Lidar Mapping Report for the U.S. Geological Survey

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Attachment 1: Flight Logs
Attachment 2: GPS IMU Images

1. Overview

1.1. Description

HI_NOAAMauiOahu_1_B20, WU 198372 is part of Task order 140G0220F0290.
This Lidar Mapping Report will cover the acquisition, processing, and derivative products of Work Unit 198372. Lidar data was collected to an aggregate nominal pulse spacing (ANPS) of ≤0.35-meters and 8-points per square meter (ppsm) to meet USGS Quality Level 1 standards. The work unit covers approximately 260.7 square miles of Molokai, 140.7 square miles of Lanai, and 44.6 square miles of Kahoolawe in the state of Hawaii. In addition to high density lidar data acquisition, new ground control survey data was collected to support lidar data production and accuracy.

Note: Between 2020 and 2023 multiple mobilizations were made to collect the data in the project area due to the extreme terrain and persistent low clouds. On March 31, 2023, it was decided between Woolpert and USGS to end the acquisition phase of the project and move onto processing with the data collected. The DPA and work unit has been clipped to the extent of the data collected. Areas of low point density and/or small data voids within the work unit have been identified with low confidence polygons.

Figure 1.1.1 – HI_NOAAMauiOahu_1_B20

1.2. Purpose

This project will support USGS and the 3DEP mission, FEMA, and state and local agencies.

1.3. Specifications

Data and reporting for this task order were acquired and produced to meet the "*National Geospatial Program Lidar Base Specification Version 2.1*", and the American Society of Photogrammetry and Remote Sensing (ASPRS) "*Positional Accuracy Standards for Digital Geospatial Data (Edition 1, Version 1.0)*". Maximum Surface Height Rasters (MSHR) and Swath Separation Images (SSI) will also be delivered.

1.4. Spatial Reference

Geospatial data products were produced using the following spatial data reference system:

- Horizontal Datum: NAD83 (PA11)
- Horizontal Projection: UTM 4N
- Horizontal Units: Meters
- Horizontal EPSG Code: 6634
- Vertical Datum: NAVD88
- Geoid Model: 12B
- Vertical Units: Meters
- Height Type: Orthometric

1.5. Task Order Deliverables

All data products produced as part of this task order are listed below. All tiled deliverables had a tile size of 500-meters x 500-meters. The delivery tiles are named in accordance with the US National Grid convention. This delivery's tiled dataset contains a total of 5,044 tiles.

1.5.1. Lidar Data

- Classified lidar point cloud data in compressed LAZ format:
    - Class 1 – Default / Processed, but not Classified
    - Class 2 – Bare Earth Ground
    - Class 7 – Low Noise
    - Class 9 – Water
    - Class 17 – Bridge Decks
    - Class 18 – High Noise
    - Class 20 – Ignored Ground
- Breaklines used for hydro-flattening:
    - Rivers 30.5-meters / 100-feet and greater in width as PolylineZ features in Esri geodatabase format
    - Waterbodies greater than 2-acres as PolygonZ feature classes in Esri geodatabase format
    - Bridges used in DEM generation as PointZ feature classes in Esri .shp format
- Hydro-flattened bare earth digital elevation model (DEM): 0.5-meter pixel size, 32-bit floating-point with no bridges or overpass structures, in GeoTIFF format.
- Intensity Images: 0.5-meter pixel, 8-bit, 256 gray scale intensity images (normalized to 16-bit intensity), in GeoTIFF format.

1.5.2. Metadata

- Tile index: Esri .shp format.
- Swath polygons: Georeferenced, polygonal representation of the detailed extents of each lidar swath as polygon feature class in an Esri file geodatabase format.
- Maximum height separation rasters: 1.0-meter pixel size, 32-bit floating-point, GeoTIFF format.
- Swath separation images: 1.0-meter pixel size, GeoTIFF format.
- Lidar Mapping Report in PDF Format.
- Product level xml metadata for LAZ, Bare Earth DEM, Breaklines, Intensity, SSI, and MSHR products.

2. Lidar Data Acquisition

The lidar data for was acquired by Woolpert acquisition partners Kodiak and Resource Mapping Hawaii (RMH), based on the specifications listed below:

- Resolution: 8 points per square meter, with 0.35-meter nominal point spacing.
- Overlap: At contractor's discretion, but enough to ensure there are no data gaps between usable portions of the swath and to ensure the aggregate nominal point density (ANPD) is achieved
- Acquisition Window: August 2, 2022, through July 9, 2023
- Acquisition Conditions:
    - Daytime Acquisition.
    - No snow is on the ground.
    - Rivers are within their channels at or below their normal levels.
    - Sky is sufficiently clear of clouds, smoke, and atmospheric haze.
- Control: Airborne Global Positioning System (ABGPS) and Inertial Measurement Unit (IMU) data to be used along with differentially-corrected GPS ground control points.
- Data Voids are not allowed except:
    - Where caused by waterbodies.
    - Where caused by areas of low near infra-red (NIR) reflectivity (i.e. asphalt, composition roofing).
    - Where caused by lidar shadowing from buildings or other features.
    - Where appropriately filled-in by another swath.
    - Where identified by low confidence polygon.

2.1. Lidar Sensor Information

Aerial lidar data was acquired using the RIEGL VQ-780 II-S and Optech Galaxy Prime lidar sensor systems.

2.2. Timeline

Lidar data was collected from August 2, 2022, through July 9, 2023. A total of 325 individual flight lines were collected. Flight logs are contained in Attachment 1: Flight Logs.

2.3. GNSS and IMU Equipment

Prior to mobilizing to the project site, flight crews coordinated with required air traffic control personnel to ensure airspace access. Crews were on-site, operating a Global Navigation Satellite System (GNSS) Base Station for airborne GPS support.

Flight navigation during acquisition was performed using Integrated Geospatial Innovations' CCNS (Computer Controlled Navigation System). The pilots are skilled at maintaining their planned trajectory, while holding the aircraft steady and level. If atmospheric conditions were such that the trajectory, ground speed, roll, pitch and/or heading could not be properly maintained, the mission was aborted until suitable conditions occur.

Base stations were set by acquisition staff to support the aerial data acquisition. Table 1.10.1 lists the Station ID and coordinates for all base stations operated during acquisition. GPS/IMU graphics are contained in Attachment 2: GPS IMU Images.

Figure 1.10.1. Flight Coverage by Lift

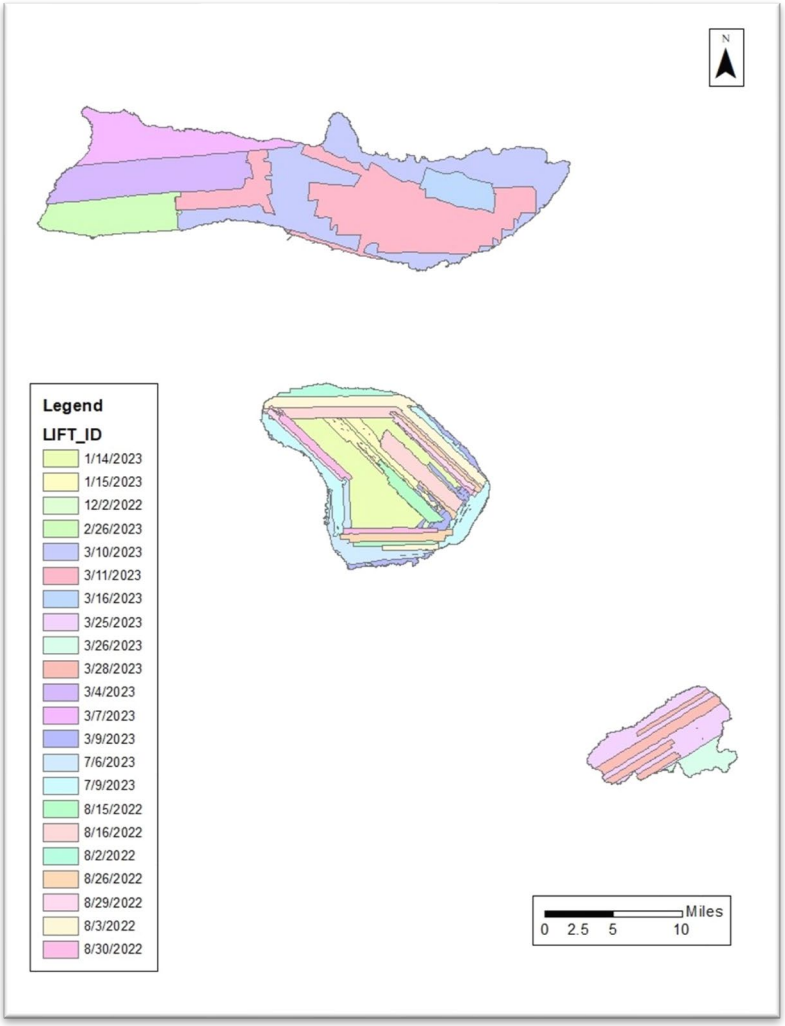


Table 1.10.1. GNSS Base Stations

Station Name	Longitude (DMS)	Latitude (DMS)	Ellipsoid Height L1 Phase Center (M)
104_2021_HI	21°08'01.78190"	-157°03'13.13714"	163.509
105_2021_HI	21°08'50.69344"	-157°11'57.74206"	322.931
106_2021_HI	21°03'32.56310"	-156°50'03.32212"	21.720
M 1	21°05'09.17737"	-157°01'24.91202"	18.208

2.4. Acquisition Quality Assurance

Woolpert worked with acquisition team partners Kodiak and RMH to develop a quality assurance and validation plan to ensure the acquired lidar data meets the USGS Lidar Base Specification. During the initial quality check, the lidar data was processed immediately following acquisition to verify the coverage has appropriate density, distribution, and no unacceptable data voids. The spatial distribution of the geometrically usable first return lidar points was reviewed for density by verifying the points spaced so that 90% of the cells in a 2*NPS grid placed over the data contain at least one lidar point. The Nominal Point Spacing (NPS) assessment was conducted against single swath, first return data located within the geometrically usable center portion (typically ~90%) of each swath. The data coverage was reviewed for unacceptable data voids to determine no area greater than or equal to $(4 \times ANPS)^2$ exhibited data coverage gaps.

Accompanying GPS data was post processed using differential and Kalman filter algorithms to derive a best estimate of trajectory. The quality of the solution was verified to be consistent with the accuracy requirements of the task order. Any required re-flights were scheduled at the earliest opportunity.

3. Lidar Data Processing

3.1. Processing Summary

Once the lidar data passed initial QC, the dataset was corrected for aircraft orientation and movement. This process used airborne inertial, orientation, and GPS data collected during acquisition along with ground-based GPS data. The data was subject to geometric calibration that further corrected each laser point. This calibrated dataset was used to create the LAS point cloud. LAS point data was initially classified into “ground” and “non-ground”, then further refined using the classes specified by the task order. Breaklines were drawn to denote hydrological features. After the hydro-flattening process, the final deliverable products were created.

3.2. GPS-IMU Trajectory Processing

Kinematic corrections for the aircraft position were resolved using aircraft GPS and static ground GPS (1-Hz) for each geodetic control (base station) for three subsystems: inertial measurement unit (IMU), sensor orientation information, and airborne GPS data.

Post-processing of the IMU system data and aircraft position with attitude data was completed to compute an optimally accurate and blended navigation solution based on Kalman filtering technology, or the smoothed best estimate of trajectory (SBET).

For more information, see the GPS/IMU graphics in Attachment 2: GPS IMU Images. Software used included POSPac Software v. 5.3, IPAS Pro v.1.35., and Novatel Inertial Explorer v8.60.6129.

3.2.1. Trajectory Quality

The GNSS trajectory and high-quality IMU data are key factors in determining the overall positional accuracy of the final sensor data. Within the trajectory processing, there are many factors that affect the overall quality, but the most indicative are the combined separation, the estimated positional accuracy, and the Positional Dilution of Precision (PDOP).

3.2.2. Combination Separation

Combined separation is a measure of the difference between the forward-run and the backward-run solution of the trajectory. The Kalman filter was processed in both directions to remove the combined directional anomalies. In general, when these two solutions match closely, an optimally accurate and reliable solution is achieved. The data for this task order was processed with a goal to maintain a combined separation difference of less than 10-cm.

3.2.3. Estimated Positional Accuracy

Estimated positional accuracy plots the standard deviations of the east, north, and vertical directions along a time scale of the trajectory. It illustrates loss of satellite lock issues, as well as issues arising from long baselines, noise, and/or other atmospheric interference.

3.2.4. PDOP

The PDOP measures the precision of the GPS solution in regard to the geometry of the satellites acquired and used for the solution. Lidar data for this task order was processed with a goal to maintain an average PDOP value below 3.0. Brief periods of PDOP over 3.0 are acceptable due to the calibration and control process if other metrics are within specification.

3.3. Boresight and Geometric Calibration

After the initial phase was complete, a formal reduction process was performed. Boresight calibrations (omega, phi, kappa) are performed, and a block adjustment is made to ensure relative accuracy. The laser point position was then calculated by associating the SBET position to each laser point return time, scan angle, intensity, etc. Raw laser point cloud data was created for the whole project area in LAS format with each point containing the corresponding scan angle, return number (echo), intensity, and x, y, and z information. Automated line-to-line calibrations were then performed for system attitude parameters (pitch, roll, heading), mirror flex (scale) and GPS/IMU drift to test the relative calibration. Calibrations were performed on ground classified points from paired flight lines. Every flight line was used for relative accuracy calibration. Statistical reports were generated for comparison and used to make the necessary adjustments to remove any residual systematic error.

3.4. Relative Accuracy: Interswath (Overlap) Consistency

This project required the interswath accuracy to meet ≤ 8-cm RMSDz. Accuracy was assessed in accordance with "*National Geospatial Program Lidar Base Specification Version 2.1*".

The interswath (overlap) consistency was calculated using 14 sample locations in nonvegetated areas of swath overlap with only single returns. The achieved interswath accuracy is RMSDz= 0.018 meters.

3.5. Relative Accuracy: Intraswath Precision

This project required the intraswath accuracy to meet ≤ 6-cm RMSDz. Accuracy was assessed in accordance with the "*National Geospatial Program Lidar Base Specification Version 2.1*".

The intraswath precision was calculated using 14 sample locations in flat/open terrain against single swath and first-return points only. The achieved intraswath accuracy is RMSDz= 0.051 meters.

3.6. Lidar Data Classification

LAS data was initially classified as ground and non-ground points "first and only" as well as "last of many" lidar returns. In determining ground classification steps were utilized that classify points to low noise in order to derive the best ground model. Not all points that theoretically could be bare earth get classified to ground class at the risk of impacting the surface model in the form of pits or spikes. Additional filters were created to meet the task order classification specifications. Statistical absolute accuracy was assessed by direct comparisons of ground classified points to ground RTK survey data. Based on the statistical analysis, the lidar data was then adjusted to reduce the vertical bias when compared to the survey ground control of higher accuracy.

The bare-earth (Class 2 - Ground) lidar points were subject to a manual quality control step to verify the quality of the Digital Elevation Model (DEM) as well as a peer-based review. This included a review of the DEM surface to remove artifacts and ensure topographic quality. After the bare-earth surface was finalized, it was used to generate all hydro-breaklines through a semi-automated process.

All Ground (Class 2) lidar data inside of the Lake Pond and Double Line Drain hydrological flattening breaklines were then classified to Water (Class 9) using TerraScan/LP360 algorithms. A buffer of 0.35-meters was also used around each hydro-flattened feature to classify these Ground (Class 2) points to Ignored Ground (Class 20). All Lake Pond Island and Double Line Drain Island features were checked to ensure that the Ground (Class 2) points were reclassified to the correct classification after the automated classification was completed.

All data was manually reviewed, and any remaining artifacts were removed. Industry-standard LAS files were then created. Final statistical analysis was performed per tile on the LAS files classes to verify final classification metrics and full LAS header information. Those classes include:

- Class 1: Processed, but Unclassified
- Class 2: Bare Earth
- Class 7: Low Noise
- Class 9: Water
- Class 17: Bridge Deck
- Class 18: High Noise
- Class 20: Ignored Ground

Classified LAS files were evaluated through a series of manual quality control steps as well as a peer-based review to eliminate remaining artifacts from the Ground class. This included a review of the DEM surface to remove artifacts and ensure topographic quality. 5,044 files were produced and clipped to the DPA. Software used included proprietary software, GeoCue LP360, TerraScan v23, and Global Mapper v20.

3.7. Hydrologic Flattening

The lidar task order required compilation of breaklines defining the following types of waterbody features:

- Lakes, reservoirs, and ponds:
    - Minimum of 2-acres or greater.
    - Compiled as closed polygons collected at a constant elevation.
- Rivers and streams:
    - Nominal width of 30.5-meters / 100-feet.
    - Compiled in direction of flow, with both sides maintaining an equal elevation gradient.

Woolpert used the following steps to hydrologically flatten the waterbodies and for gradient hydrologic flattening of the double line streams within the existing lidar data:

- Newly acquired lidar data was used to manually compile the hydrologic features in a 2D environment using the lidar intensity and bare earth surface. Open Source imagery was used as reference as necessary.
- An integrated software approach combined the lidar data and 2D breaklines. This process “draped” the 2D breaklines onto the 3D lidar surface model to assign an elevation. A monotonic process was performed to ensure the streams flowed consistently in a downhill gradient. A secondary step within the program verified an equally matching elevation of both stream edges. The breaklines that characterize the closed waterbodies were draped onto the 3D lidar surface and assigned a constant elevation at or just below ground elevation.
- All classified ground points inside the hydrologic feature polygons were reclassified to Water (Class 9).
- All classified Ground points were reclassified from within a buffer along the hydrologic feature breaklines to Buffered Ground (Class 20). The buffer distance was approximately the task order designed Nominal Pulse Spacing distance.
- Breaklines used for bridge removal during the hydrologic flattening were included with the hydrologic breakline geodatabase deliverable. These breaklines produce a more aesthetically pleasing DEM appearance.
- The lidar ground points and breaklines were used to generate a DEM.
- Quality control was performed by reviewing the hydrologically flattened DEM and hydrologic breakline features. An approach combining commercial off the shelf software and proprietary methods reviewed the overall connectivity of the hydrologic breaklines.

Breaklines defining waterbodies greater than 2-acres were provided as a PolygonZ feature class. All lake breaklines compiled as part of the flattening process were provided in an Esri file geodatabase. Breaklines used for DEM generation were provided as PointZ features in Esri shapefile format.Software used included TerraScan v23, TerraModeler v20, Esri ArcMap v10.7, and GeoCue LP360.

3.8. Digital Elevation Model

TerraScan was used to add the hydrologic breakline vertices and export the lattice models using triangulated model-z interpolation method. Ground lidar points in conjunction with the hydro breaklines and bridge breaklines were used to create 0.5-meter hydro-flattened bare-earth raster DEM files. Automated routines in ArcMap generated a 32-bit floating point raster GeoTIFF file for each tile. 5044 files were produced and clipped to the DPA. Two tiles of the bare earth have been removed due to not having ground points within to triangulate a surface. Each surface was checked for surface anomalies or incorrect elevations found within the surface. Excluded files are 4QGJ150440.tif and 4QGJ155440.tif.Software used included TerraScan v23, GDAL 2.4.0, Esri ArcMap v10.7, and Global Mapper v20.

3.9. Intensity Imagery

Intensity images represent reflectivity values collected by the lidar sensor during acquisition. Proprietary software generates intensity images using first returns and excluding those flagged with a withheld bit. Intensity images are linearly scaled to a value range specific to the project area to standardize the images and reduce differences between individual tiles. Appropriate horizontal projection information as well as applicable header values are written during product generation. 5,044 files were produced and clipped to the DPA.

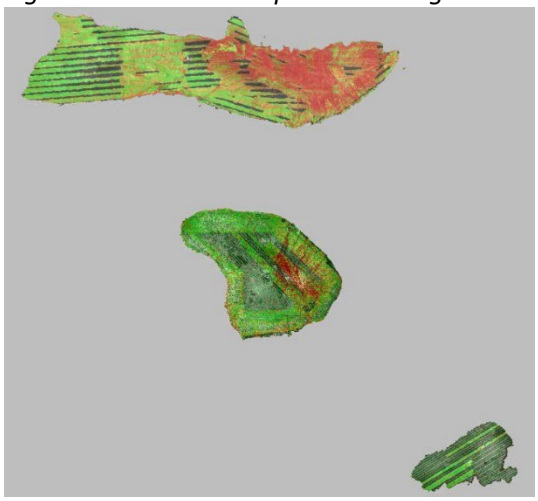
3.10. Swath Separation Image

The swath separation image was generated to visualize the DZ between the overlapping areas of the flight lines. To generate this surface a point insertion method was applied as the primary algorithm. Last returns were used, and points flagged as withheld or classified as noise were excluded. A GeoTIFF was created, and the color ramp is based on a QL1 data product. The GSD for the raster is 1 meter, which is two times the DEM post spacing. Intensity values were modulated to 50% to ensure there is no oversaturation of intensities values throughout the surface. After all calculations and surfaces were made, 5044 files were produced and clipped to the data extent. Software used was LAStools.

The color ramp for the swath separation image is as follows:

- Less than 8-cm: Green
- 8 to 16-cm: Yellow
- 16 to 24-cm: Orange
- Greater than 24-cm: Red

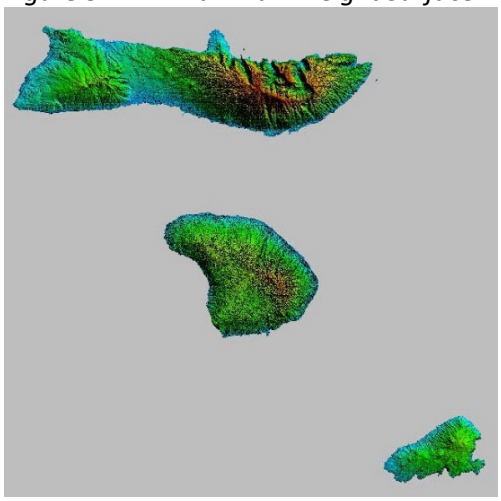
Figure 3.10.1 Swath Separation Image



3.11. Maximum Height Surface Raster

This raster is a proof of performance check that the withheld bit flag was used properly in the point cloud. Using all returns in the point cloud and excluding any points flagged as withheld, a raster is generated at twice the pixel size as the DEM deliverable using the same delivery tile index. This raster is generated as a 32-bit floating-point GeoTIFF with each pixel being generated as highest-hit elevation. The raster is then visually reviewed for anomalies that might indicate improperly classified noise. Any issues encountered are then corrected in the point cloud and a new/updated raster is generated. 5,044 files were produced and clipped to the DPA. The GSD for the surface is 1 meter, which is two times the DEM cell size. Software used included TerraScan v23, LAStools, LP360 v2022 and Esri ArcMap v10.7

Figure 3.11.1. Maximum Height Surface Raster



3.12. Low Confidence Polygons

Low confidence polygons were generated in areas where there was limited density or voids inside of the DPA due the extreme terrain or weather during acquisition. Some of the low confidence polygons coast are due to extinction of the laser in the water that we were not able to fill due to lack of coverage.

3.13. Metadata

FGDC CSDGM/USGS MetaParser-compliant metadata was produced in XML format. The metadata includes a complete description of the task order client information, contractor information, project purpose, lidar acquisition and ground survey collection parameters, lidar acquisition and ground survey collection dates, spatial reference system information, data processing including acquisition quality assurance procedures, GPS and base station processing, geometric calibration, lidar classification, hydrologic flattening, and final product development.

Other metadata deliverables included:

- Tile index
- Georeferenced, polygonal representation of the detailed extents of each acquired lidar swath.

4. Accuracy

4.1. Horizontal Accuracy

This data set was produced to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for a 0.11 m RMSEx / RMSEy Horizontal Accuracy Class which equates to Positional Horizontal Accuracy = +/- 0.29 m at a 95% confidence.

4.2. Classified Point Cloud

The LAS data set was produced to meet ASPRS Positional Accuracy Standard for Digital Geospatial Data (2014) fora 10-cm RMSEz Vertical Accuracy Class.

4.3. Digital Elevation Model

The Bare-Earth DEM data set was produced to meet ASPRS Positional Accuracy Standard for Digital Geospatial Data (2014) for a 10-cm RMSEz Vertical Accuracy Class.