Digital Elevation Model Technologies and Applications: The DEM Users Manual, 3rd Edition

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Amar Nayegandhi, CP, CMS

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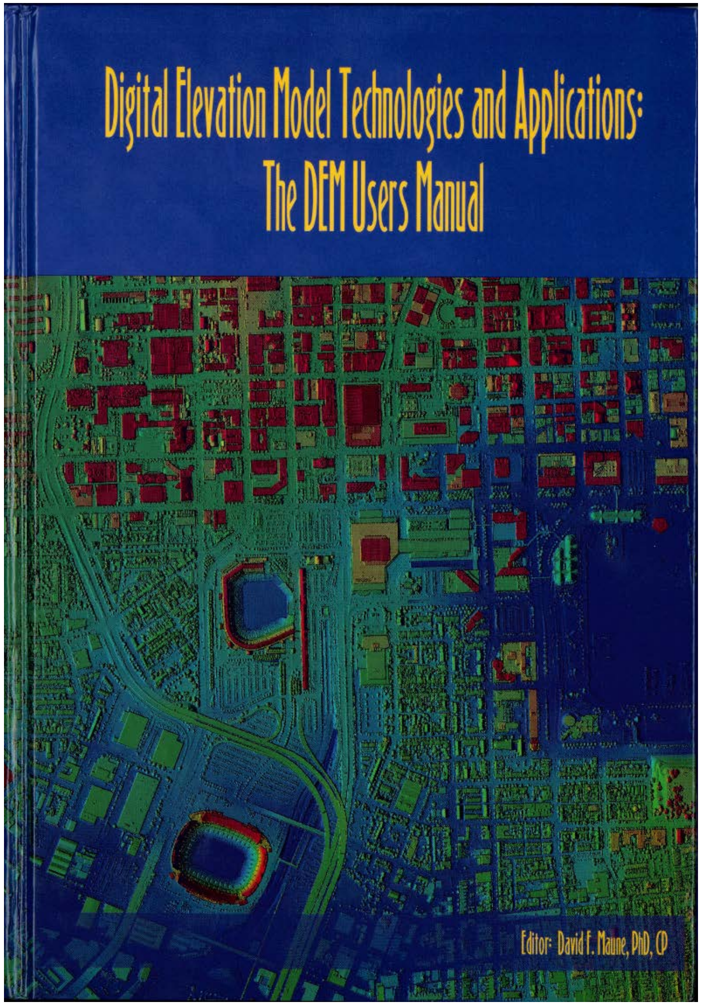
1^{st} edition (2001) & 2^{nd} edition (2007)



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DEM status in 2007 (2nd edition)

- We had no DEM standard products other than the lower-resolution National Elevation Dataset (NED)
- We had no national Lidar standards or specifications other than the FEMA Guidelines (2' & 4' contour accuracy) for the NFIP
- The 2nd edition's User Requirements Menu and sample SOWs helped users develop their own non-standard DEM products

Table 13.1 User Requirements Menu

Project Area Name of Project Area:
Project Boundary: ☐ Rectangular ☐ Non-Rectangular ☐ Project Extent Shapefile provided
Over-edge buffer width outside Shapefile area:

General Surface Description
Elevation Surface (choose one or more)
☐ Digital surface model (first/top reflective surface)
☐ Digital terrain model (bare earth)
☐ Bathymetric surface
☐ Mixed surface
☐ Point cloud
Elevation Type (choose one)
☐ Orthometric height
☐ Ellipsoid height
☐ Other

Data Model Types (choose one or more) * Designate either feet or meters
☐ Mass Points ☐ Grid (post spacing = feet/meters) * ☐ Contour Lines
☐ Breaklines ☐ Grid (post spacing = arc-seconds) ☐ Cross Sections
☐ TIN (average point spacing = ☐ feet or ☐ meters) * ☐ Other, e.g. concurrent imagery

Source (choose one)
☐ Cartographic ☐ Photographic ☐ IFSAR ☐ Lidar ☐ Sonar
If multi-return system, choose one or more: ☐ First return ☐ Last return ☐ All returns

Vertical Accuracy - General (choose one or more with explanation) ☐ Other
☐ 1' contour equivalent ($Accuracy_z$ = 0.60 ft) ☐ 5' contour equivalent ($Accuracy_z$ = 2.98 ft)
☐ 2' contour equivalent ($Accuracy_z$ = 1.19 ft) ☐ 10' contour equivalent (Accuracyz = 5.96 ft)
☐ 4' contour equivalent ($Accuracy_z$ = 2.38 ft) ☐ 20' contour equivalent ($Accuracy_z$ = 11.92 ft)

Vertical Accuracy - Specific (choose one or more; FVA is mandatory, SVA and CVA are optional)
☐ Fundamental Vertical $Accuracy_z$ = (ft or cm) at 95% confidence level in open terrain = $RMSE_z$ x 1.9600
☐ Supplemental Vertical $Accuracy_z$ = (ft or cm) = 95th percentile in other specified land cover categories
☐ Consolidated Vertical $Accuracy_z$ = (ft or cm) = 95th percentile in all land cover categories combined

Horizontal Accuracy (choose one) ☐ $Accuracy_r$ = $RMSE_r$ x 1.7308
☐ $Accuracy_r$ = ☐ feet or ☐ meters* *Designate either feet or meters

Accuracy Reporting (choose one vertical and one horizontal at the 95 percent confidence level)
☐ Tested (meters/ft) vertical accuracy or ☐ Compiled to meet (meters/ft) vertical accuracy
☐ Tested (meters/ft) horizontal accuracy or ☐ Compiled to meet (meters/ft) horizontal accuracy

Surface Treatment Factors (optional – explain with separate text) ☐ Vegetation
☐ Hydro-enforcement ☐ Hydro-conditioning ☐ Buildings
☐ No data areas (Voids) ☐ Suspect areas ☐ Artifacts

Horizontal Datum (choose one) **Vertical Datum** (choose one) **Geoid Model** (choose one)
☐ NAD 83 (default) ☐ NAVD 88 (default) ☐ MSL ☐ GEOID03 (default)
☐ WGS 84 ☐ MLLW ☐ Other ☐ Other

Coordinate System (choose one) ☐ UTM zone ☐ State Plane zone
☐ Geographic ☐ Local ☐ Other

Units Note: Choose one vertical (V) and one horizontal (H) units; V and H units may differ
☐ Elevations to decimal places ☐ U.S. Survey Feet ☐ Meters
☐ Northings/Eastings to decimal places ☐ U.S. Survey Feet ☐ Meters
☐ Decimal degrees to decimal places or ☐ DDDMMSS to decimal places

Data Format (specify desired format(s) for each product type)
Vector data Format(s)
Mass points and TINs Format(s)
Gridded DEMs Format(s)

File Size/Tile Size Maximum file size, if applicable: Mb / Gb / Other
Tile Size, if applicable ☐ ft x ft ☐ meters x meters ☐ Other

Metadata Compliant with FGDC's "Content Standards for Digital Geospatial Metadata"

Delivery Schedule Date(s) when deliverables are to be submitted by the Producer to the Customer

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Progress during the past decade

- 2010: USGS' draft *Lidar Guidelines and Base Specifications*, V.13
- 2011: *National Enhanced Elevation Assessment* (NEEA)
- 2012: USGS' *Lidar Base Specification*, V1.0
- 2013: USGS' *3D Elevation Program* (3DEP) (QL2 Lidar & QL5 IfSAR)
- 2013: ASPRS' *LAS Specification*, V1.4, and
- 2014: ASPRS *Positional Accuracy Standards for Digital Geospatial Data*
- 2014: USGS' *Lidar Base Specification*, V1.2
- 2015: USACE's EM 1110-1-1000, *Photogrammetric and Lidar Mapping*
- 2016: FEMA's Elevation *Guidance for Flood Risk Analysis & Mapping*
- 2017: *NEEA Update and Coastal/Offshore Elevation Requirements and Benefits Study* -- vision for a "3D Nation" from the tops of the mountains to the depths of the sea.

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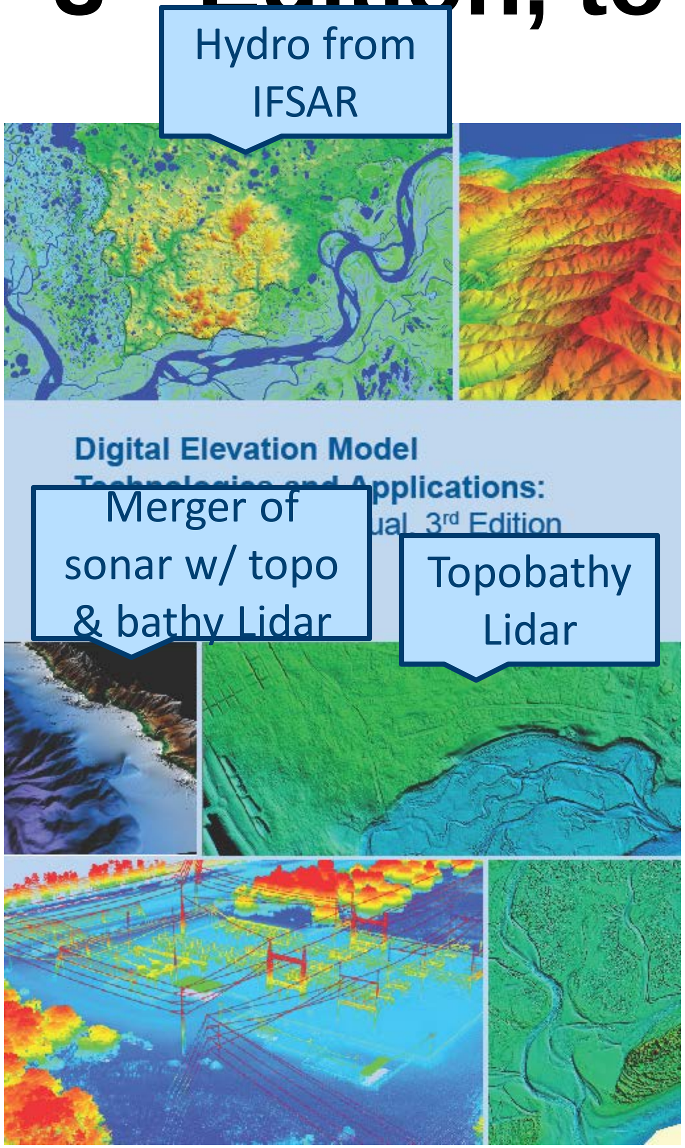
3rd Edition, to be published in 2017



The 3rd edition supports our vision of a future seamless, consistent, high-accuracy, high-resolution *3D Nation*, from the tops of the mountains to the depths of the sea, that is cost-effective and up-to-date. This includes submerged topography.

Every chapter supports this vision – even the front cover

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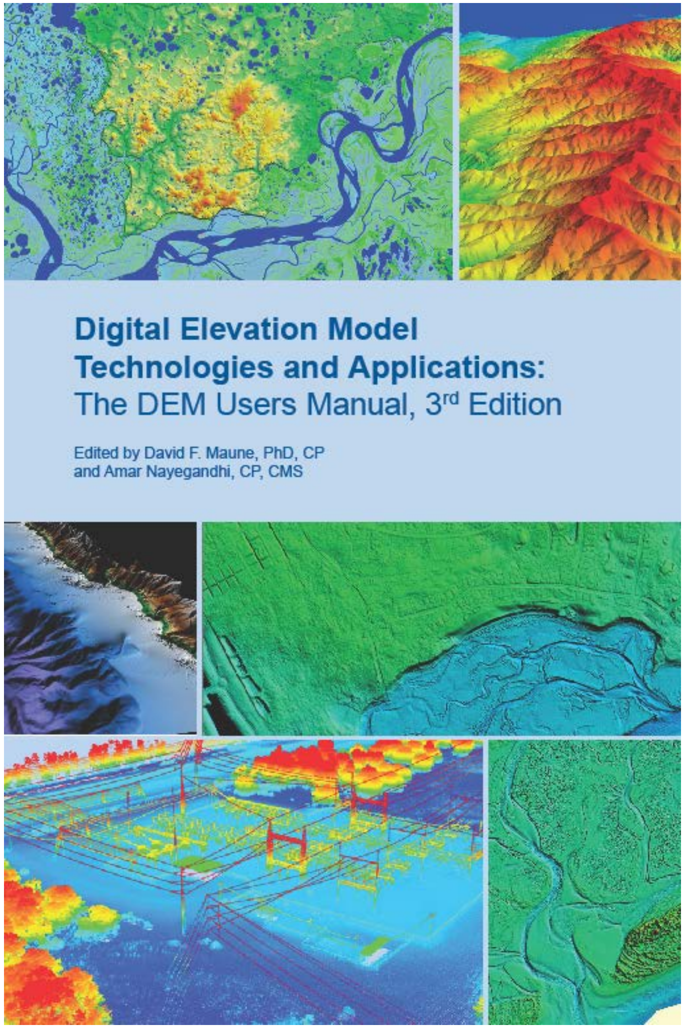
3rd Edition, to be published in 2017



1. Introduction to DEMs
2. Vertical Datums
3. Standards, Guidelines & Specifications
4. The National Elevation Dataset
5. The 3D Elevation Program
6. Photogrammetry
7. IfSAR
8. Airborne Topographic Lidar
9. Lidar Data Processing
10. Airborne Lidar Bathymetry
11. Sonar
12. Enabling Technologies
13. DEM User Applications
14. DEM User Requirements and Benefits
15. Quality Assessment of Elevation Data
16. Sample Elevation Datasets

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Ch. 1: Introduction to DEMs

(Dave Maune, Karl Heidemann, Stephen Kopp, Clayton Crawford)

Definitions and terminology

Raster, vector, point cloud data

DEMs, DTMs, DSMs

Mass points and breaklines (2D, 2.5D and 3D)

TINs, Terrains, LAS datasets

Contours

3D surface modeling

Terrain visualization, virtual reality

Hydrologic surface modeling:

- Hydro-flattening
- Hydro-enforcement
- Hydro-conditioning

Elevation derivatives (hillshades, slope, aspect and curvature maps, profiles, cross-sections)

Different types of maps

Different interpolation methods for creating DEMs from TINs

Improved Appendix A (Acronyms), Appendix B (Definitions), and Index

Hydro-flattened vs. hydro-enforced

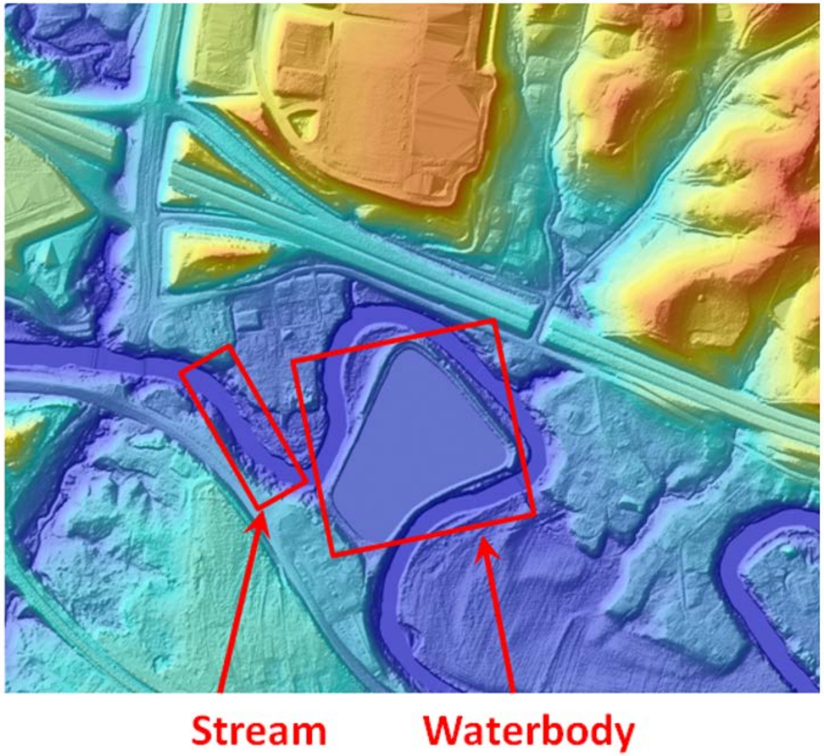

Figure 1.35. Hydro-flattened lidar DTM.

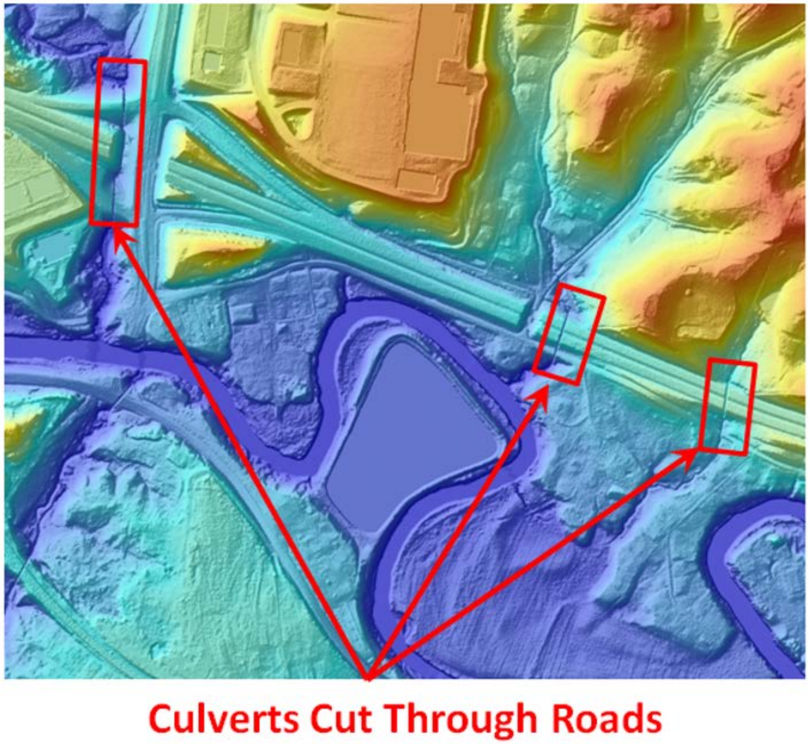

Figure 1.37. Hydro-enforced hydrologic surface.

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Ch. 2: Vertical Datums (Dru Smith)

Reference Surfaces (where is zero height or elevation?)

Sea level and ocean tides

Tidal datums (MHHW, MLHW, MHW, MSL, MLW, MHLW, MLLW)

The Geoid (elevations follow the rules of gravity)

The Ellipsoid (GPS coordinates follow the rules of geometry)

Heights:

- Orthometric heights
- Ellipsoid heights
- Dynamic heights

Vertical datums (NAVD88, NGVD29, PRVD02, ASVD02, NMVD03, GUVD04, VIVD09, IGLD85)

Horizontal datums (NAD83, WGS84)

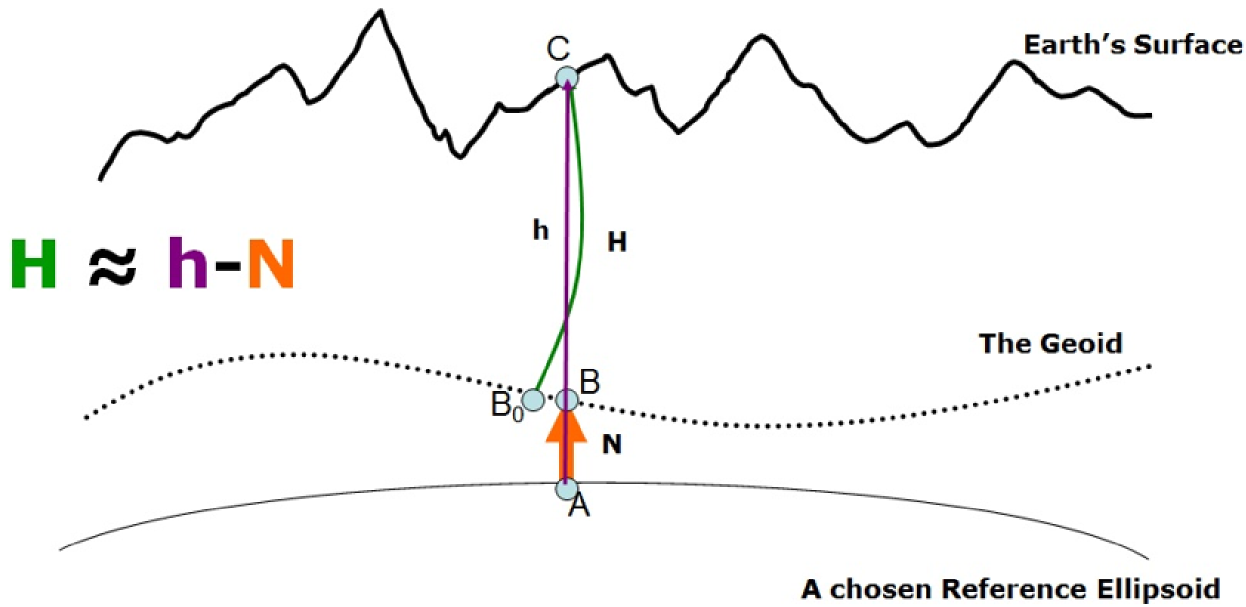
Converting heights/vertical datums

Geoid undulations

Transformation tools

Future vertical datums resulting from NGS' GRAV-D and datum adjustments (in 2022, all x/y and z coordinates will change)

Orthometric heights are what most people call “elevations”



H (Orthometric Height; B_0 to C)
=Distance along plumb line from the geoid to the surface

h (Ellipsoid Height; A to C)
= Distance along ellipsoidal normal from the reference ellipsoid to the surface

N (Geoid Undulation; A to B)
= Distance along ellipsoidal normal from the reference ellipsoid to the geoid

Figure 2.8. The relationship between ellipsoid heights (h, purple), orthometric heights (H, green) and geoid undulations (N, orange).

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Ch. 3: Standards, Guidelines and Specifications (Dave Maune)

FGDC Standards, including:

- *National Standard for Spatial Data Accuracy (NSSDA)*
- *Standards for Nautical Charting Hydrographic Surveys*

ASPRS Standards & Specs:

- *Positional Accuracy Standards for Digital Geospatial Data* (defines new vertical accuracy classes w/ NVA and VVA)
- *LAS Specification*, V1.4

USGS Lidar Base Specification V1.2

NOS *Hydrographic Surveys Specifications and Deliverables*

NDEP *Guidelines for Digital Elevation Data* (defines old vertical accuracies: FVA, CVA and SVA)

USACE EM 1110-1-1000, *Photogrammetric & Lidar Mapping*

Geodetic Control Standards and Guidelines

USGS Lidar Base Specification, v1.2

Table 3.12. Lidar density and absolute vertical accuracy

Quality Level (QL)	Aggregate Nominal Pulse Spacing (ANPS) (m)	Aggregate Nominal Pulse Density (ANPD) (pts/m²)	$RMSE_Z$ (non-vegetated) (cm)	NVA at 95% confidence level (cm)	VVA at 95th percentile (cm)
QL0	≤0.35	≥8.0	≤5.0	≤9.8	≤14.7
QL1	≤0.35	≥8.0	≤10.0	≤19.6	≤29.4
QL2	≤0.71	≥2.0	≤10.0	≤19.6	≤29.4
QL3	≤1.41	≥0.5	≤20.0	≤39.2	≤58.8

Table 3.13. Lidar relative vertical accuracy and minimum DEM cell sizes

Quality Level (QL)	Smooth Surface Repeatability (cm)	Swath Overlap Difference, $RMSD_Z$ (cm)	Swath Overlap Difference, Maximum (cm)	Minimum DEM Cell Size (m)	Minimum DEM Cell Size (ft)
QL0	≤3	≥4	±8	0.5	1
QL1	≤6	≥8	±16	0.5	1
QL2	≤6	≥8	±16	1	2
QL3	≤12	≥16	±32	2	5

QL2 lidar or better -- acceptable for the 3DEP

QL3 lidar or worse -- not acceptable for the 3DEP, except for QL5 IfSAR in Alaska

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IHO standards for depth uncertainty at the 95% confidence level

Table 3.1. Summary of Minimum Standards for Hydrographic Surveys

Order	**Special**	**1a**	**1b**	**2**
Description of areas.	Areas where under-keel clearance is critical	Areas shallower than 100 metres where under-keel clearance is less critical but *features* of concern to surface shipping may exist.	Areas shallower than 100 metres where under-keel clearance is not considered to be an issue for the type of surface shipping expected to transit the area.	Areas generally deeper than 100 metres where a general description of the sea floor is considered adequate.
Maximum allowable THU 95% *Confidence level*	2 metres	5 metres + 5% of depth	5 metres + 5% of depth	20 metres + 10% of depth
Maximum allowable TVU 95% *Confidence level*	a = 0.25 metre b = 0.0075	a = 0.5 metre b = 0.013	a = 0.5 metre b = 0.013	a = 1.0 metre b = 0.023
Full Sea floor Search	Required	Required	Not required	Not required
Feature Detection	Cubic *features* > 1 metre	Cubic *features* > 2 metres, in depths up to 40 metres; 10% of depth beyond 40 metres	Not Applicable	Not Applicable

$$\pm\sqrt{[a^2 + (b * d)^2]}$$

Where:
a represents that portion of the *uncertainty* that does not vary with depth
b is a coefficient which represents that portion of the *uncertainty* that varies with depth
d is the depth
b x d represents that portion of the *uncertainty* that varies with depth

These IHO standards will probably be used by NGS to establish bathymetric lidar equivalents to USGS' topographic lidar Quality Levels (QL0, QL1, QL2 and QL3) with:

- $QL0_B$ (IHO Special Order)
- $QL1_B$ (IHO Special Order)
- $QL2_B$
- $QL3_B$
- $QL4_B$ (IHO Order 1a)

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Ch. 4: The National Elevation Dataset

(Dean Gesch, Gayla Evans, Michael Oimoen, Samantha Arundel)

Background, rationale, history

Specifications and production

Source data

Production processing

Spatially referenced metadata

Accuracy and data quality

- Absolute vertical accuracy
- Relative vertical accuracy

Comparison with other large-area elevation datasets

Applications

The National Elevation Dataset and acronym (NED) were retired when the 3D Elevation Program (3DEP) became operational

Current developments and future directions

USGS is developing a new line of science products known as the Coastal National Elevation Database (CoNED) which integrates recent high resolution coastal lidar data (both topo and bathy) and a temporal component from captures on different dates

Coastal National Elevation Database (CoNED)

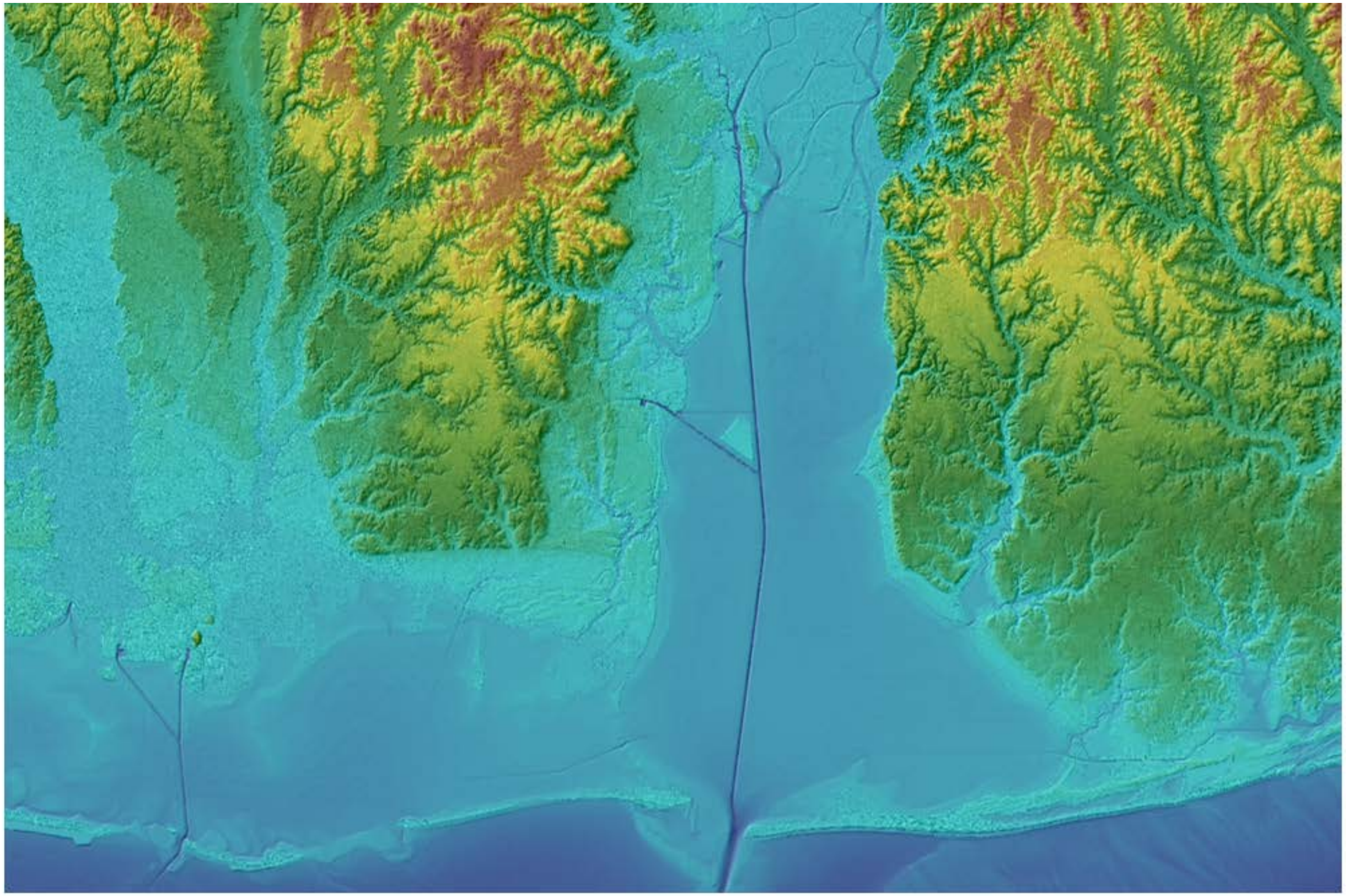

Figure 4.12. The Coastal National Elevation Database (CoNED) coverage of Mobile Bay, Alabama. CoNED is a merged topographic-bathymetric dataset that facilitates applications at the coastal land/water interface and is distributed as part of *The National Map* elevation products.

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Ch. 5: The 3D Elevation Program (3DEP)

(Jason Stoker, Vicki Lucas, Allyson Jason, Diane Eldridge, Larry Sugarbaker)

Background, rationale, history

USGS commitment to manage national elevation data assets

Assessment of requirements and Benefit/Cost Analysis (NEEA)

3DEP development, based on QL2 lidar, 8-year cycle, + QL5 IfSAR for Alaska

Data acquisition procedures

U.S. Interagency Elevation Inventory (USGS and NOAA)

USGS Lidar Base Specification

Broad Agency Announcement (BAA) process

Acquisition trends

3DEP data quality assurance

3DEP products and services

3DEP data dissemination

Current development and future directions:

- Geiger-mode lidar
- Single-photon lidar

Typical lidar point cloud being collected for the 3DEP

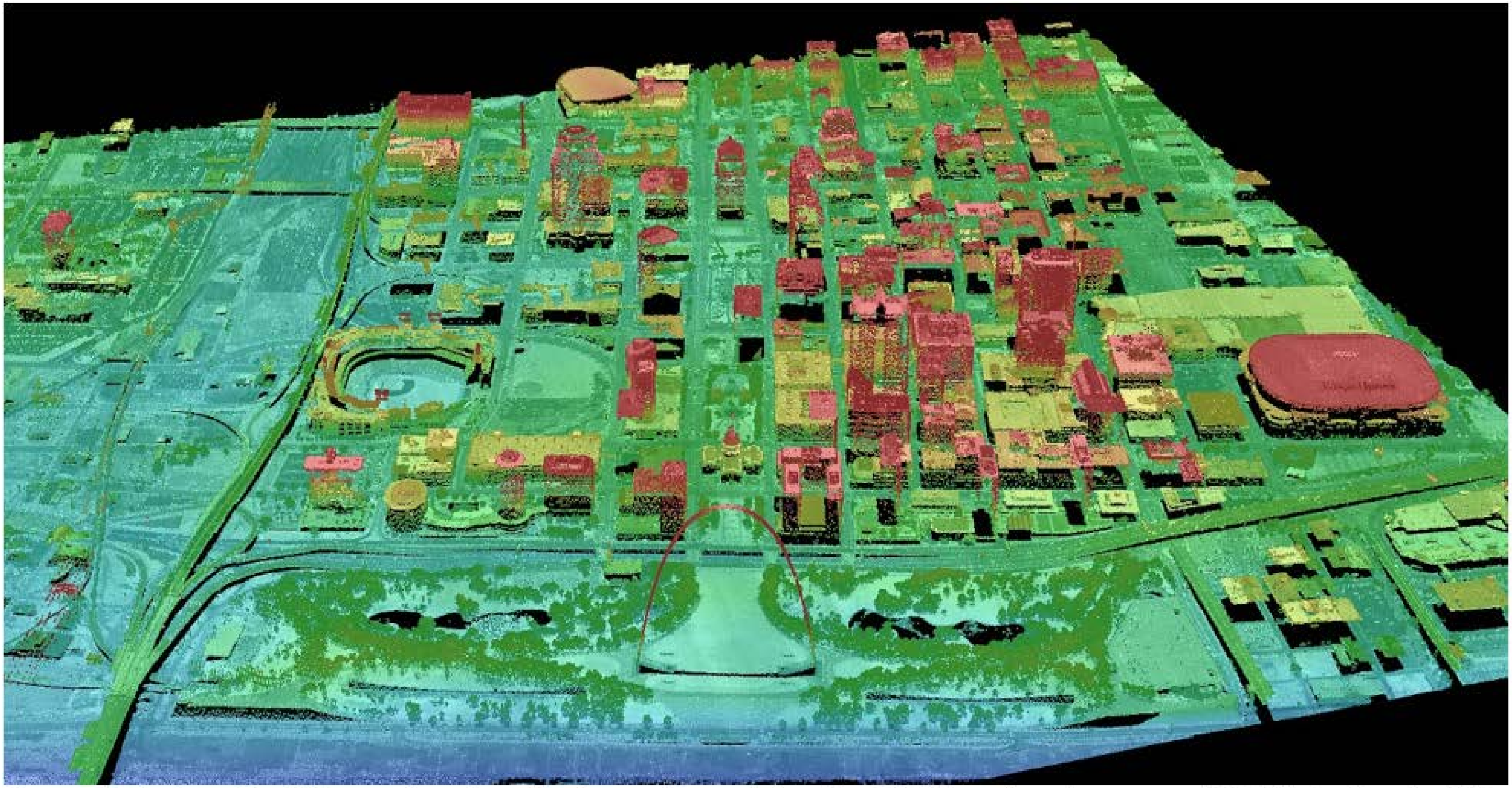

Figure 5.1. A typical lidar point cloud being collected for the 3D Elevation Program (3DEP). St. Louis, MO. Source: USGS

Ch. 6: Photogrammetry (J. Chris McGlone)

Sensor types:

- Airborne digital systems
- Satellite imagery

Project planning considerations

Georeferencing & aerotriangulation

Photogrammetric data collection methods:

- Softcopy stereoplotters
- Manual elevation compilation
- Automated elevation collection
    - Semi-global matching (SGM)
    - Structure from motion (SfM)

Post-processing & quality control

Data deliverables

Enabling technologies

Calibration procedures

Capabilities and limitations

Comparisons with competing / complementary technologies

DEM user applications

Cost considerations

Technological advancements

True-ortho vs. standard ortho

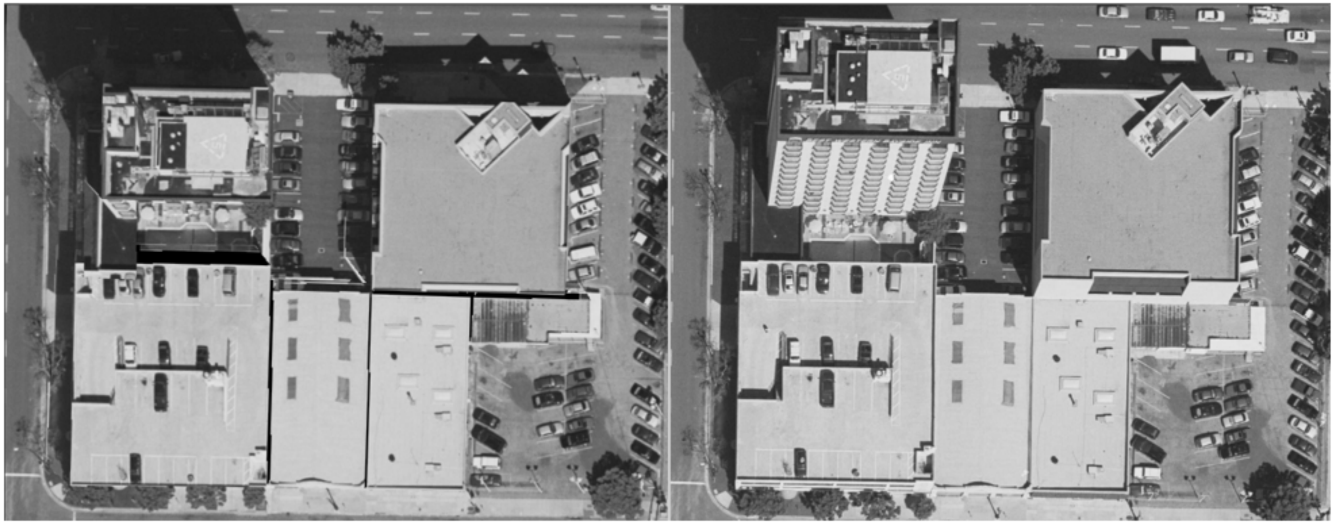

Figure 6.8. True orthoimage (left) and standard orthoimage (right). In the left image the tall building is in its true X/Y position and data from another image has been mosaicked into the occluded area. In the right image, windows and sides of buildings are clearly visible.

Ch. 7: IfSAR (Scott Hensley, Lorraine Tighe)

- Technology Overview
- Developmental History
- IfSAR Mapping Techniques
- IfSAR Data Post Processing
- IfSAR Quality Control
- IfSAR Data Deliverables
- Cost Considerations
- IfSAR Present Operating Status
  - Airborne IfSAR Systems
  - Spaceborne IfSAR Systems
- Comparison with Other Technologies
- User Applications
- Mapping Alaska – America's Last Frontier
- Technology Advancements

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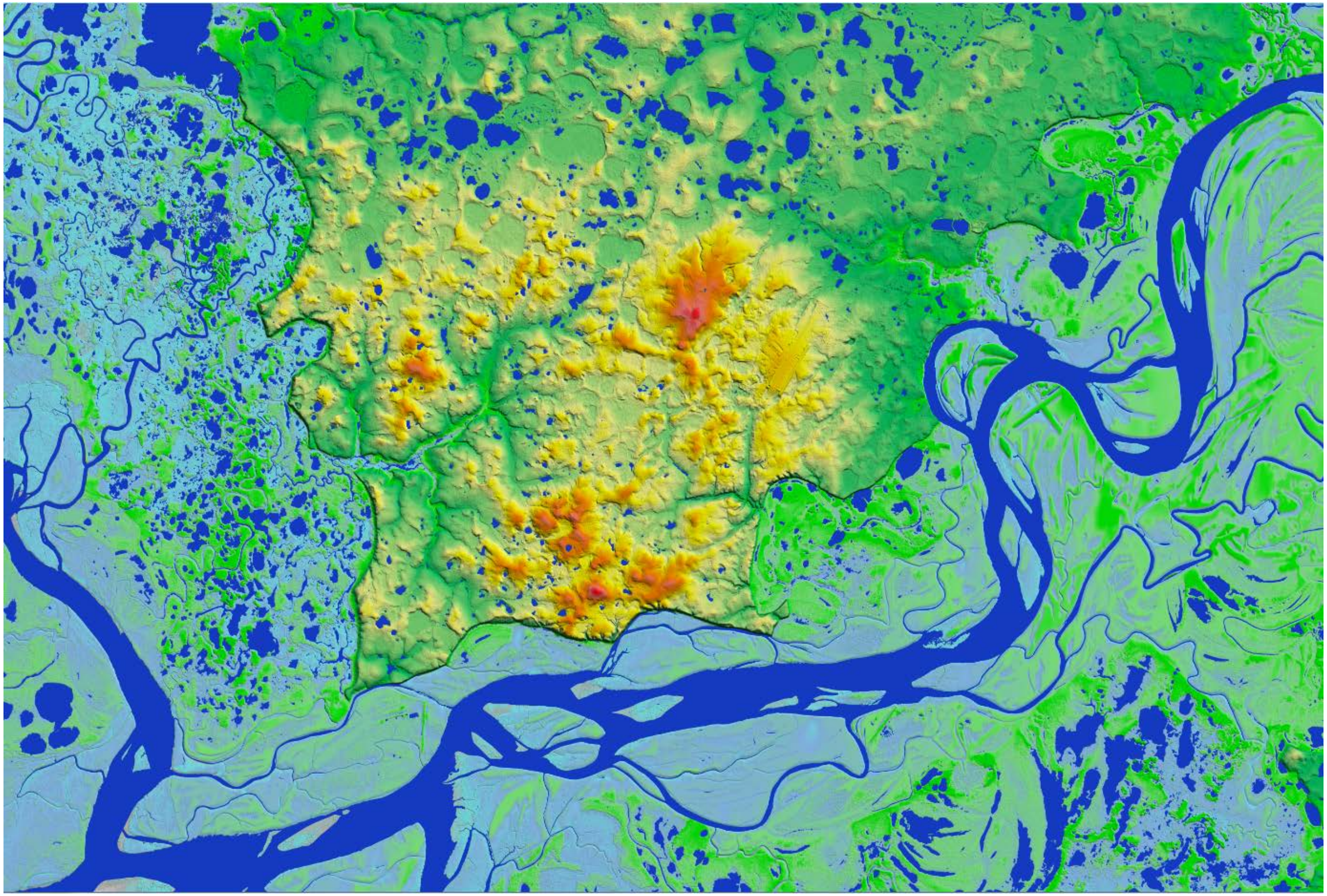
IfSAR DTM of Alaska hydro features



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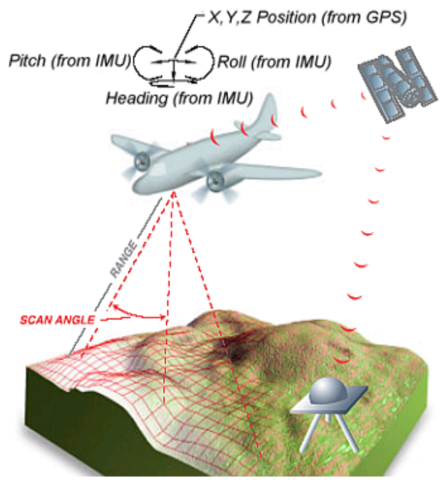
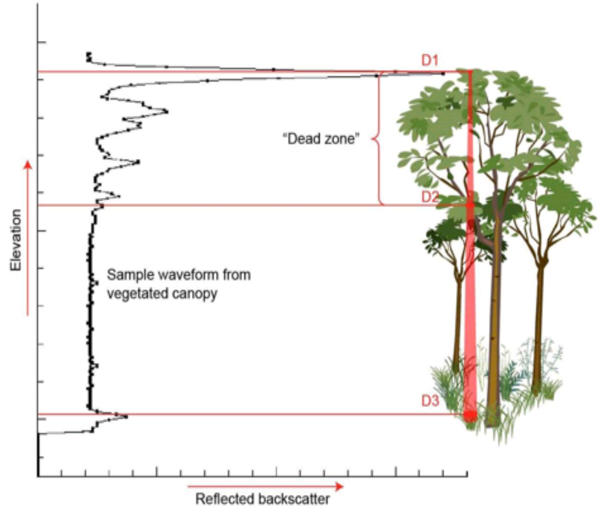
Ch. 8: Airborne Topographic Lidar

(Amar Nayegandhi)

- Introduction
- Basic Concepts
  - Light and the Electromagnetic Spectrum
  - Attenuation and Reflectance
  - Laser Ranging
  - Transmit Laser pulse characteristics
  - Laser Scanning techniques
  - Discrete return vs. Waveform-resolving Lidar
  - Detection Methodology
  - Linear vs. Photon-based lidar
  - 3-D Flash Lidar Technology
  - Geiger Mode Lidar
- Developmental History
- Airborne Lidar Operations
- Data Processing
- Current Sensor Technology
- Comparison with Overlapping Technologies
- User Applications

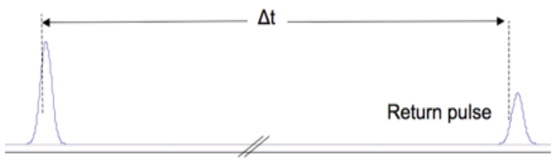
Ch. 8: Airborne Topographic Lidar

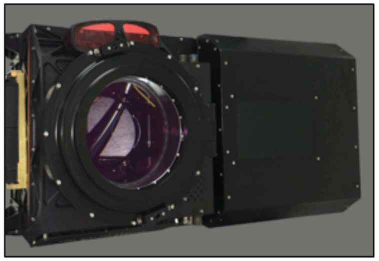




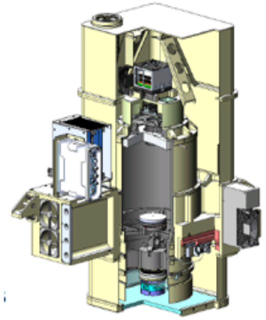
RIEGL LMS-Q1560

Leica ALS 80





Sigma Space HRQLS2 Single Photon Lidar



Harris Geiger Mode Lidar

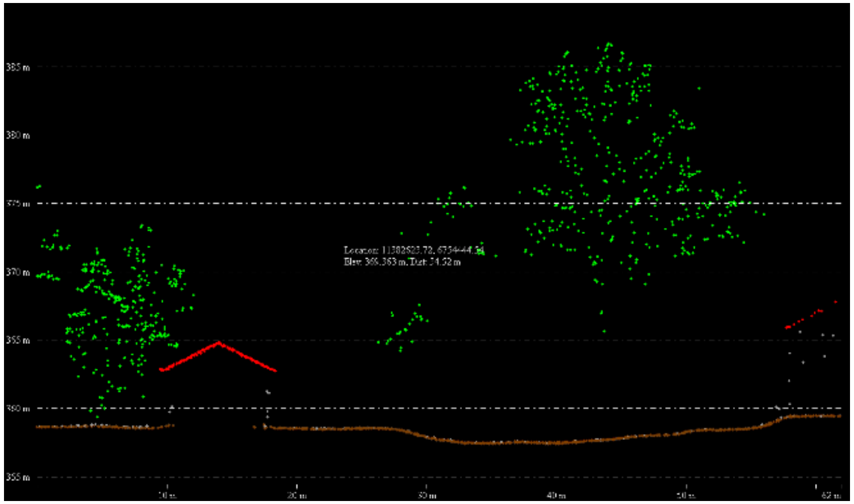
Optech Galaxy

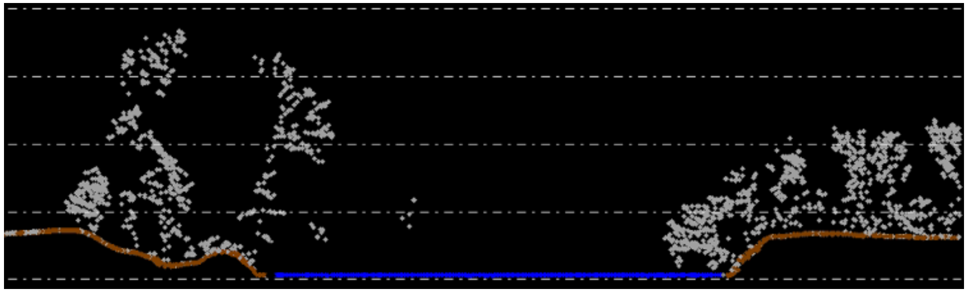
Ch. 9: Lidar Data Processing (Josh Novac)

- Introduction
- Lidar Processing
  - Concepts and Approaches
  - Automated Filtering
    - Filtering Ground/Non-Ground points
    - Noise
    - Structures
    - Vegetation
    - Other above ground features
  - Manual Editing
- Breakline Processing
  - Concepts and Approaches
  - Automated Processing Options
    - Water
    - Structures
    - Other
  - Manual Processing Options
    - Lidargrammetry
    - Elevation Conflation
- DEM Processing
  - Concepts and Approaches
  - Processing Techniques
    - Terrain
    - Point Cloud
    - Other
  - Incorporating Breaklines
    - Hydro-Flattening
    - Hydro-Conditioning
    - Hydro-Enforcement
  - DSM Processing

Ch. 9 Lidar Data Processing

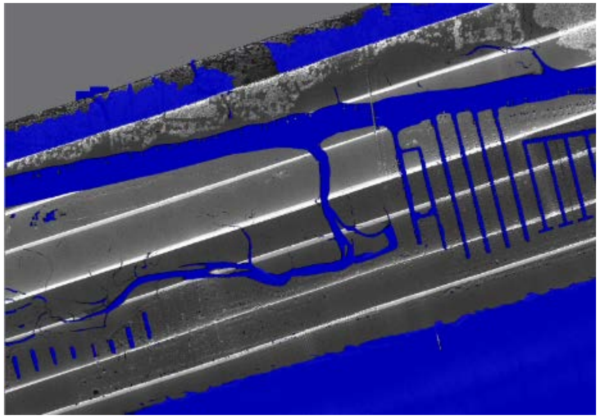
Lidar Processing

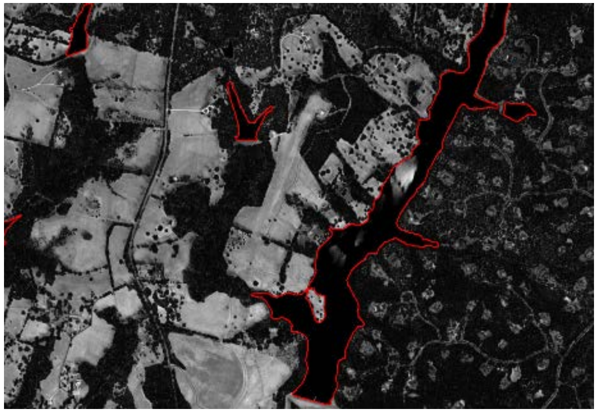




Two examples of Lidar classification. The top picture represents a higher level of classification including vegetation and buildings. The bottom example shows ground/non-ground and water classified.

Breakline Processing

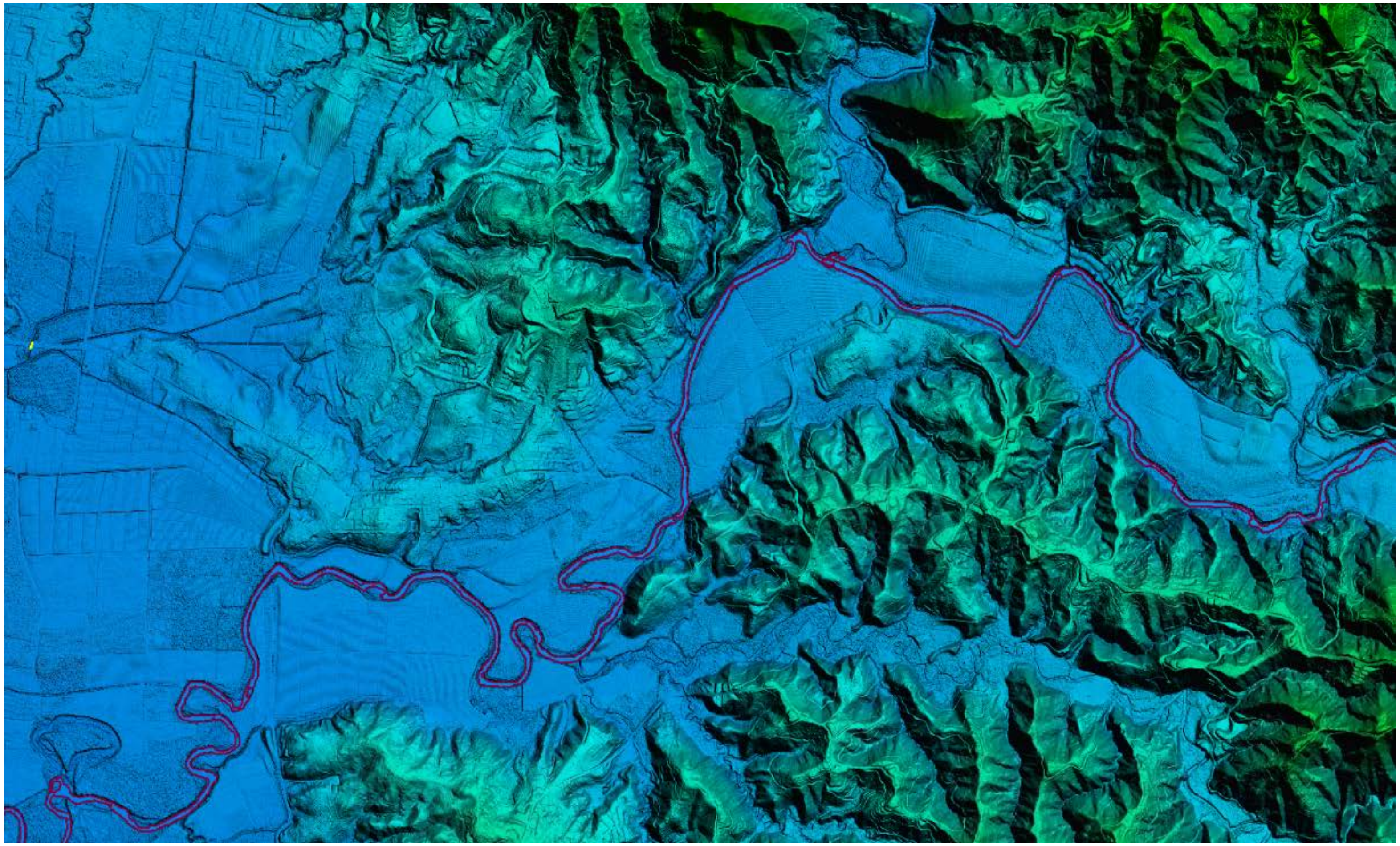




Two examples of breakline extraction. The top image represents detailed breaklines extracted using automated methods in eCognition. The bottom represents ponds collected through a combination of automated and manual methods.

Ch. 9: Lidar Data Processing

DEM Processing



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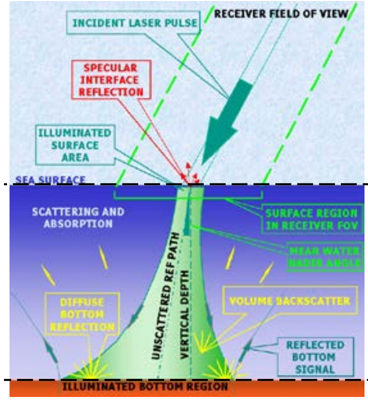
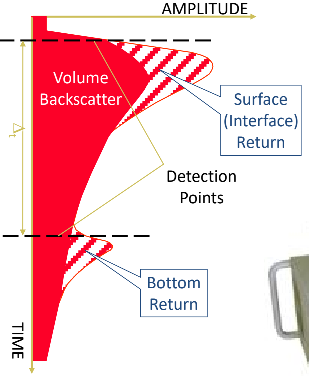
Ch. 10: Airborne Lidar Bathymetry

(Jennifer Wozencraft and Amar Nayegandhi)

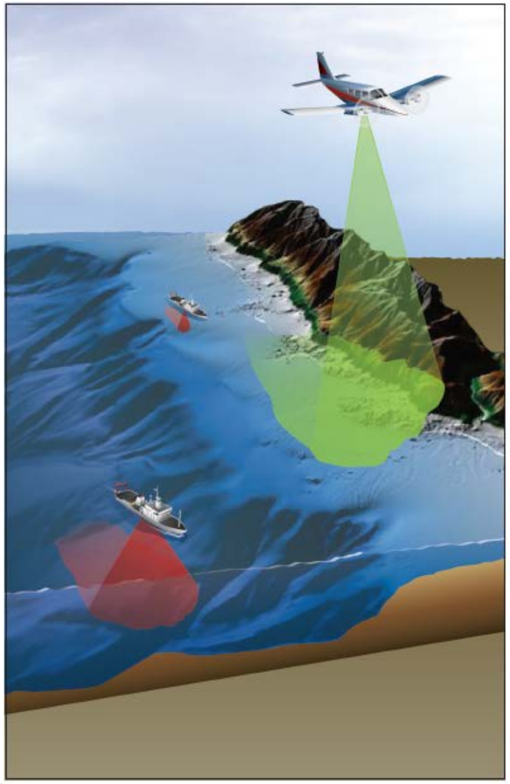
- Introduction
  - Bathymetric vs Topobathymetric Lidar
- Basic Concepts
  - Refraction at air/water interface
  - State of the sea surface
  - Bubbles and breaking waves
  - Optical properties of the water column
  - Beam attenuation coefficient, Diffuse Attenuation Coefficient (K_d) and the Secchi Depth
  - Characteristics of the sea floor
- Basic System Design
  - Laser Transmitter Unit
  - Scanner Unit
  - Receiver Unit
  - Enabling Technologies
- Developmental History
- Data Processing
- Expectations from ALB Systems
- ALB Eye Safety Features
- Depth Penetration & Accuracy
- Current Sensor Technology
- Comparison with Overlapping Technologies
- User Applications

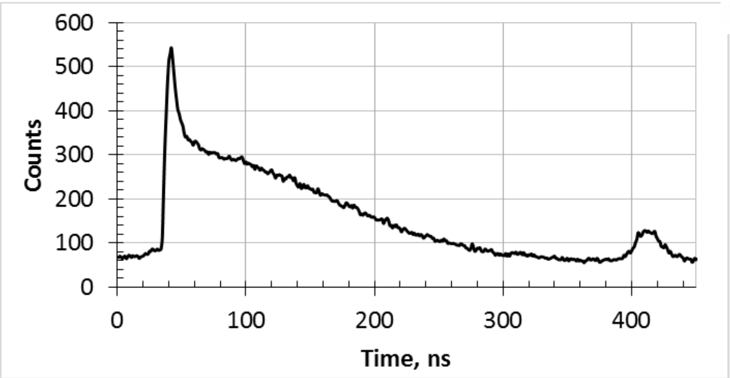
Ch. 10: Airborne Lidar Bathymetry





	Bathymetric Lidar Quality Levels				
	$QL0_B$	$QL1_B$	$QL2_B$	$QL3_B$	$QL4_B$
Pulse Spacing	≤0.7m	≤2.0 m	≤0.7 m	≤2.0 m	≤5.0 m
Point Density	≥2.0 pts/m²	≥0.25 pts/m²	≥2.0 pts/m²	≥0.25 pts/m²	≥0.04 pts/m²
Depth (m)	Bathymetric Accuracy RMSE (cm)				
	$QL0_B$	$QL1_B$	$QL2_B$	$QL3_B$	$QL4_B$





Ch. 11: Sonar (Guy Noll)

Technology overview

Developmental history

Basic principles of acoustic mapping:

- Acoustic sources
- Directional transmit/receive transducers

Types of sonars:

- Vertical beam sonar
- Multibeam sonar
- Side scan sonar
- Interferometric/focusing/Doppler

Present operating status:

Platforms and installation

Calibration procedures

Planning considerations

Capabilities and limitations

Comparisons with complementary and competing technologies

Post processing

Quality control

Data deliverables

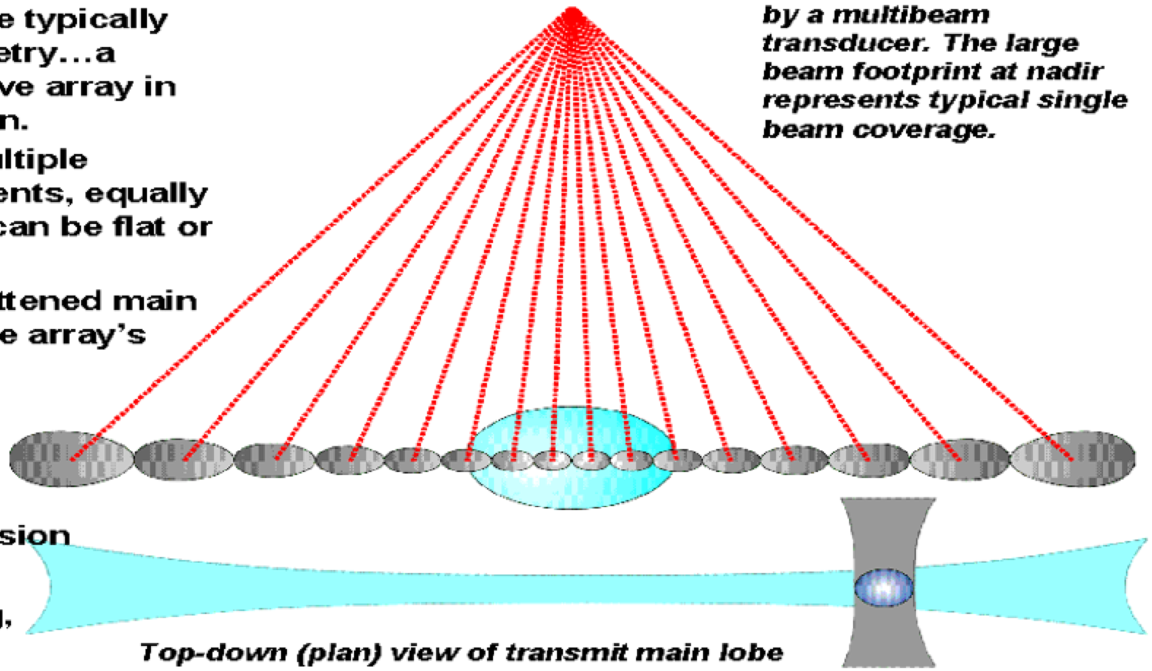
Cost considerations

Technology advancements

Individual beams in a multibeam transducer form a swath

- Multibeam transducers are typically based on cross-fan geometry…a transmit array and a receive array in an "L" or "T" configuration.
- Each array consists of multiple identical transducer elements, equally spaced, in a line. Arrays can be flat or curved.
- Each array produces a flattened main lobe which is narrow in the array's long axis.
- The intersection of the two flattened main lobes results in a narrow beam.
- Every "firing" or transmission of the array is called a "ping". During one ping, all beams are transmitted & received.

Transverse view of 16 near-nadir beams formed by a multibeam transducer. The large beam footprint at nadir represents typical single beam coverage.



Top-down (plan) view of transmit main lobe and receive main lobe intersection as projected onto the seafloor…with highlighted cross product.

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Ch. 12: Enabling Technologies

(Bruno Scherzinger, Joe Hutton, Mohamed Mostafa)

GNSS positioning technologies:

- GNSS single point positioning
- Differential GNSS
- Precise phase interferometry positioning
- Precise point positioning (PPP)

Local, regional and global differential GNSS

Continuously Operating Reference Stations (CORS)

Types of sensors

Error sources

GNSS-aided Inertial Navigation technologies (GNSS-AINS):

- Inertial navigation systems (INS)
- GNSS-AINS for direct georeferencing

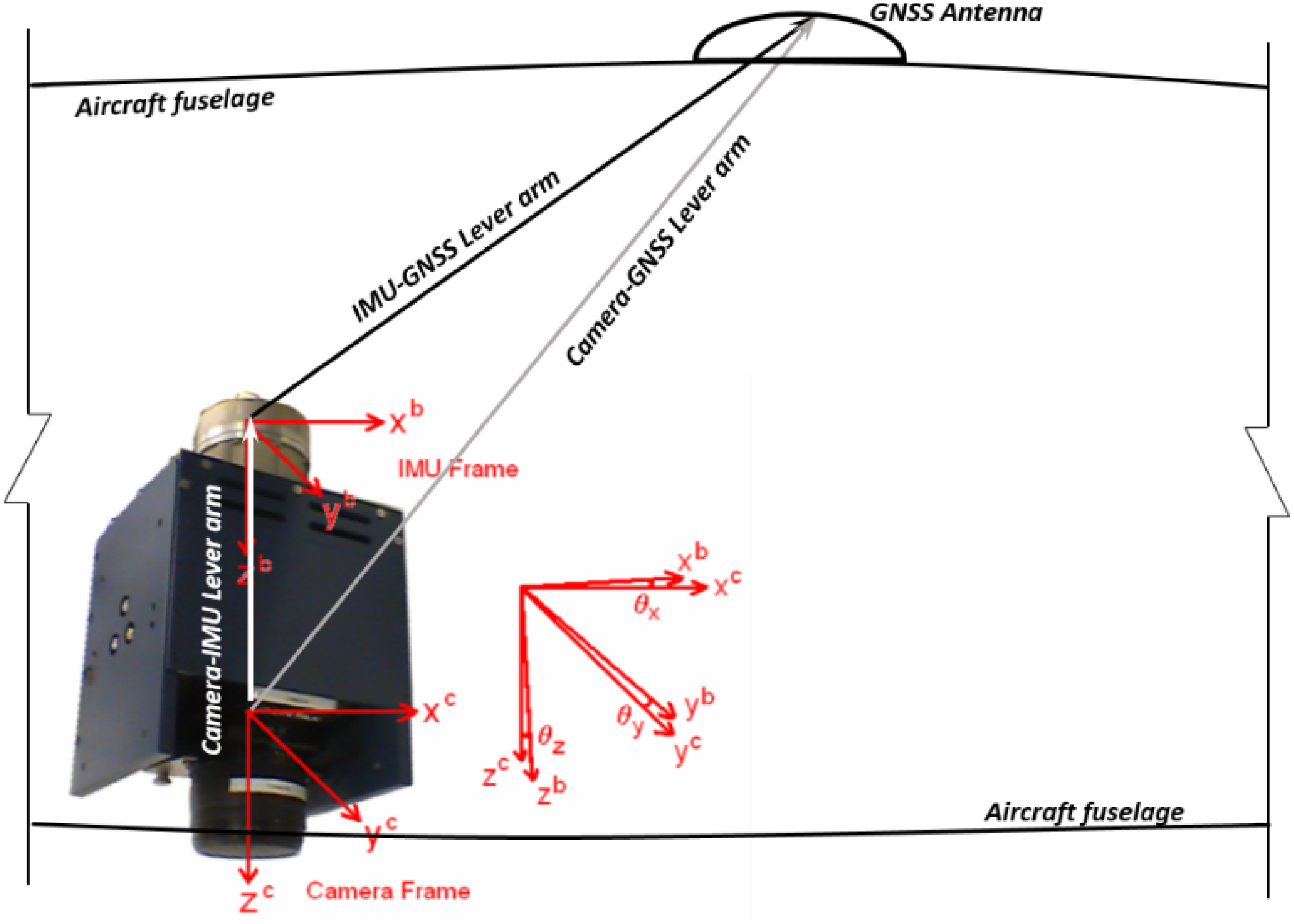
Direct georeferencing systems for airborne DEM generation

- Types of airborne DG systems
- Boresight calibration
- Post processing

Motion sensing system for multibeam sonar bathymetry

- Types of sensors

IMU-GNSS and Camera-GNSS lever arm calibration



Ch. 13: DEM User Applications

(Dave Maune)

NEEA's 27 Business Uses

General mapping applications (digital orthophotos, topographic maps, flood maps)

Special mapping applications (soils, geologic, wetland, forestry, wildlife habitat, cultural resources, urban and regional planning maps)

Coastal mapping applications (Digital Coast, SLR viewing, shoreline delineation, coastal management and engineering, coastal flood hazard mapping)

Underwater applications

Transportation applications (land, aviation and marine navigation and safety)

Technical applications (national resources conservation, H&H modeling, water supply, stormwater, subsidence)

Military applications

Commercial applications (precision agriculture, mining, renewable energy, oil and gas, telecommunications, recreation)

Individual applications (elevation certificates, individual parcel topographic maps)

Includes graphic examples of 27 Major Business Uses in the NEEA

Table 13.1. DEM Business Uses Documented in the NEEA Study

1. Natural resources conservation	15. Sea level rise and subsidence
2. Water supply and quality	16. Wildfire management, planning and response
3. River & stream resource management	17. Homeland security, law enforcement, and disaster response
4. Coastal zone management	18. Land navigation and safety
5. Forest resources management	19. Marine navigation and safety
6. Rangeland management	20. Aviation navigation and safety
7. Wildlife and habitat management	21. Infrastructure and construction management
8. Agriculture and precision farming	22. Urban and regional planning
9. Geologic resource assessment, hazard mitigation	23. Health and human services
10. Resource mining	24. Real estate/banking/mortgage/insurance
11. Renewable energy resources	25. Education K-12 and beyond
12. Oil and gas resources	26. Recreation
13. Cultural resources preservation and management	27. Telecommunications
14. Flood risk management	

These Business Uses did not include general mapping applications or individual applications

Ch. 14: DEM User Requirements and Benefits (Dave Maune)

DEM User Requirements:

Need for all users to focus on standardized QL2 lidar or better, standard 3DEP deliverables:

- Standard metadata
- Standard raw point cloud
- Standard classified point cloud
- Standard hydro-flattened, bare-earth raster DEM
- Standard breaklines
- Common data upgrades that do not compromise standardization and interoperability

Benefits of 3DEP Standard Prod:

- Single authoritative source of high quality & consistent 3DEP data at lower costs to all
- Standard 3DEP products that use common hardware/software, standard training for data users and producers
- Easier generation of derivative products from standard source
- >5:1 Return on Investment
- Planned data updates
- Seamless data from tops of mountains to depths of the sea

Highest ROI from QL2 Lidar with 6-10 year update cycle

Option #	Quality Level	Update Frequency	Annual Total Costs	Annual Total Benefits	Benefit/Cost Ratio	Net Benefits (Benefits - Costs)
1	1	Annual	$1,646M	$1,111M	0.674	($536M)
2	1	2-3 years	$659M	$1,110M	1.685	$451M
3	1	4-5 years	$366M	$1,066M	2.914	$700M
4	1	6-10 years	$206M	$800M	3.887	$594M
5	1	>10 years	$110M	$403M	3.671	$293M
6	2	Annual	$1,006M	$923M	0.917	($84M)
7	2	2-3 years	$402M	$922M	2.291	$520M
8	2	4-5 years	$224M	$888M	3.970	$664M
9	2	6-10 years	$126M	$674M	5.356	$548M
10	2	>10 years	$67M	$339M	5.049	$272M
11	3	Annual	$760M	$697M	0.917	($63M)
12	3	2-3 years	$304M	$696M	2.291	$392M
13	3	4-5 years	$169M	$673M	3.983	$504M
14	3	6-10 years	$95M	$501M	5.278	$406M
15	3	>10 years	$51M	$252M	4.970	$201M
16	4	Annual	$487M	$361M	0.741	($126M)
17	4	2-3 years	$195M	$360M	1.851	$166M
18	4	4-5 years	$108M	$346M	3.198	$238M
19	4	6-10 years	$61M	$256M	4.204	$195M
20	4	>10 years	$32M	$129M	3.962	$96M
21	5	Annual	$241M	$190M	0.788	($51M)
22	5	2-3 years	$96M	$190M	1.970	$93M
23	5	4-5 years	$53M	$180M	3.365	$126M
24	5	6-10 years	$30M	$131M	4.369	$101M
25	5	>10 years	$16M	$66M	4.118	$50M

B/C Ratio >5:1 computed using conservative benefits ($1.3B/yr)

B/C Ratio >50:1 if computed using potential benefits ($13.3B/yr)

Actual B/C Ratio is increasing as Lidar costs are decreasing substantially

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Ch. 15: Quality Assessment (Jen Novac, 100-page tutorial approved by Karl Heidemann, incl. 96 images)

Standards, Guidelines and Specs

Quantitative Assessments:

- Accuracy assessments (relative and absolute vertical accuracy)
- Absolute horizontal accuracy assessments
- Accuracy reporting

Qualitative Assessments:

- Source data QA/QC
- Breakline QA/QC
  - Breakline completeness
  - Breakline variance
  - Breakline topology
- Macro level review of DEM data
- Micro level review of DEM data:
  - DEM visualization and display
  - DEM raster types (DSMs, bare-earth DTMs, bathymetric and topobathymetric DEMs)
  - Qualitative reviews
  - Artifacts/over-smoothing
  - Inconsistent editing
  - Hydro-flattening or enforcement
  - Edge-matching
- QA/QC of contours
- QA/QC of metadata

Boresight / Calibration

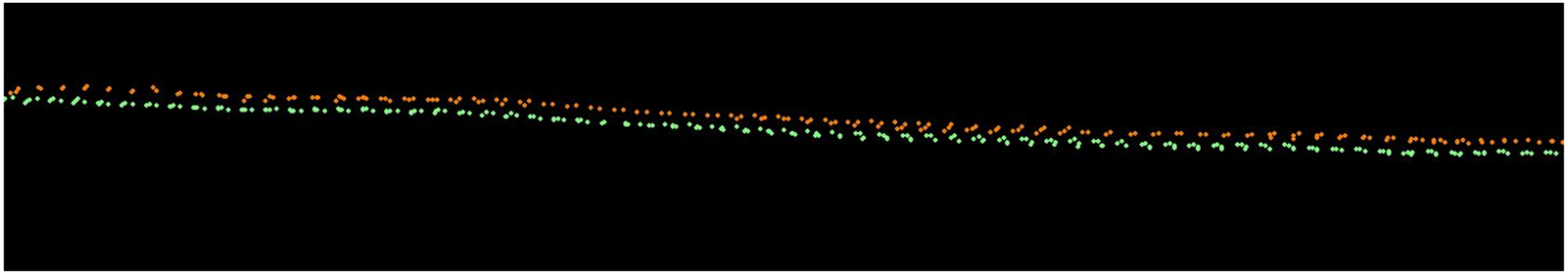
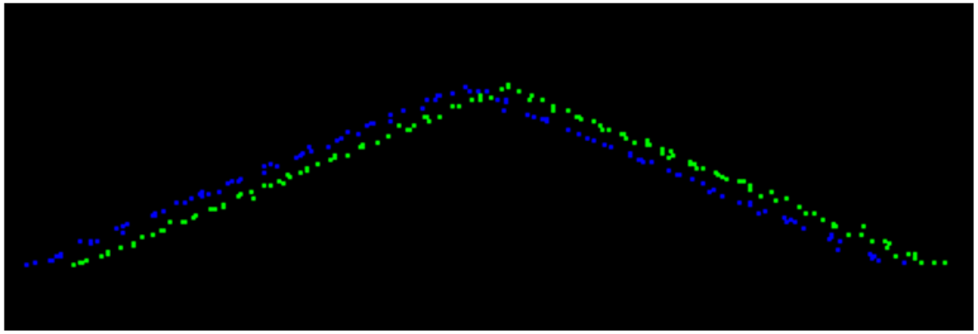


Figure 15.4. This profile shows two different swaths, each colored differently. There is approximately 1.5 feet of vertical difference between the two overlapping swaths due to poor calibration/boresight techniques. These two swaths should have consistent z elevations and should overlap each other.



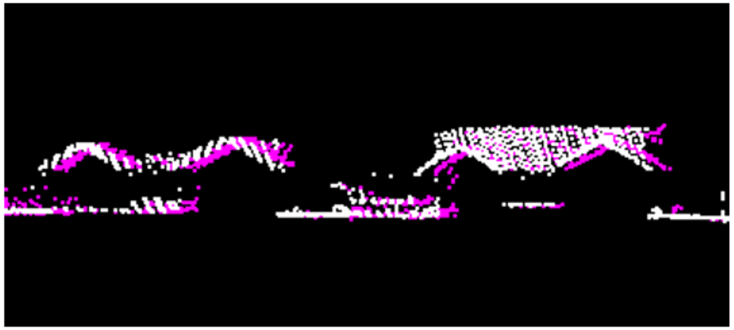


Figure 15.5. The image on the left shows two swaths (blue/green points) from a single rooftop where horizontal misalignments result in vertical offsets of approximately 20 cm between the two swaths. The image on the right also shows vertical offsets (20 cm) between two swaths (pink/white points) resulting from horizontal misalignments between the swaths, but this image shows several rooflines.

ΔZ Ortho Relative Accuracy Eval.

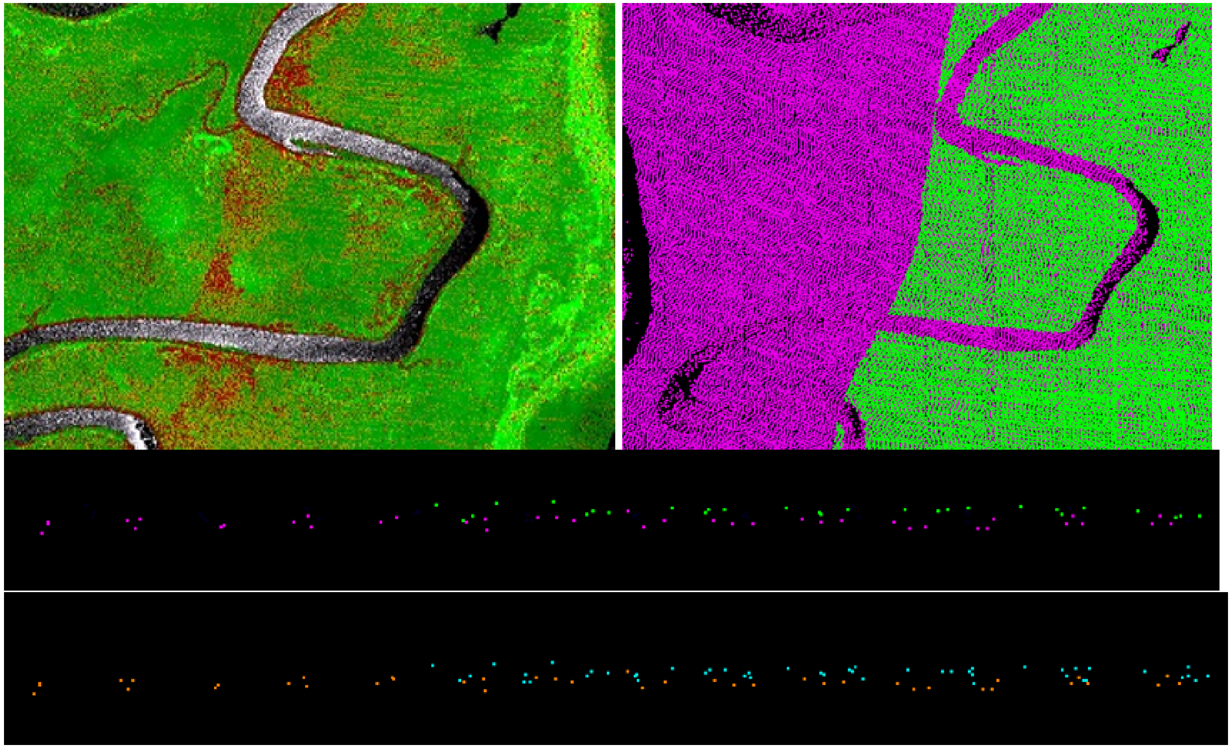


Figure 15.10. The top left image is a single return ΔZ ortho where a diagonal line of red is visible in the middle of the image. The rest of the image is green, indicating the rest of the data is within the project specifications for inter-swath relative accuracy. The top right image shows the lidar point cloud colored by flight line. A comparison of the two top images shows that the line of red visible in the ΔZ ortho occurs at the edge of the green flight line where roll errors may exist. The top profile also shows lidar points colored by flight line. In the profile, points from the green flight line are visibly separated from the purple flight line. These points are approximately 11 cm above the purple flight line and as the user moves towards the center of the swath, both flight lines will eventually match in elevation. As the rest of the data is calibrated correctly, these points at the edges of flight lines will be flagged as withheld and not used in any of the data processing for bare earth ground or other products. The bottom profile shows the lidar points colored by class where orange points are the final ground and turquoise points are those flagged as withheld.

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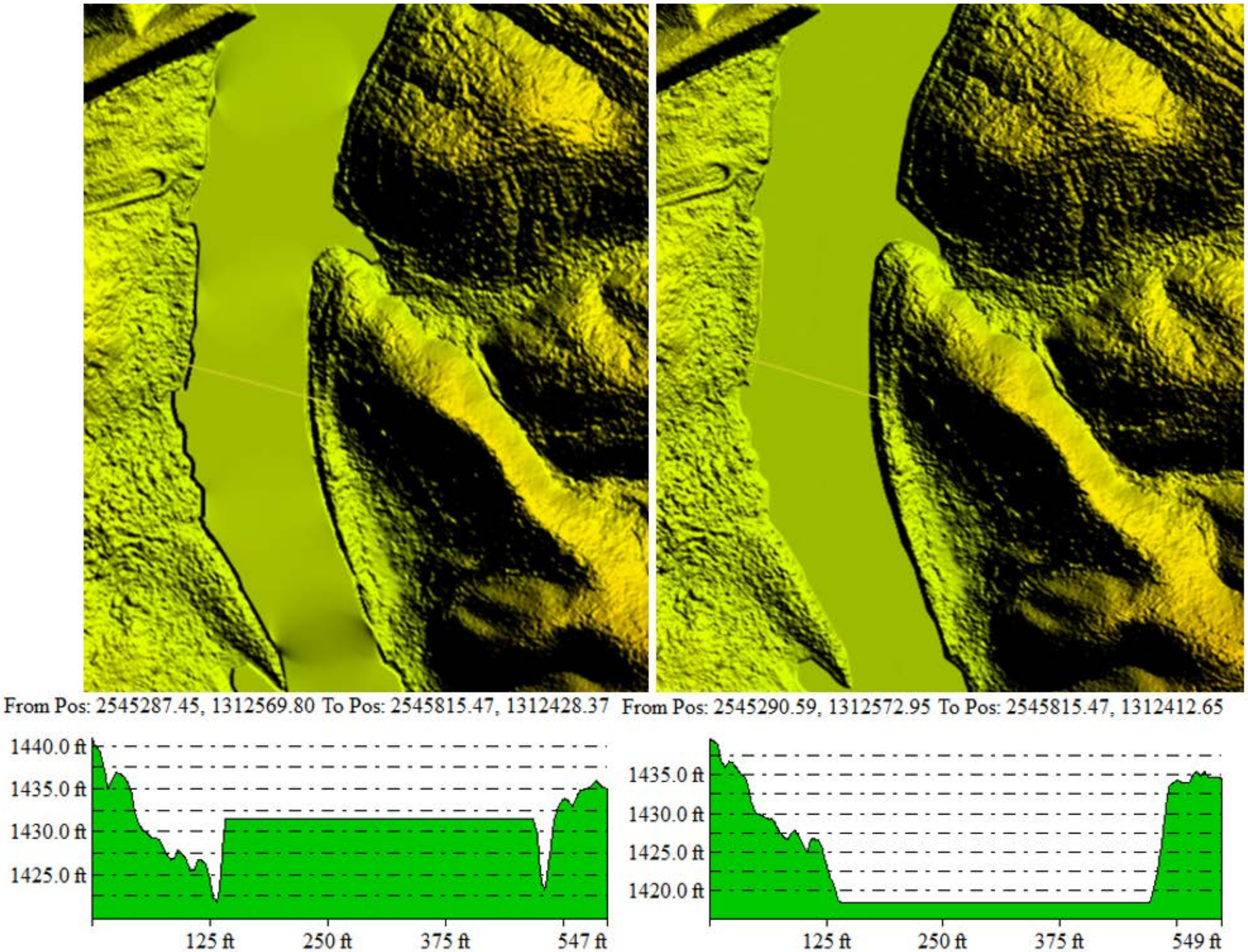
“Floating” hydro breakline vertices
(just one of dozens of hydro issues explained)



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Bridge Removal Interpolation Artifact
(aka "Bridge Saddle")

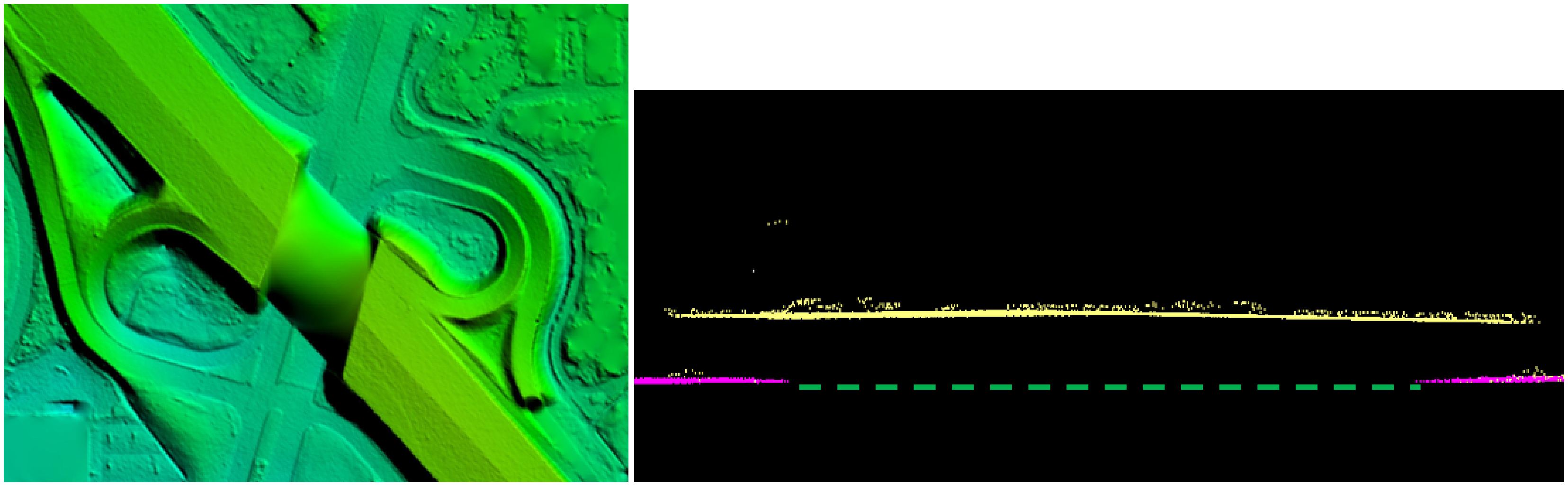


Figure 15.79. The image on the left shows an interpolated area or bridge saddle is present in the bare-earth DEM where a bridge was removed. The profile on the right shows that all elevated bridge points (yellow) have been correctly filtered from the ground surface (purple). The interpolated area in the bare-earth DEM is expected and acceptable if clients or project specifications do not require the removal of such interpolation artifacts. Lidar projects processed to USGS Lidar Base Specifications must have these artifacts corrected and removed from the final bare earth DEMs, as shown in Figure 15.80.

Lidar projects processed to USGS specifications must have "bridge saddles" corrected and removed in the final bare earth DEMs to create a continuous surface beneath the bridge.

Building Removal Interpolation

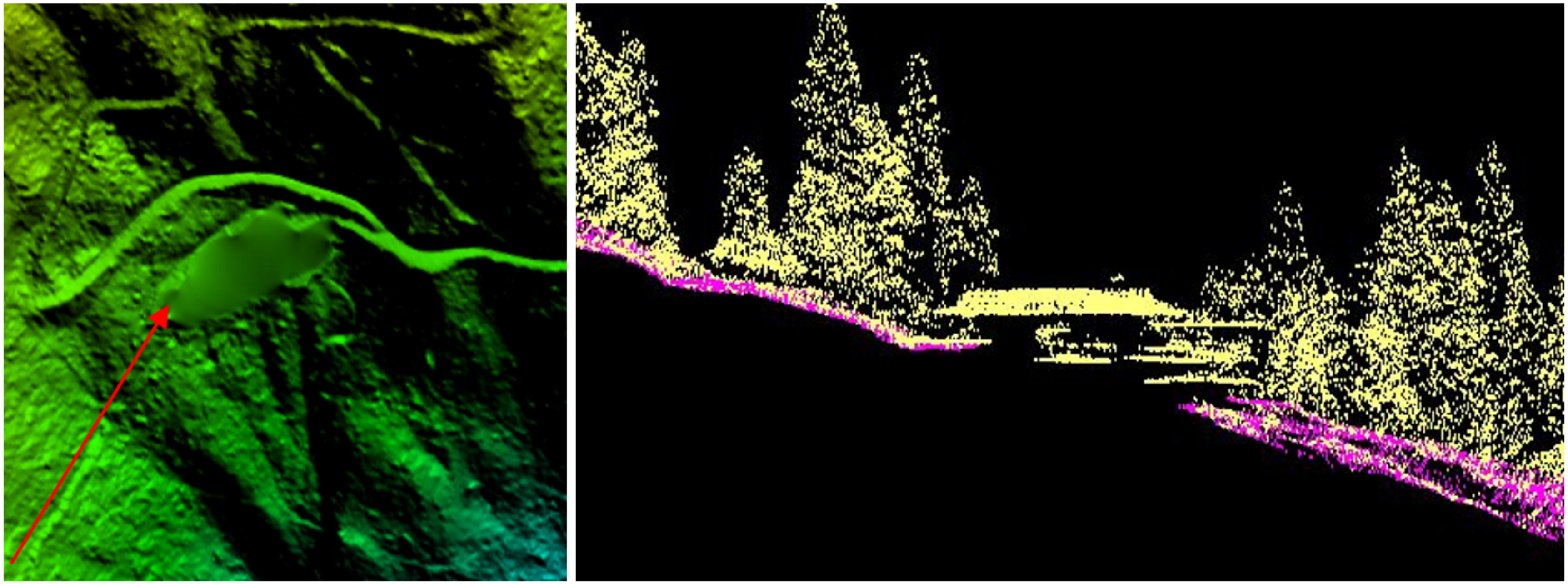
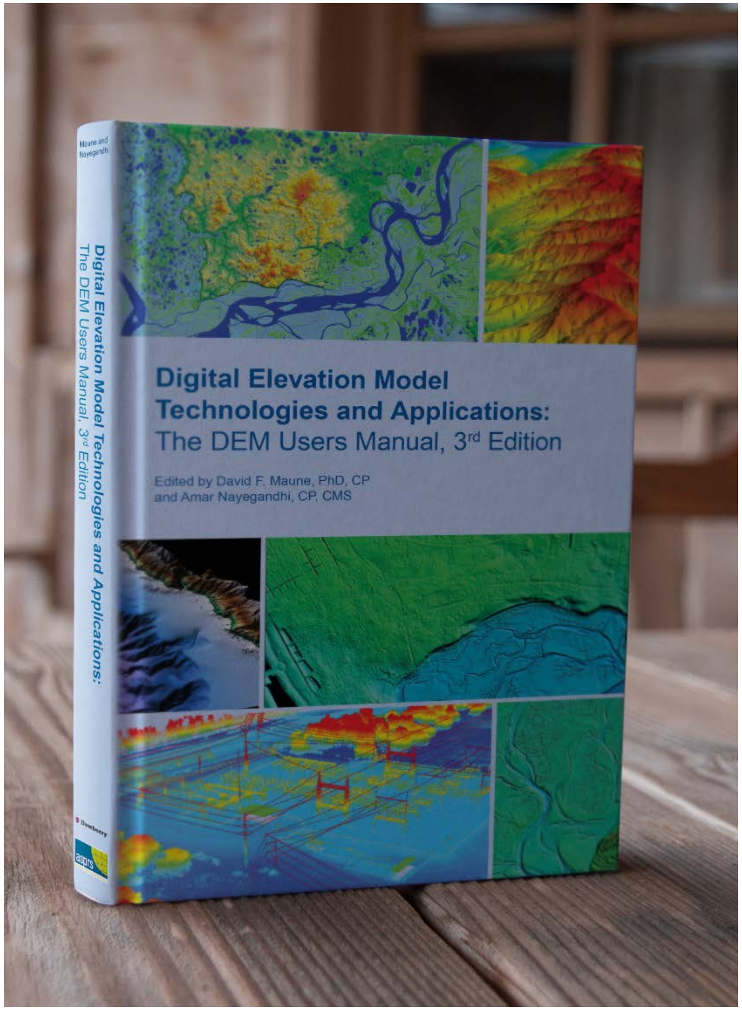


Figure 15. 75. The image on the left shows a bare-earth DEM where interpolation resulting from the removal of a building on a slope is more visible than building removal interpolation that occurs on flat terrain. The image on the right is profile of the lidar data used to create the bare-earth DEM. The profile shows that all above-ground features (yellow), including vegetation and structures, have been removed from the bare-earth ground surface (pink).

Hardcopy and eBook



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