Towards Reliable TLS Intensity Measurements: Assessing Repeatability and Temperature-Induced Effects

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SUMMARY

Intensity values recorded by terrestrial laser scanners (TLS) contain valuable information about surface properties and structures. This makes them a promising tool for damage monitoring and surface characterization. However, the repeatability of TLS intensity values remains poorly understood and is influenced by numerous instrumental and environmental factors. While the effects of incidence angle and distance on intensity have been widely studied, little attention has been given to influences such as ambient temperature or warm-up effects.

This study investigates the repeatability of TLS intensity measurements under varying ambient and instrument temperatures. Using a Z+F Imager 5016, a strong linear correlation was identified between measured intensity and ambient temperature, with a nearly linear increase of up to 15% between 0 °C and 40 °C across several target materials. Experiments with a Leica RTC360 revealed substantial intensity variations during the first 15 minutes of operation, even under constant ambient temperature conditions, depending on the time interval between successive scans.

Based on these experimental findings, the potential for compensation was explored. Preliminary tests using (1) an instrument-based approach utilizing internal temperature sensor data, and (2) a measurement-based approach indicate that these thermal effects are systematic and can be strongly reduced. Initial results suggest that the standard deviation of temperature-induced intensity variation can be lowered by a factor of up to five, demonstrating the feasibility of compensating these influences.

The results confirm the presence of a temperature-induced effect on TLS intensity measurements. While the preliminary compensation models show promise, the primary contribution of this work is the detailed quantification of these thermal influences, highlighting the need for temperature consideration in high-precision TLS applications.

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1. INTRODUCTION

By employing LiDAR technology, terrestrial laser scanning (TLS) systems generate high-resolution three-dimensional point clouds, enabling accurate spatial representation of structures and surfaces. In addition to geometric data, TLS instruments record the intensity of the reflected laser signal, which is related to the reflectance properties of the scanned surfaces.

Traditionally, intensity information was utilized primarily as a secondary parameter to enhance scan registration (Alba et al., 2012) or to support object classification (Li and Cheng, 2018). Recently, however, the potential of TLS intensity data has received increasing attention in standalone applications. These include snow cover analysis (Anttila et al., 2012), detection of water damage in tunnels (Tan et al., 2016), and the assessment of degradation in historic buildings (Armesto-González et al., 2010). Furthermore, relationships between surface moisture content and intensity values have been demonstrated, suggesting the feasibility of using intensity data for surface condition monitoring (Laasch et al., 2023; Jin et al., 2020).

However, reliable interpretation of such measurements requires that intensity variations reflect surface properties rather than instrumental or environmental artifacts. Despite growing interest, the repeatability of TLS intensity measurements has not been systematically investigated. Intensity values are influenced by factors such as incidence angle, distance, surface material, and environmental conditions (Pfeifer et al., 2007). While the impacts of incidence angle and distance have been extensively characterized and compensation models developed (Kaasalainen et al., 2011; Tan et al., 2016), other effects, such as ambient temperature and instrument warm-up, have received comparatively little attention.

One such artifact is the warm-up effect, characterized by intensity fluctuations during the initial scanning period, typically lasting 30 to 60 minutes (Tsakiri et al., 2015; Laasch et al., 2023). This phenomenon is attributed to internal temperature changes within the instrument electronics. Although the impact of ambient temperature on the geometric accuracy of point clouds has been studied (Janßen et al., 2021), its effect on intensity measurements remains poorly quantified.

The present study addresses this gap by systematically investigating the repeatability of TLS intensity measurements under varying ambient and instrument temperatures. Using a Z+F Imager 5016 and a Leica RTC360, this research identifies and quantifies the magnitude of temperature variations and warm-up dynamics on intensity values. Furthermore, to assess the feasibility of mitigation, two preliminary compensation approaches are explored, serving as a first step toward compensating for these thermal effects.

The paper is organized as follows. Section 2 outlines the experimental methodology and data pre-processing. Section 3 presents the results regarding ambient temperature and instrument warm-up effects. Section 4 evaluates preliminary compensation approaches, followed by the conclusion in Section 5.

2. METHODS

2.1 Experimental Setup

This study synthesizes experimental results from two complementary bachelor's theses, designed to investigate distinct aspects of thermal stability in TLS. To isolate specific environmental and instrumental influences, different scanner models and environments were employed for each measurement series. The Z+F Imager 5016 was utilized in a climate chamber to test ambient temperature effects (see Section 2.1.1), while the Leica RTC360 was employed in a standard laboratory setting to focus on instrument-specific warm-up characteristics (see Section 2.1.2).

2.1.1 Measurement series 1: Ambient Temperature

To investigate the influence of ambient temperature on TLS intensity measurements, controlled laboratory experiments were conducted using a Z+F Imager 5016 laser scanner. The measurements took place inside a climate chamber (4.0 × 3.0 × 2.2 m) as shown in Figure 1, where the ambient temperature was systematically varied. Five experimental runs were conducted to cover a range from 0 °C to 40 °C, simulating scenarios of gradual cooling, heating, and stepwise temperature changes (see Table 1). For these profiles, the temperature was changed linearly between the defined time stamps. Prior to each experiment, the climate chamber was held at a constant starting temperature for at least 0.5 h to ensure the scanner was fully acclimatized to the initial conditions. To eliminate battery heating as a variable, the scanner was operated via mains power throughout the experiments.

During these temperature variations, the scanner repeatedly measured a fixed target set positioned on a table at a distance of approximately 3.15 m (see Figure 1). The target set was designed to represent diverse surface characteristics, consisting of four Spectralon targets with nominal reflectivities of 99%, 60%, 40%, and 20% used as reference targets with known reflectivity, as well as three sandstone samples, one quartz block, and one beech wood block.

To ensure comparability across the temperature profiles, all experiments utilized identical scan settings (point spacing: 6.7 mm at 10 m, quality: "normal"), resulting in a scan duration of approximately 1.5 min. The scan time series are captured with a fixed 5-minute cycle time between the start of consecutive scans. Before and after each scan, the scanner recorded internal sensor data, including temperature, current, and voltage. Additionally, two external sensors were placed in close proximity to the targets and recorded the temperature and moisture every two minutes.

Figure 1: Experimental setup in the climate chamber, with the targets on the table (left) measured by the Z+F Imager 5016 (right).

Table 1: Experimental and temperature settings for the five measurement runs, detailing the duration, scan count, and specific climate chamber temperature profiles.

ID	Description	Duration [hrs]	Number of scans	Time-temperature profile
1.1	25 °C → 30 °C → 10 °C	7.5	97	00:00 – 25.0 °C 02:00 – 31.4 °C 07:30 – 6.4°C
1.2	7 °C → 30 °C (stepwise)	9	115	00:00 – 8.4 °C 01:00 – 8.4 °C 02:00 – 16.4 °C 03:00 – 16.4 °C 04:00 – 21.4 °C 05:00 – 21.4 °C 06:00 – 26.4 °C 07:00 – 26.4 °C 08:00 – 31.4 °C 09:00 – 31.4 °C
1.3	10 °C → 40 °C	9	115	00:00 – 11.4 °C 04:30 – 26.4 °C 09:00 – 41.4 °C
1.4	30 °C → 0 °C (stepwise)	19	205	00:00 – 31.4 °C 02:30 – 31.4 °C 05:30 – 21.4 °C

				08:00 – 21.4 °C 11:00 – 11.4 °C 13:30 – 11.4 °C 16:30 – 1.4 °C 19:00 – 1.4 °C
1.5	30 °C → 0 °C	16.5	205	00:00 – 31.4 °C 16:30 – 1.4 °C

2.1.2 Measurement Series 2: Internal Temperature

A second experimental setup was designed to investigate instrument-dependent intensity variations under stable ambient conditions. A Leica RTC360 was employed in a climate-controlled laboratory (stable at approx. 20.6 °C) to measure various targets at a distance about 1.5 m (see Figure 2). The scan duration is approximately 2:40.

The target set included among other Spectralon reference targets (5% and 80%), various sandstone samples (Blue and Yellow Berne, Oberkirchen, Bentheim, Kordel) and seven distinct plaster facades. Three measurement campaigns were conducted to analyze the influence of sensor heating. Each campaign consisted of 40 repeated scans with varying waiting times between consecutive scans: 0 min (continuous scanning), 5 min, and 10 min.

Figure 2: Experimental setup in measurement laboratory, with the targets on the table (right) measured by the Leica RTC360 (left).

2.2 Data Pre-processing

To ensure identical target coordinates across all measurements, all scans within each experiment were registered to a common reference frame. Registration was performed using Z+F Laser Control (Zoller + Fröhlich, 2025) for measurement series 1 and Leica Cyclone REGISTER 360 PLUS (Leica, 2025) for measurement series 2.

Subsequently, the points of individual targets were extracted from each scan's point cloud using the *InsituRadi* Python library (Laasch et al., 2025). For each target t in a given scan s, the mean intensity ($\bar{I}_{t,s}$) and its standard deviation $\left(\sigma_{I_{t,s}}\right)$ were calculated based on all extracted points. The corresponding internal sensor values were retrieved from the raw sensor data and synchronized with the scan timestamps using a custom Python script.

For measurement series 1, the intensity values were normalized to facilitate direct comparison between targets with different absolute reflectance. The normalized intensity was calculated by identifying the highest $\bar{I}_{t,s}$ of a given target across all scans s of an experiment and dividing all other mean intensity values of that target by this maximum. This scales the intensity of every target to a range of 0 to 1, where 1 represents the maximum recorded value.

For measurement series 2, the different targets are not compared directly to each other and therefore no normalization is required.

3. Results

3.1 Ambient temperature effects (measurement series 1)

To cover the full ambient temperature range from 0 °C to 40 °C, data from two separate experiment runs (1.3 and 1.5, see Table 1) were combined.

Figure 3 illustrates a distinct positive correlation between temperature and intensity. For the Spectralon 60% target, the measured intensity rose by approximately 14.4% as the temperature increased from 0°C to 40°C. This trend is consistent across all investigated materials (see Table 2). On average, the intensity increased by 14.7% between 0 °C and 40 °C, corresponding to a mean intensity gradient of 0.37% per °C. These results demonstrate that ambient temperature has a clear and quantifiable influence on TLS intensity values.

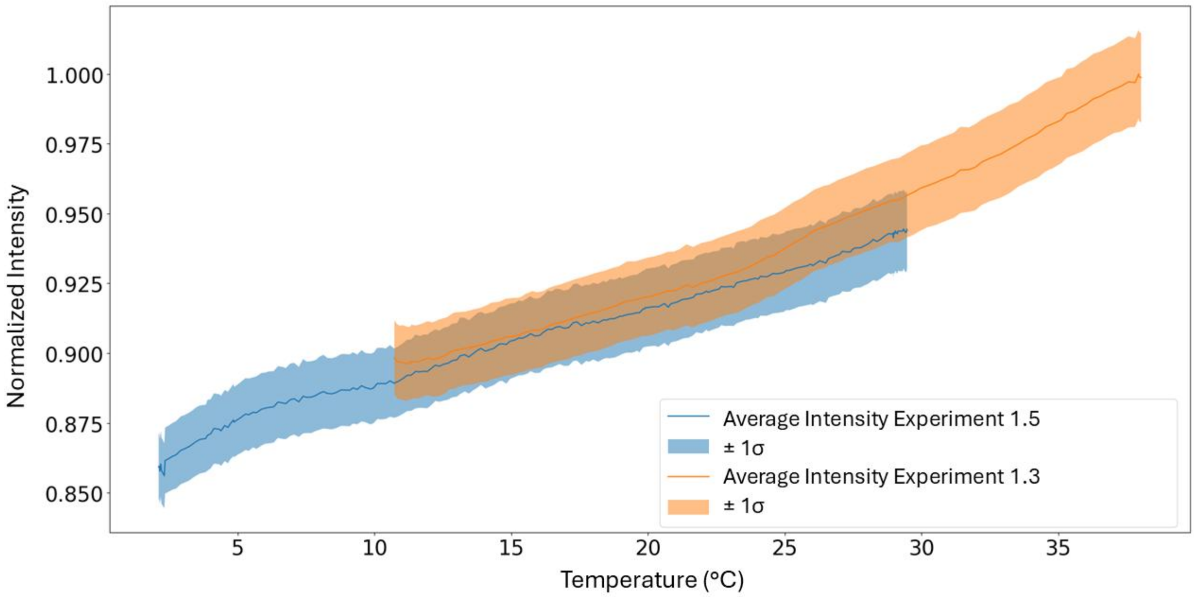

Figure 3: Intensities change and standard deviation for the Spectralon 60% target plotted against ambient temperature, combining data from experiment runs 1.3 and 1.5.

When analyzing the consistency of this trend, the temperature range where the two experiments overlapped was examined. A systematic bias was observed between the repeated datasets, amounting to approximately 1.5% for the Spectralon 60% target. This offset may be attributed to external factors not explicitly controlled in the setup, such as variations in air humidity, fluctuations in the laser's emitted power after restarting the instrument, or other uncharacterized environmental influences. Despite this offset, the bias is considered minor in the context of the overall measurement uncertainty. The magnitude of the bias lies within the 1σ standard deviation of the individual points on the target surface (measurement noise). Consequently, while a small systematic offset exists, it does not undermine the validity of the temperature-dependent trend.

However, while the general trend is consistent, a detailed examination of Table 2 reveals that the magnitude of the effect is not uniform across all materials. The total intensity increase and the corresponding temperature gradients vary between the different samples. This variability indicates that the thermal influence is target-dependent. Consequently, simply applying a single global compensation factor to all intensity values is insufficient. The cause of these material-specific differences is not yet fully understood. Potential factors could include temperature-dependent changes in the reflectance of the materials themselves. Additionally, the targets were positioned at slightly varying distances, meaning the laser beam traversed different path lengths through the conditioned air. This variation leads to differences in cumulative atmospheric transmission, implying that the thermal effect on intensity is likely range-dependent. Further investigation is required to isolate these specific mechanisms.

Table 2: Quantification of the thermal influence for all targets, showing the total relative percentage increase and the mean intensity gradient over the combined experiment runs 1.3 and 1.5 with a temperature range from 0 °C to 40 °C.

Target	Difference [%]	Gradient [%/°C]
42 b Beech	19.3	0.5
Bentheimer sandstone	16.4	0.4
Gelber Berner sandstone	13.0	0.3
Oberkirchner sandstone	14.7	0.4
Quarzit	11.1	0.3
Spectralon 20	14.8	0.4
Spectralon 40	14.6	0.4
Spectralon 60	14.4	0.4
Spectralon 99	13.6	0.3

3.2 Instrument warm-up effects (measurement series 2)

Figure 4 shows the intensity evolution for the Spectralon 80% target over repeated scans at a constant ambient temperature. The data reveal a systematic increase in measured intensity as the number of consecutive scans increases. Although access to the internal temperature data is not available for the Leica RTC 360 to confirm the temperature directly, this drift will likely be attributed to the internal thermal warm-up of the instrument during continuous operation (Janßen et al., 2021).

This warm-up-related effect is substantially reduced when a waiting period between scans is introduced. In the experiments where scans were triggered every 5 or 10 minutes, the intensity levels remained significantly more stable compared to the continuous scanning mode. This suggests that the pauses allow the instrument to cool down and return closer to its initial thermal state before the next acquisition. Consequently, the choice of scanning interval determines the length of the initial unstable warm-up phase, dictating how much early data must be discarded.

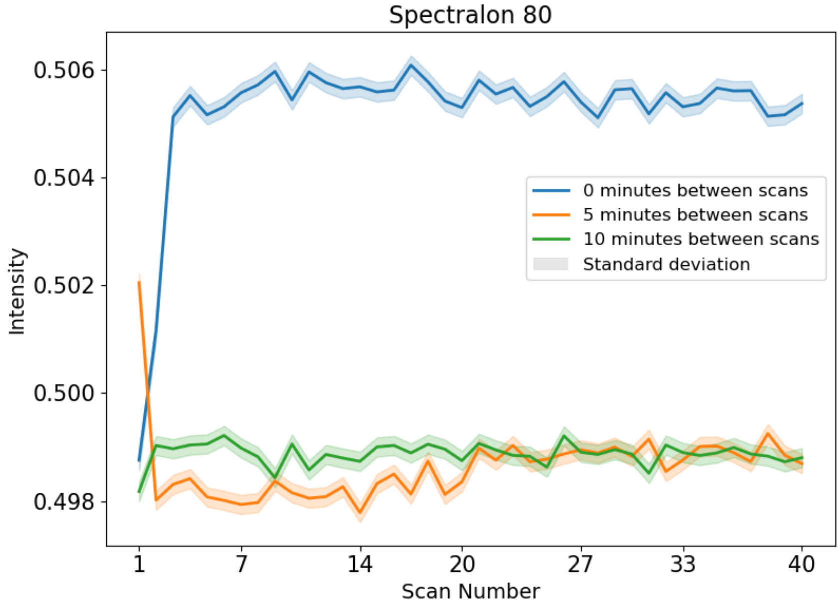

Figure 4: Intensity change and standard deviation of the Spectralon 80% target over repeated scans at constant ambient temperature. The curves compare continuous scanning against scanning with fixed intervals of 5 and 10 minutes.

Figure 5 illustrates the Pearson correlations for all targets within a single continuous measurement campaign (no cooldown). With the exception of the Spectralon 5% target, all targets exhibit strong positive mutual correlations. This implies that the intensity variations are primarily driven by a common systematic factor – likely the internal instrument temperature – that affects most targets similarly.

The Spectralon 5% target, however, shows markedly lower and partially negative correlations with the other targets. This deviation is likely attributed to its very low reflectance, which results in a reduced signal-to-noise ratio, making it more susceptible to measurement noise and background effects rather than the systematic thermal trend.

Notably, targets with similar material properties, such as the sandstone samples, exhibit even higher inter-target correlations with one another than with the other materials. It is not yet clear why this material-specific clustering occurs, and further investigations are necessary to understand the underlying cause.

Taken together, the systematic warm-up drift observed in Figure 4 and the strong inter-target correlations shown in Figure 5 align with the findings of measurement series 1. These combined results further support the hypothesis that internal instrument temperature is a dominant factor influencing TLS intensity, regardless of whether the heat source is environmental or operational.

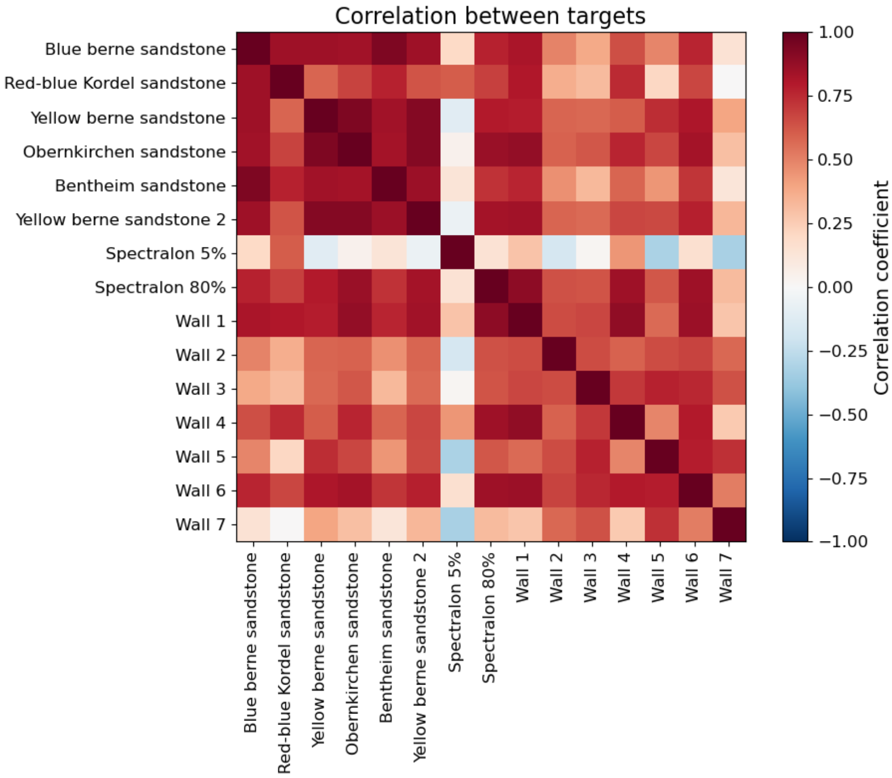

Figure 5: Correlation matrix displaying the Pearson correlation coefficients between the intensity variations of different targets during a continuous measurement campaign (measurement series 2, no cooldown).

4. Preliminary compensation approaches

To mitigate temperature-induced intensity variations observed in the previous section, two compensation methods were tested. These methods represent a first attempt to compensate the intensity for temperature effects using basic normalization techniques, rather than elaborated or fully optimized compensation algorithms.

The first method utilizes the scanner's internal temperature sensor. A linear regression model was established using the comprehensive dataset (experiment runs 1.3 and 1.4) to define the general relationship between internal temperature and intensity. To apply the compensation, a specific reference temperature is selected. For any given measurement, a compensation factor is calculated as the ratio of the modeled intensity at the reference temperature to the modeled intensity at the actual measured temperature of the current scan. This factor is then applied to all uncompensated intensities in that scan. Consequently, the compensated intensities reflect the values as they would appear if the scan had been performed at the reference temperature.

The second method relies on an external reference target placed within the scan scene. This approach assumes that the reflectance of the reference target is stable and that any observed intensity changes are solely due to temperature effects. A reference scan is selected as the baseline. For every subsequent scan, a scalar compensation factor is calculated as the ratio of the reference target's mean intensity in the baseline scan to its mean intensity in the current scan. This factor is then applied globally to all other targets in that scan.

Both compensation methods were applied to three experiment runs: 1.1, 1.2, and 1.5. To quantify the improvement, the spread of the mean intensities for each target was analyzed before and after compensation. The improvement metric is defined as the ratio of the standard deviation of the uncompensated means to the standard deviation of the compensated means ($\sigma_{\mathrm{uncomp}}/\sigma_{\mathrm{comp}}$).

Table 3 summarizes these results. A ratio greater than 1 indicates a reduction in spread. The data shows that both methods successfully decrease the standard deviation in every experiment run, improving measurement consistency. In some cases, method 1 outperforms method 2, while in others method 2 is more effective. However, these are merely initial proof-of-concept results. Why the performance varies between methods, and how to develop a robust, generalized compensation model for complex real-world scenarios, requires further investigation.

Table 3: Average improvement ratio ($\sigma_{uncomp}/\sigma_{comp}$) across all targets for the two compensation methods. A higher value indicates better compensation.

Experiment	Average improvement method 1	Average improvement method 2
1.1	5.3	4.7
1.2	5.0	4.8
1.5	3.4	4.5

5. Conclusion

This study investigated the repeatability and temperature dependence of terrestrial laser scanning (TLS) intensity measurements, with a particular focus on ambient temperature effects and instrument warm-up behavior. Controlled laboratory experiments using a Z+F Imager 5016 and a Leica RTC360 demonstrated that TLS intensity values are significantly influenced by temperature-related effects, which can lead to systematic intensity variations of up to approximately 15% over a temperature range of 0 °C to 40 °C.

The results from measurement series 1 clearly showed a positive correlation between measured intensity and rising ambient temperature across all investigated target materials, including Spectralon reference targets and natural stone samples. However, while the general trend was uniform, the magnitude of the intensity increase varied between materials. This suggests that thermal influence is not purely instrumental but is also affected by target-specific properties or range-dependent atmospheric transmission. Additionally, residual deviations between repeated runs indicated that internal instrument temperature plays a dominant role, particularly during non-stationary thermal conditions.

Measurement series 2 further confirmed the presence of instrument-dependent warm-up effects, even under constant ambient temperature conditions. Consecutive scans without sufficient cooldown time resulted in a systematic increase in intensity values, whereas introducing waiting periods between scans substantially reduced this effect. The strong correlation of intensity changes across different targets (and particularly within material groups, such as sandstones) supports the hypothesis that these variations originate primarily from the instrument's internal thermal state.

Based on these findings, two preliminary compensation approaches were evaluated. A sensor-based method using linear regression with internal temperature data, and a sensor independent method using a stable reference target, both proved effective in reducing temperature-induced intensity variations. These methods achieved standard deviation reductions by factors of up to 5.3 and 4.8, respectively. These results serve as a proof-of-concept, demonstrating that thermal effects are systematic and compensable.

Overall, this study demonstrates that ambient temperature and instrument warm-up have a non-negligible impact on TLS intensity measurements. For high-precision applications, such as surface condition monitoring, these factors must be explicitly considered. While the proposed methods offer a promising path toward radiometric compensation, future work is required to develop robust models that account for material-specific responses and complex environmental conditions. These findings contribute to the broader goal of enabling robust, reproducible, and physically interpretable use of TLS intensity data.

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Declaration of generative AI and AI-assisted technologies in the writing process
During the preparation of this work, the authors used ChatGPT and Google Gemini in order to improve readability and language. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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BIOGRAPHICAL NOTES

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