Rapid 3D Modeling Using Photogrammetry Applied to Google Earth

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ABSTRACT: Low-cost digital photogrammetry using structure-from-motion (SfM) has made it possible for nearly anyone with a digital camera to create dense and precise point cloud models of the physical environment. However, the general requirement for large sets of photos in SfM can present a problem to those with limited resources or limited access to certain locations. This study examined the feasibility of using screen images of Google Earth's proprietary high-resolution 3D models—not the crowdsourced SketchUp models—in creating point cloud and textured mesh models using SfM. The three study locations included a residential neighborhood in Tokyo, Japan; a portion of the University of California, Santa Barbara (UCSB) campus; and Mount Herard in Colorado. These locations represented a dense urban environment, a mixed environment, and a natural environment, respectively, where Google's proprietary models existed. Light detection and ranging (LiDAR) data provided an additional data source for evaluating results at UCSB and Mount Herard. Simulated flights were "flown" in Google Earth at each location with screen capture software used to record 45° oblique video of the ground. Individual images were then extracted from the videos and used in Agisoft PhotoScan Professional, an SfM software program, to produce point cloud and textured mesh models of each location. Results of this study support the feasibility of using screen images of Google Earth for SfM modeling. While SfM succeeded in creating models for all three locations that visually resembled Google Earth's own models, quantitative analysis showed that SfM worked best in the built-up areas of Tokyo and UCSB but struggled with the natural environment of Mount Herard. Comparison of sample distances within the SfM models and Google Earth showed planimetric errors of 1% or less and vertical errors of 5% or less for Tokyo and UCSB; however, absolute errors at Mount Herard—which was compared to LiDAR instead of Google Earth—spanned a range of under 10 m for areas of high relief to values exceeding 100 m for areas with low relief or low texture. The varying qualities of these models reflected not so much limitations of SfM but its reliance on a number of factors that impacted final model quality, such as image quality and operator skill in performing each step of the SfM workflow.

KEYWORDS: 3D modeling, SfM, photogrammetry, Google Earth, SketchUp

Introduction

Photogrammetry describes a broad array of techniques used to derive physical measurements from 2D images, and digital photogrammetry describes any type of photogrammetry involving digital images (Mikhail, Bethel, & McGlone, 2001). Whereas photography converts 3D information into a 2D format—i.e., the photograph, photogrammetry reverses the process by deriving 3D measurements from the 2D images.

Structure from motion (SfM) represents a popular photogrammetric method that uses the principle of parallax to derive 3D measurements based on shifts in image features from different photographs taken at different vantage points. However, measurements derived using SfM inherently contain no scale or unit information since source images also lack that information (Falkingham, Bates, & Farlow, 2014). Properly scaling SfM measurements requires additional measurement information such as georeferenced camera locations or measured distances between fixed ground control points (GCPs).

The recent emergence of affordable SfM software programs has made it possible for nearly anyone with a digital camera to generate precise measurements of the physical world in the form of point cloud and textured mesh models (Kersten & Lindstaedt, 2012; Smith, Carrivick, & Quincey, 2015; Verhoeven, 2011; Westoby, Brasington, Glasser, Hambrey, & Reynolds, 2012). These programs semi-automate the SfM process by allowing users to simply upload photos and process them through a mediated workflow, which shields users from the complex inner workings of SfM. The accessibility of SfM software can be especially advantageous to users in non-technical fields or to those with limited resources. However, the requirement for large sets of photographs presents a challenge for reasons such as limited access to site locations or the inability to collect images from critical vantage points, such as from the sky overhead.

One workaround to the image collection problem involves the use of Google Earth. In its efforts to map Earth, Google has created photorealistic 3D models of numerous locations worldwide using reality capture techniques such as LiDAR and photogrammetry, as well as manual modeling. In the earlier years of Google Earth, Google also relied on crowdsourcing using their SketchUp software program for collecting models of built-up structures. However, these publicly-sourced models suffered from inconsistent quality and had uncertain levels of reliability in dimensioning and georeferencing. In 2012, Google sold SketchUp to Trimble Navigation, Ltd., and moved to relying on its own proprietary reality capture techniques to more faithfully integrate those models with Google's overall mapping program (McClendon, 2012).

The newer proprietary 3D models in Google Earth more faithfully model physical features on Earth when compared to crowdsourced and other public data sources. Consequently, the high-fidelity quality of these models essentially transforms Google Earth into a virtual 3D flight simulator of the real world. When used for image acquisition for SfM, users can take unlimited "aerial photos" of a scene while "flying" around in Google Earth at any viewing angle and altitude. However, the convenience of this approach comes with some drawbacks. First, Google's proprietary models have no accompanying measures of reliability, so errors and uncertainties in Google's models will propagate to the SfM models. Second, this approach only works in the few areas where Google's high resolution models exist. In spite of these drawbacks, Google's models may represent the only 3D window to the world for many modelers, and the speed, convenience, and cost of using this approach may sufficiently outweigh its limitations.

In this study, three test areas were selected where SfM 3D models could be created from

Google Earth images and where high quality models were also available from LiDAR data. The purpose was to measure the discrepencies between the two sets of models and so quantify the anticipated accuracy of Google Earth-based SfM 3D models of urban and natural terrain.

Method

Study Locations

The three locations chosen for this study represented a dense urban environment, a mixed environment, and a natural environment—all of which had Google's proprietary high resolution models. These three locations consisted of a residential neighborhood in the Shinjuku ward in Tokyo, Japan (UTM 384900 mE, 3949700 mN, Zone 54, Northern Hemisphere); portions of the University of California, Santa Barbara (UCSB) campus (UTM 239000 mE, 3811900 mN, Zone 11, Northern Hemisphere); and Mount Herard in Colorado (UTM 456500 mE, 4189190 mN, Zone 13, Northern Hemisphere).

Workflow overview

This study used the Agisoft PhotoScan Professional SfM software along with a five phase workflow consisting of ground control setup, image acquisition, SfM processing, digital surface model (DSM) generation, and measurement and analysis.

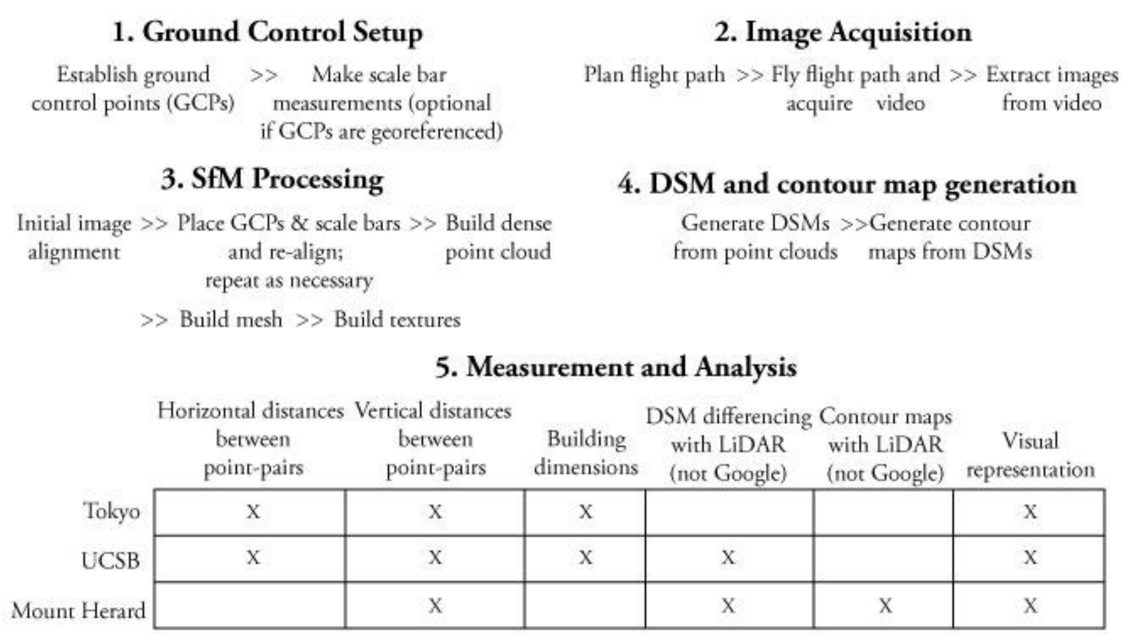

Figure 1. Overview of workflow for this study.

Ground Control Setup

Ground control points (GCPs) anchor abstract computer-generated models to locations in the real world. In this study, the GCPs tied the SfM models to locations in Google Earth's 3D virtual world. Pairs of GCPs also served as end points for scale bars representing real-world (or Google Earth) Euclidean distances used for scaling the final models. Coordinates for the GCPs were taken directly from Google Earth using WGS84-based Universal Transverse Mercator (UTM) grid coordinates and the software's default elevation value. Google Earth documentation did not clearly specify its vertical coordinate reference system (CRS) but it was assumed to be EGM96.

Image Acquisition

The flight planning process involved covering each study area with parallel flight lines in Google Earth, which involved literally drawing lines on the ground in the software program. Close spacing of these flight lines ensured maximum sidelap, while the back-and-forth flight directions maximized multi-directional coverage of 3D objects on the ground. Time constraints limited each study area to one flight line, each oriented in only one direction and flown at only one altitude—300 m for Tokyo and UCSB and 1,000 m for Mount Herard. The camera was set at a 45° downward looking angle to maximize coverage of both vertical and horizontal surfaces in a single pass.

Figure 2. Flight lines for UCSB.

Video acquisition was performed using the Microsoft Expression 4 Screen Capture Software on a WQHD (2560x1440 pixel) monitor, which delivered video images at an effective 3.2 megapixel (MP) resolution (2464x1312 pixel) after accounting for the removal of borders and non-image elements. Even though Agisoft recommended using images with a minimum resolution of 5 MP (Agisoft LLC, 2016), a previous investigation on use of low-cost cameras in PhotoScan indicated a minimum image resolution of 2 MP was sufficient for the software to function (Chen & Clarke, 2014). Therefore, a regular HD (1920x1080 pixel) monitor would have delivered images at slightly below an effective 2 MP—after border and non-image element removal—and may not have worked in this experiment. The open source VLC media player was used to extract individual still images from the videos for use in SfM.

SfM Processing

Implementing the SfM modeling workflow involved five steps in PhotoScan as shown in

Figure 3. The first step involved performing automatic image alignment to roughly align the images and place their respective "cameras" in space, since these images lacked geotags. As part of the alignment process, the software also made a first attempt to estimate camera lens characteristics—an important feature for correcting image distortions since Google Earth did not provide this information. If successful, the initial image alignment step placed some or all images into their correct locations and generated a sparse point cloud of tie points—i.e., points representing key features detected in multiple images—that vaguely resembled the modeled scene.

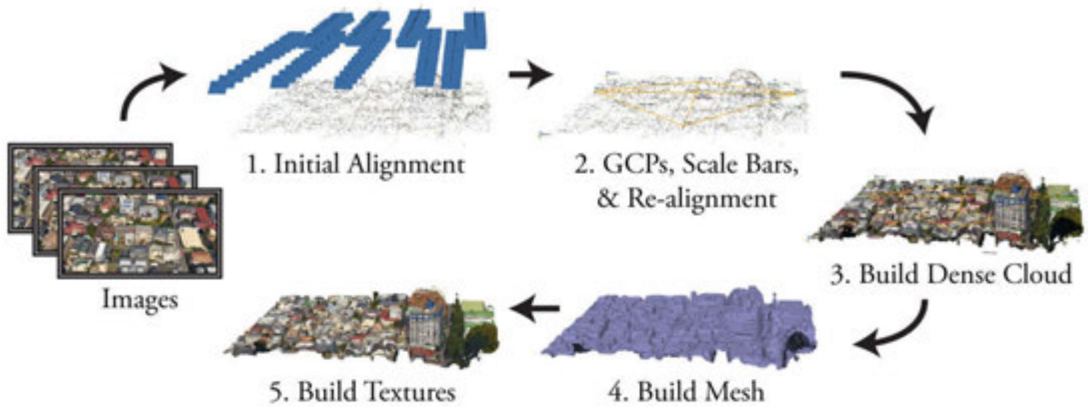

Figure 3. SfM modeling workflow.

The second step involved iteratively establishing GCPs and scale bars in a subset of images and further refining the alignment of all images. (Scale bars were only used for Tokyo and Mount Herard.) Upon reaching a satisfactory state, the camera parameters were calibrated one final time to optimize their parameters based on the refined image locations.

With all images correctly placed and all GCPs and scale bars established, the third step used SfM to generate a dense point cloud of coordinates based on information in the images. At this point, the resulting point cloud contained millions of points that collectively provided a photorealistic 3D rendering of the modeled environment. The point cloud could be used as-is for measurement and visualization purposes or further processed for other purposes. However, using point clouds for visualization can result in pixelated images, which can be more pronounced in areas with sparser point densities.

Generating a textured mesh of the point cloud can remedy the point cloud pixelation problem and provide a photo-realistic 3D model of the mapped environment. In the PhotoScan workflow, these last two steps involved generating a meshed surface based on the point cloud and then applying image-based texture—i.e., texture mapping—to the mesh for photorealism.

Digital Surface Model and Contour Map Generation

Digital surface models (DSMs) provide a convenient and simple approach to comparing the height values of different point clouds. DSMs were generated for UCSB and Mount Herard using the Esri ArcGIS "LAS Dataset to Raster" tool applied to each location's individual SfM and LiDAR point clouds. DSM cells were sized to reduce voids and noise resulting in 2 m cells for UCSB and 30 m cells for Mount Herard. The DSM for UCSB's SfM point cloud used the maximum height value per cell due to points existing along vertical features, e.g., walls. DSMs for all other point clouds used average values since they generally did not include or capture vertical features.

Both LiDAR data sets for UCSB and Mount Herard required transformations to match the CRS for Google Earth, i.e. UTM (WGS84) for horizontal coordinates and EGM96 for elevations. For the small UCSB study area, a manual transformation was performed in a software program called CloudCompare by aligning salient features—e.g., corners of buildings—in the LiDAR point cloud to the same features in the SfM point cloud. However, the absence of discrete and distinguishable features in the point clouds for Mount Herard made it necessary to perform an actual CRS transformation on the LiDAR data using the U.S. National Oceanic and Atmospheric Administration (NOAA) VDatum software program. The Mount Herard LiDAR data set originally used UTM (NAD83)/NAVD88 and the UCSB LiDAR originally used California State Plane Zone 5 (NAD83)/NAVD88.

Contour maps were also generated for Mount Herard using ArcGIS to provide a qualitative assessment of horizontal accuracy.

Measurements and Analysis

The primary goal of data analysis involved quantifying deviations of measurements in the SfM point clouds from measurements in Google Earth's models, which would ideally have involved using a complete set of data from Google. Unfortunately, the non-availability of Google's proprietary data made it necessary to use alternative approaches.

Horizontal and vertical distances. In all three study areas, distance measurements were made between pairs of GCPs and pairs of random points. These measurements were separated into horizontal (planimetric) and vertical components to prevent large horizontal distance values from masking significant deviations in the vertical component. Vertical distances were simply the elevation differences between two points while horizontal distances were calculated using the equation for Euclidean distance

$$D_h = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$$

SfM point clouds for the Tokyo and UCSB study areas contained enough detail to identify GCPs and random measurement points to allow for assessment of horizontal deviations from Google Earth distances. However, horizontal deviations were not calculated for Mount Herard due to insufficient detail in its SfM point cloud; instead, a qualitative assessment of horizontal deviation was performed using contour maps.

Point cloud elevation values—i.e., vertical coordinates—were calculated in ArcGIS by finding the elevation value of the nearest neighbor in the point clouds for each individual point, while elevation values from Google Earth were manually determined by reading the on-screen value associated with each individual point.

Building measurements were also performed for the Tokyo and UCSB study areas to assess small area deviations from Google Earth.

Digital surface models. Analysis using digital surface models examined differences in elevation on a cell-by-cell basis using the map algebra equation

$$DSM_{Diff} = DSM_{SfM} - DSM_{LiDAR}$$

The UCSB assessment of DSM_{Diff} took a qualitative approach due to the abundance of time-varying elements in the study area, such as vegetation, marshlands, and the beach, which would have skewed statistical numbers. For Mount Herard, assessment of DSM_{Diff} employed the use of descriptive statistics, a histogram, a cumulative distribution function (CDF), and visualization of the geographic distribution of errors.

Results

Horizontal measurements. Horizontal measurements between pairs of GCPs and pairs of random points for Tokyo and UCSB showed differences of less than one percent between Google Earth and the SfM point clouds (Table 1 and Table 2). In the column "Type, G/R," G identifies distances between pairs of GCPs while R identifies point-pair distances between random points.

Table 1. Horizontal distances between pairs of points.

Pair Number	Tokyo					UCSB				
	Type	PhotoScan	Google	Difference		Type	PhotoScan	Google	Difference	
	G/R	meters	meters	meters	%	G/R	meters	meters	meters	%
1	G	112.45	113.44	-1.00	-0.9%	G	167.86	166.33	1.53	0.9%
2	G	207.47	208.53	-1.07	-0.5%	G	72.07	72.13	-0.06	-0.1%
3	G	143.67	145.02	-1.35	-0.9%	G	122.59	122.01	0.57	0.5%
4	G	107.98	108.06	-0.08	-0.1%	R	241.02	241.97	-0.95	-0.4%
5	G	120.41	121.42	-1.00	-0.8%	R	218.24	219.04	-0.79	-0.4%
6	G	122.15	122.80	-0.65	-0.5%	R	276.11	274.23	1.88	0.7%
7	R	46.03	45.68	0.35	0.8%					
8	R	89.17	89.23	-0.06	-0.1%					
9	R	60.08	59.96	0.12	0.2%					

Table 2. Measurement of building dimensions.

Building	Dimension	Tokyo				UCSB			
		PhotoScan	Google	Difference		PhotoScan	Google	Difference	
		meters	meters	meters	%	meters	meters	meters	%
1	L	24.3	24.5	-0.2	-0.8%	105.6	106.2	-0.6	-0.6%
	W	26.1	26.4	-0.3	-1.1%	92.4	93.2	-0.8	-0.9%
	H	21.0	20.1	0.9	4.5%	13.3	13.4	-0.1	-0.7%
2	L	25.8	25.7	0.1	0.5%	46.0	46.1	-0.1	-0.2%
	W	27.6	27.8	-0.2	-0.8%	66.2	66.7	-0.5	-0.7%
	H	5.3	5.1	0.2	4.3%	12.7	12.6	0.1	0.8%
3	L	7.9	7.9	0.0	0.0%	49.9	50.2	-0.3	-0.6%
	W	12.3	12.3	0.0	0.0%	55.5	55.7	-0.2	-0.4%
	H	8.3	8.1	0.2	2.5%	11.1	11.2	-0.1	-0.9%

Since GCPs could not be precisely located in the point clouds for Mount Herard, visual analysis using isolines—i.e., contour maps—was used to compare the SfM data to

LiDAR data (Figure 4). The visual isoline analysis indicated a general overall conformance of horizontal positions to actual conditions —though not necessarily to Google Earth—although deviations at specific locations varied widely.

Vertical measurements. The SfM process produced mixed results in vertical measurements for the sampled point locations. Vertical measurements in the built-up areas of Tokyo and UCSB showed little to no deviation from Google Earth within Google Earth's fine sub-centimeter resolution for vertical point-to-point distances and coarse 1 meter resolution for elevations (Table 2 and Table 3). However, the all-natural area of Mount Herard exhibited significant vertical deviations with values approaching or exceeding 100 m, representing over 10% of the overall height range for the entire modeled area.

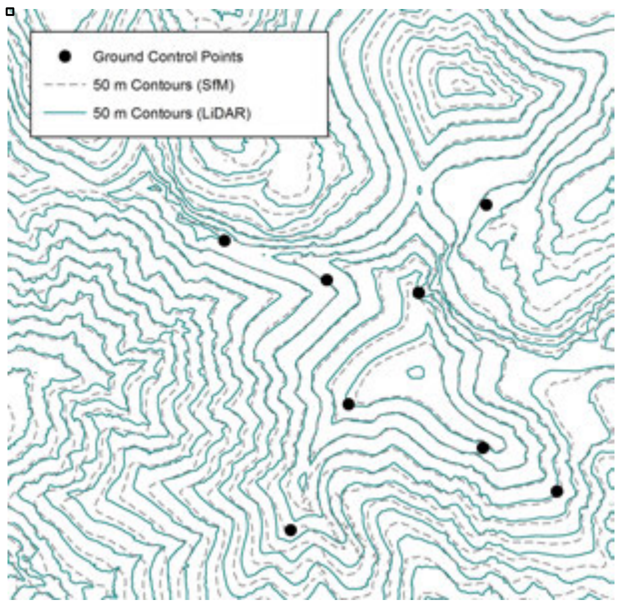

Figure 1. Contour map of Mount Herard comparing SfM to LiDAR.

Table 3. Elevation differences between pairs of points.

Pair Number	Tokyo				UCSB				Mount Herard			
	Type	PhotoScan	Google	Difference	Type	PhotoScan	Google	Difference	Type	PhotoScan	Google	Difference
	G/R	meters	meters	meters	G/R	meters	meters	meters	G/R	meters	meters	meters
1	G	-2	-2	0	G	0	0	0	G	119	22	97
2	G	-4	-4	0	G	0	-1	1	G	-72	-153	81
3	G	-1	-1	0	G	-1	-1	0	G	-33	-53	20
4	G	-2	-2	0	R	1	2	-1	G	-151	-75	-76
5	G	1	1	0	R	1	1	0	G	-63	-32	-31
6	G	-3	-3	0	R	0	-1	1	G	-89	-175	86
7	R	0	0	0					G	-36	22	-58
8	R	0	1	-1					G	27	54	-27
9	R	0	0	0					R	38	149	-111
10									R	64	96	-32
11									R	25	-53	78

DSM analysis. For UCSB, an extended time difference between the LiDAR data set and Google's data prevented the use of the DSM data for descriptive statistics. Deviations shown in Figure 5 provide an indication of time-varying changes which would have significantly skewed any statistical results. Most of these changes appeared to be due to vegetative growth, erosion or land subsidence, and a new building addition as seen in the bottom left of the figure. Removing the effects of these time-varying elements showed that most areas of the Google Earth-based SfM model conformed to actual site conditions by +/- 1 m, within the range of the vertical resolution of Google Earth.

Unlike at UCSB, the geographic scale of the Mount Herard study area permitted the use of a comprehensive cell-by-cell comparison of the data. The descriptive statistics and histogram in Figure 6 illustrate that SfM produced elevations values exceeding those in the LiDAR data by a mean value of 23.9 m, although with a standard deviation of 23.6 m. These numbers, however, masked the geographic distribution of the actual elevation differences that showed the lowest deviation values for areas of high topographic relief and the highest values for smooth areas with low relief (Figure 7).

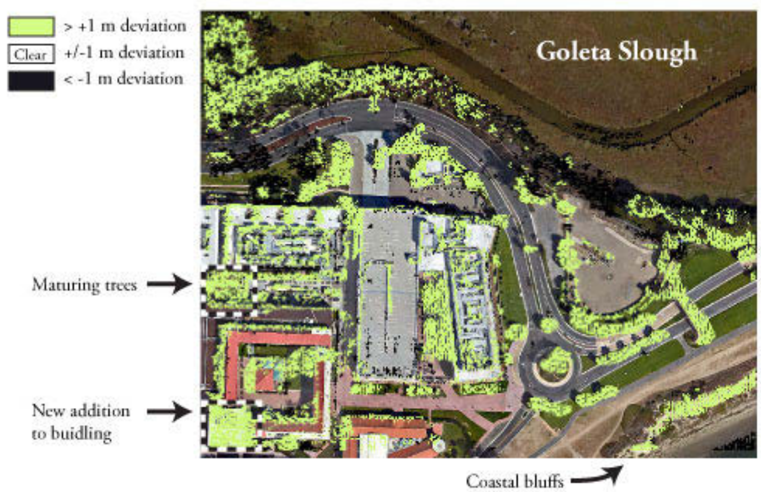

Figure 5. Visualized elevation differences between SfM and LiDAR at UCSB using 2 m DSM cells.

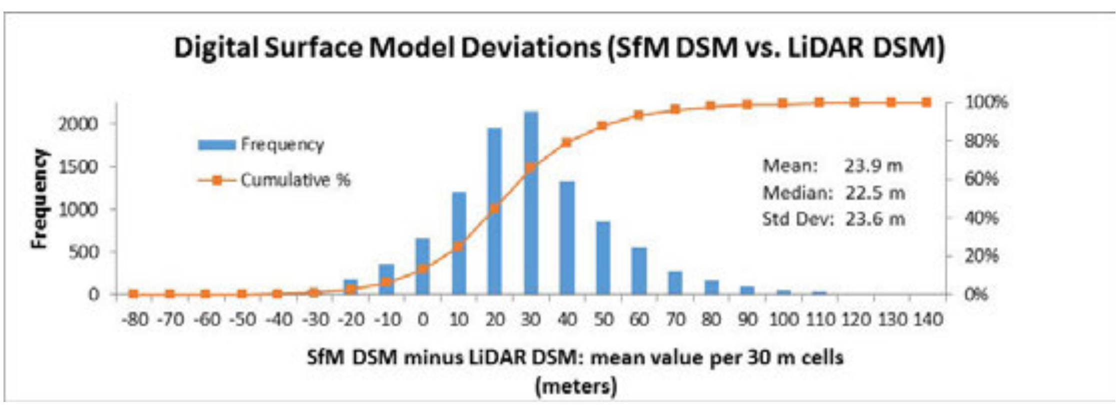

Figure 6. Elevation differences between SfM and LiDAR DSMs at Mount Herard using 30 m DSM cells.

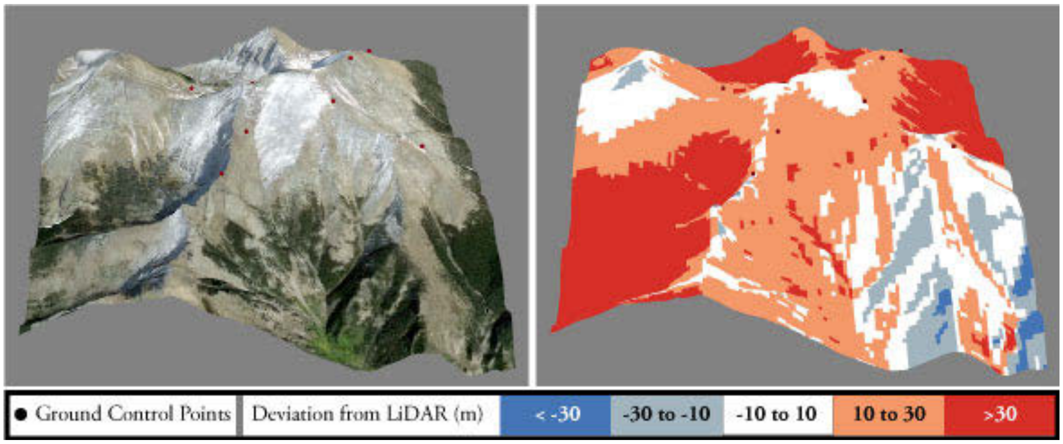

Figure 7. Visualization of DSM differences between SfM and LiDAR at Mount Herard.

Google versus LiDAR. The availability of LiDAR data for Mount Herard made it possible to examine errors in Google Earth's model compared to actual physical measurements. Table shows vertical distances between point-pairs in Google Earth and the LiDAR data for Mount Herard using the same point-pairs as shown in Table 3.

Table 4. Elevation differences between pairs of points for Google Earth and LiDAR.

Pair Number	Mount Herard				
	Type	Google	LiDAR	Difference	
	G/R	meters	meters	meters	% vs. LiDAR
1	G	22	28	-6	-22%
2	G	-153	-140	-13	9%
3	G	-53	-46	-7	16%
4	G	-75	-74	-1	1%
5	G	-32	-7	-25	372%
6	G	-175	-172	-3	2%
7	G	22	23	-1	-6%
8	G	54	30	24	79%
9	R	149	149	0	0%
10	R	96	122	-26	-21%
11	R	-53	-27	-26	95%

Visual representation. The SfM process accompanied by meshing and texture mapping produced models that appeared nearly identical to the Google Earth models, complete with imperfections (Figures 8 to 10).

Discussion

Although Agisoft PhotoScan, the SfM software, successfully reconstructed Google Earth's 3D models in all three study areas, measurements of the resulting point clouds showed significant variability in their accuracies compared to Google Earth and to real-world LiDAR data.

Information content. SfM relies on the information content in digital images to reconstruct measurements in 3D environments. Three factors influencing this information content include the quality of the camera and its images, the different perspectives of the environment captured by those images, and qualities of the environment itself (Agisoft

LLC, 2016).

Figure 8. Visual comparison of Google Earth and PhotoScan models for Tokyo.

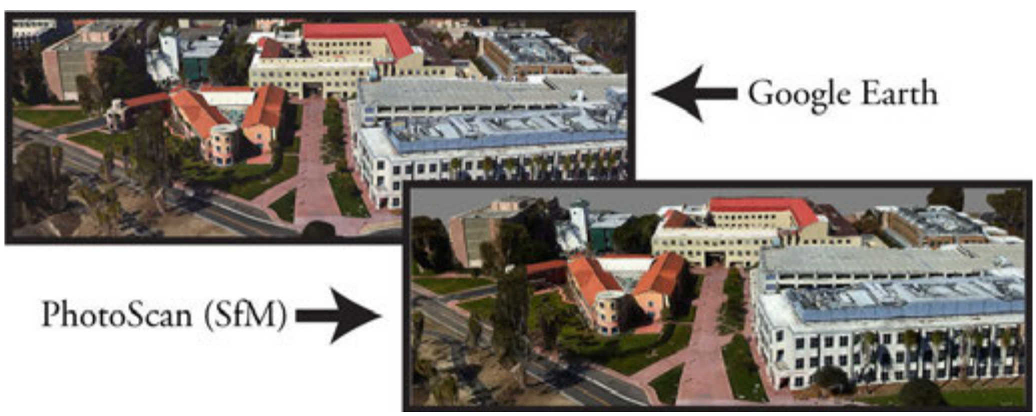

Figure 9. Visual comparison of Google Earth and PhotoScan models for UCSB.

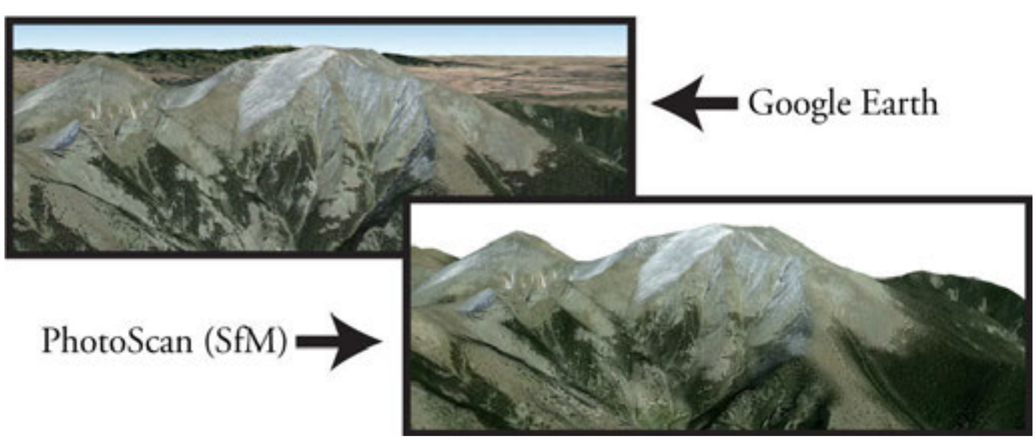

Figure10. Visual comparison of Google Earth and PhotoScan models for Mount Herard.

While the 3.2 MP resolution of the images used in this study was sufficient to work with PhotoScan, use of a newer 4K resolution monitor (3840 x 2160 pixels) would have generated higher resolution 8 MP images with greater information density that could have translated into higher resolution models.

Limited perspectives of the three study areas perhaps played a greater role in influencing the quality of the final models than image resolution. Images for all three study areas used single flight lines oriented in a single direction and flown at a single height—300 m above ground for Tokyo and UCSB and 1,000 m above ground for Mount Herard. Movement of the "camera" (i.e., view of Google Earth in the computer screen) along a horizontal plane produced significantly more information on horizontal movement than vertical movement, resulting in the relatively lower deviations in horizontal measurement values. Additionally, the relatively high altitude of the cameras coupled with the low resolution of the images meant greater coverage at the expense of information density, resulting in a reduction of very fine details in the SfM models—a quality most evident in built-up structures. Providing a wider range of perspectives, such as close-up images or flying at multiple altitudes, would likely have improved the quality of the models.

Surfaces characteristics in the mapped environment played an equally important role in determining model quality due to their impact on the ability of SfM software to identify key features for image pair matching. PhotoScan does not perform well with low or untextured surfaces, whether in the form of color or topographic relief (Agisoft LLC, 2016). This limitation explained why the built-up environments of Tokyo and UCSB—with their buildings, road markings, and other discrete features—produced significantly better results than the all-natural environment of Mount Herard. Even within the SfM model of Mount Herard, areas with high topographic relief—such as peaks and sharp ridges—produced accurate measurements (+/- 10 m compared to LiDAR) while smooth, rounded, and featureless valleys produced errors of up to 100 m. Use of additional ground control points could have mitigated errors in those problematic areas.

Computation. The significant amount of time required to generate SfM models constrained the final quality level for two of the three study areas. SfM is computationally intensive and the entire SfM process—image alignment, point cloud generation, and building textured meshes from images and point clouds—often required many hours to perform on a single workstation. Even with a relatively well-equipped computer (Intel i7-4790 processor, 32 GB RAM, AMD R9 280 graphics card with 3 GB RAM), PhotoScan could only construct one point cloud for the Tokyo study area to the highest quality level (i.e., ultra high quality) in under six hours. Point clouds for UCSB and Mount Herard were constructed at the next highest level (i.e., high quality) due to failure of the software to complete the point cloud generation process within six hours at the ultra high quality level.

Errors and Uncertainties. Regardless of how realistic Google Earth-based SfM models may appear, they will always contain errors and uncertainties at two levels—between the SfM model and Google Earth and between Google Earth and reality. Errors between the SfM model and Google Earth can be characterized through sampling of locations in the Google Earth software, such as those used in this study, although the coarse resolution of vertical measurements can add a certain level of uncertainty. However, the absence of quality measures comparing Google's model to reality makes it impossible to characterize its reliability and, by extension, the reliability of the SfM models in representing the real physical world. The sampling of errors in Google Earth, shown in Table, showed the degree to which Google's model deviated from reality at Mount Herard and provided an indication of the imperfections—usually to an unknown degree—that exist in Google Earth.

Conclusions

This study demonstrated the feasibility of reconstructing Google Earth's 3D models using SfM software and screen images of Google's proprietary high-resolution models. While all three case studies produced reconstructed models that appeared nearly identical to Google's models, sample measurements showed varying degrees of errors in the SfM models—the built-up environments of Tokyo and UCSB exhibited the lowest error values while the natural environment of Mount Herard had a wide range of error values, some exceeding 100 m. Errors in SfM modeling could be attributed to and mitigated by actions taken in specific steps in the SfM workflow. However, errors inherent in Google Earth itself were impossible to quantify without actual physical measurements. The variability of SfM errors and the unknown errors and uncertainties in Google's models makes SfM from Google Earth images unsuitable for applications that require accurate measurements. Nevertheless, for the vast numbers of users who have no such requirements, this approach provides a fast, convenient, and affordable approach to modeling the real physical world.

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