CSRF 2024

Title:

Point Cloud Fusion Algorithm for High-Quality Digital Surface Model Generation from Multi-Date Stereo Images

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Outline

- **Introduction**
- **Methodology**
  - Align and Fusion methodology
  - Real Context Validation
- **Results**
- **Conclusion**

Introduction

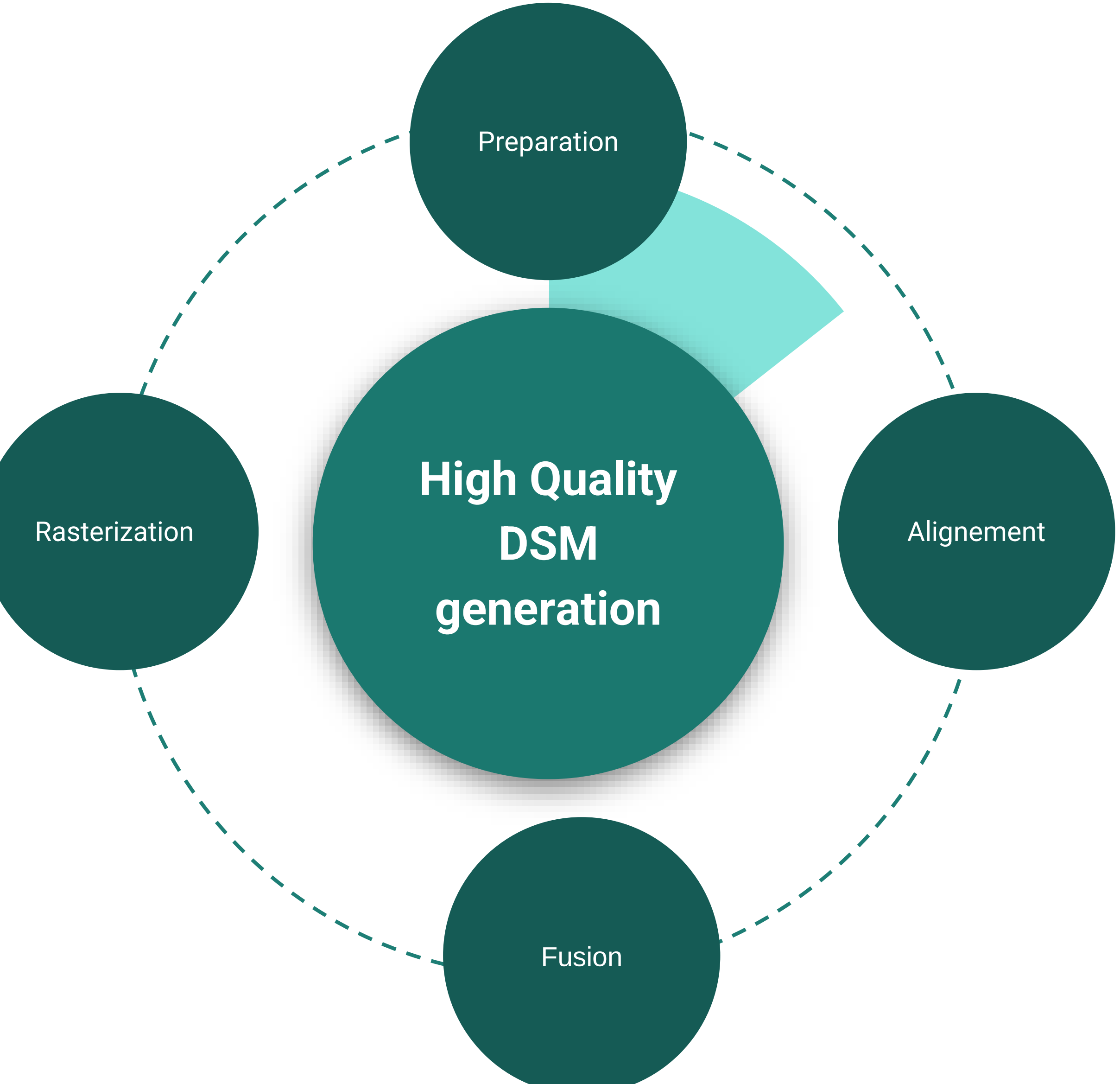
- **Digital Surface Models (DSMs) → applications in Precision Agriculture**
  - Evaluating the suitability of terrain for agricultural use
  - Crop yield monitoring
  - Biomass estimation
- **Other models baseline**
  - Digital Elevation Model (DEM)
  - Provide spatial information in geomorphological applications, attributes like: slope, aspect, profile curvature and flow direction

Introduction

- **DSM generation techniques**
  - Historically aerial photogrammetry and LiDAR, nowadays optical satellite imagery as interferometry
  - Stereo Method:
    - Dense point clouds acquired form stereoscopic satellite imagery
    - Three-dimensional points capturing terrain features
    - Cloud Fusion brings quality and accuracy
      - Integration of multiple view-point information

Introduction

- **High Quality DSM generation :**
  - Point clouds fusion
  - Multiple date stereo images
  - Point clouds generated by Context-Aware Reconstruction of Scenes (CARS) software
- **Comparison :**
  - Satellite Stereo Pipeline (S2P) point cloud fusion results

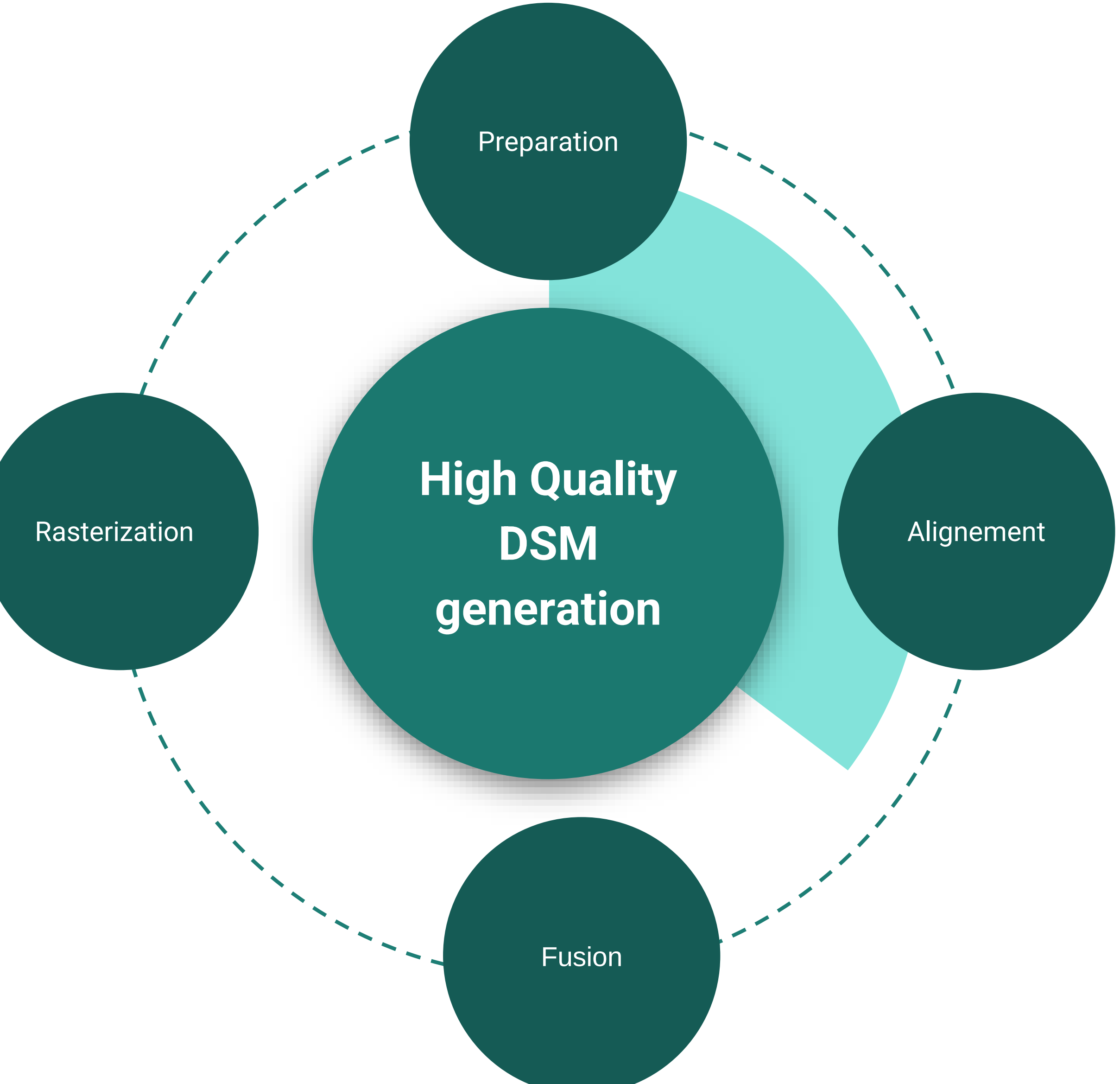


Methodology

Goal of Align and Fusion methodology :

Iterative procedure to fusion P point clouds from different multi-date image pairs to create one DSM over a Region Of Interest (ROI)

1. **PREPARATION:**
   - Pre-alignment processing of the point clouds composed from each image pair.
2. **ALIGNEMENT**
3. **FUSION**
4. **RASTERIZATION**

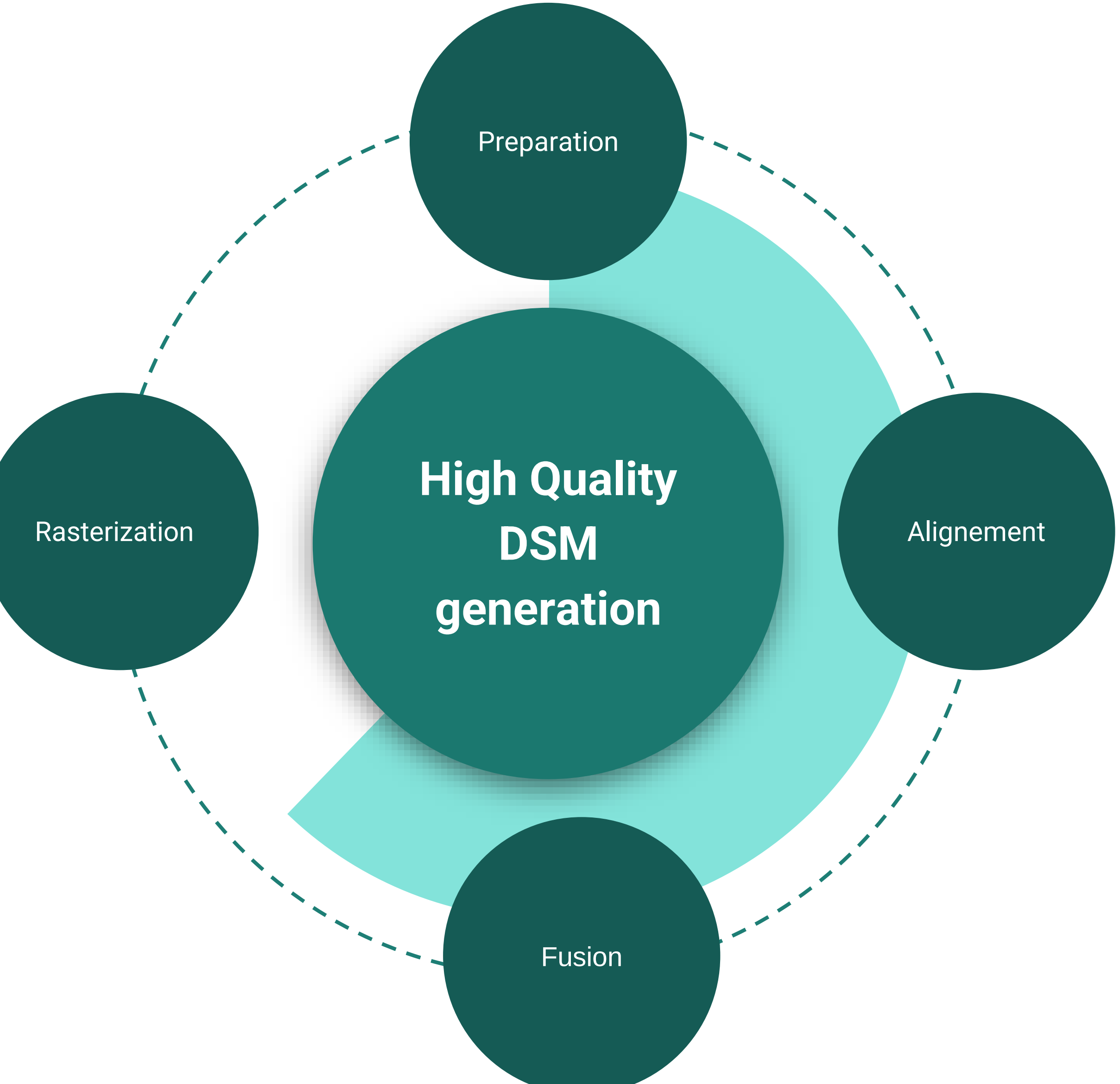


Methodology

Goal of Align and Fusion methodology :

Iterative procedure to fusion P point clouds from different multi-date image pairs to create one DSM over a Region Of Interest (ROI)

1. **PREPARATION**
2. **ALIGNEMENT:**
   - 3D point clouds not aligned due to pointing errors of Rational Polynomial Coefficient models (RPCs) →Normalized Cross Correlation based translation to correct the lack of alignment
3. **FUSION**
4. **RASTERIZATION**

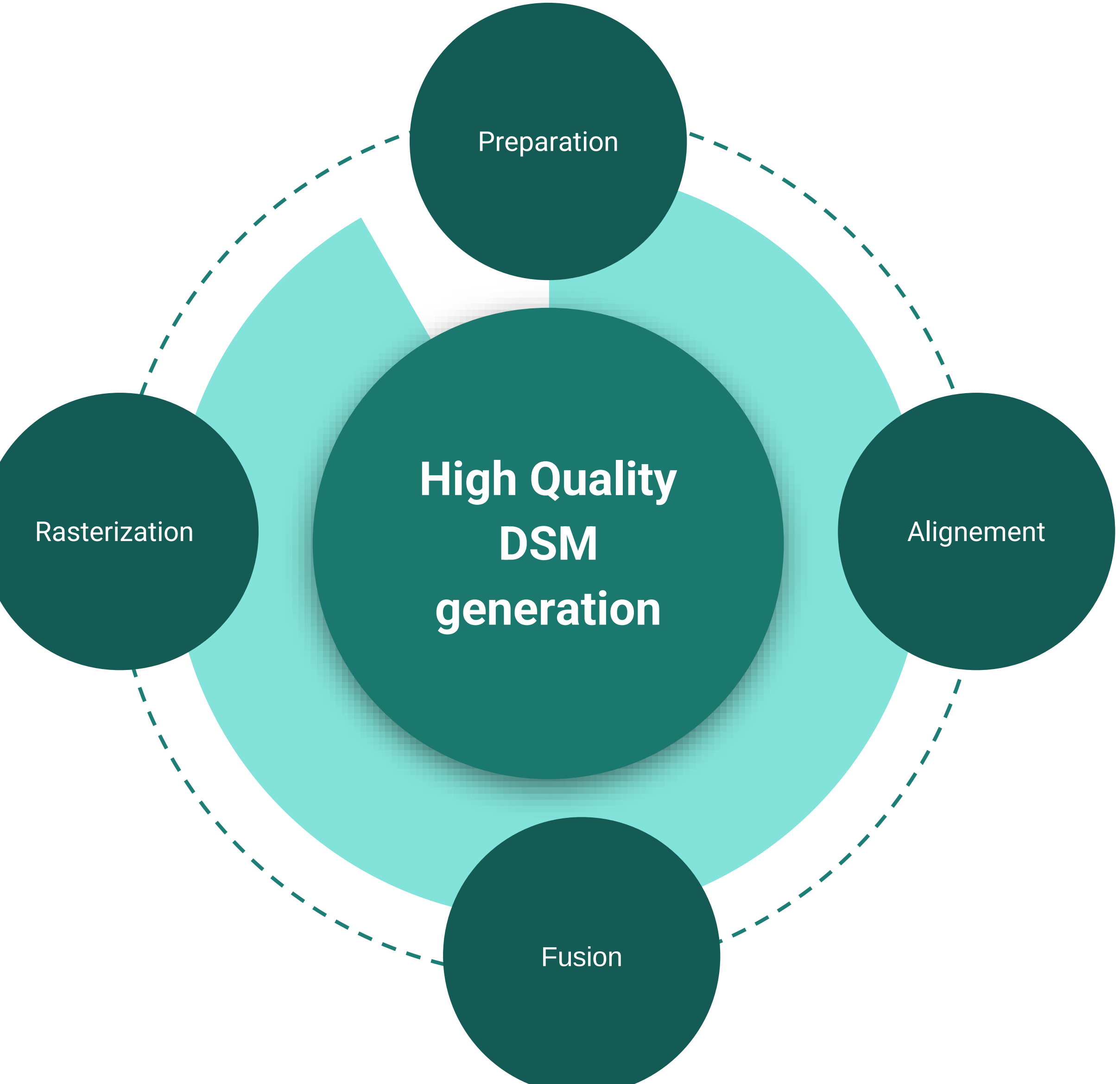


Methodology

Goal of Align and Fusion methodology :

Iterative procedure to fusion P point clouds from different multi-date image pairs to create one DSM over a Region Of Interest (ROI)

1. **PREPARATION**
2. **ALIGNEMENT**
3. **FUSION:**
   - Combination of all aligned point clouds into a single matrix
4. **RASTERIZATION**



Methodology

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Iterative procedure to fusion P point clouds from different multi-date image pairs to create one DSM over a Region Of Interest (ROI)

1. **PREPARATION**
2. **ALIGNEMENT**
3. **FUSION**
4. **RASTERIZATION:**
   - Generation of georeferenced raster image.

Methodology

1. **PREPARATION:** Pre-alignment processing of the point clouds composed from each image pair.
   - Multiple point cloud generation, each per tile.
     - Generation of a single point cloud by merging
     - Node spacing selected according to image resolution
     - Projection of pixels onto this grid

Generation of two-dimensional matrix, each cell estimates the z-height

Methodology

1. **PREPARATION:** Pre-alignment processing of the point clouds composed from each image pair.

- Multiple point cloud generation, each per tile.
  - Generation of a single point cloud by merging
  - Node spacing selected according to image resolution
  - Projection of pixels onto this grid

  → Generation of two-dimensional matrix, each cell estimates the z-height

- Filling the gaps
  - Grayscale-closing interpolation → single pixel holes filled
  - Larger holes, kept as non data

  → Generation of processed DSMs: the referential DSM and DSM-p to be fused → E_{ref} and E_p

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Generation of processed DSMs:
the referential DSM and DSM-p to be fused → E_{ref} and E_p

- Filling the gaps II
  - holes filled by lowest hole edge values (ground level)

Generation of processed DSMs before alignment:
the referential DSM and DSM-p to be fused → D_{ref} and D_p

Methodology

2. ALIGNEMENT: 3D point clouds not aligned due to pointing errors of Rational Polynomial Coefficient models (RPCs) [1]

- Usual method for adjusting the parameters of distinct cameras
  - Scale-invariant Feature Transform algorithm matching [2]
    - Sensitivity to noise and radiometric changes
- Error induced in the point clouds → 3D translation
- Strategy proposed by Facciolo [3]
  - Compute : Normalized Cross Correlation (NCC)
  - Maximization problem to select the most appropriate translation

$$NCC(\mathbf{u},\mathbf{v}) \equiv \frac{1}{|\hat{\Omega}|}\sum_{j\in\hat{\Omega}} \frac{(\mathbf{u_j}-\mu_{\mathbf{u}}(\hat{\Omega}))(\mathbf{v}_j-\mu_{\mathbf{v}}(\hat{\Omega}))}{\sigma_{\mathbf{u}}(\hat{\Omega})\sigma_{\mathbf{v}}(\hat{\Omega})}$$

$$(dx^*, dy^*) = \arg\max_{dx,dy} NCC(\mathbf{u}, \mathbf{v}_{dx,dy})$$

Methodology

3. **FUSION:** Combination of all aligned point clouds into a single matrix

$$M(x,y,k) = \begin{cases} E_{ref}(x,y) & \text{if } k = 0 \\ E_{p,aligned}(x,y) & \text{for } k = 1, 2, \ldots, P \end{cases}$$

- *x,y* pixel location, and *k* a single value from one of the point clouds
- dimension of variable *k* → maximum number of fused point clouds
- for each *x,y* → k-medians clustering analysis of the height values along *k*
- K-medians clustering analysis to validate the height values estimated from distinct point clouds.

Methodology

3. RASTERIZATION: Generation of georeferenced raster image.

The resolution and the boundaries of the region of interest are defined by:

$$\text{width} = \left\lfloor \frac{x_{\max} - x_{\min}}{r} \right\rfloor + 1$$

$$\text{height} = \left\lfloor \frac{y_{\max} - y_{\min}}{r} \right\rfloor + 1$$

where

- x_min, x_max → maximum and minimum in CRS (y_min, y_max)
- r → resolution of the DSM grid

Matrix initialized with NaNs and updated by fusion procedure.

DSM smoothed applying weighted Gaussian filter.

Raster image creation:

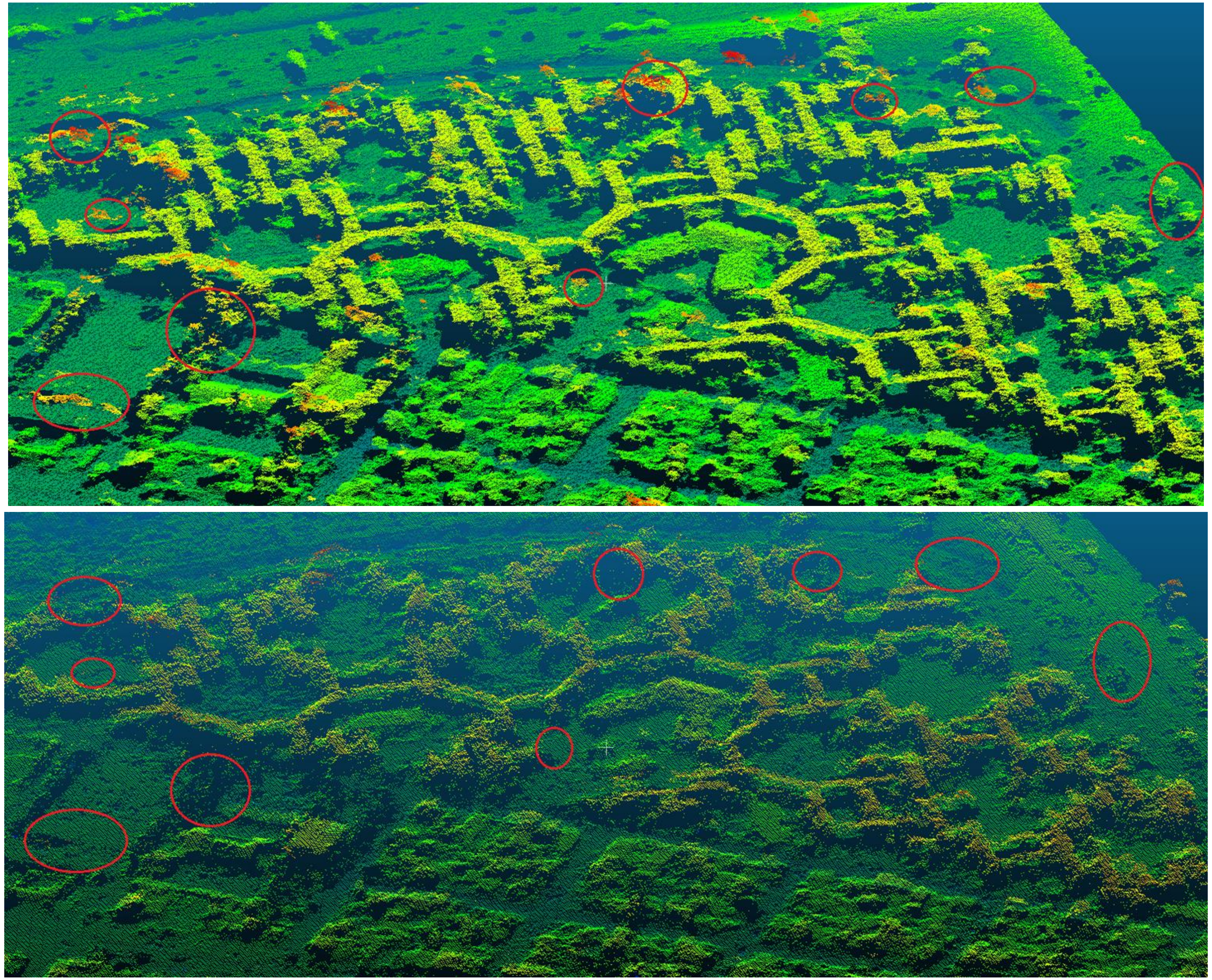
- image georeferenced using corners' geographic coordinates

Methodology

Real Context Validation :

- **Dataset:**
  - IARPA challenge dataset (Buenos Aires, Argentina)
  - 30cm resolution NITF images from World-Wiew 3 satellite
    - Converted to GEOM with corresponding Rational Polynomial Coefficients (RPC)
  - Image pairing criteria:
    - Angle between points of views of the images between 5º-45º
    - Temporal proximity
- **Metrics**:
  - Completeness (percentage of pixels with valid values)
  - Root Mean Square Error
  - Standard Deviation

Results



Original and fused point clouds.

- **Top**: Original DSM generated by CARS.
- **Bottom**: Fusion of 8 DSMs by applying the procedure .

It can be seen that in most of the occluded and vegetated areas, ground data has been obtained after the fusion (examples in red circles, where tree crowns, represented as groups of points higher than the ground with reddish colours, have been removed and ground points have been obtained).

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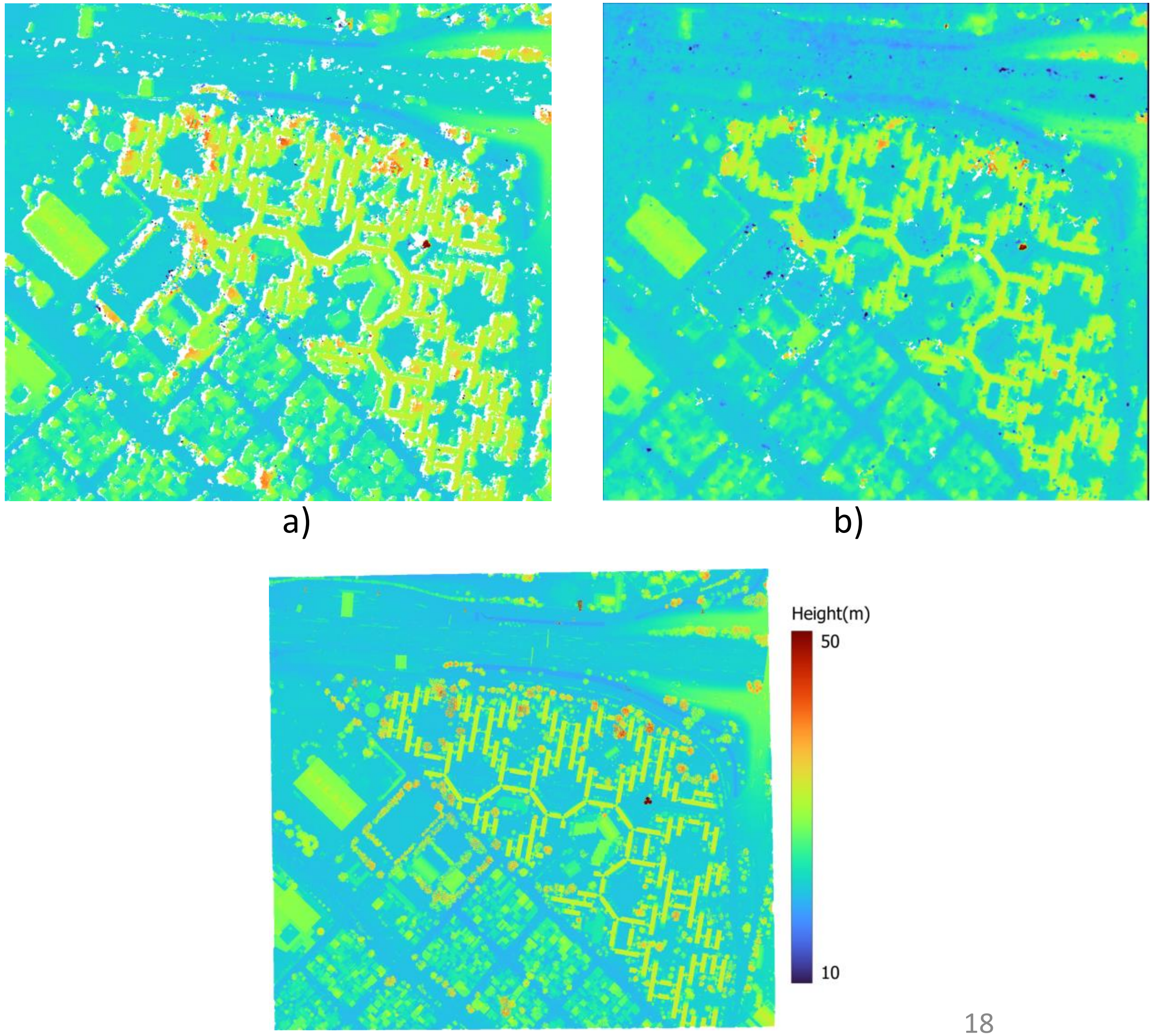
Results

DSM comparison:

- **a)** Best individual DSM (from one pair only) among the ones used in the fusion.
- **b)** Fused DSM obtained from 8 DSMs from individual pairs.
- **c)** DSM obtained by LiDAR, used as ground truth.



a) b) c)

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Results

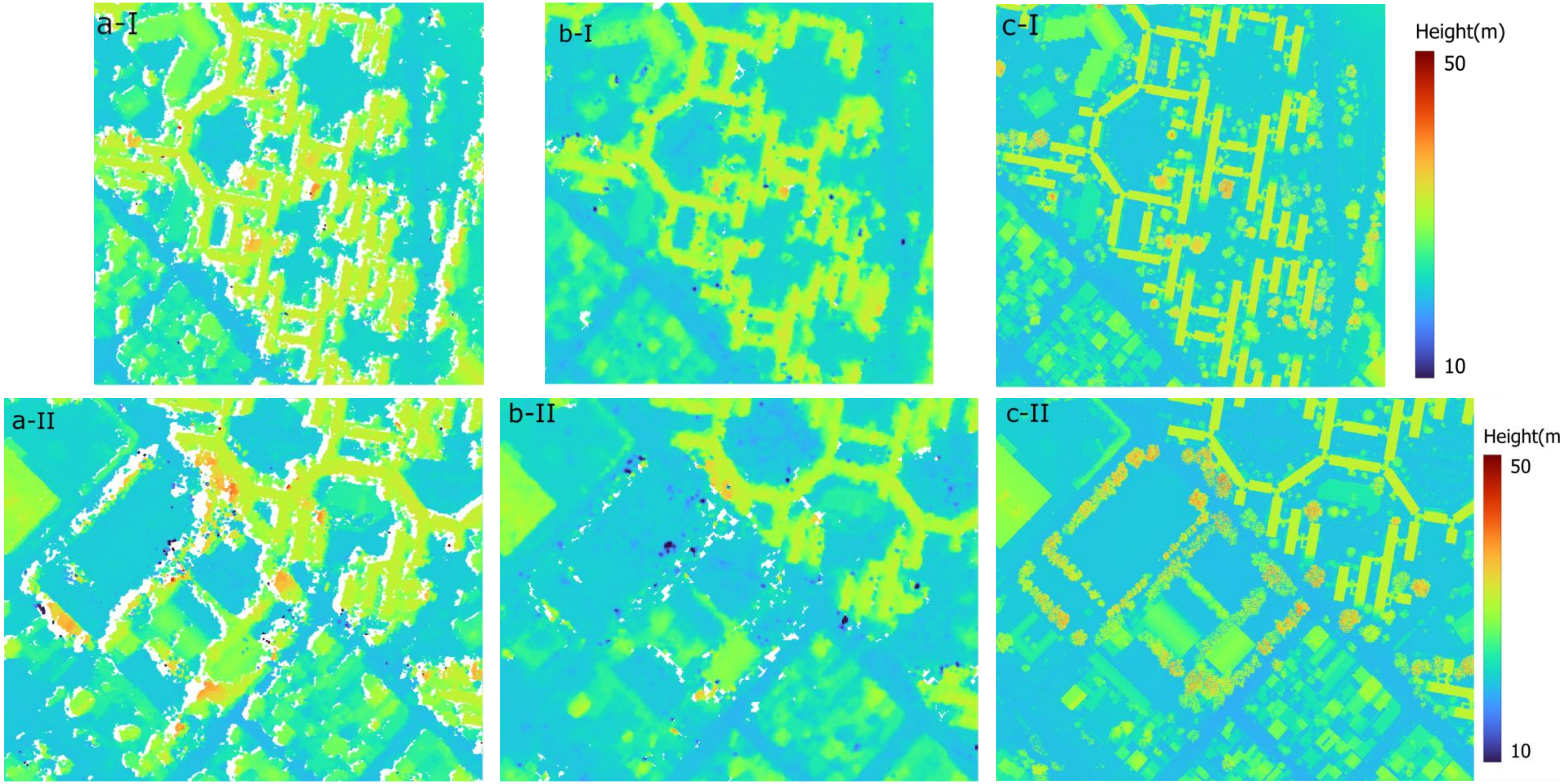
Sections of the DSM where different types of surfaces are shown.

Horizontally:

- I) area with buildings and trees,
- II) area with trees on a flat sports field.

Vertically:

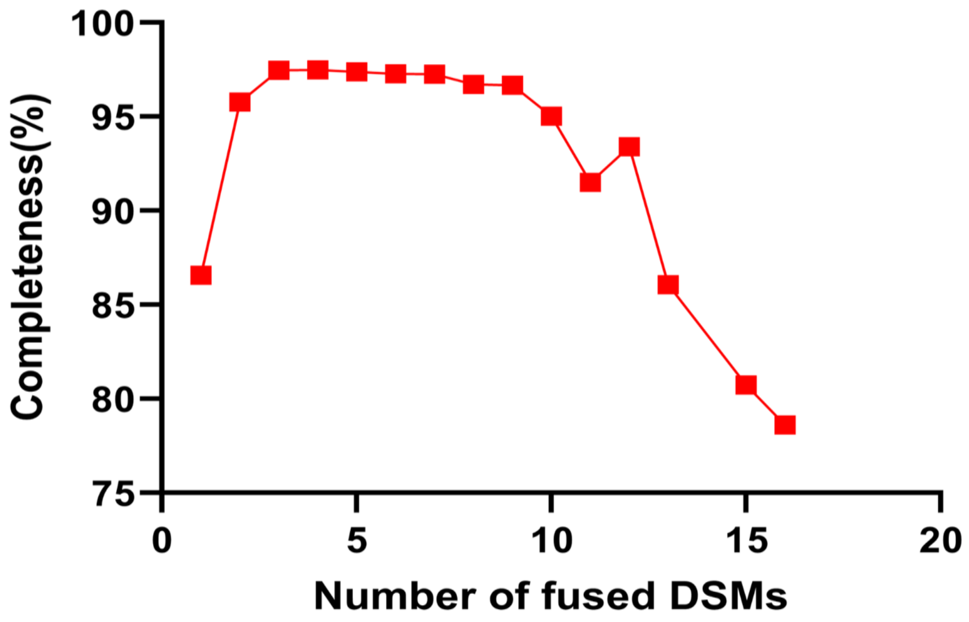
- a) Best individual DSM (lowest RMSE value)
- b) Fused DSM.
- c) DSM obtained by LiDAR, used as ground truth.



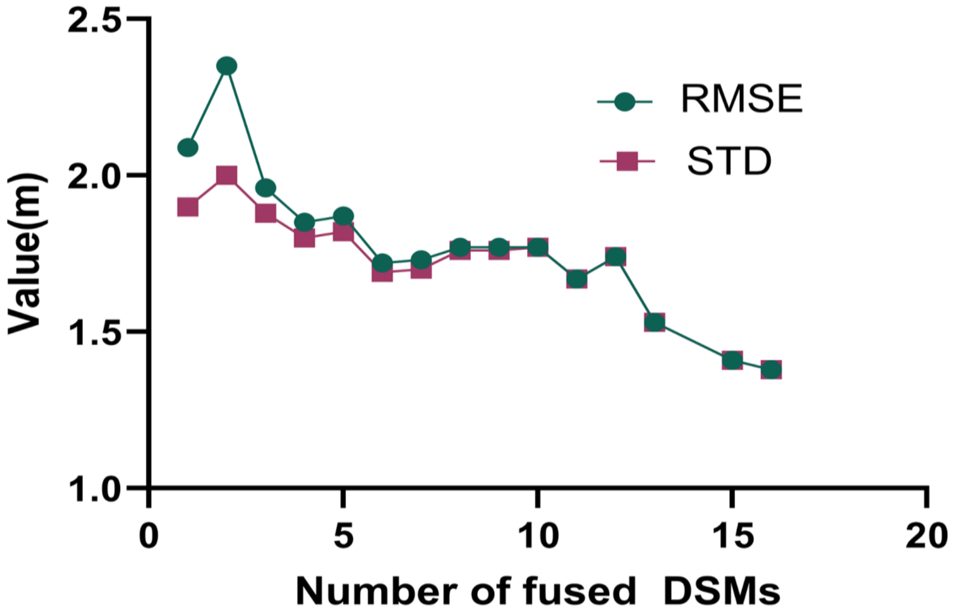
Results

Metrics of the results obtained.

Completeness of the resulting DSM.

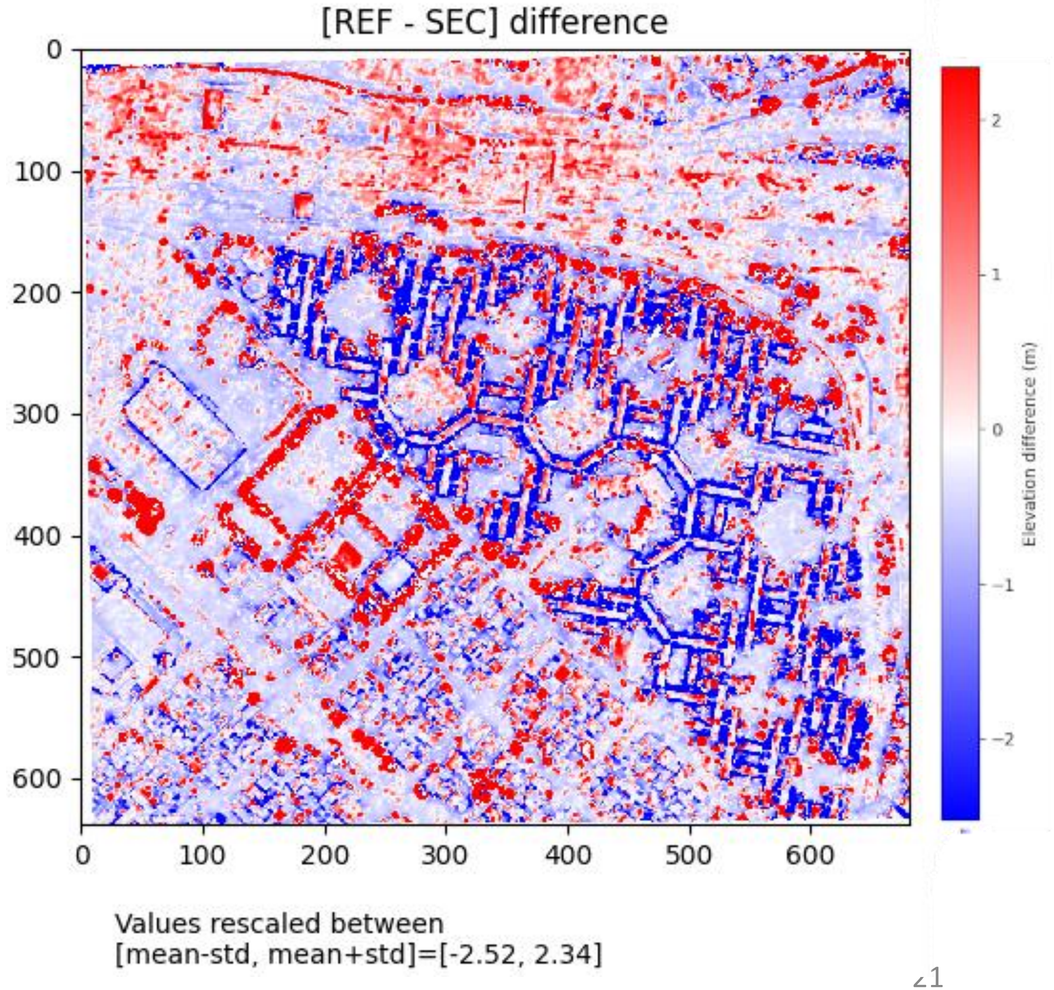


STD and RMSE values.



Results

Difference between the fused DSM from 8 point clouds and the actual LiDAR value.



Conclusions

1. A new method was developed to generate high-quality DSMs by fusing point clouds from stereo images taken on different dates.

1. The approach uses the CARS software, which improves upon previous software like S2P.

1. Fusion enhances DSM quality, particularly regarding completeness and error metrics.

1. The method is effective in mixed terrains, showing potential for use in precision agriculture and other fields that require detailed terrain models.

1. Combining multiple DSMs leads to a more complete and accurate terrain representation, addressing issues like shadows and temporal data variations.

Conclusions

6. The results support previous findings that DSM fusion improves quality, but in this study, fewer DSMs were needed.

6. Adding too many DSMs reduces completeness, as more pixels are marked as non-data; this behavior may differ from previous studies due to algorithm or data differences.

6. The method allows trees to be excluded from DSMs by using images from the leafless season or various perspectives to cover occluded areas.

6. Errors in the merged DSM are mainly concentrated in tree areas, affecting error metrics compared to LiDAR, which includes trees.

6. While the fused DSM improves RMSE and STD, it greatly enhances completeness, solving the issue of data gaps in shadowed areas.

6. DSM quality could be further improved by generating DSMs from all image pairs, organizing by parameters, and selecting the best ones, as well as incorporating images from multiple dates to cover more area and account for vegetation changes; this remains a topic for future work.