



Commercial Satellite Data Acquisition Program



Vantor Precision3D DEM Product Quality Assessment Report

Commercial Satellite Data Acquisition Program Vantor Precision3D DEM Product Quality Assessment Report

Signature/Approval Page

Approval by:



5/6/2026

Melissa Yang Martin
Commercial Satellite Data Acquisition Program Manager
Earth Science Division
Headquarters/NASA

Date

Accepted by:



5/6/2026

Dana Ostrenga
Commercial Satellite Data Acquisition Project Manager
Earth Science Division
GSFC/NASA

Date

Preface

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Abstract

The evaluation summarized in this report was conducted by subject matter experts (SMEs) funded by NASA's Commercial Satellite Data Acquisition (CSDA) Program. The SMEs evaluated the quality of the Vantor Precision3D DEM products for the NASA Earth science research and applications community. The results of the evaluation help to inform NASA program management on the quality of the data for NASA science.

Authored and prepared by

Connor Anderson

CSDA DEM Subject Matter Expert
Science Systems and Applications Inc
National Aeronautics and Space Administration

Jaime Nickeson

CSDA Technical Science Coordinator
Science Systems and Applications Inc
National Aeronautics and Space Administration

Frederick Policelli

CSDA Project Scientist
Goddard Space Flight Center
National Aeronautics and Space Administration

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Acronyms & Abbreviations

3DEP	3-Dimensional Elevation Program, USGS
API	Application Programming Interface
ATBD	Algorithm Theoretical Basis Document
CONUS	Conterminous United States
CE90	Circular Error 90%
CEOS	Committee on Earth Observation Satellites
CSDA	Commercial Satellite Data Acquisition Program
DEM	Digital Elevation Model
DMS	Degrees, Minutes, Seconds
DSM	Digital Surface Model
DTM	Digital Terrain Model
EDAP	Earthnet Data Assessment Pilot, ESA
EO	Earth Observation
ESA	European Space Agency
ESRI	Environmental Systems Research Institute, Inc.
EULA	End User License Agreement
FAIR	Findable, Accessible, Interoperable and Reusable
GCP	Ground Control Point
GEGD	Global Enhanced GEOINT Delivery
GEOINT	Geospatial Intelligence
GeoTIFF	Geographic Tag Image File Format
GSFC	Goddard Space Flight Center
JSON	JavaScript Object Notation
KML	Keyhole Markup Language
LE90	Linear Error 90%
LiDAR	Light Detection and Ranging
NASA	National Aeronautics and Space Administration
NLCD	National Land Cover Database
PDAL	Point Data Abstraction Library
QGIS	Quantum Geographic Information System, open-source software package
RMSE	Root Mean Square Error
UAS	Unmanned Aerial Vehicle
USGS	United States Geological Survey
WGS84	World Geodetic System 1984

Executive Summary

The Commercial Satellite Data Acquisition (CSDA) Program serves as the central mechanism through which NASA identifies, evaluates, and acquires commercial satellite data in support of its Earth science research and application objectives. These data provide cost-effective opportunities to enhance and complement existing Earth observation capabilities from NASA, other U.S. government agencies, and international partners. This report advances NASA's Earth science mission by contributing to the growing body of CSDA Program documentation on data acquired from the commercial Earth observation sector, specifically the Vantor Precision 3D data.

In this report, CSDA provides an evaluation of the quality of data provided by the Vantor (formerly Maxar) Precision3D (version 2.0) elevation products. Precision3D is a digital topographic dataset that is derived from images collected from Vantor's fleet of optical satellites. In addition to estimating surface feature elevations, Vantor uses a proprietary workflow to provide estimates of bare Earth elevations. Vantor provides the Precision3D data in three formats: 3D mesh, point cloud, and 2D raster. Here we provide an evaluation of the Precision3D Digital Surface Model (DSM) and Digital Terrain Model (DTM) raster product quality for their ability to advance NASA's Earth system science research and applications. This evaluation of Vantor's Precision3D DSM and DTM for horizontal and vertical accuracy was carried out by NASA subject matter experts (SMEs) enlisted to evaluate the quality of these data products. The guidelines used for this assessment follow the joint European Space Agency (ESA)/NASA assessment guidelines for Digital Elevation Models (DEMs), which are in draft form at the time of writing of this report.

Only the documents provided by Vantor for the evaluation were considered as part of the assessment. Any document that is not listed in this report was not considered in the evaluation. The product metadata was determined to be adequate to work with the data. Additional information from the vendor on the number of images, image IDs, and date of imagery used to produce the Precision3D DEMs would be very helpful to inform users on the quality and timeliness of the DEM data. Vendor documentation was minimal. A review of vendor methodology was not possible because no user guide or algorithm theoretical basis document (ATBD)-like document were provided for review.

An independent assessment of the Precision3D DTM and DSM vertical and horizontal accuracies was performed by the CSDA team through comparisons to airborne lidar data collections. Various samples sites across the United States (US) and Senegal were used, which allowed for the evaluation of Precision3D DTM and DSM performance over a variety of surface characteristics. Horizontal accuracy results (DSM: 0.47 m CE90; DTM: 1.6 m CE90) were in agreement with the specifications provided by Vantor. Vertical accuracy results of the Precision3D DSM (6.6 m LE90) varied by land cover type, with over half of the land cover types exceeding the values provided by Vantor (3 m LE90). The Precision3D DTM vertical accuracy results (2.8 m LE90) were generally in agreement with Vantor specifications (3 m LE90).

Overall, the evaluation supports the use of Precision3D data for NASA Earth science research and applications, where the data characteristics (e.g., vertical accuracy, temporal range of underlying imagery, missing surface features, etc.) are compatible with the specific science objectives and use cases.

1. Background

The Commercial Satellite Data Acquisition (CSDA) Program was established by NASA's Earth Science Division (ESD) in 2020 following the successful completion of the Private-Sector Small Constellation Satellite Data Product Pilot. The program's primary objective is to identify, evaluate, and acquire commercial remote sensing data that enhances NASA's Earth science research and applications. CSDA provides structured on-ramping opportunities for emerging commercial satellite data vendors, enabling NASA to continuously integrate innovative data sources as the private sector evolves. By leveraging these partnerships, NASA's ESD aims to accelerate scientific discovery and expand applications of Earth observation data for societal benefit.

Since the initial pilot, the Program has conducted three on-ramp activities, resulting in the addition of several vendors into sustainment. In 2024, CSDA streamlined its evaluation process by introducing high-quality, SME-led data assessments, accelerating reviews and strengthening NASA's engagement with the rapidly growing commercial data ecosystem. This evaluation framework not only ensures NASA gains timely access to high-quality, mission-relevant commercial data, but also provides valuable feedback to private-sector providers, fostering innovation, improved data products, and alignment of industry capabilities with NASA's evolving scientific needs.

1.1. Vantor Precision3D Products

Vantor's Precision3D product development began in 2015 when then Maxar (then DigitalGlobe/MacDonald Detweiller Associates) entered into a joint venture with Vricon, to create digital elevation products for US Defense Department applications. After Maxar acquired Vricon in 2020, the products were then marketed as Maxar Precision3D products.

Vantor offers multiple Precision3D products. The base-level products include the 3D Surface Model (TIN mesh product), DSM (2D raster), True Ortho (2D raster), and Point Cloud (3D point cloud). These DEM products are produced from Vantor's repository of high-resolution commercial satellite imagery. Vantor's Precision 3D product suite also includes several derived products: 3D Terrain Model (TIN mesh product), DTM (2D raster), Digital Height Model (2D raster), Classification (raster; land cover classification), Buildings (vector; building footprints and heights), Vegetation (vector; vegetation footprints and heights), Textured 3D Objects (TIN mesh product), and Roads (vector; road centerlines). These products are derived from the base-level products using automated processing workflows. The CSDA program acquired and evaluated only the base level- DSM (2D raster) and the derived DTM (2D raster) products from Maxar (now Vantor). The Precision3D DSM represents the average elevation for all surface features within each pixel. The Precision3D DTM represents the average bare earth elevation within each pixel, and it is derived from the Precision3D 3D Surface Model.

2. Cal/Val Maturity Matrices

2.1. Summary Cal/Val Maturity Matrix





Data Provider Documentation Review			Validation Summary	Key	
Product Information	Metrology	Product Generation		Not Assessed	Not Assessable
Product Details	Metrological Traceability Documentation	Calibration Algorithm	Vertical Accuracy Validation Method	Basic	
Availability & Accessibility	Uncertainty Characterization 	Geometric Processing	Vertical Accuracy Validation Results	Good	
Product Format, Flags & Metadata	Ancillary Data 	Retrieval Algorithm	Horizontal Accuracy Validation Method	Excellent	
User Documentation 		DEM Derivative Processing	Horizontal Accuracy Validation Results	Ideal	 Not Public

Figure 1. Summary Maturity Matrix for Vantor Precision3D product.

2.2. Detailed Validation Maturity Matrix

Validation Summary	Detailed Validation			
Vertical Accuracy Validation Methodology	Vertical Accuracy	Validation Dataset	Validation Method	Validation Completeness
Vertical Accuracy Validation		DSM Validation Results Compliance		
Results Compliance		DTM Validation Results Compliance		
Horizontal Accuracy Validation Methodology	Horizontal Accuracy	Validation Dataset	Validation Method	Validation Completeness
Horizontal Accuracy Validation Results Compliance		Validation Results Compliance		


Key
Not Assessed
Not Assessable
Basic
Good
Excellent
Ideal
 Not Public

Figure 2. Detailed Validation Maturity Matrix for the optical domain, showing the Validation Summary column from the Summary Validation Maturity Matrix.

3. Data Provider Documentation Review

3.1 Product Information

Product Details	
Grade: Good	
Justification	Product details contain a suitable amount of information regarding the data product. No information is included about the underlying Vantor imagery used to generate the DEM. Reference documents contain minimal information about the product.
Product Name	Precision3D Digital Surface Model Precision3D Digital Terrain Model
Product Type	Digital Elevation Model
Data Type	Raster DSM, DTM: IEEE754 Single Precision Floating Point Data Filling Mask: 8-bit Unsigned Integer
Sensor Name	Multiple satellites: GeoEye-1, WorldView-1, WorldView-2, and WorldView-3
Sensor Type	Data Source: Panchromatic and Multispectral imagery
DEM Type	Photogrammetric
Version	Version 2.0
Software	Vricon E f19d507a626dfc5d83c53ac287d256382a57e3c9 (v24.13.33) @ci
Measured Quantity Name	Elevation
Measured Quantity Units	Elevation in meters referencing the WGS84 ellipsoid.
Temporal Coverage	Precision3D uses all available Vantor images (monoscopic and stereoscopic) available to create a DEM (2008-Present).
Temporal Resolution	Vendor provides the acquisition date of the first and last image used to compute elevations for each tile.
Coordinate Reference System	Product projected into corresponding UTM zone.
Horizontal Datum	WGS84 G1674
Vertical Datum	Ellipsoid
DEM Data Format	DSM: GeoTIFF DTM: GeoTIFF Filling Mask: GeoTiff
Ancillary Data Format	GeoTIFF, ESRI Shapefile, KML, JSON
Stated Horizontal Accuracy	3 m absolute CE90; 1 m relative CE90

Stated Vertical Accuracy	3 m absolute LE90; 1 m relative LE90
Spatial Coverage	DSM product: Global DTM product: Partial global coverage as of November 2024 (Figure 4)
Post Spacing	Product provided with post spacing of 1 m. Default resolution is 0.5 m.
Pixel Type	Point
Product Locator	The product is available for search within the Global Enhanced GEOINT Delivery (GEGD) Pro API for licensed users.
Conditions for Access	All data used in this evaluation were purchased by CSDA under U.S. Government-wide license. Licenses can be found on the CSDA website (https://www.earthdata.nasa.gov/about/csda/commercial-datasets)
Copyright	Limited in accordance with the accompanying Vricon EULA
Limitations on Public Access	Not for public access, for purchase only.

Availability & Accessibility	
Grade: Good	
Justification	DEM metadata meets 16/17 FAIR principles. Unfulfilled principles are: I3: (Meta)data include qualified references to other (meta)data. Metadata are not publicly available but are searchable in the Global Enhanced GEOINT Delivery (GEGD) Pro API for licensed users (https://evwhs.digitalglobe.com/myDigitalGlobe/login).
Compliant with FAIR principles	94%
Data Management Plan	A vendor data management plan was not provided.
Availability Status	Data are available to customers through a vendor provided API.

Product Format, Flags & Metadata	
Grade: Good	
Justification	Orders are delivered in a directory with standard structure format. The naming conventions result in the file paths exceeding the default maximum Windows file path character limit. DEM provided in GeoTIFF format with a suitable amount of metadata. Pixel-level mask for pixels filled with elevations from other DEM products. Improvements could be made by providing a list of source images, the average/median image date per pixel, and the number of images per pixel.
Product File Format	GeoTIFF, JSON, ESRI Shapefile, KML
Metadata Conventions	
Analysis Ready Data?	Yes

User Documentation	
Grade: Basic	
Justification	Vantor provided a product specification document that includes information regarding the data product. However, this document does not contain processing details, nor is it publicly available. Vantor does not provide an ATBD. Finding information on the Precision3D product was difficult. Most information regarding methodology was acquired through recorded presentations.
<i>Document</i>	<i>Reference</i>
Product User Guide	No specific user guide was provided. The Precision3D Data Products Specification Document (Vantor, 2024) was used.
ATBD	None.

3.2 Metrology

Metrological Traceability Documentation	
Not Assessable	
Justification	No traceability chain provided.
References	<ul style="list-style-type: none"> • None

Uncertainty Characterisation	
Not Assessable	
Justification	Vantor compared the elevations of their data products to ground control points across multiple continents. No information was provided regarding where this analysis took place, how ground control points were collected, or the number of ground control points. There is insufficient detail to complete an assessment.
References	<ul style="list-style-type: none"> Precision3D Data Products Specification Document (Vantor, 2024)

Ancillary Data	
Grade: Basic	
Justification	<p>The vendor provides a ‘No Data’ fill mask and a water mask. Information on the formation of the ancillary data is not provided publicly.</p> <p>Vendor provides a filling mask GeoTIFF indicating which raster cells were filled with an outside data source.</p>
References	Information was provided within a proprietary document.

3.3 Product Generation

Calibration Algorithm	
Not Assessable	
Justification	No calibration algorithm documented.
References	<ul style="list-style-type: none"> None

Geometric Processing	
Not Assessable	
Justification	No geometric processing information documented.
References	<ul style="list-style-type: none"> None

Retrieval Algorithm	
Not Assessable	
Justification	No retrieval algorithm documented.
References	<ul style="list-style-type: none"> • None

DEM-Specific Processing	
Not Assessed	
<i>Additional Processing 1</i>	
Justification	No DEM derivative products.

4. Detailed Validation - Vertical

4.1 Validation Dataset

The CSDA DEM evaluation team selected 52 sites across the conterminous US (CONUS), totaling 15,821 square kilometers, as evaluation sites (Figure3) for the Precision3D DEM datasets. The evaluation site names and sizes are provided in Appendix Table A1.

The site selection process began by assembling a list of potential evaluation site locations across the US that had both high quality lidar data collected during the growing season and Vantor’s Precision3D DTM coverage at the time (Figure 4). Additionally, the lidar point density needed to be sufficient for generating a 1 m DEM. The list of potential evaluation sites included sites used by the NASA’s Surface Topography and Vegetation Study, as these were valuable sites with additional coincident datasets. The site selection criteria excluded datasets in the northeast US, due to a lack of growing season lidar acquisitions, as well as much of the western US, due to lack of Precision3D DTM coverage. The final evaluation site locations were selected from the remaining list based on surface topography, diversity of land cover, and vegetation density. This process ensured that the evaluation sites represented a sufficient variety and spatial extent of different surface characteristics. The variety of surface characteristics allowed for the characterization of vertical error across multiple topographic features, vegetation types, and vegetation densities. Twenty-four of the 52 CONUS evaluation sites overlapped with established Surface Topography and Vegetation evaluation sites.

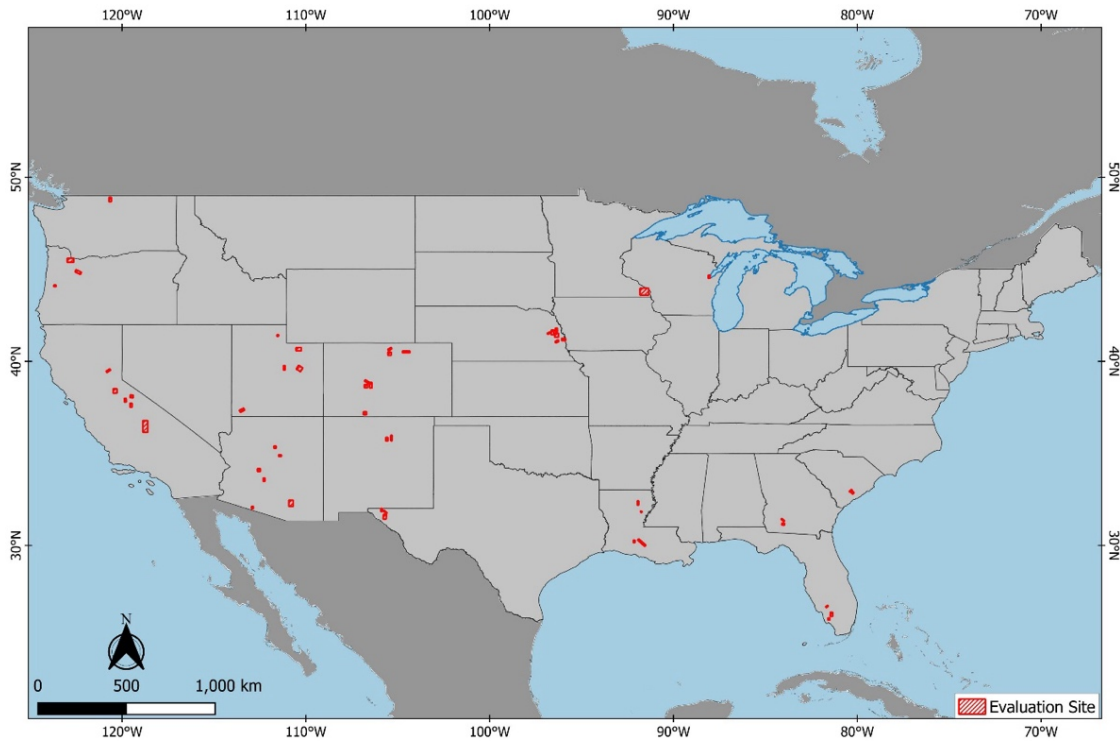


Figure 3. Location of US-based study sites for the Precision3D evaluation indicated in red. These sites cover a variety of surface characteristics.

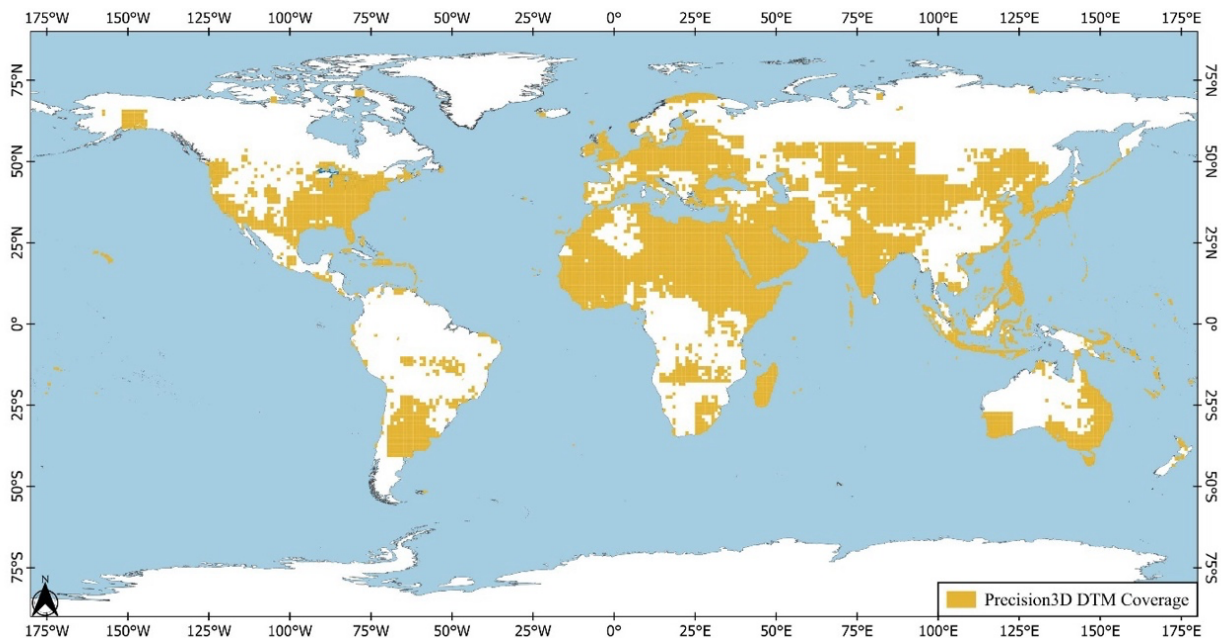


Figure 4. Precision3D DTM spatial coverage as of November 21, 2024. The Precision3D DSM has global coverage and did not limit our evaluation site selection.

Airborne lidar data were used to validate the accuracy of the Vantor Precision3D DTM and DSM products. These data typically offer high horizontal and vertical accuracy and are the standard for validating elevation data. Coverage of high resolution airborne lidar has historically been limited

due to the acquisition cost. The 3D Elevation Program (3DEP), managed by the United States Geological Survey (USGS) National Geospatial Program, was started in 2015 in response to a call to action for high-quality topographic data within the US. One action taken by 3DEP was the development of lidar data quality standards (available online: <https://www.usgs.gov/ngp-standards-and-specifications/lidar-base-specification-online>). As of 2025, all the conterminous US has, or is in the process of collecting, lidar data that meets the 3DEP standards (USGS, 2025). The USGS hosts topographic datasets online that meet the 3DEP standards and are freely available without use restrictions (<https://rockyweb.usgs.gov>). This Precision3D evaluation was performed almost exclusively within the US due to the large volume of high-quality publicly available lidar datasets.

Data from 26 lidar collections overlapping our evaluation sites were downloaded from the USGS. The 3DEP lidar reference sites used in the evaluation are listed in Appendix Table A1. Each lidar dataset contained point clouds classified using the American Society of Photogrammetry and Remote Sensing (ASPRS) standard classification scheme. Further processing of the 3DEP point cloud data was required to remove additional noise missed during vendor processing. The lidar returns, except those classified as noise, were then processed into 1×1 m raster DSMs by taking the maximum elevation of all lidar returns within each grid cell. Note that any vehicles present during lidar data acquisition are also included in the DSM generated. To create the DTMs, also at a raster cell size of 1×1 m, only lidar ground class returns were processed, taking the mean elevation of all the ground returns within each grid cell. In order to ensure that the Precision3D DSM and DTM elevations were compared with actual lidar returns, there was no interpolation used to fill raster cells that had no lidar returns, and they were labeled as ‘No Data’. The lidar DTM had more ‘No Data’ cells than the lidar DSM as all lidar returns were used, as opposed to the DTM that used only ground returns. Point clouds were reprojected to the same horizontal coordinate reference system and vertical coordinate reference system (WGS84 Ellipsoid) as the Precision3D DEMs before reference DEM generation. Lidar point cloud processing was performed using the open-source Point Data Abstraction Library (PDAL) (Howard Butler et al., 2024). The PDAL workflows (referred to as pipelines) used to process the 3DEP lidar are provided in Appendix B.

Vehicles were present within the lidar point clouds and subsequent DSMs. The lidar DSMs were co-registered and compared to Vantor Precision3D DSM, which did not contain vehicles, for roadways and parking lots. Visual inspection of the elevation differences indicated that vehicles had negative elevation differences between 1-5 m. This range was buffered to 0.5-6 m to account for possible vertical errors in the Precision3D DSM. Negative elevation differences between 0.5-6 m along roadways and within parking lots were identified and used to generate a vehicle mask. The roadway boundaries for each evaluation site were pulled from the Microsoft road dataset (Microsoft, 2025), and parking lot boundaries were manually digitized in QGIS across all evaluation sites. Areas within the vehicle mask were excluded from the evaluation of the Precision3D DSM. Areas of temporal change (e.g., timber harvest, forest fires, excavation, building demolition or construction, etc.) between the reference lidar collection and the Precision3D DEMs were identified through manual interpretation and removed from both the Precision3D DSMs and DTMs.

Fourteen locations, totaling 1.2 square kilometers, were selected as evaluation sites in Senegal (Figure 5). The 14 sites occurred across multiple dryland ecosystem sub-types along precipitation and aridity gradients. Vegetation type and structure vary by latitude and precipitation, and site cover types included mixed woodland/grassland, savanna/shrubland, and agropastoral. Airborne

lidar data were collected at each site using an Uncrewed Aircraft System (UAS) through a collaborative effort of the University of Maryland College Park Department of Geographical Sciences, NASA Goddard Space Flight Center, and the Centre de Suivi Ecologique, Senegal. Data were acquired between February 20th and 26th, 2023. Each site was flown with a DJI Matrice 600 Pro equipped with a Riegl MiniVUX-SYS laser scanner system at an altitude of 25 m above ground level and a speed of 4 m/s. The resulting point cloud data had densities ranging from 500-4500 points/m² depending on the height of the surface feature. Lidar returns from these acquisitions were processed into DSMs and DTMs with a horizontal resolution of 1 m for use as validation datasets for the Senegal sites. Additional processing was required for the Senegal sites as the point clouds provided these data were not classified. The processing involved using the Simple Morphological Filter (Pingel et al., 2013) to identify ground and non-ground returns. Noise points were identified using the Extended Local Minimum Filter (Chen et al., 2012). The PDAL pipelines used to process the UAS lidar for Senegal are provided in Appendix B.

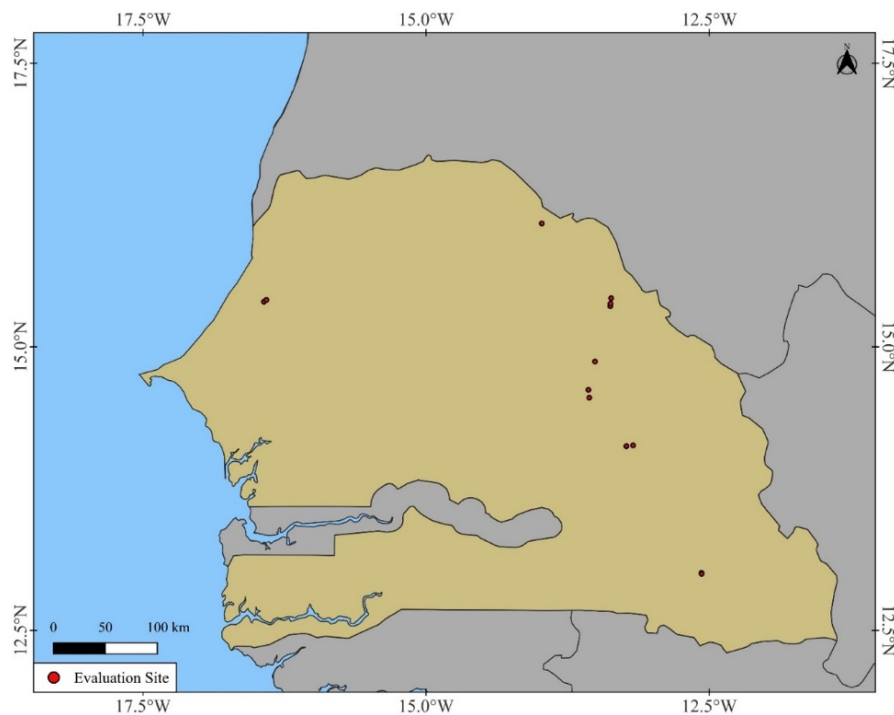


Figure 5. Location of Senegal-based study sites for the Precision3D evaluation. The evaluation sites are located along a vegetation density gradient in the Sahel region of Africa.

An “Excellent” grade was assigned to the validation data. The lidar data were of sufficient quality and resolution to assess the accuracy of the Precision3D DEMs. Temporal mismatches between the reference lidar and the Precision3D DEMs were managed by manually excluding areas with visually apparent change. It is possible that temporal mismatches of small spatial extents, such as removal of individual trees, were not completely masked due to the total spatial extent of the evaluation sites and the difficulty in determining whether a feature was missing due to a systematic error or a temporal mismatch.

4.2 Validation Methodology

Precision3D DSMs and DTMs were delivered as a tiled dataset for each evaluation site. Tiles were 8192 x 8192 pixels with a spatial resolution of 1 m. The tiles intersecting each evaluation site were mosaicked together and then co-registered to their respective reference lidar DSMs and DTMs (Appendices 3 and 4, respectively). Co-registration was performed using the methods described in Nuth and Kääb (2011) to ensure that the DEMs were aligned both horizontally and vertically. The MN_SE_Driftless_1, LA_Catahoula_Concordia_2017_D17_1, and CA_SierraNevada_B22_3 evaluation sites were too large to complete the co-registration with single DEMs. Instead, each individual Precision3D DEM tile was co-registered to the reference lidar DEM. Once co-registered, the per pixel difference between the Precision3D DEM elevation and the lidar DEM elevation was calculated by subtracting the lidar elevation from the Precision3D elevation. Precision3D errors were grouped by National Land Cover Database (NLCD) cover type (USGS, 2025), slope, and terrain aspect. Flat terrain (slope less than or equal to 2°) was used to determine the errors, by NLCD cover type, to reduce the effect of slope on elevation errors. The NLCD Barren class was manually edited to remove areas incorrectly classified as Barren. For example, areas of sparse forest were commonly misidentified as Barren. Misidentified areas were removed to ensure that the performance of the Precision3D DSM and DTM products more accurately captured areas with direct line-of-sight to the surface. No other NLCD cover classes were edited. Barren land was used to determine error over varying slopes to reduce the effect that cover type may have on elevation errors. A series of statistics (minimum, maximum, mean, median, standard deviation, root mean square error [RMSE], and linear error 90% [LE90]) were computed to quantify the overall vertical error as well as the vertical error within each of NLCD class.

Due to the 1 m Precision3D resolution and the extensive spatial extent of the evaluation sites, random points were sampled across all US evaluation sites. 750,000 points were randomly sampled by NLCD cover class on flat terrain for the Precision3D DSM, and 500,000 points were randomly sampled for the Precision3D DTM. Fewer sample points were generated for the Precision3D DTM evaluation due to the higher number of 'No Data' values in the reference lidar DTM data. The lidar DTMs were generated using ground returns classified by the vendor without interpolation to fill grid cells with no intersecting lidar returns, i.e., they were labeled as No Data. This resulted in sparser coverage depending on the cover type while ensuring that each Precision3D elevation retrieval was compared to actual reference lidar return data.

Overall vertical error statistics were computed by selecting a random sample of points weighted by the land cover type proportion in the conterminous US (Table 1). A total of 3 million points were set to be randomly sampled to compute the overall vertical error statistics for the Precision3D DSM and 2 million points were set to be sampled for the Precision3D DTM. However, the final number of points randomly sampled to compute the overall statistics was slightly less due to rounding. In total, 2,999,993 points were used to compute the overall statistics proportional to land cover type for the Precision3D DSM and 1,999,994 points were used for the Precision3D DSM.

. Table 1. The proportion of each National Land Cover Database (NLCD) cover class within the conterminous US. The water, perennial ice/snow, and cover classes unique to Alaska were excluded.

NLCD Land Cover Class	Percent Coverage
Developed, Open Space	3.03%
Developed, Low Intensity	1.56%
Developed, Medium Intensity	0.74%
Developed, High Intensity	0.26%
Barren	1.08%
Deciduous Forest	9.89%
Evergreen Forest	12.07%
Mixed Forest	3.83%
Shrub/Scrub	22.99%
Grassland/Herbaceous	14.61%
Pasture/Hay	6.63%
Cultivated Crops	17.15%
Woody Wetland	4.61%
Emergent Herbaceous Wetlands	1.55%

We also downloaded the USGS 3DEP 1/3 arc-second (10 m) raster DEM data for each CONUS evaluation site to calculate slope and aspect. These DEM products are produced by the USGS, and they represent bare earth elevations. Slope and aspect images were computed for each evaluation site using the Horn algorithm (Horn, 1981).

250,000 points were randomly sampled per slope class, which ranged from zero to 90° with step sizes of five degrees, for both the Precision3D DSM and DTM. The evaluation sites had few areas with slopes ranging from 75-85° that intersected the Barren landcover class. All raster cells that intersected these areas were included as the spatial extent of these slope classes was too small to generate 250,000 random points. There were no slopes ranging from 85-90° that intersected the Barren land cover class. One million points were randomly sampled per aspect class for both the Precision3D DSM and DTM. Aspect classes ranged from 0-359° with step sizes of 15°.

The Precision3D DSM vertical error statistics by landcover type and aspect were calculated both with and without roadways and parking lots due to the presence of vehicles in the reference lidar. Roads and parking lots were not removed for the calculation of vertical error by slope as those samples were taken from the Barren land cover class, which doesn't include these features. It was possible that the randomly sampled points could sample vehicles within the reference lidar data, which would not be errors from the Precision3D product or the processing workflow. It was not possible to manually remove vehicles from the reference lidar DSM due to the total area of all evaluation sites. Instead, roadways were masked using the Microsoft road dataset (Microsoft, 2025), and parking lots were manually digitized in QGIS and removed. Results were calculated both with and without the masking of roadways and parking lots because the removal of these features also resulted in random removal of samples that were in close agreement with the reference data.

The vertical error of the Precision3D products at the Senegal evaluation sites was computed separately from the US-based sites due to the differences between the two reference lidar datasets. Errors were not categorized by slope or aspect for the Senegal sites due to the small size of the evaluation sites and the relatively flat terrain.

An “Excellent” grade was assigned to the validation methodology, as it was reproducible and a state-of-the-art methodology was used for the evaluation.

4.3 Validation Completeness

Vertical accuracy validation completeness was given an “Excellent” grade. The evaluation of the Precision3D DSM and DTM was not carried out globally. However, the validation was completed over a large spatial extent using high-quality airborne lidar data as a reference. The evaluation sites covered a variety of surface characteristics, that permitted assessment of how different surface characteristics affect the Precision3D DEM products. Temporal differences in the reference data were minimized by masking out areas of change.

4.4 Validation Results Compliance

Differences in elevation were compared by NLCD cover type for areas with slopes less than or equal to 2° for the Precision3D DSM (Table 2). Large minimum and maximum error values for the Precision3D DSM were due to interpolation around vertical features. Interpolation errors in stereo-photogrammetric DSMs are typically due to obscuration of the surface due to viewing geometries or shadowing. The largest of these errors were observed in higher intensity urban (developed) cover types. Large positive errors were present where the ground surface adjacent to tall buildings or where gaps between tall buildings were obscured. Large negative errors were caused by small positional differences between buildings in the Precision3D DSM and the reference lidar and the incomplete representation of a building’s shape. For example, the rounding of a building’s rooftop or a wavy edge.

Table 2. Precision3D DSM vertical errors (m) by NLCD cover type over terrain with slopes less than or equal to 2°. Points were randomly sampled from each cover type to generate the overall statistics. The number of points sampled per cover type for the overall statistic was proportional to the percent area for each class across the CONUS (Table 1).

Cover Type	Minimum	Maximum	Median	Mean	StD	RMSE	LE90	Count
Developed, Open Space	-84.2	42.3	0.3	0.0	3.0	3.0	3.8	750,000
Developed, Low Intensity	-48.0	52.0	0.3	0.0	2.9	2.9	3.2	750,000
Developed, Medium Intensity	-39.3	45.8	0.2	0.3	3.2	3.3	2.9	750,000
Developed, High Intensity	-49.5	56.1	0.3	0.2	1.7	1.7	2.1	750,000
Barren	-31.5	22.9	0.1	0.0	1.1	1.1	1.3	750,000
Deciduous Forest	-35.9	33.5	-0.1	-0.7	6.3	6.3	10.9	750,000
Evergreen Forest	-63.4	72.1	0.2	0.8	6.8	6.8	11.3	750,000
Mixed Forest	-32.3	47.5	0.4	1.8	6.3	6.5	11.4	750,000
Shrub/Scrub	-57.4	50.8	0.1	0.1	3.4	3.4	3.5	750,000
Grassland/Herbaceous	-45.8	60.6	0.1	0.7	5.0	5.0	6.6	750,000
Pasture/Hay	-32.9	39.4	0.3	0.1	2.3	2.3	2.6	750,000
Cultivated Crops	-34.8	27.8	0.2	0.2	1.7	1.7	2.0	750,000
Woody Wetlands	-50.5	36.8	0.0	0.1	5.1	5.1	8.3	750,000
Emergent Herbaceous Wetlands	-36.3	30.2	0.2	0.2	3.5	3.5	4.8	750,000
Weighted Average	-63.4	64.0	0.2	0.3	4.5	4.5	6.6	2,999,993

Trees were a common source of error within the developed cover types, specifically for the Developed Open Space and Developed Low Intensity cover classes. It is probable that some errors included within the random sample for developed cover types were due to vehicles. Consistent large errors were present in forested areas, with in LE90 values larger than 10 m. Positive errors were caused by the omission of tree canopy gaps. Negative errors were caused by the omission of trees in areas of sparse tree cover (Figures 6 and 7). Comparatively, the Precision3D DSM performed well on Barren land, with RMSE of 1.1 m and an LE90 of 1.3 m. This cover class, devoid of surface features, offers a direct line of sight from the satellite to the Earth surface. The LE90 values for nine of the fourteen NLCD cover classes were larger than the Vantor-specified 3 m product vertical accuracy (LE90) within our evaluation sites. The overall LE90 for the Precision3D DSM evaluation sites was 6.6 m, when accounting for US land cover class distribution.

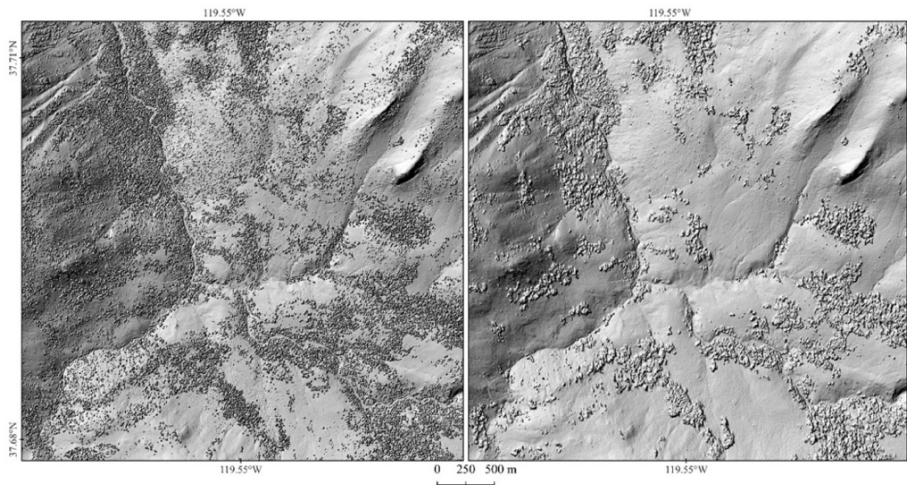


Figure 6. Shaded relief of the reference lidar DSM (left) and the Precision3D DSM (right) for a forested area in Yosemite National Park, California. Stem density varies throughout the displayed area. Note the locations of missing trees in the Precision3D DSM shaded relief.

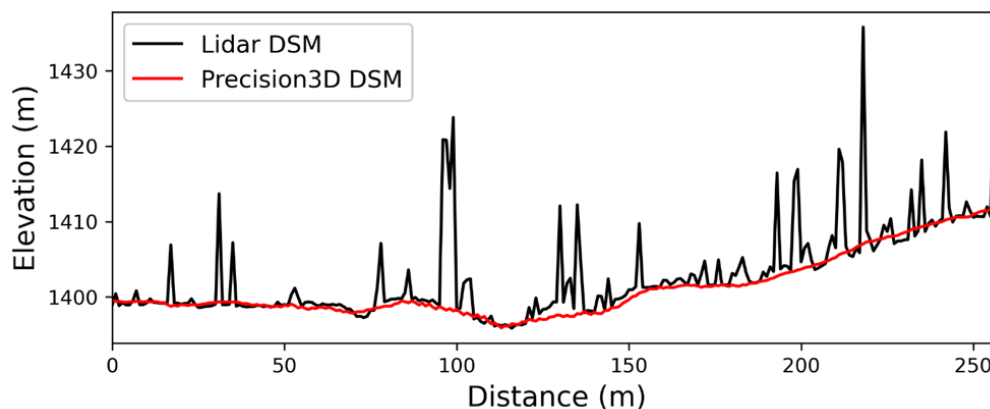


Figure 7. Elevation cross section for the Precision3D DSM (red) and the reference lidar DSM (black) at the evaluation site in Washington state, USA. The cross section shows multiple, large trees that were not represented in the Precision3D DSM product. The Precision3D DSM was co-registered to the reference lidar DSM using the methods described in Nuth and Kääb (2011) before computing the cross section.

The evaluation sites in California included areas with extremely tall tree species, such as Giant sequoia (*Sequoiadendron giganteum*) that range from 100 ft to over 300 ft in height. These may have contributed to the large LE90 values for the Deciduous Forest, Evergreen Forest, and Mixed Forest cover classes. The LE90 values for these three forest classes (10.9, 11.3, and 11.4 m, respectively) were recalculated with the exclusion of the California evaluation sites. The LE90 values after removing the California sites were 11 m for the Deciduous Forest class, 8.9 m for the Evergreen Forest class, and 11.4 m for the Mixed Forest class. The small reduction in LE90 values for the Deciduous and Mixed Forest cover types indicate that the large errors in these cover classes were present across all US evaluation sites. Large vertical errors were reduced within the Evergreen Forest cover class when excluding the California evaluation sites, but the LE90 value remained higher than the non-forested cover classes despite the 2.4 m reduction in LE90.

Differences in elevation between the Precision3D DTM and the reference lidar ground points were computed for areas with slopes less or equal to 2°. The Precision3D DTM performed well, with 10 of the 14 NLCD cover classes having LE90 values less than 3 m (Table 3). Large positive and negative vertical errors were uncommon in the DTM product. Vertical accuracy of the Precision3D DTM is lowest in the forested classes, as shown with high LE90 values in Table 3.

Table 3. Precision3D DTM vertical errors (m) by NLCD cover type over terrain with slopes less than or equal to 2°. Points were randomly sampled from each cover type to generate the overall statistics. Number of points sampled per cover type for the overall statistic is proportional to the percent area for each cover class across the CONUS (Table 1).

Cover Type	Minimum	Maximum	Median	Mean	StD	RMSE	LE90	Count
Developed, Open Space	-14.9	18.7	-0.1	-0.2	0.9	0.9	1.2	500,000
Developed, Low Intensity	-17.6	19.2	-0.1	-0.2	0.7	0.7	0.9	500,000
Developed, Medium Intensity	-10.5	14.3	-0.2	-0.2	0.6	0.6	0.9	500,000
Developed, High Intensity	-9.5	11.1	-0.2	-0.2	0.6	0.7	1.0	500,000
Barren	-20.8	13.0	-0.3	-0.5	1.1	1.2	1.6	500,000
Deciduous Forest	-19.9	26.9	0.6	1.5	4.0	4.2	7.1	500,000
Evergreen Forest	-19.4	41.1	0.0	0.7	3.0	3.1	4.8	500,000
Mixed Forest	-22.2	34.0	1.1	1.5	4.4	4.7	8.5	500,000
Shrub/Scrub	-27.2	30.3	0.0	-0.1	0.7	0.7	0.6	500,000
Grassland/Herbaceous	-18.8	25.5	0.0	0.1	1.4	1.4	0.7	500,000
Pasture/Hay	-18.1	20.2	-0.1	-0.3	1.3	1.3	1.4	500,000
Cultivated Crops	-17.7	17.3	-0.1	-0.2	1.1	1.1	1.3	500,000
Woody Wetlands	-15.0	21.3	0.7	1.6	3.2	3.5	6.1	500,000
Emergent Herbaceous Wetlands	-17.5	16.3	-0.2	-0.1	1.3	1.3	1.8	500,000
Overall	-26.5	41.1	0.0	0.3	2.3	2.3	2.8	1,999,994

The poor performance of the Precision3D DTM product in heavily treed cover classes is demonstrated visually in Figure 8, a site in Louisiana where topography is obscured by tree canopy cover and is not well captured in the Precision3D DTM product compared with the reference lidar DTM product.

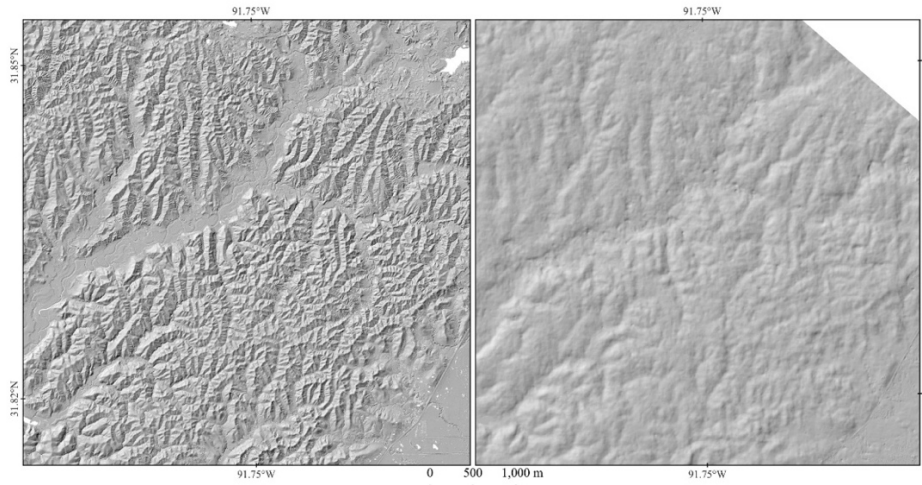


Figure 8. Shaded relief image of the reference lidar DTM (left) and the Precision3D DTM (right) for dense forest in Louisiana. The lidar DTM captures the drainage network under the tree canopy that the Precision3D DTM fails to capture.

Flattening of hilltops, as shown in the transect in Figure 9, was observed at the Organ Pipe Cactus National Monument evaluation site in Arizona, but errors such as these were not captured in the random sample. Vantor uses proprietary software to estimate bare earth elevations from the Precision3D DSM product using a land cover classification as input for the estimation. The flattened hilltops were caused by commission errors in the land cover classification used by Vantor. In this instance, shrub/scrub was misclassified as forest, which resulted in their DTM code attempting to remove suspected trees from a cover class where they did not exist. Vertical accuracy of the Precision3D DTM and DSM were similar for the Barren class on flat terrain with direct line of sight to the earth surface. The overall LE90 value for the Precision3D DTM at our evaluation sites was 2.8 m when accounting for US land cover distribution.

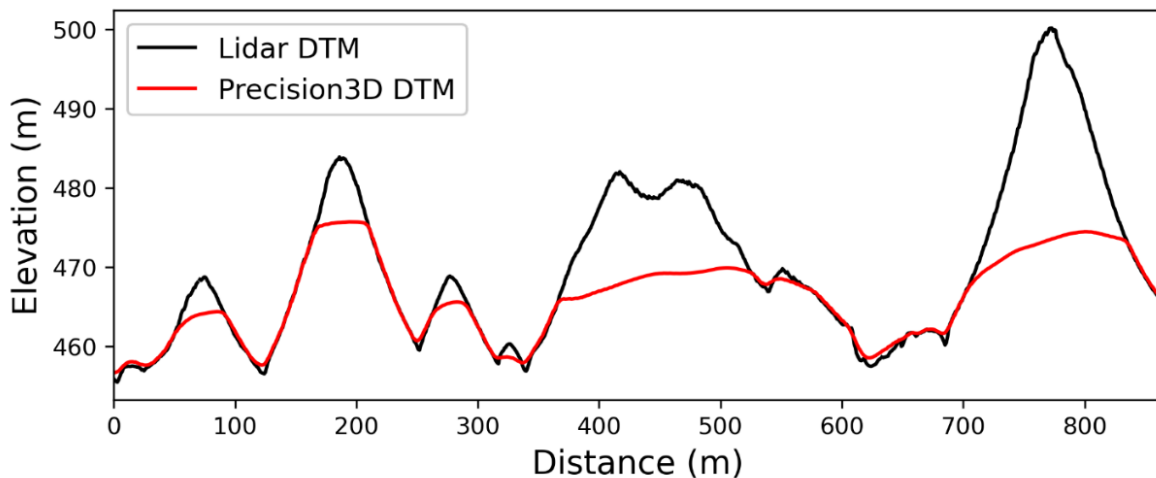


Figure 9. Elevation cross section for the Precision3D DTM (red) and the reference lidar DTM (black) at the Organ Pipe Cactus National Monument evaluation site in Arizona, USA. The cross section shows hilltops that were falsely removed during the Precision3D DTM processing workflow. The Precision3D DTM was co-registered to the reference lidar DTM using the methods described in Nuth and Kääb (2011) before computing the cross section.

The Precision3D DSM and DTM vertical errors (Tables 4 and 5, respectively) were evaluated for the Barren class with slopes ranging from 0-85° in 5° increments. It was not possible to sample 250,000 random points for the slope class due to limited data for that slope class across evaluation sites. Instead, all available pixels in the 75-80° and the 80-85° slope classes were used to generate the statistics. There were no instances of 85-90° slopes within the Barren class at our evaluation sites. Both products show a general trend of decreasing accuracy as the slope increases. Large positive and negative errors were more common at steeper slopes.

Table 4. Precision3D DSM vertical errors (m) by slope. 250,000 points were randomly sampled per slope class for Barren land as determined by the NLCD classification.

Slope (degrees)	Minimum	Maximum	Median	Mean	StD	RMSE	LE90	Count
0-5	-24.1	25.7	0.1	-0.1	1.4	1.4	1.3	250,000
5-10	-27.1	17.8	0.1	0.0	0.9	0.9	0.8	250,000
10-15	-25.4	18.4	0.0	0.0	0.9	0.9	0.9	250,000
15-20	-31.4	20.3	0.0	-0.1	0.9	0.9	1.0	250,000
20-25	-28.4	18.7	-0.1	-0.1	1.0	1.0	1.1	250,000
25-30	-22.7	19.1	-0.1	-0.1	1.1	1.1	1.2	250,000
30-35	-24.9	36.7	-0.1	-0.1	1.2	1.2	1.4	250,000
35-40	-25.4	43.3	-0.1	-0.1	1.3	1.3	1.5	250,000
40-45	-27.9	43.9	-0.1	-0.2	1.5	1.5	1.9	250,000
45-50	-19.8	38.8	-0.3	-0.3	1.9	1.9	2.7	250,000
50-55	-31.1	41.6	-0.5	-0.5	2.3	2.3	3.4	250,000
55-60	-37.3	58.9	-0.7	-0.7	2.7	2.8	4.1	250,000
60-65	-29.7	40.5	-0.9	-0.9	3.3	3.4	5.2	250,000
65-70	-70.5	58.3	-1.1	-1.2	4.4	4.5	6.5	250,000
70-75	-49.2	65.5	-1.5	-1.9	5.5	5.8	8.5	180,683
75-80	-86.0	119.9	-2.7	-3.2	7.8	8.4	11.8	37,649
80-85	-87.6	134.1	-6.1	2.4	34.4	34.5	44.1	1,814

Table 5. Precision3D DTM vertical errors by slope. 250,000 points were randomly sampled per slope class for Barren land as determined by the NLCD classification. Errors are provided in meters.

Slope (degrees)	Minimum	Maximum	Median	Mean	StD	RMSE	LE90	Count
0-5	-21.1	24.9	-0.4	-0.5	1.0	1.1	1.3	250,000
5-10	-30.8	31.5	-0.6	-0.6	0.8	1.0	1.3	250,000
10-15	-31.9	16.1	-0.6	-0.6	0.8	1.0	1.3	250,000
15-20	-31.2	31.2	-0.6	-0.6	0.9	1.1	1.4	250,000
20-25	-35.0	34.5	-0.6	-0.6	1.0	1.2	1.5	250,000
25-30	-23.5	14.1	-0.6	-0.6	1.1	1.2	1.7	250,000
30-35	-29.9	35.7	-0.5	-0.5	1.2	1.3	1.7	250,000
35-40	-19.5	41.3	-0.5	-0.5	1.2	1.3	1.7	250,000
40-45	-37.1	33.3	-0.4	-0.4	1.5	1.5	2.0	250,000
45-50	-29.3	40.8	-0.4	-0.2	1.9	1.9	2.7	250,000
50-55	-45.4	70.5	-0.3	-0.1	2.4	2.4	3.2	250,000
55-60	-45.4	66.9	-0.3	0.0	2.9	2.9	3.9	250,000
60-65	-43.7	64.5	-0.2	0.2	3.5	3.5	4.7	250,000
65-70	-49.9	138.2	-0.1	0.5	4.7	4.7	5.9	250,000
70-75	-48.1	136.9	-0.2	0.9	7.6	7.6	7.1	250,000
75-80	-51.1	137.9	-0.4	2.2	14.2	14.4	10.2	65,009
80-85	-51.0	138.1	0.8	12.1	35.1	37.1	62.8	2,100

The Precision3D DSM and DTM vertical errors were grouped by aspect in step sizes of 15° (Appendix D Tables D1 and D2, respectively). Inspection of the LE90 values for each aspect group indicates larger errors for east-southeast aspects for both the Precision3D DSM (Figure 10) and DTM (Figure 11). However, this trend was significantly reduced when considering land cover type and is more pronounced in the DTM plot (Figure 11). 500,000 points were randomly sampled within the NLCD forested cover classes (Deciduous Forest, Evergreen Forest, and Mixed Forest) and the Barren land cover class for each aspect category. In Figures 10 and 11, the LE90 for the forested cover classes grouped by aspect represent the upper limit of the error bars, and the LE90 for the Barren cover class grouped by aspect represent the lower limits for the error bars. Forested cover classes were used to establish the upper limits of the error bars as those classes overall had the highest vertical errors. The Barren cover class was used to establish the lower limit of the error bars as the sensor has direct line-of-sight to the surface, which corresponds to the maximum achievable accuracy by the Precision3D DEMs. Inspection of the vertical error over the Barren class by aspect (lower limit of the error bars) indicates minimal change in vertical error across all aspects. This suggests that the larger errors associated with east-southeast aspects are the result of cover type.

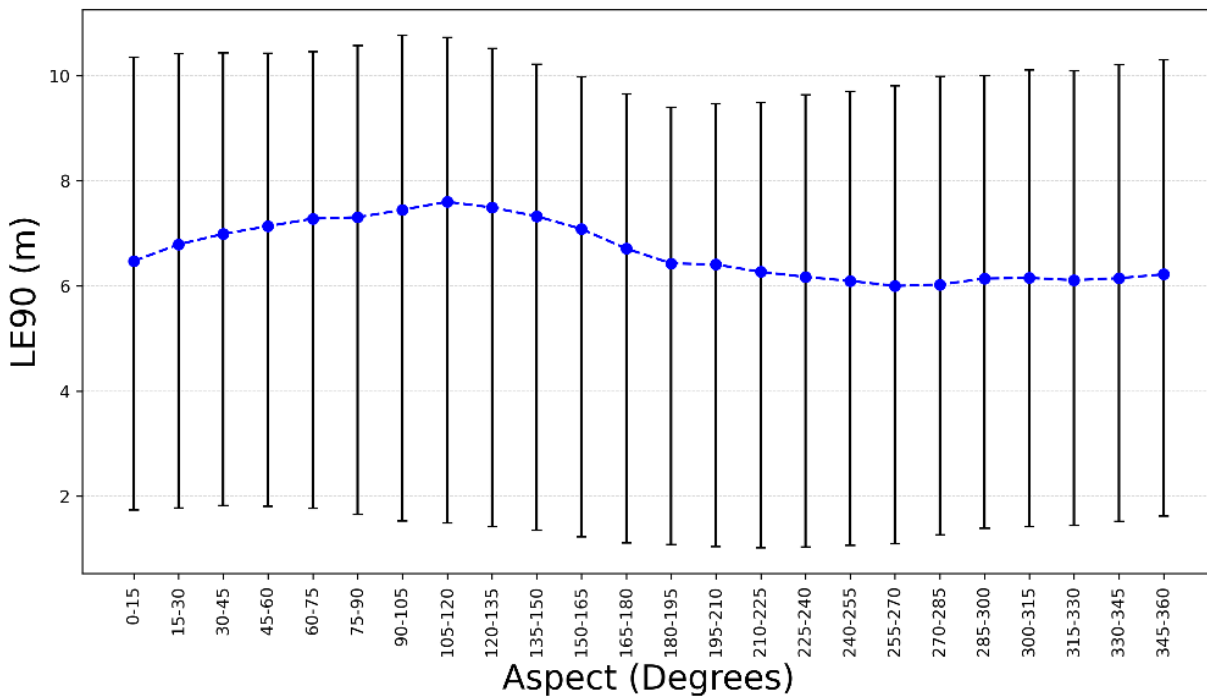


Figure 10. Vertical error (LE90) for the Precision3D DSM for each aspect group. The LE90 calculated without considering land cover type (blue). Error bars represent the LE90 values for each aspect when only considering forest land cover types (upper limits) and the Barren land class (lower limits).

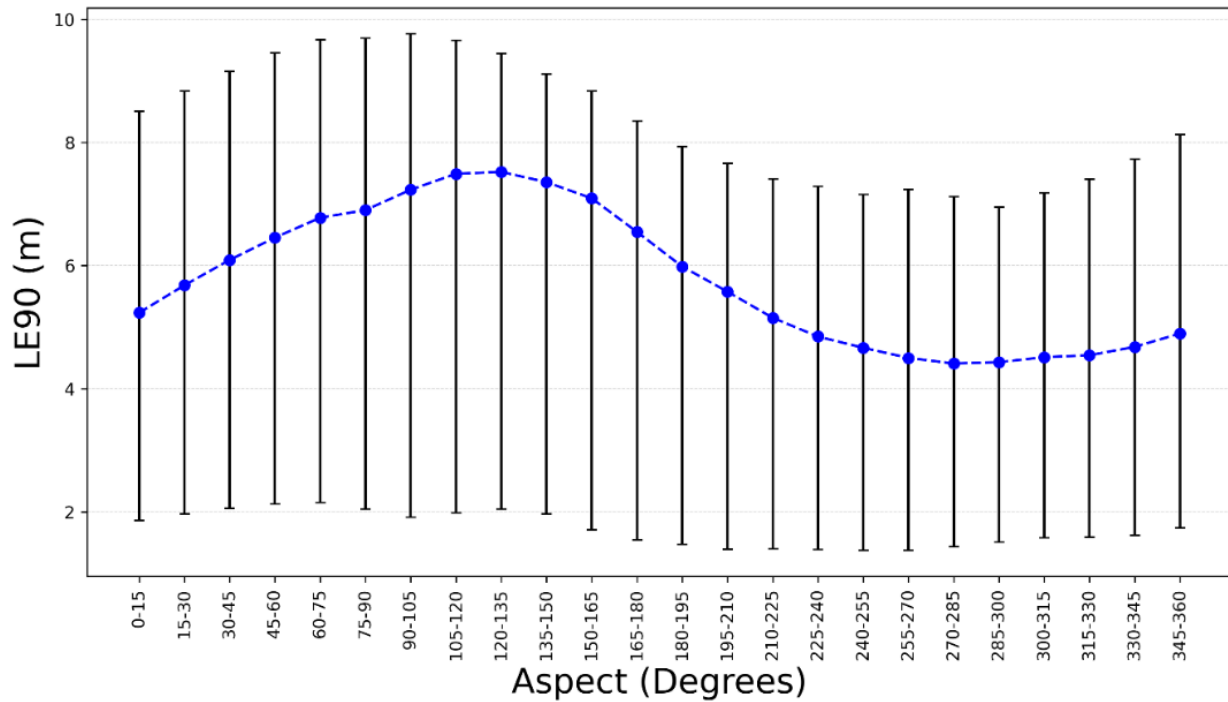


Figure 11. Vertical error (LE90) for the Precision3D DTM for each aspect group. The LE90 calculated without considering land cover type is shown in blue. Error bars represent the LE90 values for each aspect when only considering forest land cover types (upper limits) and Barren land class (lower limits).

The vertical accuracy of the Precision3D products was variable for the Senegal evaluation sites (Table 6). The Precision3D DTM achieved a LE90 of 0.4 m, while the Precision3D DSM achieved a LE90 of 3.7 m. Vegetation at these sites is dominated by trees less than 15 m tall with increasing stem density southward along a precipitation gradient. The Precision3D DSM struggled to capture the vegetation at the 14 evaluation sites, even at high stem densities (Figure 12). These errors resulted in a significant left tail to the Precision3D DSM error distribution, which indicated a significant underestimation of tree height and failure to capture trees within the DSM (Figure 13).

Table 6. Precision3D DTM and DSM vertical errors at across all Senegal evaluation sites. Errors are provided in meters.

Product	Minimum	Maximum	Median	Mean	StD	RMSE	LE90	Count
Precision3D DTM	-2.4	6.4	0.0	0.1	0.4	0.4	0.4	1,155,859
Precision3D DSM	-16.8	9.1	0.2	-0.4	2.2	2.3	3.7	1,185,757

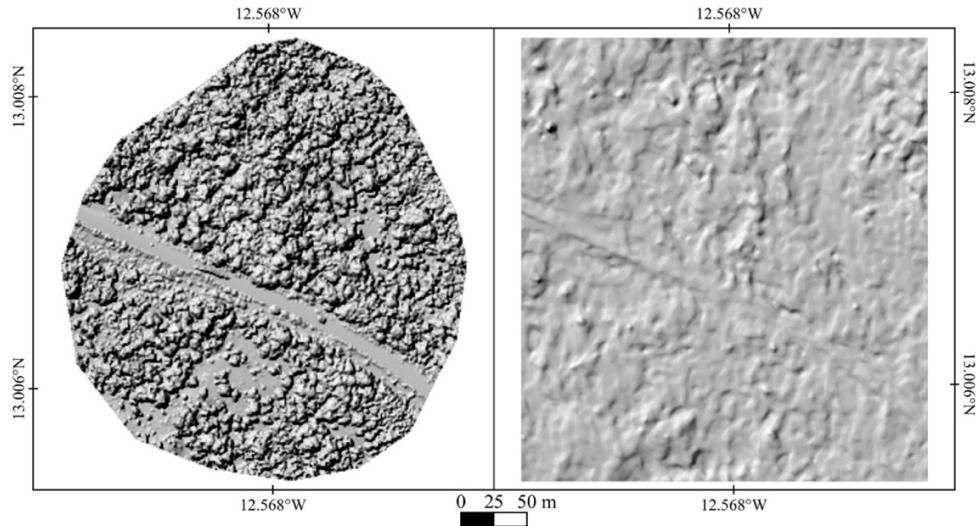


Figure 12. Shaded relief of the reference lidar DSM (left) and the Precision3D DSM (right) for a densely forested evaluation site in Senegal. The lidar DSM captures the variable tree heights and shapes, while the Precision3D DSM does not capture the same surface characteristics.

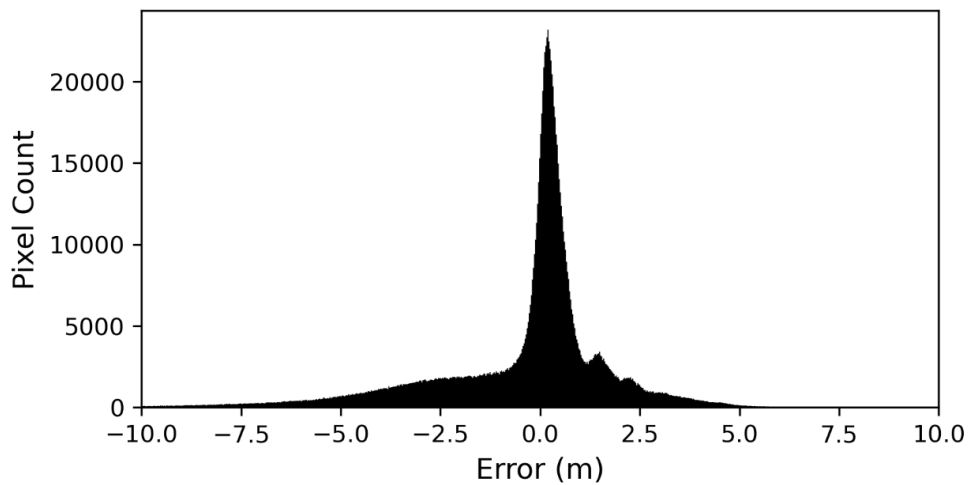


Figure 13. Histogram of the Precision3D DSM errors for all Senegal evaluation sites, showing a strong left tail in the error distribution. The left tail indicates the underestimation of surface elevations.

5. Detailed Validation - Horizontal

5.1 Validation Dataset

The evaluation dataset was graded as “Excellent” due to the high spatial resolution and high horizontal accuracy. The reference validation dataset used for the horizontal validation is the same dataset used for vertical accuracy, described in section 3.1.1.

5.2 Validation Methodology

Horizontal accuracy was assessed by calculating the horizontal offset between the Precision3D DEM and the reference lidar DEM. Horizontal offsets were computed using the co-registration methods described in Nuth and Kääb (2011). Each Precision3D DEM was co-registered to the corresponding reference lidar DEM (Appendix D). Circular error at the 90th percentile (CE90) and horizontal RMSE were computed using the calculated horizontal offsets. The horizontal offsets represent the relative error between the Precision3D DEM product and the more accurately geolocated lidar data. This approach was given a “Basic” grade. Horizontal differences were not calculated at the pixel-level, and this approach does not provide an estimate of the absolute horizontal accuracy of the Precision3D DTM and DSM products.

5.3 Validation Completeness

The horizontal accuracy validation completeness was graded as “Basic”. The methodology used to assess the horizontal accuracy of the Precision3D DEMs was limited to a single metric for each evaluation site. This methodology did not account for pixel-level horizontal errors or categorize horizontal errors using ancillary data (e.g., landcover type, slope, or aspect).

5.4 Validation Results Compliance

The geolocation of the Precision3D DSM aligned well with the reference lidar DSM in the US and Senegal, with a horizontal RMSE of 0.5 m and a CE90 of 0.5 m (Figure 14, left). Co-registration results with the Precision3D DTM indicate larger shifts, with a horizontal RMSE of 1.33 m and a CE90 of 1.59 m (Figure 14, right). The largest translation vectors for the DTM product were calculated for the Minnesota_SE_Driftless_1, CA_SierraNevada_B22_3, and Senegal evaluation sites. Overall, the relative horizontal accuracy of the Precision3D DEMs was assessed as “Excellent”. The horizontal accuracy of the Precision3D DEMs is tied to the geolocation accuracy of the imagery used to compute the DEMs, which varies by sensor (DigitalGlobe Inc., 2016). The CE90 calculated from the relative horizontal translations was less than the 3 m CE90 horizontal accuracy specification reported by Vantor (Precision3D Data Products Specification Document, 2024). Additional analysis would be needed to determine the absolute horizontal accuracy or pixel-level horizontal errors.

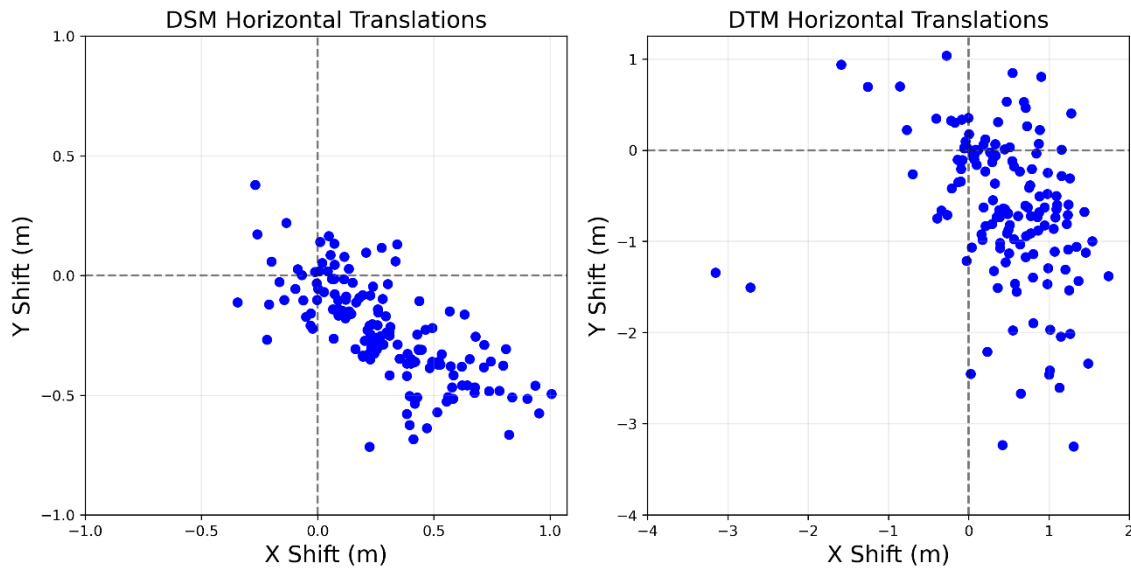


Figure 14. Horizontal translations used to spatially align the Precision3D DSM (left) and Precision3D DTM (right) to the reference lidar DEM in the US and Senegal. Translation values were computed using the methods described in Nuth and Käb (2011). A horizontal RMSE of 0.5 m and a CE90 of 0.47 m was calculated for the Precision3D DSM product. A horizontal RMSE of 1.3 m and a CE90 of 1.6 m was calculated for the Precision3D DTM product.

6. Summary

The vertical accuracy of the Precision3D DEM data was found to be variable by land cover type. Precision3D DSM LE90 values at the US evaluation sites were higher than the 3 m product specification for half of the NLCD land cover types. The overall LE90 value for the Precision3D DSM, when accounting for national land cover type proportions, was 5.5 m for US evaluation sites. Additionally, the Precision3D DSM had an LE90 value of 3.7 m for the Senegal evaluation sites where it struggled to accurately capture the tree canopy. Comparatively, the Precision3D DTM had LE90 values higher than the 3 m LE90 product specification for four of the fourteen NLCD cover classes. The overall LE90 value for the Precision3D DTM when accounting for national land cover type proportions was 2.8 m for the US evaluation sites. Both Precision3D DSM and DTM products had poorer accuracy in forested cover types. The variable vertical accuracy by land cover type and the omission of trees in the Precision3D DSM resulted in a “Basic” grade for the vertical accuracy, as the Precision3D DSM showed partial agreement with the claimed 3 m LE90. The Precision3D DTM showed good agreement with Vantor’s reported accuracy at the evaluation sites despite the omission of topography under tree canopies and the flattening of hilltops in the Precision3D DTM. The Precision3D DTM was given a “Good” grade for vertical accuracy.

The horizontal accuracy of the Precision3D DEM data at the selected evaluation sites showed excellent agreement with Vantor’s claim of 3 m CE90. This resulted in an “Excellent” grade for the horizontal accuracy.

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APPENDIX A Evaluation sites

Table A1. Evaluation site name, area, and reference lidar information. Reference lidar were downloaded from the USGS 3D Elevation Program (3DEP) FTP site.

Evaluation Site Name	Area (km ²)	3DEP Reference Lidar Datasets	Survey Start Date	Survey End Date	Non-Vegetated Vertical Accuracy (95% CI) cm
AZ_Coconino_2019_B1_1	135	AZ_Coconino_B1_2019	7/16/2022	10/11/2022	11.3
AZ_Coconino_2019_B1_2	144	AZ_Coconino_B1_2019	7/16/2022	10/11/2022	11.3
AZ_MaricopaPinal_2020_B20_1	183	AZ_MaricopaPinal_1_2020	10/2/2020	12/18/2021	9.89
AZ_OrganPipeCactusNM_2020_B20_1	105	AZ_OrganPipeCactusNM_2020_B20	9/19/2020	9/26/2020	7.84
AZ_PimaCounty_2021_B21_1	822	AZ_PimaCo_2_2021	9/27/2021	11/17/2021	10.7
AZ_Yavapai_2021_B21_1	255	AZ_Yavapai_2_2021	9/13/2021	11/17/2021	8.3
CA_SierraNevada_B22_1	196	CA_SierraNevada_B22	6/4/2022	9/23/2022	9.74
CA_SierraNevada_B22_2	471	CA_SierraNevada_B22	6/4/2022	9/23/2022	9.74
CA_SierraNevada_B22_3	1692	CA_SierraNevada_B22	6/4/2022	9/23/2022	9.74
CA_YosemiteNP_2019_D19_1	241	CA_YosemiteNP_2019_D19	10/7/2019	10/23/2019	6.99
CA_YosemiteNP_2019_D19_2	240	CA_YosemiteNP_2019_D19	10/7/2019	10/23/2019	6.99
CA_YosemiteNP_2019_D19_3	209	CA_YosemiteNP_2019_D19	10/7/2019	10/23/2019	6.99
CO_CameronPeakWildfire_2021_D21_1	295	CO_CameronPeakWildfire_2021_D21	9/7/2021	9/22/2021	9.76
CO_CameronPeakWildfire_2021_D21_2	169	CO_CameronPeakWildfire_2021_D21	9/7/2021	9/22/2021	9.76
CO_EasternColorado_2018_A18_1	331	CO_EasternColorado_2018_A18	4/30/2018	7/25/2018	9.41
CO_Southwest_NRCS_2018_D18_1	281	CO_Southwest_NRCS_2018_D18	10/5/2018	11/3/2018	6.32
CO_WestCentral_2019_A19_1	256	CO_WestCentral_2019_A19	8/21/2019	9/19/2019	9.29
CO_WestCentral_2019_A19_2	375	CO_WestCentral_2019_A19	8/21/2019	9/19/2019	9.29
CO_WestCentral_2019_A19_3	229	CO_WestCentral_2019_A19	8/21/2019	9/19/2019	9.29
FL_Southwest_2018_D18_SUPPLEMENTAL_1	270	FL_Southwest_2018_D18_SUPPLEMENTAL	5/8/2018	10/29/2018	17.5
FL_Southwest_2018_D18_SUPPLEMENTAL_2	106	FL_Southwest_2018_D18_SUPPLEMENTAL	5/8/2018	10/29/2018	17.5
FL_Southwest_2018_D18_SUPPLEMENTAL_3	95	FL_Southwest_2018_D18_SUPPLEMENTAL	5/8/2018	10/29/2018	17.5
GA_Central_2019_B19_1	126	GA_Central_2019_B19	2/2/2020	3/28/2020	12.33
GA_Central_2019_B19_2	148	GA_Central_2019_B19	2/2/2020	3/28/2020	12.33
LA_Catahoula_Concordia_2017_D17_1	498	LA_Catahoula_Concordia_2017_D17	10/6/2019	11/21/2019	17.8
LA_Catahoula_Concordia_2017_D17_2	121	LA_Catahoula_Concordia_2017_D17	10/6/2019	11/21/2019	17.8
LA_Catahoula_Concordia_2017_D17_3	50	LA_Catahoula_Concordia_2017_D17	10/6/2019	11/21/2019	17.8
LA_NortheastDOTD_2017_C20_1	155	LA_NortheastDOTD_2017_C20	3/8/2018	9/3/2019	8.02
MN_SE_Driftless_2021_B21_1	1699	MN_SE_Driftless_2021_B21	4/25/2021	5/15/2022	6.94
NE_PostSpringFlood_OrthoLidar_2019_D19_1	113	NE_PostSpringFlood_OrthoLidar_2019_D19	6/1/2019	6/7/2019	10.4
NE_PostSpringFlood_OrthoLidar_2019_D19_2	160	NE_PostSpringFlood_OrthoLidar_2019_D19	6/1/2019	6/7/2019	10.4
NE_PostSpringFlood_OrthoLidar_2019_D19_3	388	NE_PostSpringFlood_OrthoLidar_2019_D19	6/1/2019	6/7/2019	10.4
NE_PostSpringFlood_OrthoLidar_2019_D19_4	175	NE_PostSpringFlood_OrthoLidar_2019_D19	6/1/2019	6/7/2019	10.4
NE_PostSpringFlood_OrthoLidar_2019_D19_5	355	NE_PostSpringFlood_OrthoLidar_2019_D19	6/1/2019	6/7/2019	10.4
NE_PostSpringFlood_OrthoLidar_2019_D19_6	315	NE_PostSpringFlood_OrthoLidar_2019_D19	6/1/2019	6/7/2019	10.4
NM_HermitsPeak_D23_1	199	NM_HermitsPeak_D23	9/17/2023	10/8/2023	15.6
NM_HermitsPeak_D23_2	209	NM_HermitsPeak_D23	9/17/2023	10/8/2023	15.6
OR_OLCMetro_2019_A19_1	699	OR_OLCMetro_2019_A19	5/8/2020	9/3/2020	7.31
OR_WesternWildfires_A22_1	101	OR_WesternWildfires_1_A22	6/2/2020	9/7/2022	7.3
OR_WesternWildfires_A22_2	398	OR_WesternWildfires_2_A22	5/7/2020	9/3/2020	9.8
SC_SavannahPeeDee_2019_B19_1	115	SC_SavannahPeeDee_2019_B19	1/20/2020	3/12/2020	8.7
SC_SavannahPeeDee_2019_B19_2	151	SC_SavannahPeeDee_2019_B19	1/20/2020	3/12/2020	8.7
TX_DesertMountains_2018_D19_1	435	TX_DesertMountains_2018_D19	9/11/2019	10/20/2019	11.99
TX_DesertMountains_2018_D19_2	152	TX_DesertMountains_2018_D19	9/11/2019	10/20/2019	11.99
TX_DesertMountains_2018_D19_3	130	TX_DesertMountains_2018_D19	9/11/2019	10/20/2019	11.99

UT_FEMA_FS_FlamingGorge_2020_B20_1	306	UT_FEMA_FS_FlamingGorge_2020_B20	8/8/2020	11/20/2020	14.31
UT_FEMA_FS_FlamingGorge_2020_B20_2	693	UT_FEMA_FS_FlamingGorge_2020_B20	8/8/2020	11/20/2020	14.31
UT_FEMA_FS_FlamingGorge_2020_B20_3	73	UT_FEMA_FS_FlamingGorge_2020_B20	8/8/2020	11/20/2020	14.31
UT_FEMA_FS_FlamingGorge_2020_B20_4	209	UT_FEMA_FS_FlamingGorge_2020_B20	8/8/2020	11/20/2020	14.31
UT_WestEast_B22_1	480	UT_WestEast_B22	7/23/2020	9/2/2020	9.18
WA_NorthCentral_2021_B21_1	241	WA_NorthCentral_2021_B21	8/25/2021	5/4/2022	7.23
WI_BrownRusk_2020_B20_1	136	WI_BrownRusk_2020_B20	5/7/2020	5/7/2020	6.66

APPENDIX B PDAL Lidar Processing Pipelines

Table B1. PDAL Pipeline for DSM Processing of USGS 3DEP Lidar

```
1. {
2.   "pipeline":[
3.     {
4.       "type": "readers.las",
5.       "filename": "#"
6.     },
7.     {
8.       "type": "filters.reprojection",
9.       "in_srs": "#",
10.      "out_srs": "#"
11.    },
12.    {
13.      "type": "filters.assign",
14.      "value": ["Classification = 7 WHERE Classification == 18"]
15.    },
16.    {
17.      "type": "filters.hag_nn"
18.    },
19.    {
20.      "type": "filters.assign",
21.      "value": ["Classification = 7 WHERE HeightAboveGround > 125"]
22.    },
23.    {
24.      "type": "filters.outlier",
25.      "method": "radius",
26.      "radius": 0.5,
27.      "min_k": 4,
28.      "where": "((HeightAboveGround > 15) && (Classification == 1))"
29.    },
30.    {
31.      "type": "filters.range",
32.      "limits": "Classification[1:6],Classification[10:17]"
33.    },
34.    {
35.      "type": "writers.gdal",
36.      "filename": "#",
37.      "gdaldriver": "GTiff",
38.      "output_type": "max",
39.      "radius": 0.5,
40.      "resolution": "1.0",
41.      "dimension": "Z"
42.    }
43. ]
44. }
```

Table B2. PDAL Pipeline for DTM Processing of USGS 3DEP Lidar

```
1. {  
2.   "pipeline": [  
3.     {  
4.       "type": "readers.las",  
5.       "filename": "#"  
6.     },  
7.     {  
8.       "type": "filters.expression",  
9.       "expression": "Classification == 2"  
10.    },  
11.    {  
12.      "type": "filters.reprojection",  
13.      "in_srs": "#",  
14.      "out_srs": "#"  
15.    },  
16.    {  
17.      "type": "writers.gdal",  
18.      "filename": "#",  
19.      "gdaldriver": "GTiff",  
20.      "output_type": "mean",  
21.      "radius": 0.5,  
22.      "resolution": "1.0",  
23.      "dimension": "Z"  
24.    }  
25.  ]  
26. }
```

Table B3. PDAL Pipeline code used for processing of Senegal UAS Lidar DSM.

```
1. {
2.   "pipeline":[
3.     {
4.       "type": "readers.las",
5.       "filename": "#"
6.     },
7.     {
8.       "type": "filters.reprojection",
9.       "in_srs": "#",
10.      "out_srs": "#"
11.    },
12.    {
13.      "type": "filters.smrf",
14.      "scalar": 1.25,
15.      "slope": 0.1,
16.      "threshold": 0.4,
17.      "window": 3.0
18.    },
19.    {
20.      "type": "filters.elm",
21.      "threshold": 2.0
22.    },
23.    {
24.      "type": "filters.hag_nn"
25.    },
26.    {
27.      "type": "filters.assign",
28.      "value": ["Classification = 7 WHERE HeightAboveGround > 30"]
29.    },
30.    {
31.      "type": "filters.outlier",
32.      "method": "radius",
33.      "radius": 1.0,
34.      "min_k": 4,
35.      "where": "((HeightAboveGround > 3) && (Classification != 7))"
36.    },
37.    {
38.      "type": "filters.range",
39.      "limits": "Classification[0:2]"
40.    },
41.    {
42.      "type": "writers.gdal",
43.      "filename": "#",
44.      "gdaldriver": "GTiff",
45.      "output_type": "max",
46.      "radius": 0.5,
47.      "resolution": "1",
48.      "dimension": "Z"
49.    }
50. ]
51. }
```

Table B4. PDAL Pipeline for DTM Processing of Senegal UAS Lidar

```
1. {
2.   "pipeline":[
3.     {
4.       "type": "readers.las",
5.       "filename": "#"
6.     },
7.     {
8.       "type": "filters.reprojection",
9.       "in_srs": "#",
10.      "out_srs": "#"
11.     },
12.     {
13.       "type": "filters.smrf",
14.       "scalar": 1.25,
15.       "slope": 0.1,
16.       "threshold": 0.4,
17.       "window": 3.0
18.     },
19.     {
20.       "type": "filters.range",
21.       "limits": "Classification[2:2]"
22.     },
23.     {
24.       "type": "writers.gdal",
25.       "filename": "#",
26.       "gdaldriver": "GTiff",
27.       "output_type": "mean",
28.       "radius": 0.5,
29.       "resolution": "1",
30.       "dimension": "Z"
31.     }
32. ]
33. }
```

APPENDIX C Precision3D DSM and DTM Co-Registration Results

Table C1. Horizontal (x, y) and vertical (z) translations required to align the Precision3D DSM to their respective reference lidar DSM. Translations were computed using the Nuth and Kaab (2011) co-registration methods.

DSM Site Name/Tile Name	Lidar Reference Dataset ID	X Shift (m)	Y Shift (m)	Z Shift (m)
AZ_Coconino_2019_B19_1	AZ_Coconino_B1_2019	0.23	-0.20	2.38
AZ_Coconino_2019_B19_2	AZ_Coconino_B1_2020	0.28	-0.10	2.38
AZ_MaricopaPinal_2020_B20_1	AZ_MaricopaPinal_1_2020	0.13	0.03	1.98
AZ_OrganPipeCactusNM_2020_B20_1	AZ_OrganPipeCactusNM_2020_B20	0.22	-0.72	2.47
AZ_PimaCounty_2021_B21_1	AZ_PimaCo_2_2021	0.33	0.06	1.64
AZ_Yavapai_2021_B21_1	AZ_Yavapai_2_2021	0.26	-0.15	1.22
CA_SierraNevada_B22_1	CA_SierraNevada_B22	0.28	0.12	2.51
CA_SierraNevada_B22_2	CA_SierraNevada_B22	0.07	-0.01	0.64
CA_SierraNevada_B22_3_1183556w_362626n	CA_SierraNevada_B22	0.63	-0.16	-0.73
CA_SierraNevada_B22_3_1183602w_363051n	CA_SierraNevada_B22	1.01	-0.49	-0.08
CA_SierraNevada_B22_3_1183607w_363517n	CA_SierraNevada_B22	0.84	-0.51	-0.22
CA_SierraNevada_B22_3_1183613w_363943n	CA_SierraNevada_B22	0.44	-0.11	-0.69
CA_SierraNevada_B22_3_1183618w_364409n	CA_SierraNevada_B22	0.43	-0.25	-0.39
CA_SierraNevada_B22_3_1184102w_360838n	CA_SierraNevada_B22	0.78	-0.48	-2.61
CA_SierraNevada_B22_3_1184108w_361304n	CA_SierraNevada_B22	0.44	-0.31	-1.89
CA_SierraNevada_B22_3_1184114w_361730n	CA_SierraNevada_B22	0.81	-0.31	-1.86
CA_SierraNevada_B22_3_1184120w_362155n	CA_SierraNevada_B22	0.49	-0.22	-1.30
CA_SierraNevada_B22_3_1184125w_362621n	CA_SierraNevada_B22	0.46	-0.23	-1.59
CA_SierraNevada_B22_3_1184131w_363047n	CA_SierraNevada_B22	0.65	-0.35	-0.49
CA_SierraNevada_B22_3_1184137w_363513n	CA_SierraNevada_B22	0.90	-0.52	-0.18
CA_SierraNevada_B22_3_1184143w_363938n	CA_SierraNevada_B22	0.57	-0.15	-0.21
CA_SierraNevada_B22_3_1184149w_364404n	CA_SierraNevada_B22	0.52	-0.37	0.09
CA_SierraNevada_B22_3_1184630w_360833n	CA_SierraNevada_B22	0.82	-0.67	0.41
CA_SierraNevada_B22_3_1184636w_361259n	CA_SierraNevada_B22	0.52	-0.36	-0.98
CA_SierraNevada_B22_3_1184642w_361725n	CA_SierraNevada_B22	0.68	-0.25	-1.36
CA_SierraNevada_B22_3_1184648w_362151n	CA_SierraNevada_B22	0.72	-0.29	-0.89
CA_SierraNevada_B22_3_1184654w_362616n	CA_SierraNevada_B22	0.74	-0.36	-0.59
CA_SierraNevada_B22_3_1184700w_363042n	CA_SierraNevada_B22	0.71	-0.38	-0.27
CA_SierraNevada_B22_3_1184706w_363508n	CA_SierraNevada_B22	0.53	-0.33	-0.25
CA_SierraNevada_B22_3_1184712w_363933n	CA_SierraNevada_B22	0.43	-0.31	0.61
CA_SierraNevada_B22_3_1184719w_364359n	CA_SierraNevada_B22	0.49	-0.36	0.03
CA_SierraNevada_B22_3_1185158w_360828n	CA_SierraNevada_B22	0.68	-0.47	1.38
CA_SierraNevada_B22_3_1185204w_361254n	CA_SierraNevada_B22	0.74	-0.48	1.50
CA_SierraNevada_B22_3_1185210w_361720n	CA_SierraNevada_B22	0.80	-0.38	1.21
CA_SierraNevada_B22_3_1185217w_362146n	CA_SierraNevada_B22	0.94	-0.46	1.15
CA_SierraNevada_B22_3_1185223w_362611n	CA_SierraNevada_B22	0.95	-0.58	0.88
CA_SierraNevada_B22_3_1185229w_363037n	CA_SierraNevada_B22	0.58	-0.42	0.20
CA_SierraNevada_B22_3_1185236w_363503n	CA_SierraNevada_B22	0.40	-0.35	0.15
CA_SierraNevada_B22_3_1185242w_363928n	CA_SierraNevada_B22	0.49	-0.36	1.50
CA_SierraNevada_B22_3_1185249w_364354n	CA_SierraNevada_B22	0.42	-0.36	-0.07
CA_YosemiteNP_2019_D19_1	CA_YosemiteNP_2019_D19	0.11	-0.02	1.04
CA_YosemiteNP_2019_D19_2	CA_YosemiteNP_2019_D20	0.34	0.13	1.74
CA_YosemiteNP_2019_D19_3	CA_YosemiteNP_2019_D21	0.00	-0.03	1.00
CO_CameronPeakWildfire_2021_D21_1	CO_CameronPeakWildfire_2021_D21	0.29	-0.17	0.82

CO_CameronPeakWildfire_2021_D21_2	CO_CameronPeakWildfire_2021_D22	0.26	-0.14	0.84
CO_EasternColorado_2018_A18_1	CO_EasternColorado_2018_A18	0.24	-0.05	1.97
CO_Southwest_NRCS_2018_D18_1	CO_Southwest_NRCS_2018_D18	0.09	-0.14	0.24
CO_WestCentral_2019_A19_1	CO_WestCentral_2019_A19	-0.06	-0.10	0.85
CO_WestCentral_2019_A19_2	CO_WestCentral_2019_A20	-0.03	-0.21	1.30
CO_WestCentral_2019_A19_3	CO_WestCentral_2019_A21	-0.05	-0.17	0.78
FL_Southwest_2018_D18_SUPPLEMENTAL_1	FL_Southwest_2018_D18_SUPPLEMENTAL	0.04	0.02	2.64
FL_Southwest_2018_D18_SUPPLEMENTAL_2	FL_Southwest_2018_D18_SUPPLEMENTAL	-0.07	0.00	2.74
FL_Southwest_2018_D18_SUPPLEMENTAL_3	FL_Southwest_2018_D18_SUPPLEMENTAL	-0.22	-0.27	2.62
GA_Central_2019_B19_1	GA_Central_2019_B19	0.12	-0.18	1.86
GA_Central_2019_B19_2	GA_Central_2019_B19	0.15	-0.03	1.71
LA_Catahoula_Concordia_2017_D17_2	LA_Catahoula_Concordia_2017_D17	0.27	-0.29	2.04
LA_Catahoula_Concordia_2017_D17_3	LA_Catahoula_Concordia_2017_D17	0.00	-0.10	1.84
LA_Catahoula_Concordia_2017_D17_1_0913144w 300110n	LA_Catahoula_Concordia_2017_D17	0.48	-0.39	2.77
LA_Catahoula_Concordia_2017_D17_1_0913148w 295644n	LA_Catahoula_Concordia_2017_D17	0.53	-0.37	2.79
LA_Catahoula_Concordia_2017_D17_1_0913646w 300539n	LA_Catahoula_Concordia_2017_D17	0.64	-0.46	3.66
LA_Catahoula_Concordia_2017_D17_1_0913649w 300113n	LA_Catahoula_Concordia_2017_D17	0.67	-0.49	3.45
LA_Catahoula_Concordia_2017_D17_1_0913653w 295647n	LA_Catahoula_Concordia_2017_D17	0.57	-0.38	2.64
LA_Catahoula_Concordia_2017_D17_1_0914148w 301008n	LA_Catahoula_Concordia_2017_D17	0.62	-0.46	3.32
LA_Catahoula_Concordia_2017_D17_1_0914152w 300542n	LA_Catahoula_Concordia_2017_D17	0.58	-0.47	3.05
LA_Catahoula_Concordia_2017_D17_1_0914155w 300116n	LA_Catahoula_Concordia_2017_D17	0.58	-0.51	3.02
LA_Catahoula_Concordia_2017_D17_1_0914159w 295650n	LA_Catahoula_Concordia_2017_D17	0.62	-0.38	3.31
LA_Catahoula_Concordia_2017_D17_1_0914651w 301437n	LA_Catahoula_Concordia_2017_D17	0.38	-0.42	3.70
LA_Catahoula_Concordia_2017_D17_1_0914654w 301011n	LA_Catahoula_Concordia_2017_D17	0.43	-0.51	3.61
LA_Catahoula_Concordia_2017_D17_1_0914658w 300545n	LA_Catahoula_Concordia_2017_D17	0.56	-0.51	3.20
LA_Catahoula_Concordia_2017_D17_1_0914701w 300119n	LA_Catahoula_Concordia_2017_D17	0.55	-0.53	4.00
LA_Catahoula_Concordia_2017_D17_1_0915154w 301906n	LA_Catahoula_Concordia_2017_D17	0.38	-0.58	3.98
LA_Catahoula_Concordia_2017_D17_1_0915157w 301440n	LA_Catahoula_Concordia_2017_D17	0.41	-0.68	3.75
LA_Catahoula_Concordia_2017_D17_1_0915200w 301014n	LA_Catahoula_Concordia_2017_D17	0.40	-0.62	4.10
LA_Catahoula_Concordia_2017_D17_1_0915204w 300548n	LA_Catahoula_Concordia_2017_D17	0.31	-0.21	4.52
LA_Catahoula_Concordia_2017_D17_1_0915701w 301909n	LA_Catahoula_Concordia_2017_D17	0.40	-0.50	3.91
LA_Catahoula_Concordia_2017_D17_1_0915704w 301443n	LA_Catahoula_Concordia_2017_D17	0.47	-0.64	3.43
LA_Catahoula_Concordia_2017_D17_1_0915707w 301017n	LA_Catahoula_Concordia_2017_D17	0.42	-0.54	3.75
LA_NortheastDOTD_2017_C20_1	LA_NortheastDOTD_2017_C20	0.05	0.16	2.56
MN_SE_Driftless_1_0912430w_435721n	MN_SE_Driftless_2021_B21	0.14	-0.16	-0.06
MN_SE_Driftless_1_0912437w_435256n	MN_SE_Driftless_2021_B21	0.22	-0.33	0.54
MN_SE_Driftless_1_0912444w_434831n	MN_SE_Driftless_2021_B21	0.25	-0.31	0.55
MN_SE_Driftless_1_0912451w_434405n	MN_SE_Driftless_2021_B21	0.19	-0.33	0.28
MN_SE_Driftless_1_0912458w_433940n	MN_SE_Driftless_2021_B21	0.21	-0.23	-0.27
MN_SE_Driftless_1_0912505w_433514n	MN_SE_Driftless_2021_B21	0.20	-0.27	-0.07
MN_SE_Driftless_1_0913038w_435726n	MN_SE_Driftless_2021_B21	0.23	-0.30	1.34
MN_SE_Driftless_1_0913044w_435301n	MN_SE_Driftless_2021_B21	0.25	-0.26	1.08

MN_SE_Driftless_1_0913051w_434836n	MN_SE_Driftless_2021_B21	0.23	-0.35	1.75
MN_SE_Driftless_1_0913057w_434410n	MN_SE_Driftless_2021_B21	0.20	-0.34	1.27
MN_SE_Driftless_1_0913104w_433945n	MN_SE_Driftless_2021_B21	0.16	-0.31	0.73
MN_SE_Driftless_1_0913110w_433519n	MN_SE_Driftless_2021_B21	0.23	-0.28	0.77
MN_SE_Driftless_1_0913645w_435731n	MN_SE_Driftless_2021_B21	0.31	-0.42	1.44
MN_SE_Driftless_1_0913651w_435306n	MN_SE_Driftless_2021_B21	0.38	-0.37	1.35
MN_SE_Driftless_1_0913657w_434840n	MN_SE_Driftless_2021_B21	0.51	-0.57	2.00
MN_SE_Driftless_1_0913703w_434415n	MN_SE_Driftless_2021_B21	0.35	-0.35	1.50
MN_SE_Driftless_1_0913709w_433949n	MN_SE_Driftless_2021_B21	0.23	-0.30	1.25
MN_SE_Driftless_1_0913716w_433524n	MN_SE_Driftless_2021_B21	0.45	-0.31	1.21
MN_SE_Driftless_1_0914252w_435735n	MN_SE_Driftless_2021_B21	0.39	-0.33	1.07
MN_SE_Driftless_1_0914258w_435310n	MN_SE_Driftless_2021_B21	0.40	-0.37	1.15
MN_SE_Driftless_1_0914304w_434845n	MN_SE_Driftless_2021_B21	0.34	-0.29	0.83
MN_SE_Driftless_1_0914309w_434419n	MN_SE_Driftless_2021_B21	0.30	-0.24	0.57
MN_SE_Driftless_1_0914315w_433954n	MN_SE_Driftless_2021_B21	0.27	-0.25	0.49
MN_SE_Driftless_1_0914321w_433528n	MN_SE_Driftless_2021_B21	0.31	-0.23	0.60
MN_SE_Driftless_1_0914900w_435739n	MN_SE_Driftless_2021_B21	0.28	-0.29	1.21
MN_SE_Driftless_1_0914905w_435314n	MN_SE_Driftless_2021_B21	0.31	-0.25	1.08
MN_SE_Driftless_1_0914910w_434848n	MN_SE_Driftless_2021_B21	0.24	-0.33	0.32
MN_SE_Driftless_1_0914916w_434423n	MN_SE_Driftless_2021_B21	0.23	-0.25	-0.13
MN_SE_Driftless_1_0914921w_433958n	MN_SE_Driftless_2021_B21	0.22	-0.21	0.05
MN_SE_Driftless_1_0914926w_433532n	MN_SE_Driftless_2021_B21	0.26	-0.21	-0.04
NE_PostSpringFlood_OrthoLidar_2019_D19_1	NE_PostSpringFlood_OrthoLidar_2019_D19	0.07	0.13	1.65
NE_PostSpringFlood_OrthoLidar_2019_D19_2	NE_PostSpringFlood_OrthoLidar_2019_D20	0.18	-0.09	1.36
NE_PostSpringFlood_OrthoLidar_2019_D19_3	NE_PostSpringFlood_OrthoLidar_2019_D21	0.09	-0.10	1.86
NE_PostSpringFlood_OrthoLidar_2019_D19_4	NE_PostSpringFlood_OrthoLidar_2019_D22	0.23	-0.08	2.36
NE_PostSpringFlood_OrthoLidar_2019_D19_5	NE_PostSpringFlood_OrthoLidar_2019_D23	0.30	-0.04	2.93
NE_PostSpringFlood_OrthoLidar_2019_D19_6	NE_PostSpringFlood_OrthoLidar_2019_D24	0.19	-0.08	1.50
NM_HermitsPeak_D23_1	NM_HermitsPeak_D23	0.03	-0.07	2.45
NM_HermitsPeak_D23_2	NM_HermitsPeak_D24	0.00	-0.06	0.26
OR_OLCMetro_2019_A19_1	OR_OLCMetro_2019_A19	0.21	0.10	0.09
OR_WesternWildfires_A22_1	OR_WesternWildfires_A22	-0.03	-0.16	4.29
OR_WesternWildfires_A22_2	OR_WesternWildfires_A23	0.12	-0.10	-3.28
SC_SavannahPeeDee_2019_B19_1	SC_SavannahPeeDee_2019_B19	0.09	-0.17	-1.21
SC_SavannahPeeDee_2019_B19_2	SC_SavannahPeeDee_2019_B20	-0.02	-0.22	-0.32
Senegal_230220_134217	Senegal_230220_134217	-0.35	-0.11	5.02
Senegal_230220_160421	Senegal_230220_160421	-0.21	-0.12	5.99
Senegal_230223_085011	Senegal_230223_085011	0.06	-0.01	2.61
Senegal_230223_092637	Senegal_230223_092637	-0.20	0.06	2.78
Senegal_230223_105654	Senegal_230223_105654	-0.17	-0.03	1.60
Senegal_230224_103852	Senegal_230224_103852	0.05	0.09	1.32
Senegal_230224_114919	Senegal_230224_114919	0.11	0.08	1.58
Senegal_230224_145307	Senegal_230224_145307	0.02	0.05	1.33
Senegal_230225_085946	Senegal_230225_085946	-0.10	-0.06	2.51
Senegal_230225_095401	Senegal_230225_095401	-0.14	-0.10	3.00
Senegal_230225_110217	Senegal_230225_110217	-0.09	0.03	2.51
Senegal_230225_172547	Senegal_230225_172547	-0.26	0.17	1.60
Senegal_230227_160049	Senegal_230227_160049	-0.14	0.22	2.53
Senegal_230227_170229	Senegal_230227_170229	-0.27	0.38	2.84
TX_DesertMountains_2018_D19_1	TX_DesertMountains_2018_D19	0.01	0.02	1.58
TX_DesertMountains_2018_D19_2	TX_DesertMountains_2018_D19	0.01	0.14	1.59
TX_DesertMountains_2018_D19_3	TX_DesertMountains_2018_D19	-0.01	0.01	1.47

UT_FEMA_FS_FlamingGorge_2020_B20_1	UT_FEMA_FS_FlamingGorge_2020_B20	0.07	-0.26	0.48
UT_FEMA_FS_FlamingGorge_2020_B20_2	UT_FEMA_FS_FlamingGorge_2020_B20	0.07	-0.14	1.46
UT_FEMA_FS_FlamingGorge_2020_B20_3	UT_FEMA_FS_FlamingGorge_2020_B20	0.12	-0.09	1.03
UT_FEMA_FS_FlamingGorge_2020_B20_4	UT_FEMA_FS_FlamingGorge_2020_B20	0.16	-0.11	0.72
UT_WestEast_B22_1	UT_WestEast_B22	0.11	-0.15	0.85
WA_NorthCentral_2021_B21_1	WA_NorthCentral_2021_B21	0.07	-0.08	0.08
WI_BrownRusk_2020_B20_1	WI_BrownRusk_2020_B20	0.14	-0.15	1.13

Table C2. Horizontal (x, y) and vertical (z) translations required to align the Precision3D DTM to their respective reference lidar DTM. Translations were computed using the Nuth and Kaab (2011) co-registration methods.

DTM Site Name/Tile Name	Lidar Reference Dataset ID	X Shift (m)	Y Shift (m)	Z Shift (m)
AZ_Coconino_2019_B19_1	AZ_Coconino_B1_2019	0.42	-3.23	-0.56
AZ_Coconino_2019_B19_2	AZ_Coconino_B1_2020	0.65	-2.67	-0.91
AZ_MaricopaPinal_2020_B20_1	AZ_MaricopaPinal_1_2020	0.51	0.03	1.82
AZ_OrganPipeCactusNM_2020_B20_1	AZ_OrganPipeCactusNM_2020_B20	0.75	-0.41	2.26
AZ_PimaCounty_2021_B21_1	AZ_PimaCo_2_2021	0.71	0.47	0.97
AZ_Yavapai_2021_B21_1	AZ_Yavapai_2_2021	1.10	-0.60	0.86
CA_SierraNevada_B22_1	CA_SierraNevada_B22	1.09	-0.65	-1.98
CA_SierraNevada_B22_2	CA_SierraNevada_B22	0.74	-0.63	-1.24
CA_SierraNevada_B22_3_1183556w_362626n	CA_SierraNevada_B22	0.18	-0.63	-0.57
CA_SierraNevada_B22_3_1183602w_363051n	CA_SierraNevada_B22	0.94	-0.83	-1.52
CA_SierraNevada_B22_3_1183607w_363517n	CA_SierraNevada_B22	0.45	-0.64	-1.58
CA_SierraNevada_B22_3_1183613w_363943n	CA_SierraNevada_B22	1.22	-0.81	-4.32
CA_SierraNevada_B22_3_1183618w_364409n	CA_SierraNevada_B22	0.63	-0.23	-3.32
CA_SierraNevada_B22_3_1184102w_360838n	CA_SierraNevada_B22	0.55	-1.98	-3.63
CA_SierraNevada_B22_3_1184108w_361304n	CA_SierraNevada_B22	0.88	-0.51	-2.34
CA_SierraNevada_B22_3_1184114w_361730n	CA_SierraNevada_B22	0.80	-1.40	-4.78
CA_SierraNevada_B22_3_1184120w_362155n	CA_SierraNevada_B22	1.34	-1.06	-2.19
CA_SierraNevada_B22_3_1184125w_362621n	CA_SierraNevada_B22	0.88	-0.68	-0.52
CA_SierraNevada_B22_3_1184131w_363047n	CA_SierraNevada_B22	0.48	-0.70	-1.27
CA_SierraNevada_B22_3_1184137w_363513n	CA_SierraNevada_B22	0.99	-1.29	-1.55
CA_SierraNevada_B22_3_1184143w_363938n	CA_SierraNevada_B22	1.37	-1.43	-1.13
CA_SierraNevada_B22_3_1184149w_364404n	CA_SierraNevada_B22	1.07	-1.11	-3.49
CA_SierraNevada_B22_3_1184630w_360833n	CA_SierraNevada_B22	0.51	-0.82	-4.22
CA_SierraNevada_B22_3_1184636w_361259n	CA_SierraNevada_B22	1.46	-1.12	-3.31
CA_SierraNevada_B22_3_1184642w_361725n	CA_SierraNevada_B22	0.64	-1.03	-2.55
CA_SierraNevada_B22_3_1184648w_362151n	CA_SierraNevada_B22	0.98	-1.47	-3.53
CA_SierraNevada_B22_3_1184654w_362616n	CA_SierraNevada_B22	0.94	-0.63	-1.60
CA_SierraNevada_B22_3_1184700w_363042n	CA_SierraNevada_B22	0.29	-0.81	-0.45
CA_SierraNevada_B22_3_1184706w_363508n	CA_SierraNevada_B22	1.25	-1.54	-2.05
CA_SierraNevada_B22_3_1184712w_363933n	CA_SierraNevada_B22	0.17	-0.98	0.83
CA_SierraNevada_B22_3_1184719w_364359n	CA_SierraNevada_B22	0.71	-0.61	0.21
CA_SierraNevada_B22_3_1185158w_360828n	CA_SierraNevada_B22	0.39	-1.02	-0.81
CA_SierraNevada_B22_3_1185204w_361254n	CA_SierraNevada_B22	0.86	-0.88	-0.93
CA_SierraNevada_B22_3_1185210w_361720n	CA_SierraNevada_B22	0.43	-0.64	-0.79
CA_SierraNevada_B22_3_1185217w_362146n	CA_SierraNevada_B22	0.60	-1.55	-2.77
CA_SierraNevada_B22_3_1185223w_362611n	CA_SierraNevada_B22	1.74	-1.38	-3.52
CA_SierraNevada_B22_3_1185229w_363037n	CA_SierraNevada_B22	1.06	-0.86	0.98
CA_SierraNevada_B22_3_1185236w_363503n	CA_SierraNevada_B22	0.80	-1.90	-1.46
CA_SierraNevada_B22_3_1185242w_363928n	CA_SierraNevada_B22	1.16	0.00	0.89

CA_SierraNevada_B22_3_1185249w_364354n	CA_SierraNevada_B22	0.39	-1.07	-1.77
CA_YosemiteNP_2019_D19_1	CA_YosemiteNP_2019_D19	1.09	-0.50	-0.11
CA_YosemiteNP_2019_D19_2	CA_YosemiteNP_2019_D20	1.28	0.40	1.17
CA_YosemiteNP_2019_D19_3	CA_YosemiteNP_2019_D21	-0.03	-1.21	-0.24
CO_CameronPeakWildfire_2021_D21_1	CO_CameronPeakWildfire_2021_D21	1.26	-0.31	0.20
CO_CameronPeakWildfire_2021_D21_2	CO_CameronPeakWildfire_2021_D22	1.44	-0.68	0.48
CO_EasternColorado_2018_A18_1	CO_EasternColorado_2018_A18	1.54	-1.00	1.95
CO_Southwest_NRCS_2018_D18_1	CO_Southwest_NRCS_2018_D18	1.24	-0.60	-0.67
CO_WestCentral_2019_A19_1	CO_WestCentral_2019_A19	-0.17	0.30	1.29
CO_WestCentral_2019_A19_2	CO_WestCentral_2019_A20	-0.34	-0.66	0.61
CO_WestCentral_2019_A19_3	CO_WestCentral_2019_A21	-0.39	-0.75	0.40
FL_Southwest_2018_D18_SUPPLEMENTAL_1	FL_Southwest_2018_D18_SUPPLEMENTAL	-0.06	0.02	2.40
FL_Southwest_2018_D18_SUPPLEMENTAL_2	FL_Southwest_2018_D18_SUPPLEMENTAL	-0.14	-0.10	2.57
FL_Southwest_2018_D18_SUPPLEMENTAL_3	FL_Southwest_2018_D18_SUPPLEMENTAL	-0.10	-0.21	2.50
GA_Central_2019_B19_1	GA_Central_2019_B19	-0.13	-0.35	1.55
GA_Central_2019_B19_2	GA_Central_2019_B19	-0.10	-0.13	1.39
LA_Catahoula_Concordia_2017_D17_2	LA_Catahoula_Concordia_2017_D17	0.69	0.53	3.08
LA_Catahoula_Concordia_2017_D17_3	LA_Catahoula_Concordia_2017_D17	-3.15	-1.34	2.71
LA_Catahoula_Concordia_2017_D17_1_0913144w_300110n	LA_Catahoula_Concordia_2017_D17	0.04	-1.07	1.98
LA_Catahoula_Concordia_2017_D17_1_0913148w_295644n	LA_Catahoula_Concordia_2017_D17	-0.10	-0.34	2.44
LA_Catahoula_Concordia_2017_D17_1_0913646w_300539n	LA_Catahoula_Concordia_2017_D17	0.73	0.26	1.82
LA_Catahoula_Concordia_2017_D17_1_0913649w_300113n	LA_Catahoula_Concordia_2017_D17	-0.40	0.35	2.31
LA_Catahoula_Concordia_2017_D17_1_0913653w_295647n	LA_Catahoula_Concordia_2017_D17	-0.27	-0.71	2.30
LA_Catahoula_Concordia_2017_D17_1_0914148w_301008n	LA_Catahoula_Concordia_2017_D17	0.29	-0.13	2.03
LA_Catahoula_Concordia_2017_D17_1_0914152w_300542n	LA_Catahoula_Concordia_2017_D17	0.54	0.85	2.14
LA_Catahoula_Concordia_2017_D17_1_0914155w_300116n	LA_Catahoula_Concordia_2017_D17	0.27	-0.02	3.10
LA_Catahoula_Concordia_2017_D17_1_0914159w_295650n	LA_Catahoula_Concordia_2017_D17	0.05	-0.05	2.80
LA_Catahoula_Concordia_2017_D17_1_0914651w_301437n	LA_Catahoula_Concordia_2017_D17	0.31	-0.08	2.70
LA_Catahoula_Concordia_2017_D17_1_0914654w_301011n	LA_Catahoula_Concordia_2017_D17	0.45	0.01	2.51
LA_Catahoula_Concordia_2017_D17_1_0914658w_300545n	LA_Catahoula_Concordia_2017_D17	0.47	0.53	2.86
LA_Catahoula_Concordia_2017_D17_1_0914701w_300119n	LA_Catahoula_Concordia_2017_D17	0.21	-0.23	3.07
LA_Catahoula_Concordia_2017_D17_1_0915154w_301906n	LA_Catahoula_Concordia_2017_D17	0.19	0.06	2.95
LA_Catahoula_Concordia_2017_D17_1_0915157w_301440n	LA_Catahoula_Concordia_2017_D17	0.21	0.12	2.74
LA_Catahoula_Concordia_2017_D17_1_0915200w_301014n	LA_Catahoula_Concordia_2017_D17	0.00	0.35	2.78
LA_Catahoula_Concordia_2017_D17_1_0915204w_300548n	LA_Catahoula_Concordia_2017_D17	0.33	-0.06	2.77
LA_Catahoula_Concordia_2017_D17_1_0915701w_301909n	LA_Catahoula_Concordia_2017_D17	0.77	-0.72	2.86
LA_Catahoula_Concordia_2017_D17_1_0915704w_301443n	LA_Catahoula_Concordia_2017_D17	0.07	-0.10	1.24
LA_Catahoula_Concordia_2017_D17_1_0915707w_301017n	LA_Catahoula_Concordia_2017_D17	0.36	-1.51	-6.75
LA_NortheastDOTD_2017_C20_1	LA_NortheastDOTD_2017_C20	0.07	-0.05	1.52
MN_SE_Driftless_1_0912430w_435721n	MN_SE_Driftless_2021_B21	-0.70	-0.26	-2.34
MN_SE_Driftless_1_0912437w_435256n	MN_SE_Driftless_2021_B21	0.48	-0.91	-1.20
MN_SE_Driftless_1_0912444w_434831n	MN_SE_Driftless_2021_B21	0.71	-0.94	-0.42

MN_SE_Driftless_1_0912451w_434405n	MN_SE_Driftless_2021_B21	0.50	-0.87	-0.83
MN_SE_Driftless_1_0912458w_433940n	MN_SE_Driftless_2021_B21	0.50	-1.13	-1.08
MN_SE_Driftless_1_0912505w_433514n	MN_SE_Driftless_2021_B21	1.01	-1.97	-1.13
MN_SE_Driftless_1_0913038w_435726n	MN_SE_Driftless_2021_B21	1.13	-2.61	-1.48
MN_SE_Driftless_1_0913044w_435301n	MN_SE_Driftless_2021_B21	1.15	-2.05	0.08
MN_SE_Driftless_1_0913051w_434836n	MN_SE_Driftless_2021_B21	0.77	-0.91	0.19
MN_SE_Driftless_1_0913057w_434410n	MN_SE_Driftless_2021_B21	1.01	-2.42	-0.25
MN_SE_Driftless_1_0913104w_433945n	MN_SE_Driftless_2021_B21	0.46	-1.23	0.24
MN_SE_Driftless_1_0913110w_433519n	MN_SE_Driftless_2021_B21	0.71	-1.17	0.49
MN_SE_Driftless_1_0913645w_435731n	MN_SE_Driftless_2021_B21	0.86	-0.73	0.38
MN_SE_Driftless_1_0913651w_435306n	MN_SE_Driftless_2021_B21	1.23	-0.71	0.80
MN_SE_Driftless_1_0913657w_434840n	MN_SE_Driftless_2021_B21	0.77	-0.39	0.36
MN_SE_Driftless_1_0913703w_434415n	MN_SE_Driftless_2021_B21	0.80	-1.14	0.29
MN_SE_Driftless_1_0913709w_433949n	MN_SE_Driftless_2021_B21	1.24	-1.09	0.00
MN_SE_Driftless_1_0913716w_433524n	MN_SE_Driftless_2021_B21	0.56	-0.97	0.92
MN_SE_Driftless_1_0914252w_435735n	MN_SE_Driftless_2021_B21	0.61	-0.72	0.61
MN_SE_Driftless_1_0914258w_435310n	MN_SE_Driftless_2021_B21	0.57	-1.46	0.58
MN_SE_Driftless_1_0914304w_434845n	MN_SE_Driftless_2021_B21	0.23	-2.21	-1.58
MN_SE_Driftless_1_0914309w_434419n	MN_SE_Driftless_2021_B21	0.02	-2.45	-3.20
MN_SE_Driftless_1_0914315w_433954n	MN_SE_Driftless_2021_B21	0.35	-0.73	-1.70
MN_SE_Driftless_1_0914321w_433528n	MN_SE_Driftless_2021_B21	0.16	-0.92	-0.13
MN_SE_Driftless_1_0914900w_435739n	MN_SE_Driftless_2021_B21	0.38	-0.66	1.01
MN_SE_Driftless_1_0914905w_435314n	MN_SE_Driftless_2021_B21	1.08	-0.74	0.92
MN_SE_Driftless_1_0914910w_434848n	MN_SE_Driftless_2021_B21	1.16	-0.28	-0.93
MN_SE_Driftless_1_0914916w_434423n	MN_SE_Driftless_2021_B21	1.26	-2.01	-2.23
MN_SE_Driftless_1_0914921w_433958n	MN_SE_Driftless_2021_B21	0.49	-0.69	-0.36
MN_SE_Driftless_1_0914926w_433532n	MN_SE_Driftless_2021_B21	0.79	-0.21	-0.28
NE_PostSpringFlood_OrthoLidar_2019_D19_1	NE_PostSpringFlood_OrthoLidar_2019_D19	-0.28	1.04	1.59
NE_PostSpringFlood_OrthoLidar_2019_D19_2	NE_PostSpringFlood_OrthoLidar_2019_D20	0.98	-0.25	1.09
NE_PostSpringFlood_OrthoLidar_2019_D19_3	NE_PostSpringFlood_OrthoLidar_2019_D21	0.84	-0.03	1.56
NE_PostSpringFlood_OrthoLidar_2019_D19_4	NE_PostSpringFlood_OrthoLidar_2019_D22	0.87	0.07	2.40
NE_PostSpringFlood_OrthoLidar_2019_D19_5	NE_PostSpringFlood_OrthoLidar_2019_D23	0.37	0.31	2.81
NE_PostSpringFlood_OrthoLidar_2019_D19_6	NE_PostSpringFlood_OrthoLidar_2019_D24	0.54	-0.12	1.10
NM_HermitsPeak_D23_1	NM_HermitsPeak_D23	-0.09	0.34	3.48
NM_HermitsPeak_D23_2	NM_HermitsPeak_D24	0.30	-0.55	0.25
OR_OLCMetro_2019_A19_1	OR_OLCMetro_2019_A19	0.90	0.80	-0.02
OR_WesternWildfires_A22_1	OR_WesternWildfires_A22	-1.59	0.94	0.41
OR_WesternWildfires_A22_2	OR_WesternWildfires_A23	0.98	-0.48	-1.61
SC_SavannahPeeDec_2019_B19_1	SC_SavannahPeeDec_2019_B19	-0.21	-0.42	-2.55
SC_SavannahPeeDec_2019_B19_2	SC_SavannahPeeDec_2019_B20	0.88	0.22	-2.19
Senegal_230220_134217	Senegal_230220_134217	1.31	-3.25	1.82
Senegal_230220_160421	Senegal_230220_160421	1.49	-2.34	1.32
Senegal_230223_085011	Senegal_230223_085011	0.07	-0.01	1.17
Senegal_230223_092637	Senegal_230223_092637	0.08	0.00	1.21
Senegal_230223_105654	Senegal_230223_105654	-0.08	-0.11	-0.59
Senegal_230224_103852	Senegal_230224_103852	-0.02	0.03	0.89
Senegal_230224_114919	Senegal_230224_114919	-0.04	0.10	1.01
Senegal_230224_145307	Senegal_230224_145307	-0.22	0.32	1.10
Senegal_230225_085946	Senegal_230225_085946	-0.06	0.03	2.19
Senegal_230225_095401	Senegal_230225_095401	0.10	-0.16	2.20
Senegal_230225_110217	Senegal_230225_110217	-0.77	0.22	2.28
Senegal_230225_172547	Senegal_230225_172547	-2.72	-1.51	1.58

Senegal_230227_160049	Senegal_230227_160049	-1.26	0.70	2.41
Senegal_230227_170229	Senegal_230227_170229	-0.86	0.70	2.70
TX_DesertMountains_2018_D19_1	TX_DesertMountains_2018_D19	0.12	0.00	1.51
TX_DesertMountains_2018_D19_2	TX_DesertMountains_2018_D19	0.33	0.07	1.56
TX_DesertMountains_2018_D19_3	TX_DesertMountains_2018_D19	0.00	0.18	1.44
UT_FEMA_FS_FlamingGorge_2020_B20_1	UT_FEMA_FS_FlamingGorge_2020_B20	0.31	-1.32	-0.89
UT_FEMA_FS_FlamingGorge_2020_B20_2	UT_FEMA_FS_FlamingGorge_2020_B20	0.21	-0.83	0.65
UT_FEMA_FS_FlamingGorge_2020_B20_3	UT_FEMA_FS_FlamingGorge_2020_B20	1.20	-1.31	-0.08
UT_FEMA_FS_FlamingGorge_2020_B20_4	UT_FEMA_FS_FlamingGorge_2020_B20	1.00	-2.46	-0.41
UT_WestEast_B22_1	UT_WestEast_B22	0.39	-0.73	-0.18
WA_NorthCentral_2021_B21_1	WA_NorthCentral_2021_B21	0.56	-0.18	-0.90
WI_BrownRusk_2020_B20_1	WI_BrownRusk_2020_B20	0.33	-0.37	1.40

APPENDIX D Precision3D DSM and DTM Vertical Error by Aspect

Table D1. Precision3D DSM vertical errors by aspect. One million points were randomly sampled per aspect group, which contained all land cover types. Errors are provided in meters.

Aspect (degrees)	Minimum	Maximum	Median	Mean	StD	RMSE	LE90	Count
0-15	-52.8	60.8	0.0	0.0	4.4	4.4	6.5	1,000,000
15-30	-54.8	65.2	0.0	0.2	4.5	4.5	6.8	1,000,000
30-45	-52.5	98.6	0.1	0.4	4.6	4.6	7.0	1,000,000
45-60	-52.7	60.8	0.1	0.5	4.7	4.7	7.1	1,000,000
60-75	-59.0	69.8	0.1	0.6	4.8	4.8	7.3	1,000,000
75-90	-58.3	65.1	0.1	0.7	4.8	4.9	7.3	1,000,000
90-105	-60.5	65.2	0.2	0.7	4.9	4.9	7.4	1,000,000
105-120	-59.0	64.2	0.2	0.7	5.0	5.0	7.6	1,000,000
120-135	-64.0	86.9	0.2	0.7	4.9	5.0	7.5	1,000,000
135-150	-56.9	62.5	0.2	0.6	4.8	4.8	7.3	1,000,000
150-165	-67.8	62.8	0.2	0.5	4.7	4.7	7.1	1,000,000
165-180	-60.3	61.2	0.2	0.3	4.5	4.5	6.7	1,000,000
180-195	-58.2	79.3	0.2	0.2	4.4	4.4	6.4	1,000,000
195-210	-58.1	65.5	0.1	0.1	4.4	4.4	6.4	1,000,000
210-225	-60.0	61.7	0.1	0.0	4.3	4.3	6.3	1,000,000
225-240	-70.9	60.6	0.1	0.0	4.3	4.3	6.2	1,000,000
240-255	-58.2	57.5	0.1	-0.1	4.2	4.2	6.1	1,000,000
255-270	-57.9	58.3	0.1	-0.1	4.2	4.2	6.0	1,000,000
270-285	-54.5	100.6	0.1	-0.2	4.2	4.2	6.0	1,000,000
285-300	-57.7	80.3	0.0	-0.2	4.2	4.2	6.1	1,000,000
300-315	-56.0	72.7	0.0	-0.2	4.2	4.2	6.2	1,000,000
315-330	-57.1	71.6	0.0	-0.2	4.2	4.2	6.1	1,000,000
330-345	-53.4	90.1	0.0	-0.2	4.2	4.2	6.1	1,000,000
345-360	-60.0	71.8	0.0	-0.1	4.2	4.2	6.2	1,000,000

Table D2. Precision3D DTM vertical errors by aspect. One million points were randomly sampled per aspect group, which contained all land cover types. Errors are provided in meters.

Aspect (degrees)	Minimum	Maximum	Median	Mean	StD	RMSE	LE90	Count
0-15	-42.3	81.2	0.0	0.6	3.5	3.6	5.2	1,000,000
15-30	-42.6	51.8	0.0	0.6	3.7	3.7	5.7	1,000,000
30-45	-39.9	47.3	0.0	0.6	3.8	3.9	6.1	1,000,000
45-60	-46.6	55.0	0.0	0.6	4.0	4.0	6.5	1,000,000
60-75	-47.3	58.3	0.0	0.6	4.1	4.2	6.8	1,000,000
75-90	-40.5	55.4	-0.1	0.5	4.2	4.3	6.9	1,000,000
90-105	-56.9	54.3	-0.1	0.4	4.4	4.5	7.2	1,000,000
105-120	-41.8	59.8	-0.1	0.3	4.6	4.6	7.5	1,000,000
120-135	-65.3	43.5	-0.1	0.3	4.6	4.6	7.5	1,000,000
135-150	-65.5	54.5	-0.1	0.2	4.5	4.5	7.4	1,000,000
150-165	-44.7	44.6	-0.1	0.2	4.4	4.4	7.1	1,000,000
165-180	-43.5	48.4	-0.1	0.2	4.1	4.1	6.6	1,000,000
180-195	-42.5	56.0	-0.1	0.3	3.8	3.9	6.0	1,000,000
195-210	-43.2	52.0	-0.1	0.3	3.6	3.7	5.6	1,000,000
210-225	-41.0	47.6	0.0	0.4	3.5	3.5	5.1	1,000,000
225-240	-57.2	46.3	0.0	0.5	3.4	3.4	4.8	1,000,000
240-255	-43.9	40.3	0.0	0.5	3.3	3.3	4.7	1,000,000
255-270	-40.1	69.5	0.1	0.6	3.3	3.3	4.5	1,000,000
270-285	-43.7	60.4	0.1	0.6	3.2	3.3	4.4	1,000,000
285-300	-41.5	65.6	0.1	0.6	3.2	3.3	4.4	1,000,000
300-315	-58.9	41.7	0.1	0.6	3.2	3.3	4.5	1,000,000
315-330	-39.8	84.5	0.1	0.6	3.3	3.3	4.5	1,000,000
330-345	-60.2	51.5	0.1	0.6	3.3	3.4	4.7	1,000,000
345-360	-48.6	85.5	0.0	0.6	3.4	3.4	4.9	1,000,000