GBT MEMO 216

Michael Goldman
December 29, 2000

Range Scan Program
Triplet Retroreflector Use

Here we define procedures for using triplet retroreflector assemblies mounted at the rim of the GBT main reflector surface. The ground frame coordinates of scan reference points of the feed arm rangefinders are found by using these assemblies.. Those coordinates are needed to locate the rangefinder positions, for GBT pointing determinations. Laboratory calibration and mounting of the assemblies is described, corrections to measured ranges are specified, survey adjustments of feed arm rangefinder scan point positions are reviewed.

Introduction.

Rangefinder reflector target assemblies located at the rim of the GBT main dish have been proposed for use as components of the telescope's rangefinder metrology system [Payne-1], [Wells-1]. They refer to such an assembly as a "retrosphere." One target on each assembly can be located in position with respect to the ground frame of reference by range trilateration from ground-based rangefinders ZY101 to ZY112. This target's position can also be found with respect to a local frame of reference defined for the reference scan points of the feed arm rangefinders ZY113 to ZY118 by trilateration from those rangefinders to the *other* targets in each assembly.. By adjusting the network of points generated by the set of measured ranges, the feed arm rangefinder scan points can be located. It then becomes possible to relate the main reflector surface to the ground. Telescope coordinate systems and geometry are discussed in [Gold-1].

A cube prism target and a cat's-eye ball retroreflector target can only be viewed from their front half-space. To tie ground-referenced coordinates and local coordinates of a group of feed arm rangefinders to one another, one must locate targets from both their front and rear half-spaces simultaneously. This can not be done with a single target. But it can be accomplished for a triplet assembly of three targets mounted rigidly with respect to one another. One mounts a ball reflector midway between two cube corner prisms so that the prisms face towards a given direction and the ball reflector faces in the opposite direction; the center of the ball reflector coincides with the optical centroid of the two prisms. When one measures distance from a rangefinder to each of the cube prisms and also knows the distance between the fiducial reference points of the prisms, one can calculate the range to the centroid of these two fiducial points, by computing the length of a median of the triangle formed by the two points and the rangefinder's scan reference point.

Proposed Use.

Range measurements to triplet assemblies are used, first of all to find feed arm ranger scan point locations with respect to the telescope's ground frame of reference. Measured tie distances, for this purpose, can also be obtained by direct ranging between feed arm rangers and ground benchmark monument targets, and ranging between ground-based and feed arm rangers. But the latter measurements are in general insufficient to tie tipping-structure-related coordinates to the ground reference frame. Additional distance ties are needed, via points around the rim of the main telescope dish. Triplet retroreflector assemblies provide the needed tie points.

An important issue which must be defined precisely and resolved is: "What does one do with measured range distances, after one has acquired them. How are they to be used?" The answer to this question is complicated, and depends on the particular mission assigned to the rangefinder during an astronomical observing run.

Some measurements are non-astronomical in nature, and are used to characterize or check out the static surface shape or pointing of the telescope, or acquire target or rangefinder reference coordinates. Measurements to check out target locations as part of telescope maintainance checkouts belong to this mission category. The telescope is stationary during these measurements. Measured ranges, after appropriate adjustment, are logged. Target reference locations in the data bases could then be updated. As another mission, target coordinate data for different telescope elevations might be analyzed to study the validity of the finite element model of the telescope. Newly-measured target point locations might be compared to previous locations, to check for structure changes, and warning flags could be generated to signal a structural shift. These missions are straightforward, and the uses and subsequent treatment of the acquired measurement data are well-defined. Software codes to implement these missions will have to be generated, however.

In some observing programs, range measurements are made periodically during sidereal tracking; they are in turn acquired, reduced, time-extrapolated, adjusted, to provide adjusted ranges and target and rangefinder position coordinates in either the ground or geometric elevation coordinate frames. The data is then logged. At some subsequent time after the observing run, the adjustment data is used to analytically reconstruct main-reflector-surface shape and/or pointing during the run. Software codes to perform these reconstructions and graphic user interfaces will have to be provided.

The employment of the laser metrology system for real-time application is of potential importance. At present it is *unknown territory*! Precise mission statements do not (yet) exist! At low radio frequencies, e.g. below 15 GHz, real-time analyzed range measurements may not be needed. For centimeter and millimeter wave observing, real-time metrology may be beneficial. If this is to be, precise mission statements and analyses of rangefinder scan programs and treatment of measured data will have to be written. Mission analysis documents do not presently exist. Until such detailed analyses and documentation is prepared, real-time applications are only "the music of the future."

Calibration.

Each assembly is calibrated in the metrology laboratory before lifting onto the telescope. Cube-corner-prism and ball correction constants are measured. To calibrate, an assembly is mounted kinematically against mechanical limit stops, using a special rod and plate fixture attached temporarily to the assembly (cf. Figure). Next, the cube corner prisms are ranged by a laboratory rangefinder. The assembly is then flipped by 180°, leaving the location of the front plate surface fixed, but exposing the ball to view instead of the prisms. The ball is then ranged. The ranges are reduced, using the measured correction constants. The measured reduced range from the ball center to the laser scan point is compared to the predicted range (calculated using the measured reduced range to the prism fiducial points and the triangle median formula). The perpendicular distance of the of the ball center to the line joining the cube prism fiducial reference points is also measured. That distance is designed to be zero, but a small deviation may be generated in actual manufacture of an assembly. The distance appears as an extra parameter in the computation of ball range from a feed arm rangefinder.

The Triplet Assembly Database.

Data concerning the rim triplet assemblies is stored in the "RIM RETROREFLECTOR TRIPLET DATABASE." Geometric elevation frame coordinates of rim targets, at the tipping structure's reference elevation, are stored in this data base. Those coordinates are the best available current values, computed or measured, for the cube prism fiducial points and ball reflector reference point (the ball center point), corresponding to the surface rigging elevation (50.8°). Reflector correction constant magnitudes, $|P_c|$, are also stored. Current, updated elevation frame coordinates of feed arm ranger scan reference points should also be available in this database, for the reference elevation. A list of cosines, of the angle between the ray from ball center to rangefinder scan point and the ray from ball center to the assembly top plate's normal, is also included, together with a measured range correction constant H_{corr} for each assembly.

The following nomenclature is used for the rim assembly retroreflectors. For the j'th assembly (j = 1...10) the (down-looking) ball reflector's name is ZDG_j, the (upward-looking) left prism reflector's name is ZUG_j and the right prism reflector's name is ZUG_{j+10} Here left and right are as seen by looking downward towards the main reflector dish from above.

Timing Input Signals.

To use rangefinders during an astronomical observing run, it is necessary that they possess the capability to track rim triplet targets while the tipping structure moves. Timing signals to trigger rangefinder scans will have to be generated. Rim target visibility andrangefinder drive aiming coordinates must also be generated. The ultimate source of observing schedule information will either be a schedule software file entered from a computer monitor keyboard to the "TELESCOPE OPERATOR INITIATED SCHEDULING REQUESTS" server, or a time series of input data from the telescope's "COMMANDED TRACK" server. The input program describing the observing schedule will generate requests for commanded tipping structure elevation, azimuth and their first two time derivatives versus time of observation. The state vector describing the commanded angles, and their time derivatives versus time of observation, has to be made available to the metrology system computers (ZIY and ZY) prior to observation. Such information can come directly from the POINTING MODEL as a time series of data, or from a schedule file generated in the "SCHEDULER FOR RETROREFLECTOR SCANS."

To aim a ground-based rangefinder at down-looking ball retroreflectors (type ZDG targets) on the main reflector dish rim, during an astronomical observing run, the scheduled trajectory of commanded elevation, azimuth, and their first two time derivatives must be made available to the "LINE-OF-SIGHT VISIBILITY COMPUTATIONAL PROCESSOR" for that rangefinder, a computational module residing in its ZY computer. This computational module prepares a schedule of scan target availability versus time for the rangefinder and generates a request for rangefinder beam aiming coordinates versus time from the "RANGEFINDER ATTITUDE COMPUTATIONAL PROCESSOR." The generated schedule of rangefinder aiming coordinates versus time is then ported to the "SCAN EVENT GENERATOR FOR GROUND RANGEFINDERS," which generates scan drive and start-stop signals.

The schedule generated for each ground-based rangefinder to scan a given rim ball target will have to be compatible with the mission of tracking that target's location during the observing run. One will have to acquire sampled range distance data from several ground-based rangefinders, taken at different scan measurement times, to calculate target location at some extrapolated time. Program triggers will have to be generated to request the adjustment of time-extrapolated range distances from sets of ground-based rangefinders to each rim ball target, to obtain a sets of ground-based coordinates for that target during the observing run. That is, the collection of range measurements made from ground-based rangefinders to each rim target during the observing run will be fed into a DYNAMIC RANGE INTERPOLATION COMPUTATION PROCESSOR, followed by adjustment using "RANGE ADJUSTMENT CODES" to generate a time series of ground frame coordinates of the ball target during the observing run. That is, a calculated spatial trajectory of each ball target is generated for the duration of the observing run.

While ground-based rangefinders are being employed to track the trajectory of the rim ball targets from below during the observing run, feed arm rangefinders are employed in tracking the rim prism targets from above. This can not be done directly. No feed arm rangefinder can range to a ball target (it always faces away from the feed arm). But a feed arm ranger can accurately track the ball target indirectly, by measuring range to its two adjacent cube corner prism targets. The range rate of any prism target to any feed arm rangefinder is small. One measures range indirectly to a ball, from a feed arm rangefinder, by ranging to each of its adjacent upward-looking cube corner prisms (type ZUG targets), and then extrapolating (or interpolating) the range measurements to the same time as the extrapolated ground ranging of the ball. The pair of time-extrapolated prism ranges can then be converted to a "calculated extrapolated range" from feed arm rangefinder to ball center [Gold-2]. This is done by computing the median chord length (from the rangefinder scan reference point) of the triangle formed by the rangefinder scan reference point and the two prism target fiducial reference points, and applying a small correction to account for displacement of the ball center from the line joining the two prism fiducial points. The calculation is discussed in the next section of this note.

Range Distance Reduction.

The range reduction algorithms for the upward-looking cube corner prisms viewed from the feed arm rangefinders, are the same as for surface targets viewed by these rangefinders, and is given elsewhere. An additional calculation is needed to obtain the range from a feed arm ranger scan point to the center of the ball reflector of a triplet assembly, given the two reduced ranges measured from that scan point to the fiducial points of the assembly's two cube prism targets. Denote the prism targets by T_{j_1} and T_{j_2}. Assume that they are scanned from feed arm rangefinder ZY_i, when the tipping structure is at commanded angles AZ,EL. Let

$$(2.1) \qquad d_1 = d_{ij_1}(AZ, EL)\ , \quad d_2 = d_{ij_2}(AZ, EL)\ , \quad d_{12} = d(T_{j_1}, T_{j_2})\ .$$

The fixed distance d_{12} between the two prism fiducial reference points is set and accurately measured during assembly manufacture. Nominally $d_{12} = 25.000$ inches. The range from the scan reference point S_i of rangefinder ZY_i to the centroid of the points T_{j_1} and T_{j_2} is then the length of the median line from S_i to the chord between the target points.

The design of the triplet assembly places the reference points of the three targets on a line, with the ball center B mid-way between the prism reference points, and all three points lying in the top plate surface of the assembly, with the prism faces parallel to the plate surface. The assembly is mounted on the telescope main dish rim and oriented so that the normal to the plate points to the approximate centroid of the feed arm rangefinder scan points, A ,which is a point which has been located by an optical target. (Tò do this, a small alignment telescope is temporarily mounted on the assembly's top plate, with its axis $\perp$ to the plate. The assembly orientation is set by viewing point A through the telescope, and locking down the assembly. The assembly's mount has a two-angle adjustment to set orientation).

If, as built, the ball reflector's center point is displaced parallel to the top plate, the range error is of second order, and is small. If the ball center lies above (or below) the top plate, the range from S_i to the ball center will be decreased (increased) from that of the prism centroid to S_i by the projection of this distance along the chord from the ball center to S_i.

The distance of the ball center from the prism centroid point is measured in the calibration laboratory using the flip measurements discussed earlier, and is the correction parameter listed in the triplet assembly data base (H_{corr}). Reference coordinates for the prism fiducial points, the ball center point, feed arm rangefinder scan points, and feed arm rangefinder group aiming point are also listed in the triplet assembly database. The projection of the ball center point's perpendicular displacement vector from the line of prism centers (which is nearly normal to the plate) taken along the chord from the ball center to S_i is also in the database. (Exact coordinates aren't needed to get an acceptable correction since it is small; nominal or calculated coordinates are adequate).

The formula for computation of the distance from ball center B to rangefinder scan reference point S_i is

$$(2.2)\quad d(S_i,\, B) = \sqrt{\frac{(d_1)^2}{2} + \frac{(d_2)^2}{2} - \frac{(d_{12})^2}{4}} - \left(\widehat{E}_{BS} \cdot \widehat{E}_{BA}\right) \cdot H_{corr}\,.$$

Here, distances d_1 and d_2 are measured ranges time-extrapolated or interpolated to an extrapolated ground measurement time. The particular extrapolation times to be specified are based on the particular the nature of the scheduled astronomical observation run.

Dynamic Range Correction.

When measuring range to a rim ball target from a ground rangefinder, the logged time of measurement is the mid-time of the target illumination. The range which is measured is the range at that time. An explicit correction for range rate Doppler and range rate acceleration is not normally needed. In particular, no corrections are needed for sidereal rate telescope motions. It is expected that only in programs for fast-scan on-the-fly mapping will a range rate Doppler correction be used. This correction is given in [Gold-2]. It is a term added during the reduction of range. Range Doppler correction for scans between feed arm rangers and rim targets are not needed.

Dynamic Range Interpolation.

Interpolation codes are given in [Gold-2]. Client-server interface codes will have to be defined and written to handle the data flow for the interpolation computations.

Range Adjustments.

For stationary telescope measurement data, range trilaterations can be made using the commercial STAR*NET codes. Data handling interfaces are being written to handle the data flow for static adjustments. The issue of real-time data handling has not yet been addressed.

Data Logging And Database Updating.

Data logging protocols for the various observing missions do not yet exist, and have to be defined. Appropriate code will have to be written.

Discussion And Summary.

The retroreflector triplet assemblies to be placed at the rim of the GBT main reflector dish have been described, and their principle of operation outlined.

Calibration methods for the triplet assemblies have been developed and are available. The range reduction algorithm for obtaining range from a feed arm rangefinder to a rim triplet ball center is given above. One prototype triplet assembly has been manufactured, and awaits availability of a ball reflector. Upon installation of the ball, the unit will be calibrated and tested.

Mission definitions and analyses for rangefinder use, and detailed software source code do not yet exist. Software codes still have to be generated for adjustment and subsequent handling of the measurement data. Development of those codes requires availability of the mission documentation.

References.

[Gold-1] M.A. Goldman, *GBT Coordinates And Coordinate Transformations,*GBT Memo 165, February 1997.

[Gold-2] M.A. Goldman, *Dynamical Rangefinder Measurements,* Memo, June 1998.

[Payne-1] J.M. Payne, *Pointing The GBT,* GBT Memo 84,

[Wells-1] D.C. Wells, *The GBT Precision Pointing System,* GBT Memo 85, September 1992.

Appendix A. Triplet Assembly Locations.

The preferred locations for the assemblies, in order of priority are the following.

Priority 1:
H44L-T-07, H44R-T-07.

Priority 2:
H39L-T-15, H39R-T-15.

Priority 3:
H29L-T-24, H29R-T-24.

Priority 4:
H23L-T-14, H23R-T-14.

Priority 5:
H42L-T-10, H42R-T-10.

Priority 1 is the highest priority. The notation refers successively to the hoop strip number, right/left position, azimuthal tier number on the main reflector. It is not essential to place the triplet assemblies at these exact locations; an adjacent location is also acceptable.

RETRORREFLECTOR TRIPLET Assembly