ReflectDetect: A software tool for AprilTag-Guided In-Flight Radiometric Calibration for UAV Optical Data

Luca Joshua Francis[1], Lewis Gabriel B. Geissler[1], Nathan Okole[2], Bela Gipp[1], Cyrill Stachniss[3], and René Heim[3,2,*]

[1]Institute of Computer Science, University of Göttingen, Goldschmidtstraße 7, 37077 Göttingen, Germany

[2]Sensors & Data Analysis, Institute of Sugar Beet Research, Holtenser Landstraße 77, 37079 Göttingen, Germany

[3]Photogrammetry & Robotics Lab, University of Bonn, Nussallee 15, 53115 Bonn, Germany

[*]Corresponding author: `rheim@uni-bonn.de`

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 is using reflectance calibration targets to establish a mapping between sensor readings and reflectance values. Using a single calibration target while holding the UAV-mounted camera close above it has been criticized as a large portion of the hemisphere is invisibly shaded.

ReflectDetect, the proposed open-source tool, addresses these challenges by allowing in-flight radiometric calibration through automated detection via two different approaches. The first approach uses geotagging and leverages high-precision coordinates of the reflectance targets, the second is using AprilTag based detection, a visual fiducial system frequently used in robotics. These approaches allow setting up a reliable calibration system to account for varying environmental conditions, reduce human error, and increase efficiency through a user-friendly command-line interface. ReflectDetect's open-source nature enables users to easily design new calibration studies and methods to eventually improve radiometric calibration in UAV remote sensing. ReflectDetect is available under the GNU General Public License v3.0 on GitHub: https://github.com/reflectdetect/reflectdetect.

Keywords: UAV, Radiometric calibration, Open-Source, Geotagging, AprilTags.

1. Introduction

UAVs have transformed remote sensing in vegetation science by offering centimeter-level spatial resolution, on-demand temporal flexibility, and multi-sensor integration that surpass close-range, airplane-based, and satellite-based methods (Aasen et al., 2018). 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 (Maes and Steppe, 2019; Abdulridha et al., 2023; Yang et al., 2024). To effectively study these dynamic landscapes, consistent and comparable time-series data are essential, which is achieved through accurate radiometric calibration. Calibration methods, such as the Empirical Line Method (ELM), convert digital sensor readings by the camera into meaningful reflectance values, thereby improving data accuracy compared to the commonly used single gray reference target method. Nevertheless, challenges remain.

While some studies report minimal differences in calibration accuracy under stable weather conditions, they highlight challenges posed by dynamic conditions, such as variable cloud cover and lighting, which are common during UAV flights (Daniels et al., 2023). Often the Simple Empirical Line Method (Simple ELM), using only a single reflectance target, is applied. The Simple ELM 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 (Aasen et al., 2018). 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 (Aasen et al., 2018). 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 (Eltner et al., 2022; Shin et al., 2020; Fawcett and Anderson, 2019; Cao et al., 2019; Chakhvashvili et al., 2021). The majority of methodologies developed for in-flight radiometric calibration are still predominantly manual or semi-automated (Daniels et al., 2023), despite the fact that manual and semi-automated methodologies are inherently time-consuming and susceptible to error, thereby underscoring the necessity for the development of fully automated methodologies. Although approaches such as the one proposed by Ban and Kim (2021), 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.

The main contribution of this work is to overcome the aforementioned limitations by proposing a fully automated software tool, that improves the usability of in-flight radiometric calibration in UAV-based 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 RTK-GNSS receivers. By geotagging the calibration targets, the first module can detect the targets in georeferenced images. 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 uses AprilTags, a visual fiducial system that is frequently used in robotics, for target detection (Wang and Olson, 2016). AprilTags robustness against false positive detections makes them ideal for UAV applications such as visual localization (Wang and Olson, 2016), object tracking (Krogius et al., 2019), and in this case, calibration target detection. The possibility for a high frequency at which reflectance targets are seen in the collected imagery then allows accounting for the variability of light intensity during the flight. In between cases when targets are found in the imagery, interpolating the intensities ensures consistent calibration data across varying conditions mid-flight. Packaged in a user-friendly, open-source Command-Line Interface (CLI), this solution simplifies the calibration process, reduces human error, and enhances efficiency.

2. System Architecture and Methods

ReflectDetect enables users to automatically detect reflectance targets within aerial imagery and use the extracted intensities of these targets to calibrate the camera intensity readings. ReflectDetect does not evaluate the quality of reflectance targets and does not support the user in choosing the appropriate size or other properties of the reflectance targets. Therefore, some general knowledge about radiometric calibration is helpful when using this tool. The ReflectDetect workflow and functions, written in Python 3 (Van Rossum and Drake Jr, 1995), are outlined below. For a comprehensive overview of the implemented functions, the user can consult the documentation in the online repository[1]. Example datasets for each module (i.e. geolocation module and AprilTag module) are provided for reproducible testing. In the example data, 1.4 x 1.4 m square-shaped reflectance targets at 3%, 21% and 56% have been used.

ReflectDetect uses one of its two modules to detect calibration targets in the imagery, then processes the extracted intensities of the calibration targets similarly for both modules: First, interpolation is used to find approximate intensity values for images that do not contain targets, allowing ReflectDetect to use the ELM for each image separately. The calibrated reflectance images are then saved for further analysis.

2.1 The Geolocation Module

The geolocation module 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

[1] https://github.com/reflectdetect/reflectdetect
[2] Agisoft LLC, St. Petersburg, Russia

identification of calibration targets within the orthophotos by examining the geotagged coordinates of each corner of the reflectance targets. This approach offers the advantage of allowing for calibration even when targets are only partially visible or when incomplete sets of targets are present.

By setting a no-data value (e.g., 0, 65535), irrelevant data is excluded during the extraction of the target intensity values, for example when a target is only partially visible. 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.

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
```

2.2 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. This allows for target detection and calibration without the need for preprocessing of images. A detector[3] based on Wang and Olson (2016) scans each image for AprilTags and ReflectDetect

[3]https://github.com/robotpy/mostrobotpy

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 some preliminary manual testing, as well as reported maximum detection ranges[5]. While detection 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.

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 images to reflectance using fitted model
        Save converted images
    end for
end procedure
```

2.3 CLI Arguments for Intra-Processing Adjustments

As recapturing an already executed UAV mission is difficult and labor-intensive, Reflect-Detect provides a flexible CLI that allows users to adjust many key parameters to fine-tune

[4] https://github.com/AprilRobotics/apriltag-imgs/tree/master/tag25h9
[5] https://doc.rc-visard.com/latest/en/tagdetect.html

the detection and calibration process.

During processing, the user is able to reduce the detected target area (default is to 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, information about the execution of the workflow is displayed and figures with detected targets and bounding boxes, as shown in Figure 1, are generated for review. Additionally, debug mode will display a graph of the temporal interpolation, as seen in Figure 2.

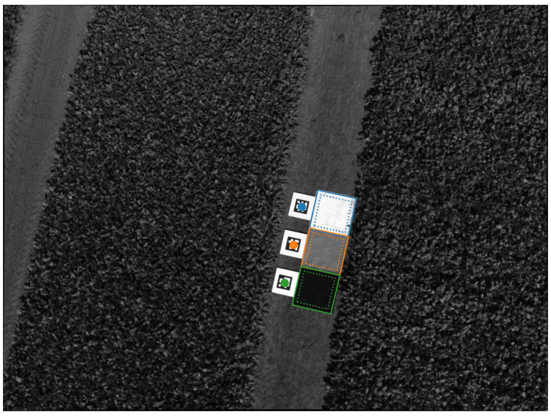

Figure 1: Three detected calibration targets with solid colored bounding boxes. Dotted lines show the areas where DNs were extracted. Colored dots indicate the positions of the corresponding AprilTags.

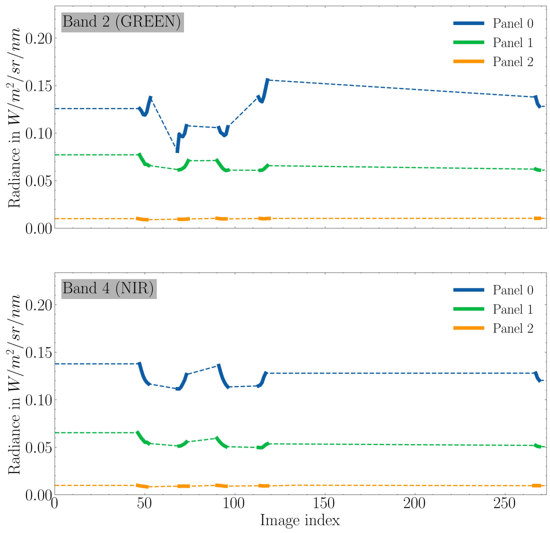

Figure 2: Extracted (solid lines) and interpolated (dotted lines) intensities for two spectral bands across a sequence of images. The lines show intensity changes for 3 different calibration targets during the whole flight.

3. Discussion

ReflectDetect is an automated dual-module system for radiometric calibration of UAV imagery, integrating geolocation and AprilTag detection of reflectance targets. The Geotagging Module uses geographic metadata embedded within orthophotos to detect calibration targets and reliably extracts intensity data. However, this approach depends on the accuracy of geotagged data, as errors in the geolocation can affect target detection and calibration results. The AprilTag Module provides a robust alternative, as their detection rates have been thoroughly studied (Wang and Olson, 2016). Our reflectance calibrated spectral signatures have been compared against the classic ELM provided by e.g. for the Micasense camera series[6] and found to be of similar in shape but more robust (Figure 3). The variance across 100 spectra that have been obtained from the provided example data is highest after the Micasense ELM, most noticable in the red edge and NIR band. This is line with the findings of other research (Cao et al., 2019; Fawcett and Anderson, 2019, Chakhvashvili et al., 2021) 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 settings and under different illumination dynamics.

3.1 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. When targets are obscured or missing, linear interpolation is used in between detection events to ensure consistent calibration over time (Figure 2). 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. The example data shows that higher frequencies of detected reflectance targets reduce intervals between calibration events 2. Compared to ELM - and ground-based methods, the presented approach offers several advantages, as mentioned by Aasen et al. (2018). 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. DLSs can be problematic because their angle and the radiation they receive change during flight (Aasen

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

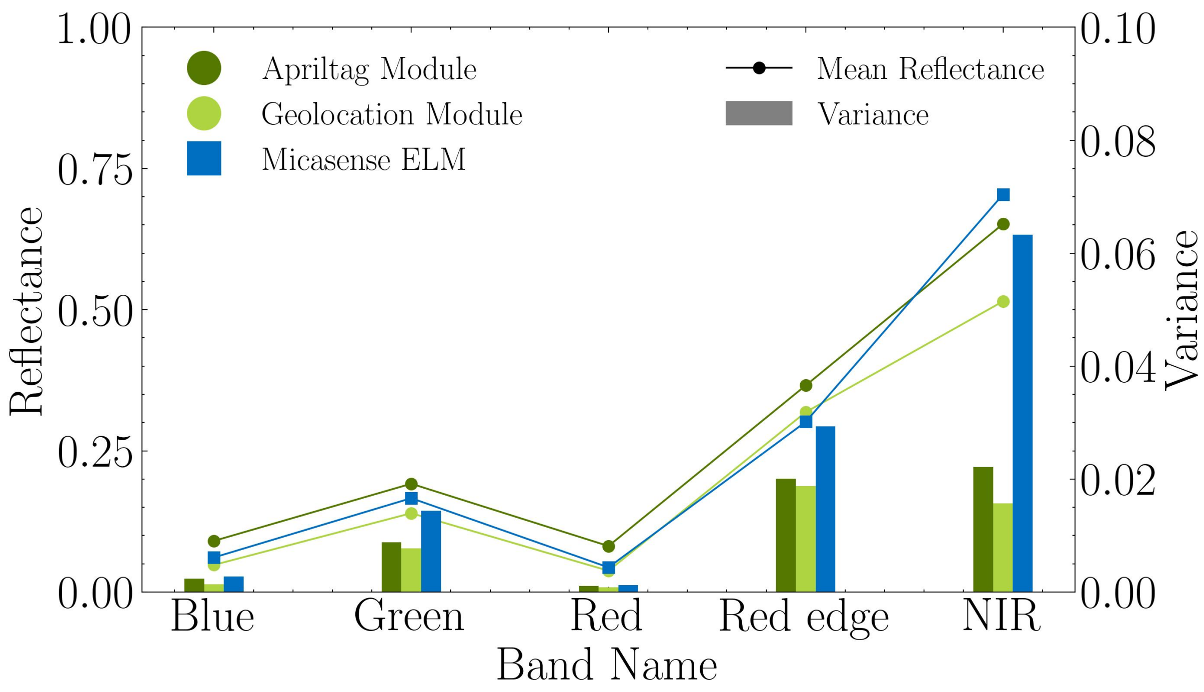

Figure 3: Multispectral reflectance signatures (line plots) obtained from identical locations in the provided example data after reflectance calibration. The average of 100 reflectance signatures from the classic Micasense ELM method are compared to the presented reflectance calibration using the AprilTag module and the Geolocation module. The variance for each band in each signature is represented as bar plots. Variance is higher for the classic Micasense ELM, most noticeable in the red edge and NIR band.

et al., 2018). While the ReflectDetect modules effectively automate the calibration process, future work should focus on testing their performance and robustness under diverse environmental conditions. This includes investigating whether placing additional AprilTag targets at shorter intervals could enhance calibration accuracy, particularly for larger study areas. Our software enables researchers to explore these aspects, providing tools to test new hypotheses and compare with other radiometric calibration methods.

3.2 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 (Aasen et al., 2018) and each requires a sensor-specific calibration procedure to generate robust spectral data that can be compared within and across datasets and studies. This comparability is the foundation to scientific progress overall and necessitates a collaborative effort to provide FAIR (Findable, Accessible, Interoperable, and Reusable) research tools for advancing goals in phenotyping (Papoutsoglou et al., 2023), ecology (Manzano and Julier, 2021), computational science (Barker et al., 2022), and plant pathology (Grünwald et al., 2024). The implementation of open science standards for sharing data, code, and related research outputs has been a topic under discussion (Reichman et al., 2011; Serwadda et al., 2018) while the 2016 guidelines on sharing data in a "FAIR" manner marked a key point in the reproducibility debate (Wilkinson et al., 2016). These guidelines have since been extended to include software and protocols, recognizing that much of the scientific process generates such products (Barker et al., 2022). 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.

Contributions

Luca Joshua Francis: Conceptualization, Software, Writing – original draft.

Lewis Gabriel B. Geissler: Conceptualization, Software, Writing – original draft.

Rene Heim: Conceptualization, Supervision, Writing – review & editing.

Nathan Okole: Writing – review & editing.

Cyrill Stachniss: Conceptualization, Writing – review & editing.

Bela Gipp: Writing – review & editing.

Acknowledgements

This work has partially been funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy, EXC-2070 - 390732324

- PhenoRob

References

Aasen, H., Honkavaara, E., Lucieer, A., & Zarco-Tejada, P. (2018). Quantitative remote sensing at ultra-high resolution with uav spectroscopy: A review of sensor technology, measurement procedures, and data correction workflows. *Remote Sensing*, *10*(7), 1091. https://doi.org/10.3390/rs10071091

Abdulridha, J., Min, A., Rouse, M., Kianian, S., Isler, V., & Yang, C. (2023). Evaluation of stem rust disease in wheat fields by drone hyperspectral imaging. *Sensors*, *23*(8), 4154. https://doi.org/10.3390/s23084154

Ban, S., & Kim, T. (2021). Automated reflectance target detection for automated vicarious radiometric correction of uav images. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XLIII-B1-2021*, 133–137. https://doi.org/10.5194/isprs-archives-xliii-b1-2021-133-2021

Barker, M., Chue Hong, N. P., Katz, D. S., Lamprecht, A.-L., Martinez-Ortiz, C., Psomopoulos, F., Harrow, J., Castro, L. J., Gruenpeter, M., Martinez, P. A., & Honeyman, T. (2022). Introducing the fair principles for research software. *Scientific Data*, *9*(1). https://doi.org/10.1038/s41597-022-01710-x

Cao, S., Danielson, B., Clare, S., Koenig, S., Campos-Vargas, C., & Sanchez-Azofeifa, A. (2019). Radiometric calibration assessments for UAS-borne multispectral cameras: Laboratory and field protocols. *ISPRS Journal of Photogrammetry and Remote Sensing*, *149*, 132–145. https://doi.org/10.1016/j.isprsjprs.2019.01.016

Chakhvashvili, E., Siegmann, B., Bendig, J., & Rascher, U. (2021). Comparison of Reflectance Calibration Workflows for a UAV-Mounted Multi-Camera Array System. *2021 IEEE International Geoscience and Remote Sensing Symposium IGARSS*, 8225–8228. https://doi.org/10.1109/IGARSS47720.2021.9555143

Daniels, L., Eeckhout, E., Wieme, J., Dejaegher, Y., Audenaert, K., & Maes, W. (2023). Identifying the optimal radiometric calibration method for uav-based multispectral imaging. *Remote Sensing*, *15*(11), 2909. https://doi.org/10.3390/rs15112909

Eltner, A., Hoffmeister, D., Kaiser, A., Karrasch, P., Klingbeil, L., Stöcker, C., & Rovere, A. (Eds.). (2022). *UAVs for the Environmental Sciences: Methods and Applications*. wbg Academic.

Fawcett, D., & Anderson, K. (2019, October 22). Investigating impacts of calibration methodology and irradiance variations on lightweight drone-based sensor derived surface reflectance products. In C. M. Neale & A. Maltese (Eds.), *Remote Sensing for Agriculture, Ecosystems, and Hydrology XXI* (p. 13). SPIE. https://doi.org/10.1117/12.2533106

Grünwald, N. J., Bock, C. H., Chang, J. H., De Souza, A. A., Ponte, E. M. D., du Toit, L. J., Dorrance, A. E., Dung, J., Gent, D., Goss, E. M., Lowe-Power, T. M., Madden, L. V., Martin, F. N., McDowell, J., Naegele, R. P., Potnis, N., Quesada-Ocampo, L. M., Sundin, G. W., Thiessen, L., . . . Zeng, Q. (2024). Open access and reproducibility in plant pathology research: Guidelines and best practices. *Phytopathology®*, *114*(5), 910–916. https://doi.org/10.1094/phyto-12-23-0483-ia

Krogius, M., Haggenmiller, A., & Olson, E. (2019). Flexible layouts for fiducial tags. *2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. https://doi.org/10.1109/iros40897.2019.8967787

Maes, W., & Steppe, K. (2019). Perspectives for remote sensing with unmanned aerial vehicles in precision agriculture. *Trends in Plant Science*, *24*(2), 152–164. https://doi.org/10.1016/j.tplants.2018.11.007

Manzano, S., & Julier, A. C. M. (2021). How fair are plant sciences in the twenty-first century? the pressing need for reproducibility in plant ecology and evolution. *Proceedings of the Royal Society B: Biological Sciences*, *288*(1944), 20202597. https://doi.org/10.1098/rspb.2020.2597

Papoutsoglou, E. A., Athanasiadis, I. N., Visser, R. G. F., & Finkers, R. (2023). The benefits and struggles of fair data: The case of reusing plant phenotyping data. *Scientific Data*, *10*(1). https://doi.org/10.1038/s41597-023-02364-z

Reichman, O. J., Jones, M. B., & Schildhauer, M. P. (2011). Challenges and opportunities of open data in ecology. *Science*, *331*(6018), 703–705. https://doi.org/10.1126/science.1197962

Serwadda, D., Ndebele, P., Grabowski, M. K., Bajunirwe, F., & Wanyenze, R. K. (2018). Open data sharing and the global south—who benefits? *Science*, *359*(6376), 642–643. https://doi.org/10.1126/science.aap8395

Shin, J.-I., Cho, Y.-M., Lim, P.-C., Lee, H.-M., Ahn, H.-Y., Park, C.-W., & Kim, T. (2020). Relative radiometric calibration using tie points and optimal path selection for uav images. *Remote Sensing*, *12*(11), 1726. https://doi.org/10.3390/rs12111726

Van Rossum, G., & Drake Jr, F. L. (1995). *Python reference manual*. Centrum voor Wiskunde en Informatica Amsterdam.

Wang, J., & Olson, E. (2016). Apriltag 2: Efficient and robust fiducial detection. *2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. https://doi.org/10.1109/iros.2016.7759617

Wilkinson, M. D., Dumontier, M., Aalbersberg, I. J., Appleton, G., Axton, M., Baak, A., Blomberg, N., Boiten, J.-W., da Silva Santos, L. B., Bourne, P. E., Bouwman, J., Brookes, A. J., Clark, T., Crosas, M., Dillo, I., Dumon, O., Edmunds, S., Evelo, C. T., Finkers, R., ... Mons, B. (2016). The fair guiding principles for scientific data management and stewardship. *Scientific Data*, *3*(1). https://doi.org/10.1038/sdata.2016.18

Yang, S., Li, L., Fei, S., Yang, M., Tao, Z., Meng, Y., & Xiao, Y. (2024). Wheat yield prediction using machine learning method based on uav remote sensing data. *Drones*, *8*(7), 284. https://doi.org/10.3390/drones8070284

A. Appendix

Figure 4: 3 AprilTags of the tag25h9 family placed next to 3 calibration targets

Citation for this Paper

```
@unpublished{francis2025,
 author={Francis, Luca Joshua and Geissler, Gabriel Lewis and Okole, Nathan and Gipp, Bela
and Stachniss, Cyrill and Heim, Rene },
 title={ReflectDetect: A software tool for AprilTag-Guided In-Flight Radiometric Calibration
for UAV Optical Data},
 year={2025},
 month={02}
}
```