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Surface Water and Ocean Topography (SWOT) Mission

SWOT Science Team Meeting

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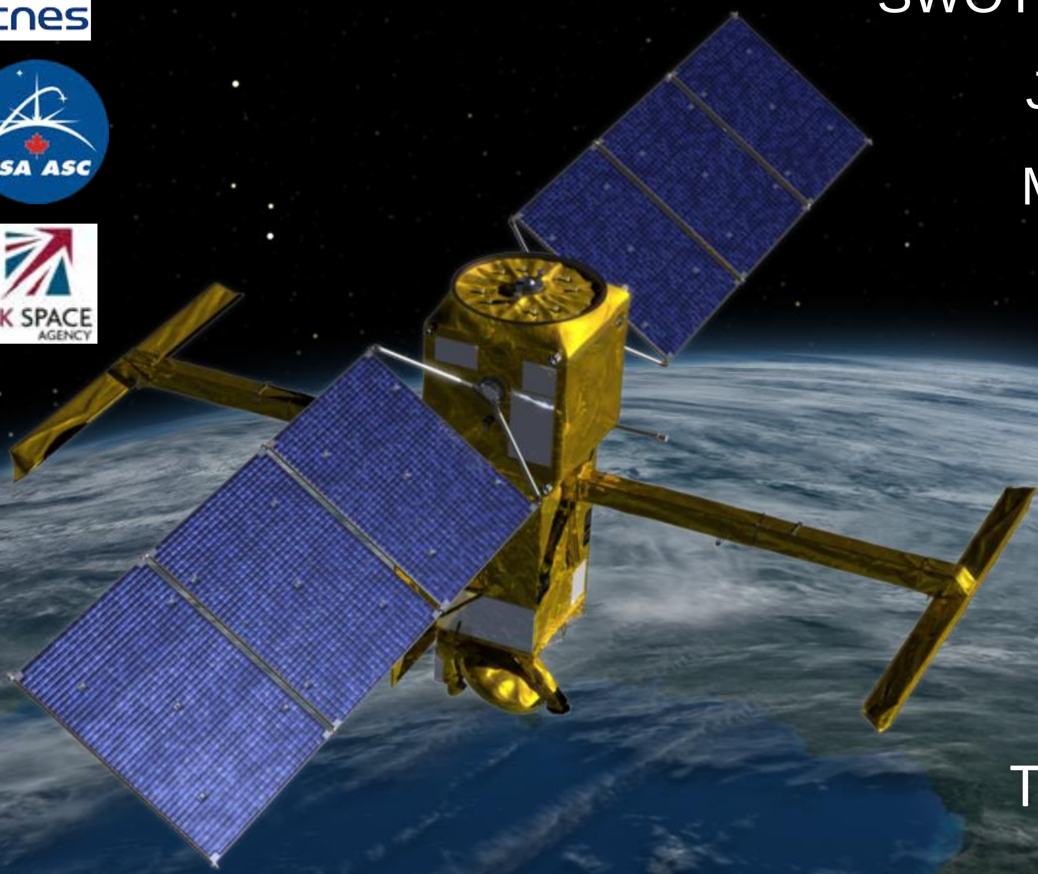
Montreal, Canada



Update on Layover Results

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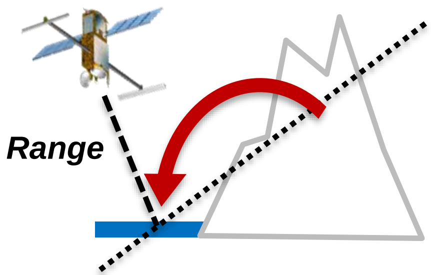
CL#18-3584

Layover Introduction

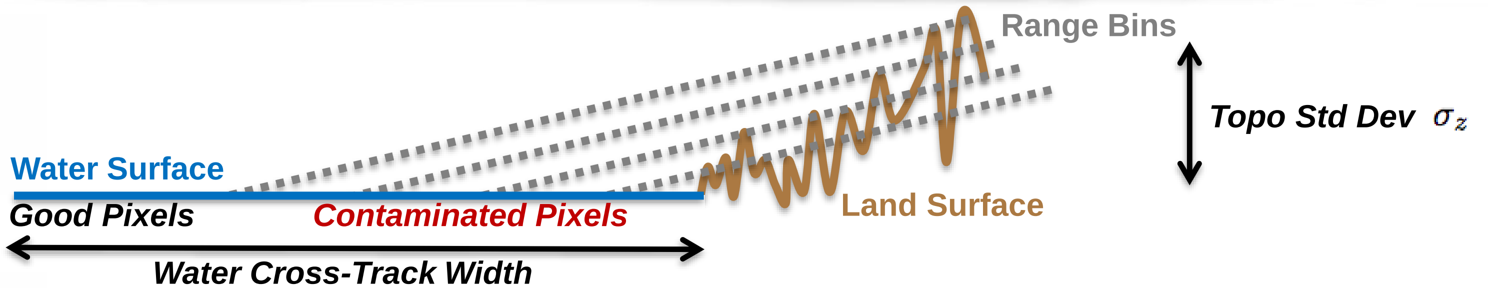


- Layover occurs when topographic variations cause multiple radar pulse echoes from different parts of target surface to arrive simultaneously at radar receiver such that they cannot be distinguished
- Layover is mainly determined by viewing geometry and cannot be feasibly mitigated by changes in instrument hardware or algorithm design
- Layover has been major concern for SWOT hydrology for long time
  - Language had been written into science requirements to exclude layover from performance assessments (requirements not applicable in areas)
  - Project and science community have still been very interested in what effect of layover would be on SWOT science and data interpretability
- This talk summarizes results of recent science assessment of layover impacts on SWOT
  - Development and validation of model for layover-induced measurement errors
  - Quantification of impact of measurement errors on science objectives at continental/global scales

Analytical Layover Model Approach

- Cannot readily evaluate layover impact, including algorithm mitigations, on continental/global scale through direct simulation because coverage of high-fidelity DEMs is insufficient
- Instead, develop analytical model to evaluate on large scales for science assessment
  - Develop model theoretically rather than empirically so model can predict beyond span of simulated data set
  - Must have large-scale knowledge of model input parameters
  - Validate model with direct simulations based on large (but not continental scale) data set of high-fidelity lidar DEMs
  - Model is intended to provide statistical characterization of layover as it impacts science
    - Will not predict errors for given pixel, or possibly even for given reach/lake
    - Only need to capture representative error distribution, not actual errors
  - Some aspects of model need empirical tuning (algorithm detection performance, twiddle factors, etc.)

Key Analytical Model Parameters



- Roughness metric as parameter for describing topography (SRTM):
  - We do not need to model layover error exactly for each precise location on ground (ie, each pixel) because hydro processing averages over wide areas anyway
  - Analytical model is intended to give statistical characterization of layover error, not prediction of error for specific pixels
  - Standard deviation of topographic heights over local window (e.g., 1x1 km box) is relatively robust parameter over quality of different DEMs
- Cross-track width of water body (GRWL):
  - Mapping of topography into slant plane gives cross-track projection
  - For rivers, first-order quantity of interest is river width divided by sinϕ, where ϕ is river flow direction relative to cross-track direction
- Imaging geometry and measurement parameters (various sources):
  - Incidence angle (important for layover geometric mapping)
  - Water/land contrast (to determine relative contribution of land contamination)
  - Resolution (to determine number of looks available for averaging)
- Algorithm flagging performance parameters (false alarm/missed layover detection) are empirically tuned based on simulations

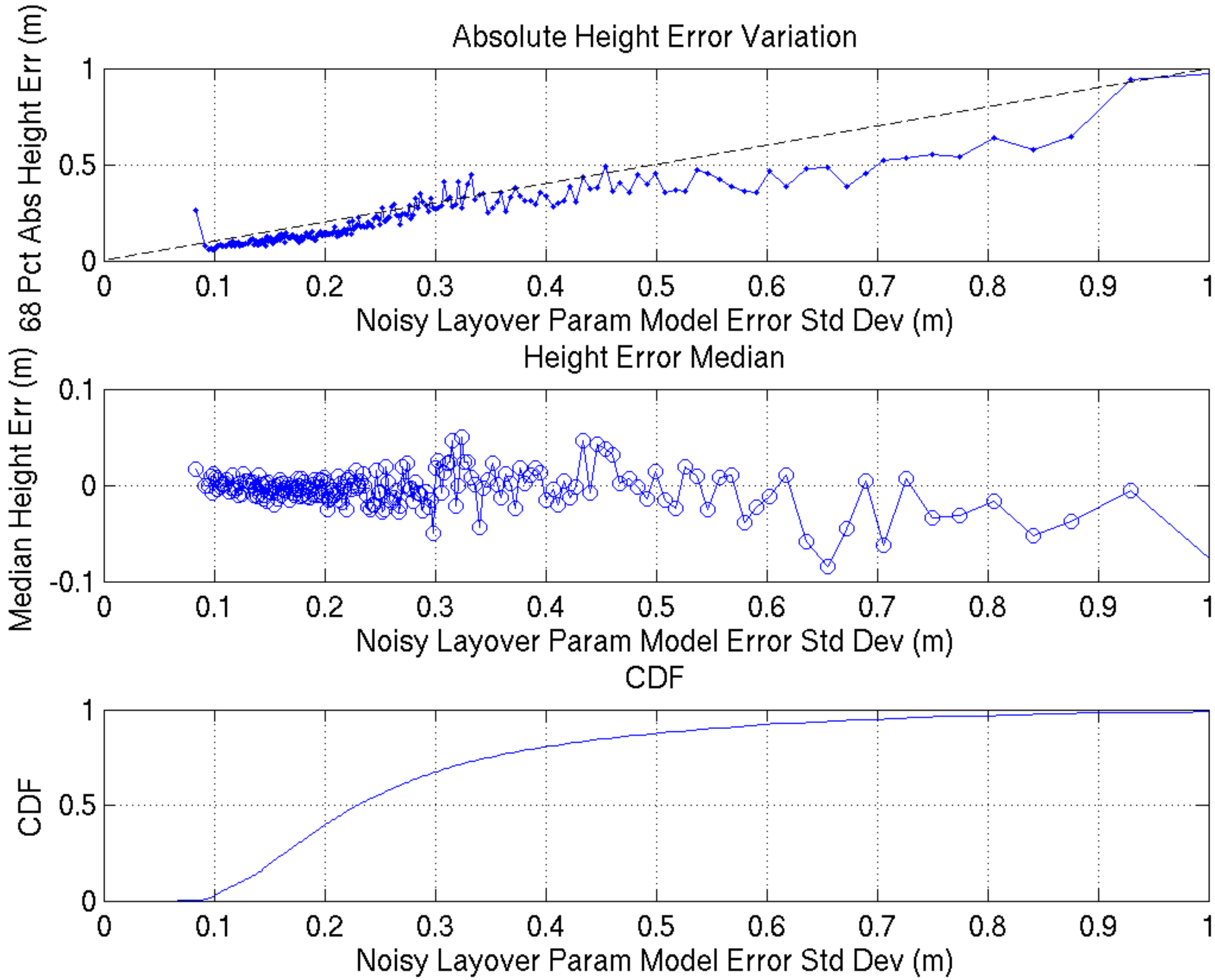
Analytical Model Validation

Plots show node-level layover+noise error (no systematic error); sim 68pct abs height errors are computed over nodes within bins of model error

Model agrees quite well with simulated data over large data set that covers variety of conditions

Details:

- *No-flagging sim case*
- *Model Pm=1, Pfa=0*
- *Model SNR adjusted -3 dB vs. SWOT estimate since simulation was pessimistic*



Layover Impact on Science: Objectives

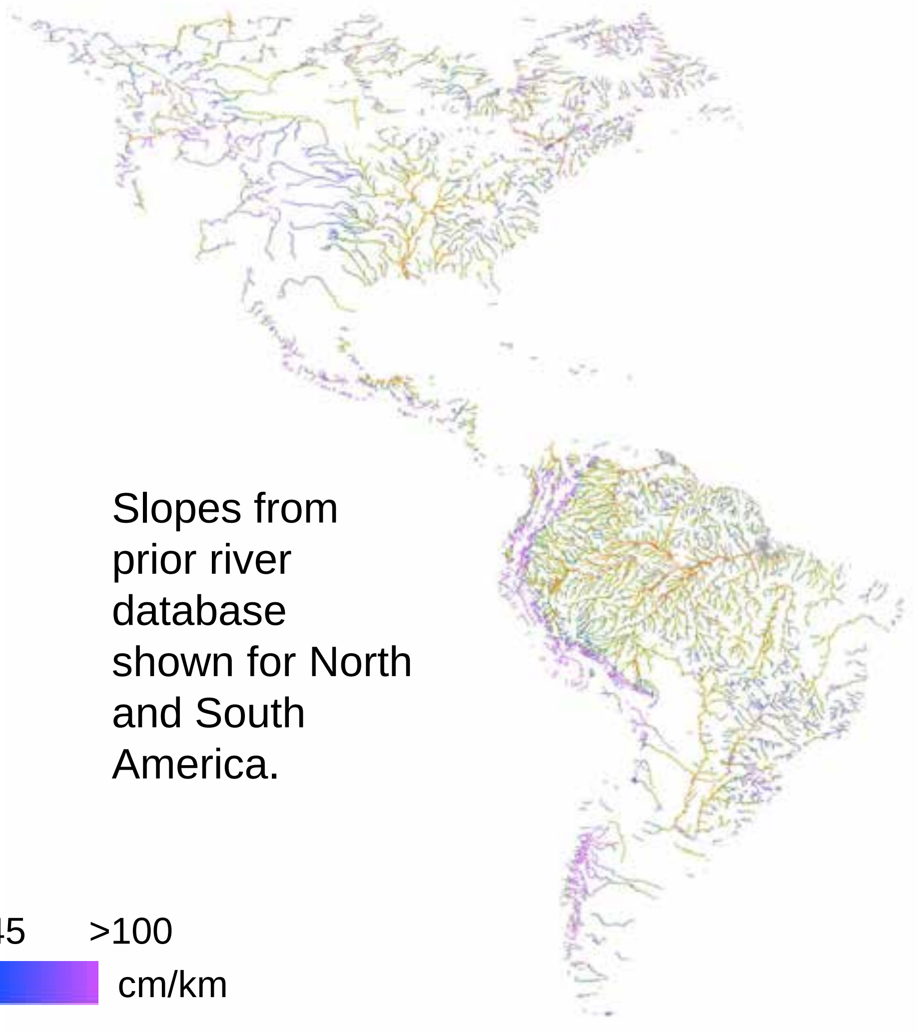
- In response to Standing Review Board request to evaluate impact of layover errors on hydrological science, JPL developed and validated a conceptual model for predicting layover errors as a function of topographic variability.
- We apply this model to global river reaches using SRTM topographic variability and the SWOT a priori river dataset. We predict height and slope uncertainty with and without layover
- We assess the overall impact on science by propagating these errors to discharge uncertainty, assessing how layover impacts SWOT ability to estimate discharge
- We evaluate the impact of layover by comparing height, slope, and discharge errors with and without layover.

Model inputs: Topographic roughness from SRTM

- Topographic roughness is assessed using topographic standard deviation ($\widetilde{\sigma_z}$) measured from SRTM over 1 km x 1 km areas.
- Values of $\widetilde{\sigma_z}$ range from 1 m to ~100 m over the entire SRTM database. Examples shown at right

Model inputs: SWOT prior river database

- SWOT prior river database (UNC) covers all rivers greater than ~90 m in width, between ±60° latitude
- Database includes ~1E6 nodes, ~200,000 reaches, and includes SRTM height & slope, Landsat width, etc.
- Each reach is connected with a 1 km^2 area; $\widetilde{\sigma_z}$ and width give node & reach height & slope error estimates

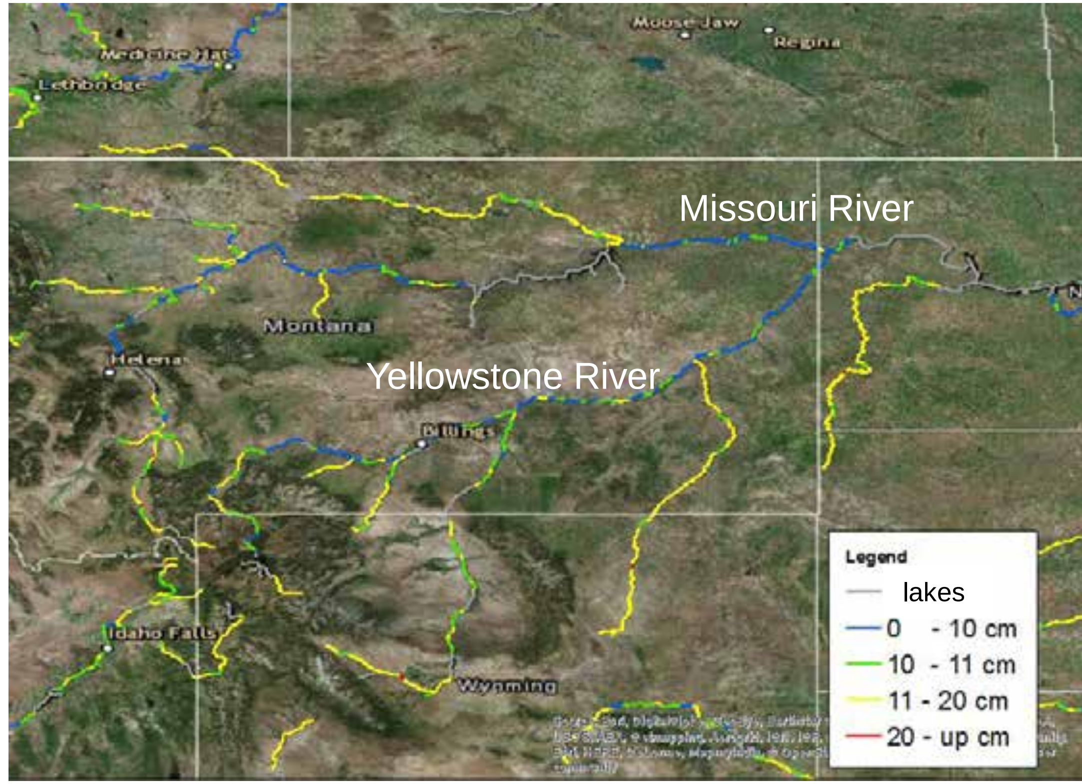


Slopes from prior river database shown for North and South America.

0 5 15 45 >100 cm/km

Example reach height errors

- Height uncertainty at reach-scale (~10 km)
- Errors are primarily controlled by width: mainstem Missouri & Yellowstone are generally lowest error class, narrower rivers have higher errors.
- $\widetilde{\sigma_z}$ generally less important than width in governing height errors

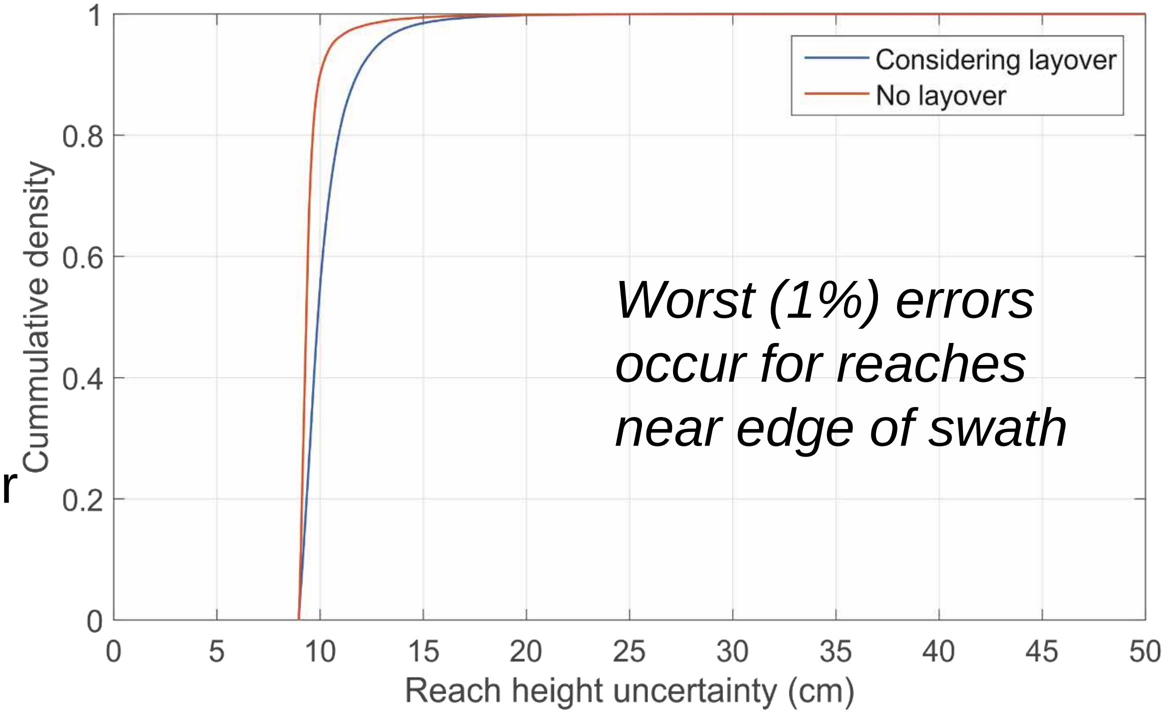


Example errors in the upper Missouri River basin. Each reach displays the minimum observation error across all passes

Global reach height errors

- All reaches & passes merged to assess global error characteristics
- Height errors increase minimally: 68th percentile increases from 9.4 to 10.4 cm
- Reaches with height error <10 cm decreases from 95% to 60% due to layover
- The impact of a 1-2 cm increase on discharge science is minimal (shown in later slides)

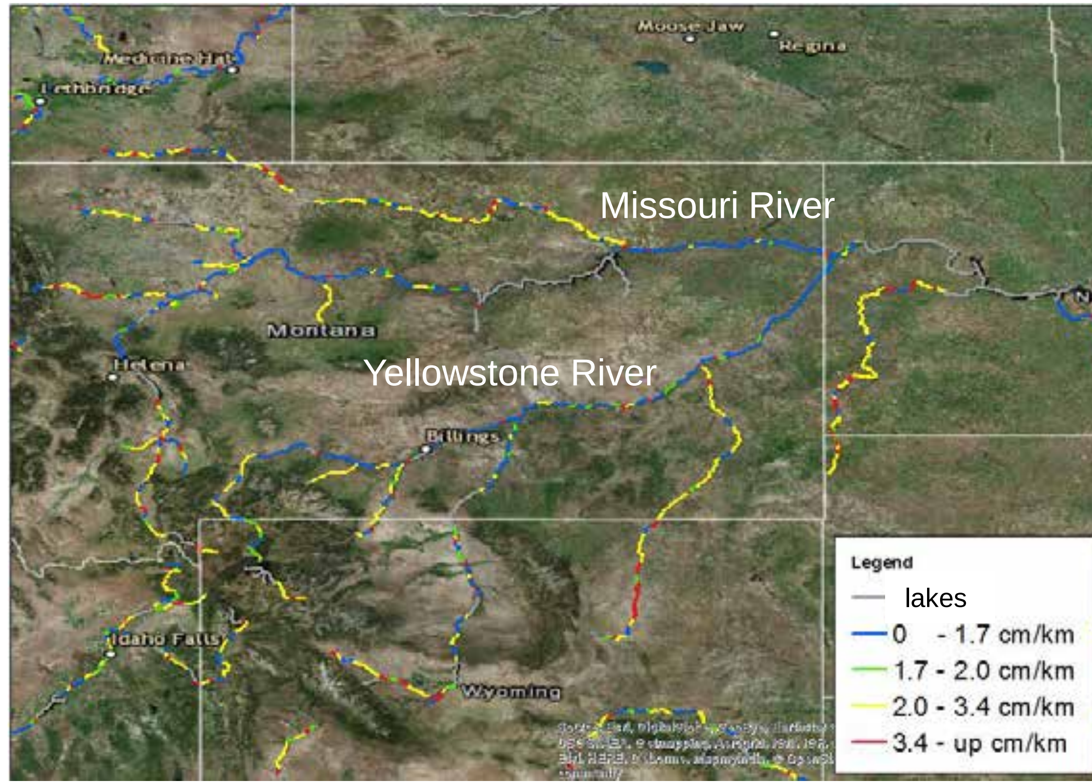
Height errors without layover are very close to science requirement of 10 cm for a 100 m river.



Minimum value: ~9.0 cm occurs in wide reaches where a large number of pixels results in low KaRIN random error.

Example reach slope errors

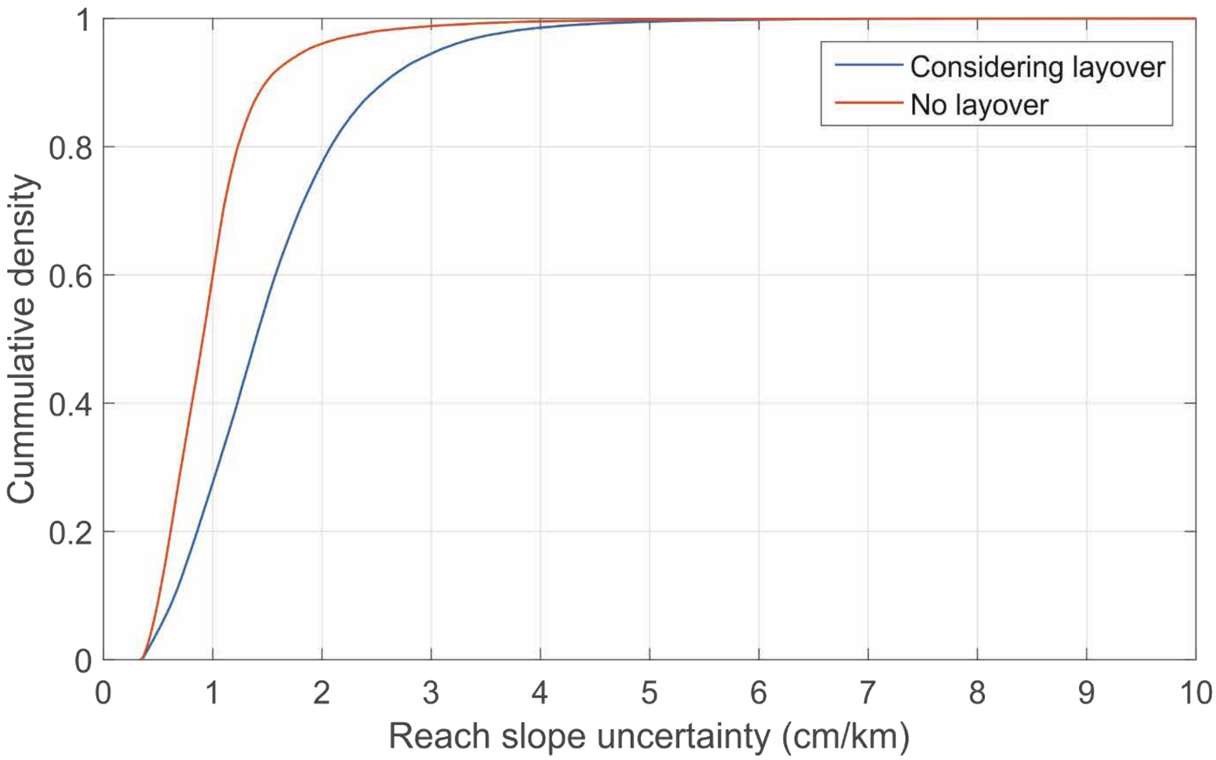
- Slope uncertainty at reach-scale (~10 km)
- Slope errors are controlled by both width and $\widetilde{\sigma_z}$: some parts of mainstem Missouri & Yellowstone have higher errors, while some narrower rivers have lower errors.



Example errors in the upper Missouri River basin. Each reach displays the minimum observation error across all passes

Global reach slope errors

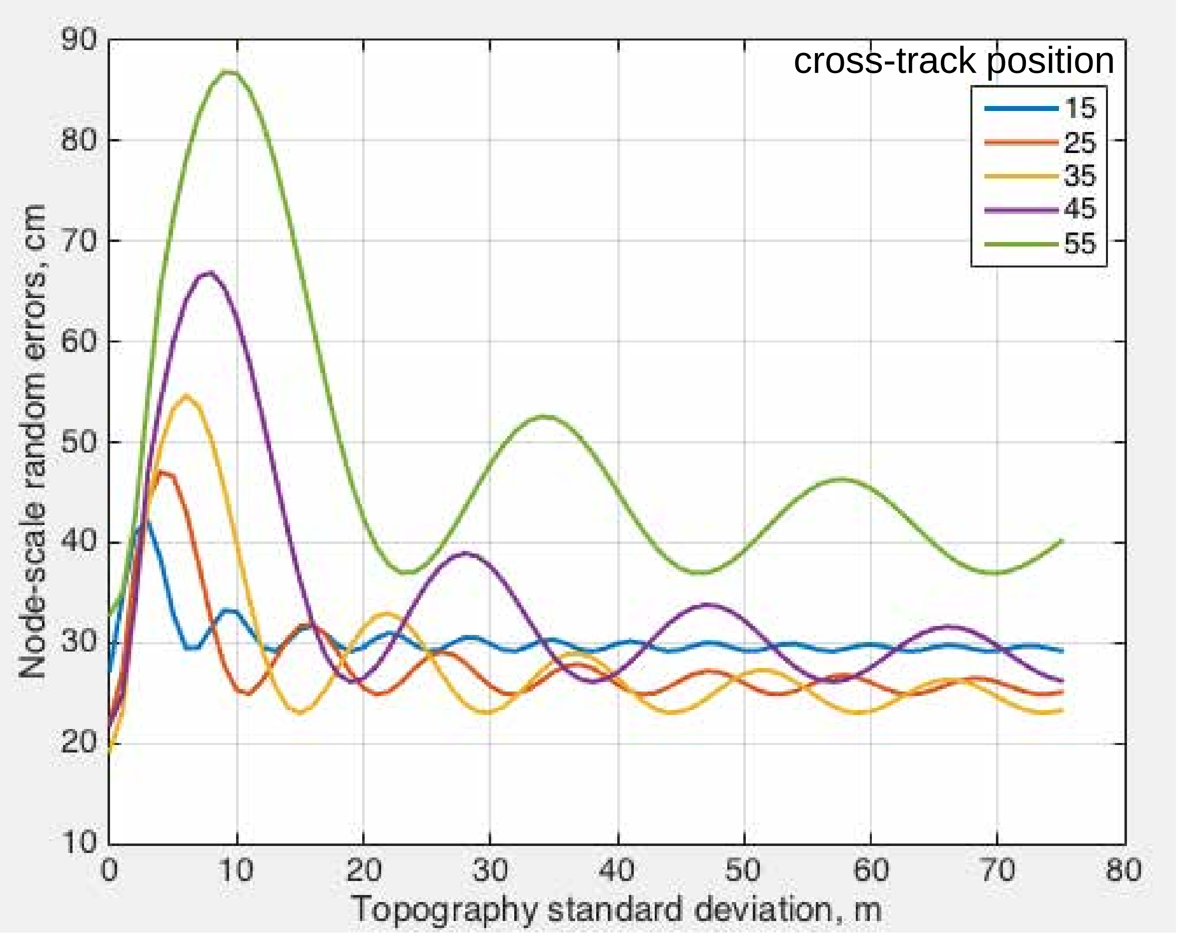
- Slope errors increase moderately: 68th percentile increases from 1 cm/km to 1.7 cm/km.
- Reaches with slope errors < 1.7 cm/km decreases from 90+% to 68% due to layover
- Even considering areas of high layover, which we don't have to consider, we likely meet the SRD requirements.



Later slides will address how increased slope uncertainty propagates to discharge

Why is Layover Impact Not Worse?

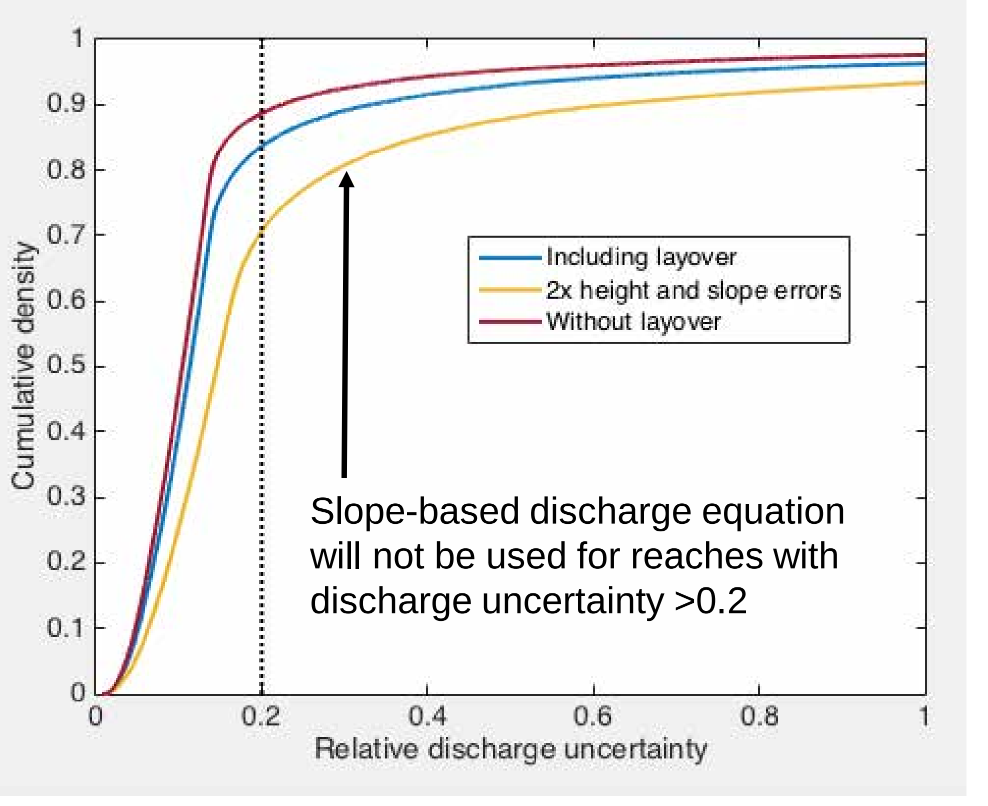
- As phase wraps, layover error becomes increasingly stochastic at the reach level
- Counterintuitively, this may result in a peak in layover impact at a comparatively moderate topographic roughness.



Caveat: these findings depend on an assumption that topographic roughness is evenly distributed between 0 and $\widetilde{\sigma_z}$. This assumption is currently being tested.

Global discharge uncertainty

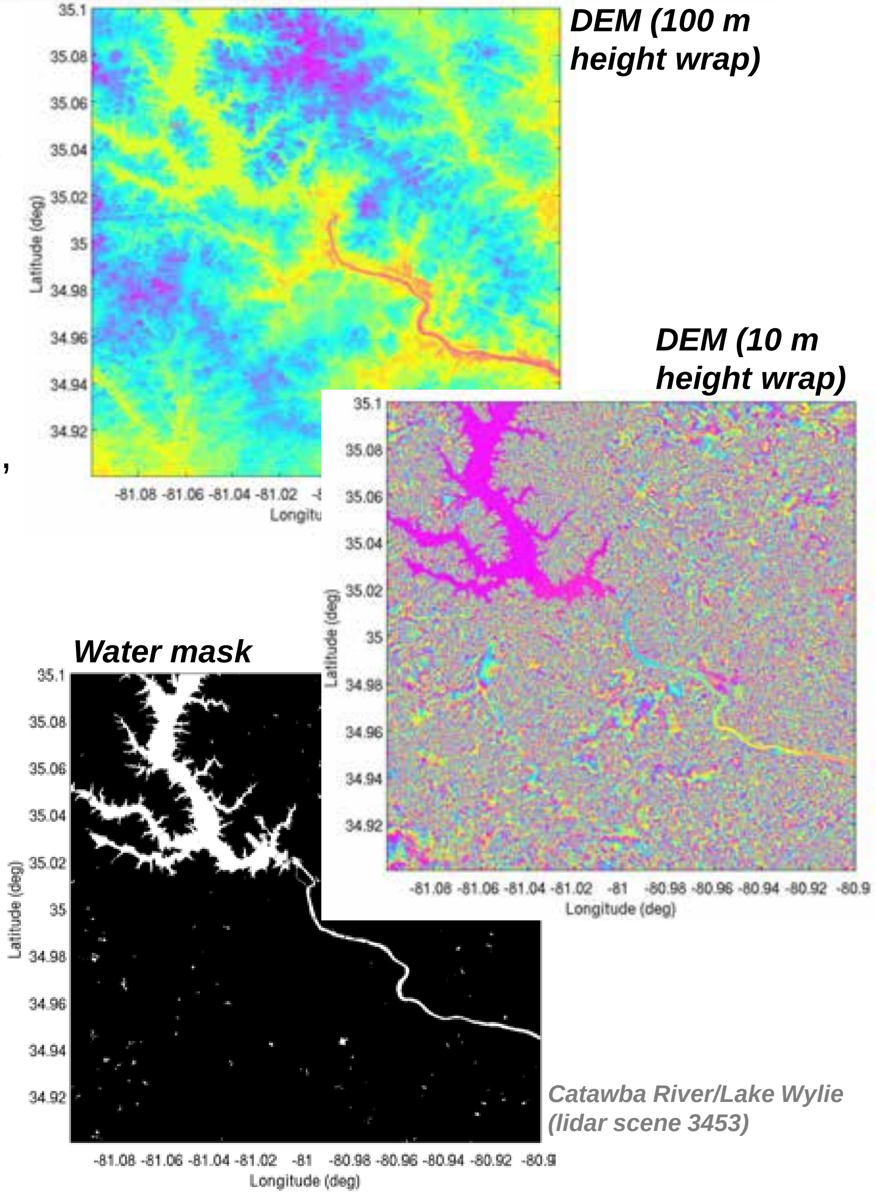
- Discharge errors increase minimally: 68th percentile increases from 12% to 13%
- Layover increases the number of reaches for which slope errors will be too high to use Manning's equation: from 12% to 17% of total reaches. Height and width alone will be used to estimate discharge for these reaches.
- Doubling layover-induced height and slope errors results in further degradation, though ~70% of reaches retain discharge uncertainty <0.2



Algorithms to estimate discharge without slope exist. The discharge algorithm working group will test these approaches for cases with higher layover error.

Key Takeaways on How Layover Typically Affects SWOT Measurement

- **Layover causes primarily random errors (biases are small)**
  - Competing layover echoes are typically large enough to wrap phase and look random at SWOT averaging scales
- **Magnitude of errors due to layover is significant, but not dominating**
  - Land is usually much darker than water, so layover contamination is smaller than desired water signal (on average)
- **Layover errors will vary with site**
  - Analysis here describes "average" behavior, but different sites will experience different errors
    - ♦ Higher/lower magnitude of random error
    - ♦ Higher/lower spatial correlation of errors
- **Layover effects will be widespread, but with relatively low magnitude**



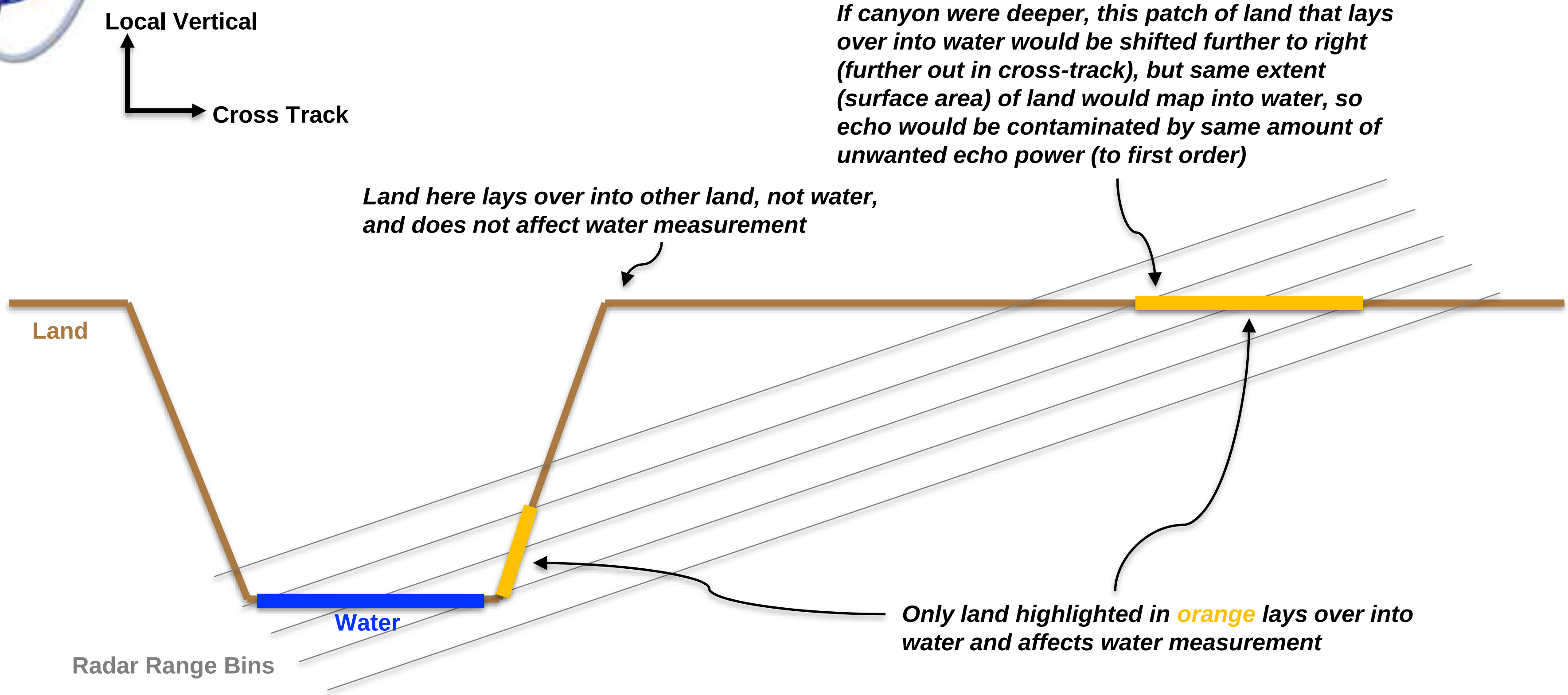
Catawba River/Lake Wylie (lidar scene 3453)

Backup

Next Steps on Layover

- **Layover Impacts on Lakes**
  - Preliminary analysis conducted by Y. Sheng suggests small impact on lakes larger than 1 km^2, moderate impact on smaller lakes.
  - More robust analysis will be possible using LOCNES (lake equivalent of RiverObs).
- **Analysis of Extreme Cases**
  - Ongoing analysis at JPL examines the case of the Colorado River in the Grand Canyon. Results will help assessment of layover impact in areas of extreme topography.
- **Inversion of Unknown Parameters for Discharge**
  - Analysis of discharge errors from layover currently only includes direct impacts on height and slope.
  - Impacts on inversion of unknown parameters remains unknown and will require further analysis.

Grand Canyon Illustration



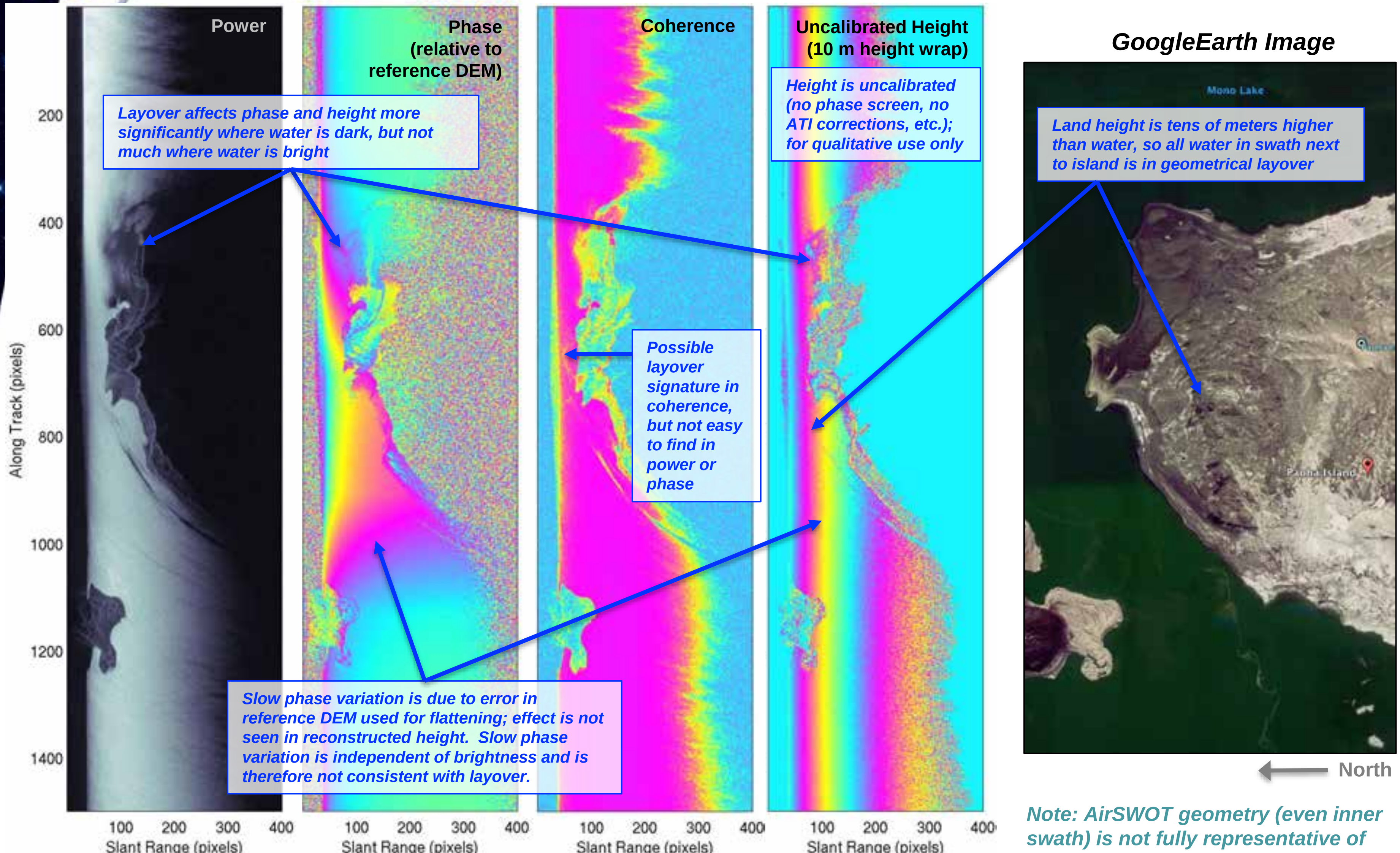
Degree of layover contamination is determined by (1) power of undesired land echo relative to desired water echo and (2) phase of undesired land echo relative to desired water echo. Increasing canyon depth does not change land power contribution. Increasing canyon depth beyond ambiguity height (height for phase wrap) does not increase relative phase difference, on average; increased height variation distributes phase over 0-2pi so that layover gives random error that averages out rather than bias.

At steep SWOT incidence angles of ~ 1 to 4 deg, "canyon" depth to put 100 m wide river completely in layover is only w*tan(theta_inc) = 1 to 7 m (!); ambiguity height is 10-60 m, increasing roughly linearly over swath from near to far.

At some point, making terrain more rugged just causes more land-land layover, which we don't care about.

AirSWOT Layover Signature Example

AirSWOT inner swath (SWOT-like incidence angles) from Mono Lake



Note: AirSWOT geometry (even inner swath) is not fully representative of SWOT for layover due to shorter range

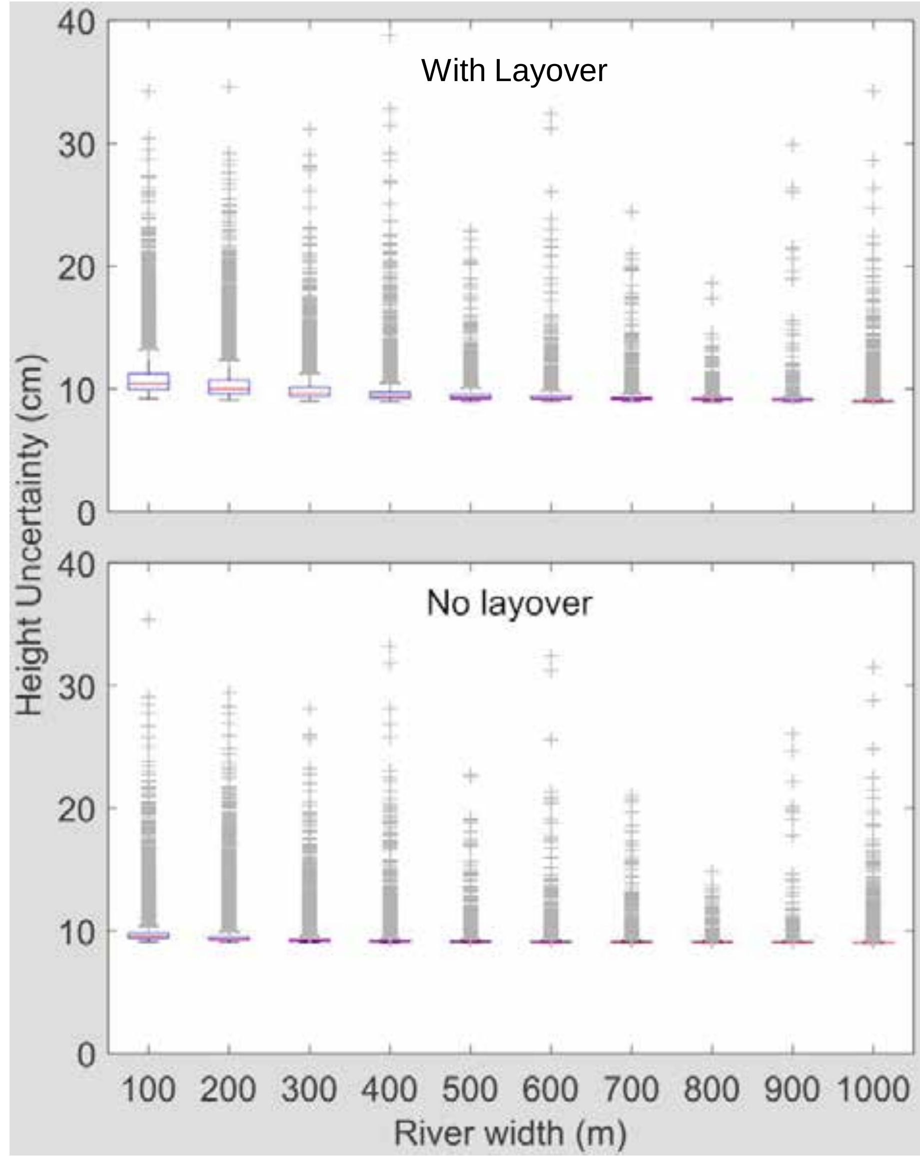
AirSWOT data: 20160416 214905 m3

Estimating discharge uncertainty

- River discharge (Q) using Manning's equation is given by: $Q = \frac{1}{\boldsymbol{n}}(\boldsymbol{A_0} + \delta A)^{5/3} W^{-2/3} S^{1/2}$, where n and A_0 are unmeasured parameters (provided by Science Team), $\delta A \approx W \delta H$, and H, W and S are SWOT height, width, and slope
- Here, we assess the direct effect of layover on increases in errors in H and S using error propagation
- As part of future work, we will estimate the indirect effect of layover on ST ability to invert flow equations to obtain estimates of n and A_0.

Global reach height errors

- Even for the narrowest SWOT-observable rivers (100-150 m wide), height errors show minimal change due to layover.
- Height errors for wider rivers do not change appreciably due to layover.



Global reach slope errors

- Narrowest rivers see modest increases in slope error when compared with the no-layover case
- For example, median slope errors for 100-150 m wide rivers increased from ~1.5 to 1.8 cm/km (20%). 75th percentile increased slightly more.