LVIS: Wide-Swath, Full Waveform Characterization and Mapping Antarctic Ice Sheet Topography in Support of IceBridge

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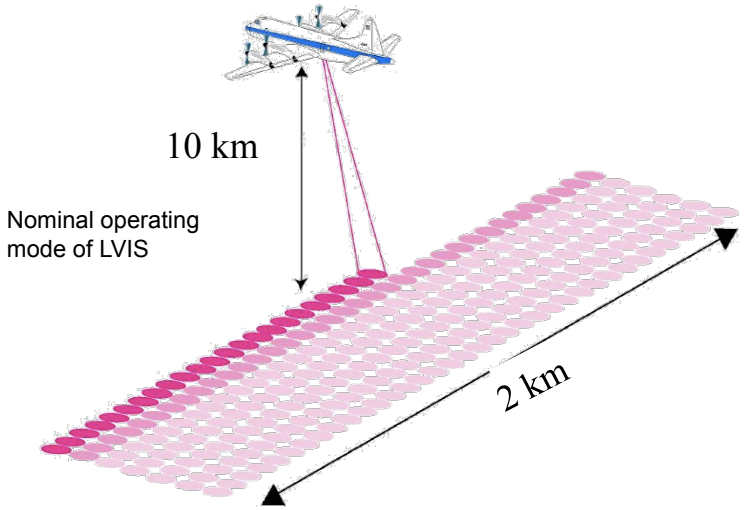
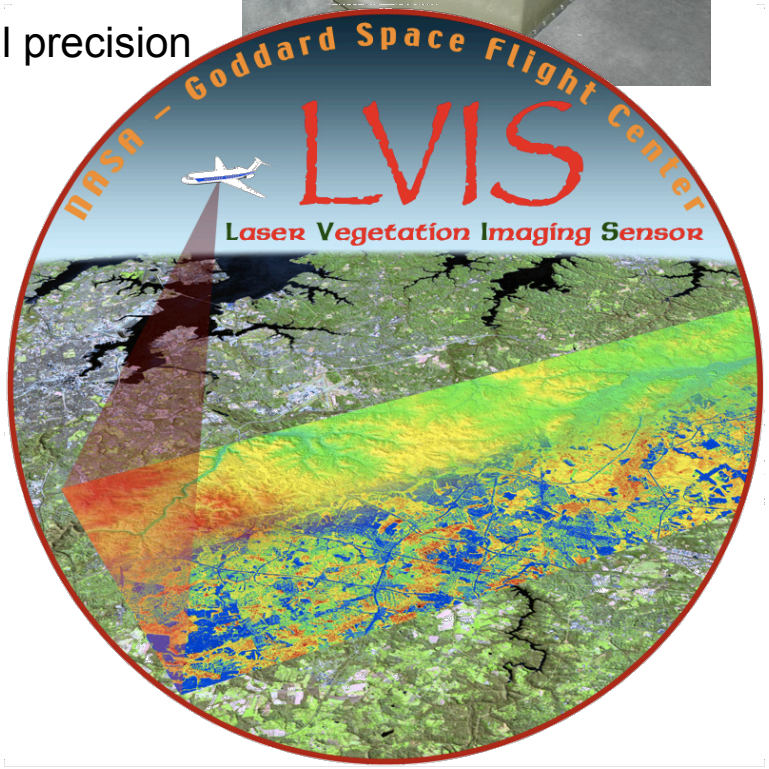
NASA's Land, Vegetation and Ice Sensor (LVIS)

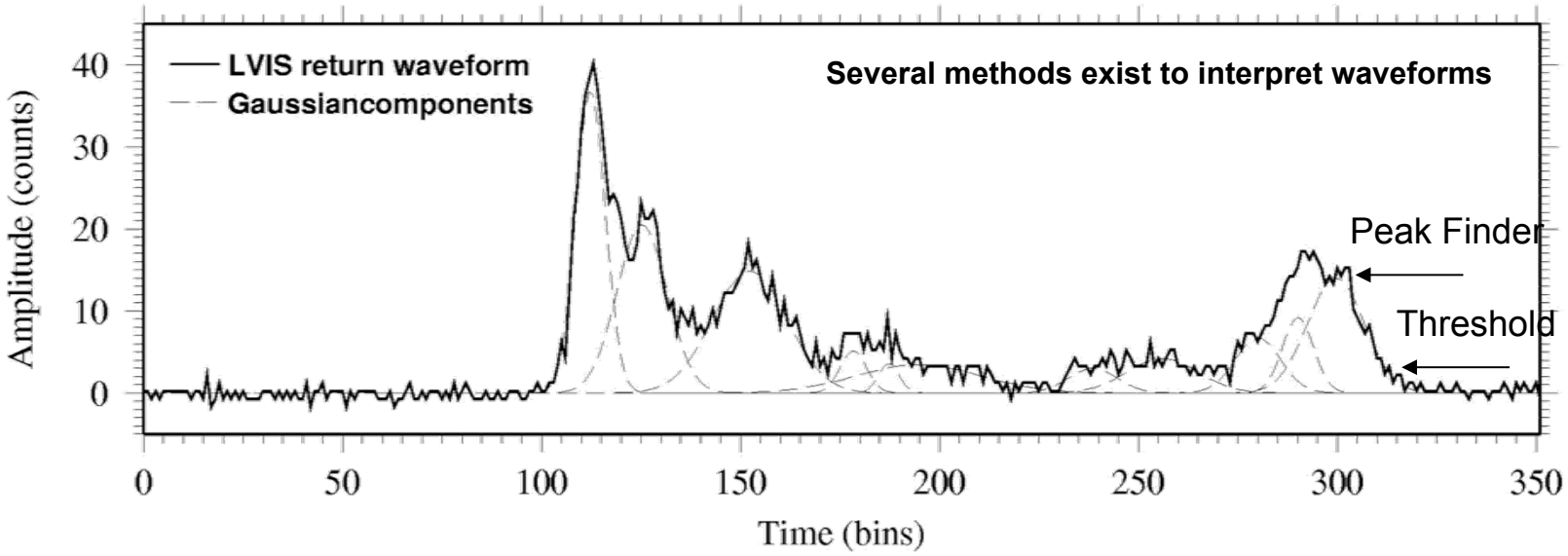
- **NASA's Land, Vegetation and Ice Sensor (LVIS) is a medium/high-altitude (10km), medium-footprint (5-25m) Waveform-Digitizing Lidar.**
  - Measures surface topography and topographic extent (e.g., crevasse depth), and structure for *every* footprint.
  - Digitally records the shape of each outgoing (transmitted) and returning laser pulse (waveform).
  - Nominal mode: 20m footprint/2km swath from 10km.
  - Over ice: <10 cm vertical precision, ~1m horizontal precision
  - 1064nm wavelength, 8 ns (FWHM) laser pulse.
  - Auto nadir-stabilization maximizes coverage.



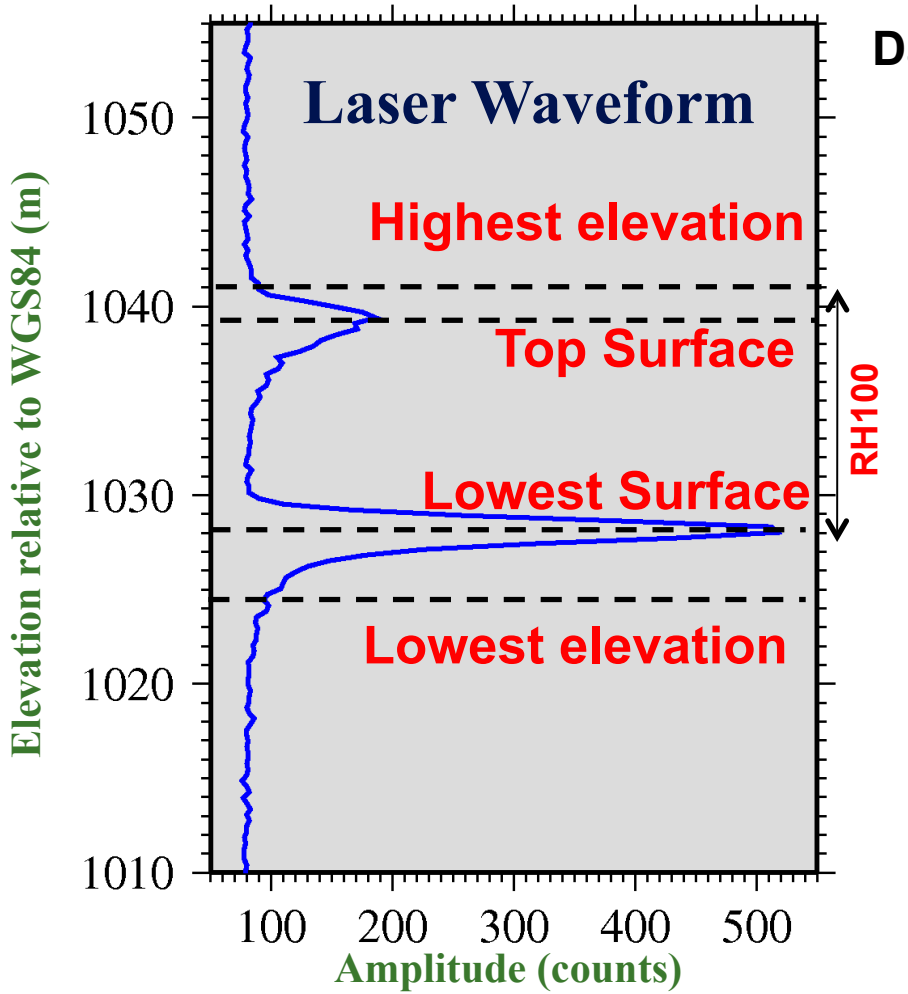


LVIS Measurement Process

- Record time of flight of pulse of light from laser to reflecting surface
  - gives range to surface
- Record pointing of laser at time of shot using INS
  - Gives vector range to surface
- Calculate position of instrument at time of laser shot
  - Gives origin of range vector in global reference frame such as WGS84
- Post-mission processing combines information to produce precise and accurate laser footprint position and elevation (Hofton et al., 2000; Luthcke et al., 2002)
- Advanced sensors record the shape of the returning laser pulse to enable precise geolocation of different reflecting surfaces and provide an information-rich data set for future re-analysis.



LVIS Data Products



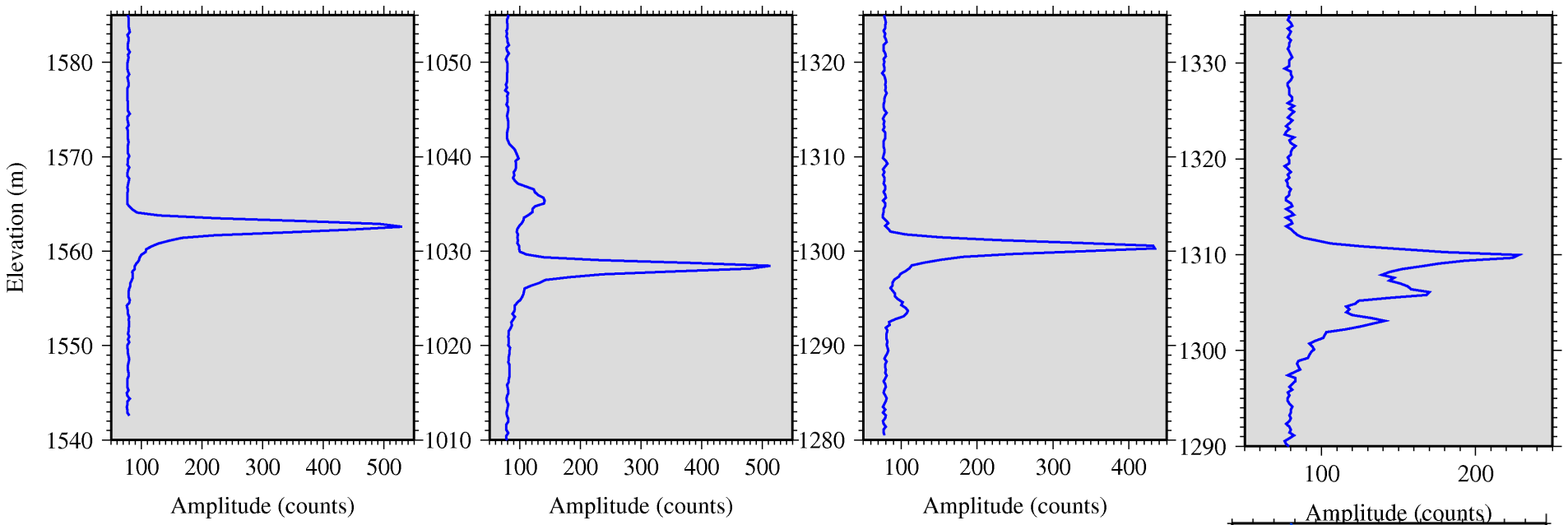
Data products include:

- "Ground" elevation: zg (elevation using center of lowest mode)
- Top surface elevation: (elevation using center of highest mode)
- Vertical distribution of intercepted surfaces (entire waveform).
- Vertical extent (e.g., feature depth or height): RH100
- Energy quartiles (RH25/50/75)
- Other products:
  - Waveform centroid
  - ICESat GLA12 match
  - De-correlation, Entropy

Work with cryo community to explore these

- Recorded waveform represents the entire time history of interaction between the laser pulse and the surface of the Earth.
- Allows extraction of multiple data products, and to apply, reapply algorithms.

Example LVIS Waveforms over Ice

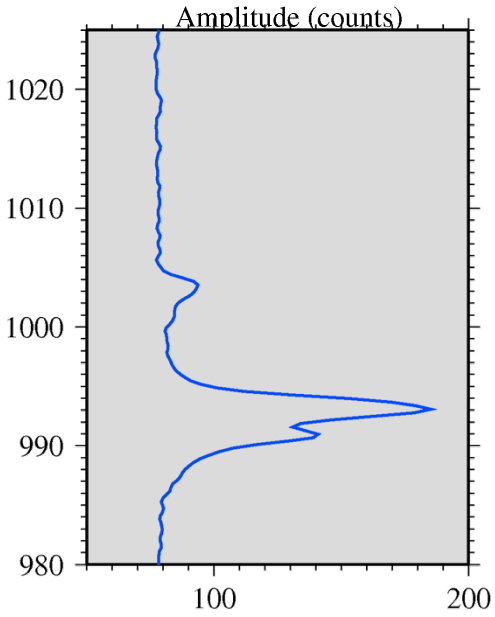


Return pulses vary:

from simple to multi-mode to complex.

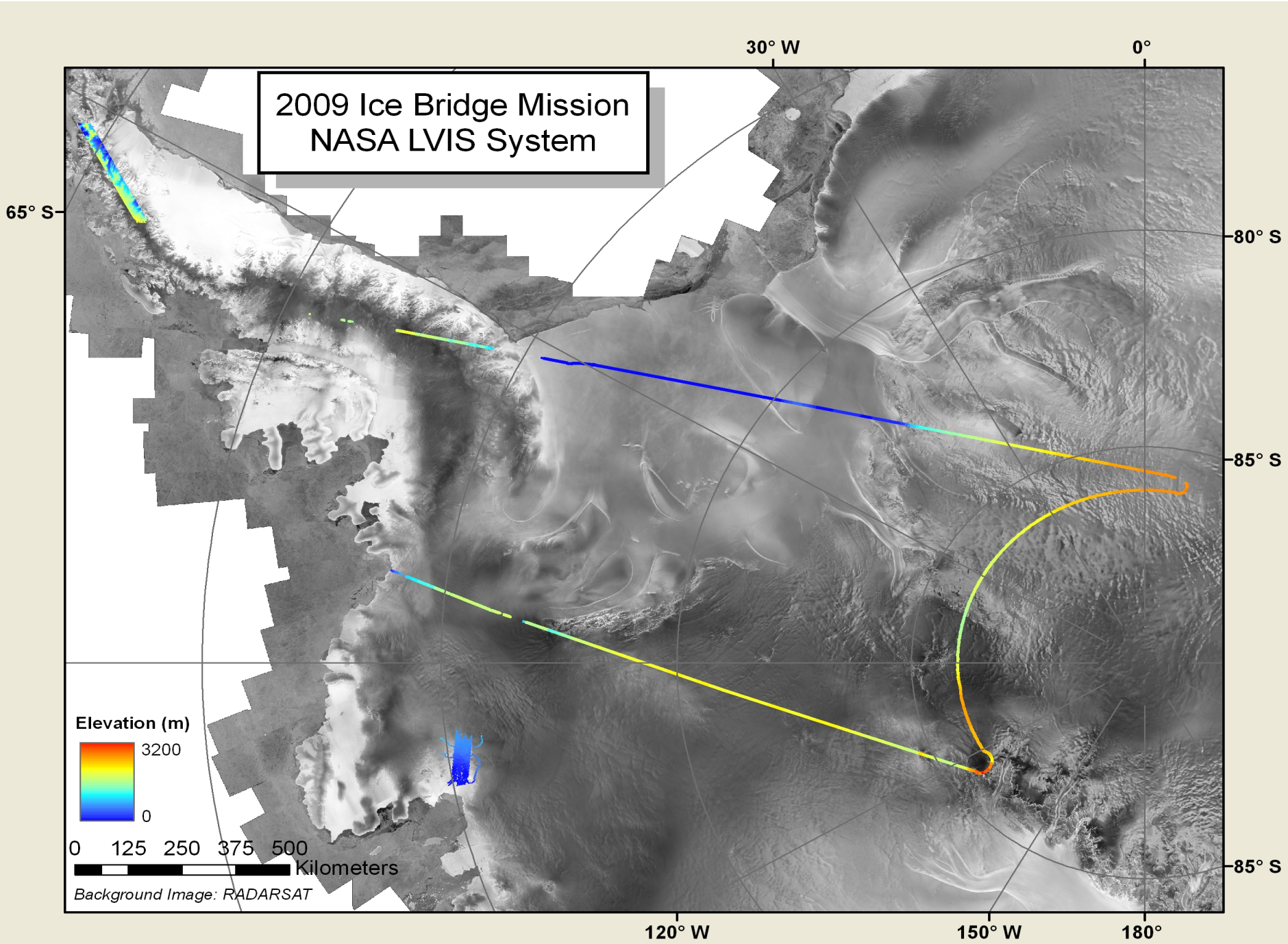
Processing techniques:

- Thresholding
- Pulse-finding
- Gaussian-decomposition
- Pattern-matching and correlation

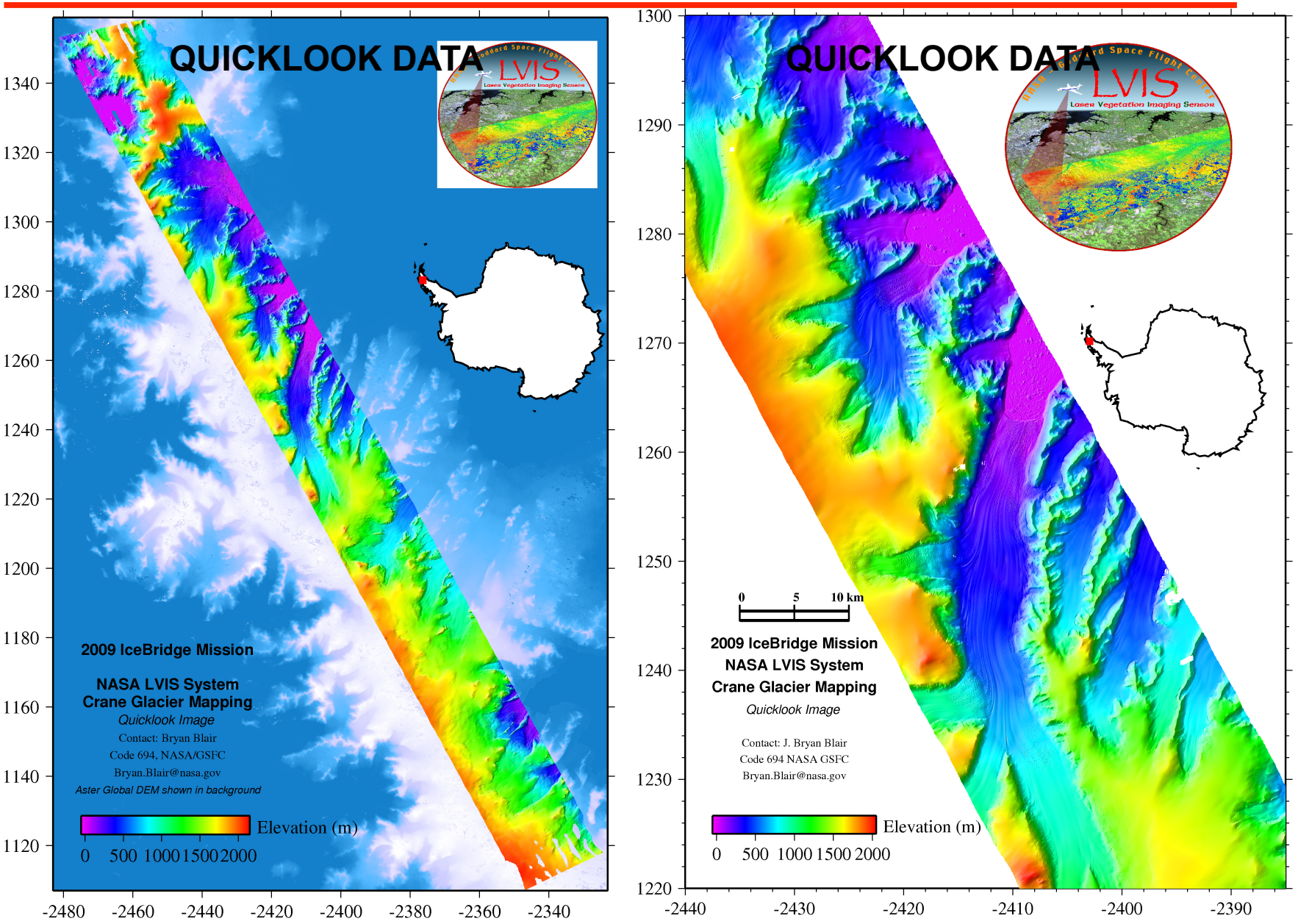


LVIS Lidar Remote Sensing of Antarctica, 2009

- **Land, Vegetation and Ice Sensor (LVIS) data over Antarctica 09**
  - **Three ~11-hr flights: PIG, Peninsula and ICESat "Pole hole"**
  - **~25m wide footprints, 1.6-2km wide swath (from 35,000-38,000' altitude)**
  - **Some additional data collected on transit lines**
  - **Best effort deployment only**
    - **Funded only for data collection**
- **LVIS Lidar uniquely measures surface vertical and spatial structure across multi-km scales**
- **These data form the basis for future repeat surveys and comparison with past and future satellite data sets.**
- **Full utilization of satellite data.**

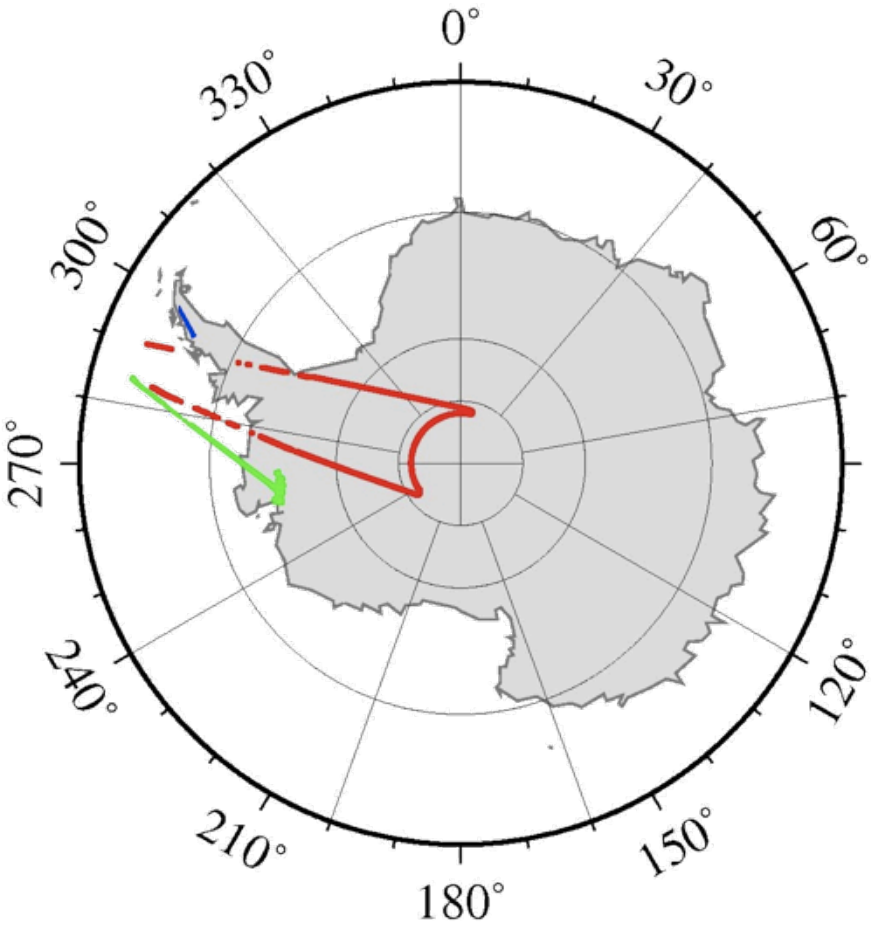

2009 Ice Bridge Mission
NASA LVIS System
30° W
0°
65° S
80° S
85° S
85° S
120° W
150° W
180°
Elevation (m)
3200
0
0 125 250 375 500
Kilometers
Background Image: RADARSAT

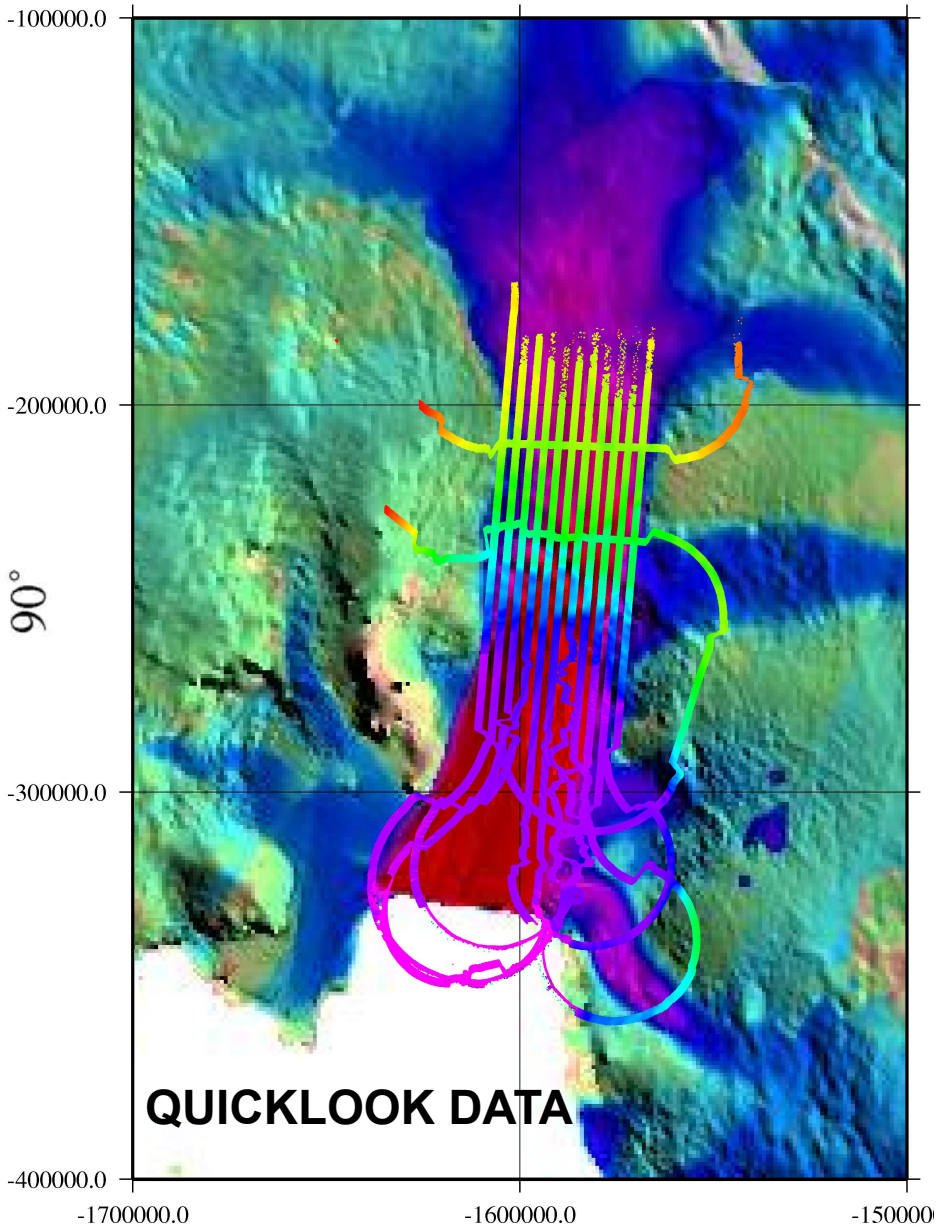
LVIS Peninsula Flight – Crane Glacier



Pine Island and Pole Hole

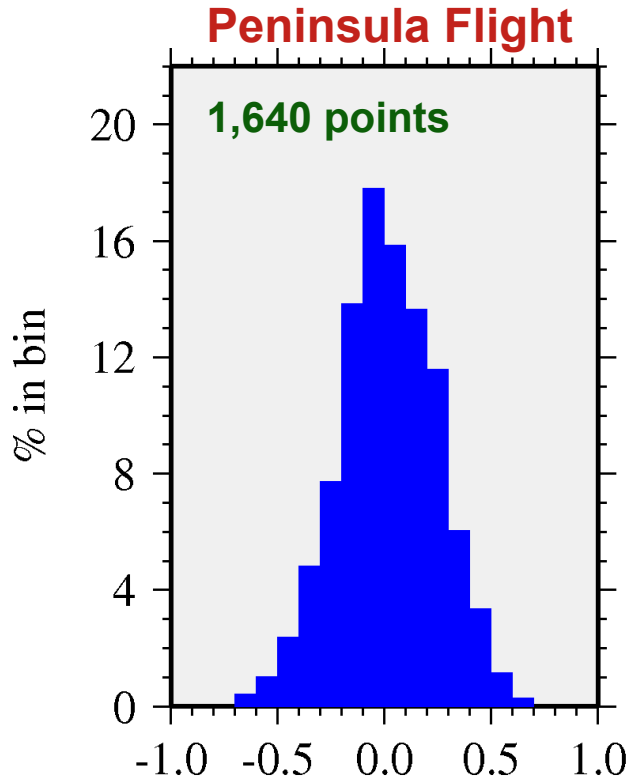
ICESat “Pole Hole”

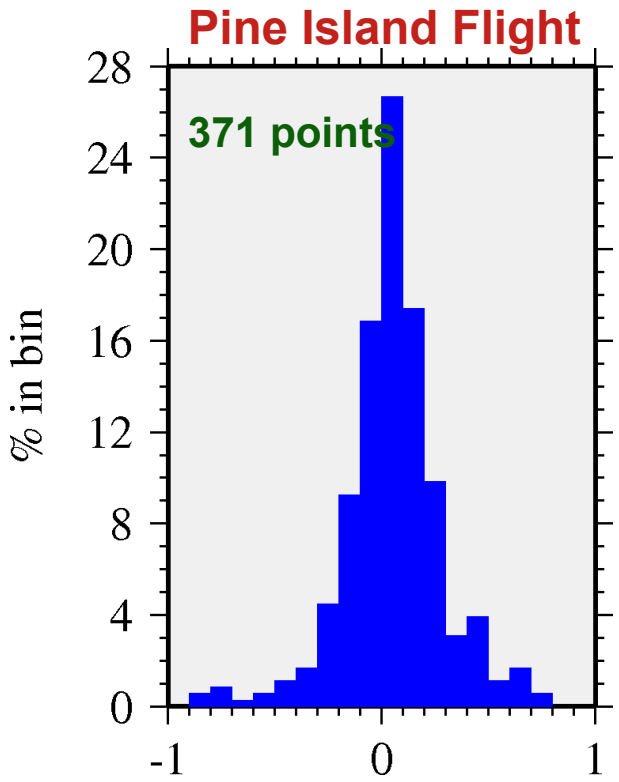




Data Precision, Antarctica 2009

- **Assessing elevation differences between coincident LVIS footprints**





Elevation difference between coincident footprints (m)

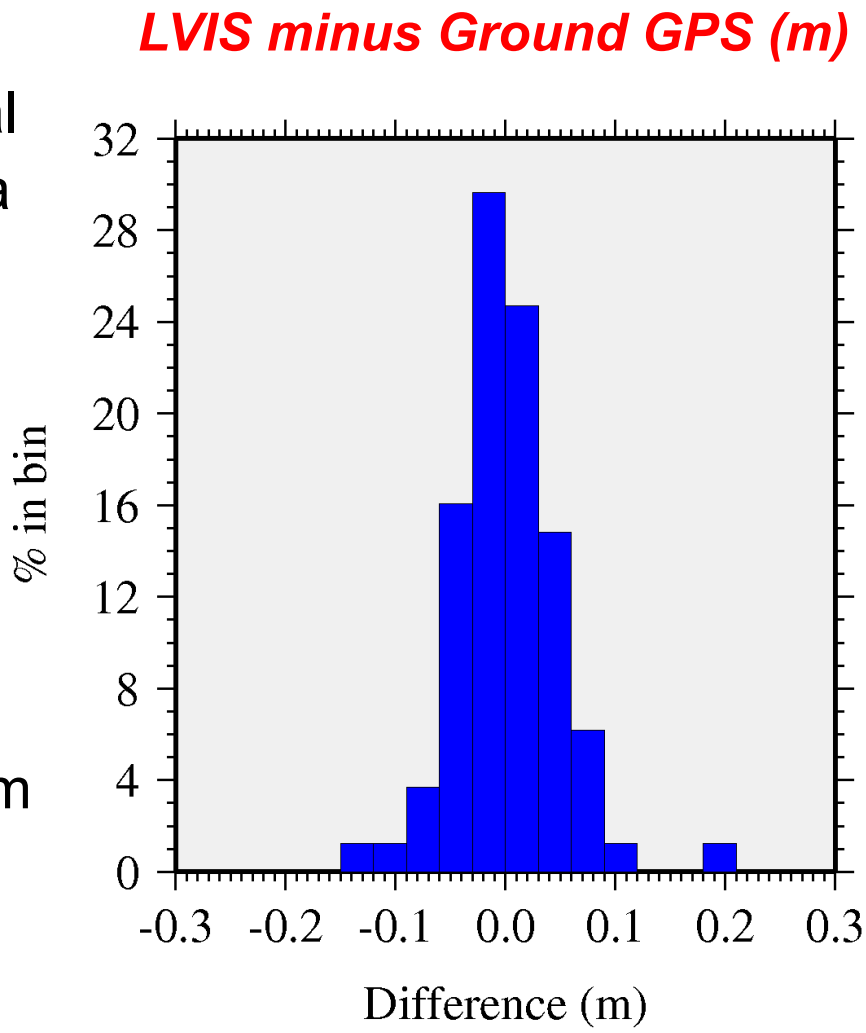
Mean difference:	**0.01m**
Standard deviation (1σ):	**0.23m**

Mean difference:	**0.03m**
Standard deviation (1σ):	**0.18m**

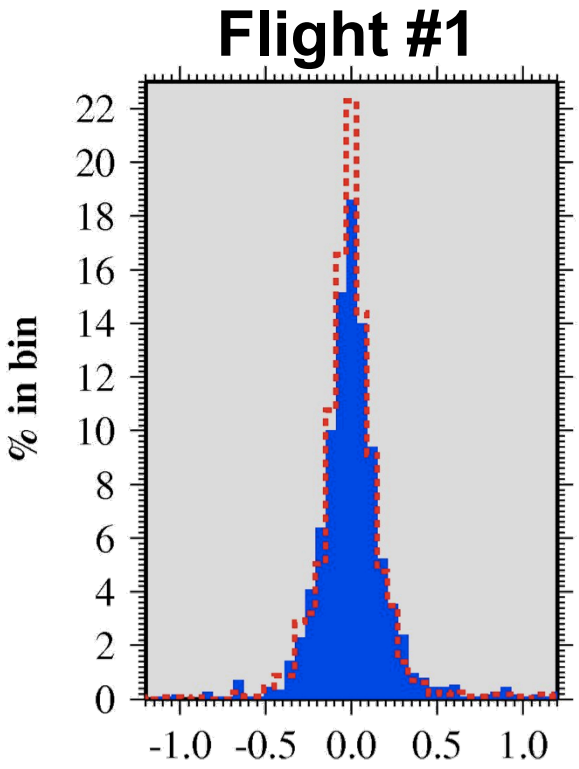
- **Note: These preliminary results use PPP trajectories (i.e., no base stations) and preliminary waveform processing and calibration parameters (QUICKLOOK DATA).**

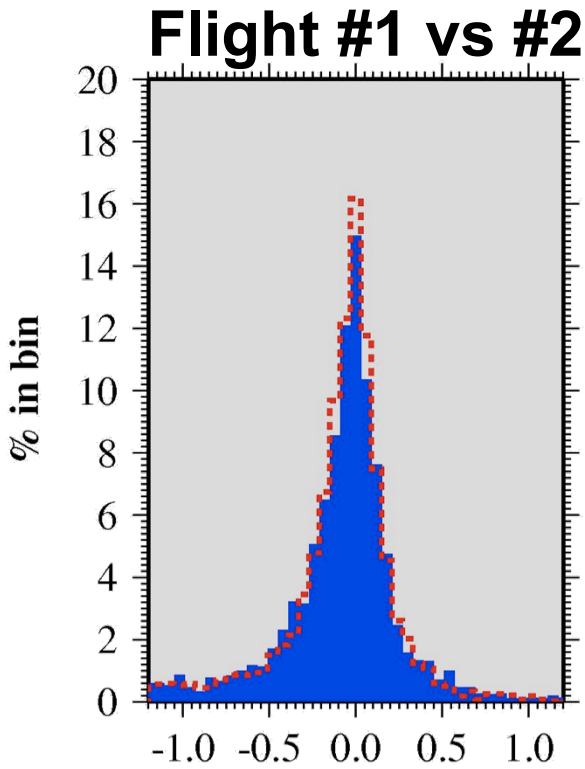
Data Accuracy, Antarctica 2009

- Ground survey using differential kinematic GPS data from Punta Arenas airport parking lot
- LVIS elevations compared to closest GPS measurement
- 82 comparison points
- Mean = 0.003m
- Standard deviation (1σ) = 0.04m
- LVIS data from Crane Glacier flight



Crossovers over a rough surface: Jakobshavn



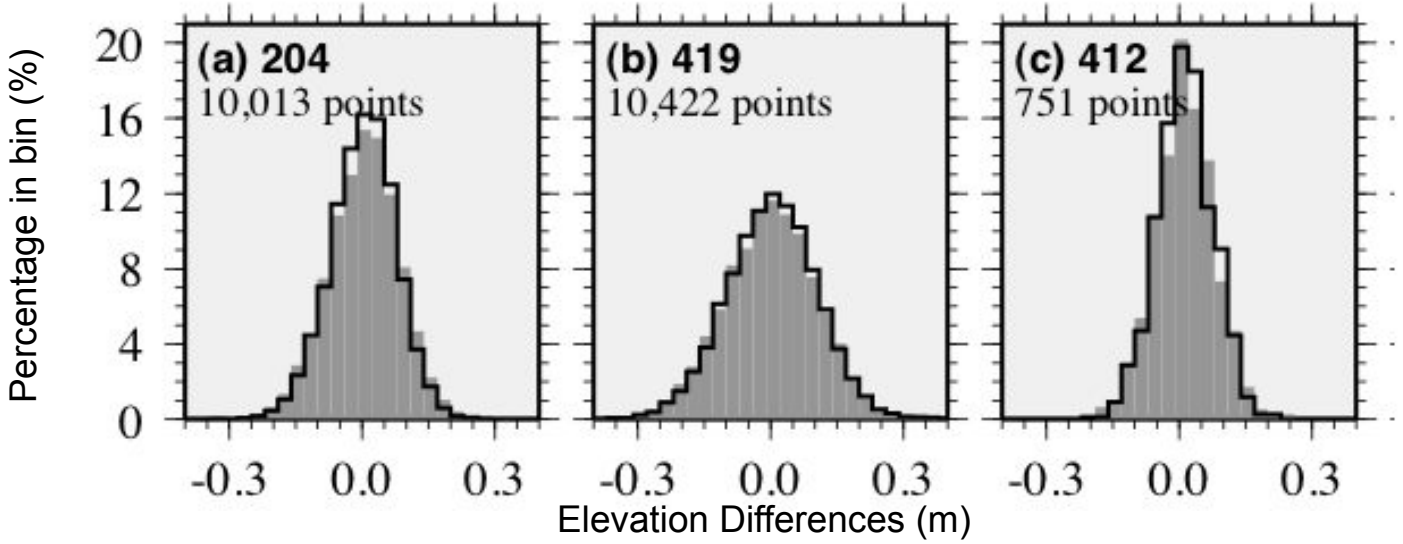


Histograms of elevation differences between footprint pairs at Jakobshavn glacier on 9/20/07 and 9/21/07.

Comparison	Flight 1	Flight 1 vs 2
Mean difference (m)	0.00m	-0.08m
Standard deviation (1σ) (m)	0.16m	0.33m

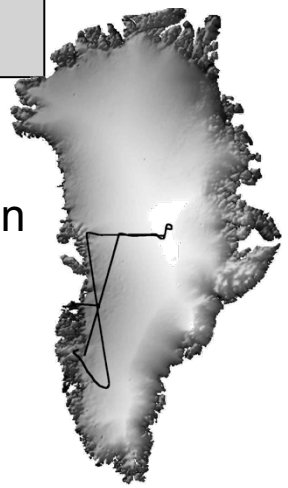
LVIS Performance in Greenland, 2007

Histograms of elevation differences along 800km long lines:



Mean difference	**0.00 m**	**0.00 m**	**0.01 m**
Standard deviation (1σ)	**0.08 m**	**0.11 m**	**0.06 m**

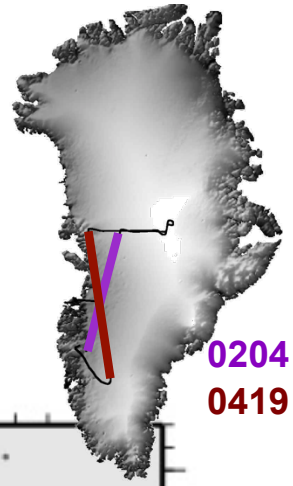
- LVIS data collected on 9/20/07 and 9/21/07 from ~27,000' in P3-B.
- Two ~850km long transects over ice sheet plus ~35 km long transect in the Summit area.

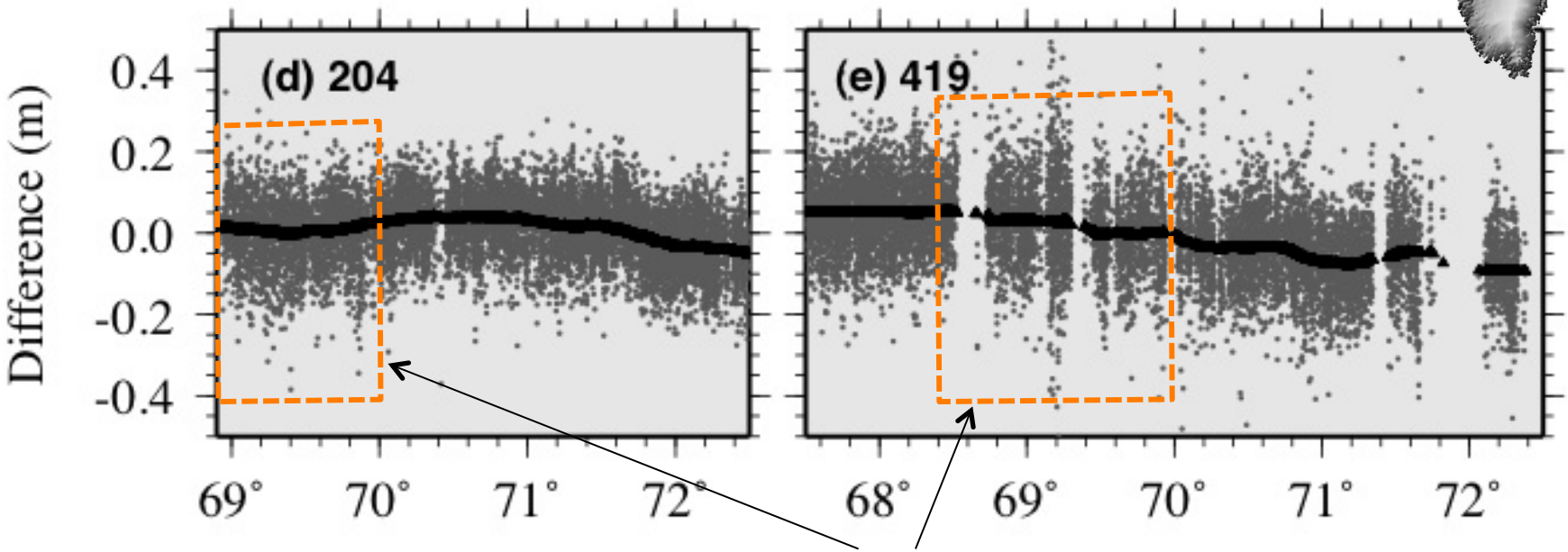


From: Hofton et al. (2008), Geophysical Research Letters, DOI:10.1029/2008GL035774

Long-track Performance of LVIS Data in Greenland

- **On average, elevation differences between coincident LVIS footprints had means of 0.0m, but along-transect variations of up to 5 cm occurred (likely caused by errors in the atmospheric model applied in the GPS trajectory calculations).**





- ***Feeder zone of Jakobshavn Glacier – rough terrain***

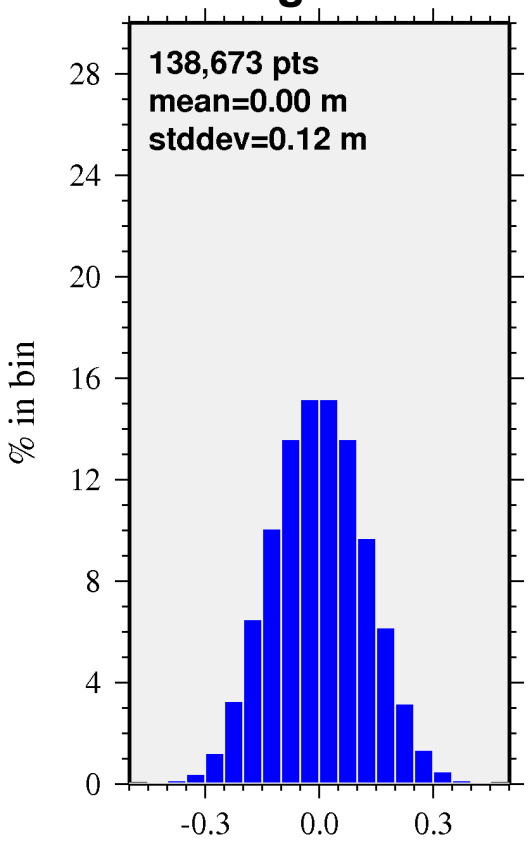
From: Hofton et al. (2008), Geophysical Research Letters, DOI:10.1029/2008GL035774

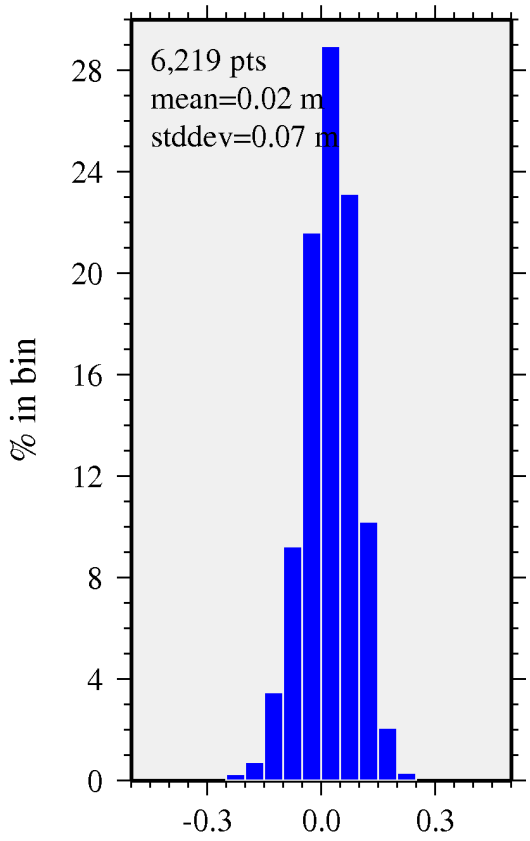
Lidar sensor intercomparison (ATM, LVIS)

- Data from N Greenland 2009 (interior, smooth ice), ICEsat track 0314
- Icesat: 4/4/09, LVIS: 4/14/09 and 4/15/09, ATM 4/20/09 (2 passes)
- Sensors have comparable precision (as expected) – but don't forget they are measuring different things

ATM to ATM

Footprints within 0.2m of each other





Elevation difference between coincident footprints (m)

LVIS to LVIS

Footprints within 1m of each other

138,673 pts

Mean=0.00m

Stddev=0.12m

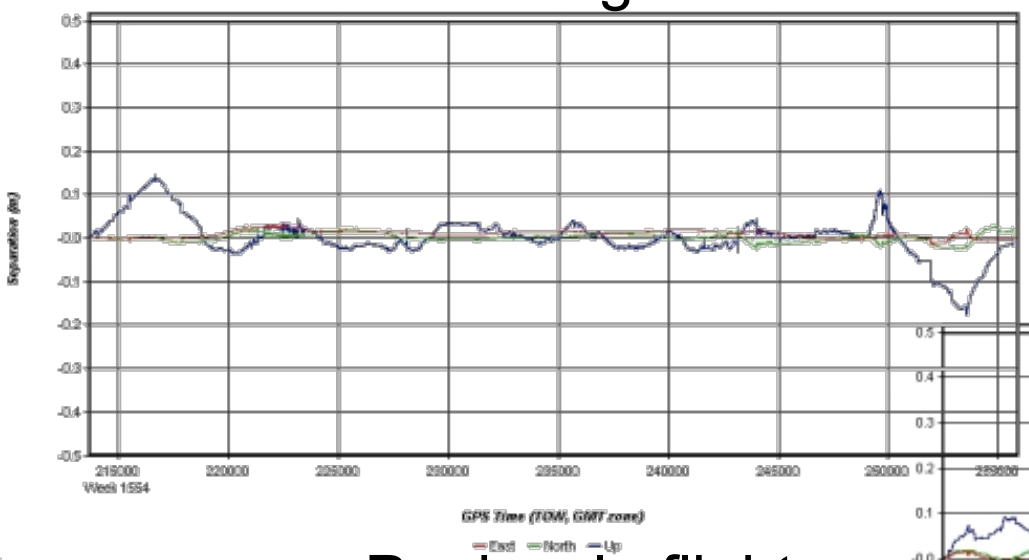
6,219 pts

Mean=0.02m

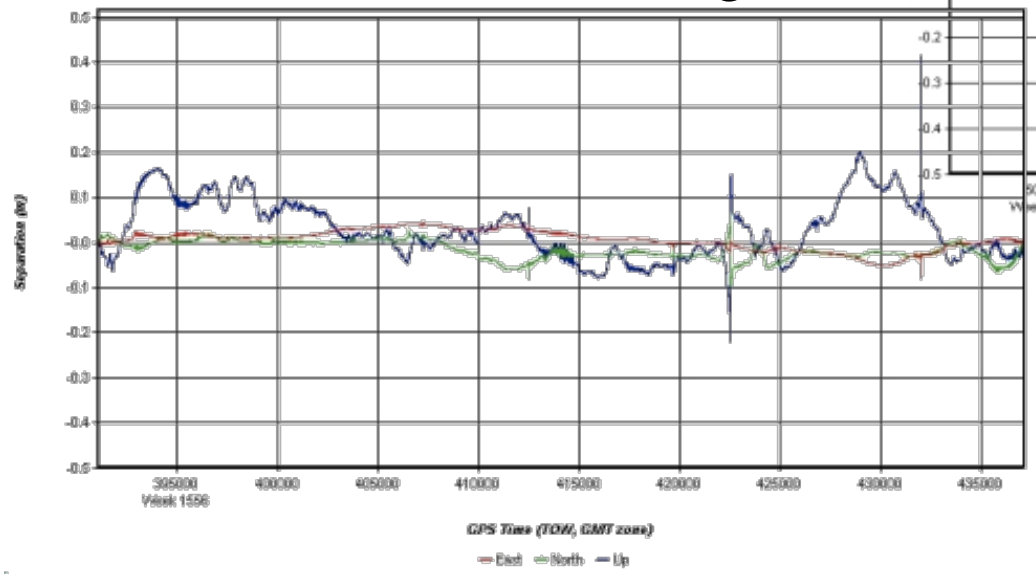
Stddev=0.07m

PPP Trajectories

PIG flight

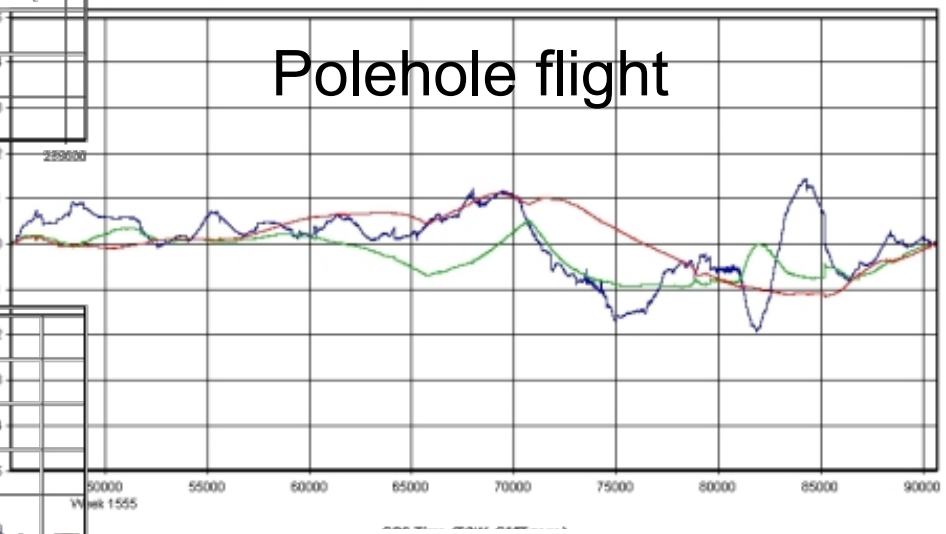


Peninsula flight



- **Encouraging results from Antarctica**
- **Combined separations < 20cm**

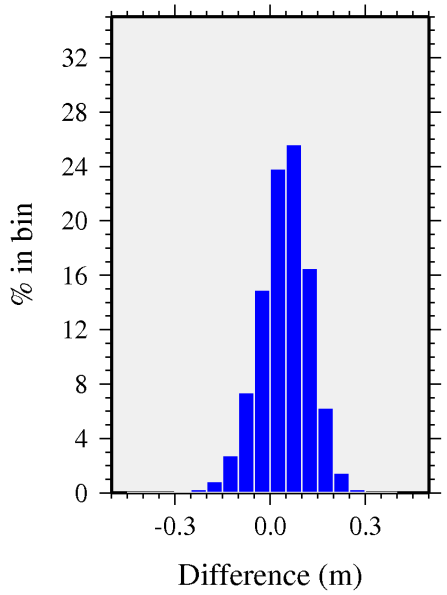
Polehole flight



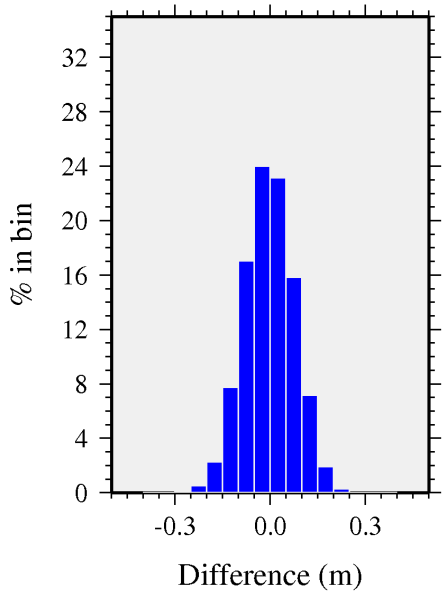
- **PPP in Polar regions powerful tool for true high altitude operations (Global Hawk)**

Intersensor Comparisons: LVIS and ATM

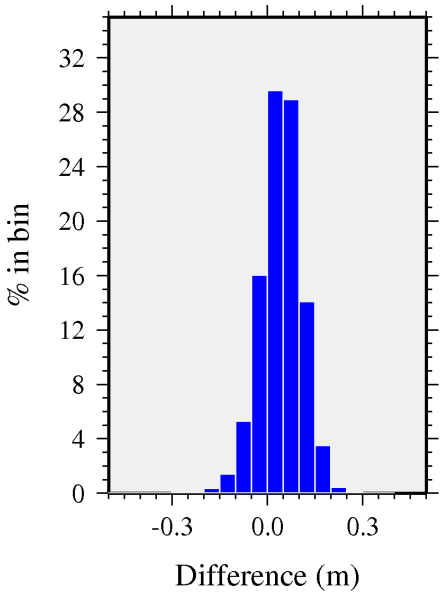
ATM1 to LVIS 1



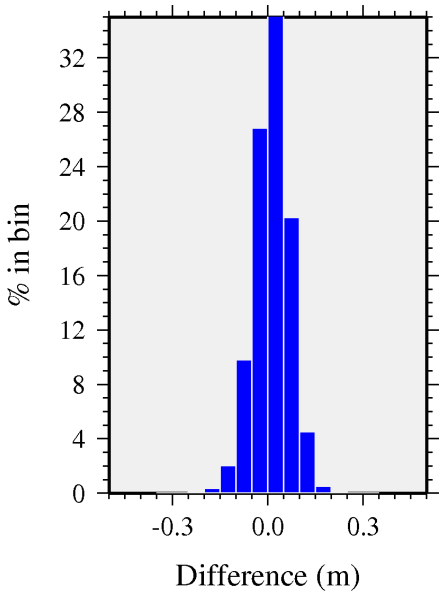
ATM1 to LVIS 2



ATM1 to LVIS 2



ATM2 to LVIS 2

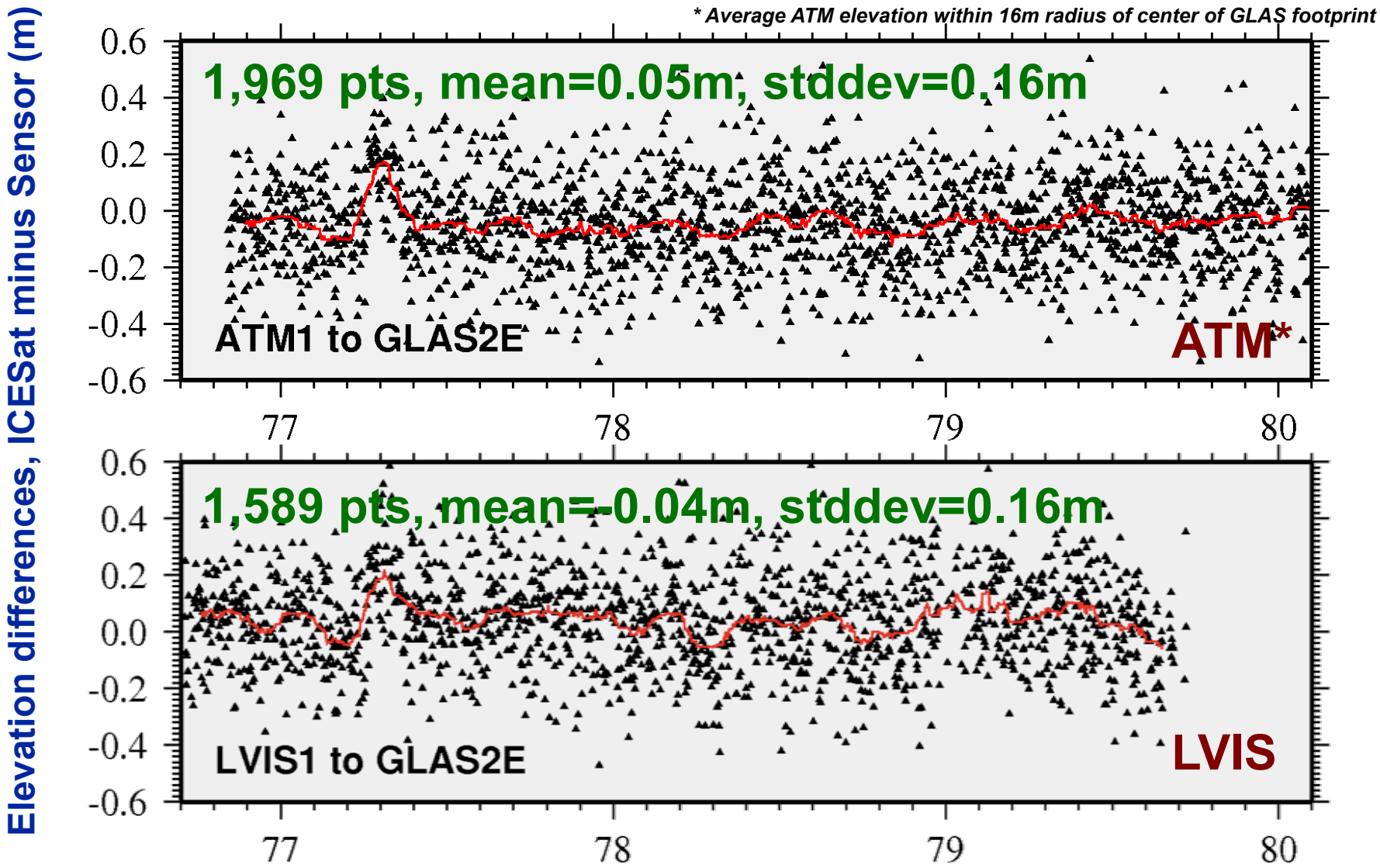


# pts	6132	2152	6086	2167
Mean (m)	0.05	0.00	0.04	0.01
Stddev (m)	0.11	0.11	0.10	0.09

Comparing average elevation of all ATM footprints within LVIS footprint to LVIS elevation

- **Elevation changes from ATM to LVIS data are precise at ~10cm level**

LVIS and ATM to ICESat L2E

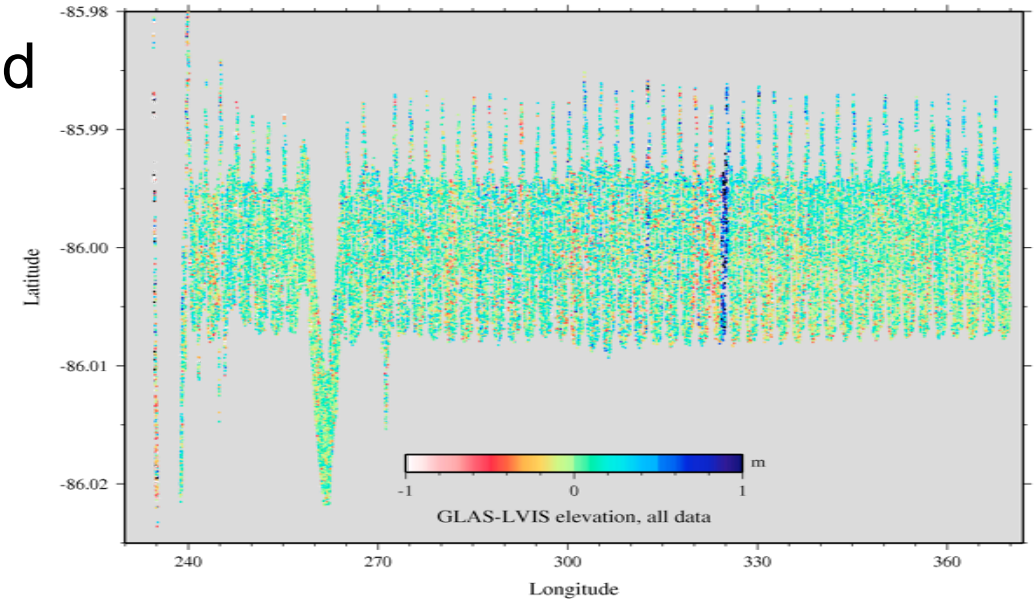


- ATM and LVIS comparisons to GLAS have similar precision

Data uses: ICESat Calibration

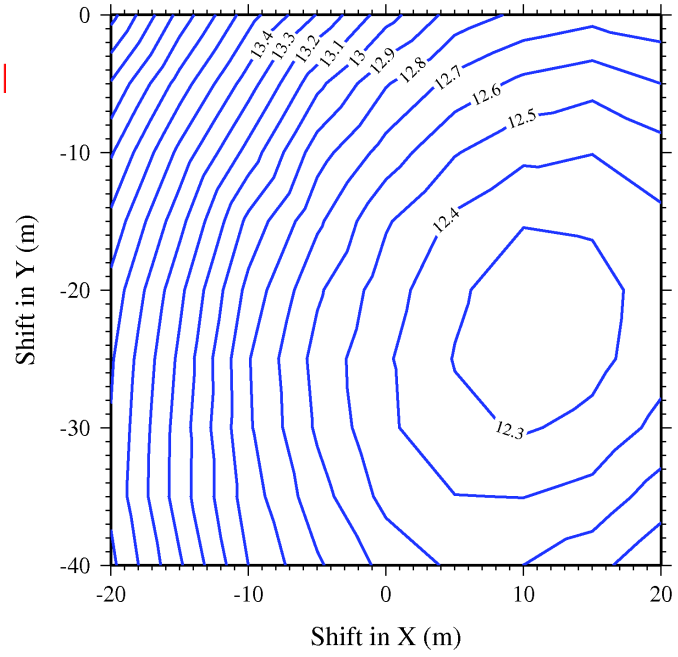
- **LVIS polehole flight (10/29/09) intersected 0.5 million ICESat footprints including those from final (L2f) ICESat campaign**
  - **Short ICEsat L2F campaign but LVIS swath still crossed ~60 L2F tracks**
- **Comparison enables mean campaign bias to be derived as well as track to track biases**
  - **Same analysis on data from all Icesat laser campaigns enables campaign to campaign biases to be derived (currently estimated over ocean) and accuracy of Icesat mass balance estimates to be improved**

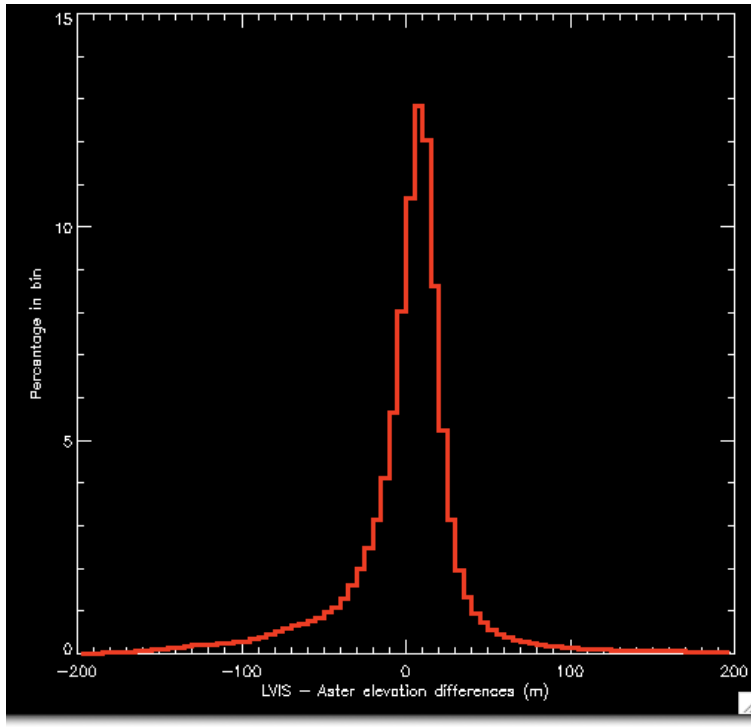
Ideally this flight is repeated annually or bi-annually in order to get an estimate of annual signal in region
AND
Do something similar in Greenland.



Validating Spaceborne DEMs: ASTER GDEM

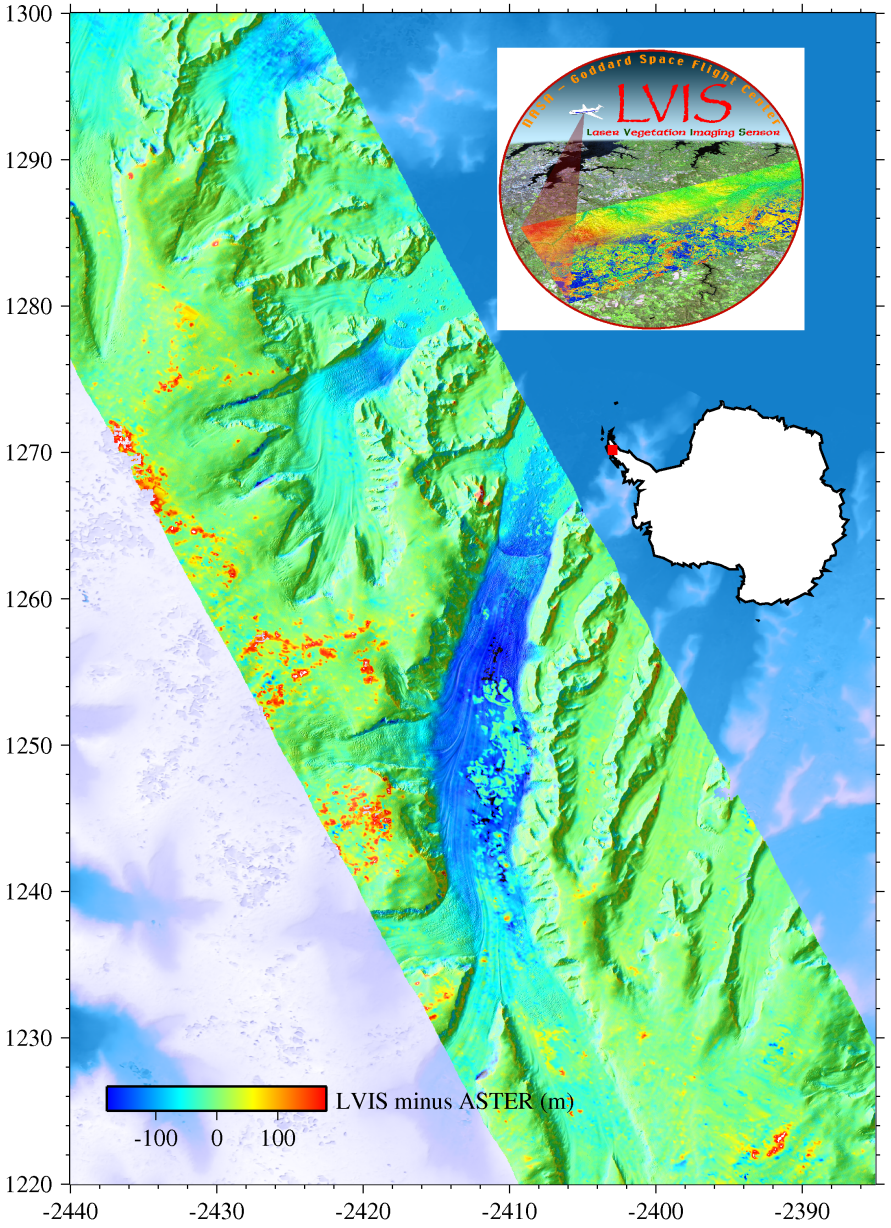
- **Validate horizontal and vertical relative positioning of LVIS and ASTER GDEM by shifting 2 datasets relative to each other and minimizing differences**
- **Results show offsets of 7m (vertical), 25m (horizontal)**
  - **Similar results found for GDEM comparisons in Japan (Abrams et al. 2010) (E-W -16.4m and N-S 20.7m)**
  - **Values within average geolocation error for Level 1B ASTER scenes**





Surface Change Demo: Comparison to Aster GDEM

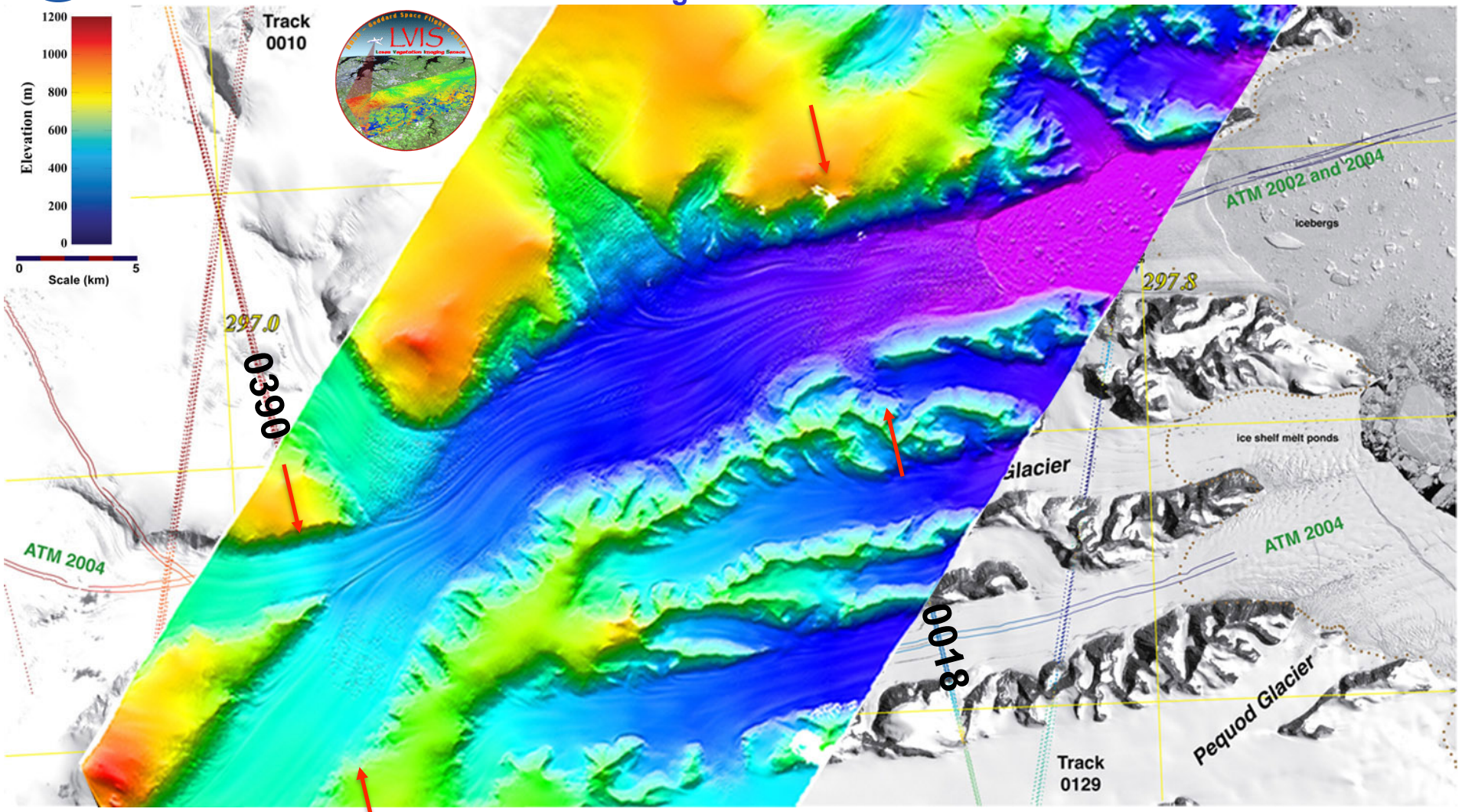
- Quicklook data compared to ASTER GDEM
- Demonstrates potential of IceBridge/LVIS data for obtaining elevation change over entire glacier systems.
- Ignoring obvious ASTER-related issues (yellows, reds), Crane has significant thinning (blues) up to 30km from front – but time period is not known.



Crane Glacier from LVIS 2009 ICE Bridge Data

LVIS = Land Vegetation and Ice Sensor

GEST Goddard Earth Sciences and Technology Center



Contact: J. Bryan Blair Code 694 NASA GSFC
Bryan.Blair@nasa.gov

Elevation (m)

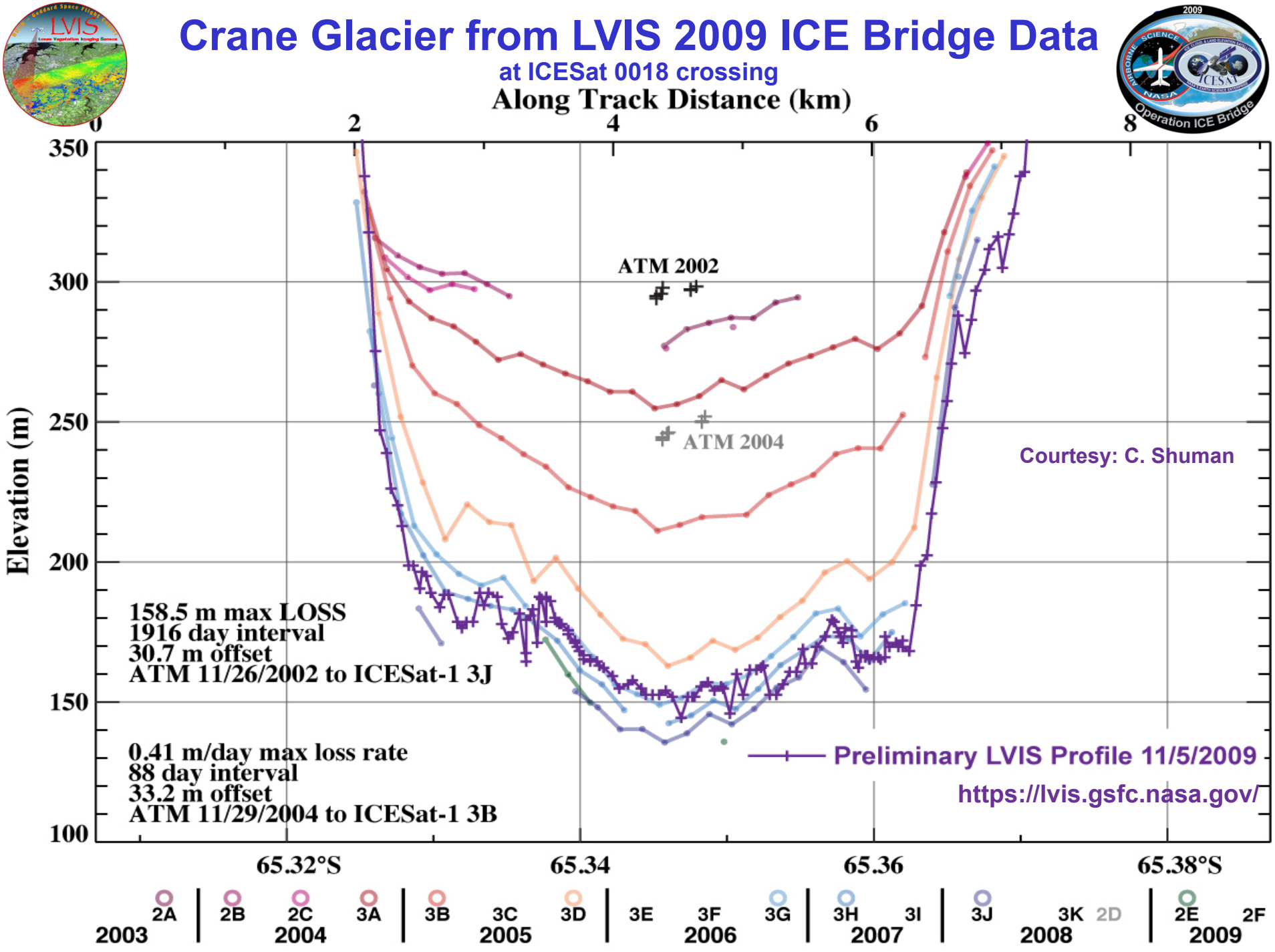
500 1000 1500 2000

A small portion of the area that LVIS on the NASA DC-8 mapped in >7.5 hours on 11/5/2009. The entire image is 26 x 260 km (~16 x 160 miles). The total area is ~7,000 sq. km - this is the largest, contiguous area ever mapped with LVIS, 16 lines stitched together ("mowing the lawn") and the footprints are ~20 m in diameter spread across ~2 km wide swaths, and the DC-8 did it in one flight.

https://lvis.gsfc.nasa.gov/index.php

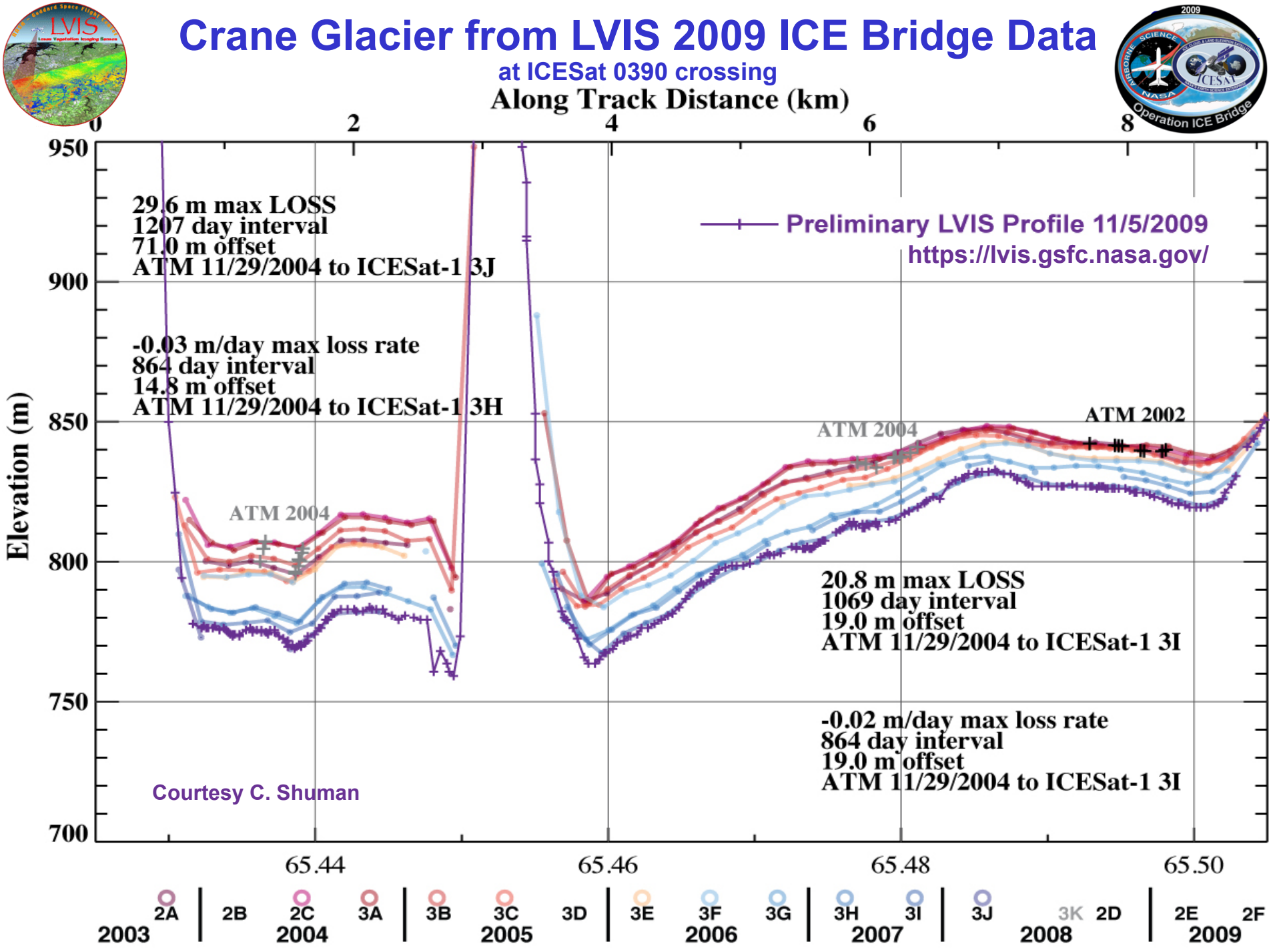
Crane Glacier from LVIS 2009 ICE Bridge Data

at ICESat 0018 crossing



Crane Glacier from LVIS 2009 ICE Bridge Data

at ICESat 0390 crossing



Status of Data

- **LVIS Antarctica deployment was "best effort"**
  - Data collection only
  - We didn't receive any data processing money for this campaign
  - Not only a funding issue – staffing is the limit. Working with Tom on this
- **Competing for staff with other projects for which data processing is supported**
  - Without $ input AND ~6 month-at-a-time commitment from Icebridge we cannot hire and commit to data processors, and other projects will continue to take precedence.
- **With dedicated data processors, delays will go away.**
  - Release ANT09 data within 2-3 months
    - Data quality appears good (no major issues during collection)
    - PPP trajectory quality good
    - No issues expected in generating release data – good training data set for new hires
  - We're not prepared to general release "quicklook" data
    - Potential systematic errors or lack of thorough validation
- **Additional funding required**

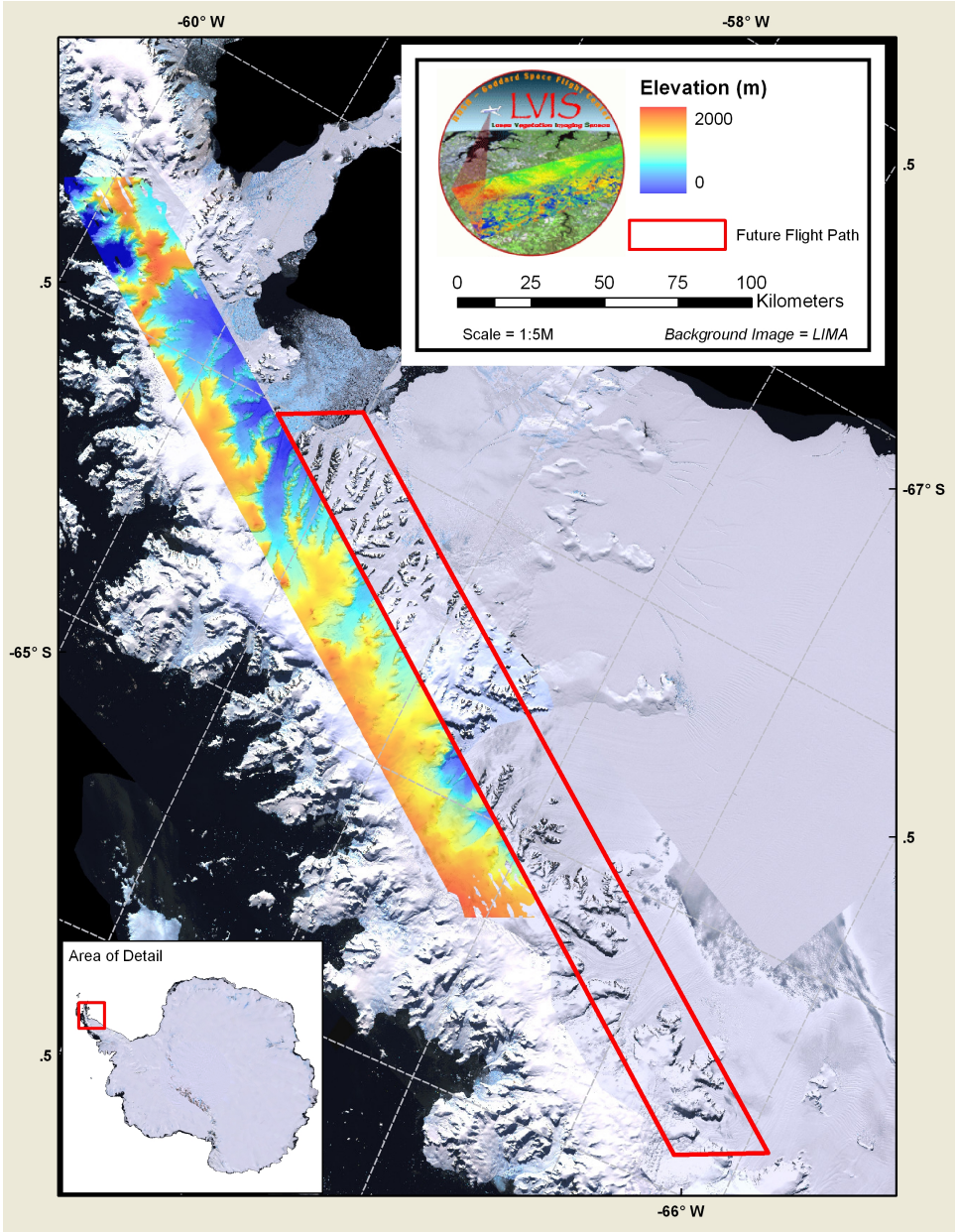
2010 Flights

- **Crane/Peninsula Repeat**
  - Validation of GRACE mascon box mass change result plus information gained from having sub-box resolution; ICESat-2/DESDynI dh/dt modeling studies (Luthcke, others).
- **PIG repeat + 2nd flight to fill between existing swaths gives 100% map of PIG (Joughin/Smith, others)**
- **Peninsula Box #2 – similarly sized to existing box but to E and S of Crane covering outlet glaciers and remnant Larsen B/C shelves**
  - Prepare for looking at shelf collapse processes and related response of outlet glaciers on several glaciers (see info from BAS)
- **Pole Hole**
  - To get annual change estimates for the region where we now have tied down the ICESat inter-campaign biases (enabling correction of ICESat dh/dt estimates (Luthcke, Smith, Shuman, others).

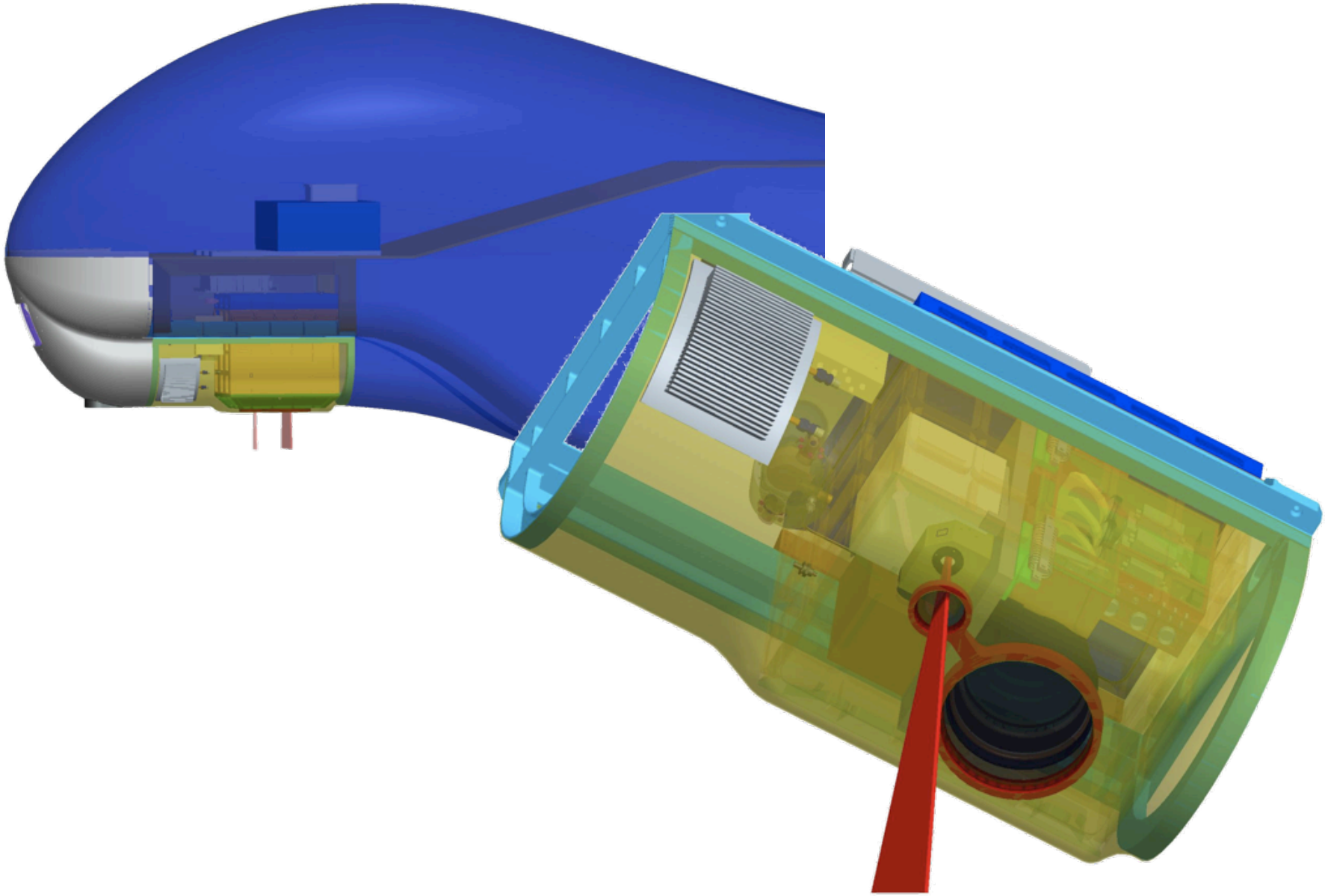
Extending Coverage over Peninsula

Potential (approximate) 2nd Peninsula Box – gets 100% coverage of many outlet glaciers in preparation for possible collapse of remnant Larsen B and C.

- Builds on last years center line coverage with atm, radar and gravimeter coverage



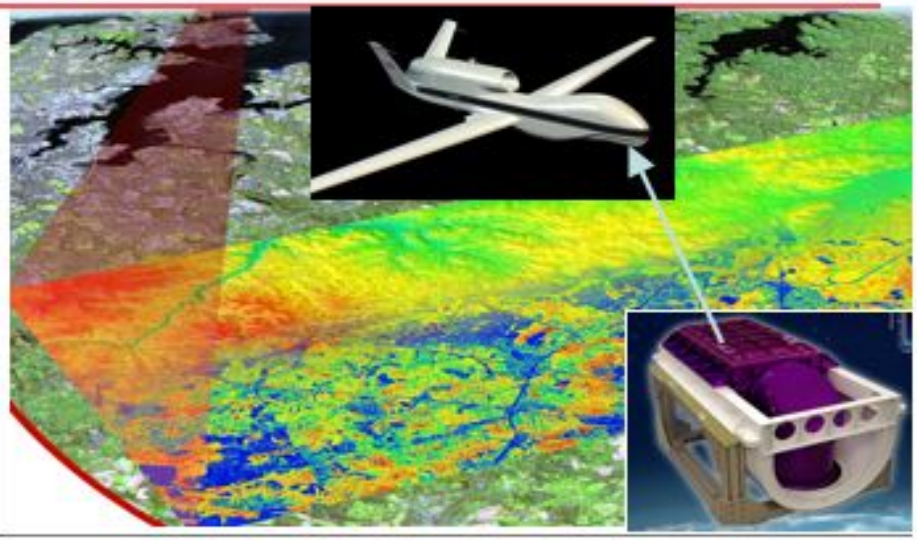
LVIS on the Global Hawk



LVIS on the Global Hawk – ESTO/ARRA

Objectives:

- Integrate LVIS capability onto the Global Hawk (GH)
- Update the LVIS design (provides advantages for lower altitude LVIS facility instruments).
- Automate LVIS operations for GH (hands-off, turn-key operations).
- Operational capability and data storage for 30+ hours of GH operations.
- Reliability improvements – improved electrical system design, packaging, thermal control, component testing, ruggedization, housekeeping data collection, performance and health monitoring.



Approach:

- Repackage LVIS design to fit into existing Cloud Precipitation Lidar (CPL) enclosure on GH
- Optimize receiver for altitude and space constraints
- Updated digitization system
- Automate control and data collection system
- Additional detector to avoid saturation issues
- Bench-top functional checkout
- Perform mechanical and electrical integration and testing at DFRC in the Global Hawk

Co-Is/Partners

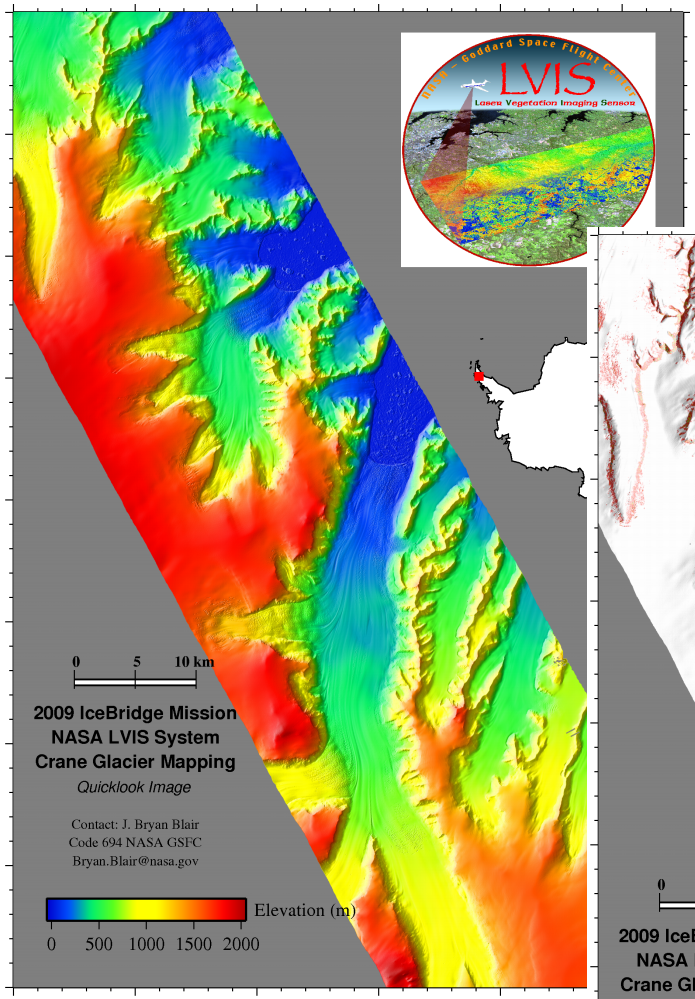
Dryden (DFRC), Northrop Grumman, Sigma Space, Welch Mechanical Design

Key Milestones:

• Instrument design	- October 09
• Performance review	January 10
• Electrical integration on GH	April 10
• Mechanical integration on GH	August 10

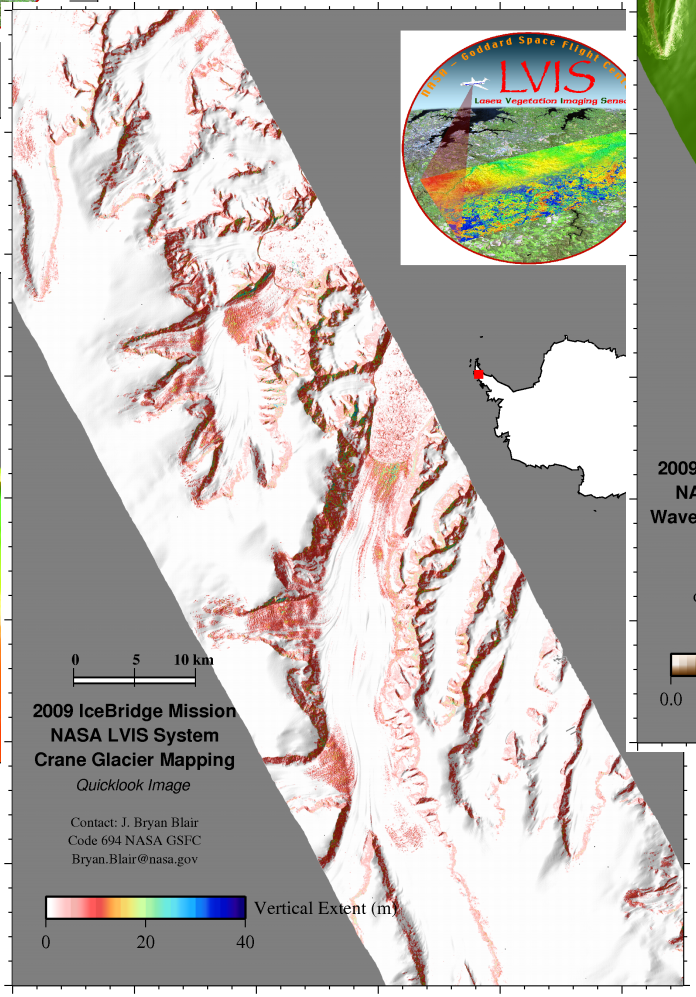
$TRL_{in} = 5$, $TRL_{out} = 6$

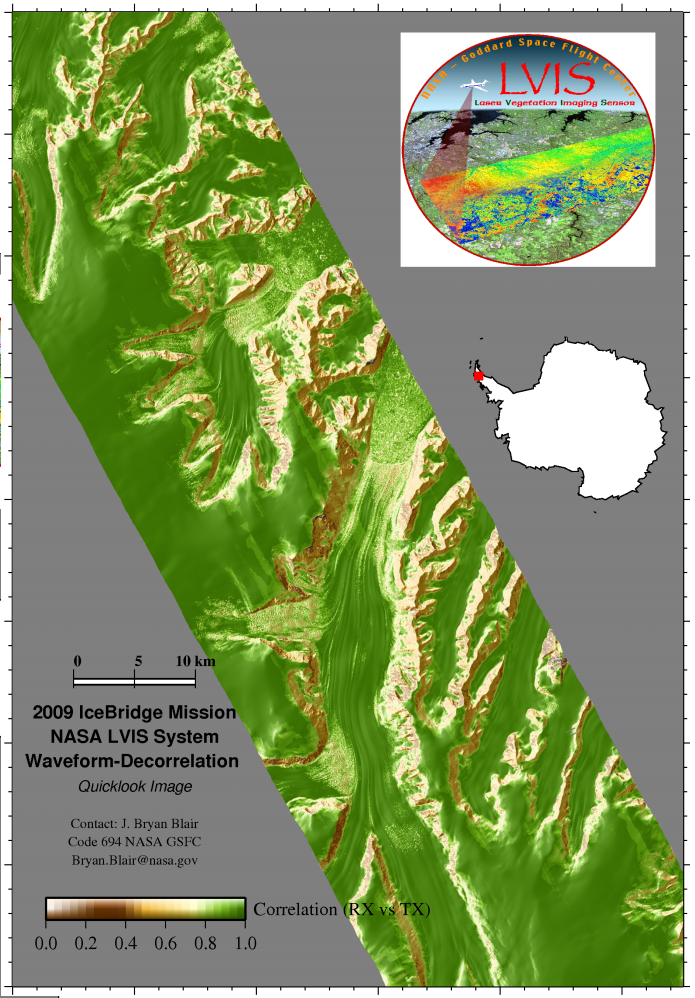
Advanced Waveform Products



Highest/lowest Surface Elevation

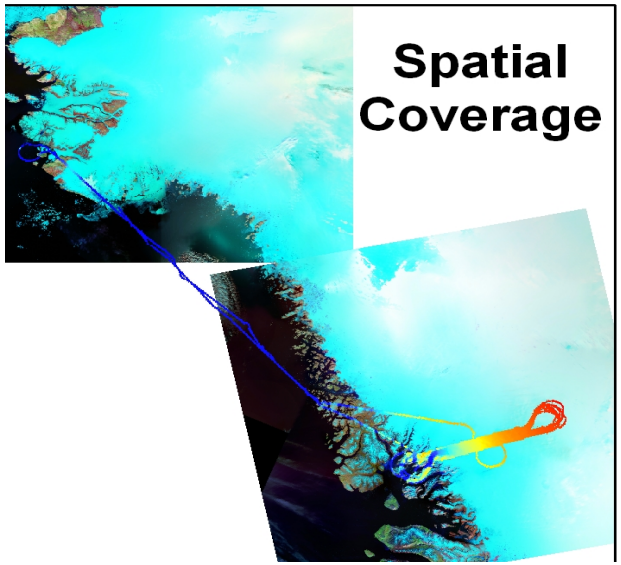
Vertical extent – crevasse depth

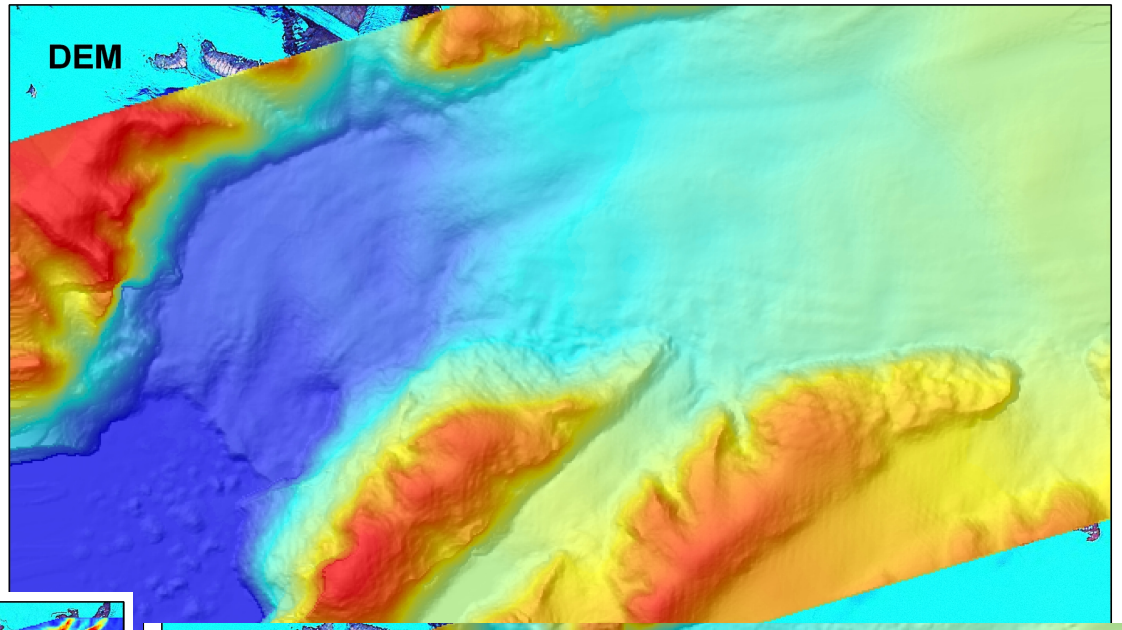


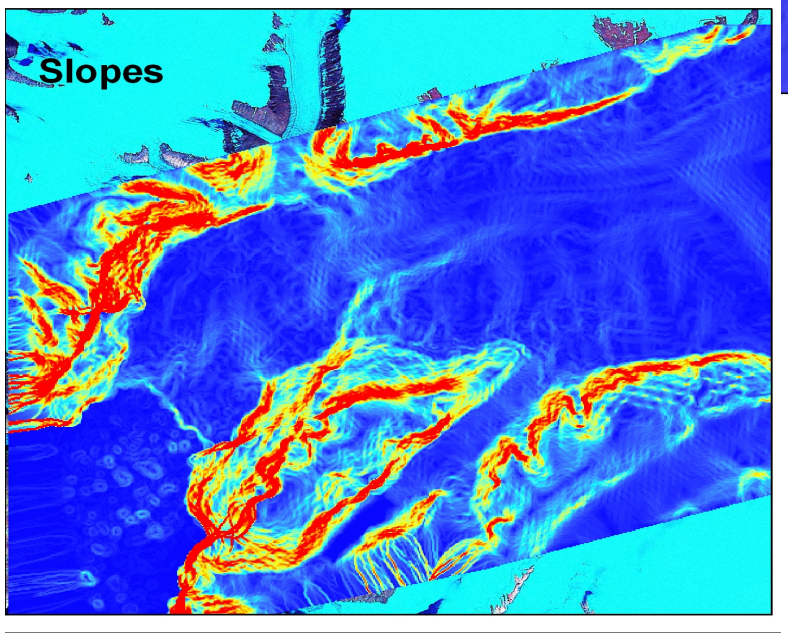


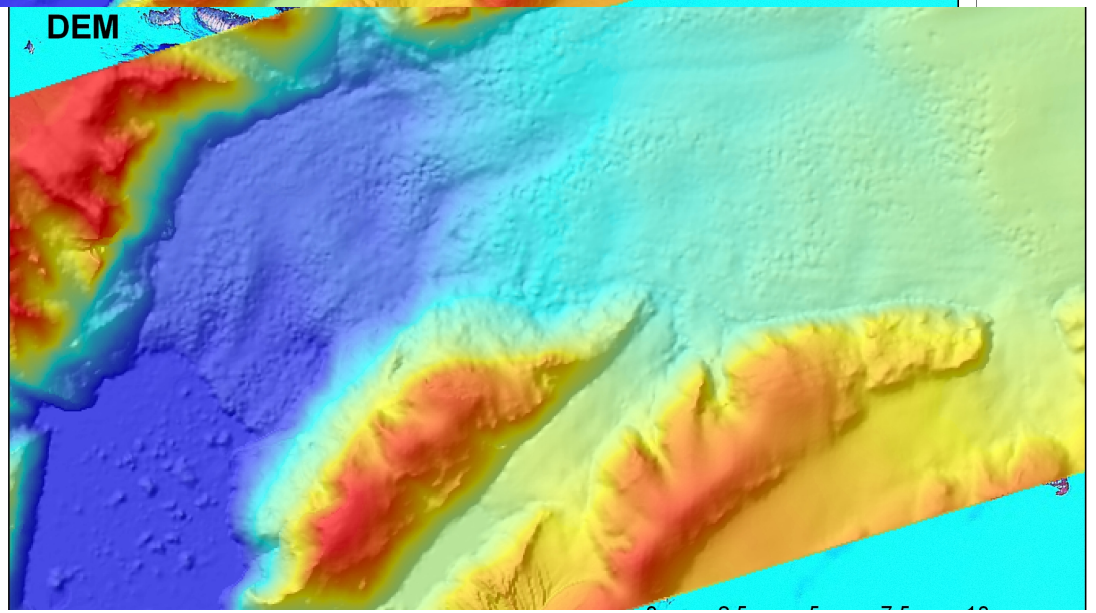
Roughness De-correlation

Rink Glacier, Greenland



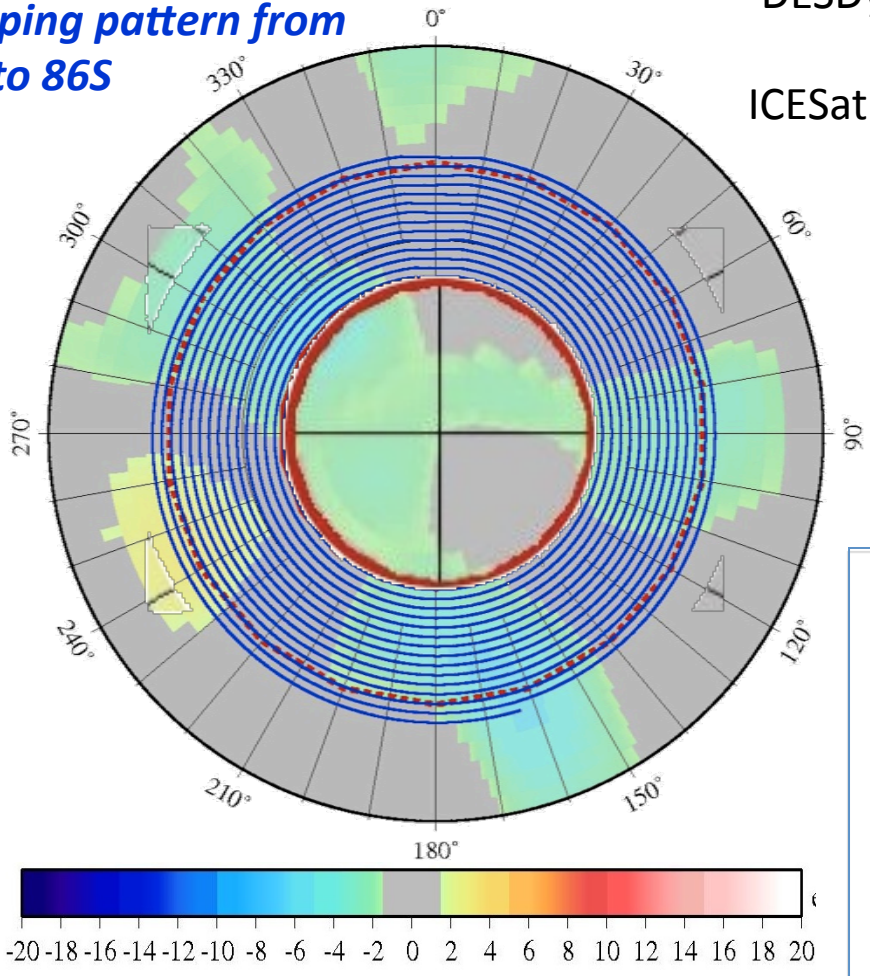






South 'Pole Hole' Mapping Using the Global Hawk

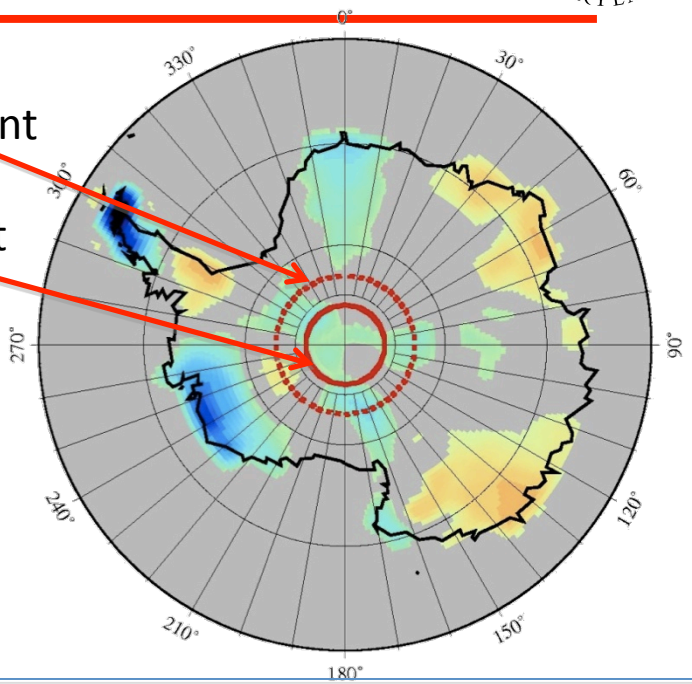
Example spiral mapping pattern from 83S to 86S



Eq. cm h_20/year from GRACE. From S. Luthcke, Code 698, NASA

DESDynI extent

ICESat1 extent



- **Assuming an average of 20 science hours per 30 hour flight available after entry into area.**
- **A *spiral mapping* pattern within the pole hole with adjacent tracks spaced 10 km apart requires ~220 hrs onsite (i.e. 11 flights).**
- **Could deploy 4 times/year for ~1 month.**
- **Using existing LVIS (3km swath, 25m footprints), ~30% of land area is imaged and more with a wider swath.**

Global Hawk Antarctic Costs (per deployment)

- **Remote base locations:**
  - Punta Arenas, Chili – approx. 2200. nm from the South Pole.
    - Estimated ability to fly the entire coastline of Antarctica in a single flight.
    - The primary risk of that site is gaining permission to use the site and other foreign issues, etc.
  - RAAF Base Edinburgh, South Australia - approx. 3,333 nm from the South Pole.
    - Estimated ability to fly approx. 75% of the Antarctic coastline in a single flight…
    - Already used by the USAF GH

- **Estimate for a deployment that includes 350 flight hours:**
  - Flight costs (12 flights): 350 hrs x $3500 = $1,225K
  - Transport of aircraft both ways, flight costs: 2 x 23 hrs x $3500 = $160K
  - Transport of GCS to site and back (by ship, then truck): $80K
  - Mission-specific Costs:
    - Mission Planning: $45K
    - Satcom Coverage: $20K
    - Personnel Costs: 10 people x $220/day x 45 days = $100K
    - Personnel Flt. Costs (round trip): $1400. X 10 = $14K
  - Misc. Margin = 20%

- **Approx. Cost per deployment = 1,972. K**

- **Non-recurring costs include travel to survey the site for GH logistics**