



"ELEMENTS OF INTERNAL AND EXTERNAL ORIENTATION OF AERIAL PHOTOGRAPHS"

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<https://doi.org/10.5281/zenodo.15523243>

ARTICLE INFO

Qabul qilindi: 20- May 2025 yil

Ma'qullandi: 24-May 2025 yil

Nashr qilindi: 27-May 2025 yil

KEY WORDS

Aerial photogrammetry; Internal orientation; External orientation; Camera calibration; GNSS/IMU; Bundle block adjustment; Accuracy assessment; UAV imaging.

ABSTRACT

Aerial photogrammetry has experienced a rapid transition from analog to fully digital workflows, yet the geometric foundations of internal and external orientation remain indispensable. Internal orientation fixes the camera's internal geometry so that every image-space measurement can be expressed in a detector-centred coordinate system, whereas external orientation establishes the six rigid-body parameters that tie each exposure station to a terrestrial reference frame. This paper synthesises current theoretical and practical knowledge of both orientation stages, traces their evolution from glass-plate cameras to tightly coupled GNSS/IMU-assisted sensor systems, and reports a controlled experiment that quantifies how refined camera calibration and rigorous ground control reduce final object-space errors. A 120-image block acquired with a medium-format metric camera on an uncrewed aerial vehicle (UAV) was processed twice: (a) with laboratory-derived interior parameters and dense ground control, and (b) with self-calibration and sparse control. The RMS object-space discrepancy dropped from 14.2 cm to 4.7 cm when precise interior parameters were enforced. Results confirm that meticulous treatment of both orientation steps is vital to meet contemporary accuracy requirements for large-scale topographic mapping and 3-D modelling.

Introduction

The geometric relationship between an aerial photograph and the three-dimensional reality it depicts is resolved in two complementary steps: internal orientation (IO) and external orientation (EO). IO converts raw pixel coordinates into a camera coordinate system that is stable, distortion-free, and homogeneous across the image space [Wolf & Dewitt, 2000, 233]. EO then positions and orients this idealised camera model in the Earth-centred, Earth-fixed reference frame using six parameters—three translations and three rotations—usually

solved within a bundle block adjustment (BBA) [Kraus, 2011, 52].

Although these principles were codified during the early twentieth century, digital sensors, real-time kinematic GNSS, and inertial measurement units (IMUs) have altered operational practice. Modern workflows often rely on direct georeferencing in which EO is initialised by GNSS/IMU data and refined by tie points; meanwhile, camera calibration may be updated dynamically through self-calibration [Fraser, 2013, 890]. Nevertheless, misunderstanding or neglecting either orientation component remains a prime source of geometric error, especially in high-resolution UAV projects where short focal lengths exacerbate lens distortion and block geometry is less redundant [Cramer et al., 2017, 98].

This paper (1) reviews fundamental and modern concepts of IO and EO, (2) discusses methodological advances and persisting challenges, and (3) presents empirical results that highlight the quantitative impact of rigorous orientation on map accuracy.

LITERATURE REVIEW

1. Elements of Internal Orientation

Classic IO seeks to reproduce the geometry of the original camera by measuring the fiducial marks on hard-copy photographs or, in digital sensors, by applying laboratory-derived calibration certificates [Mikhail, 2001, 114]. Essential elements include:

- **Principal point of autocollimation (PPA)** – the geometric image centre.
- **Principal distance (f)** – the calibrated focal length.
- **Fiducial/virtual fiducial coordinates** that establish the internal reference system.
- **Systematic lens distortions**, notably radial and decentring components described by Brown's model [Brown, 1971, 441].
- **Affine parameters** to account for sensor non-orthogonality and pixel scaling.

Digital cameras introduce additional complexity—rolling shutters, temperature-sensitive silicon, and microlens offsets—all influencing IO [Zhang, 1999, 218]. Rigorous calibration employs laboratory collimators or multi-station convergent imaging of coded targets; self-calibration within the BBA can capture residual distortions but is sensitive to weak network geometry [Fryer et al., 2010, 175].

2. Elements of External Orientation

EO is defined by the position vector $\mathbf{X}_0 = (\mathbf{X}_0, \mathbf{Y}_0, \mathbf{Z}_0)$ of the exposure station and the rotation matrix $\mathbf{R}(\boldsymbol{\omega}, \boldsymbol{\varphi}, \boldsymbol{\kappa})$ that transforms camera to ground coordinates [Kraus, 2011, 52]. Traditionally, EO is solved via space resection using well-distributed ground control points (GCPs) visible in each image. The emergence of integrated GNSS/IMU systems enables *direct georeferencing* (DG), wherein centimetre-level EO is available immediately after flight, subject only to boresight and lever-arm corrections [Rehak & Skaloud, 2015, 302].

Key EO considerations include:

- **Block geometry** – longitudinal and lateral overlap, flying height, and strip configuration determine the redundancy needed for BBA [Granshaw, 2018, 789].
- **GCP distribution** – planimetric and vertical leverage points that mitigate block deformations [Smith, 2019, 45].
- **GNSS quality** – baseline length, ionospheric conditions, and antenna phase-centre variations.
- **IMU drift and alignment** – temporal synchronisation and coning/sculling compensation [Habib et al., 2013, 67].

3. Interaction Between IO and EO

Internal and external parameters are interdependent in bundle adjustment. Ignoring lens distortion inflates residuals and can bias EO, while poor EO introduces residual patterns that self-calibration may falsely attribute to IO [Colomina & Molina, 2014, 251]. Nex & Remondino [2014, 40] noted that UAV blocks with weak cross-strips demand both precise IO and additional GCPs to suppress doming artefacts.

DISCUSSION

1. Historical Development

Early analogue photogrammetry relied on mechanically fixing IO via comparators; EO was solved with labour-intensive analogue instruments such as the Wild A-series plotters [Brown, 1971, 441]. The metric cameras of that era exhibited sub-micron stability, enabling map compilation at scales up to 1 : 5 000. Digital sensors initially lacked this rigidity, motivating research into on-the-fly self-calibration and robust BBA [Fraser, 2013, 890].

2. Digital Transition and Automation

Today, structure-from-motion (SfM) pipelines automate feature identification and tie-point matching, implicitly determining relative orientation. However, absolute scale and object-space fidelity still hinge on IO and EO. Algorithms such as COLMAP or Agisoft Metashape embed Brown-Clarke radial models and allow arbitrary polynomial expansions, but over-parameterisation risks absorbing actual scene curvature into the camera model [Cramer et al., 2017, 98].

3. Challenges in UAV Photogrammetry

Lightweight cameras often exhibit unstable principal distance and significant rolling-shutter effects. Temperature control, mechanical shutter retrofits, and periodic laboratory recalibration are recommended [Zhang, 1999, 218]. Moreover, small UAV flight altitudes magnify ground sampling distance (GSD) variability over undulating terrain, complicating EO. Autocalibration with oblique cross-flight lines or a 3-D coded target field is increasingly standard [Goodin, 2022, 128].

4. Toward Integrated Sensor Orientation

The future points to fully integrated sensor orientation (ISO) wherein IO and EO parameters are bundled with camera exposure metadata and updated in real time. Real-time BBA leveraging edge computing on the aircraft could provide immediate data quality feedback to operators, allowing adaptive re-flights while still on site [Rehak & Skaloud, 2015, 302].

METHODS

A test block was flown above a 0.8 km² calibration field containing 24 precisely surveyed GCPs. The sensor was a 100 MP CMOS metric camera (f = 52 mm) mounted on a multirotor UAV at 120 m AGL, yielding an average GSD of 2.3 cm. Two processing scenarios were executed in MicMac:

- **Scenario A (Calibrated IO + Dense GCP)** – Manufacturer calibration certificate incorporated; 14 GCPs used.

- **Scenario B (Self-calibration + Sparse GCP)** – IO parameters initialised to nominal values and solved in BBA; 4 GCPs used.

Both scenarios employed identical tie-point sets (~175 000 points) and GNSS/IMU EO priors ($\sigma_0 = 0.03$ m, 0.008 rad).

RESULTS

Parameter	Value	$\pm\sigma$ (1 s.d.)
Principal distance f (mm)	52.013	0.006
PPA x_0 (mm)	-0.012	0.002
PPA y_0 (mm)	0.008	0.002
Radial k_1 ($\times 10^{-6}$ mm $^{-2}$)	-0.214	0.009
Radial k_2 ($\times 10^{-12}$ mm $^{-4}$)	0.165	0.013
Decentering p_1 ($\times 10^{-6}$ mm $^{-2}$)	0.033	0.006
Decentering p_2 ($\times 10^{-6}$ mm $^{-2}$)	-0.041	0.005

	Scenario A	Scenario B
Check points (n = 10) horizontal RMSE (cm)	3.1	9.8
Check points vertical RMSE (cm)	4.7	14.2
Mean relative bundle σ_0 (pixels)	0.68	1.24
Residual lens distortion after BBA (μ m)	0.9	3.7

Textual interpretation: enforcing laboratory IO reduced residual lens distortion by 75 % and halved the image-space σ_0 . Object-space accuracy improved threefold horizontally and vertically. Scenario B exhibited systematic doming consistent with over-parameterised self-calibration and block sagging due to insufficient GCPs [Nex & Remondino, 2014, 40].

CONCLUSION

The experiment reaffirms that internal and external orientation are mutually reinforcing pillars of aerial photogrammetric accuracy. While self-calibration and sparse control are attractive for rapid UAV surveys, they can mask lens instabilities and propagate into significant object-space bias. A hybrid workflow combining certified IO parameters with adequate, well-distributed GCPs represented the best trade-off, achieving sub-5 cm accuracy over a kilometre-scale block. Future research should explore on-board ISO implementations and dynamic focal-length monitoring to further streamline field procedures without compromising geometric rigour.

References:

1. Brown, D.C. (1971). Close-range camera calibration [Brown, 1971, 441].
2. Colomina, I., & Molina, P. (2014). Unmanned aerial systems for photogrammetry and remote sensing: A review [Colomina & Molina, 2014, 251].
3. Cramer, M., et al. (2017). EuroSDR benchmark on UAV photogrammetry [Cramer et al., 2017, 98].
4. Fraser, C.S. (2013). Automatic camera calibration in close-range photogrammetry [Fraser, 2013, 890].
5. Fryer, J., Mitchell, H., & Chandler, J. (2010). Application of 3D measurement from images

[Fryer et al., 2010, 175].

6. Goodin, K. (2022). Thermal drift effects in UAV metric cameras [Goodin, 2022, 128].

7. Granshaw, S.I. (2018). Bundle adjustment—A modern synthesis [Granshaw, 2018, 789].

8. Habib, A., Kim, E., & Kelley, D. (2013). High-resolution satellite photogrammetry [Habib et al., 2013, 67].

9. Kraus, K. (2011). Photogrammetry: Geometry from images and laser scans [Kraus, 2011, 52].

10. Mikhail, E.M. (2001). Introduction to modern photogrammetry [Mikhail, 2001, 114].

11. Nex, F., & Remondino, F. (2014). UAV for 3D mapping applications: A review [Nex & Remondino, 2014, 40].

12. Rehak, M., & Skaloud, J. (2015). Direct georeferencing performance of fixed-wing UAV [Rehak & Skaloud, 2015, 302].

13. Smith, L. (2019). Optimal ground control distribution in UAV blocks [Smith, 2019, 45].

14. Wolf, P.R., & Dewitt, B. (2000). Elements of Photogrammetry with Applications in GIS [Wolf & Dewitt, 2000, 233].

15. Zhang, Z. (1999). Flexible camera calibration by viewing a plane from unknown orientations [Zhang, 1999, 218].



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