Evaluation of Handheld Apple iPad Lidar for Measurements of Topography and Geomorphic Change

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Abstract

High-resolution topographic data are used in geomorphic and hydrologic research for many purposes, including topographic change detection, development of computational meshes for hydraulic models, characterizing channel and hillslope geometry, measuring vegetation structure and density. These data can be collected in a variety of ways, ranging from manual surveying with a Total Station or GPS system, airborne LiDAR, terrestrial laser scanning (TLS), and Structure-from-Motion (SfM) photogrammetry using images collected from drones or pole-mounted cameras. These methods can be very time consuming to collect, and the equipment they require can be very costly. With the release of the 2020 iPad Pro and iPhone 12 Pro, Apple added a LiDAR sensor to their devices, enabling them to be used as hand-held 3D scanners. This new technology has the potential to enable very rapid collection of high-resolution topographic data at low cost. Here, we investigate how well iPad-based LiDAR characterizes topography and topographic change in hillslope and fluvial environments. A 2020 iPad Pro using two apps (3D Scanner and Polycam) was used to collect topographic data over areas ranging from about 100 – 600 m^2. These same areas were scanned with a Topcon GLS-2000 TLS system, and aerial imagery were collected with a UAV and processed with Agisoft Metashape to create SfM point clouds. Ground-based targets visible in the datasets were surveyed with an RTK-GNSS system and used to register and scale the datasets. The datasets were aligned using the ICP algorithm in CloudCompare, and cross-sections and topographic differences were extracted from each dataset and compared. Our analysis indicates that transects collected with the iPad LiDAR have mean absolute differences with TLS and SfM data within 3 cm, making these data comparable to other high-resolution topographic data collection methods.

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1. INTRODUCTION

High-resolution topographic data are used in geomorphic and hydrologic research for many purposes, including topographic change detection, development of computational meshes for hydraulic models, characterizing channel and hillslope geometry, and measuring vegetation structure and density. These data can be collected in a variety of ways, ranging from manual surveying with a Total Station or GPS system, airborne LiDAR, terrestrial laser scanning (TLS), and Structure-from-Motion (SfM) photogrammetry using images collected from drones or pole-mounted cameras. These methods can be very time consuming to collect, and the equipment they require can be very costly.

With the release of the 2020 iPad Pro and iPhone 12 Pro, Apple added a LiDAR sensor to their devices, enabling them to be used as hand-held 3D scanners. While the engineers designing these phones and tablets probably had augmented reality (AR) apps and games in mind for these sensors, this new technology also has the potential to enable very rapid collection of high-resolution topographic data at low cost. However, the capability of these sensors to provide useful topographic data for research in geomorphology and hydrology has not been thoroughly evaluated.

Here, we investigate how well iPad-based LiDAR characterizes topography and topographic change in hillslope and fluvial environments. We present data collected with two iPad LiDAR scanning apps and compare them to TLS data, real-time kinematic global navigation satellite system (RTK-GNSS) data, and drone-derived structure from motion (SfM) data. We also extract profiles from the iPad LiDAR data and explore how hydraulic metrics such as hydraulic radius and cross-sectional area compare to those calculated from more traditional methods.

2. IPAD LIDAR DATA ACQUISITION AND PROCESSING WORKFLOW

Several third-party applications have been developed to take advantage of the built-in LiDAR sensor in the 2020 and later iPad Pro tablets. Here, we have used two applications: Polycam and 3d Scanner App.

Both applications have similar functionality. In general, the workflow involves opening the software and initiating a new scan. This activates the tablet's camera and LiDAR sensor, and the display shows the image in the camera overlain with a series of dots, which cover areas not yet scanned and stored in memory. Moving the tablet around causes the dots to disappear, and they are replaced by a wireframe surface. It is important to move slowly and smoothly when collecting scans, because otherwise the iPad's inertial measurement unit (IMU) positioning may become uncertain, leading to so-called 'drift' in the scan. When the scan is complete, the data are processed and a 3D textured model is produced. The video below shows the process of collecting a scan using the 3d Scanner App.

[VIDEO] https://res.cloudinary.com/amuze-interactive/video/upload/vc_auto/v1638817536/agu-fm2021/86-50-43-A7-8D-A0-81-A1-9A-28-21-D7-D8-14-91-44/Video/RPReplay_Final1638386027.MOV_sfgxtp.mp4

After on-tablet processing, the scan can be exported as a 3D model or 3D point cloud. The 3D model generated in the video above is presented below. The model is hosted on the web service Sketchfab and is interactive. Use the scroll wheel to zoom in and out, rotate the model by left-clicking and dragging, and pan the model by right-clicking and dragging.

While 3D models as shown above may be sufficient for some purposes, it may be beneficial to be able to place the scan or point cloud in real-world coordinates. To do this, we have collected scans by placing markers or targets in the area prior to scanning. The locations of the targets are collected with RTK-GNSS survey equipment, and the targets are also captured in the iPad scan. Both the surveyed target locations and the iPad scans are brought into CloudCompare software (https://www.danielgm.net/cc/), and the 'Align' tool is used to identify the targets in the point cloud, assign the GNSS coordinates (in the projected UTM coordinate system to ensure all units are in meters) to them, and compute a translation/rotation matrix which is applied to the entire scan dataset. Analyses shown in subsequent panels on this poster used this approach.

3. COMPARISON OF IPAD LIDAR, TERRESTRIAL LASER SCANNER, AND DRONE-BASED STRUCTURE-FROM-MOTION

An area behind the Engineering Research Center at Colorado State University was used as a controlled study site to compare topographic data collected with the 3d Scanner App and Polycam applications on a 2020 iPad Pro against data collected with a terrestrial laser scanner (TLS), and against topography generated using Structure from Motion (SfM) on imagery collected from a quadcopter drone (UAV). The area had many topographic features, including a large pile of sand/gravel sediment, a flat dirt surface with tractor tire tracks, concrete retaining walls, and some shrubby vegetation.

Methods

Data collection

Prior to collection of any data, portable targets were placed on the ground across the study area. A Topcon GR-5 RTK-GNSS system was used to survey the coordinates of the center of each target; these were collected in UTM NAD83 Zone 13N coordinates.

iPad LiDAR data were collected with both the 3d Scanner App and Polycam App. Polycam scans were collected with default app parameters. The 3d Scanner App has 2 data collection modes: 'Low Res' and 'High Res'. In 'Low Res' mode, default capture settings cannot be changed; in 'High Res' mode, settings such as Max Depth, Resolution, Confidence, and Masking can be adjusted. Here, scans in 'High Res' mode used a Max Depth of 2.7 m, Resolution of 3 mm, Confidence of High, and Masking of None.

TLS data were collected with a Topcon GLS-2000S terrestrial laser scanner. The scanner was set to the highest resolution (0.1 inches at 30 ft range from the scanner) and a full-dome scan was collected from a single instrument location.

UAV images were captured with a DJI Mavic 2 Pro quadcopter drone. Images were collected with 80% overlap in two directions (checkerboard pattern). The images were brought into Agisoft Metashape Professional structure-from-motion (SfM) software and aligned with 'High' accuracy. Visible targets were identified in each image, and camera alignment was optimized recursively following the workflow described in Over et al. (2021). Once aligned and optimized, the images were used to generate a 'High Quality' dense point cloud.

The iPad LiDAR and TLS scans were registered in real-world coordinates by identifying the surveyed targets in each point cloud and using their known coordinates with the 'Align' tool in CloudCompare to compute the transformation/rotation matrix for each dataset.

Data comparison

To assess the accuracy of each method, the TLS scan was considered the 'reference' and each other dataset was compared against the TLS scan. The multi-scale model-to-model cloud comparison (M3C2) algorigthm (Lague et al., 2013) was used to compare the iPad and UAV/SfM point clouds to the TLS point cloud. The mean M3C2 distance, the mean absolute M3C2 distance (mean absolute error, or MAE), and the standard deviation of M3C2 distances were computed for each comparison.

In addition, profiles were extracted from the 3D point clouds generated with each method. Profiles are numbered 1 through 5, and the location of each profile is shown below:

Each extracted profile was compared to the TLS profile, and the mean absolute error of the each profile relative to TLS was computed.

Results

Scan characteristics

Each 3D point cloud contained the following number of points:

UAV SfM: 68,610,298 points

TLS: 5,736,853 points

Polycam: 1,529,240 points

3d Scanner App (low res): 3,660,212

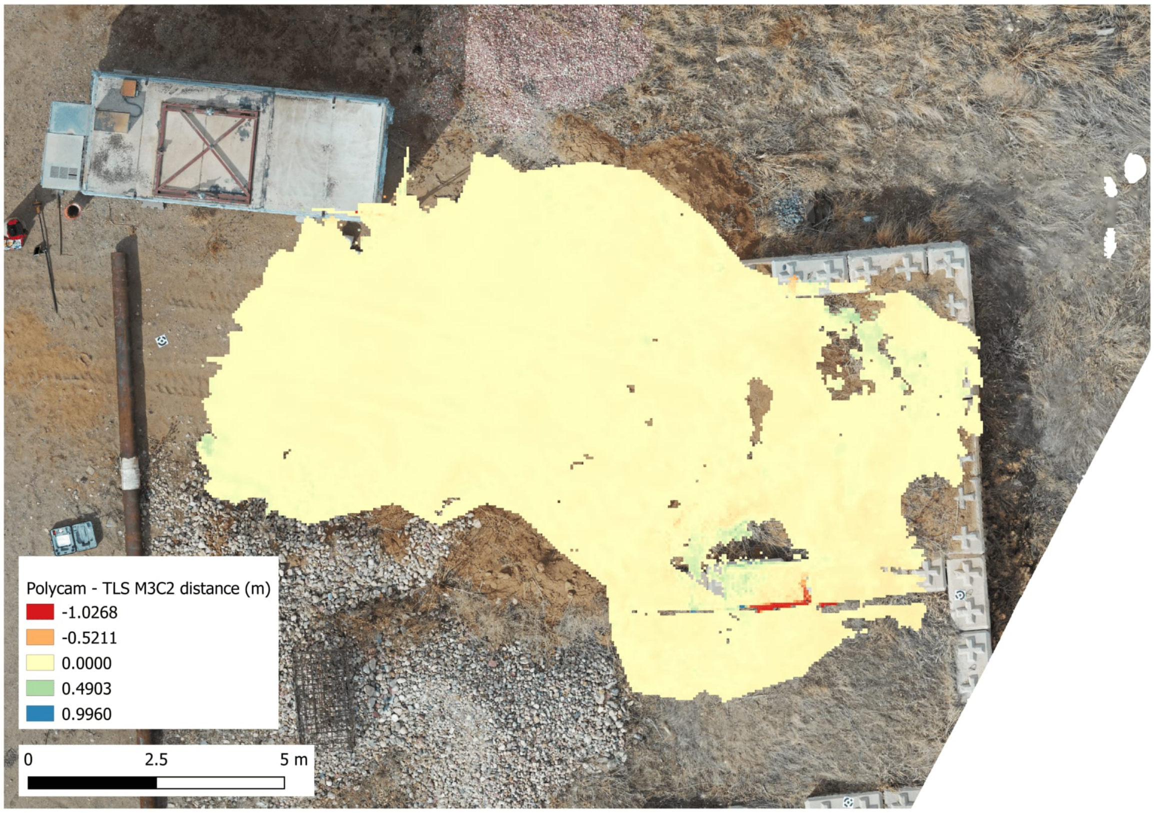
3d Scanner App (high res): 1,236,749

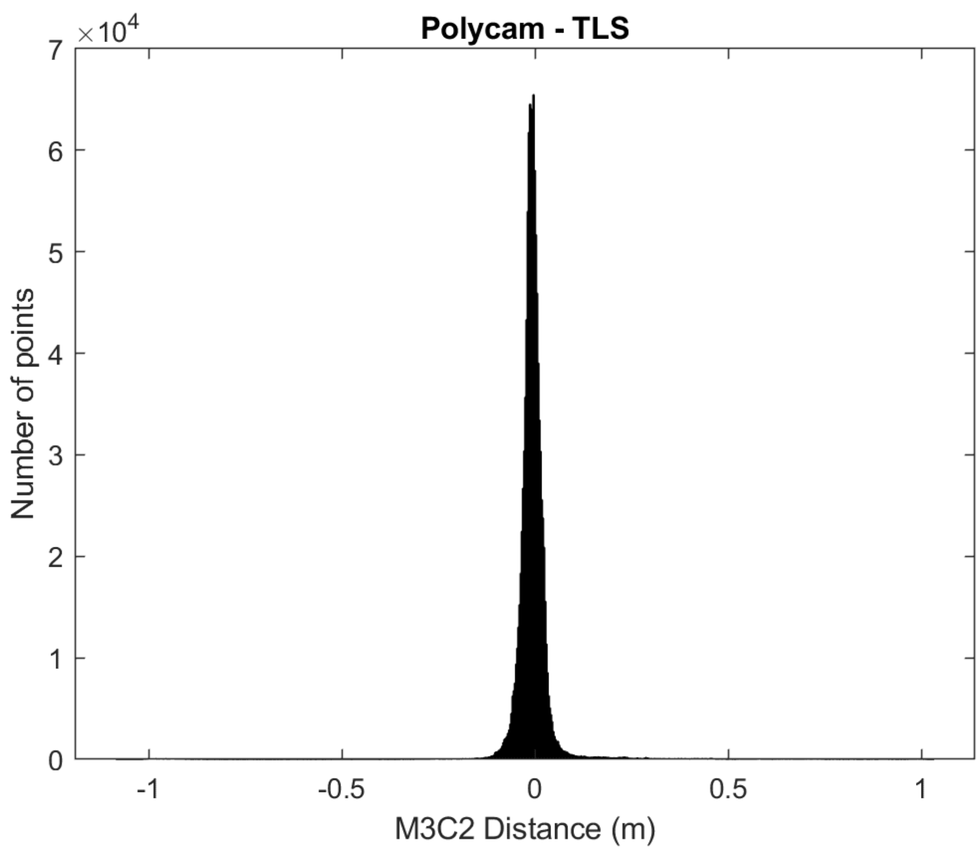
Overall, the UAV SfM data had the most points and the highest point density, followed by the TLS. The low-res 3d Scanner App had over twice the number of points as the Polycam app, even though they covered similar areas. The high-res 3d Scanner App had the lowest number of points, although it covered the smallest area because we had to stop data collection when the iPad's memory became full during the scan.

Surface comparisons

The following images show M3C2 distances computed between the iPad and SfM data and the TLS data, both spatially as a 5-cm resolution raster image and statistically as a histogram. The mean, mean absolute (MAE), and standard deviation of the M3C2 distances are provided below each histogram.

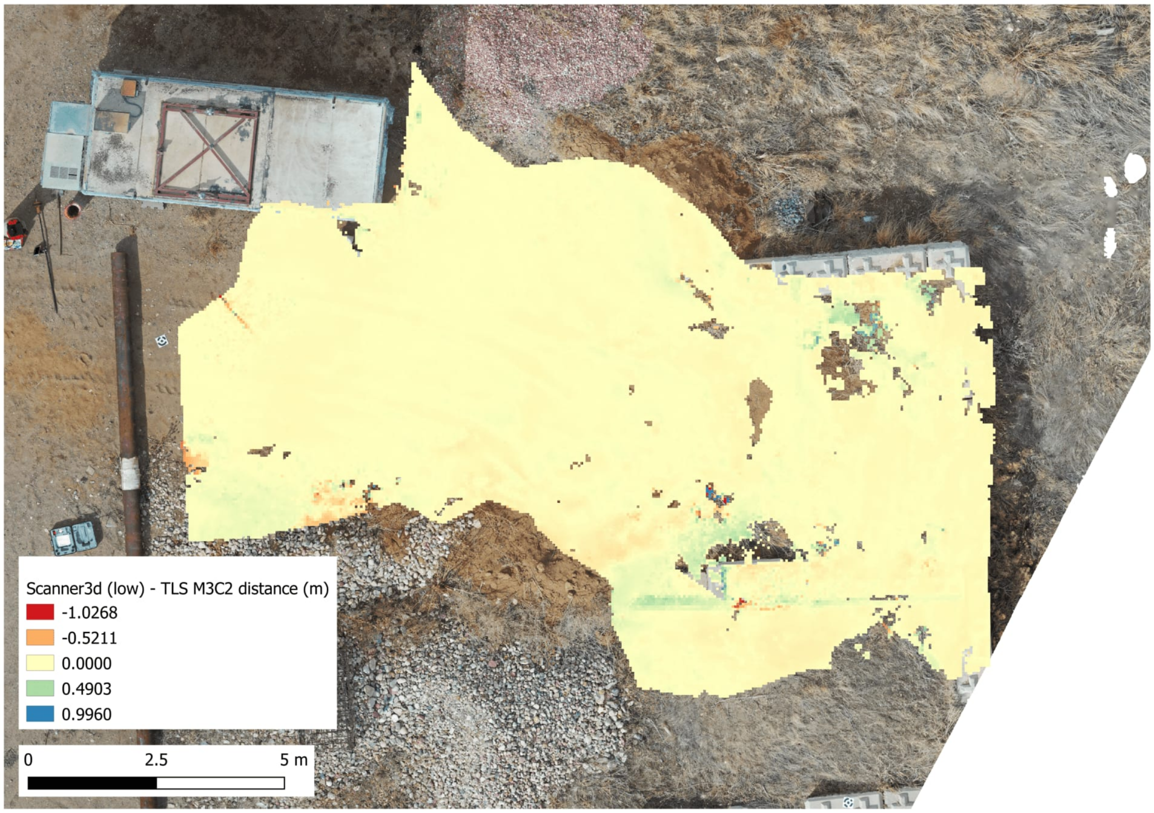
Polycam vs. TLS

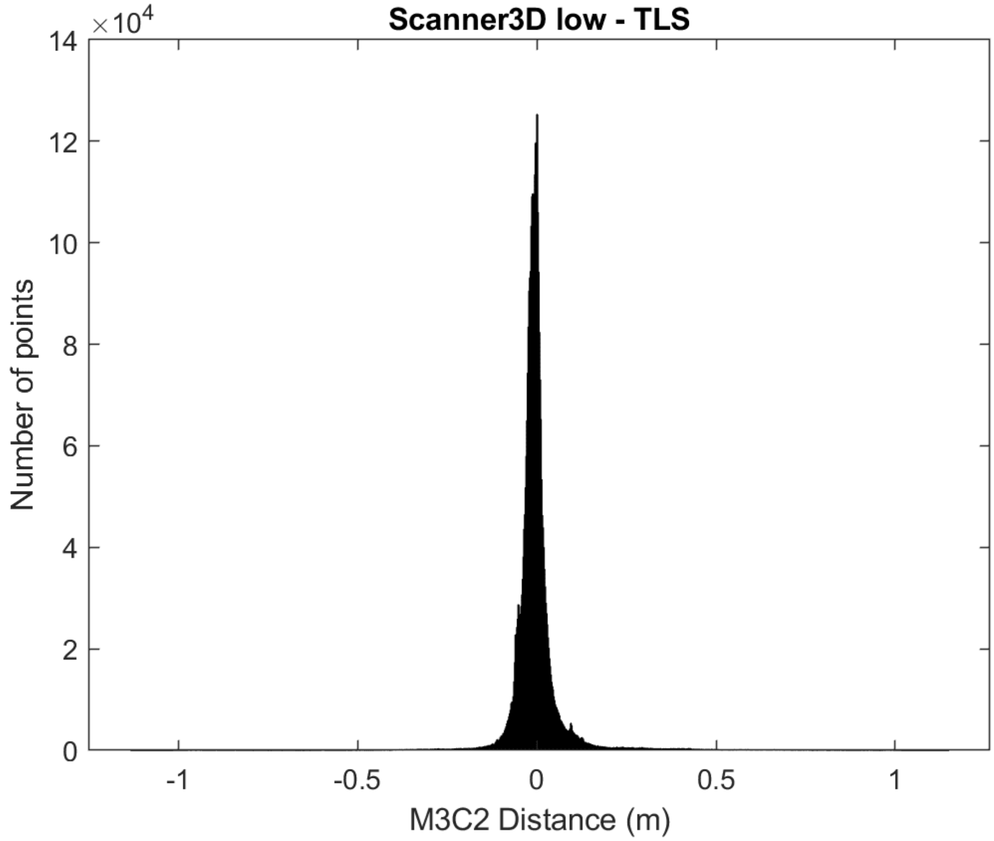




Mean M3C2 distance: -0.0057 m
MAE M3C2 distance: 0.028 m
Std. Deviation M3C2 distance: 0.075 m

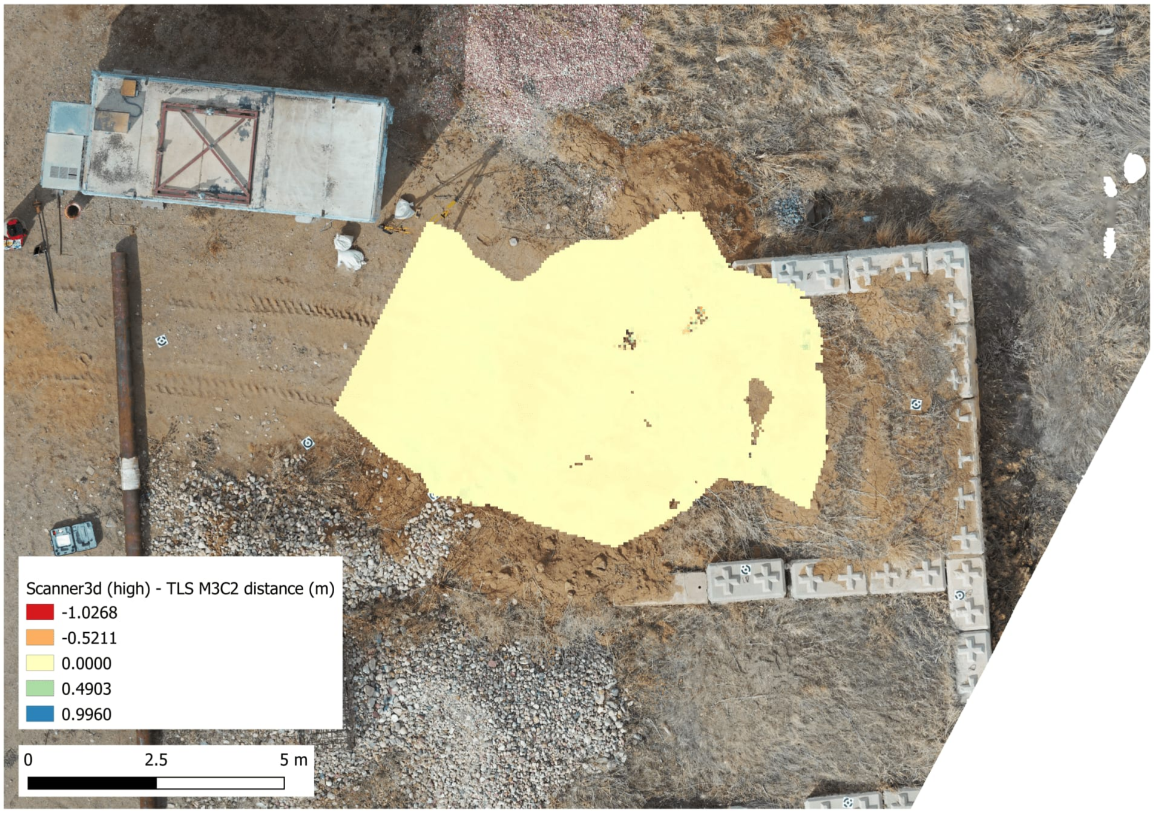
Scanner3D (low res) vs. TLS

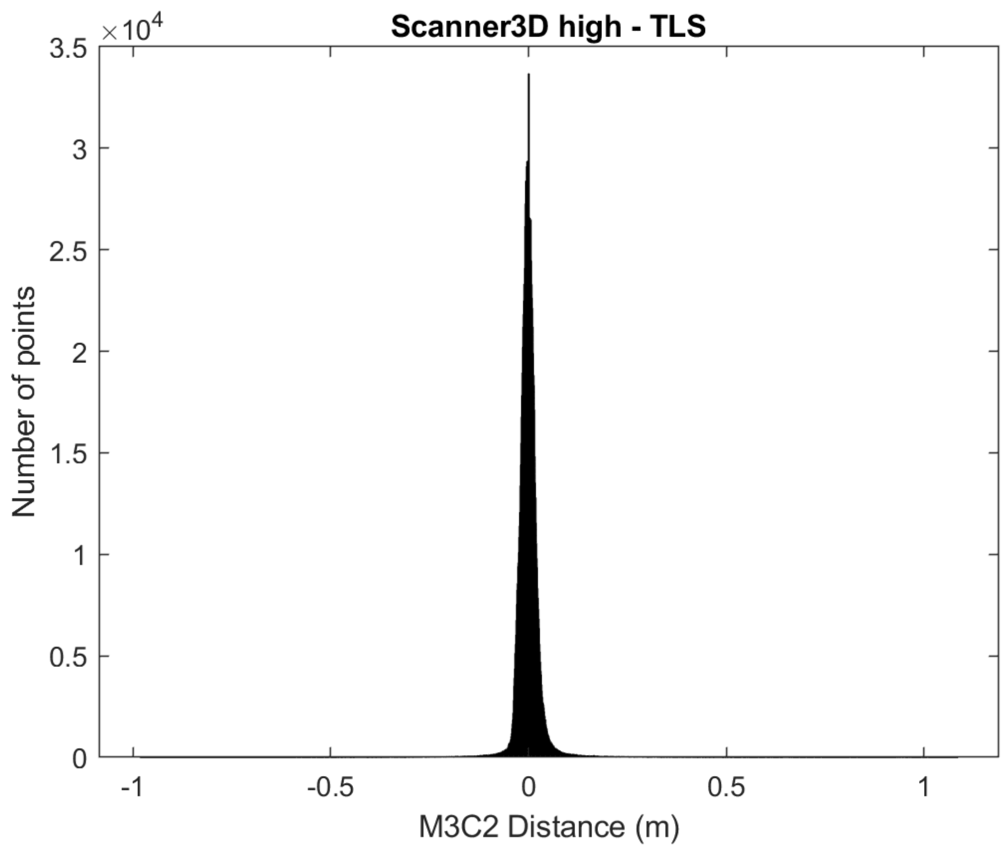




Mean M3C2 distance: -0.0017 m
MAE M3C2 distance: 0.037 m
Std. Deviation M3C2 distance: 0.083 m

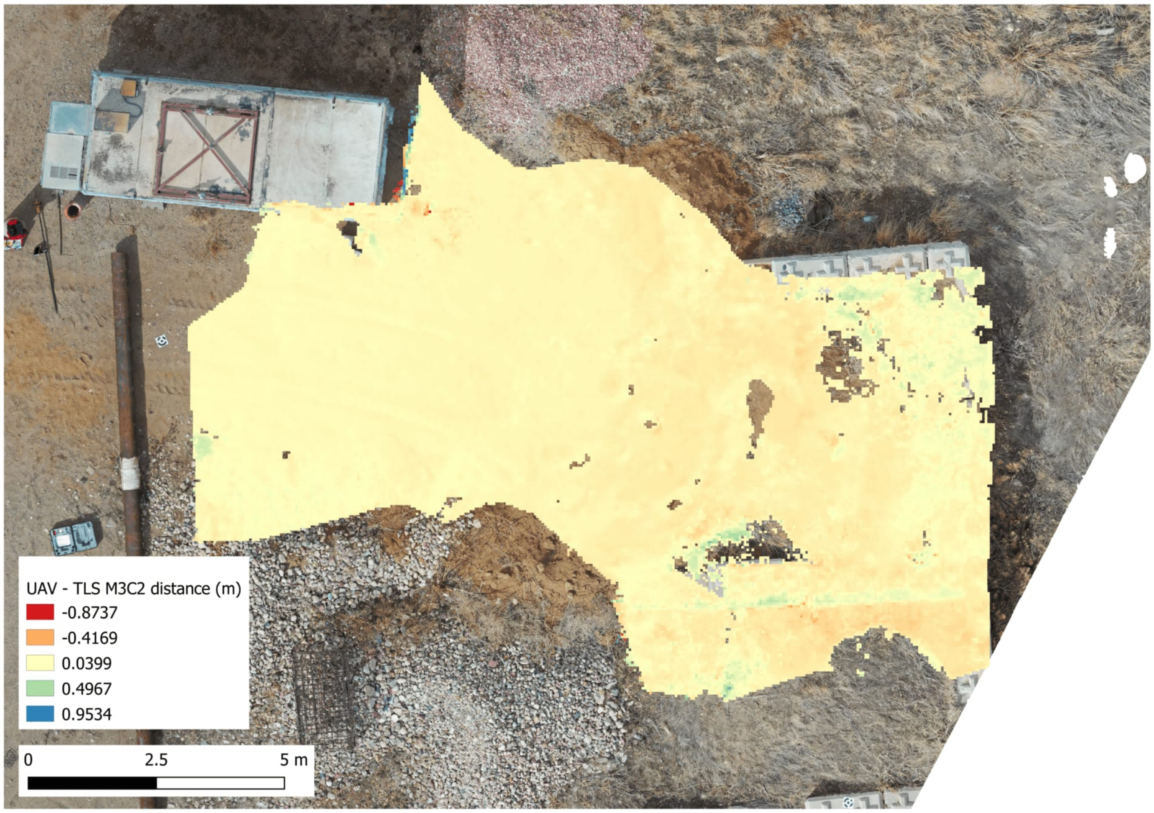
Scanner3D (high res) vs. TLS

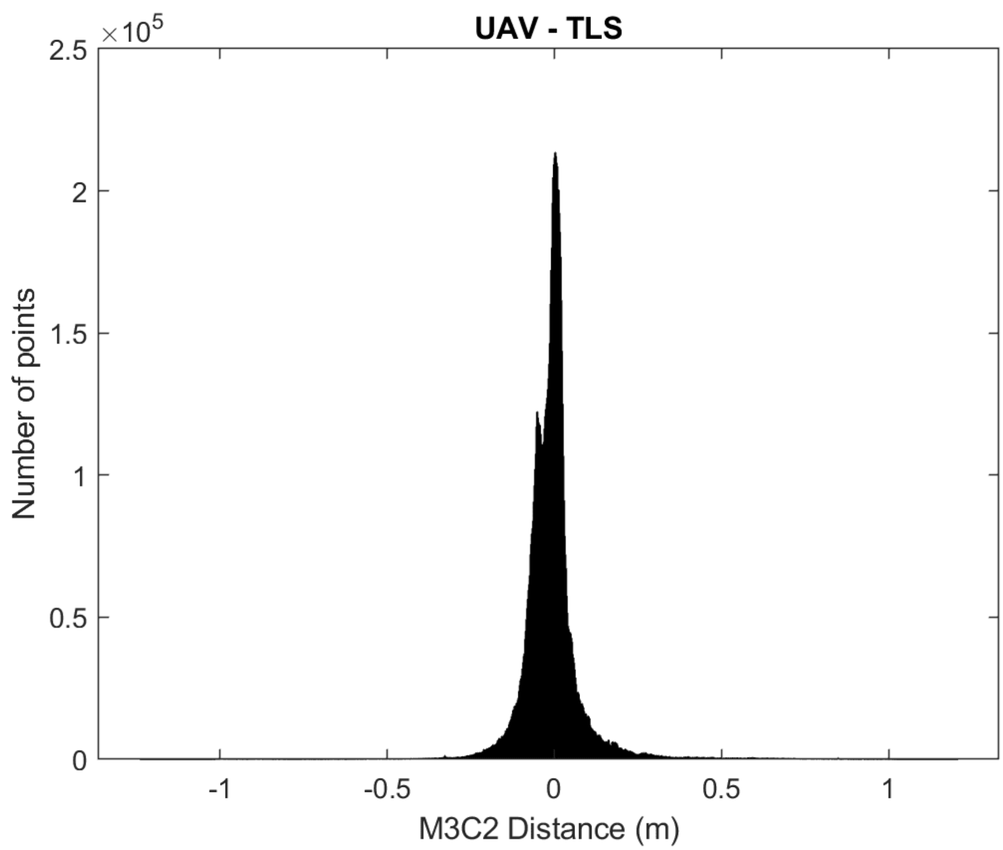




Mean M3C2 distance: 8.5e-05 m
MAE M3C2 distance: 0.018 m
Std. Deviation M3C2 distance: 0.039 m

UAV SfM vs. TLS



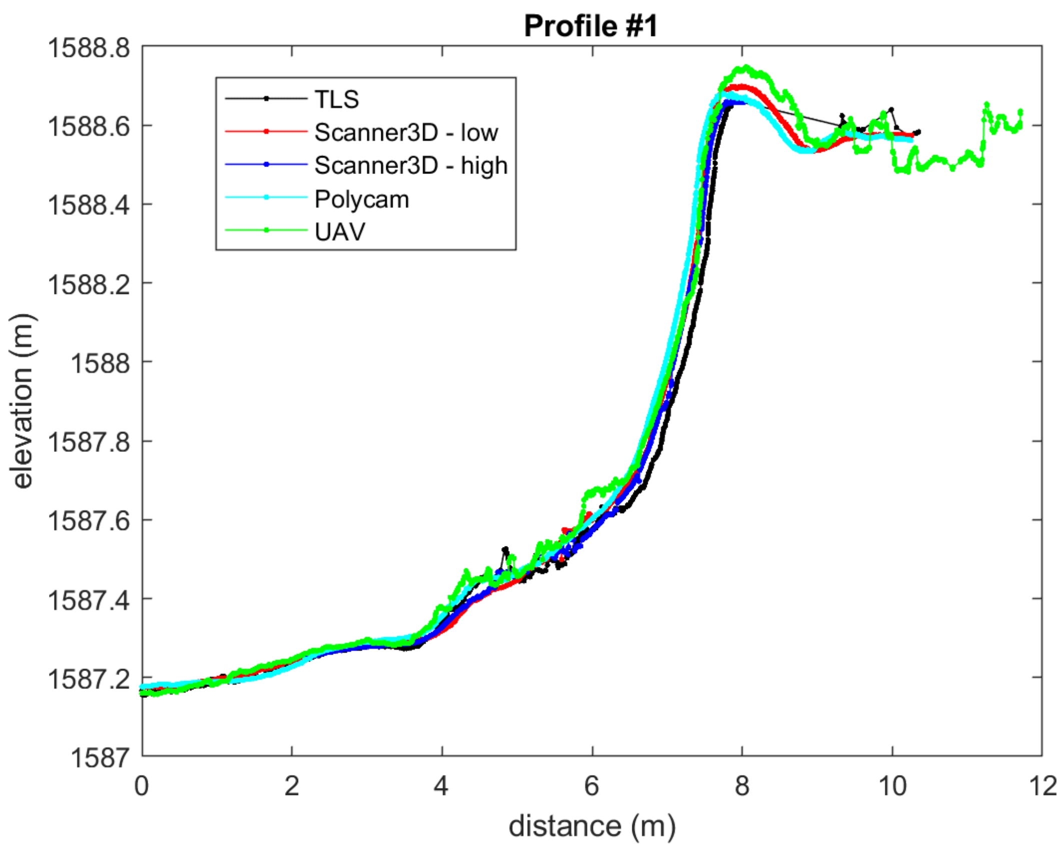


Mean M3C2 distance: -0.0071 m

MAE M3C2 distance: 0.054 m
Std. Deviation M3C2 distance: 0.097 m

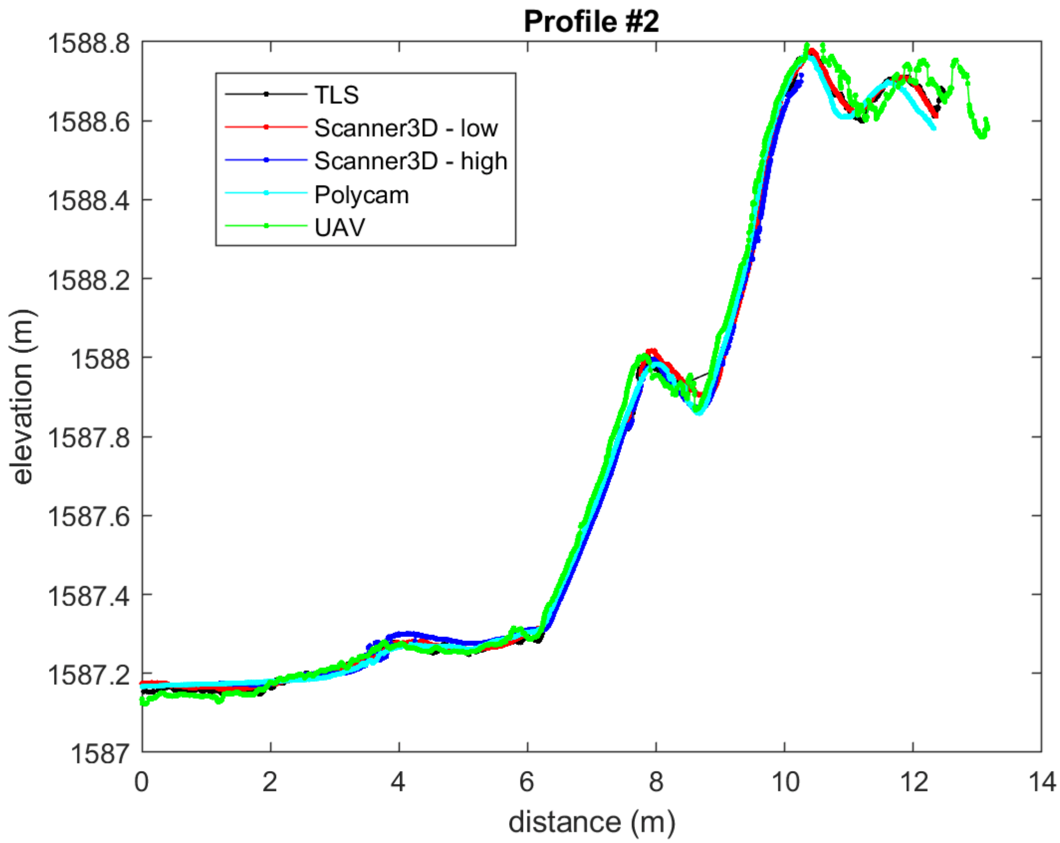
Comparison of extracted profiles

The figures below show the extracted profiles, and beneath each figure the mean absolute error computed between the TLS profile and the iPad LiDAR / UAV SfM profile is given.



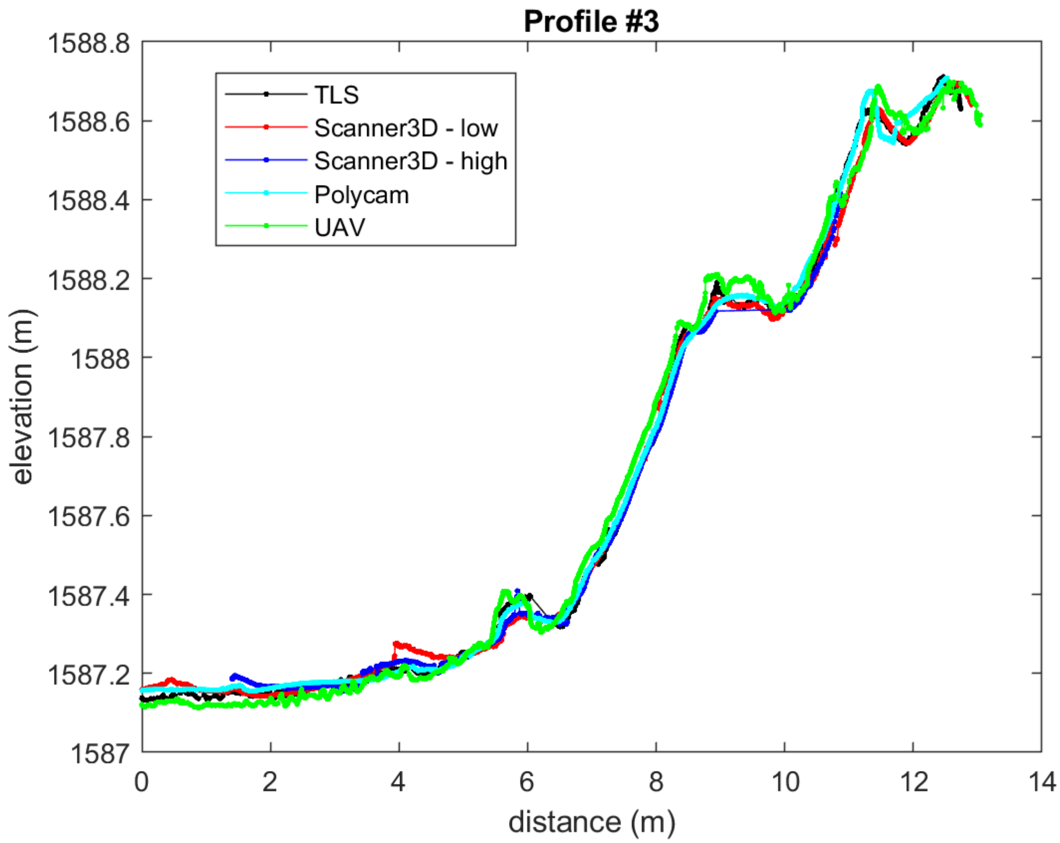
Mean Absolute Errors (vs. TLS profile):

3d Scanner App (low-res): 0.034 m
3d Scanner App (high-res): 0.030 m
Polycam: 0.042 m
UAV: 0.043 m



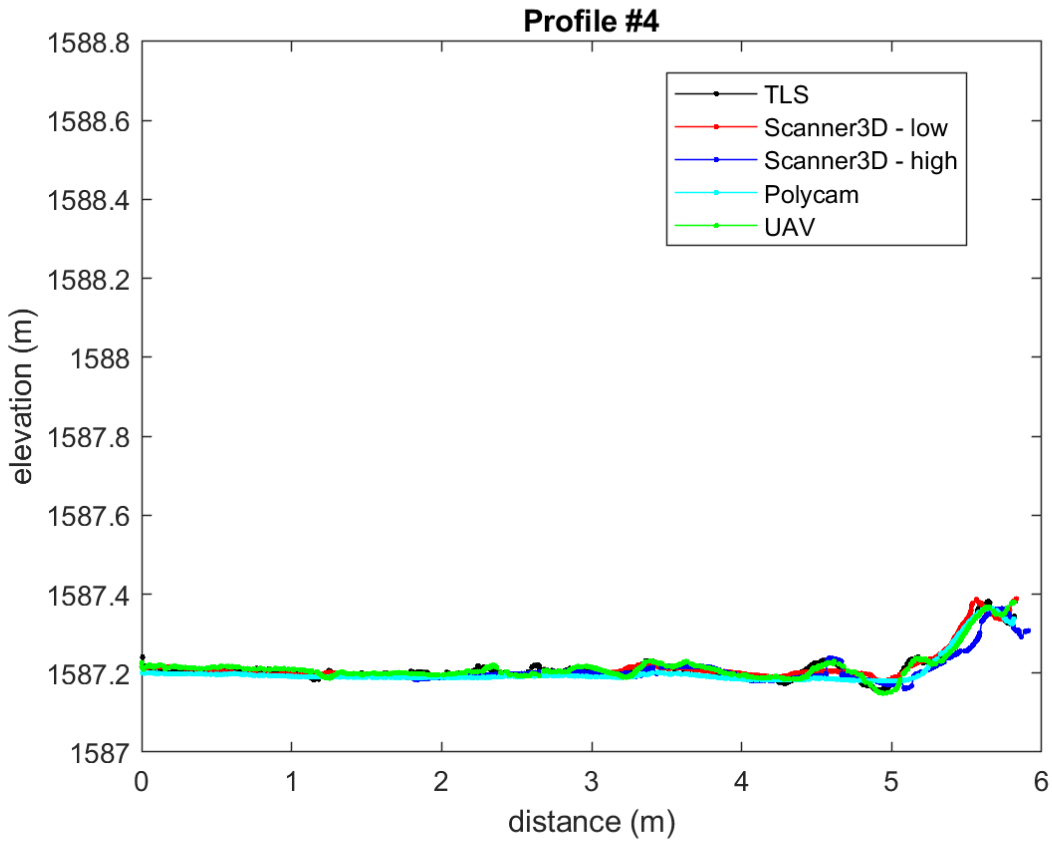
Mean Absolute Errors (vs. TLS profile):

3d Scanner App (low-res): 0.012 m
3d Scanner App (high-res): 0.020 m
Polycam: 0.017 m
UAV: 0.026 m



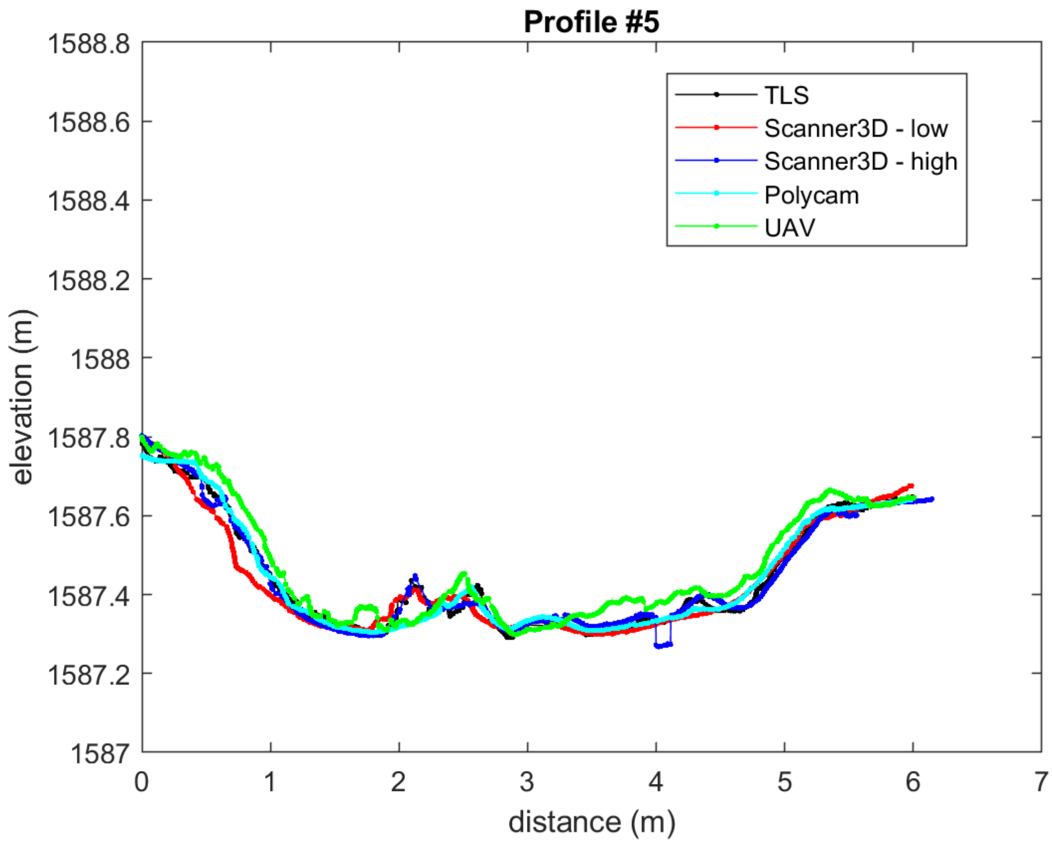
Mean Absolute Errors (vs. TLS profile):

3d Scanner App (low-res): 0.020 m
3d Scanner App (high-res): 0.018 m
Polycam: 0.015 m
UAV: 0.030 m



Mean Absolute Errors (vs. TLS profile):

3d Scanner App (low-res): 0.0094 m
3d Scanner App (high-res): 0.014 m
Polycam: 0.012 m
UAV: 0.0078 m



Mean Absolute Errors (vs. TLS profile):

3d Scanner App (low-res): 0.02 m
3d Scanner App (high-res): 0.015 m
Polycam: 0.015 m
UAV: 0.037 m

4. EXTRACTION OF STREAM CHANNEL CROSS-SECTIONS: IPAD LIDAR VS. RTK-GNSS

Stream channel cross-section data are commonly used for hydraulic calculations, hydraulic modeling, and topographic change detection. These data are typically collected with traditional surveying techniques, such as with a total station or real-time kinematic global navigation satellite system (RTK-GNSS) equipment.

As part of an ongoing project investigating channel geomorphic changes after wildfire, cross sections in small watersheds have been surveyed with RTK-GNSS. Additionally, at some locations, iPad LiDAR scans encompassing the cross section were collected at the same time. Here we present data from one location where this was done as a real-world example of using iPad LiDAR to characterize channel geometry.

The field site, Montgomery Creek, is located in the Cache la Poudre watershed in the northern Colorado Front Range. The watershed has a drainage area of approximately 1 km^2 and it partially burned in the 2020 Cameron Peak Fire.

Methods

In the field, rebar was installed to monument cross-sections for repeat surveys that will take place over several years. Additionally, marks (x's or circular targets) were spray painted onto boulders or large stable logs to serve as persistent targets that could be used for iPad LiDAR and/or TLS scan registration.

The coordinates of the spray-painted targets were collected with a Topcon GR-5 RTK-GNSS system. Cross section topography was also collected with the RTK-GNSS system. Point spacing in the cross section was generally closer than 1 meter, although satellite signal inconsistency led to few data points being collected on one side of the floodplain.

After the RTK-GNSS data were collected, an iPad LiDAR scan using the 3d Scanner App at low resolution was collected.

The iPad LiDAR point cloud was exported at high resolution and brought into CloudCompare software along with the RTK-GNSS data. The targets were identified in the point cloud and the coordinates were used to register the iPad scan in real-world coordinates.

Within CloudCompare, a polyline connecting the RTK-GNSS cross-section points was generated, and that line was used to extract the points from the iPad LiDAR point cloud along the polyline.

The topographic cross sections were quantitatively compared by computing the mean difference and the mean absolute difference along the profile. Additionally, to explore how the iPad LiDAR vs. RTK-GNSS cross-sections may compare for standard hydraulic calculations (such as conveyance using the Manning equation), the relationship between maximum depth (h), hydraulic radius ($R = A/P$, where A is wetted cross-sectional area and P is the wetted perimeter), and wetted cross-sectional area A was determined for each cross section.

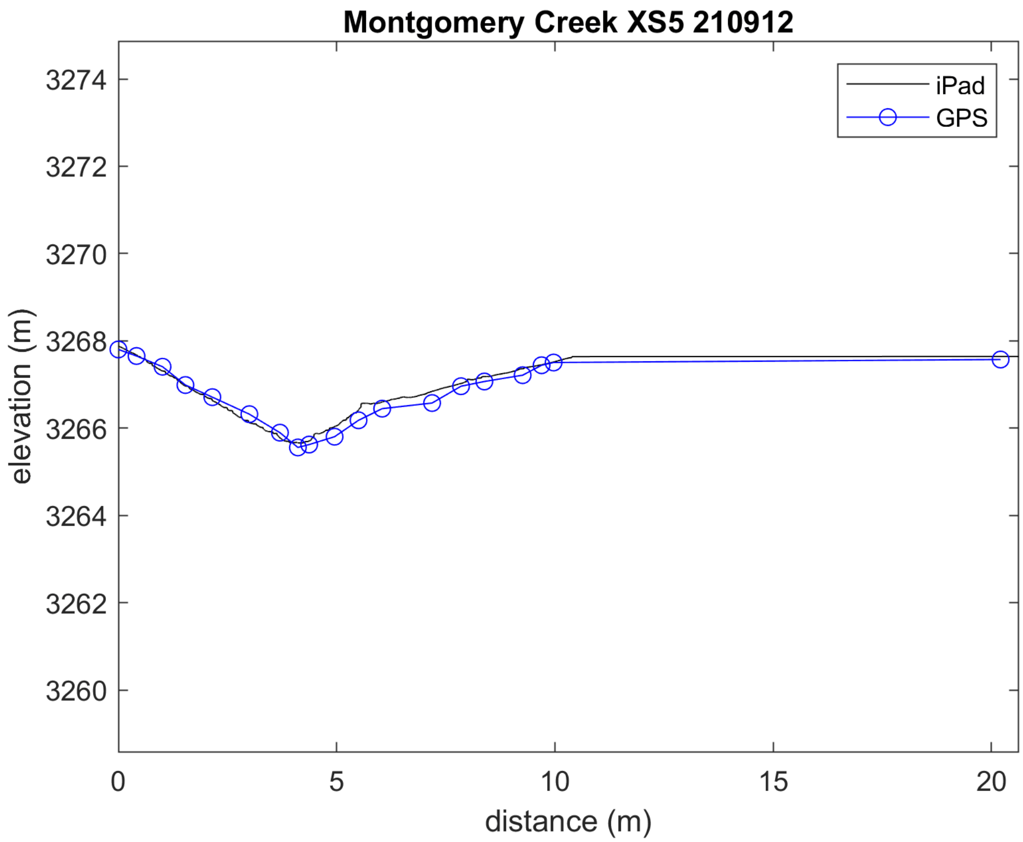
Results

The low-resolution 3d Scanner App iPad scan of the study area had 15,975,660 points.

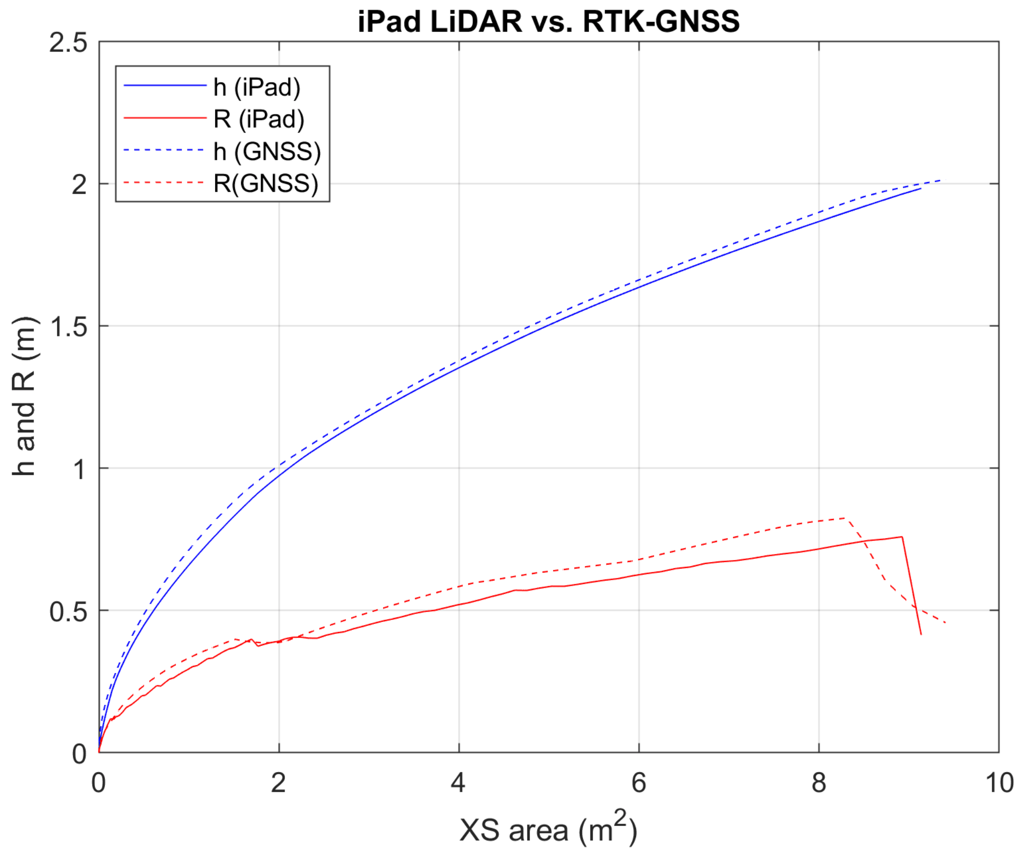
The 3D model of the iPad data is shown below. This is an interactive model - click the play button icon to load the viewer, then explore the model with your mouse. The wheel will zoom in and out, right click and drag will translate, left click and drag will rotate.

The image below shows the iPad LiDAR point cloud with the surveyed and anlyzed cross-section drawn across it.

The figure below shows the cross section extracted from the registered iPad LiDAR point cloud, along with the RTK-GNSS surveyed cross section. The mean difference between the two cross sections is -0.057 m; the mean absolute difference is 0.11 m.



The figure below shows the relationship between depth (*h*) and cross sectional area (*A*), and between hydraulic radius (*R*) and cross-sectional area (*A*), at the cross section computed using the iPad-extracted cross section and the RTK-GNSS surveyed cross section.


iPad LiDAR vs. RTK-GNSS
h (iPad)
R (iPad)
h (GNSS)
R(GNSS)
h and R (m)
XS area (m2)
0
0.5
1
1.5
2
2.5
0
2
4
6
8
10

5. SUMMARY AND CONCLUSIONS

The primary findings of this research are as follows:

1. The LiDAR sensor on the 2020 Apple iPad Pro is capable of characterizing topography with accuracy to within a few centimeters of that measured with terrestrial laser scanners or survey-grade GNSS equipment. To achieve these results is is necessary to be slow and deliberate when collecting the scan to avoid 'drift'.
2. 3d Scanner App and Polycam produced results of similar accuracy when compared to TLS data. The 'high res' 3d Scanner App had the highest accuracy, but rapidly filled the iPad's memory and was unable to scan the entire study area.
3. The iPad scans were not registered or vertically oriented correctly when exported, so having objects or targets with known coordinates is necessary to translate/rotate the scans into the appropriate orientation and placement.
4. The Montgomery Creek comparison between the iPad-extracted cross section and the RTK-GNSS cross section had a larger error than the lab data comparison, so using the iPad LiDAR for analyses such as topographic differencing may not be possible in that environment. However, the hydraulic relationships computed using the iPad and RTK-GNSS cross sections were very similar, suggesting that iPad-derived topographic data may be useful for hydraulic calculations and modeling.

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ABSTRACT

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