National Radio Astronomy Observatory

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Subject: Scientific Requirements for GBT Metrology

GBT metrology systems affect science only to the extent that they affect the radio-frequency response of the GBT to celestial sources. The most important consequences of dimensional errors in the GBT are

(1) reduction of on-axis gain or aperture efficiency,

(2) degradation of the beam pattern (increased sidelobe levels, beam broadening), and

(3) pointing errors.

The radio-frequency degradation due to a small dimensional error ϵ is usually proportional to $(\epsilon/\lambda)^2$, where λ is the observing wavelength. For example, random surface errors change the reflector efficiency η by

$$\Delta\eta \approx \exp\left[-\left(\frac{4\pi\epsilon}{\lambda}\right)^2\right] - 1 \approx -\left(\frac{4\pi\epsilon}{\lambda}\right)^2.$$

The lost power is scattered into sidelobes whose power is also proportional to $(\epsilon/\lambda)^2$. Likewise for pointing, the relative gain change ΔG at an angle ϵ off the axis of a beam of FHWM $\theta \sim \lambda/D$ is

$$\Delta G \approx \exp\left(-\frac{4\ln(2)\epsilon^2}{\theta^2}\right) - 1 \approx -4\ln(2)D^2\left(\frac{\epsilon}{\lambda}\right)^2.$$

Thus accurate metrology is most important for observations at the shortest wavelengths, and for a few other experiments requiring the highest precision.

The scientific requirements on the three numbered items are:

(1) Reasonable aperture efficiency at $\lambda \approx 3$ mm. The usual criterion $\eta \approx 0.5$ implies rms surface errors of the main reflector relative to the best-fit paraboloid be $\epsilon \approx \lambda/16 \approx 0.2$ mm. Accurate flux-density measurements also require that η be known accurately, even if η is low. Such measurements compare a program source strong point-source calibrator. To transfer the calibrator flux scale requires at least that the elevation dependence of gain be a known and stable function, and that time-dependent gain variations (primarily thermal) be small between successive calibration scans. High and stable aperture efficiency also requires that the telescope be well collimated. Some collimation errors are more important than others. For example, small axial or lateral displacements of feeds at the secondary focus have little effect on radio-frequency performance, but a small axial displacement of the subreflector itself has a large effect (Baars, J. W. M. 1966, NRAO Electronics Division Internal Report No. 57).

(2) Scientific requirements on the beam pattern vary greatly depending on the experiment. VLBI observations are insensitive to extended emission and the delay beam is normally smaller than the primary beam, so sidelobe levels are not important. For single-dish mapping of moderately extended sources, sidelobes are undesirable but not necessarily fatal if they are at least stable— stable sidelobes can often be removed by deconvolution algorithms such as CLEAN. Generally, the strongest near-in sidelobes cause the most trouble. These might be generated by reflector surface errors having correlation lengths comparable with the aperture size or by poor collimation (subreflector position or orientation errors). Observations of very extended emission ($\sim 100\theta$ or larger) can be contaminated by the combined signals from numerous far-out sidelobes, thus limiting dynamic range. Since the GBT beam is so small ($\theta \sim 7''$ at $\lambda \sim 3$ mm), nearby Galactic molecular clouds qualify as being "very extended." Probably the largest controllable source of far-out sidelobes will be surface-panel adjustment errors. Reflector errors with correlation length about equal to the panel size (~ 2 m) will scatter power into a sidelobe "pedestal" of width $\sim 50\theta$.

(3) The traditional requirement is for rms pointing errors $\leq \theta/10$. At $\epsilon = \theta/10$, $G = 0.97$, so there is little reduction of gain and flux calibration is fairly accurate. Some observations, such as on-the-fly mapping, can tolerate pointing errors (differences between commanded and actual positions) up to $\sim \theta/5$ rms so long as the actual positions are recorded to $\sim \theta/10$ accuracy. There will even be some tracking observations for which $\geq \theta/5$ pointing errors are acceptable. For example, Barry Turner would like to know whether diffuse interstellar clouds are homogeneous or lumpy. He can answer this question by comparing spectra obtained at non-overlapping positions within a cloud without having to know those positions well. Such observations could be made as soon as the aperture efficiency is good enough in the 3 mm band, even if the pointing is poor.

Since the GBT metrology system only measures distances between various points on the telescope and on the ground, it cannot correct for fluctuating pointing errors caused by atmospheric refraction above the telescope. These errors may well exceed $\theta/10 \approx 0.7$ arcsec for $\lambda \approx 3$ mm, so it will probably be necessary to use offset pointing at the highest frequencies, much as phase calibration is needed at the VLA. Fortunately, the GBT need not be used for absolute position measurements because interferometers are much better. Astronomers who want very precise pointing can offset from known position calibrators, and they will depend on the GBT metrology system only to measure the position *difference* between the calibrator and program accurately and maintain the offset over the time between successive observations of the position calibrator (e.g., over position differences of $\sim 10°$ and over time intervals of ~ 1 hour). Offset pointing should work well because the GBT is so sensitive that the sky density of "strong" pointing calibration sources is high. The absolute pointing capability of a good metrology system is convenient for observations which can tolerate the positional uncertainties introduced by the atmosphere, since it frees the astronomer from having to do pointing calibrations every time the telescope moves to a significantly different position on the sky. Thus the absolute positional errors of the metrology system should be ideally be no larger than the positional errors introduced by the atmosphere. Unfortunately, this quantity is not well known for Green Bank. It might be estimated from interferometer data on ~ 100 m baselines (old Green Bank interferometer data?).

All of these dimensional accuracies must be maintained during sidereal-rate tracking and also during scanning observations. On-the-fly mapping is normally used to image sources fully resolved by the primary beam, so the integration time per pixel needed to reach a given sensitivity is independent of the telescope diameter D. For a fixed integration time per pixel, the angular scan rate for the GBT would be only 12/100 that of the NRAO 12 m on Kitt Peak. Likewise, the correlator dump time limits the scan rate in pixels s^{-1}, so this angular scan rate limit also scales as D^{-1}. The shortest correlator dump times at both the 12 m and the GBT are about 0.1 s. At the NRAO 12 m, on-the-fly mapping is rarely done with scan rates > 50 arcsec s^{-1}, so the GBT will probably not be scanned much faster than this when observing at mm wavelengths. At cm wavelengths, it is possible that scan rates which are a significant fraction of the slew rate (20° min^{-1}) will be requested for continuum imaging of large areas (e.g., monitoring the Galactic plane at $\lambda = 2$ cm). For such observations, actual (not commanded) telescope positions must be measured while the telescope is moving very rapidly, but the position accuracy requirments are not stringent ($\theta/10 \sim 5''$). For example, the 5 GHz PMN continuum survey of the southern sky was made with the NRAO 7-beam receiver on the Parkes 64 m telescope running at its slew rate, and the final position accuracy achieved was 6$''$ rms.

(4) Since the GBT aperture is unblocked, spectral-line standing waves should have very low amplitudes. Even so, Jay Lockman noted that standing waves (e.g., between the main reflector and subreflector) may be significant after long integrations. If this proves to be the case, then changes in the distances between the main reflector and subreflector of order $\lambda/4$ will reverse the "phase" of the standing waves. The GBT metrology system might be called upon to measure such distances with accuracy $\sim \lambda/16$ in order to stabilize the standing waves.

Summary: The science requires that the metrology system measure *all* dimensions along the beam path which are needed to ensure good radio-frequency performance. These dimensions include the orientation of the main reflector (for pointing), errors in panel heights relative to the best-fit paraboloid (reflector efficiency and sidelobes), the position and orientation of the subreflector so that one focus coincides with the main reflector focus and the other coincides with the feed phase center (pointing, aperture efficiency, and sidelobes), and possibly the distances between the main reflector and subreflector. The metrology system must work with high accuracy while the observations are being made and the telescope is scanning at rates up to $\sim 60''$ s^{-1} (mm wavelengths) and with reduced accuracy at nearly slew speeds (cm wavelengths).