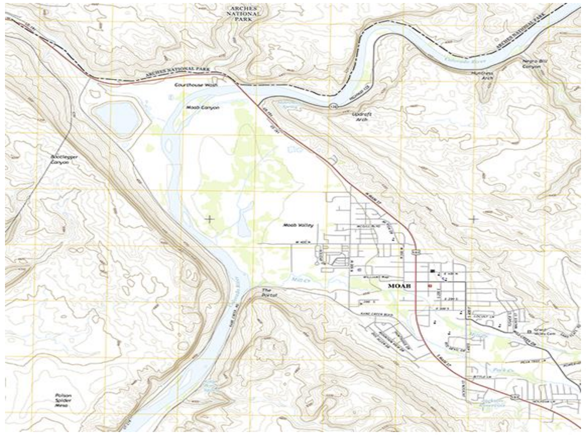
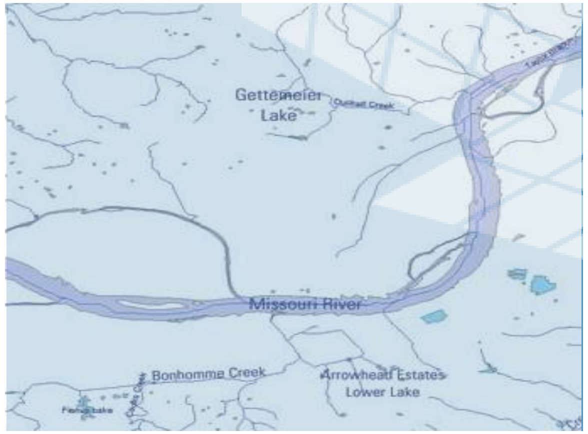
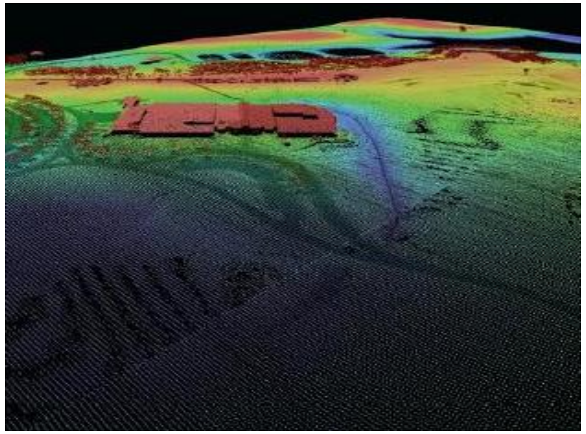
GPS/GNSS applications in support of the USGS 3D Elevation Program (3DEP)







Josh Nimetz

GPS/GNSS applications in support of the USGS 3D Elevation Program (3DEP)

60th Meeting of the Civil GPS Service Interface Committee

September 22, 2020

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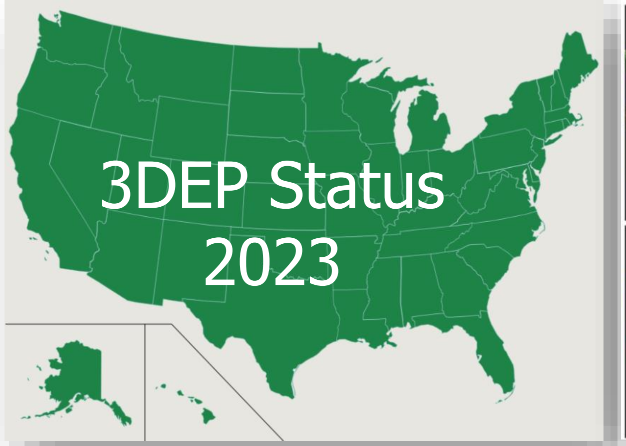
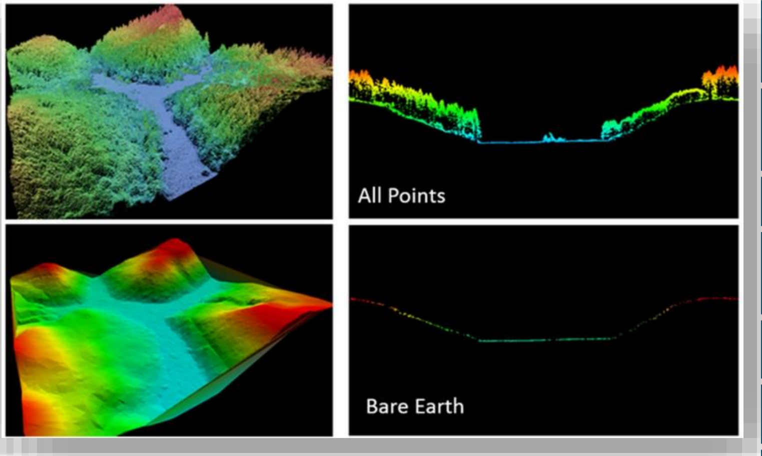
3D Elevation Program (3DEP) Goal

- Complete acquisition of nationwide lidar (IfSAR in AK) by 2023 to provide the **first-ever national baseline of consistent high-resolution elevation data – both bare earth and 3D point clouds – collected in a timeframe of less than a decade**
- Address Federal, state and other mission-critical requirements
- Realize ROI 5:1 and potential to generate $13 billion/year
- Leverage the expertise and capacity of private mapping firms
- Achieve a 25% cost efficiency gain
- Completely refresh national data holdings

		Annual Benefits	
Rank	Business Use	Conservative	Potential
1	Flood Risk Management	$295M	$502M
2	Infrastructure and Construction Management	$206M	$942M
3	Natural Resources Conservation	$159M	$335M
4	Agriculture and Precision Farming	$122M	$2,011M
5	Water Supply and Quality	$85M	$156M
6	Wildfire Management, Planning and Response	$76M	$159M
7	Geologic Resource Assessment and Hazard Mitigation	$52M	$1,067M
8	Forest Resources Management	$44M	$62M
9	River and Stream Resource Management	$38M	$87M
10	Aviation Navigation and Safety	$35M	$56M
:			
20	Land Navigation and Safety	$0.2M	$7,125M
	Total for all Business Uses (1 – 27)	**$1.2B**	**$13B**





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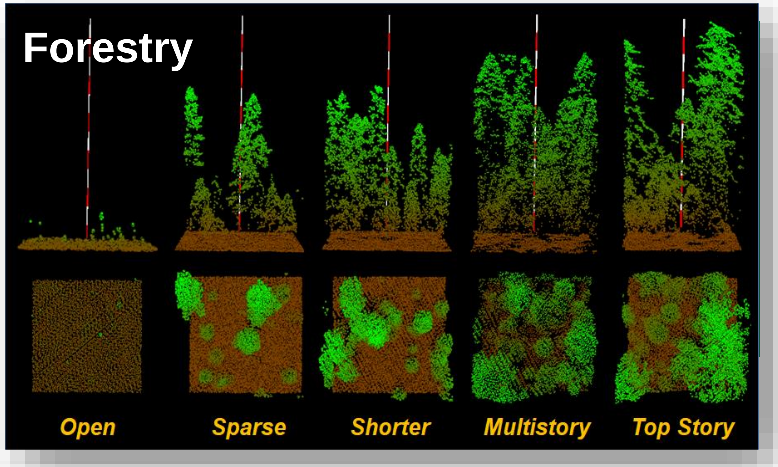
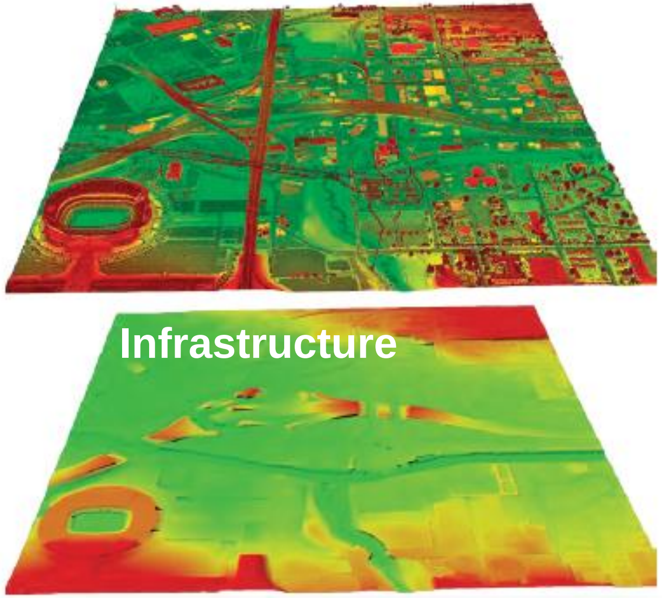
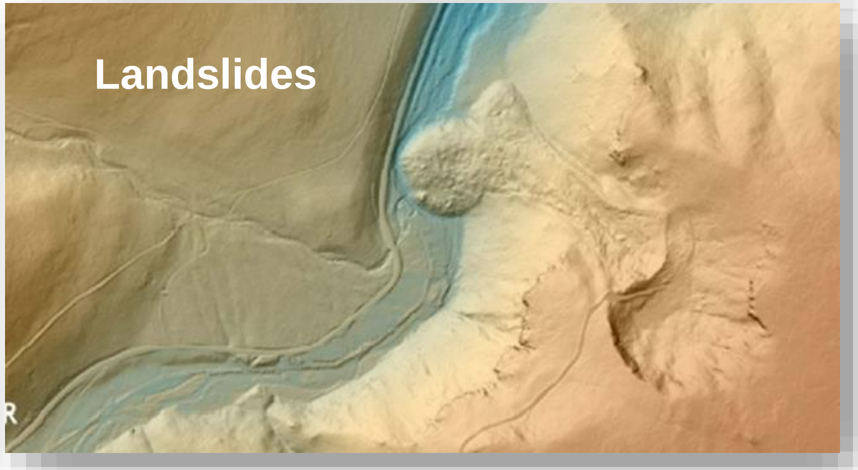
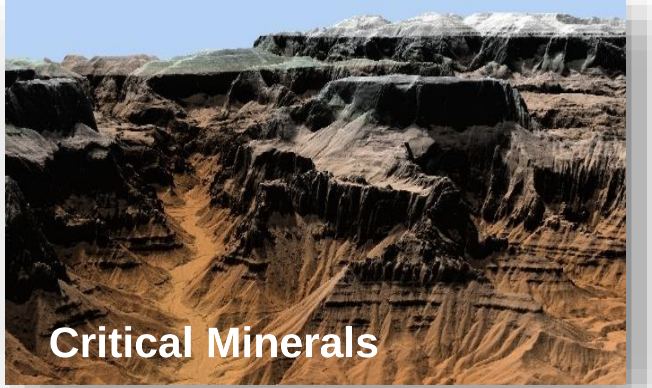
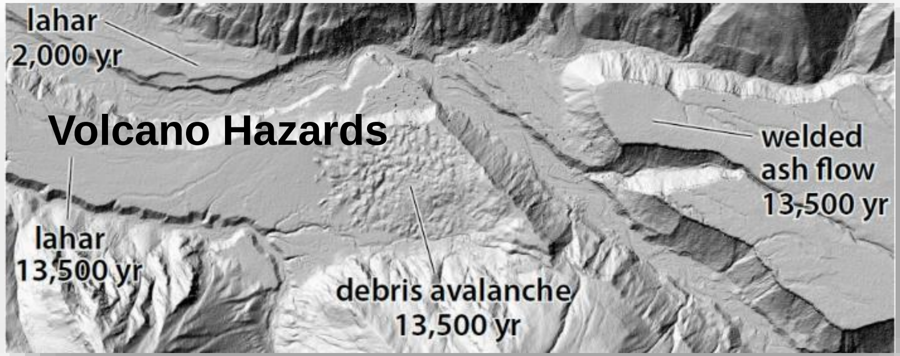
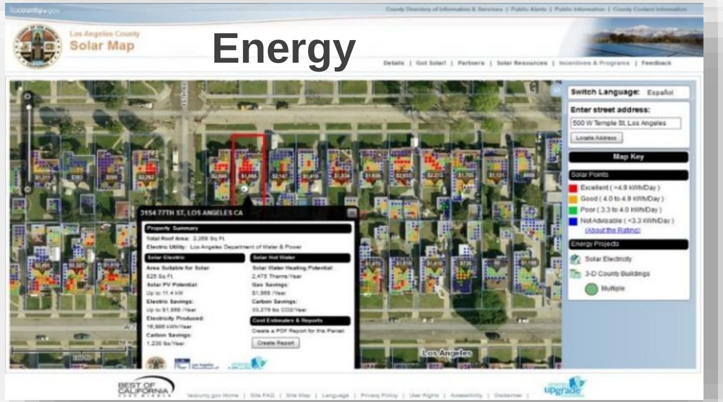






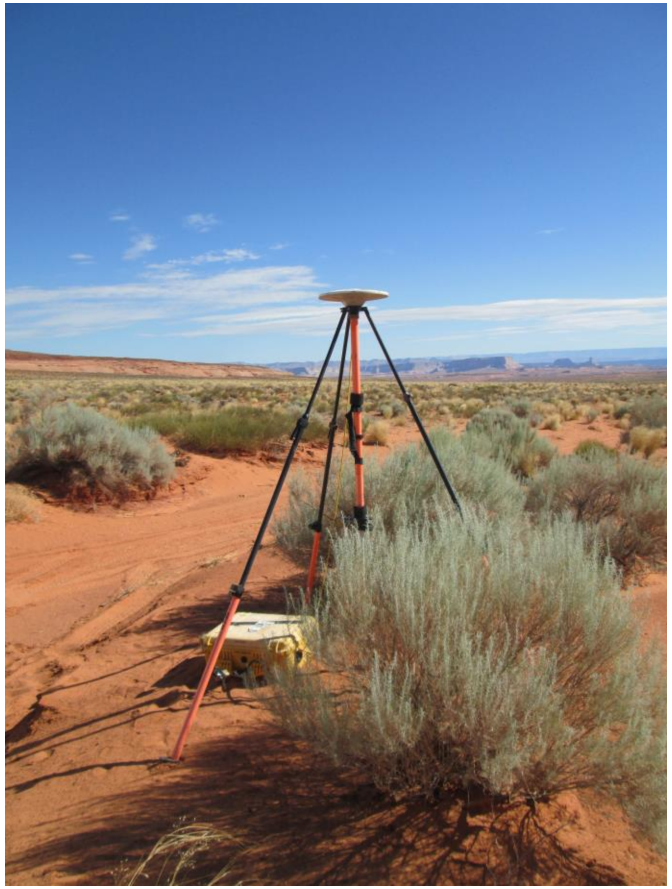






GPS/GNSS – The Foundation of 3DEP Data

- **Trillions of 3D coordinates (lidar points) covering the surface of the U.S.**
- **3DEP based on active remote sensing technologies, namely large format airborne lidar data collected and processed by commercial contractors** ***(Alaska collected with airborne IfSAR)***
- **Data fidelity is designed to be ≥ 2 lidar measurements per square meter over conterminous U.S. and outlying islands (for many projects, ≥ 8 measurements psm!)**
- **Lidar data are controlled and validated with multi-constellation GNSS data**
  - **Airborne multi-constellation GNSS controls lidar sensor positions**
  - **Ground-based multi-constellation GNSS observations produce ground truth for vertical control and data validation**



GNSS reference station (base station) outside LeChee Arizona

Airborne GNSS-inertial Systems for Large Format Airborne Lidar

- *GNSS-inertial market owned by two companies – Applanix (Trimble) and NovAtel (Hexagon | Leica Geosystems)*

Large format airborne lidar companies (4)

TELEDYNE OPTECH
Everywhereyoulook™

RIEGL®

L3HARRIS™
FAST. FORWARD.

HEXAGON | Leica Geosystems

LN200 fiber optic gyroscopes (FOG)

μIRS ring laser gyroscopes (RLG)

IMU-ISA-100C (FOG)

applanix
A TRIMBLE COMPANY

HEXAGON | NovAtel

Position and Orientation System (POS)

Sensor Position Attitude Navigation (SPAN)

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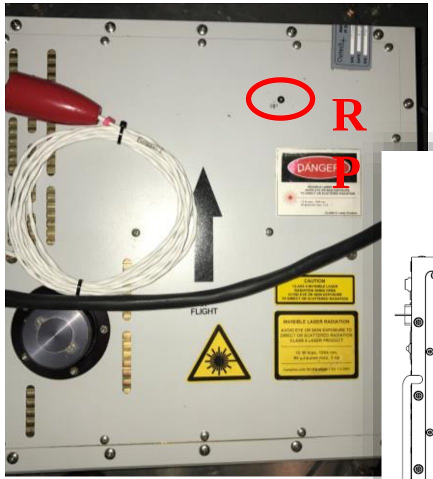
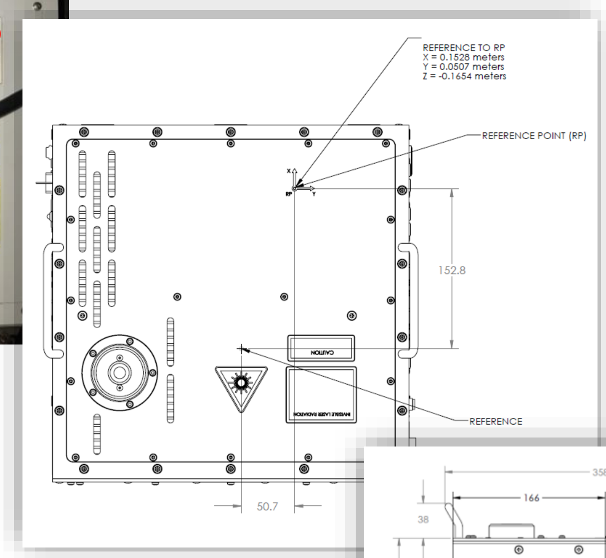
+ Exterior and Interior Orientation

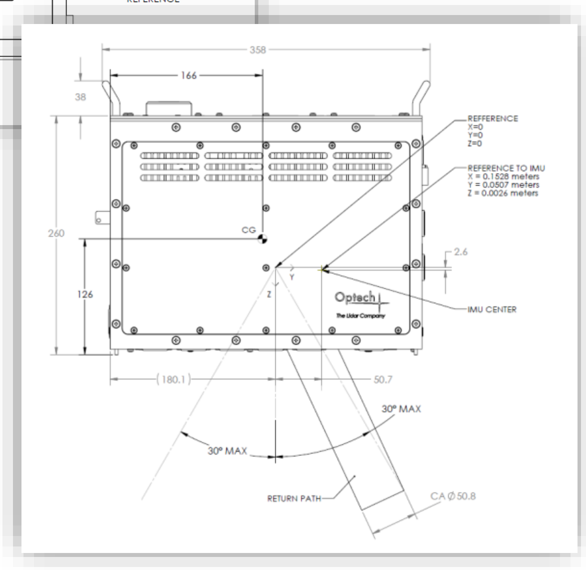
- **How position, attitude, and acceleration (GNSS-inertial) data are physically tied to lidar measurements**

Exterior Orientation:
Airborne GNSS Lever-Arms – measurement for each of three axes between antenna reference point and LiDAR sensor reference point. Right thumb down rule.



Optech Orion H300 reference point - Image





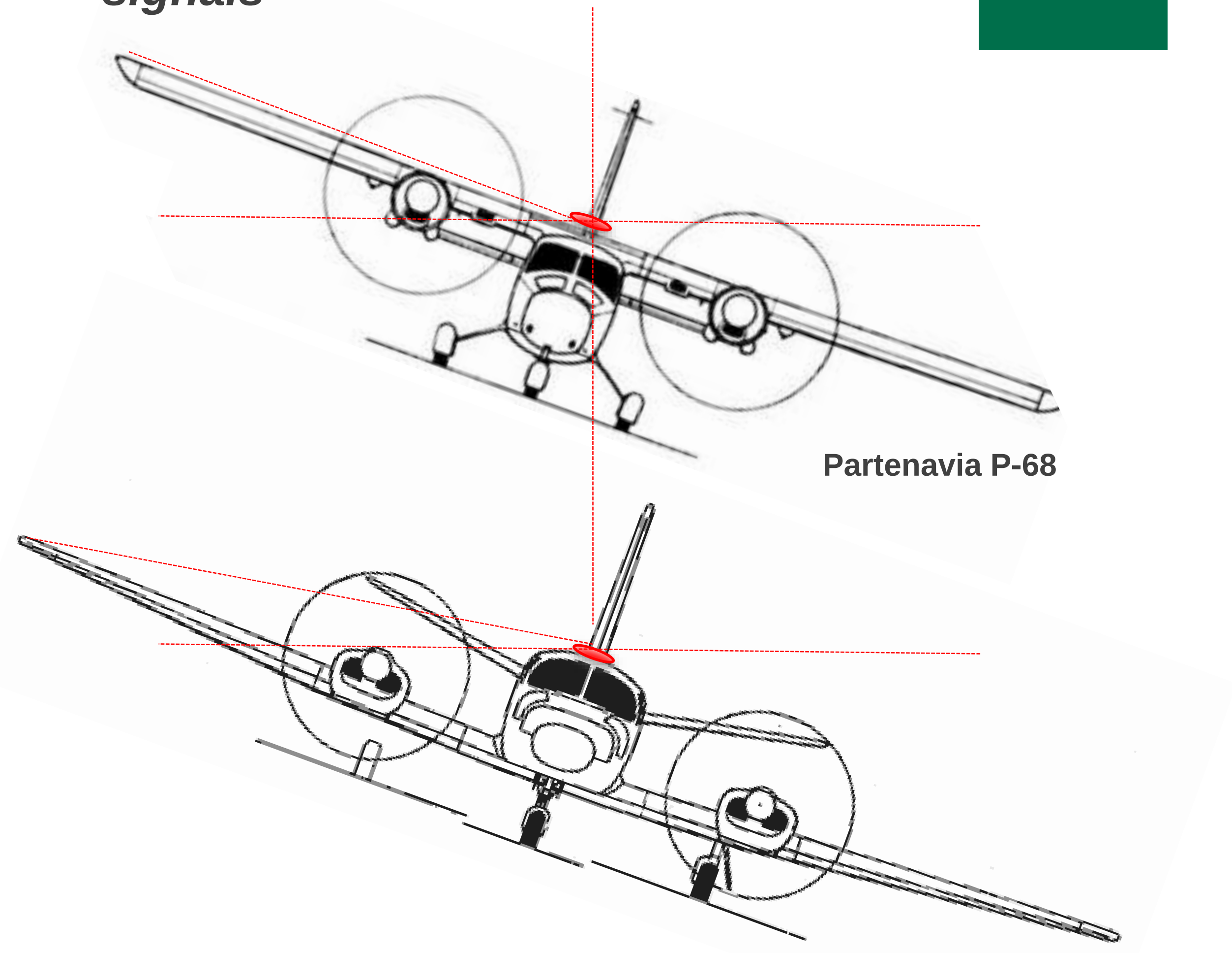
Optech Orion C200 schematics

Interior Orientation:
Lidar sensor reference frame including IMU and optical center; offsets and mounting angles

+ Airborne GPS-inertial – The Early Days

- Pre-planning was essential
  - Number of GPS Svs – 4, 5, 6, maybe even 7!
  - PDOP ruled the day
- AGPS baseline lengths kept short (~ 25 km) to maintain bias correlation to one or two reference stations
- Dual frequency - a real boon for kinematic positioning
- Many processing options: start/stop times, KAR initialization, omitting/adding SVs, changing the mask, ionospheric and tropospheric modeling, more KAR settings…
- Comparing the forward/reverse solution of one reference station to another
- When AGPS is as good as it can be, sync up with IMU data and process through the Kalman filter

Bank angles ≤ 20° to mitigate masking signals



Partenavia P-68

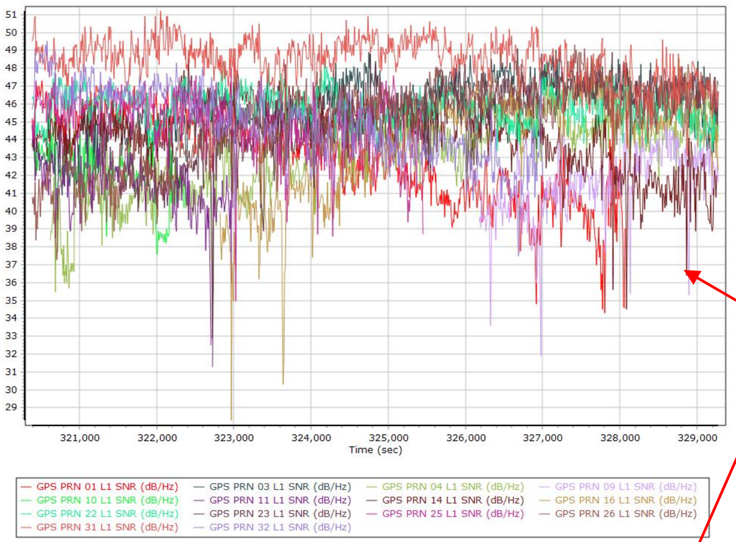
Cessna 402

+ Airborne GNSS-inertial – Present Day

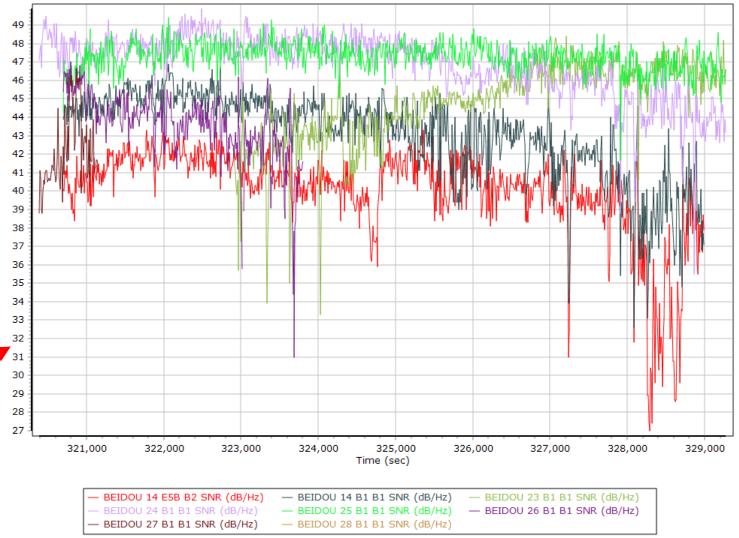
- **Multi-constellation GNSS has become essential to modern airborne remote sensing ops such as those conducted for 3DEP (and other survey and mapping applications)**

- **More SVs = lower PDOP and quicker integer resolution**
- **Tightly / deeply coupled GNSS-inertial (more on this later)**
- **Processing environment is much more "black box", but also much more robust**

GPS L1 SNR



BEIDOU SNR



Modern GNSS Constellations

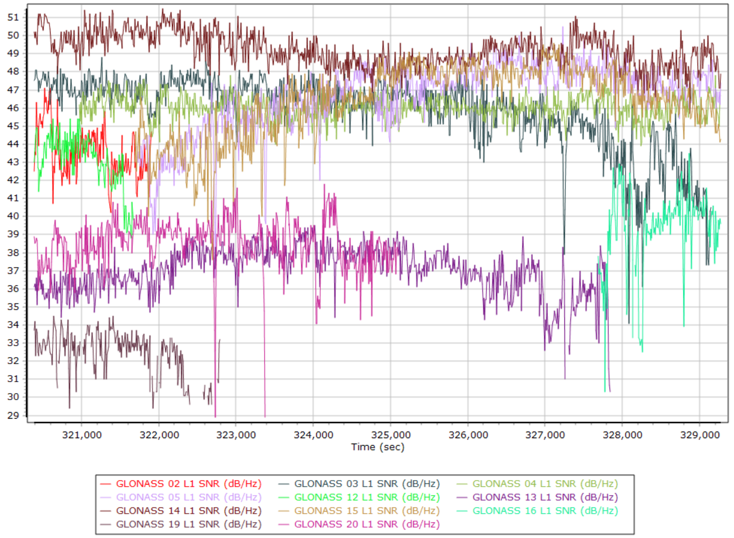
- **GPS:** Simultaneous L1 C/A, L2C, L2E, L5
- **GLONASS:** Simultaneous L1 C/A, L2 C/A, L2 P, L3 CDMA10
- **BeiDou (COMPASS):** B1, B2
- **Galileo:** Simultaneous L1 BOC, E5A, E5B, E5AltBOC11

↑ **Global Coverage**

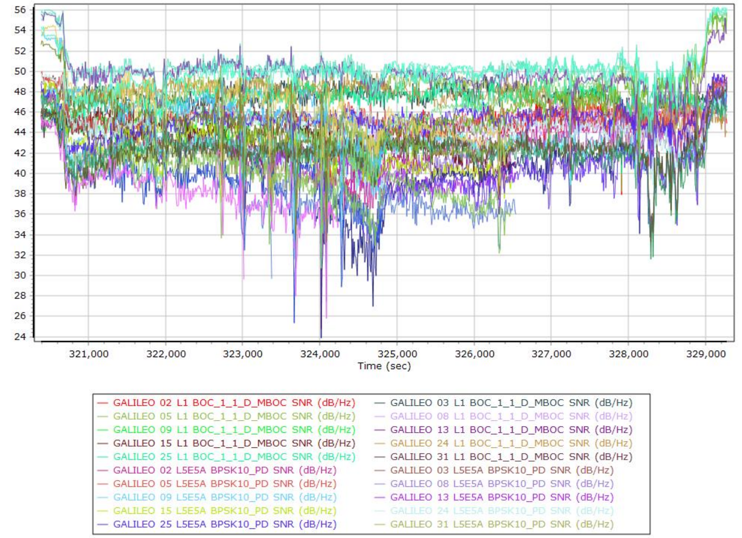
- **QZSS:** L1 C/A, L1 SAIF, L2C, L5
- **SBAS:** Simultaneous L1 C/A, L5 - L-Band:
- **OmniSTAR:** VBS, HP, XP and G2, Trimble CenterPoint RTX

*Advanced Trimble Maxwell® 6 Custom GNSS survey technology (two chipsets), used in **POS AV AP60***

GLONASS L1 SNR



GALILEO SNR



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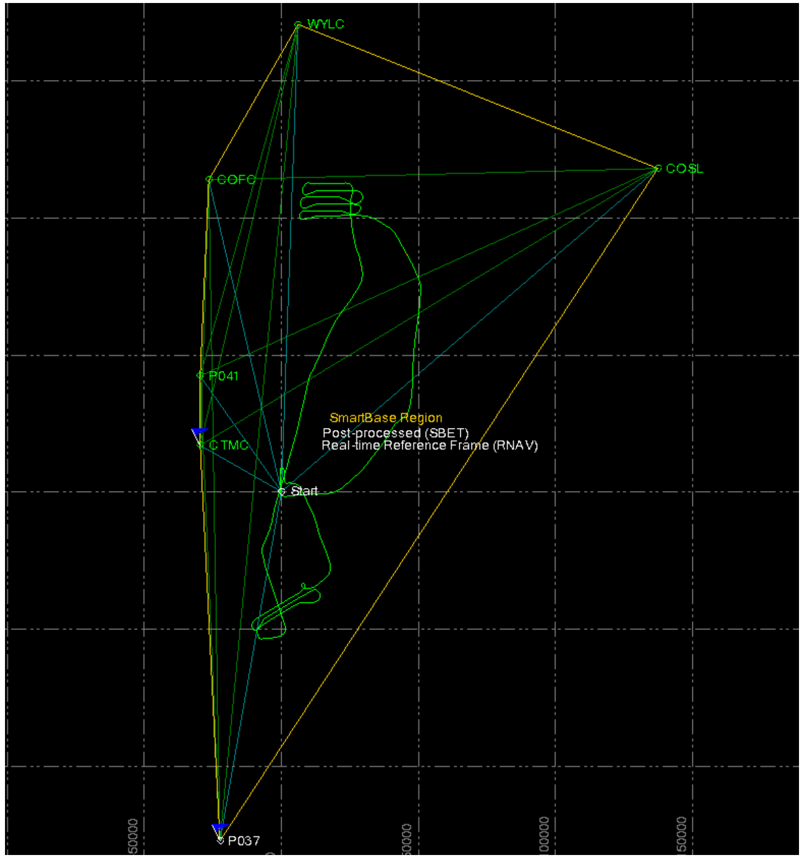
+ Airborne GNSS-inertial – Present Day

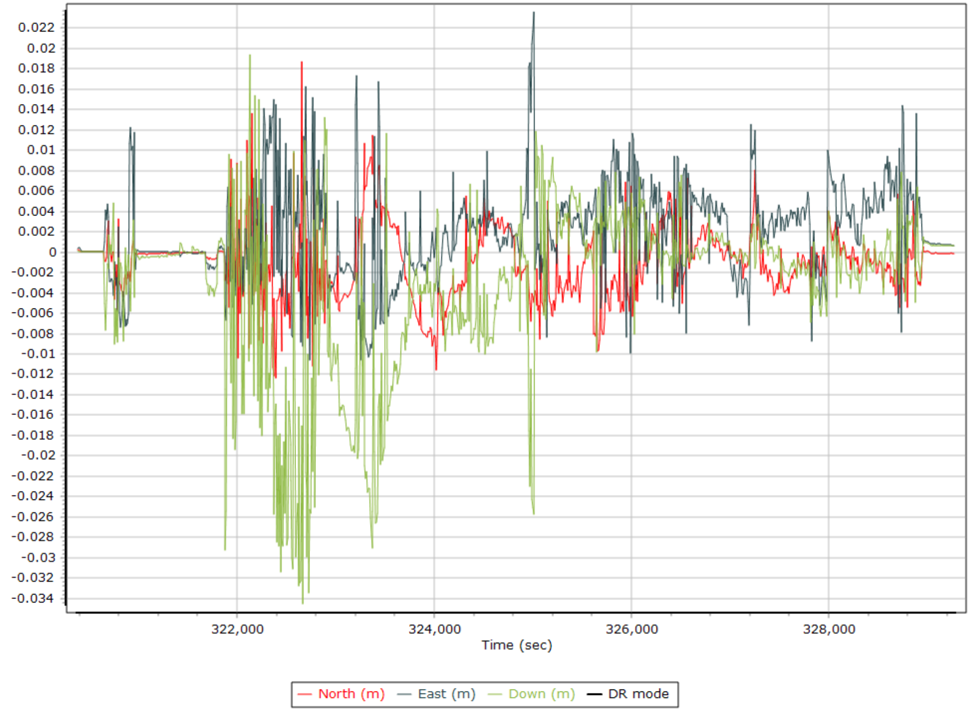
- **Trajectory data almost always processed “tightly coupled”**
- “The absolute position and velocity accuracy of the GNSS is used to compensate for the errors in the IMU measurements. The stable relative position of the INS can be used as a bridge to span times when the GNSS solution is degraded or unavailable.”
  NovAtel SPAN Brochure

Applanix SmartBase Network employing Trimble VRS technology – corrections computed from surrounding CORS and applied to virtual roving reference station



- **Unbound errors in IMU inputs can grow leading to “drift”. Raw GNSS can help constrain, but not fix these errors.**
- **Therefore flight line duration typically limited to ≤ 20 minutes**

Smoothed Best Estimate Trajectory – inertially aided kinematic ambiguity resolution forward/reverse separation



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+ Accuracy

NovAtel SPAN with tactical-grade IMU and modern GNSS chipsets

Applanix POS with tactical-grade IMU and modern GNSS chipsets

GNSS-Inertial data is a critical component and typically constitutes largest error source of a calibrated, boresighted, and adjusted lidar dataset

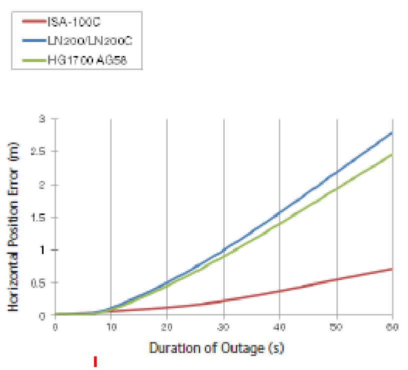
- GNSS Error greatest in the vertical component of the lidar

- However, angular IMU error is predominant and manifests in the horizontal component of the lidar

SPAN SYSTEM ATTITUDE ACCURACY (DEGREES)[1] RMS

RTK[2]			Post Processed[3]		
Roll	Pitch	Heading	Roll	Pitch	Heading
0.007	0.007	0.010	0.003	0.003	0.004

SPAN PERFORMANCE



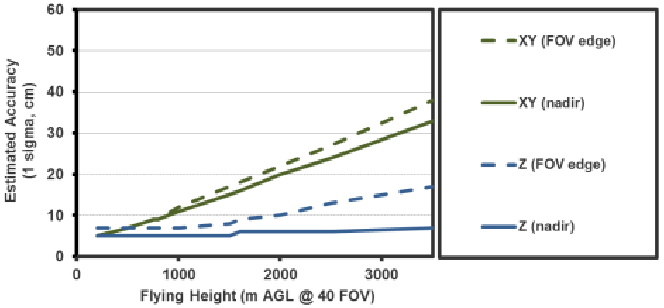
Example GNSS-inertial system specs

PERFORMANCE SPECIFICATIONS[1] (RMS ERROR)
Airborne Applications

	SPS	RTX[2]	RTX Post-Processed[4]	SmartBasePost-Processed[4]
Position (m)	1.5 H 3 V	<0.1 H <0.2 V	<0.1 H <0.2 V	<0.05 H <0.1 V
Velocity (m/s)	0.030	0.030	0.0050	0.0050
Roll & Pitch (deg)	0.005	0.005	0.0025[5]	0.0025[5]
True Heading[2] (deg)	0.030	0.020	0.0050	0.0050

Of course, there are many other lidar error sources…but that's a topic for another presentation

Leica ALS80-HP Product Specifications



Example Lidar system specs

Optech Galaxy Specifications

Parameter	Specification
Laser Configuration	
Topographic laser	1064-nm near-infrared
Laser classification	Class IV (US FDA 21 CFR 1040.10 and 1040.11; IEC/EN 60825-1)
Beam divergence	0.25 mrad (1/e)
Operating altitudes (1,2,3,4)	150-4700 m AGL, nominal
Effective pulse repetition frequency	Programmable, 35-550 kHz
Laser range precision (5)	< 0.008 m, 1 σ
Scan angle (FOV)	Programmable, 0-60°
Swath width	Programmable, 0-115% of AGL
Scan frequency	Programmable, 0-120 Hz advertised (0- 240 scan lines/sec)
Sensor scan product	2000 maximum
Absolute horizontal accuracy (2,3)	1/ 10,000 × altitude; 1 σ
Absolute elevation accuracy (2,3)	< 0.03-0.20 m RMSE from 150-4700 m AGL

+ Accuracy

Absolute vertical accuracy of 3DEP lidar data and lidar-derived bare earth DEMs tested against ground truth captured with…GPS/ GNSS!*

[*ASPRS Positional Accuracy Standards for Digital Geospatial Data*](#)

Table B.7 Vertical Accuracy/Quality Examples for Digital Elevation Data

Vertical Accuracy Class	Absolute Accuracy			Relative Accuracy (where applicable)		
	RMSEz Non-Vegetated (cm)	NVA at 95% Confidence Level (cm)	VVA at 95th Percentile (cm)	Within-Swath Hard Surface Repeatability (Max Diff) (cm)	Swath-to-Swath Non-Veg Terrain (RMSDz) (cm)	Swath-to-Swath Non-Veg Terrain (Max Diff) (cm)
1-cm	1.0	2.0	3	0.6	0.8	1.6
2.5-cm	2.5	4.9	7.5	1.5	2	4
5-cm	5.0	9.8	15	3	4	8
10-cm	10.0	19.6	30	6	8	16
15-cm	15.0	29.4	45	9	12	24
20-cm	20.0	39.2	60	12	16	32
33.3-cm	33.3	65.3	100	20		
66.7-cm	66.7	130.7	200	40		
100-cm	100.0	196.0	300	60		
333.3-cm	333.3	653.3	1000	200		

PHOTOGRAMMETRIC ENGINEERING & REMOTE SENSING

GNSS reference station (base station) somewhere in the Cascades

****** ***Ground truth sometimes surveyed with classical optical methods in GPS/GNSS-denied environments***

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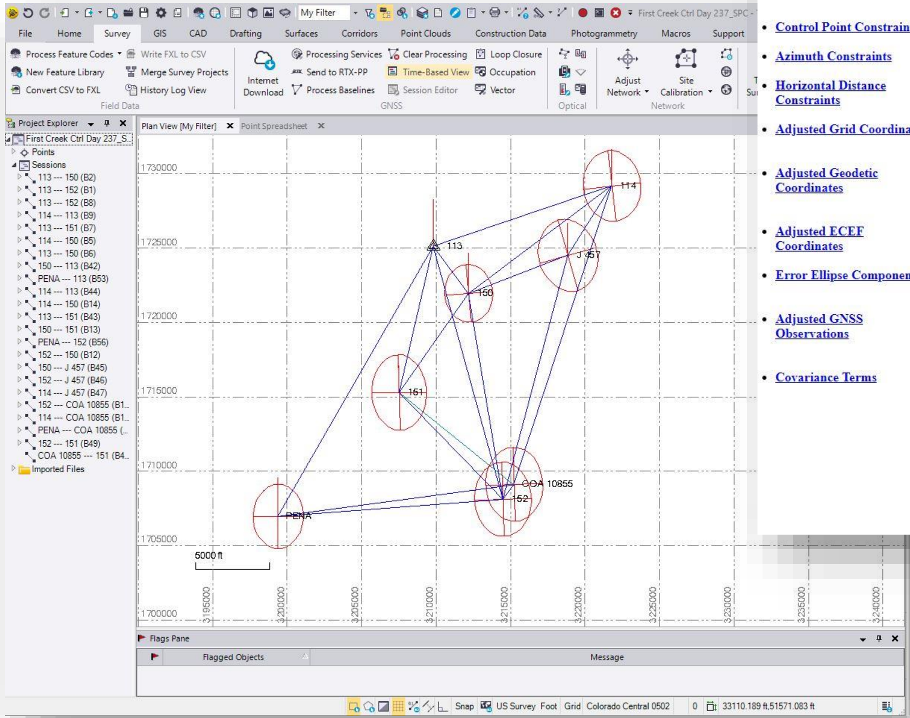
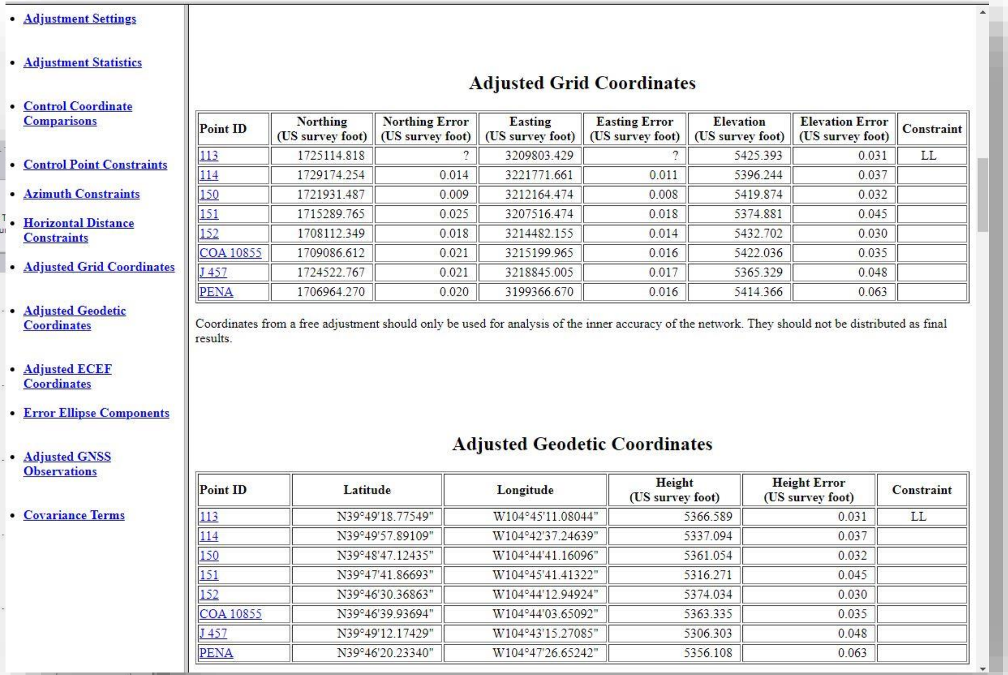
+ Accuracy



Network adjustment with error ellipses



- Adjustment Settings
- Adjustment Statistics
- Control Coordinate Comparisons
- Control Point Constraints
- Azimuth Constraints
- Horizontal Distance Constraints
- Adjusted Grid Coordinates
- Adjusted Geodetic Coordinates
- Adjusted ECEF Coordinates
- Error Ellipse Components
- Adjusted GNSS Observations
- Covariance Terms

Adjusted Grid Coordinates

Point ID	Northing (US survey foot)	Northing Error (US survey foot)	Easting (US survey foot)	Easting Error (US survey foot)	Elevation (US survey foot)	Elevation Error (US survey foot)	Constraint
113	1725114.818	?	3209803.429	?	5425.393	0.031	LL
114	1729174.254	0.014	3221771.661	0.011	5396.244	0.037	
150	1721931.487	0.009	3212164.474	0.008	5419.874	0.032	
151	1715289.765	0.025	3207516.474	0.018	5374.881	0.045	
152	1708112.349	0.018	3214482.155	0.014	5432.702	0.030	
COA 10855	1709086.612	0.021	3215199.965	0.016	5422.036	0.035	
J 457	1724522.767	0.021	3218845.005	0.017	5365.329	0.048	
PENA	1706964.270	0.020	3199366.670	0.016	5414.366	0.063	

Coordinates from a free adjustment should only be used for analysis of the inner accuracy of the network. They should not be distributed as final results.

Adjusted Geodetic Coordinates

Point ID	Latitude	Longitude	Height (US survey foot)	Height Error (US survey foot)	Constraint
113	N39°49'18.77549"	W104°45'11.08044"	5366.589	0.031	LL
114	N39°49'57.89109"	W104°42'37.24639"	5337.094	0.037	
150	N39°48'47.12435"	W104°44'41.16096"	5361.054	0.032	
151	N39°47'41.86693"	W104°45'41.41322"	5316.271	0.045	
152	N39°46'30.36863"	W104°44'12.94924"	5374.034	0.030	
COA 10855	N39°46'39.93694"	W104°44'03.65092"	5363.335	0.035	
J 457	N39°49'12.17429"	W104°43'15.27085"	5306.303	0.048	
PENA	N39°46'20.23340"	W104°47'26.65242"	5356.108	0.063	

Network adjustment results

Static GPS/GNSS processing methodologies may be employed to produce adjusted ground truthing coordinates. These are known as "checkpoints"

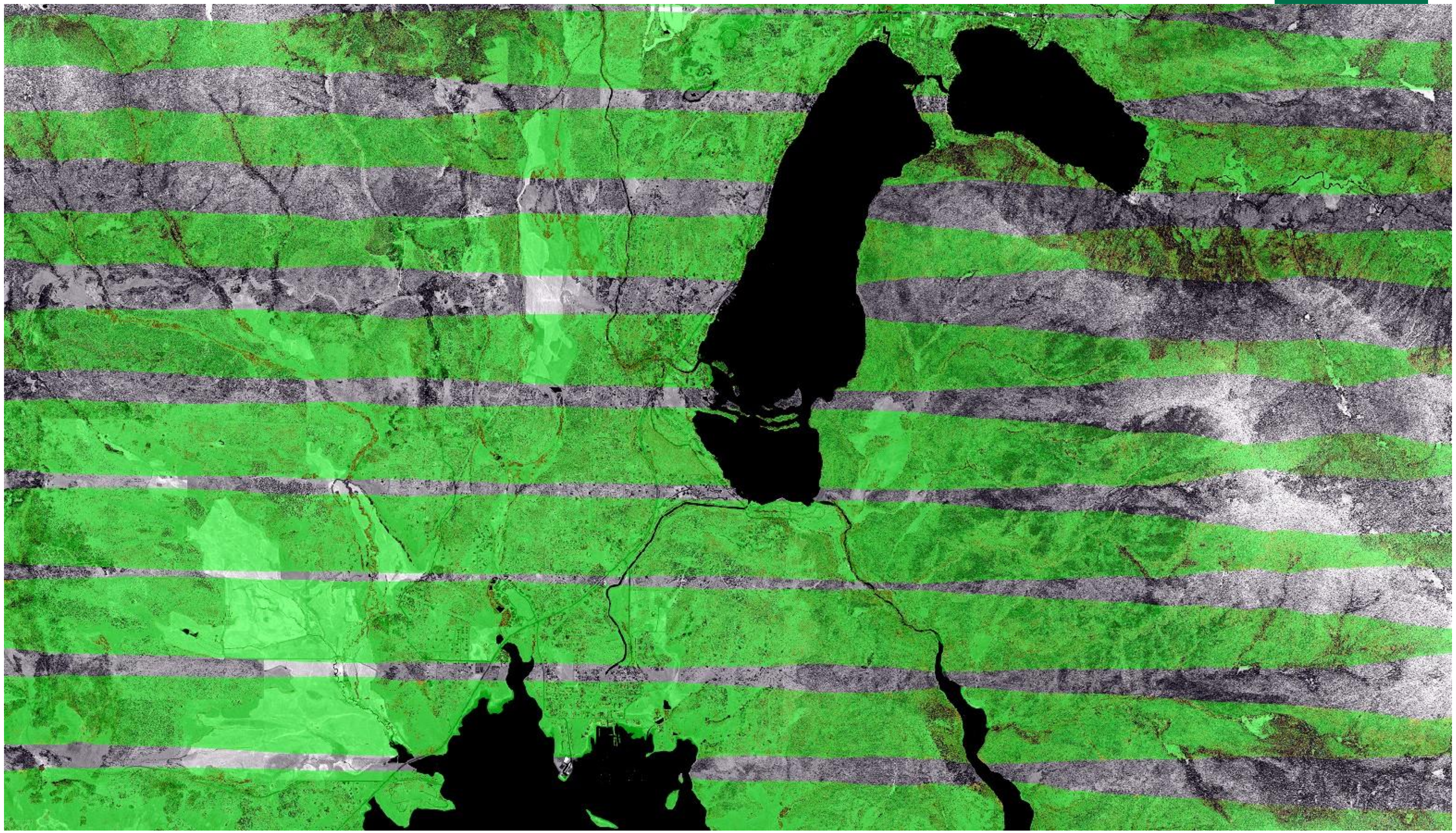
3DEP checkpoint survey examples

+ Accuracy

Absolute vertical accuracy reporting is necessary. However, other indicators of quality are equally, if not more important in assessing the overall quality of the lidar dataset.

This swath separation intensity image shows an excellent goodness of fit between swaths (flight lines). Green color in overlapping swaths indicates vertical separation of ≤ 8 cm

Scene from lidar dataset near Grand Lake in the Rocky Mountains of Colorado



Thank you!

Any questions?

jnimetz@usgs.gov
720-576-1838

Special thanks to Merrick, QSI, and Woolpert for providing some of the graphics used in this presentation

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