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California Institute of Technology
Pasadena, California

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Advances in Understanding of SWOT Phenomenology

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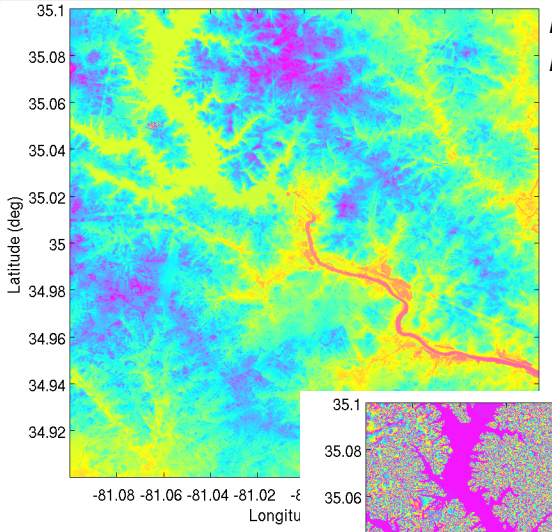
SWOT HR Phenomenology

- Outline:
  - More on layover analysis
  - Dark water update
  - Phase unwrapping introduction (not new, but perhaps useful to discuss)
  - AirSWOT status update

- Material in this package was shameless stolen from many others, including:
  - Albert Chen
  - Michael Denbina
  - Mike Durand
  - Heresh Fattahi
  - Alex Fore
  - Brent Williams
  - Xiaoqing Wu

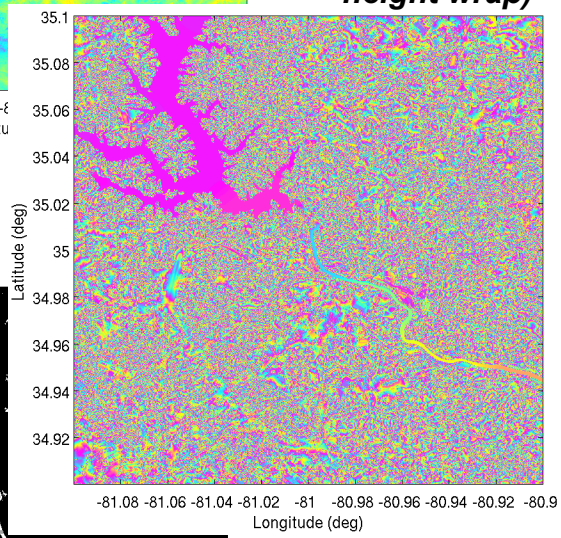
Key Takeaways on How Layover Typically Affects SWOT Measurement

- **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**

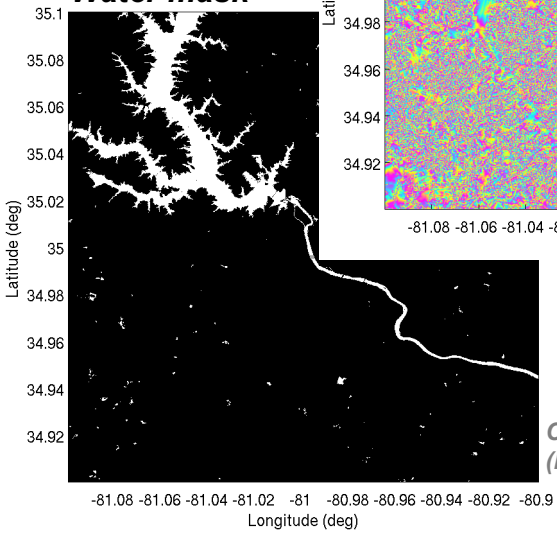


DEM (100 m height wrap)

DEM (10 m height wrap)



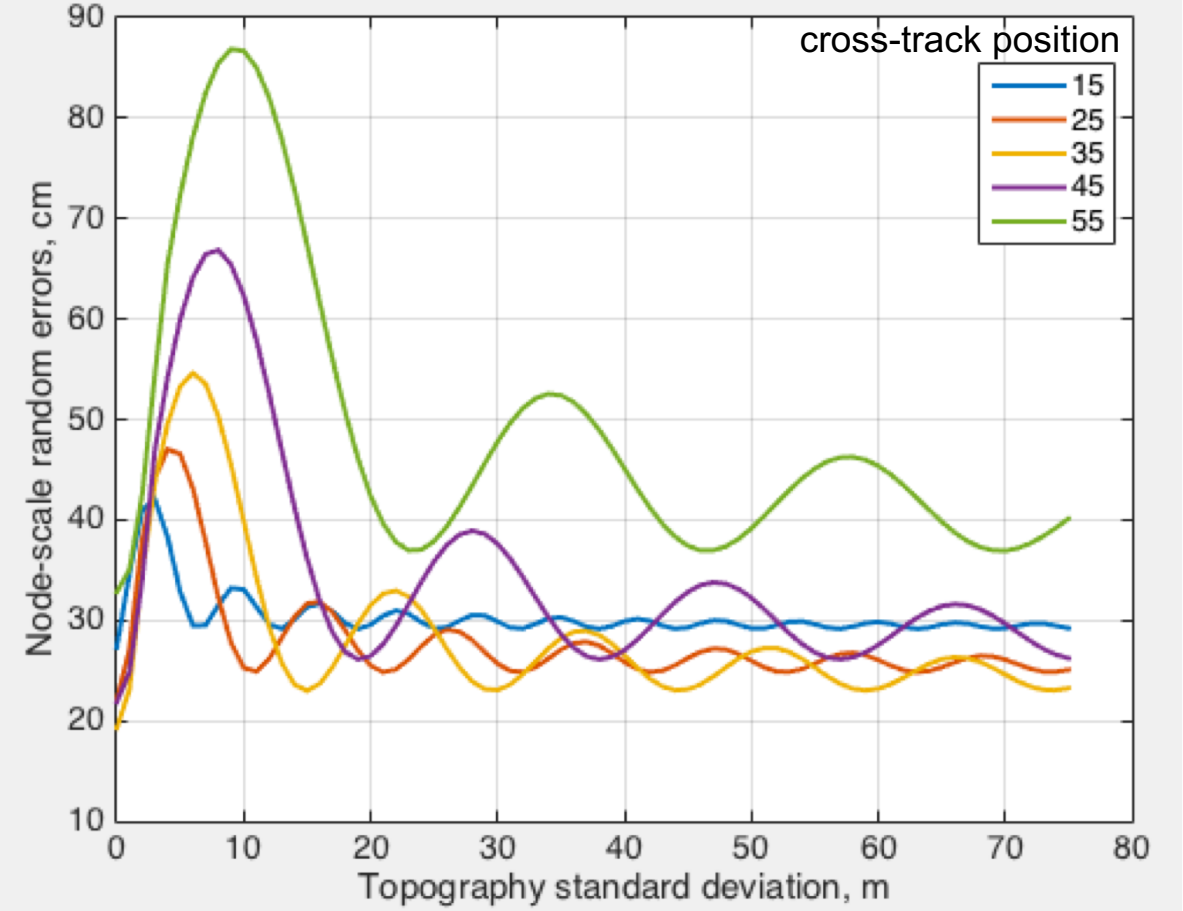
Water mask



Catawba River/Lake Wylie (lidar scene 3453)

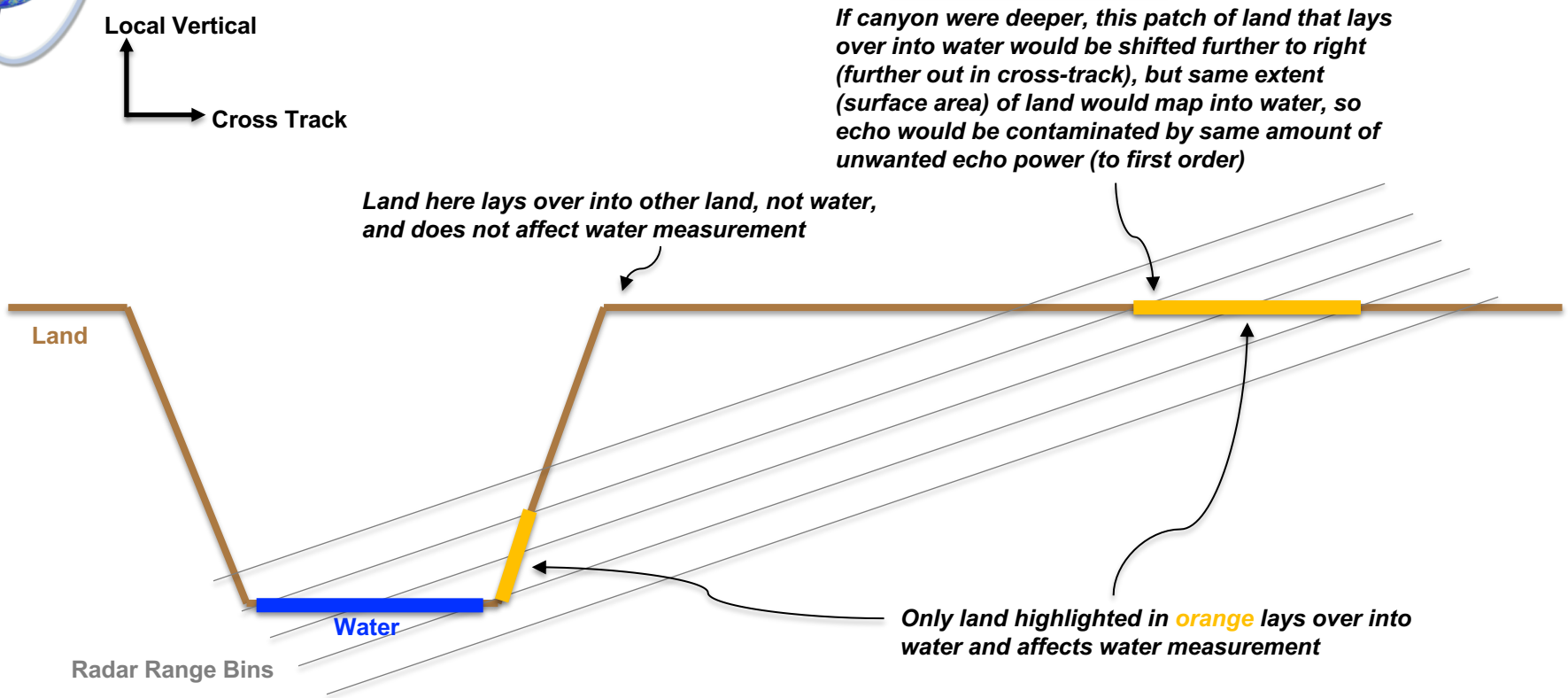
Why is Layover Impact Not Worse?

- 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.

Grand Canyon Illustration



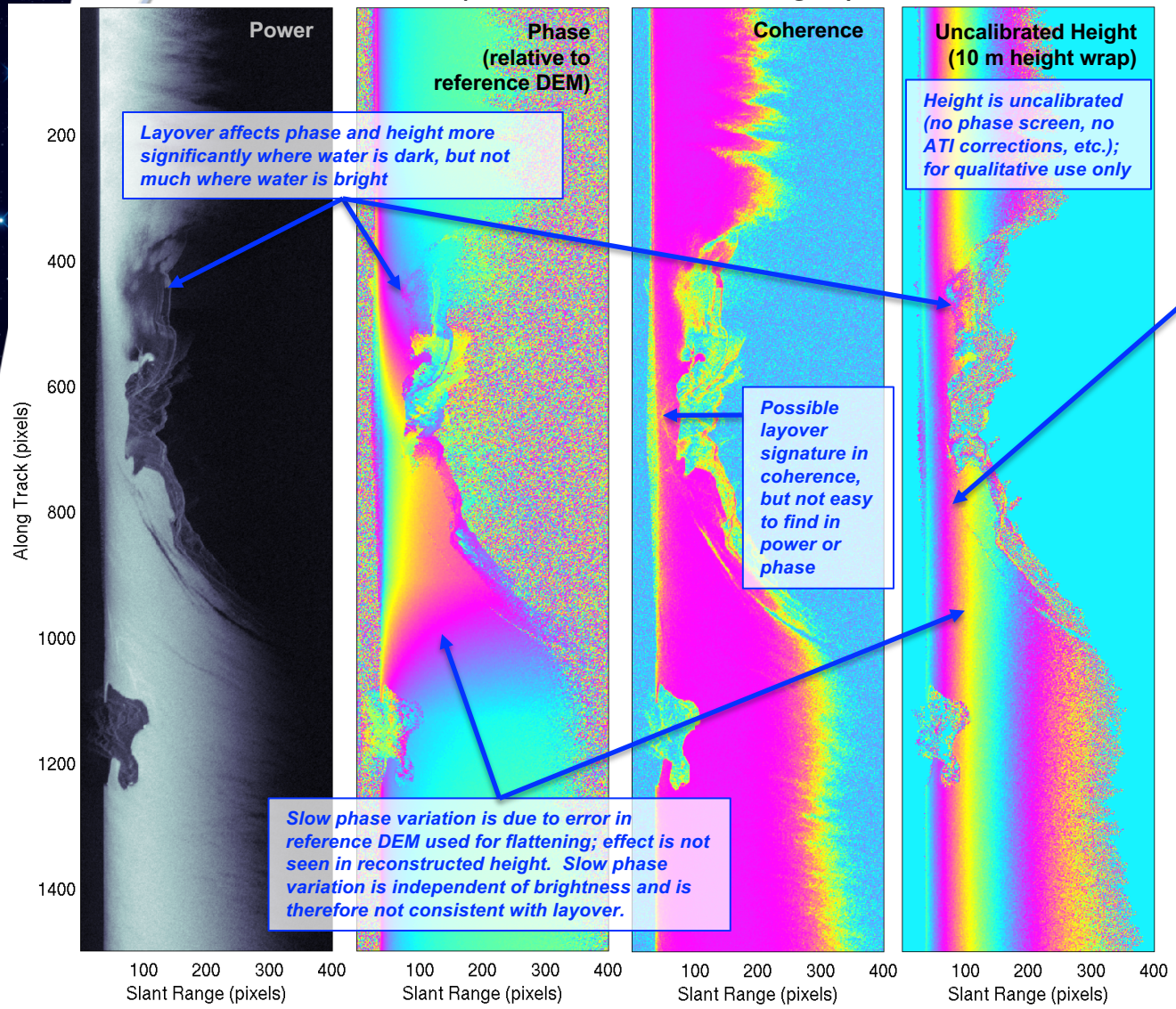
Degree of layover contamination is determined by (1) power of undesired land echo relative to desired water echo and (2) phase of undesired land echo relative to desired water echo. Increasing canyon depth does not change land power contribution. Increasing canyon depth beyond ambiguity height (height 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.

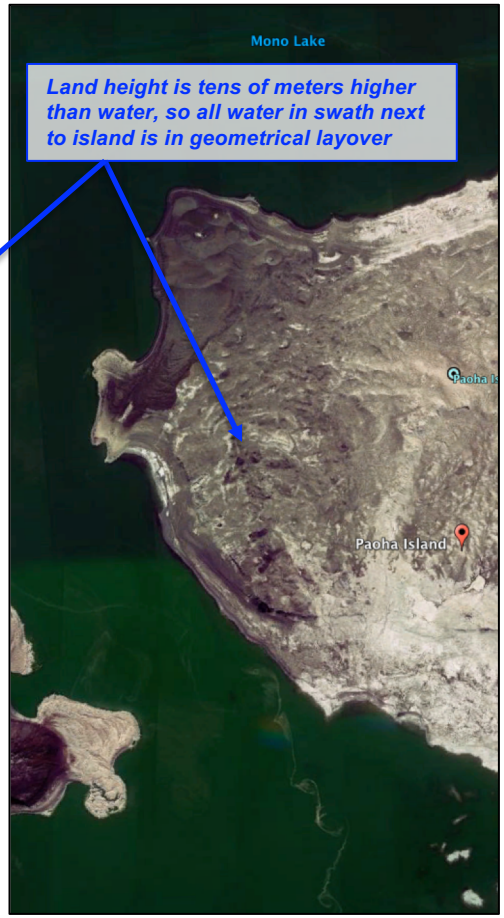
AirSWOT Layover Signature Example

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



AirSWOT data: 20160416 214905 m3

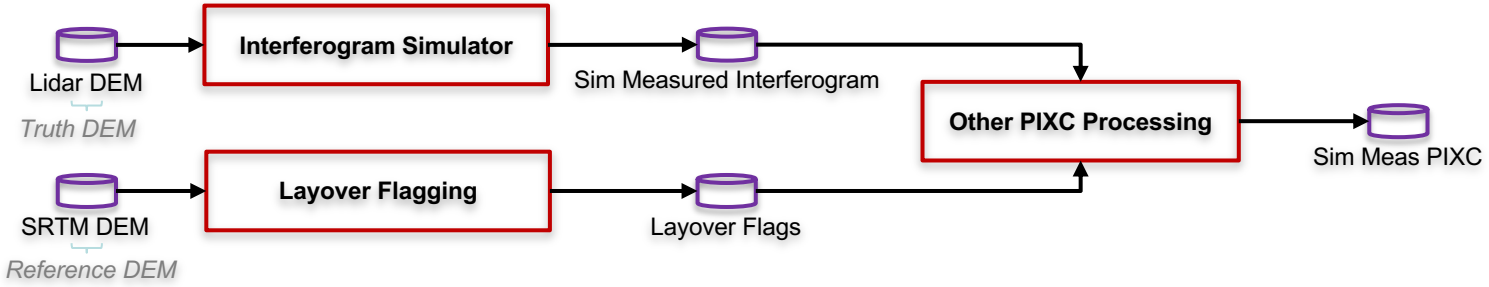
GoogleEarth Image



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

Layover Flagging Approaches

- Data-driven approaches:
  - Investigated but abandoned because effects of layover are too subtle
    - Layover effects are hidden in other random noise
    - Can perhaps identify visually if know where to look, but automated algorithm would not be able to detect layover robustly
  - Corollary: Layover does not actually contribute that much error on average since land is much darker than water
- Approaches based on prior data (DEM, sigma0 knowledge):
  - Flag and discard pixels where predicted layover error from simulation exceeds threshold
    - Zero threshold gives geometric flagging; infinite threshold gives no flagging
    - Discard layover pixels for height estimation, but keep for area estimation
  - In order to evaluate, must simulate observations with high-fidelity (e.g., lidar) truth data and run prototype processing with lower-fidelity reference DEM (e.g., SRTM)
    - Would not be fair assessment to use truth DEM as reference DEM
    - Assessments limited to areas where high-fidelity DEMs are available



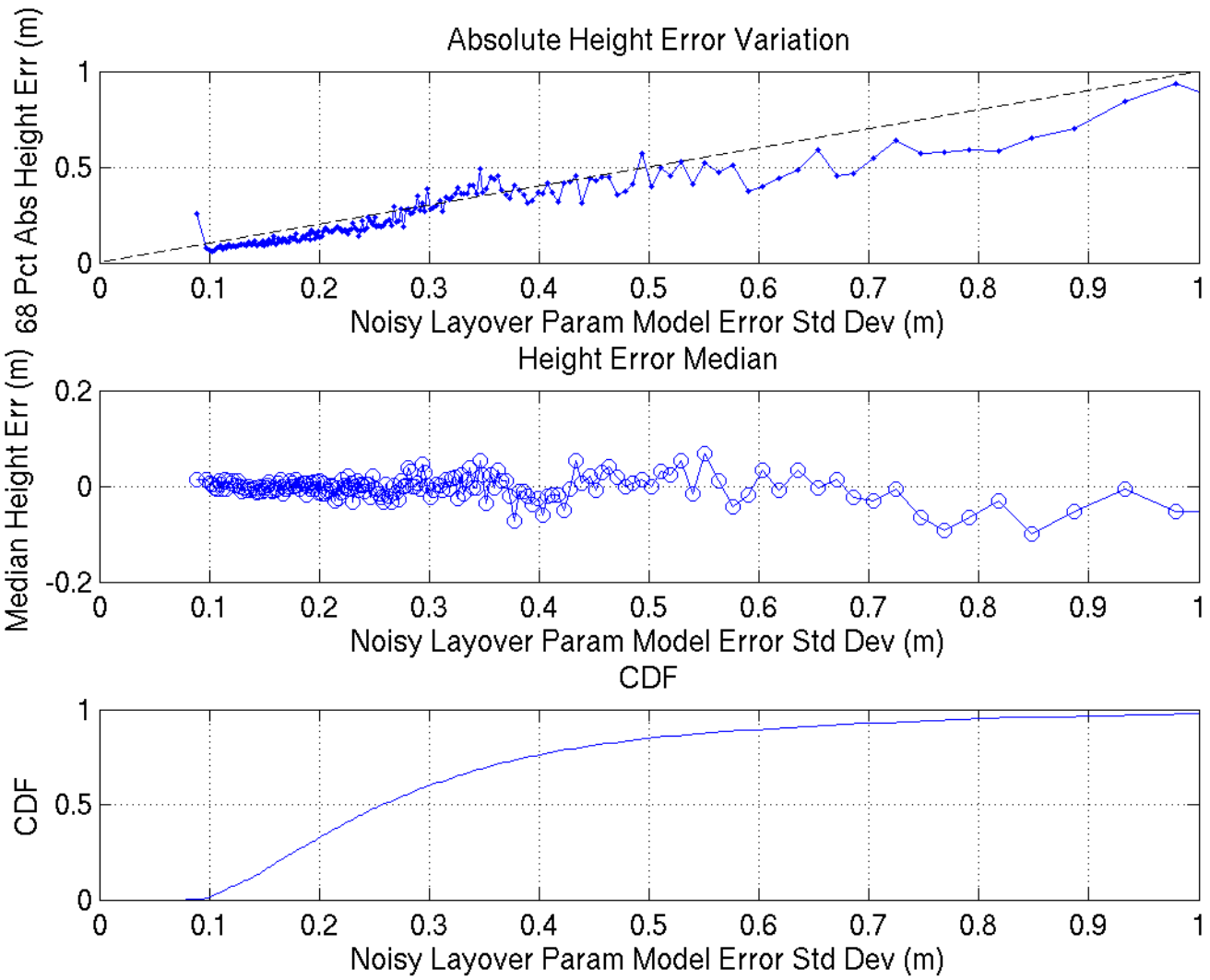
Model Validation for Flagging Case

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:

- *With-flagging sim case*
- *Model Pm=0.53, Pfa=0.09*
- *Model SNR adjusted -3 dB vs. SWOT estimate since simulation was pessimistic*



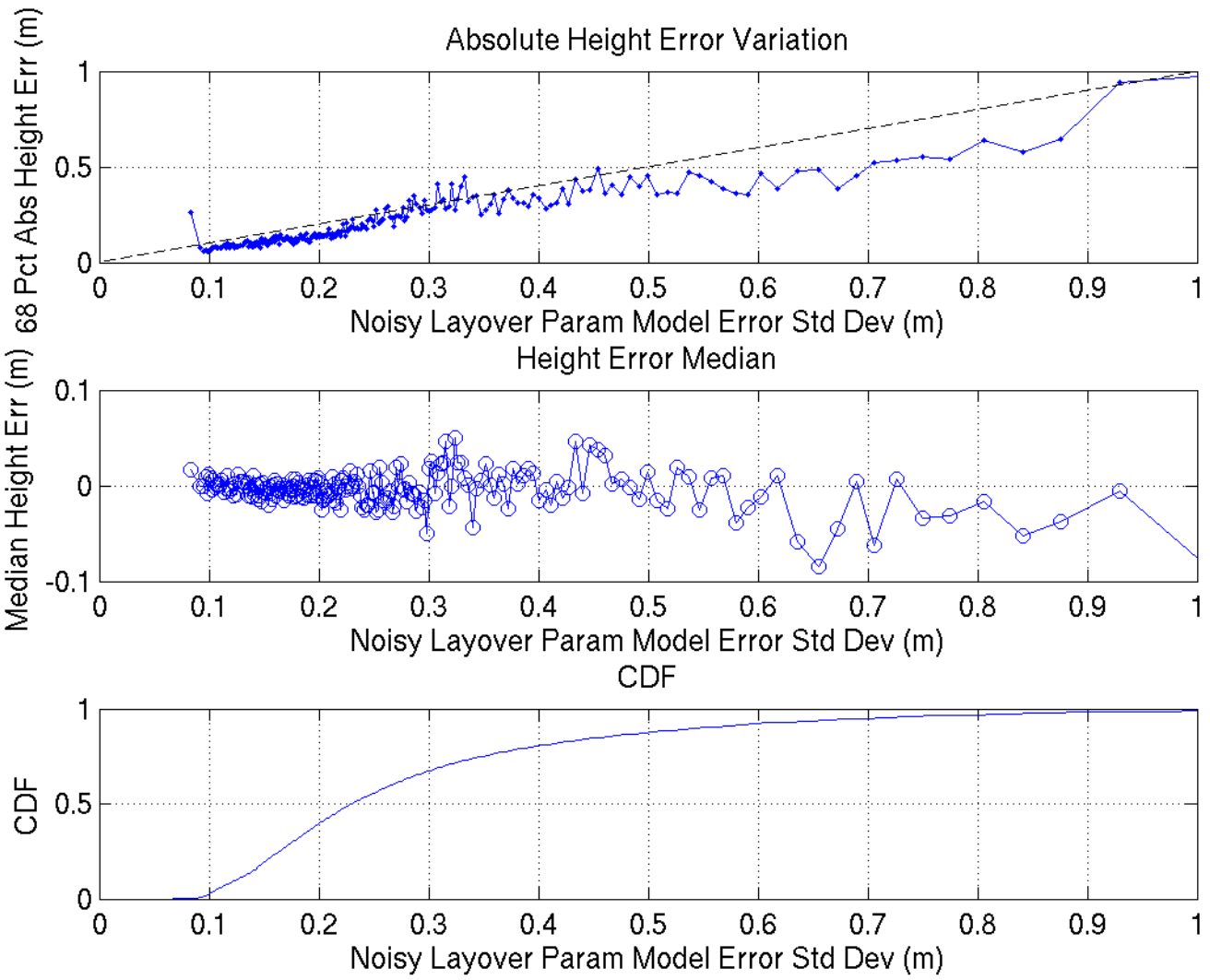
Model Validation for No-Flagging Case

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

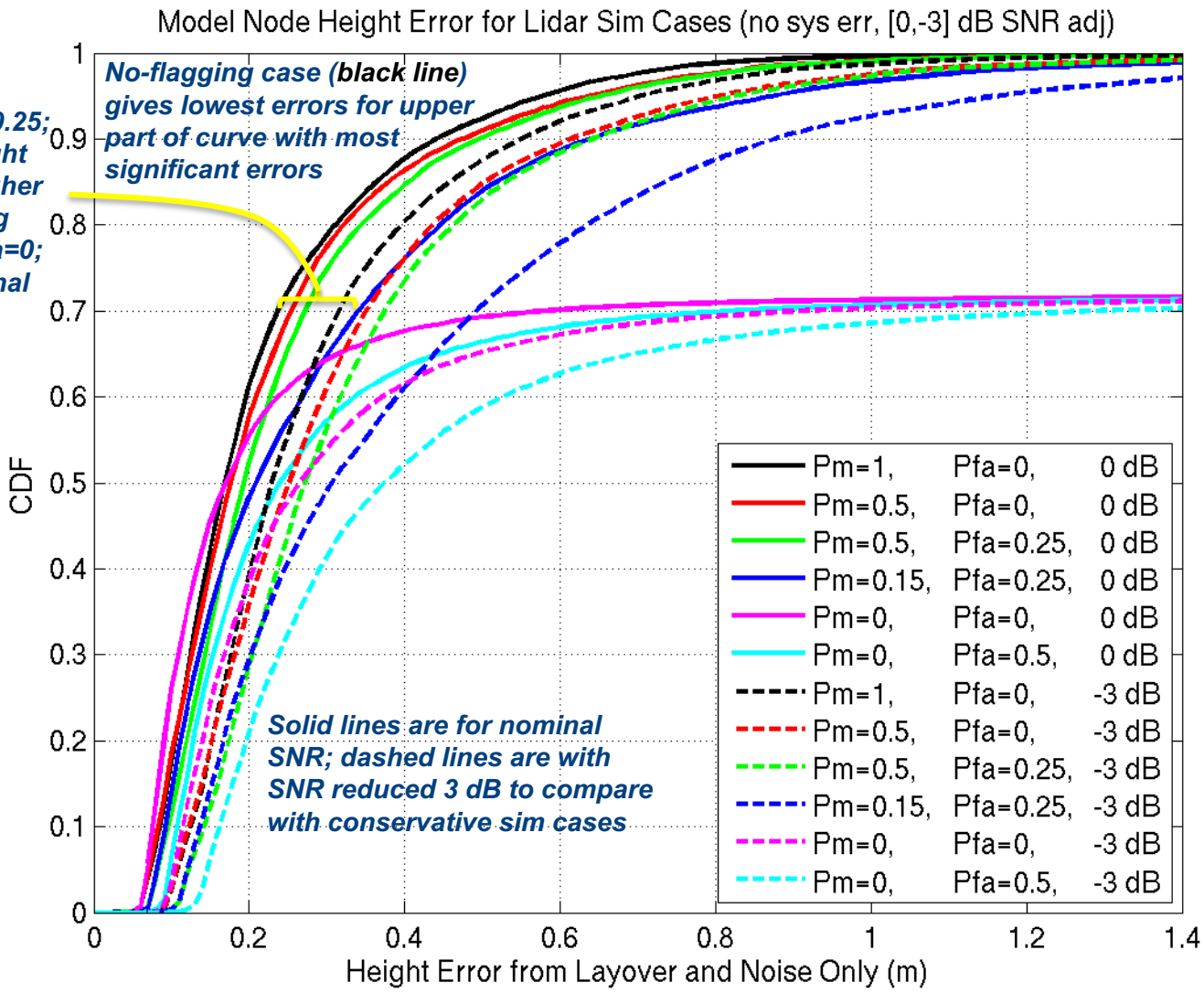
Details:

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



Node Height Error CDFs vs. Pm, Pfa, SNR

Model default (Pm=0.15, Pfa=0.25; blue) gives height errors ~50% higher than no-flagging case (Pm=1, Pfa=0; black) for nominal SNR



Cases with Pm=0 (magenta, cyan) discard all pixels for many nodes; represented as very large error in model

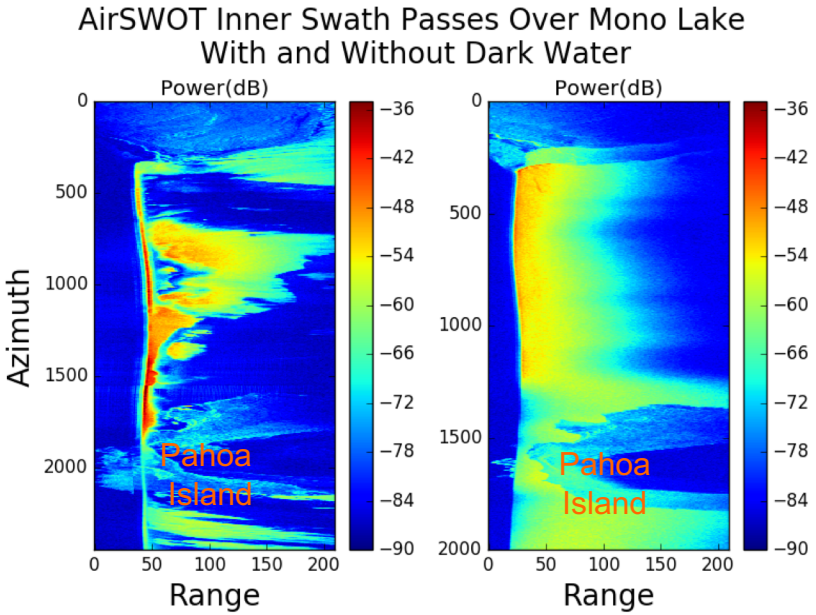
Curves are arranged in rough order of increasing amount of discarded data (layover or nonlayover), which correlates with increasing height error

Effectiveness of Layover Flagging

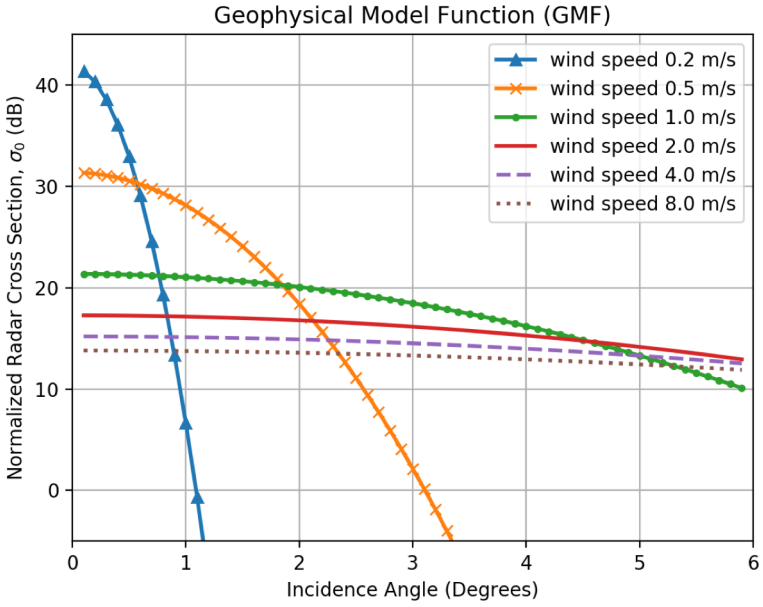
- Simulations and analytical model agree that binary flagging does not reduce height/slope error, even with truth DEM for flagging
  - Pixels with layover are (on average) still more helpful for beating down noise than harmful due to layover biases
  - Result makes sense considering that layover effects are small compared to noise, so no-flagging is better approximation to inverse-variance weights than binary flagging/weighting
- **Need to stop thinking about layover in geometric terms**
  - Relevant question is *not* "where does layover occur?"
    - Answer is "almost everywhere, to at least some degree"
  - Relevant question is "how badly does layover hurt the height and slope measurements?"
    - Answer is "usually not that badly"
- Baseline flagging approach for now is to do nothing
  - Will investigate continuous weights instead of binary flagging and approaches for predicting layover impact (possibly even bias correction), but these are ambitious

Dark Water: Phenomenology

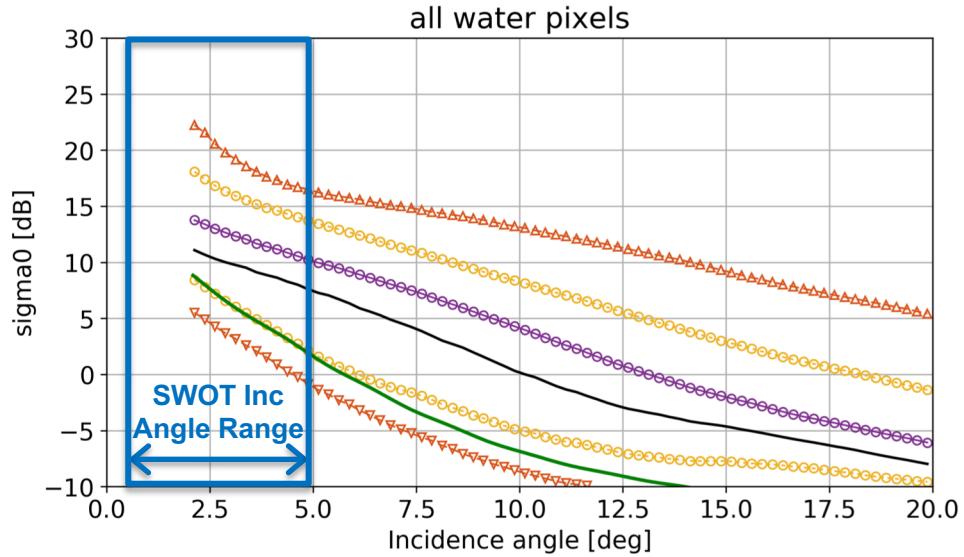
- Various causes of “Dark Water”
  - Calm water can be dark at SWOT incidence angles (~1-5 deg.)
  - Rain causes signal attenuation/dropout
  - Vegetation (persistent, though possibly seasonal, more difficult to mitigate)
  - Low SNR part of swath can cause missed detection of water
- Impacts area, height/slope, and location estimates
  - Not detectable as water from power measurements only
  - Low SNR, so height/slope/location estimates very noisy
- Detecting dark water pixels can ameliorate impact on area estimates by extending undetected water to that expected by a prior mask

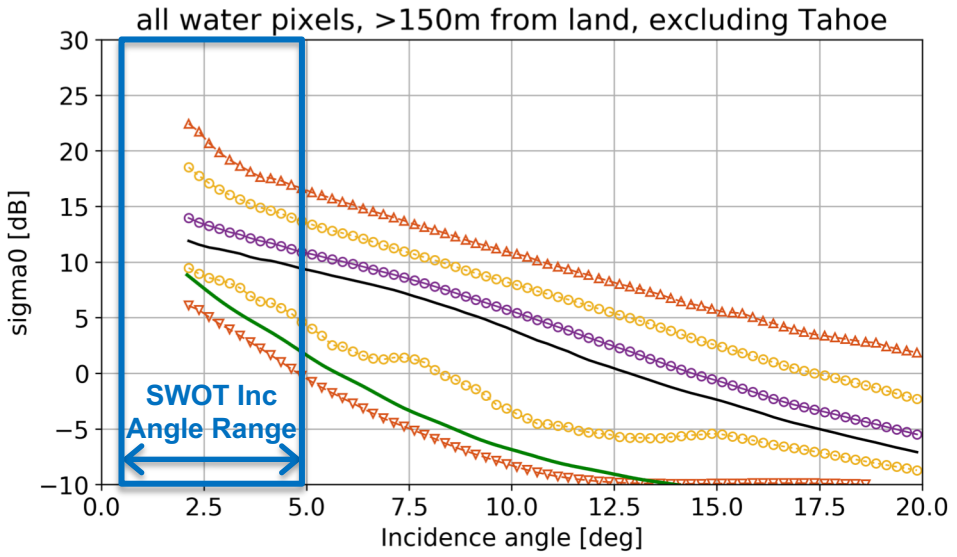


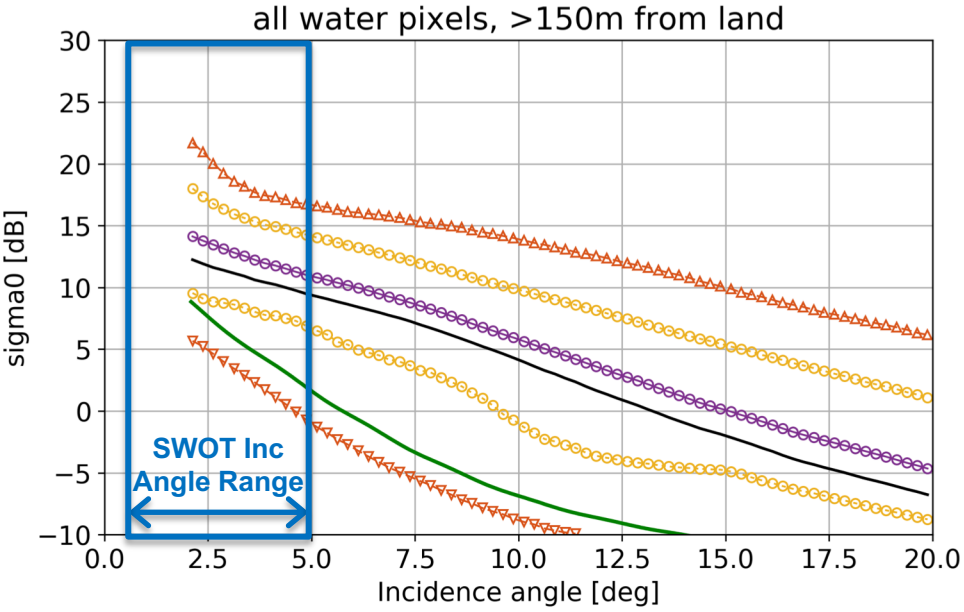
surface wind: ~3-4 m/s (left), ~5-7 m/s (right)

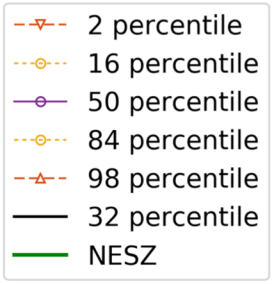


AirSWOT Updated Sigma0 Study





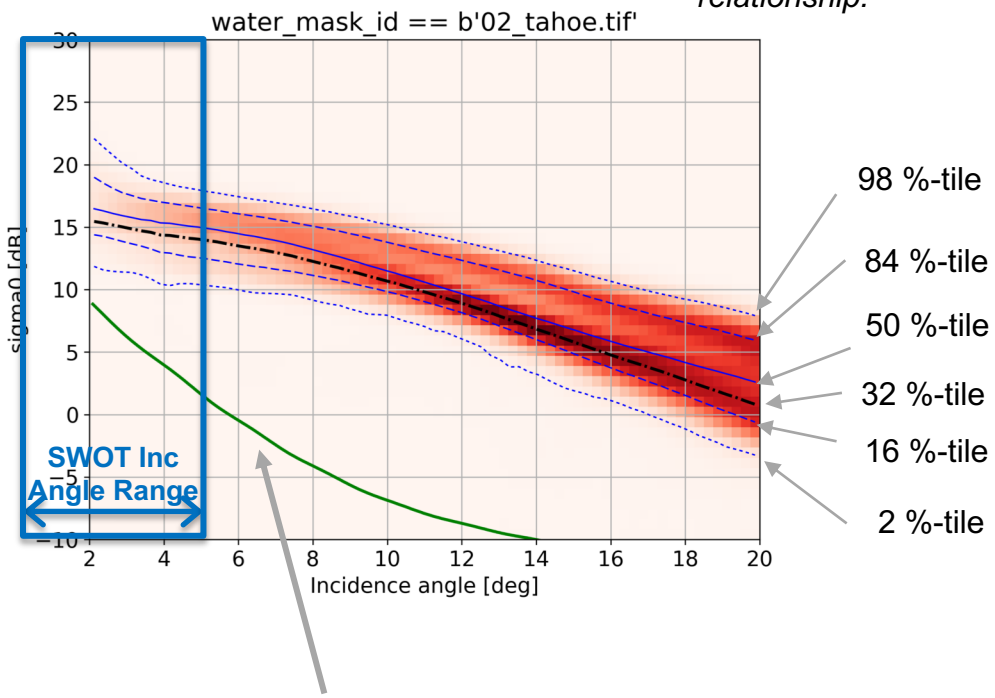


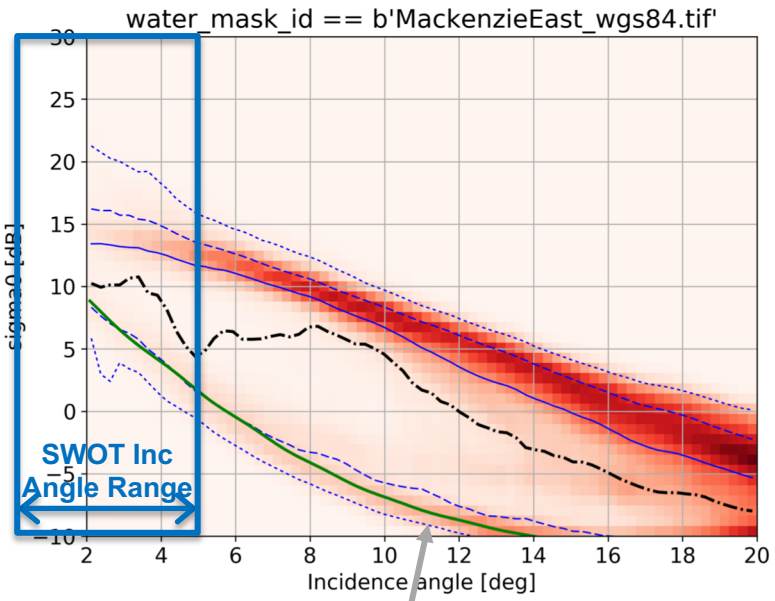


- AirSWOT data set
  - Total: 343 flight lines, 483 million water pixels
  - At PDR: 61 flight lines, 158 million water pixels
- Overall results similar as before
  - 32 percentile sigma0 around 10dB for SWOT incidence angles

Lake Examples With and Without Dark Water

Intensity of red coloring is 2-D histogram showing sigma0/incidence angle relationship.





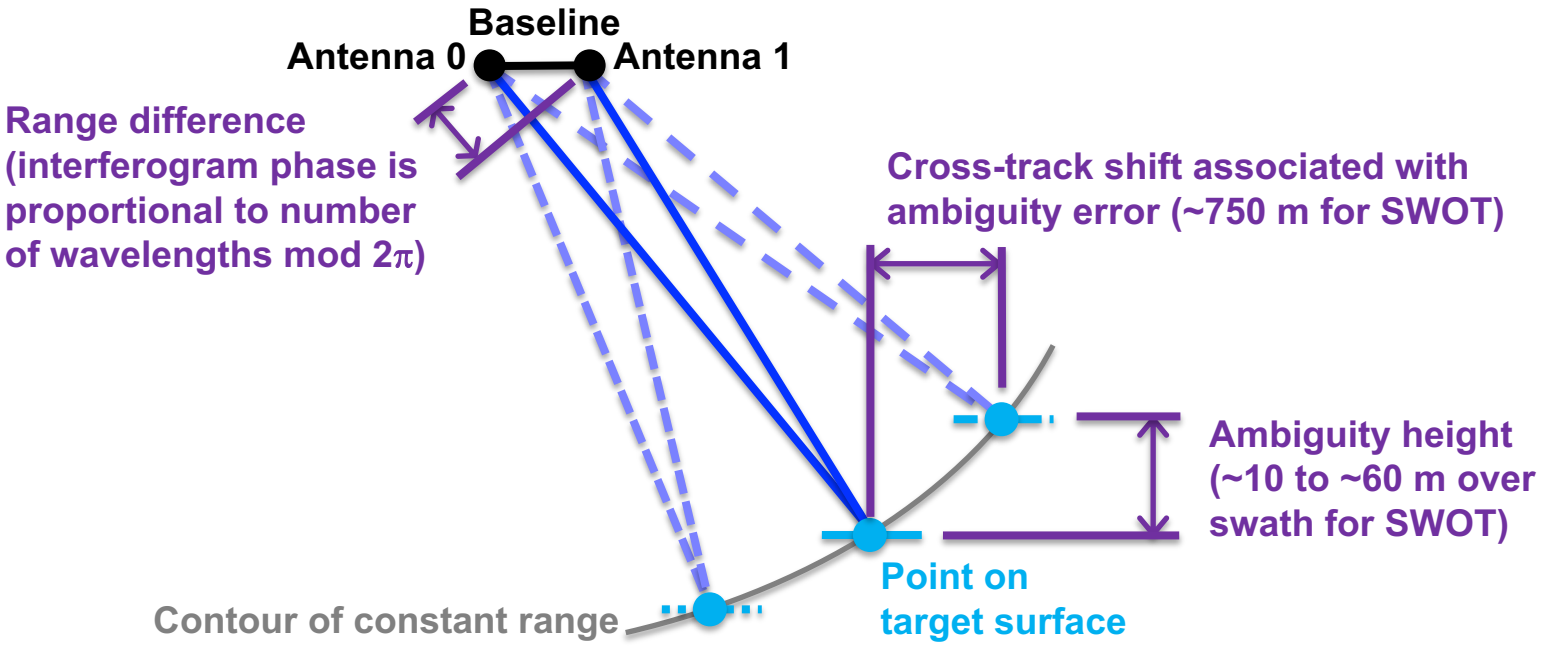
Noise-equivalent sigma0 (NESZ)

2nd population of dark/specular water for this case (below noise floor)

Other AirSWOT Dark Water Conclusions

- *Caveat: All conclusions about dark water from AirSWOT data set are subject to limitations of AirSWOT data from sampling bias, spatial/temporal coverage, calibration error, water mask error, etc.*
- **Statistics by water body are relatively similar to statistics by pixel**
  - Determined by segmenting images and taking statistics over segments instead of by pixel
- **Dark water is highly variable temporally; water bodies are seldom always dark but are commonly dark at least sometimes**
  - Determined by examining sigma0 of given geographic location observed at different times by AirSWOT
- **Dark water is generally more likely near shore**
  - Inferred from examining sigma0 vs. distance from land
  - However, results supporting this conclusion are sensitive to errors in water mask

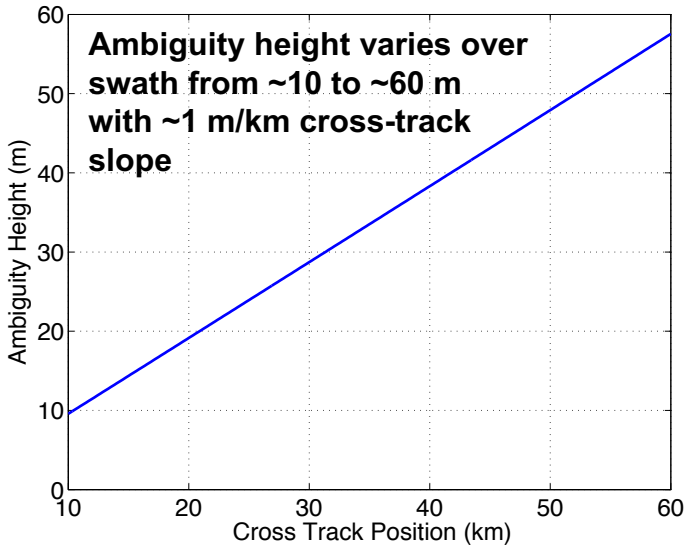
Phase Unwrapping

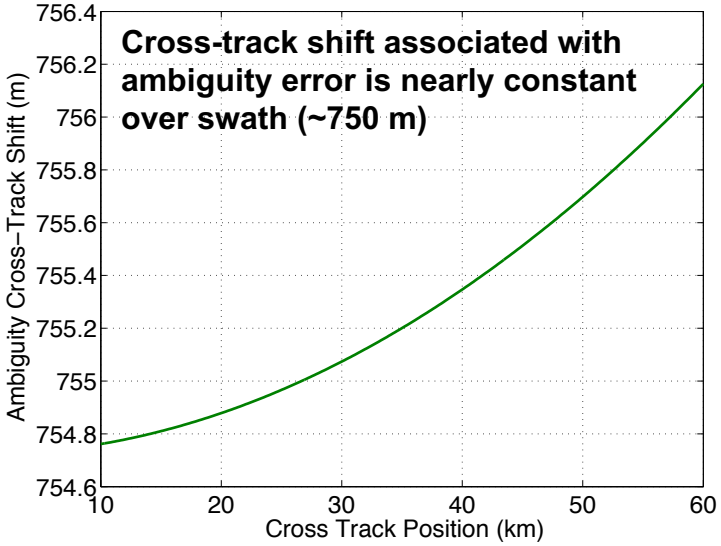


- Interferometric phase is precise measure of difference in range between point on ground and two radar antennas separated by known baseline
- Phase can only determined modulo 2π radians
  - Multiple points in space have same range and interferometric phase; target location is ambiguous
  - Target location is geolocated incorrectly if incorrect phase ambiguity is assumed

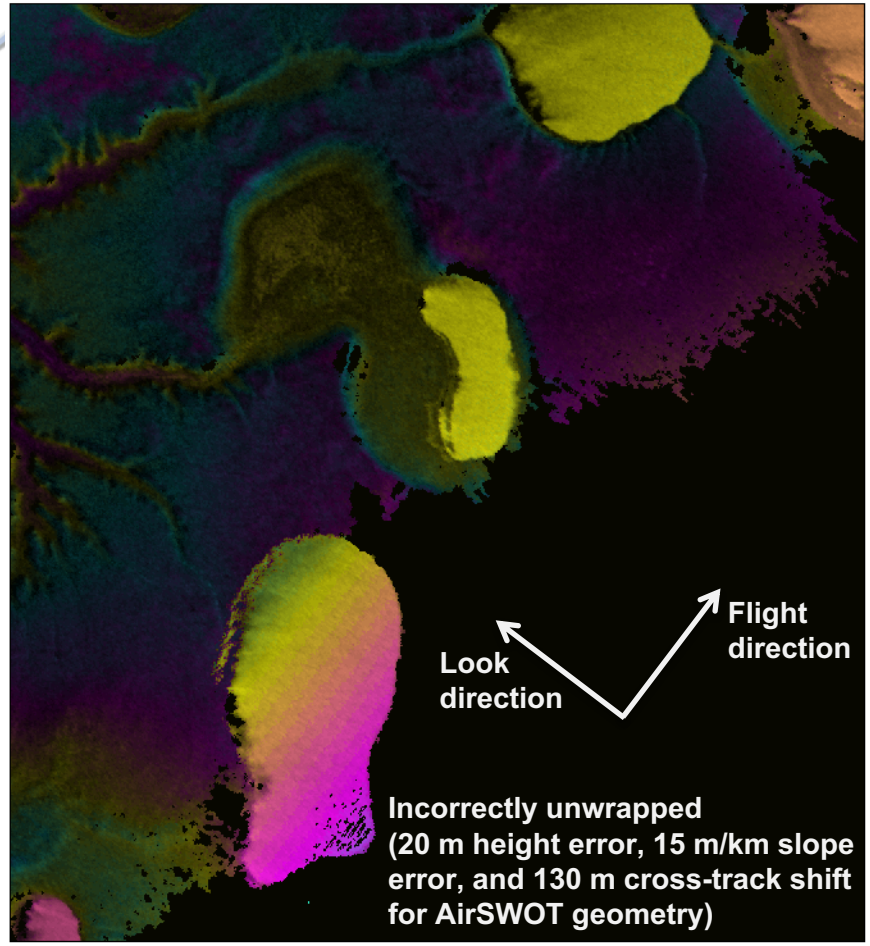
Phase Unwrapping Effects and Algorithms

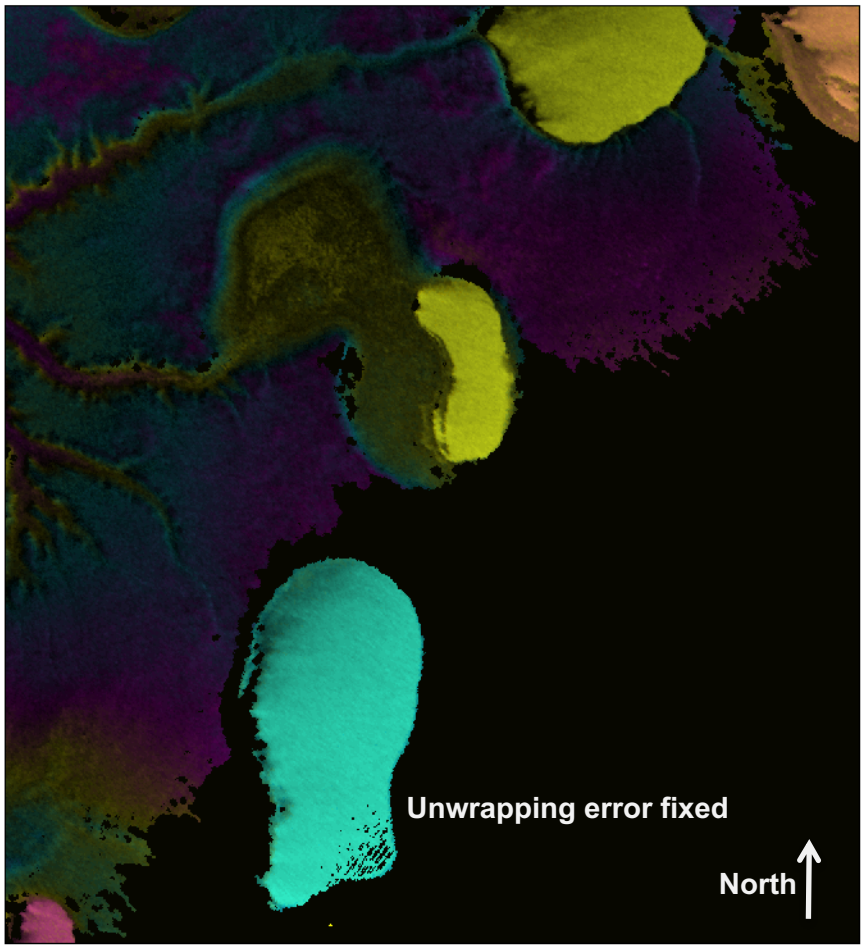
- Many algorithms exist for spatial unwrapping to get regions of pixels that are unwrapped correctly relative to each but not absolutely
- **Absolute ambiguity resolution on region basis is unique challenge for SWOT**
  - Small ambiguity heights require high vertical accuracy for reference DEM
  - Low coherence over land implies many small regions (harder than few large regions)
  - SWOT algorithm attempts to match measured height to reference DEM and horizontal geolocation to prior water mask
  - Unwrapping error contributors:
    - Reference DEM error
    - Prior water mask error
    - Change in actual water body height, shape, size, or location
    - SWOT height measurement or water detection error





AirSWOT Phase Unwrapping Error Example

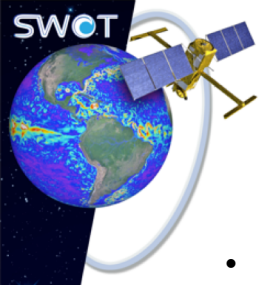




AirSWOT Line 20150615005432
(Near Yukon River, Alaska)

Grayscale represents radar reflectivity
Color represents height (shown with 30 m wrap)

Note: Unwrapping errors will cause larger cross-track shifts (~750 m) and smaller slope errors (~1 m/km) for SWOT than for AirSWOT



AirSWOT Update

- Outer swath processing has become quicker and more automated
  - All 2015 and most 2017 outer-swath data have been processed
- Channel 5, used for outer-swath ATI corrections, failed during ABoVE 2017 flights
  - Campaign was flown and data are being processed using alternate channel 3 for outer-swath ATI
  - Results from channel 3 seem comparable to results from channel 5
  - Channel 5 is working again in lab, but root cause of issue is not known
  - Recommendation from vendor is wholesale hardware upgrade that would affect all channels; decision is still pending
- Inner swath transmit antenna has exhibited large pointing variations
  - Radiometric calibration changes by ~3 dB; unknown but likely large impact on interferometric phase
  - Issue is intermittent
  - Looking into how often issue occurs and whether we can detect and discard bad lines