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VSHOT MEASUREMENT UNCERTAINTY AND SENSITIVITY STUDY

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ABSTRACT

The Video Scanning Hartmann Optical Tester (VSHOT) is a slope-measuring tool for large, imprecise reflectors. To study the accuracy of VSHOT as well as its sensitivity to changes in test setup variables, a series of experiments were performed with a very precise, astronomical-grade mirror. The slope errors of the reference mirror were much smaller than the resolution of the VSHOT, so that any measured slope errors were caused by the instrument itself rather than the mirror. The VSHOT exceeded its accuracy goals by achieving about $\pm 0.5\%$ (68% confidence) error in the determination of focal length and ± 0.1 mrad (68% confidence) error in the determination of RMS slope error. Displacement of the test mirror from the optical axis caused the largest source of measured errors.

INTRODUCTION

The Video Scanning Hartmann Optical Tester (VSHOT) is a slope-measuring tool for large, imprecise reflectors. It is a laser ray trace device developed to measure the optical quality of point-focus solar concentrating mirrors. A unique tool was needed because of the diverse geometry and very large size of solar concentrators, plus their large optical errors. Designers usually seek the lowest cost mirror design with root mean square (RMS) slope error of less than 2.5 milliradians (mrad). Additionally, a device was needed that provides the input values required by computer codes that predict flux distributions (e.g. CIRCE, OPTDISH). Many popular optical evaluation tools are unable to meet these aforementioned criteria. For example, interferometers are best suited for measuring optical errors orders of magnitude smaller than are present in solar concentrators.

Laser ray trace systems for solar concentrators have been under development for many years at the National Laboratories and have the advantage of measuring slope directly. This is inherently better than deriving slopes from surface shape measurements. An early example is a system developed at Sandia National Laboratories for measuring line-focus (trough) concentrators (Hansche, 1978). The VSHOT is based heavily on the SHOT system (Wendelin et al, 1991) developed at the Solar Energy Research Institute, now the National Renewable Energy Laboratory (NREL). The VSHOT was developed by SunLab, a partnership between Sandia and NREL. The name VSHOT credited the origin of the system, with the addition of the "V" highlighting the use of a monochrome, 8-bit CCD video camera, one of numerous functional improvements in the new system. In the interests of brevity, and since the fundamental concepts remain the same as described previously for the SHOT, only a short system description will be provided here.

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Figure 1. Schematic of the VSHOT

Figure 1 is a schematic of the system showing the key components. It operates by scanning the laser beam in a predefined pattern across the surface of the mirror to be tested, at each point measuring the slope. Once testing is complete, a polynomial description of the surface of the form

$$z(x - \Delta x, y - \Delta y) = \sum_{i=0}^k \sum_{j=0}^i B_{i,j} (x - \Delta x)^{i-j} (y - \Delta y)^j$$

is fit to the measured slope data. In this equation, k is the order of the fit and the Δx and Δy terms compensate for the positioning of a mirror's vertex at a location off the optical axis of the VSHOT. High-order fits are possible, but a 2nd-order fit is often used in order to determine the mirror's error from the ideal parabolic shape of a point-focus solar concentrator. For a mirror located on the optical axis, the 2nd-order equation becomes

$$z(x,y) = B_{0,0} + B_{1,0}x + B_{1,1}y + B_{2,0}x^2 + B_{2,1}xy + B_{2,2}y^2$$

This Zernike-type polynomial has the advantage that the coefficients relate in simple fashion to key optical parameters. The tilt of the mirror in each direction with respect to the optical axis is

$$\text{tilt } x = \arctan(B_{1,0}), \text{ tilt } y = \arctan(B_{1,1})$$

The focal length in each direction is

$$f_x = \frac{1}{4B_{2,2}}, \text{ and } f_y = \frac{1}{4B_{2,0}}$$

The focal length and RMS slope error from the 2nd order fit are the key output parameters. The RMS slope error,

$$RMS = \sqrt{\sum_{i=1}^N (R_{x,i}^2 + R_{y,i}^2) / N}$$

where R_x and R_y are the x - and y -direction slope error from that predicted by the fit at each point. RMS sometimes called sigma, is often used as a figure-of-merit for concentrator quality, and must be presented together with the focal length to have meaning. For example, a mirror with an excellent RMS slope error of only ± 0.05 mrad and focal length of 250" is a poor mirror for a system designed for a 200" focal length.

The initial design targets for the VSHOT were accuracy of better than $\pm 5\%$ in focal length and ± 0.25 mrad in RMS slope error (preferably ± 0.1 mrad). This study was intended to investigate both the measurement accuracy and sensitivity to changes in test setup variables. It has an advantage over a prior study of the SHOT accuracy that used relative comparisons (Wendelin et. Al, 1995) because the use of the high-quality, astronomical optic provided an absolute measure of accuracy as well as the desirable situation that the measured errors were known to be caused by the VSHOT instrument itself rather than the test mirror.

Figure 2 shows the VSHOT coordinates in (a) two dimensions and (b) three dimensions. For a perfect mirror, which the mirror for this study approximates, error in the measurement of the slope, β , at each point, P , may be caused by

an errors in any one of three parameters: 1) the outgoing angle, α , of the laser scanner; 2) the location of the return spot, H, and 3) the distance between the laser source and the vertex of the mirror, S. The accuracy and repeatability of the VSHOT does change with the geometry of the experimental setup. However, the results of this study are representative of typical test conditions for prototype solar concentrators.

Figure 2a. VSHOT coordinates in 2-Dimensions

Figure 2b. VSHOT coordinates in 3-Dimensions

EXPERIMENTAL APPROACH

The reference value of the 16" diameter test article's focal length was measured independently using the Foucault knife-edge test as described by Ojeda-Castañeda (1992). This resulted in a focal length of $79.16'' \pm 0.08''$. The uncertainty comes from the mechanical measurement of the set-up and from the uncertainty in focus position due to diffraction. The reference mirror's RMS slope error is effectively 0 since its optical errors are much smaller than the resolution of the VSHOT.

The experimental campaign was begun with ten repetitions of a typical experimental setup, the baseline tests, to establish the VSHOT repeatability. Then selected test setup variables were changed to investigate their effect on the VSHOT output. The baseline test setup was as follows ($S = 256.9''$, $\Delta x = \Delta y = 0''$, 188 point test pattern spaced at 1" intervals in a 15.4" diameter circle. This completely filled the mirror's reflective surface. A total of 37 experiments were performed, beginning with run 8. The baseline tests were originally begun with run 1, but an error with the apparatus was discovered in run 7 and corrected. The process was started over again with run 8.

RESULTS

basis for throwing out points?

A description of the experiments and their results are listed in Table 1. Listed first are the controlled testing variables: the distance between the laser scanner and the vertex of the test article (S) and the number of data points tested (# Pts). Next are the results from a second order fit of the data: the focal length in X- and Y-directions (F_x , F_y); the root mean square of the error vector magnitudes from the best second-order fit including all points tested (RMS) and then excluding points with error vector magnitude greater than 3 standard deviations (RMS2); with the number of points excluded (# pts omit) also listed. RMS2 is of interest in this study because it is a more conservative measure of changes in measured slope error caused by the test equipment. Statistics predict only 3 of 1000 points should meet this criteria for omission if all measurements are from the same population. Please note that RMS2 is calculated from the best fit generated using all the data points.

The baseline tests, runs 8-17, were ten experiments performed sequentially with no changes in the test setup. Run 0 is the average of the results from the ten baseline tests and is used frequently in the remainder of this paper. It is sometimes referred to as "the baseline." With the sole exclusion of run 8, the baseline tests exhibited an unexpectedly high number of outlier error vectors. As mentioned previously, statistics suggest that these points were not from the same population as the others. Figure 3 is a vector error plot produced by the VSHOT from run 10 that illustrates the non-normality of these outlier points. The remainder of the population has a characteristic CCW rotation caused by imperfect alignment of the video calibration target. This behavior was also seen in runs 18-22. In run 22, background lighting changes due to nearby welding and open windows were specifically noted by the operator.. There was no conclusive explanation for this effect, but since runs 8-22 were all performed on a different day from rest of the tests, a leading theory was that background lighting changes may have affected most of the runs on that day, not just run 21.

The effect of these unexplained outlier points on this study was to increase the variation of the results, most extensively the RMS slope error. Despite this fact, the variation observed was very small and will be discussed later. The inclusion of the RMS2 metric also serves to exclude the impact of these outlier points.

SYSTEM ACCURACY

The VSHOT proved to be quite accurate as evidenced by Table 2 which lists the average accuracy results from the baseline tests and from all tests. Two types of error afflict measurement systems: random (repeatability) and bias error. The repeatability of the VSHOT is best described by the standard deviation of the results from the baseline tests. However, the bias error is best described by effects of many different test setups. These errors will each be discussed for the two key outputs: focal length and figure-of-merit RMS slope error.

The focal length measured by the VSHOT, F_{avg} , is the average of F_x and F_y . The repeatability of this measurement was $\pm 0.02\%$. The bias error in F changes every time the experimental setup changes but can be represented by the results from all 37 runs here in the simplified form of a mean and standard deviation: $0.24\% \pm 0.45\%$.

In the determination of the mirror's RMS slope error, the repeatability of the VSHOT is 0.024 mrad. However, if lighting irregularities did indeed as speculated cause the outlier points seen in Figure 4, the RMS2 standard deviation from the baseline tests, 0.003 mrad, may be a better representation of the system's repeatability. The accuracy (any deviation from 0 is an error) is again represented in simplified form by the mean and standard deviation from all runs: $0.095 \text{ mrad} \pm 0.078 \text{ mrad}$.

As is evidenced by these results, the repeatability of the VSHOT is excellent. In general, the accuracy of the VSHOT is also very good with an average of almost 0.2% error in focal length and 0.1 mrad error in RMS slope error. However, the large standard deviations about the mean accuracy values indicates significant variability across runs. The next section discusses the effect of different test setup variables on the results.

TABLE 1. DESCRIPTION AND RESULTS OF THE 37 EXPERIMENTS

Run #	Comments	S (in)	# Pts	Fx (in)	Fy (in)	RMS (mrad)	RMS2 (mrad)	# pts omit
8	Baseline Setup, T= 52-56 F	256.9	188	79.46	79.31	0.049	0.049	0
9	T= 57 F	256.9	188	79.48	79.32	0.104	0.050	5
10	T= 57 F	256.9	188	79.48	79.34	0.111	0.052	9
11	T= 58 F	256.9	188	79.51	79.34	0.116	0.058	9
12	T= 53 F (cold air from outside)	256.9	188	79.49	79.35	0.074	0.048	7
13	T= 57 F	256.9	188	79.48	79.32	0.087	0.047	4
14	T= 57 F	256.9	188	79.47	79.32	0.058	0.048	4
15	T= 59 F	256.9	188	79.47	79.33	0.076	0.052	5
16	T= 57 F	256.9	188	79.46	79.32	0.092	0.047	7
17	T= 59 F	256.9	188	79.45	79.33	0.114	0.049	9
Average of Baseline Tests				79.48	79.33	0.088	0.050	5.9
Std Deviation of Baseline Tests				0.02	0.01	0.024	0.003	2.8848
18	Double # of points.	256.9	386	79.48	79.32	0.100	0.048	25
19	Halved # of points	256.9	97	79.49	79.35	0.125	0.046	8
20	Repeat of 019	256.9	97	79.47	79.31	0.088	0.046	3
21	Randomize points	256.9	188	79.45	79.30	0.084	0.045	11
22	Background lighting, welding	256.9	188	79.49	79.34	0.117	0.048	13
23	Repeat of std setup	256.9	188	79.47	79.31	0.048	0.048	0
24	Rotated 90 deg CCW	256.9	188	79.46	79.31	0.048	0.048	0
25	Rotated 180 deg CCW	256.9	188	79.45	79.30	0.064	0.052	4
26	Rotated back to 0 Deg	256.9	188	79.45	79.29	0.050	0.050	0
27	Mirror tilted 0.58 deg left	256.9	188	79.49	79.30	0.054	0.051	1
28	Mirror tilted 0.78 deg down	256.9	188	79.49	79.31	0.043	0.043	0
29	Moved 24" right, aim centered	258.6	188	77.62	78.39	0.320	0.300	1
29b	run 29 w/ 0" offset in fit	258.6	188	77.61	78.38	0.156	0.102	2
30	Moved 9" down aim centered	258.1	188	79.32	78.98	0.064	0.064	0
30b	run 30 w/ 0" offset in fit	258.1	188	79.32	78.98	0.058	0.057	1
31	Reposition to baseline setup	257.8	188	79.36	79.19	0.051	0.051	0
32	Repeat	257.8	188	79.36	79.19	0.051	0.051	0
33	Minimum system warm up	257.8	188	79.37	79.19	0.050	0.050	0
34	Repeat 33	257.8	188	79.36	79.19	0.051	0.051	0
35	Moved back to 323"	323.2	188	79.37	79.22	0.052	0.052	0
36	repeat 35	323.2	188	79.37	79.22	0.051	0.051	0
37	Moved closer to 202"	202.1	188	79.63	79.51	0.061	0.027	6
38	repeat 37	202.1	188	79.62	79.51	0.102	0.028	6
39	Camera position 2	202.1	188	79.64	79.73	0.047	0.045	1
40	Cam at Pos 2, zoomed in	202.1	188	79.64	79.73	0.046	0.044	1
41	Cam at Pos 4	249.1	188	79.36	79.66	0.398	0.155	5
42	Repeat of 41, c=15.3"	249.1	180	79.32	79.50	0.313	0.126	3
43	Cam pos 5, c=15.3"	249.0	180	79.80	79.69	0.076	0.076	0
44	Repeat of 43, c=15.3"	249.0	180	79.80	79.69	0.077	0.077	0
45	Repeat 43, new mount	255.9	180	79.82	79.70	0.079	0.077	1

TABLE 2. ACCURACY OF THE VSHOT COMPARED TO THE REFERENCE VALUE FOR FOCAL LENGTH

Run	Fx (in)	Fy (in)	D(Fx) %	D(Fy) %	D(Favg) %	RMS (mrad)	Error Type
Run 0 (Avg 8-17)							
Average	79.48	79.33	0.40%	0.21%	0.31%	0.088	Bias
Std. Dev.	0.02	0.01	0.02%	0.02%	0.02%	0.024	Random
All runs							
Average	79.31	79.31	0.29%	0.19%	0.24%	0.095	Bias
Std. Dev.	0.28	0.28	0.55%	0.36%	0.45%	0.078	Random

FIGURE 3. VECTOR PLOT OF RESIDUAL FIT ERRORS FROM 2ND-ORDER FIT OF RUN 10

SYSTEM SENSITIVITY

The accuracy results presented in the previous section indicated that significant variation was observed over the many tests performed. This section discusses in greater depth the sensitivity of the results to changes in the experimental setup. Table 3 shows the effect of numerous changes in the experiment setup on the VSHOT outputs. For each variable examined, one or more comparisons are presented. An effort has been made to focus on comparisons where only one test setup variable was changed at a time. As was done previously (Wendelin et Al., 1991), the value E2 was calculated to determined the changes in the fit coefficients. For the comparison of 2nd-order fits of run A and B,

$$E2 = ((B_{20}(A) - B_{20}(B))^2 + (B_{21}(A) - B_{21}(B))^2 + (B_{22}(A) - B_{22}(B))^2)^{1/2}$$

The offset and tilt terms (B_{00} , B_{10} , B_{11}) are omitted from the calculation because these describe the offset and tilt of the mirror, a function of the experimental setup, not the surface shape of the test article. Additionally, Table 3 lists the percentage change of F_x , F_y , RMS, and RMS2 due to different test setup variables. RMS2 is the root mean square error excluding outlier points with slope error greater than 3 standard deviations for that fit. Two questions must be answered in evaluating the sensitivity study results: 1) are changes statistically significant, and 2) are changes meaningful. To address the former, asterisks have been placed next to all changes that are statistically significant as defined by having greater than 3 standard deviations difference from the to run which it is compared. The standard deviation used for all comparisons was calculated from the repetitions of the baseline tests. The importance of statistically significant changes will be addressed below when discussing individual test setup variables.

Test Pattern

The test pattern is described by interrelated parameters. First is the boundary geometrical definition. This, combined with the spacing of the points determines the total number of points. Finally, there is a Boolean variable that determines if the point locations are randomized about the standard Cartesian grid. Randomization is useful in measuring optical errors with a feature size similar to the grid spacing. Because of the precision of the optic, no such errors were expected and this feature was used in run 21 only to determine its measurement sensitivity. The only change in the test pattern that was found to be statistically significant in this test was reducing the size of the circle boundary from 15.4" to 15.3" (this also caused a small reduction in the number of points from 188 to 180). This

slightly improved the slope errors measured in RMS and RMS2 as would be expected because there was less chance of a portion of the beam missing the mirror's edge or striking a defect located there.

Mirror Rotation and Tilt

Neither of these factors proved to be statistically significant. The tilt of the mirror, 0.58° for run 27 and 0.78° for run 28, was modeled correctly by the fit to approximately $\pm 5\%$, only slightly more than the predicted $\pm 2\%$ (95% confidence) uncertainty of the measured values.

TABLE 3. SENSITIVITY OF THE VSHOT TO CHANGES IN TEST SETUP

Test Variable	Runs Compared	E2 x 10 ⁵	Diff (Fx) %	Diff (Fy) %	Diff (RMS) %	Diff (RMS2) %
# of points						
	18 0	0.745	0.00%	-0.01%	13.77%	-4.10%
	19 0	0.744	0.02%	0.04%	42.43%	-6.58%
	20 0	0.745	0.00%	-0.02%	-0.11%	-7.00%
Randomization of points						
	21 0	0.745	-0.04%	-0.03%	-4.93%	-10.20%
Smaller test pattern -0.1" OD						
	42 41	0.973	-0.05%	-0.20% *	-21.22% *	-18.84% *
Rotation of mirror						
	24 0	0.745	-0.03%	-0.02%	-45.67%	-3.80%
	25 0	0.745	-0.03%	-0.03%	-27.33%	3.63%
	26 0	0.745	-0.03%	-0.04%	-43.02%	0.90%
Tilt of mirror						
	27 0	0.744	0.02%	-0.03%	-38.31%	2.55%
	28 0	0.744	0.02%	-0.02%	-51.45%	-14.03%
Combined offset & tilt						
	29 0	0.787	-2.33% *	-1.18% *	262.83% *	502.78% *
	30 0	0.748	-0.19% *	-0.43% *	-27.10%	29.09% *
Incorrect X,Y offsets in fit						
	29b 29	817.729 *	-0.02%	-0.01%	-51.09% *	-65.92% *
	30b 30	127.482 *	0.00%	0.00%	-8.92%	-11.33%
Reposition						
	31 0	0.747	-0.15% *	-0.18% *	-42.31%	2.14%
	32 0	0.747	-0.15% *	-0.17% *	-41.73%	3.17%
	45 44	1.083	0.02%	0.02%	3.42%	0.93%
Minimal system warm-up time						
	33 31	1.205	0.01%	0.01%	-2.25%	-2.25%
	34 32	1.208	0.01%	0.00%	-1.10%	-1.10%
Distance, S						
	35 0	0.747	-0.13% *	-0.14% *	-41.48%	3.61%
	36 0	0.747	-0.13% *	-0.14% *	-42.02%	2.66%
	37 0	0.741	0.19% *	0.23% *	-31.07%	-45.11% *
	38 0	0.741	0.19% *	0.23% *	15.37%	-43.18% *
Camera Location						
	39 38	1.079	0.01%	0.28% *	-22.41%	63.94% *
	43 42	0.964	0.60% *	0.23% *	-75.73% *	-39.64% *
	44 42	0.964	0.61% *	0.23% *	-75.50% *	-39.07% *
Camera Zoom						
	40 39	1.204	0.00%	0.00%	-1.71%	-1.83%
Combined and Other						
	41 0	0.747	-0.15% *	0.43% *	351.47% *	211.96% *
	43 0	0.738	0.40% *	0.45% *	-13.69%	52.83% *
	44 0	0.738	0.41% *	0.45% *	-12.88%	54.26% *

* Statistically significant change >3 std. deviations

Combined Offset and Tilt

This was by far the largest error producing test variable, and a correlation between the distance the mirror was moved from the optical axis and the error was seen. In run 29, the mirror was moved 24" or 10.6° to the right and tilted 5.3° to center the return pattern on the source spot (the middle of the target). Even for this worst case, the resulting effect on measurement error was still moderate- on average less than -2% in F_{avg} . The RMS slope error was 260% larger for a total of 0.32 mrad. The error vector plot had the characteristic CCW rotation seen in most tests and visible in Figure 3, but with larger slope errors. The cause of this is not known for certain, but it is believed that the imperfect

alignment (rotation specifically) of the video calibration target may cause larger errors the further the test article is placed from the optical axis of the system.

The tilt of the mirror was again determined very accurately by the system, this time less than 2% for both runs 29 and 30. Another interesting result is the error caused by performing the second-order fit with 0" X and Y offsets rather than the correct 24" and 9" offsets. This mistake could easily happen, as the author can himself attest, when performing the fit at a later date. The results of this test are labeled runs 29b and 30b. These are the only runs to have statistically significant differences in the metric E_2 . Surprisingly, the results from this fit for focal length are well within the systems repeatability, and for RMS and RMS2 the results are just beyond the 3 standard deviation cutoff. However, the fit incorrectly calculated the tilt of the test articles in this case with 160% and 99% error for runs 29b and 30b respectively. The code will be improved to make it more difficult for an operator to accidentally make this mistake in the fitting process.

Repositioning of the Mirror

Repositioning of the mirror at approximately the same distance, S, from the target and with no intended changes in other test variables led to statistically significant changes in the focal length but not the RMS or RMS2 slope errors. However, these error were very small, less than 0.2%, and are not deemed meaningful.

System Warm-Up Time and Environmental Temperature

There was concern that certain components such as the laser, the camera, and in particular the scanner would be sensitive to temperature and warm-up time. To address the warm-up issue, runs 33 and 34 were performed in succession after turning the system on for the first time that day. The result was statistically insignificant. Another concern was the effect of ambient temperature on the scanner. Manufacturer information indicated that a drift in gain and offset values of 20 $\mu\text{rad}/^\circ\text{C}$ typical and 50 $\mu\text{rad}/^\circ\text{C}$ worst case was to be expected. Since ambient temperature was not controlled, its effect on the measurements was generally confounded with the other variables. However, temperature was carefully monitored during the baseline tests, and no correlation with measurement error was found.

Mirror to Target Distance, S

Three distinctly different values for S were tested in this study, all larger than the radius of curvature (2F). This spread out the return spot pattern so it filled a larger portion of the target. The effect of changing S on the measurement focal length was statistically significant and of similar magnitude to repositioning the mirror. Again this was deemed negligible. However, when S was reduced as in runs 37 and 38, so did RMS2.

This interesting effect is believed to be caused by scanner positioning uncertainty. Referring back to figure 2a, as the distance S approaches 2F, the error in the measurement of β due to an error in α decreases for a perfect mirror. At the limiting case for a perfect mirror with $S = 2F$, any error in α is permissible so long as the beam strikes the mirror because all return spots will land on the source.

Camera Location and Zoom

The camera was repositioned and the video calibration repeated to test the effect of camera location on the VSHOT output. Changes were found to be statistically significant and second in magnitude to the combined offset and tilt effect. Again, the effect on focal length was negligible, but meaningful for RMS and RMS2. Runs 42 and 43 had a change of -75% (-0.23 mrad) and -40% (-0.05 mrad) in RMS and RMS2 respectively. Run 39 differed significantly from run 38 in RMS2. When view in percentage, 64%, this seems large, but it was only a change of 0.018 mrad. The cause of the camera location induced errors is unknown, but will be investigated.

Other

In some cases, more than one test variable changed simultaneously. Run 41 is an example of this because both the camera and the mirror were moved. While the focal length error was again small, the RMS and RMS2 slope errors were very large at 0.398 and 0.155 mrad respectively. This error seems larger than one might expect from the individual effects of camera location and repositioning. It is possible that a problem with the video calibration procedure caused these results. Runs 43 and 44 with combined mirror position, camera location, and test pattern changes showed statistically significant effects.

CONCLUSIONS

This study was successful by providing both the measurement accuracy and sensitivity of the VSHOT and also identifying areas for further investigation. On average the VSHOT measured the reference mirror's focal length with $\pm 0.5\%$ (68% confidence) error and its RMS slope error with ± 0.1 mrad (68% confidence). It is recommended that mirrors be positioned on the optical axis of the VSHOT, at a distance near 2F to achieve the most accurate results.

Measurement repeatability was excellent with the exception of statistical outlier points in the RMS slope error calculation. These outliers were seen mostly on runs 8-22 performed a different day from the rest. Since the operator noted changing background lighting conditions for run 22 due to nearby welding and open windows, it was hypothesized that this situation may have been occurring all day.

To predict measurement uncertainty for different test setups and help explain some errors measured in this study, the development of an analytical uncertainty model is recommended.

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