Systematic vertical error in UAV-derived topographic models: Origins and solutions

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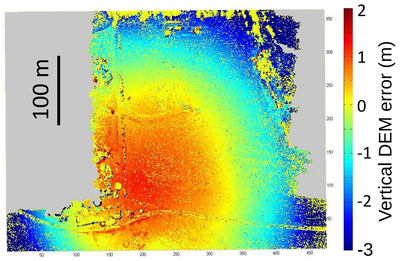
1. Introduction and background

UAVs can provide valuable image data for DEM generation in geomorphological studies. However, the resulting DEMs can contain systematic vertical error, expressed as a 'doming'; projects processed with camera self-calibration, in software based on structure-from-motion, and with minimal control points, are particularly vulnerable.



LEFT: An extreme example of metre-magnitude DEM error resulting from processing UAV imagery with Photosynth. Reproduced from [1].

For individual stereo pairs, doming distortion results from error in the description of radial lens distortion[2-4]. For self-calibration of lens distortion, recent work has characterised critical ambiguous camera configurations[5]. Here[6] we demonstrate that:

- doming observed in stereo image pairs scales up as more images are included (i.e. parallel-axis image networks),
- doming is inevitable in self-calibrated parallel-axis UAV image networks and,
- doming error can be mitigated by including convergent images in the image network.

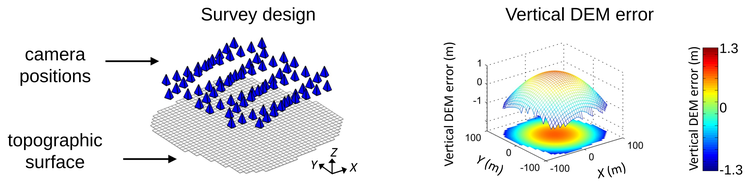
2. Method

To determine expected DEM error in UAV image networks we processed synthetic data with close-range photogrammetry software (VMS, www.geomsoft.com) using the following workflow:

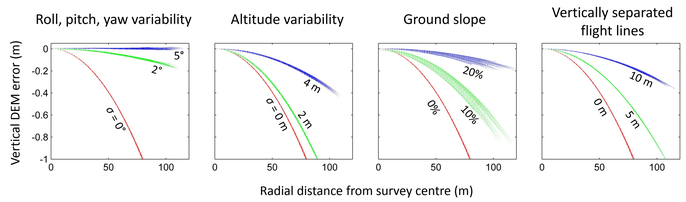
1) Define a grid of 3D points to represent the ground surface.
2) Construct a UAV imaging survey by defining a camera model and appropriate camera positions.
3) Simulate observations of the ground points in each image, applying pseudo-random offsets (with a standard deviation of 0.5 pixels) to represent measurement noise.
4) Process the resulting image network using a self-calibrated bundle adjustment.
5) Determine the DEM error by comparing the adjusted 3D point coordinates with their initial estimates.

3. Results: Parallel and near-parallel image sets

Simulations of overlapping flight lines with parallel, vertically oriented imagery show metre-level DEM doming error:



Exploring doming error magnitude for practical survey variability shows strongest sensitivity to variation in camera angles:

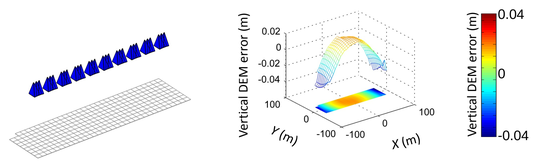


ABOVE: Vertical DEM deformation, plotted by radial distance from the survey centre, for simulations in which UAV roll, pitch and yaw or altitude are subject to natural variability (standard deviations shown), for surveys over sloping ground, or when overlapping flight line sets are vertically separated.

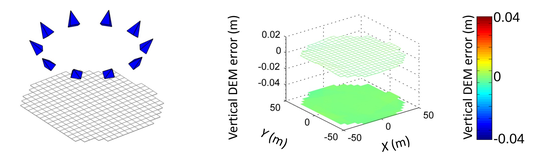
4. Results: Convergent image sets

Sensitivity to camera angle suggests that mitigation of systematic error (with self-calibration) is best reduced through collection of convergent imagery (e.g. [3, 4, 6, 7]):

Image strip augmented with images inclined at 5°



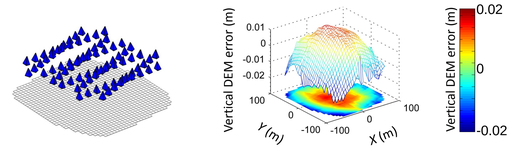
Orbital imagery (40° inclination)



5. Practical solutions for UAV image acquisition

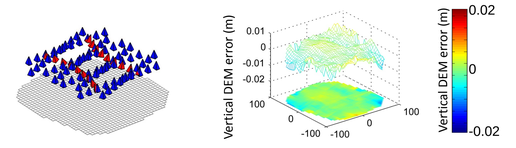
If camera angle cannot be altered in-flight, and imaging during turns is not possible – install the camera at an angle:

Forward-looking camera (5°)

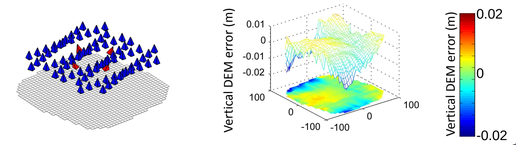


If nadir imagery is required – augment existing flight plans:

Fixed-wing UAVs: Gently banked overpasses (20°)



Rotor-UAVs with movable camera: Additional images inclined at 30°



6. Conclusions

The near-parallel viewing conditions present in many UAV image datasets exposes ambiguities between the computed topographic surface shape and radial lens distortion in self-calibrated bundle adjustment, leading to systematic doming error. To mitigate:

- If possible, pre-calibrate cameras in convergent image networks.
- Include convergent imagery in UAV surveys, particularly if self-calibration is necessary (as typical with compact cameras).
- Using broadly distributed control points in the bundle adjustment will reduce doming error, but not remove its systematic nature.

References

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