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ANALYSIS OF LASER SCANNER INTENSITY DATA FOR THE IDENTIFICATION OF CAVE ART

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Abstract

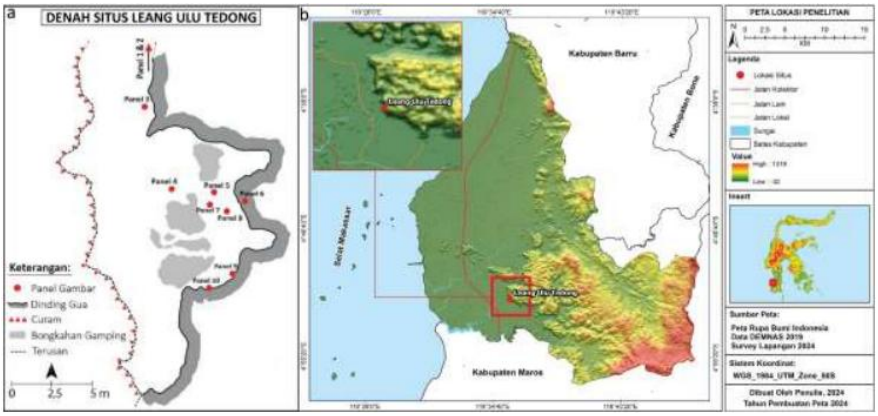
Rock art documentation has traditionally relied on digital photography; however, this approach remains highly dependent on lighting conditions and visual interpretation. This study aims to analyze the differences in intensity value between rock art and surrounding rock surfaces and to evaluate the potential of Terrestrial Laser Scanner (TLS) intensity data as a supporting parameter for rock art[1] documentation and identification. Data were acquired at Leang Ulu Tedong and Leang Tedongnge using a Leica BLK360 TLS and professional digital cameras. Point cloud data were processed in Cloud Compare through Red, Green, Blue (RGB) and intensity visualization, intensity extraction using a grid sampling method, and statistical analysis with a paired sample t-test. Photographic images were enhanced using the DStretch plugin in ImageJ and compared with the point cloud visualizations. The results show that the mean intensity value of rock art areas were consistently lower than those of the surrounding rock surfaces across all observation panels. Statistical analysis indicated that all calculated t-values exceeded the critical t-value ($\alpha = 0.05$), confirming significant differences between the two surface types. Furthermore, the comparison of visualization methods demonstrates that TLS intensity data provide complementary radiometric information, supporting more objective, comprehensive, and reliable rock art documentation and identification.

Keywords: *Terrestrial Laser Scanner, Point Cloud Intensity, Rock Art, Cloud Compare, DStretch.*

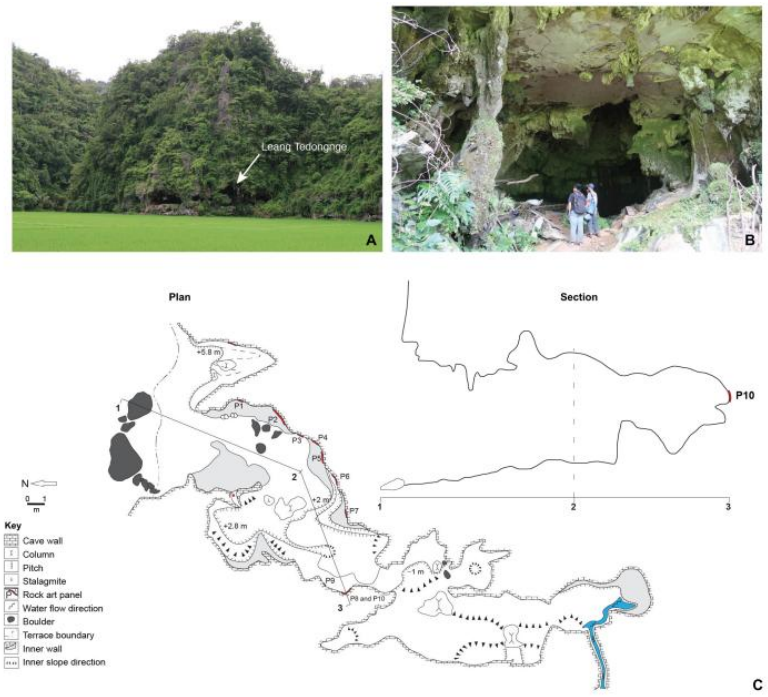
INTRODUCTION

Prehistoric caves are cultural heritage sites that preserve important information about human life in the past, particularly through the cave paintings found on their walls and ceilings. Rock art—including handprints, animal figures, anthropomorphic figures, and geometric shapes—serves as evidence of prehistoric humans' symbolic activities and holds significant scientific value in archaeological research. The karst region of South Sulawesi is one of the main centers for rock art in Indonesia. Sites such as Leang

Tedongnge and Leang Ulu Tedong contain 51,200-year-old cave paintings, which play a crucial role in understanding the cultural development of prehistoric humans (Oktaviana 2015; Brumm et al. 2021; Oktaviana et al. 2024; Sabri et al. 2025). The locations of these two research sites are shown in Picture 1.



(a)



(b)

Picture 1. Research Locations at (a) Leang Ulu Tedong dan (b) Leang Tedongnge (Source: Brumm et al. 2021; Sabri et al. 2025).

Rock art found in cave environments is a cultural heritage that is vulnerable to degradation due to natural processes occurring on the rock surface. Common forms of degradation include rock exfoliation, the formation of mineral crusts caused by water

seepage in karst rock, and other weathering processes that can cover or remove the pigment layer (Ilmi et al. 2022; Huntley et al. 2021). These conditions cause discoloration, a decrease in chromaticity, and a reduction in visual contrast between the rock art and the rock surface, making it increasingly difficult to identify and document the rock art. This vulnerability highlights the importance of implementing documentation methods capable of objectively recording surface characteristics and supporting efforts to preserve cultural heritage. To date, rock art documentation has generally been conducted using digital photography, which can then be combined with image enhancement techniques such as Decorrelation Stretch (DStretch) to improve the visibility of pigments (Defrasne 2014). Although effective in clarifying the visual presentation, both approaches still depend on lighting conditions, image quality, and the researcher's visual interpretation (Oktaviana 2015).

Terrestrial laser scanner (TLS) has been increasingly applied in cultural heritage documentation because it can provide detailed three-dimensional representations of archaeological sites. In addition to geometric information, TLS data provide intensity information that can be used to characterize the properties of scanned surfaces. Balaguer-Puig et al. (2017) demonstrated that TLS intensity values are influenced by surface characteristics, including colour, texture, roughness, and albedo, as well as acquisition conditions such as the distance between the scanner and the target. These findings indicate that TLS intensity can provide additional information for the interpretation and characterization of surface features in archaeological environments. The potential of TLS intensity for rock art documentation has also been demonstrated by Jalandoni et al. (2021), who showed that intensity information can contribute to the detection and characterization of rock art features that are difficult to identify from conventional visualization alone.

Advances in TLS technology offer an alternative method of digital documentation capable of generating high-precision three-dimensional point cloud data while simultaneously recording radiometric attributes in the form of laser reflectance values (Theodolita et al., 2025). One widely used device is the Leica BLK360, which operates at a wavelength of approximately 830 nm (near infrared), meaning the intensity values it produces can potentially represent differences in the reflectance characteristics of material surfaces (Shan and Toth 2018; Nováková et al. 2022). The use of the Leica BLK360 for documenting cultural heritage has also been demonstrated by Kartini et al. (2023). In addition to generating three dimensional geometric information, TLS intensity attributes also have the potential to be used to identify pigments in rock art based on differences in surface reflectance responses (Jalandoni et al. 2021; Halimun et al. 2025).

Differences in characteristics between two data sets can be statistically evaluated through hypothesis testing, one of which uses the paired observations approach when data

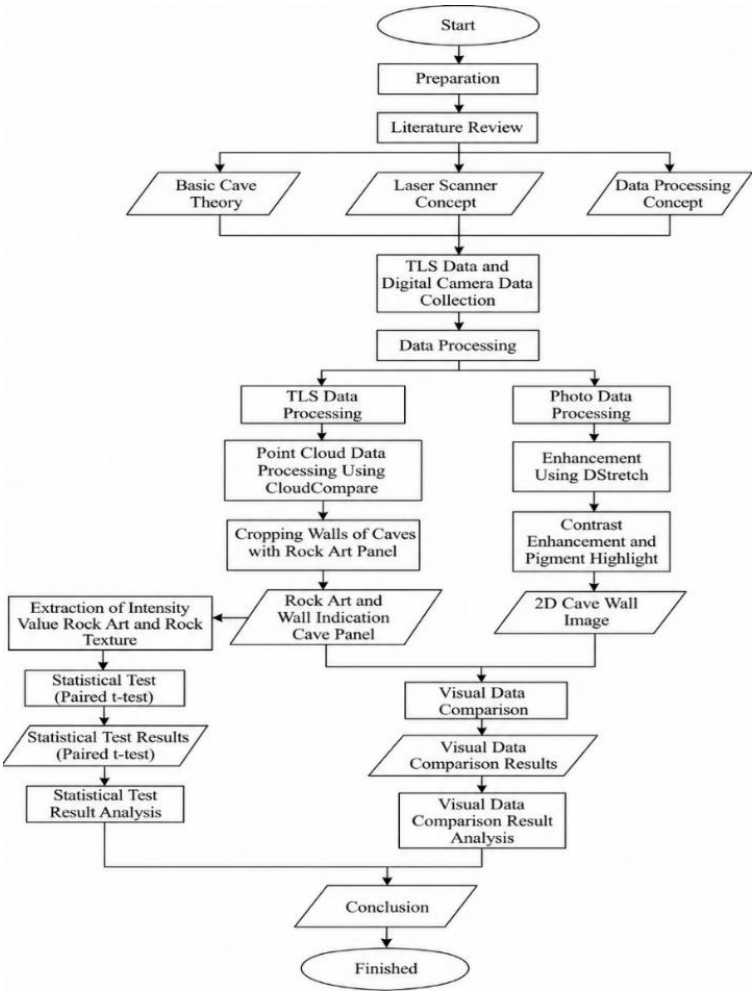
are obtained in pairs of interrelated observations (Walpole et al. 2012; Montgomery and Runger 2018). In this study, the paired sample t-test was used to determine whether the difference in intensity values between areas indicated as rock art and the surrounding rock surfaces was statistically significant.

Nevertheless, most studies still focus on three-dimensional geometric modeling, while the use of intensity values as quantitative parameters to distinguish between rock faces and rock surfaces remains relatively limited, particularly for data acquired using the Leica BLK360 in Indonesian karst cave environments. Furthermore, studies that integrate TLS intensity analysis with visual evaluation using Red, Green, and Blue (RGB) point clouds, camera documentation, and DStretch are still rare. Given these conditions, this study aims to analyze differences in intensity values between rock art and rock surfaces using a Paired Sample T-Test, as well as to compare RGB- and intensity-based point cloud visualizations with digital camera documentation and DStretch to evaluate the potential of TLS intensity attributes as supporting parameters for the digital documentation of rock art.

RESEARCH METHOD

This study utilized a Terrestrial Laser Scanner (TLS) and a professional camera as the primary instruments in the data acquisition process. TLS technology was used to generate a three-dimensional model (point cloud) and obtain intensity values representing surface reflectance characteristics, while professional cameras were used to document the visual condition of the cave wall panels. Data acquisition was conducted at two prehistoric cave sites in the karst region of South Sulawesi, namely Leang Ulu Tedong and Leang Tedongnge. The research stages are presented in Picture 2.

Data acquisition was performed using a Leica BLK360 Terrestrial Laser Scanner (TLS) and a professional digital camera. The Leica BLK360 was used to capture three-dimensional point cloud data along with intensity value attributes representing the laser's reflectance response from the object's surface. This device operates at a wavelength of approximately 830 nm (near infrared/NIR) and is capable of generating high-precision point clouds for the purpose of documenting three-dimensional objects. Visual documentation was performed using a Canon G7 X Mark II at the Leang Tedongnge site and a Canon EOS R at the Leang Ulu Tedong site to obtain high-resolution images as reference data for visual analysis. The specifications of the instruments used in this study are presented in Picture 3.



Picture 2. Study Flowchart.



(a) (b) (c)

Picture 3. Instruments used in the study (a) Leica BLK360 (b) Canon G7 X Mark II and (c) Canon EOS R (Source: leica-geosystems.com; id.canon).

The primary research data consisted of TLS scan results and photographic documentation of cave wall panels suspected of containing rock art. The study was conducted at two prehistoric cave sites in the karst region of South Sulawesi: Leang Ulu Tedong and Leang Tedongnge. From each site, five observation panels were selected to

represent areas of rock art with varying visual conditions. These panels served as the objects of analysis for intensity value extraction, statistical testing, and visual comparisons between RGB-based point clouds, intensity-based point clouds, camera documentation, and image enhancement results using DStretch. The primary data used in this study are presented in Pictures 4 and 5.



(a) (b) (c) (d) (e)

Picture 4. Primary Research Data Leang Ulu Tedong (a) Panel 1 (b) Panel 2 (c) Panel 3 (d) Panel 4 and (e) Panel 5 (Source: Research Center for Archaeometry, BRIN, 2026).



(a) (b) (c) (d) (e)

Picture 5. Primary Research Data Leang Tedongnge (a) Panel 1 (b) Panel 2 (c) Panel 3 (d) Panel 4 and (e) Panel 5 (Source: Research Center for Archaeometry, BRIN, 2018).

Point cloud data processing was performed using Cloud Compare software for panel cropping, RGB- and intensity-based data visualization, and intensity value extraction via the grid sampling method. Meanwhile, photographic data was processed using ImageJ with the DStretch plugin to enhance color contrast, making the rock pigments easier to observe. The processed results from both types of data were then analyzed using a Paired Sample T-Test and compared visually to evaluate the potential of TLS intensity attributes in rock image identification.

RESULTS AND DISCUSSION

Intensity Value Characteristics in Cliff Image Areas and Rock Surfaces

Intensity values were obtained by extracting point cloud data from TLS scans using Cloud Compare software. Extraction was performed on areas of rock outcrops and rock surfaces as a comparison using the grid sampling method, ensuring that the distribution of sample points was relatively uniform and derived from the same surface. This approach aims to minimize the influence of geometric variations so that the intensity values obtained better

represent the surface characteristics of the material. Picture 6 illustrates the grid sampling method.



(a) (b)

Picture 6. Example of Determining *Region of Interest* (ROI) Using the Grid Sampling Method on Panel 2 of the Leang Ulu Tedong Rock Art: (a) Area Indicating Rock Formations and (b) Area Indicating Rock Art.

Picture 6 shows an example of determining the Region of Interest (ROI) using the grid sampling method on areas of the image depicting rocky outcrops and rock surfaces. Each ROI is divided into nine grids (3 × 3); then, a single point is selected from each grid, resulting in nine sample points in the area indicated as a rocky outcrop and nine sample points on the rock surface as a comparison. The points are placed systematically and in pairs with a relatively uniform spatial distribution to minimize the influence of variations in sampling positions. This approach aims to ensure that the differences in intensity values analyzed better represent the surface reflectance characteristics rather than differences in the distribution of observation points.

Tables 1 and 2 present descriptive statistics for intensity values at five observation panels in Leang Ulu Tedong and five observation panels in Leang Tedongnge. The parameters shown include the number of observation points, the average intensity values for the rock art areas and rock surfaces, the difference between the averages of the two data sets, and the range of intensity values from minimum to maximum in each area.

Table 1. Characteristics of the Intensity Values of Rock Art Areas and Rock Surfaces at the Leang Ulu Tedong Observation Panel.

Panel	Number of Points (n)	Average Rock Art Intensity (X)	Average Rock Intensity (Y)	Average Difference (X−Y)	Minimum–Maximum Rock Art Intensity	Minimum–Maximum Rock Intensity
1	9	0.134861	0.222461	-0.087600	0.071519 - 0.187335	0.179034 - 0.290089
2	9	0.179840	0.266923	-0.087084	0.116579 - 0.311574	0.233371 - 0.308782
3	9	0.195525	0.307688	-0.112163	0.139132 - 0.340475	0.236454 - 0.366217
4	9	0.186268	0.331480	-0.145212	0.127977 - 0.292195	0.252262 - 0.369772

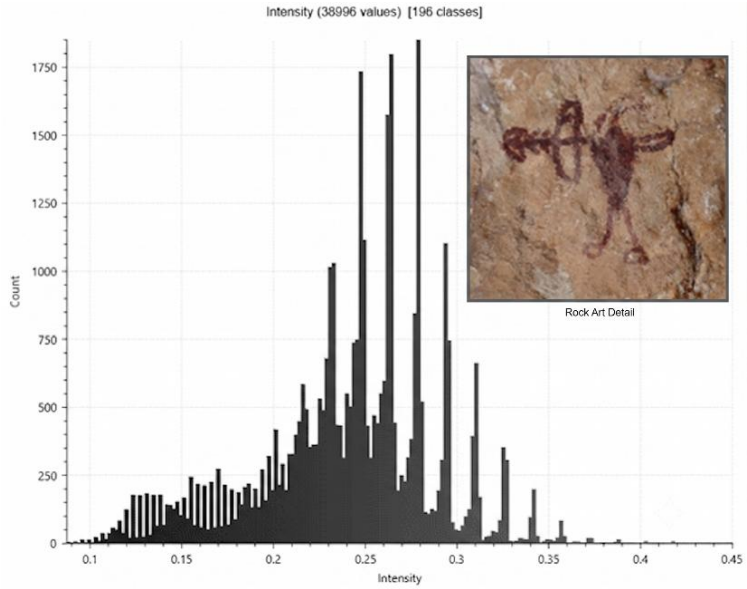
Panel	Number of Points (n)	Average Rock Art Intensity (X)	Average Rock Intensity (Y)	Average Difference (X−Y)	Minimum–Maximum Rock Art Intensity	Minimum–Maximum Rock Intensity
5	9	0.197294	0.324456	-0.127162	0.150668 - 0.234897	0.290517 - 0.386542

Table 2. Characteristics of the Intensity Values of Rock Art Areas and Rock Surfaces at the Leang Tedongnge Observation Panel.

Panel	Number of Points (n)	Average Rock Art Intensity (X)	Average Rock Intensity (Y)	Average Difference (X−Y)	Minimum–Maximum Rock Art Intensity	Minimum–Maximum Rock Intensity
1	9	0.150376	0.343052	-0.192675	0.124056 - 0.190616	0.28426 - 0.390509
2	9	0.197865	0.326462	-0.128596	0.179995 - 0.22649	0.221897 - 0.43389
3	9	0.268439	0.399207	-0.130767	0.186404 - 0.445563	0.316228 - 0.443244
4	9	0.209432	0.364718	-0.155286	0.155291 - 0.282475	0.320058 - 0.405417
5	9	0.228112	0.396200	-0.168088	0.150484 - 0.433646	0.29192 - 0.472068

Based on these two tables, the average intensity values in the rock art areas are consistently lower than the average intensity values on the rock surfaces across all observation panels. At Leang Ulu Tedong, the average intensity of the rock art ranges from 0.134861 - 0.197294, while the average intensity of the rock surface ranges from 0.222461 - 0.331480. Meanwhile, at Leang Tedongnge, the average intensity of the rock art ranges from 0.150376 - 0.268439, while the average rock surface intensity ranges from 0.326462 - 0.399207. The average difference (X−Y) across all panels is negative, indicating that the laser reflectance response in the rock art areas tends to be lower than that of the surrounding rock surfaces.

Picture 7 shows that the visualization of the intensity value distribution is largely concentrated in the range of approximately 0.20–0.30, with the highest frequency occurring in the range of 0.24–0.28. This distribution exhibits a pattern that is not entirely normal, characterized by the presence of several frequency peaks (multimodal) and a distribution that tends to skew toward higher intensity values (right-skewed). This pattern indicates variations in the reflectance characteristics of the observation panel's surface, influenced by differences in material properties and surface conditions.



Picture 7. Histogram of the Intensity Value Distribution in Panel 2 of the Cadas Leang Ulu Tedong Image.

Statistical Evaluation of Differences in Intensity Values Between Surfaces

The descriptive characteristics of the intensity values in the previous subsection indicate a tendency for differences between the areas of rock formations and rock surfaces. To ensure that these differences did not occur by chance, a statistical test was conducted using a Paired Sample T-Test on Table 3 and Table 4. This test was chosen because the intensity data were obtained from pairs of observation points located in relatively the same positions between the rock art areas and the reference rock areas. The hypothesis was tested at a 5% significance level ($\alpha = 0.05$) with a total of nine data pairs for each observation panel.

Table 3. Summary of Results from the Paired-Sample T-Test in Leang Ulu Tedong.

Panel	Number of points (n)	Average Difference ($\bar{d}$)	Calculated t-value	Table t-value (α=0.05)	Decision
1	9	-0.087600	6.530745	2.306	Significantly different
2	9	-0.087084	3.774249	2.306	Significantly different
3	9	-0.112163	5.961540	2.306	Significantly different
4	9	-0.145212	6.744679	2.306	Significantly different
5	9	-0.127162	12.468167	2.306	Significantly different

Table 4. Summary of Results from the Paired-Sample T-Test in Leang Tedongnge.

Panel	Number of points (n)	Average Difference ($\bar{d}$)	Calculated t-value	Table t-value (α=0.05)	Decision
1	9	-0.192675	7.711820	2.306	Significantly different
2	9	-0.128596	5.056541	2.306	Significantly different
3	9	-0.130767	5.846801	2.306	Significantly different
4	9	-0.155286	10.691953	2.306	Significantly different
5	9	-0.168088	5.947371	2.306	Significantly different

The results of the statistical tests at Leang Ulu Tedong are presented in Table 3, while the results of the tests at Leang Tedongnge are shown in Table 4. All observation panels yielded calculated t-values greater than the critical t-value (2.306). At Leang Ulu Tedong, the calculated t-values ranged from 3.774249 to 12.468167, while at Leang Tedongnge they ranged from 5.056541 to 10.691953. The mean difference ($\bar{d}$) across all panels was also negative, indicating that the mean intensity value of the rock art area was lower than the mean intensity value of the rock surface.

Although the statistical analysis consistently showed significant differences across all observation panels, the use of nine paired observation points per panel represents a relatively limited sampling density considering the spatial heterogeneity of cave rock surfaces. Variations in surface texture, pigment distribution, weathering, and other local surface conditions may not be fully represented by the selected sampling points. Therefore, the statistical results should be interpreted within the spatial coverage represented by the sampled ROIs. Future studies should increase the number and spatial density of observation points or apply point-by-point or pixel-by-pixel intensity analysis to provide a more comprehensive representation of intensity variations across the entire rock art surface.

Based on these results, the null hypothesis (H_0) is rejected and the alternative hypothesis (H_1) is accepted for all observation panels. These results indicate that there is a significant difference between the intensity values of the rock art areas and the rock surfaces, both at Leang Ulu Tedong and Leang Tedongnge. The consistency of the test results across all panels indicates that the observed differences in intensity values are not random variations resulting from the sampling process, but rather reflect differences in surface reflectance characteristics recorded by the Terrestrial Laser Scanner (TLS) sensor. These results support the findings of Jalandoni et al. (2021), who stated that intensity information from TLS scans can be used to identify variations in the surface material characteristics of cultural heritage objects. In the context of this study, this capability is demonstrated by significant differences between rock art and rock areas across all observation panels, thereby highlighting the potential of intensity attributes as

quantitative parameters that can support a more objective process of documenting and identifying rock art.

Factors Affecting Variations in Intensity Values

Statistical test results show that intensity values in the rocky areas of the image differ significantly from those of the surrounding rock surfaces. These differences indicate that the laser reflection response recorded by the TLS is influenced by the surface characteristics of the object. According to intensity values represent the backscattered energy that returns to the sensor after interacting with the object's surface. Additionally, Nováková et al. (2022) explain that the magnitude of intensity values is influenced by material properties, surface characteristics, and data acquisition conditions.

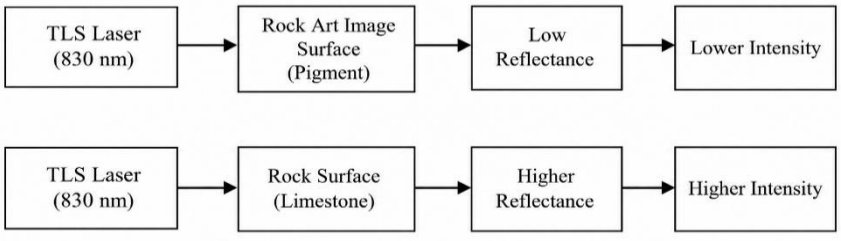
One of the main factors affecting intensity values is material composition. The rocky image area consists of mineral pigments, while the reference area consists of natural carbonate rock. Differences in the reflectance characteristics of these two materials result in different laser reflection responses. In this study, the average intensity values of the rock image areas tended to be lower than those of the rock surfaces, indicating differences in the optical properties between the two surfaces. This finding is consistent with the research by Jalandoni et al. (2021) which showed that TLS intensity attributes can represent variations in surface characteristics based on differences in material reflectance responses.

In addition to material composition, variations in intensity values are also influenced by the physical conditions of the surface, such as surface roughness, weathering, and moisture. Shan and Toth (2018) explain that rougher or moister surfaces tend to reduce the amount of laser energy reflected back to the sensor, resulting in lower intensity values. Scanning geometry factors, such as the laser beam's angle of incidence and scanning distance, can also affect intensity values. However, in this study, these effects were minimized through the application of a grid sampling method and the acquisition of adjacent point pairs—an approach also employed in the study by Halimun et al. (2025).

In tropical karst cave environments, surface conditions such as moisture, weathering crusts, mineral deposits, and biological growth may also modify the laser-return intensity independently of the presence of pigment. These factors may create similar intensity responses between altered unpainted rock surfaces and pigmented areas, potentially leading to false-positive interpretations if intensity is used as the sole indicator of rock art. In the present study, these environmental effects were not independently isolated or mathematically normalized. Therefore, TLS intensity should be interpreted together with visual and contextual information rather than as a standalone indicator of pigment presence. Future studies should incorporate measurements of environmental and

surface conditions and develop appropriate correction or normalization procedures to reduce these effects.

The mechanism behind the difference in laser reflection response between the painted rock areas and the rock surface is illustrated in Picture 8. A TLS laser with a wavelength of 830 nm emitted toward the object's surface will produce a reflectance response that depends on the characteristics of the scanned material. Rock art surfaces composed of pigment layers tend to have lower reflectance, resulting in less reflected energy returning to the sensor and yielding lower intensity values. Conversely, the surrounding rock surfaces have relatively higher reflectance, resulting in greater reflected energy and being recorded as higher intensity values. This illustration is consistent with research findings showing that the average intensity values in the rocky areas of the image are consistently lower than those of the rock surfaces across all observation panels.



Picture 8. Illustration of the Difference in Laser Reflection Responses Between Rock Art Areas and Rock Surfaces

Another factor that influences the intensity value is the characteristics of the instrument used. The Leica BLK360 emits a laser beam at a wavelength of approximately 830 nm, which falls within the near-infrared (NIR) spectrum. At this wavelength, the reflectance response is strongly influenced by the material's reflectance properties toward near-infrared radiation (Shan and Toth 2018; Nováková et al. 2022). Therefore, differences in the composition of pigments and carbonate rocks can result in different intensity responses when scanned using TLS. Although the extraction of intensity values in this study was performed using a grid sampling method with relatively closely spaced points to minimize the influence of scanning geometry, factors such as the laser beam incidence angle and scanning distance still have the potential to cause small variations in the obtained intensity values (Kaasalainen et al. 2011; Shan and Toth 2018).

However, the intensity responses observed in this study are specifically associated with the approximately 830 nm wavelength used by the Leica BLK360. Different pigment materials and archaeological residues may exhibit different reflectance characteristics across the electromagnetic spectrum. Consequently, the intensity differences identified in this study should not be generalized to all pigment types or laser wavelengths. Future studies using multispectral or hyperspectral approaches, as well as

laser scanners operating at different wavelengths, could provide a more comprehensive understanding of the spectral responses of different rock art pigments.

Overall, variations in intensity values result from the interaction between material characteristics, surface conditions, and the TLS scanning system. The consistency of these intensity differences across all observation panels indicates that intensity attributes have the potential to serve as radiometric parameters that can be utilized to support the documentation and identification of rock outcrops (Jalandoni et al. 2021).

Comparison of RGB, Intensity, Camera, and DStretch-Based Point Cloud Visualizations

The visualizations of the documentation results were compared to evaluate each method's ability to represent the surface characteristics of rock images. The comparison was conducted between RGB-based point clouds, intensity-based point clouds, digital camera documentation, and images processed using DStretch. RGB and camera visualizations preserve the natural colors of the surface, while intensity visualizations display the laser energy reflection response of the material. Meanwhile, DStretch enhances color contrast, making the details of the rock surface easier to observe. A comparison of the characteristics of RGB, intensity, digital camera, and DStretch-based point cloud visualizations is presented in Table 5.

Table 5. A Comparison of the Characteristics of Point Cloud Visualizations Based on RGB, Intensity, Digital Camera, and DStretch.

Method	Information Displayed	Advantages	Limitations
RGB point cloud	Natural surface colors on a 3D model	Displays both the 3D shape and the color of objects, allowing for a realistic representation of field conditions	The contrast between the rock and the surrounding terrain is relatively low, so certain details are less prominent
Intensity point cloud	Laser reflectance values (grayscale)	Shows differences in material reflectance characteristics without being influenced by natural color	Does not display color information, so interpretation requires an understanding of the distribution of intensity values
Digital Camera	Color, texture, and surface detail	High resolution and visual representation that most closely matches field conditions	Highly influenced by lighting conditions, shadows, and shooting angle
DStretch	Image resulting from colour contrast enhancement	Improves the visibility of rock features by enhancing spectral contrast	The processed colours no longer represent the original condition of the object

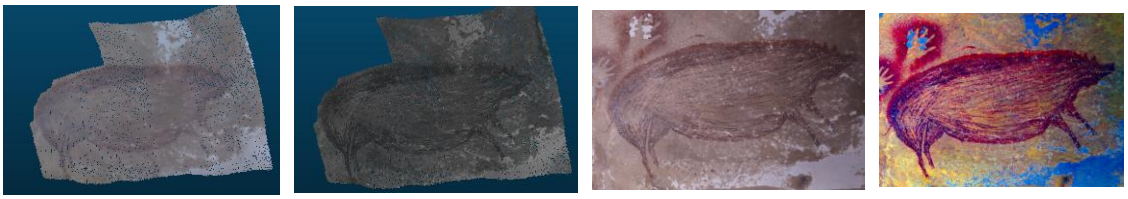
RGB point cloud visualization preserves the natural colors of the surface, allowing for a realistic representation of the object's condition; however, the contrast between the cliff and the rock is relatively low. Intensity visualization displays variations in reflectance values on a grayscale, making it easier to observe differences in surface characteristics without being influenced by color information, as demonstrated by Jalandoni et al. (2021). Documentation using a digital camera produces high textural detail and visual resolution, but image quality is greatly influenced by lighting conditions during acquisition. Meanwhile, Defrasne (2014) explains that DStretch can enhance color contrast, making rocky areas in the image easier to identify through spectral transformation, although the resulting colors no longer represent the object's natural condition.

The visualization results in Picture 9 and Picture 10 show the differences in the characteristics of the representations produced by each method on the observation panel.



(a) (b) (c) (d)

Picture 9. Comparison of Visualizations: (a) RGB-Based Point Cloud, (b) Intensity-Based Point Cloud, (c) Digital Camera Documentation, and (d) DStretch Processing Results, in Panel 5 of the observations at Leang Ulu Tedong.



(a) (b) (c) (d)

Picture 10. Comparison of Visualizations: (a) RGB-Based Point Cloud, (b) Intensity-Based Point Cloud, (c) Digital Camera Documentation, and (d) DStretch Processing Results, in Panel 2 of the observations at Leang Tedongnge.

RGB visualizations and camera documentation display surface conditions in their original colours, while intensity visualizations simplify the information into tonal variations that represent the laser's reflectance response to surface materials. On the other hand, DStretch-processed images enhance color contrast through spectral transformation, making the boundaries between rocky areas and rock surfaces appear clearer (Defrasne

2014). These differences indicate that each method serves a complementary function, with TLS intensity data providing additional radiometric information not obtained through conventional photographic documentation, as demonstrated in the study by Halimun et al. (2025).

RGB-based point cloud visualization preserves the natural colours of the surface, enabling a realistic three-dimensional representation of the object's condition. However, the contrast between the rock-face areas and the rock surface is relatively low, so the boundaries between surfaces are not always clearly visible. Therefore, RGB visualization is more suitable for documenting the existing condition of an object (Kartini et al. 2023).

Intensity-based visualization displays differences in laser energy reflectance values as a grayscale image. Compared to RGB visualization, this method shows variations in surface reflectance characteristics more clearly, making it easier to observe differences between rocky and non-rocky areas in the image. These results are consistent with the statistical tests in this study and align with the findings of Jalandoni et al. (2021) which show that TLS intensity attributes can be used to distinguish surface material characteristics.

Documentation using a digital camera produces a visual representation that most closely resembles field conditions, with high detail in texture and color. However, image quality is greatly influenced by lighting conditions, shadows, and the angle of the shot, so the legibility of rock images can vary from panel to panel (Oktaviana 2015).

Processing results using DStretch provide the greatest visual contrast enhancement compared to other methods. According to Defrasne (2014), this technique can clarify areas of rock features that are less visible in the original image through spectral color transformation, making it effective for improving pigment readability. However, the resulting colors are the product of digital processing and do not represent the actual color conditions in the field.

Overall, the four methods have complementary functions in rock image documentation Shan dan Toth (2018) explain that TLS intensity data is a radiometric attribute that can be utilized as supplementary information in addition to three-dimensional geometry, while Jalandoni et al. (2021) demonstrate that this attribute has the potential to be used to distinguish surface material characteristics. Thus, the RGB point cloud provides a three-dimensional representation with natural colors, intensity data provides more objective radiometric information, digital cameras produce realistic visual documentation, and DStretch improves image readability by enhancing contrast. The combination of these four methods results in more comprehensive documentation compared to using any single method in isolation.

The Potential of Using TLS Intensity for Image Documentation and Identification

The research results show that the intensity attribute in TLS data has the potential to serve as radiometric information that supports the documentation and identification of rock images. This is evidenced by the results of the Paired Sample T-Test, which indicate a significant difference between the intensity values of rock image areas and rock surfaces across all observation panels. These differences indicate that intensity values can represent variations in surface reflectance characteristics and can therefore be used as a quantitative parameter to distinguish between the two types of surfaces. This finding aligns with the research by Jalandoni et al. (2021) which states that TLS intensity attributes can be utilized to identify differences in material characteristics of cultural heritage objects.

The use of intensity values is not intended to replace photographic documentation but to complement it. The integration of RGB point cloud visualization, intensity, digital camera imagery, and DStretch results in more comprehensive documentation, as each method offers complementary strengths. RGB provides color and three-dimensional geometric information; the camera produces realistic visuals; DStretch enhances the visibility of pigments; and intensity provides more objective radiometric information regarding surface characteristics.

Although intensity values are still influenced by factors such as material characteristics, surface roughness, humidity, and scan geometry (Shan and Toth 2018), the results of this study indicate that TLS intensity attributes have the potential to serve as supporting parameters in the documentation and identification of rock images. This potential can be further developed through the normalization of intensity values or the application of automatic classification methods in future research.

Another important direction for future research is the radiometric normalization of TLS intensity values. Although spatially adjacent paired samples were used in this study to reduce geometric variation, the measured intensity values were not mathematically corrected for differences in scanning distance and laser incidence angle. Future studies should implement correction or normalization algorithms for these geometric factors to improve the comparability of intensity values acquired from different scanner positions and scanning configurations.

The quantitative differences in intensity values identified in this study also provide a basis for the development of automated classification approaches. Future research could integrate RGB information and TLS intensity attributes as input features for supervised machine learning models. With a larger and more representative training dataset, such an approach could potentially support the automatic mapping and

classification of rock art, including pigments that have undergone substantial visual degradation.

In addition, comparative measurements using instruments operating at different wavelengths could further improve the characterization of rock art materials. Testing wavelength regions such as green, red, and short-wave infrared (SWIR), as well as integrating multispectral or hyperspectral data, could help characterize wavelength-dependent reflectance responses and contribute to establishing spectral signatures for different pigment materials. This approach may improve the discrimination of pigment types that cannot be consistently differentiated using the single 830 nm wavelength employed in the present study.

CONCLUSION

This study demonstrates that TLS intensity data have potential as a complementary radiometric parameter for the documentation and identification of rock art. Across all observation panels at Leang Ulu Tedong and Leang Tedongnge, the Paired Sample T-Test showed significant differences between the intensity values of rock art areas and surrounding rock surfaces, with rock art areas consistently exhibiting lower mean intensity values. These findings indicate that TLS intensity can capture differences in surface reflectance characteristics and provide quantitative information that complements conventional visual documentation. The comparison of RGB point clouds, intensity-based point clouds, digital camera images, and DStretch-enhanced images further demonstrates that these methods provide complementary information on geometry, natural colour, radiometric response, and pigment visibility, respectively. However, TLS intensity should not be interpreted as a standalone indicator of pigment presence because the measured values may also be affected by surface and environmental conditions, scanning geometry, and the specific 830 nm wavelength of the Leica BLK360. Therefore, integrating TLS intensity with visual and contextual information provides a more comprehensive approach to rock art documentation, while future improvements in radiometric normalization, spatial sampling density, multispectral analysis, and automated classification may further enhance its application for rock art identification and cultural heritage documentation.

DECLARATION OF AI USE

During the preparation of this manuscript, the authors utilized ChatGPT and Claude to assist with language translation, refinement of sentence structure, and improvement of readability. The authors subsequently reviewed and edited all AI-assisted content as necessary and assume full responsibility for the accuracy, integrity, and final content of the published work.

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