structural transients and oscillations excited by wind gusts and are outside the bandwidth of the telescope servo drive system. Thus, the telescope cannot be positioned fast enough to track out these components but it may be possible for corrections to be applied by means of a higher response servo; for example, by slightly tilting the subreflector about two axes so that its focus can be made to move in the primary focal plane.

A few considerations leading to the positioning method are:

1. The pointing problem is solved when the telescope pointing vector or radio beam is defined with respect to gravity and true azimuth. (Refraction is a separate problem). The telescope, or instrumental, coordinate system changes with respect to an ideally stable coordinate system fixed to the ground due to the effects of loading, temperature, foundation, and wind. In general, rotation about any axis in the three cardinal planes of the instrumental coordinate system can result in a pointing change. Translation of the instrumental coordinate system does not cause a pointing change inasmuch as the angle between source flux and pointing vector remains constant. Conversely, pointing as determined by the positioning measurements must be independent of translations. Also, translation must be considered in regards to light beam acquisition and displacement linearity and limits.

2. The dominant part of pointing uncertainty is due to changes in that part of the telescope structure supporting the elevation axis. Confirmation of this awaits a study of the final telescope structure but seems likely after reviewing the ideas and calculations of past designs of large

telescopes. For example, Findlay and Von Hoerner planned to reference the pointing of the 100 and 65 meter NRAO telescopes to a stable platform at the elevation axis intersection with the azimuth axis. Other examples are the many telescopes built around an isolated central tower supporting a master equatorial reference.

For the GBT, there is the capability of altering the pointing vector by means of the active surface control but only over time intervals too long to track out higher frequencies and probably with unacceptable wear of the panel positioning components. Apart from any active surface adjustment, it is possible to very accurately measure the distance between four or more points on the backup structure near the surface with respect to the elevation axis and this can be done in two orthogonal planes thus defining the aperture change relative to the elevation axis. This is counterproductive, of course, if the measured points are not by themselves stable and this would be expected to be a problem. Furthermore, translations and rotations of the optics will change the pointing vector. From these considerations, the following emerges:

A. Active surface measurement can be used to stabilize the pointing vector against changes in telescope surface and optics. That is, the pointing vector change from some reference pointing direction (radio source) together with a surface/optics measurement can be computed for any subsequent surface profile and optics geometry. This measurement does not require a ground based frame of reference.

B. The fine positioning system stabilizes the pointing vector against instrumental rotations taking place at or below the elevation axis.

C. Changes between the aperture (and pointing vector) and elevation axis are expected to be less than A or B above and may possibly be disregarded especially if the backup structure is shielded. If significant pointing errors are found to originate in this area, then distance measuring can be considered for generation of additional pointing corrections.

3. It is advantageous for the positioning system to measure the particular structural changes responsible for pointing uncertainty. Identifying these would facilitate analysis and improvement. For example, effects of a particular path length between mirrors of a multiple reflection system could be difficult to separate from the total.

4. At least an order of magnitude improvement in pointing uncertainty is required from the fine positioning system over that provided by conventionally used shaft encoders at the elevation and azimuth axes. The improvement would come about due to three factors:

A. The conventional system azimuth position is referenced to the telescope turntable; the fine position directly to the elevation axis.

B. The conventional system elevation angle is referenced to the support tower; the fine position to a stable platform held normal to gravity.

C. The fine positioning system, but not the conventional, measures elevation axis tilt relative to gravity which, if uncompensated, results in an azimuth pointing error proportional to the tangent of the elevation angle.

From experiences at present large telescopes, it seems that a conventional positioning system has an absolute pointing uncertainty in the neighborhood of ten to twenty arc seconds rms for each rotation (under favorable conditions). It is anticipated that the accuracy of the conventional system will be about the same for the GBT.

Consider an instrumental rectangular coordinate system with the origin at the intersection of the azimuth and elevation axes. Let the x coordinate coincide with the elevation axis, z with the azimuth axis, then the y coordinate is normal to the x,z plane and is arbitrarily called the orthogonal axis. To describe the pointing, the positioning system obviously must measure rotation of the pointing vector about z for azimuth and x for elevation with respect to a stable reference frame. The pointing vector also changes if the azimuth axis tilts or if the azimuth and elevation axes become nonorthogonal. Azimuth axis tilt is present if the instrumental z axis is not parallel to the gravity vector. z axis tilt could result, for example, from a nonuniform shift in the azimuth track or foundation; nonorthogonality from unequal support tower heights. Azimuth axis tilt means that z and x rotate together and this rotation can be in any direction. It can be resolved into y,z and x,z plane components. If the tilt is in the y,z plane, the pointing vector changes only in elevation. If tilt is in the x,z plane, the pointing vector change is primarily in azimuth with a second order elevation term that may be neglected for small tilts. Nonorthogonality of the azimuth and elevation axes shows a similar rotation in the x,z plane and superposition is imposed to account for both. The pointing changes caused by x and z axes tilts are:

$$\text{delta } A = \text{secant } E\,(A_{x,z} \sin E + Q_e \sin E)$$

or:

$$\text{delta } A = (A_{x,z} + Q_e) \tan E$$

and:

$$\text{delta } E = A_{y,z}$$

where:

delta A; delta E	= azimuth; elevation pointing vector change due to tilts of x,z axes
E	= pointing vector elevation
Ax,z; Ay,z	= azimuth axis tilt in x,z; y,z plane
Qe	= elevation to azimuth axes departure from orthogonality

This shows that the effect of azimuth and elevation axes tilts can be compensated in elevation if the positioning system measures elevation with respect to a stable reference fixed to gravity. For azimuth, however, rotation of the elevation axis in the x,z plane must be separately measured and an azimuth correction term generated.

Another pointing error results if the pointing vector is nonorthogonal to the elevation axis. This collimation error shows, to first order, in azimuth but may be stable enough to be neglected as discussed in 2C before. Of course, a constant collimation error, as well as constant axes tilts, (inevitable from construction tolerances), are determined during calibration and permanently placed in the telescope pointing equation.

Operation of the fine positioning system is as follows:

Two reference tables rotate with azimuth so as to always remain approximately aligned beneath each end of the elevation axis. The reference table plane is stabilized normal to the gravity vector using torque motors in a two axis null seeking positioning servo. The sensing elements are either inclinometers or a signal autocollimator with a mirror or prism at the pintle bearing foundation. Inclinometers require compensation of the telescope azimuthal velocity and acceleration and these are accurately known. Both angular and centripetal accelerations must be compensated. It is assumed that these are the only disturbing accelerations requiring compensation at the turntable where the structure is stiff. Adequate compensation does not seem possible at the elevation axis because of support tower flexibility.

At each end of the elevation axis there is a two axis reference platform allowing rotation in the x,z (tilt) and y,z (elevation) planes. A dual axis autocollimator uses a mirror at the reference platform and a source/detector on the stabilized table in a two channel null seeking servo. Torque motors drive the platform so that the mirror is always normal to the light beam on the table. The stators of the encoders measuring rotations in the x,z and y,z planes are fixed to the platform; thus, the encoder reference is stabilized to the reference table and then to gravity. The servo error signals are insensitive to translation (assuming perfect mirrors) hence the rotating tables do not have to be exactly aligned with the elevation axis but only close enough for acquisition of the light beam. The light beams are contained in tubes for additional stability.

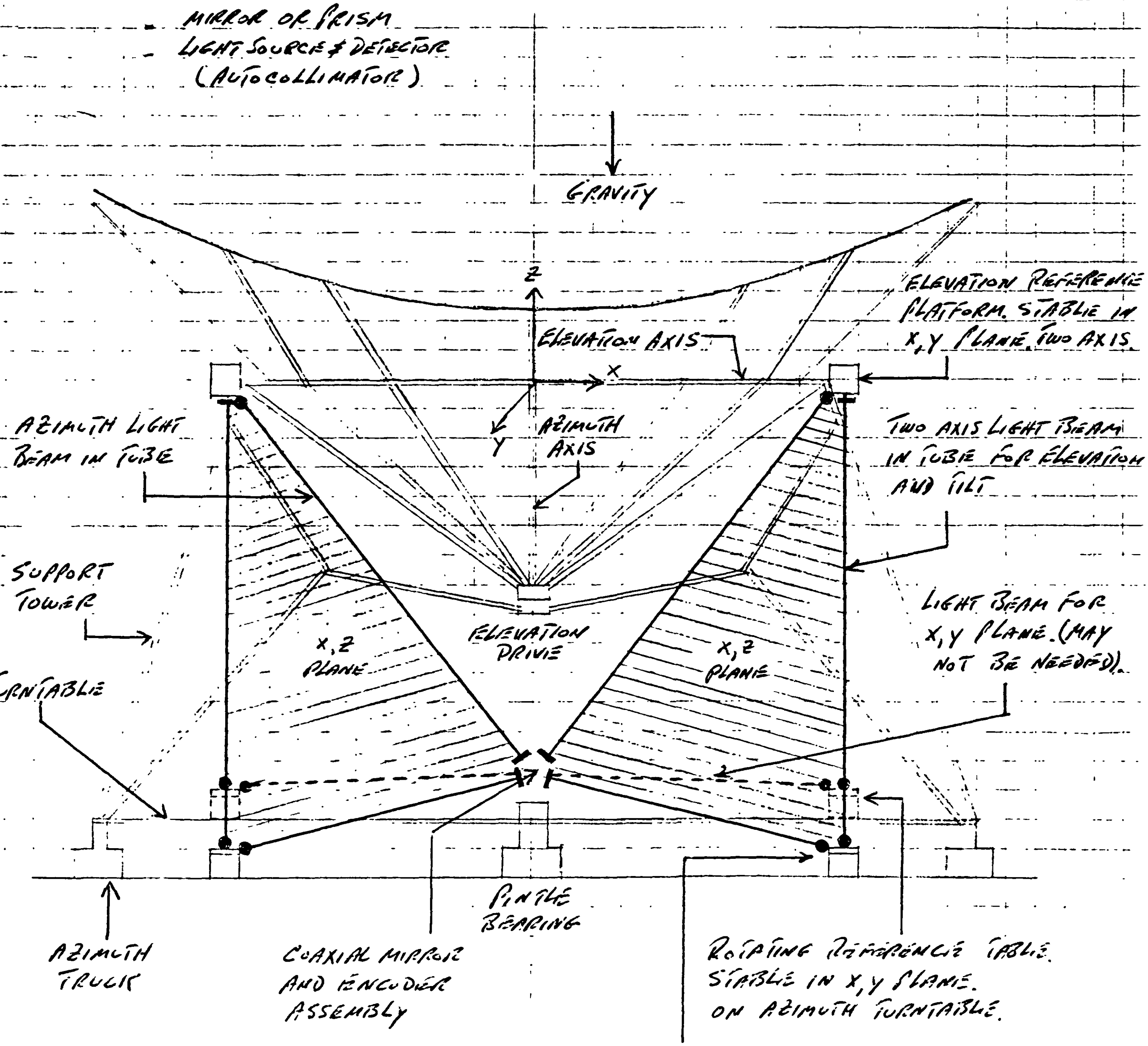
Also on each elevation reference platform is a light source and detector in collimation with a mirror at the telescope azimuth pintle bearing. There are two mirrors coaxially arranged so that both rotate about the z axis. Each mirror is directly coupled to its own precision encoder so that azimuth rotation of each end of the elevation axis is independently measured. Each encoder rotor and mirror are driven by a motor in a null seeking servo loop that keeps the mirror normal to the light beam the source of which is itself stabilized at the elevation axis platform. As before, the light beams are contained in tubes. A second mirror on each azimuth encoder assembly links the rotating reference tables. The stators of the azimuth encoders are secured to foundation at the pintle bearing. It is assumed that this foundation does not rotate about the z axis. Azimuth measurement is not affected by small translations or tilts at this point. The reference platforms at the elevation axis are likewise assumed to be stable about an axis parallel to z; that is, the towers are assumed not to twist about this axis (but bending is expected and compensated).

The elevation axis reference platforms and the rotating reference tables are closely temperature controlled with the light beams passing through high quality radomes of minimum thickness. All light beams are contained in tubes of four inches or so diameter and flexible end sections to allow for small displacements. There are several possible ways to minimize temperature and pressure gradients in the tubes so to stabilize the refractive index and "seeing" fluctuations of the light beams.

It may be necessary to measure distance between the reference table and reference platform in addition to tilt angle in the x,z plane. This will not be known until the details of structural deformations are analyzed or measured. Difference of the distances at the ends of the elevation axis is the important quantity. If distance information is needed, it would not be too difficult or expensive to add the required components at the reference surfaces.

The positioning system encoder outputs are combined to generate the pointing corrections. Rotation about each axis is measured at two encoders so that summing or cross correlation is used to determine true rotation. Azimuth and elevation are measured directly; pointing corrections from elevation axis tilt are calculated from rotation in the x,z plane. If the pointing corrections are applied to the main telescope drive then frequencies outside the servo system response appear as position errors which can be used for pointing correction in a high response servo at the subreflector. It is also possible to use subreflector positioning alone for the entire pointing correction although, of course, this would preclude fine pointing for prime focus observations.

GBT FINE POSITIONING



ALTERNATE ROTATING REFERENCE TABLE ON SEPARATE TRACK ON GROUND. TOO EXPENSIVE/INCONVENIENT FOR GBT.

NOT EXACTLY TO SCALE. THE REFERENCE TABLES AND PLATFORMS ARE ESTIMATED TO BE 1 CUBIC METER AND TO WEIGH LESS THAN 200 POUNDS.