GBT MEMO 125

Evaluating GBT Performance during the Commissioning Phase

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1 Introduction.

A wide variety of astronomical experiments will be conducted on the GBT. Although each experiment can place specific demands upon the telescope, all rely upon its inherent properties (e.g. system temperature, antenna efficiency, ability to point, and beam shape). These properties are of interest to both engineers and astronomers, and they need to be measured.

Telescope commissioning serves two purposes, to optimize the telescope parameters for most efficient operation and to provide astronomers with as many of the characteristics of the telescope as may be relevant to their observations. These characteristics must be readily available to observers in a form useful to the them, probably through a database manager. Since some of the characteristics change with time, better optimization parameters are determined, and hardware is added or replaced from time to time, an historical record of telescope parameters and characteristics must be maintained. The history is valuable to track changes in the system and to learn from experience to improve telescope performance.

The GBT presents an interesting challenge because there are more free parameters on this telescope than we have ever dealt with before: adjustable surface, six degrees of freedom on the subreflector, three degrees of freedom at prime focus, a receiver turret with rotation within some turret positions, and so forth. Without a careful calibration plan to isolate variables and deal with them one, or at most a few at a time, gain and pointing optimization will converge much too slowly, if at all. Section 5 on the proposed calibration sequence is written with parameter isolation in mind.

We begin with a very brief statement of the astronomical objectives of the GBT. Section 3 lists the characteristics of interest to observers and engineers, and Section 4 outlines the requirements for information access and record keeping. The test and calibration procedures are described in Section 6.

2 Motivation: Types of Observing

The four main categories of GBT observations are continuum measurement and mapping, spectral line measurements and mapping, VLBI, and pulsar timing and searches. Here we mention a few typical, but not necessarily most taxing types of observing.

Continuum observations range from simple broadband flux density measurements, with either scans through a source or on-off difference measurements, to maps of large areas of the sky. Extreme receiver stability, subtraction of sky noise and ground pickup variations, and accurate intensity calibrations are of greatest importance. Bandwidths of 500 MHz or more mean that a sensitivity of 10^{-5} of the system noise may be achieved in 20 seconds. Gain stabilization techniques such as load and beam switching or rapid telescope motion are very common.

Very sensitive spectral line observations require long integrations at a specific location in the sky. An astronomer will look for signals at very precise radio frequencies in the spectra. Such an identification requires that both the baseline of a spectrum be flat and the sky frequency be well-calibrated. Baselines can be corrupted by standing waves which may be generated by scattering off the feed arm and other reflections within the telescope. Since the Earth moves over the course of the observation, the apparent frequency of the spectral line will shift due to the Doppler effect, and the telescope local oscillator may have to be updated frequently to compensate for the frequency shift.

Pulsar timing experiments are special cases of continuum observations, with the pulse time signature providing its own signal and reference phases. These measurements are usually carried out between about 0.3 and 3 GHz. Profiles of the pulsar's pulsed radio emission are formed by integrating the signal over a certain time interval. The integration time, up to several hours, depends on the pulsar's flux density. Each profile is time-stamped to assign a specific time-of-arrival to the pulsar's pulse. The times-of-arrival are compared with a model of the pulsar's rotation to better constrain, among other things, its rotation period, position, and proper motion. Since pulsar periods are sometimes known to better than a nanosecond, and average arrival times can be measured as accurately as 100 nanoseconds, it is extremely important that observatory time be accurately communicated to the telescope.

Very Long Base Line Interferometry requires station frequency stability of a part in 10^{15} over periods of minutes or more and timing accuracy with respect to other VLBI stations of better than 1 microsecond. Since the detailed structure of a VLBI map requires accurate visibility curves over large hour angle ranges, accurate telescope gain curves and stable pointing are also important. Phase-referenced measurements require frequent changes of telescope position to calibrator sources. The moves are typically two degrees every minute or less.

One of the more demanding observing techniques that will be used on the GBT is some form of on-the-fly mapping. This involves rapidly scanning the telescope across the sky while continuously collecting data. This reduces the effects of changes in receiver gain and atmospheric noise. On-the-fly mapping is more efficient for large maps than grid mapping because it reduces the overhead of moving from one grid point or line to another. It requires that data be recorded rapidly and that we know precisely where the telescope is pointed at any given instant. Data rates in spectral line mapping and pulsar searches can run into the megabytes per second range.

3 Telescope System Characteristics

Telescope commissioning cannot be considered complete until all telescope system parameters that may affect an observation have been determined. Some of these parameters are fixed by the hardware and need only be recorded, others vary with time, and others must be optimized with a measurement procedure. In this section we list the data sets required to characterize the telescope and its environment along with a few auxiliary data collections, such as radio source calibrator lists, which are required for routine calibration. These data sets are to be accessible in the manner described in Section 4.

- All-sky pointing corrections – This is a best-fit solution for the parameters in a pointing equation from a set of az/el encoder minus actual radio source position offsets for all directions in the sky. This data set consists of the pointing equation used, the coefficients derived, the measured offsets, and the relevant conditions at the time of measurement. Graphical displays include contour displays of the analytical pointing offset and smoothed residuals as functions of az/el or ha/dec, and selected line plots of offsets and residuals as functions of one coordinate (az, el, ha, dec) given the value of the corresponding coordinate mate.

- Local pointing offsets – These are solutions for limited numbers of pointing coefficients from one or more measurements of pointing offsets in a limited part of the sky. The data set and display are smaller versions of the all-sky set and display. Local pointing solutions are useful for determining both offsets for a given receiver and offsets due to changing weather and telescope conditions. A history of local offset determinations can be a valuable guide to the need for a new all-sky solution, as a diagnostic of changes in the telescope geometry, and a means of communicating the most recent pointing information from observer to observer.

- Receiver pointing offsets – Each receiver will have pointing offsets for each feed with respect to the nominal feed center as defined for the all-sky and local pointing offset solutions.

- Prime focus receiver position – The prime focus receiver will be maintained at the position of maximum aperture efficiency as a function of telescope elevation. Since this position function depends only on the surface and feed arm positions, it should be the same for all prime focus receivers. In this data set are either the analytical functions (one for each of two coordinates) and their coefficients or a table of coordinates. The data should be available as a line plot of position (one of two coordinates) as a function of elevation and as a line plot of one coordinate position vs the other with elevation tick marks on the curve.

- Subreflector position – The Gregorian subreflector will be positioned for maximum telescope sensitivity as a function of elevation. This data set contains either the analytical functions (three translational and three rotational coordinates) and their coefficients or a table of coordinates. The data should be available as line plots of position in one or more coordinates as a function of elevation.

- Active surface positioning function – The active surface positioners will each have a zero offset, and there will be an open-loop positioning function that will describe the position of every actuator as a function of telescope elevation. This data set should contain the analytic positioning functions and function coefficients including zero offsets at the telescope rigging angle. Useful graphical displays are a contour plot of the surface offset at a specified elevation and line plots of positions of selected actuators as a function of elevation.

- Aperture efficiency curves – Each receiver feed will have a different aperture efficiency dependence as a function of elevation. This data set consists of the equation used to represent the gain dependence, the coefficients derived, the measured aperture efficiency values, the radio sources and assumed flux densities, and the relevant conditions at the time of measurement, e.g. the active surface algorithm and status. The graphical display is a line plot of the derived curve and the measure values as a function of elevation.

- Beam maps – Each receiver feed will produce a different beam shape on the sky depending on its illumination pattern, offset, and polarization characteristics. This beam shape will be at least a weak function of telescope elevation even with optics optimization in full operation. This data set consists of the beam map data (all four polarization parameters where possible) and all of the parameters and conditions relevant to the observation. Graphical display will be a contour beam map. Since we cannot map the beam of all receiver feeds at all frequencies and elevations, these data sets will be accumulated over time as the observing need arises. A representative set of maps should be recorded as a part of the commissioning process.

- Low-level sidelobe maps – To determine the response of the GBT to interference and to widely distributed radiation on the sky we want to have a full sky map of the antenna's response to a level between about -20 and -30 dBi. Two all-sky sidelobe maps should be made as part of the commissioning process, one at 21-cm Gregorian focus, and one at prime focus, somewhere between 500 and 1000 MHz. Others can be added as needed. This data set consists of the recorded observations and the relevant conditions at the time of measurement. Graphical displays are contour and grey scale plots of selected angular extent and response level range.

- Holographic surface maps – This data set includes the original holographic amplitude and phase measurements, the derived surface map, the derived best-fit paraboloid parameters, and the relevant conditions at the time of measurement. Graphical displays are contour and grey scale plots of the measured amplitude and phase, the surface deviation from the best-fit paraboloid, and the aperture illumination amplitude.

- Spectroscopic baselines – Although the GBT should have improved spectroscopic baselines as compared to the 140-ft, the problem will not go away completely. Since baselines can be affected by so many factors such as far sidelobes, dish reflections, cable reflections, and receiver and spectrometer stability, we need to compile a representative set of baseline measurements as a guide for the observer and to watch for system degradations. New measurements can be added as they become available in the course of regular observations. A representative set of baselines for each receiver consists of total power observations of blank sky at night and at roughly 1-hour intervals during the day at several selected meridian declinations, and on-off observations of a few moderately strong continuum sources. The on-off pair should be of a standard duration, such as five minutes. The total bandwidth should be as wide as possible consistent with 100 kHz or better resolution. The data set is a standard total power spectrometer observation and the display is a standard spectrum line plot.

- Reflectometry – At least in the process of testing spoiler panels on the feed arm, we will make swept-frequency measurements of the reflection coefficients of one of the low-frequency Gregorian feeds as installed near the Gregorian focus. The measurement will offer some information on the remaining reflections that could affect spectroscopic baselines. This information may be helpful in interpreting measured spectrometer baselines. This data set consists of the measured phase and amplitude of the reflected signal as a function of frequency plus the Fourier transform of this data to produce a return loss-vs-distance data set. The data header should include the relevant measurement parameters and conditions. Graphical displays are line plots of the phase and amplitude data arrays.

- System temperature and telescope tipping data – Each receiver feed will have its own system temperature dependence on elevation due to changing ground pickup and atmospheric radiation. These data will be simple records of system temperature as a function of elevation, possibly at different azimuths, along with the parameters associated with the measurements. The predicted ground pickup as a function of elevation from known optics and feed parameters should be recorded with these data to permit a separation of the spillover and atmospheric contribution to the system temperature dependence. Graphical display will be a plot of measured temperature vs elevation, and line plots of the atmospheric and spillover contributions.

- Atmospheric monitor tipping data – If a full-time atmospheric opacity monitor is available, its solution for atmospheric opacity and the estimated error of each measurement should be recorded continuously. Graphical display is a plot of the measured opacity, with error bars, as a function of time over selected time ranges.

- Weather data – All data from the weather monitor stations should be recorded continuously with a sampling interval somewhere between a few tens of seconds to a few tens of minutes, to be determined later, along with notable conditions such as peak wind gusts. Graphical display is a plot of a selected parameter, with error bars, as a function of time over selected time ranges.

- Clock offsets – Precision time will be distributed to the GBT from the master Observatory clock as a one-second UTC tick. A table of offsets from the master clock tick should be maintained for all distribution points. Any changes to the distribution system should result in a new table with the changes recorded along with the date of each change. Any offsets that are a continuous function of time, such as the offset with respect to GPS, should be recorded in a continuously appended data set. Any known significant offset dependencies, such as cable delay as a function of temperature, should be recorded as data sets of delay and the independent parameter vs time over the appropriate time scale (daily, seasonal, etc.). Graphical displays are line plots of delay vs time and delay vs independent parameter.

- Front-end data – All of the receiver parameter information presently available on the Green Bank "Telescope Installation Data" sheet should be put in the GBT characteristics history. Any other data pertaining to receiver performance, such as nominal bias levels, cold station temperatures, LO drive level, IF frequency ranges, etc., will be useful additions to this data set. Updates to the front-end parameters should result in a new table entry with the date of change when known or discovered. Old data tables should be retained. Graphical displays include line plots of gain, noise calibration temperature, receiver temperature, and system temperature as functions of frequency within the receiver passband.

- Detector curves – We generally assume that the continuum detectors are close to square law and that our spectrometer samplers are ideal clippers, but for measurement accuracies better than 5 or 10% this has sometimes not been the case. Each detector used for astronomical measurements should have a detector curve recorded for it. The most practical form is the differential detector response as a function of input or DC output level. Where cross-product information is available from a detector set, both amplitude and phase curves should be included.

- Interference – The interference data base now being assembled at the 140-ft will be carried over to the GBT. As part of GBT commissioning we should record a sample of all frequencies within the available receiver passbands with a resolution of 40 kHz or better for at a couple of times of day using the spectral processor or the new spectrometer. The interference monitoring antenna on top of the GBT feed arm should be measured simultaneously to determine how well the monitor measurement reflects the interference environment of the telescope receivers. The spectral processor data base at the 140-ft consists of bursts of 1-second spectra for 15 minutes in each 40-MHz passband. The GBT interference monitor data base will be something like a continuous series of 1-minute spectrum analyzer sweeps throughout the day at selected frequency sweep widths throughout the monitor's frequency range. Graphical displays include a grey-scale of the time-frequency data array, line plots of spectra at selected times, and line plots of power as a function of time at selected frequencies.

- Sensor curves under quiescent conditions – There will be a fair number of sensors on the telescope to monitor non-repeatable changes in the structure. For example, the quadrant detector on the feed arm will show changes in the position of the arm due to temperature differentials and wind. The output of this sensor will be a function of telescope position under quiescent conditions due to gravitational deformations. Since the quiescent output of a sensor will be part of the repeatable pointing correction solution, this part of the sensor output must be subtracted from its reported error. The quiescent curve for each sensor must be measured as part of telescope commissioning, or when the sensor becomes available, and recorded as part of the history data base. They should be accessible as analytical curve coefficients, where appropriate, and as graphical line plots. A partial list of sensors and their quiescent curve independent variable is given below

Feed arm quadrant detector (elevation and cross-elevation)

Tilt meters, if any (azimuth and elevation)

Laser positions of the feed arm (elevation)

Laser positions of surface (elevation)

- Miscellaneous system information – Below is a sample list of miscellaneous system parameters that will affect some types of observations. Most of these will be indirectly calibrated through astronomical observations, but a record of subsystem measurements will be helpful to both notify observers of significant changes in the telescope parameters and as a diagnostic of component integrity. These are parameters that might normally go into an engineer's notebook.

  I.F. cable delays

  Servo response times and resonances (antenna drive, subreflector, prime focus drives, etc)

  Relative phase between backend channels (for polarization)

  Spectrometer response to narrowband interference

  Switching delay of the noise calibrator(s) in each receiver

  Settling time of the LO after a frequency change

  Beam switch and chopper settling times and delays

  Software response times to system commands

4 Record Keeping and Access

The two primary reasons for maintaining a history of the GBT characteristics are to make everything known about the system available to the observers and to help the telescope experts diagnose system problems. All of the information must be available in a form that is most useful to either observers or engineers.

The data should be recorded in a standard FITS format so that they are accessible to a variety of data analysis packages, AIPS++ in particular. Since contributions to the history archive will be made by a variety of people, there probably needs to be a minimum annotation standard to assure reasonable completeness and ease of retrieval. Most information about the data sets should be automatically contained in the data headers. Nothing should be deleted from the history archive. Any erroneous entries in the archive need to be flagged and be accompanied by a comment.

Observers and engineers will want to retrieve data by category (e.g. receiver data), by keyword (e.g. pointing), and by time and date ranges. Aids to archive search and retrieval such as menus and graphical interfaces will be very helpful. Since the form and number of data sets does not change much with time, a full blown relational data base manager may not be required, but this needs to be investigated. Each data set will have a well defined form, specific data display tasks may be associated with each to minimize the effort required to display information. Beyond that, users will want to do things like scan through old monitor data, overlay curves from two different calibration sets, and get hard copies of data displays.

5 Testing Sequence

This section is an outline of the initial testing and calibration sequence of the GBT. More details of the specific measurements are given in Section 6 on test and calibration procedures.

A testing sequence needs to be defined in order to minimize the time required for the commissioning of the GBT. Some subsystems of the GBT can be tested before the telescope is completely assembled. Determination of some telescope parameters must await the measurement of others. For example, we must convince ourselves that a receiver is working properly before we proceed with telescope pointing corrections, which, in turn, must be done before antenna gain can be optimized. The following test sequence lists the procedures which are required to bring the GBT into Phase I of operations (Norrod, 1995a). Some of the tests will need to be visited more than once and become part of a regular testing and calibration suite. We assume that the digital continuum receiver and the spectral processor will be available for continuum and spectral line measurements, respectively.

1. **Backend intensity response.** The intensity response of all of the spectrometer and the continuum detectors should be recorded over

their full operating range. This can best be done in the lab or off-line at the telescope while connected to one of the receivers or a test setup with enough RF gain to drive the backends. These tests can be performed at the 140-foot telescope on the spectral processor now and on the digital continuum receiver when it is ready for operations (July 1995).

2. **Frequency test.** Some of the frequency calibration of the GBT RF system can be conducted immediately after the GBT LO system is operational in March 1996 (Norrod, 1995b). Three tests are required. The first is a static frequency check as described in Section 6.8. The second is a comparison of the LO Doppler tracking at selected positions on the sky by comparison with frequency tracks computed with independent software. The third is the measurement of a selected set of astronomical lines of known frequency. The first and third frequency tests should be performed thereafter as a standard operational procedure. The same frequency tests must be applied to off-line Doppler tracking algorithms. Since the LO router will not be installed at the 140-ft, and the PLL will be different on the GBT, at least part of these tests need to be repeated at the GBT.

3. **Standing waves.** The dominant standing waves on the GBT are expected to come from reflections between its feed arm and the Gregorian receiver feed and from reflections from the slots between the main reflector panels in both Gregorian and prime focus operation. The feed arm reflections will be minimized by installing metal panels, or "spoilers", at predetermined locations on the feed arm. The effectiveness of the spoilers will be tested with a swept-frequency network analyzer measurement using the L-band Gregorian feed while the top portion of the feed arm is still on the ground. Since the locations of the spoilers may need to be refined, the test for reflections should be conducted before the feed arm is mounted on the telescope.

4. **Time synchronization.** The overall control of the GBT is distributed among independent modules which perform single tasks. This control scheme requires the modules to perform their tasks at very specific times. Therefore, it is extremely important that time be synchronized between modules. A "synchronization accuracy" needs to be determined for each module, and the modules should be tested for time synchronization once they are installed on the telescope.

5. **Receiver calibration.** Each GBT receiver will be calibrated for gain, receiver temperature, and secondary noise calibration intensity in the lab before being mounted on the telescope. Similar measurements may be made on the telescope as necessary.

6. **Receiver system temperature.** The temperature of the receiver systems on the telescope as a function of telescope elevation may be measured after the telescope surface is installed but before surface setting is complete or accurate pointing corrections are determined. These measurements should be combined with what is known about spillover from feed measurements and diffraction calculations to separate atmospheric noise from spillover radiation components of the elevation dependence of system temperature.

7. **Preliminary far sidelobes and spectral baselines.** Measurements of average far-sidelobe levels and daytime spectral baseline performance may be made after the telescope surface is installed but before surface setting is complete or accurate pointing corrections are determined. Using the sun as a test source, as much of the GBT's far-sidelobe pattern as possible should be scanned at 5° declination intervals, and 5-minute spectral baseline total-power pairs should be sampled on a 15° x 15° RA/Dec grid over the daytime sky with the 21-cm Gregorian and 800 MHz prime-focus receivers.

8. **Pointing.** The telescope pointing vector is defined as the direction of the prime focus beam peak when the position of the prime focus feed is optimized for maximum efficiency for all elevations. At least for the initial commissioning of the telescope, the same pointing corrections will be used for prime focus and Gregorian operation except for individual feed offset corrections. Any pointing differences for Gregorian gain optimization will be third order effects. The first prime focus all-sky pointing solution will rely on the predicted gain-optimized feed position computed from structural models. A second solution will be made after finding the gain-optimized feed position track from radio source measurements as described below. First pointing will be determined at some frequency between 0.8 and 1.2 GHz, and a temporary 10 GHz prime focus receiver for initial pointing refinement is presently under discussion. Pointing accuracies will be about 20 and 3 arcseconds rms, respectively

9. **Receiver box offsets.** After the main pointing solution is determined, the pointing offset of each receiver feed needs to be measured. This can be done quickly with one or two radio sources, possibly at a few widely separated elevations. As each new receiver is added to the system, the receiver box offsets will be determined.

10. **Tracking stability.** Once the GBT is able to point, it should be checked for its ability to track a source. This is done by pointing the telescope such that the half power point of its beam is located on a point source. If the GBT adequately tracks the source, the output of a total power detector should remain relatively constant with time. This can be done early in the prime-focus pointing process above.

11. **Prime focus feed position optimization.** Since the prime-focus plate scale can be accurately computed, a simple algorithm can be written for coordinated offset of the prime-focus feed and the main reflector pointing to maintain the beam peak at a constant position on the sky while the feed position is scanned. A few dozen radio source measurements over the full range of elevations will suffice to determine the optimum lateral and axial feed offset track. In principle, the GBT is not astigmatic, but all measurements, such as the determination of axial focus, should be made with the intention of confirming this fact.

12. **Holographic surface setting.** Holography of the GBT will be required to bring the telescope into the desired Phase I of operations (Norrod, 1995a). The most accurate holographic images of a radio telescope's surface are made at high frequencies. The source used in the holography of the GBT will most likely be one of the 12 GHz (Ku-band) geostationary satellites (Maddalena, Norrod, and White, 1991). After holography, measured antenna efficiencies should improve for frequencies higher than about 3 GHz. The prime focus pointing might be refined after setting the surface, but the change should be small. Before resetting the surface on the basis of holography measurements, an aperture efficiency measurement should be made at the shortest wavelength allowed by the pointing accuracy as a comparison for post-resetting efficiency. See Section 15.

13. **Subreflector position optimization.** Motion of the subreflector is quite complicated, because it has six degrees of freedom, although only three (one rotation and two translation) are needed to track gravity-

induced deformations of the surface and feed arm, to first order. Since we shall initially assume that prime-focus and Gregorian main reflector pointing are the same, determining the best subreflector position as a function of elevation is a gain optimization problem. The empirical task of finding the best subreflector position track will be greatly simplified by initial computations of the track from predicted structural deformations and geometric and physical optics models of the subreflector (Wells and King, 1995). These same models can be used to establish locally orthogonal subreflector offsets from the predicted track to quickly search for the best gain position on a few dozen radio sources at different elevations. After the subreflector track is refined empirically, we are then free to let the two pointing offsets be free parameters and conduct another search for maximum gain in each of the six orthogonal motions of the subreflector while keeping the beam position fixed on the sky as was done at prime focus. Here again, we know enough about the telescope geometry to predetermine an algorithm of scanning the subreflector in any direction while keeping the beam fixed on the sky. If the Gregorian gain-optimized pointing solution is within the errors of the prime-focus solution, we can adopt the Gregorian solution at prime focus. If not, we need to understand why.

14. **Surface tracking optimization.** All initial determinations of pointing and feed and subreflector tracking will be made with a surface positioning algorithm computed from predicted structural deformations of the structure. If the surface laser-ranging system is not available early in the commissioning process, a first-order refinement of the surface tracking algorithm may be done by optimizing the telescope gain at a full range of elevations by allowing one or more of the low-order surface-setting algorithm terms to be free scanning parameters. Any induced pointing offsets caused by the scanning process should be very small, by definition. Since several satellites are available at different elevations, holographic measurements may be of some help in evaluating the surface setting algorithm.

15. **Aperture efficiency curves.** After pointing and gain optimizations are complete, curves of aperture efficiency as a function of elevation must be measured for use by the first regular observers to use the telescope. Each receiver feed and polarization will require its own curve. Both relative and absolute aperture efficiency should be determined

as accurately as possible by measuring the antenna temperature of a dozen or so relatively strong continuum sources, whose flux densities are well known and whose declinations allow them to be measured over most of the elevation range of the telescope.

16. **Beam mapping.** Maps of the telescope beam should be made in each polarization of each receiver feed with observations of an unpolarized point source. Unwanted sidelobes and beam squint in circular polarization may appear in the maps. The prime-focus beam squint arises from the asymmetric geometry of the GBT, and the magnitude of the squint is expected to be about one-tenth of a beam width (Srikanth 1993). Point sources should be carefully chosen at low frequencies to minimize confusion. At frequencies where the beam shape may be a function of telescope elevation a number of maps at different elevations are needed.

17. **Receiver rotation.** Since the GBT is steered in azimuth and elevation, the orientation of a radio source does not remain fixed with respect to the telescope beam. The source will appear to rotate with parallactic angle. This rotation is undesirable for source mapping and some polarization observations. Some of the effects of rotation can be removed by physically rotating the receiver at a rate equal in magnitude to the time-rate-of-change of parallactic angle (Ghigo, 1990). A test should be conducted to ensure that the receivers rotate at the proper rate and that the polarization vector of the main beam rotates accordingly. This can be done by observing a linearly-polarized point source (e.g. 3C 286 and 3C 138) as it transits the telescope. Since the electric vector illumination of the telescope changes with feed rotation, beam maps should be made at 30° or 45° degree intervals of feed rotation between 0° and 180°.

18. **Refined far-sidelobe maps and system temperature tipping curves.** After the telescope feed and mirror tracking is optimized, the measurements of far sidelobes and the curves of system temperature as a function of elevation may need to be repeated. In particular, the sidelobes within 100 beamwidths or so of the main beam will have changed with mirror and feed alignment so extended beam maps will be needed at frequencies where high dynamic range is important.

6 Test and Calibration Procedures.

A calibration procedure serves at least one of two purposes, to determine the optimum setting of various telescope parameters (focus, pointing coefficients, surface adjustments, etc.) or to determine the telescope characteristics at the time of astronomical measurements (gain, beam shape, system temperature, etc.). Some telescope characteristics, such as receiver gain, change somewhat unpredictably with time and must be monitored frequently or as an integral part of the receiving system. Calibration scans may be liberally scattered between astronomical scans. Other characteristics, such as antenna efficiency, are relatively stable functions of antenna position and may be determined infrequently (days to months).

Nearly all receivers incorporate a signal source, which is assumed to be relatively stable with time, for secondary intensity calibration. This can be a diode noise source, a cooled resistive load, or a chopper wheel.. Intensity calibrations are transferred from astronomical sources of known strength to this secondary source which, in turn, is compared with measurements of unknown sources. The secondary source may be injected rapidly as part of the receiver switching cycle or before and after measurements of several minutes duration.

The following is a list of typical single dish calibration procedures with a brief description of each. The procedures were adapted from Fisher and Maddalena (1992). New calibration schemes are likely to come along in the future, a number of specialized procedures may be unknown to the authors, and the number of variations on the basic calibration schemes are too numerous to state in detail, so this list is not exhaustive. The descriptions are brief because the details are best worked out in cooperation between the implementors of telescope control and data analysis. Many of these procedures require only a continuum receiver, but, since this is really a special case of a spectrometer, we should assume that any of them could apply to a spectrometer and that the measured telescope characteristics may be a function of frequency.

6.1 Gain Optimization.

This procedure finds the optimum setting of one of the prime focus feed or the subreflector positioning coordinates, e.g. prime focus axial focus position. The telescope starts off-source to determine the radiometer baseline. It then centers the source in the beam and scans the position of the feed or subreflector over a range wide enough to determine the gain peak position. A function such as a parabola is then fit to the data (intensity versus position) to determine the peak intensity position. If the nominal optimum position is not known beforehand, the full range of travel of the feed or subreflector may need to be scanned to avoid peaking on a secondary maximum. This procedure assumes that the radiometer baseline is not dependent on the scanned parameter. This is usually a good assumption, but, if it is not, a more time-consuming procedure of measuring on-off source pairs at each of a range of parameter settings is required. Only relative intensities are important here so the source strength and a secondary calibration value are not required. Weather conditions may make these measurements difficult at some frequencies because of changing sky noise so a number of scans may be needed to check for consistency.

6.2 Pointing Offsets.

6.2.1 Five-point maps.

This procedure determines the local pointing offset by measuring the telescope response to a source at the cardinal half-power beam offsets relative to the source response when it is centered in the beam. The nominal beamwidth in the two directions and a fairly accurate initial pointing setting are required for this simple measurement to succeed. The method assumes that the telescope beam is Gaussian in shape. The result could either be a measured position for the source or offsets from the known source coordinates. Only relative intensities are important here so the source strength and a secondary calibration value are not required.

6.2.2 Pointing and efficiency cross scans.

This is a pair of orthogonal scans across a known continuum radio source with a secondary calibration noise source fired at each end of both scans. The scans are usually at constant declination and constant right ascension. Data reduction for this procedure is to pick off the calibration signals at either end on the scans and use them to establish a temperature scale for the data. This could involve a linear interpolation between each calibration pair, if there is a possibility of gain drift during the scan, but usually a simple average is sufficient. A beam function, usually a Gaussian, is then fit to the central part of the scan from which the beamwidth, peak intensity, and beam center position are determined. The temperature calibration is applied to the peak intensity to get the source antenna temperature from which the antenna efficiency may be derived. The analysis should be sophisticated enough to correct the peak intensity for the fact that one or both scans do not cause the source to go through the center of the beam. Efficiencies must be corrected for atmospheric absorption using Equation 1 below.

A similar, yet more sophisticated, method for the determination of pointing offsets using strong astronomical masers has been proposed by Heiles and Maddalena (1993). The method is better than the continuum source method at high frequencies because it mostly eliminates the effects of the variability of the atmosphere on the baseline. Application of the method is restricted to the frequencies of strong masers.

If Gaussian fitting is not appropriate due to beam distortion, pointing and peak intensity will have to be determined with a more restricted parabolic or Gaussian fit or, better yet, beam pattern matching when the beam shape is known.

6.3 All-sky pointing determination.

This procedure is a best fit of the pointing error model for the telescope to a set of two-dimensional pointing offsets strategically-spaced around the sky. The pointing offsets are the differences between the indicated telescope position and the actual position of observed sources as determined with the procedures described above. The GBT pointing equations currently under discussion are given in Condon (1992).

6.4 On-Off gain calibration.

This procedure determines the relative strengths of a radio source and the secondary noise source of the receiver. If the secondary source temperature is known, the antenna temperature, $T_{\rm A}$, of the radio source is determined. If the source flux density, S, is also known, the antenna aperture efficiency, η, may be calculated:

$$\eta = \frac{2kT_{\rm A}\exp[\tau(z, az)]}{SA_{\rm e}} \tag{1}$$

where k is Boltzmann's constant, $A_{\rm e}$ is the projected area of the telescope dish, and $\tau(z, az)$ is the atmospheric opacity as explained below. Several sets of off-source-cal-off, off-source-cal-on, on-source-cal-off sequences are averaged to determine the source/cal ratio. The off-source position is not important as long as it is beyond any significant sidelobes. A slightly more complicated sequence would use off-source positions on two or four sides of the source to compensate for first-order changes in the background radiation as a function of sky position. Accurate source and telescope positions are assumed.

6.5 All-sky antenna efficiency determination.

Just like all-sky pointing, a model for the behavior of the antenna aperture efficiency can be fit to a large sample of aperture efficiency measurements for the purpose of interpolation to any position on the sky. To date, most models have been convenient mathematical functions with no particular connection to the root cause of efficiency variations. Each antenna and frequency requires some subjective judgement about what function is most appropriate.

6.6 System temperature determination.

This is a simple determination of the ratio of the system noise power to the strength of the secondary noise source. This ratio multiplied by the secondary source temperature, T_{cal}, produces the system temperature, T_{sys}. The data are normally a series of cal-on, C_{on}, and cal-off, C_{off}, measurements, typically one per second. The equation is then

$$T_{\mathrm{sys}} = T_{\mathrm{cal}} \frac{\mathrm{C_{off}}}{\mathrm{C_{on}} - \mathrm{C_{off}}}. \tag{2}$$

6.7 Automated receiver calibration

Calibration of receiver gain, noise temperature, and noise cal values can be calibrated in the lab or on the telescope with subsystems of the telescope monitor and control which control the DCR and the LO. An automated receiver calibration will make a hot/cold load measurement and compare the difference to the total system power and to the internal receiver noise calibrator at selected frequency intervals within the receiver passband. If C is the data count from the DCR, then

$$T_{\mathrm{cal}} = (\frac{C_{\mathrm{on}}}{C_{\mathrm{off}}} - 1)(T_{\mathrm{cold}} + T_{\mathrm{rx}}) \tag{3}$$

The measurement of T_{cal} may also be made with the hot termination, using Equation 3, as a check on system linearity. The receiver temperature is computed from

$$T_{\rm rx} = \frac{(T_{\rm hot} - T_{\rm cold})\, C_{\rm cold}}{C_{\rm hot} - C_{\rm cold}} - T_{\rm cold} \tag{4}$$

The measurement program should accept values for $T_{\rm hot}$, $T_{\rm cold}$, start frequency, end frequency, and frequency interval.

6.8 CW frequency test.

This procedure injects one or more narrow-band signals of known frequency into a spectrometer passband as a check on the frequency calibration of the system. The data analysis task is to scan the passband for narrow-band signals and determine their location to a fraction of a channel width by measuring the relative response of adjacent channels around each peak. The instrumental frequency profile of the individual spectrometer channels is required to convert adjacent-channel intensities into a sub-channel frequency offset. Alternatively, if the frequency of the injected signal can be varied, the frequency can be adjusted until the intensities in adjacent frequencies channels are equal. The result may be either a report of the frequencies found or the differences between the known and measured frequencies. The narrow-band signals must be considerably stronger than the integrated spectrometer noise, but the exact strengths are not important.

6.9 Measuring atmospheric opacity with tipping scans.

This procedure determines the attenuation in the atmosphere by measuring the system noise temperature at a series of antenna elevation angles. The data could be collected with a set of discrete measurements at various elevations or with a continuous scan from zenith to near the horizon. The data analysis task is to fit the measurements with something like a sec(z) function, where z is the telescope zenith angle, to determine the excess noise per airmass. An extension of this procedure is to run scans at various azimuths, az, to look for a wedge in the atmospheric attenuation and to check for local deviations in attenuation (clouds) in particular directions. The ultimate goal is to derive the optical depth of the atmosphere as a function of sky position to be used in correcting measured flux densities, $S_{\rm m}$.

$$S = S_{\rm m} \exp[\tau(z, az)] \tag{5}$$

Models for tipping data can be quite involved. The variation in system noise with antenna elevation is due to both changing atmospheric path length and changing ground pickup from feed and subreflector spillover. Between 10 to 20% of the antenna response in the sky is more than 5 degrees away from the beam center and, hence, seeing a different airmass. Also, there are various ways to account for the non-planar atmosphere. The simple sec(z) model must be extended to account for these and other secondary effects.

During extremely bad weather conditions, weather balloon soundings of local conditions may better reflect τ than the more traditional tipping method. Some combination of antenna tipping, radiosonde data, and water vapor radiometry will produce the best results.

6.10 Polarization calibration.

A method for completely calibrating and correcting for instrumental polarization errors which uses the parallactic angle rotation of an elevation-azimuth telescope and a partially polarized source is given in Stinebring *et al* (1984). If the full polarization properties of the telescope are not required, a subset of the measurements outlined by Stinebring et al. would be sufficient. The extent of the calibration depends upon which source polarization parameters are to be measured. In the case of extended radio sources this will involve correcting a two-dimensional map with the beam map described in complex polarization vectors.

6.11 Beam mapping.

This is a sky map of a strong point radio source to get the beam response function of the telescope to as low a level and as far from the center of the main beam as is necessary to interpret a map of a radio source of unknown intensity distribution. It could be as simple as a set of scans in one direction spaced at the Nyquist sampling interval or a set of point samples spaced at the same interval in both directions with the gain assumed to be constant throughout the observations. Additional complications include the possibility of scanning in orthogonal directions and weaving the two sets of scans together, adding a secondary noise calibration at either end of each scan, or compensating for the fact that the data are not taken on evenly spaced grid points or scan lines. The product for the observer is usually a digital map that can be used to clean or deconvolve a map of a distributed source.

Near the wavelength limit of a telescope the beam shape can be a strong function of antenna position. In principle, one would like to be able to map the antenna beam shape at various antenna positions near which the unknown source measurements are to be taken and interpolate between the beam maps to get an approximation of the beam shape at any instant.

6.12 Holography.

Holography is used to measure the amplitude and phase distributions across the telescope aperture. A two-dimensional map of a source, usually a satellite, is made by scanning the telescope across the source. Telescope pointing and focus are, of course, critical to the procedure, and are periodically checked over the course of the observation. The signal phase is referenced to a separate antenna that keeps the mapped source near the peak of its main beam. This procedure produces a complex beam map which is Fourier-transformed into an aperture phase and amplitude distribution. Adjustments to the reflector surface can be made after the phase distribution is known. A more detailed description is given in Maddalena *et al.* (1991).

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