APRIL 30, 2013

Technical Data Report

Pacific Northwest National Laboratory

Hanford Site-Wide Probabilistic Seismic Hazard Analysis (PSHA) LiDAR Survey

Prepared For:

Pacific Northwest National Laboratory
902 Battelle Blvd.
P.O. Box 999, MSIN K6-75
Richmond, WA 99352

Prepared by:

Watershed Sciences, Inc. (WSI)
Portland Office
421 SW 6th Ave.
Suite 800
Portland, OR 97204
PH: 503-505-5100
FX: 503-546-6801

Pacific Northwest NATIONAL LABORATORY

WSI Applied Remote Sensing and Analysis

Table of Contents

Overview

WSI has collected Light Detection and Ranging (LiDAR) data for the Pacific Northwest National Laboratory (PNNL). The data set contains the Hanford study area. The data were collected between March 24th and March 25th, 2013 and delivered to the client on April 30th, 2013.

Project Overview	
Study Area	Hanford Site-Wide PSHA Study Area
AOI Acres	64,340.6
TAF Acres	66,323.1
Acquisition Dates	3/24-3/25/2013
Delivery Date	4/30/2013

Project Extent

The study area of this project is located near Kennewick, Washington. The Columbia River bisects the study area; the northwestern portion falls within Benton County, while the southeastern portion lies in Walla Walla County and extends across the Oregon border into Umatilla County. The primary purpose of the data set is to support quaternary geologic studies for the Hanford Site-Wide Probabilistic Seismic Hazard Analysis (PSHA).

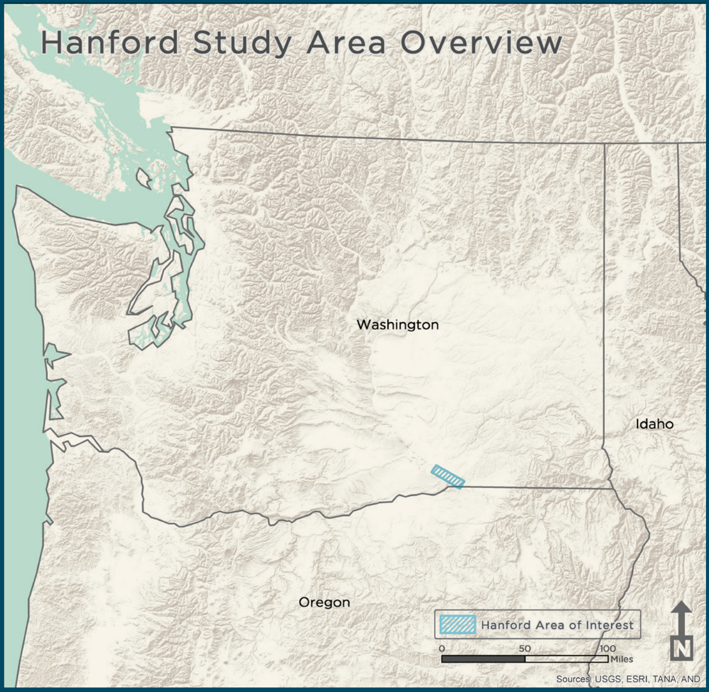
The area of interest (AOI) is 64,340.6 acres. The total area flown (TAF) equaled 66,323.1 acres, and was calculated by buffering the AOI by 100 meters.

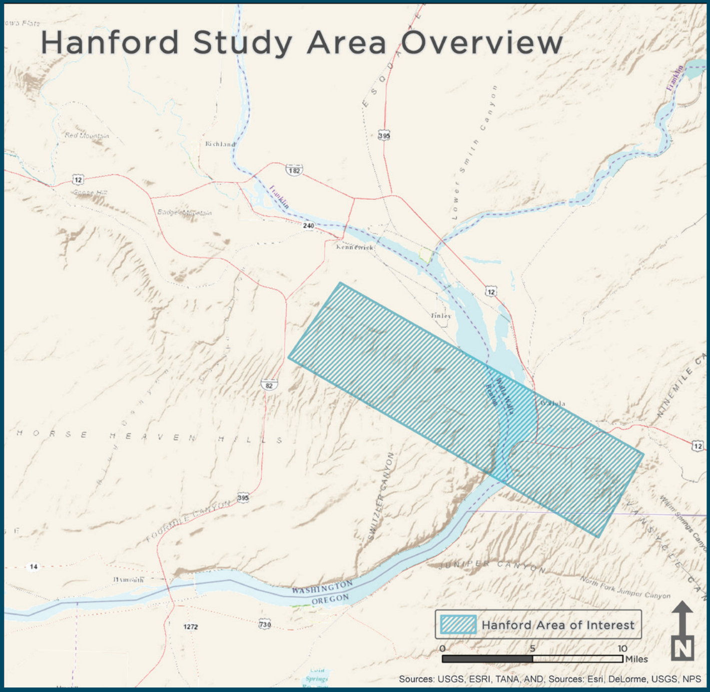
Deliverables include *.las files and ASCIIs with respective metadata and reference shapefiles.

PROJECTION
Washington State Plane South FIPS 4602

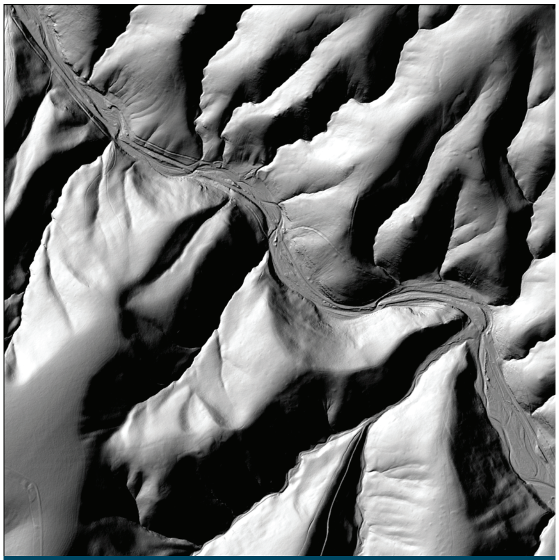
DATUM
Horizontal:
North American Datum of 1983 (2011)
Vertical:
North American Vertical Datum 1988, GEOID 12A

UNITS
Meters





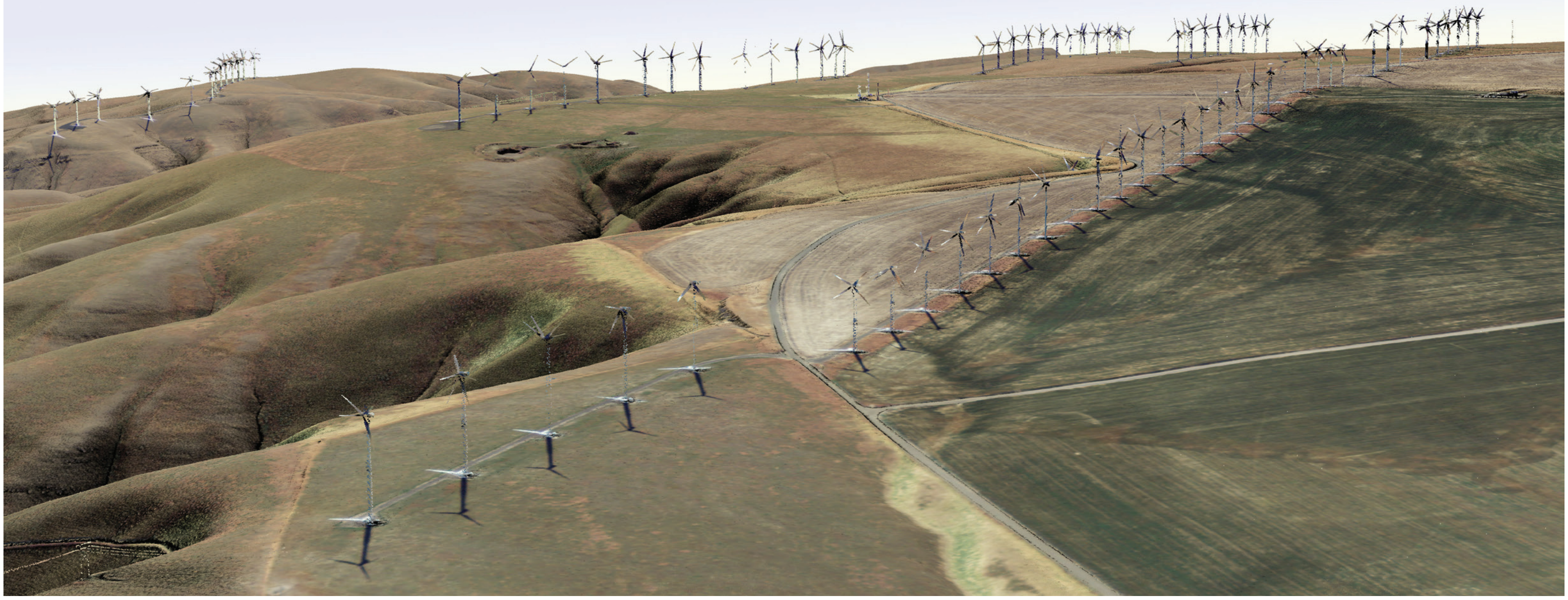
Deliverables



Bare Earth (BE) hillshade of the Vansycle Canyon in the PNNL Hanford study area

The following data have been provided to PNNL on an external drive from WSI:

- LiDAR 8 ppsm data in *.las and ASCII format (including X, Y, Z, return number, intensity, GPS time stamp, scan angle, and flightline)
    - All returns
    - Ground returns only
    - First returns only
- Vector Datasets: ESRI shapefiles of the following data
    - Total Area Flown (TAF)
    - Tiling scheme for deliverable products
    - Location of RTK checkpoints
- Technical Data Report
- LiDAR Animation
- Supplementary Red Image map of TAF in ArcGRID format



LiDAR point cloud of wind turbines in the eastern portion of the study area. Point cloud is colored with extracted RGB values from NAIP imagery.

Acquisition resources utilization	
Acquisition Area	66,323.1 Acres
Days on Project	2
Productivity	33,161.55 acres/ day
Flight time	10.6 hours
Field Staff	3

R7 unit set up over base station “RSI_CONTROL”

Monument cap “RSI_CONTROL”

Acquisition

For the survey of the PNNL Hanford Study Area, WSI employed a Cessna Grand Caravan 208-B fixed-wing aircraft with a crew of two airborne field professionals. LiDAR acquisition from the aircraft was accomplished with an onboard high performance laser scanning system, the Leica ALS60. A third crew member equipped with GPS receiver was stationed on the ground within the study area for the duration of each flight.

Planning

Flightlines were developed using ALTM-NAV Planner (v.3.0) software. Careful planning of the pulse rate, flight altitude, and ground speed ensured that data quality and coverage conditions were met while optimizing flight paths and ensuring the necessary ground density of greater than four points per square meter required for probabilistic hazard analysis of the Hanford study area by scientists at PNNL.

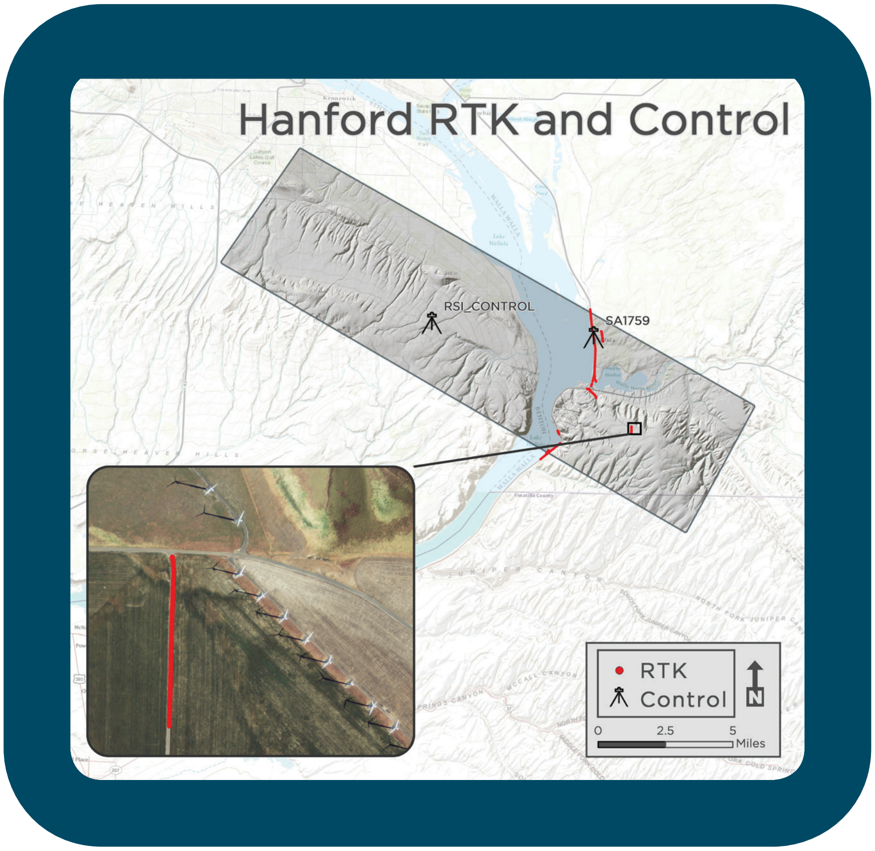
The mission planning conducted at WSI was designed to optimize flight efficiency while meeting or exceeding project accuracy and resolution specifications. In this process, known factors were prepared for, such as GPS constellation availability, photography and acquisition windows, and resource allocation. In addition, a variety of logistical barriers were anticipated, namely private property access and acquisition personnel logistics. Finally, weather hazards and conditions affecting flight were continuously monitored due to their impact on the daily success of airborne and ground operations.

Ground Survey

Ground data were collected for every mission, which included establishing and occupying survey control, collecting static positional data, and collecting ground check points using GPS real-time kinematic (RTK) survey with a roving radio relayed unit. Using the High Accuracy Reference Network (HARN) and the Continuous Operation Reference System (CORS), WSI tied to a network of points with orthometric heights determined by differential leveling.

Monumentation

Whenever possible, existing and established survey benchmarks served as control points during LiDAR acquisition. Where available, First Order National Geodetic Survey (NGS) High Accuracy Reference Network (HARN) published monuments with NAVD88 were used.



During the project, GPS files were submitted to OPUS and OPUS Projects, where daily session networks were adjusted. Upon completion of the project, a total network adjustment was performed. The final monument positions are provided below in decimal degrees with geodetic positions and ellipsoid elevations. Please see Appendix A for PLS certification.

Monument "SA1759"

List of Monuments

PID	Latitude	Longitude	Ellipsoid Height
SA1759	46 05 04.14317	-118 54 34.51942	90.577
RSI_CONTROL	46 05 24.22919	-119 02 05.40260	365.094

Monument Accuracy

FGDC-STD-007.2-1998 Rating	
St. Dev. Northing, Easting	0.02 m
St. Dev. Z	0.01 m

Receiver Equipment Specifications

Receiver Model	Antenna	OPUS Antenna ID	Use
Trimble R7 GNSS	Zephyr GNSS Geodetic Model 2	TRM55972.00	Static
Trimble R8	Integrated Antenna R8 Model 2	TRM_R8_Model 2	Static & RTK


A WSI Ground Professional collects RTK points with a roving R8 unit.

Static Positional Data

During each LiDAR mission, a ground-based technician was deployed, outfitted with two Trimble Base Stations (R7) and one RTK Rover (R8).

All static control points were observed for a minimum of one two-hour session and one four-hour session. At the beginning of every session the tripod and antenna were reset, resulting in two independent instrument heights and data files. A fixed height tripod was used. Data were collected at a recording frequency of one hertz using a 10 degree mask on the antenna.

GPS data were uploaded to WSI servers daily for WSI PLS QA/QC and oversight. OPUS processing triangulated the monument position using three CORS stations, resulting in a fully adjusted position. After multiple sessions of data collection at each monument, accuracy was calculated. Blue Marble Geographics Desktop v. 2.5.0 software was used to convert the geodetic positions from the OPUS reports.

RTK

A Trimble R7 base unit was set up over an appropriate monument to broadcast a kinematic correction to a roving R8 unit. This RTK survey allows for precise location measurement (σ ≤ 2.0 cm). All RTK measurements were made during periods with a Position Dilution of Precision (PDOP) of ≤ 3.0 and in view of at least six satellites by the stationary reference and roving receiver. For RTK data, the collector began recording after remaining stationary for five seconds, then calculated the pseudorange position from at least three one-second

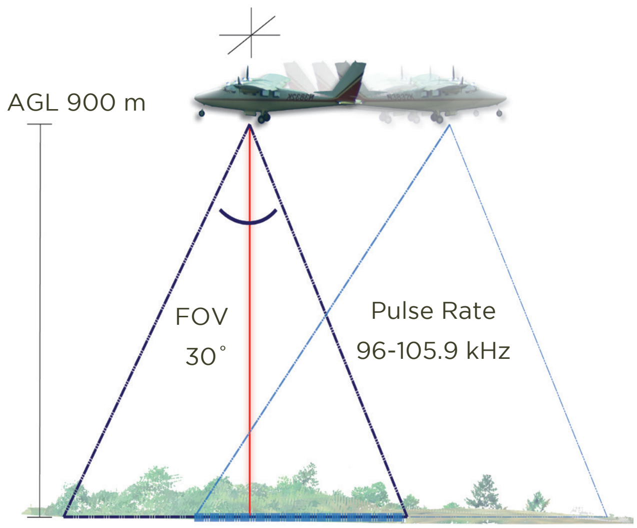
WSI collected 597 RTK points and utilized 2 monuments for the PNNL Hanford study area

GPS Specifications	
GPS Satellite Constellation	≥ 6
GPS PDOP	≤ 3.0
GPS Baselines	≤ 13 nm

GPS Specifications	Survey Control Monuments	Ground Check Points (GCPs)
Accuracy	RMSExy ≤ 1.5 cm (0.6 in)	RMSExyz ≤ 1.5 cm (0.6 in)
	RMSEz ≤ 2.0 cm (0.8 in)	Deviation from monument coordinates
Resolution	Minimum of one per 13 nautical mile spacing	≥ 50 per surveyed monument
	Minimum independent occupation of 4 hrs & 2 hrs	597 Total
Equipment	Trimble R7	Trimble R7
	R8 GNSS	R8 GNSS
	GLONASS	GLONASS

epochs with the relative error less than 1.5 cm horizontal and 2.0 cm vertical. RTK positions were collected on bare earth locations such as paved gravel or stable dirt roads, and other locations where the ground was clearly visible (and was likely to remain visible) from the sky during the data acquisition and RTK measurement periods. In order to facilitate comparisons with LiDAR data, RTK measurements were not taken on highly reflective surfaces such as center line stripes or lane markings on roads.

For each control monument, at least 50 RTK points were taken within five nautical miles of the base. The planned locations for these control points were determined prior to field deployment, and the suitability of these locations was verified on site. The distribution of RTK points depended on ground access constraints, and may not be equitably distributed throughout the study area.



Airborne Survey

All data for the Hanford project area was flown between March 24 and March 25, 2013, utilizing a Leica ALS60 sensor mounted in a Cessna 208-B Grand Caravan aircraft.

The LiDAR system was set to acquire ≥96,000 laser pulses per second (i.e. 96 kHz pulse rate) and flown at 900 meters above ground level (AGL), capturing a scan angle of 30 degrees from nadir (field of view-FOV). These settings and flight parameters are developed to yield points with an average native density of ≥8 over terrestrial surfaces. The native pulse density is the number of pulses emitted by the LiDAR system. Some types of surfaces (e.g., dense vegetation or water) may return fewer pulses than the laser originally emitted. Therefore, the delivered density can be less than the native density and lightly variable according to distributions of terrain, land cover, and water bodies.

The study area was surveyed with opposing flight line side-lap of ≥60% (≥100% overlap) to reduce laser shadowing and increase surface laser painting. The system allows up to four range measurements per pulse, and all discernible laser returns were processed for the output data set.

The LiDAR sensor operators constantly monitored the data collection settings during acquisition of the data, including pulse rate, power setting, scan rate, gain, field of view, and pulse mode. For each flight, the crew performed airborne calibration maneuvers designed to improve the calibration results during the data processing stage. They were also in constant communication with the ground crew to ensure proper ground GPS coverage for data quality. The LiDAR coverage

LiDAR Survey Specifications	
Aircraft	Cessna 208-B Grand Caravan
Sensor	Leica ALS60
Altitude	900 m AGL
Targeted Aircraft Speed	105 knots
Swath Width	482 m
Coverage	60% Sidelap, 100% Overlap
Targeted Pulse Density	≥ 8 pulses/m^2
Pulse Mode	Single
Laser Pulse Rate	96,000-106,000 Hz
Field of View	30˚
Mirror Scan Rate	61.1 Hz

Leica sensor ALS 6106 installed in the aircraft

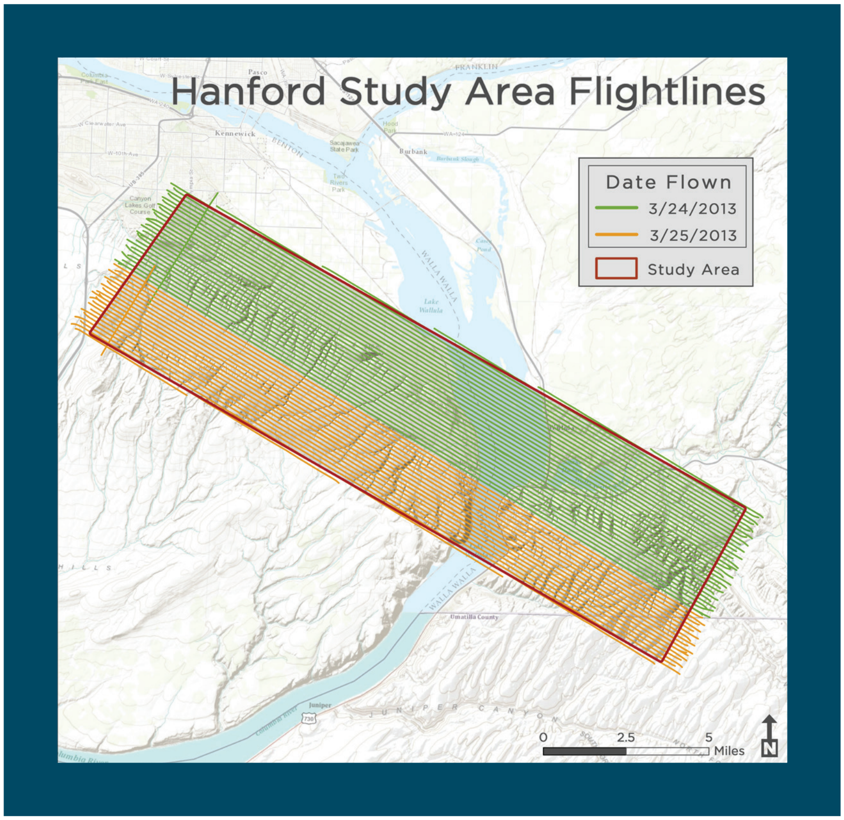
was completed with no data gaps or voids, barring non-reflective surfaces (e.g., open water, wet asphalt). All necessary measures were taken to acquire data under conditions (e.g., minimum cloud decks) and in a manner (e.g., adherence to flight plans) that prevented the possibility of data gaps. All WSI LiDAR systems are calibrated per the manufacturer and our own specifications, and tested by WSI for internal consistency for every mission using proprietary methods.

To solve for laser point position, an accurate description of aircraft position and attitude is vital. Aircraft position is described as x, y, and z and was measured twice per second (two hertz) by an onboard differential GPS unit. Aircraft attitude is described as pitch, roll, and yaw (heading) and was measured 200 times per second (200 hertz) from an onboard inertial measurement unit (IMU).

Weather conditions were constantly assessed in flight, as adverse conditions not only affect data quality, but can prove unsafe for flying.

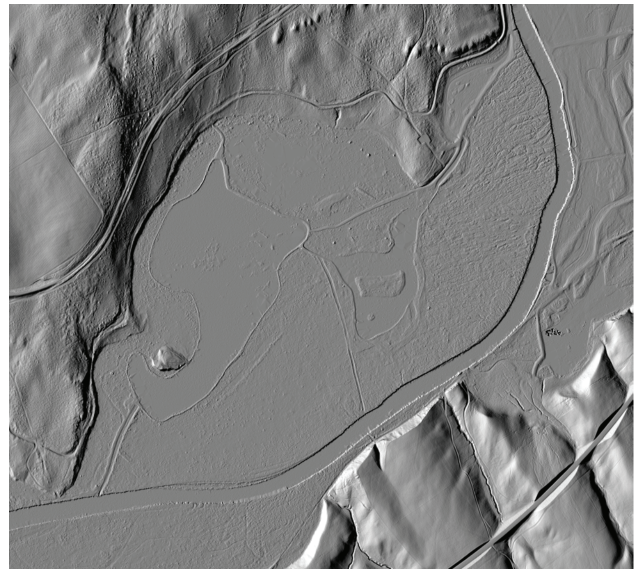
Cessna 208-B Grand Caravan

PNNL Hanford Survey flight lines and dates flown ▶



Processing

This section describes the processing methodologies for all data acquired by WSI for the PNNL Hanford Site-Wide PSHA project. All of our methodologies and deliverables are compliant with Federal and industry specifications and guidelines (USGS v.13, FGDC NSSDA, and ASPRS)



Bare Earth hillshade image of the Walla Walla River and adjacent wetland area

LiDAR

Once the LiDAR data arrived in the laboratory, WSI employed a suite of automated and manual techniques for processing tasks. Processing tasks included: GPS, kinematic corrections, calculation of laser point position, relative accuracy testing and calibrations, classification of ground and non-ground points, and assessments of statistical absolute accuracy. The general workflow for calibration of the LiDAR data was as follows:

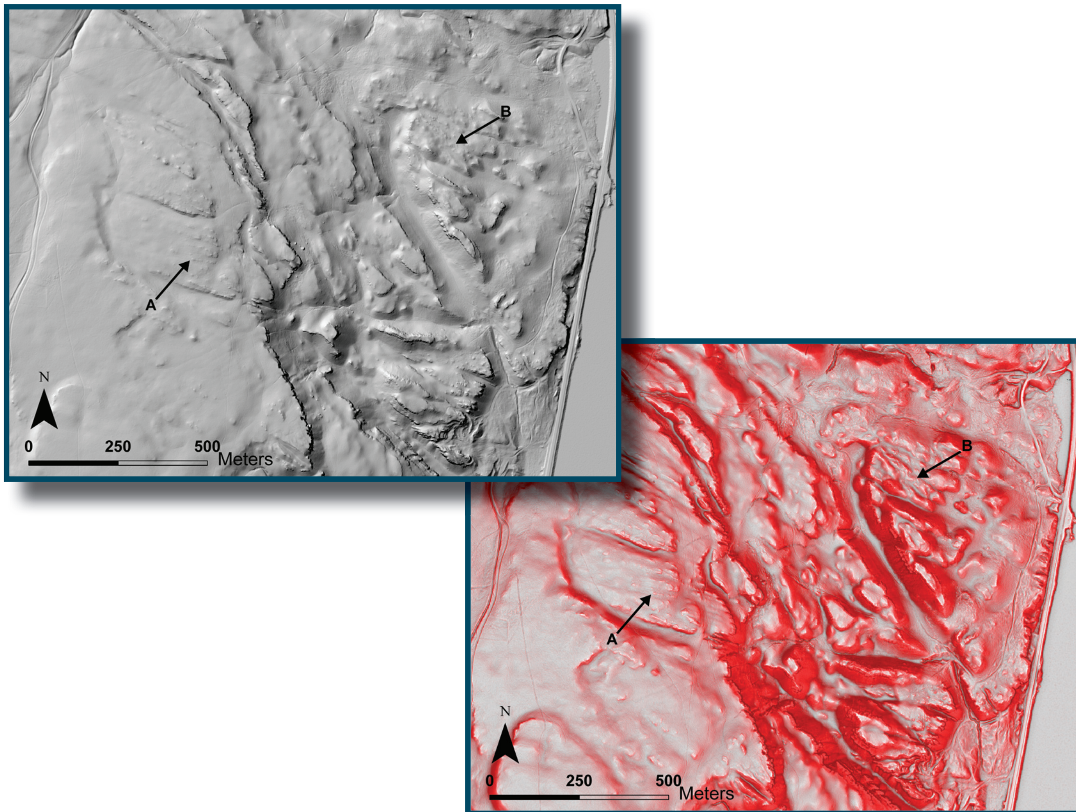
LiDAR Processing Step	Software Used
Resolve GPS kinematic corrections for aircraft position data using kinematic aircraft GPS (Collected at two hertz) and static ground GPS (one hertz) data collected over geodetic controls.	IPAS TC v. 3.2, Trimble Business Center v. 2.81,
Develop a smoothed best estimate of trajectory (SBET) file that blends post-processed aircraft position with attitude data. Sensor heading, position, and attitude are calculated throughout the survey.	IPAS TC v. 3.2
Calculate laser point position by associating SBET information to each laser point return time, with offsets relative to scan angle, intensity, etc. included. This process creates the raw laser point cloud data for the entire survey in *.las (ASPRS v. 1.2) format, in which each point maintains the corresponding scan angle, return number (echo), intensity, and x, y, z information. These data are converted to orthometric elevation (NAVD88) by applying a Geoid 12A correction.	Leica ALSPP 2.75 Build #9
Import raw laser points into subset bins (less than 500 MB, to accommodate file size constraints in processing software). Filter for noise and perform manual relative accuracy calibration.	TerraScan v. 13, Custom WSI software
Classify ground points and test relative accuracy using ground classified points per each flight line. Perform automated line-to-line calibrations for system attitude parameters (pitch, roll, heading), mirror flex (scale) and GPS/IMU drift. Calibrations are performed on ground classified points from paired flight lines. Every flight line is used for relative accuracy calibration.	TerraMatch v. 13, TerraScan v. 13, Custom WSI software
Assess fundamental vertical accuracy via direct comparisons of ground classified points to ground RTK survey data	TerraScan v. 13

Supplemental: Red Image Map

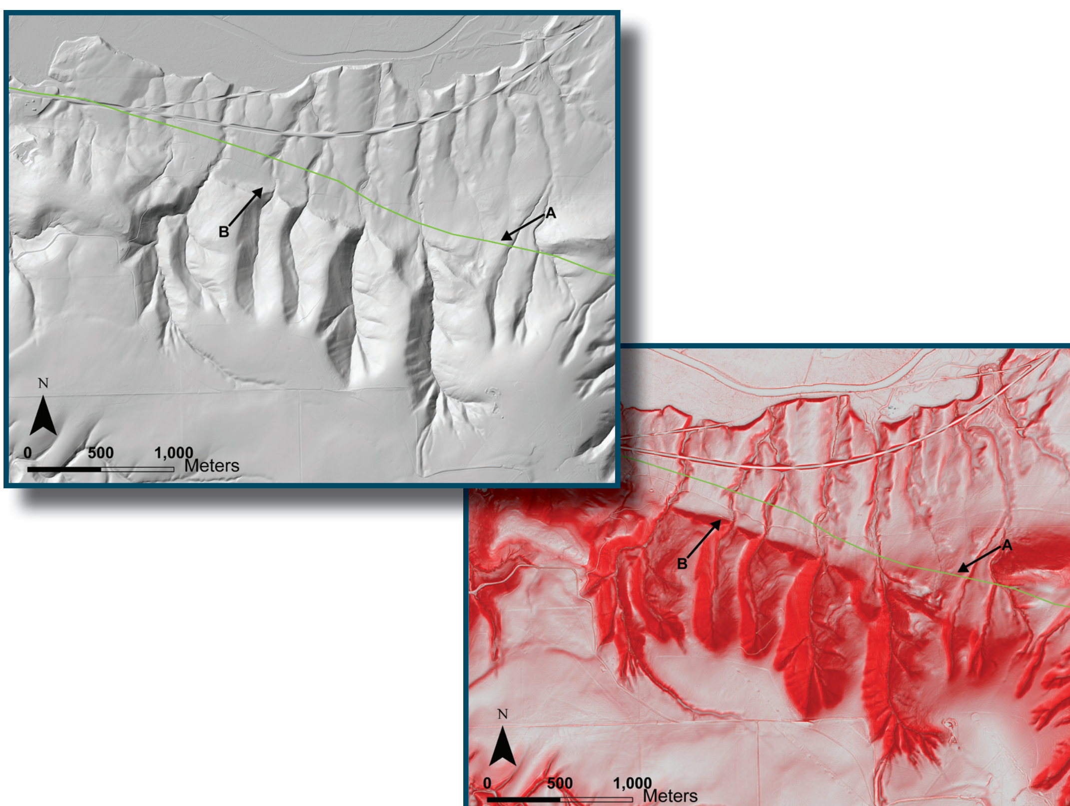
As an additional product deliverable to PNNL, WSI has created Red Image Maps (RIM) of the study area. These maps are useful for visualizing three-dimensional data and can be employed as visualization tools for fault line and landslide detection. RIMs are an integral tool in WSI's fault line and landslide detection process. As a supplementary product for PNNL, RIMs were created for the entire Hanford study area. Rollover imagery of the RIMs are included on the following page. The general workflow for the creation of a RIM is as

Red Image Map Processing Steps	Software Used
Creation of Bare Earth DEM using *.las ground model.	TerraScan v. 13, ArcGIS v. 10.1
Implementation of methodology outlined by Asia Air Survey (Chiba et al., 2008), rasters of both slope and topographic openness are created.	ArcGIS v. 10.1
Creation of additional raster datasets using neighborhood focal statistics.	ArcGIS v. 10.1- Spatial Analyst
Combine raster datasets using the Raster Calculator.	ArcGIS v. 10.1- Raster Calculator
Apply differing color ramps to each raster. Layer with varying transparencies.	ArcGIS v. 10.1, Custom WSI software
Combine layers into a single GRID file and clip to the AOI for the given study area.	ArcGIS v. 10.1

Within this area, just east of the Columbia River along the Wallula Gap, the RIM can be used to distinguish features that are at too fine of a scale to be seen in the simple bare earth hillshade. The area marked as “A” in the image contains features that are just barely visible in the hillshade, but are easily seen in the RIM. The area labeled “B” similarly contains terrain that in the RIM is seen to be substantially more varied than the hillshade suggests. This type of visualization of the ground model allows for fine geologic features that were previously obscured within the hillshade to stand out with no distortion to the data.



The second area, farther to the east across the river, shows how the visibility of fault zones can be greatly increased through the usage of the RIM. The green line cutting across the image (shown as “A”) is a USGS mapped fault within the Wallula fault system. This fault is known to be a normal fault with a general dip direction of northeast, striking to the northwest. Using this information, along with RIM, we are able to clearly make out a linear feature (marked as “B”) that fits this profile but which is not easily seen in the bare earth hillshade.



Results

Accuracy Assessment

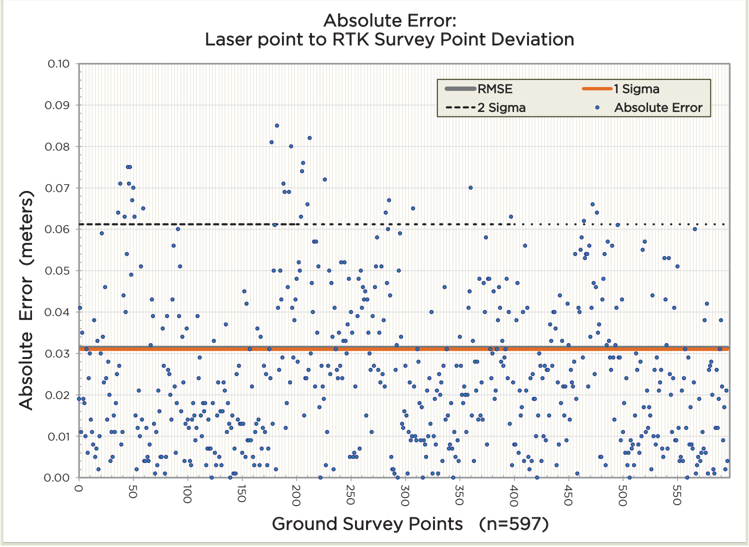
Vertical Accuracy

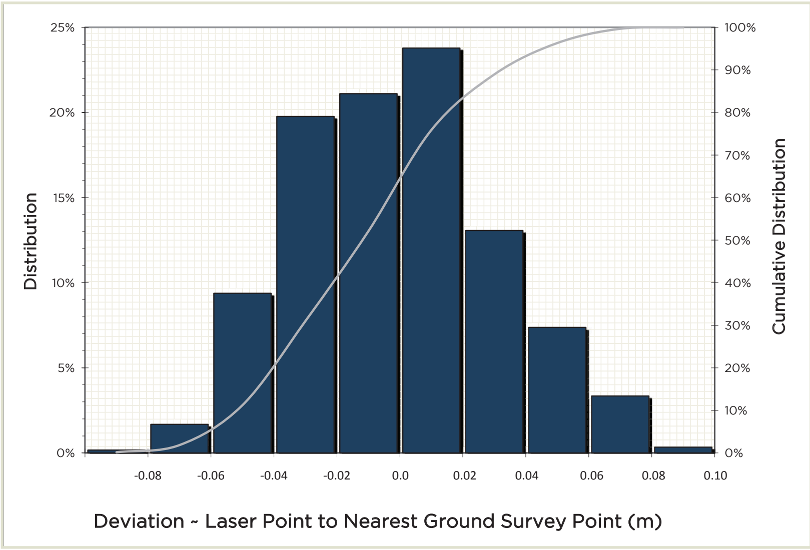
Vertical Accuracy Statistics	WSI Results (meters)
Sample Size	597 RTK points
RMSE	0.031
1 Sigma	0.031
2 Sigma	0.061
Minimum Δz	-0.082
Maximum Δz	0.085
Average Magnitude of Deviation	0.025

Vertical absolute accuracy was primarily assessed from ground check points on open, bare earth surfaces with level slope. These check points enabled an effective assessment of swath-to-swath reproducibility and fundamental vertical accuracy.

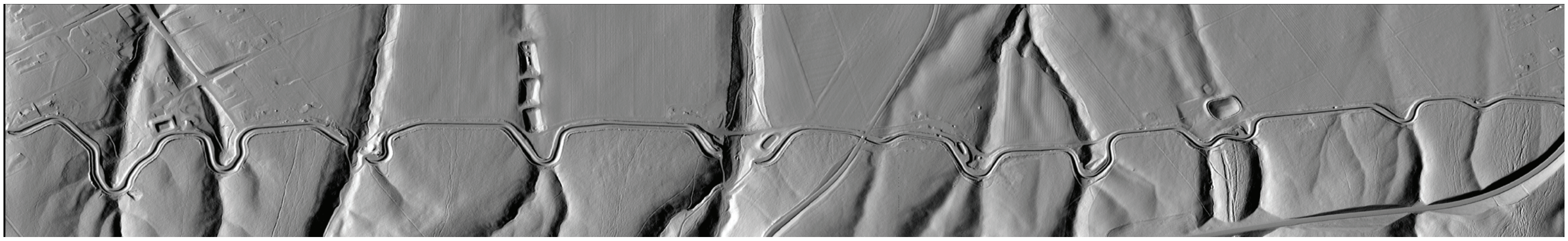
For this project, no independent survey data were collected, nor were reserved points collected for testing. As such, vertical accuracy statistics are reported as "Compiled to Meet," in accordance with the ASPRS Guidelines for Vertical Accuracy Reporting for LiDAR Data v. 1.0 (ASPRS, 2004).

The absolute vertical accuracy (RMSE) for the Hanford study area is 3.1 cm and was calculated with an RTK sample size of 597 points spread throughout the study area.





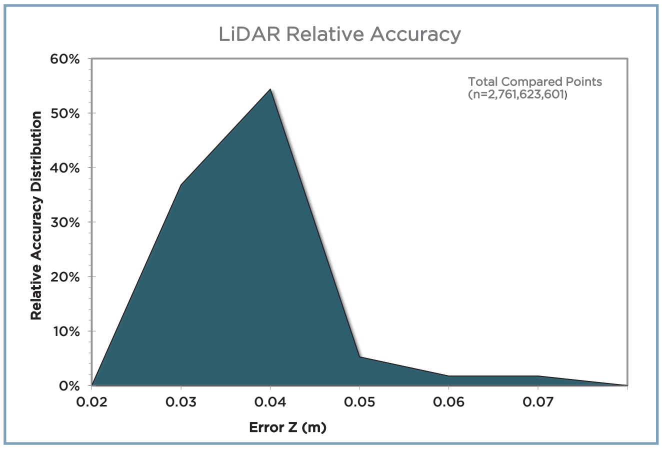
Bare earth hillshade image of agricultural canal in the northwestern portion of the study area



Relative Accuracy

Relative accuracy refers to the internal consistency of the data set and is measured as the divergence between points from different flightlines within an overlapping area. Divergence is most apparent when flightlines are opposing. When the LiDAR system is well calibrated, the line to line divergence is low (<10 cm). Internal consistency is affected by system attitude offsets (pitch, roll, and heading), mirror flex (scale), and GPS/IMU drift.

Relative accuracy statistics are based on the comparison of 57 flightlines and over two billion points. Relative accuracy is reported for the entire study area.



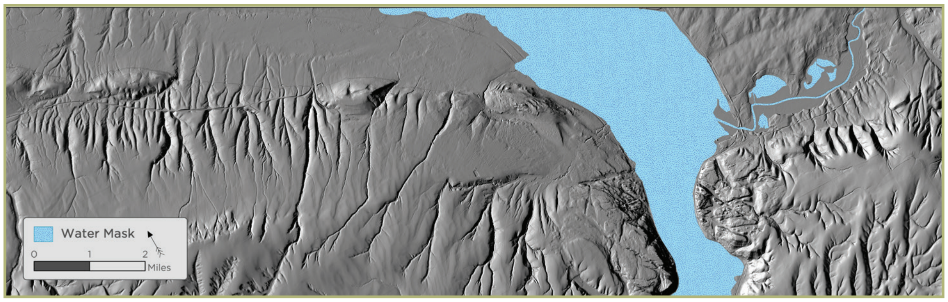
Relative Accuracy Statistics	WSI Results (meters)
Average	0.034
Median	0.034
1 Sigma	0.036
2 Sigma	0.043
Survey Points	2,761,632,601
Flightlines	57

Density Results

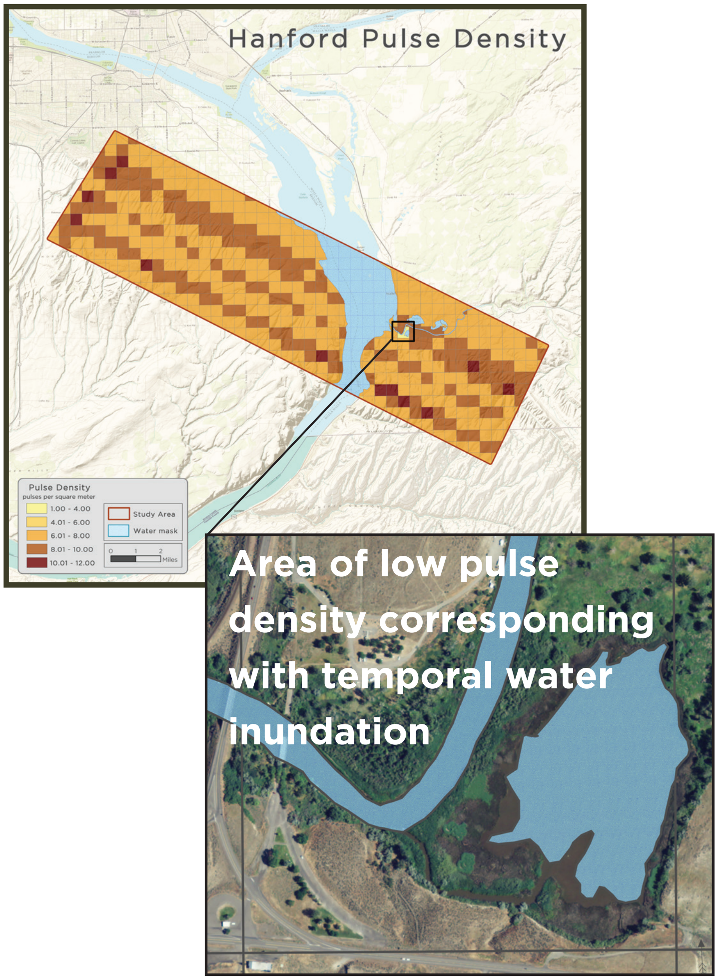
The Hanford data resolution specification was a mean of 8 pulses per square meter (ppsm), with the objective of achieving a mean ground density of 4 points per square meter (ppsm). While the achieved pulse density (7.85 ppsm) was slightly under the 8 ppsm specification, the achieved mean ground density (5.89 ppsm) was greater than the desired 4 ppsm ground density necessary for probabilistic hazard analysis of the Hanford study area.

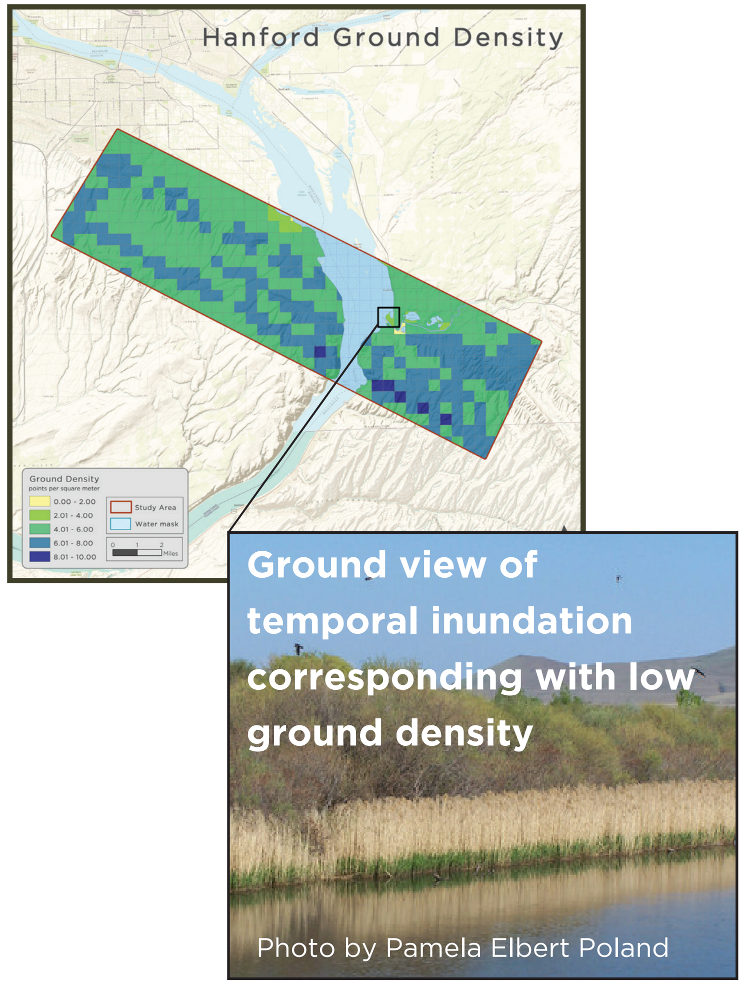
Due to the absorption of light by water, aquatic surfaces may return fewer LiDAR pulses than the laser originally emitted. The project area is bisected by the Columbia River, resulting in approximately 10% of the study area surface covered by water. A water mask was applied to the study area and regions within the mask were excluded from final pulse and ground density statistical analysis (see image below). However, locations of temporal water inundation were not excluded from statistical analysis of ground and pulse density calculations, thus accounting for decreased mean pulse and ground density results. Images on the following page show ground and pulse densities for the entire area of interest (AOI), as well as illustrate areas with low densities attributed to the presence of water. Density histograms have been calculated based on first return laser point density and ground-classified laser point density.

Average Pulse Density	Average Ground Density
7.9 pulses/m^2	5.9 points/m^2

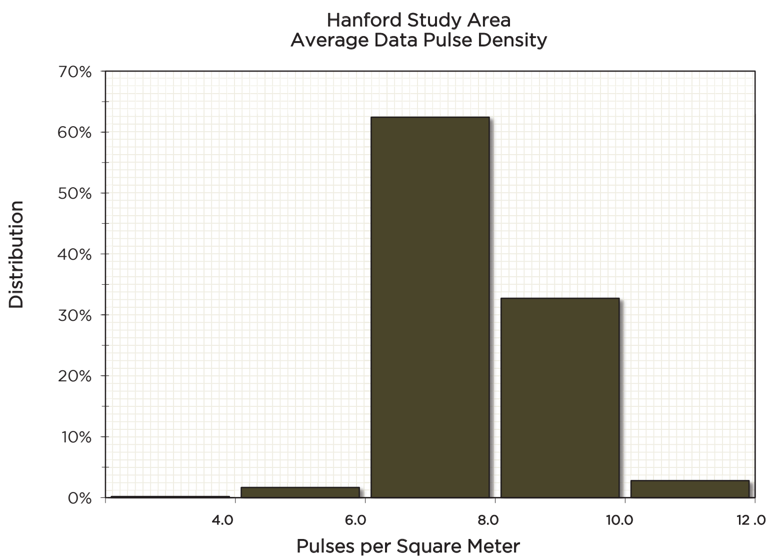


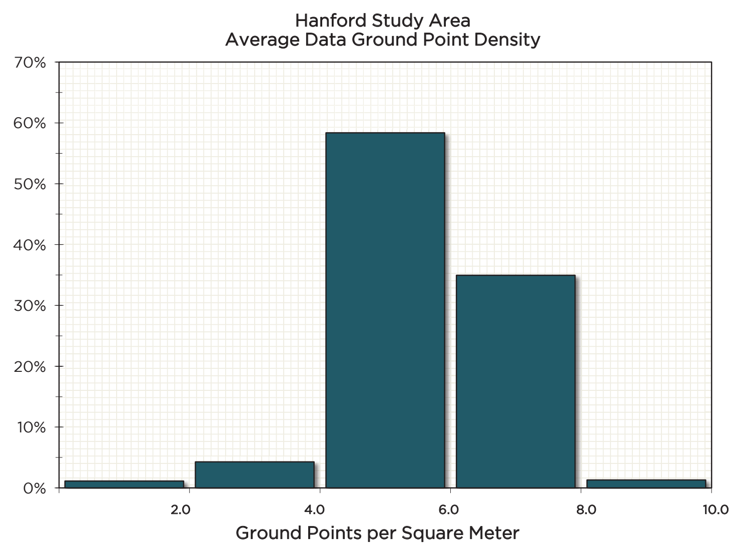
Pulse and Ground Density Maps





Pulse and Ground Density Charts





Best Practices

WSI Standards

WSI has high standards and adheres to best practices in all efforts. In the field, rigorous quality control methods include deployment of base stations at pre-surveyed level one monuments and collecting RTK, and efficient planning to reduce flight times and mobilizations.

In the laboratory, quality checks are built in throughout processing steps, and automated methodology allows for rapid data processing. There is no off-shoring, which allows for in-house, US citizen-based project control for all data collection and processing. WSI's innovation and adaptive culture rises to technical challenges and the needs of clients like PNNL. Reporting and communication to our clients are prioritized through regular updates and meetings.

Appendix A

Watershed Sciences provided LiDAR services for the PNNL Hanford Site Seismic Study Area as described in this report.

I, Mathew Boyd, have reviewed the attached report for completeness and hereby state that it is a complete and accurate report of this project.

Mathew Boyd
Principal
WSI

I, Christopher W. Yotter-Brown, being first dully sworn, say that as described in the Ground Survey subsection of the Acquisition section of this report was completed by me or under my direct supervision and was completed using commonly accepted standard practices. Accuracy statistics shown in the Accuracy Section have been reviewed by me to meet National Standard for Spatial Data Accuracy.

Christopher W. Yotter-Brown, PLS Oregon & Washington
WSI
Portland, OR 97204

REGISTERED
PROFESSIONAL
LAND SURVEYOR
4/19/
OREGON
JULY 13, 2004
Christopher W. Yotter - Brown
60438 LS
RENEWAL DATE: 6/30/2014

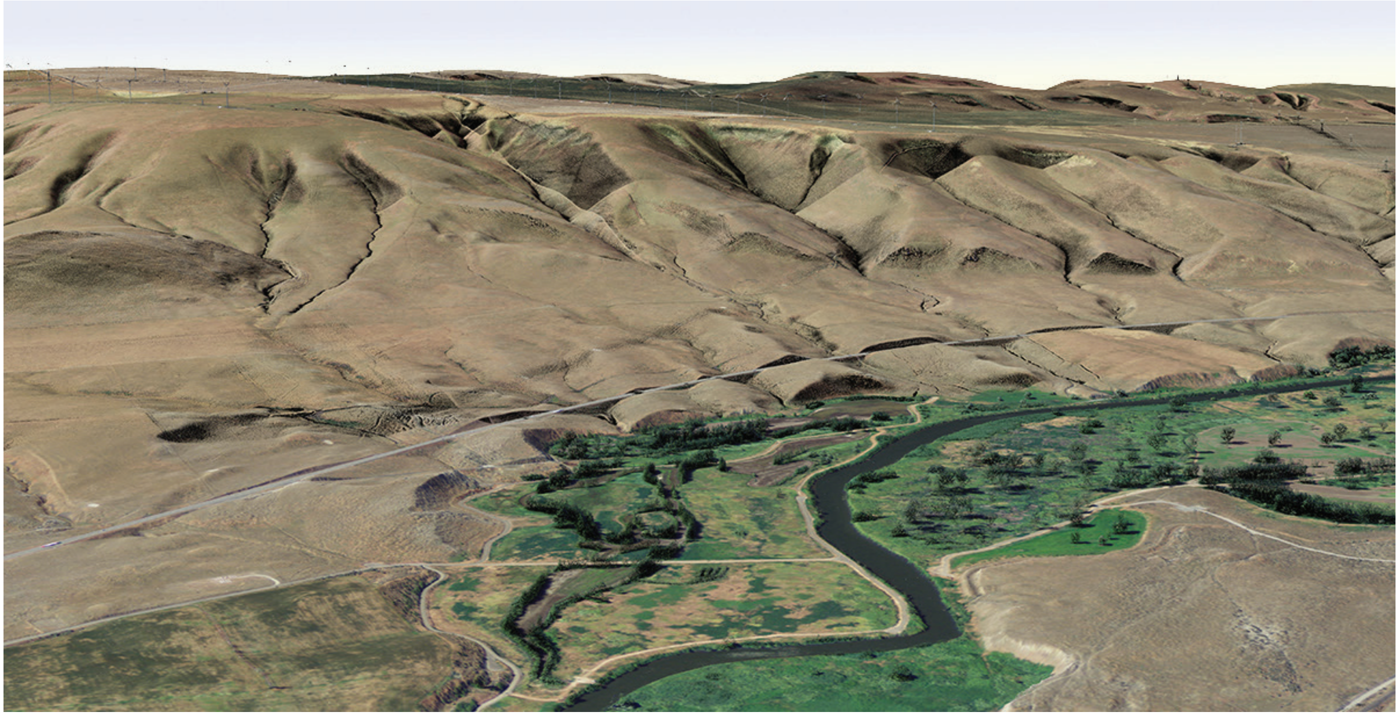
Appendix B: References

Chiba, T., Kaneta, S., and Suzuki, Y., 2008, Red Relief Map: New Visualization Method for Three Dimensional Data, *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Science*, v. 37, p. 1072-1076.

POINT OF CONTACT

Susan Jackson
Chief Marketing Officer
Oakland, CA
PH: 510-910-8669
E: sjackson@wsidata.com

Thank You



LiDAR point cloud of the Walla Walla River Valley in the northeastern portion of the study area. The point cloud is colored by RGB values extracted from NAIP imagery.

Portland Office
421 SW 6th Ave.
Suite 800
Portland, OR 97204
PH: 503-505-5100
FX: 503-546-6801