GBT MEMO 161

Approaches to the GBT vibration problem

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1 The basic problem

We expect that the beam formed by the GBT will move on the sky due to structural vibrations much of the time unless we develop techniques to stabilize the beam. The vibrations, which we expect will be mainly in cross-elevation, will be induced by at least three causes: wind turbulence, azimuth drive stiction and position switching. Vibrations caused by position switching can be minimized by shaping acceleration profiles to minimize jerk [GP95, Woo95, vH96], but we expect that there will be significant residual vibrations in many cases. Vibrations caused by stiction are likely to be reduced by "dithering" the torques on the azimuth drives, but there might be residual vibrations even after this enhancement to the drive servos. With these expected enhancements to GBT technology, it seems likely that vibrations due to position switching and stiction will prove to be minor nuisances. **The primary GBT vibration problem is that vibrations caused by wind turbulence are likely to be the major technical limitation for high frequency work throughout the life of the telescope.**[1]

2 Sensors to measure the vibrations

There are at least four types of sensors which are candidates for measuring the state of the vibrational modes of the GBT: (1) accelerometers, (2) quadrant detector [PS96], (3) laser rangefinders and (4) strain gauges. We have reason to expect that (1), (2) and (3) are all sensitive enough to monitor vibrational amplitudes smaller than 1 mm; the capability of strain gauges for this application has not yet been reviewed. Information about the state of the modes will be contained in rangefinder data, especially in the surface servo data, but it will not be a regularly sampled time series, and so will be harder to interpret. The quadrant detector and the accelerometers are analog systems which can produce properly sampled regular time series data which we can use to track the state of the vibration modes of the GBT.

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[1] This statement about the wind-induced vibration problem assumes, of course, that the *static* errors in the surfaces and in the pointing due to structural model limitations, temperature differentials and average wind forces are going to be corrected successfully by the laser metrology technology.

3 Can the subreflector stabilize the beam?

Rapidly changing beam pointing errors due to vibration or wind gusts can be corrected, at least in principle, by moving the subreflector. The subreflector actuators are capable of applying such fast corrections with bandwidths of at least 1 Hertz. There are several potential mechanical problems with this concept: (1) positive feedback, (2) excessive wear and (3) gear train backlash.

The feedback problem is that the system will oscillate if the energy added to the arm by the reaction forces of the sinusoidal subreflector translational motions at modal frequencies is greater than the damping (dissipation of the energy) of the vibrational motions which the subreflector is attempting to compensate. Because the subreflector magnifies displacements around its first focal point, and because the prime focal point probably doesn't move very much due to the vibrations,[2] it seems likely that the translational motion needed is almost the same as the motion of the feedarm, i.e. that the subreflector needs to be almost stationary. If so, then the actuators will move sinusoidally without producing significant reaction forces.[3] This has two favorable implications: (1) the subreflector is unlikely to "pump" feedarm vibrations, and (2) wear on the gear train and ball screws due to reaction forces will be minimal. Another favorable fact is that cross-elevation vibrations will mostly be tracked by the single "Z" actuator, which will probably be the easiest actuator to replace if we do experience extra wear due to vibration tracking.

4 Active damping

John Payne [PSS96] has demonstrated a driven mass which can be used to "pump" the GBT vibrations or, when driven out-of-phase, to add to the effective damping coefficient for the vibrations. This device has some maximum power level, and presumably has the potential to largely attenuate wind-induced vibration up to the wind speed at which wind noise power coupled into the structure is comparable to the active damper's maximum power. It should also be able to attenuate residual vibrations induced by stiction and step motions.

5 Modelling, filters and wind measurements

We need to develop models of the vibrational behavior of the GBT and the resulting optical effects. The eigenvectors (mode shapes) of the principal modes are needed; they will be multiplied by a sinusoid and added to the static geometry, and the best-fitting paraboloid analysis repeated as a function of sinusoid phase to determine the trajectory of the prime focal point for the principal modes. The trajectories of the Gregorian feed and the subreflector relative to this trajectory will be produced. These trajectories will then imply the appropriate trajectory for the subflector actuators which will maintain nearly stigmatic imaging from the moving prime focal point to the moving Gregorian feed. One key question is: is the motion of the prime focal point due to the vibration modes indeed small?

We will need to develop a "mode-tracking filter" which will accept quadrant detector and/or accelerometer signals and will produce an optimum estimate of the current phase and amplitude

[2] This statement is conjecture, it hasn't been properly demonstrated by computation yet.

[3] This idea was suggested by Bob Wilson during a GBT Advisory Committee meeting

of each of the principal vibration modes. The phase and amplitude will vary continuously due to the wind (and ground) noise applied to the structure. This software can be tested on experimental data acquired with the active damping system, as discussed above. The outputs of such a filter are the appropriate signal for controlling the subreflector.

The MMA will probably also have a wind vibration problem [HFE+96], and so modelling ideas used in that project may be relevant to our case.

6 Action items recommended before acceptance

- Hardware development
  - We should procure samples of the Analog Devices ADXL05AH ($28 in q1-24 in 1995) and/or Motorola MMAS40G ($26 in q25) accelerometers and should measure their noise power spectra to determine if they are suitable for this application.[4]
  - We should demonstrate an ability to measure wind speed noise with bandwidth up to about 2 Hz (0.5 sec timeconstant), in order to be able to correlate it with vibration variations. Probably this will involve procuring one or more hot-wire (or equivalent) anemometers.
  - We should verify that the subreflector actuator motors are capable of sustained sinusoidal motions without overheating.
  - We should demonstrate the active damping concept. The experiment might proceed along the following lines: while recording continuously with accelerometer(s), observe the random vibration noise induced by wind and ground motion, then slowly increase damper drive power, let vibration amplitude build, slowly decrease damper drive power, let vibration amplitude decay naturally by about half, then enable the out-of-phase damper drive to prove the increase of decay rate and let it operate until approximately at random noise level again, then disable out-of-phase damper drive and observe the increase of random vibration noise. The experiment should be repeated at several stages of the GBT construction.
- M&C development
  - We should implement an acceleration profile algorithm [GP95, Woo95, vH96].
  - We should test the subreflector plus actuator assembly with sinusoidal motions in the range 0.5 to 2 Hz generated by M&C software to verify that the gear train backlash is negligible and that the achievable amplitude of motion is comparable to the feedarm vibration amplitudes which have been predicted by JPL [GMP94] for light winds.
  - We should demonstrate that the M&C software and hardware has the capability to log samples of accelerometer and/or quadrant detector data at rates of up to 20 Hz[5]. This may involve procuring additional A-to-D converter cards, power supplies, cabling, signal conditioning devices, etc.

[4] I estimate that the ADXL05AH will be just barely good enough for the GBT. NRAO owns two Allied Signal QA-2000 inertial-navigation-grade accelerometers (QA-2000-1 was $2235 in q1 in 1995). There is a tradeoff: we can get $\approx 100\times$ lower noise for $\approx 100\times$ higher price; other accelerometers are available with intermediate price-performance.

[5] 5 Hz with 2 Hz lowpass filter will probably be sufficient for GBT operation.

- Modelling and analysis development
  - We should attempt to decide which of the acceleration profile algorithms [GP95, Woo95, vH96] is optimal.
  - We need to compute the eigenvectors of the asymmetric structural model. (L. King expects to do this at NCSA.)
  - We should develop an algorithm to determine and track the amplitude and phase of a vibrational mode from accelerometer and/or quadrant detector time-series data. In combination with the eigenvectors and optical analysis, this algorithm will enable predicting the proper amplitude and phase of subreflector motion to stop the beam motion.
  - We should compute the variation of cross-polarization and/or spillover as a function of vibration phase as the subreflector tracks the vibrations. There may be an optimum combination of motions which will minimize such variations. After the telescope is built, we should try to measure these effects.

7 Action items recommended after acceptance

- We should verify the eigenvectors by installing accelerometers at multiple nodes and checking the that the cross-power spectra agree with the eigenvectors.

References

[GMP94] Wodek Gawronski, Jeff Mellstrom, and Ben Parvin. Dynamic pointing modelling and simulation 100m Green Bank Telescope. Original memo with notes added by bob hall on 12/6/94, distributed 1995-01-12., National Radio Astronomy Observatory, November 1994. A summary of this report by B. Hall and L. King is: '..the beam pointing analysis for the worst case wind given in the 11/7/94 report is 14 arcsec for a wind velocity of 6 m/s gusting to 7 m/s..'.

[GP95] Wodek Gawronski and Ben Parvin. Simulations of the GBT antenna with the Command Preprocesor. GBT Memo 134, National Radio Astronomy Observatory, June 1995. '..we present here the simulation results of the slewing of the GBT antenna with the new command preprocessor (CPP).. developed by S. Tyler at JPL.. jerk is smooth, and vibrations are not excited.. [in version B (CPP-B)] the acceleration.. is of sinusoidal pattern.. $a = \pm a_{max}(1 - \cos 2\pi\omega)$.. to avoid.. abrupt changes in acceleration, which cause oscillations of the antenna..'.

[HFE+96] M. A. Holdaway, S. M. Foster, D. Emerson, J. Cheng, and F. Schwab. Wind velocities at the Chajnantor and Mauna Kea sites and the effect on MMA pointing. MMA Memo 159, NRAO, August 1996. Pointing errors as a function of wind speed and the wind power spectrum shape are discussed. '..if [the static] pointing [errors are] calibrated every 10 minutes, wind induced pointing errors [of the current MMA antenna design] are [predicted to be] reduced to 0.25-0.5 of the static wind pointing error..'.

[PS96] J. M. Payne and D. Schiebel. Slant range test of quadrant detector. GBT Memo 158, National Radio Astronomy Observatory, September 1996. '..fluctuations vary from 30 microns during the night to a peak value of 300 microns during the middle of the day.. seems a reasonable expectation that the values in the GBT will be similar or even less than those measured..'.

[PSS96] J. M. Payne, D. Schiebel, and F. R. Schwab. Dynamic test on the GBT. GBT Memo 159, National Radio Astronomy Observatory, October 1996. '..[a driven mass] is used to excite the structure and to permit measurements on the existing alidade structure of the two principal modes of oscillation and the structural damping associated with these modes.'.

[vH96] Sebastian von Hoerner. Preventing oscillations of large radio telescopes after a fast stop. GBT Memo 152, National Radio Astronomy Observatory, May 1996. '..it is shown that these oscillations can be prevented if the acceleration driving the telescope has the form $A(t) = \sin^n t$, and for a duration measured in multiples of the oscillation wavelength..'.

[Woo95] David Woody. Fast position switching of resonant structures. In an Email message sent on 1995-07-07 to P. Napier, J. Cheng, J. Payne and `<lugten@toby.berkeley.edu>`, Woody `<dpw@mm.ovro.caltech.edu>` said. '..the trajectory I have come up with has a gaussian velocity profile, $v(t) = \frac{S}{t_0\sqrt{\pi}} e^{-\frac{t}{t_0}^2}$, where t_0 is the characteristic gaussian width and S is the distance from A to B. The position vs. time is the integral of the velocity.. the Error Function.. position asymtotically approaches the final position with a deviation given by $\Delta p(t) \approx 10^{-(\frac{t}{t_0})^{1.45}}$. This gives excellent settling characteristics..', July 1995.