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REVIEW PANEL REPORT FOR THE GBT PRECISION TELESCOPE CONTROL SYSTEM IN-PROGRESS REVIEW

INTRODUCTION and SUMMARY

An in-progress review for the Green Bank Telescope Precision Telescope Control System (GBT PTCS) was held in Green Bank on December 3-4, 2003. The members of the Review Panel were: Peter Napier, EVLA Project, NRAO, Patrick Wallace, Space Science & Technology Dept., Rutherford Appleton Laboratory, and David Woody, Owens Valley Radio Observatory, Caltech. The agenda and material presented at the Review is available at:

http://wiki.gb.nrao.edu/bin/view/PTCS/InProgressReview

The team has done a significant amount of work since the review in April 2003 and good progress was made in achieving significantly better pointing performance. The panel was very appreciative of the material sent out ahead of time and thanks the team members for their excellent presentations.

The team indicates that the GBT should now be "usable" for Q-band observations in benign conditions, that is, winds less than 2.5m/sec and minimal solar loading. The blind pointing accuracy is σ_2=5.1arcsec (2-D RMS of pointing residuals after initial daily pointing update) using "traditional" pointing constants. Applying the thermal corrections decreases this to σ_2=4.6arcsec. The offset pointing accuracy is σ_2=2.7arcsec for timescales up to one hour. The surface RMS is <500microns at the rigging angle. The open loop FEA based surface corrections work well and the surface errors increase slowly away from the rigging angle.

The panel also congratulates the team on adding the temperature sensors and getting this data along with the normal housekeeping and pointing data into a "database" that allows easy analysis and interpretation of the data this early in the project. When this is implemented in the real time system, it will make the GBT one of the very first radio telescopes to successfully incorporate temperature measurements into the pointing model.

Reaching this early milestone is an excellent start for the project. The astronomers should recognize and benefit from the progress already made by the PTCS team. But difficult challenges still remain before the goal of usable observations at 3mm are possible even in benign conditions. This will require a factor of two or three improvement in the above performance parameters.

There was a nice presentation of how the observing parameter space can be represented as three coordinates of wind, time-of-day (temperature), and water vapor (opacity and seeing). The usable conditions are limited along each axis with 3mm opacity and benign conditions being down at the origin. We have yet to achieve 3mm performance even in benign conditions and once sufficient performance is achieved in the most benign conditions the acceptable performance conditions along the wind and time-of-day axis will have to be moved out enough to get a reasonable amount of observing time. At this point it is not clear how the observing time would increase as you pushed out along any given axis and in what direction it will be easiest to make improvements.

This report will briefly summarize the work undertaken since the April CoDR followed by the proposed path to better performance. Recommended short term tasks and a discussion of the leading concerns will be given at the end.

PROGRESS SINCE APRIL 2003

Laser Range Finders (LRFs)

A major effort was undertaken to evaluate the use of the LRFs for surveying selected targets on the GBT. This effort revealed many operational difficulties with the LRFs and a limited amount of data was obtained for trilateration tests. The simple distance measurement noise was consistent with expectations of 50-100microns, but it was also demonstrated that the geometry of the LRFs and retroreflectors can result in significant amplification of this noise when determining the absolute position of a target.

It took significant effort to get even limited LRF data in carefully planned observations. It was clear that the system was not ready to provide the data necessary to improve the performance of the telescope on a routine basis and that it would take much more work to improve both the hardware and software for the LRFs. Even the reduced use of the LRFs in an Engineering Measurement System (EMS) as was proposed during the April CoDR would have been problematic.

The project decided to pursue a more incremental approach to improving the telescope performance to reach Q-band observations this winter and free up resources by postponing further work on the LRFs at least until late next spring. The panel concurs with this decision as long as reactivating the LRF effort remains a viable option. It is likely that the LRF or similar system will be required to ultimately reach the GBT performance goals at 3mm. The panel notes that, because a proper assessment of "constrained solution" treatments of the LRF readings has yet to be made, the achievable accuracy is still unknown, the trilateration experiments notwithstanding. However, the panel recognizes that the poor reliability of the LRFs and the amount of effort required to bring them into service are, under present circumstances, enough to justify the postponement.

Improved pointing

The main effort this fall was to install and evaluate temperature sensors on the telescope and work on incorporating thermal corrections to the traditional pointing model. 19 temperature sensors were installed on the telescope and several days spread over two months were dedicated to obtaining pointing and focus data. Pointing constants were solved for and then applied during a subsequent one day verification test

One of the most important results of this effort was the discovery of an incorrect solution and implementation of the "traditional" pointing terms. Correcting this error significantly improved the blind pointing. In addition, it was found that fitting and applying corrections based on the temperature sensors noticeably reduced the pointing residuals.

The thermal model was developed by forming combinations of temperature readings to produce a few terms which were expected to result in either elevation or azimuth pointing errors. The coefficients for these terms along with the traditional pointing model were determined from fits to the several days of data. The data were filtered to select benign conditions of wind less then 2.5m/sec and minimal solar loading.

The validity of the traditional pointing constants plus thermal corrections were verified during a day of pointing and focus measurements. The results were excellent and indicated that the GBT is ready for "useable" observations at frequencies as high as 50GHz. The blind pointing accuracy is σ_2=5.1arcsec using just the "traditional" pointing constants. Applying the thermal corrections decreases this to σ_2=4.6arcsec. The offset pointing accuracy is σ_2=2.6arcsec for timescales up to one hour.

Tests carried out after the review appeared to show that the refraction predictions are not being correctly calculated and are about 9% too high. If this turns out to be the case, the gravity terms in the pointing model will need to be revised; however, it is not expected that the blind pointing accuracy figures will change significantly.

Surface figure

Both standard holography using communication satellites and out of focus (OOF) mapping techniques were utilized to measure the GBT surface. The standard holography had a surface resolution of ~2m and produced excellent looking maps with some very intriguing features. It also indicates that the initial panel setting was much better than some of us expected. Successful transformation of the raw data into surface maps was accomplished just before the review and it is premature to over interpret the results. Sanity checks and other tests are required before surface adjustments are attempted.

Some raw aperture efficiency data at Q-band was presented, but as with the holography data, it was hot-off-the-press and too early to draw solid conclusions.

This preliminary data is consistent with or even better than initial specifications for the delivered antenna from the manufacturer and offers reason to expect that the antenna will be able to meet the desired goal of 3mm observations in benign conditions.

PROPOSED ADDITIONAL INSTRUMENTATION

Several more instruments are in progress or planned for implementation in the next several months. The more prominent ones are listed below along with comments from the panel.

More temperature sensors (priority?)

It is proposed to add up to ten more temperature sensors at positions yet to be identified.

This seems like a good idea since the first set of 19 sensors has proven very useful. Adding significantly more sensors, several dozen even, might be justified. But the location and treatment of the temperature data begs for a better understanding of the thermal distortions of the telescope. This realistically can only be done using FEA. There is only limited progress that can be made using simple seat-of-the-pants algebraic combinations of temperature readings to reduce the data to a manageable set of terms and coefficients. A more sophisticated model and/or an FEA approach is probably required.

Quadrant detector (in place)

The quadrant detector has been put back on the telescope to monitor the feed arm position. It was refurbished and tested in the lab. Measurements indicate that it has deviations from linearity amounting to several mm of error as a function of elevation. The deviations are much higher order than the simple sine and cosine dependence expected by Hooke's law.

This kind of instrumentation will be very valuable in determining the feed arm position and its effect on pointing and focus. The error is a factor of a few larger than is required and will complicate the interpretation of the observations. The panel wondered if a simple video camera mounted at the same position might serve this task. Matching range of motion to the field of view should give the required dynamic range of a few hundred to one. The target could be a spare LED X array with known spacing to make an easy to recognize and self-calibrating pattern. Commercial pattern recognition software might be available to produce simple position coordinates for this task.

Inclinometers (high priority)

It is proposed to install precision two-axis inclinometers on the elevation bearing castings. The inclinometer at the bearing the elevation encoder is mounted on would essentially define the reference orientation of the encoder relative to vertical. It is proposed that these sensors will help with alidade thermal and wind effects.

Inclinometers have proven to be very useful in some specific applications on telescopes. OVRO uses bubble type tiltmeters from Geomechanics mounted on the azimuth axis of the alidade for real time pointing corrections. The JCMT has used inclinometers to help determine azimuth track errors. In most cases great care is taken to avoid the effects of telescope centripetal and linear accelerations on the sensors. Inclinometers mounted near the GBT elevation bearings will see significant accelerations during anything but benign tracking. They might prove to be a valuable diagnostic tool for looking at track tilts or irregularities during slow azimuth rotations. They should also be useful during optical star tracking when pointing errors can be measured without having to move off source to obtain radio pointing data. Incorporating the inclinometer reading into a real time pointing model will not be trivial and the data will be redundant with the part of the alidade thermal model used to predict elevation corrections.

Star tracker (moderate priority)

A cooled CCD camera with 100mm f/5 and 300mm f/4.3 lenses has been bought and is being evaluated in the laboratory. This system will give good sensitivity at night and possibly work on many stars during clear days. There was not enough time during the meeting to review the details of the star tracker implementation plan.

The panel agrees that a star tracker is an excellent idea. Most radio observatories now include optical telescopes just for the convenience of servo performance monitoring and pointing model data collection. Even a simple uncooled video camera with a frame grabber on a well-designed refractor gets most of the needed information. The telescope design is not trivial, but several observatories have proven working designs and in particular ALMA has just implemented two such telescopes on their prototype antennas.

Probably two optical telescope systems are required; one mounted on primary near the elevation axis and the other on the feed arm. Both telescopes should point along the nominal radio beam direction. The field of view needs to be large enough to see the reference star in the worst conditions, including radio-to-optical collimation errors. It may also be necessary to have a separate optical pointing model so that you can separate out sources of pointing errors. (There is in any case the need to apply a different refraction model.) The apparent difference in the star positions for the two optical telescopes will help determine what the feed arm is doing.

However, during subsequent e-mail discussions, panel members expressed doubts that on the equipment purchased the pixel size of 19arcsec (at 100mm focal length, or even the 6arcsec pixels at 300mm) would prove adequate. Although there are compact spacecraft star trackers that can approach 1arcsec accuracy by pattern-recognition of multiple star images, it is not clear that this technique is available for GBT without significant programming effort. A more dependable approach would be to use, instead of a camera lens, an f/15 refracting telescope of say 100mm aperture, like the ALMA ones mentioned earlier. Using the SBIG CCD, this would produce 0.8arcsec pixels, adequately sampling the 2-3arcsec images that can typically be expected at the GBT site. For testing the antenna, all that is needed is for one star to be visible somewhere in the CCD frame in an integration of 1sec or less, and that should happen most of the time. In any case, fields for testing can be chosen where there are bright stars in the field.

Accelerometers (low priority)

It is proposed to install accelerometers on the GBT, mainly to monitor structural health.

This seems reasonable.

SUGGESTIONS FOR SHORT TERM EFFORT

There is more progress that can probably be made using the existing instrumentation and data. The thermal data, good traditional pointing model and holography results are very new and the team is still working through the interpretation and potential use of this information. Most of the suggestions listed below are probably part of their plan, but we list them here just to make sure they are not overlooked.

The greatest short term improvements in the GBT performance will most likely come from using the holography data to make corrections to the rigging angle surface setting and elevation dependent surface tuning. This should be the highest priority. It will be important to make surface figure maps as a function of thermal loading and elevation. These maps will determine the magnitude and character of the surface deformation errors that the PTCS will have to deal with.

There may still be added information in the pointing data that can be discerned by looking various correlation plots. In particular, most observatories have found that plotting elevation error vs. azimuth to be very revealing.

Most the data presented were for relatively benign thermal conditions. Since there is now a thermal model based upon fitted coefficients, you can plot observed pointing errors vs. the thermal model predictions for all of the data, including when the thermal gradients are large. There may be large scatter in such a plot but the underlying correlation should still be apparent. A valid thermal model should improve the pointing a little bit even in the presence of large thermal gradients.

Wind clearly has a large effect on pointing: the magnitude or predictability of this effect is not known. The feed arm position and wind data seem to show a correlation, as expected. It is probably worth some work to work on determining if there is a repeatable correlation of the pointing error as a function of wind direction relative to the telescope orientation. This might result in a crude wind pointing model that improves the pointing.

Note that even if a thermal and wind model do not result in Q-band usability in other than benign conditions, they should help at longer wavelengths and any improvements will increase the science produced by the GBT.

It would be useful for the project to pull together all of the available data of time-of-day (thermal), wind and opacity/seeing to produce some joint probability statistics on the occurrence of these important environmental constraints which will impact 3 mm observing. This will help answer such important questions as "what fraction of 3 mm observations will be made under benign conditions" and "does improving wind or thermal performance produce the largest increase in 3 mm observing time". Answers to these questions will help determine the extent to which the LRFs will be needed in the future.

CONCERNS

Pointing

The pointing in benign conditions is greatly improved but still needs a factor of two or three improvement. There are no obvious long term or orientation dependent effects but the residuals show variations between successive "jacks" on the five minute time scale even while tracking a north celestial source. Interestingly, the half power "stare" tracks show that the tracking errors are on the order of 1arcsec over ~30min. It is common for telescopes to have short term pointing errors that are significantly larger than the tracking errors but this will have to be improved for the GBT to meet the 3mm goals. These short term pointing errors can't be a result of thermal changes because the measured temperatures don't change enough on the five minute timescale and the half power stare data indicates it is not in the azimuth track or structure vibrations in benign conditions. This is the same concern that was expressed in the report from the April CoDR when the offset pointing was given as ~3arcsec and remains relatively unchanged now at 2.7arcsec.

The star tracker and quadrant detector will be very important for investigating these problems and should be given the highest priority for new instrumentation. They will allow you to collect 2-D data on fast timescales while simply staring at a source and while performing a radio "jack" scan. They will also help determine what parts of the pointing errors are just above the elevation axis in the tilting structure versus problems associated with the feed arm.

It is good news that the wind does not seem to excite the feed arm resonance. But the motions of the telescope probably can excite the feed arm resonance. This might be affecting the "jack" scans. Again the quadrant detector will help diagnosis these kinds of problems.

Surface

Surface measurements are just now becoming available but it is expected that thermal distortions will limit the performance at some point. The elevation pointing changes associated with thermal changes during the night are significant and could indicate that the surface will deform even during low wind nighttime observations. In the absence of the LRFs there is not a concrete plan to correct for such distortions. Thus it is important to complete repeated holography measurements over a 24 hour period, possibly with simultaneous thermal imaging, to evaluate how serious this problem is.

Lack of FEA

It was pointed out during the CoDR that it was important for the project to develop or at least have easy access to Finite Element Analysis, FEA, for the telescope. FEA is the basis upon which you can develop a physical understanding of what effects thermal gradients and mechanical loads have on the telescope. We realize that this kind of expertise is not easy to come by, but that does not reduce the importance of having FEA capability. The GBT is a very complex structure and it is important that the FEA model of the antenna used during its development be maintained and kept operable as the FEA tools evolve if you want to improve its capability now and in the future.