SoftwareX 30 (2025) 102150

Contents lists available at ScienceDirect

SoftwareX

journal homepage: www.elsevier.com/locate/softx

ReflectDetect: A software tool for AprilTag-guided in-flight radiometric calibration for UAV-mounted 2D snapshot multi-camera imagery

Luca Joshua Francis [a], Lewis Gabriel B. Geissler [a], Nathan Okole [b], Bela Gipp [a], Cyrill Stachniss [c], René Heim [b,c,*]

[a] Institute of Computer Science, University of Göttingen, Goldschmidtstraße 7, 37077 Göttingen, Germany
[b] Sensors & Data Analysis, Institute of Sugar Beet Research, Holtenser Landstraße 77, 37079 Göttingen, Germany
[c] Photogrammetry & Robotics Lab, University of Bonn, Nussallee 15, 53115 Bonn, Germany

ARTICLE INFO

Keywords:
Agriculture
Drones
Python
Radiometric calibration
Reflectance
Remote sensing
Vegetation science

ABSTRACT

Unmanned Aerial Vehicles (UAVs) equipped with optical sensors have transformed remote sensing in vegetation science by providing high-resolution, on-demand data, enhancing studies in forestry, agriculture, and environmental monitoring. However, accurate radiometric calibration of UAV imagery remains challenging. A common practice, using a single calibration target while holding the UAV-mounted camera close above it, is being criticized as the hemisphere is invisibly shaded and the reference images are not collected under flight conditions. *ReflectDetect* addresses these challenges by allowing in-flight radiometric calibration through automated detection via two different approaches: 1) a geotagging approach leveraging high-precision coordinates of the reflectance targets and 2) AprilTag based detection, a visual fiducial system frequently used in robotics. A brief statistical analysis and example data is provided to reassure the quality of the calibration results. ReflectDetect is available through a command-line interface and open-source (https://github.com/reflectdetect/reflectdetect). It now enables users to design new in-flight calibration studies to eventually improve radiometric calibration in applied UAV remote sensing.

1. Metadata

Nr	Code metadata description	*Metadata*
C1	Current code version	*v0.1.13*
C2	Permanent link to code/repository used for this code version	https://github.com/reflectdetect/reflectdetect
C3	Permanent link to reproducible capsule	*n.a.*
C4	Legal code license	GPL-3.0 license
C5	Code versioning system used	*git*
C6	Software code languages, tools and services used	*Python, VBScript*
C7	Compilation requirements, operating environments and dependencies	*ExifTool* (https://exiftool.org/)
C8	If available, link to developer documentation/manual	https://reflectdetect.readthedocs.io/en/latest/
C9	Support email for questions	lucajoshua.francis@stud.uni-goettingen.de, okole@ifz-goettingen.de, rheim@uni-bonn.de

2. Motivation and significance

UAVs have transformed remote sensing in vegetation science by offering centimetre-level spatial resolution, on-demand temporal flexibility, and multi-sensor integration that surpass close-range, airplane-based, and satellite-based methods [1]. UAVs equipped with optical sensors produce multi-band raster data, enabling relevant applications in forestry, agriculture, and environmental studies, such as plant health monitoring, biomass estimation, and crop yield prediction, supporting sustainable management practices [2]. To effectively study these dynamic landscapes, consistent and comparable time-series data are essential, which is achieved through accurate radiometric calibration and the resulting reflectance factors. Currently, the majority of studies are implementing consumer-friendly 2D snapshot multi-cameras such as the Parrot Sequoia, MicaSense RedEdge and Maia S2 that are all available for €15,000 or less. However, the normalization of dynamic illumination conditions in UAV remote sensing still poses a problem as the calibration methods that these commercial systems are complementing

* Correspondence: René Heim, Photogrammetry & Robotics Lab, University of Bonn, Nussallee 15, 53115 Bonn, Germany.
E-mail address: rheim@uni.bonn (R. Heim).

https://doi.org/10.1016/j.softx.2025.102150
Received 29 November 2024; Received in revised form 12 March 2025; Accepted 24 March 2025
Available online 28 March 2025
2352-7110/

are not sufficient [1,3].

A common method to obtain reflectance factors is the empirical line method (ELM), which involves placing a set of radiometric reference targets in the studied scene and using their known spectral reflectance response, in combination with an absolute radiometric calibration, to convert digital sensor readings to reflectance factor values [1]. Although some studies propose multipoint ELM-based methods [21–23], in practice, the simplified ELM (sELM), which uses only a single reflectance target, is more commonly applied. The sELM requires users to hold their drone, with the camera attached, close to the calibration target. If this is done without care, direct shading can occur and severely affect the calibration result. However, even when direct shading is avoided, the drone covers a large part of the hemisphere, blocking the diffuse and direct portions of light that the camera should fully perceive at that moment [1]. Further, to account for atmospheric and topographic variations, at least two reference targets should be used to cover the desired range of reflectance values, typically 0–50 % for vegetation [1,4]. Using more than two targets reduces uncertainties and helps assess sensor linearity, improving the accuracy of reflectance measurements. To avoid these problems for robust calibration, in-flight calibration is suggested [5–8]. Most methodologies developed for in-flight radiometric calibration are still predominantly manual or semi-automated [3], despite the fact that manual and semi-automated methodologies are inherently time-consuming and susceptible to error. This underscores the necessity to develop fully automated calibration workflows. Although approaches such as the one proposed by Ban and Kim [9], using homogeneity and variance filtering for automated reflectance target detection and the ELM for calibration—are steps toward automation, they are still semi-automated and not open-source, limiting their broader adoption.

To overcome the limitations of the sELM for radiometric calibration, we are proposing *ReflectDetect,* a fully automated software tool that allows in-flight radiometric calibration in UAV remote sensing. It offers two modules to facilitate the detection of custom-built or commercially available reflectance targets. The first module harnesses the now frequently used and widely available professional-grade sub-centimeter accuracy of RTK-GNSS receivers and allows the automated detection of the user's calibration targets. While this module integrates well in the later stages of the image processing pipeline when raw images have already been processed into georeferenced orthophotos, the second module allows for calibration directly using the raw images at the start of the pipeline. It innovatively uses AprilTags, a visual fiducial system that is frequently used in robotics, for target detection [10]. AprilTags robustness against false positive detections makes them ideal for UAV mapping applications and calibration target detection. Both modules allow for calibration of the collected imagery whenever calibration targets are visible in the scene, minimizing uncertainty caused by environmental variability during the flight mission. In cases where targets are not present in the imagery, *ReflectDetect* uses linear interpolation between the calibration values of the nearest available images that contain targets to find consistent calibration data across varying conditions mid-flight. This method assumes that environmental factors, such as cloud cover and lighting, change gradually, making linear interpolation a reasonable approach to bridging calibration gaps. While rapid, localized changes could introduce some deviations, linear interpolation remains the most effective balance between accuracy and practicality, as alternative methods such as averaging calibration values or employing higher order interpolation either ignore gradual variations or demand more frequent calibration events than are available. Packaged in a user-friendly, open-source command-line interface (CLI), this solution simplifies the calibration process, reduces human error, and enhances efficiency.

3. Software description

ReflectDetect enables users to automatically detect reflectance targets within aerial imagery and use the extracted intensities of these targets for radiometric calibration. *ReflectDetect* does not evaluate the quality of reflectance targets. Therefore, some general knowledge about radiometric calibration is helpful when using this tool. The *ReflectDetect* workflow and functions, written in Python 3, are outlined below. For a comprehensive overview of the implemented functions, the user can consult the documentation in the online repository[1] (https://github.com/reflectdetect/reflectdetect). Example datasets for each module (i.e. geolocation module and AprilTag module) are provided for reproducible testing. In the example data, 1.4 × 1.4 m square-shaped reflectance targets at 3 %, 21 % and 56 % have been used (Fig. 1). Either of the two modules, depending on the type of input, can be used to detect calibration targets in the imagery. The intensities of the calibration targets are extracted in each image where geolocations or AprilTags are detected. Thus, each image can be radiometrically calibrated individually using our multipoint ELM. When some images do not contain calibration targets, linear interpolation is used to find approximate intensity values. The calibrated reflectance images are then saved for further analysis.

3.1. Software architecture

3.1.1. The geolocation module

The geolocation module (Table 1) works on georeferenced orthophotos as band-stacked images and leverages user-provided precise geographic coordinates of the calibration targets. In testing, the photogrammetry software Metashape[2] was used to generate stacked and georeferenced orthophotos. This module supports any polygonal target, provided that all corner coordinates are accurately measured and supplied. *ReflectDetect* begins with the identification of calibration targets within the orthophotos by examining the geotagged coordinates of each corner of the reflectance targets. If a target is only partially visible, our method might try to collect intensity values outside the data region of the image, because the .tiff image files typically used to save the georectified image data can include regions without data. To ensure these irrelevant values can be excluded from further calculations by our program, an appropriate no-data value (e.g., 0, 65,535) based on the value of the no-data regions in the .tiff files needs to be set by the user. For each image with visible targets, the system extracts the mean intensity values for each spectral band at the target's location. To save memory during execution, the dataset is split into batches of the minimal size that still allows for correct interpolation.

3.1.2. The AprilTag module

By deploying AprilTags containing unique IDs next to the calibration targets in the experimental scene, each target can be detected using its associated AprilTag. Thus, the AprilTag module (Table 2) allows for target detection and calibration without the need for preprocessing of images. A detector[3] based on Wang and Olson [10] scans each image for AprilTags and *ReflectDetect* associates the detected tags with the calibration targets using the predefined mapping of IDs to targets. The tag is positioned adjacent and centered to the side of its associated target, making it possible to find the corners of the target using vector math based on the known dimensions of the tag and target. Because of this approach, targets are expected to be rectangular. Since each target is linked to a unique ID, they can be independently detected.

In the example data, the tag family tag25h9[4] is used. All tags were printed at A1 size. These properties are based on preliminary manual testing, as well as reported maximum detection ranges.[5] While detection

[1] https://github.com/reflectdetect/reflectdetect
[2] Agisoft LLC, St. Petersburg, Russia
[3] https://github.com/robotpy/mostrobotpy
[4] https://github.com/AprilRobotics/apriltag-imgs/tree/master/tag25h9
[5] https://doc.rc-visard.com/latest/en/tagdetect.html[6]https://github.com/micasense/imageprocessing/blob/master/

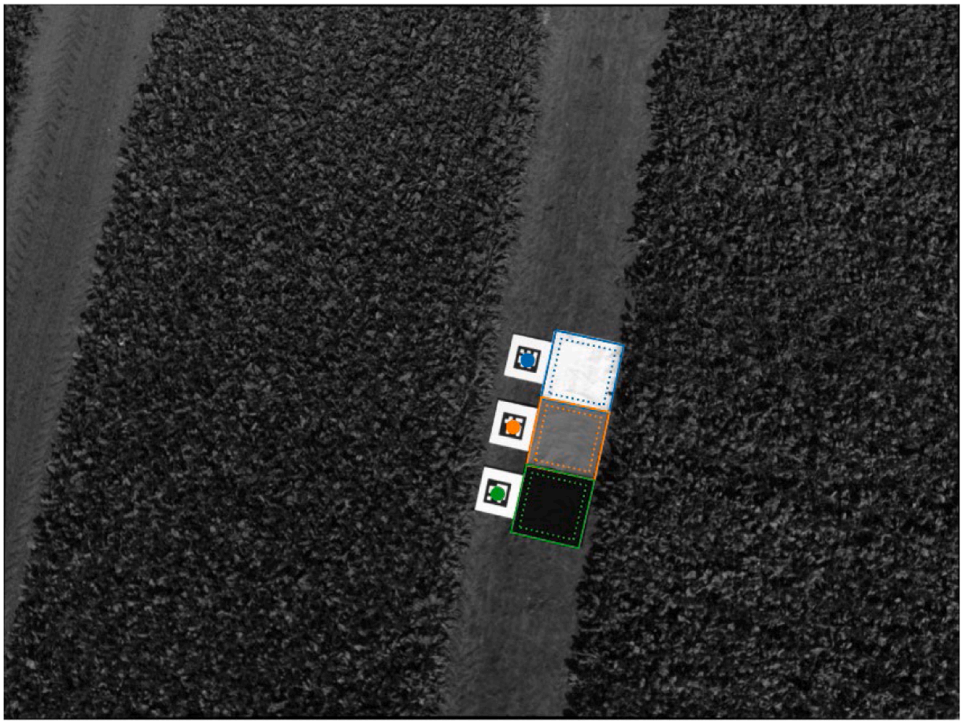

Fig. 1. Three detected calibration targets with solid-colored bounding boxes. Dotted lines show the areas where DNs were extracted. Colored dots indicate the positions of the corresponding April-Tags.

Table 1
Pseudocode for the geolocation module.

Algorithm 1 Geolocation Module: Input Validation
Procedure GEOLOCATION MODULE (*args*)
Load dataset from *args*
Validate orthophoto and dataset folders
Validate target properties and geolocation files
Validate the connection between target locations and properties
End procedure
Algorithm 2 Geolocation Module: Main Processing
Procedure START
Load all orthophoto paths
Detect targets visible in each photo
Split photos into batches based on visibility
For each batch in batches do
Extract intensities from visible targets
Interpolate intensities
Fit model using the ELM method
Convert orthophotos to reflectance using fitted model
Save converted orthophotos
End for
End procedure

Table 2
Pseudocode for the AprilTag module.

Algorithm 3 AprilTag Module: Input Validation
Procedure APRILTAG MODULE (*args*)
Initialize EXIFTool
Load dataset from *args*
Validate dataset folder and images folder
Validate target properties and tag size
Load AprilTag detector and configure tag family
End procedure
Algorithm 4 AprilTag Module: Main Processing
Procedure START
Load all image paths
Split images into batches based on number of bands
For each batch in batches do
Extract intensities from AprilTag detection
Interpolate intensities
Fit model using the ELM method
Convert orthophotos to reflectance using fitted model
Save converted orthophotos
End for
End procedure

errors were not a problem during testing, these properties should only be seen as a starting-off point for future research and were chosen with only the circumstances of this study in mind.

3.1.3. The radiometric correction module

We implemented radiometric correction based on Micasense recommendations[6] in *ReflectDetect*. This included unbiasing images by accounting for the dark pixel offset, compensating for imager-level effects, compensating for optical chain effects, normalizing images by exposure and gain settings, amd converting to a common unit system (radiance).

3.2. Software functionalities

3.2.1. CLI arguments for intra-processing adjustments

ReflectDetect provides a flexible CLI that allows users to adjust many key parameters to fine-tune the detection and calibration process. During processing, the user can reduce the detected target area (default: 80 %), focusing on the central region to avoid edge bleeding and improve the accuracy of mean Digital Number (DN) extraction. Multiple arguments specific to the AprilTag module allow for the correction of incorrectly placed tags, for example, changing the expected rotation of a tag or the expected distance between the tag and the target. To allow the user to ensure correct detection and calibration of the imagery, a debug mode is accessible. If the debug mode is enabled, verbose information about the execution of the workflow is displayed and figures with detected targets and bounding boxes (Fig. 1), are generated for review. Additionally, debug mode will display a graph of the temporal interpolation (Fig. 2).

3.3. Sample code snippets analysis

Sample code is provided on our github repository: https://github.com/reflectdetect/reflectdetect

4. Illustrative example

The supplementary material contains further visualizations (S1), a workflow (S2), and a video explaining the usage of *ReflectDetect*.

5. Impact

We are providing *ReflectDetect*, an automated dual-module system for radiometric calibration of UAV imagery, by integrating geolocation and AprilTag detection of reflectance calibration targets. The geolocation module uses geographic coordinates embedded within georeferenced orthophotos to detect calibration targets and reliably extracts intensity data. While this approach facilitates the robust detection of reference targets, it depends on the accuracy of coordinate points that must be collected in combination with the reflectance targets and the quality of the preceding orthorectification workflow. Errors in the collected coordinates and changes applied by the orthorectification software can affect target detection and therefore calibration results. Because the software tools that provide orthorectification workflows are criticized for their black-box nature [5], we recommend the use of the AprilTag module to work directly on the raw image data. It provides an innovative approach for reflectance target detection using AprilTags, fiducial markers that are now widely used in other fields such as localization of autonomous systems [11]. AprilTag detection rates have been thoroughly studied and are robust even under extreme observation angles [10]. For validation, our reflectance calibrated spectral signatures have been compared against the sELM, that is provided along with commercial 2D snapshot multi-cameras such as the Micasense camera series.[6] We performed a two-way ANOVA on a dataset of 500 spectra to evaluate the effects of calibration type (Fig. 3; AprilTag, Geolocation, sELM) and band (B = blue, G = green, R = red, RE = red edge, NIR = near-infrared), as well as their interaction on reflectance values. Given the factorial design, we conducted a sliced ANOVA to assess the effect of the calibration method on reflectance within each band separately. Post-hoc pairwise comparisons with Bonferroni adjustment were performed using estimated marginal means within each band. For all bands (B, G, R, RE, NIR), there were significant differences between sELM and both the AprilTag and Geolocation methods ($p < 0.0001$). Differences between the AprilTag and Geolocation methods were not statistically significant across bands ($p > 0.05$). The effect sizes varied across bands, with the largest contrasts observed in the NIR and RE bands. These findings suggest that sELM consistently produced significantly different values compared to the other sources, whereas differences between the AprilTag and Geolocation methods were generally not significant. To assess the similarity in spectral shape we assessed the angular distance, defined as $(d(A, B) = cos^{-1}(\textit{cosine similarity}(A, B))$ between the calibrated spectral reflectance signatures. This metric captures the actual angle between vectors in the embedding space, with smaller values indicating greater similarity. This analysis was based on the same dataset ($n = 500$). The results indicate that the methods AprilTag and Geolocations consistently showed a small cosine distance (0.0098), suggesting high similarity. However, the reflectance signature resulting from the sELM method differs more substantially from both, the AprilTag (0.1011) and Geolocation method (0.1054). This indicates distinct spectral shapes. These findings align with the results of the ANOVA, where sELM consistently showed significant differences in spectral reflectance magnitude from the other two methods, while AprilTag and Geolocation remained similar across bands. The data and code used for the statistical analysis are available in our GitHub repository (see Section 3.3). In summary, our findings are in line with the findings of other research [5–7] and emphasized the need for in-flight radiometric calibration that can account for topographic and illumination variability. The presented *ReflectDetect* software now enables other researchers, after printing their own set of AprilTags or providing the coordinates of their in-scene calibration targets, to test reflectance calibration in different environmental settings, from different observation angles, and under different illumination dynamics.

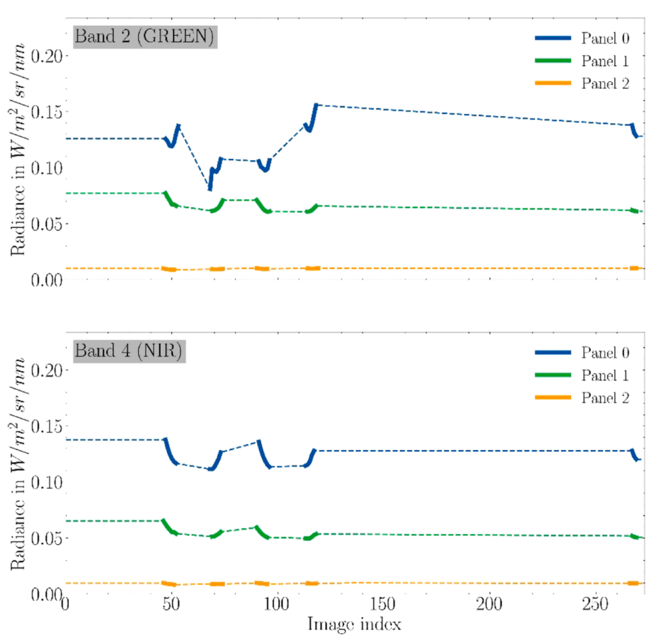

Fig. 2. Extracted (solid lines) and interpolated (dotted lines) intensities for two spectral bands across a sequence of images. The lines show intensity changes for 3 different calibration targets during the whole flight.

5.1. Advantages of in-flight empirical line calibration

During testing, calibration targets were strategically placed to be captured multiple times during flights (see example data), to account for irradiance changes throughout the flight. Variation in illumination intensities during data capture presents a key challenge. To ensure accurate radiometric calibration, linear interpolation is used to create a more uniform spectral dataset, improving the quality of subsequent image analysis. Compared to the sELM method, where only a single calibration panel is used, before and after each flight mission, the *ReflectDetect* example data shows that the method achieves higher frequencies of detected reflectance targets and therefore reduces intervals between calibration events (Fig. 2).

ReflectDetect also offers several other advantages over the sELM approach. It avoids the shading and blocking of the hemisphere over the reflectance targets that occurs when the UAV is held directly above the targets at low altitude. Additionally, it eliminates the need for a downwelling light sensor (DLS), an irradiance sensor mounted on top of the drone. This kind of sensor has been used in different studies to improve on the calibration workflow [19,20]. While the DLS is intended to

[6] AgEagle Aerial Systems Inc., Kansas, USA

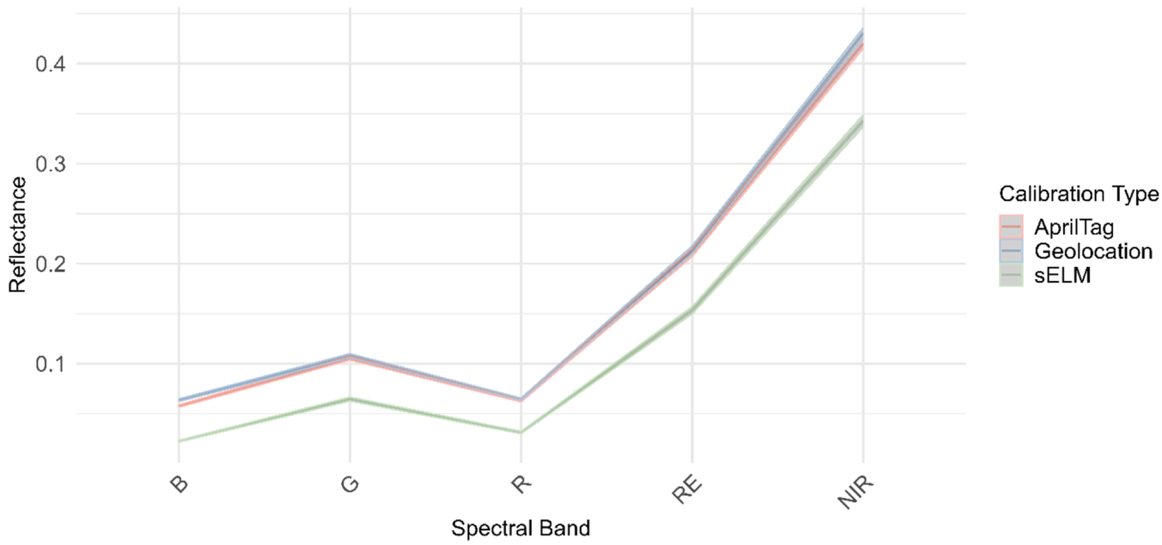

Fig. 3. Multispectral reflectance signatures obtained from identical locations of orthorectified and georeferenced multispectral images - as provided in the example data - after reflectance calibration. The average of 500 individual reflectance signatures from each calibration type are visually compared. The ribbon around each spectra indicates the standard error for each band.

correct for changes in light intensities received by the sensor during flight, it was also found to be unreliable as the ground could receive a different amount of energy compared to the DLS due to clouds casting shadows from oblique illumination angles [1]. As *ReflectDetect* allows for continuous calibration target detection in each image, future research could focus on investigating whether placing additional calibration targets in the scene further increase the stability of radiometric calibration in the red edge and NIR bands as already shown in the provided example dataset. This could be important particularly for larger study areas.

5.2. Advantages of open-source software and modular extension of camera specific calibration functions

ReflectDetect uses MicaSense-specific calibration functions to correct lens distortions and other camera-specific effects inherent in the deployed imaging system. However, many other optical sensors are available, and each requires a sensor-specific calibration procedure to generate robust spectral data that can be compared within and across datasets and studies. In addition to the importance of using comparable datasets, transparency in workflow documentation is crucial for ensuring reliable and trustworthy scientific results. During the development of *ReflectDetect*, we discovered that Agisoft Metashape introduces a shift in pixel values when exporting individual orthophotos (not the orthomosaic). This shift led to significant discrepancies in calibration results, particularly in the magnitude of reflectance values. Identifying the source of these differences was not straightforward, and it was not until we compared pixel value distributions between the original images and those after export that we pinpointed the orthophoto export as the cause. Agisoft Metashape may, by default, apply an automatic contrast adjustment after the orthophoto generation, which often goes unnoticed. These changes can improve the visual appearance of the orthophoto but also alter the actual distribution of pixel values. This can be problematic for quantitative analysis, as the original values may be distorted. To ensure the comparability of our calibration modules, we applied quantile mapping to adjust the pixel value distribution, aligning it with the raw images. These findings not only led us to recommend the AprilTag module as the primary method to be used, but also highlighted how non-transparent processes in commercial software can negatively affect research outcomes. Solutions that strive for being user-friendly, transparent, and would be complementary with *ReflectDetect* are being developed [24], but are often not fully open.

We emphasize here that transparency and comparability are the foundations to scientific progress overall and necessitate a collaborative effort to provide FAIR (Findable, Accessible, Interoperable, and Reusable) research tools for advancing goals in phenotyping [12], ecology [13], computational science [14], and plant pathology [15]. The implementation of open science standards for sharing data, code, and related research outputs has been a topic under discussion [16,17] while the 2016 guidelines on sharing data in a "FAIR" manner marked a key point in the reproducibility debate [18]. These guidelines have since been extended to include software and protocols, recognizing that much of the scientific process generates such products [14]. With *ReflectDetect* being open source, it allows researchers using different camera systems to develop and integrate their own calibration functions tailored to their equipment. This flexible and collaborative approach enables precise corrections that account for the unique characteristics of various cameras, resulting in more accurate reflectance measurements. It further fosters community-driven enhancements of *ReflectDetect* and other tools, benefiting the broader remote sensing community. *ReflectDetect* is distributed under the GNU General Public License v3.0 and can be found under https://github.com/reflectdetect/reflectdetect.

6. Conclusions

ReflectDetect is an innovative, fully automated reflectance calibration software, programmed in Python 3, that allows in-flight calibration of 2D snapshot multi-camera data. It can be easily installed via the pip package installer (see documentation[7]) for Python and allows users to adjust many key parameters to fine-tune the detection and calibration process. It is intended to facilitate and spark new research in the field of UAV remote sensing as the normalization of the dynamic illumination conditions in this field still poses significant problems.

CRediT authorship contribution statement

Luca Joshua Francis: Writing – original draft, Software, Conceptualization. **Lewis Gabriel B. Geissler:** Writing – original draft,

[7] https://github.com/reflectdetect/reflectdetect/blob/main/README.md#installation

Software, Conceptualization. **Nathan Okole:** Writing – review & editing, Methodology. **Bela Gipp:** Writing – review & editing. **Cyrill Stachniss:** Writing – review & editing, Conceptualization. **René Heim:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

All authors declare that they have no conflicts of interest.

Acknowledgements

This work has been funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – 521313940 and partially been funded by the DFG under Germany's Excellence Strategy, EXC-2070 - 390732324 – PhenoRob. We are grateful to Thomas Läbe for his invaluable support, inspiration, and insightful comments on the use of AprilTags and the photogrammetry chain.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.softx.2025.102150.

References

[1] Aasen H, Honkavaara E, Lucieer A, Zarco-Tejada P. Quantitative remote sensing at ultra-high resolution with UAV spectroscopy: a review of sensor technology, measurement procedures, and data correction workflows. Remote Sens 2018;10:1091. https://doi.org/10.3390/rs10071091.

[2] Maes WH, Steppe K. Perspectives for remote sensing with unmanned aerial vehicles in precision agriculture. Trends Plant Sci 2019;24:152–64. https://doi.org/10.1016/j.tplants.2018.11.007.

[3] Daniels L, Eeckhout E, Wieme J, Dejaegher Y, Audenaert K, Maes WH. Identifying the optimal radiometric calibration method for UAV-based multispectral imaging. Remote Sens 2023;15:2909. https://doi.org/10.3390/rs15112909.

[4] Wang C, Myint SW. A simplified empirical line method of radiometric calibration for small unmanned aircraft systems-based remote sensing. IEEE J Sel Top Appl Earth Obs Remote Sens 2015;8:1876–85. https://doi.org/10.1109/JSTARS.2015.2422716.

[5] Cao S, Danielson B, Clare S, Koenig S, Campos-Vargas C, Sanchez-Azofeifa A. Radiometric calibration assessments for UAS-borne multispectral cameras: laboratory and field protocols. ISPRS J Photogramm Remote Sens 2019;149:132–45. https://doi.org/10.1016/j.isprsjprs.2019.01.016.

[6] Fawcett D, Anderson K. Investigating impacts of calibration methodology and irradiance variations on lightweight drone-based sensor derived surface reflectance products. In: Neale CM, Maltese A, editors. Remote sens. agric. ecosyst. hydrol. xxi. Strasbourg, France: SPIE; 2019. p. 13. https://doi.org/10.1117/12.2533106.

[7] Chakhvashvili E, Siegmann B, Bendig J, Rascher U. Comparison of reflectance calibration workflows for a UAV-mounted multi-camera array system. In: 2021 IEEE Int. Geosci. Remote Sens. Symp. IGARSS. Brussels, Belgium: IEEE; 2021. p. 8225–8. https://doi.org/10.1109/IGARSS47720.2021.9555143.

[8] Eltner A, Hoffmeister D, Kaiser A, Karrasch P, Klingbeil L, Stöcker C, et al. UAVs for the environmental sciences: methods and applications. editors. Darmstadt: wbg Academic; 2022.

[9] Ban S, Kim T. Automated reflectance target detection for AUTOMATED vicarious radiometric correction of uav images. Int Arch Photogramm Remote Sens Spat Inf Sci 2021:133–7. https://doi.org/10.5194/isprs-archives-XLIII-B1-2021-133-2021. XLIII-B1-2021.

[10] Wang J, Olson E. AprilTag 2: efficient and robust fiducial detection. In: 2016 IEEERSJ Int. Conf. Intell. Robots Syst. IROS; 2016. p. 4193–8. https://doi.org/10.1109/IROS.2016.7759617.

[11] Kalaitzakis M, Cain B, Carroll S, Ambrosi A, Whitehead C, Vitzilaios N. Fiducial markers for pose estimation. J Intell Robot Syst 2021;101:71. https://doi.org/10.1007/s10846-020-01307-9.

[12] Papoutsoglou EA, Athanasiadis IN, Visser RGF, Finkers R. The benefits and struggles of FAIR data: the case of reusing plant phenotyping data. Sci Data 2023;10:457. https://doi.org/10.1038/s41597-023-02364-z.

[13] Manzano S, Julier ACM. How FAIR are plant sciences in the twenty-first century? The pressing need for reproducibility in plant ecology and evolution. Proc R Soc B Biol Sci 2021;288:20202597. https://doi.org/10.1098/rspb.2020.2597.

[14] Barker M, Chue Hong NP, Katz DS, Lamprecht A-L, Martinez-Ortiz C, Psomopoulos F, et al. Introducing the FAIR Principles for research software. Sci Data 2022;9:622. https://doi.org/10.1038/s41597-022-01710-x.

[15] Grünwald NJ, Bock CH, Chang JH, De Souza AA, Ponte EMD, du Toit LJ, et al. Open access and reproducibility in plant pathology research: guidelines and Best practices. Phytopathology® 2024. https://doi.org/10.1094/PHYTO-12-23-0483-IA. PHYTO-12-23-0483-IA.

[16] Reichman OJ, Jones MB, Schildhauer MP. Challenges and opportunities of open data in ecology. Science (1979) 2011;331:703–5. https://doi.org/10.1126/science.1197962.

[17] Serwadda D, Ndebele P, Grabowski MK, Bajunirwe F, Wanyenze RK. Open data sharing and the Global South—Who benefits? Science (1979) 2018;359:642–3. https://doi.org/10.1126/science.aap8395.

[18] Wilkinson MD, Dumontier M, IjJ A, Appleton G, Axton M, Baak A, et al. The FAIR Guiding Principles for scientific data management and stewardship. Sci Data 2016;3:160018. https://doi.org/10.1038/sdata.2016.18.

[19] Swaminathan V, Thomasson JA, Hardin RG, Rajan N, Raman R. Radiometric calibration of UAVmultispectral images under changing illuminationconditions with a downwelling light sensor. The Plant Phenome Journal 2024;7:e70005. https://doi.org/10.1002/ppj2.70005.

[20] Xie J, Y Shen, and H Cen. "Real-time reflectance generation for UAV Multispectral imagery using an onboard downwelling spectrometer in varied weather conditions." arXiv preprint arXiv:2412.19527 (2024). https://ui.adsabs.harvard.edu/abs/2024arXiv241219527X/abstract.

[21] Deng L, Hao X, Mao Z, Yan Y, Sun J, Zhang A. Asubband radiometric calibration method for UAV-based multispectralremote sensing. IEEE Journal of Selected Topics in Applied EarthObservations and Remote Sensing 2018;11(8):2869–80. https://ieeexplore.ieee.org/document/8386850.

[22] Mamaghani B, & Salvaggio C (2019a). Comparative study of paneland panelless-based reflectance conversion techniques for agri-cultural remote sensing. ArXiv. https://arxiv.org/abs/1910.03734.

[23] Luo S, Jiang X, Yang K, Li Y, Fang S. Multispectralremote sensing for accurate acquisition of rice phenotypes: impacts ofradiometric calibration and unmanned aerial vehicle flying altitudes. Front Plant Sci 2022;13:958106. https://www.frontiersin.org/journals/plant-science/articles/10.3389/fpls.2022.958106/full.

[24] Kobe M, Graß R, Boedeker H, Wehner C, & Mollenhauer H (2025). PyExpress - automating workflows for 3D point cloud reconstruction of image data (1.0.0). Zenodo. https://doi.org/10.5281/zenodo.14245920.

Citation for this Paper

```
@article{Francis2025,
 author={Luca Joshua Francis, Lewis Gabriel Geissler, Nathan Okole, Bela Gipp, Cyrill
Stachniss, Rene Heim},
 title={ReflectDetect: A software tool for AprilTag-guided in-flight radiometric calibration
for UAV-mounted 2D snapshot multi-camera imagery},
 journal={SoftwareX},
 volume={30},
 pages={6},
 year={2025},
 month={03}
}
```