GBT Panel Actuator Errors and Calibration

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Introduction

This memo summarizes the magnitudes of errors introduced by the un-calibrated panel actuators. It also presents a plan for compensating these errors to the point where they are nearly insignificant in the surface error budget. The plan involves gain and offset compensation of the actuators over the inner ±0.5" of the stroke, *at the sacrifice of some accuracy* (due to transducer non-linearity) over the outer, 0.5" to 1.0", part of the stroke. The win in this plan is computing simplicity in the real-time VME computer. The memo then presents the details of the resulting interface between the active surface on the telescope control system. Finally, means of achieving the required gain calibrations are discussed.

Panel-Actuator Errors

GBT panels have a specified accuracy of 0.003" (75 um) rms. The goal of the active surface is to achieve a setting accuracy that is considerably less than this. Even in "closed-loop" operation, panel-actuator errors are significant because only a small subset (about 100) of the actuators will be actively monitored. The rest will be positioned "open-loop" based on a surface model.

Data on over 1200 LVDTs (position transducers for the GBT panel actuators) were acquired by Schiebel and over 500 data sets were analyzed by Salter, Schiebel and Vance. This is summarized in GBT Memo 80. The analysis includes estimates of the surface error due to non-linearity and temperature dependence of the LVDTs. In particular, the error due to non-linearity is 0.0036" (90 um) rms. This error can be reduced to 0.0016" (40 um) rms by subtraction of the average distribution as described in the memo. The error due to the temperature dependence of the LVDTs is 0.0004" (10 um) rms. The analysis takes into account data over a ±1.1" span.

The analysis in Memo 80 assumed that the ±1" stroke of the LVDTs would be used. However, the GBT Specification, Rev B, presents a surface error budget where rms deviations from a best-fit paraboloid, due to gravity, wind, and thermals, are specified to be <0.048". Hopefully the as-built will be close to this. If one assumes a gaussian error distribution, the 5-sigma point is 0.25". Analysis of model 95B by King corroborates this by showing that gravitational deformations of the surface are within ±0.24". Thus, to compensate the structure, a stroke of about ±0.25" is required. As shown in Table 1, the linearity error over a ± 0.5" stroke is considerably better than that for a ± 1" stroke, and even the linearity error over a 1.0" stroke is better than that for a 1.1" stroke. The analysis assumes a uniform (as opposed to gaussian) actuator length distribution over the specified stroke. The second column in the table, Mean Linearity Error, is the antenna surface error due to the non-linear response of the LVDTs. For a ±1" stroke, this error is about the same as the panel rms error, but for a ±0.5" stroke, it is less than one third the panel rms error. Details of this analysis are included in Appendix A.

Table 1: Linearity with 1" and 0.5" stroke			
Stroke	Mean Linearity Err. (in.)	RMS of Linearity Errors (in.)	Improvement (1" / 0.5")
1.0"	0.00280	0.000798	-
0.5"	0.000855	0.000346	3.24

The spread in LVDT **displacement sensitivity**, or gain, in millivolts per thousandths of an inch of displacement per volt of excitation (mv/mil/V), is specified by the manufacturer, Schaevitz. Analysis of 34 randomly selected LVDTs yielded the following:

Table 2: LVDT Gain Data	
Average Gain (mv/mil/V)	0.365059
Standard Deviation of gain	0.009138
Gain error for 0.25" displacement (in.)	0.00625"
Gain error for a uniform distribution of actuators from -0.25" to +0.25"	0.0037" rms

The last entry in the table assumes a *uniform* distribution of actuators (as opposed to gaussian) over this stroke; thus it yields a *pessimistic* result.

As stated in GBT Memo 80, the **temperature sensitivity** of the LVDTs can be characterized in two parts, gain and offset. The gain is a change in the basic slope of the LVDT curve. For a 1" stroke, the measured gain change would introduce a 0.0004" rms surface error. It would be one-quarter of this, 0.0001", for a ±.25" stroke. The memo further states that only the variance of the offset term is significant. This was measured to be 0.00035", and does not scale with stroke.

Errors in the electronics are specified to be less than ± 0.2% of the span, i.e., less than ± 0.002 * 2" = ± 0.004" (peak-to -peak). If these are offset errors, they would be insignificant, so long as they are constant. Since the electronics are in a temperature controlled room, this would be the case. Based on knowledge about the electronics and some experience with it, most probably the errors are primarily gain errors. Assuming a gaussian distribution and a ±0.25" stroke (5 sigma), this error is equivalent to 0.0016" rms. As with offset, gain would be nearly constant due the electronics being in a temperature controlled environment.

Positioning accuracy is typically better than 0.0005", peak, in the lab. It may be a bit worse in the field, but assuming an error of 0.0005" rms is probably reasonable.

Table 3: Summary of Actuator Positioning Errors, Uncompensated, 0.25" stroke	
Error Source	Error, rms inches (microns)
LVDT gain	<0.0037 (< 92.5)
LVDT non-linearity	0.000346 (8.7)
LVDT temperature, gain	0.0001 (2.5)
LVDT temperature, offset	0.00035 (9.0)
Electronics gain	0.0016 (40)

Compensation Scheme

The interface to the active surface system consists of commands and responses which, ideally, are calibrated in microns. One LSB of the 16-bit integer command or response corresponds to 1 micron. The question is: how accurate must the active surface system be to make the interface sufficiently "ideal"? The panel rms is 0.003". As shown in Table 3, the only actuator errors in this regime are LVDT gain and electronics gain. Thus compensation of only these two errors will yield a positioning accuracy that is significantly superior to the panels. Assuming we can calibrate the gains, the compensation scheme for commands to the active surface will simply consist of a linear fit, i.e., each command will first be multiplied by a gain term , and then an offset term (unique terms for each actuator), related to the surface's "home" position, will be added to it. Thus a command of "0" would place a given actuator on the design paraboloid when the telescope is at the rigging angle. A command of "1000" would place the actuator 1000 microns above the design paraboloid, and a command of "-2000" would place the actuator 2000 microns below the design paraboloid. The response to a position query would be similar.

If strokes larger than 0.5" are required for some applications in the future, other compensation schemes may be required. If they are straightforward enough, they can be executed in the real-time Active Surface Master computer. Otherwise, they can be implemented as a second layer of compensation executing in the pointing control computer which commands the active surface.

System Calibration

The actuators are presently installed on the telescope. It is necessary, and appears possible, to calibrate them there. However, until we learn how the as-built telescope behaves, and optimum calibration scheme cannot be designed. This is not an excuse to do nothing now. A preliminary calibration system should be developed this year and used as soon as possible. It will point the way to better and better ways to calibrate the actuators.

Several approaches to calibration are possible. For instance, using a commercial laser interferometer and some knowledge about the telescope geometry, one could acquire data on one actuator at a time, to a high degree of precision. One could also physically go to each actuator with a specially designed calibration device. Neither of these methods are particularly attractive because they are quite labor intensive, error prone, and, to some extent, dangerous. A much more attractive approach is to make use of the laser ranging system. The measurement noise in this system is larger than one would like, but by using it in nearly ideal conditions, with some cleverness, the desired calibration accuracy will likely be achieved.

There are almost an infinite number of ways to use the laser ranging system to calibrate the panel actuators. The following is, hopefully, a reasonable first cut.

- 0 - Take data on calm, overcast nights.
- 1 - Break the surface up into patches which can be measured on a fairly short time-scale, say 15 minutes.
- 2 - Move *every other* actuator to -0.5".
- 3 - Take readings on *every* actuator in the patch.
- 4 - Repeat steps 2 and 3 for displacements of -0.25, 0, +0.25 and 0.5 inches.
- 5 - Repeat steps 2, 3, and 4 but swapping the roles of the moving and stationary actuators.
- 6 - Repeat 2, 3, 4, and 5 for all patches on the telescope.

The short time span for each measurement set would hopefully keep thermals at bay. Moving every other actuator provides a large number of controls which can be used either as sanity checks or to correct for systematic variations. (Since the corner cubes are not directly over the centers of the actuators, the "stationary" actuators mentioned above will probably not appear stationary. This and similar effects appear straightforward to model, although this needs to be confirmed.) The resulting data would be analyzed off line to produce a gain term for each actuator.

Gains for each actuator would be produced in "counts per inch ." From these would be derived correction factors, m, for each actuator such that, from the command interface, a command delta of 24500 counts produces a displacement delta of 1 inch. This correction factor would be valid over the range of ±0.5". Offsets for each actuator would be derived from various sources. Initially, the LVDT readings after a 10 minute system warm up would become the offsets. Later these offsets would be refined using photogrammetry, holography and laser ranging.

Real Time Command Processing

The processing of position commands to the active surface would be very straightforward. As is implied above, the processing involves the simple equation for a straight line, $y = mx + b$, where "y" is the real command to the servos in the slave processors, "x" is the ideal command to the active surface, and "m" and "b" are the constants addressed in the above section. To process position requests (i.e., where are the actuators?), the inverse of this equation needs to be applied. Possibly two sets of constants can be kept in the master processor if multiplying turns out to be significantly faster than dividing.

file: gbt/actsurf/calibration/sys_cal3.wpd

Appendix A
Linearity Analysis for 1" and 0.5" stroke

Schiebel aquired a vast amount of data on many of the LVDTs used on the panel actuators. In particular, he calibrated approximately 1200 units against a linear inductosyn (a more expensive and more accurate position encoder) in a temperature chamber at 5 temperatures. The data is presently archived on CD ROM and is also available as read-only files in the in the directories under /doc/gbt/subsys/actsurf/lvdtdata.

The linearity of the LVDTs using ±1" and ± 0.5" strokes was compared as follows. Eighty LVDTs were randomly selected from those calibrated by Schiebel. They were all selected from the calibration runs at 7.2 °C. The group of 80 was divided into two groups of 40. For each LVDT a straight line was fit through the data from 1" to -1", then the difference between the measured data and the best fit data was taken. The difference was then converted into inches (from A/D counts). Finally the standard deviation of the resulting points was computed, and tabulated as the "rms1" for each LVDT. This procedure was repeated using only calibration data from ±0.5; these results were tabulated as "rms2". Finally the means and standard deviations of all the "rms1" and "rms2" data were tabulated. This is shown on Table A-1.

The two groups of 40 LVDTs have similar mean "rms1" and "rms2" values; they differ by 2%. The standard deviations, especially on the larger stroke differed by much more than this , but this is mostly due to one LVDT that had a poor response near the end of its stroke. Hopefully all this implies that the analysis sample size is sufficient. The two sets of 40 were combined and the means of "rms1" and "rms2" tabulated. The mean for the shorter stroke is about 3 times smaller than that of the larger stroke.

Table A-1: Non-linearity analysis data

LVDT s/n	rms1	rms2	LVDT s/n	rms1	rms2
100	0.00191	0.00052	1295	0.003883	0.00115
1008	0.00278	0.000759	1318	0.001657	0.000413
1035	0.00275	0.000985	1344	0.003111	0.000845
1111	0.003086	0.000442	1385	0.002124	0.001375
1620	0.002144	0.00063	1418	0.002616	0.000529
104	0.00275	0.000616	1458	0.003371	0.001421
198	0.003208	0.001144	1489	0.001884	0.000739
220	0.002293	0.000755	1522	0.001479	0.000781
229	0.003206	0.001323	1559	0.00346	0.000616
257	0.002922	0.001106	1592	0.003064	0.00068
284	0.002567	0.000497	1603	0.006094	0.001619
312	0.002589	0.000774	1659	0.002464	0.000593
350	0.001092	0.00048	1681	0.001864	0.000645
373	0.002527	0.000587	1708	0.002665	0.001364
398	0.0028	0.000951	1756	0.003229	0.00093
429	0.003658	0.000834	1795	0.002865	0.001084
461	0.002167	0.001148	1814	0.002253	0.001194
508	0.004266	0.000908	1862	0.004147	0.001997
533	0.002908	0.000998	1883	0.001966	0.000702
598	0.003231	0.000539	1912	0.002155	0.001631
619	0.003102	0.001507	1959	0.002875	0.000304
642	0.00208	0.001006	1990	0.003052	0.000607
693	0.002307	0.00053	2007	0.00167	0.001053
712	0.003374	0.001047	2044	0.00278	0.000655
748	0.003043	0.001085	2094	0.003397	0.000701
791	0.003358	0.000563	2105	0.002409	0.000349
813	0.003272	0.000831	2135	0.002587	0.000448
856	0.002122	0.000403	2180	0.003087	0.000698
894	0.004355	0.001743	2201	0.001925	0.00091
919	0.003337	0.001179	2249	0.004266	0.000954
961	0.003264	0.000649	2287	0.002727	0.000868
989	0.003192	0.001084	2319	0.002447	0.000773
1008	0.002792	0.000762	2260	0.001604	0.000602
1039	0.003035	0.001068	2290	0.001604	0.000602
1098	0.002423	0.000376	2409	0.002315	0.00053
1105	0.001853	0.000548	2456	0.002342	0.000687
1165	0.003623	0.00126	2478	0.003387	0.000756
1198	0.002496	0.001179	2513	0.004802	0.000821
1210	0.00255	0.001058	2537	0.002487	0.000667
1256	0.002505	0.001154	2530	0.002852	0.000889
Mean of rms's	0.002823425	0.0008757		0.00277415	0.00085455
rms of rms's	0.000636271	0.000321854		0.00094073	0.000371685
mean rms1/mean rms2		3.224192075			3.246328477

"Note: rms1 is over +/1", and rms2 is over +/-0.5"