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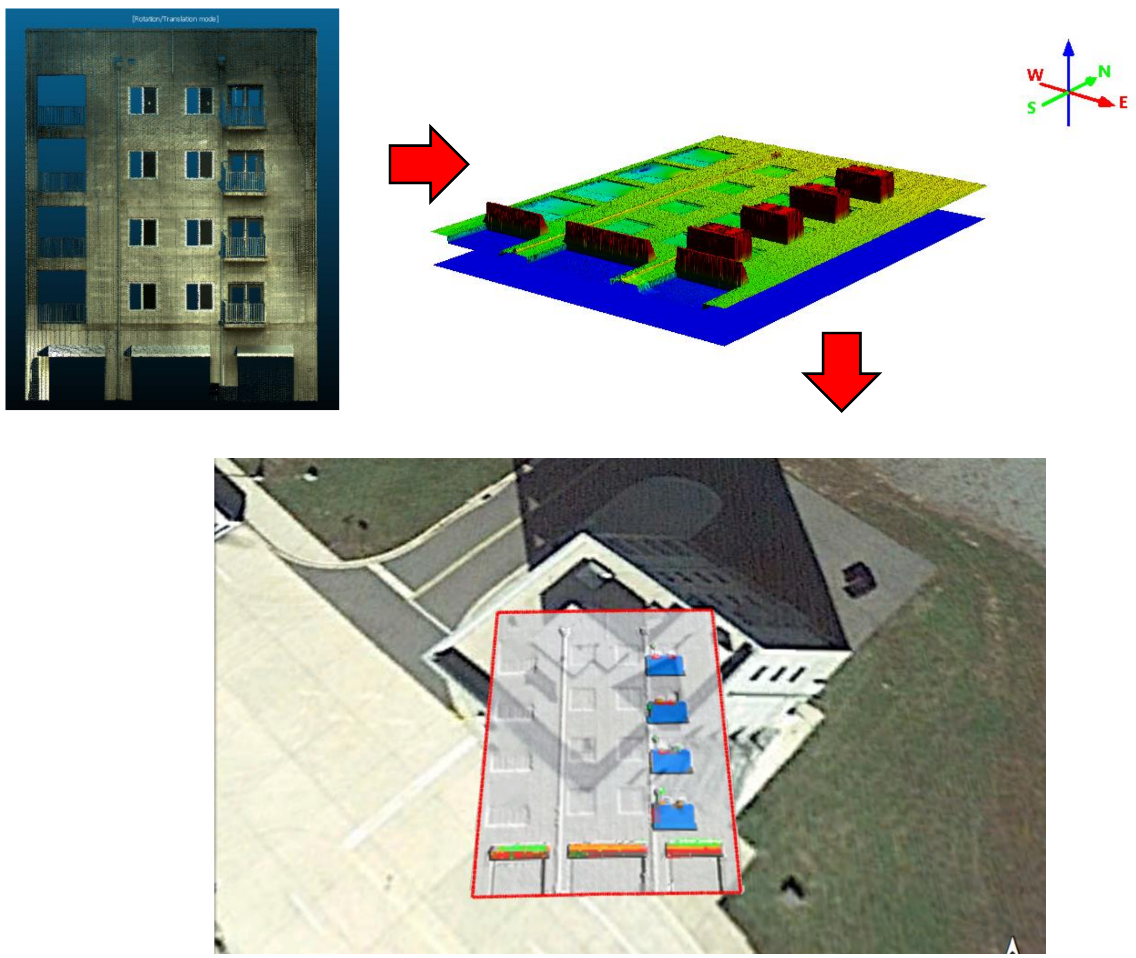
Geointelligence – Geospatial Data Analysis and Decision Support

Creation, Transformation, and Orientation Adjustment of a Building Façade Model for Feature Segmentation

Transforming 3D Building Point Cloud Models into 2D Georeferenced Feature Overlays

S. Bruce Blundell and Philip Devine

December 2019



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Abstract

This project involves the creation of 3-dimensional models of building façades from ground-derived point clouds and extracting features from the façades as encoded overlays. These features include balconies, window wells, overhangs, or other exterior fixtures. Point data of a building façade, acquired from high-resolution terrestrial scans, are transformed in space so that a normal to the façade surface is in the vertical direction. The point cloud is then converted into a gridded model, which can be investigated in like manner to a digital terrain model through breakline, elevation difference, and slope analysis. A backplane of constant z values is created underneath the façade to act as a "bare earth" surface. The orientation of the backplane in space is carefully adjusted to be parallel to the façade's exterior, providing more accurate feature extraction through difference analysis. Raster overlays are created as color-mapped classes or continuous values of breakline, elevation difference, or slope that capture the form of façade feature objects. To complete the attribution of façade features, georeferencing information from the original building model is associated with each overlay product. This allows for the display of the overlays in a georeferenced visualization environment such as a Geographic Information System (GIS) or Google Earth.

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Preface

This study was conducted for the Geospatial Research Laboratory (GRL) under PE 62784/ Proj 855/ Task 23, "GeoICUE/TREADSTONE." The technical monitor was Dr. Jean D. Nelson.

The work was performed under the Data and Signature Analysis Branch (TRS) of the TIG Research Division (TR), U.S. Army Engineer Research and Development Center-Geospatial Research Laboratory (ERDC-GRL). At the time of publication, Ms. Jennifer L. Smith was Chief, Data Signature and Analysis Branch; Ms. Martha Kiene was Chief, TIG Research Division; and Mr. Ritchie Rodebaugh was Director of the Technical Directorate. The Deputy Director of ERDC-GRL was Ms. Valerie L. Carney and the Director was Mr. Gary Blohm.

COL Teresa A. Schlosser was Commander of ERDC, and Dr. David W. Pittman was the Director.

1 Introduction

1.1 Background

Terrestrial laser scanning has become an important tool for modeling and rendering the complexity and structure of the urban environment. The development and analysis of building façade models support three-dimensional (3D) modeling of the urban landscape and has applications for street-level rendering of structures, fly-through virtual environments, and mission planning.

Previous research on this topic has segmented individual façades from terrestrial point clouds for feature extraction to support urban modeling. Xia and Wang (2019) extracted edges and windows from point cloud façade models with complex features. They defined an objective function that considers both window edge intersections and their vertical elevations on the building face. Features were separated by minimizing the objective function. The authors tested the method on both static and mobile scanning datasets.

To efficiently extract window boundary points from façade point cloud models for structural analysis, Zolanvari and Laefer (2016) introduced the Slicing Method. In this approach, the façade is sliced into limited sections to separate window and door openings from the structural portions of the walls. The method was later improved to extract the geometry of complex 3D building models using a local point density analysis technique (Zolanvari et al. 2018).

Li et al. (2017) developed an adaptive approach to segment facades from urban terrestrial scans. The researchers used a data-driven method to decompose an input point cloud into depth planes or layers. The technique allowed for the detection and labelling of similar elements in each depth plane. Optimization of these elements across depth planes enabled the reconstruction of façade model geometry.

A study by Wang et al. (2018) combined information from the 3D point cloud and 2D optical images. The process begins with image feature extraction, which are then mapped to the point cloud. An optimization method is then employed together with structural information to extract façade features.

Another approach involves reducing the point cloud data to a raster image for feature extraction. Using a point cloud projection algorithm, Li et al. (2016) converted voluminous point cloud data into an image space. Façade features were extracted from the image using morphological filtering. Finally, the façade was reconstructed through an inverse transformation of the point cloud projection, converting the image space into a 3D space.

1.2 Objectives

This effort, under the GeoICUE/TREADSTONE project at the Engineer Research and Development Center – Geospatial Research Laboratory (ERDC-GRL), was conceived in support of that project's goal to improve data visualization of structures in dense urban environments with a view toward data reduction and contextualization.

In support of this goal, the objective was to develop a strategy and workflow to process terrestrial scan data of urban structures to create encoded overlays of a building façade's surface features. These features, such as balconies or window wells, may be extruded from the façade surface toward the scanner or intruded away from it. The final feature overlays would be available for import into a geospatially-enabled software environment for further analysis.

1.3 Approach

In this work, high-resolution terrestrial scanning data was leveraged of the interiors and exteriors of various structures from an ongoing data collection effort called Captur3D, a task under the GRL project Automated Man-Machine Learning and Processing for 3D-Terrain (AMP3D). Point cloud datasets were processed to create 3D building façade models. These were converted from points to gridded form in order to reduce the data and to allow faster processing of raster overlays of extracted and segmented façade surface features. These overlays were then attributed with geospatial positioning information from the façade model. This enables the visualization of the overlays in an environmental context provided by a georeferenced application such as a geographic information system (GIS) or Google Earth.

After acquiring the point cloud data from the Captur3D field collection, the major steps in the building façade processing workflow are:

1. Crop out the façade point cloud.
2. Transform the data into the horizontal plane.
3. Create a gridded Digital Surface Model (DSM) and shaded relief image of the model.
4. Create a gridded "backplane" of constant elevation underneath the transformed façade model to be used in forming a difference model.
5. Carefully adjust the orientation of this plane so that it is parallel to the base surface of the façade wall.
6. Georeference the backplane for further post-processing.
7. Perform breakline, differencing, and slope analysis on the façade and backplane models to create raster overlays of the façade's extruded and intruded features.
8. Georeference the overlays for post-processing and display.

The procedures involved in this workflow have evolved over the course of this work using a variety of software packages. In the end, four key software tools were chosen or developed to provide the final product. Two commercial tools were selected for the initial steps in the workflow. Much of the pre-processing was performed using Cloud Compare software. Conversion of the façade point cloud to a gridded model was then performed in QT Modeler.

The rest of the workflow steps were carried out by using two tools developed in-house at ERDC-GRL. The first of these is the *Building Façade Model Orientation and Georegistration Tool*, created for this project in MATLAB, to generate, orient, and georeference a backplane for the façade model. The second is the *DEM Breakline and Differencing Tool for Micro-Terrain and Canopy Extraction*, a legacy tool created in-house in the ENVI/IDL environment (hereafter referred to as the "Breakline Tool"). This tool provides for elevation model analysis of the façade and backplane to extract surface feature overlays. These overlays are then returned to the *Building Façade Model Orientation and Georegistration Tool* for georeferencing in world coordinates.

2 Methods

In this chapter, the methods used in pursuit of the objective to create georeferenced overlays of façade features from ground scans of buildings are described in detail. These methods can be grouped into four distinct phases: data collection, pre-processing, backplane creation and adjustment, and feature overlay processing and extraction. Also described are the algorithms and processing steps used in ERDC-GRL's in-house developed tools for façade manipulation and overlay creation from gridded elevation models.

2.1 Data collection

The point cloud data used in this project were collected in November 2018 by the ERDC Captur3D team at the Asymmetric Warfare Training Center (AWTC) site in Fort AP Hill, VA using the Leica ScanStation C10, a survey grade terrestrial Light Detecting and Ranging (LiDAR) scanning system. The Leica C10 is set up on a level tripod and collects up to 50,000 points per second with 10 cm point spacing at a 100 m range (Figure 1).

Figure 1. Leica C10 Terrestrial LiDAR scanner setup.

The Leica C10 scanner relies on surveyed points for geo-registration. These point locations were collected at the AP Hill AWTC site using survey-grade Global Positioning System (GPS) receivers (Figure 2). To collect building exterior point clouds, the C10 scanner was positioned in view of at least four surveyed points, identified by co-located spherical targets. The scanned targets allowed the sensor to calculate its own XYZ position.

Figure 2. Survey points installed at the AWTC site (Fort AP Hill, VA).

Individual scans took approximately 30 minutes to collect from sensor setup to takedown. The resulting point cloud is extremely dense and accurate. Point clouds collected with the C10 are often used as ground truth when testing the accuracies and capabilities of new sensors.

In total, the Captur3D team collected 3D point cloud data on nine building exteriors throughout the roughly 90,000 m^2 AWTC area. The building exterior used in this study is displayed in Figure 3. The point cloud data has an absolute accuracy of 3 cm and an average point spacing of 5 cm.

Figure 3. Building exterior point cloud at the AWTC site (Fort AP Hill, VA).

2.2 Data pre-processing

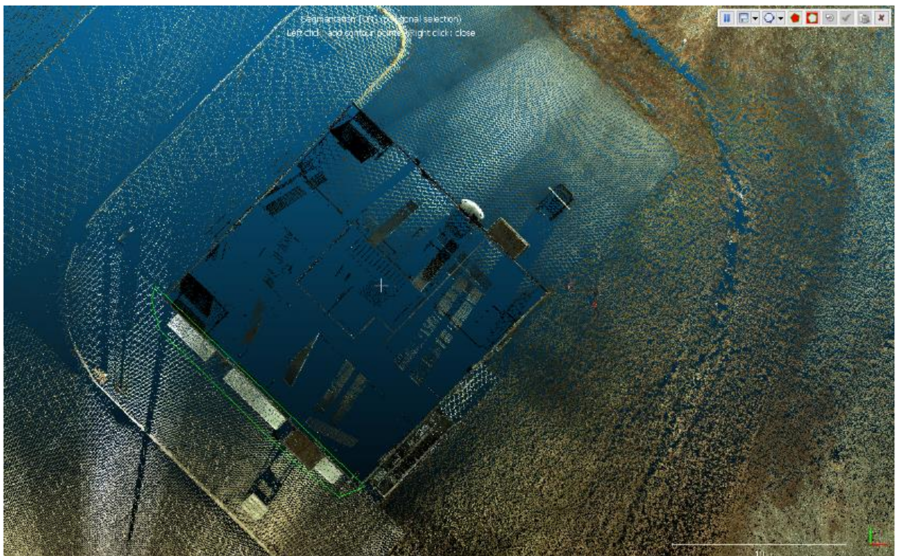
Features on building façades, such as doorframes, window frames, building edges, and physically extruding features, such as balconies or overhangs provide greater situational awareness and enhance 3D products of the urban environment. In this workflow, point clouds of building exteriors are modified for follow-on edge detection and feature extraction. These functions were performed with the previously mentioned "Breakline Tool." The Breakline Tool processes Digital Elevation Models (DEMs) of terrain created from airborne LiDAR data. It was developed to find breaklines in high-resolution DEMs and extract features through analysis of slope, terrain ruggedness, and elevation differencing with a bare earth model.

In order to extract exterior features on building façades, the original LiDAR point cloud must be cropped and separated into individual building façades. Each façade is then rotated into the horizontal, and finally converted into a gridded raster file format. These tasks were performed with CloudCompare and QT modeler software.

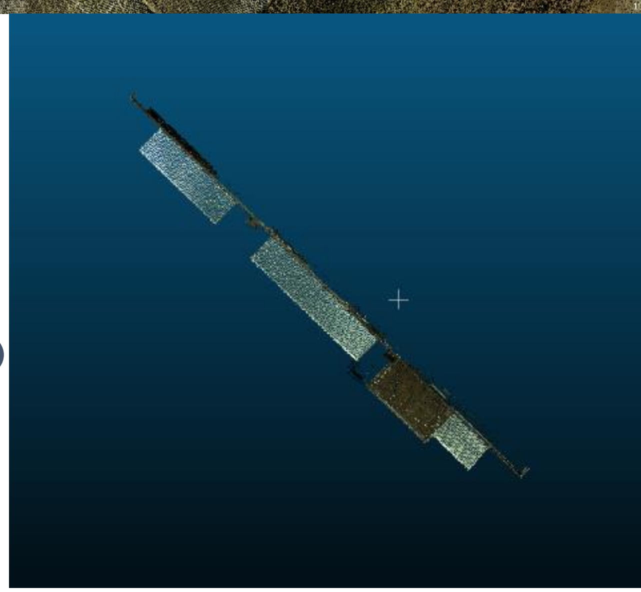
The ‘Segment Tool’ in CloudCompare crops the point cloud data into individual building façades. The user segments the points in a façade by drawing a polygon around it in the point cloud viewer (Figure 4(a)), allowing analysis on the chosen façade. After the façade is separated, the same segmentation tool in CloudCompare is used to remove all ground and extraneous floating points (Figure 4(b)).

Figure 4. Cropping building façades with Segment Tool in CloudCompare.

(a)



(b)

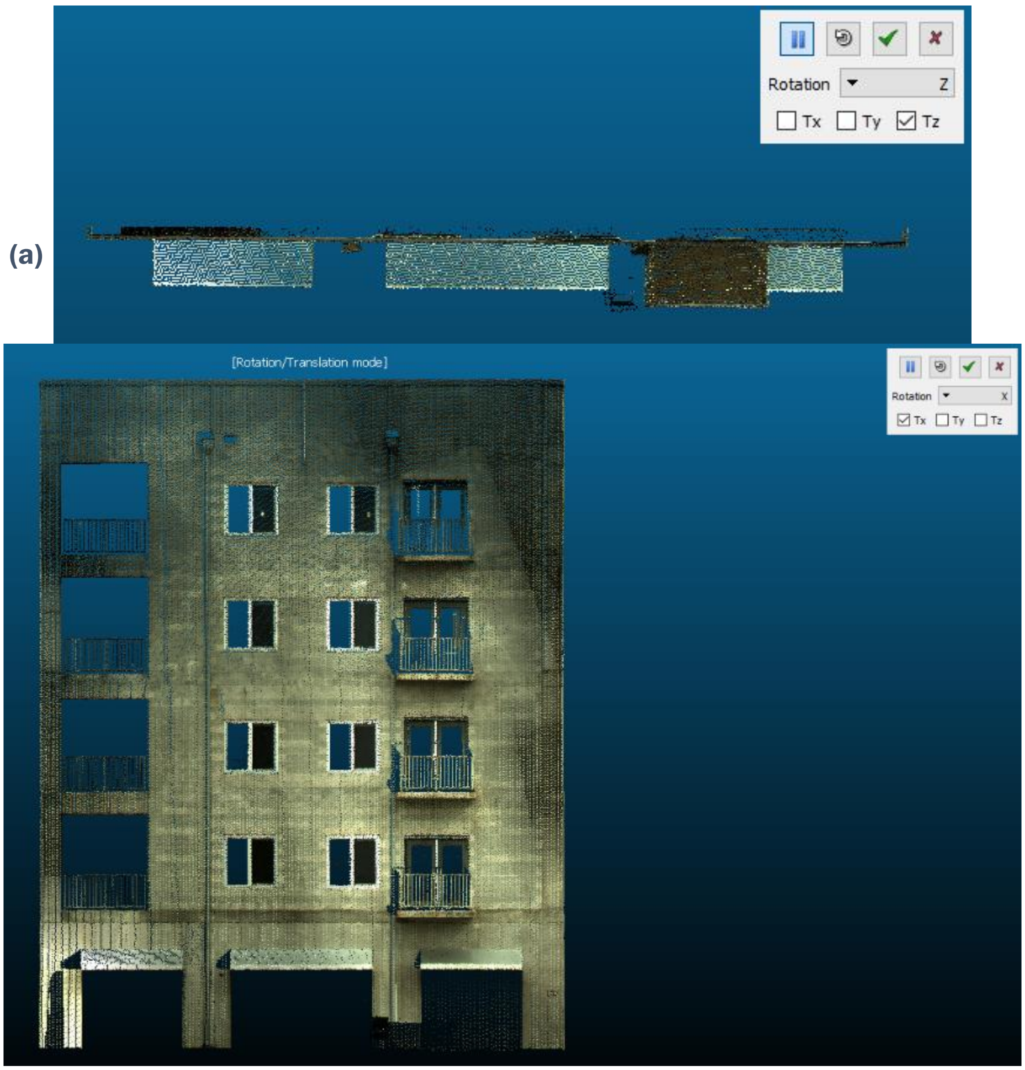


The next pre-processing step is to rotate the point cloud about the z and x-axes, so the building façade is parallel to the horizontal plane. This step is performed in CloudCompare using the ‘Translate/Rotate’ tool. The first movement is rotating the façade about the z-axis, so that the façade’s footprint is aligned with the x-axis (Figure 5(a). Next, is rotating the façade about the x-axis into the horizontal (Figure 5(b)). Dividing the rotation into two separate movements rather than rotating about the x and z-axes at the same time provides more control over the point cloud's movements, and limits tilt in the final data. The translation matrix in the CloudCompare console is saved so the data can be inversely rotated back to its original position.

Figure 5. Building façade rotation in CloudCompare.

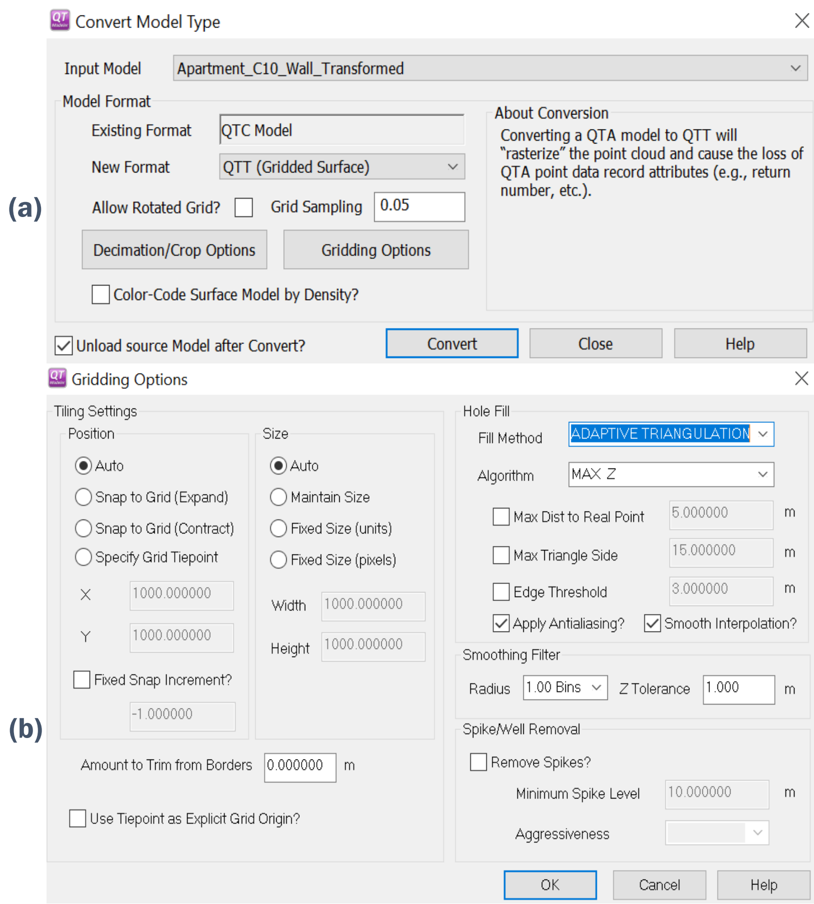
(a)

(b)



The last pre-processing step is to rasterize the point cloud into a gridded DEM in GeoTIFF format for input into the Breakline Tool. A number of tools can be used for this purpose such as QT Modeler, ArcGIS, and CloudCompare. QT Modeler point cloud manipulation software was chosen for this workflow. Required parameters include a pixel size, calculation method, and an interpolation method. The conversion and gridding process in the QT Modeler user interface is shown in Figure 6. Three separate DEMs were created with grid resolutions (pixel sizes) of 10 cm, 5 cm, and 1 cm. Each grid cell represents the maximum elevation, or *z* value, at that location in the model. Empty voids were interpolated by averaging surrounding pixel elevation values with an adaptive triangulation method. Multiple DEMs were created in this fashion to test the effect of grid resolution on the façade feature output from the Breakline Tool.

Figure 6. QT Modeler parameter settings for point cloud conversion (a) and gridding (b).



The resulting gridded surface models of a building façade allows the Breakline Tool to analyze them as if they were open terrain with features characterized by discontinuities. The creation of a backplane underneath the façade acting as a bare earth model also allows extraction of features by model differencing. Figure 7 depicts a gridded façade model output from QT Modeler in "terrain view" with color-mapped elevation values in the direction normal to the façade surface.

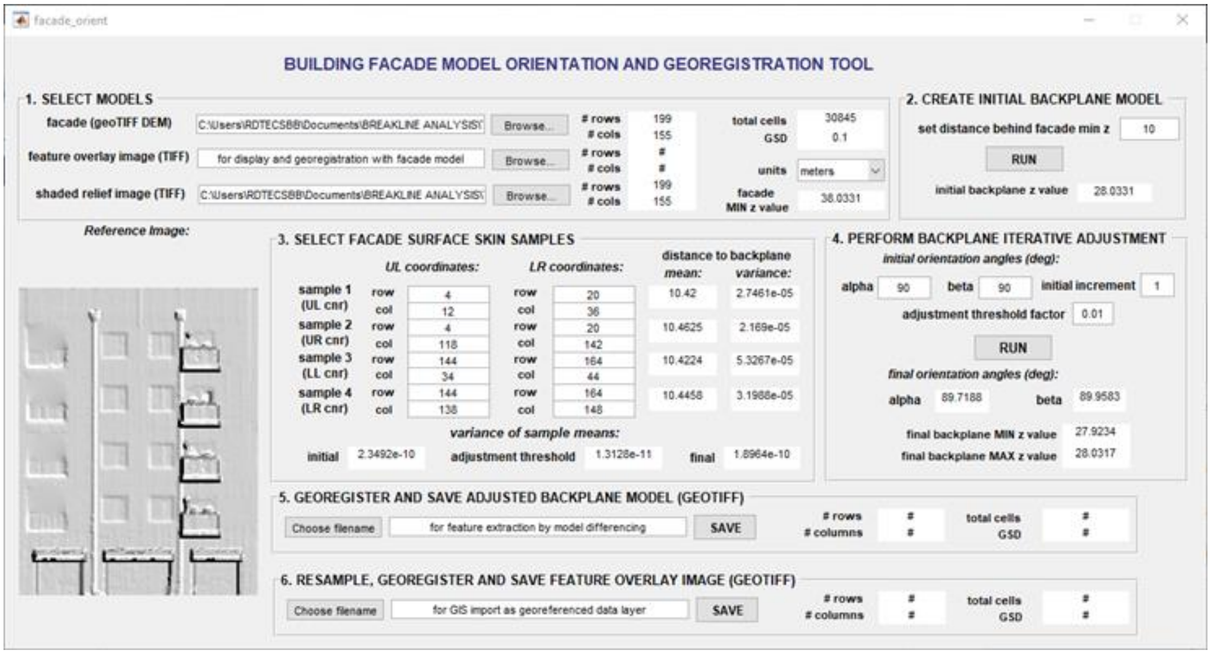
Figure 7. Gridded surface model derived from point cloud.

2.3 Façade tool development

Once the gridded model is prepared and properly transformed, it is ready for input into the *Building Façade Model Orientation and Georegistration Tool* (hereafter referred to as the "Façade Model Tool"). This step is required before façade feature extraction can be performed in the Breakline Tool.

The Façade Model Tool was created for this project. Its Graphical User Interface (GUI) is shown in Figure 8. The Façade Model Tool performs three main functions: (1) creation of a backplane underneath the façade, acting as a pseudo-"bare earth" model that will allow for later differencing analysis; (2) iterative adjustment of the backplane to be more perfectly parallel to the façade surface or "skin"; and (3) georegistering the backplane and/or previously created façade feature overlays. The user can choose the distance between the façade model and the backplane, as well as a threshold factor that controls the accuracy of the orientation adjustment.

Figure 8. Building facade model tool user interface.



To exercise the functions in the Façade Model Tool, the user proceeds through a sequence of operations as follows:

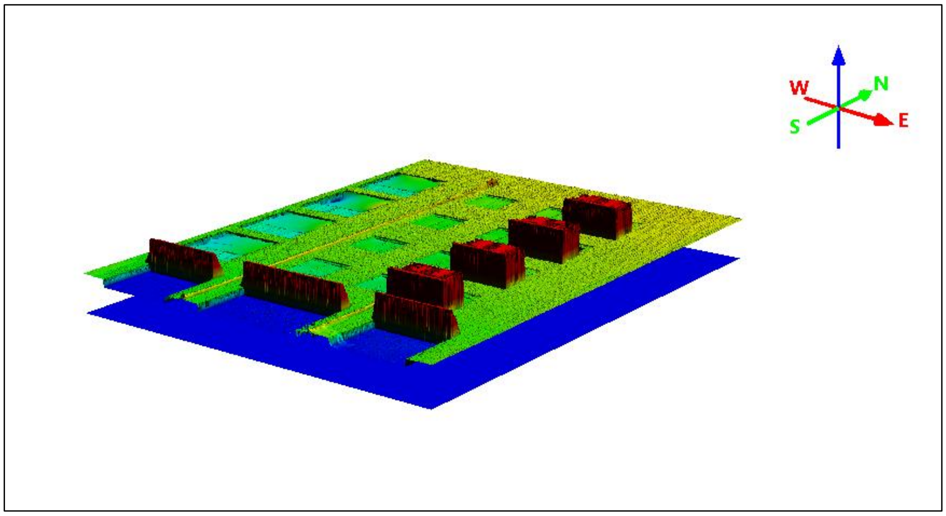
1. *Select models*. This consists of identifying the façade model, its accompanying shaded relief image, and optionally, a previously created feature overlay image that requires georegistering to the façade model.
2. *Create initial backplane model*. In this step, an un-adjusted backplane model is created behind the façade at a user-specified distance upon depressing 'RUN'. The default is 10 m.
3. *Select façade skin surface samples*. Four skin surface sample subsets must be identified for orientation adjustment. These should be small rectangular regions, one near each corner of the façade to provide a more robust geometry for the computed orientation angle corrections. In selecting the sample areas, inclusion of features that depart from the skin surface should be scrupulously avoided. Their corner coordinates are normally found by displaying the shaded relief image in a separate application (e.g., Microsoft "Paint") that provides image pixel locations.
4. *Perform backplane iterative adjustment*. Here, the user chooses a small initial angle increment. The default is 1 degree. An "adjustment threshold factor," which controls the accuracy of the final iterative solution, may also be selected (default 0.01). Depressing the 'RUN' button begins the backplane orientation adjustment process, described in more detail below. Upon completion, the computed final orientation angles are provided.

5. *Georegister and save adjusted backplane model*. In this step, the adjusted backplane is saved as a GeoTIFF file and the georeferencing information from the façade DSM is incorporated into the GeoTIFF header.
6. *Resample, georegister, and save feature overlay image*. In this optional step, a feature overlay image file, created earlier, that was selected in the first step is georeferenced and saved in the same manner as the adjusted backplane in step 5.

2.4 Backplane orientation adjustment overview

After rotation of the building façade DSM by approximately 90 degrees about a horizontal axis, the model is oriented in terrain view. The z values of the DSM now represent distances perpendicular to the ground surface, nominally represented by the x-y plane. This allows any surface extrusions or intrusive depressions in the building's exterior surface or "skin" (e.g. balconies, window wells, overhangs) to act as anomalies in a separate application (described below) designed to identify or extract terrain features characterized by elevation differences from a baseline surface or by measurable breaks-in-slope. For actual terrain, elevation difference analysis is enabled by the derivation of a "bare earth" surface from the normal first-surface DSM, devoid of the anomalies of vegetation canopy and buildings or other structures. For this application, the purpose of the bare earth surface is served by the creation of a backplane a small distance underneath (behind) the façade DSM (Figure 9). When first created, the backplane will be nominally parallel to the skin of the building. However, any slight deviations from the parallel condition will affect the accuracy of segmentation of features that are extruded above or intruded below the skin by a small amount. The goal of this effort is to carefully adjust the orientation of the backplane in 3D space relative to the façade model in an iterative fashion so it is as parallel as possible to the building's exterior surface. After such adjustment, elevation difference analysis will be more accurate and sensitive to minor skin surface features.

Figure 9. Facade in terrain view with backplane.

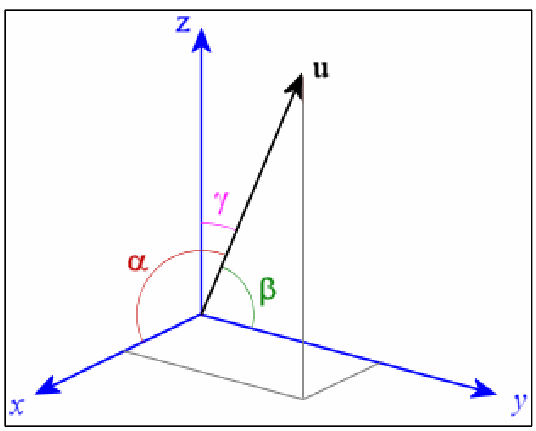


2.5 Backplane creation and orientation approach

The first step in the process is to create a backplane of constant *z* values that will undergo orientation adjustment. The minimum *z* value is found in the rotated façade DSM, $min(z_{fac})$, and the backplane is created a specified distance *d* below this value. Call this the base z value (z_b), or the height of the backplane above the *x*-*y* plane. Thus $z_b = min(z_{fac}) - z_d$.

Let $\boldsymbol{u}$ = normal vector to the backplane passing through the origin (Figure 10).

Figure 10. Backplane normal vector angles in 3D space.



Let α, β, γ be the angles made by vector $\boldsymbol{u}$ with the *x, y,* and *z*-axes respectively. The cosines of these angles are known as the direction cosines of $\boldsymbol{u}$.

The normal equation of an unbounded plane in 3D space is

$$x \cos \alpha + y \cos \beta + z \cos \gamma - |\boldsymbol{u}| = 0$$

But $$|\boldsymbol{u}| = z_b \cos \gamma$$

and $$x \cos \alpha + y \cos \beta + \cos \gamma \, (z - z_b) = 0$$

Since any one angle can be represented in terms of the other two, the normal equation of the plane in terms of α and β is first found, knowing that the sum of squares of the direction cosines equals 1.

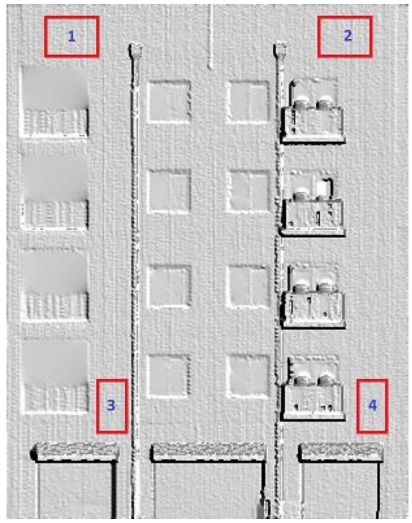
$$\cos^2 \alpha + \cos^2 \beta + \cos^2 \gamma = 1$$

$$\cos \gamma = (1 - \cos^2 \alpha - \cos^2 \beta)^{1/2}$$

and $$x \cos \alpha + y \cos \beta + (1 - \cos^2 \alpha - \cos^2 \beta)^{1/2} (z - z_b) = 0$$

At this point the backplane is parallel to the x-y plane, $\alpha = \beta = \pi/2$ and the equation reduces to $z = z_b$, a plane of constant z values. However, due to imprecision in the process of transforming the façade point cloud into terrain view, the building façade's skin as a plane in 3D space will be, in general, only approximately parallel to the x-y plane. An attempt to make the façade skin and the backplane as parallel as possible to each other will be made by adjusting the orientation of the backplane in incremental fashion, first about the x axis and then about the y axis. To do this, four façade skin DSM sample subsets should first be identified, one near each corner of the façade model. This is shown in Figure 11. The mean elevation value for each skin sample is computed. The angles α and β are then iteratively incremented in turn to minimize the z differential between the means of the façade skin samples and the means of their respective sample subsets on the backplane.

Figure 11. Selection of skin sample subsets.



From the equation above, solve for z in terms of α, β, x, y, and z_b.

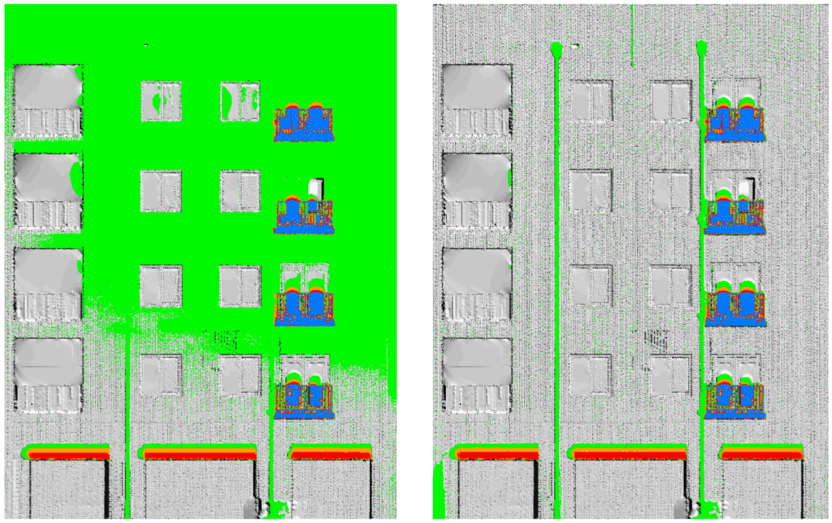
$$z\,(1 - \cos^2 \alpha - \cos^2 \beta)^{1/2} = z_b\,(x \cos \alpha + y \cos \beta) - x \cos \alpha - y \cos \beta$$

$$z = z_b - (x \cos \alpha + y \cos \beta) \,/\, (1 - \cos^2 \alpha - \cos^2 \beta)^{1/2}$$

This expression represents the final equation of the backplane after adjustment of the rotation angles α and β, within a specified tolerance, to render the backplane parallel to the façade skin. The backplane is then transformed with this equation by replacing the constant z_b values with new z values determined by α and β and each x, y location in the backplane model.

The backplane orientation adjustment algorithm described above significantly increases the precision of feature segmentation by range differencing. This is demonstrated in Figure 12, which shows a difference overlay with four color-mapped classes. In Figure 12(a), the façade skin bleeds unavoidably into the lowest difference class in green; Figure 12(b) shows improved results after backplane adjustment. The overlay creation process is described in the following section.

Figure 12. Results of backplane orientation adjustment.

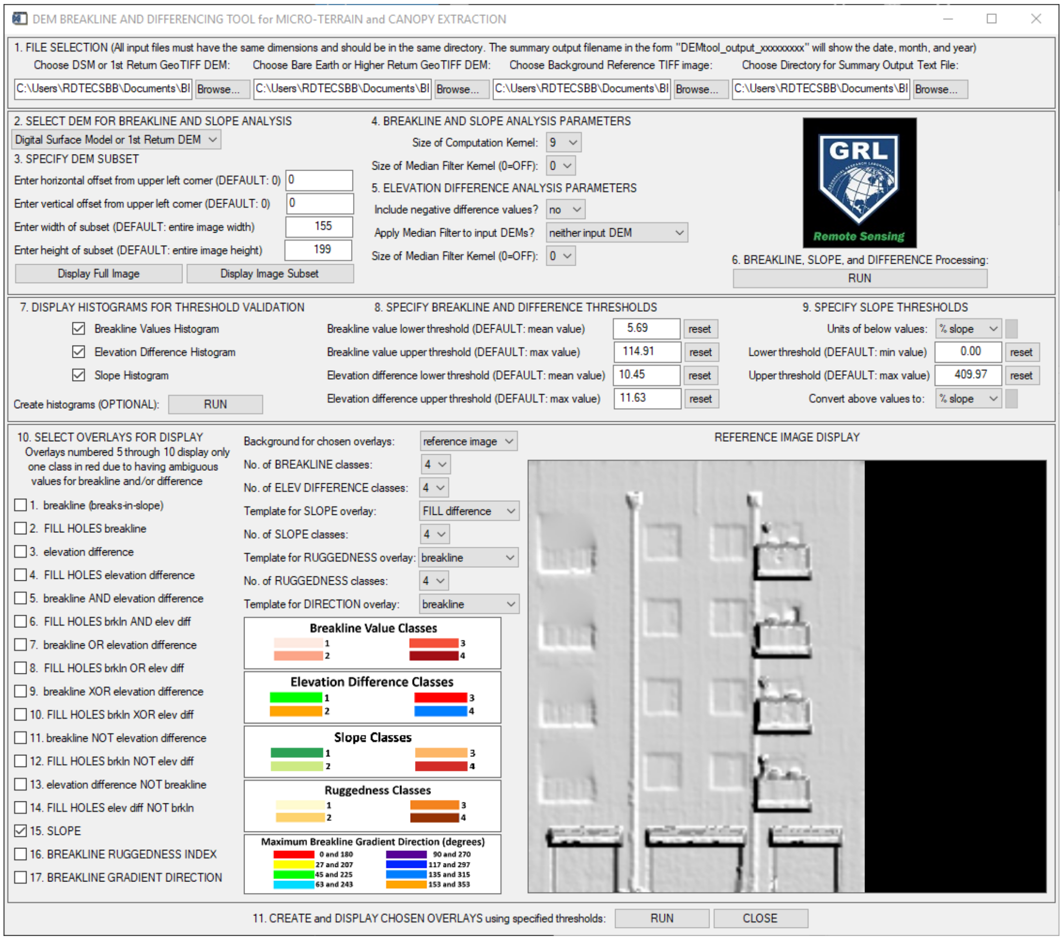


(a) before (b) after

2.6 Overlay creation by breakline, differencing, and slope analysis

Once the façade gridded model and its properly adjusted backplane are created with the Façade Model Tool, they are ready for input into the Breakline Tool. Its GUI is shown in Figure 13. The Breakline Tool was originally designed to process gridded elevation models for extraction of vegetative canopy and micro-terrain features such as gullies, small escarpments, or other fine-scale terrain irregularities. Its capability in finding subtle breaks-in-slope or discontinuities in a gridded elevation model surface will be leveraged for this project to segment extruded and intruded features on the façade model skin.

Figure 13. DEM breakline tool user interface.



These changes in slope over relatively short horizontal distances are found in the elevation model by an adaptation of a numerical technique known as cubic spline interpolation. The algorithm computes a so-called "breakline" value for azimuthal slope change (rather than slope itself) for each cell in the model grid based on a floating computation kernel that is passed over the entire model. This breakline value can be described as a directed second derivative, calculated from a 5-point linear sequence of elevation values in the matrix grid during the spline interpolation process. The associated direction of the sequence is the azimuth, in model space, of the connecting line in the matrix. Because the 5-point linear sequence used in the calculations for each grid cell is centered on the cell, the azimuthal directions are reported as a departure angle from the vertical or grid column direction. After computing the breakline value for a sequence of azimuthal directions, the maximum value is saved for each cell along with its associated direction.

To form a breakline overlay, model cells are identified with maximum breakline values in a chosen range of upper and lower thresholds. The user then chooses the number of color-mapped classes to display over a background image. This image is typically a 2D shaded-relief version of the elevation model. Highlighted contiguous cells that form a linear shape on the shaded relief image can be recognized as a façade feature of a particular type.

The Breakline Tool can also perform feature extraction by differencing with a bare earth model or, in the case of building facades, with the backplane output from the Façade Model Tool. The user can choose a range of elevation differences to be used for the difference overlay along with the number of classes to show features on the building's face at a particular distance range from the backplane.

Elevation difference overlays can be compared to breakline overlays for feature analysis and can interact through the selection of various Boolean overlay combinations. These include AND, OR, and NOT operations and may be useful in increasing the fidelity of segmentation of a feature type or combination of types. For each breakline and difference overlay combination, a "filled" version is available in which a closing operation is performed on the overlay pixels to fill small holes and provide a smoother graphic appearance.

In addition to the standard breakline and difference overlays, there are three special-purpose overlays available: slope, breakline ruggedness index, and breakline direction. The slope overlay is computed using the same computation kernel and cubic spline interpolation approach used for the breakline overlay. Ruggedness is computed for each model cell as the geometric mean of three measures of local elevation change: breakline value, slope, and the variance of elevation found within the computation kernel. The direction overlay is a version of the breakline overlay, color-mapped by the direction of maximum gradient. As an option, the user can intersect any of the three special-purpose overlays with any of the Boolean combinations of breakline and difference by choosing one as a template from a separate menu associated with the overlay.

To use the Breakline Tool, the user proceeds through a series of operations numbered in sequence. The first step is to select input files for the façade model the backplane, and the shaded relief background image. Then the user selects various processing parameters such as the size of the computation kernel and choice of median filter, if desired. Available kernel sizes are 5x5, 9x9, 17x17, and 33x33. These sizes are determined by kernel geometry limitations in selecting the sequence of grid locations for cubic spline interpolation. Smaller kernel sizes allow for detection of more fine-scale discontinuities in the gridded model. A median filter may be chosen for breakline and slope analysis, and separately for differencing. Available filter sizes are 3x3, 5x5, or 7x7.

Pressing the first ‘RUN’ button will then create the breakline, slope, and differencing model data. When this processing step completes, the user selects upper and lower thresholds for these three models. The user can now choose the particular overlays and Boolean combinations desired, along with the number of color-coded classes. Finally, processing can begin with the second ‘RUN’ button to create and display the selected overlays. Each overlay is displayed separately over the shaded relief reference image as a layer of adjustable transparency. The overlay and reference image combination can be saved in several standard image formats including TIFF. The overlay data itself can also be saved without the reference image background as a TIFF file, enabling importation into a GIS.

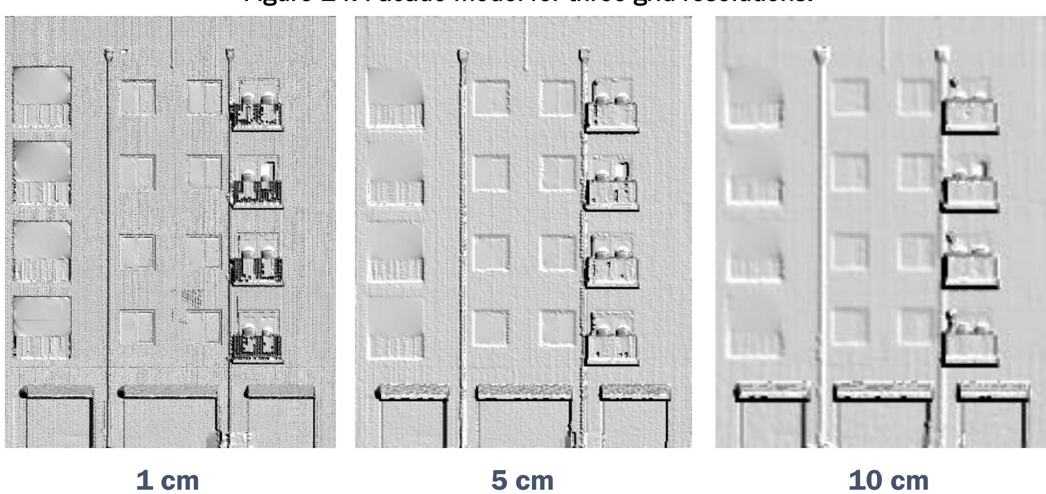
As an option, the Breakline Tool can also create separate histograms for breakline, elevation difference, and slope values for the input data and chosen computational parameters. These are useful for choosing particular thresholds for overlay creation. When applied to terrain models, careful threshold choices based on the histograms can often isolate grid cell subsets of the model that spatially correlate with ground features or particular canopy characteristics. For this façade application, examination of these histograms may also provide insight into threshold selection.

While examination of the histograms may prove useful, the Breakline Tool processing scheme is designed to allow for rapid trial-and-error analysis by adjusting thresholds and overlay choices. Once the initial parameters are chosen and the first ‘RUN’ process is performed, the calculations required for creating overlay subsets of model cells and their Boolean combinations proceed rapidly.

3 Results and Discussion

To demonstrate the efficiency and practicality of the façade feature extraction workflow, the authors took advantage of a high resolution and high fidelity point cloud dataset of urban terrain collected by the Captur3D team at the AWTC site at Fort A.P. Hill, VA. From this data, a point representation of a façade with definable features such as window wells, balconies, and overhangs was selected and excised. Gridded DSM models were then created of the façade at three resolutions (1, 5, and 10 cm) to be able to compare the quality of feature overlays derived from them. This provided a means to estimate the minimum data density in gridded form required to extract feature information of reasonable quality. Shaded relief images of the three gridded façade models are shown in Figure 14. At low resolution, although the fine structure in complex features such as balconies can be lost, the building's skin becomes smoother, showing less irregularity due to range uncertainty. This may act as an advantage in creating difference overlays between the façade model and the backplane.

Figure 14. Facade model for three grid resolutions.



In the following sections, façade feature overlay results from differencing, breakline, and slope analysis in the Breakline Tool are described.

3.1 Difference overlays

Processing for the selected façade began by creating adjusted backplanes for the three models in Figure 14. This allowed for differencing overlays to be developed in the Breakline Tool. Using a 3-class overlay, thresholds were chosen for the three models to extract the major extruded features of balconies and overhangs. In addition, the finely tuned backplane orientation adjustment allowed for the capture of low-profile vertical pipes on the façade surface. For each level of resolution, the overlays were created to cover the same fraction of the façade area. This allowed the comparison of the overlay quality across resolutions. Statistics for the three overlays are provided in Table 1 and graphic results are displayed in Figure 15.

Table 1. Difference Overlay Statistics.

Model resolution	# model cells	# overlay cells	% overlay coverage	Data reduction
high res (1 cm)	3015215	1304	11	---
med res (5 cm)	122673	3277	11	96%
low res (10 cm)	30845	395	11	99%

In the overlays shown, each color class encompasses 0.4 m of range from the façade skin toward the sensor. The range classes arranged in order away from the skin are represented by the colors green, red, and blue. In each case, the difference overlay algorithm detected the same features with approximately the same quality. Each overlay covered the same fractional area of the model. Some detail in the structure of the balconies is lost in the transition from 1 cm to 5 cm resolution. The fidelity of some straight-line features begins to suffer in the transition to 10 cm resolution. For the extruded features shown in Figure 15, a grid resolution of 5 cm may be optimal in capturing them by differencing with high fidelity. This represents a 96% reduction in data storage requirements over the 1 cm high-resolution model.

Figure 15. Differencing extruded feature overlays for three grid resolutions.

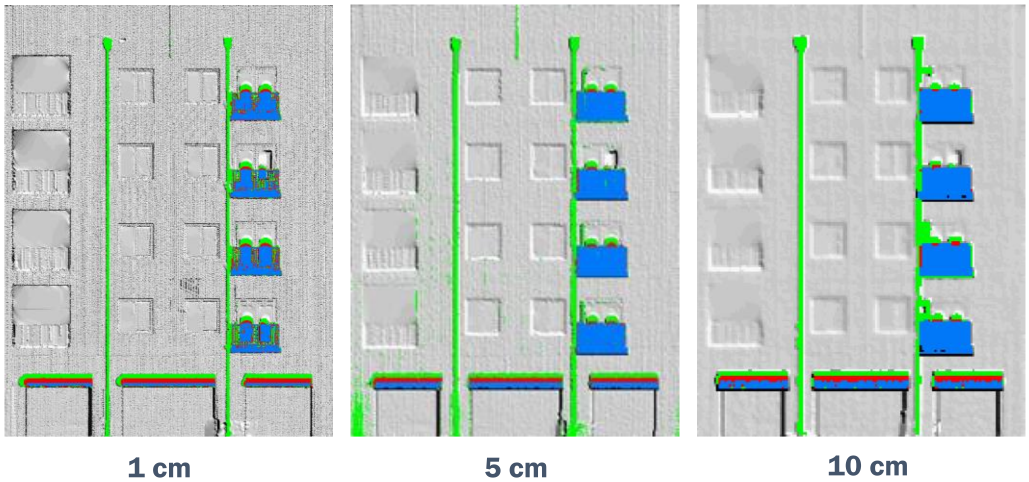
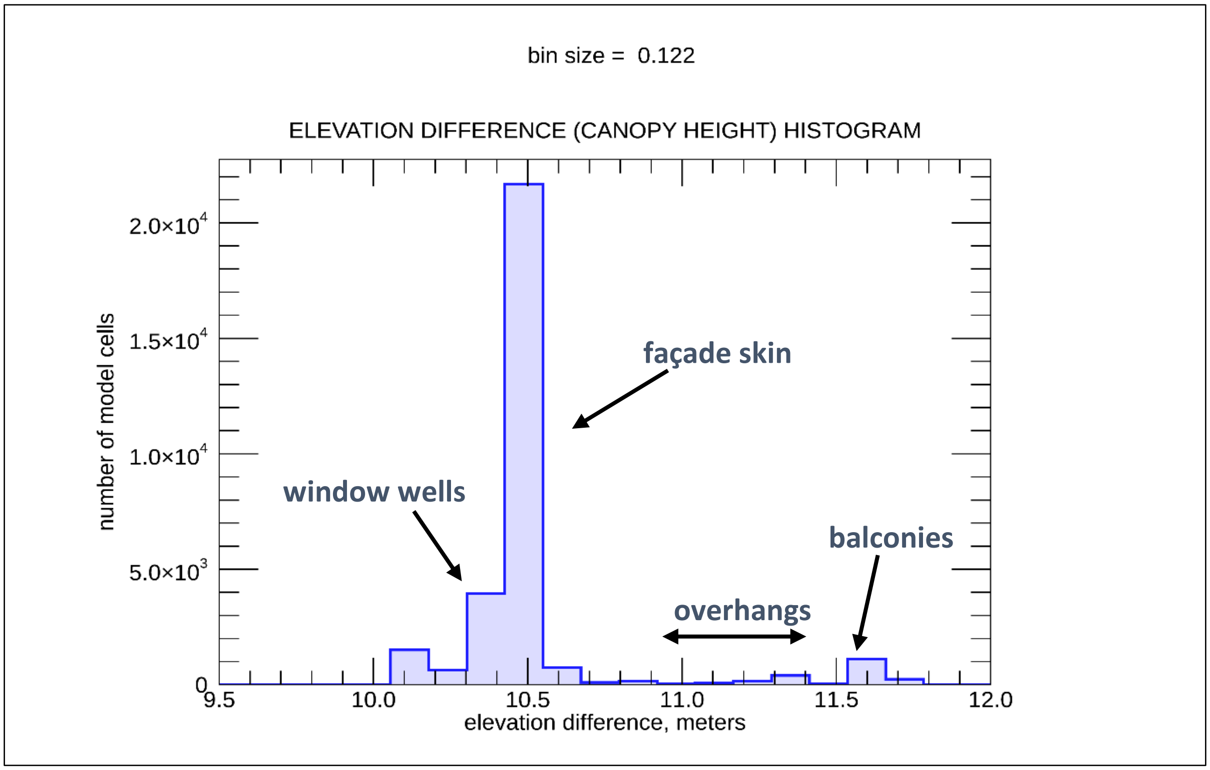


Figure 16 shows a histogram of elevation differences between the façade and the adjusted backplane for the 10 cm resolution model. For this model, grid cell subsets for major features tended to fall into separate histogram bins, as indicated in the figure. This was helpful in choosing upper and lower thresholds for difference templates used in the slope analysis described in the following sections. These templates were intersected with slope overlays for more accurate feature extraction.

Figure 16. Elevation difference histogram for the 10 cm facade model.

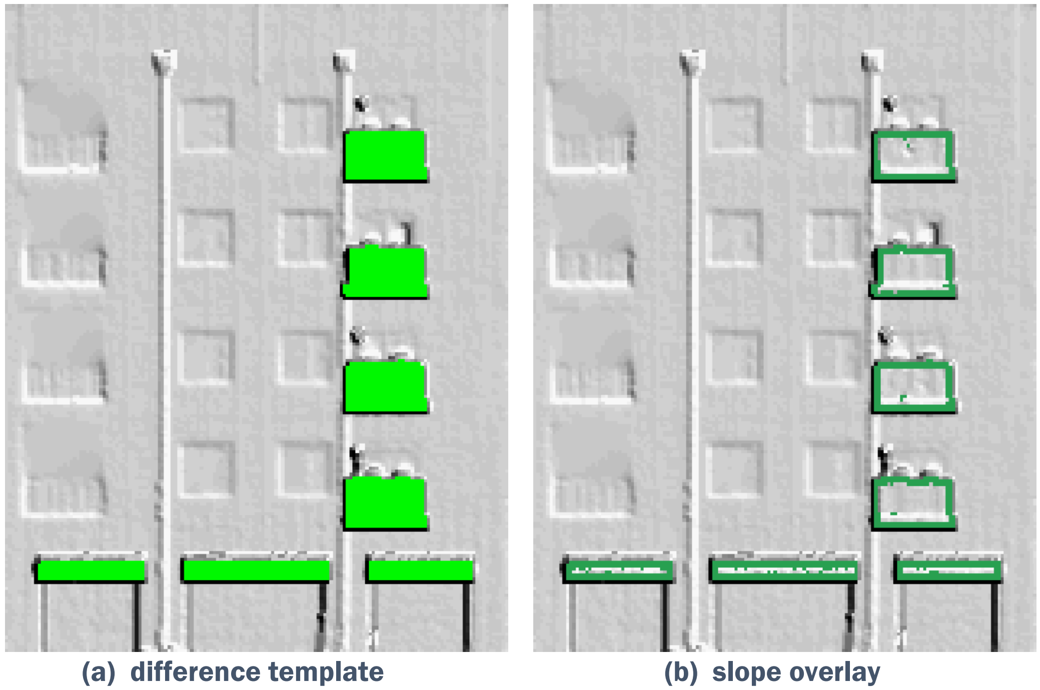


3.2 Slope overlays

In addition to creating difference overlays, façade features were extracted with the Breakline Tool through breakline and slope analysis. The computations for these overlays by themselves do not require the backplane. It is required, however, if these overlays use the difference overlay in a Boolean combination. Difference overlay templates intersected with slope overlays were used to extract both extruded (above the façade skin) and intruded (below the skin) features.

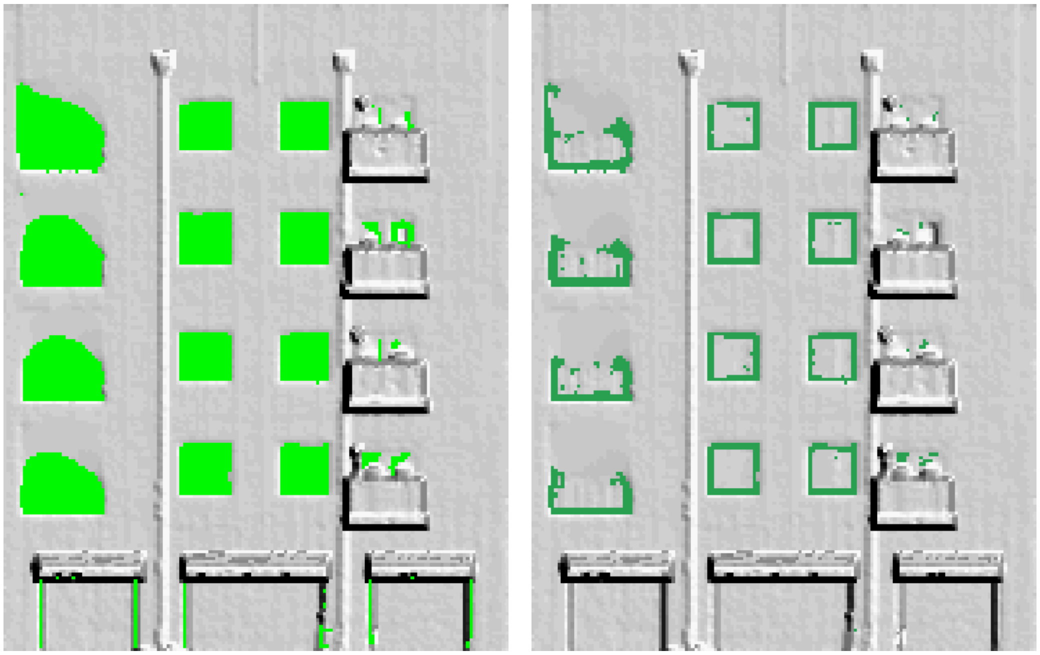
It was found that the 10 cm model reduced small-scale irregularities on the façade skin that can cause unwanted cells to be included in a slope overlay near the minimum chosen threshold. Figure 17 depicts the results of the slope analysis for extruded balconies and overhangs using a computation kernel size of 5x5 after choosing appropriate thresholds by trial-and-error. Figure 17(a) shows the 1-class filled difference overlay used as a template for the intersection with slope. A difference range of 80 cm was found to be sufficient to capture the balcony faces as well as the sloping overhang surfaces. The percent slope threshold range was chosen to be 70-800 to capture the model cells with higher slopes. This resulted in an overlay with edge outlines of these features without extracting interior detail (Figure 17(b)).

Figure 17. Slope analysis for extruded features (10 cm model).



The same procedure was followed using a Boolean overlay combination to segment the intruded window wells lying just below the façade skin. To capture these features, the 10 cm model was processed with a 9x9 computation kernel. A difference overlay was then created to be used as a template for a final slope overlay. The more subtle window well features required a difference template with a narrower difference range of 12 cm just below and just above the façade skin in order to separate them from the rest of the model. This overlay is shown in Figure 18(a). It was intersected with a slope overlay with a percent slope threshold range of 12-50. The final result appears in Figure 18(b). The outlines of the center window wells are well segmented, but the wells on the left side are not closed completely at the top. This is due to the lack of a relatively hard break-in-slope with the façade skin at the top of these features.

Figure 18. Slope analysis for intruded features (10 cm model).



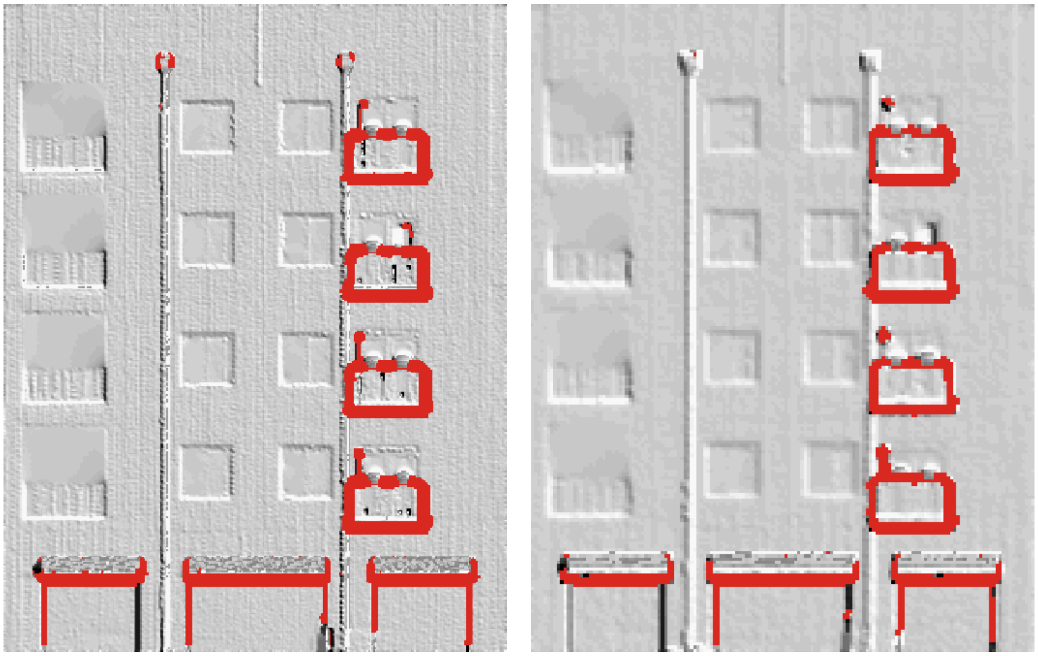
(a) difference template (b) slope overlay

3.3 Breakline overlays

For the breakline analysis, results were compared from the two lower resolution models (5 cm and 10 cm) that provided good results from the differencing and slope analyses. In both cases, clean overlays were created showing the outlines of the extruded balcony and overhang features that were similar to the slope overlay output. It was found, however, that these overlays could be produced without the creation of a difference overlay template for intersection as a preliminary step. Only careful threshold selection was required. While good results were obtained for extruded features, such was not the case with the intruded window wells, whether or not a difference overlay was employed.

Figure 19 shows the extruded feature results for both models. For the 5 cm model, a 9x9 computation kernel was used and a median filter of size 3x3. These Breakline Tool processing choices were made to reduce the effects of fine-scale irregularities in the model, resulting in a cleaner overlay appearance. For the 10 cm model, the median filter was retained. However, since this lowest resolution model significantly reduces the role of discontinuities in the spatial structure, the smallest computation kernel size of 5x5 was used for detection of breaklines. Figure 19(a) depicts the outlines of balconies and overhangs. Figure 19(b) shows that, for these features, the 10 cm model results in a slight loss of visible overlay fidelity.

Figure 19. Breakline analysis for extruded features.



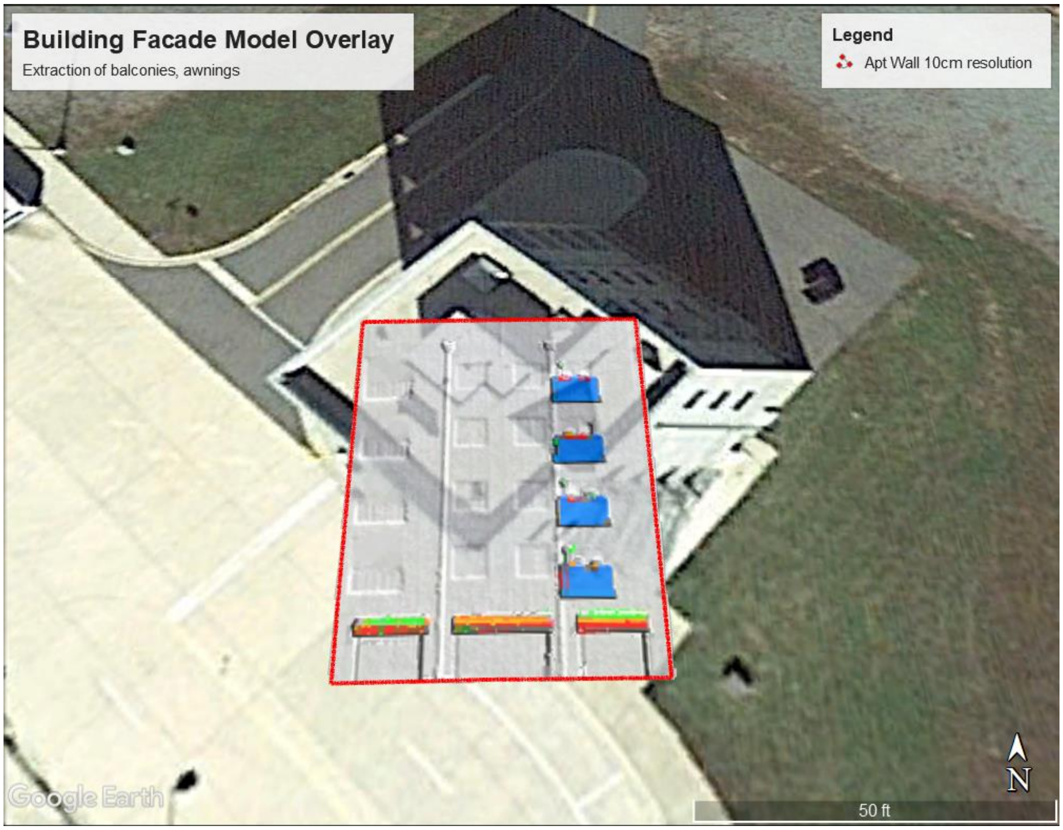
(a) 5 cm model (b) 10 cm model

3.4 Overlay georeferencing and visualization

As a final processing step, feature overlays may be attributed with georeferencing information from the GeoTIFF header for the original gridded façade model. This includes the GeoTIFF coordinate reference system and other cartographic information. As described earlier, this function is performed in the Façade Model Tool after saving the overlay as a TIFF image in the Breakline Tool. This allows the overlay to be co-registered with the façade model as well as to basemap or image data in a georeferenced visualization environment such as a GIS or Google Earth. The Breakline Tool provides the option of saving the overlay data by itself or as a color-mapped layer over the shaded relief image.

As an example of this Façade Model Tool feature, a georeferenced difference overlay of extruded features over the shaded relief image was created. It was then imported into Google Earth and its transparency was adjusted so that ground features were visible underneath. Figure 20 shows this result, with the feature overlay appearing over the building at Fort AP Hill, VA from which it was derived.

Figure 20. Google Earth visualization of georeferenced overlay.



4 Summary and Conclusions

This work was undertaken in support of the TREADSTONE project at ERDC-GRL and its goals to improve data visualization and optimize the rendition of 3D structures in urban landscapes. The use of point cloud models derived from ground scan collections were explored in the field to model building facades and extract their exterior features as raster overlays. These overlays may serve as inputs into other software environments for visualization or geospatial analysis.

Point cloud data was used of buildings collected under a separate effort (Captur3D) with a terrestrial lidar scanner. This data had high point density and high positional accuracy. A cropped point cloud was manipulated in a series of steps to prepare it for facade feature extraction.

A workflow was developed to segment a high-resolution point cloud of a building and transform it in 3D space into a horizontal “terrain view” to create gridded façade models at three different raster resolutions. Each model was paired with a backplane model of constant elevation values above the x-y plane. The backplane models underwent precise orientation adjustment to allow for the creation of accurate surface feature overlays by differencing. The application of algorithms for additional breakline and slope analyses also proved effective in capturing both intruded and extruded façade surface features.

Pre-processing functions were performed on a point cloud dataset in CloudCompare and QT Modeler software for point cloud segmentation, transformation, and rasterization. A façade model was converted from points to raster form to speed processing, reduce file size and prepare the model for overlay analysis. A Façade Model Tool was built for this project to perform orientation adjustment and georegistration functions. This prepared the model for creation of surface feature overlays in the legacy Breakline Tool, originally designed for extraction of micro-terrain features and canopy by breakline analysis, slope analysis, and model differencing. The Breakline Tool allows for Boolean combinations of these basic extraction modes.

After orientation adjustment, extruded surface features were successfully extracted by differencing for all three gridded resolutions at 1, 5, and 10 cm. The quality of the overlays did not visibly deteriorate for the 5 cm grid model, and did so only slightly for the 10 cm grid. These two resolutions represent a data reduction of 96% and 99%, respectively, over the 1 cm model.

Using slope analysis, separate overlays were created for extruded features (balconies and overhangs) and intruded features (window wells) with respect to the façade skin surface. Slope overlays intersected with difference overlays were employed after choosing appropriate thresholds for each. The extruded features overlay showed their outlines where slope was at a maximum. The intruded features overlay showed the outlines of the window wells in the same manner. Both of the slope overlays resulted in successful extraction of the target features at the lowest grid resolution of 10 cm.

An extruded feature overlay using the breakline approach instead of slope showed very good results at both the 5 and 10 cm grid resolutions. Captured features were similar to those of the extruded feature slope overlay. For the extruded feature breakline overlay, intersection with a difference overlay was not required. Extracting the intruded window wells with the breakline approach was not successful, and a clean overlay of these features was not obtained.

The Façade Model Tool can graft georeferencing information from the façade model GeoTIFF file header onto that of any feature overlay created in the Breakline Tool. This capability was demonstrated for a difference overlay and imported it into Google Earth display of the overlay superimposed over its source building at Fort A.P. Hill.

In this work, it has been shown that terrestrial point cloud scans of building exteriors can be converted into gridded models that can then be rotated and adjusted in 3D space for analysis as if they were digital models of terrain. The high spatial resolution of the original scans need not be preserved in gridded form. It was found that a 5 cm grid resolution may be a good working minimum for larger features such as balconies, and for lower-profile features such as exterior piping. In some cases, a 10 cm resolution may suffice, as seen in Figures 17 and 18. These lower resolution models represent a 96 and 99% data reduction from the high-resolution 1 cm model and can significantly lower requirements for data storage and throughput in an operational setting for urban mission planning.

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Acronyms and Abbreviations

AMP3D	Automated Man-Machine Learning and Processing for 3D Terrain
AWTC	Asymmetric Warfare Training Center
DEM	Digital Elevation Model
DSM	Digital Surface Model
ERDC	Engineer Research and Development Center
GIS	Geographic Information System
GPS	Global Positioning System
GRL	Geospatial Research Laboratory
GUI	Graphical User Interface
LiDAR	Light Detection and Ranging
USACE	U.S. Army Corps of Engineers

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14. ABSTRACT

This project involves the creation of 3-dimensional models of building façades from ground-derived point clouds and extracting features from the façades as encoded overlays. These features include balconies, window wells, overhangs, or other exterior fixtures. Point data of a building façade, acquired from high-resolution terrestrial scans, are transformed in space so that a normal to the façade surface is in the vertical direction. The point cloud is then converted into a gridded model, which can be investigated in like manner to a digital terrain model through breakline, elevation difference, and slope analysis. A backplane of constant *z* values is created underneath the façade to act as a "bare earth" surface. The orientation of the backplane in space is carefully adjusted to be parallel to the façade's exterior, providing more accurate feature extraction through difference analysis. Raster overlays are created as color-mapped classes or continuous values of breakline, elevation difference, or slope that capture the form of façade feature objects. To complete the attribution of façade features, georeferencing information from the original building model is associated with each overlay product. This allows for the display of the overlays in a georeferenced visualization environment such as a Geographic Information System (GIS) or Google Earth.

15. SUBJECT TERMS

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Buildings – Facades
Geospatial data
Terrestrial lidar scanning
Point cloud
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