Minimum LiDAR Data Density Considerations

for the

Pacific Northwest

Watershed Sciences, Inc

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I. INTRODUCTION

LiDAR data is an essential tool not only in the creation of digital elevation models (DEMs) used across the United States, but also in other forms of analyses. For example, public and private foresters use LiDAR data for stand characterization and measurement, operational planning, and wildland fire assessment. Hydrologists rely on LiDAR data to assess streams and rivers, floodplain morphology, dams and reservoirs, and watershed health. Urban applications of LiDAR include building characterization and urban planning, as well as transportation and utility monitoring. Geologists use LiDAR data to identify and characterize faults, assess landslides, volcano mapping, and for various mineral and mining applications. Numerous risk/hazard analyses are based in part on LiDAR data (e.g. flood potential studies, tsunami inundation mapping, post-disaster characterization, etc). It is important to recognize this wide array of applications, in addition to DEM creation, when considering standards of minimum LiDAR density specification.

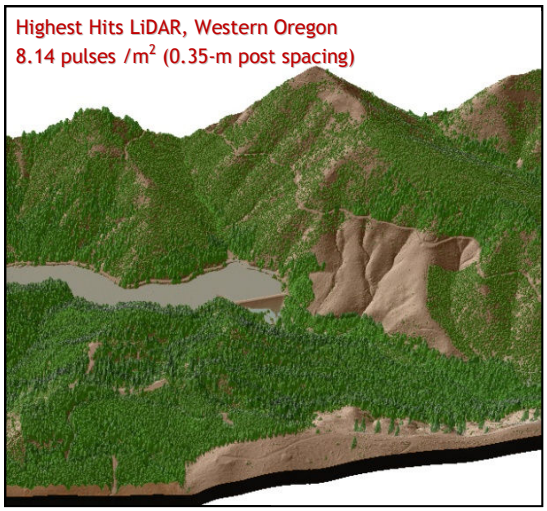
LiDAR-Based Applications

- Flood Hazard Mapping
- Forest Characterization
- Landslide Detection
- Watershed Health
- Wildland Fire Fuel Calculations

This paper considers current and relevant peer-reviewed literature in support of establishing recommended LiDAR resolutions for many of the applications currently taking place in the Pacific Northwest (PNW), which may require a higher data density than elsewhere in the U.S. due to regional topography and land cover. LiDAR resolution is measured in two ways. To avoid confusion, this paper reports both measures of resolution:

- **Pulse Spacing**: the average distance between pulses for any given area.
- **Pulse Density**: calculated as pulses per unit area, commonly measured as pulses per square meter.

Although there is no national standard for required LiDAR data density, the Federal Emergency Management Agency (FEMA) specifies a pulse spacing of ≤5 meters (> 0.04 pulse/m^2), to meet their needs (FEMA, 2009). The US Geological Survey (USGS) is proposing a minimum national standard LiDAR pulse spacing of ≤2 meters (> 0.25 pulse/m^2), with a "Buy-up" option for increased LiDAR resolution (U.S. Geological Survey (USGS), National Geospatial Program, 2009, v.12).

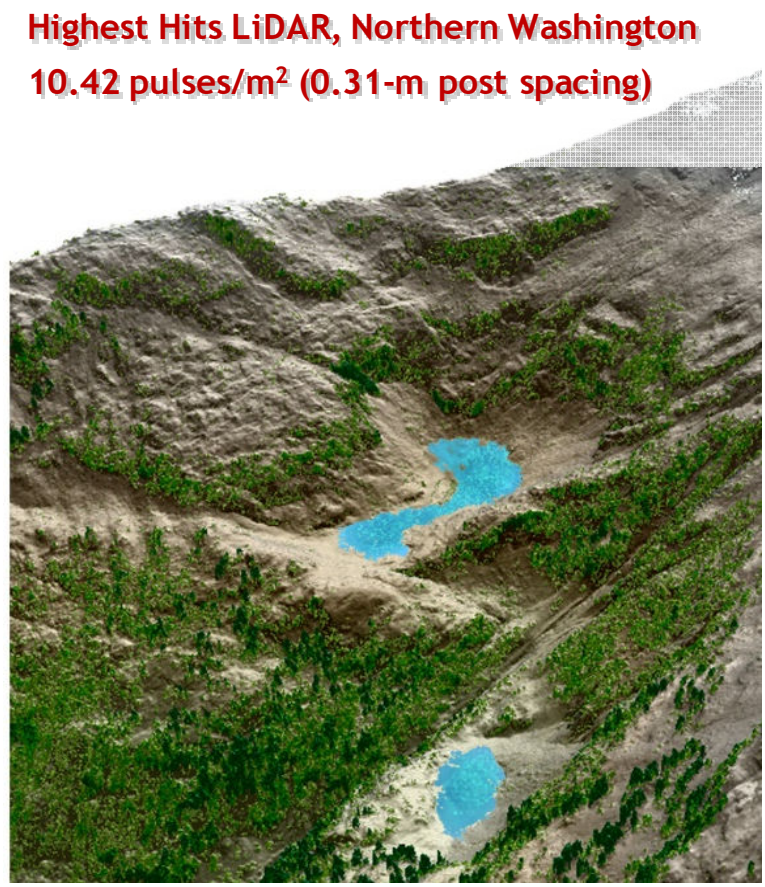


The literature presented in this paper illustrates that for most applications in the PNW, the proposed national standard of 0.25 pulses/m^2 is inadequate. Even though LiDAR density of 4 pulses/m^2 is considered to be "Buy-up" by the USGS, this review finds that this specification falls short of the minimum necessary in the PNW. To adequately meet the multiple applications of LiDAR analysis in the Pacific Northwest, 8 pulses per square meter is a preferred resolution specification.

II. NATIONAL STANDARDS

Federal Emergency Management Agency (FEMA)

Currently, FEMA's guidelines specify that for hydraulic modeling and terrain maps, the LiDAR contractor "must produce a bare-earth DEM, with the minimum regular point spacing, no greater than 5 meters" (0.04 pulses/m^2) (FEMA, 2009). FEMA guidelines recognize the challenges posed by some land covers and acknowledge that "high point densities may allow satisfactory data collection in areas of dense foliage." (FEMA, 2009).



U.S. Geological Survey (USGS) Proposed Base LiDAR Specification v.12

The USGS has prepared a draft document proposing a national set of **minimum** LiDAR specifications in support of the National Geospatial Program (NGP). In this document, USGS proposes a minimum "Nominal Pulse Spacing (NPS) no greater than 2 meters" (0.25 pulses/m^2) (USGS, National Geospatial Program, 2009). The proposed standard also stipulates that bare-earth surface DEMs should have a "cell size no greater than 3 meters or 10 feet, and no less than the design Nominal Pulse Spacing." (USGS, National Geospatial Program, 2009). The USGS recognizes that while this defines a minimum requirement, "it is expected that local conditions in any given project area, specialized applications for the data, or the preferences of cooperators, may mandate more stringent requirements. The USGS encourages the collection of more detailed, accurate, or value-added data." (USGS, National Geospatial Program, 2009). As a result, a common USGS Buy-up option is higher nominal pulse spacing (USGS, National Geospatial Program, 2009).

Table 1. National Standard Comparison

LiDAR Data Minimum Specifications		
	FEMA	USGS
Pulse Spacing	≤ 5-meter	≤ 2-meter
LiDAR Pulse Density	> 0.04 pulse/m^2	> 0.25 pulse/m^2

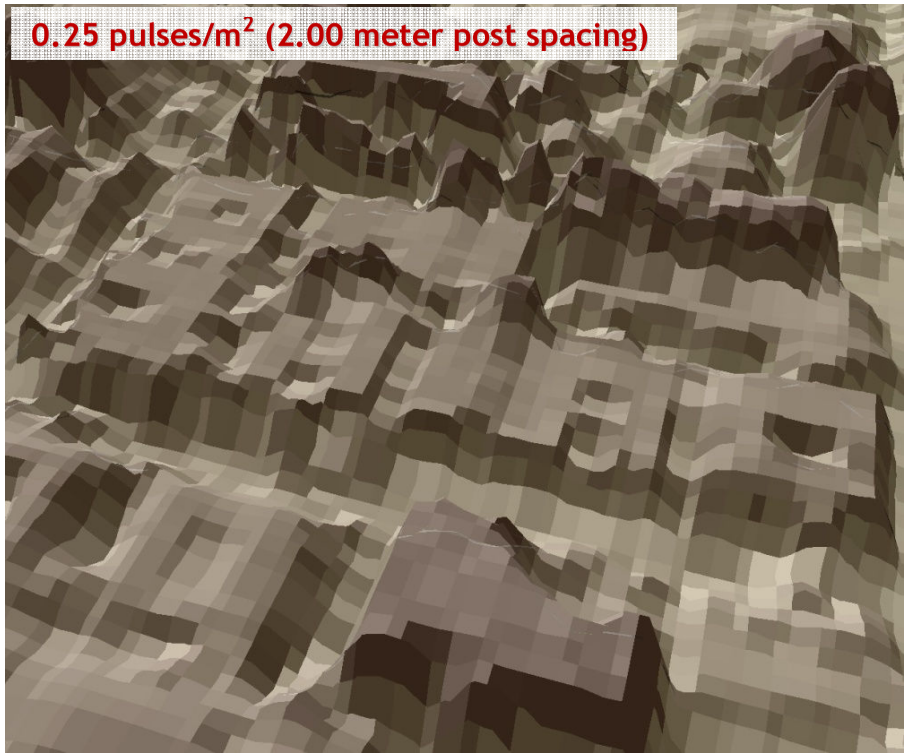
III. RECOMMENDED RESOLUTION FOR LIDAR APPLICATIONS

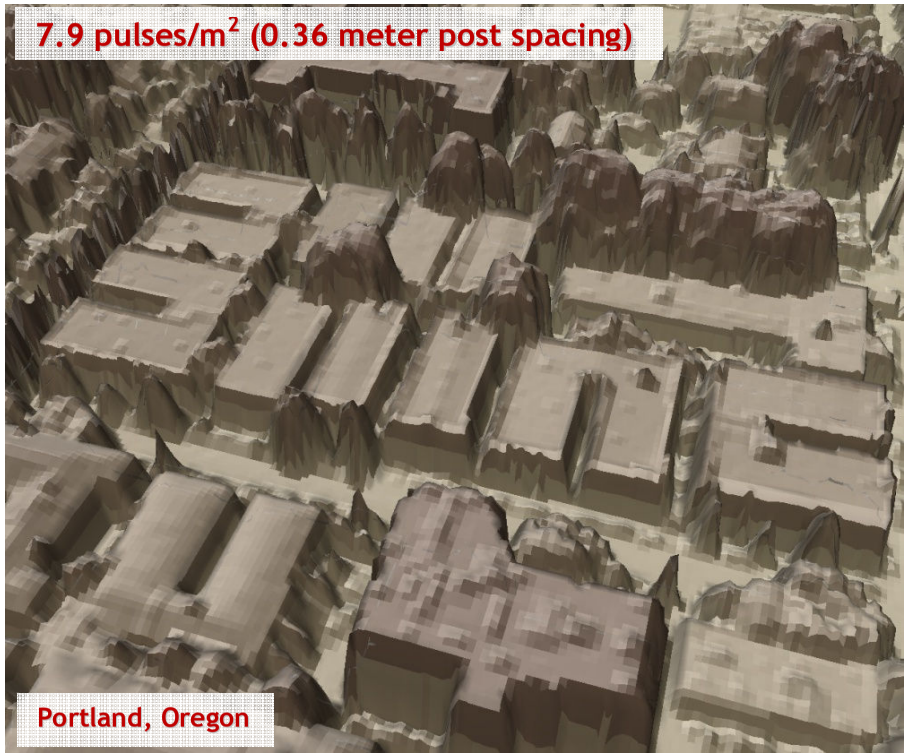
A. General Applications

Discipline	Application	Recommended Resolution (pulses per sq m)		Publication
		Low	High	
Geology	Landslides	4 (0.50 m post spacing)	4 (0.50 m post spacing)	Collins and Sitar, 2008
	Morphology	5 (0.45 m post spacing)	8 (0.35 m post spacing)	Cavalli *et. al.* 2008
Urban Planning	Building Classification	4 (0.50 m post spacing)	8 (0.35 m post spacing)	Lohani and Singh 2008
				Chen *et. al.* 2008
				Denniss 2009
Fire Modeling	Fire Loads	4 (0.50 m post spacing)	8 (0.35 m post spacing)	Anderson *et. al.* 2005a
				Anderson *et. al.* 2006a
	Mapping Burns	4 (0.50 m post spacing)	6 (0.41 m post spacing)	Wang and Glenn 2009

B. Pacific Northwest-Specific Applications

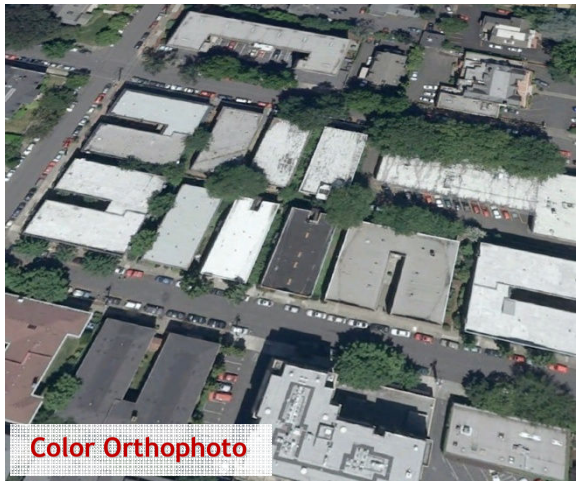
Forestry	Tree Species Identification	4 (0.50 m post spacing)	6 (0.41 m post spacing)	Gatziolis and Andersen 2008
				Holmgren *et. al.* 2008
				Suratno *et. al.* 2009
	Forest Measurement and Monitoring	4 (0.50 m post spacing)	4 (0.50 m post spacing)	Andersen *et. al.* 2005b
	Tree Height Measurements	4 (0.50 m post spacing)	6 (0.41 m post spacing)	Andersen *et. al.* 2006b
				St. Onge and Achaichia 2001
	Vegetation Characterization	4 (0.50 m post spacing)	8 (0.35 m post spacing)	Laes *et. al.* 2008
				Evans *et. al.* 2009
	DTM Accuracy Under Canopy Cover	4 (0.50 m post spacing)	6 (0.41 m post spacing)	Reutebuch *et. al.* 2003



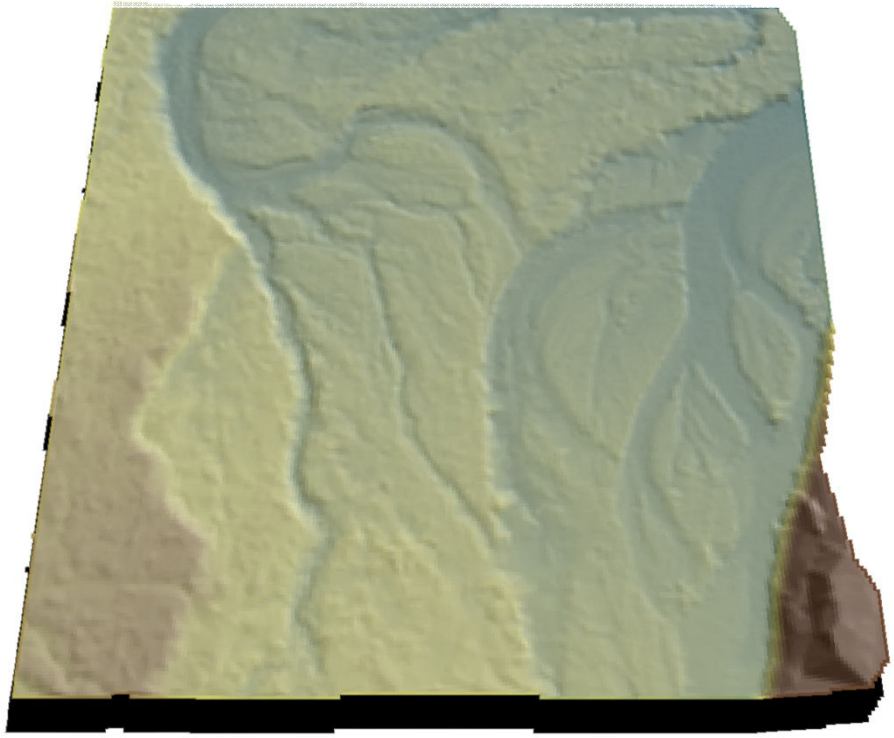


An Urban LiDAR Scene: Highest Hit Raster derived from LiDAR Data at low (left) and high (right) resolutions. The high resolution LiDAR data allows for building edge detection and accurate surface description. A corresponding color orthophoto is displayed left bottom.

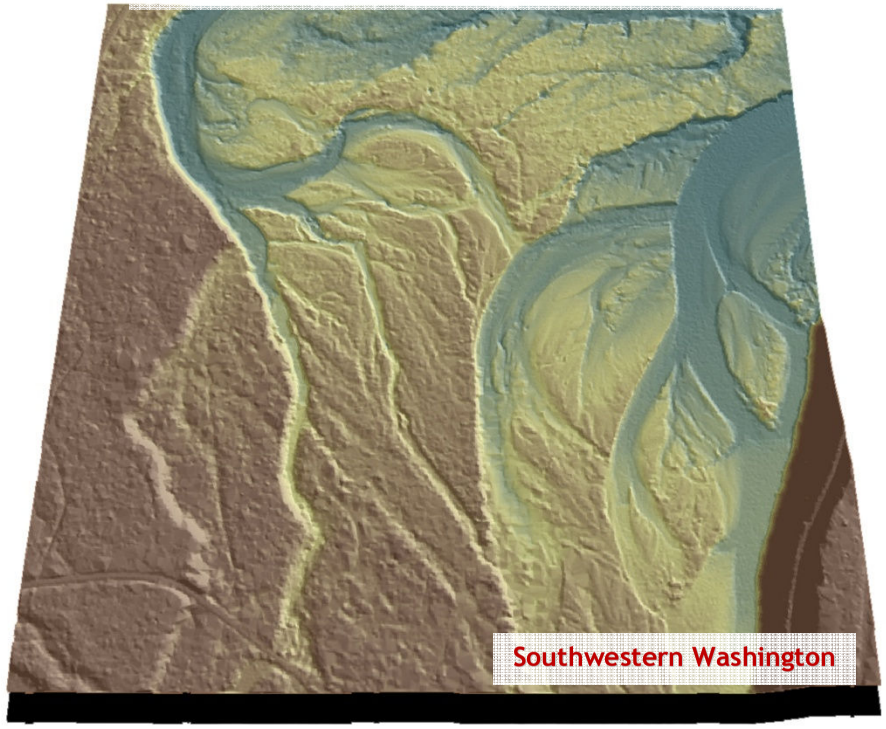
Chen *et al.* (2008) demonstrated that incorrectness in their building models was due to "an insufficient point cloud density (i.e. 0.2 points per m squared)." They also stated that "if the density of LiDAR point clouds improves, a higher reconstruction rate can be expected" (Chen *et al.*, 2008).



0.25 pulses/m^2 (2.00 meter post spacing)



8.1 pulses/m^2 (0.35 meter post spacing)

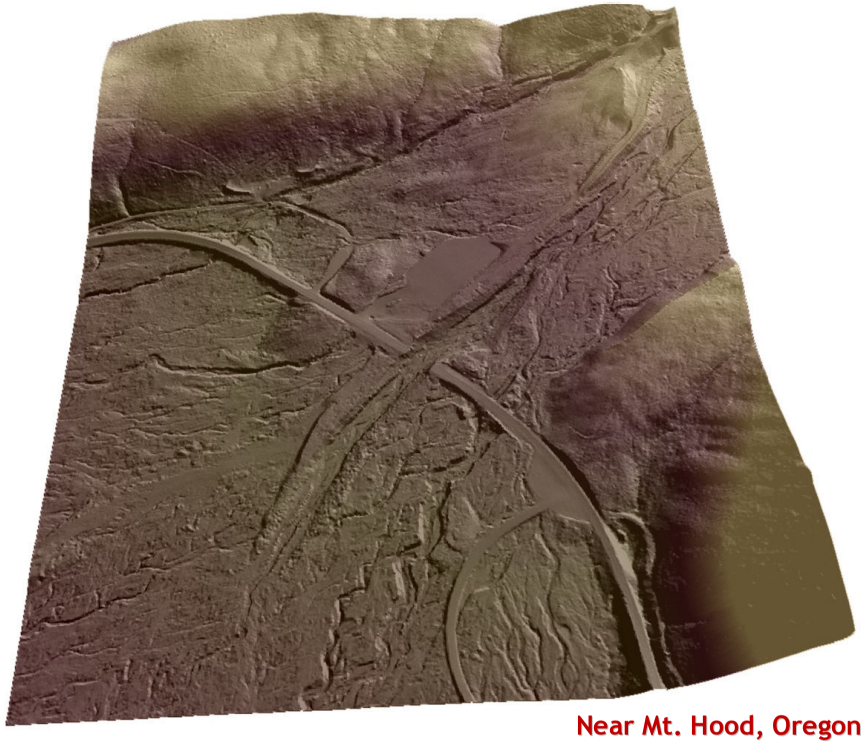


River Morphology: Low resolution data (left) fails to capture alluvial detail and ground returns. The high resolution LiDAR (right) are being used with hydraulic river models to update FEMA floodplain maps for the Lewis River. This same system has experienced prolonged flooding events that have closed Interstate Highway 5 (I-5) twice in the past four years. I-5 is the major transportation and commerce route between Portland, Oregon and Seattle, Washington.

Booth *et al*. (2009) determined that "an advantage of the high resolution of LiDAR-derived DEMs is that it allows more objective and quantitative analysis of fine-scale land surface features associated with a host of geomorphic processes, including landsliding."

Color Orthophoto

LiDAR Derived DEM Based on 6.0 pulses/m^2
(0.41 meter post spacing)



Color Orthophoto

Near Mt. Hood, Oregon

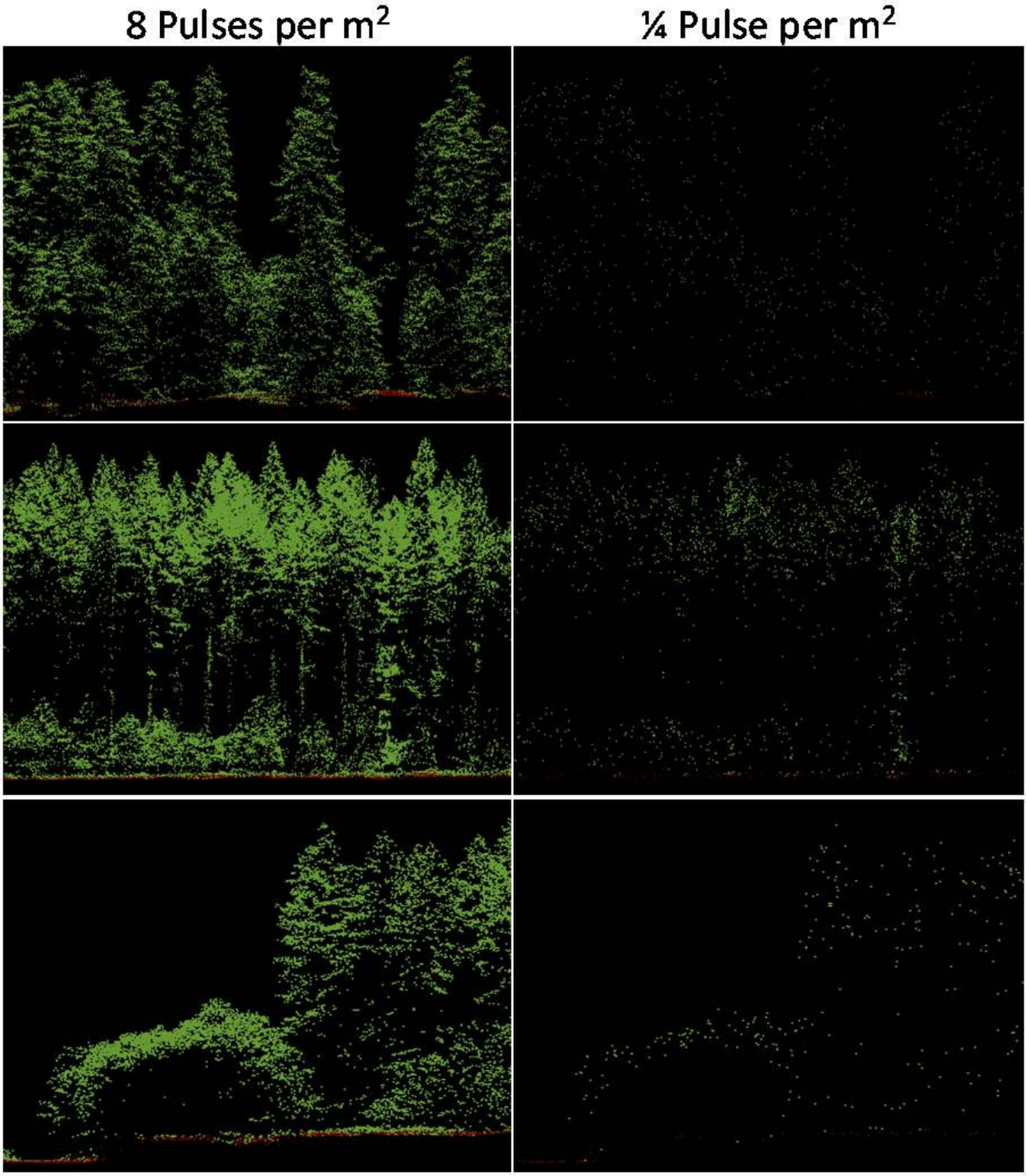
Flood Damage Assessment: High resolution data were used to rebuild/relocate Highway 30 near Mount Hood after a major flood event destroyed several miles and closed the highway for three months.

Schultz (2007) used LiDAR data with an average spacing of 2 m (.25 p/m^2) to map landslides near Seattle, WA. He concluded that "The resolution of the LiDAR data appears to be inadequate to resolve many landslides boundaries within landslide complexes." Additionally, several large landslides located in heavily wooded areas were missed in the survey (Schultz, 2007).

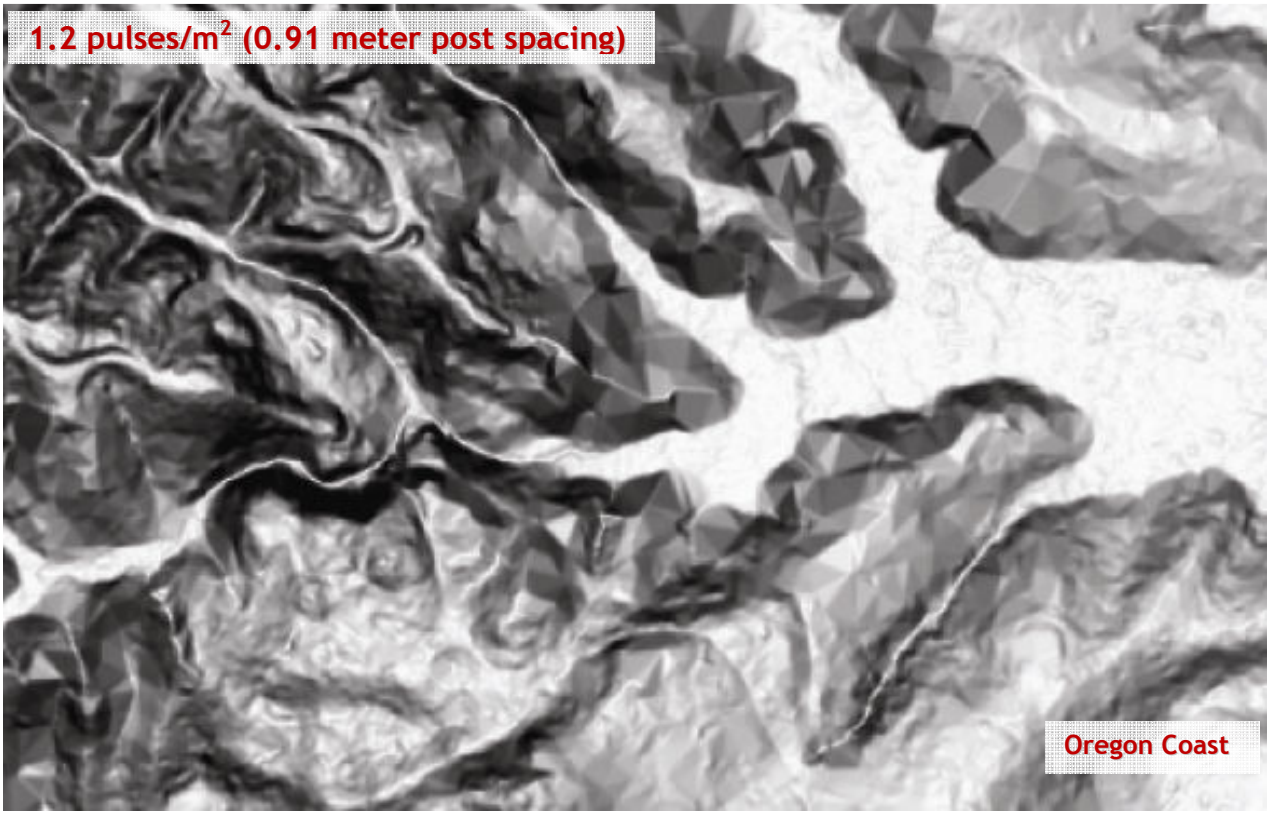
Collins and Sitar (2008) used LiDAR acquired at 0.5 m post spacing (4 pulses/m^2) to document landslides along the California coast. They stated that the use of "high resolution terrestrial LiDAR scans, provide new insight into the failure mechanisms of these coastal bluffs" (Collins and Sitar, 2008).

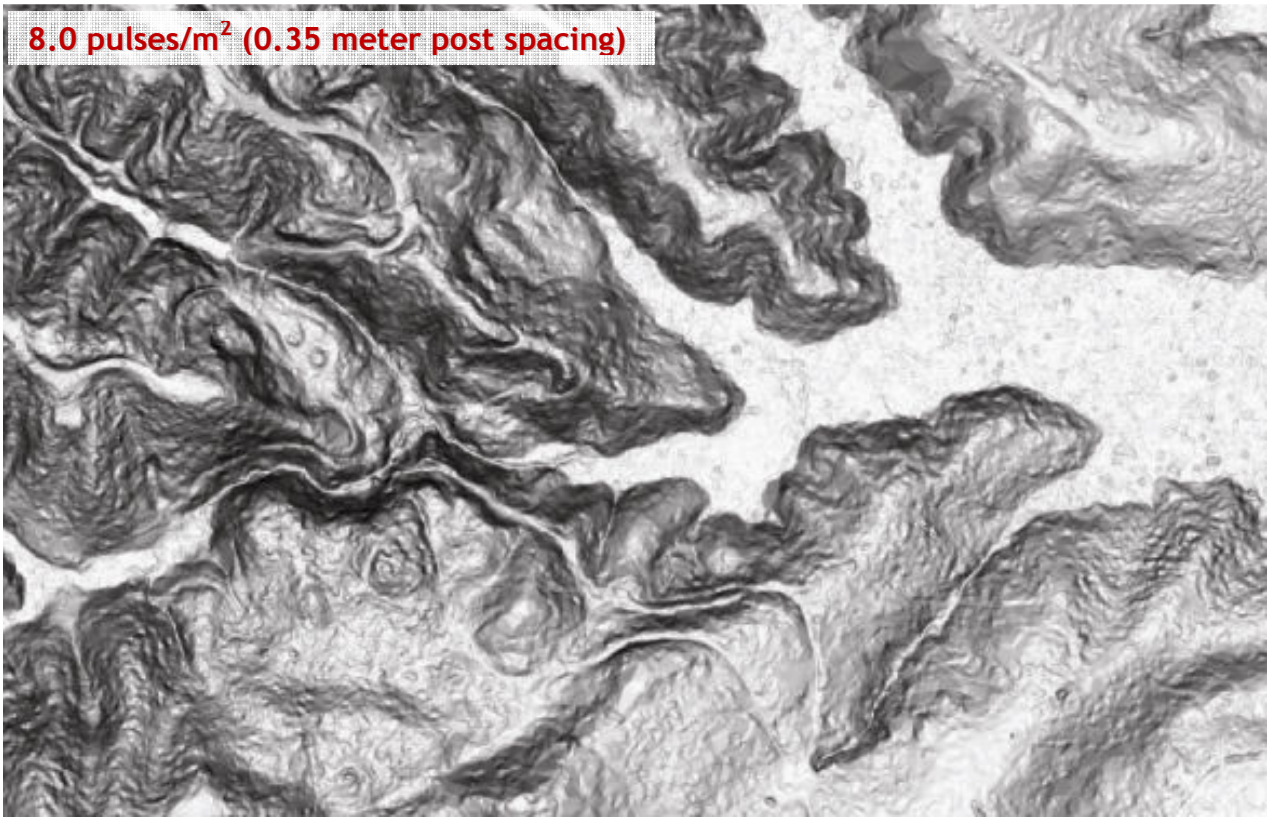
Ten meter cross-section of LiDAR point data, illustrating high and low pulse densities

Ground points are displayed as red. Note vegetation detail and increased ground returns in high-resolution data.



LiDAR-derived DEMs, illustrating high and low pulse densities on the Oregon Coast.





(Imagery provided by Ian Madin, DOGAMI)

IV. OREGON-BASED RELATIONSHIP BETWEEN RESOLUTION AND PERCENTAGE OF GROUND POINTS

Not all pulses emitted from the laser will measure the ground. Depending on vegetation and land cover, few pulses, and in some cases, no laser pulses, will reach the ground. In order to relate pulse density to ground point density, a mathematical relationship has been calculated from public-domain LiDAR surveys collected in Oregon in the last two years. For these surveys, totaling over 5.2 million acres, a resolution of 8 pulses per square meter was achieved. It was found that for any one pulse emitted, the probability of being classified as ground was only 14%. The large sample size and geographic distribution make this statistic robust and informative. The table below displays the data used for this relationship and expected ground densities using the same 14% probability of a ground return for any given resolution specification. If this relationship is applied to the USGS proposed specifications of 0.25 pulses/m^2, the resulting ground classified points would have a density of only 0.04 pulses/m^2 (i.e., >5 meter ground point spacing that cannot support even moderate raster resolutions). As shown in the table below, this density is far lower than the 0.14 pulses/m^2 necessary to create the 3-m DEM required under the proposed USGS specifications (USGS, 2009).

Table 3. Relationship between Pulse and Ground Point Densities and Resulting DEM Resolution.

	Pulse per m^2	Ground Points per m^2	Pulse Spacing (m)	Ground Point Spacing (m)	Probability of Laser Hitting Ground	Minimum DEM Raster Resolution (m)
Actual PNW Data	8.17	1.15	0.35	0.93	14%	≥ 1
Various Resolutions	4	0.56	0.50	1.34		≥ 2
	2	0.28	0.71	1.89		≥ 2
	1	0.14	1.00	2.67		≥ 3
	0.5	0.07	1.41	3.78		≥ 4
	0.25	0.04	2.00	5.35		≥ 6

V. DISCUSSION

While the minimum resolution standard proposed by USGS is designed to satisfy basic applications, such as DTM developments, the literature and acquisition statistics suggests that this resolution standard is not suitable to the Pacific Northwest. In short, this low resolution LiDAR data standard will fail in all of the common applications of LiDAR data. Recent peer-reviewed studies suggest that the minimum resolution will not sufficiently capture terrain and landscape features. Robust LiDAR acquisition statistics also support a high resolution of 8 pulses per square meter. Many, if not all, of the common LiDAR applications in the PNW demand higher pulse densities that range from 4-8 pulses per square meter.

VI. References

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