Video Scanning Hartmann Optical Tester (VSHOT) Uncertainty Analysis

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VIDEO SCANNING HARTMANN OPTICAL TESTER (VSHOT) UNCERTAINTY ANALYSIS

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Abstract

The VSHOT is a proven tool that has been used on heliostat, dish, and trough mirror facets to provide accurate surface slope deviations that characterize optical quality. These data are used to estimate optical performance within the overall system. A study of the uncertainty and sensitivity of this instrument was completed in 1997 and since then the hardware and software have been upgraded with new technology. To ensure that both industry and laboratory users understand the accuracy of the data provided by the VSHOT, we have conducted a new uncertainty analysis.

This purely analytical work is based primarily on the geometric optics of the system and shows sensitivities to various design and operational parameters. We discuss sources of error with measuring devices, instrument calibrations, and operator measurements for a parabolic trough test. In this paper, we include both the random (precision) and systematic (bias) errors for VSHOT testing and their contributions to the uncertainty. The contributing factors that we considered in this study are target tilt, target face to laser output distance, instrument vertical offset, scanner tilt, distance between the tool and the test piece, camera calibration, and scanner/calibration. The results shown in this work estimate the 2σ slope error uncertainty for a parabolic trough line scan test to be from ±0.21 - 0.46 mrad for any given single slope error measurement. The 2σ RMS uncertainty for slope errors for a single scan is ±0.33 mrad, ±0.6 mm (±0.01%) for focal length and ±0.02 mrad for test article tilt. Experimental data taken on a highly accurate telescope mirror is consistent with these results.

Keywords: slope error, optical characterization, mirror testing, parabolic trough

1. Introduction

The VSHOT is a laser ray-trace system designed to characterize (both in the lab and field) the optical surfaces of solar concentrators. Originally designed to test point-focus (dish) concentrators, it was later modified to include characterization of line-focus (trough) concentrators and has been used to test mirror panels for heliostats. The VSHOT uses computer-controlled laser scanning and digital-camera image acquisition to provide optical surface contour data.

The laser scans a mirror in a pattern predefined by the user. At each scanned position, the laser beam is reflected back to a target and the location is imaged using a camera. The surface slope is calculated at each position using the laser output angle and return-spot location. A Zernike Polynomial is used to mathematically fit the surface using the slope data.

A previous uncertainty analysis [1] used a 16-inch telescope mirror to conduct an experimental analysis. The distance between the mirror and the VSHOT ranged from 6.3–8.2 m and represents only a small fraction of the capability of the laser scanner output angles (4^{o} vs 80^{o}). That study concluded the uncertainty in slope error was roughly 0.1 mrad (2σ) and 0.8% in focal length. Since the hardware and software have been significantly upgraded in the intervening years, we decided that a new analysis was needed and should include both analytical and experimental aspects.

The analytical study we conducted assumed a parabolic trough with a 6-m aperture and a 1.71-m focal length. The full 80^{o} cone angle for the scanner 'sees' the entire aperture at a distance of 4.928 m from the vertex of the trough. This arrangement was selected because it typically represents the vast majority of VSHOT tests conducted. For this same reason, only vertical slices across the aperture were analyzed.

The experimental work consisted of measurements on a highly accurate, parabolic mirror. The mirror diameter was 0.762 m with a design focal length of 3.429 m. Full mirror scans and vertical slices were acquired along with various mirror offsets and rotations to determine the sensitivity of calculated results.

2. Analysis

2.1. Zernike Polynomial

A Zernike Polynomial is used to mathematically describe common optical surfaces [2].

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

The order is k and the Δx and Δy terms compensate for known position offsets of the mirror vertex relative to the coordinate origin. These two terms are useful when fitting the data from an actual test, but for the purpose of this analysis, we set them equal to zero. A second order expansion is appropriate for parabolic surfaces and can be adapted to both axisymmetric and single axis curvatures.

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

The meaning of each of the terms is shown in Table 1 below.

$B_{0,0}$	Piston term, displacement of the optic along the z axis
$B_{1,0}$	Tilt term about x axis; =tan($tilt_x$) ~ $tilt_x$ for small angles typical of this type testing
$B_{1,1}$	Tilt term about y axis; =tan($tilt_y$) ~ $tilt_y$ for small angles typical of this type testing
$B_{2,0}$	Focal length term in vertical direction; = $\frac{1}{4f_y}$, where f_y is the focal length
$B_{2,1}$	Cross term indicating astigmatism
$B_{2,2}$	Focal length term in horizontal direction; = $\frac{1}{4f_x}$, where f_x is the focal length

Table 1. Zernike Polynomial term definition.

We chose to conduct the analysis for a typical single axis curvature parabolic trough using simulated vertical slices because this is representative of the majority of VSHOT field tests. This results in a simplified Zernike Polynomial which is a function of y only, where the simplified B_i coefficients retain the same relative meaning as in the table above.

$$z(y) = B_0 + B_1 y + B_2 y^2$$

The slope is the derivative with respect to y of this equation and results in a simple linear expression that can be easily fit to the data.

$$\frac{dz}{dy} = B_1 + 2B_2 y$$

In our analysis, the test piece has an ideal parabolic shape and oriented perfectly to the coordinate system. This allows us to calculate directly the value of y. When slope is plotted as a function of y position, the interpretation is straightforward. A linear fit yields an intercept and slope (of the fit) that correspond to the overall tilt and focal length. When the uncertainties described below are accounted for, this simplified approach allows for an estimate of slope error, focal length and tilt for fixed values of a given contributor. Assessing the impact of these contributors in combination as they vary stochastically is more complex.

2.2. Uncertainty Contributions

Measurement error is defined as the difference between the true and measured value [3]. The measurement uncertainty in this analysis is applied to the calculated value of the reflective surface slope, focal length, and test-article tilt. The slope (or slope error) is of primary interest, so we first address the impacts of measurement error on it and then summarize the impacts on focal length and test-article tilt. We consider six random error sources and seven systematic error sources in this uncertainty analysis. These uncertainties (listed in Table 2) are the important variables that are associated with setting up a test and calibrating the system.

Each of these uncertainties are quantified by their random and systematic errors. Random error uncertainty comes from hardware vendor data on repeatability or precision. All but the camera calibration random errors will vary over the short time while measurements are being taken. Systematic uncertainty can be difficult to quantify but is associated with the operator's ability to take the measurement. We determined those values based on experience, judgment or some approach specific to each uncertainty. We assumed the systematic errors are fixed for a given test but vary randomly over time where a large number of tests are conducted, each with a new setup and new set of errors. The impact of these uncertainties was calculated in a MATLAB program that modeled the test configuration and generated a return spot location as a function of laser output angle over the range of $\pm 40^{o}$ (± 0.69 radian). The test configuration modeled (focal length, and distance to the target) clearly affects the modeled results, however we believe that these results are generally applicable since the typical test conditions do not vary far from the modeled one. Figure 1 shows the outgoing and return laser paths for the geometry modeled.

Description	**Measuring Device**	**Random (2σ)**	**Systematic (2σ)**
Target tilt	Bubble level	±0.208 mrad (0.012^{o})	±0.416 mrad (0.024^{o})
Target face to laser scanner output	Calipers	0.0127 mm	±0.5 mm
Instrument vertical location	Human eye	N/A	±1.59 mm
Scanner tilt	Inclinometer	±0.087 mrad (0.005^{o})	±0.523 mrad (0.03^{o})
Distance from target to test piece	Laser range finder	±1.27 mm	+0.751 mm
Camera calibration	Prosilica GE2040 GigE Camera, 4.2 Mpixel	1.49 ± 0.084 mm	±0.374 mm
Scanner/calibration	Cambridge closed-loop galvanometer model 6220	±8 μrad	±0.62 mrad (0.36^{o})

Table 2. VSHOT uncertainties listed as 95% confidence level (2σ).

Figure 2 shows how random error uncertainty impacts the slope error for two selected contributors: target distance and target tilt. The distance from the target to the test piece is the largest single random contributor to slope error. Figure 3 shows how systematic uncertainty impacts the slope error for two selected contributors: target vertical location and scanner tilt. Note that there are resolution errors in the MATLAB program on the order of 0.01 mrad that show as apparent noise in the data for both figures. This is not significant compared to the overall uncertainty. There is also a gap in the center around output angle = 0^{o} to account for hole in the target for the laser ray paths.

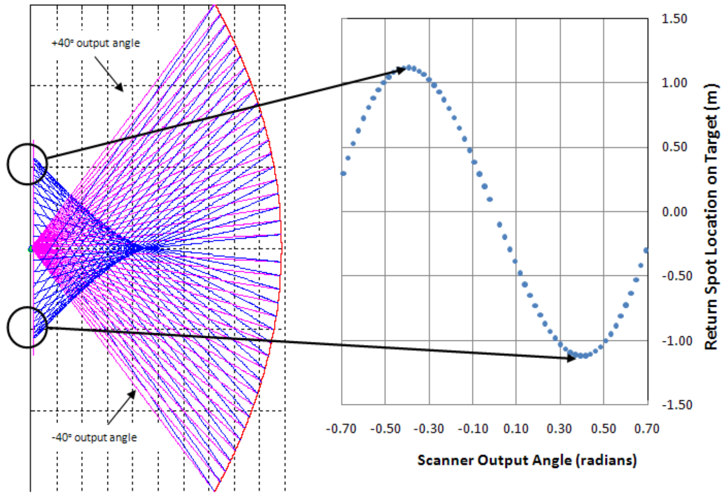

Figure 1. Left figure shows outgoing rays (magenta) and reflected rays (blue). Right figure shows return spot location. Circled areas show location where return spot 'turns around' on target.

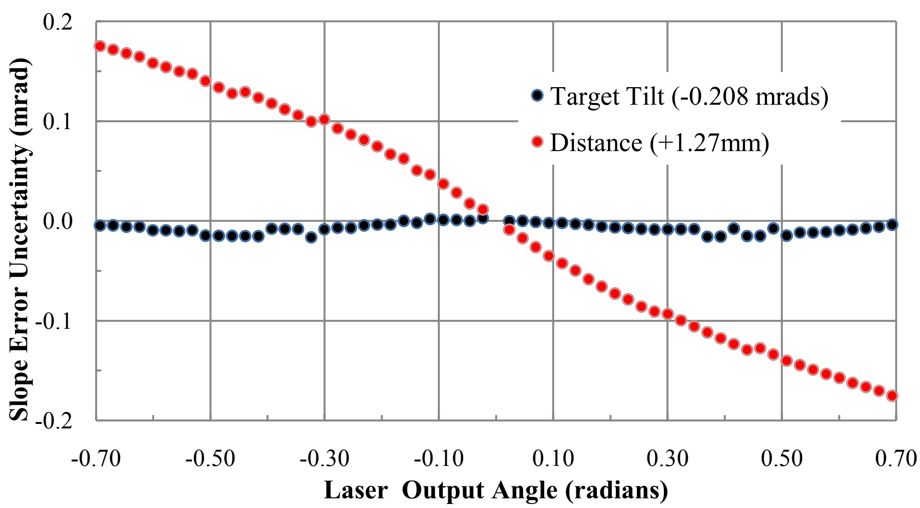

Figure 2. Slope error impact for fixed values of random error in selected contributors.

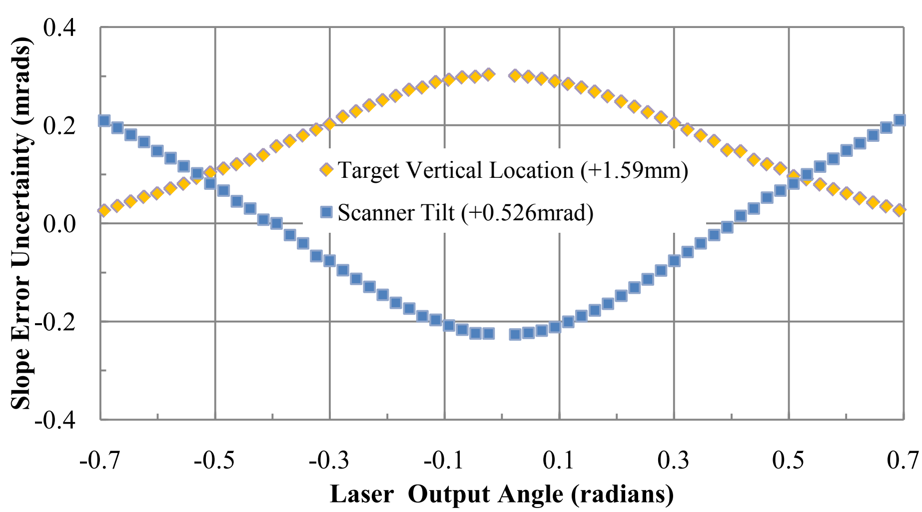

Figure 3. Slope error impact for fixed values of systematic error in selected contributors.

As mentioned before it is not always straightforward to determine the systematic errors. In the case of the target tilt we assumed that the operator when measuring would be unable to be consistent to within twice the random error due to instrument placement by hand, target flatness, etc. The scanner output mirrors are located just behind the target. Although the calipers used for the measurement of target face to scanner output are very accurate, it is difficult for the operator to place them exactly at the intended locations. Thus this systematic error is relatively large compared to its random error. For the instrument vertical location (laser output origin relative to the test piece vertex) the operator sets the laser output to its (0, 0) angular value and then checks the position on the test piece by eye. We estimated that this can be done to within 1/16th inch or 1.6 mm. There is no random error for this as no quantifiable method is used for the measurement. The scanner apparatus (laser tilt) is leveled before each test to within 0.52 mrad establishing its systematic error. Distance from the target to the test piece is measured with a laser range finder with an accuracy of 1.3 mm. We estimate that the systematic uncertainty for the operator to place and aim the rangefinder yields an error of 0.75 mm based on a geometric evaluation. The two uncertainties for the camera and scanner are far more difficult to determine.

For a given test, the camera is calibrated by placing an accurately printed grid of dots over the target and processing the resulting image. After reviewing data from twelve recent camera calibration files and recognizing that various camera positions (with different target viewing extent) were used, we calculated a normalized value of 0.673 ±0.038 pixels/mm for the random error corresponding to 1.49 ±0.084 mm on the target for a single pixel. This calculation assumes that the centroid of the return spot image can be determined by the software to within a pixel. Since this error does not have a zero mean, a positive error uses more pixels than a negative error. When combined with the discrete association of a pixel location with the corresponding centroid, this results in a somewhat 'random' looking effect. The systematic errors were based on a pooled calculation of the y-direction fit errors in the processing over the same twelve camera calibration files.

The laser scanner has a very high resolution so its random error is very small. There are systematic errors introduced during the scanner calibration. Calibration is done by manually directing the laser to specified positions on an accurate grid at a known distance and orientation relative to the scanner. This is done periodically and any time the scanner is shipped. After calibration, the VSHOT software processes the data and generates a fit with errors in the x and y direction. We used three recent calibration files to extract the pooled standard deviation representing the systematic error of ±0.62 mrad.

3. Uncertainty Estimates

3.1. Slope Error

The uncertainties are assumed to be independent of each other and have Gaussian distributions. All of the uncertainties, except for the camera calibration, are assumed to be symmetric about the true value. The random uncertainty, U_R , is used to estimate the combined effect of random slope errors, $U_{R,i}$. The systematic uncertainty, U_S , is used to estimate the combined effect of systematic slope errors, $U_{S,i}$.

$$U_R = \left(\sum_{\mathrm{i}=1}^{\mathrm{N}} U_{R,i}^2 \right)^{\frac{1}{2}}$$

$$U_S = \left(\sum_{\mathrm{j}=1}^{\mathrm{M}} U_{S,i}^2 \right)^{\frac{1}{2}}$$

A first step in this analysis was to assign the 2σ values to each of the uncertainty contributors and calculate the resulting random and systematic slope errors, $U_{R,i}$. and $U_{S,i}$., at each laser output angle across the aperture. These individual slope errors were then combined using the equations above to yield the standard uncertainties, U_R and U_S , at each output angle. For the random errors, this process was done for both positive and negative values of each uncertainty because the camera calibration values are not symmetric. The largest fraction of the random standard uncertainty is from the distance from target to test piece at about 70%. The camera calibration contributes almost 20% and the laser tilt under 10%. The remaining uncertainties have very little impact. For the systematic standard uncertainty, the largest contributor is the instrument vertical offset at about 40%. The scanner calibration contributes less than 30%, the laser tilt 20% and the distance from target to test piece less than 10%. These contributions vary across the aperture so these values reported are averages. In comparison to the random slope errors, the systematic errors are more than twice the magnitude and increase near the center of the scanner range.

The overall uncertainty, U_{RSS} , combines the random and systematic uncertainties using the Root Sum Square uncertainty model. Although in practice the random and systematic uncertainties do not affect the test results in the same way, we have assumed that for the purposes of this analysis that they are equivalent.

$$U_{RSS} = \pm[{U_R}^2 + {U_S}^2]^{\frac{1}{2}}$$

We again used the 2σ values for the calculation of U_{RSS} across the aperture. Figure 4 shows these results for both the positive and negative values of the uncertainties (the camera calibration random uncertainty is the only reason for the difference between positive and negative values). Thus for a single scan the individual 2σ values range from 0.21 mrad at the turnaround points to 0.46 mrad at the vertex with an average of 0.32 mrad. This corresponds to the combined expected uncertainty for given single measured value.

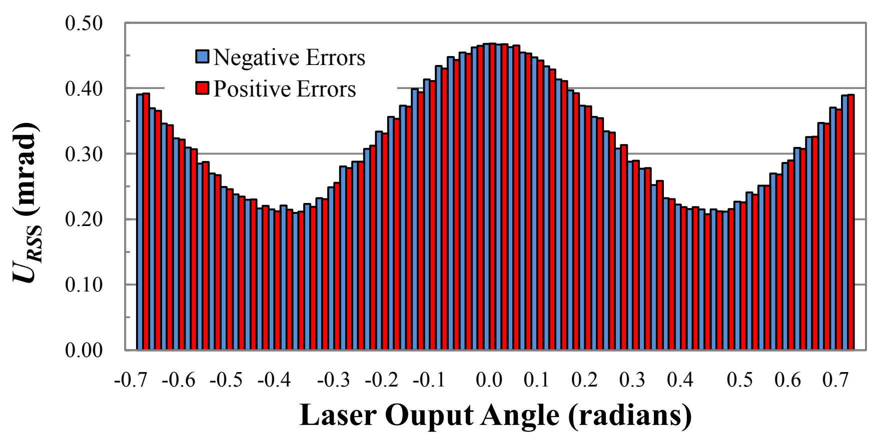

Figure 4. Overall 2σ uncertainty.

To estimate the combined effect of the different uncertainties over a large number of tests we used a simplified error propagation analysis. At each output angle the positive and negative values of U_{RSS} were used to estimate a value for the overall uncertainty one could expect for a single scan. These values were used in a MATLAB program to generate a random set of slope errors. This program was run 20,000 times. A histogram (Figure 5) of the slope errors yields the 2σ uncertainty of 0.33 mrad. This error should be representative of variation between tests where vertical slices are used to characterize a single axis parabolic trough mirror with an RMS slope error. Although not specifically analyzed we would expect similar values for errors in the x direction.

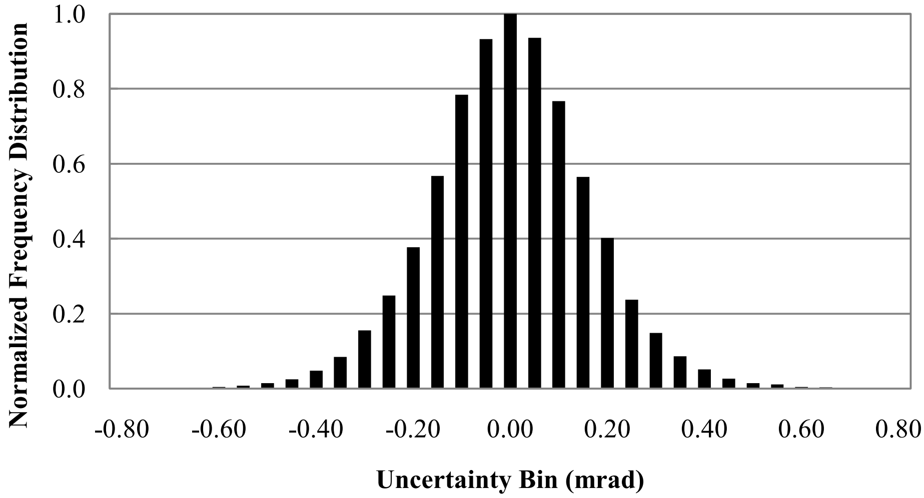

Figure 5. Histogram of slope error uncertainty U_{RSS} (mrad).

3.2 Focal Length and Tilt

The same basic process was used to determine the uncertainty on calculated focal length and test article tilt. These 2σ values are calculated using a fit to the simplified linear equation with slope error as a function of *y*. The resulting linear coefficients yield the focal length and tilt as described earlier. Neither the focal length nor the tilt are very sensitive to any of the uncertainty contributions. Only the distance measurement from the target to the test piece had a small effect, ±0.6 mm, on the focal length. All of the uncertainties have a relatively small effect on the calculated tilt term and all are less than 0.2 mrad. For field testing, a practically achievable tilt error of 1 mrad is considered low.

The same type of error propagation analysis was used the estimate the combined effect of the uncertainties on focal length and tilt. This process was identical to that for slope error but required the additional step of fitting the slope error as a function of *y* to the simplified linear equation. The resulting focal length uncertainty was ±0.6 mm and the tilt uncertainty is ±0.02 mrad. These values are extremely small compared to both desired errors in focal length to maintain good optical performance and acceptable errors in test set up for tilt.

4. Reference Mirror Testing

We procured a custom-made, axisymmetric parabolic mirror of very high quality to test using our laboratory VSHOT apparatus. This mirror has a diameter of 0.762 m with a design focal length of 3.419 m. We assume there is essentially zero slope error for its parabolic contour. A number of tests of the full mirror surface were conducted to determine the calculated slope errors, focal length and tilt. The mirror was set 4.74 m from the VSHOT vertex so the scanner output angle required was only 5^o (0.08 radian).

A number of tests scanning the full mirror surface were conducted with very consistent results in slope error, focal length and tilt returned by the VSHOT software. This indicates good repeatability, although there were insufficient trials for statistically significant results to be quantified. The range of 2σ slope error was from 0.1-0.2 mrad. However, the calculated focal length was consistently about 0.7% less than the design value. Since the focal length was not independently verified it is possible that the actual value was slightly shorter than the design specification. Calculated values for tilt were in the 0.1-0.2 mrad range, well within the expected ability of the operators to align the test piece during set up. Two tests were conducted after purposely tilting the mirror, first about the *x* axis and then about both *x* and *y* axes. The actual tilt of the mirror was not accurately measured so a comparison with the calculated values (~30 mrad) is not possible. The calculated slope errors and focal length were well within the range of values from the other full mirror scan results indicating this level of tilt had no effect on those results.

Following the last full mirror scan a series of vertical slice data were acquired. The slices were spaced at about every 5 cm along the width of the mirror. These data were compared with the last full mirror scan and analyzed using the same Zernike coefficients. Figure 6 shows the full mirror scan results for *dz/dx* and *dz/dy* slope errors with the slice data superimposed. It is clear that the slice data matches very well with the full mirror data with variations not exceeding about 0.02 mrad. However, if the slice data are analyzed *individually* to obtain Zernike coefficients, those new coefficients will result in smaller slope errors. If this is true for a reference mirror it is likely to be magnified for parabolic trough mirrors with presumably greater surface contour variations. To avoid this potential underestimation of slope errors slice data should be analyzed against a consistent focal length, either the design value or overall best fit value.

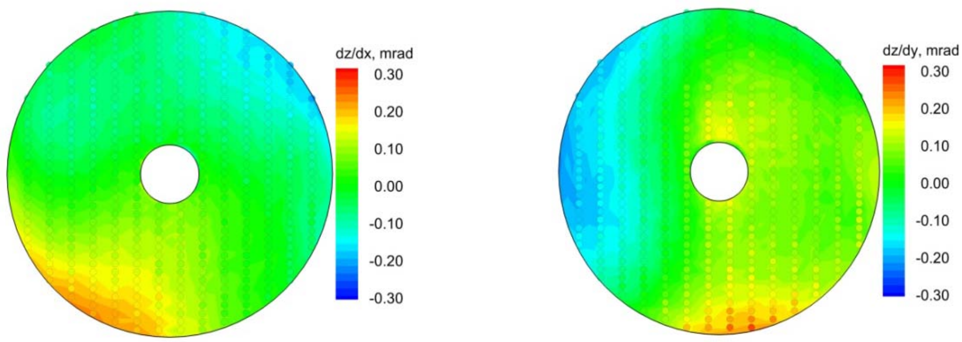

Figure 6. VSHOT generated slope errors in x direction (left) and y direction (right). Slice data has been superposed over full mirror scan. Center hole corresponds to circular hole in target. Every 3rd data point in the slice is shown to enhance visual interpretation.

5. Summary

We completed an uncertainty analysis for the VSHOT assuming the typical test configuration simulating a single axis parabolic trough taking vertical slices. For an individual slope error measurement the 2σ uncertainty ranges from ± 0.21 to ± 0.46 mrad depending on the laser output angle. The 2σ uncertainty in the RMS slope error for a full line scan is ±0.33 mrad. . The corresponding calculated focal length uncertainty was ± 0.6 mm and the tilt uncertainty was ± 0.2 mrad. Although slightly higher than the results from the previous experimental uncertainty analysis, we must remember that the current study was purely analytical. These values are well within the desired tolerances for parabolic troughs and thus we can conclude that VSHOT remains a viable and valuable tool for measurement of parabolic trough mirrors and for solar concentrator mirrors in general.

6. Acknowledgements

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7. References

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14. ABSTRACT *(Maximum 200 Words)*

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