ODiSI-B Sensor Strain Gage Factor Uncertainty

Abstract Luna has updated our strain sensor calibration tool to support NIST-traceable measurements, to compute both linear and quadratic gage factors, extended the calibration range from 0-5500 to 0-10000 microstrain ($\mu\varepsilon$), and has updated our gage factor uncertainty estimate. Luna measured linear and quadratic Strain Gage Factors of -6.685 $\mu\varepsilon$/GHz and -4.0x10^{-5} $\mu\varepsilon$/GHz^2, and estimates a measurement uncertainty of ± 0.011 $\mu\varepsilon$/GHz in the linear term (0.16%) and ± 1.0x10^{-5} $\mu\varepsilon$/ GHz^2 in the quadratic term.

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1 Introduction

Luna’s Optical Distributed Sensor Interrogator (ODiSI) instruments use swept-wavelength interferometry to produce a high spatial resolution map of the sensor Rayleigh scatter pattern. By comparing a sensor measurement Rayleigh scatter pattern to a reference pattern, the scatter pattern optical frequency shift as a function of sensor length can be determined and scaled to a strain or temperature change. This Engineering Note details the method for determining the strain calibration coefficients (or strain gage factors), estimates the degree of uncertainty associated with the gage factor values, and presents data on the variability of strain gage factor measurements within a single fiber spool. Since Luna originally published the first revision of this document in 2015 Luna has made substantial improvements to the calibration fixture and has implemented a quadratic in place of a linear curve fit, resulting in reduced strain gage factor uncertainties and improved measurement traceability.

2 Strain Calibration Procedure and Fixture

The strain gage factors (linear and quadratic terms) of a particular sensor may be calibrated in a straightforward manner by recording the optical frequency spectral shift for a known applied strain and computing the best quadratic curve fit the frequency response. A diagram of the fixture used to apply a known strain to a fiber segment is shown in Figure 1. A picture of the fixture Luna is shown in Figure 2. The fixture consists of a linear translation stage with micrometer actuator at one end of a steel rail and another movable stage at the far end of the rail. The fixture is mounted in an aluminum box with transparent lid that is closed during operation to keep temperature stable and shield the fiber from air currents. Optical fiber clamps are positioned on both stages. The fiber is inserted into the clamps and the micrometer is used to apply extensive strain to the fiber segment. The micrometer is then stepped through a series of displacements, with the optical frequency shift $\Delta\nu$ of the Rayleigh scatter for the sensor portion between the clamps recorded with an ODiSI-B unit for each step. The strain is calculated by dividing the displacement ΔL by the initial gap between the clamps of L. A least squares fit is performed to find a quadratic expression for strain ε as a function of optical frequency shift $\Delta\nu$. Sample calibration data with fit results and a plot of the fit residuals from Luna's strain calibration software utility is shown in Figure 3.

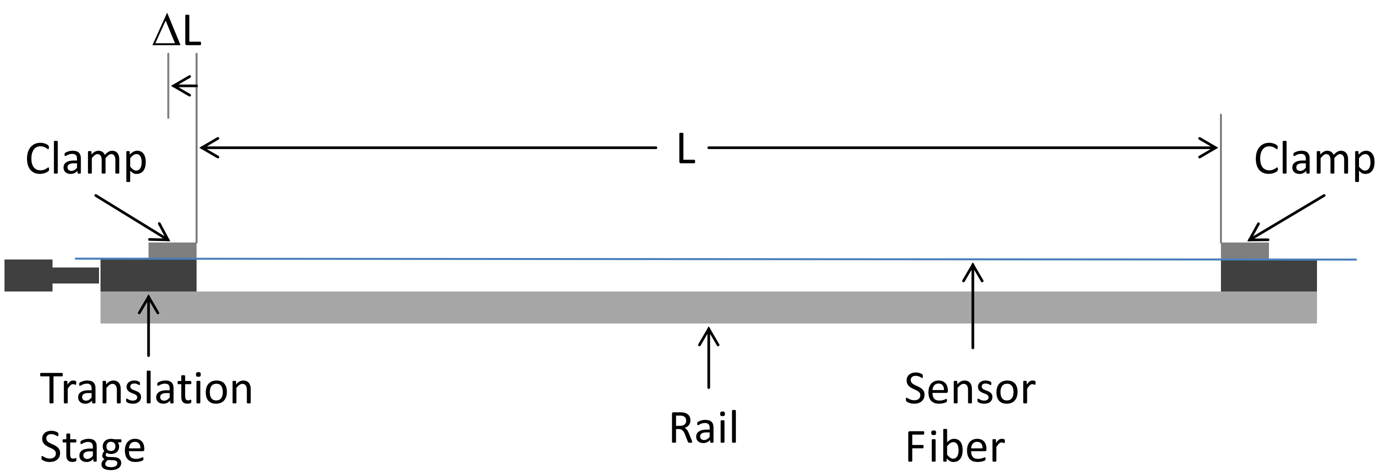

Figure 1. Diagram of optical fiber strain gage factor calibration fixture.

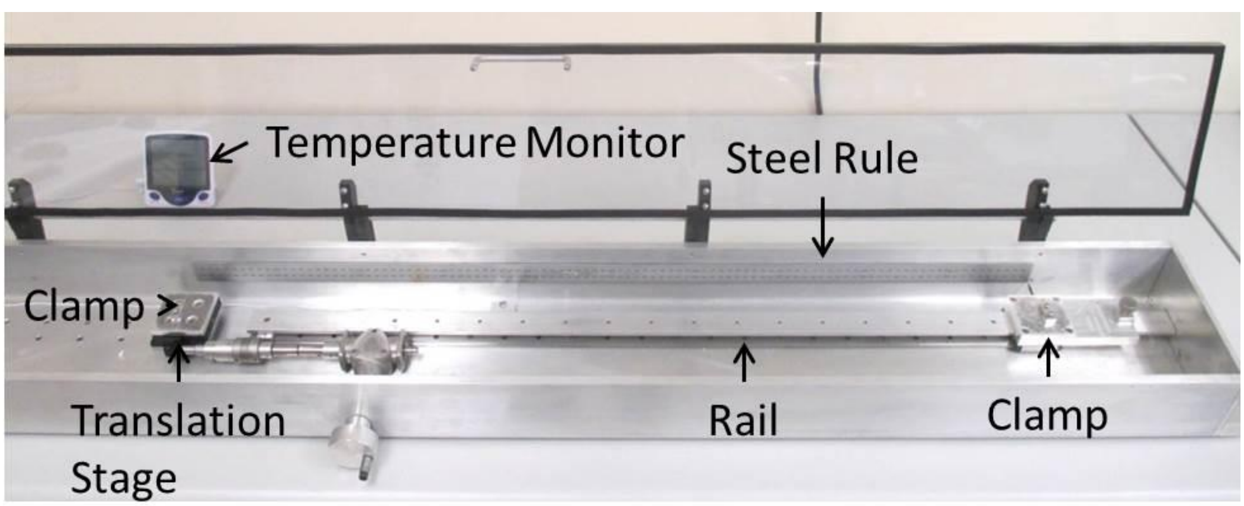

Figure 2. Picture of optical fiber strain gage factor calibration fixture.

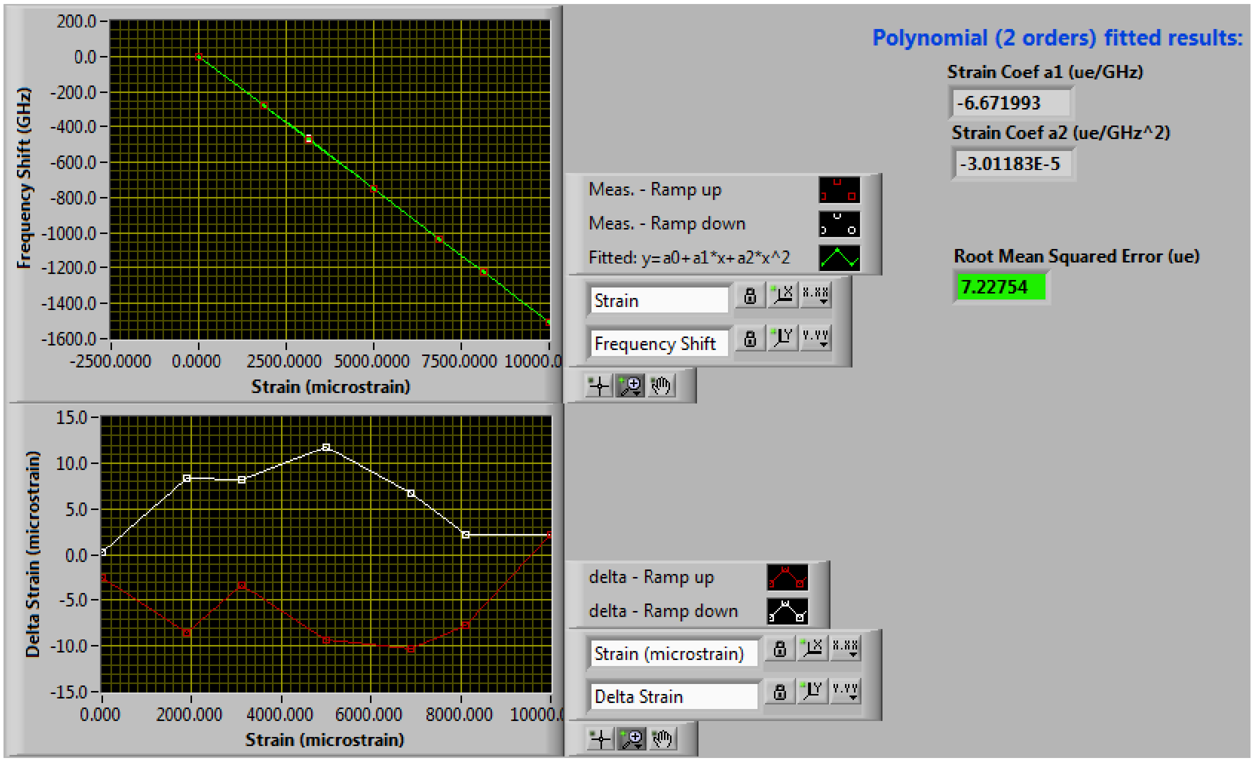

Figure 3. Top graph: least squares fit to optical frequency shift vs. strain data; Bottom graph: fit residuals are typically ≤ 0.1% of the full strain range.

To improve quality of the calibration, the following “best practices” were established:

- The micrometer displacement ΔL is cycled at least 5 times to a displacement at least 120% of the highest test level, so that if the fiber slipped position in the clamps due to the loading force induced by the displacement, such slippage was likely to happen during the cycling stage and not during the gage factor measurement.
- The optical fiber segment is pre-strained by roughly 100 $\mu\varepsilon$ to insure that no measurements are taken while the fiber is untensioned and the effects of gravity on the horizontal fiber orientation don’t influence the low-strain results.
- The test data was taken in a ramp up from low to high strain, then a ramp back down from high to low strain. If the fiber slips in the clamps, or if there is any other error that causes a unidirectional drift in the optical frequency shift readings, the error will be readily apparent in the fit residual plot as a difference in optical frequency shift residuals between the ramp up and ramp down. In Figure 3 the difference between the start and end Frequency Shift values was under 3 $\mu\varepsilon$ for a 10000 $\mu\varepsilon$ excursion, and the Root-Mean_Square of the strain residual to the curve fit was 7.2 $\mu\varepsilon$, less than 0.1% of the test range, representing a level of hysteresis that well below other sources of gage factor uncertainty. Calibrations with strain fit residual RMS values above 0.2% of the test range are rejected.
- The temperature of the rail was monitored with a thermistor and monitor unit with NIST-traceable calibration while acquiring measurements so that the error caused by thermal expansion of the rail is known.

- The sampling spacing of ΔL is set to be one full revolution of the micrometer dial to minimize errors associated with periodic deviations in the micrometer screw thread.

NIST traceability for the strain computation is achieved by using a calibrated steel rule to measure L and a calibrated micrometer head to induce ΔL; the calibration of both rule and micrometer is performed using apparatuses at the rule and micrometer manufacturers that are traceable to NIST standards. The steel rule and micrometer calibration certificates are presented in the Appendix of this document. Further, the ODiSI-B unit optical frequency is calibrated against a HCN gas cell reference with every scan. All ODiSI gas cell references are compared to a NIST standard gas cell to assure traceability of the optical frequency shift measurement.

3 Strain Gage Factor Uncertainty

The primary sources of uncertainty in the strain gage factors are the uncertainties in the measured values ΔL and L used to calculate strain and in the spectral shift calculation . Strain ε is calculated by dividing the displacement ΔL by the initial gap between the clamps of *L*:

$$\varepsilon = \frac{\Delta L}{L} \ . \tag{1}$$

The Rayleigh scatter optical frequency shift $\Delta\nu$ of the sensor fiber is measured for the segment of fiber under strain using an ODiSI-B instrument.

The strain gage factors γ_0, γ_1 and γ_2 are calculated by performing a quadratic least squares fit of strain ε to optical frequency shift $\Delta\nu$, expressed as:

$$\varepsilon = \gamma_0 + \gamma_1 \Delta\nu + \gamma_2 \Delta\nu^2 . \tag{2}$$

While the zero-order term γ_0 is useful for fitting purposes, it generally does not exceed a few $\mu\varepsilon$ in practice; further strain is a relative value evaluated between measured and reference states; for these reasons γ_0 is not recorded. The third term in Equation (2) is also quite small compared to the second; for a total strain range of 10,000 $\mu\varepsilon$ the quadratic component typically reaches a maximum value of less than 100 $\mu\varepsilon$ in magnitude.

The uncertainty of the strain gage factor γ_1 as a function of the uncertainty of the components of the calculation above is expressed as:

$$u_{\gamma_1} = \sqrt{\left(\frac{\partial \gamma_1}{\partial \Delta L}\right)^2 u_{\Delta L}{}^2 + \left(\frac{\partial \gamma_1}{\partial L}\right)^2 u_L{}^2 + \left(\frac{\partial \gamma_1}{\partial \Delta \nu}\right)^2 u_{\Delta\nu}{}^2} \ . \tag{3}$$

In the above expression we have dropped terms associated with the uncertainty in γ_0 or γ_1 because, as discussed above, the linear term in the right hand side of Equation (2) dominates, so differences in the constant and quadratic terms have little effect on the slope.   Also, we can simplify the final expression for the uncertainty in γ_1 using the approximation:

$$\gamma_1 \cong \frac{\Delta L}{L \Delta \nu} \tag{4}$$

Substituting the expressions in equations (1), (2) and (4) into equation (3) we find:

$$u_{\gamma_1} = |\gamma_1| \sqrt{\left(\frac{u_{\Delta L}}{\Delta L}\right)^2 + \left(\frac{u_L}{L}\right)^2 + \left(\frac{u_{\Delta \nu}}{\Delta \nu}\right)^2} \; . \tag{5}$$

Thus if we estimate the uncertainties associated with the inputs ΔL, L and $\Delta\nu$ we can use Equation (5) to calculate the expected uncertainty in the strain gage factor γ_1.
We can write a similar expression to define the uncertainty of strain gage factor γ_2:

$$u_{\gamma_2} = \sqrt{\left(\frac{\partial \gamma_2}{\partial \Delta L}\right)^2 u_{\Delta L}{}^2 + \left(\frac{\partial \gamma_2}{\partial L}\right)^2 u_L{}^2 + \left(\frac{\partial \gamma_2}{\partial \Delta \nu}\right)^2 u_{\Delta \nu}{}^2 + \left(\frac{\partial \gamma_2}{\partial \gamma_1}\right)^2 u_{\gamma_1}{}^2} \; . \tag{6}$$

This time we need to include a term that includes $\delta\gamma_2$ / $\delta\gamma_1$ because a small change in the slope fit can cause a large change in the estimated quadratic fit term. Substituting the expressions in equations (1), (2) and (4) into equation (6) we find:

$$u_{\gamma_2} = \sqrt{\left(\frac{\gamma_1}{\Delta \nu}\right)^2 \left(\left(\frac{u_{\Delta L}}{\Delta L}\right)^2 + \left(\frac{u_L}{L}\right)^2 + \left(\frac{u_{\Delta \nu}}{\Delta \nu}\right)^2\right) + \left(\frac{u_{\gamma_1}}{\Delta \nu}\right)^2} = \sqrt{2}\left|\frac{u_{\gamma_1}}{\Delta \nu}\right| \; . \tag{7}$$

Thus the uncertainty of the quadratic gage factor can be easily calculated from the uncertainty of the linear gage factor.

Next we will estimate the uncertainty of each component of the calculation.

Displacement ΔL Uncertainty:

The uncertainty of ΔL is dominated by the accuracy of the micrometer actuator for the linear stage, how accurately a certain position can be set by the test engineer, and by the change in rail length due to any temperature change during the measurement. The micrometer actuator is manufactured by Mitutoyo (model 148-801), has 13 mm travel, with 0.5 mm per revolution, and graduations of 10 μm. The calibration certificate indicates measured errors were -1.8 to +0.9 μm over the travel range, with a 1 μm measurement uncertainty, so we will use a position accuracy estimate of ±3 μm over the range of travel. We estimate the set point accuracy of the micrometer to also be ±3 μm. The rail temperature is monitored with a thermocouple probe and monitor unit with 0.1°C resolution and 1°C accuracy (Thomas Scientific model number 1226L99); the largest temperature change we have observed during the 10-15 min it takes to collect the data is 0.1°C. Given L = 1000 mm, a thermal expansion coefficient of 16.0 ppm/°C for 316 stainless steel, and a temperature change uncertainty of 0.1°C, we calculate an uncertainty in the rail length of 0.0016 mm. The total uncertainty when setting the micrometer at two positions and measuring a displacement ΔL is:

$$u_{\Delta L} = \sqrt{0.003^2 + 0.003^2 + 0.003^2 + 0.003^2 + 0.0016^2}\,mm = 0.0062mm \quad . \tag{8}$$

We also considered compression of the rail in response to force equal and opposite that applied to the fiber by the micrometer. Because the rail has a much larger cross sectional area compared to the fiber, we estimate the error in ΔL to be less than 1% of the uncertainty estimated in equation 5, so we will neglect this term.

Strain Application Length *L* Uncertainty:

The uncertainties in measuring *L* are dominated by the error in determining where the clamps grip the fiber, and in the accuracy of the steel rule used to measure the gap. We estimate a ±1 mm uncertainty in the estimate of where the clamps grip the fiber, and ±0.25 mm accuracy of the steel rule over its 1 m length. Thus, assuming both error sources apply to the position measurement of each clamp, we estimate the uncertainty in the measurement of L to be:

$$u_L = \sqrt{1^2 + 1^2 + 0.25^2 + 0.25^2}\,mm = 1.46mm \quad . \tag{9}$$

Optical Frequency Shift $\Delta\nu$ Uncertainty:

The ODiSI-B center wavelength and sweep range are set by calibrating to the onboard HCN gas absorption cell. The wavelength accuracy is conservatively estimated at 1.5 pm (0.1875 GHz), and the wavelength scale accuracy is similarly estimated at 0.005%. For the data set depicted in Figure 3, there is a maximum optical frequency shift of 1500 GHz, so the scale accuracy limit would imply a 0.075 GHz uncertainty.

The combined optical frequency shift uncertainty when measuring the Rayleigh scatter spectral shift between a reference and test state is:

$$u_{\Delta\nu} = \sqrt{0.1875^2 + 0.1875^2 + 0.075^2}\,GHz = 0.276GHz\,. \tag{10}$$

Next, we can use Equations (5) and (7) to calculate the uncertainty of the linear and quadratic gage factors from the uncertainty of each component of the calculation.

Total Linear Strain Gage Factor γ_1 Uncertainty:

Equation (5) gives the expected uncertainty for the linear gage factor for a pair of measurements for two micrometer displacements. If we only consider the case in which we calculate the gage factor from the two points with the largest difference in displacement, the total strain gage factor uncertainty is estimated from Equation (5) to be:

$$u_{\gamma_1} = 6.6853\sqrt{\left(\frac{0.0062}{10}\right)^2 + \left(\frac{1.46}{1000}\right)^2 + \left(\frac{0.276}{1500}\right)^2}\ \frac{\mu\varepsilon}{GHz} = 6.6853 * 0.00160\frac{\mu\varepsilon}{GHz} = 0.0107\frac{\mu\varepsilon}{GHz} \quad (11)$$

Performing a least squares linear regression with seven points (as shown in Figure 3) will lead to lower uncertainty than only using the two points with the largest displacement, so Luna expects this uncertainty estimate to be conservative.

The largest term in Equation (11) relates to the gage length L uncertainty. Compared to the previous test fixture, we are using a steel rule with improved accuracy to measure the gage length, and the new fixture supports a longer gage length (690 mm previously vs. 1000 mm now). These improvements have resulted in a reduction in the uncertainty of the linear strain gage factor from 2.7% to 1.6%.

Total Quadratic Strain Gage Factor γ_2 Uncertainty:

Equation (7) relates the uncertainty in the quadratic gage factor to the uncertainty in the linear gage factor. If we use the appropriate numbers from our calibration station, we find:

$$u_{\gamma_2} = \sqrt{2}\,\frac{0.0107}{1500}\,\frac{\mu\varepsilon}{GHz^2} = 1.01x10^{-5}\,\frac{\mu\varepsilon}{GHz^2}\,. \quad (12)$$

As with the linear gage factor uncertainty, Luna regards Equation (12) to be a conservative estimate.

4 Strain Gage Factor Variability

Luna's sensor fiber is delivered by the manufacturer on spools with length of typically several hundred to several thousand meters apiece. We set aside fiber segments (generally from the beginning and end of the spools, at a minimum) for the purpose of characterizing these fiber segments for strain and temperature response. Testing is non-destructive, and these spool segments are archived and are available for further testing if warranted. Sensors manufactured from a given spool are assigned strain gage factors that are averaged over the test segments for that spool. For a spool delivered in the 3rd quarter of 2015 Luna set aside additional fiber segments from multiple locations along the spool length as the spool was consumed. Strain gage factor calibration results from both the 2015 and 2016 fixtures, from 8 sensor fiber segments, are shown in Table 1. Because we have changed the calibration fit from linear to quadratic and are calibrating over a broader strain range, the linear gage factors between the two measurements are not directly comparable. To compensate for these factors, we can calculate an equivalent linear gage factor from the quadratic components as follows:

$$\gamma_{1,Equivalent} = \frac{\partial\varepsilon}{\partial\Delta\nu} = \gamma_1 + 2\gamma_2\Delta\nu\,. \quad (13)$$

Equation (13) should be calculated for the optical frequency shift value at the middle of the calibration range of the 2015 calibration (at 375 GHz); this result is tabulated in the final column of Table 1.

Table 1. Strain Gage Factor Measurements on Fiber Segments from a Single Spool

Test Segment Designation	2015 Fixture	2016 Fixture			
	γ_1 (με/GHz)	γ_1 (με/GHz)	γ_2 (με/GHz^2)	Residual RMS Strain (με)	Equiv. 2015 γ_1 (με/GHz)
OFD00076E_OutsideEnd	-6.6231	-6.6929	-4.65E-05	6.6	-6.6557
OFD00076E_4006	-6.6130	-6.6776	-3.89E-05	6.0	-6.6465
OFD00076E_4007	-6.6205	-6.6885	-4.96E-05	6.0	-6.6488
OFD00076E_4008	-6.6190	-6.6984	-4.95E-05	7.9	-6.6588
OFD00076E_509m	-6.6144	-6.6825	-3.59E-05	9.5	-6.6538
OFD00076E_656m	-6.6076	-6.6848	-3.64E-05	7.0	-6.6557
OFD00076E_753m	-6.6084	-6.6721	-3.02E-05	7.1	-6.6479
OFD00076E_InsideEnd	-6.6192	Broken Termination			
Mean	-6.6157	-6.6853	-4.10E-05	7.2	-6.6525
Standard Deviation	0.0057	0.0083	7.02E-06	1.1	0.0043

We observe a difference in the mean equivalent values for the linear gage factor γ_1 from current fixture versus the 2015 fixture value of 0.0368 με/GHz. This difference exceeds the 2015 and 2016 linear gage factor uncertainty estimates of ± 0.0179 and ± 0.0107 με/GHz. The difference is likely due to mis-scaling of the 2015 gage length L or displacement ΔL measurements because of a systematic error in the steel rule or micrometer we used in the 2015 fixture. Since we have better documentation of the steel rule and micrometer calibration for the 2016, we are much more confident in the new results.

The standard deviation of the values for the strain gage factors γ_1 and γ_2 noted in Table 1 are below the uncertainty estimates in Equations (11) and (12), indicating that the strain gage factors are not likely to vary by more than their uncertainty estimates along a 1 km spool length. Also, the consistency of the strain gage factor results across the spool gives us some confidence that our uncertainty estimates are not too low.

With the previous strain calibration fixture, Luna completed multiple strain gage factor measurements on fiber segments from 5 separate spools. This data showed that the linear strain gage factor results for the other 4 spools were within 0.2% of spool OFD00076E1, shown in Table 1. Luna has not yet completed calibrating fiber segments from additional spools with the new test fixture, but we expect to find similar levels of variation, and we will update this Technical Note with additional test results when they become available.

5 Strain Gage Factor Summary

In this Technical Note we have described the new strain gage factor calibration fixture and test procedure, estimated a measurement uncertainty, and have demonstrated variation in gage factor measurement spanning seven measurements over one spool from our fiber manufacturer that are generally within our uncertainty estimate. The strain gage factors for spool OFD00076E1 are of -6.685 $\mu\varepsilon$/GHz and $-4.0\text{x}10^{-5}$ $\mu\varepsilon/GHz^2$, and we estimate a measurement uncertainty of ± 0.011 $\mu\varepsilon$/GHz in the linear term (0.16%) and ± $1.0\text{x}10^{-5}$ $\mu\varepsilon/ GHz^2$ in the quadratic term. Measurements with the previous strain calibration fixture indicated that the results for the linear strain gage factor for this spool are within 0.2% of 4 other spools. Until Luna compiles further measurements, the values above represent Luna's best estimate of the strain gage factors to use if the sensor source spool is unknown. Luna has established sensor manufacturing procedures that associate the strain gage factors of a sensor with the measurements from its source spool; these values are included in the sensor calibration file recorded on the USB drive shipped with each sensor. Measurements with the current strain calibration fixture are made over a 0-10000 $\mu\varepsilon$ range, compared to the 0 to 5500 $\mu\varepsilon$ range of the previous fixture. NIST-traceable calibration of the steel rule used to measure the fixture gage length, of the micrometer used to measure the fixture displacement, and of the absorption gas cell to measure frequency shift assures full traceability of the strain calibration. Since measurement variation over the length of a single spool and over multiple spools showed less variation than the uncertainty estimate, Luna is confident that the uncertainty estimate is conservative, and that sensor fiber manufacturing variation routinely yields sensors with a real gage factor variation within this uncertainty limit. Luna plans to continue to add to the strain gage factor measurement data base as we manufacture new sensors from new shipments from our fiber manufacturer, to track gage factors corresponding the spool each sensor was manufactured from, and to refine and upgrade the strain calibration test fixture better accuracy.

Appendix: Steel Rule Certification Letter

Starrett

ATTN: QUALITY ASSURANCE
MCMASTER-CARR SUP CO
1901 RIVERSIDE PARKWAY
DOUGLASVILLE, GA. 30135

May 27, 2016

STANDARD LETTER OF CERTIFICATION

THIS IS TO CERTIFY THAT THE ITEM LISTED BELOW MEETS THE REQUIREMENTS OF ACCURACY OF THE APPLICABLE SPECIFICATION ON DATE OF SHIPMENT.

STANDARDS AND EQUIPMENT USED FOR INSPECTION ARE CERTIFIED ACCURATE WITH REFERENCE TO 68 DEGREES F, TRACEABLE TO MASTER STANDARDS AT THE NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY, GAITHERSBURG, MD. CALIBRATION IS PERFORMED WITH TRANSFER STANDARDS WHICH ARE PROGRESSIVELY MORE ACCURATE IN THE ORDER OF 4 TO 1.

WE ATTEST THAT OUR MEASURING AND TEST EQUIPMENT, AND CALIBRATIONS PERFORMED ON THE ITEM(S) LISTED BELOW, ARE IN ACCORDANCE WITH ISO/IEC 17025, ANSI/NCSL Z540-1, ISO GUIDE 25 AND MIL-STD-45662A.

YOURS VERY TRULY,
THE L.S. STARRETT COMPANY

Susan Mason (for)

DEXTER J. CARLSON,
CHIEF INSPECTOR

YOUR ORDER NO:	QA 95571190
STARRETT ORDER NO:	2553323
CATALOG NO:	C636-1000mm RULE
SERIAL NO:	16221029
N.I.S.T. TEST NO:	683/282436
SPECIFICATION:	GGG-R-791H

~ **Accuracy for Rules 0- 72":** End grind to the first / last inch line, 1" (+/-.0025")
From the Zero "0" end of the scale to graduations located in the range of: first 6" (+.004"/-.0035"),
6"-12" (+.005"/-.0035"), 12"-18" (+.006"/-.0035"), 18"-36" (+.007"/-.0035"), 36"-48"(+.010"/-.0050"),
48"-60"(+.011"/-.0060"), 60"-72"(+.012"/-.0070)

Scale Accuracy: **For Rules 0-1000mm:** End grind to the first / last 25 mm line, 25mm (+/-.065mm)
From the Zero "0" end of the scale to graduations located in the range of: first 150mm (+.100 /-.090)
150 - 300mm (+.150 /-.090), 300 - 600mm (+.200 /-.090), 600 - 1000mm (+.250 /-.110),
Over All Length: 150mm +.100 /-.050 300mm +.150 /-.090 450mm +.200 /-.090 600-1000mm +.250 /-.110

The estimated uncertainties reflect a Confidence Probability of approximately 95%.
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Athol, MA 01331-1915 - USA
Tel.: 978 249-3551 / Fax: 978 249-8495
www.starrett.com

Appendix: Steel Rule Calibration Certificate

Starrett

THE L. S. STARRETT COMPANY
CALIBRATION LABORATORY
121 Crescent Street • Athol, MA 01331-1915
Telephone (978) 249-3551 • Fax (978) 249-4101

ACCREDITED
Calibration Lab
Cert. No. 760.01

ATTN: QUALITY ASSURANCE
LUNA INNOVATIONS
3155 STATE STREET
BLACKBURG, VA 24060
ATTN: STEVE KREGER

CAL DATE: 10/20/15
TEMP IN F: 69 Degrees
HUMIDITY: 45%

CALIBRATION CERTIFICATE

THIS IS TO CERTIFY THAT THE ITEMS LISTED BELOW MEETS THE REQUIREMENTS FOR ACCURACY FOR THE APPLICABLE SPECIFICATION AND COMPLIES WITH THE TECHNOLOGICAL REQUIREMENTS OF THE CUSTOMER'S REFERENCED PURCHASE ORDER ON THE DATE OF SHIPMENT. STANDARDS AND EQUIPMENT USED FOR INSPECTION ARE CERTIFIED ACCURATE WITH REFERENCE TO 68 DEGREES F. TRACEABLE TO MASTER STANDARDS AT THE NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY,GAITHERSBURG,MD WE ATTEST THAT OUR MEASURING AND TEST EQUIPMENT AND CALIBRATIONS PERFORMED ON THE ITEM (S) LISTED BELOW, ARE IN ACCORDANCE WITH ISO 17025-2005 AND ANSI/NCSL Z-540-1
ANY NUMBER OF FACTORS MAY CAUSE THE CALIBRATED ITEM TO DRIFT OUT OF CALIBRATION BEFORE THE SPECIFIED NEXT CAL DATE. IT SHALL BE THE RESPONSIBILITY OF THE END USER TO ENSURE THAT THE CALIBRATED ITEM REMAINS WITHIN CALIBRATION FOR THE DURATION OF THE END USER'S ASSIGNED CALIBRATION INTERVAL. THE REPORTED UNCERTAINTY IS BASED ON SIMPLE ACCEPTANCE WHICH IS DOCUMENTED IN THE B89.7.3.1-2001 AND HAS NOT BEEN USED TO ADJUST THE TOLERANCE FOR THE CALIBRATED ITEM.

STARRETT ORDER NO: 2490991 CUSTOMER ORDER NO: STEVE KREGER

MFG: STARRETT CAT NO: C635-1000mm STEEL RULE S/N:15413055

WAS INSTRUMENT OPERABLE AND WITHIN CALIBRATION WHEN RECEIVED? YES
IMPACT OF REJECT: NEW

CAL. PROCEDURE NO: 259

REQUIRED ACCURACY: For Rules 0-1800mm: End grind to the first / last 25 mm line, 25mm (+/-.065mm)
From the Zero "0" end of the scale to graduations located in the range of: first 150mm (+.100/-.090)
150 - 300mm (+.150/-.090), 300 - 600mm (+.200/-.090), 600 - 1000mm (+.250/-.110).

SPECIFICATIONS: GGG-R-791H CALIBRATED BY: # 8570

S/N OF STANDARDS USED. 40-257 CAL. DATE: 9-18-15 NEXT CAL: 9-18-16

N.I.S.T. TEST REF: 683/282436 CAL. DATE: 8-2-12 NEXT CAL: 8-2-17

LIMITATION / COMMENT: REF: GRAINGER SOURCING PO# 4814523756

SEE DATA ON PAGE 2

DEXTER J. CARLSON, CHIEF INSPECTOR, Kathleen M Polana for DC
ESTIMATED UNCERTAINTY is +/- 8.3 microns, with k=2. The uncertainties reflect a Confidence Probability of approximately 95%
This Certificate or Report shall not be reproduced except in full, without the written approval of the Chief Inspector of The L.S. Starrett Co

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ES

Appendix: Micrometer Calibration Certification

Mitutoyo

Certificate of Calibration

ACCREDITED
CERT. #0750.0[illegible]
CALIBRATION

NAME & ADDRESS: THOR LABS INC
NEWTON, NJ 07860

CODE NUMBER: 148-801

SERIAL NUMBER: 5003040

I.D. No.: N/A

CONDITION: NEW

DESCRIPTION: MICROMETER HEAD

CONTROL NO.: 827707

RANGE: 0 - 13 mm

RANGE (MM)	FORWARD ERROR (µm)	REVERSE ERROR (µm)
0.0	0.00	-1.20
3.0	-1.20	-1.40
5.0	0.00	-1.80
7.5	0.90	-1.20
10.0	-0.10	-0.90
13.0	-0.60	-

Measurement Uncertainty (k=2): ± 1 µm.
This uncertainty represents an expanded uncertainty expressed at approximately the 95% confidence level using a coverage factor of k=2.
Procedure Used: CLTM-11 REV. E "As-found" = "As-left" data

This is to certify that the gages listed have been compared with Mitutoyo Masters, which are traceable to the National Institute of Standards and Technology, at a measuring temperature of 20° C ± 0.5° C, RH 30% to 50%.

Calibrated by: Levelle Johnson, Calibration Technician Date: NOVEMBER 02,2015 N.I.S.T. Number: Test No. 683/283809-13

THIS CERTIFICATE SHALL NOT BE REPRODUCED EXCEPT IN FULL WITHOUT THE WRITTEN PERMISSION OF THE MITUTOYO CALIBRATION LAB.

MITUTOYO AMERICA CORP. PRIMARY STANDARDS LAB., 965 CORPORATE BLVD., AURORA, IL 60502
PHONE (888) 648-8869 FAX (630) 978-6477

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Product Support Contact Information

Lightwave Division:	3155 State Street Blacksburg, VA 24060
Main Phone:	1.540.961.5190
Toll-Free Support:	1.866.586.2682
Fax:	1.540.961.5191
Email:	solutions@lunainc.com
Website:	www.lunainc.com

Specifications of products discussed in this document are subject to change without notice. For the latest product specifications, visit Luna's website at www.lunainc.com.

Technical Note EN-FY1602

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