LiDAR Intensity Variability in UAV-Based Agricultural Monitoring: Insights from a Winter Wheat Field Trial

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Abstract: This study examines the UAV LiDAR intensity readings for agricultural monitoring of a winter wheat field trial. Employing a Riegl MiniVUX-1-UAV on a DJI Matrice 600 pro UAV, the research analyzes the influence of incidence angles on LiDAR intensity. It compares the LiDAR estimated reflectance with ground-based measurements of canopy reflectance in the same wavelength using a field spectroradiometer. The study reveals a strong correlation ($R^2 = 0.87$) between incidence angle and LiDAR intensity for steep angles (over 20°). Whereas a good correlation was found between the sun reflectance and the LiDAR based reflectance over metal calibration targets, those measurements were not significantly correlated over the winter wheat plots. However, these results only stem from a single campaign relatively early in the growing stage. Further research is needed to understand the complex interactions of UAV LiDAR with winter wheat plants compared to sunlight reflectance.

1. Introduction

The integration of Light Detection and Ranging (LiDAR) on Unmanned Aerial Vehicles (UAVs) has provided new opportunities for enhancing precision agriculture practices (RIVERA et al., 2023). LiDAR, as an active sensor, offers substantial potential in agricultural monitoring due to its operational independence from atmospheric and illumination conditions. HÜTT et al. (2023) presented a methodology that uses LiDAR metrics estimated from UAV LiDAR for agricultural applications, illustrating its potential to enhance the monitoring of winter wheat.

Previous studies have demonstrated a significant correlation between plant structural properties, such as plant height, and the estimation of various crop traits. These traits can be derived from UAV LiDAR data and are increasingly accessible through 3D reconstruction methods like Structure from Motion (SfM). Additionally, passive reflectance measurements of sunlight, extensively utilized in determining key crop traits such as biomass (BAZZO et al., 2023), can be effectively combined with plant structural properties, including plant height, as demonstrated by TILLY et al. (2015).

While UAV LiDAR's potential in agricultural monitoring is already recognized (MONTZKA et al. 2023), the specific utility of LiDAR intensity measurements in precision agriculture has yet to be fully established. UAV LiDAR, particularly when using an infrared laser, holds potential in agricultural monitoring. GENÉ-MOLA et al. (2019), for example, used LiDAR reflectance to differentiate different apple types by analyzing fruit reflectance with different LiDAR wavelengths.

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 DOI: 10.24407/KXP:1885708025

This study's key question is the correlation between LiDAR intensity and the measurement of reflected sunlight. Both methods aim to estimate surface reflectance, raising the question: shouldn't their wavelengths yield comparable reflectance values over plants if their wavelengths are similar? Furthermore, the incidence angle - the angle at which the LiDAR signal strikes the plant surface- is highly important in this aspect (KAASALAINEN et al. 2018). As HU et al. (2020) emphasized, accurately accounting for this angle is vital for precise reflectance measurements of plants.
Therefore, this research aims to explore UAV LiDAR reflectance measurements in winter wheat monitoring. Specifically, it examines the correlation with passive sunlight reflectance and evaluates the influence of incidence angle on the accuracy of these measurements.

2. Material and Methods

2.1 Study site and field trial setup

The study site was an experimental field at the Campus Klein-Altendorf (CKA, www.cka.uni-bonn.de), approximately 20 km southwest of Bonn, Germany (50.616160° N, 6.995049° E). The region experiences a warm temperate climate with mild summers and winters and an average annual temperature of around 9.4 °C (UNI BONN 2024). The area receives consistent annual precipitation of about 603 mm, spread relatively evenly throughout the year.
The winter wheat field trial at CKA consists of 120 plots, each measuring 7 m × 1.5 m, organized in five rows. The trial design includes buffer plots to minimize border effects and contamination between nitrogen treatments. These treatments are 0, 120, and 240 kg N ha^{-1}, each applied across the rows, encompassing six different winter wheat varieties.
During the UAV survey, six metal calibration panels, each measuring 50 × 50 cm, were strategically placed adjacent to the field. These panels varied in shades from black to white, providing a range of reflectance levels for calibration purposes. Additionally, for precise georeferencing, five checkerboard targets (60 × 60 cm) with white reflective foil were strategically positioned at the corners of the field trial.

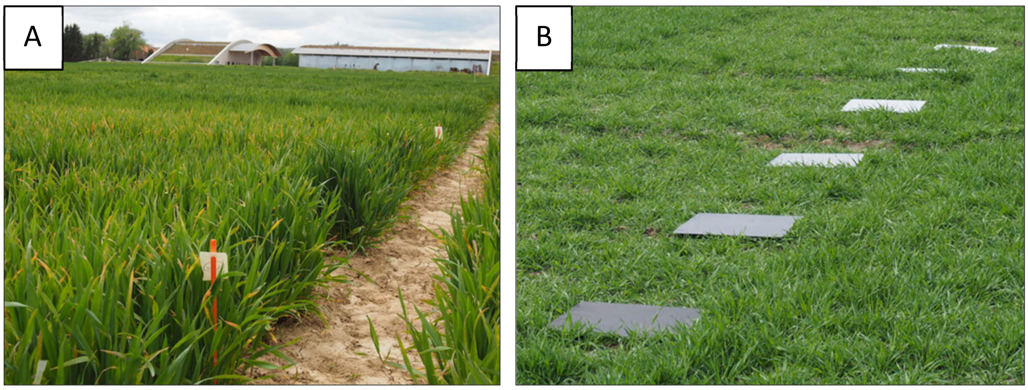

Fig. 1: A: Close-up view of the winter wheat field trial on the day of the UAV LiDAR flight (10.05.2021). B: Calibration panels positioned next to the field

2.2 Measurements with the ASD FieldSpec3

The ASD FieldSpec3 (FS3) is a multifunctional field spectrometer tailored for hyperspectral remote sensing applications in field conditions. It captures spectral data across a continuous range from 350 to 2500 nm with a data acquisition time of one second per spectrum. This device measures and records the shape of the radiant energy, termed radiance, storing the data as spectral signatures (ASD INC. 2010). The spectral resolution varies with the measured wavelength, achieving a resolution of 3 nm full width at half mean (FWHM) at 700 nm, decreasing to 10 nm (FWHM) at 1400 nm and 2100 nm. The FS3 incorporates a fiber optic cable, which conveys the measured radiant energy to the internal holographic diffraction grating that separates and reflects the wavelength components for their independent measurement.

The data collection was conducted on May 12, 2021, from 11:30 AM to 1:39 PM. This timing was strategically chosen to align with the solar noon to minimize shadow effects and maximize solar intensity. Before initiating the sample collection, the FS 3 spectrometer was switched on and warmed up for at least 30 minutes.

The FS3 measurements were conducted by a two-person team. One person carried the field spectrometer on their back and held a pole. This pole was equipped with a pistol grip attached to the FS 3's fiber optic cable, positioned one meter above the plant surface. These bare fibers have a 25° field of view. Therefore, the approximate diameter of the circular footprint measured by the spectrometer from this height is around 44 cm (ASD INC. 2010). Measurements were conducted solely in plots designated for later destructive sampling, located in rows 2 and 4. These plots included all six cultivars under each of the three nitrogen treatments. Each plot was measured six times to ensure consistency. Calibration of the FS3 was performed every 10 minutes or more frequently if there were changes in lighting conditions.

2.4 UAV LiDAR flight

The DJI Matrice 600 Pro UAV, equipped with the Riegl MiniVUX-1-UAV laser scanner, was utilized for UAV LiDAR data collection. The relevant parts of the UAV flight were conducted at a reduced altitude of 15 meters and a low speed of 3 m/s on May 10, 2021, from 12:08 to 12:13 PM. During the flight, the field trial was overflown ten times (Fig. 2). This setup was chosen to induce varied incidence angles during the scanning of the wheat plots, hypothesizing a significant influence on LiDAR intensity values. The low flight speed aimed to increase point density, thus potentially enhancing the quality of the data collected.

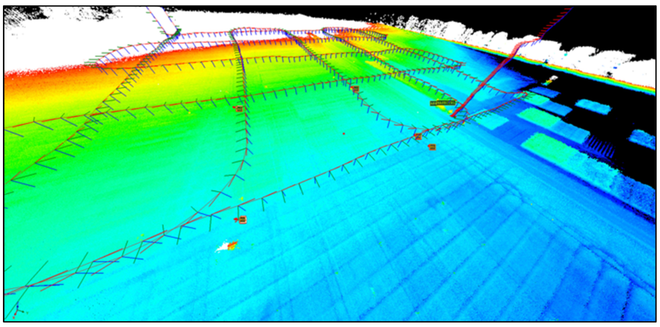

Fig. 2: 3D visualization of the UAV flight performed over the wheat field trial.

2.5 Processing and analysis of the UAV LiDAR data

The UAV flight trajectory was accurately estimated by integrating the GPS data from the UAV LiDAR system with correction data from the DGPS Base Station positioned adjacent to the field at a known coordinate point. The correction process was conducted using PosPac software (Version 8.4., Applanix, Richmond Hill, Ontario, Canada). Subsequent extraction of the LiDAR point cloud occurred within the Riegl processing software RiProcess (Version 1.9.2.2,

RIEGL, Horn, Austria). In this process, the reflectance is estimated for each LIDAR point based on the intensity of the LiDAR measurements.
To enhance the spatial accuracy of the point cloud, the known positions of five checkerboard targets (60 × 60 cm), placed around the field during the survey were utilized within RiPrecision software (Version 1.4.2, RIEGL, Horn, Austria). These target positions were measured using the same TOPCON DGPS (GR-5) system that collected the correction data but operated in a Base/Rover configuration.
All ten overpasses of the UAV were used to generate a separate point cloud, with turning and non-straight parts of flight being excluded from further analysis. The data from one overflight is shown in Fig.3. All point clouds from the individual overflights were then analyzed using a script in LAStools (Version: 20230313, rapidlasso GmbH, Gilching, Germany):

- Point Cloud Filtering: The point cloud underwent a filtering process, where any areas with a point density lower than 5 points per square meter were excluded from further analysis.
- Ground Classification: We utilized the LASground_new tool for ground classification. The default settings were retained, except for the offset parameter, which was reduced to zero to fit the specific characteristics of plant monitoring.
- Canopy Metric Extraction: LAScanopy was the chosen tool for extracting point cloud metrics. This was explicitly applied to the calibration panels and the plots where the Field Spectroradiometer 3 (FS3) measurements occurred.
- Angle Analysis Workflow: The standard LAS software does not include an angle analysis. To incorporate this, we modified the workflow by replacing the intensity attribute with the angle attribute, allowing for the analysis of angles alongside the standard metrics.

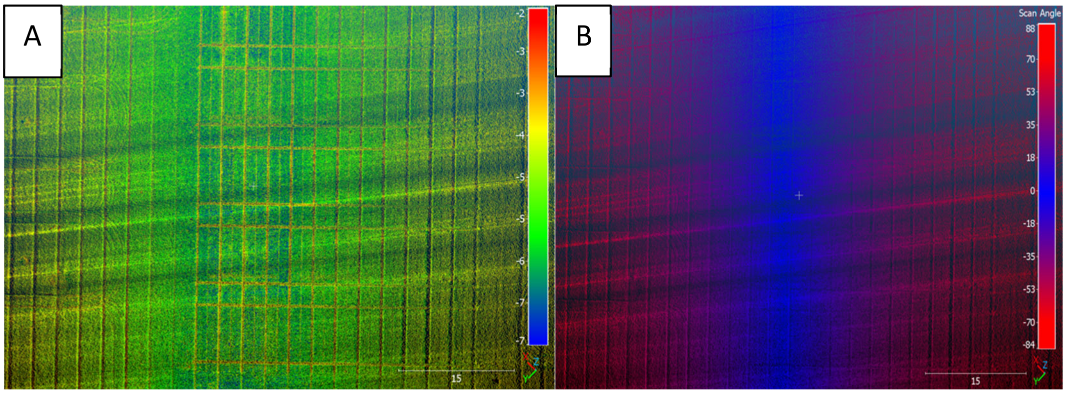

Fig. 3: A: Top View Point cloud reflectance visualization of a single flight strip. The flight direction was vertical to the image. B: Scan angle of the same strip as in A.

2.6 Analysis of the field spec spectra and combination with UAV LiDAR metrics

Reflectance measurements for the calibration panels, obtained from a prior campaign, were correlated with LiDAR-derived point cloud metrics. The LiDAR points on these panels were processed as detailed previously and cross-referenced with the FS3-measured sunlight reflectance at 905 nm, matching the UAV LiDAR system's laser wavelength (Riegl 2019). LiDAR observations with an incidence angle higher than 60° were left away for this comparison.

Spectral analysis of the FS3 data over the winter wheat trial was conducted using the hsdar package in R (LEHNERT et al. 2022). Each spectrum underwent smoothing with a Savitzky-Golay filter, set to a filter length of 25. Subsequently, we extracted the reflectance at the key 905 nm wavelength from every spectrum across the observation plots and calibration panels. Data from two plots were omitted due to anomalously high spectral variation.
The RS3 reflection data was then combined with each LiDAR observation. This comparison aimed to understand the relationship between LiDAR intensity, RS3 optical reflectance, and LiDAR angle under similar conditions.

3. Results

3.1 UAV LiDAR reflectance of the calibration panels

Reflectance values for the calibration panels obtained from the FS3 and UAV LiDAR closely matched, with most data points clustering near the 1:1 line (Fig. 4). The UAV LiDAR reflectance values for panels with higher reflectivity were systematically lower than those measured by the FS3, with this underestimation becoming more pronounced at increased incidence angles.

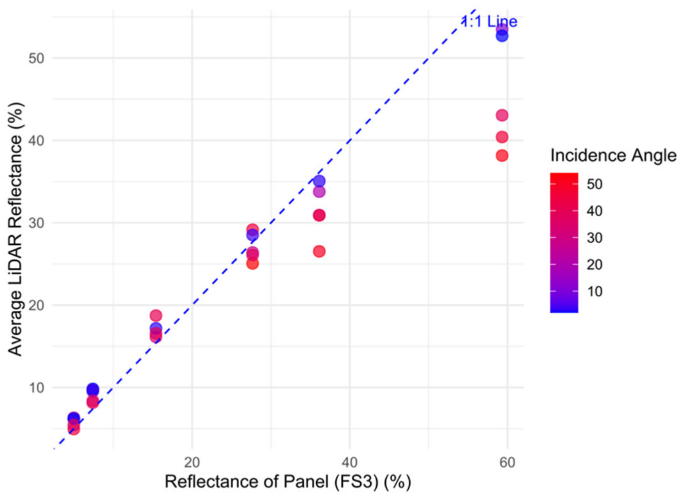

Fig. 4: A scatter plot showing the relationship between FS3 and mean UAV LiDAR reflectance values. Only LiDAR observations with an incidence angle lower than 60° were considered

3.2 UAV LiDAR reflectance angle correlation over winter wheat field plots

The analysis indicated a strong correlation ($R^2 = 0.87$) between the UAV LiDAR incidence angle and the reflectance values for angles greater than 20° (Fig. 5).

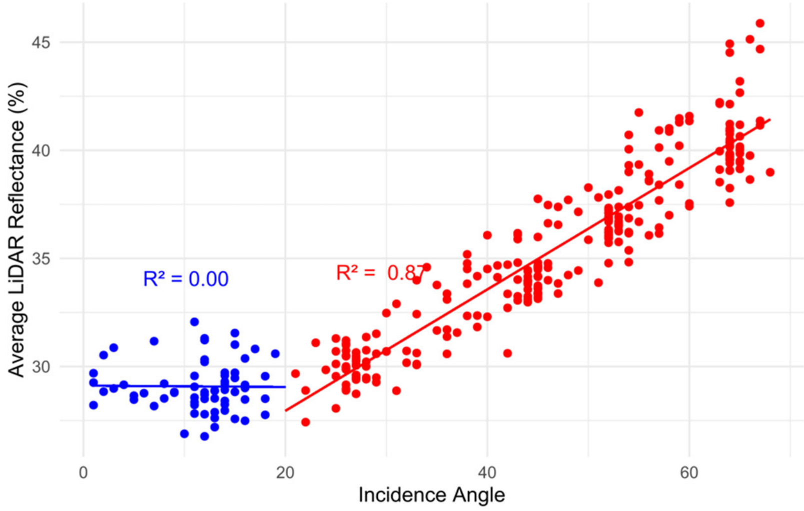

Fig. 5: Comparison of the average LiDAR reflectance in each plot with the incidence angle

3.3 Reflectance comparison of the UAV LiDAR and the FS3

If all incidence angles were considered, no significant correlation was found between the Fieldspectroradiometer reflectance at 905 nm and the UAV LiDAR reflectance. When the analysis was restricted to incidence angles lower than 20°, a slight negative linear correlation ($R = -0.43$, $R^2 = 0.19$) was observed, as depicted in Figure 6. The UAV LiDAR reflectance exhibited limited variation and was generally lower than the FS3-measured reflectance.

3.4 Reflectance and Crop Treatment Relationship

Fig. 6 also displays a pattern relating reflectance to winter wheat treatment. Plots without nitrogen treatment (represented by green dots in Fig. 6), characterized by lower plant density and biomass, corresponded to higher UAV LiDAR reflectance and lower FS3 reflectance. Conversely, plots with the highest nitrogen treatment showed an opposite trend, with some anomalies.

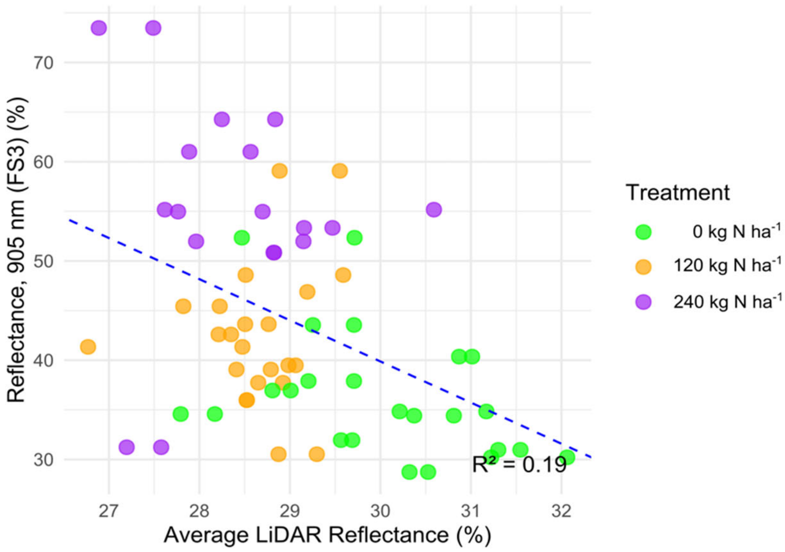

Fig. 5: Mean sunlight reflectance measured by the FS3 and Average LiDAR reflectance for measurement with an incidence angle of < 20°

4 Discussion

4.1 Incidence angle's influence on LiDAR intensity

Our analysis revealed a strong correlation between incidence angle and LiDAR intensity, especially for angles over 20°. Notably, for lower off-nadir angles (below 20°), the incidence angle does not significantly influence LiDAR reflectance. This insight is crucial for precision agriculture, highlighting the importance of strategic UAV flight path planning. Hütt (2023) underscored this point by advocating for higher-altitude UAV flights in monitoring winter wheat with LiDAR. The rationale behind this recommendation aligns well with the present study's findings; higher flights tend to produce lower incidence angles over a larger area, enhancing the uniformity and reliability of LiDAR intensity readings. Thus, understanding the influence of incidence angle is not just a technical detail but a key factor in optimizing LiDAR-based agricultural surveys for accuracy and comprehensiveness. This finding suggests that to maximize the accuracy of reflectance values, UAV flight paths should be designed to maintain incidence angles below 20°.

4.2 Comparing passive and active reflectance measurements

One intriguing aspect of the study is comparing passive optical reflectance (sunlight reflection) and active LiDAR reflectance. Although these are fundamentally different processes, the calibration panels showed similar reflectance values for both methods. This observation raises questions about the potential for using LiDAR reflectance in analyzing plant characteristics. Our findings indicate that plots with lower biomass and less density, which notably did not receive nitrogen treatment, exhibit higher LiDAR reflectance. A possible hypothesis is that higher reflectance observed in plots with lower biomass and less density might be influenced by a higher ground reflection, which was already made by Hütt et al. (2023).

4.3 Methodological considerations

Our study analyzed data from individual UAV overpasses, unlike Hütt et al. (2023), who used a combined point cloud from multiple overpasses and higher altitude flights. This approach allowed us to examine the influence of incidence angle with more specificity. However, it also limited the number of data points available for analysis, potentially affecting our conclusions' robustness and limiting the ability to estimate other crop traits from the structural properties derived from the point cloud. Furthermore, the findings stem from a single measurement campaign early in the vegetation period. Repeated analysis, including dates later in the growing season, is needed to get more robust insights.

5 Conclusion and Outlook

In conclusion, this study underscores the nuanced role of incidence angle in UAV LiDAR intensity measurements in agricultural settings. It opens new opportunities for further exploration into using UAV LiDAR in precision agriculture. This includes aspects such as optimizing flight paths and interpreting reflectance data. An exciting prospect for future studies is the potential for data fusion with multispectral datasets like the one provided by JENAL et al. (2021). Future studies should also investigate varying conditions across different seasons and growth stages over multiple years to better understand UAV LiDAR's utility in agriculture.

6 Literature

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