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

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Unmanned aerial vehicles (UAVs) equipped with consumer cameras are increasingly being used to produce high resolution digital elevation models (DEMs). However, although such DEMs may achieve centimetric detail, they can also display broad-scale systematic deformation (usually a vertical 'doming') that restricts their wider use. This effect can be particularly apparent in DEMs derived by structure-from-motion (SfM) processing, especially when control point data have not been incorporated in the bundle adjustment process. We illustrate that doming error results from a combination of inaccurate description of radial lens distortion and the use of imagery captured in near-parallel viewing directions. With such imagery, enabling camera self-calibration within the processing inherently leads to erroneous radial distortion values and associated DEM error.
Using a simulation approach, we illustrate how existing understanding of systematic DEM error in stereo-pairs (from unaccounted radial distortion) up-scales in typical multiple-image blocks of UAV surveys. For image sets with dominantly parallel viewing directions, self-calibrating bundle adjustment (as normally used with images taken using consumer cameras) will not be able to derive radial lens distortion accurately, and will give associated systematic 'doming' DEM deformation. In the presence of image measurement noise (at levels characteristic of SfM software), and in the absence of control measurements, our simulations display domed deformation with amplitude of $\sim$2 m over horizontal distances of $\sim$100 m. We illustrate the sensitivity of this effect to variations in camera angle and flight height. Deformation will be reduced if suitable control points can be included within the bundle adjustment, but residual systematic vertical error may remain, accommodated by the estimated precision of the control measurements.
Doming bias can be minimised by the inclusion of inclined images within the image set, for example, images collected during gently banked turns of a fixed-wing UAV or, if camera inclination can be altered, by just a few more oblique images with a rotor-based UAV. We provide practical flight plan solutions that, in the absence of control points, demonstrate a reduction in systematic DEM error by more than two orders of magnitude.
DEM generation is subject to this effect whether a traditional photogrammetry or newer structure-from-motion (SfM) processing approach is used, but errors will be typically more pronounced in SfM-based DEMs, for which use of control measurements is often more limited. Although focussed on UAV surveying, our results are also relevant to ground-based image capture for SfM-based modelling.