Optical Backscatter Reflectometer Length Measurement Accuracy

Contents

1 Introduction

Luna's Optical Backscatter Reflectometers (OBRs) operate on a principle know as Optical Frequency Domain Reflectometry (OFDR). In OFDR, a tunable laser is used as a source for an interferometer formed by a reference arm internal to the instrument and a measurement arm that is connected in line with the Device Under Test (DUT).[1] As the laser is swept through an optical frequency range, interference fringe data is collected and analyzed. A Fourier Transform is applied to the raw interferometer fringe data to produce a record of reflection events observed as a function of the optical time delay which occurs when light propagates from the instrument to the reflection event and back. This Fourier Transform relationship between the optical frequency domain, in which the raw data is collected, and the optical time-of-flight domain, in which the results are presented, is integral to the determination of the OBR length accuracy: length measurement accuracy is primarily constrained by knowledge of the optical frequency range of the acquisition scan.

2 Length Measurement

The time delay increment $\delta\tau$ between adjacent data points in the optical time delay domain is simply given by the inverse of the optical frequency scan range $\Delta\nu$.

$$\delta\tau = \frac{1}{\Delta\nu} \tag{1}$$

The optical time delay between two reflection events is computed by using cursors to measure the x-axis index separation between the reflection amplitude peaks corresponding to each event and multiplying index difference by $\delta\tau$. Length is calculated in the same maner, but using a length increment δl instead of $\delta\tau$. The length increment δl between successive data points is found by assuming a group index of refraction n and scaling the time delay to length.

$$\delta l = \frac{c \cdot \delta\tau}{2n} \tag{2}$$

In the above equation, c is the vacuum speed of light, 2.998 x 10^8 m/s.

In all of Luna's OFDR-based instruments, a laser monitor interferometer is used to sample the measurement interferometer fringe data in equal units of optical frequency. The optical frequency scan range $\Delta\nu$ is the number of sample points S times the laser monitor frequency increment $\delta\nu_{lm}$.

$$\Delta\nu = S \cdot \delta\nu_{lm} = \frac{S}{\tau_{lm}} \tag{3}$$

For example, if the optical time delay between paths in the laser monitor interferometer is τ_{lm} = 400 ns, and the measurement interferometer data is sampled after each full laser monitor interferometer fringe is detected, the measurement interferometer is sampled in $\delta\nu_{lm}$ = 2.5 MHz increments, and a data record 2,000,000 points long would span $\Delta\nu$ = 5 THz of optical frequency. When the data collected over a 5 THz span is Fourier Transformed into the optical time domain, the time domain increment would be $\delta\tau$ = 0.2 ps, equivalent to a length increment of about δl = 20 μm for n = 1.5. Because we know exactly how many data points are sampled in a given scan, precise knowledge of the laser monitor interferometer delay τ_{lm} is crucial to accurately determining the scan optical frequency range $\Delta\upsilon$ and the time delay increment $\delta\tau$, which is used as the basis for all length measurements.

On the OBR 4600 and 5T-50 the laser monitor interferometer delay is corrected during the calibration process using a gas absorption cell on-board the instrument. Calibrations are initiated by the user; Luna suggests that calibrations be performed at least daily for best results. The OBR 4200 does not have an on-board gas cell, so laser monitor calibrations can only be performed at Luna's manufacturing facility. During the laser monitor calibration process, the gas cell spectrum is acquired along with the laser monitor interferometer signal, and the center optical frequency of each gas cell absorption peak is calculated and plotted against the known gas cell line optical frequencies. A least squares linear regression is applied to obtain the slope and offset. If there has been no change in the laser monitor interferometer delay since the last calibration, the slope of the line fit will be one and the offset will be zero; if the slope is not one, the laser monitor delay is rescaled appropriately, and if the offset is not zero, the center frequency of the scan is adjusted to compensate. Thus the length scaling accuracy is dependent on the quality of the gas cell absorption line center frequency line fit.

The expression for the slope of a least squares regression of the form $y = a + bx$ for N (x,y) points is the following, where x and y are the independent and dependent variables, respectively, and the horizontal bars indicate the average values of each variable:

$$b = \frac{\frac{1}{N}\sum_i x_i y_i - \overline{x}\,\overline{y}}{\frac{1}{N}\sum_i x_i^2 - \overline{x}^2} \tag{4}$$

If we assume the uncertainties of the tabulated gas cell line center frequency (x-axis) values are small compared to the uncertainties of the measured (y-axis) values and can be neglected, and that the uncertainty of each measured value is independent of each other, we can propagate the uncertainty of the y values $u_{y,i}$ to the uncertainty in the slope u_b using the Kline-McClintock relationship:

$$u_b^{\ 2} = \sum_i \left(\frac{\partial b}{\partial y_i} u_{y,i} \right)^2 \tag{5}$$

If we further assume that the uncertainty magnitude of each measured gas cell line is the same, applying equation (5) to the equation for b yields a compact result.

$$u_b = u_y \frac{\sqrt{\sum_i \left(\bar{x} - x_i\right)^2}}{\sum_i x_i^2 - N\bar{x}^2} \tag{6}$$

If we consider a 20 nm laser scan centered at 1546.7 nm, there are 26 HCN gas cell lines in the scan range (see Reference 2 for a discussion of gas cell line frequency values and accuracies). If the uncertainty of each measured line is 0.1 pm = 0.125 GHz, we calculate a slope uncertainty of u_b = 34 x 10^{-6}, meaning that immediately after calibration we expect a length scaling uncertainty of 34 microns per m. Luna considers this level of uncertainty to be a worst-case scenario, and that typical laser monitor delay calibration accuracy, and thus length accuracy, will be much better in practice.

In between calibrations, the optical time delay of the laser monitor may drift due to temperature changes within the optical network housing. The normalized change in laser monitor time delay $\Delta\tau/\tau$ for a change in ambient temperature of the instrument ΔT is given by:

$$\frac{\Delta\tau}{\tau} = \frac{1}{l}\frac{\partial l}{\partial T}\Delta T + \frac{1}{n}\frac{\partial n}{\partial T}\Delta T = \left(\alpha_l + \alpha_n\right)\Delta T \tag{7}$$

The quantity α_l is the thermal expansion coefficient of the fiber, approximately 0.55 x 10^{-6} per °C for fused silica; the quantity α_n is the thermo-optic coefficient, approximately 8.6 x 10^{-6} per °C for germanium-doped core fused silica optical fiber.[3] The DUT also experiences a similar length response to temperature; this is important to keep in mind when comparing length measurements made on the same DUT over time.

Similarly, the optical time delay of the laser monitor may change between calibrations due to drift in strain state of the optical fiber ε, either because of the slow relaxation of strain imparted during the optical network assembly or because of aging of the fiber coating. The optical time delay response to strain has terms corresponding to the physical stretching of the fiber and the change in index of refraction: [3]

$$\frac{\Delta\tau}{\tau} = \left(1 - p_e\right)\varepsilon \tag{8}$$

p_e is the effective strain-optic coefficient and has a value of roughly 0.22 for germanosilicate optical fibers. Drift in the strain state of the laser monitor fiber tends to occur very gradually, however, so it is not a significant factor when the laser monitor time delay is calibrated frequently, as for the OBR 4600 and 5T-50.

3 Length Error Specifications

OBR 4600 and OBR 5T-50

The maximum expected time of flight measurement error τ_{max_err} is expected to be within the bounds given by summing the effects of the gas cell fit uncertainty and the error due to the effects of temperature drift.

$$\frac{\tau_{\max\_err}}{\tau} = 34x10^{-6} + 9.2x10^{-6}\left|\Delta T\right| \tag{9}$$

Since length measurements are scaled by the user determined group index of refraction, length measurement error will also be subject to inaccuracies in n. For a given index of refraction error n_{err}, the maximum length error l_{max_err} is thus expected to be within the bounds given by the following expression.

$$\frac{l_{\max\_err}}{l} = 34x10^{-6} + 9.2x10^{-6}\left|\Delta T\right| + \frac{\left|n_{err}\right|}{n} \tag{10}$$

If the ambient temperature where the instrument is located remains within +/- 12°C from when the instrument was last calibrated, and the laser monitor interferometer temperature change is the same as the ambient temperature change (as is expected), and if group index is well known so that the error associated with it is relatively small, Luna expects a worse case length error of 0.015%.

OBR 4200

Since the instrument laser monitor interferometer is only calibrated at Luna's manufacturing facility, the interferometer length may experience substantial drift in between calibrations due to changes in the instrument temperature and long term drift in the delay coil strain state.

$$\frac{\tau_{\max\_err}}{\tau} = 34x10^{-6} + 9.2x10^{-6}\left|\Delta T\right| + 0.78\left|\varepsilon\right| \tag{11}$$

Luna estimates a worse case time of flight error to be within 0.06%.

4 Measurement Example: OBR 4600 Repeatability

Two spools of SMF28e placed in an insulated box were scanned using six OBR 4600s operating in extended range mode immediately after calibration (Figure 1). Spool length measurements with each instrument returned constant results to six significant figures after repeated calibrations, and showed variations between instruments in the last of six significant figures as seen in Table 1 below. Over the test duration the spool temperatures were constant to within 0.1°C. The results show that repeatability of the length measurement between multiple OBR 4600 instruments has a standard deviation of 10 ppm or better. The theoretical estimate for length error due to the gas cell fit uncertainty described in Section 2 of 34 ppm thus appears to be conservative; users will typically observe much better performance.

Figure 1: OBR 4600 spool length measurement test setup

OBR Serial Number	Short Spool Length (m)	Long Spool Length (m)
14084279	163.808	2030.37
14094280	163.805	2030.36
14084278	163.806	2030.36
12044222	163.809	2030.39
0703ENG2	163.809	2030.37
11014164	163.807	2030.37
Standard Deviation (m)	0.0016	0.011
Normalized Standard Deviation	1.0E-05	5.4E-06

Table 1. Spool length test results for multiple instruments.

5 Summary

Luna's Optical Backscatter Reflectometers offer a uniquely advantageous combination of reflection amplitude sensitivity, length range, resolution and accuracy. Length measurement error for the OBR 4600 and OBR 5T-50 is dominated by errors in the gas cell calibration, instrument temperature changes since the last calibration, and user knowledge of the group index of refraction. Assuming the group index of refraction is well known, length measurement accuracy for the OBR 4600 and 5T-50 is expected to be better than 0.0034% immediately after calibrating the instrument, a process which typically takes a few minutes. If the instrument temperature is kept within ±12°C of the temperature when the instrument was last calibrated, Luna estimates length accuracies within 0.015%. For the OBR 4200, drift in the strain state and changes in the temperature of the laser monitor interfereometer delay coil are the dominant error sources; Luna estimates length accuracies within 0.06%.

Please contact Luna for further technical assistance related to the content discussed in this Technical Note.

6 References

1 Soller, Brian, Dawn Gifford, Matthew Wolfe, and Mark Froggatt. "High resolution optical frequency domain reflectometry for characterization of components and assemblies." *Optics Express* 13.2 (2005): 666-674.

2 Gilbert, Sarah L., William C. Swann, and Chih-Ming Wang. "Hydrogen cyanide H13C14N absorption reference for 1530 nm to 1560 nm wavelength calibration-SRM 2519a." *NIST special publication* 260 (2005): 137.

3 Meltz, Gerald, and William W. Morey. "Bragg grating formation and germanosilicate fiber photosensitivity." *International Workshop on Photoinduced Self-Organization Effects in Op*. International Society for Optics and Photonics, 1991.

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