Lightwave Analyzer Length Measurement Accuracy

Lightwave Analyzer systems do not directly measure physical length, but instead measure optical time-of-flight which is then converted to length. Because this conversion depends on environmental conditions such as temperature or strain, the reported length can appear to change over long time periods. This change in length is real and demonstrates proper operation of the systems. This document describes various other causes of changes in measured lengths and recommended operation to minimize impact on length-sensitive measurements.

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1 Introduction

Luna's Lightwave Component Analyzers (LWAs) operate on a principle know as Optical Frequency Domain Reflectometry (OFDR) in which systems report distance of features by measuring optical time-of-flight within a device (or fiber) under test (DUT).

In typical laboratory environments, apparent length drift is most often caused by temperature-dependent changes in the fiber itself rather than wavelength calibration error. This document quantifies those effects and compares their relative magnitudes.

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 DUT (See Figure 1.1). As the laser is swept through an optical frequency range, interference fringe data is collected and analyzed at the S and P detectors. 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 delay domain, in which the results are presented, is integral to the determination of the LWA length accuracy: length measurement accuracy is primarily constrained by our ability to estimate the optical frequency range of the acquisition scan.

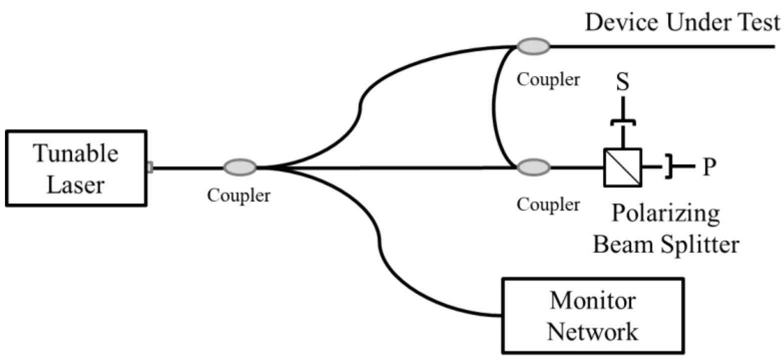

Figure 1.1 *Simplified optical network diagram for a LWA system. The Monitor Network includes monitor interferometer, gas cell, and power measurements.*

In practice, customers may observe slow or step-like changes in reported fiber length over time, even when the physical fiber appears unchanged. These effects are commonly referred to as length drift.

The purpose of this application note is to explain the primary physical and system-level mechanisms that contribute to apparent length drift in OFDR measurements. Rather than indicating an instrument malfunction such as wavelength calibration, most observed drift arises from well-understood effects related to environmental conditions and the intrinsic thermo-optic and mechanical behavior of optical fiber.

1.1 Overview

The goals of this document are the following:

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- Clarify how OFDR systems convert optical time-of-flight into a reported fiber length
- Describe the role of wavelength calibration and monitor interferometer delay in this conversion
- Identify system-level contributors to apparent length drift, including gas cell uncertainty and temperature-dependency of gas cell line shifts
- Quantify the dominant environmental effects that cause true changes in optical path length, such as temperature variation and applied strain

Where possible, typical magnitudes and time scales are provided to help distinguish between calibration-related effects and genuine changes in the DUT.

In OFDR measurements, reported fiber delay (length) reflects the optical path length, not solely the physical length of the fiber. As a result, changes in refractive index due to temperature, and strain appear as changes in measured length. In most practical scenarios, environmental effects in the fiber itself dominate over residual calibration uncertainty in the OFDR system.

Understanding these contributions allows for the ability to distinguish between expected physical behavior and true measurement anomalies, and to design experiments and installations that minimize unwanted drift.

2 Time of Flight vs. Length

As mentioned above, the LWA systems do not directly measure physical distance of a DUT and its features. Instead, the systems measure the optical time-of-flight delay of light propagating through the DUT and convert that delay into a reported length using an assumed refractive index. Understanding this distinction is essential for interpreting apparent length changes observed in OFDR measurements.

2.1 Time-of-Flight and path length

As the laser frequency is swept, the light backscattered from a position z along the DUT produces a beat frequency with the reference arm of the interferometer according to the optical delay difference between the reference path length and that location. This beat frequency is the product of the laser sweep rate and path delay difference, τ. Assuming a perfectly linear sweep, a single feature on the DUT will produce exactly one tone, whose frequency is proportional to its position.

The measured tone is then converted to a reported length using the effective refractive index n, scan range, and number of samples. The delay sample spacing is given by

$$\Delta x = \frac{c}{2n\Delta v} \tag{1}$$

where c is the speed of light in m/s, and $\Delta\nu$ is the optical frequency acquisition range in Hz. The factor of 2 is used because we are measuring a reflection which doubles the optical path length. Here we can see that errors can only arise from the refractive index and estimation of the scan range. We will discuss acquisition range errors in section 3.

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As a result, any change in refractive index appears as a change in reported length , regardless of whether it is caused by a physical elongation of the fiber or a change in refractive index due to temperature.

2.2 Refractive index

The effective refractive index of an optical fiber is not constant. It can depend on many factors including temperature, mechanical strain, fiber material, and waveguide geometry. Changes in refractive index modify the speed of light in the fiber and therefore its optical time-of-flight. Even if the physical length of the fiber remains fixed, a change in refractive index alone will produce a measurable change in OPL and consequently in the reported length.

This is a fundamental property of interferometry and coherent measurements and is not unique to the LWA system.

2.3 Practical Interpretation

For most applications, the reported OFDR length should be interpreted as an optical length metric rather than an absolute geometric measurement. When monitoring length over time, observed changes should be evaluated in the context of temperature stability, mechanical changes, and fiber construction or mounting.

Later sections of this note quantify these effects and provide guidance on distinguishing calibration-related artifacts from true changes in the fiber's optical path length.

Common Misconceptions About OFDR Length Measurements

OFDR measures physical length directly.
OFDR measures optical time-of-flight and reports length using an assumed refractive index. Changes in refractive index alone will appear as changes in reported length even if the physical fiber length is unchanged.

If the fiber isn't moving, the length should not change.
A mechanically fixed fiber can still exhibit measurable length changes due to temperature-dependent refractive index and thermal expansion effects. These changes are expected and often dominate observed drift.

Length drift indicates instrument instability.
In most cases, observed length drift reflects real changes in the fiber's optical path length rather than instability in the OFDR system. System-level calibration effects are typically much smaller and affect all distances uniformly.

All fibers respond the same way to temperature.
Different fiber constructions (bare fiber, coated fiber, jacketed cable) exhibit different thermo-mechanical behavior. Jacket materials can introduce additional strain that significantly alters the apparent length response.

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3 Wavelength Linearization and Monitor Interferometer Errors

Accurate conversion from measured beat frequency to distance in an OFDR system requires a precise and repeatable mapping between acquisition time and optical frequency (or wavelength). This process, commonly referred to as wavelength linearization, is a critical step in OFDR signal processing and directly impacts the accuracy of the reported fiber length.

3.1 The monitor interferometry system

In the LWA, a monitor interferometer with a fixed optical delay is used to track the instantaneous frequency sweep of the laser. The phase evolution of this interferometer provides a reference against which the backscattered signal from the fiber under test is resampled to uniform frequency spacing.

The monitor interferometer delay, τ_{m}, sets the scale factor between measured phase, ϕ_m and optical frequency, ν, as

$$\nu \propto \frac{\phi_m}{\tau_m} \tag{2}$$

Any uncertainty or drift in the estimated monitor delay will therefore appear as a proportional scaling error in optical frequency, and consequently as a proportional error in the reported fiber length. Changes in the monitor delay are corrected for by recording the spectrum of a gas absorption cell during the laser sweep while simultaneously collecting laser monitor interference fringe data.

3.2 Wavelength References Using a Gas Cell

To determine the monitor interferometer delay, the systems use a gas absorption cell that provides discrete, well-characterized wavelength references. The positions of multiple absorption lines across the laser sweep are identified using the optical frequency values derived from the monitor interferometer and compared against certified reference values.

Individual absorption line centers have finite uncertainty due to:

- Manufacturer-specified reference uncertainty
- Signal-to-noise limitations in line detection
- Line shape asymmetry and fitting error

Rather than relying on a single line, the LWA systems perform a linear fit between the measured and reference line positions across the sweep. This approach significantly reduces sensitivity to uncertainty in any individual line and improves the robustness of the delay estimate.

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:

$$b = \frac{\frac{1}{N}\sum_i x_i y_i - \bar{x}\bar{y}}{\frac{1}{N}\sum_i x_i^2 - \bar{x}^2} \tag{3}$$

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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:

$$u_b^{\,2} = \sum_i \left(\frac{\partial b}{\partial y_i} u_{y,i} \right)^2 \tag{4}$$

If we further assume that the uncertainty magnitude of each measured gas cell line is the same, applying equation (4) to the equation for *b* yields a compact result.

$$u_b = u_y \frac{\sqrt{\sum_i \left(\bar{x} - x_i\right)^2}}{\sum_i x_i^2 - N\bar{x}^2} \tag{5}$$

If we consider a 40 nm laser scan (5000 GHz) centered at 1546.7 nm, there are 54 NIST certified HCN gas cell lines in the scan range (see Reference [1] for a discussion of gas cell line frequency values and accuracies). If the uncertainty of each measured line is 0.04 pm ≈ 0.05 GHz, we calculate a slope uncertainty of $u_b = 0.5 \times 10^{-6}$, meaning that immediately after calibration we expect a length scaling uncertainty of 0.5 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, with respect to gas cell line accuracy will be much better in practice.

3.2.1 Absorption Line Shifts

Gas absorption cells provide stable and repeatable optical frequency references for wavelength calibration in OFDR systems. While these references are highly reliable, the absorption line centers are not strictly static and can exhibit small shifts in response to changes in temperature and pressure. Understanding the origin and magnitude of these shifts helps contextualize their contribution to apparent length drift. Figure 3.1 shows the expected line shift as a function of temperature change.

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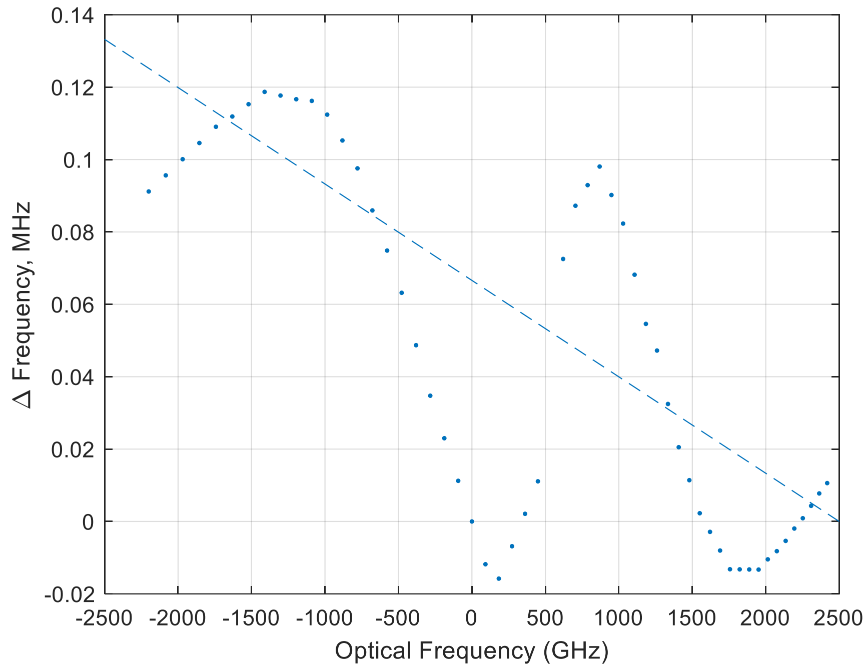

Figure 3.1 Change in center optical frequency (in MHz) per degree Celsius change in the gas cell temperature. Note that the optical frequency at 0 GHz is line 'P6'

There will be a 133 kHz total linear change over a 5000 GHz scan per 1 °C of internal temperature change, equivalent to approximately 0.025 ppm error in sensor length per degree C change. The gas cells are rated for 25 deg C, so a 40 °C deviation from nominal rating would correspond to approximately 1 ppm of global length scaling error.

The instrument's optical spectrum calibration can be verified using a fiber coupled gas absorption cell as a test device by generating spectral Return Loss or Insertion Loss data that shows the gas cell absorption centers, curve fitting the observed absorption line peaks to extract the peak center and comparing these values to the tabulated gas cell line centers. Figure 3.2 below shows that the errors of 32 HCN gas cell measurements. The standard deviation for the fit errors for each individual line is generally well below 1 pm. Errors in the instrument's estimate of the spectral scan range would result from variation in the observed slope of the gas cell line center fit values versus the tabulated values. Slope variation associated with the data below is well below levels needed to support less than +/- 5 ppm time delay scaling errors.

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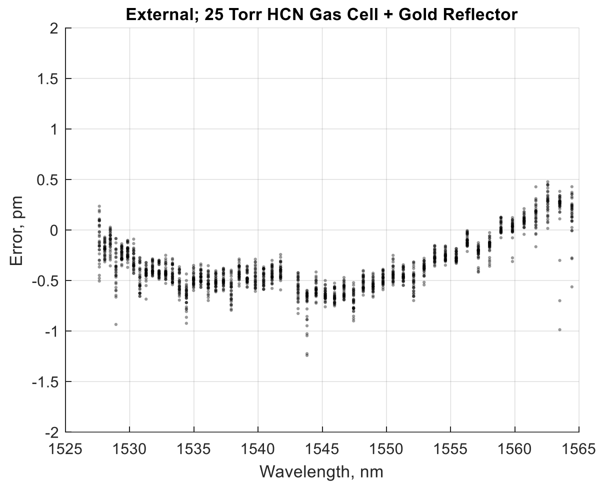

Figure 3.2 External gas cell errors measured on a 7601-CL

3.3 Impact on Reported Fiber Length

In practice, the contribution of gas cell uncertainty is typically small and is usually negligible compared to length changes caused by environmental effects in the fiber itself. Additionally, because monitor delay errors affect all measurements uniformly, they do not produce localized artifacts along the fiber.

As a result, slow or spatially varying changes in reported length are unlikely to originate from wavelength linearization error alone and should instead be examined in the context of fiber temperature or strain.

By enabling vertical cursors, it is possible to quickly make a differential measurement. First move the cursors close to the beginning and ending feature you wish to measure. Then double clicking on the feature will snap the nearby cursor to the feature of interest. It is then possible to read the length difference between the cursors, see Figure 3.3.

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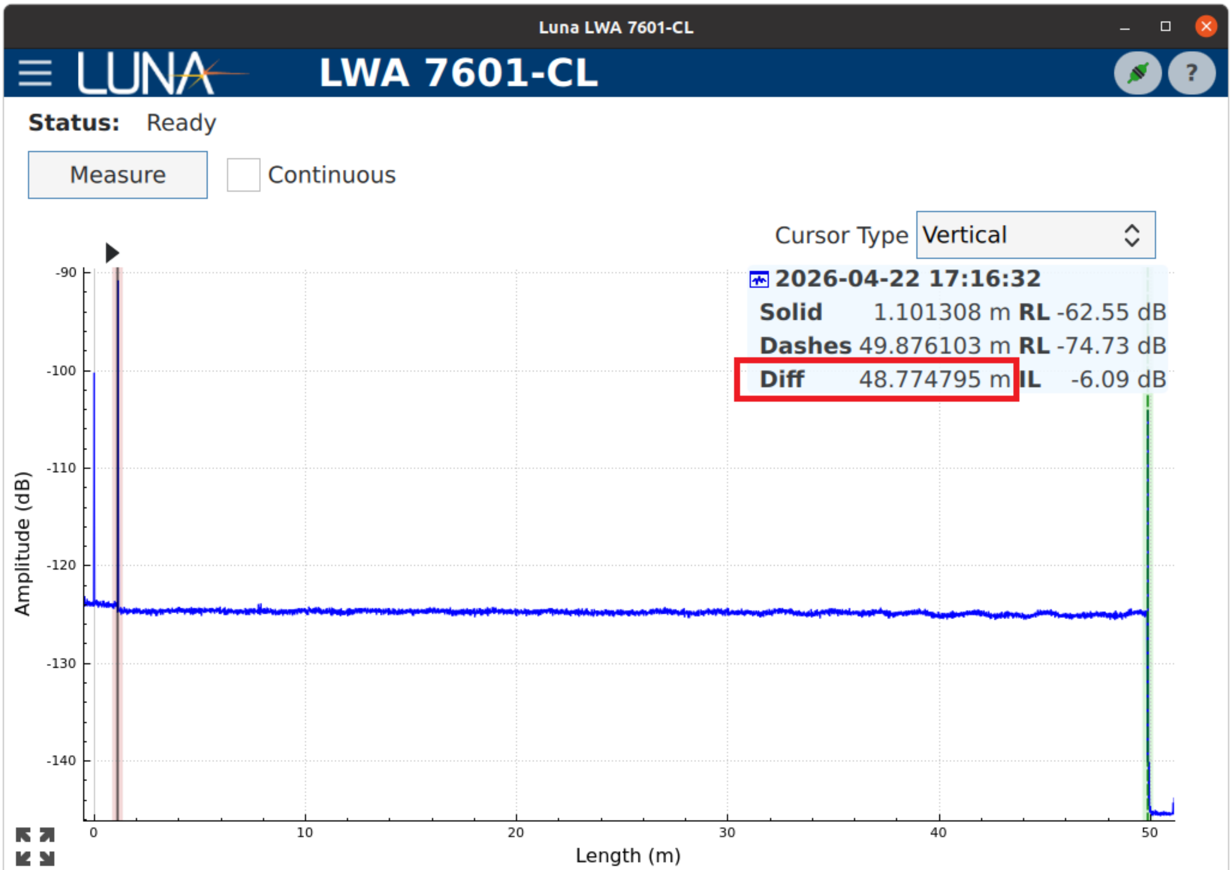

Figure 3.3 UI Interface with spatial averaging showing two-point length measurement.

For best system stability, allow proper time for system temperature to stabilize and avoid rapid or large ambient temperature changes between critical measurements.

For the LWA 7601, we estimate errors of 0.5 ppm gas cell fit error and 1 ppm temperature dependent error. Therefore, we can safely set an estimated system error of 10 ppm for the LWA 7601. In addition, we have some uncertainty within the event estimate, due to the peak-finding algorithm and sample resolution. The total length error (for a DUT measured in reflection) could be expressed by

$$L_{err} = 2 \cdot 10^{-6}\, m + L \cdot 10\, ppm \tag{6}$$

where L is the event delay in meters.

4 Fiber Length Changes

In most delay measurements, the dominant contributor to apparent length drift is not wavelength calibration or system stability, but genuine changes in the optical path length of the DUT. These changes are a result of the combined effects of temperature-dependent refractive index, thermal expansion, and mechanically induced strain.
This section describes the physical mechanisms responsible for these effects and highlights how different fiber constructions and installation conditions influence the observed response.

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4.1 Thermal Effects in Bare Optical Fiber

For a bare silica fiber that is free to expand, changes in optical path length with temperature arise from two mechanisms. First is thermal expansion, which changes the physical length of the fiber. Second is the thermo-optic effect, which changes the refractive index of the guided mode. Given the standard refractive index of SMF fiber is 1.468, This can be expressed as

$$\frac{1}{l}\frac{\partial l}{\partial T}\Delta T + \frac{1}{n}\frac{\partial n}{\partial T}\Delta T = (\alpha_l + \alpha_n)\Delta T \quad (7)$$

where l is the physical length of the DUT, and n is the group refractive index of the DUT so that we have α_l, the thermal expansion coefficient, and α_n, the thermal-optic coefficient.

The thermal expansion coefficient of fused silica is approximately 0.5-0.6 ppm per °C . The thermo-optic coefficient in standard silica fiber is 1.0×10^{-5} per °C. The standard refractive index of SMF fiber is 1.468, so we have a combined effective sensitivity of approximately 6.8 ppm per °C. This has been experimentally demonstrated in [2].

As a result, even small temperature variations can produce measurable changes in reported length. For example, a 10 m length of bare fiber will exhibit an apparent length change on the order of 60–80 µm per °C. Experimental results for a 11.77 meter bare fiber sensor are shown in Figure 4.1

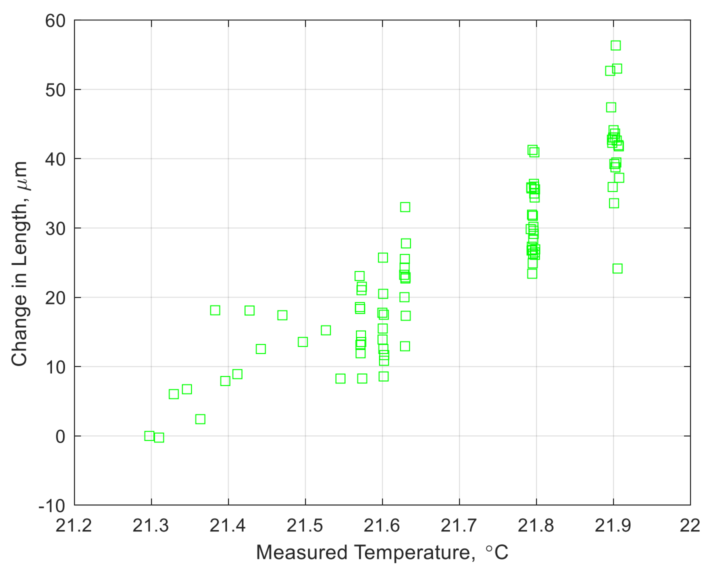

Figure 4.1 Effect of temperature change on an 11.77 meter bare fiber sensor demonstrating a thermal sensitivity of approximately 6.9 ppm per °C measured on the LWA 7601.

4.2 Jacketed Fiber and Thermo-Mechanical Coupling

When a fiber is enclosed within a protective jacket, its thermal response becomes more complex. Jacket materials generally have thermal expansion coefficients that differ significantly from that of silica. As temperature changes, differential expansion between the jacket and the glass induces additional axial strain in the fiber.

This axial strain is influenced by jacket material and thickness, fabrication/construction, and mounting conditions. Because of this, jacketed fibers often exhibit apparent length changes that vary greatly and can be significantly larger than those of bare fiber. Experimental results for a

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jacketed 6.04 meter fiber jumper are shown in Figure 4.2.

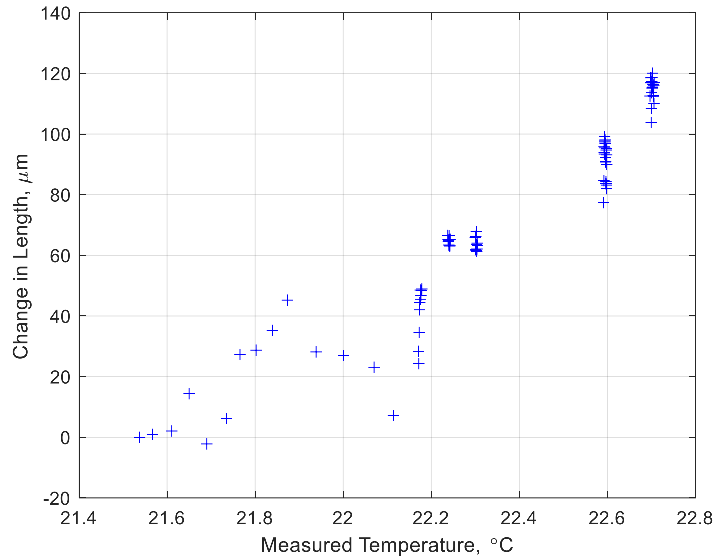

Figure 4.2 Effect of temperature change on an 6.04 meter yellow-jacketed jumper fiber demonstrating a thermal sensitivity of approximately 13.2 ppm per °C.

Because these effects introduce additional strain, jacketed fibers often exhibit apparent length changes that are significantly larger than those of bare fiber. Figure 4.3 shows an example for the many layers of a constructed fiber optic cable that can each impart thermally induced strain onto the fiber optic core.

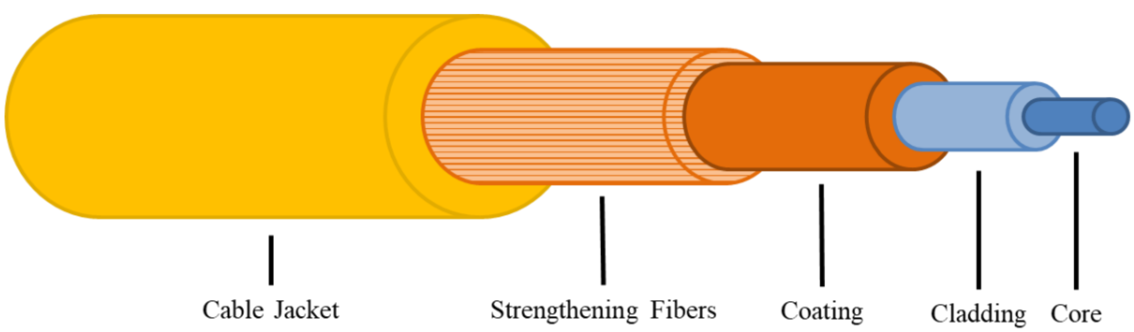

Figure 4.3 Example construction of a jacketed fiber optic cable.

Polymer jacket materials exhibit thermal expansion coefficients of 50–200 ppm/°C. Partial strain transfer to the fiber core can therefore increase effective cable delay temperature coefficients above that of bare silica fiber. Therefore, effective sensitivities of 10–50 ppm per °C or more are not uncommon, depending on construction of the specific DUT [2, 3].

Importantly, this response reflects real mechanical strain applied to the fiber and is therefore correctly measured by the OFDR system. An example measurement of a bare-fiber under temperature-controlled conditions is shown above in Figure 4.1. Here the environment temperature change was measured to be less than 1°C, resulting in a total length change of around 40 microns for a 11.7 meter fiber jumper.

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4.3 Thermal Effects on the Optical Network

The thermal mechanisms described in Sections 4.1 and 4.2 apply to the device under test (DUT) and to the internal optical network of the OFDR system. The internal measurement path contains fiber optic components whose optical path length varies with temperature in the same manner as external fiber, with internal electrical components acting as a heat source.

Following power-on from room temperature, internal electronics generate heat that gradually raises the temperature of the optical assembly. As shown in Figure 4.4, the internal optical network typically requires approximately 1.5–2 hours to reach thermal equilibrium. During this warm-up period, the effective internal optical path length may change by up to 0.4 mm. Because this change occurs within the measurement path of the instrument, it appears as a uniform offset in reported length.

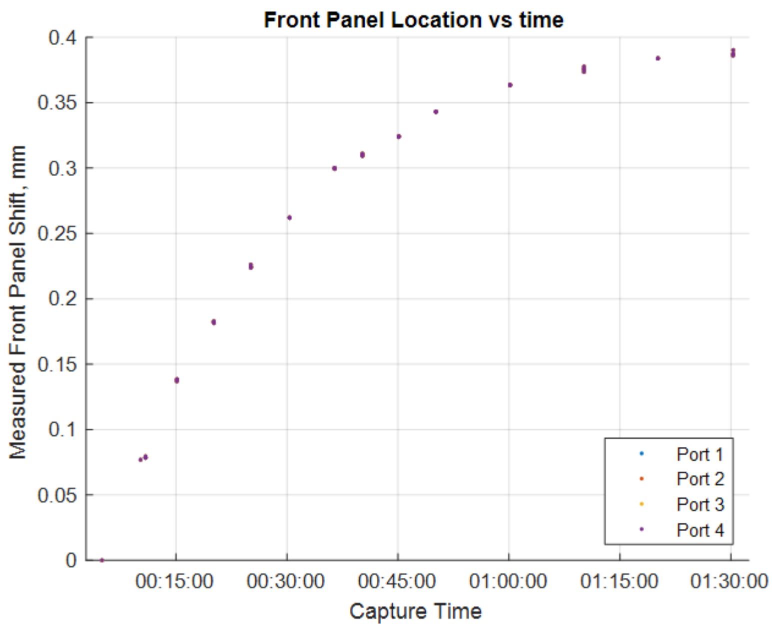

Figure 4.4 Front panel shift measured from cold-startup.

4.3.1 Front Panel Reference Calibration

Upon startup, the user software performs a calibration of the front panel reference location and defines this position as 0 m delay. Subsequent measurements assume this reference position remains constant. Additional front panel recalibration is performed only when scan modes are changed.

If the internal optical network continues to thermally drift after startup, the calibrated zero-delay reference may no longer represent the true optical reference position, resulting in a global length offset in reported measurements. If an offset is observed, manually initiate the calibration procedure to recalculate front panel location.

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4.3.2 Practical Implications

Whenever possible, a differential measurement approach is recommended. Measuring relative changes within the DUT (rather than absolute front-panel-referenced length) reduces sensitivity to internal reference drift and improves long-term stability.

For applications requiring maximum absolute length stability allow sufficient warm-up time and time for fiber to thermally equalize and settle before acquiring critical measurements in addition to maintaining a stable ambient environment around the instrument.

As with external fiber, these internal changes are predictable thermo-optic and thermal expansion effects, not random instrument instability.

5 Summary

We have explained several mechanisms that could cause length changes in an OFDR delay measurement, including system uncertainties and environmental impacts. The relevance of each drift mechanism depends on whether the user is performing absolute length metrology or monitoring relative changes. While each effect arises from a different physical origin, their relative magnitudes are not comparable. Understanding these relative scales helps distinguish between expected behavior and true system-level errors. Table 1 summarizes the typical contribution of each effect to apparent length drift, expressed in parts per million per degree Celsius (ppm per °C.).

Effect	Typical magnitude (ppm per °C.)	Notes
Instrument Wavelength linearization / gas cell residuals	< 1	Uniform scale effect
Instrument Gas cell pressure-induced line shifts	< 1	Typically correctable
Test Device Bare fiber thermo-optic + expansion	6–8	Intrinsic silica response
Test Device Jacket-induced thermo-mechanical strain	10–50	Strongly construction dependent

Table 1. Representative relative contributions to apparent OFDR length drift per °C. Environmental effects on the fiber under test dominate observed drift, while instrument-related contributions are typically much smaller and uniform across distance.

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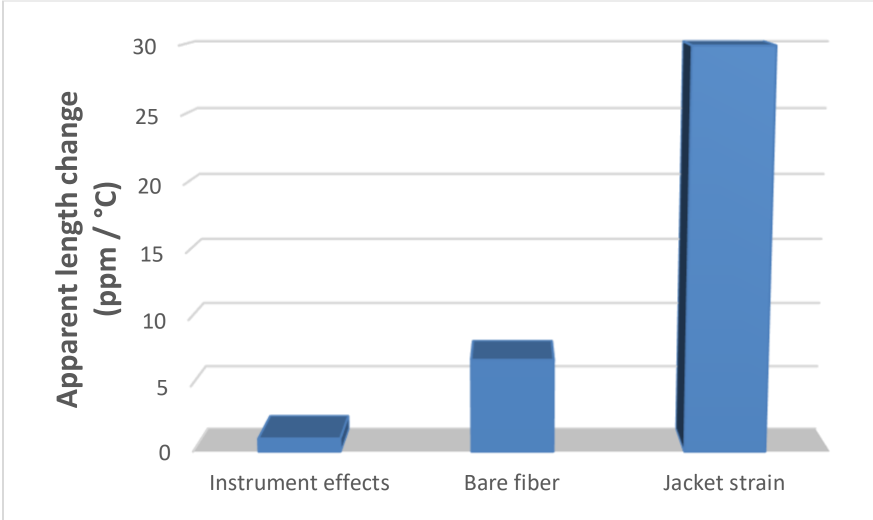

Figure 5.1 Visual representation of relative length change contributions.

5.1 Practical Guidance

Observed length drift effects the combined influence of instrument calibration**,** optical reference stability, and fiber-environment interactions**.** Understanding the relative magnitude and spatial signature of these effects allows users to correctly interpret measurement results and avoid misattributing normal behavior to system error.

5.1.1 Use Spatial Signatures to Identify the Source

By looking at the length changes of spatial features, it is possible to determine whether these length changes are global or distributed. If length changes show a uniform slope across the full measurement range, this typically will indicate wavelength linearization or monitor-network related effects. On the other hand, if the length changes are localized or specific to segments, this usually indicates that there are environmental effects acting on the fiber such as temperature gradients or localized strain.

5.1.2 Best Practices for measurements

- For absolute length stability
    - Allow sufficient warm-up time for the instrument
    - Maintain a stable ambient temperature around the system
    - Avoid rapid environmental changes during measurements
    - Use reference sections of fiber when possible
    - Focus on differential changes rather than absolute reported length
    - Expect and plan for temperature-induced drift as part of the signal
- Additional precaution on jacketed fiber
    - Apparent length drift can be an order of magnitude larger than bare fiber
    - Thermal expansion and contraction of the jacket can dominate the response
    - Small mechanical disturbances (handling, routing changes) may introduce measurable strain
    - Whenever possible, characterize the temperature response of specific fiber or device construction under representative conditions.

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5.2 Conclusion

The LWA systems measure optical time-of-flight, not physical length directly. The reported length reflects a conversion that depends on refractive index, wavelength calibration, and environmental conditions affecting the fiber.

Small wavelength-scale effects (e.g., gas cell line shifts) can produce measurable global length offsets, but these are typically ppm-level or smaller. Environmental effects acting on the fiber, especially temperature and jacket-induced strain, are often the dominant contributors to observed length drift. The spatially resolved nature of OFDR enables users to distinguish between calibration-related effects and true distributed changes in the fiber.

Understanding the relative magnitude of each contribution allows users to interpret results correctly and design measurements with appropriate controls.

Please contact Luna for further technical assistance related to the content discussed in this Technical Note or see the support portal at https://support.lunainc.com/.

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6 Works Cited

[1] S. L. Gilbert, W. Swann and C.-M. Wang, "Hydrogen cyanide H12C14N absorption reference for 1530 nm to 1560 wavelength calibration-SRM 2519a," *NIST special publication,* vol. 260, p. 137, 2005.

[2] F. Azendorf, A. Dochhan and M. Eiselt, "Temperature dependent latency of jumper cables," in *Photonic Networks; 19th ITG-Symposium*, 2018.

[3] A. D. Kersey, M. A. Davis, H. J. Patrick, M. LeBlank, K. P. Koo, C. G. Askins, M. A. Putnam and J. Friebele, "Fiber Grating Sensors," *Journal of lightwave technology,* vol. 15, no. 8, pp. 1442-1463, 1997.

[4] B. Soller, D. Gifford, M. Wolfe and M. Froggatt, "High resolution optical frequency domain reflectometry for characterization of components and assemblies.," *Optics Express,* vol. 13, no. 2, pp. 666-674, 2005.

[5] G. Meltz and W. Morey, "Bragg grating formation and germanosilicate fiber photosensitivity," *International workshop on photoinduced self-organization effects in optical fiber,* vol. 1516, pp. 185-199, 1991.

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