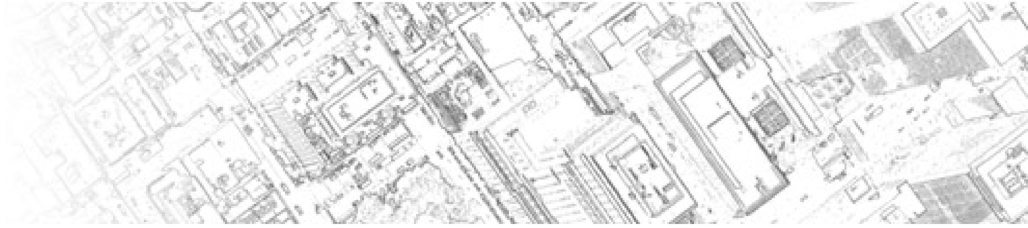

Whitepaper

SimActive's Photogrammetry Software:

Correlator3D™

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Executive Summary

Gathering vast amounts of aerial or satellite imagery is no longer a challenge as digital sensors provide for unparalleled image acquisition capability. The problem is to interpret the imagery efficiently. Image processing remains the limiting factor in production. Through patented innovative algorithms, SimActive pushes the boundaries of the traditional approach to the photogrammetry problem, providing highly accurate geospatial data. The result is Correlator3D™, a best-in-class photogrammetry solution. A simple interface model is used featuring only a single window for any processing task. It provides an uncluttered intuitive interface enabling users to quickly accomplish specific tasks. The use of the GPU in combination with the CPU produced unmatched processing speeds for creation of geospatial data. A complete guide to the software is demonstrated here through examples and analysis of results.

1 Introduction

The last few years have seen a rapid rise in sensor technologies for surveying applications. Acquiring vast amounts of aerial and satellite imagery is simpler than it has ever been before. However, some important challenges still remain. One of which is the processing of raw data into useful information. Although there has been significant progress in photogrammetric software, there remain severe limitations. Current technology is highly complex and inefficient at keeping up with the influx of geospatial data now so readily available. Due to the complex nature of image processing, designing an easy to use interface is difficult, often leading to cumbersome processes to achieve a desired goal. Furthermore, sheer computational power is proving to be a rising challenge in keeping up with the immense amounts of data.

SimActive has approached these issues in an innovative way that will meet the needs of today and grow to the needs of the future. Development work started almost as soon as the digital sensor began to show its dominance in image acquisition back in 2003. In collaboration with the Canadian Department of National Defence, SimActive engineers developed a new generation of photogrammetric software to meet the growing needs of the geospatial industry: Correlator3D™.

Correlator3D™ is a patented end-to-end photogrammetry solution for the generation of high-quality geospatial data from satellite and aerial imagery. The software produces dense digital surface models (DSM), digital terrain models (DTM), orthomosaics and vectorized 3D features. The software has been designed for speed and ease of use and features a highly simplified user interface. Users only have to specify which inputs and outputs are needed and almost no other parameter tweaking is required. Highly-trained personnel are no longer mandatory.

Correlator3D™ has three advantages. Firstly, Correlator3D™ uses the world's first and only GPU-enabled autocorrelation engine for generating digital surface models. This ensures matchless processing power to support rapid production of large datasets. Secondly, the software features completely automatic modules, which implies that no human intervention is required during processing or after the results have been generated. Manual and semi-automatic processes are available to users wishing to modify the results. Lastly, Correlator3D™ builds on patented computer vision algorithms that significantly differ from traditional photogrammetry techniques resulting in high precision geospatial data.

The following sections provide detailed descriptions of the software's functionalities. Proper use of the software and guidelines to ensure optimal results will be discussed.

2 Correlator3D – Step-by-Step Guide

This guide will provide a general overview of how to use each of the core functionalities of Correlator3D™ when processing a frame-based project. Details will be provided on preparing input data, processing modes and manual editing functions. Furthermore, several case studies will be examined using a variety of sensors and project topographies.

2.1 Workflow

All projects begin by preparing input data associated with the imagery. Data preparation includes the handling of EO files, camera files, input elevation models and ground control. After the data is prepared, it is ready to be processed in one of Correlator3D™'s four modes: Data Generation, DEM Editing, Mosaic Editing and Feature Extraction. Correlator3D™ workflow is depicted in Figure 1.

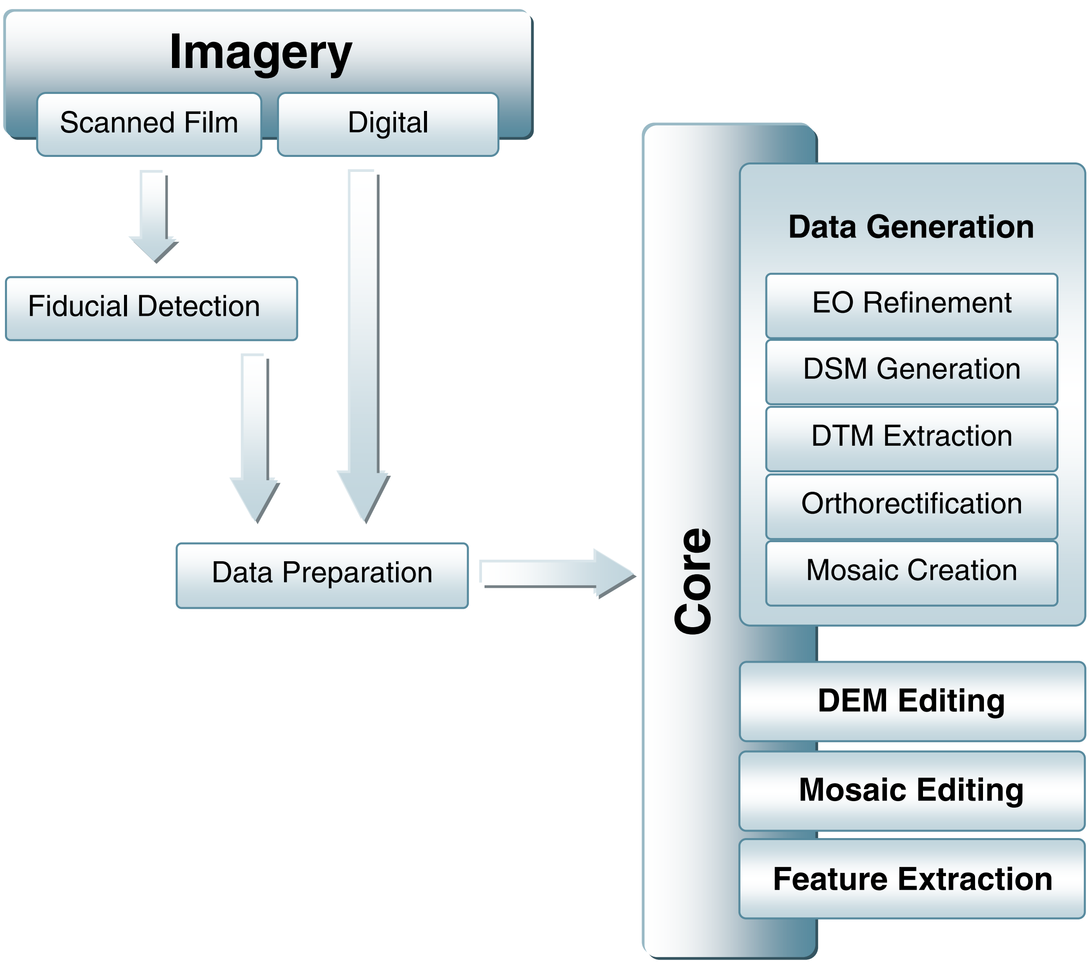


Figure 1: Correlator3D™ workflow.

2.2 Data Preparation

Correlator3D™ requires the following input files:

1. Exterior Orientation File
2. Input DEM
3. Camera Calibration File
4. GCP File Creation

2.2.1 Exterior Orientation File

Frame-based projects in Correlator3D™ begin with an exterior orientation (EO) File. Correlator3D™ requires both positional and attitude parameters (e.g. as provided by a GPS/IMU system). Units must be consistent and angular values must include omega, phi and kappa (O, P, K).

To create an EO file use the EO file creation tool under the File menu as shown in Figure 2.

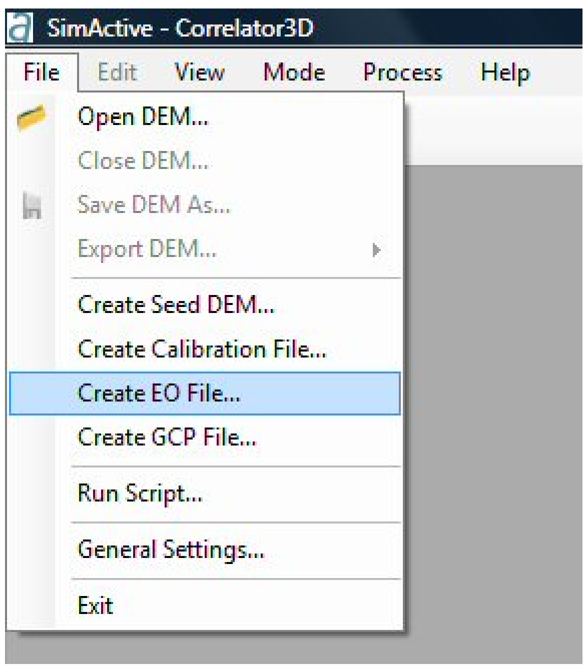


Figure 2: EO file creation.

Once selected, the EO file dialog window appears as displayed in Figure 3.

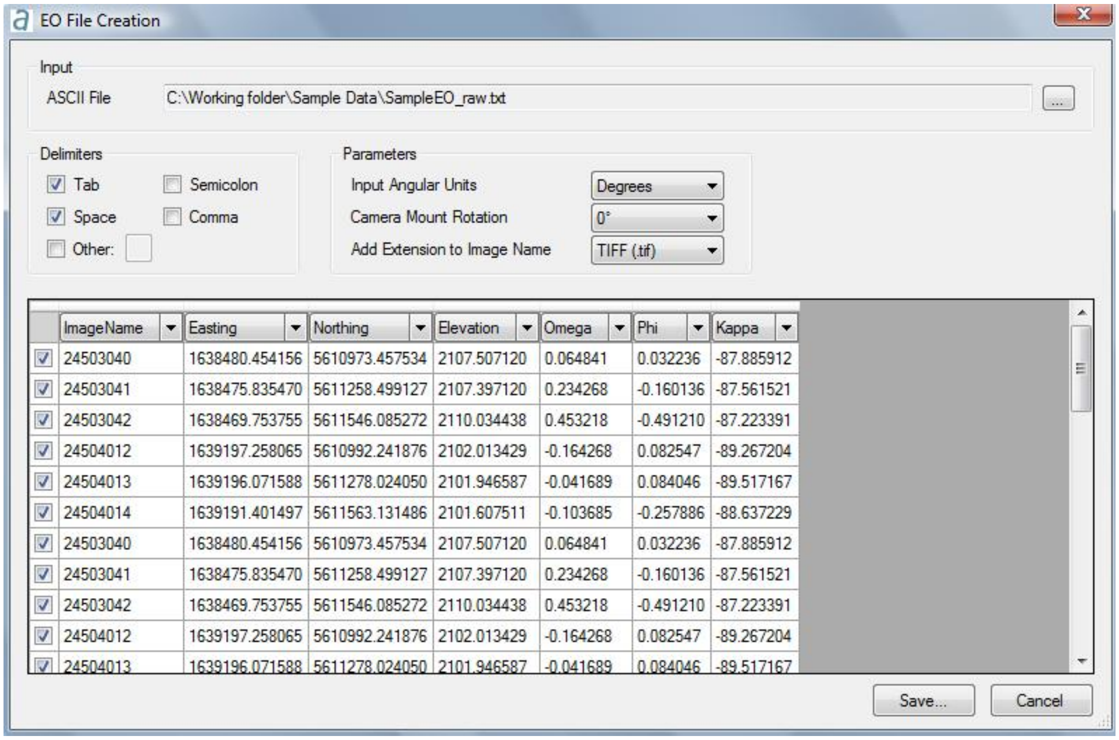


Figure 3: EO file dialog.

The input ASCII file should be arranged in columns containing the image name, positional (e.g. X, Y and Z) and attitude parameters. The correct angular units must be selected. The user must ensure positional parameters are specified in the same units.

2.2.2 Input DEM

The next step is to prepare an input coarse DEM. The input DEM is required because it accelerates processing times by reducing the search space. There are two ways to prepare an input DEM:

1. Use an existing low resolution DEM such as SRTM data (Figure 4) or any available DTM covering the project's area.

SRTM data can be freely downloaded by following these steps:

I. Go to http://srtm.csi.cgiar.org/SELECTION/inputCoord.asp
II. Specify “Input Coordinates” for Data Selection method
III. Specify the lat/long coordinates of a central part of the working project

These SRTM data will be in the geographic coordinate system. Since Correlator3D™ works in a projected system, the downloaded DEM must be first converted to the desired projection in a third-party software.

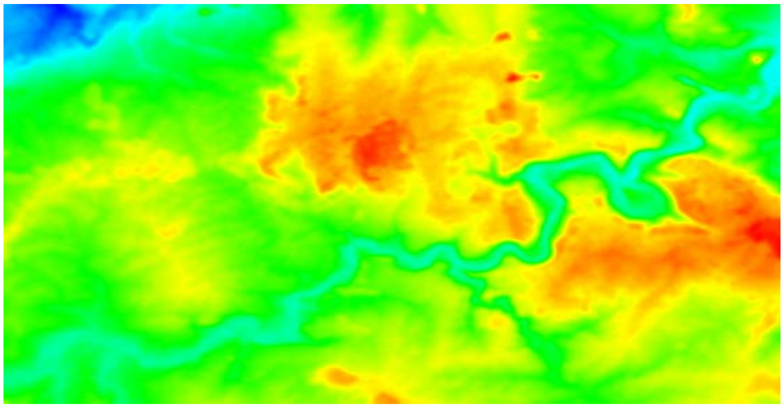


Figure 4: Sample SRTM data.

2. Create a seed DEM using Correlator3D™ as shown in Figure 5.

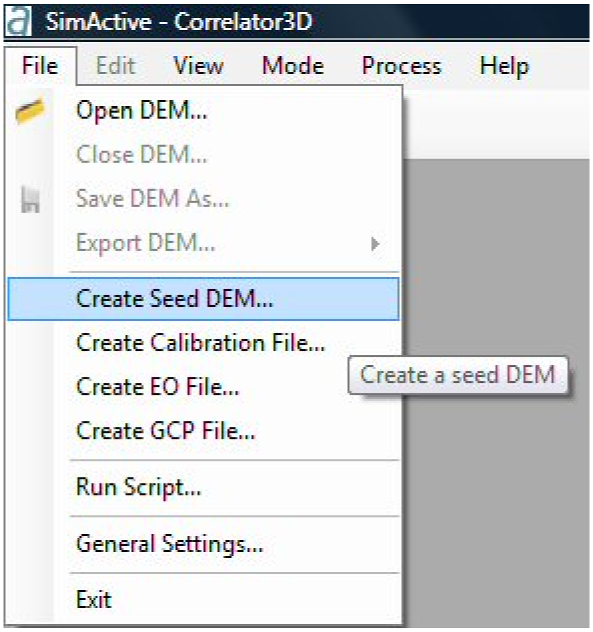


Figure 5: Creating seed DEM.

Figure 6 shows the window after selecting “Create Seed DEM...”.

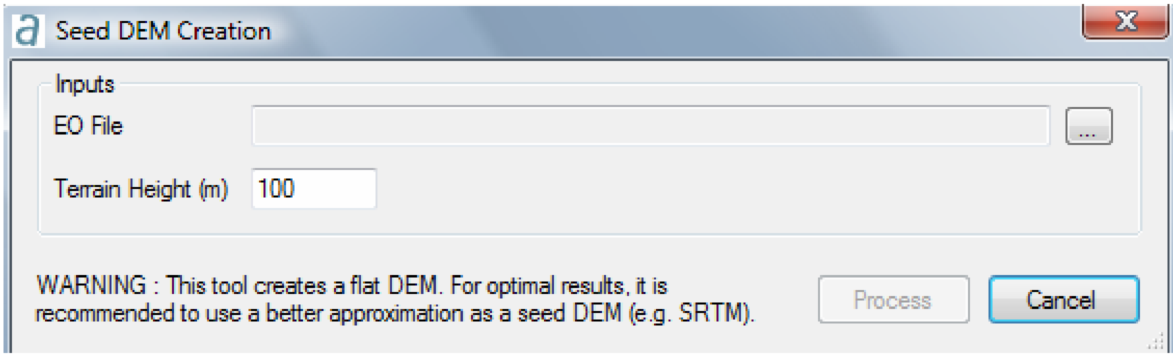


Figure 6: Seed DEM dialog.

The EO file is used to create the boundaries of the DEM according to the project's spatial coverage. It is important to set the appropriate terrain height to ensure correct results. The terrain height should be as close as possible to the average terrain height in the project.

2.2.3 Camera Calibration File

The following step is to prepare the camera calibration file. The camera calibration file consists of parameters describing the characteristics of the camera as shown in Figure 7.

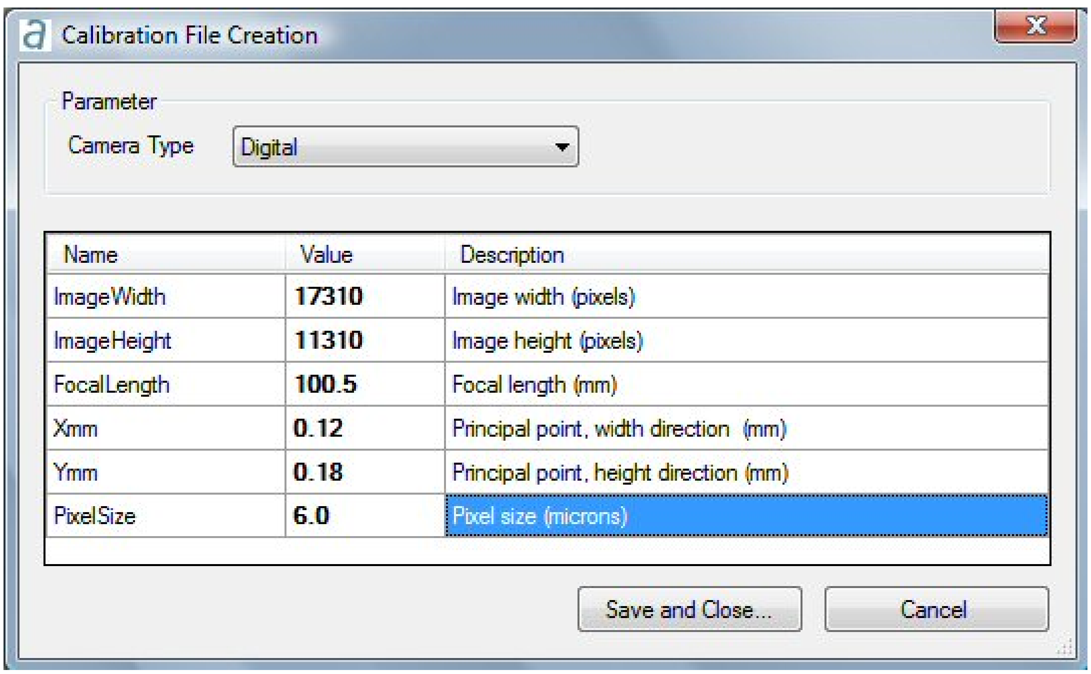


Figure 7: Camera calibration dialog.

The necessary information (e.g. the image size, pixel size, focal length etc.) can be found in the calibration report provided by the camera manufacturer.

2.2.4 GCP File Creation

GCPs can be used in the EO Refinement module as an optional input to further improve the adjustment results. The GCP file contains the XYZ and pixel coordinates of the control points. An interactive tool is used to create the GCP file as shown in Figure 8.

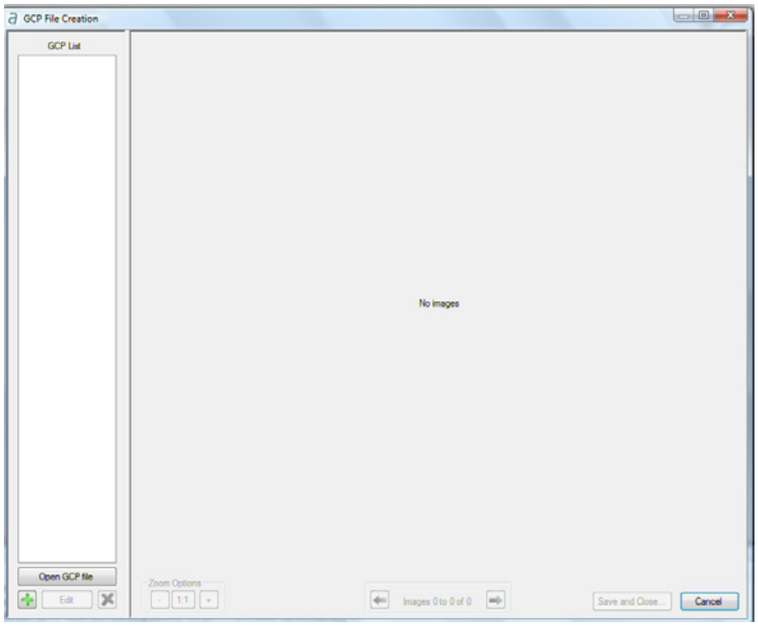


Figure 8: Opening dialog of GCP file creation.

The user needs to click the green ‘plus’ icon in the bottom left corner to add a GCP. Once the XYZ information corresponding to the GCP is provided, the software will identify all images in the project corresponding to that GCP and display them as shown in Figure 9.

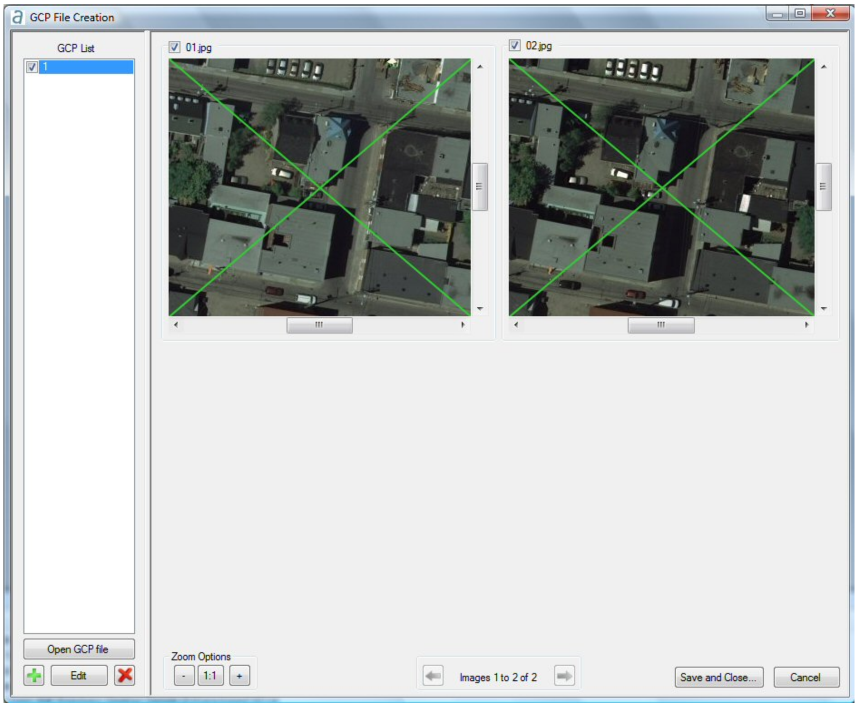


Figure 9: Interactive GCP selection using images.

Once all GCPs are entered, the file can be saved and used in EO Refinement. GCP files may be edited by clicking on the 'Open GCP file' button.

2.2.5 Data Check

Once all the input files have been prepared, it is strongly recommended to test the data integrity before committing to processing the entire project. Data checking is done by two methods.

I. Data Validation tool

The data validation tool checks data integrity. It provides a quick method to check whether syntax errors are present in the EO and camera calibration files. The output of the Data Validation tool is the RMS pixel error. This number represents the magnitude of the error present in the exterior and interior orientation information. As a rule of thumb, the RMS pixel error should be less than one. If it is not, then the EO data may need to be adjusted for optimal results.

II. Orthophoto test

Another way to check the data is by generating some coarse orthophotos. A pair of orthophotos from each flight line is generated at coarse pixel resolution (e.g. 1m) for rapid processing. Then, all orthophotos are compared. The orthophotos should align with minor shifting; otherwise the input data needs to be revised. If the orthophotos do not align, then there quite often is a camera rotation. This can often be resolved by simply adding 90, 180 or 270 degrees to the kappa values in the EO file.

2.3 Data Generation

The first of four modes in Correlator3D™ is data generation featuring fully automatic modules, namely, Exterior Orientation Refinement, Digital Surface Model Generation, Digital Terrain Model Extraction, Orthorectification and Mosaic Creation.

2.3.1 Exterior Orientation Refinement

The exterior orientation refinement module is used to calculate the global error across all images in a given project data set. This adjustment improves the EO parameters for each image in the project and creates a new refined EO file.

The process begins by selecting a subset of images with good spatial distribution over the project area. These images are then arranged in triplets. Each triplet is chosen such that two of the images are adjacent on one flight line and the third image is adjacent on a second parallel flight line. For each triplet, Correlator3D™ calculates tie points by identifying feature points common in all three images (e.g. the corner of a street). The underlying image correlation algorithms in Correlator3D™ automatically distinguish between quality tie points and outliers. As a further step, a statistical analysis ensures that only the high confidence tie points are kept instead of having users manually remove incorrect tie points.

These tie points are used for triangulating 3D points, which can then be reprojected back to the image space. In an ideal world, the projected tie points and the feature points would coincide. However, because of the measurement errors associated with the camera and GPS / IMU there will be a small shift between these points and a root mean squared error (RMSE) can be calculated.

The next step in the process is to perform minimization on each triplet of images, where a global correction on XYZOPK is iteratively determined to reduce the RMSE between the tie points and the projected points. This differs from traditional aerial triangulation as only a single correction is calculated for all images instead of one for each image. There is generally no need for full aerial triangulation with recent digital sensors, since individual errors are usually already corrected for via GPS/IMU data post processing. This implies that all that remains is a common error, which can be accounted for by a common correction applied to all images.

Once the minimization process determines that it can no longer improve the results, then the same correction on XYZOPK is applied to all images. Finally, the residual RMSE between all projected and measured points is calculated to provide an overall performance of the EO refinement process.

Using GCPs (optional) introduces a further constraint during the minimization process. The software tries to not only reduce the RMSE between the projected and measured tie points, but also to reduce the RMSE between the triangulated 3D points and the GCPs. In addition to the RMS error between projected and measured points, Correlator3D™ outputs the error between the GCPs and the triangulated 3D points.

This module is called either by clicking on the exterior refinement module icon along the top left hand side, or by selecting it under the process menu at which point the window in Figure 10 appears.

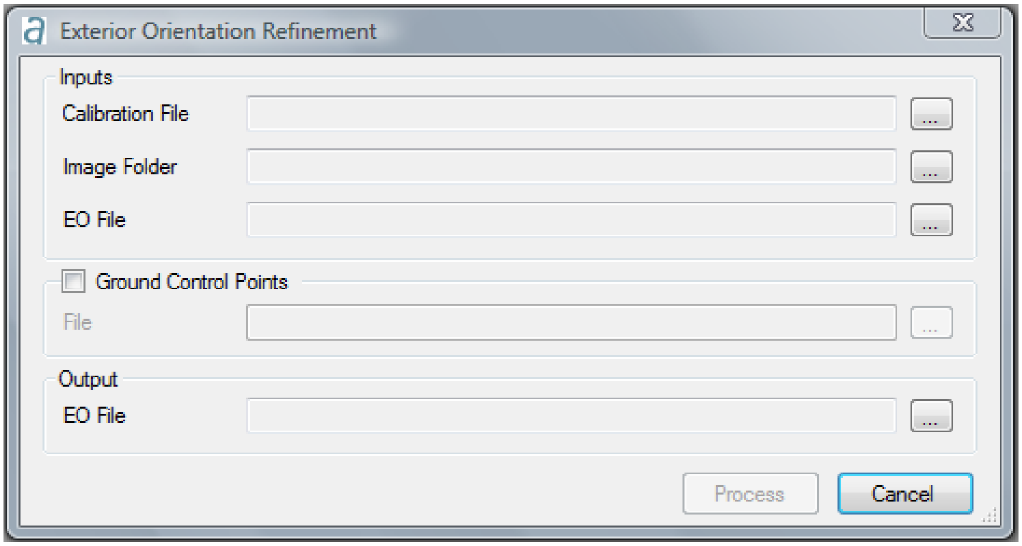


Figure 10: Exterior refinement module dialog.

Under the inputs section, the calibration and EO files created earlier must be selected along with the images for the project. Ground control points (GCPs) may increase accuracy of the results, but are not mandatory. To use GCPs, a GCP file must be specified.

Lastly, in the output section, a name must be chosen for the EO File that will be generated by the software. This EO file will contain the refined EO parameters based on the input data. This refined EO file should be used for all subsequent modules for optimal results. Refinement statistics are shown in the log window in real time. Table 1 shows some sample results for the EO Refinement module.

Parameter	**Common Error Component**
Omega	0.1776°
Phi	0.7004°
Kappa	-0.4803°
X	-0.193m
Y	-1.753m
Z	-2.670m

Table 1: Sample EO refinement results.

2.3.2 DSM Generation

The DSM generation module uses stereo imagery to generate elevation information. The traditional approach is to determine corresponding feature points in image pairs. Then, elevation information is derived by triangulation. These elevation values are interpolated to generate a DSM arranged along a regular grid. This method has the severe drawback of calculating only feature elevation points, which may not capture true ground as a result of interpolation. Instead of extracting feature points and interpolating, SimActive tackles the problem by creating a grid and calculating a correlation score for every post, thus not requiring interpolation. Consequently, this drastically reduces the risk of not capturing true ground and provides a more accurate representation of the terrain.

Furthermore, the classic approach to the correlation problem is bottom-up, meaning a point in one image is matched to the same point in another image to calculate an elevation value. Correlator3D™ instead uses a top-down approach where a solution is derived to explain the measurements observed in the images. As opposed to searching for matching points in the imagery, elevation values on the DEM are refined until they correspond with what is observed in the imagery, solving the correlation problem. Specifically, an input DEM is supplied, super-sampled to match the desired output DSM resolution and refined in the aforementioned fashion until the correlation problem is solved for every grid post.

The graphics processing unit (GPU) is used for DSM generation resulting in supremely fast processing speeds. Images are loaded into the GPU memory on a pair-by-pair basis, significantly reducing memory constraints on the system. The process begins by loading a pair of images into the GPU memory (or image tiles depending on the graphics card memory). A DSM patch corresponding to this pair of images is created and stored on disk. This process repeats until all the images have been processed. The resulting overlapping DSM patches are then optimized and merged in the following manner. A weight is associated with every point within each DSM patch based on a confidence measure. This measure is based on different metrics, including one that weights elevation values according to their distance from the centre of the DSM patches (to reduce potential occlusion problems).

Traditional multi-ray matching increases DSM accuracy, but takes substantially longer to compute because of the increased image load due to a higher overlap percentage. The idea behind the technique is to facilitate the correlation process by utilizing the higher overlap images. Using different correlation techniques, Correlator3D™ managed to leverage the improved accuracy afforded by multi-ray matching, without compromising processing speed. At the heart of this is the ability to merge different elevation measurements for the same grid post from various image pairs – effectively multi-ray matching – without the need for a higher overlap. Also, the software's ability to perform correlation in a highly robust manner allows removing the requirement for high overlap imagery.

Optionally, 3D constraints can be used for guiding the DSM process. These may contain 3D points, vector data (e.g. breaklines) and polygons. The 3D constraints are first rasterized to match the resolution of the desired DSM. Then, they are used during the minimization and help the software to solve the correlation process. Finally, the elevation values generated from the constraints will be forced in the final DSM. Importing 3D constraints guarantees the final DSM to have the exact values specified in the vector file while helping the correlation process. Figure 11 displays the DSM window.

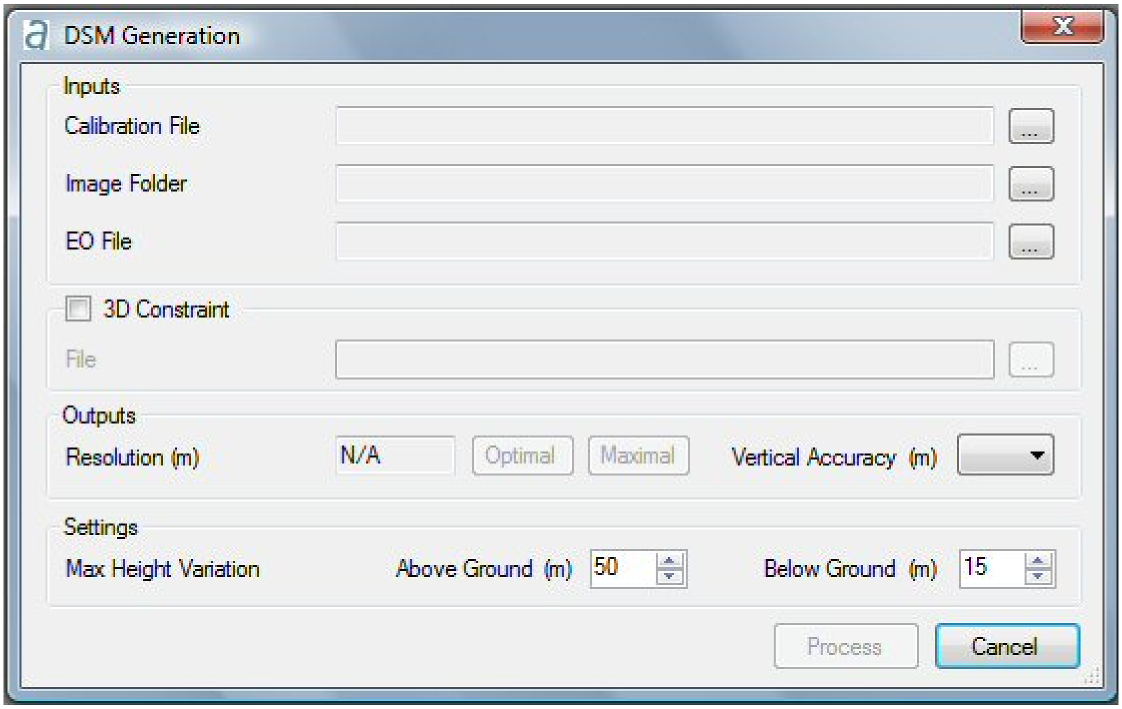


Figure 11: A DSM dialog window.

As in the EO refinement module, the user is requested to provide the input files, namely, the image folder location, the EO file and the camera calibration file. 3D constraints are an option for users who wish to force particular values in the resulting DSM. These 3D constraints can be in the form of a shapefile or a DGN file and once again, may include points, vectors and polygons. Typically, such 3D constraints will be first generated using a traditional stereoplotter.

The outputs section of the dialog consists of two fields. The “resolution” field describes the horizontal sampling of the final DSM output. The “vertical accuracy” field provides an estimate of the quality of the DSM that will be generated. Furthermore, two buttons are available for choosing a resolution. The maximal button produces the best possible resolution for the output DSM. This is 3 times the ground sample distance (GSD) of the imagery. The optimal button provides a resolution that represents the best compromise between speed and processing time to generate the DSM. Likewise, the user is free to specify a desired resolution for the DSM. If the requested resolution goes beyond the maximum resolution, then a DSM at maximum resolution will be generated first and then interpolated. Vertical accuracy can also be specified independently from the horizontal resolution. As an example, a lower resolution may be specified to increase processing speed while maintaining maximal vertical accuracy.

Lastly, the settings section has two parameters that define the “maximum height variation”. These parameters control the correlation window search space. As previously described, the DSM generation process starts with an input DEM. The elevation values on this input DEM are then iteratively modified until the image correlation problem is solved, resulting in the final DSM. When calculating by how much the elevation values are changed, the software needs to have upper and lower bounds to specify the search space size and delimit processing time. These bounds are the “above ground” and “below ground” fields. It may be easier to think of the “above ground” field as the highest point on or over the terrain such as the top of the highest building or tree, while the “below ground” field represents the lowest point such as a lake or a pit. A sample DSM is shown in Figure 12.

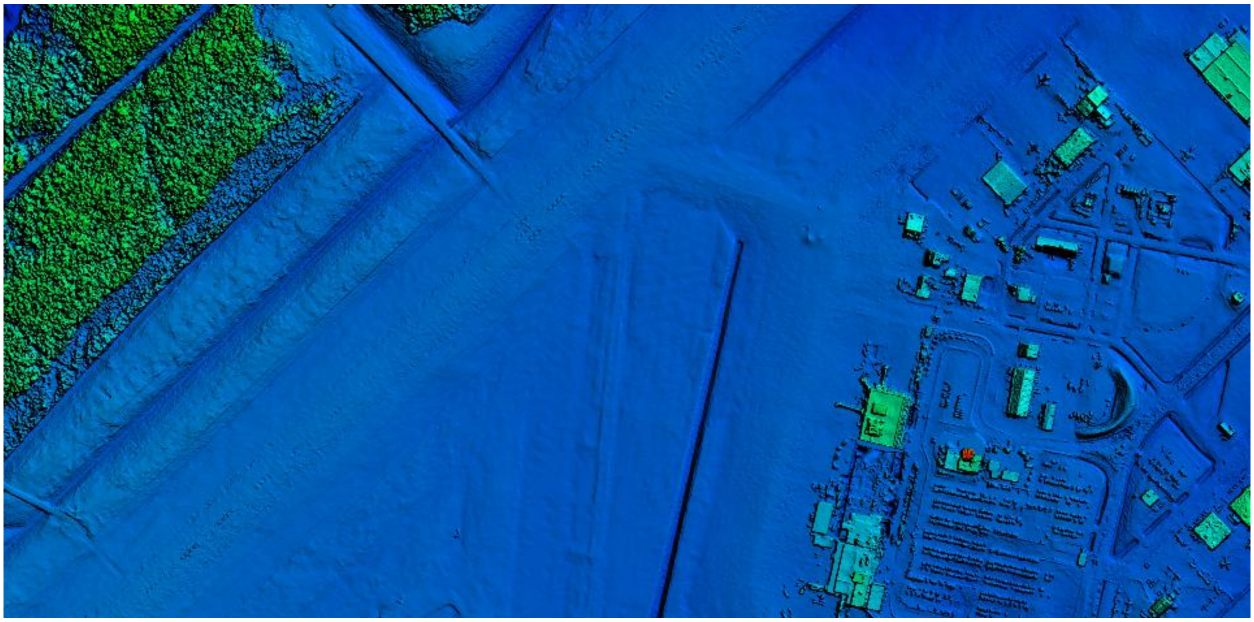


Figure 12: DSM of an airport.

2.3.3 DTM Extraction

A DTM is derived by applying a filtering algorithm on the DSM. The filtering serves to identify groups of elevation points in the DSM that appear higher relative to their neighbour. Once such a group is identified, the corresponding elevation values are removed and the resulting gap is filled by interpolation. The filter consists of a lateral window with a size specified by the user. The size determines the aggressiveness of the filter and thus, it is important to choose the right size for the situation. Generally speaking, the filter size should be large enough to allow removal for the largest 3D feature in the DSM (laterally). The size should be as small as possible to avoid removing / smoothing natural features (e.g. small hills), but should be large enough to cover wide structures (e.g. buildings).

As with the DSM, 3D constraints can also be imported to the DTM. The software will rasterize the vector data and force the final DTM to inherit these exact elevation values. The elevation data included in the 3D constraint may also help the DTM process to filter out large objects (e.g. points on the ground in dense forested environments). Lastly, in certain conditions, 3D constraints can be used to preserve features such as roads in very steep mountains.

Once a DSM is loaded, clicking on the DTM icon brings up the DTM window as shown in Figure 13.

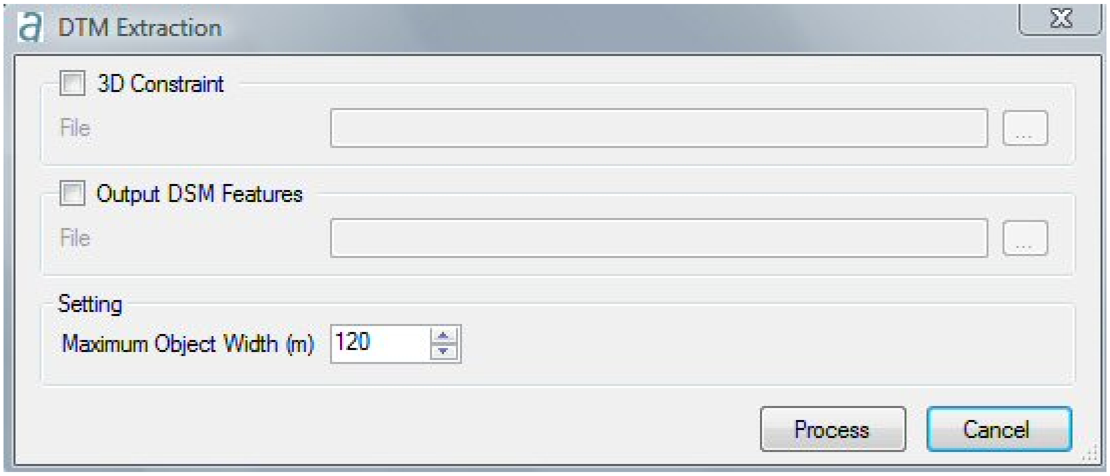


Figure 13: DTM extraction dialog.

Users have the option to save the DSM features that will be removed after the DTM extraction process completes (e.g. trees, buildings, etc.) This may be helpful for those users wishing to analyze what was removed from the DSM when extracting the DTM. Figure 14 shows a sample DTM of an airport derived from the DSM in Figure 12.

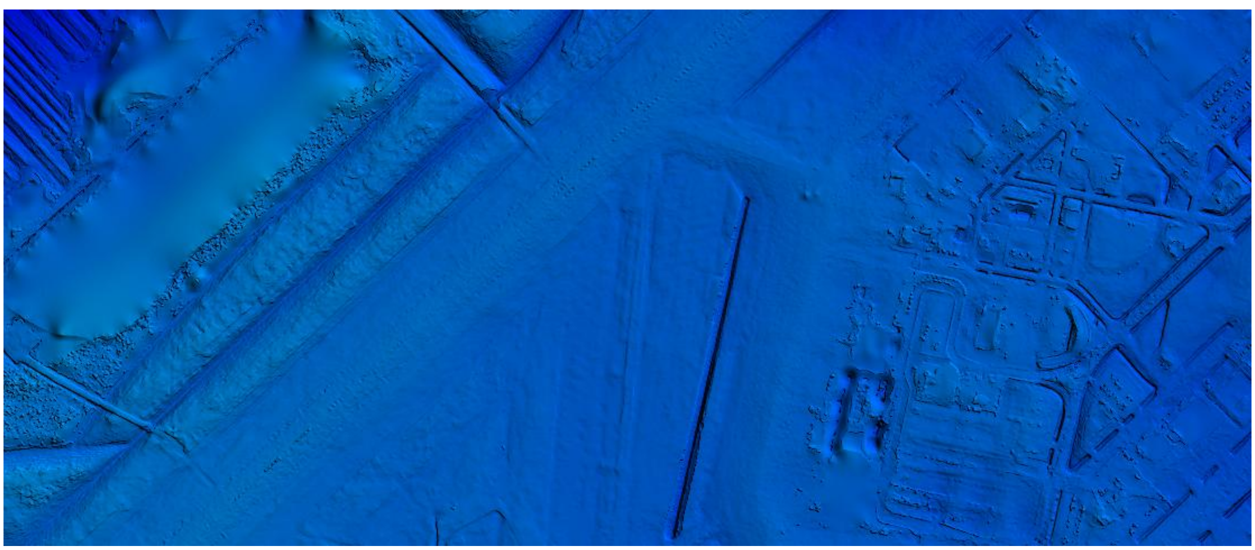


Figure 14: DTM of an airport.

2.3.4 Orthorectification

Once DEMs are prepared the user can orthorectify imagery using either a DTM or DSM. The orthorectification module generates individual orthophotos, which can then be merged using the mosaic creation module. Figure 15 shows the orthorectification dialog window.

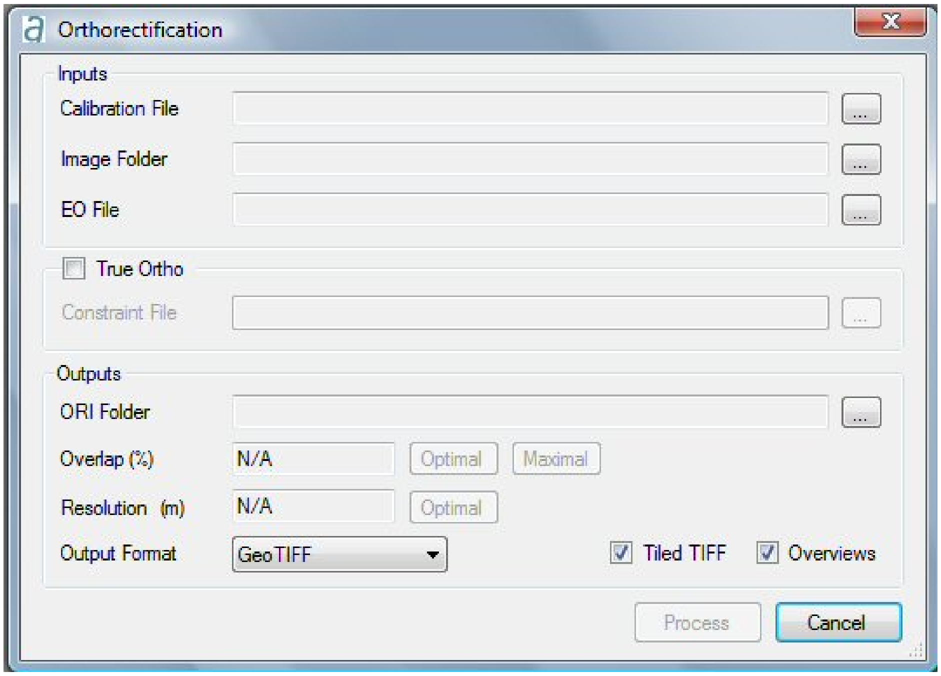


Figure 15: Orthorectification dialog window.

The inputs section is the same as for the previously presented processing modules. True orthophotos can be produced by checking the “True Ortho” box. In that case, a vector file needs to be provided as a constraint (e.g. building footprints) in order to generate true orthophotos. Additionally, the user must ensure the imagery has enough overlap to fill data voids. In the outputs section, the user is encouraged to create a separate folder to store the resulting orthorectified images. The maximal overlap refers to the natural overlap between the images. Selecting optimal will decrease the overlap by cropping the images to their most nadir sections. The optimal button for the resolution ensures the highest possible resolution is used, which corresponds to the image GSD. However, the user is free to specify an alternate desired resolution.

2.3.5 Mosaic Creation

The mosaic creation module allows merging together individual orthorectified images to obtain an image covering the entire project area. Once the inputs and outputs are specified, the process is entirely automated. Correlator3D™ will select which portion of which image must be included in the final mosaic. Local intensity adjustments and the generation of seamlines are performed to provide smooth and seamless transitions between adjacent images composing the mosaic.

Fully automatic color balancing is also applied during the mosaic creation process. The first step is to adjust image intensity. Overlapping regions are compared for similar features. Once similar features are found, the image intensity in both images is compared using a histogram. If a change in intensity is detected, the algorithm modifies the histogram using three methods:

1. Increase the average brightness
2. Adjust size of the histogram thereby changing the contrast
3. Apply a gamma correction

During these modifications, the average intensity of the entire project is preserved. This is to prevent a project from undergoing a global shift in intensity, resulting in the entire project looking lighter or darker. Hence, for every intensity change, another change is applied to counter it. Up to this point, the entire project may look more balanced, but the intensity of individual images may be unbalanced. For example, a given image may look lighter on one side due to the reflection of the sun. This is remedied by adjusting the intensity locally within each image. Such an adjustment will compensate for local variations in intensity to a more uniform balance. With the overall intensity of the project corrected, the last step is to adjust the tint of the project. The intensity adjustment algorithm as described earlier is applied for each of the three channels (i.e. red, green and blue) in the case of color images. This corrects for any tint related issues in the project. Figure 16 shows the resulting mosaic generated from images that were flown at different times during the day and under varying weather conditions. Note the color uniformity throughout the entire mosaic.

Figure 16: Sample mosaic of orthorectified images.

Once color balancing is completed, seamlines are generated automatically in Correlator3D™. The mosaic is built by adding orthophotos one after the other. Each time an orthophoto is added, overlap regions are compared and a difference map is created. The map is built by grouping pixels that pertain to the same features in each image, and then by comparing groups together. The algorithm then creates a seamline that avoids large differences in the map.

The process repeats for the next orthophoto until all orthophotos have been added to the mosaic. In order to boost processing speed and ensure the IO process does not interfere, the upcoming orthophoto is preloaded into memory for use after the seamline calculation has completed for the previous one. When merging the orthophotos together, a local intensity adjustment occurs to ensure a seamless transition between orthophotos. Even though color balancing has already been performed at this point, there still may be small variations in intensity between orthophotos. Hence, there is a local intensity adjustment performed when adding an orthophoto to a mosaic during the creation process. Lastly, the seamline has a small feathering region which controls the blending transition between orthophotos. Note that this blending occurs on all channels. The transition is strongest close to the seamline and fades out to the end of the feathering region. The mosaic creation module can be used through the dialog shown in Figure 17.

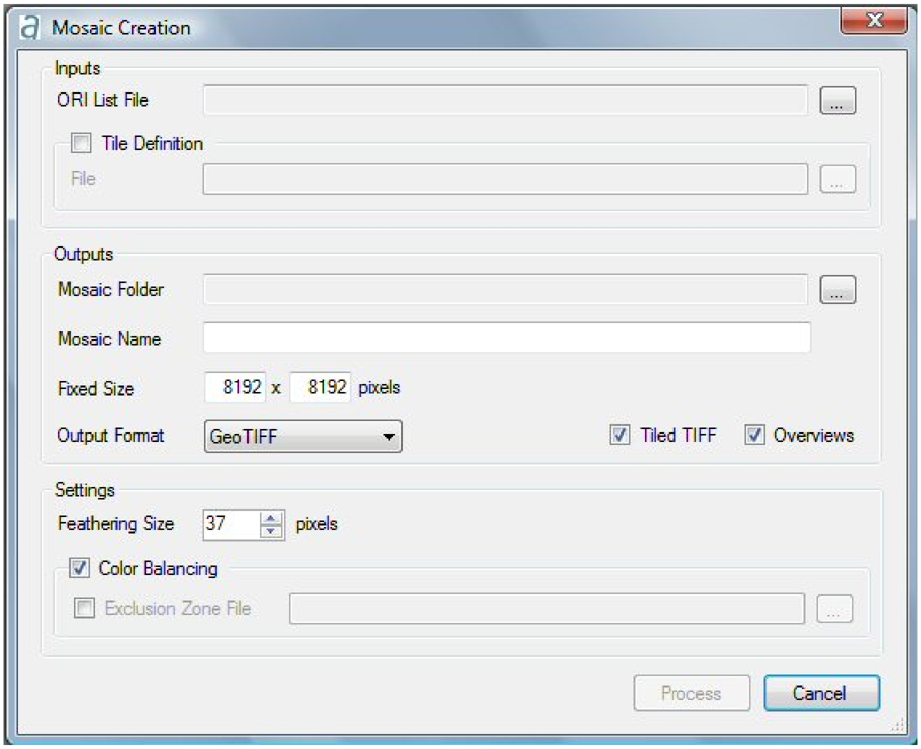
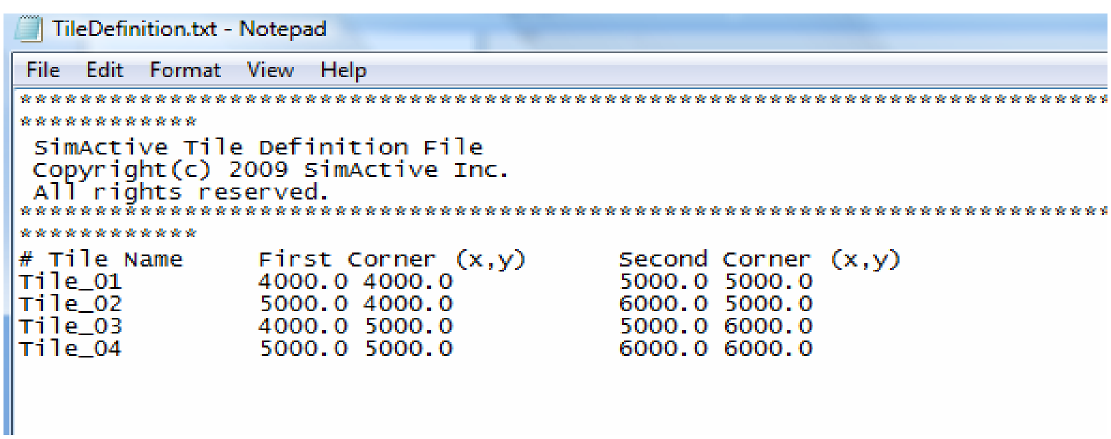


Figure 17: Mosaic creation dialog.

For the inputs section, the ORI List File is a list of orthorectified images. The file is automatically generated during orthorectification. Users may choose to provide a custom tile definition file by checking the “Tile Definition” box.

An example of a tile definition file in the form of a text file is shown in Figure 18. The boundaries of each tile are defined along a diagonal. A Shapefile could have also been used.



```
TileDefinition.txt - Notepad
File  Edit  Format  View  Help
*****************************************************************************************
 SimActive Tile Definition File
 Copyright(c) 2009 SimActive Inc.
 All rights reserved.
*****************************************************************************************
# Tile Name      First Corner (x,y)      Second Corner (x,y)
Tile_01          4000.0 4000.0           5000.0 5000.0
Tile_02          5000.0 4000.0           6000.0 5000.0
Tile_03          4000.0 5000.0           5000.0 6000.0
Tile_04          5000.0 5000.0           6000.0 6000.0
```

Figure 18: Sample tile definition file.

The Mosaic folder refers to the folder in which mosaic information will be written. This needs to be a new folder or a folder with no other information. If a custom tile definition file is not selected, then the software automatically tiles the mosaic according to the dimensions in the “Fixed Size” window. The feathering region is user controlled and is applied for all the seamlines. Color balancing will be ignored for areas specified in the exclusion zone (Shapefile polygon).

A mosaic with automatic seamlines is presented in Figure 19.

Figure 19: Automatically generated seamlines weaving around buildings along the roads.

2.4 DEM Editing

DEM Editing is the second mode of Correlator3D™. DEM editing features powerful monoscopic editing functions to alter DEMs according to specific user requirements.

The DEM editing mode consists of twelve functions that can be applied to any 3D model. The twelve functions are:

1. Polygonal Selection
2. Feature Selection
3. Load a Selection
4. Touch Up
5. Save a Selection
6. Crop
7. Delete
8. Set Elevation
9. Filter Selection
10. Delete and Fill

11. Extract DTM for a Selection
12. Paste a DEM

To begin editing, simply enter editing mode by clicking on the DEM Editing icon. A dialog window will be displayed asking the user to specify an overlay as shown in Figure 20.

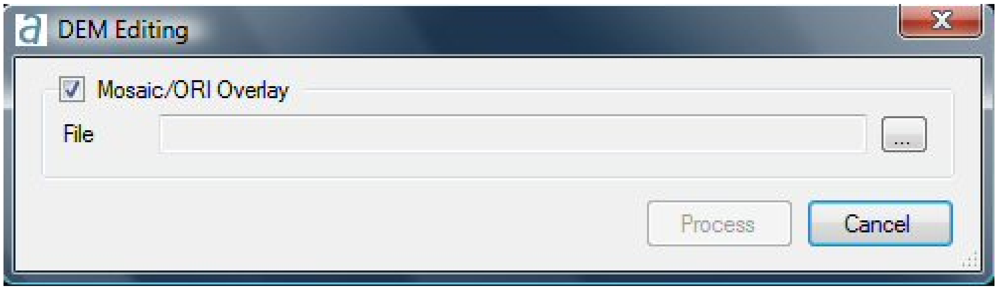


Figure 20: DEM Editing dialog.

A mosaic or orthophotos can be loaded over the DEM to be used as an aid when editing. Any region may be chosen for editing using the mouse. Multiple selections may be saved in a Shapefile. For example, several different areas may be selected in the DSM such as areas with large buildings on one side of the project and dense forestry in another part of the project. These selections can then be saved as 2D polygons in a Shapefile. Various editing functions can be applied to this shapefile such as crop, delete, apply DTM extraction algorithm, etc. Figure 21 shows the effect of using the delete and fill function on a region of buildings in the DSM. The areas highlighted in the shaded polygon are deleted and filled by an interpolation of the points along the boundary of the polygon.

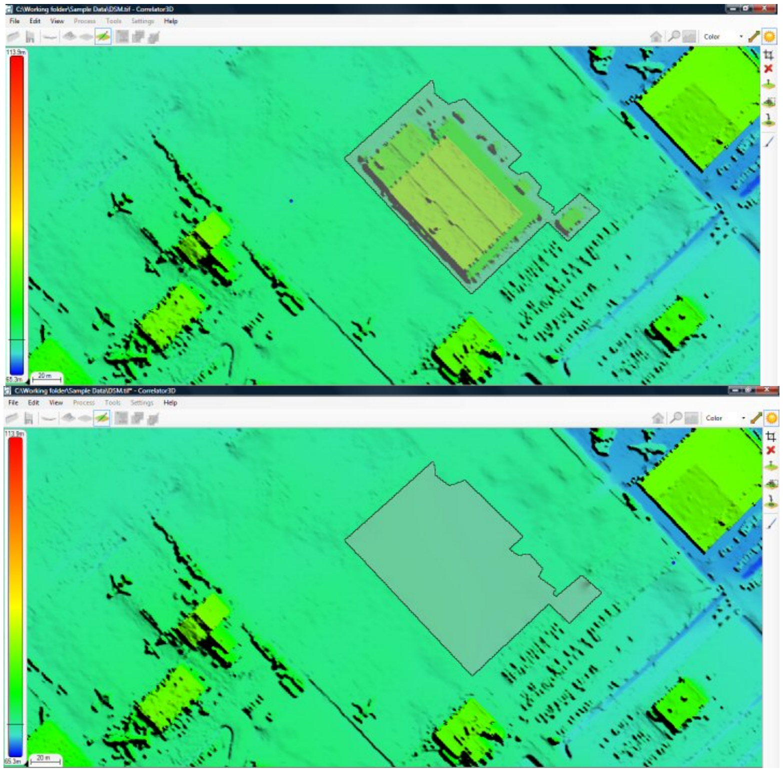


Figure 21: Before and after using delete and fill function.

The set elevation function can be used when users desire specific elevations in the DEM. The DEM editing tool is thus used to fine tune the DTM or DSM.

2.5 Mosaic Editing

Mosaic Editing is the third mode of Correlator3D™. The mosaic editing mode allows the user to interactively edit seamlines in real-time. Mosaic editing can be used to perform minor tweaks to the automatically generated seamlines, although generally speaking it is not necessary. The main purpose of the mode is for specific customer requirements that demand certain criteria for the seamlines, such as specific paths around bridges or other structures. The mosaic editing dialog is shown in Figure 22.

Figure 22: Mosaic editing dialog.

Observe that two inputs are required. The first is the ORI file which is automatically created and stored in the same folder containing the orthorectified images. The second is the tile definition file. This file is automatically created by Correlator3D™ after completing a mosaic using the mosaic creation module. After clicking on the process button, the user enters viewing mode, which enables panning the mosaic and zooming on specific regions as shown in Figure 23.

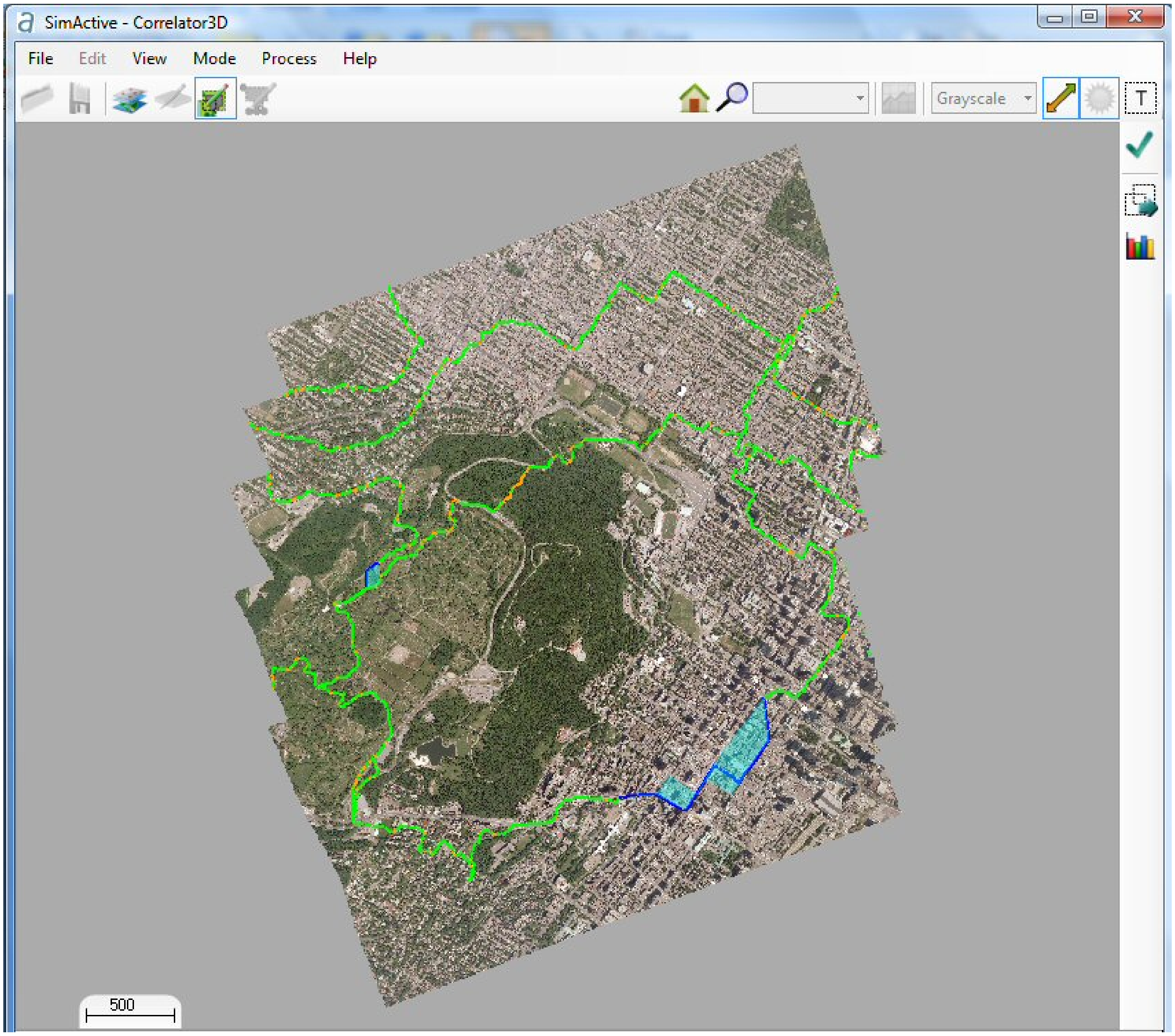


Figure 23: Viewing mode during seamline editing.

Since all seamlines are visible, the user may pan through the mosaic until a desired seamline is found. Each segment of a seamline is color-coded depending on its quality, i.e. as determined automatically by the software during the mosaic creation. Green seamlines indicate a high-confidence while yellow and red tones signify a lower confidence level. To select a particular seamline, the user must move the cursor over the seamline until a crosshair appears. The crosshair indicates that this seamline may be selected. Clicking on the seamline loads up the orthophotos involved and the user enters editing mode. Figure 24 shows two sample orthophotos involved in a particular seamline. Note that one orthophoto is displayed in light tones, while the other is depicted in dark tones. The area where they overlap is shown with no color alteration and represents the actual brightness of the mosaic. This area is observed in the center of the two orthophotos in Figure 24 where the seamline runs through.

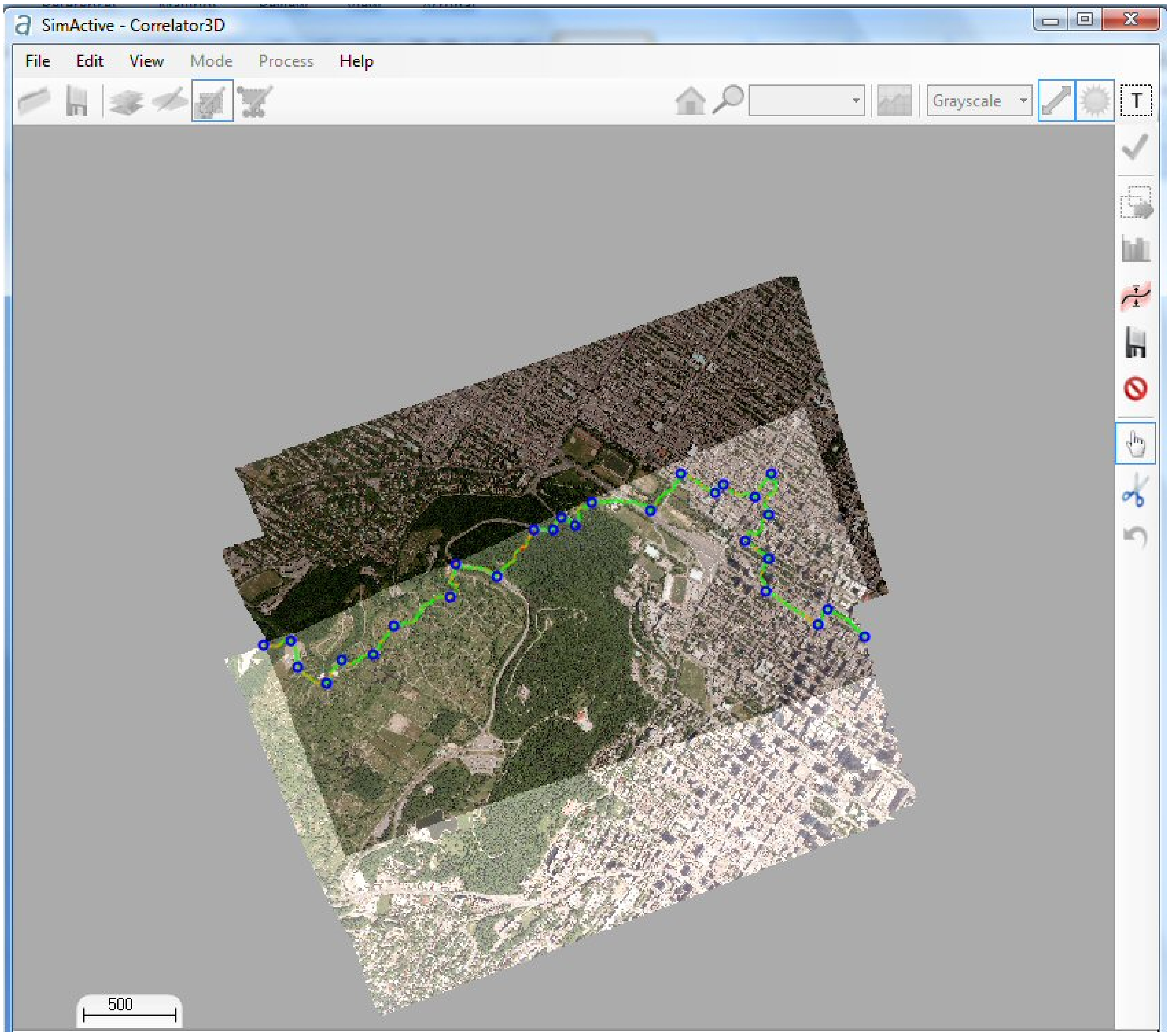


Figure 24: Editing mode in the seamline editing module.

During seamline editing, the actual seamline must remain within the overlap region of the orthophotos. Otherwise, if the seamline is dragged beyond the overlap boundary and into the region where there is no overlap, then that region will be shaded black. Hence, tonal differences to the orthophotos were introduced in order to guide the user to stay within the overlap region.

In editing mode, nine mosaic editing options are available:

1. Update mosaic
2. Export seamlines
3. Adjust mosaic colors
4. Set feathering size
5. Save current seamline

6. Discard all changes on current seamline
7. Move, add, or delete a seamline point
8. Cut, i.e. replace a series of seamline points
9. Undo last action

The user can add or remove as many points on the seamline as necessary. Points can be clicked on and then dragged to pull along the seamline in the desired direction. The cut tool is handy for editing a large number of points over a great distance. If the user is not satisfied with the changes made to the seamline, the discard button disregards all changes and brings the seamline back to its original position. Once the user is satisfied with the changes made to the mosaic, the save button confirms the changes and highlights in blue the area of the mosaic that needs to be updated as shown in Figure 25 (note that the new seamline is represented in blue).

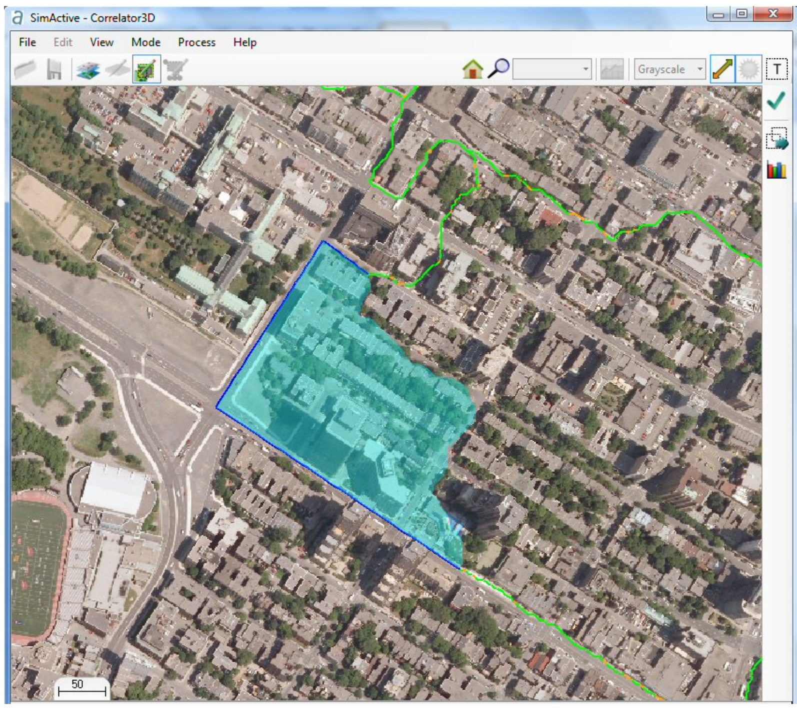


Figure 25: Mosaic region (blue) will be reprocessed after editing a particular seamline.

The final step is to select the update mosaic button. This will instruct the software to regenerate only those areas highlighted in blue. Please note that the entire mosaic is not recalculated; only those portions that were changed are reprocessed. Once this step is completed, the final mosaic is ready for use. Lastly, the export seamline button enables users to export the automatically generated seamlines, which can be saved as a shapefile.

2.6 Feature Extraction

Feature Extraction is the fourth and last mode of Correlator3D™. The feature extraction mode enables users to extract 3D polygons describing features such as buildings, roads, forests and water bodies. A DSM is supplied as an input and vectorized 3D features are produced as an output. Existing solutions are either fully automatic with limited manual options or mostly manual. The novelty of this approach is its semi-automatic design, which combines the best of both worlds. Users are only required to provide simple feedback to the software. Such feedback includes selecting desired features to be vectorized and assisting the software in creating roof geometry. Four feature types may be extracted, which include buildings, forests, water bodies and roads.

Once a DSM is loaded, clicking on the Feature Extraction mode brings up the Feature Extraction window as shown in Figure 26.

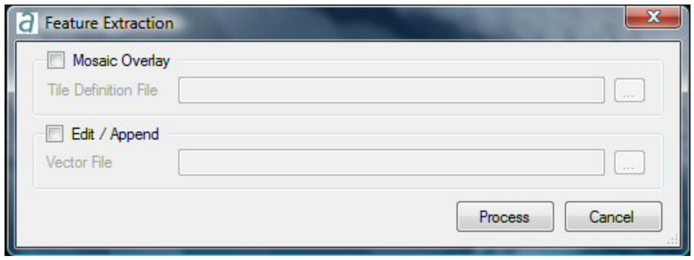


Figure 26: Feature extraction dialog.

Users have the option to overlay a mosaic, which may aid with feature extraction. Furthermore, existing vector files may be selected and edited. The following paragraph describes the process to extract a building.

The process begins with the user clicking roughly around a feature of interest. The software then automatically analyzes the user's selection and determines the boundary of that feature as shown in Figure 27.

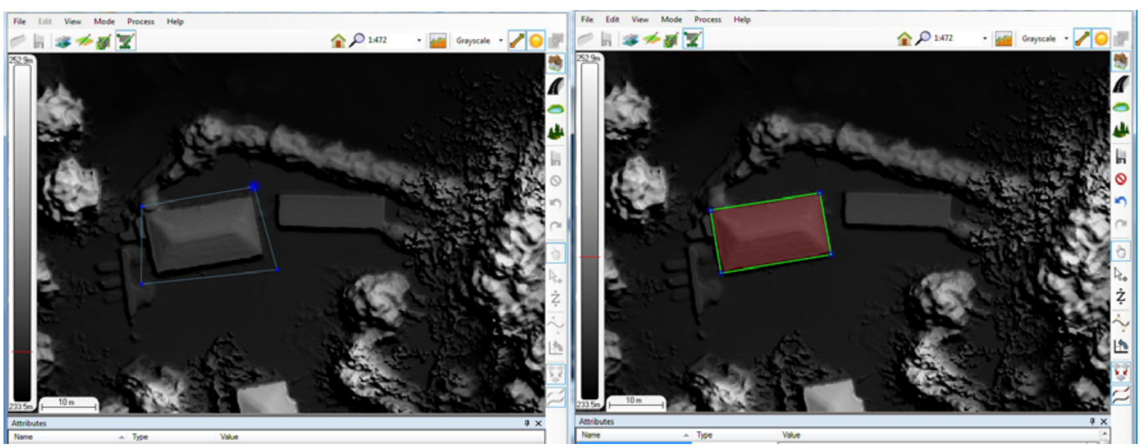


Figure 27: Before and after using the feature selection tool

After the boundary is determined, the software automatically creates a 3D polygon for that boundary. The 3D information in the DSM is used to create the 3D polygon. For buildings, the next step is to define roof geometry. This step is accomplished by the user segmenting the 3D polygon into finer sections. Figure 28 depicts the ease with which a polygon is segmented as the user is simply dragging lines or connecting points to split the polygon.

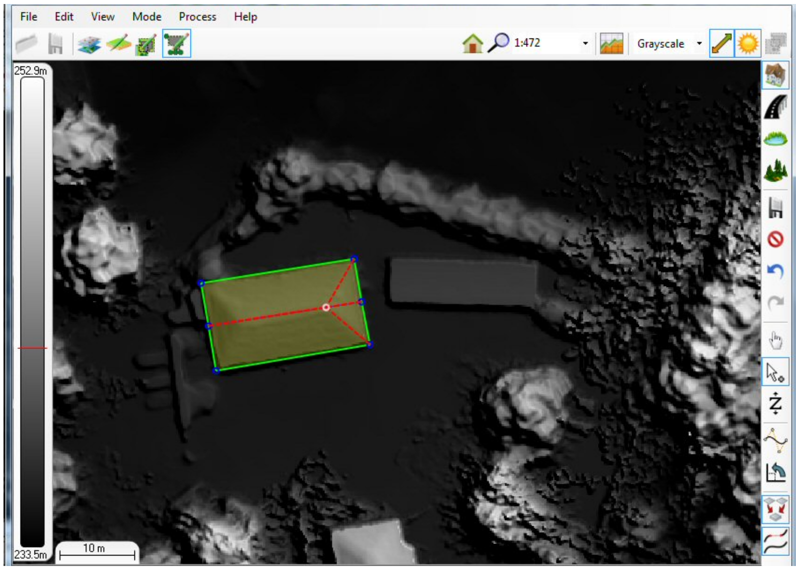


Figure 28: Red lines indicate the segmentation about to occur to the polygon.

Each time a polygon is split into two or more sections, the software automatically performs two steps. First, for each new section of the polygon, the software creates a new 3D plane based on the 3D information in the DSM. Second, this new 3D plane is compared against the DSM to see how well they match. If the new 3D plane matches the DSM almost exactly, then the software highlights that section green to let the user know this section is complete. Otherwise, a yellow or red color will be shown to indicate that further refinement may be necessary. Thus, Correlator3D™ creates 3D features using the supplied digital surface model, while semi-automatically extracting 3D information through intelligent analysis.

2.6.1 Detailed Feature Extraction Example

This section presents a complete step-by-step example of feature extraction. For this example, a DSM with a resolution of 20 cm is used. This DSM was generated using imagery at a GSD of 4 cm. The methodology to extract a building will be examined.

The first step of the feature extraction process is for the user to make an initial rough selection. The software will use this initial selection to automatically compute a refined selection. The operator then performs intermediate semi-automatic editing operations as shown in Figures 29 through to 38.

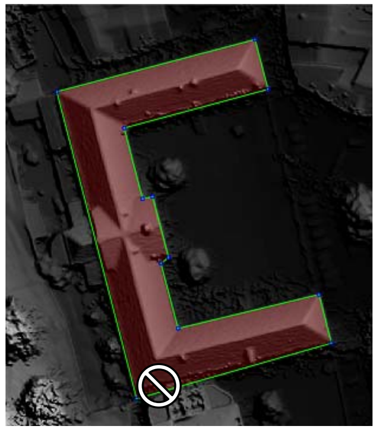


Figure 29: Two points are removed at the location indicated in white.

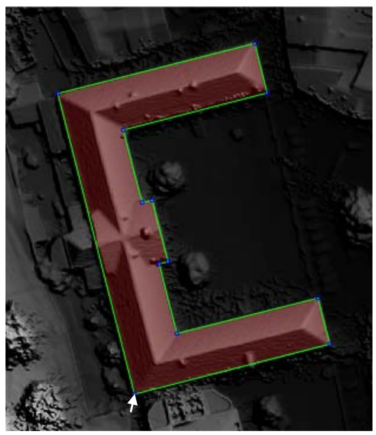


Figure 30: The lower-left corner is moved to its proper location. The automatic rectify function is also performed to create 90° angles.

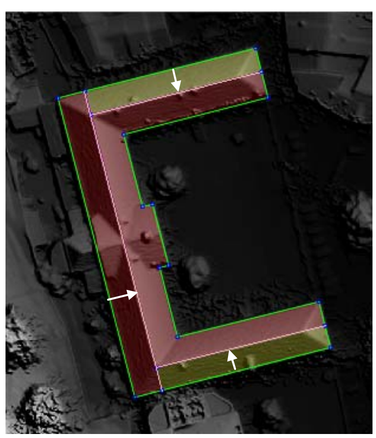


Figure 31: Major roof elements are added by splitting the polygon. First the vertical edge is created, then the two horizontal edges. Note the change in colors. The yellow color means that these surfaces are a better fit than before when they were red. The yellow color also means that further refinement is required to achieve a good fit, which would be described by the green color.

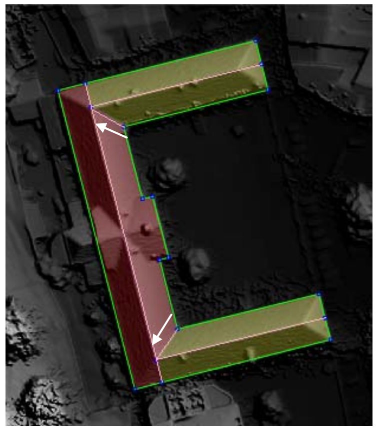


Figure 32: Two new roof elements are added by moving an existing point over another existing point, which creates a separation line. Two red areas become yellow.

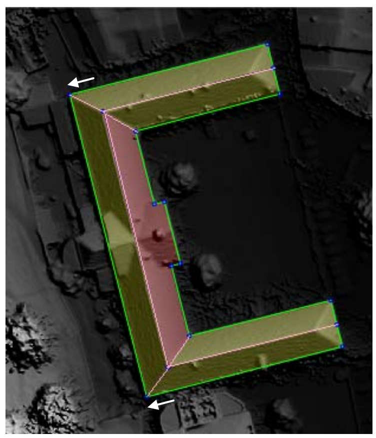


Figure 33: Two surface separations are refined, each by moving an existing point over another existing point along a common edge. This automatically merges the points and removes the edge. Another part of the feature becomes yellow, indicating an improvement in the modeling.

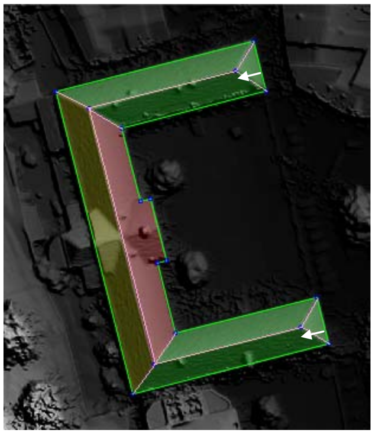


Figure 34: Triangular surfaces are created by moving a point over an existing edge shared by that point. In fact, each operation creates two triangles, one on each side of the existing edge, but these triangles are automatically merged together. Roof elements turn green to indicate a good fit.

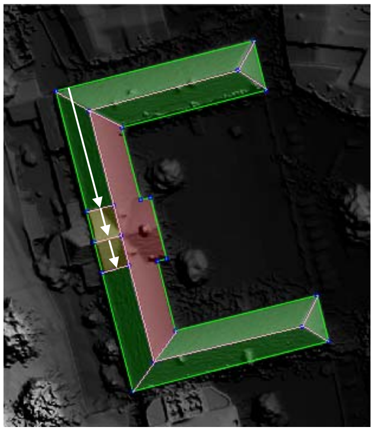


Figure 35: Three new surface elements are created by splitting the polygon. Surfaces in the center are still yellow: they require more editing.

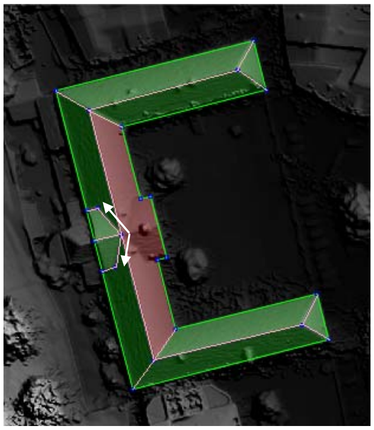


Figure 36: Two new triangular surfaces are created and automatically merged to the surface that was already green.

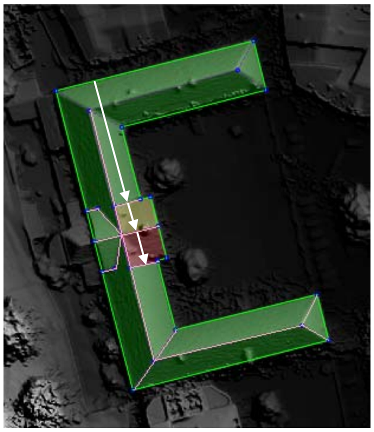


Figure 37: Modeling of the remaining red surface is improved using the same techniques as shown prior. Final result is shown in Figure 38.

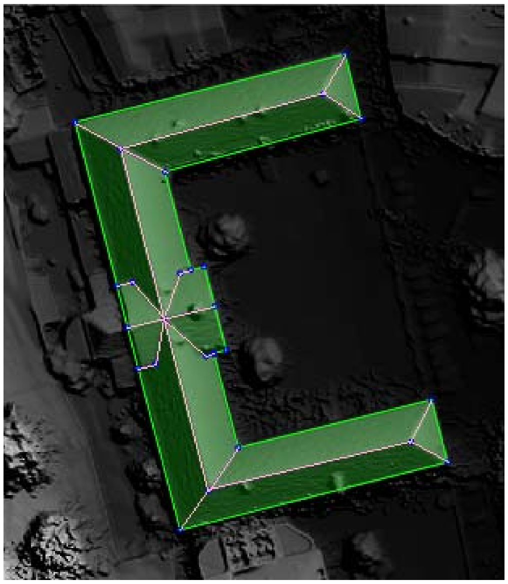


Figure 38: Final result.

At any time during the process, the user can use the elevation editing tool to see the elevations associated to a specific vertex and to edit it if necessary. In this example, no editing is necessary, but the tool can be used by the operator to verify elevations associated with three vertices as shown in Figure 39 (a). Note the difference in elevation in Figure 39 (e): there is a wall between the two roof elements.

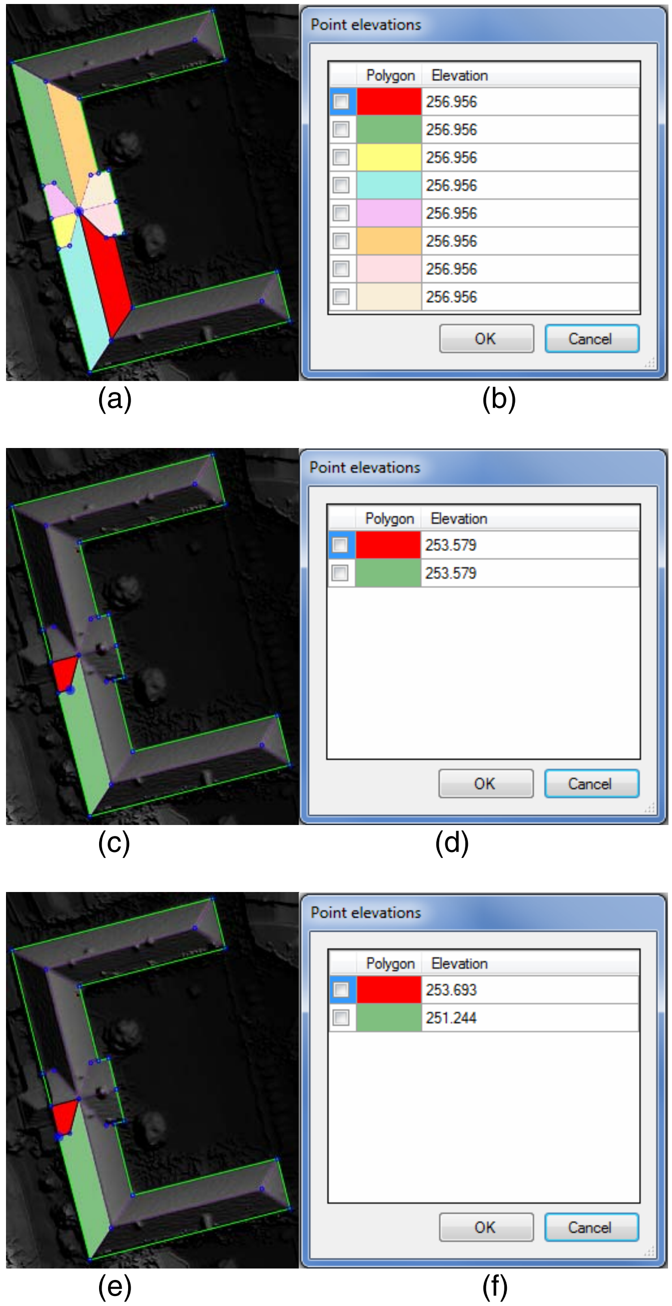


Figure 39: Selected point and surfaces (a, c and e) and corresponding elevation values (b, d and f).

Attributes can be entered using the attribute dialog box that is visible at all times. In the example of Figure 40, the operator assigned to the feature the ID "17" and the type "School". The category "Building" is automatically selected since the feature was created using the building extraction tool. The operator can also choose to add other attributes from the "<--More-->" drop down list or create a new attribute by choosing "<New...>" from that list.

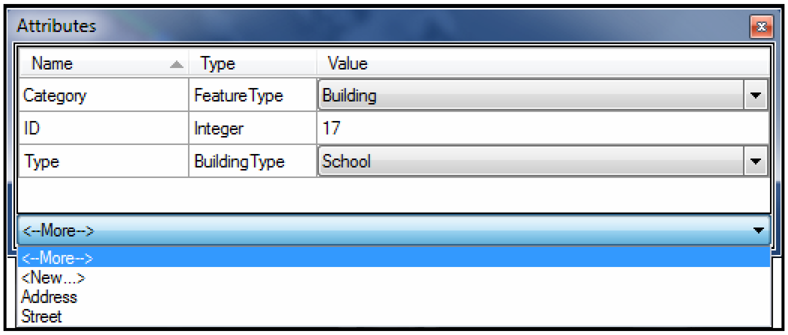


Figure 40: Attributes dialog box.

3 Analysis

Four case studies are presented showing performance, statistics and analysis of Correlator3D™ modules. The system configuration used for all case studies is presented in Table 2.

Graphics card	NVIDIA GeForce GTX 260
CPU	Intel i7 920
Operating system	Windows 7 32-bit
RAM	3 GB

Table 2: Test system configuration.

As part of the project setup, SRTM data was downloaded and used as the seed DEM. It was downloaded from http://seamless.usgs.gov/ at a resolution of 45 m. The SRTM data was chosen because it is easily accessible and offers a relatively high degree of accuracy for a seed DEM. Locating and downloading the SRTM took about 10 minutes as summarized in Table 3.

Download location	www.seamless.usgs.gov
Resolution	45 m
Time to setup	10 minutes

Table 3: SRTM data statistics.

3.1 Case Study 1

This case study evaluates the accuracy of the EO refinement module, compares elevation values for the DSM and DTM with ground truth and performs an analysis of the lateral accuracy of orthophotos generated using the SimActive DTM. The project was flown using a large format camera (10240x7100 pixels) equipped with an 80 mm lens and RGB filters. The project is composed of 5 flight lines and 112 images oriented West-East with 60% forward overlap and 50% side overlap. The mean flying height was 1660 m resulting in a 12.5 cm pixel size. The project specifications are presented in Table 4.

Images	112
GSD	0.125 m
Resolution	10240x7100

Table 4: Project specifications.

3.1.1 Exterior Orientation Refinement

The exterior orientation parameters (GPS and IMU) consisted of raw data as no post-processing, aerial triangulation or boresight calibration was performed beforehand. A total of ten (10) ground control points were inputted to the EO refinement process. These were captured using a total station with good spatial distribution over the project's area. The SRTM was used as the DEM input model.

As a first step, 12,407 tie points were automatically generated by the software. To provide an estimate of the GPS/IMU data accuracy, these tie points were used for triangulating 3D points. The 3D points were then projected back to the local image coordinate system (using the original GPS/IMU data) and compared to the original tie point locations. The RMS pixel error between the original tie points and those projected points was about 38 pixels. The EO refinement was performed and allowed the RMS pixel error to be reduced to 0.58 pixels. Table 5 provides a summary of the EO refinement process statistics.

Tie points generated by the software	12,407
Initial RMSE before EO refinement	38.06 pixels
Final RMSE after EO refinement	0.58 pixel
Processing time	28 minutes

Table 5: EO refinement process statistics.

The RMS pixel error for the 10 GCPs was calculated and the results are shown in Table 6. Note that, the actual pixel coordinates of the GCP as measured from the imagery are referred to as X1 and Y1. The coordinates of the GCP projected in the local image coordinate system (using the refined EO data) are represented by X2 and Y2. Also note that, there are actually 19 entries in Table 6 even though there were 10 GCPs used since the same GCP may appear in more than one image. Lastly, the difference between the actual pixel coordinate (X1,Y1) and the projected GCP (X2, Y2) was used for computing the RMSE.

Observe that all ground control points are individually less than a pixel accurate. This shows that a single common correction on the EO data was sufficient and that a traditional aerial triangulation was unnecessary in this case. The overall RMSE for all ground control points is 1.38 pixels. This result is exceptional especially since manually locating a particular feature point (e.g. manually locating the actual center of a manhole) is subjective and will result in errors of at least one pixel.

Entry	X1	Y1	X2	Y2	RMSE
1	2522	3207	2521.66	3206.11	0.22
2	5141	3524	5141.05	3523.77	0.05
3	4508	4247	4507.93	4247.15	0.04
4	1161	6374	1158.78	6374.01	0.51
5	3379	5588	3379.90	5588.89	0.29
6	3392	6440	3390.69	6440.28	0.31
7	4020	3029	4020.11	3028.79	0.06
8	1057	5888	1057.66	5888.33	0.17
9	6958	5958	6959.79	5958.10	0.41
10	5858	2924	5857.74	2923.53	0.12
11	2896	1723	2895.90	1722.32	0.16
12	6340	3748	6338.93	3748.89	0.32
13	3019	1604	3021.41	1605.07	0.60
14	4680	4154	4680.22	4155.78	0.41
15	1852	2299	1851.43	2299.30	0.15
16	4717	7177	4717.57	7178.12	0.29
17	4140	3088	4139.35	3089.00	0.27
18	1059	4019	1060.33	4019.76	0.35
19	1437	1740	1438.78	1738.85	0.49
RMSE for all GCPs : 1.38 pixels					

Table 6: Ground control point RMSE comparison.

3.1.2 Digital Surface Model

A DSM was generated at a horizontal resolution of 35 cm, which represented three times the GSD of the input imagery. The SRTM data was used as a seed DEM. A value of 55 m was set for the above ground variation considering that the project area did not contain any tall structures and that the SRTM is reasonably accurate. For the below height variation parameter, a value of 40 m was chosen, which is higher than typical in order to ensure any low elevations around the river would be captured. Prior to processing, the software predicted a vertical accuracy of 0.125 m for the final DSM. A total time of 11 hours (approximately 5.9 minutes per frame) was necessary for processing. Figure 40 shows the resulting DSM while Table 7 presents the specifications and statistics of the DSM generation process.

Horizontal resolution	0.35 m
Vertical accuracy	0.125 m
Above ground variation	55 m
Below ground variation	40 m
Processing time	5.9 min/frame

Table 7: SimActive DSM generation statistics.

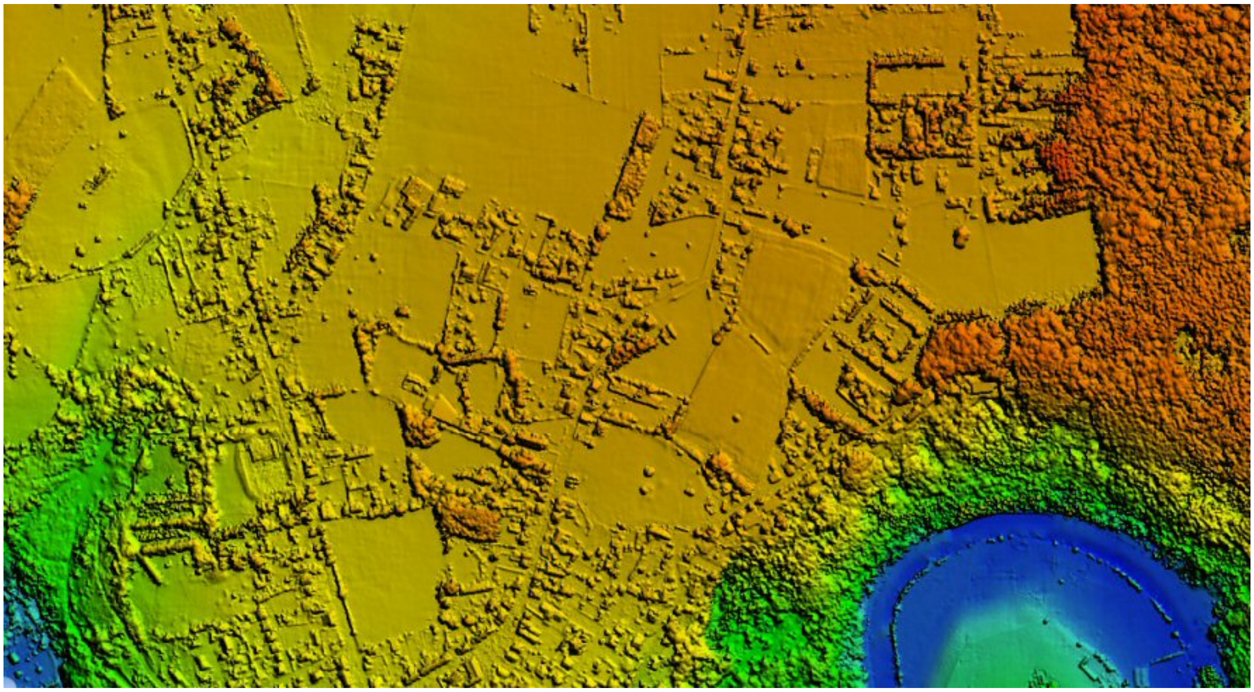


Figure 40: DSM corresponding to the data in Table 7.

To measure the final accuracy of the DSM, ground truth was compared against the elevation values generated by the software. Table 8 presents the results. Observe that the calculated RMSE on the DSM elevation values is 14.6 cm, which represents about one time the input imagery GSD. This value is consistent with the accuracy initially predicted by the software (12.5 cm), considering that the latter should hold for 95% of the points. Also, note that the observed bias was very small at 6 cm, which is within the GSD of the imagery.

Entry	Ground Truth Elevation (m)	SimActive DSM Elevation (m)	Delta(m)
01	125.421	125.56	0.13
02	165.863	166.028	0.16
03	172.439	172.40	-0.03
04	168.277	168.52	0.25
05	179.648	179.57	-0.07
06	184.99	184.99	0.00
07	193.612	193.81	0.20
08	194.534	194.67	0.14
09	116.783	116.83	0.04
10	180.848	180.65	-0.20
RMSE			**0.15**
Bias			**0.06**

Table 8: SimActive DSM comparison.

3.1.3 Digital Terrain Model

A DTM (Figure 41) was extracted from the 0.35 m DSM shown in Figure 40 and the required processing time was 12 hours (approximately 6.4 minutes per frame). A 120 m filter (i.e. a maximum object width parameter value of 120 m) was used to create this particular DTM, since after a quick inspection it was determined that the largest feature (horizontally) fitted within that window. Note that trees, buildings and other 3D structures lying on the ground were correctly removed. Figure 42 shows the 3D features (color shaded) that were removed from the DSM overlaid on the orthomosaic. Figure 43 shows a close up of Figure 42 to facilitate better viewing for the reader. Observe that the features visible from the imagery (i.e. unremoved features) consist of flat lands such as fields.

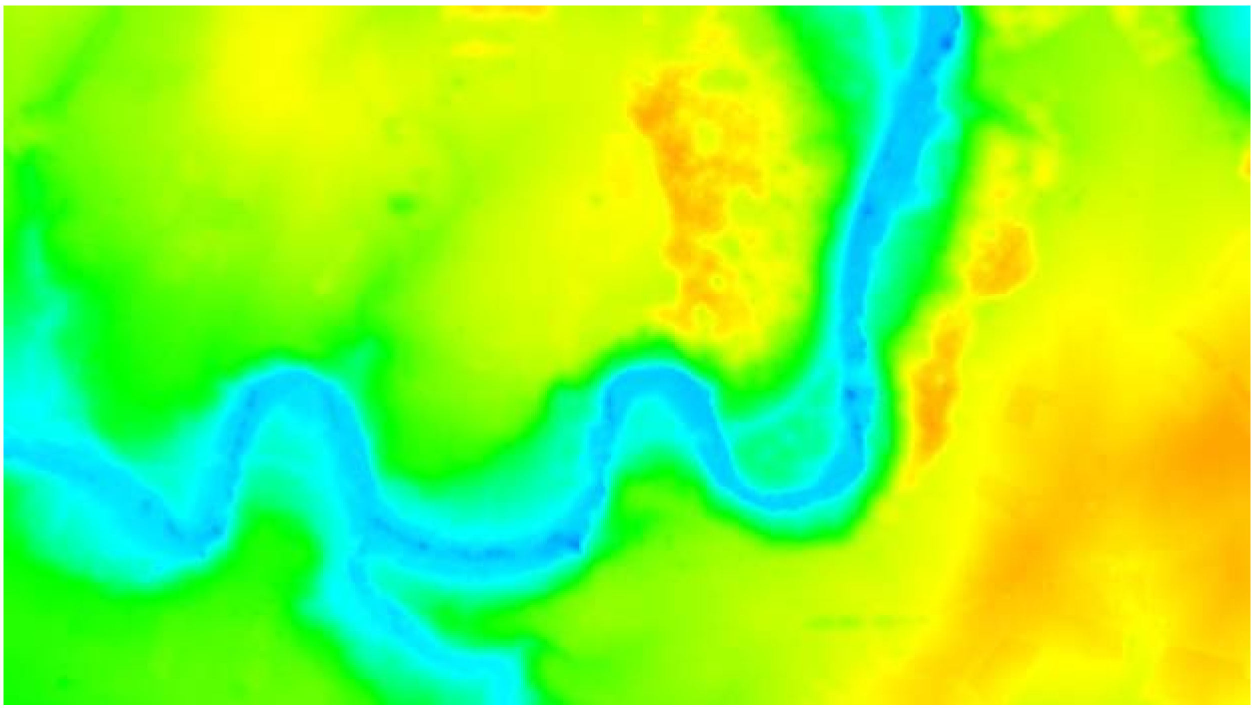


Figure 41: DTM generated using DSM in Figure 40 as an input.

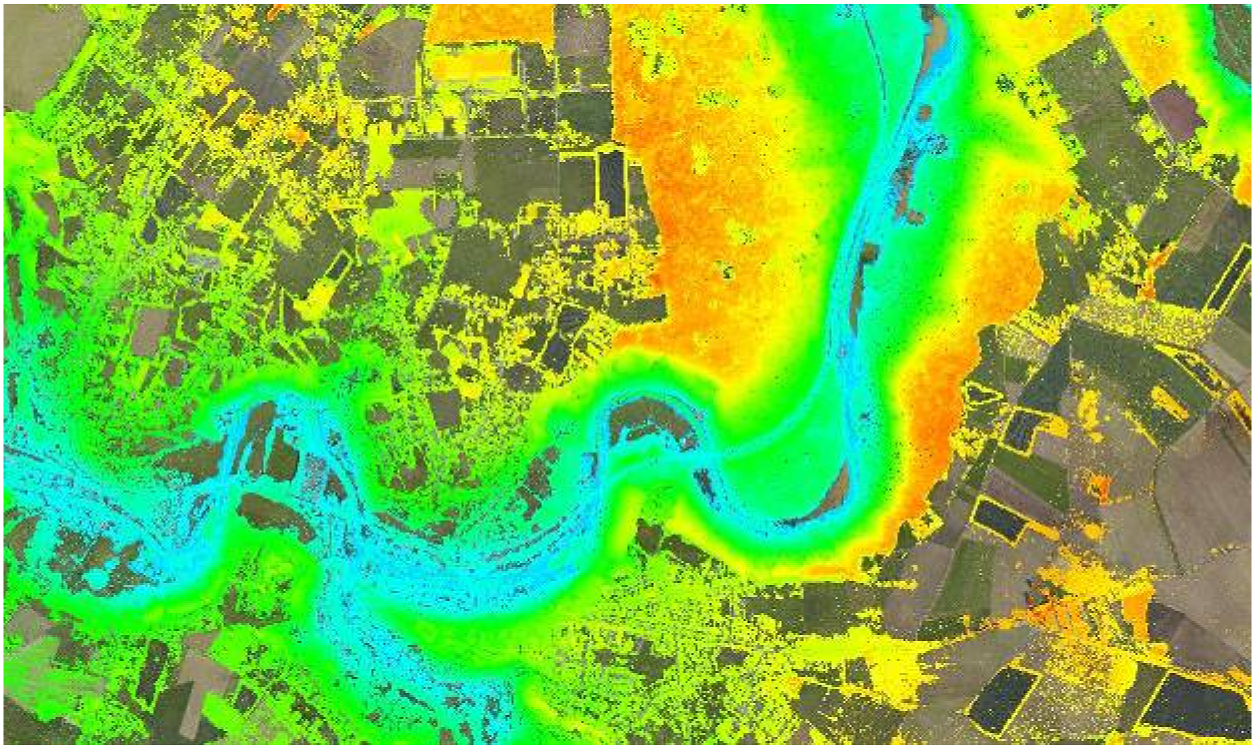


Figure 42: 3D features removed from DSM (color shaded) overlaid on the orthomosaic.

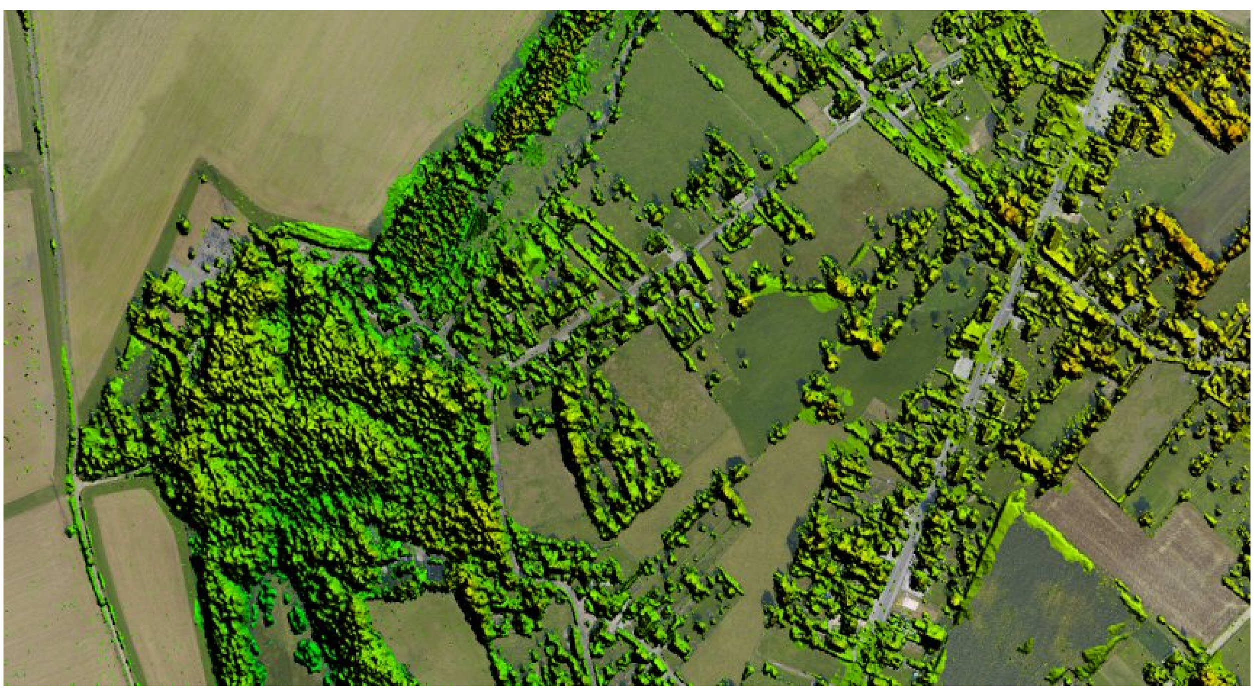


Figure 43: Close up of Figure 42.

To illustrate the effect of different filter sizes on the quality of the resulting DTM, two additional DTMs were processed using a maximum object width parameter value of 50 m and 160 m filters. The effects of using these different filter sizes are shown in Figures 44 and 45. Observe that a smaller value has the advantage of preserving the terrain topography, but may not remove all 3D structures (in this case, some regions with trees are not correctly filtered out).

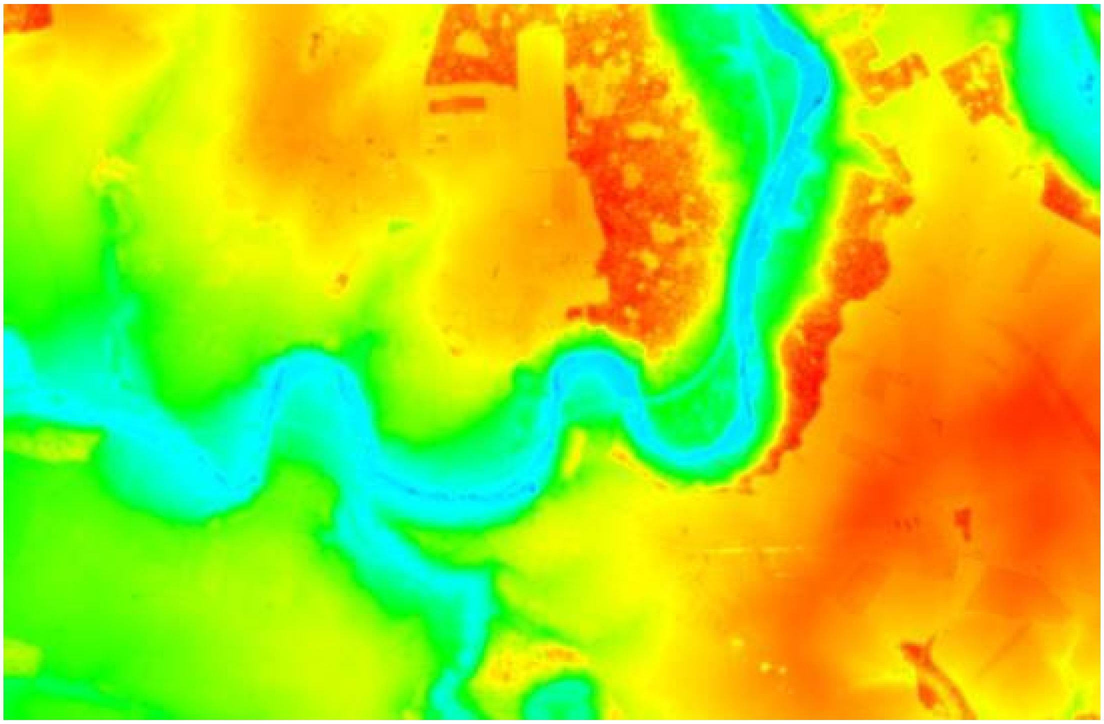


Figure 44: DTM generated using a 50m filter size.

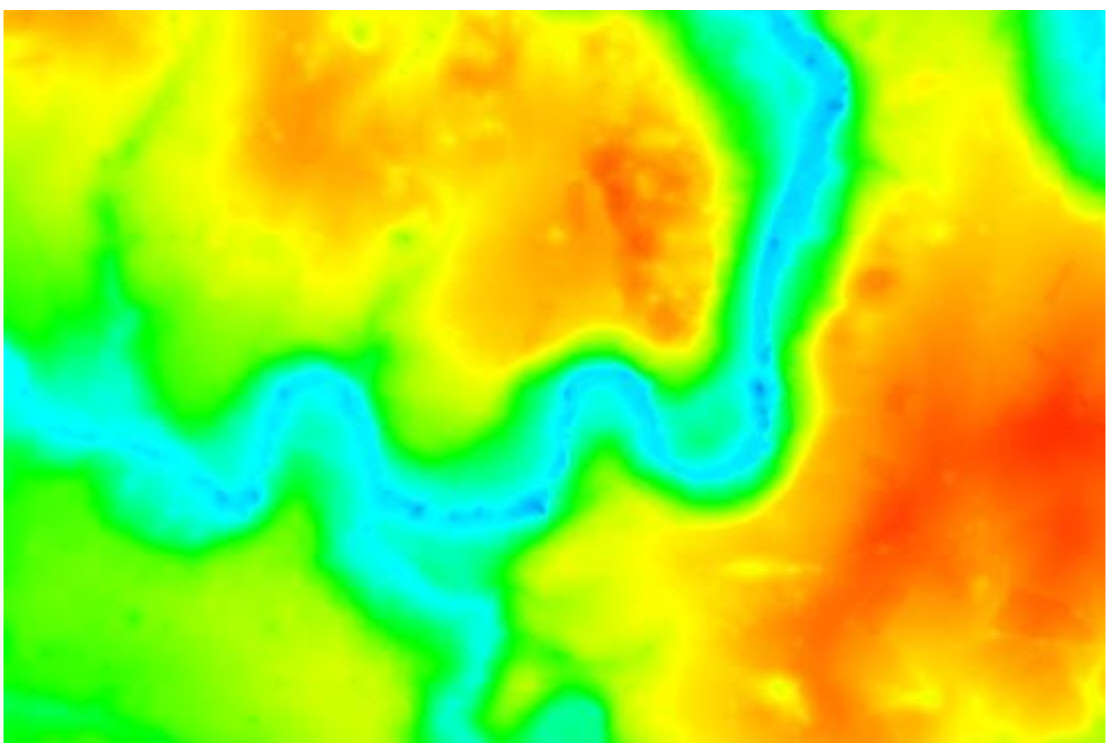


Figure 45: DTM generated using a 160m filter size.

The time taken to generate the DTM was 1.5 hours (approximately 48 seconds per frame) and 21 hours (approximately 11 minutes per frame) for Figures 44 and 45 respectively. To further evaluate the performance of the module, the DTM was compared to the DSM. More specifically, the DSM points used in Table 8 were compared against the corresponding DTM values. With the exception of one, all points were located on the ground. Therefore, the objective was to determine whether the DTM correctly preserved the terrain while only removing 3D features from the ground. The results are presented in Table 9. Note that the DTM points match almost exactly to the DSM points. The exception is the first point, which actually was located on a small building as opposed to being a ground point. Evidently, the DTM preserved the DSM points on the ground, while correctly removing the features.

Entry	SimActive DSM Elevation (m)	SimActive DTM Elevation (m)	Delta(m)
1	125.56	121.49	-4.07
2	166.03	166.06	0.03
3	172.40	172.40	0.00
4	168.52	168.56	0.03
5	179.57	179.80	0.23
6	184.99	184.98	-0.02
7	193.81	194.05	0.24
8	194.67	194.77	0.10
9	116.83	116.52	-0.31
10	180.65	180.78	0.13

Table 9: Comparison of SimActive DSM and DTM.

Once again, the filtering algorithm in the DTM module removes feature points and interpolates from the surrounding points to fill the area removed. A sample interpolation region is shown in Figure 47 (DTM) while the original DSM is displayed in Figure 46.

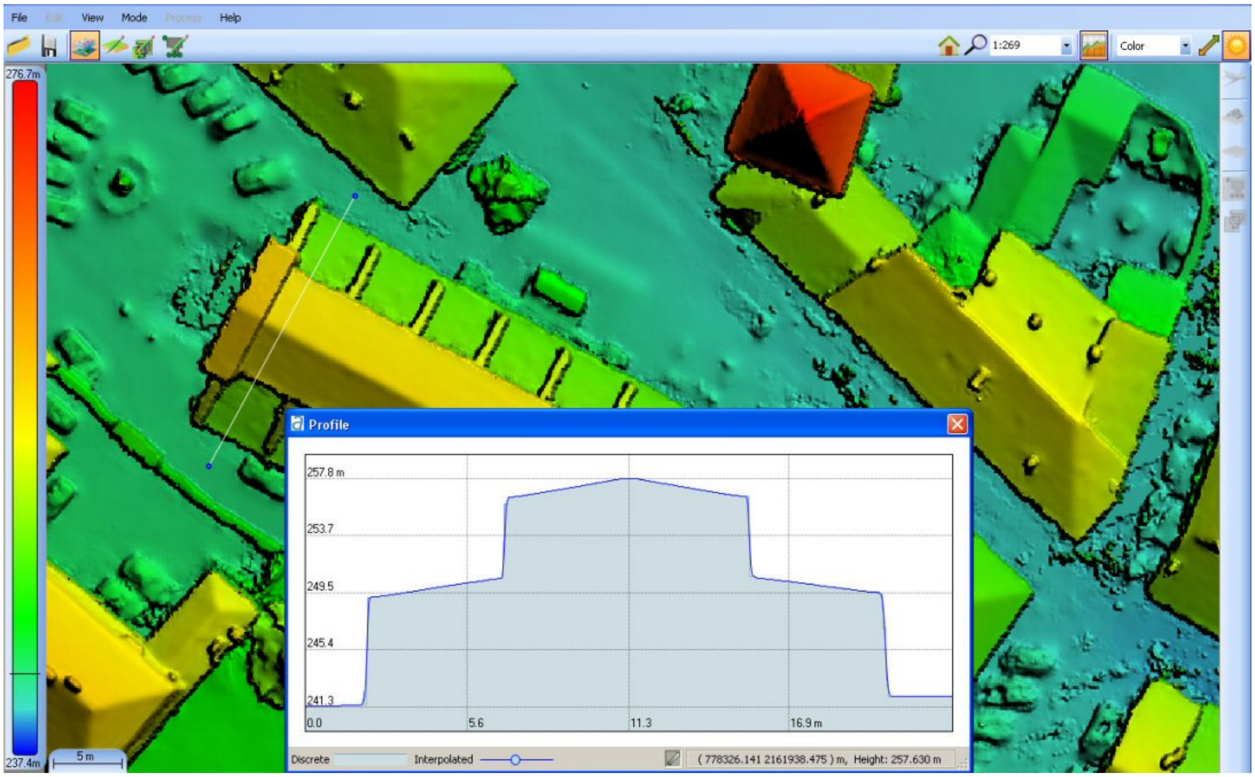


Figure 46: Sample DSM profile.

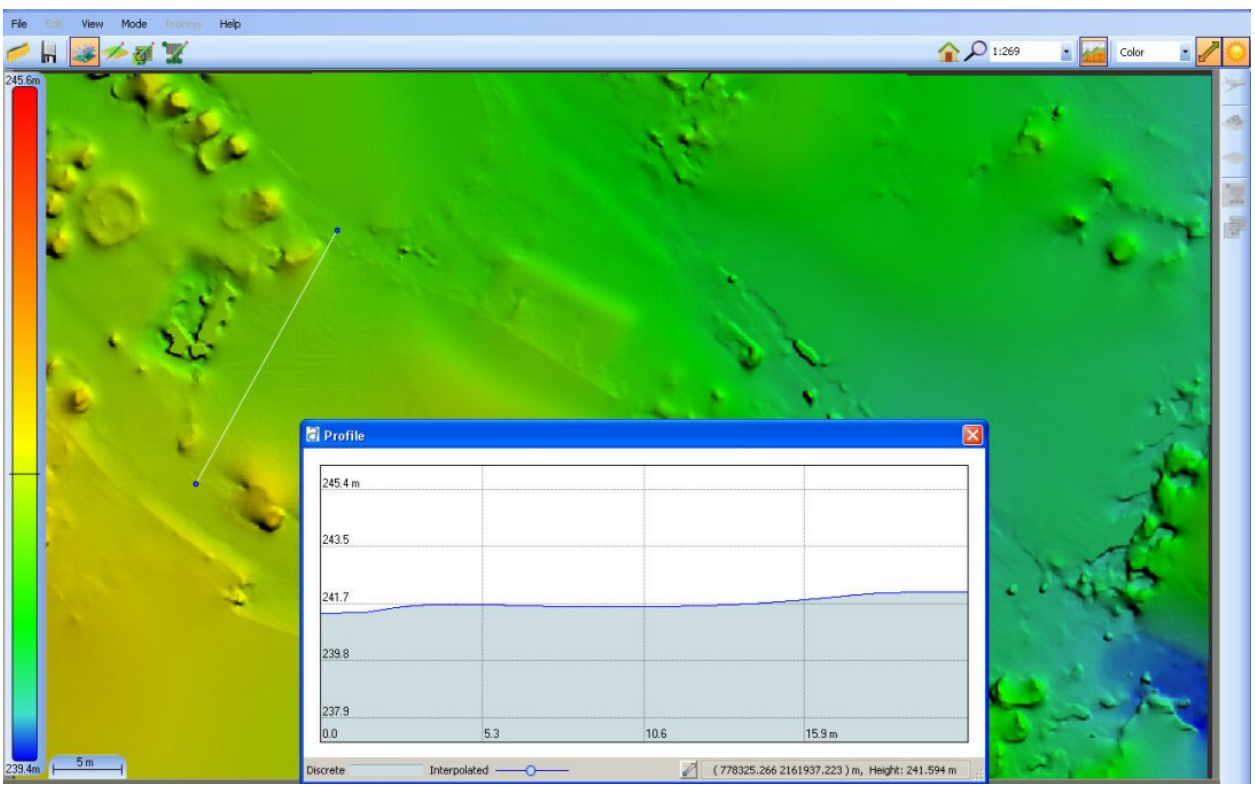


Figure 47: Sample DTM profile.

3.1.4 Orthophotos

Individual orthophotos were generated based on the refined EO values and the generated DTM. The total processing time was 1.5 hours, which implied 45 seconds for each image. The accuracy of the orthophotos was assessed using 30 control points. Table 10 summarizes the results where X1 and Y1 are the true XY coordinates dictated by the GCPs, X2 and Y2 are the XY coordinates as measured from the orthophotos. △X and △Y represent the positional differences between X2 and X1 and Y2 and Y1 respectively, of the true coordinates and the orthophoto coordinates. Note that the RMSE for △X and △Y is 0.12 m and 0.10 m respectively, well within the GSD of 0.125 m. The RMSE of the magnitude is 0.16 m, only 1.28 times the GSD. Finally, the largest positional error was 0.27 m, which is only 2.16 times the GSD.

Entry	X1(truth)	Y1(truth)	X2(measured)	Y2(measured)	△X(m)	△Y(m)
1	141770.824	115614.761	141770.94	115614.66	-0.11	0.10
2	141812.442	114219.356	141812.46	114219.30	-0.02	0.05
3	141987.284	113356.717	141987.36	113356.56	-0.07	0.15
4	142032.104	115105.515	142032.36	115105.68	-0.26	-0.16
5	142138.803	115076.901	142138.80	115077.05	0.00	-0.15
6	142276.59	114314.699	142276.62	114314.82	-0.03	-0.12
7	142489.427	116330.59	142489.38	116330.70	0.05	-0.11
8	142597.263	116901.381	142597.26	116901.42	0.00	-0.04
9	142766.596	115677.211	142766.58	115677.30	0.01	-0.09
10	142998.968	113627.7	142999.14	113627.70	-0.17	0.00
11	143441.189	114717.464	143441.27	114717.61	-0.08	-0.15
12	143562.071	116817.084	143562.06	116816.94	0.01	0.14
13	143923.105	115594.958	143923.02	115595.10	0.08	-0.14
14	144011.837	117108.482	144011.82	117108.54	0.02	-0.05
15	144163.955	113522.491	144164.22	113522.46	-0.27	0.03
16	144266.187	116452.288	144266.22	116452.38	-0.03	-0.09
17	144536.628	116469.628	144536.58	116469.54	0.05	0.09
18	144656.905	114749.777	144657.06	114749.70	-0.15	0.07
19	144870.185	115640.123	144870.18	115639.99	0.00	0.14
20	144904.756	113997.456	144904.98	113997.30	-0.22	0.15
21	145400.478	114235.501	145400.70	114235.38	-0.22	0.12
22	145706.242	115447.073	145706.40	115447.08	-0.15	0.00
23	146023.839	114682.924	146023.92	114683.04	-0.08	-0.11
24	146498.644	114318.422	146498.88	114318.36	-0.24	0.06
25	146703.578	116809.808	146703.54	116809.86	0.04	-0.05
26	147084.549	116197.001	147084.42	116197.14	0.13	-0.14
27	147423.371	117023.96	147423.42	117024.06	-0.05	-0.10
28	147651.058	115836.478	147651.00	115836.48	0.06	0.00
29	147872.066	115720.877	147871.98	115720.98	0.08	-0.10
30	147892.931	116808.654	147892.92	116808.60	0.01	0.05
RMSE					**0.12**	**0.10**

Table 10: Orthophoto positional accuracy.

3.1.5 Mosaic Creation

A mosaic was created from the individual orthophotos. The entire process took 3.5 hours to complete, which translated into less than 2 minutes per image. Automatic seamlines were generated by the software and the mosaic was also color-balanced. Figures 48 and 49 show sample seamlines for the project. Note how the seamlines avoid buildings and other structures. When not traversing roads, the seamline algorithm intelligently chooses other areas of commonality between adjacent orthophotos such as fields and rivers.

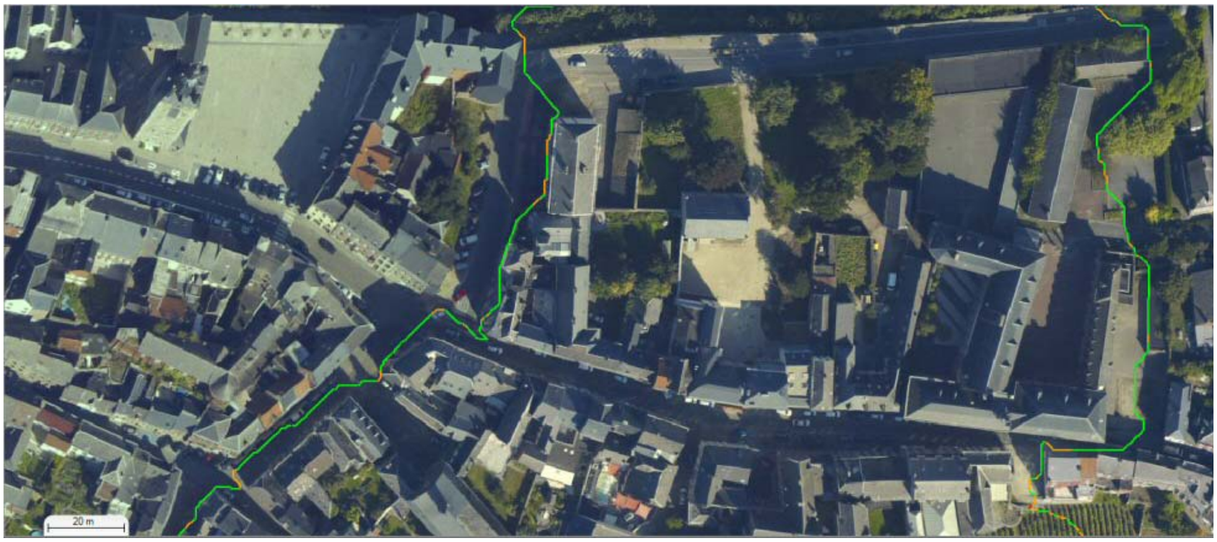


Figure 48: Automatically generated seamlines in central section of project.

Figure 49: Automatically generated seamlines in western section of project.

Histograms were also generated to analyze color balancing performance. Figure 50 shows the histograms of the overlapping region between a pair of orthophotos before color balancing was applied. Note the shift in all three channels between the orthophotos.

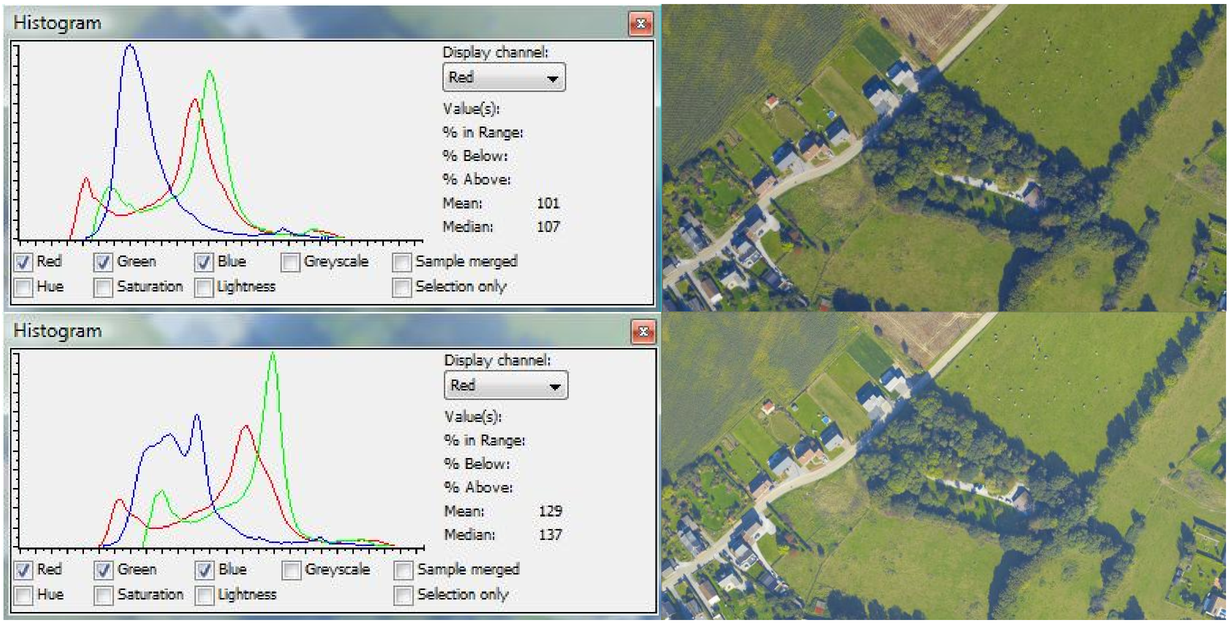


Figure 50: Histograms before color balancing.

Figure 51 shows the histograms of the same pair of orthophotos after color balancing was applied. Note there is no shift between the orthophotos any longer. In fact the bottom histogram from Figure 50 shifted to the left to align itself to the top histogram. The mean and median of both orthophotos in Figure 51 are now very similar, which in turn are similar to the top orthophoto in Figure 50. This shows the top orthophoto in Figure 50 was used as the reference orthophoto to which the bottom orthophoto was aligned. A visual inspection of both orthophotos validates this claim.

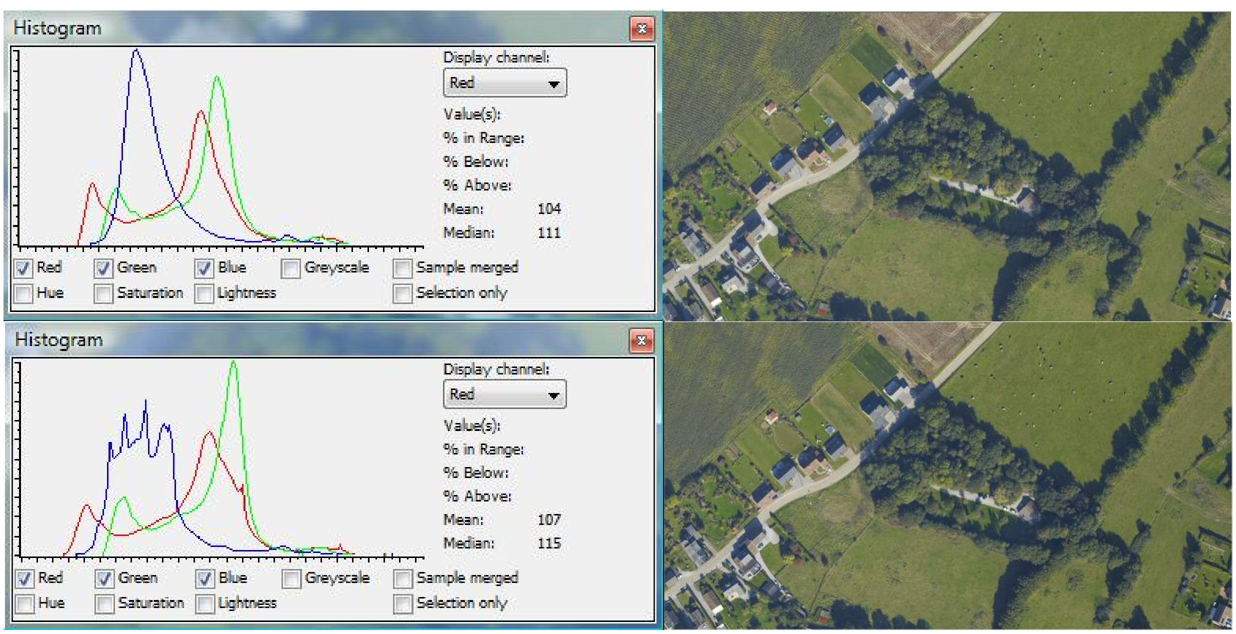


Figure 51: Histograms after color balancing.

3.1.6 Mosaic Editing

Mosaic editing was designed to be easy to use and efficient to maximize user productivity. Therefore, it is not necessary to select which orthophotos are required to change a particular seamline. All the user is required to do is select a seamline he wishes to edit and the software automatically determines which orthophotos are involved. Furthermore, as opposed to reprocessing the entire mosaic after changing the seamlines, only regions where changes were made to the mosaic need to be recalculated. This enables extremely fast editing and allows users to perform several iterations on the same region until satisfactory results are achieved. As an example, Figure 52 illustrates some changes that were applied to the mosaic (blue).

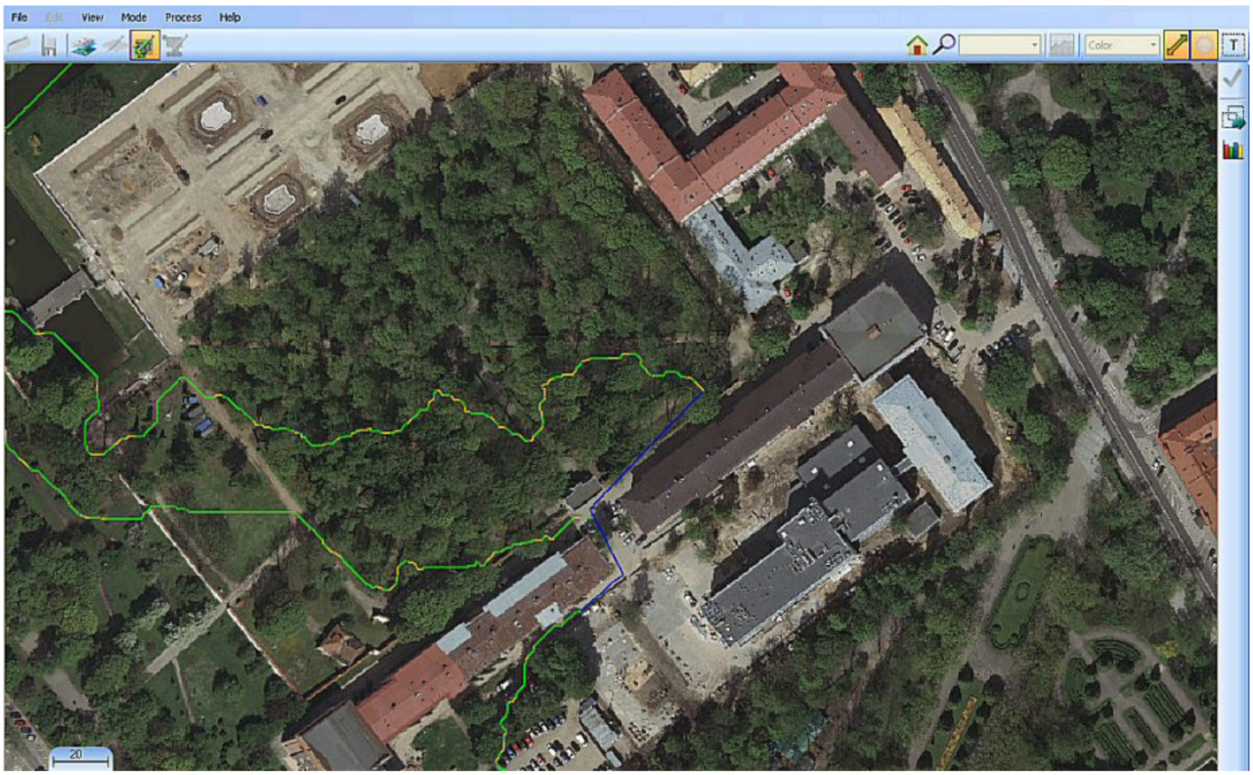


Figure 52: Mosaic with changes applied to the seamline.

Once again, the entire mosaic took about 3.5 hours to process. However, these minor changes only took several seconds to be applied. Thus, this results in huge time savings and extreme gains in productivity. The general strategy is therefore to modify one seamline at a time. The time it takes to apply a change per seamline is usually under 1 minute.

3.2 Case Study 2

This case study examines the accuracy of a DSM by comparing it with ground truth. The project was flown using a large format camera (13824x7680 pixels) and was composed of two flight lines and 5 images. The mean flying height was 1250 m resulting in a 10 cm pixel size. The project specifications are presented in Table 11.

Flying Height	1250 m
Images	5
GSD	0.1 m
Resolution	13824x7680

Table 11: Project specifications.

3.2.1 Digital Surface Model

The DSM was generated at a horizontal resolution of 0.3 m, which represented three times the GSD of the input imagery. A value of 50 m was set for the above ground variation due to the fact that the project area was residential. For the below ground variation parameter, a value of 15 m was chosen since the area was mostly flat. Prior to processing, the software predicted a vertical accuracy of 0.12m for the final DSM. A total time of 35 minutes (approximately 11 minutes per frame) was necessary for processing. Figure 53 shows the resulting DSM while Table 12 presents the specifications and statistics of the DSM generation process.

Horizontal resolution	0.3 m
Vertical accuracy	0.12 m
Above ground variation	50 m
Below ground variation	15 m
Processing time	11.5 min/frame

Table 12: SimActive DSM generation statistics.

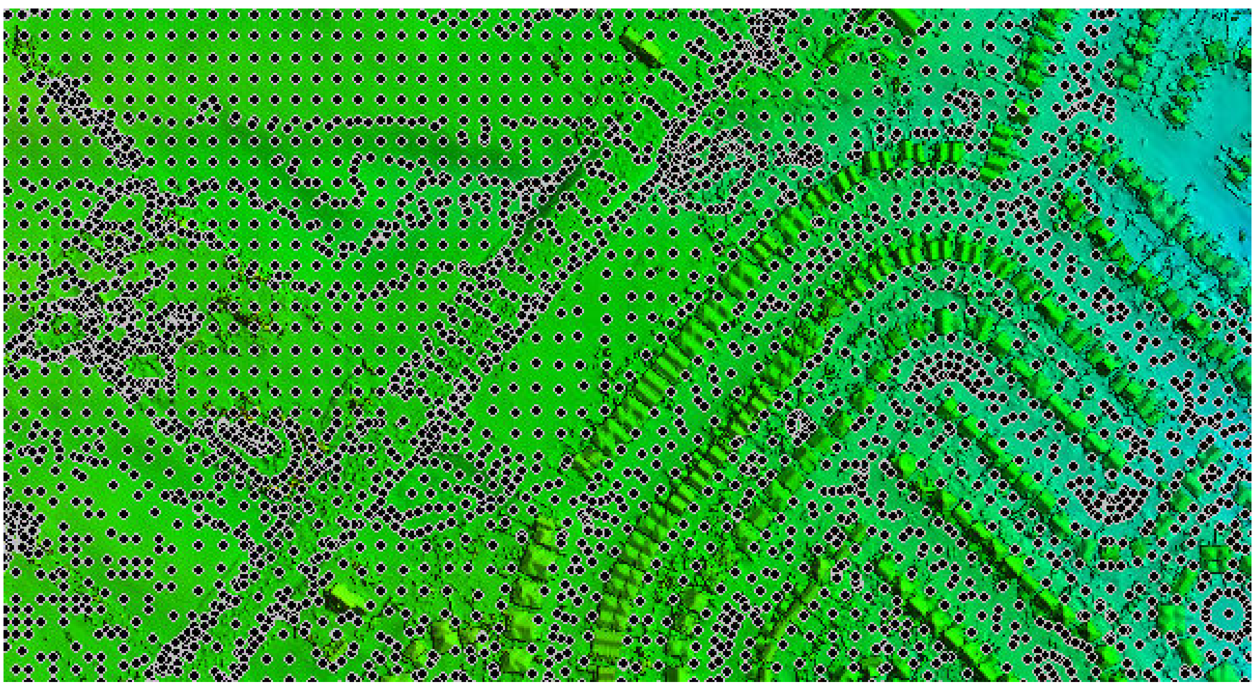


Figure 53: DSM overlaid with stereo points.

To measure the final accuracy of the DSM, a total number of 595 ground control points, collected using a stereoplotter, were compared against the elevation values generated by the software. Note, only points on the ground were used. Table 13 presents the results. Observe that the calculated RMSE on the DSM elevation values is 0.31 m, which represents about 2.6

times the input imagery GSD. Removing only 1.5% of the points reduces the RMSE to 2.1 times the GSD. Also note that the observed bias was very small at 0.08 m considering that the GSD is 0.10 m.

Number of Points	% Removed	Bias(m)	RMSE(m)
595	0	0.08	0.31
589	0.9	0.08	0.29
586	1.5	0.08	0.26

Table 13: SimActive DSM comparison.

3.3 Case Study 3

This case study examines the quality of SimActive's DSMs and DTMs. The project was flown using a large format camera (14430x9420 pixels) and was composed of 3 flight lines totalling 45 images. The mean flying height was 7250 m resulting in a 15 cm pixel size. The acquisition specifications are presented in Table 14.

Images	45
GSD	0.15 m
Resolution	14430 x9420

Table 14: Project specifications.

3.3.1 Digital Surface Model

A DSM was generated at a horizontal resolution of 0.45 m, which represented three times the GSD of the input imagery. A value of 60 m was set for the above ground variation to ensure tree peaks were captured. For the below height variation parameter, a value of 20 m was chosen to ensure any low elevations around the river would be captured. Prior to processing, the software predicted a vertical accuracy of 0.40 m for the final DSM. A total time of 6.5 hours (approximately 9.3 minutes per frame) was necessary for processing. Figure 54 shows the resulting DSM while Table 15 presents the specifications and statistics of the DSM generation process.

Horizontal resolution	0.45 m
Vertical accuracy	0.40 m
Above ground variation	60 m
Below ground variation	20 m
Processing time	9.3 min/frame

Table 15: SimActive DSM generation statistics.

Figure 54: DSM corresponding to the data in Table 15.

Figure 55 shows a closer view of certain areas in the DSM. Note the clear distinction of individual trees on the left. Likewise, note the thin road crossing the highway on the right.

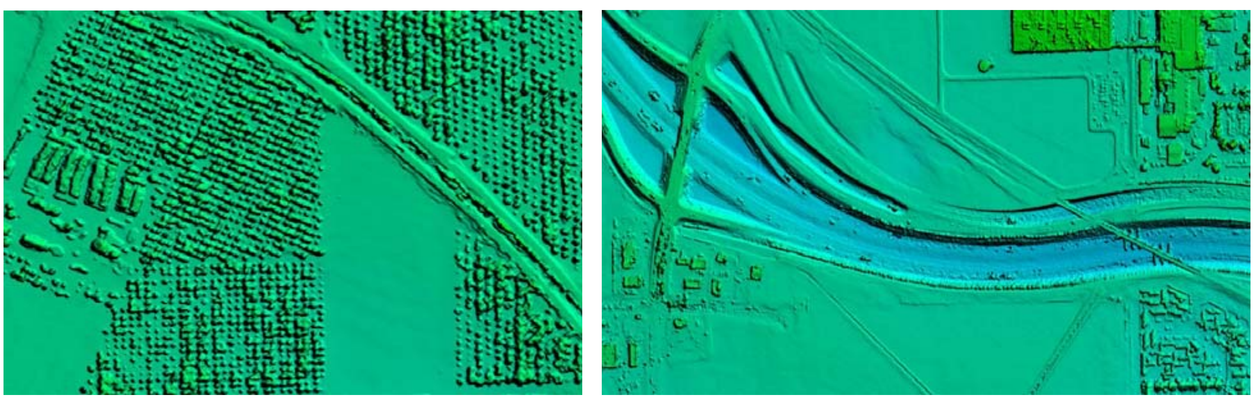


Figure 55: Close ups of specific areas from DSM in Figure 54.

3.3.2 Digital Terrain Model

The DTM (Figure 56) was extracted from the DSM using a 120 m filter size and required 4.25 hours to complete the processing. This filter size was chosen because the lateral diameter of sections of the DSM, such as the blocks of trees, was just less than 120 m. Note that all features including trees, buildings and elevated highway lanes were removed. Figure 57 shows the 3D features (color shaded) that were removed from the DSM overlaid on the orthomosaic. Observe that the features visible from the imagery (i.e. unremoved features) consist of flat lands such as fields.

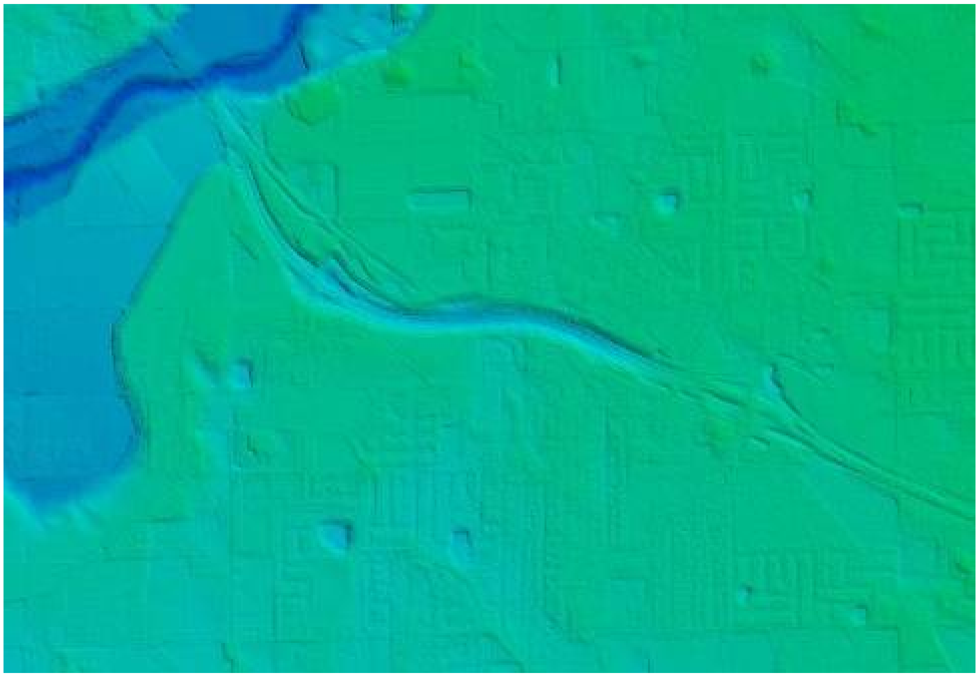


Figure 56: DTM generated from the DSM in Figure 54.

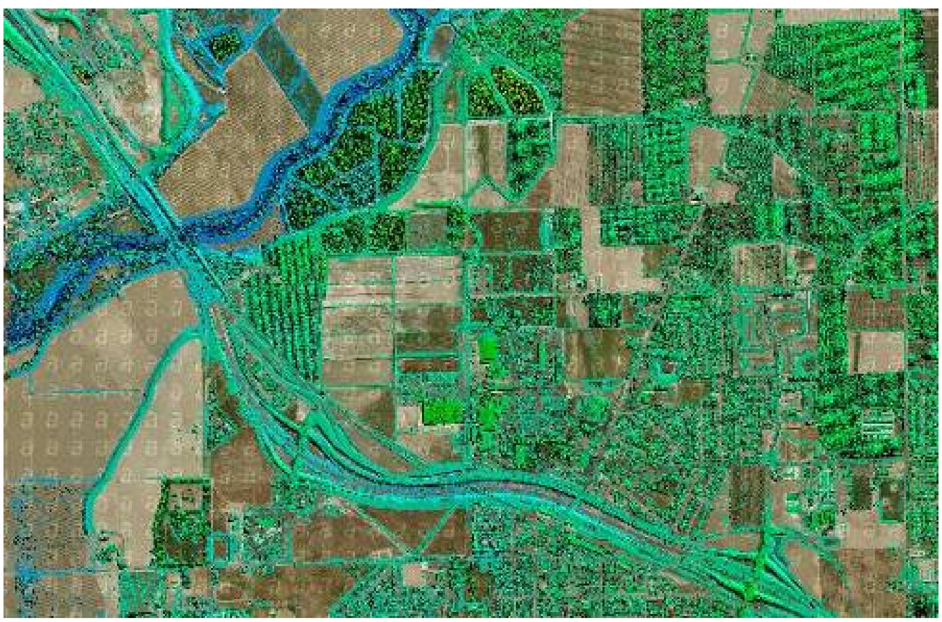


Figure 57: 3D features removed from DSM (color shaded) overlaid on the orthomosaic.

3.4 Case Study 4

This case study examines the quality of SimActive's DSMs, DTMs and mosaics. The project was flown using a large format camera (13824x7680 pixels). The project is composed of 2 flight lines and 11 images at 10 cm pixel size. The acquisition specifications are presented in Table 16.

Images	11
GSD	0.1 m
Resolution	13,824 x 7,680

Table 16: Project specifications.

3.4.1 Digital Surface Model

A DSM was generated at a horizontal resolution of 0.3 m, which represented three times the GSD of the input imagery. A value of 70 m was set for the above ground variation which was enough to cover the tallest structures in the project area. For the below height variation parameter, a value of 40 m was chosen due to the flat terrain. Prior to processing, the software predicted a vertical accuracy of 0.13 m for the final DSM. A total time of 1.5 hours (approximately 10 minutes per frame) was necessary for processing. Figure 58 shows the resulting DSM while Table 17 presents the specifications and statistics for the DSM generation process.

Horizontal resolution	0.3 m
Vertical accuracy	0.15 m
Above ground variation	70 m
Below ground variation	40 m
Processing time	10 min/frame

Table 17: SimActive DSM generation statistics.

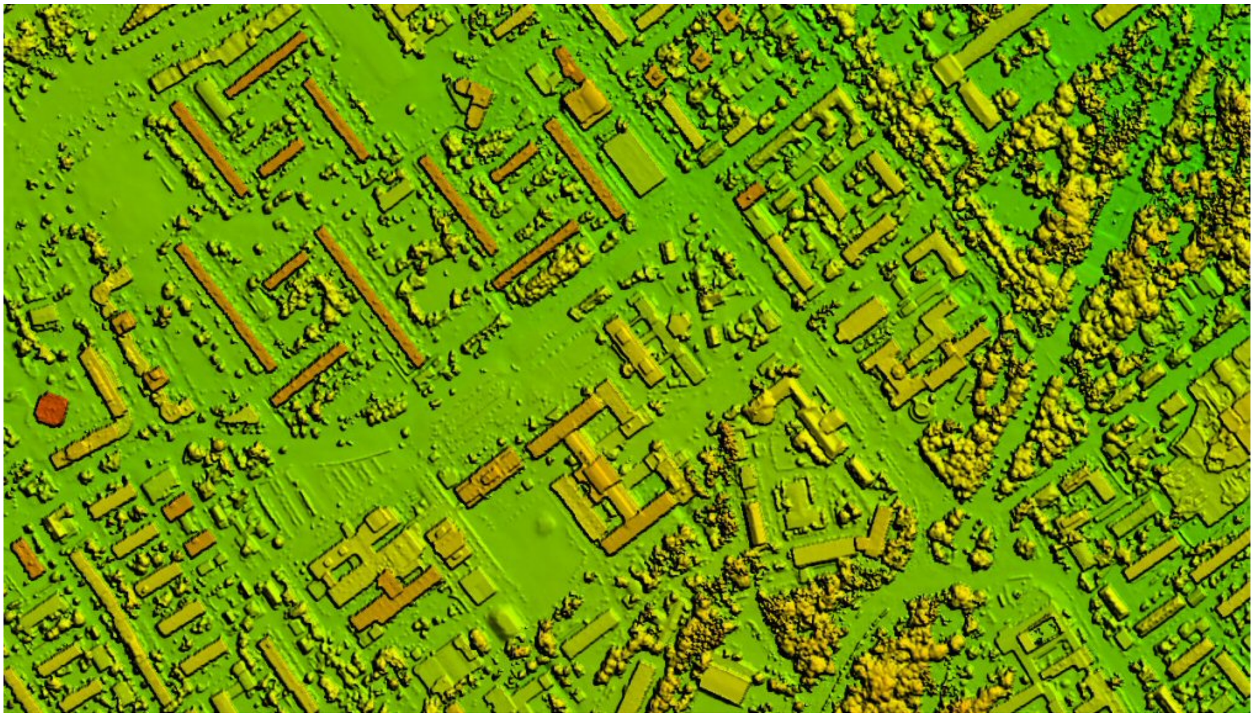


Figure 58: DSM of case study 4.

3.4.2 Digital Terrain Model

The DTM (Figure 59) was extracted from the DSM using a 120 m filter size and required 2.5 hours to complete the processing. Note how all features including trees and buildings were removed.

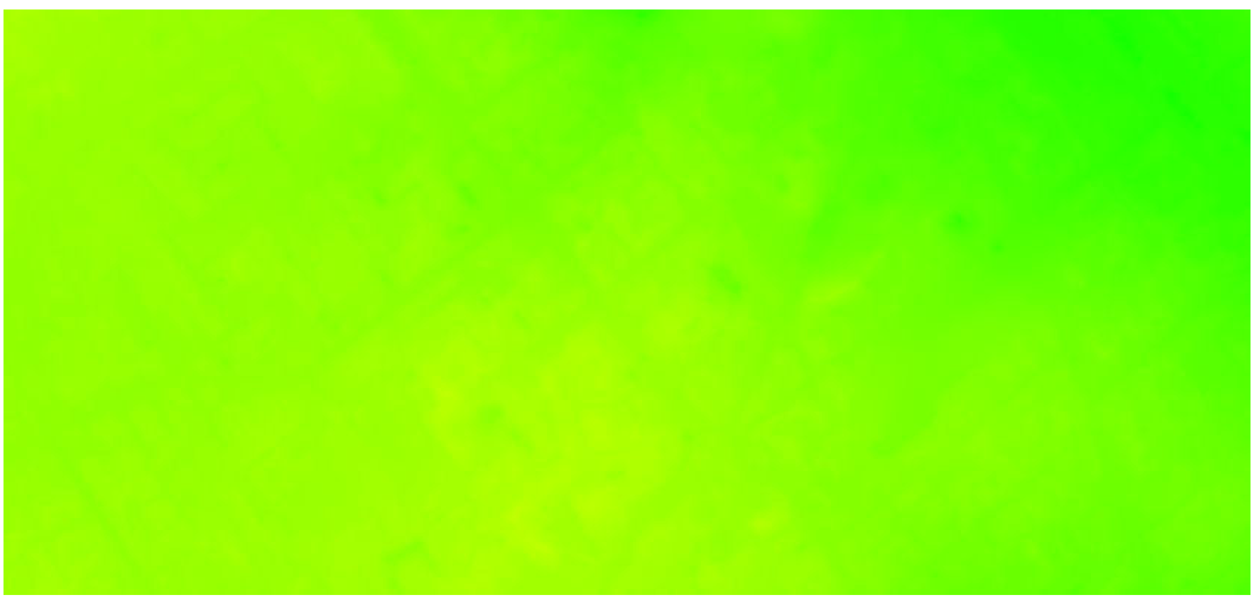


Figure 59: DTM of case study 4.

3.4.3 Mosaic

A mosaic (Figure 60) was created from the orthophotos. The entire process took 18 minutes to complete, which translated into about 1.6 minutes per image. Automatic seamlines were generated by the software and the mosaic was also color-balanced. Figure 61 shows sample seamlines for the project. Note how the seamline follows the roads.

Figure 60: Mosaic of case study 4.

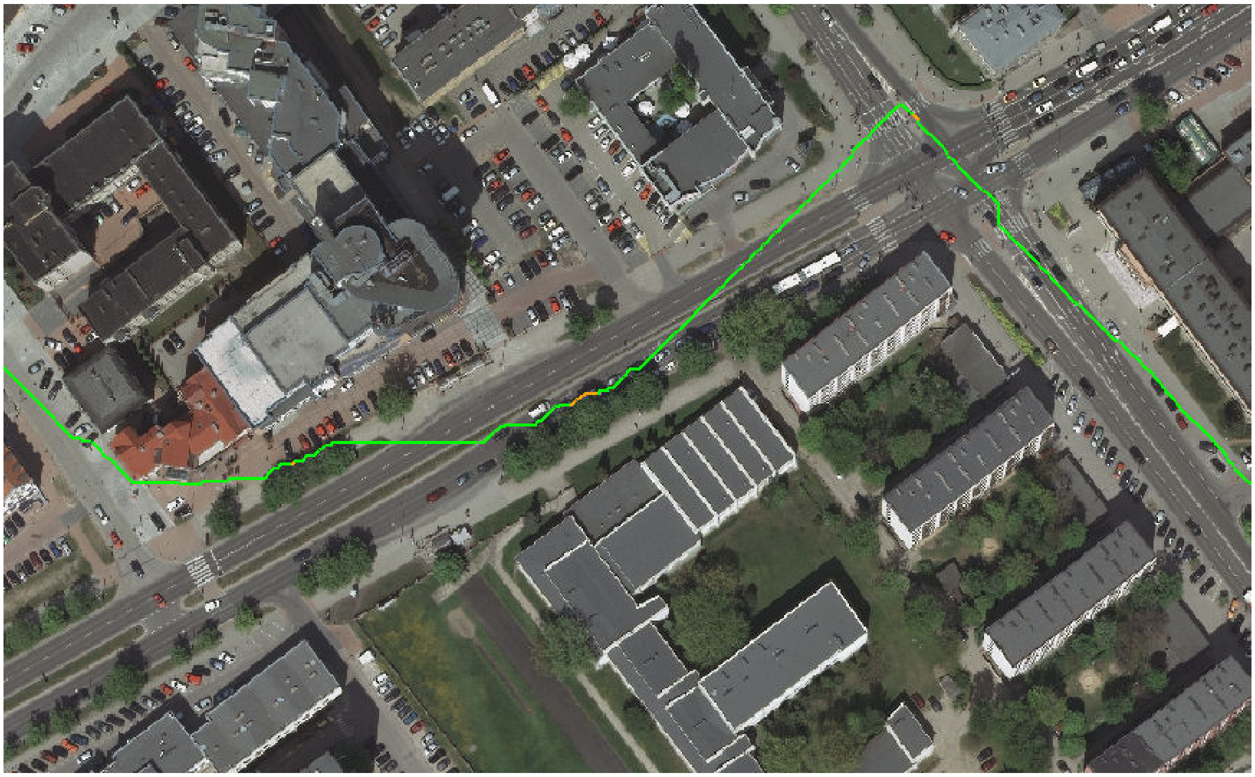


Figure 61: A seamline weaving around buildings along the roads.

3.5 Case Study 5

This case study examines the quality of SimActive's DEMs and orthophotos using satellite imagery from the GeoEye-1 Hobart sample. The resolution of the sample used is 0.5 m, which was down-sampled from 0.41 m as per legal requirements for commercial use. The acquisition specifications are presented in Table 18:

Satellite	GeoEye-1
Orbit height	680 km
Images	2
GSD	0.5 m
Resolution	37943 x 34709

Table 18: Project specifications.

3.5.1 Exterior Orientation Refinement

The exterior orientation data is provided by the rational polynomial coefficients (RPC). These RPCs were refined in order to ensure accurate DEMs and orthophotos. A total of seven (7) ground control points were inputted to the EO refinement process. These were captured using a total station with good spatial distribution over the project's area. A summary of the GCPs used is presented in Table 19.

Name	Description	Location
BASA	Intersection, south of road	(317260.274, 5810167.575, 7.468)
BASB	Intersection north of road	(317260.475, 5810169.628, 7.492)
BEACON	Center of roundabout	(317629.961, 5809970.511, 6.610)
COOK	Center of roundabout	(316263.984, 5810724.284, 8.266)
STO	Center of roundabout	(318468.194, 5809858.496, 8.205)
SWA	Center of roundabout	(317962.553, 5809891.560, 6.703)
TODD	Center of roundabout	(316204.132, 5811343.616, 7.568)

Table 19: Ground Control Point descriptions.

A SimActive GCP file was created using the seven ground control points from Table 19. This is done using the "GCP File Creation" tool as follows:

1. The user enters the name and coordinates of the GCP (Figure 62).
2. The tool computes the approximate location of the GCP in the images (Figure 63(a)).
3. The user translates each image until the feature is at the center of the green "X"(Figure 63(b)).
4. Steps 1 to 3 are repeated for each GCP.

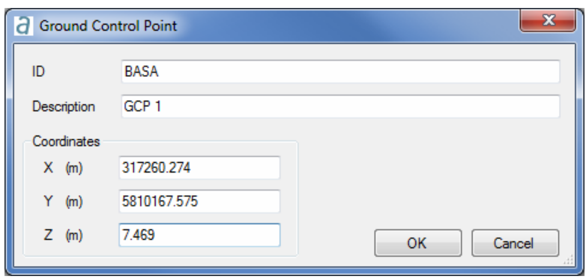
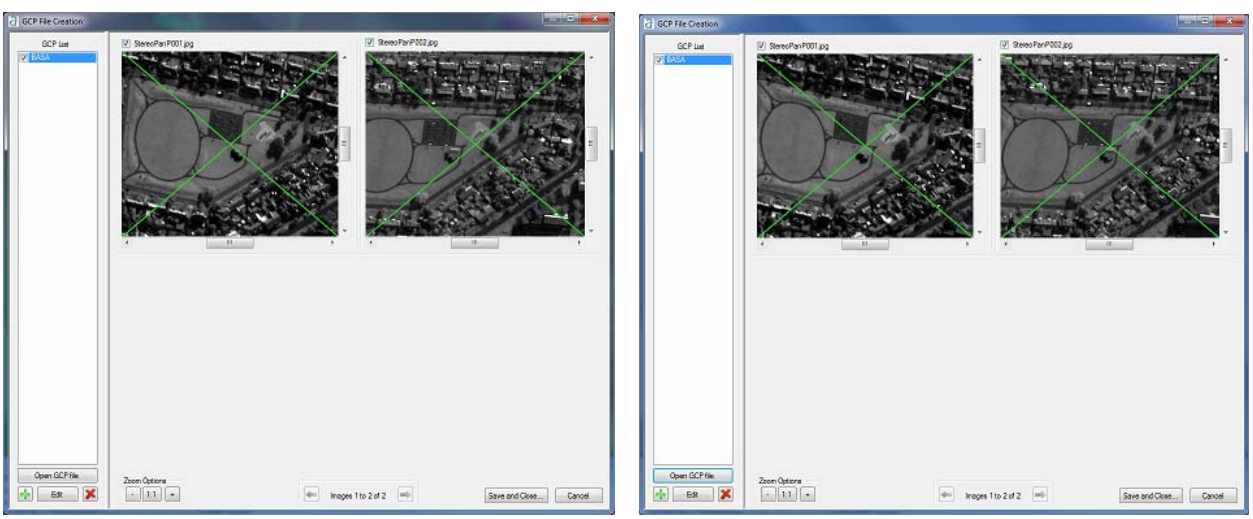


Figure 62: GCP creation dialog box.



(a) (b)

Figure 63: GCP collection window

After the GCP file is created, the next step is to run the Exterior Orientation Refinement tool. The operator must specify the two input images, their corresponding original RPC file and the newly created GCP file. Correlator3D™ will then compute the correction to apply to both RPC files. The error detected and corrected in this example is provided in Table 20.

Image	X Component	Y Component
First Image	13.292 m	0.247 m
Second Image	-24.268 m	2.366 m

Table 20: Adjustments applied during EO refinement

3.5.2 Digital Surface Model

A DSM was generated at a horizontal resolution of 1.5 m, which represented three times the GSD of the input imagery. The SRTM data was used as a seed DEM. A value of 80 m was set for the above ground variation. For the below height variation parameter, a value of 30 m was chosen to ensure any low elevations would be captured. Prior to processing, the software predicted a vertical accuracy of 0.28 m for the final DSM. A total time of 45 minutes was necessary for processing. Figure 64 shows the resulting DSM while Table 21 presents the specifications and statistics of the DSM generation process.

Horizontal resolution	1.5 m
Vertical accuracy	0.28 m
Above ground variation	80 m
Below ground variation	30 m
Processing time	45 minutes

Table 21: SimActive DSM generation statistics.

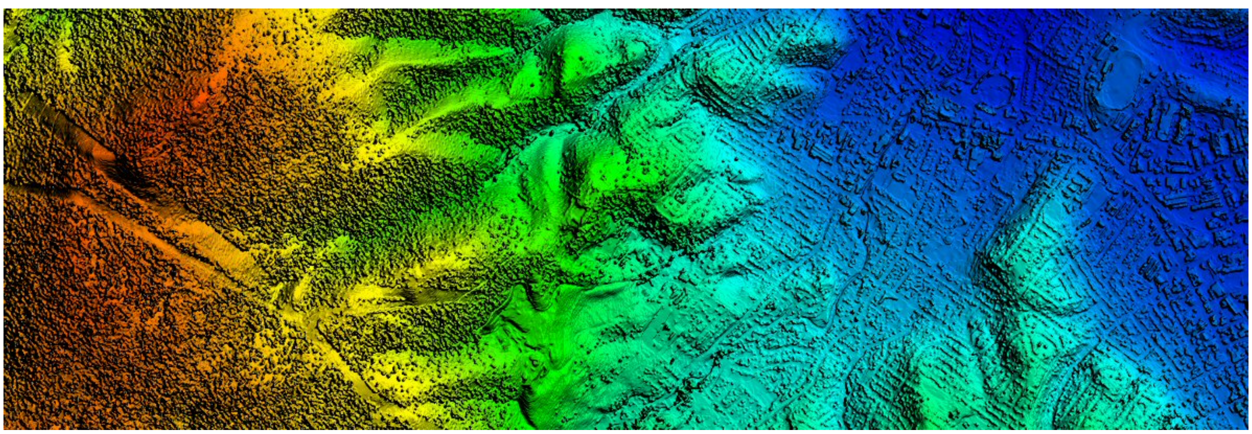


Figure 64: DSM of case study 5.

To measure the final accuracy of the DSM, seventy-four (74) ground control points were compared against the elevation values generated by the software. Table 22 summarizes the test characteristics.

Input GSD	0.5 m
Estimated error of manual GCP detection	0.5 m
Number of GCP used for analysis	74

Table 22: DSM test characteristics.

Table 23 presents the statistical analysis results comparing the 74 GCPs against the SimActive DSM. Observe that the calculated RMSE for the DSM elevation values is 0.73 m, which represents 1.46 times the input imagery GSD. Also, note that the observed bias was very small at 0.57 m.

RMS	0.727 m
Bias	0.565 m
Standard Deviation	0.461 m

Table 23: DSM analysis results.

3.5.3 Digital Terrain Model

A DTM (Figure 65) was extracted from the 1.5 m DSM shown in Figure 64 and the required processing time was 18 minutes. A 120 m filter was used to create this DTM. Note that trees, buildings and other 3D structures lying on the ground were correctly removed.

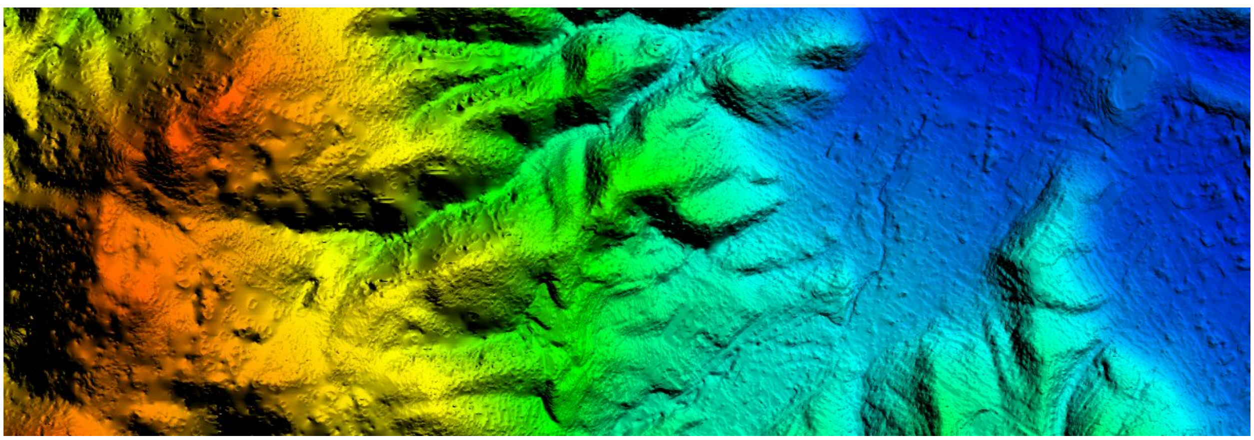


Figure 65: DTM of case study 5.

3.5.4 Orthophotos

Orthophotos were generated based on the refined RPCs and the generated DTM. The total processing time was 16 minutes, which implied 8 minutes for each image. The accuracy of the orthophotos was assessed using 74 control points. Manually identifying the GCPs in the orthophotos is subject to two types of uncertainties. First, the discrete nature of the image makes it hard to identify precisely a feature when it lies within a pixel. This potential error is estimated to be 0.5 pixel. The second uncertainty is caused by the operator. It is difficult for the operator to precisely locate the position of the feature. This error is also estimated to be 0.5 pixel. The overall error is therefore 1 pixel, which corresponds to 0.5 meters. The precision of the provided GCP is unknown. Table 24 provides the results for the absolute planar accuracy of the orthophotos.

Error	Image 1 X	Image 1 Y	Image 1 XY	Image 2 X	Image 2 Y	Image 2 XY
RMS	0.335 m	0.327 m	0.468 m	0.300 m	0.342 m	0.455 m
Bias	0.032 m	-0.061 m	0.349 m	0.036 m	-0.047 m	0.353 m

Table 24: Results of the absolute planar accuracy of the orthophotos.

Again, all the collected values indicate that there is no significant lateral shift. The average values in Table 24 are well below the level of uncertainty and indicate no absolute bias between the images and the ground control points. Likewise, the RMS is of sub pixel accuracy, which is well within the expected result of 0.5m. Table 25 shows the results for the relative planar accuracy between the orthophotos.

Error	Difference X	Difference Y	Difference XY
RMS	0.269 m	0.353 m	0.444 m
Bias	0.004 m	0.014 m	0.306 m

Table 25: Results of the relative planar accuracy of the orthophotos.

The average values in Table 25 show no relative bias between the images. RMS errors again show sub-pixel accuracy. The fact that both images were rectified on the generated DTM and that there is no bias between the images demonstrates a high degree of accuracy.

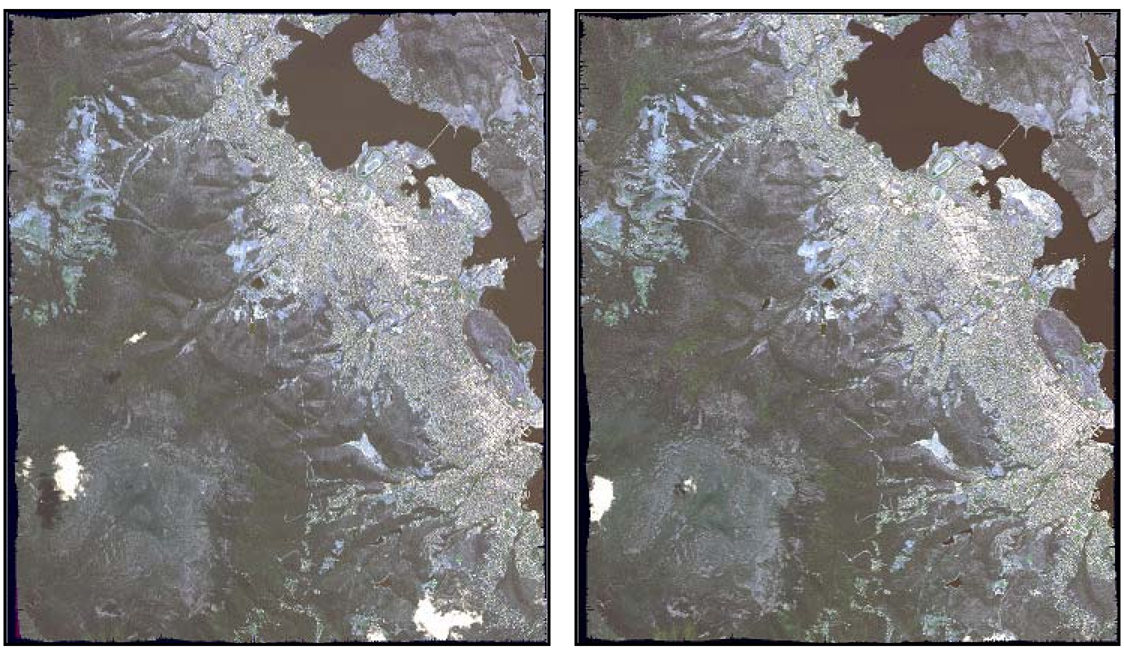
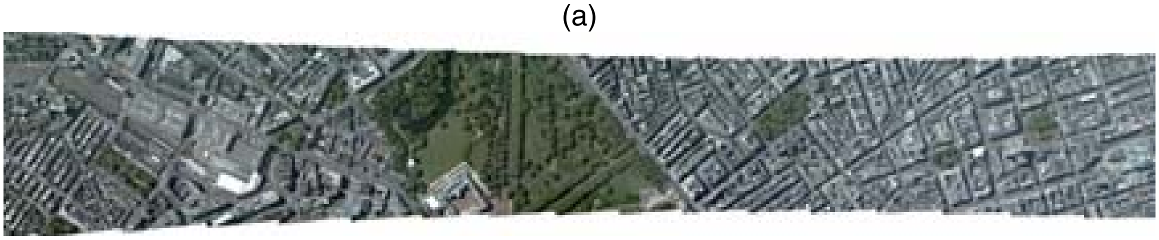


Figure 66: Orthophotos of case study 5.

3.6 A Note on Other Sensors

In addition to the frame based and satellite sensors covered in this guide, Correlator3D™ also supports equally well the push broom sensors ADS80 and VisionMap A3. A detailed analysis as provided above is beyond the scope of this whitepaper, however, some sample results are shown below. Figure 67 shows a DSM and an orthophoto obtained using VisionMap A3 imagery.

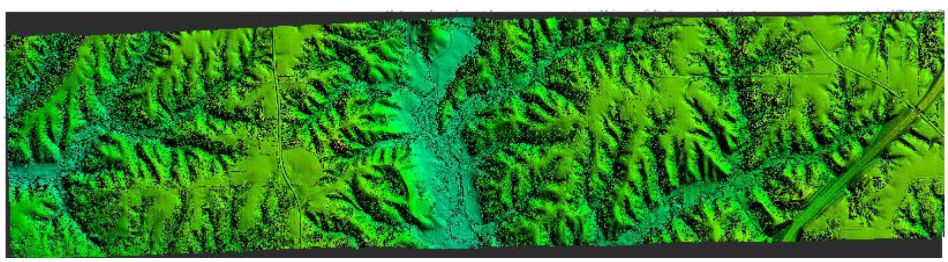
(a)



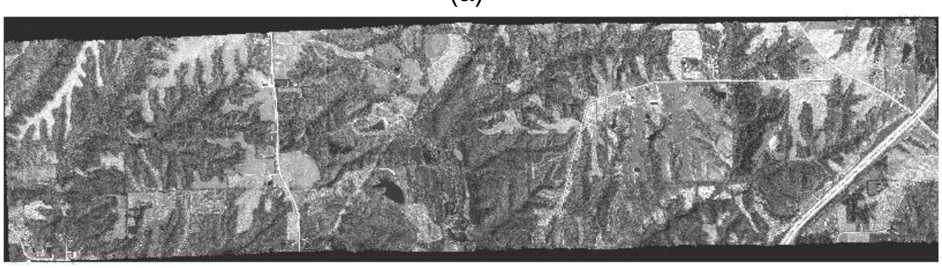
(b)

Figure 67: DSM (a) and orthophoto (b) using VisionMap A3 imagery.

Figure 68 presents the DSM and DTM using ADS80 imagery.



(a)



(b)

Figure 68: DSM (a) and orthophoto (b) using ADS80 imagery.

4 Conclusion

Through intensive tests and analyses, Correlator3D™ demonstrated its ability to perform exceptionally well. The EO refinement module improved a poorly calibrated project from 38 pixels to subpixel accuracy. The DSM module consistently produced accurate results with the RMSE being close to the input image GSD in all cases, while keeping processing speeds blisteringly fast. It was shown the DTM correctly removed features from the DSM while preserving ground data. Orthophotos generated by Correlator3D™ were provably precise with an RMSE at around one time the GSD. Lastly, the automatically generated seamlines were shown to follow roads and weave around buildings consistently. Even when not traversing the roads, the seamlines intelligently found paths through rivers and fields resulting in a seamless transition of orthophotos.

SimActive was the first and only to successfully integrate the GPU in DSM generation. Likewise, Correlator3D™ is the sole software tool of its kind to offer the full photogrammetric suite with virtually no advanced training required. The amount of automation is so significant that the user is only required to provide minimal input. Only through innovation barriers can be broken and the limits of what was thought possible can be pushed even further. It is this sheer determination to innovate that drives SimActive to push the boundaries and come up with increasingly innovative techniques that challenge the traditional approach to solving problems and lead the way to a best in class photogrammetry solution.

5 Contact Information

SimActive can provide an evaluation version of Correlator3D™ to interested parties. For more information, please contact:

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