Technical Validation of Metadata-Driven Georeferencing for UAV Imagery in Feature-Poor Environments

Abstract

Traditional photogrammetric processing of Unmanned Aerial Vehicle (UAV) imagery fails in environments lacking distinct visual features (e.g., water, snow, sea ice) due to the inability to establish reliable tie points. This report validates an alternative approach: Direct Georeferencing (DG) using onboard sensor metadata. The study confirms the functionality of the core geometric model and implements a Temporal Trajectory Refinement technique—a form of synthetic alignment—to enhance positional stability by smoothing raw Global Positioning System (GPS) data based on time and velocity vectors. The refinement process introduces minor, stabilizing positional shifts (up to 2.38 m), demonstrating a viable method for improving georeferencing reliability in challenging, feature-poor environments where traditional methods are non-operational.

1. Introduction

The accurate georeferencing of aerial imagery is fundamental to remote sensing and Geographic Information Systems (GIS). Conventional photogrammetry relies on Structure-from-Motion (SfM) algorithms that require significant image overlap and the detection of common, invariant features (tie points) across multiple images. This requirement presents a critical limitation when surveying homogeneous or dynamic surfaces such as open water, sea ice, or uniform agricultural fields.

The proposed solution is to utilize the drone's onboard sensor data—specifically GPS position, altitude, and Inertial Measurement Unit (IMU) attitude (roll, pitch, yaw)—to directly calculate the ground coordinates of each image pixel. This technique, known as Direct Georeferencing (DG), bypasses the need for tie points entirely.

The objective of this technical validation is twofold: (1) to confirm the successful operation of an open-source DG geometric model using real-world image metadata, and (2) to implement and evaluate a Temporal Trajectory Refinement technique that leverages time and velocity data to create a more stable flight path, thereby mitigating noise inherent in consumer-grade GPS/IMU sensors.

In open-ocean and similarly dynamic environments, traditional accuracy assessment approaches based on Ground Control Points (GCPs) are often infeasible due to the absence of stable, permanent reference features and the continuously changing nature of the surface. Consequently, this study focuses on validating internal consistency, geometric correctness, and physically plausible motion rather than absolute comparison to fixed ground truth.

2. Methodology

The validation was conducted using a five-image sequence acquired by a DJI platform, representing a typical short flight segment.

2.1 Data Preparation and Extraction

Five images were processed to extract essential metadata using ExifTool, including GPS latitude and longitude (converted to decimal degrees), altitude, roll, pitch, yaw, and image capture timestamps. The extracted metadata were formatted into a structured CSV file for input into the georeferencing scripts.

2.2 Core Geometric Model

The geometric model is based on a ray-tracing algorithm. For each image, the total camera orientation is calculated by combining the drone's attitude with the camera's fixed mounting angles. A ray is projected from the camera focal point through each pixel to the ground plane defined by the altitude, and the corresponding ground coordinates are computed using spherical trigonometry.

2.3 Temporal Trajectory Refinement (Synthetic Alignment)

Temporal trajectory refinement incorporates time and velocity data to stabilize raw GPS positions. The time difference (Δt) and great-circle distance traveled (Δd) between consecutive image capture points are calculated, yielding instantaneous velocity according to:

$$v = \Delta d / \Delta t$$

A rolling mean with a window size of three is applied to the GPS latitude and longitude series, reducing high-frequency positional noise and producing a smoother, physically plausible flight trajectory.

2.4 Validation Strategy and Accuracy Assessment Approach

No Ground Control Points or external reference data are incorporated into the georeferencing or refinement processes. This ensures that the resulting outputs reflect the inherent performance of the onboard sensor metadata. Due to the open-ocean context, validation relies on internal consistency checks, trajectory coherence, and relative positional comparison between raw and refined outputs rather than absolute ground truth.

3. Results

The extracted metadata confirm a consistent flight segment with a 2.0-second interval between images. Calculated velocities are stable, indicating smooth platform motion. Temporal refinement introduces small positional adjustments, with the largest shifts occurring at the sequence endpoints due to reduced averaging support.

3.1 Extracted Metadata and Calculated Velocity

The raw metadata confirms a consistent flight segment with a 2.0-second interval between images. The calculated velocities are stable, indicating a smooth flight path.

Filename	GPS Latitude (DD)	GPS Longitude (DD)	Altitude (km)	Roll (deg)	Pitch (deg)	Yaw (deg)	(Δt) (s)	Velocity (m/s)
DJI_0330.JPG	-2.181194	41.035628	0.0164	5.6	8.4	-29.4	0.0	N/A
DJI_0340.JPG	-2.181153	41.035611	0.0161	2.3	4.6	-29.1	2.0	2.49
DJI_0350.JPG	-2.181114	41.035589	0.0160	2.3	4.8	-29.0	2.0	2.49
DJI_0360.JPG	-2.181072	41.035567	0.0159	1.5	5.1	-29.0	2.0	2.63
DJI_0370.JPG	-2.181031	41.035542	0.0159	3.7	5.7	-29.0	2.0	2.70

3.2 Positional Refinement Analysis

The core geometric model was successfully executed for both the raw and temporally refined datasets. The positional shift introduced by the smoothing process is presented below, measured as the great-circle distance between the calculated image center using raw GPS and the calculated image center using smoothed GPS.

Filename	Raw Center (Lon, Lat)	Smoothed Center (Lon, Lat)	Positional Shift (meters)
DJI_0330.JPG	41.035680, -2.181242	41.035671, -2.181221	**2.24 m**
DJI_0340.JPG	41.035658, -2.181214	41.035656, -2.181215	**0.20 m**
DJI_0350.JPG	41.035636, -2.181174	41.035636, -2.181174	**0.00 m**
DJI_0360.JPG	41.035615, -2.181134	41.035615, -2.181134	**0.12 m**
DJI_0370.JPG	41.035588, -2.181086	41.035601, -2.181107	**2.38 m**

The positional shifts are non-uniform, with the largest adjustments occurring at the sequence endpoints (DJI_0330 and DJI_0370). This is a direct consequence of the rolling mean implementation, which has fewer data points to average at the boundaries, thus reflecting the inherent instability of raw GPS data at the start and end of a measurement sequence. The minimal shift in the middle images (DJI_0340 to DJI_0360) indicates that the raw GPS data was already highly consistent during the steady-state flight, and the smoothing provided marginal refinement.

4. Discussion and Conclusion

The validation confirms that the Direct Georeferencing geometric model is functional and capable of computing image footprints using metadata alone. The Temporal Trajectory Refinement technique successfully stabilizes raw GPS data and enforces a physically plausible flight trajectory, which is essential in feature-poor environments where tie-point-based photogrammetry fails.

This met two primary technical objectives of the project:

1. **Geometric Model Validation:** The core DG geometric model is functional and capable of calculating the image footprint using only the extracted metadata.

2. **Synthetic Alignment Implementation:** The Temporal Trajectory Refinement technique, using time and velocity data to smooth the raw GPS input, was successfully implemented. This technique directly addresses the supervisor's requirement for a method to infer relative position, which is crucial for maintaining trajectory integrity when raw GPS data is noisy.

The results demonstrate that the synthetic alignment process introduces a stabilizing adjustment to the raw positional data. While the magnitude of the shift is small in this test, its significance lies in its ability to enforce a physically plausible flight path, which is critical for achieving the sub-meter accuracy reported in the foundational research [1].

- **Current Workscope**

To transition this proof-of-concept into a robust operational tool, the following steps are being:

1. **Dependency Resolution:** Resolve the system-level conflicts with the GDAL and NetCDF4 Python bindings to enable the final output of georeferenced GeoTIFF and NetCDF files.

2. **Advanced Refinement:** Implement a more advanced temporal filtering technique, such as a **Kalman Filter**, which can dynamically weigh the raw GPS measurements against the predicted position based on the IMU and velocity data, providing a more optimal trajectory solution.

In open-ocean contexts, where fixed ground reference is unavailable, the significance of refinement lies in improved internal consistency rather than absolute positional accuracy. The results demonstrate that metadata-driven DG provides a viable alternative for UAV-based remote sensing in environments traditionally considered unsuitable for photogrammetric processing.

References

[1] Watts, J. H. (2023). Advancing the role and use of remote sensing for understanding the impact of sea ice on air–sea gas exchange in polar oceans. Doctoral thesis, University of Exeter.

[2] ThRiFt-BORG. Drone_data. GitHub repository. https://github.com/ThRiFt-BORG/Drone_data