To Bundle Adjust or Not: A Comparison of Relative Geolocation Correction Strategies for Satellite Multi-View Stereo

Roger Marí, Carlo de Franchis, Enric Meinhardt-Llopis, and Gabriele Facciolo

CMLA, ENS Paris-Saclay, 94235 Cachan, France

Objective

- Investigate relative geolocation correction techniques for satellite RPC camera models, i.e. compare Bundle Adjustment (BA) image based methods to geometry based methods.
- Analyze impact on Multi-View Stereo (MVS) 3D reconstructions from satellite imagery.

Relative geolocation correction techniques

3 methods are considered:

1. **NCC DSM alignment:** Omit prior BA and directly align independent DSMs $\mathbf{u}$ and $\mathbf{v}$ via a 3D translation that maximizes the Normalized Cross Correlation (NCC) between them.

$$\mathrm{NCC}(\mathbf{u},\mathbf{v}) := \frac{1}{|\widehat{\Omega}|}\sum_{t\in\widehat{\Omega}} \frac{(u_t-\mu_u(\widehat{\Omega}))(v_t-\mu_v(\widehat{\Omega}))}{\sigma_u(\widehat{\Omega})\sigma_v(\widehat{\Omega})}, \quad (1)$$

where $\widehat{\Omega} := \Omega_u \cap \Omega_v$ is the intersection of the sets of known points in the DSMs.

Justification: RPCs can be modeled as affine cameras for small areas of interest (AOIs), e.g. 2 km $\times$ 2 km [3].

2. **Bundle block adjustment:** Detect inter-image tie-points and use prior BA to minimize

$$E(\{T_m\},\{X_k\}) = \sum_k \sum_m \|T_m(P_m(X_k)) - x_{mk}\|^2, \quad (2)$$

where $\{T_m\}$ is a set of correction offsets (1 per image), $\{P_m\}$ are the original RPC projection mappings and $\{X_k\}$ are the 3D points that project on the tie-points $\{x_{mk}\}$.

Justification: RPCs inaccuracies reduce to a 2D translation for AOIs smaller than 50 km $\times$ 50 km [1, 2].

3. **BA of camera rotations:** Detect inter-image tie-points and use prior BA to minimize

$$E(\{R_m\},\{X_k\}) = \sum_k \sum_m \|P_m(R_m(X_k)) - x_{mk}\|^2, \quad (3)$$

where $\{R_m\}$ is a set of correcting rotation matrices (1 per image) and the rest is as in (2).

Justification: RPCs inaccuracies are due to errors in measurement of satellite attitude (i.e. pointing error).

MVS pipeline

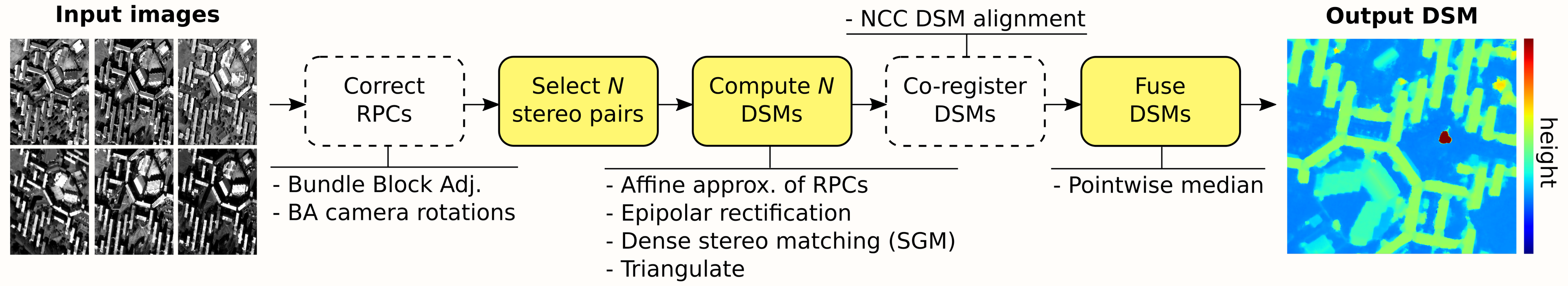

Figure 1: MVS pipeline as used in the experiments. For a fair comparison, yellow blocks are common. Dashed blocks change depending on the relative geolocation correction method employed in each case.

Selection of input pairs

- **Oracle order:** Sorts stereo pairs by decreasing completeness of the output DSM. Guarantees that the best pairs are selected, but it is expensive to compute and requires availability of ground-truth.
- **Heuristic order:** Tries to emulate the oracle order based on the satellite images metadata, e.g. intersection angle, incidence angle and proximity of acquisition date [3].
- **SIFT order:** Sorts stereo pairs in decreasing number of SIFT matches, therefore prioritizing pairs with a higher overlap of visual content.

Data and experiments

- **IARPA Multi-View Stereo 3D Mapping Challenge 2016:** 47 DigitalGlobe WorldView-3 images, with 30 cm nadir resolution, collected between 2014 and 2016 over Buenos Aires [4].
- **IEEE GRSS Data Fusion Contest 2019:** 26 DigitalGlobe WorldView-3 images collected between 2014 and 2016 over Jacksonville [5].
- **Evaluation metrics:** completeness (% of points where error w.r.t ground-truth is smaller than 1 m) and accuracy (root mean squared error). Points in water bodies not taken into account.

Figure 2: The selected AOIs projected on Google Maps.

	IARPA	JAX 113	JAX 161	JAX 251
Oracle order				
NCC DSM alignment	70.62 / 2.67	–	–	–
Bundle block adjustment - *naif*	64.39 / 2.72	–	–	–
Bundle block adjustment	70.63 / 2.74	–	–	–
BA of camera rotations - *naif*	64.50 / 2.71	–	–	–
BA of camera rotations	70.71 / 2.74	–	–	–
Heuristic order				
NCC DSM alignment	68.08 / 2.69	77.72 / 2.00	82.75 / 1.70	74.87 / 2.90
Bundle block adjustment	69.73 / 2.74	77.74 / 2.04	82.53 / 1.73	76.86 / 2.91
BA of camera rotations	69.89 / 2.75	77.72 / 2.04	82.60 / 1.72	75.91 / 2.91
SIFT order				
NCC DSM alignment	48.84 / 2.62	76.73 / 2.01	82.64 / 1.64	72.46 / 2.74
Bundle block adjustment	42.15 / 2.71	76.83 / 2.06	82.48 / 1.66	72.69 / 2.76
BA of camera rotations	42.15 / 2.71	76.79 / 2.04	82.44 / 1.66	71.14 / 2.78

Table 1: Completeness (%) / Accuracy (m) of the reconstructed DSMs for Buenos Aires (1 AOI) and Jacksonville (3 AOIs). The *naif* label indicates that outliers in the feature tracks for BA were not processed.

Results

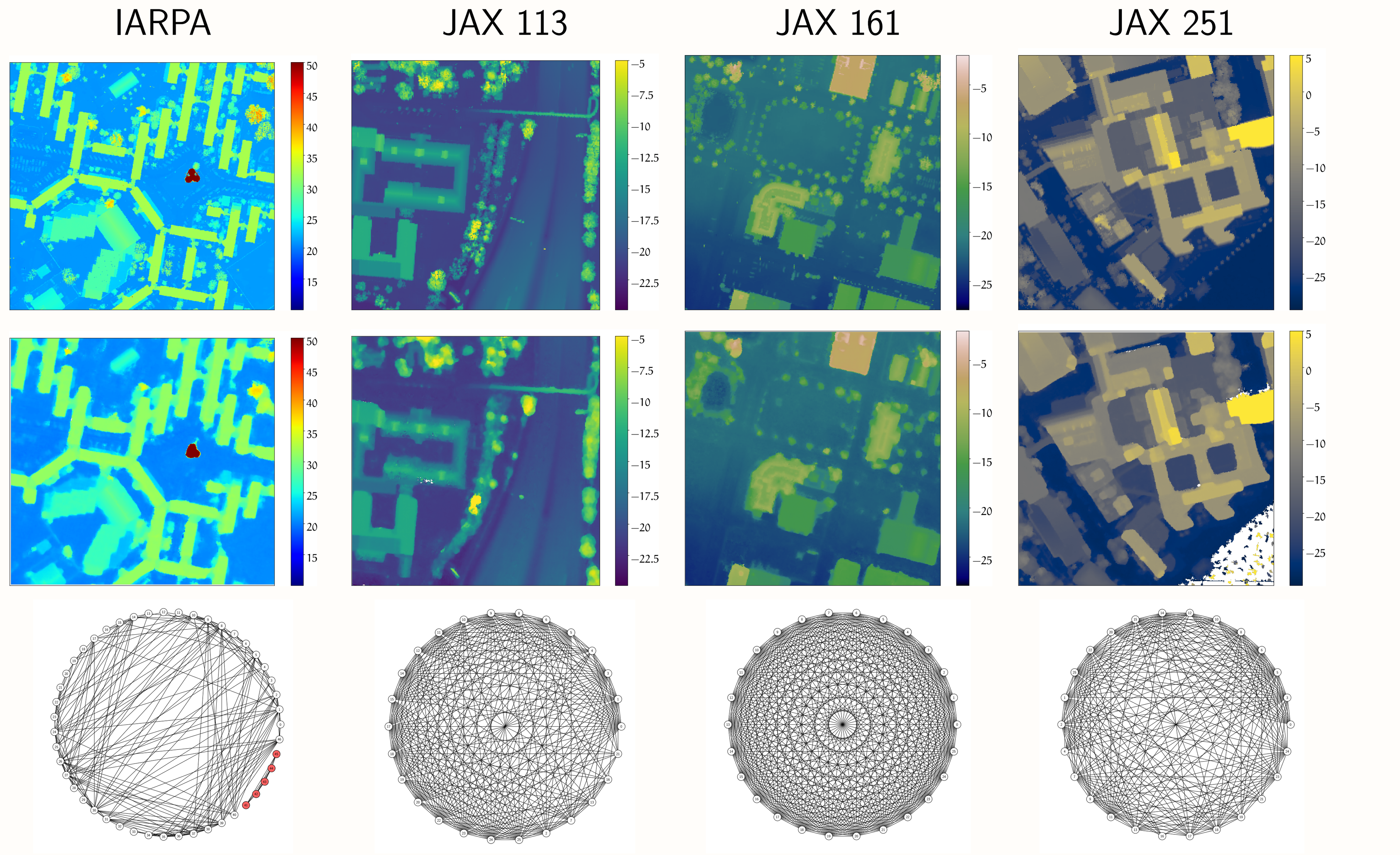

Figure 3: 1st row: Lidar ground-truth DSMs. 2rd row: MVS DSM reconstruction, where white points are unknown. 3rd row: Connectivity graph, where edges link pairs with more than 40 SIFT matches.

Conclusions and discussion

- **Image based correction.** Methods relying on BA require handling mismatches in feature tracks. If tracks do not connect all images consistently, avoid stereo pairs from disconnected sets (Fig. 3).
- **Geometry based correction.** NCC DSM alignment is sensitive to incomplete geometry, especially if missing parts are relevant w.r.t. the AOI size. Possible causes: occlusions or water bodies.
- The connectivity graph of pairwise matches could be a useful complement to the heuristic order, because it is adapted to the specific AOI and not to the entire satellite image.
- Image and geometry based correction approaches could be combined to gain robustness.

References

[1] Grodecki, Jacek and Dial, Gene, "Block adjustment of high-resolution satellite images described by rational polynomials.". *PE&RS*, 2003.

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[5] Bosch, Marc *et al.* , "Semantic stereo for incidental satellite images.". *IEEE WACV*, 2019.