LUNA

Insertion Loss and Return Loss Measurements

Principles, Measurement Procedures, and Interpretation for LWA 7600 Optical Systems

Revision 001

This document covers the measurement of Return Loss and Insertion Loss on the Lightwave Analyzer systems. This includes an overview of the concepts and how to ensure optimal measurements depending on user sensitivity requirements.

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1 Introduction

This application note provides a guide to measuring insertion loss (IL) and return loss (RL) with the LightWave Analyzer (LWA) optical system. It is intended to give users a thorough understanding of what these parameters represent physically, how measurement settings affect accuracy and resolution, and methodology on how to perform each measurement using the LWA platform.

Insertion loss and return loss are two of the most fundamental parameters in optical system characterization. Together they define how much optical power is transmitted through a device and how much power is reflected back toward the source. These values directly feed into link budget calculations, system margin analysis, and quality testing for optical components.

For a reflection-based measurement, the insertion loss measurement relies on the system's ability to measure the power reflected by random inhomogeneous variations in glass. By measuring the magnitude of these Rayleigh scatter elements before and after an event of interest, the LWA systems can calculate the power lost at the event.

Poor IL indicates a loss of power that can increase bit error rates in data links, degrade sensitivity in sensing systems, and reduce range in optical coherence tomography (OCT) and LIDAR applications. Poor RL indicates a high reflectance that can generate interference patterns, destabilize laser sources, and can produce multi-path artifacts that corrupt measurement data. Understanding and accurately measuring both parameters is therefore essential for any optical system design and test workflow.

2 Definitions and Concepts

2.1 Insertion Loss

Insertion loss quantifies the total optical power lost as light propagates through a device or component from an input reference point to an output reference point. It is defined as:

$$IL\ (dB) = 10\log_{10}\left(\frac{P_o}{P_i}\right) \qquad (1)$$

where P_o is the measured output power at a specified point and P_i is the incident input power at the reference point. Because the output power is always less than or equal to the input power in a passive device, IL is expressed as a negative number in dB, and a lower value indicates lower transmission efficiency. Luna uses a negative convention for both IL and RL because when plotting IL or RL as a function of wavelength or distance, it is more intuitive to scale the y-axis of the plot from higher values at the top to lower values at the bottom.

Key convention:

A higher insertion loss value is better. IL = 0 dB represents a theoretically perfect, lossless device. IL = -3 dB means half the optical power has been lost.

The main mechanisms that can contribute to insertion loss are absorption, scattering, coupling inefficiency, loss due to reflection, and polarization-dependent loss (PDL).

2.2 Return Loss

Return loss quantifies the optical power reflected toward the source at a discontinuity or interface such as a connector end-face, a splice, a cleaved fiber facet, or a component element or port. It is defined as:

$$RL\ (dB) = \ 10\log_{10}\left(\frac{P_{re}}{P_{inc}}\right) \qquad (2)$$

where P_{re} is the reflected power and P_{inc} is the incident power at the interface. Because the reflected power is always less than or equal to the incident power, RL is also expressed as a negative number in dB. Here, a more negative value indicates less reflected power and therefore better performance.

Key convention:

A more negative loss value indicates less return loss. RL = -60 dB means only 0.0001% (one part in one million) of the incident power is reflected. RL = -14 dB means approximately 4% is reflected, characteristic of an uncoated perpendicular glass–air interface.

The main mechanisms of reflection that drive return loss include Fresnel reflections, connector or splice discontinuities, Rayleigh backscatter, grating effects, and cavity effects.

The sign conventions of IL and RL are chosen so that they can be easily interpreted when plotted on the same graph.

2.3 The Relationship Between IL and RL

While IL and RL describe different phenomena, they are not entirely independent. Reflection at an interface reduces the transmitted power, so a component with high RL will also exhibit a small IL contribution from that reflection. However, the dominant IL mechanisms (absorption, scattering, coupling loss) produce no significant back-reflection so a component can have high IL with high RL, or low IL with low RL, depending on its loss characteristics.

In system design, it is useful to think of them as complementary diagnostics: IL characterizes the forward transmission path and directly sets the optical power budget, while RL characterizes the reverse path and governs source stability and interference susceptibility.

INSERTION LOSS (IL)	RETURN LOSS (RL)
Measures forward power loss	Measures backward reflected power
Higher value = better performance	Lower value = better performance
Reported as a negative dB value	Reported as a negative dB value
Key metric for link power budget	Key metric for source stability and interference
Primarily caused by absorption, scatter, coupling	Primarily caused by Fresnel reflections, surface quality, sudden changes in refractive index

2.4 Rayleigh Scatter Characteristics

In conventional reflectance measurements, return loss is measured directly from a discrete reflector, like the end facet of a connector. The LWA has the additional ability to exploit a much weaker, distributed reflection: Rayleigh backscatter within the waveguide.

Rayleigh scattering occurs due to the non-homogeneous nature of glass. When a fiber is drawn or a substrate is formed, random fluctuations in density and composition result in randomly distributed scattering points throughout the device. Though random, the distribution is relatively uniform. It is dependent on material composition, dopant profile, and waveguide geometry so that the average scatter level is repeatable and predictable even though instantaneous scattering events appear to have a random amplitude. This combination of statistical repeatability along with its spatial randomness makes Rayleigh scatter useful as a distributed reference signal compared with a single calibrated reflector.

The LWA systems can use Rayleigh backscatter as a continuous amplitude reference along the length of the fiber under test. For a reflection-based insertion loss measurement, the system compares the average Rayleigh scatter level immediately before an event of interest (a splice, connector, or component) to the average level immediately after it. Since the scatter coefficient of the fiber itself does not change across the event (assuming the fiber type is consistent on both sides), any drop in the average backscatter level across the event can be attributed to insertion loss at that point.

It is important to note that when calculating IL in this manner, RL is measured using the double pass of the light source (out and back), but IL is a single pass measurement so a factor of two is removed to account for this difference. See Figure 3.1 below showing RL and IL values.

$$IL\ (dB) = \frac{RL_2(dB) - RL_1(dB)}{2} \tag{3}$$

2.4.1 Measurement accuracy implications

As mentioned above, when using Rayleigh scatter levels to measure insertion loss, it is crucial to average over a distributed length to minimize the impact of the random localized variations. The wider the integration width, the more repeatable the measurement, given that the integration width contains only Rayleigh scatter events. Additionally, individual Rayleigh scatter events vary with optical frequency. Therefore, a wider spectral scan range also improves scatter level repeatability over a given time domain segment size because in OFDR, the time domain RL value is averaged over the spectral range of the laser sweep.

Furthermore, scatter level depends on the fiber or waveguide properties. This means that any change in material properties or waveguide dimensions can be mistakenly interpreted as an IL loss or even IL gain.

Lastly, Rayleigh scatter occurs continuously along any solid core fiber with amorphous structure, establishing a baseline of distributed reflection present in any measurement. It is typically well below the reflection of a connector, but it does set a practical floor for detecting weak reflections on the order of Rayleigh backscatter.

3 Measurement Parameters and Their Effects

Two parameters on the LWA platform have a significant influence on the resolution and accuracy of IL and RL measurements: the tuning range of the swept laser source, and the integration width applied during post-processing. Understanding how these parameters interact is essential for configuring measurements that are both accurate and fit for purpose.

3.1 How to measure RL and IL on the LWA

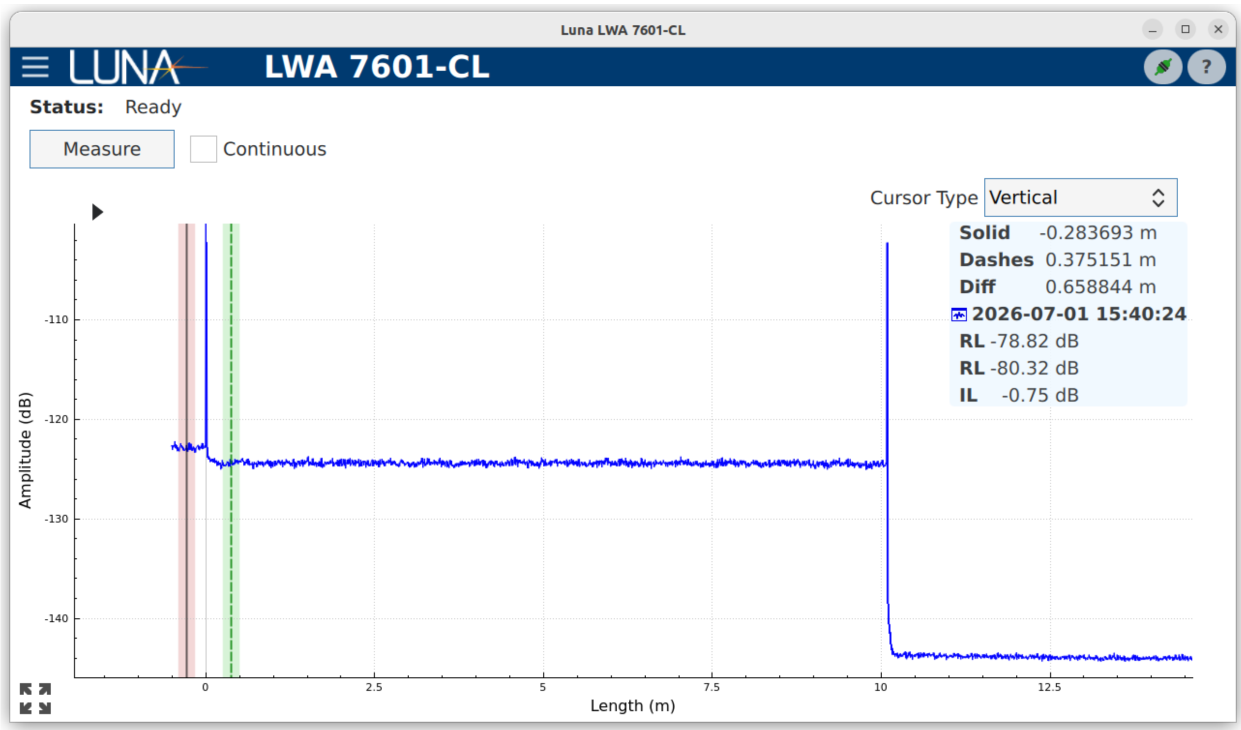

Figure 3.1 Sample measurement of front panel Insertion Loss. Note that this plot and all following plots have a Gaussian filtering with a width of 0.01024 m applied for improved visibility.

To make a RL or IL measurement, select vertical cursors from the **Cursor Type** menu in the upper right. Two vertical cursors will appear: a solid vertical cursor with a red highlighted region showing the integration range, and a dashed vertical cursor with a green highlighted region showing the integration range.
Select and drag each cursor to the desired location. Cursors will snap to bright events if placed close to an event and then double-clicking on the event.

To measure the RL of an event: center a single cursor on the reflection event and make sure the cursor width only covers the event.

To measure the IL across an event: position the two cursors over the Rayleigh scatter on either side of the reflection. For proper IL sign convention as discussed in section 2, place the solid cursor before the dashed cursor as shown in Figure 3.1. The IL value is the difference in RL values of each of the solid and dashed cursors, divided by 2 (the factor of two reflects the fact that IL is defined as a single pass value, and light passes back and forth through the event when measured in reflection).

The Information box below the **Cursor Type** menu will display the locations of each cursor, the distance between the two, as well as the RL calculated for each cursor as well as the calculated IL between the two locations. When multiple cursors are selected, the first RL displayed corresponds to the solid cursor and the second one corresponds to the dashed cursor.

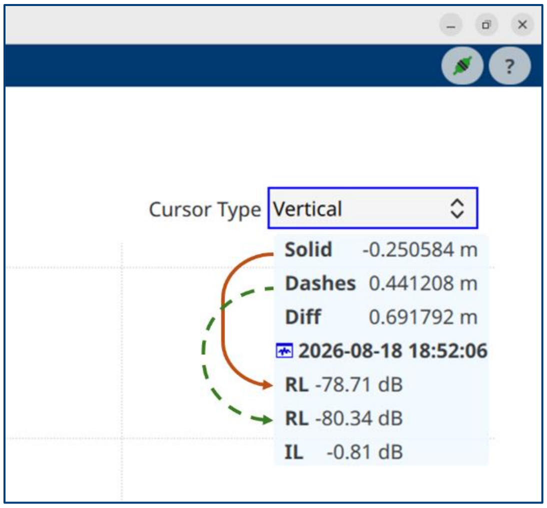

Figure 3.2 Cursor Information box

The integration width over which the cursor RL value is calculated can be changed by adjusting the "RL Width" parameter in the Measurement Settings menu, explained in further detail in Section 3.3.

3.2 Tuning range

3.2.1 Definition and Role

The tuning range is the total optical frequency span (equivalently, wavelength span) over which the laser source sweeps during a single measurement. It is typically specified in nanometers (nm) or terahertz (THz) and is set by the user prior to measurement.

In the LWA systems, the spectral tuning range determines the time domain spatial sample spacing. For a measurement in reflection, this relationship is:

$$\Delta x = \frac{c}{2n\Delta\upsilon} \qquad (4)$$

where Δx is the spatial sample spacing of the delay domain, c is the speed of light in a vacuum in m/s,n is the index of refraction, and $\Delta\upsilon$ is the optical frequency tuning range in Hz. Clearly, a wider tuning range yields finer sample spacing but is limited by laser capabilities.

The best possible spatial resolution, as defined by the minimum resolvable distance between two separate reflection events, is twice the sample spacing. But in practice, spatial resolution is degraded by waveguide dispersive effects (chromatic dispersion, modal dispersion, or polarization mode dispersion) or by motion or vibration along the test path.

Spatial resolution may also be limited by the spectral range supported by the test path, i.e. when examining events downstream of a narrow bandpass filter,

3.2.2 Effect of Tuning Range on Return Loss Measurements

Equation (4) shows that a wider tuning range decreases spatial sample spacing. For RL measurements, the tuning range is an important factor when the device under test contains multiple reflection events in close proximity. A narrow tuning range may cause two closely spaced reflections to appear as a single combined feature, making it impossible to assign the correct RL value to each interface individually.

However, when spatial resolution is limited by chromatic dispersion or motion along the test path, increasing the tuning range may not improve spatial resolution, since blurring effects of chromatic dispersion worsen over wider tuning ranges, and the blurring effects of motion along the test path worsen with longer acquisition times.

Because IL measurements are calculated using the RL measurements, improving RL consistency will produce improved IL measurement.

3.2.3 Tuning Range and Narrow Band Test Devices

Although wider tuning ranges are often preferable for better spatial resolution, the spectral response of the test device may limit the transmitted spectral range and thus limit the effective spatial resolution. Test devices with this property include wavelength selectable switches, spectral add/drop filters, or PICs with grating couplers that are designed to pass a discrete wavelength range. In these cases, using a wider laser tuning range than the bandwidth of the filter will decrease spatial sample spacing but will not improve spatial resolution past the filter element.

The user should also keep in mind that the time domain RL value is effectively the average over the entire spectral tuning range. For reflection events downstream of a spectral filter, the time domain RL value will be diminished by the portion of the scan that is outside of the filter bandpass. In these cases, to get an accurate RL value at a specific wavelength, the user should enable the Spectral Plot feature and use the spectral cursor to highlight a specific reflection event. The user can then use the spectral plot vertical or horizontal cursors to make wavelength specific RL measurements or make band center or band pass width measurements.

3.3 Integration Width

3.3.1 Definition and Role

The spatial integration width defines the time delay domain range over which the detected signal is integrated when computing IL or RL. It can be controlled under the Measurement settings shown in Figure 3.3.

In the LWA system, after the spectral domain data is collected, a Fourier transform relates the measurement to a time-of-flight or time delay domain (see Application Note on Length Measurements). The integration width defines a window on this delay axis centered at the feature of interest (the DUT input port, a specific interface, etc.).

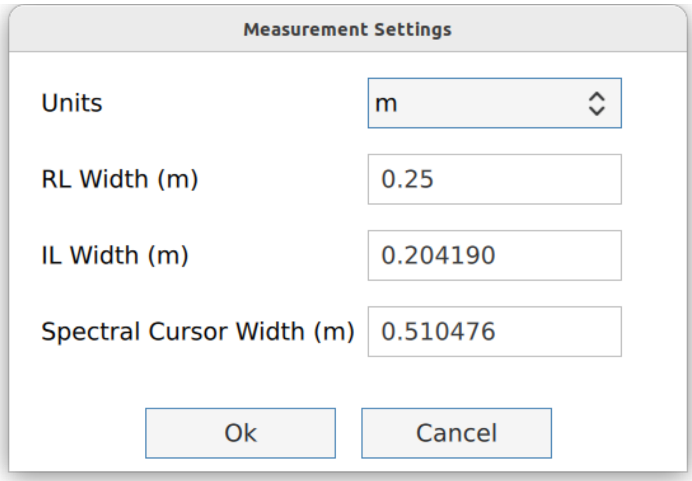

Figure 3.3 RL and IL integration widths can be edited under Menu > Settings > Measurement Settings

3.3.2 Effect on Signal-to-Noise Ratio

When making RL measurements of a discrete reflection events, the user should set the cursor integration width so that it only covers the data points associated with the peak, but not broader than the peak so that the cursor region covers a minimal portion of data corresponding to nearby Rayleigh scatter or noise floor. In cases in which the reflection event RL is close to the RL level of nearby Rayleigh scatter, including data associated with the scatter could significantly increase the reported RL value.

When making IL measurements based on two successive RL measurements of Rayleigh scatter, a wider integration window captures more of the signal energy from a given feature: averaging over spatial variations, improving SNR, and reducing measurement noise. Using a wider spectral range reduces measurement noise for similar reasons–the measurement collects more optical power and averages over natural spectral variation inherent to Rayleigh scatter.

Figure 3.4 shows calculated insertion loss variation based on the spatial variation of a cursor RL measurement of a 10 m length of telecommunication grade optical fiber that is presumed to have no appreciable insertion loss, as a function of the cursor integration width and the spectral extent of the laser sweep.

To limit IL uncertainty due to natural fiber Rayleigh scatter spatial and spectral variation so that two-sigma variation is less than 0.1 dB, Luna recommends using at least a 0.25 m integration width with at least a 5 THz scan range. For shorter spectral scan ranges, a wider integration width is needed to achieve the same level of scatter variation for example using a 0.75 m integration width with a 1.25 THz scan would also result in a two-sigma variation level below 0.1dB.

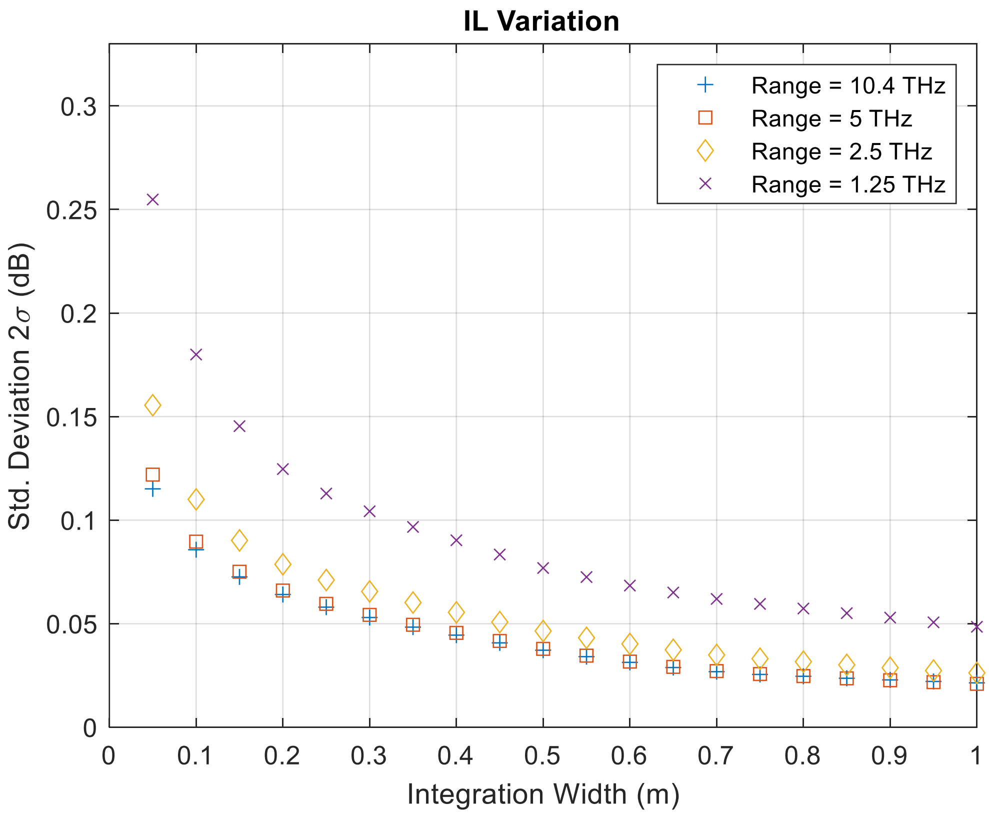

Figure 3.4 Effect of integration width and scan range on Rayleigh scatter insertion loss.

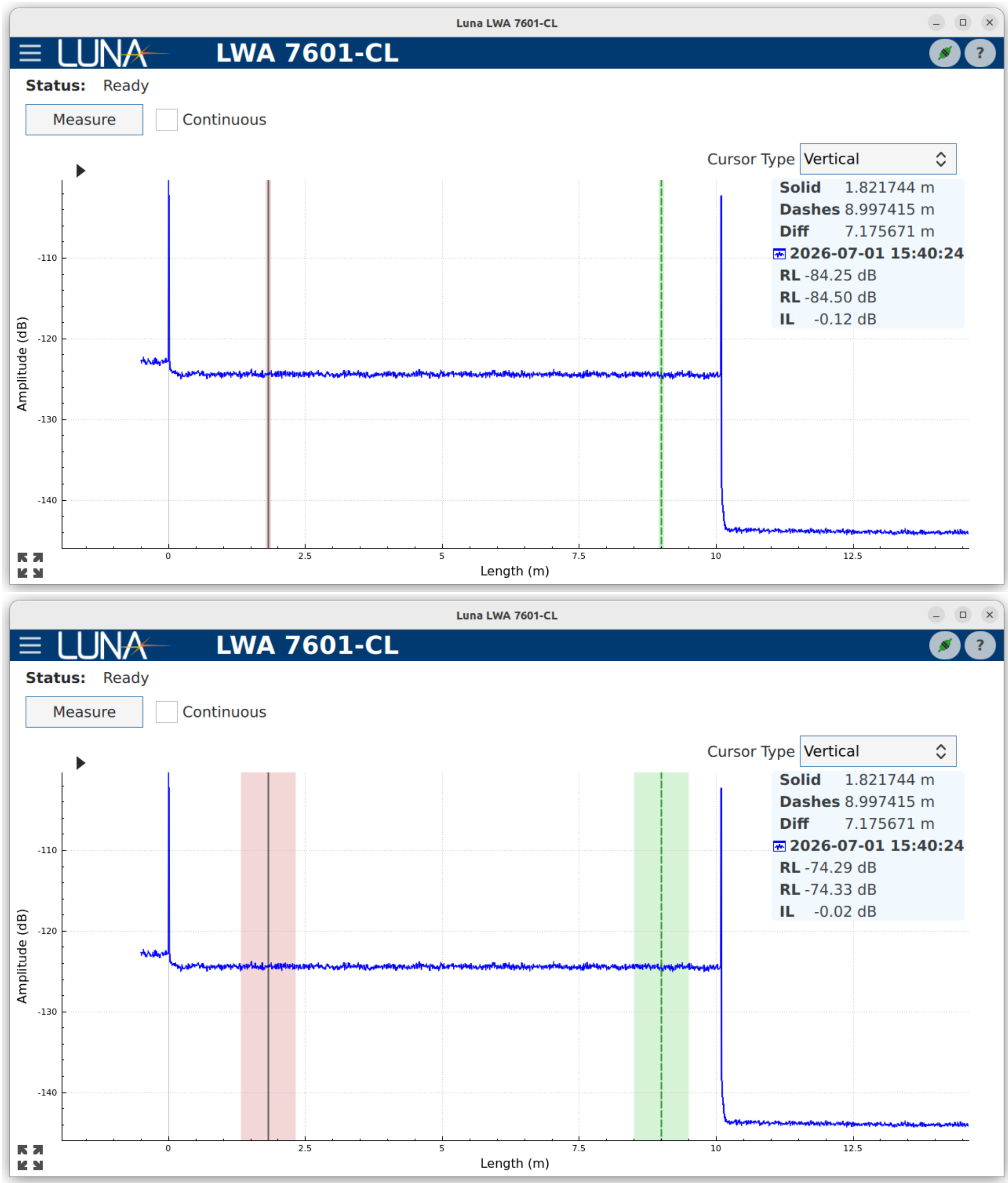

Figure 3.5 Sample measurements of a 10 m fiber jumper. (top) RL integration width set to 0.1 m. (bottom) RL integration width set to 1.0 m.

Table 1. This table gives the maximum scan range in THz for the different scan modes on the C, CL, and O band LWA systems

MAXIMUM MEASUREMENT LENGTH (m)	MAXIMUM SCAN RANGE (THz)		
	7601 C	7601-CL	7601-O
20	5	10.4	12.33
50	5	10.4	12.33
100	5	10.5	12.33
200	5	5	5
500	1.25	1.25	1.25
1000	1.2	1.2	1.2

3.3.3 Effect on Spatial and Spectral Selectivity

A narrower integration window isolates the contribution from a single, well-defined feature, suppressing contributions from nearby reflections or loss discontinuities. This is critical when measuring RL on a connector immediately followed by another connector, or when characterizing IL at a specific splice within a longer fiber assembly.

The minimum useful window width is set by the spatial extent of the feature itself. For a specular reflection (e.g., a connector end-face), the signal occupies a narrow range, and a narrow window is appropriate. For distributed scatter or a resonant cavity, the signal is spread over a wider range, and the window must be wide enough to capture the full feature.

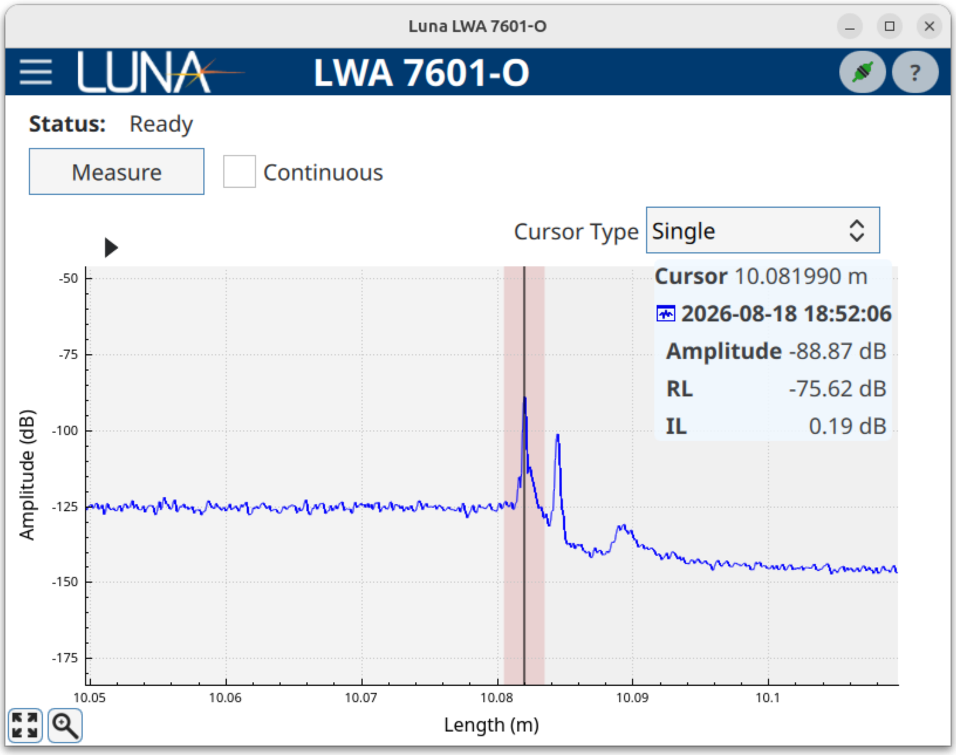

Figure 3.6 RL measurement demonstrating the importance of integration width selection. If the width were set wider, the return loss measurement would include an additional reflection source placed after the fiber end facet.

4 Other Sources of Error

4.1 Common Mode Errors

A significant practical advantage of Rayleigh-scatter-based insertion loss measurements in OFDR systems is that many conventional RL error sources are effectively cancelled by the differential nature of the measurement. Because the LWA computes IL by comparing two backscatter windows located on either side of an event on the same fiber, any error source that affects both windows equally will subtract out in the ratio. These are referred to as common-mode errors.

These might include drift in the instrument detector response since the last calibration, which might create a shift in the RL measurement, but would not impact an IL measurement since the same shift would apply to both Rayleigh scatter RL measurements and cancel out in the IL computation.

Sources of error that do not cancel come from physical differences between the two integration windows including fiber type or waveguide mismatch, additional reflections or insertion loss sources within the integration window, high polarization dependent loss (PDL), and integration windows that are too short to properly average out the Rayleigh scatter level.

COMMON-MODE ERRORS *cancel in the differential measurement*	**RESIDUAL ERRORS** *unique to one measurement window; do not cancel*
• Drift in instrument response since last calibration • Accumulated Path Losses	• Fiber or waveguide mismatch • Reflections within the integration window • Insufficient integration window length • High PDL

4.2 Polarization Variation

Two distinct polarization phenomena can affect the accuracy of Rayleigh-scatter-based IL and RL measurements, and it is useful to distinguish between them as they arise from different physical mechanisms and affect measurements in different ways.

4.2.1 Polarization state evolution along low-loss fiber

In standard single-mode fiber, the polarization state of propagating light rotates continuously along the fiber length due to birefringence from residual manufacturing stress, bending, and/or environmental perturbation. This evolution is generally slow and smooth, and the polarization state changes gradually over centimeters to meters rather than abruptly. This type of polarization variation is largely common mode for nearby measurement windows and cancels in the differential IL calculation.

The effect of slowly evolving polarization state on RL measurements is similarly small for distributed Rayleigh scatter, since the scattering process itself is polarization-insensitive. The LWA's polarization-diverse receiver architecture is designed to handle this type of variation effectively, collecting signal across two orthogonal polarization axes simultaneously so that gradual polarization rotation along the fiber does not cause signal fading or amplitude error.

4.2.2 Polarization dependence in the fiber or component under test.

The second phenomenon is fundamentally different: the device or fiber under test exhibits significant polarization dependency, in the form of high polarization mode dispersion (PMD) or high polarization dependent loss (PDL). A device with PMD may produce a large and abrupt change in the polarization state for light transiting the device, so there is a large difference in the polarization state of light returning from fiber Rayleigh scatter immediately before and after the device.

Devices with PDL transmit different amounts of optical power depending on the polarization state of the input light. In this case, the measured IL will depend on the momentary polarization state arriving at the DUT. Unlike slow polarization evolution, PMD and PDL introduce a real, physical asymmetry between polarization states that the receiver cannot recover by collecting both axes. A polarization-diverse receiver improves robustness against polarization fading but does not eliminate PDL-induced measurement uncertainty, because PDL represents a genuine difference in transmission rather than a detection efficiency issue. For IL, this manifests as a measurement that may vary between repeat measurements as the input polarization state drifts. For RL, high PDL in the path between the LWA and the

DUT can cause the two backscatter windows to experience slightly different effective scatter amplitudes, introducing a residual error that does not fully cancel.

4.3 Calibration

The LWA's polarization-diverse receiver must be properly calibrated to realize its full benefit for both phenomena. Without calibration, imbalance between the two receiver channels — typically caused by temperature changes within the internal optical network — can cause an artificially polarization-dependent measurement response that mimics PDL even in a PDL-free DUT. Proper calibration corrects for these channel imbalances and ensures that the receiver response is uniform across all input polarization states. If the system has not been calibrated recently, or if the calibration state is in question, polarization-related measurement artifacts should be considered as a potential error source before concluding that an anomalous IL or RL result reflects a real property of the DUT.

The LWA IL accuracy specification of 0.1 dB corresponds to the worst-case RMS value of the polarization angle dependent receiver calibration error. Figure 4.1 below shows the calibration pop-up menu. Following the calibration procedure optimizes the the polarization diverse receiver to be equally sensitive to all polarization states. Figure 4.2 illustrates a sample measurement where the calibration is poor. In it, the Rayleigh scatter signature for a fiber spool coiled tightly enough to induce substantial birefringence but not PDL for when the polarization diverse receiver is not well calibrated (red trace), and after calibration (blue trace).

Figure 4.3 shows the standard deviation of the maximum IL variation between four measurements of the same tightly coiled fiber with random and different input polarization states. This IL variation is a result of the PDL uncertainty mentioned in section 4.2.2.

When the polarization diverse reciever is not well calibrated as shown, the Rayleigh scatter for a fiber coil exhibits polarization dependent variation that has a sinusoidal variation with a period of twice the beat length. After calibration, this polarization dependence is removed, the Rayliegh scatter patern is more uniform versus distance, and only the normal spatial variation of the Rayleigh scatter pattern remains.

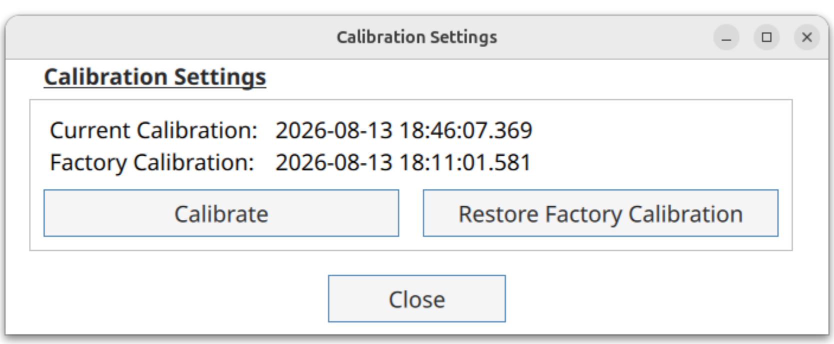

Figure 4.1 Calibration access can be found under Menu >> Settings >> Calibration

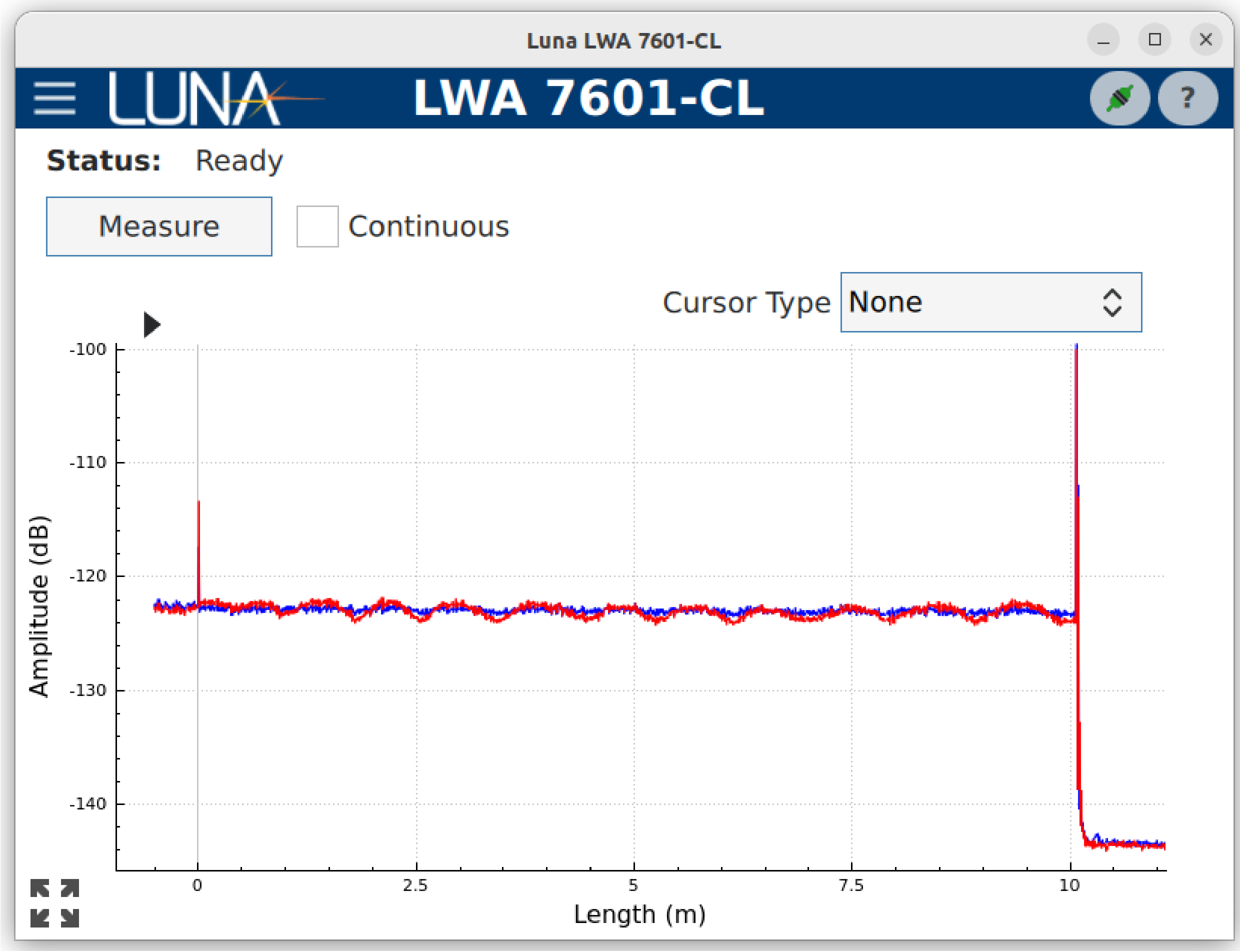

Figure 4.2 Sample measurement of the same tightly coiled fiber (1 mm diameter yellow jacketed SMF, bend radius = 20 mm) with (blue) and without (red) calibration and balance.

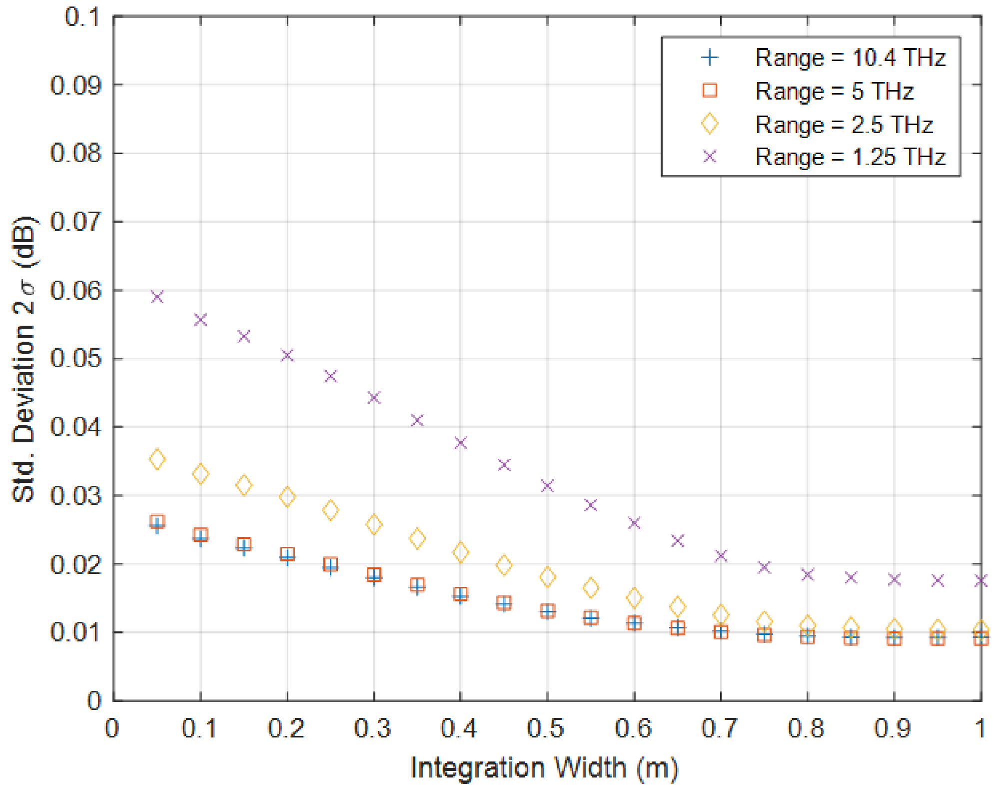

Figure 4.3 Calculated residual IL error due PDL in a tightly coiled fiber jumper.

Best Practices:

1. Leave unit powered on -OR- allow for a minimum of 1 hour instrument warm up time if starting from the unit off and at room temperature.

2. Polarization Balance Calibration and Acquisition Range Calibration procedures should be performed at least once per day, after 1 hour warm up period or if the environment has changed 5^{o}C.

3. If possible, minimize strain or tight bends in test devices to minimize added polarization drift and PDL.

5 Specification Test Conditions

The IL and RL accuracy specification applies under the following conditions. Qualifiers 1 and 2 are implicit in any OFDR or OTDR-based IL measurement and are included here for completeness; qualifiers 3 and 4 are specific to the LWA measurement architecture and are essential for achieving the specified accuracy.

1. **Measurement method.** The specification applies to measurement of insertion loss occurring at a spatially localized event, determined from the difference in Rayleigh scatter return loss immediately before and after the event. It does not apply to end-to-end IL measurements or to IL derived from absolute power levels.
2. **Fiber type consistency.** The IL measurement assumes that the same fiber type is present on both sides of the event under test, such that the intrinsic Rayleigh scatter coefficient is the same in both measurement windows.
3. **Minimum laser sweep range/ integration window length.** To achieve the specified accuracy, the spectral range of the laser sweep should be at least 5 THz and the integration width should be 0.25 m or wider as long as the device profile does not contain events within this width. A wider sweep range produces a narrower point-spread function in the OPD domain, which more effectively averages the natural spatial variation in Rayleigh scatter amplitude within each integration window. Sweeps below 5 THz will result in degraded IL accuracy due to insufficient suppression of scatter spatial variation. Wide integration widths are required to average down the natural random spatial variation in scatter amplitude to the level needed for the specified IL accuracy.
4. **Instrument warm-up.** Allow a minimum of 1 hour for the instrument to warm-up if starting from a powered-off state at room temperature before performing measurements intended to meet the specified accuracy. Measurements taken before the instrument has reached thermal equilibrium may exhibit elevated noise and drift that degrades the impact of the balance and calibration files and impacts IL accuracy.
5. **Balance and calibration.** The polarization-diverse receiver balance and calibration procedures should be performed at least once per day, after the 1-hour warm-up period has elapsed or the environment has changed 5 °C. Calibration corrects for channel imbalance in the receiver that would otherwise introduce a polarization-dependent measurement artifact; see the polarization discussion in Section 4.2 for further detail.
6. **Polarization state.** The typical accuracy value applies when the PDL contribution to measurement uncertainty is smaller than the desired IL accuracy.

6 Summary

The LWA optical systems provide high-accuracy insertion loss and return loss measurements by exploiting the Rayleigh backscatter of the fiber under test as a continuous distributed reference signal. Rather than relying on a discrete calibrated reflector or an end-to-end power reference, the system compares the average backscatter level immediately before and after an event of interest, allowing spatially localized IL to be determined with high repeatability across a wide range of fiber and component types.

The accuracy of this measurement is governed by several instrument and configuration parameters discussed throughout this document: the spectral range of the laser sweep (which determines how effectively spatial variation in the Rayleigh scatter averages down), the integration window length (which sets the spatial extent over which the pre- and post-event backscatter levels are estimated), the polarization state of light at the DUT (which determines whether PDL-induced variation contributes to measurement uncertainty), and the calibration state of the polarization-diverse receiver. The IL accuracy specifications of 0.1 dB reflect these dependencies and should be understood in the context of the qualifiers that follow.

7 Product Support Contact Information

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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-FY2601

Appendix A: Amendment History

VERSION	DATE	EDITED BY	DESCRIPTION OF CHANGES
001	8/20/2026	KMK	Document created