Measurement of Scratch Depths

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This paper describes several experiments designed to quantify the measurement performance of the GelSight Mobile system on measuring scratch-like features. The goal is to characterize system accuracy and repeatability for measurements of this type. All experiments described in this paper use the reference specimen shown in Fig. 1(a), GelSight part RSP-GT01, which has ten machined grooves with depths ranging from 0.010 mm to 0.100 mm. The specimen was calibrated by East Coast Metrology in Topsfield, MA USA, a measurement lab that is certified by the National Institute of Standards and Technology (NIST). The calibration certificate for part RSP-GT01 lists the depth of each groove at three locations per groove.

The measurements in this study were captured using the GelSight Mobile 0.5X system, shown in Fig. 1(b), which is a 3D surface measurement device that uses a proprietary gel cartridge to enable the measurement. The gel cartridge can be used for hundreds of measurements if care is taken to clean the parts before measurement and not press the device into sharp components. However, the gel cartridge is a consumable in the system and will need to be replaced when the image quality becomes degraded. The system is calibrated when the gel cartridge is replaced and the software provides a simple validation protocol to assess spatial (XY) and depth (Z) accuracy on a calibrated validation specimen. The experiments described in this white paper used two gel cartridges: one for the type 1 studies and one for the gage repeatability and reproducibility (GRR) study.

Two types of experiments were conducted on the test specimen. The first experiment was a type 1 gage study where a single operator measured the ten grooves multiple times to assess bias and repeatability. This experiment was repeated daily for seven days for a total of over seven hundred measurements on the same gel cartridge. The operator who performed the study had less than three months of experience using the GelSight system. The second experiment was a GRR study where three operators measured the ten grooves three times each for a total of ninety measurements. The gel cartridge used for the GRR study was different from the cartridge used for the type 1 studies.

(a) Groove depth reference specimen RSP-GT01

(b) GelSight Mobile 0.5X Probe

Figure 1 *(a) Test specimen used in this study, GelSight Part RSP-GT01. The specimen was measured by a lab certified by the National Institute of Standards and Technology.*

#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
9.3	18.0	26.7	35.7	44.3	54.3	63.3	69.3	80.7	85.3

Table 1 *The average groove depths in microns (µm) for the ten grooves on specimen RSP-GT01, serial A005. The measurement uncertainty in the system used to certify the depths is 3 µm.*

All 3D measurements and analysis results were captured using the GelSight Mobile software. The system was calibrated following the automated calibration protocol in the Mobile software.

GROOVE DEPTH SPECIMEN RSP-GT01

The groove depth specimen RSP-GT01 has ten grooves with different depths between the range of 0.010 mm to 0.100 mm. The specimen was measured by East Coast Metrology in Topsfield, MA using a Mahr Profilometer and Hexagon CMM 7.10.7 SF. The measurement uncertainty reported in the calibration certificate is 0.003 mm. The calibration certificate is included at the end of this report.

Each groove on the specimen was measured three times and the results were averaged. The average groove depths for the specimen with serial number A005 is shown in Table 1. The following experiment uses these values as the "true" values in the bias calculations.

TYPE 1 STUDY: ACCURACY

For the first experiment, a single gel cartridge was calibrated using the standard calibration procedure in the GelSight Mobile software. The ten grooves of specimen RSP-GT01 were measured ten times each for a measurement set of 100 measurements. The full measurement set was repeated on seven different days for a total of 700 measurements.

A typical type 1 gage study would have more than ten measurements per part, such as twenty or more. For this study, a secondary goal was to assess measurement stability over time. To keep the number of measurements manageable, the number of measurements per day was limited to ten. For each measurement, the "Offset" tool in the GelSight Mobile software was used to calculate the depth of the groove. The standard protocol of leveling the profile on both sides of the groove and using the software to calculate the minimum point of the groove was followed. The results were exported from the GelSight mobile software in CSV format and loaded into Excel.

From the ten measurements for a groove and the calibrated value in Fig. 2, the standard uncertainty u was calculated as follows:

$$u = \frac{s}{\sqrt{n}}$$

Where s is the estimated standard deviation and n is the number of samples, in this case 10. The expanded uncertainty U is calculated by multiplying the standard uncertainty by a coverage factor k to provide a specific level of confidence, usually 95 or 99 percent [1]. Due to the limited number of measurements being used in the statistical analysis, the coverage factor is chosen from the t-distribution with $n-1$ (e.g., 9) degrees of freedom [2]. The coverage value k_{99} for 99 percent confidence with 9 degrees of freedom in the t-distribution is:

$$k_{99} = 3.25$$

	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
mean	9.3	17.9	26.1	33.8	43.2	50.7	61.2	67.5	76.8	85.5
bias	0.01	0.08	0.61	1.85	1.18	3.66	2.18	1.81	3.89	0.18
uncert.	0.16	0.16	0.24	0.29	0.33	0.43	0.31	0.39	0.68	0.53
U_{99}	0.53	0.51	0.79	0.96	1.09	1.39	1.01	1.26	2.20	1.72
$\boldsymbol{U_g}$	**0.5**	**0.5**	**1.0**	**2.1**	**1.6**	**3.9**	**2.4**	**2.2**	**4.5**	**1.7**

Table 2 *The global uncertainty* $\boldsymbol{U_g}$ *is calculated by summation in quadrature of the bias and 99% confidence level expanded uncertainty* U_{99}*. All values are displayed in microns (μm).*

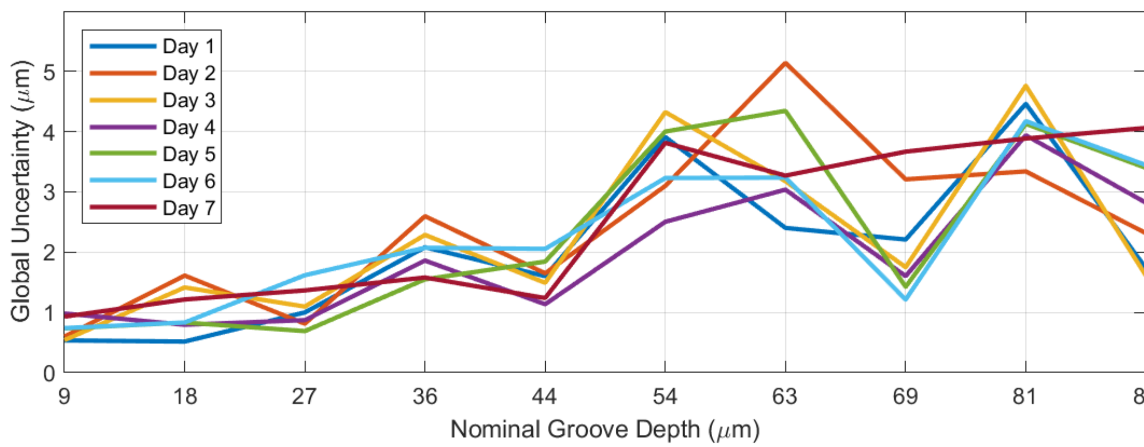

Figure 2 *The global uncertainty for each of the ten grooves across seven consecutive days of measurements. Note that the uncertainty generally increases for increasing feature depth.*

The bias is calculated as the difference between the mean m of the ten measurements and the known value C from the calibration certificate, used as the true value:

$$b = m - C$$

Note that the value from the calibration certificate has its own uncertainty, which is not considered in this analysis. The global uncertainty U_g is calculated by summation in quadrature (square root of sum of squares) of the expanded uncertainty and bias:

$$U_g = \sqrt{{U_{99}}^2 + b^2}$$

The results from the first day of the Type 1 study are shown in Table 2. The mean m, bias b, standard uncertainty, expanded uncertainty U_{99} are used to calculate to the global uncertainty U_g as defined in the formula above.

The global uncertainty results from all seven days of the study are shown in Fig. 2. The day-to-day results are similar in trend with some variability on specific measurements. Note that the measurements were performed without using the image alignment setting (the default configuration) and the measurement process involves manual selection of the profile location.

By comparing the individual components of the global uncertainty as shown in Table 2, it is clear that the measurement bias is the primary contributing factor to some of the larger uncertainties, such as the global uncertainty for groove #9.

In general, the uncertainty grows with the nominal size of the feature. This observation is consistent with the measurement principle of the GelSight Mobile probe. The photometric stereo method estimates the surface normal (slope) at every pixel of the image. The slopes are integrated to calculate the depth and any errors in slope estimation are accumulated into errors in the depth estimation. Larger depths will lead to larger errors due to the accumulation of errors. Fitting a linear model to the average uncertainty values as a function of the nominal groove depths yields a slope of 3.7% of the nominal depth. This study allows us to define a conservative error bound for scratch depth measurements at 4 μm + 4% Z, where Z is the nominal depth. Additional experiments are required to support a smaller error bound.

TYPE 2 STUDY: REPEATABILITY AND REPRODUCIBILITY

For the second experiment, a three-operator gage repeatability and reproducibility study was conducted. The ten grooves were measured three times each by three operators. A single gel cartridge and calibration was used for the entire set of 90 measurements.

The results were exported from the GelSight Mobile software and entered into Minitab. A tolerance of 30 μm was used so that the statistical results could be displayed as both a percentage of the study variance and percent tolerance. Note that the choice of a 30 μm tolerance is arbitrary and usually depends on a customer specification for the process being evaluated. The statistical results for the GRR study are shown in Table 3.

Source	StdDev (μm) (SD)	Study Vr (μm) (6 × SD)	%Study Var (%SV)	%Tolerance (SV/Toler)
Total Gage R&R	**1.3346**	**8.008**	**5.34**	**26.69**
Repeatability	0.4901	2.941	1.96	9.80
Reproducibility	1.2414	7.448	4.97	24.83
C1	1.0976	6.585	4.39	21.95
C1*C2	0.5800	3.480	2.32	11.60
Part-To-Part	24.9487	149.692	99.86	498.97
Total Variation	24.9844	149.906	100.00	499.69

Number of Distinct Categories = 26

Table 3 *Gage repeatability and reproducibility analysis of variance using Minitab software. The process tolerance was set to 30 μm for the analysis.*

SUMMARY

This report describes measurement system analysis studies for quantifying the accuracy and the repeatability of measuring small scratch depths using the GelSight Mobile 0.5X system. The scratch depth reference specimen, part RSP-GT01, is available from GelSight, Inc. so that users can perform their own measurement studies to compare to the results described in this report.

REFERENCES

[1] Bell, Stephanie. *A Beginner's Guide to Uncertainty of Measurement, Issue 2*. Crown, 2001.

[2] Joint Committee for Guides in Metrology, Working Group 1. *Evaluation of measurement data – Guide to the expression of uncertainty in measurement*, JCGM, 2010.

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Depth Gage; Calibration Certification

Customer/Address:	Gelsight Inc. 179 Bear Hill Rd, Suite 202 - Waltham, MA 02451			**P.O. Number:**	GSPO20200322M01
Certificate Date:	March 30, 2020	**Customer Rqrd. Due Date:**	March 30, 2021	**Work Order #:**	14906
Make/Model:	P/N RSP-GT01	**Serial Number:**	A005	**Certificate #/Rev:**	A005/03302020

Reference Standards Traceability

	Make / Model	**Serial Number**	**Calibration Due Date**
Equipment Used	Hexagon CMM 7.10.7 SF	3H007-4	3/23/2021
Equipment Used	OMEGA - Weather Station OM-CP-PRHTemp2000	0115-8106	3/14/2020
Equipment Used	-	-	-

Temperature Start:	67.70 F	**Pressure Start:**	29.926 inHg	**Relative Humidity Start:**	35.00 %
Temperature End:	67.00 F	**Pressure End:**	29.926 inHg	**Relative Humidity End:**	35.00 %
Deviation:	-0.70 F	**Deviation:**	0.000 inHg	**Deviation:**	0.00 %

Certification Results

Process Description: The Mahr Profilometer and Hexagon CMM 7.10.7 SF used to measure the gage fixture. Each position was measured 3 times in different spots specified below.

Measurement Uncertainty (k=2): 0.003 mm

Condition as Received	**Condition Outgoing**
Requires Calibration Certification	*Calibration Certified to the Reported Results*

Calibrated by: Charles Bauer

Authorized by: Lukasz Turolski

Date: March 30, 2020

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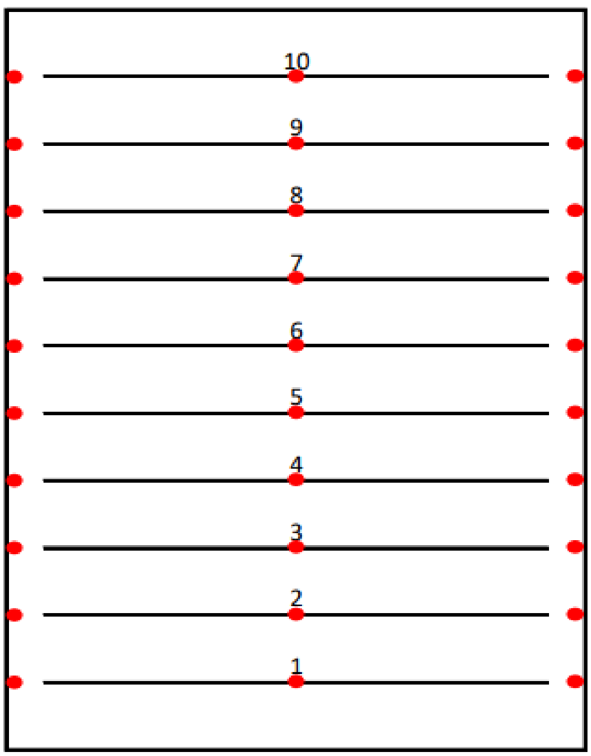
Customer Rqrd. Due Date: March 30, 2021

Work Order #: 14906

Make/Model: P/N RSP-GT01

Serial Number: A005

Certificate #/Rev: A005/03302020



Groove Depths (mm)			
10	0.009	0.010	0.009
9	0.018	0.019	0.017
8	0.028	0.026	0.026
7	0.035	0.036	0.036
6	0.046	0.042	0.045
5	0.056	0.053	0.054
4	0.063	0.063	0.064
3	0.070	0.068	0.070
2	0.080	0.080	0.082
1	0.086	0.086	0.084

 The results of this certification relate only to the items calibrated or tested. The above listed equipment's calibration was certified using standards traceable to the International System of Units (SI) through a National Metrological Institute (NMI) or through an ISO/IEC 17025:2005/17 Accredited Laboratory. Calibration and Measurement Capability represents expanded uncertainties at approximately a 95% confidence level using a coverage factor of k=2.

Calibrated by: Charles Bauer

Authorized by: Lukasz Turolski

Date: March 30, 2020