Jet Propulsion Laboratory
California Institute of Technology

AirSWOT Ka-band InSAR measurement of lake and river surface heights

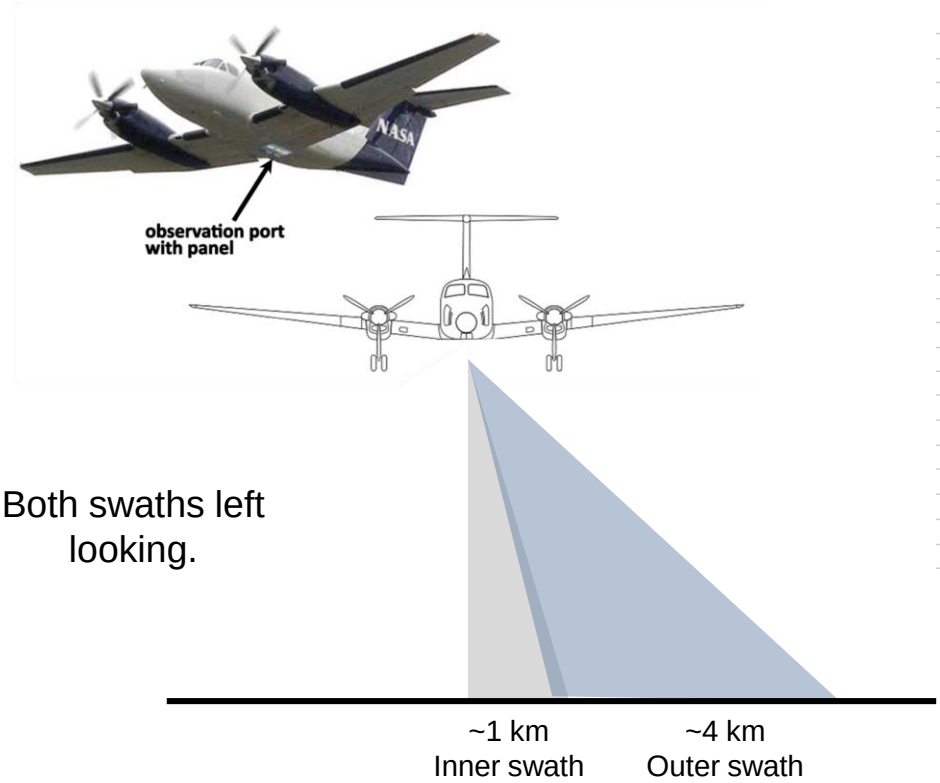
Presented by Mark Haynes and Albert Chen

With contributions from Nathan Brummel, Jack Bush, Roger Chao, Curtis Chen, Michael Denbina, Jessica Fayne, Joe Kwan, Yunling Lou, Dragana Perkovic-Martin, Ernesto Rodriguez, Mauricio Sanchez Barbetty, Craig Stringham, Wayne Tung, Xiaoqing Wu, and others.

AirSWOT Overview

- Airborne platform for radar measurements of hydrologic targets.
- Instruments:
  - Ka-band SWOT Phenomenology Airborne Radar (KaSPAR)
  - IMU (Applanix POSAV 610)
  - Digital camera system
- Integrated on Beechcraft Super King Air B200 Aircraft
- Website: https://swot.jpl.nasa.gov/airswot.htm

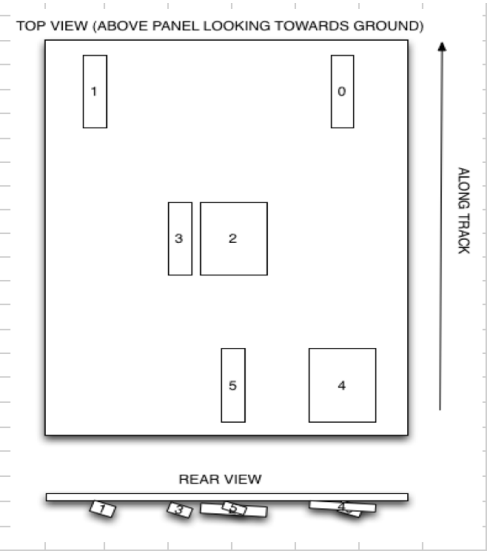
AirSWOT KaSPAR radar swaths



Both swaths left looking.

AirSWOT KaSPAR radar antennas

Antenna	Pointing Angle (deg)
0	18
1	18
2	4
3	18
4	0
5	18

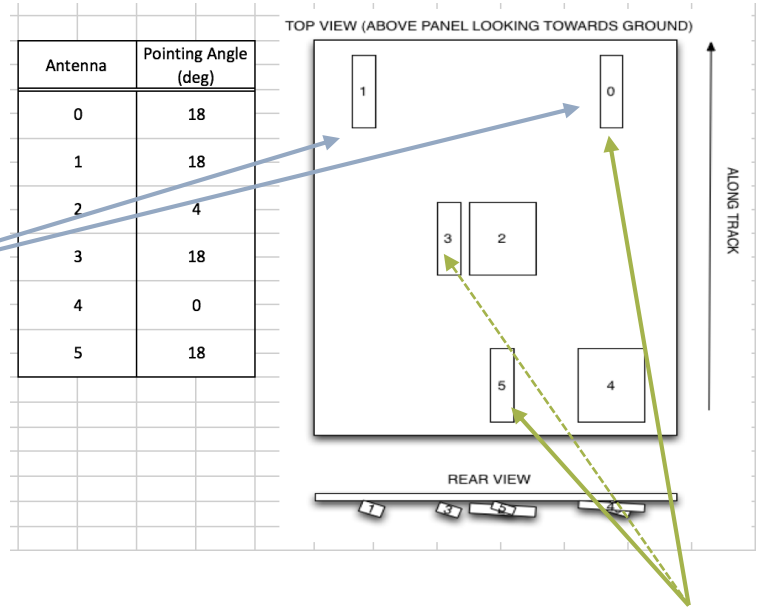


AirSWOT Overview

- Carrier Frequency: 35.75 GHz (wavelength 8.4 mm)
  - Negligible penetration into water, measures water surface height
- Incidence angles:
  - ~5 to 25 deg. for outer swath
  - ~0 to 5 deg. for inner swath (similar to SWOT)
- Stripmap SAR imaging
  - Cross-track interferometry (for surface height measurement) using antennas 0 and 1
  - Along-track interferometry (for surface radial velocity measurement) also possible
- Resolution: ~3 meters, varies from near-range to far-range

AirSWOT KaSPAR radar antennas

Antenna	Pointing Angle (deg)
0	18
1	18
2	4
3	18
4	0
5	18

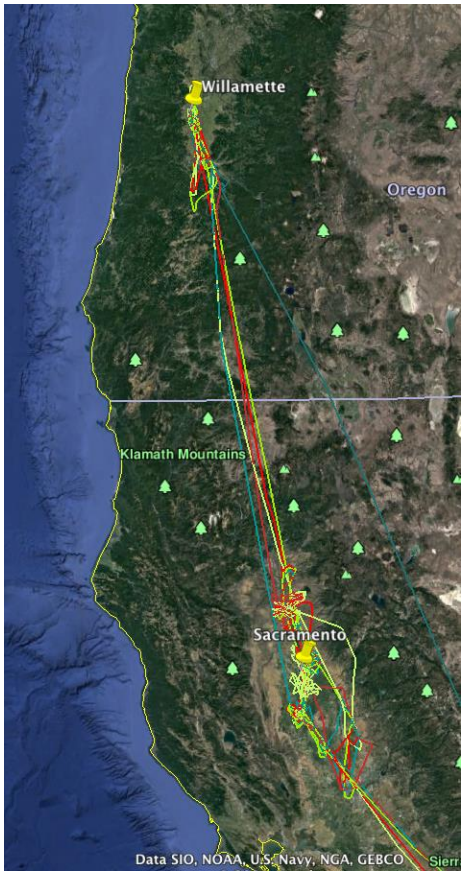


Outer swath cross-track interferometer

Outer swath along-track interferometer

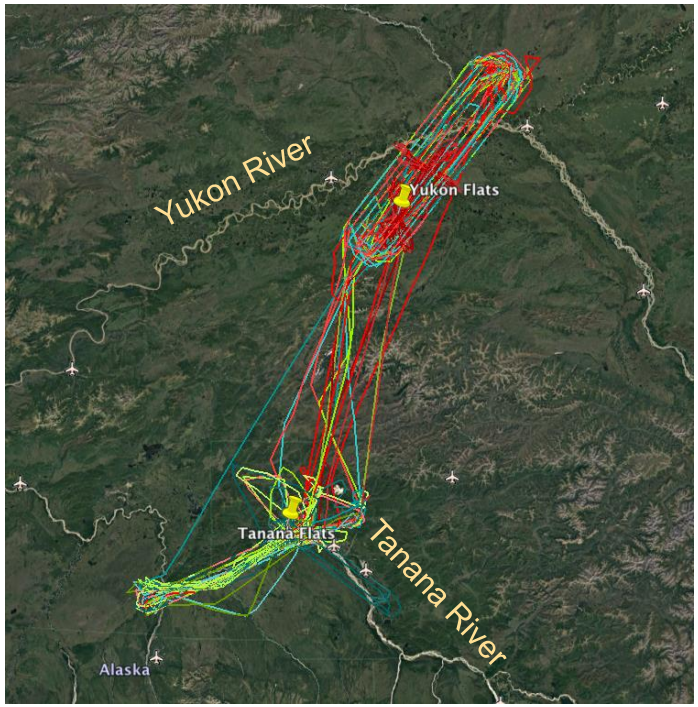
AirSWOT Selected Earlier Deployments/Flights

Willamette/Sacramento
March 2015

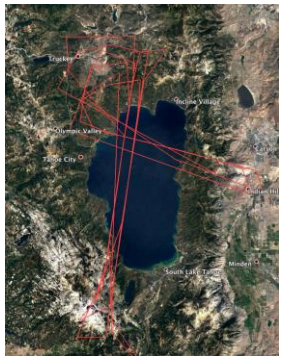


New Orleans
May 2015

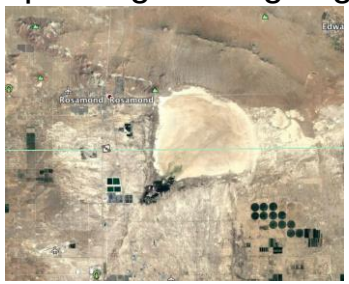
Alaska
June 2015



Lake Tahoe
Multiple Engineering Flights

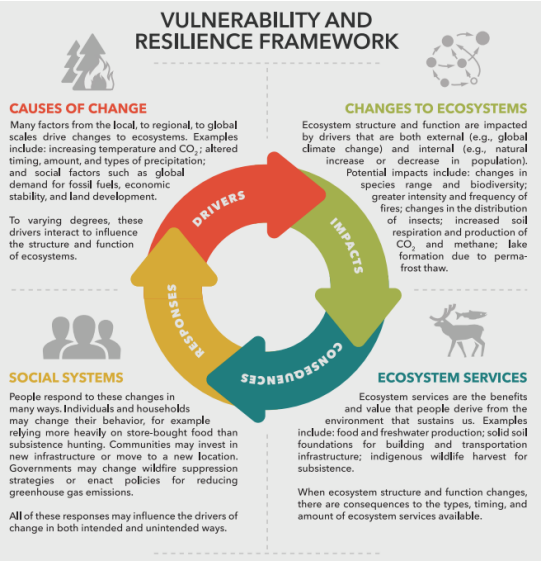


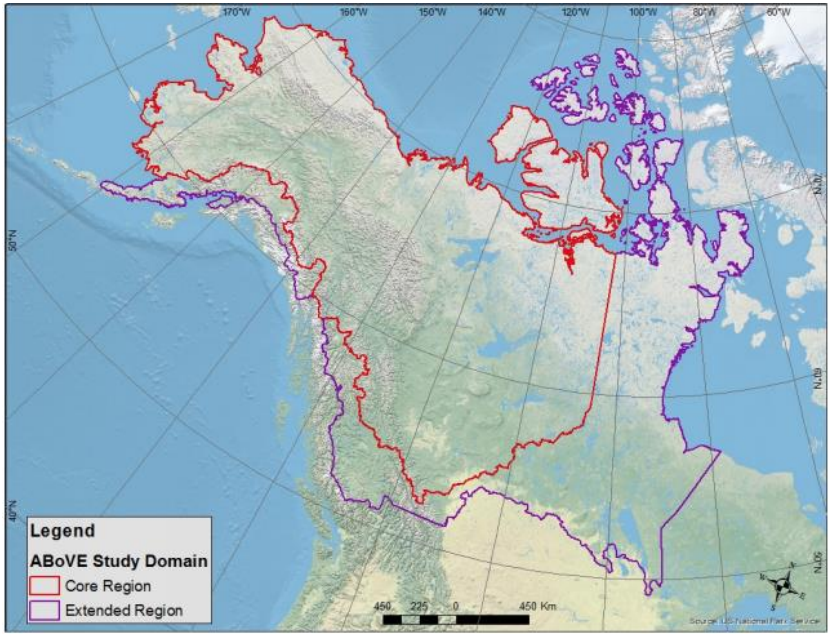
Rosamond
Multiple Engineering Flights



AirSWOT ABoVE Deployment

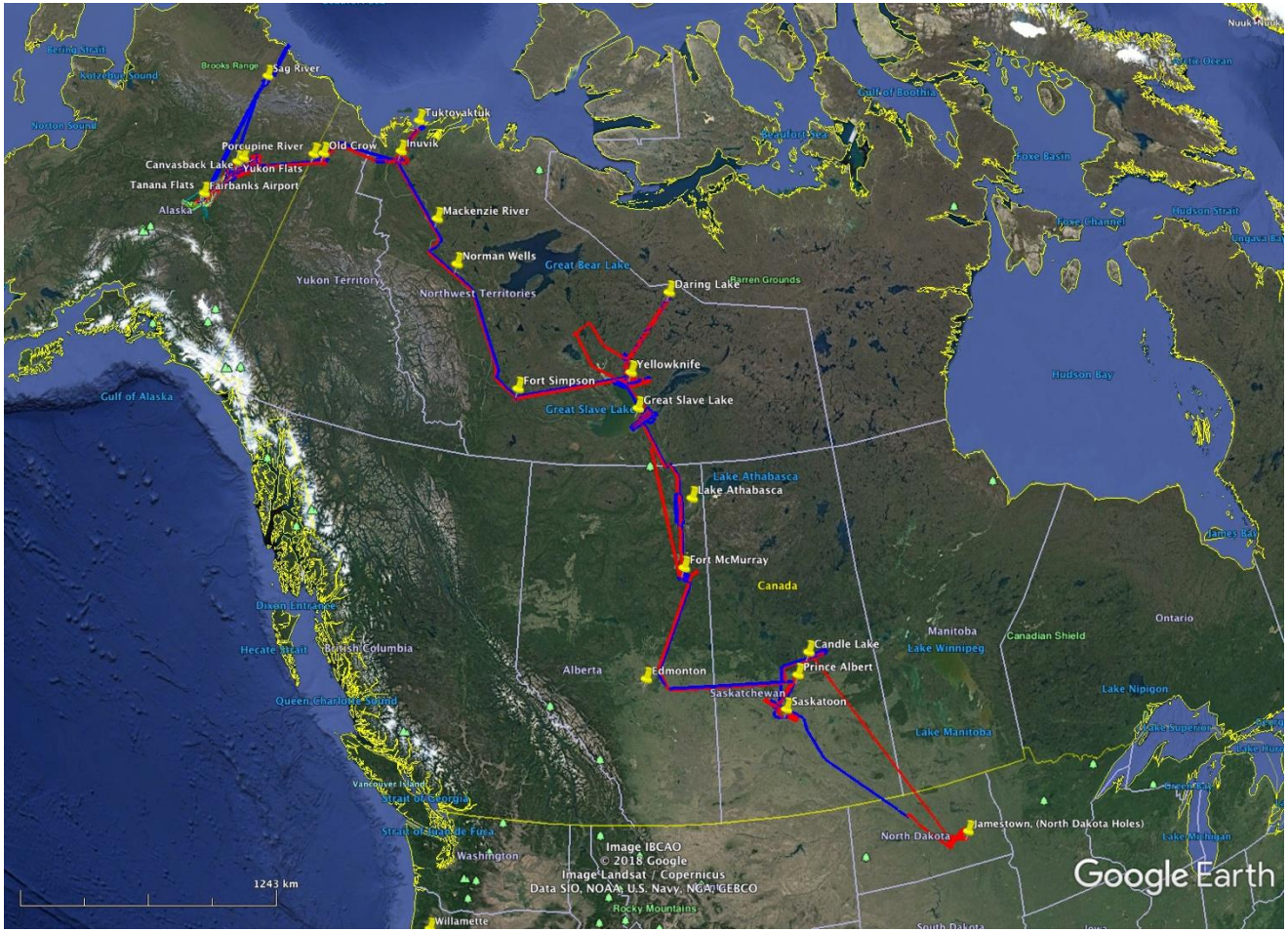
- **A**rctic-**Bo**real **V**ulnerability **E**xperiment (ABoVE)
  - Field-work + airborne campaign
  - Multiple airborne sensors, including AirSWOT
    - Overlapping swaths to facilitate inter-comparison
  - AirSWOT acquired data in July, August 2017





AirSWOT ABoVE Deployment

AirSWOT ABoVE Flight Tracks

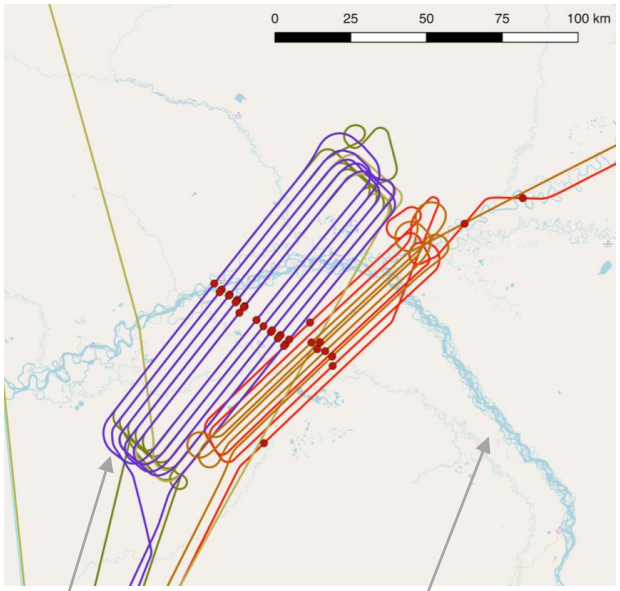


- Blue tracks: July 2017
- Red tracks: August 2017
- Total: 133 flight lines
- ~25 TB raw data

AirSWOT ABoVE Deployment

Selected Study Areas

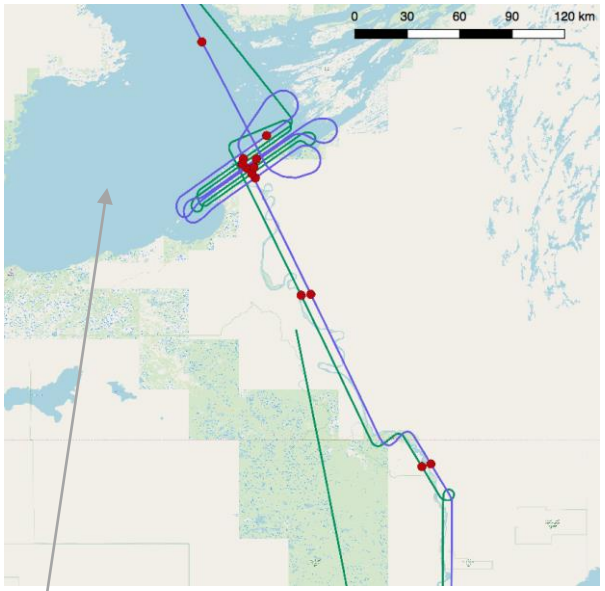
Yukon Flats, Alaska



This area was also imaged by AirSWOT during June 2015 campaign (multi-temporal analysis)

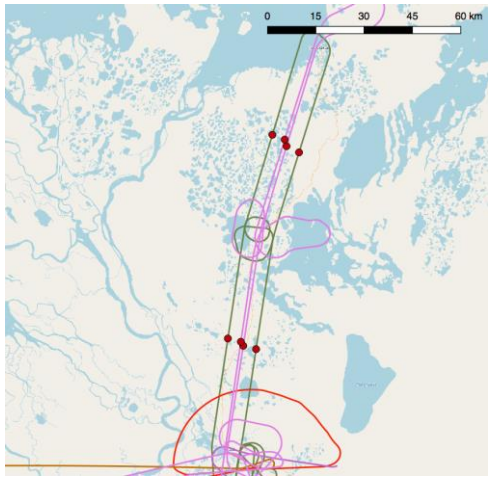
Yukon River

NW Territories, Canada



Great Slave Lake (deepest lake in N.A., and 2nd largest in Canada NW Territories)

Inuvik, Canada



Near Inuvik, Canada, at Mackenzie River Delta

AirSWOT Flight Planning Process

- Step 1: PIs create the lines using flight planning software

Flight Plan Report: pavelky_0074 (Saskatoon McMurray June 6)

Created by pavelky on Jun 6, 2017 at 9:27 AM. Estimated flight time: 3 hrs 40 min.

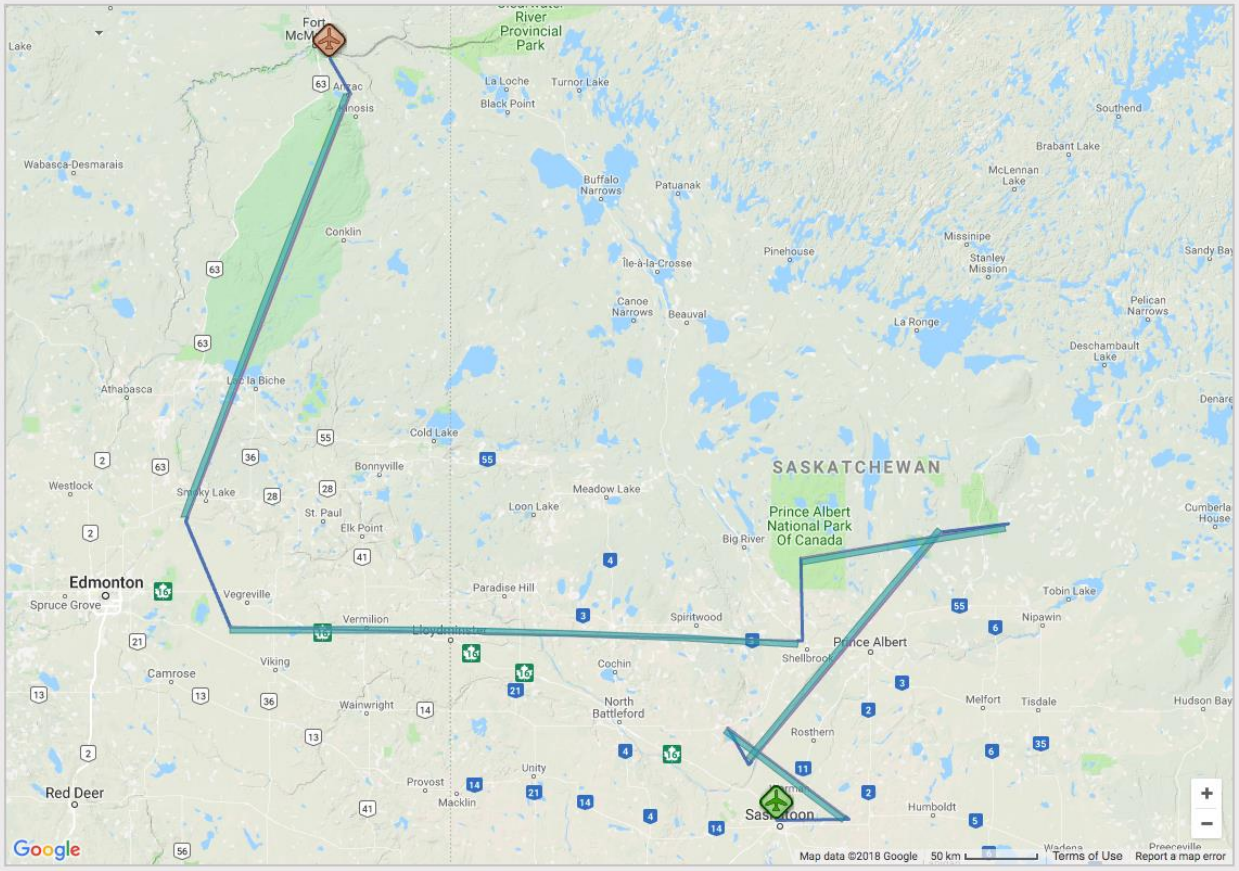
Comments:

Instrument: **Ka-band (AirSWOT)**

Plan status: **Preliminary**

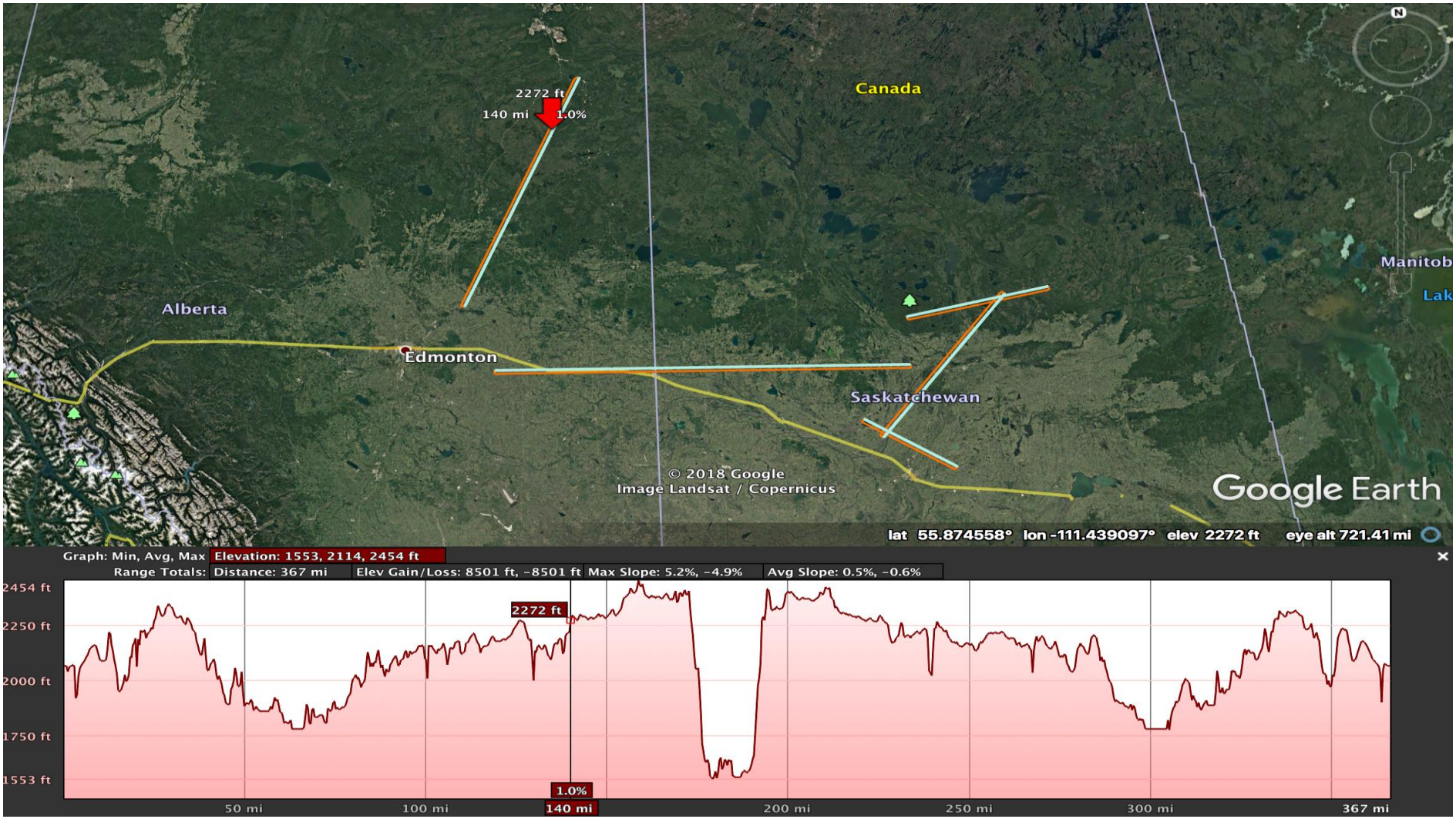
Related Plans | **Plan Summary** | Flight Map (with KML files) | Configuration

Takeoff Airport (CYXE)	0 min	0 km
Transit to Line pave10_307aa	10 min total 25 min	48 km total 48 km
+ 1. Line **pave10_307aa**	12 min 37 min	101 km 149 km
Transit to Line pave01_040aa	8 min 46 min	28 km 177 km
+ 2. Line **pave01_040aa**	24 min 1 hr 10 min	201 km 378 km
Transit to Line pave09_261aa	10 min 1 hr 20 min	41 km 420 km
+ 3. Line **pave09_261aa**	16 min 1 hr 36 min	137 km 557 km
Transit to Line pave02_271aa	12 min 1 hr 48 min	55 km 612 km
+ 4. Line **pave02_271aa**	46 min 2 hrs 33 min	383 km 995 km
Transit to Line pave11_021aa	14 min 2 hrs 48 min	79 km 1,074 km
+ 5. Line **pave11_021aa**	35 min 3 hrs 22 min	291 km 1,365 km
Transit to Landing	18 min 3 hrs 40 min	25 km 1,391 km
Landing Airport (CYMM)	3 hrs 40 min	1,391 km



AirSWOT Flight Planning Process

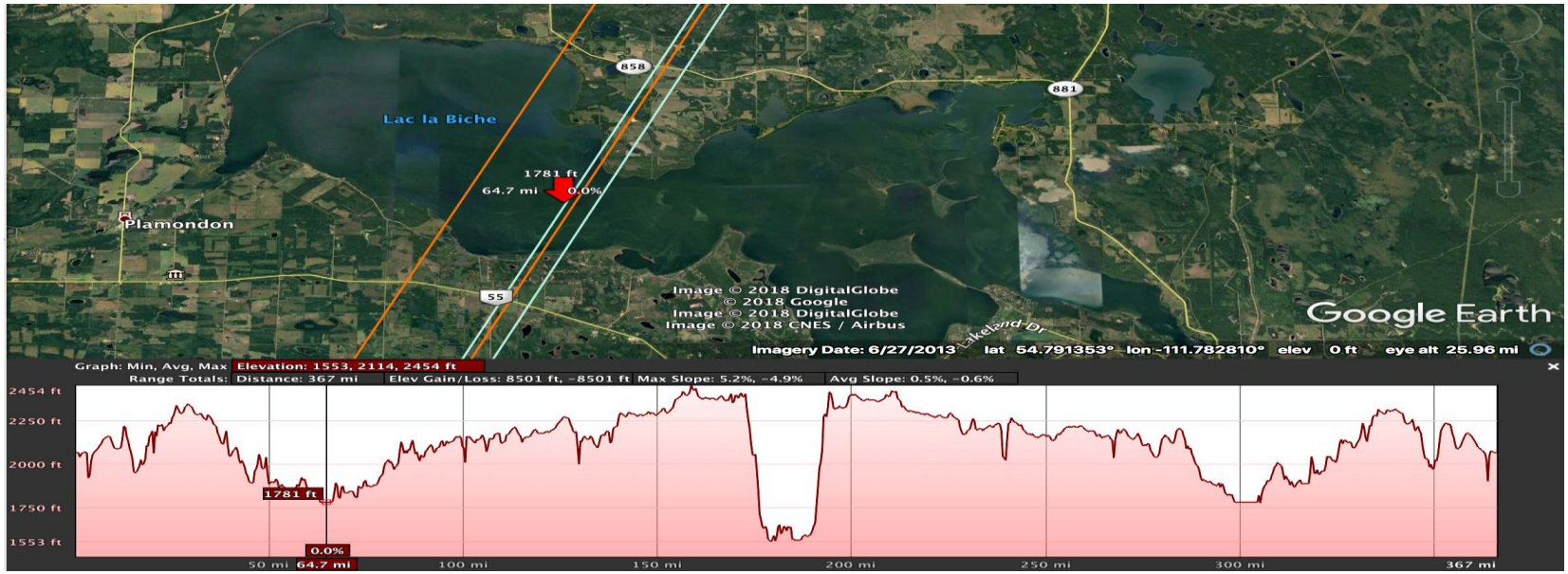
- Step 2: Instrument Engineer goes through each line to obtain proper ground elevation



AirSWOT Flight Planning Process

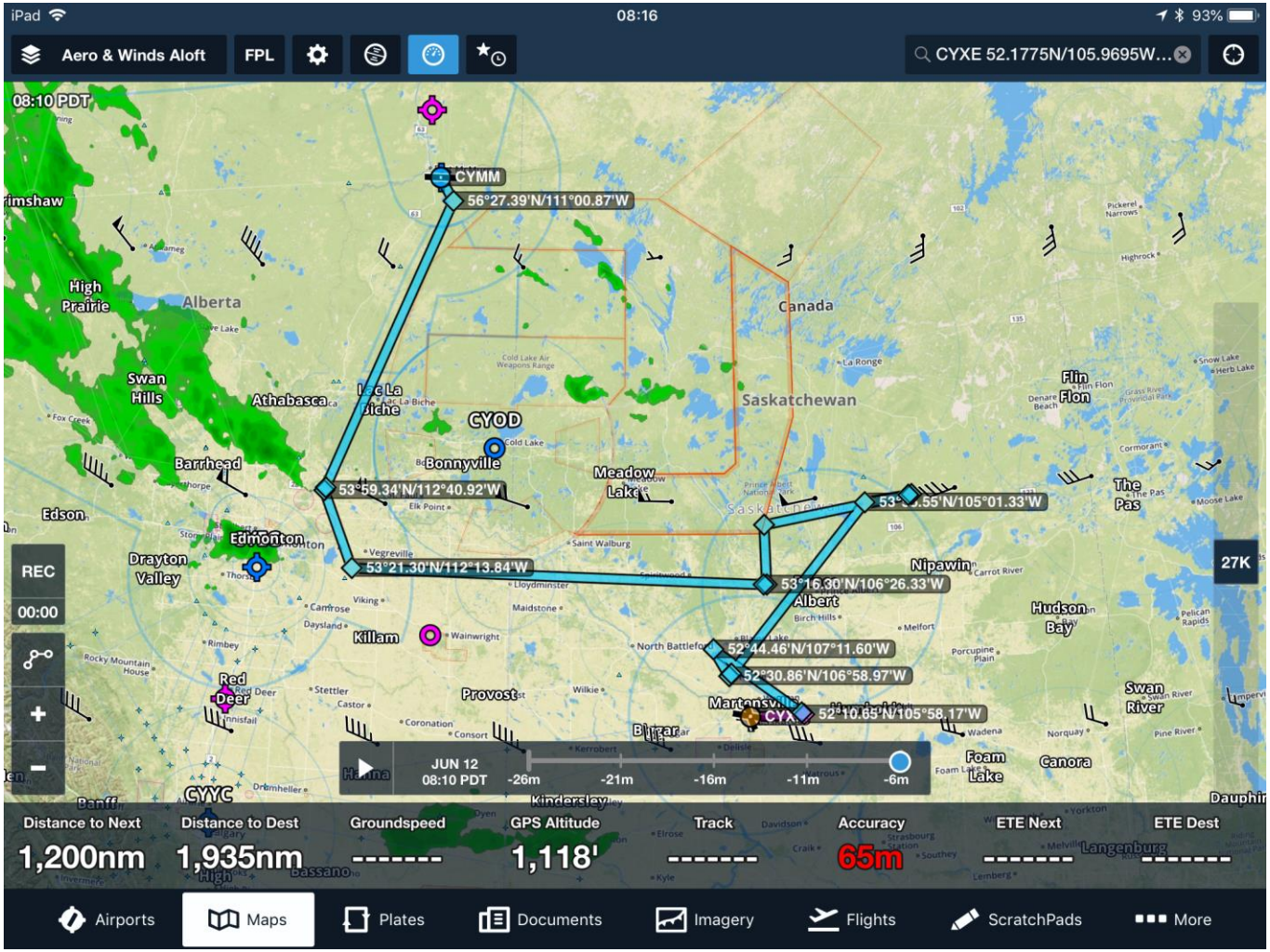
- Step 3:: Radar parameters are generated for each line

						Google Earth				Visual Inspection						OUTER SWATH		INNTER SWATH	
	Description	Latitude	Longitude	Grd Alt Mid	DAQ Time	MIN	AVG	MAX	DIFF	MIN	AVG	MAX	DIFF	UAVSAR	TEST	MIN	MAX	MIN	MAX
PAVE_0074	PAVE10_307_PRE	N 52 11.62	W 106 00.27	503	12	435	523	585	150	435	502.5	570	135	524	503	-457	603	337	603
	PAVE10_307_POS	N 52 44.46	W 107 11.60	503		435	523	585	150	435	502.5	570	135	524	503	-457	603	337	603
	PAVE01_040_PRE	N 52 32.11	W 106 57.27	464	24	433	497	566	133	322	442.5	563	241	464	464	-496	564	298	564
	PAVE01_040_POS	N 53 55.55	W 105 01.33	464		433	497	566	133	322	442.5	563	241	464	464	-496	564	298	564
	PAVE09_261_PRE	N 53 58.16	W 104 23.85	552	16	450	536	684	234	453	552	651	198	498	552	-408	652	386	652
	PAVE09_261_POS	N 53 46.11	W 106 27.36	552		450	536	684	234	453	552	651	198	498	552	-408	652	386	652
	PAVE02_271_PRE	N 53 16.34	W 106 29.03	623	46	480	630	745	265	495	609	723	228	579	623	-337	723	457	723
	PAVE02_271_POS	N 53 21.30	W 112 13.84	623		480	630	745	265	495	609	723	228	579	623	-337	723	457	723
	PAVE11_021_PRE	N 54 00.85	W 112 39.94	626	35	475	643	747	272	477	601.5	726	249	631	626	-334	726	460	726
	PAVE11_021_POS	N 56 27.39	W 111 00.87	626		475	643	747	272	477	601.5	726	249	631	626	-334	726	460	726



AirSWOT Flight Planning Process

- Step 4: Coordinates are converted into ForeFlight and sent to flight crew



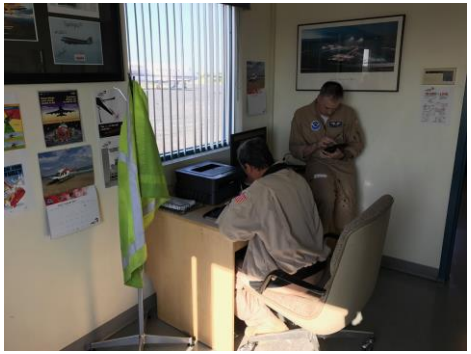
AirSWOT Daily Operation

- 0700: Flight crew hold preflight telecon with PIs to confirm weather condition, flight line priorities, and takeoff time.

- 0730: Flight crew head to airplane

- 0930 ~ 1430: Take off and execute the flight plan

AirSWOT Daily Operation



- 1500: Post flight telecon with PIs & home base to report issues during the flight, weather outlook for the next sortie etc.

- 1800: Flight crew tag up with PIs and go out for dinner

AirSWOT Pictures

Leaving marks with the locals…

AirSWOT Pictures

AirSWOT Pictures

AirSWOT Processing Overview

Reference DEM

A priori water mask

Phase 1

- Raw data ingestion.
- Radar data matched with corresponding IMU data.
- Sorting into bundles.

Phase 2

- Line-by-line processing.
  - SAR image formation
  - Interferogram formation, phase unwrapping
  - Initial phase drift estimation.
  - Initial height reconstruction.

Diagnostic plots for quality assessment, debugging

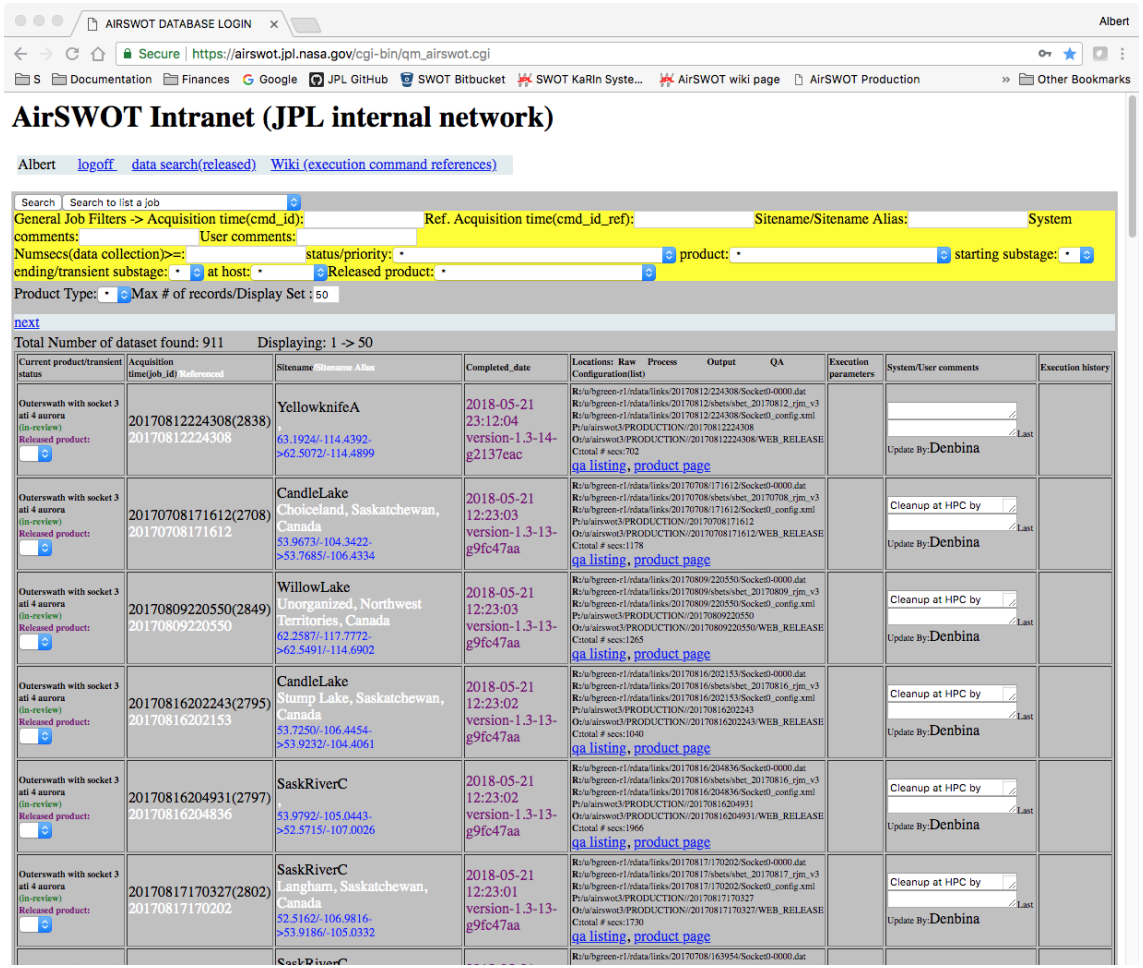
Phase 3

- Least-squares estimation of phase drift for AirSWOT self-consistency.
- Final height reconstruction.
- Regridding/projection to output coordinates.

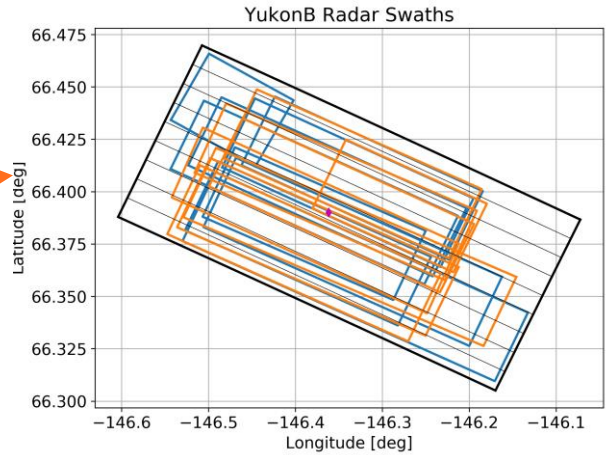
Diagnostic plots for height self-consistency assessment.

AirSWOT Processing: Computing system

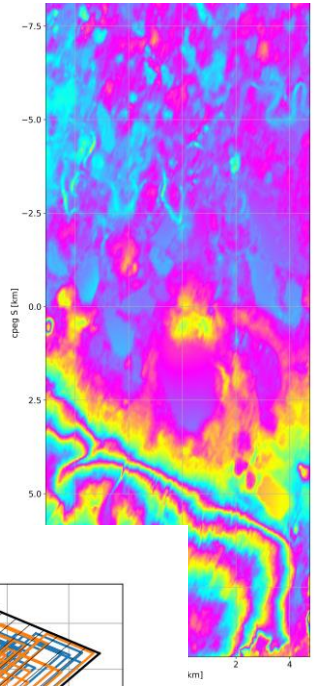
- Raw data transferred from radar to AirSWOT servers (Section 334)
- Phase 1 and 2 computing done on JPL HPC clusters (aurora and halo)
    - Web interface facilitates submitting compute jobs and tracking status
- Phase 3 done on AirSWOT servers.

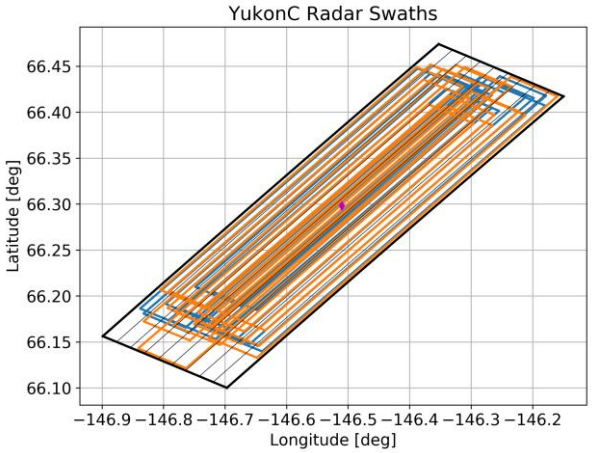


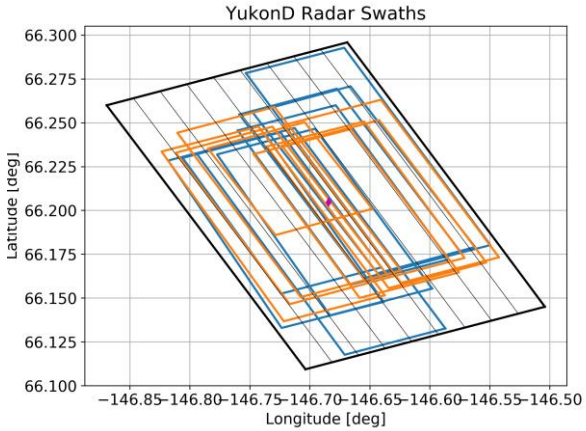
AirSWOT Processing: Phase 1

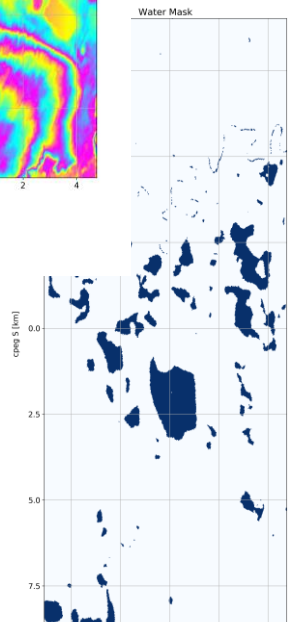


Reference DEM





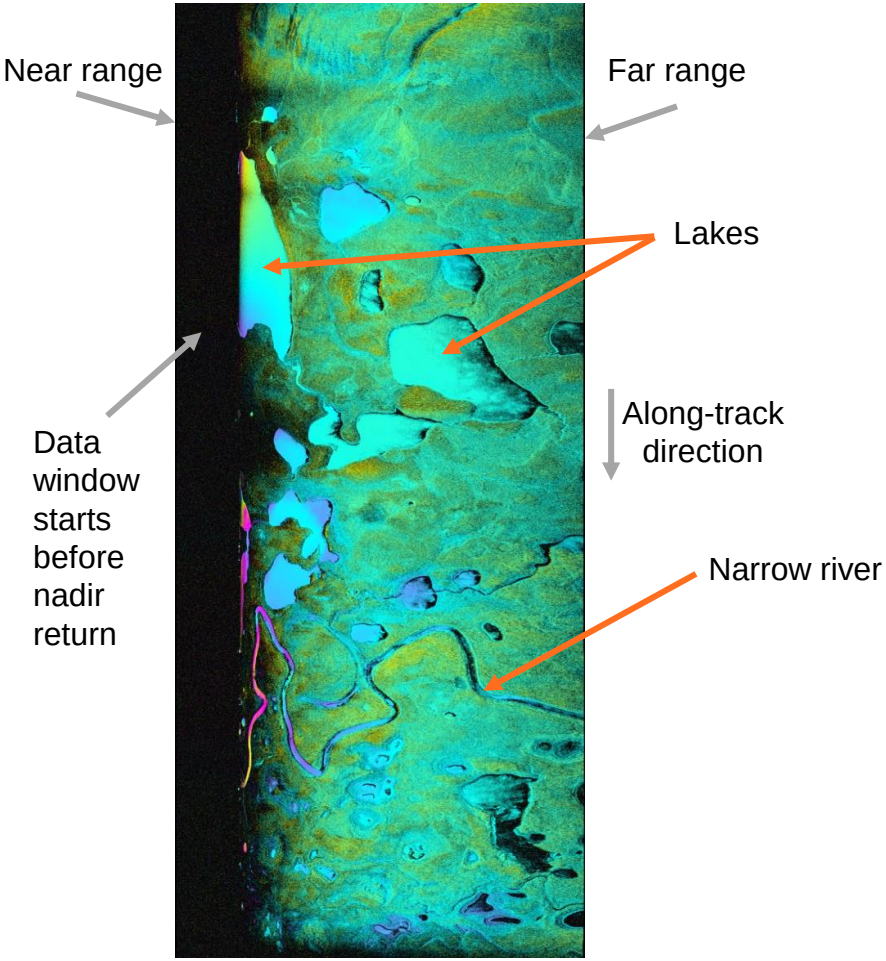




A priori Water Mask

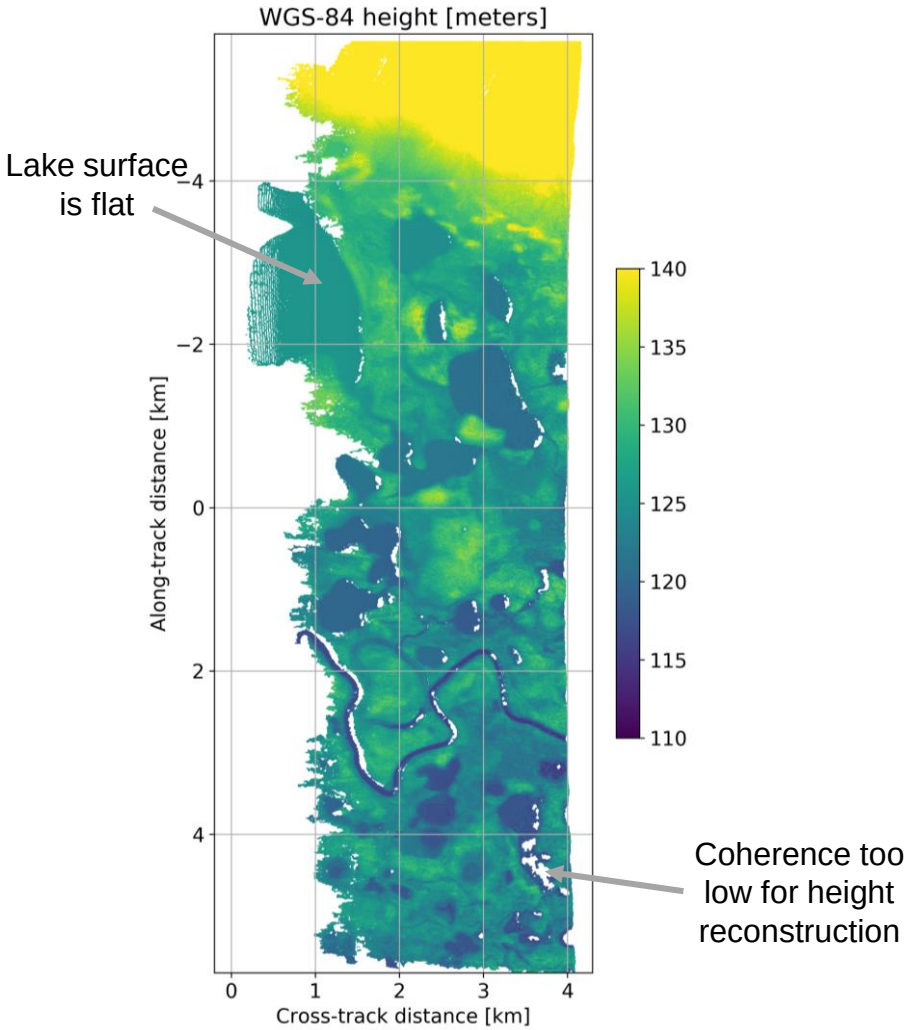
AirSWOT Processing: Phase 2

Interferogram:
Color → Phase
Brightness → Coherence



YukonD, 20150612-220705

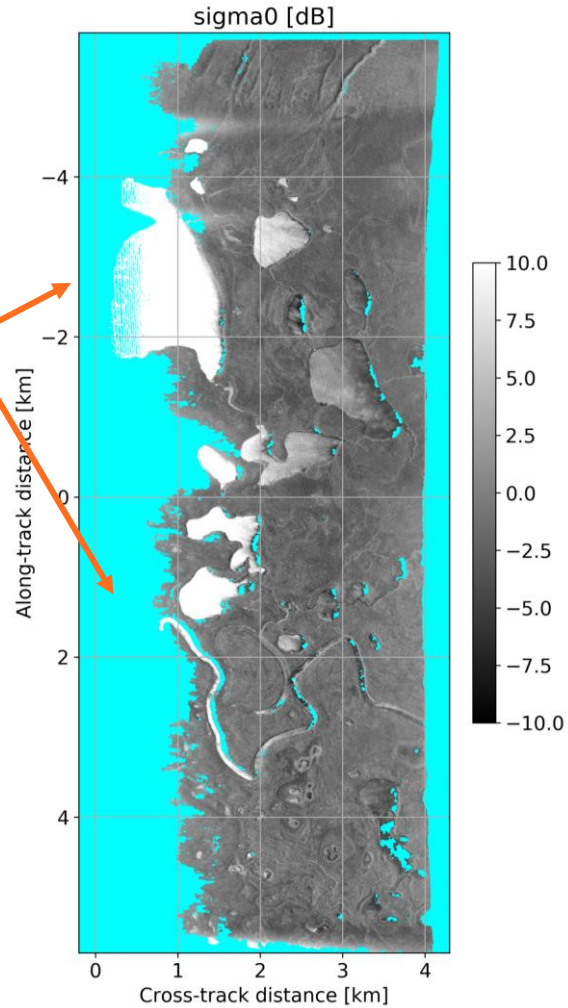
Height Reconstruction Result



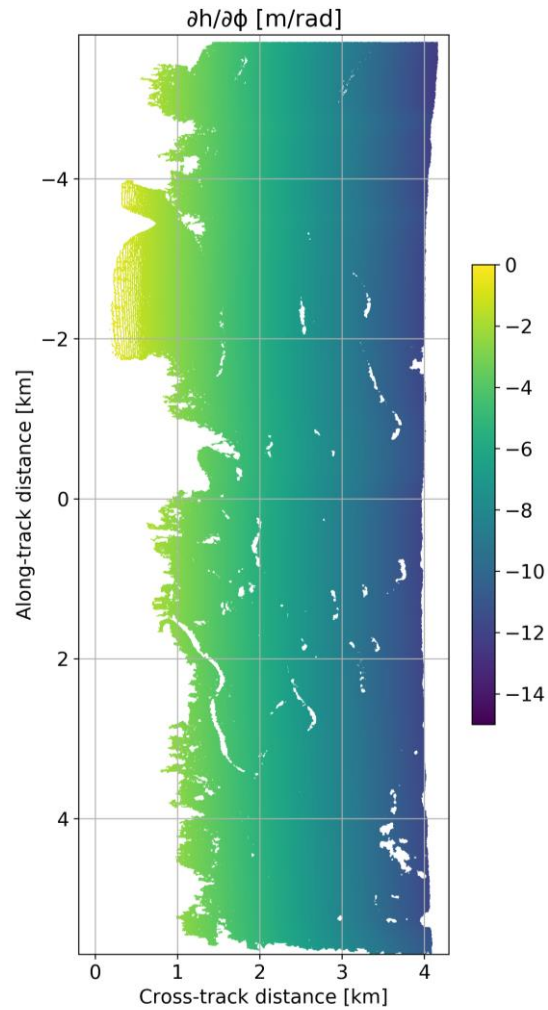
AirSWOT Processing: Phase 2

High sigma0 for water near nadir → good SNR

Backscatter coefficient

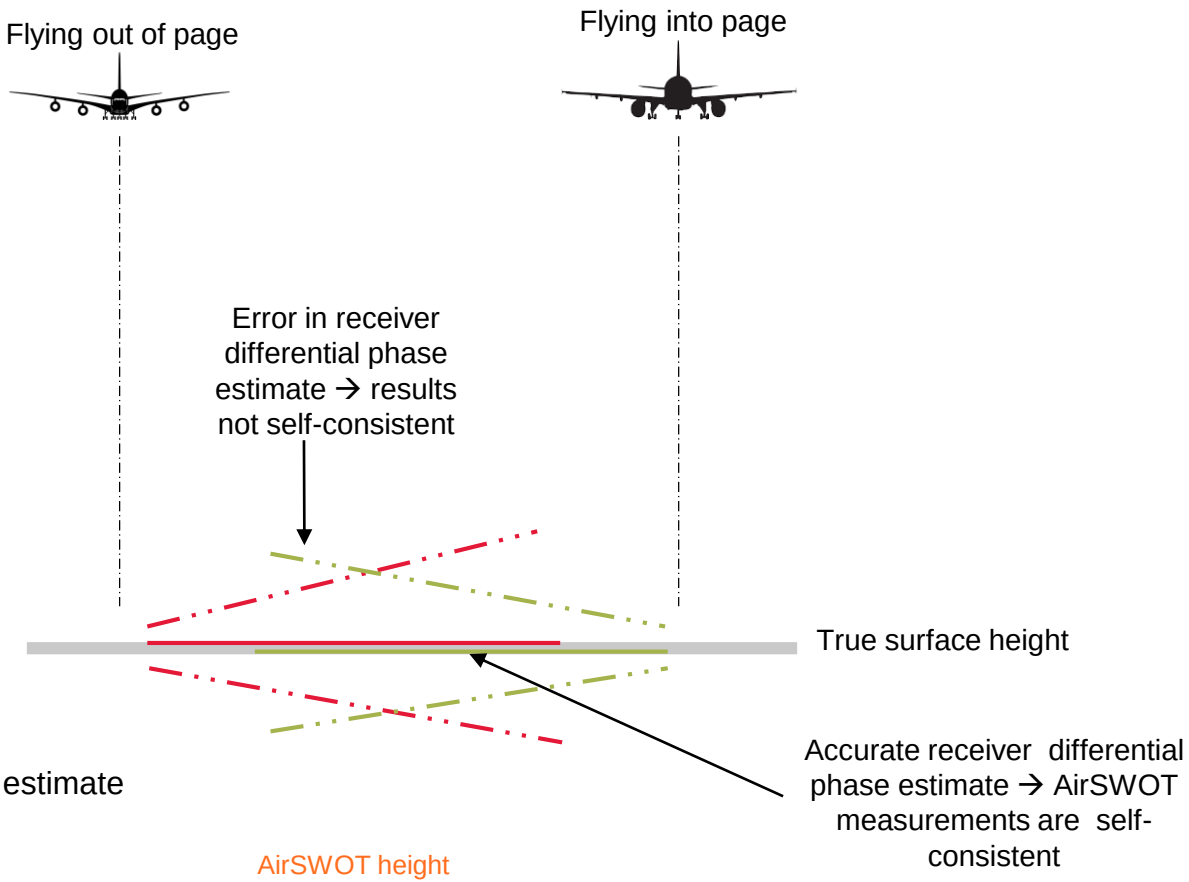


Height Sensitivity



- Height sensitivity computed during height reconstruction.
- Height sensitivity increases across swath.
- Uncalibrated receiver differential phase results in a cross-track height ramp

AirSWOT Processing: Phase 3



Least-squares formulation to estimate receiver differential phase:

$$\underbrace{\begin{bmatrix} \frac{dh}{d\phi_1} & \frac{dh}{d\phi_2} & 0 & \cdots & 0 \\ \vdots & & & & \\ \cdots & \frac{dh}{d\phi_i} & 0 & \cdots & \frac{dh}{d\phi_j} \\ \vdots & & & & \end{bmatrix}}_{A} \underbrace{\begin{bmatrix} \phi_1 \\ \vdots \\ \phi_M \end{bmatrix}}_{\vec{x}} = \underbrace{\begin{bmatrix} h_1 - h_2 \\ \vdots \\ h_i - h_j \\ \vdots \end{bmatrix}}_{\vec{b}}$$

Height Sensitivities

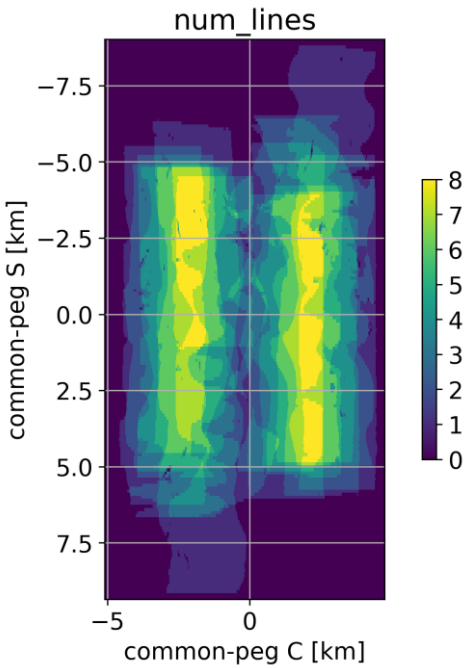
Differential Phase

AirSWOT height inconsistency

We call this “bundle adjustment.”

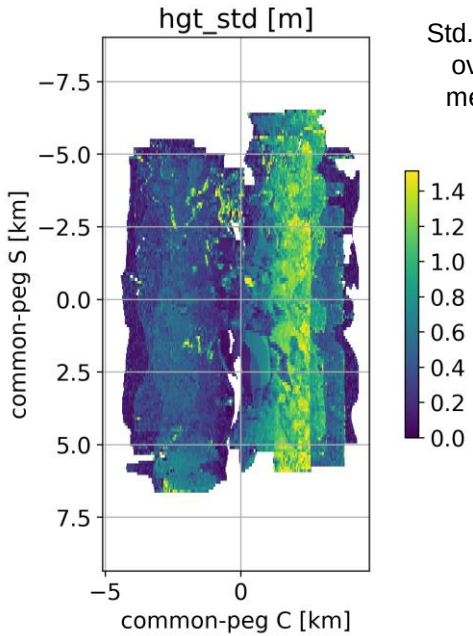
AirSWOT Processing: Phase 3

Each pixel imaged up to 8 times.



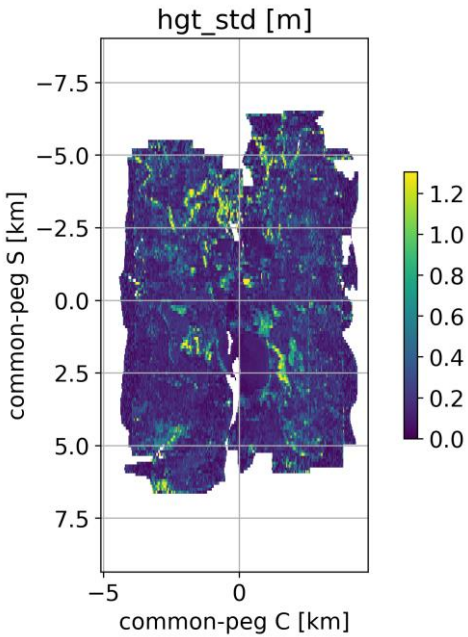
Bundle adjustment uses coordinate system aligned with flight directions.

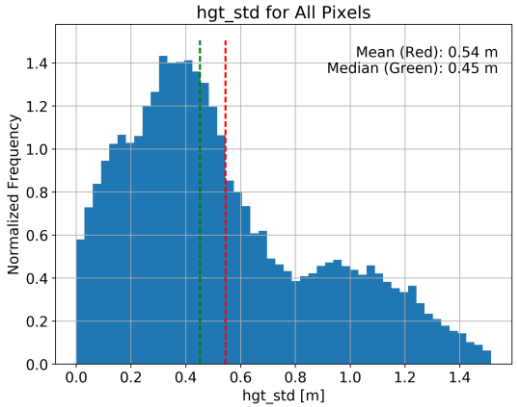
Before Bundle Adjustment

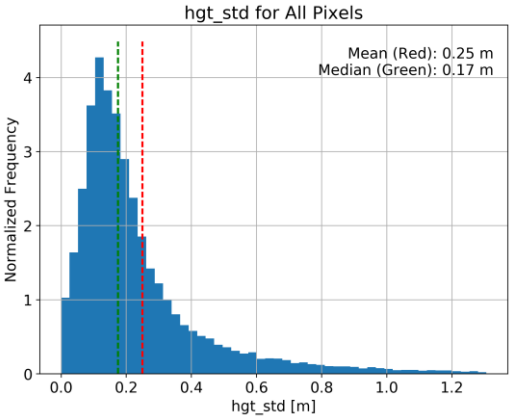


Std.dev. computed over AirSWOT measurements.

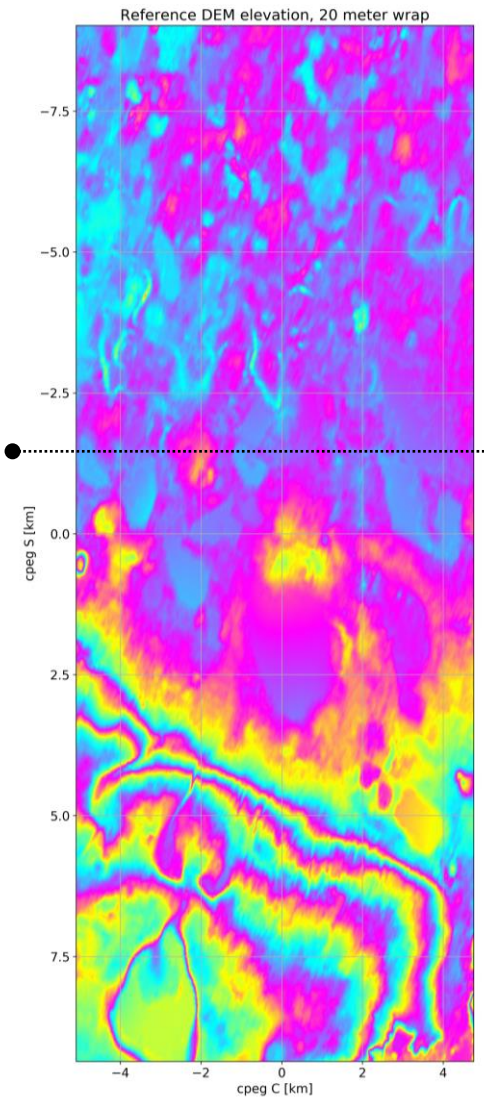
After Bundle Adjustment



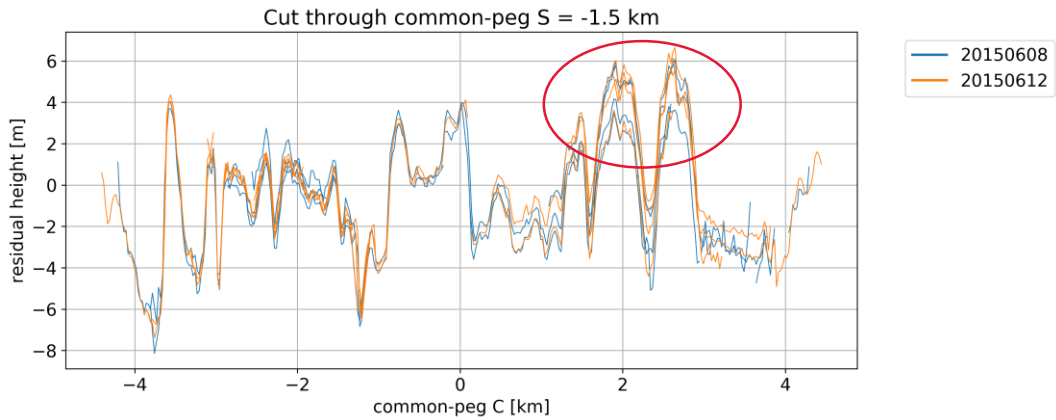




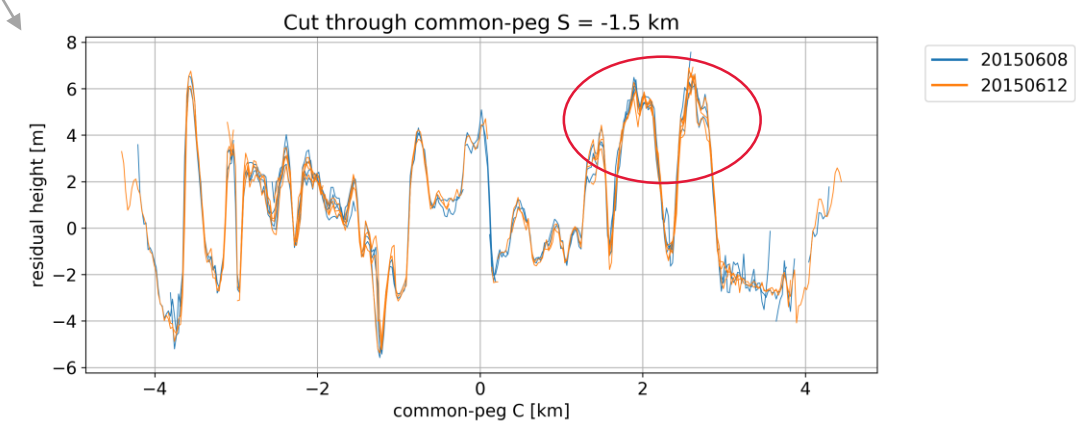
AirSWOT Processing: Phase 3



Before Bundle Adjustment

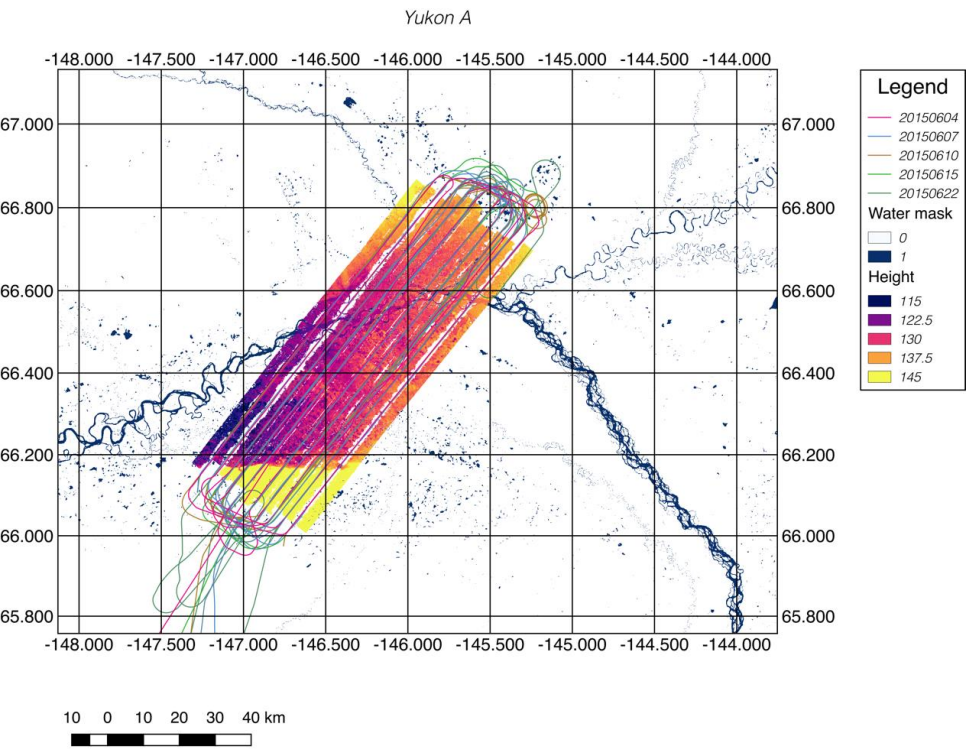


After Bundle Adjustment

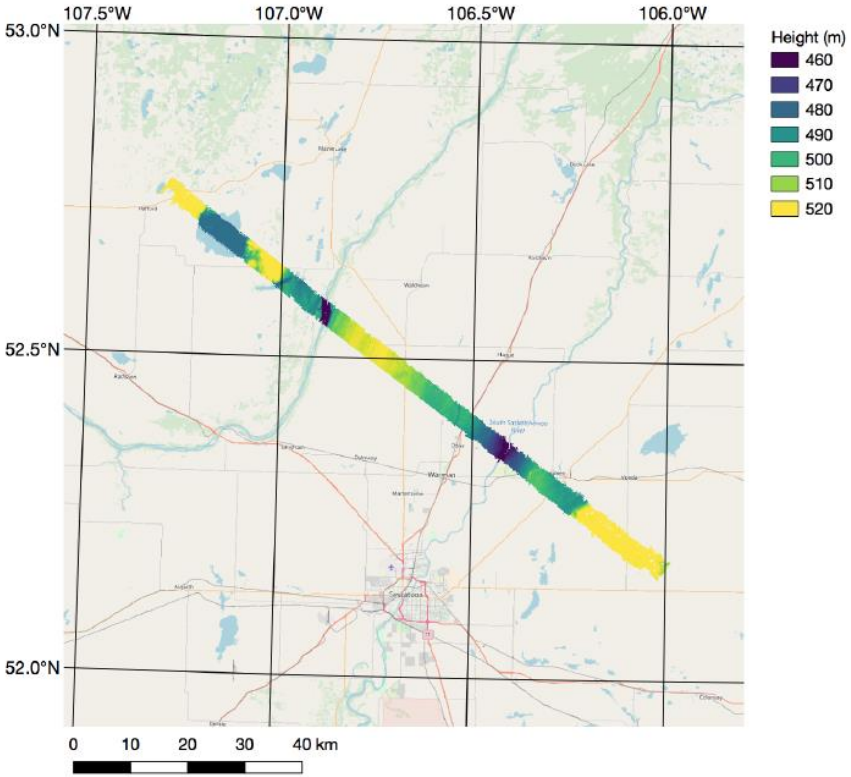


AirSWOT Processing: Final Results

Mosaic of height results from 2015 Yukon, Alaska flights.

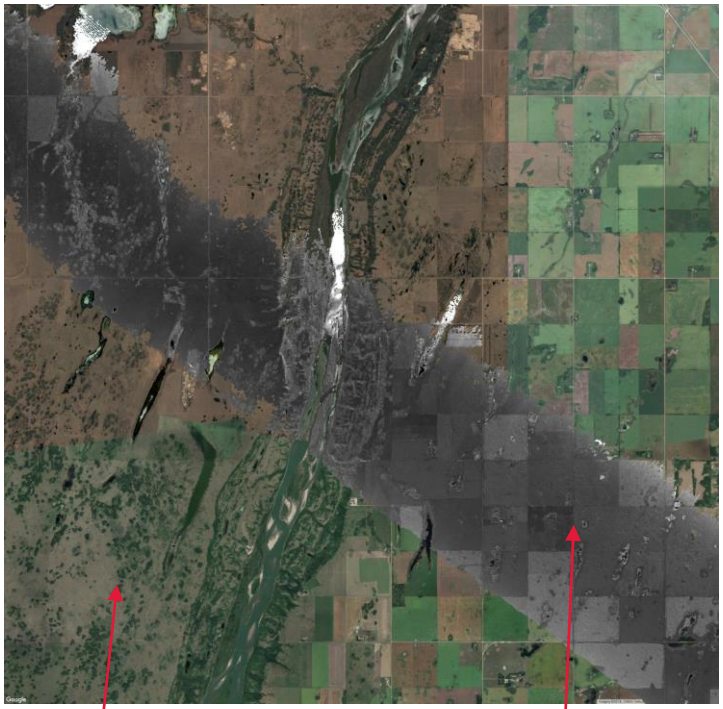


Results from ABoVE 2017 flights, near Saskatoon, Saskatchewan.



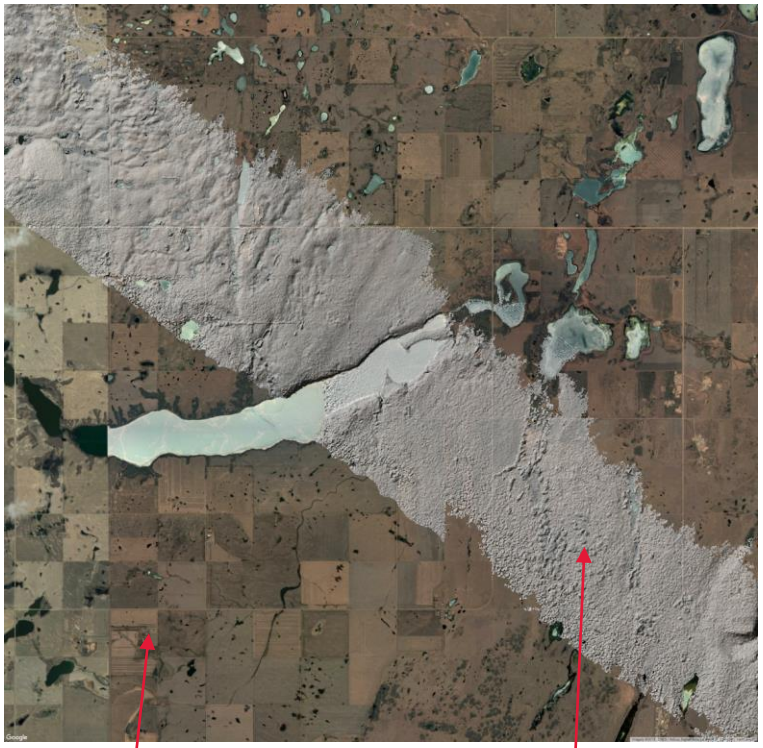
AirSWOT Processing: Final Results

ABoVE 2017, near Saskatoon, Canada



Google Earth imagery

AirSWOT radar backscatter

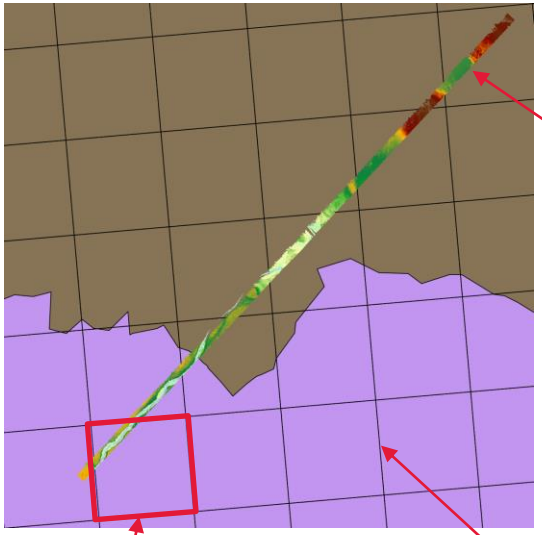


Google Earth imagery

AirSWOT height,
visualized as shaded relief image

ABoVE Deployment Results

- ABoVE processed results will also be distributed in GeoTiff format with the ABoVE standard grid and file-name convention
  - AirSWOT uses ABoVE “C” (fine resolution) tiles
  - Facilitates inter-comparison amongst datasets



AirSWOT image

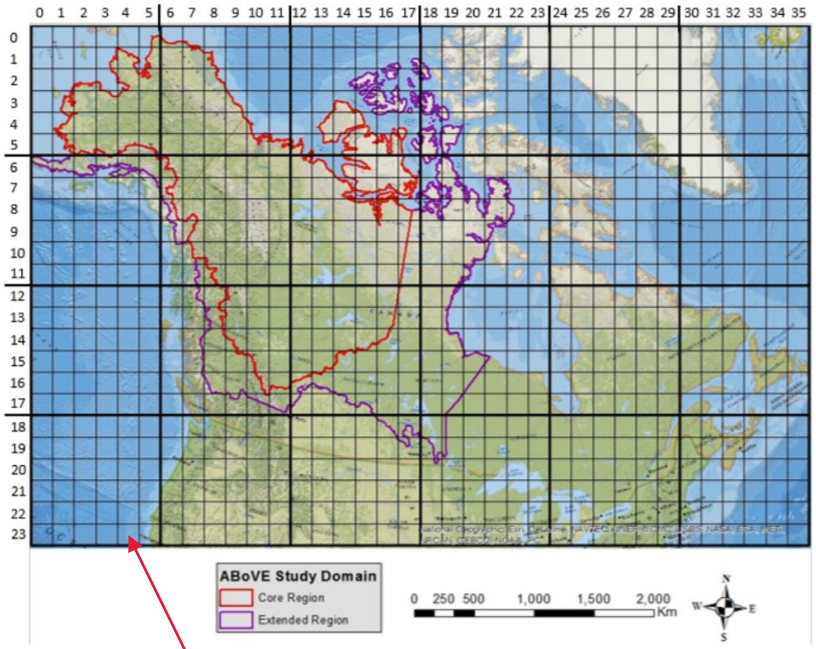
ABoVE “C” tile boundaries

This portion distributed as

ABoVE.AirSWOT_Radar.20170816204931.Ch089v106.001.201809010718.tif

Sensor | Data acquisition time | ABoVE Tile ID | Version | Production Date

ABoVE ”B” grid tiles



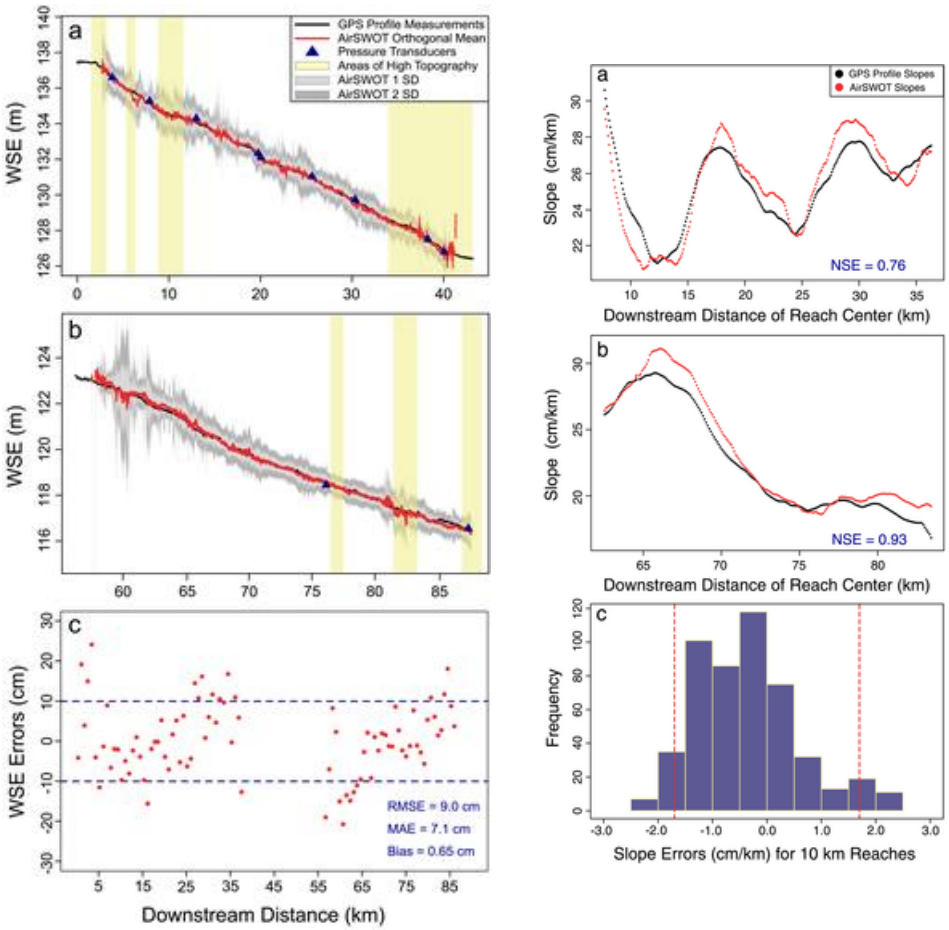
Each moderate resolution “B” tile contains 6x6 fine resolution “C” tiles.

Projection Specifications:
Canada_Albers_Equal_Area_Conic
WKID (EPSG): 102001 Authority: ESRI

Projection: Albers
False_Easting: 0.0
False_Northing: 0.0
Central_Meridian: -96.0
Standard_Parallel_1: 50.0
Standard_Parallel_2: 70.0
Latitude_Of_Origin: 40.0
Linear Unit: Meter (1.0)

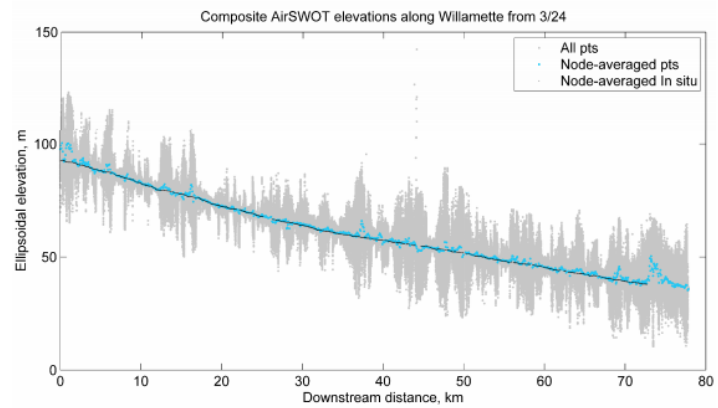
Selected initial science results

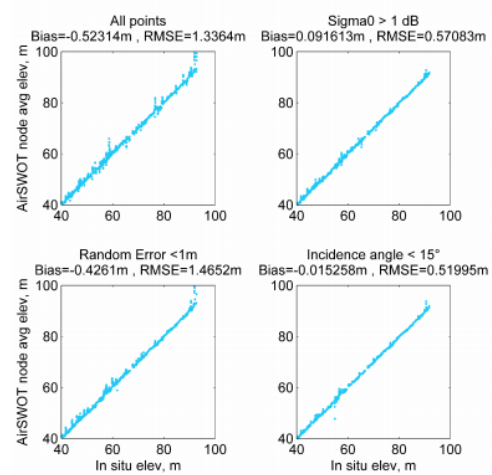
AirSWOT heights vs. in-situ data, Tanana River



E. Altenau et al., "Airswot measurements of river water surface elevation and slope: Tanana river, AK," *Geophysical Research Letters*, vol. 44, pp. 181–189, Jan. 2017.

AirSWOT heights vs. in-situ data, Willamette River

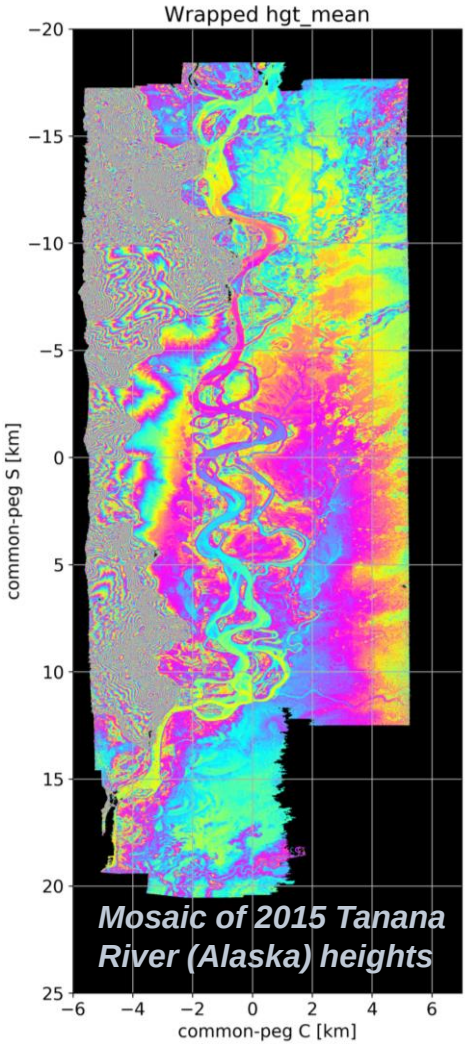




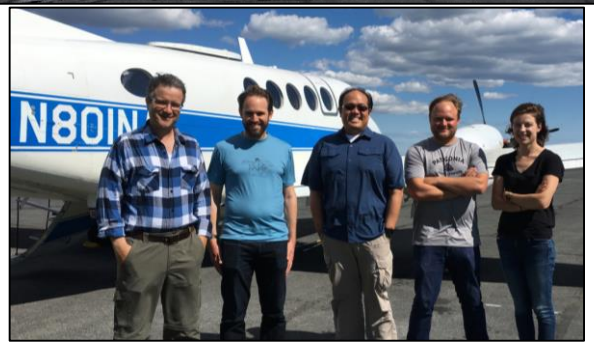
Above, AirSWOT elevations from all flights extracted from river mask and averaged at 1050 'nodes' along the river centerline. At right, in-situ data averaged to the same nodes compared to unfiltered and filtered AirSWOT.

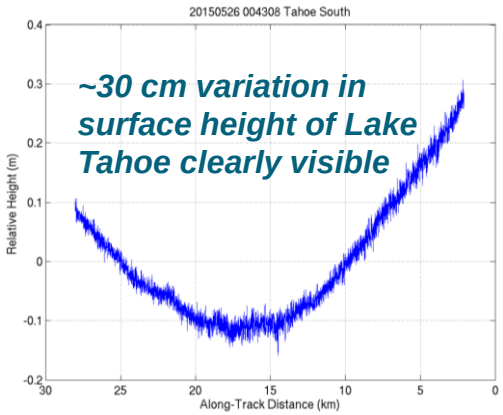
Tuozzolo, S., et al., "Characterizing AirSWOT Elevation Accuracy on the Willamette River, Oregon," presented at AGU Fall Meeting, 13 Dec., 2016.

Questions?



AirSWOT and UAVSAR Deployed in Alaska for ABoVE 2017





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