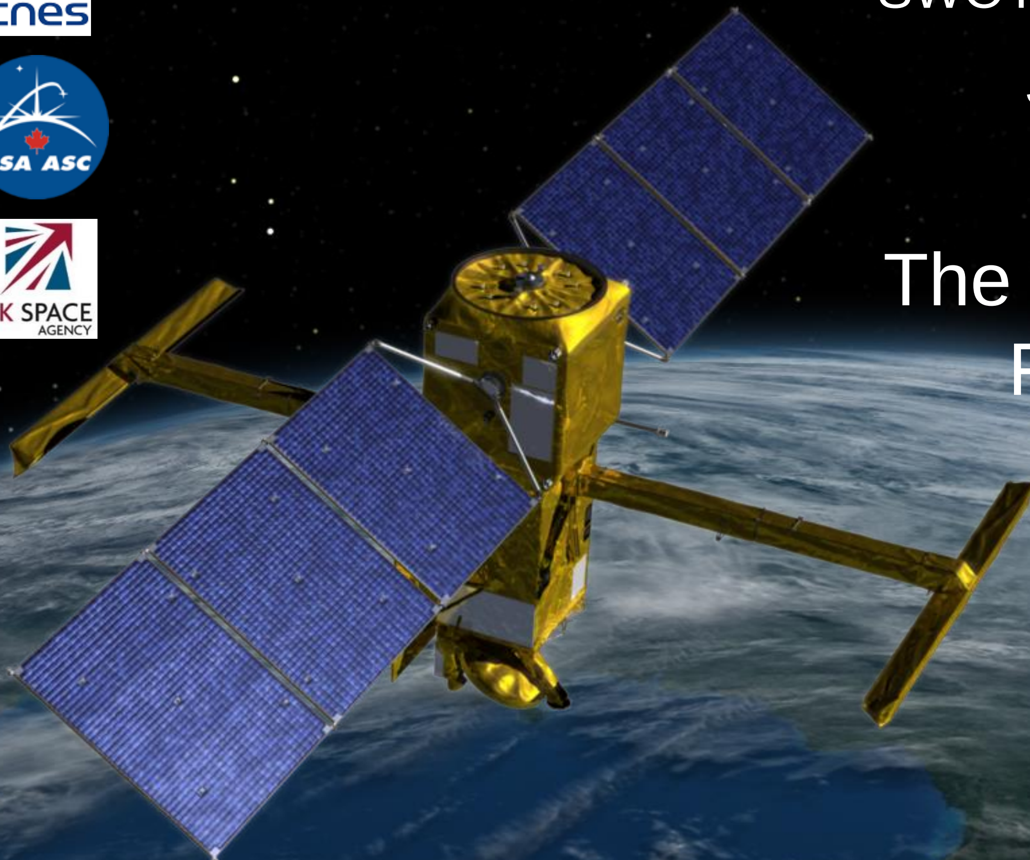
National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Surface Water and Ocean Topography (SWOT) Mission

SWOT Science Team Meeting

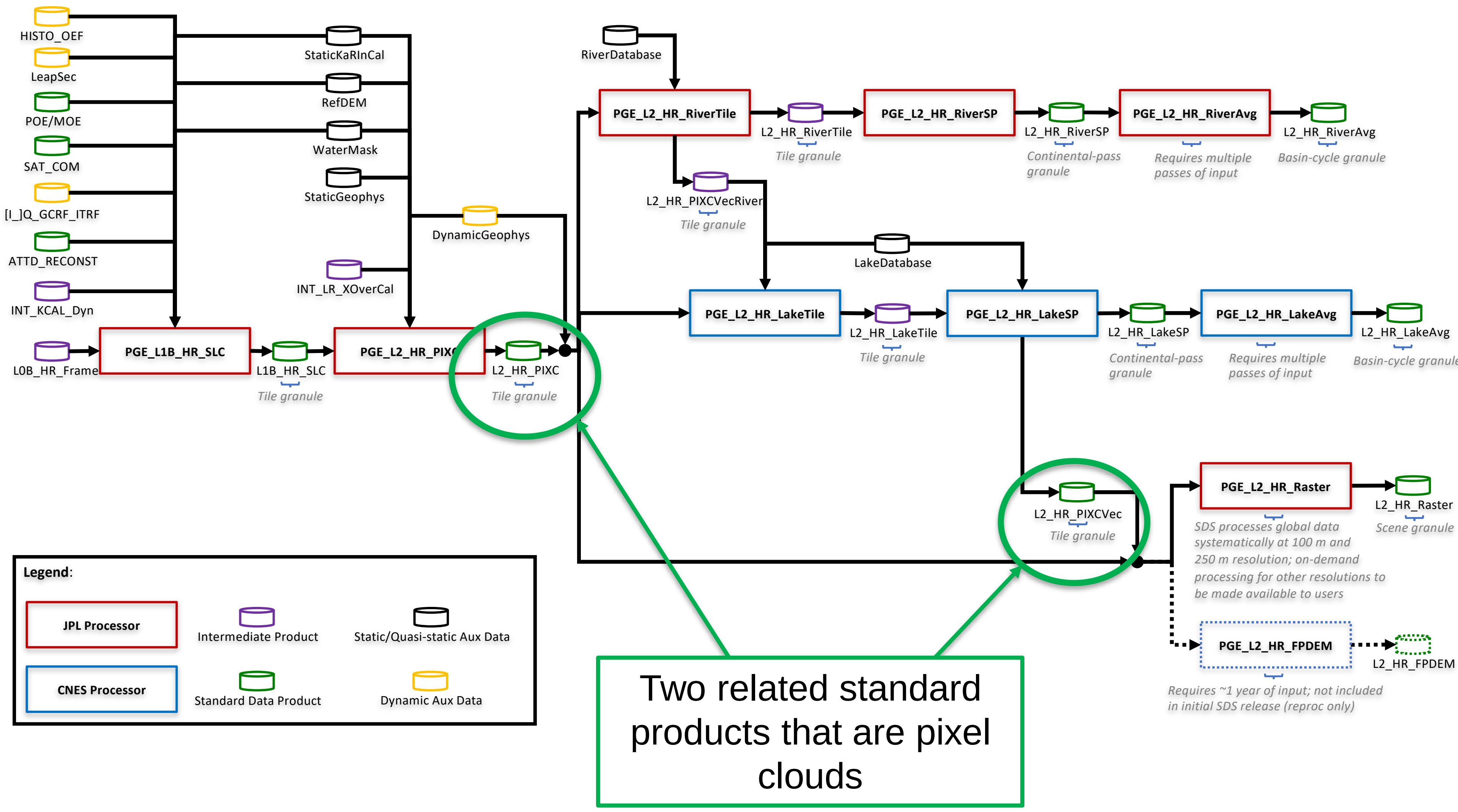
June 17-20, 2019



The Pixel Cloud Product: Format, Contents and Status

Brent Williams
Pixel Cloud Algorithm Developer

High Rate Algorithm Flow

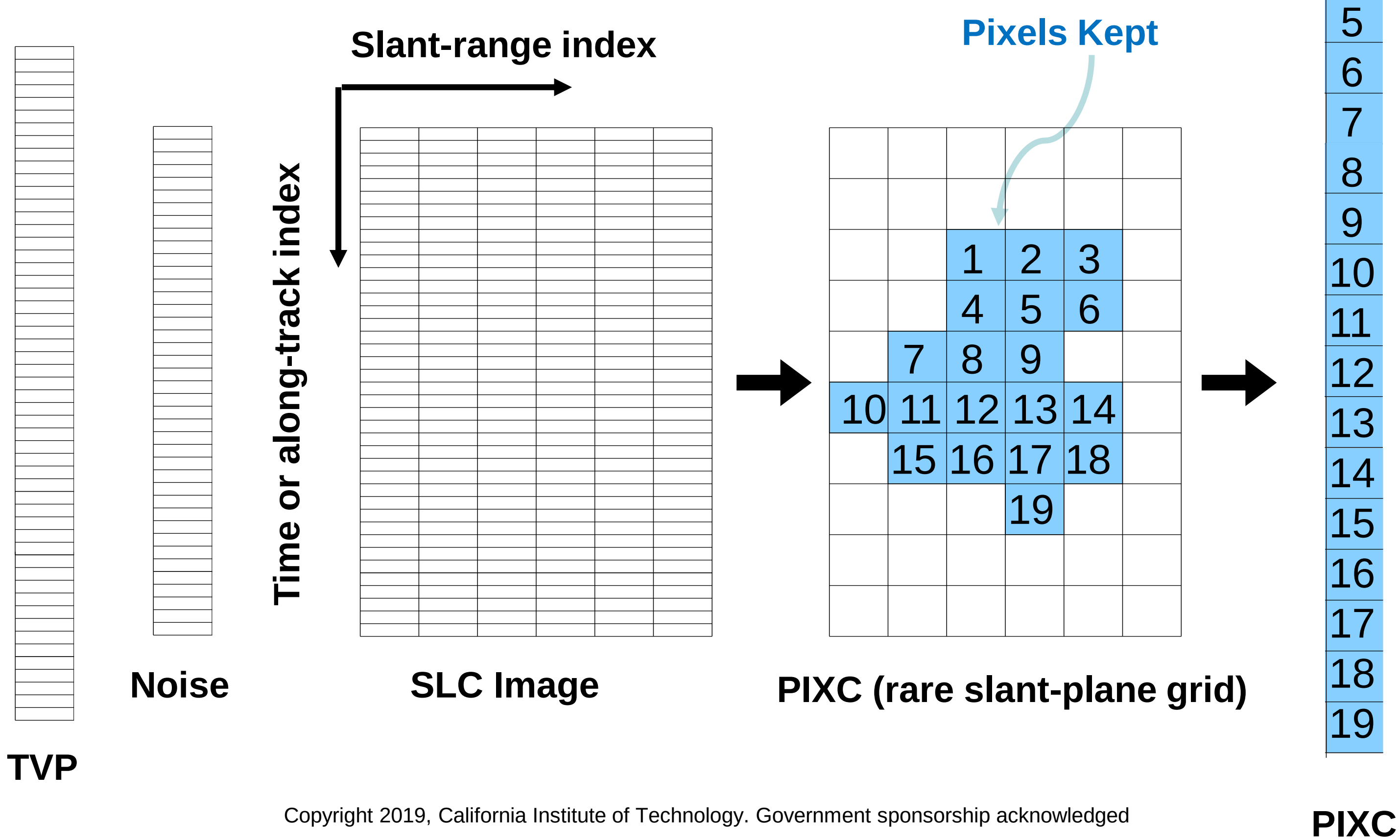


Intended Users

- PIXC and PIXCVec are expert products, intended users are:
  - Hydrologists interested in studying fine-scale details in a local region
    - Higher spatial resolution, but noisier than vector products
    - Users who want to use their own customized algorithms for height reconstruction and geolocation
  - Users interested in low level data for calibration/validation and downstream algorithm development
  - Possibly other applications around inland water
    - Lowest level of data available that is geolocated
    - Studies like Ka-band scattering, rain, ice/snow, soil moisture, urban sprawl, inland water body wind vector/wave height estimation etc…
- The “raster” product can also serve most/many hydrology users that need finer scale measurements than the vector product, but don’t need detail and additional complexity of the pixel cloud

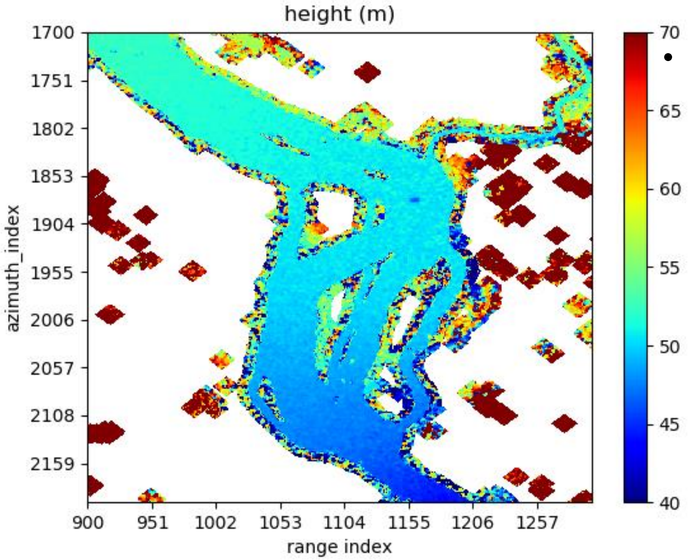
L2_HR_PIXC Format

- NetCDF format with global attributes and 3 groups
  - Pixel Cloud (PIXC) group (1D list of kept 2D rare radar-grid pixels)
  - TVP group (1D at SLC posting, with larger extent)
    - Sensor information (e.g., spacecraft position, velocity, attitude)
  - Noise group (1D at SLC posting, with SLC extent)



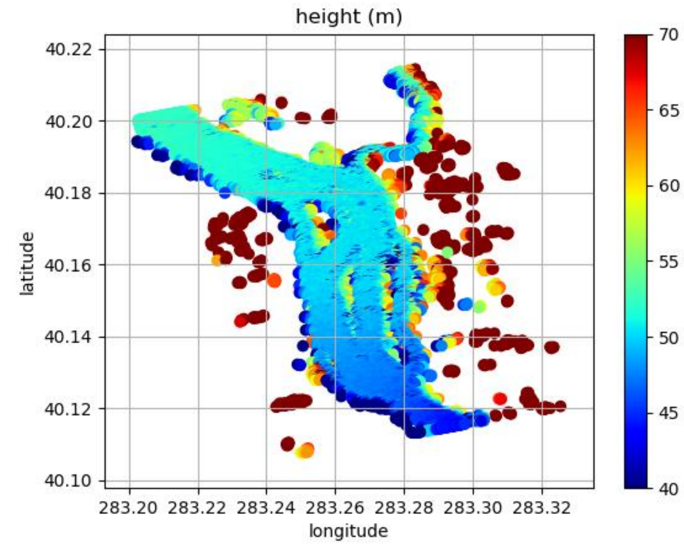
Pixel Cloud Example

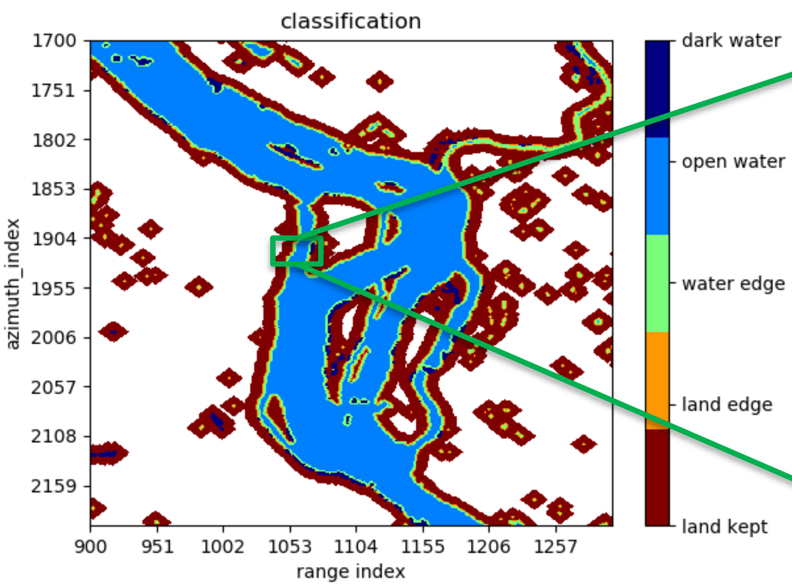
Slant-plane

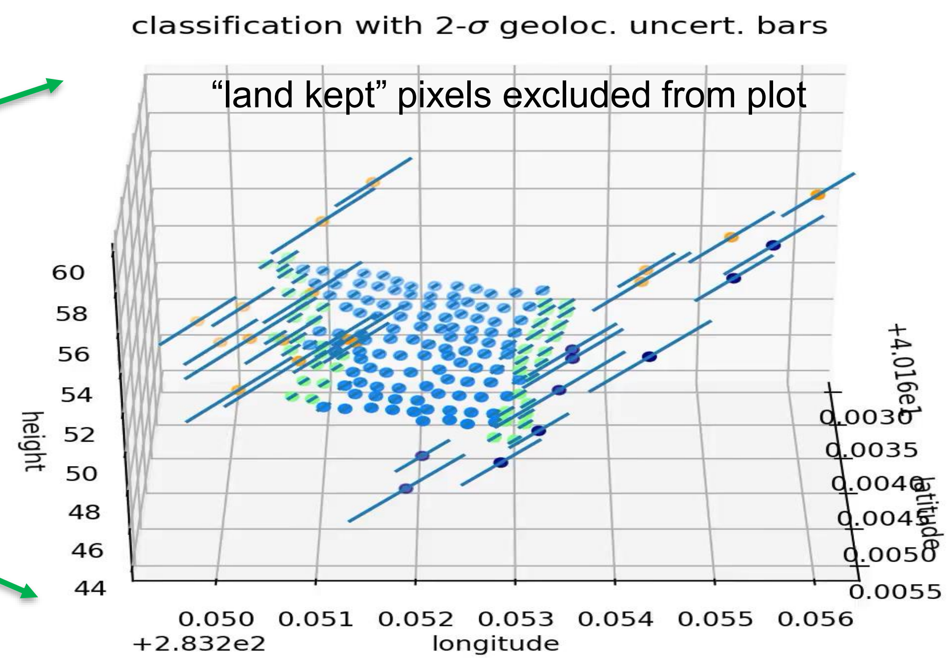


- Can be viewed either as a sparse 2d slant-plane image or as 3-d geolocated point cloud for each pixel cloud variable.

Ground-plane

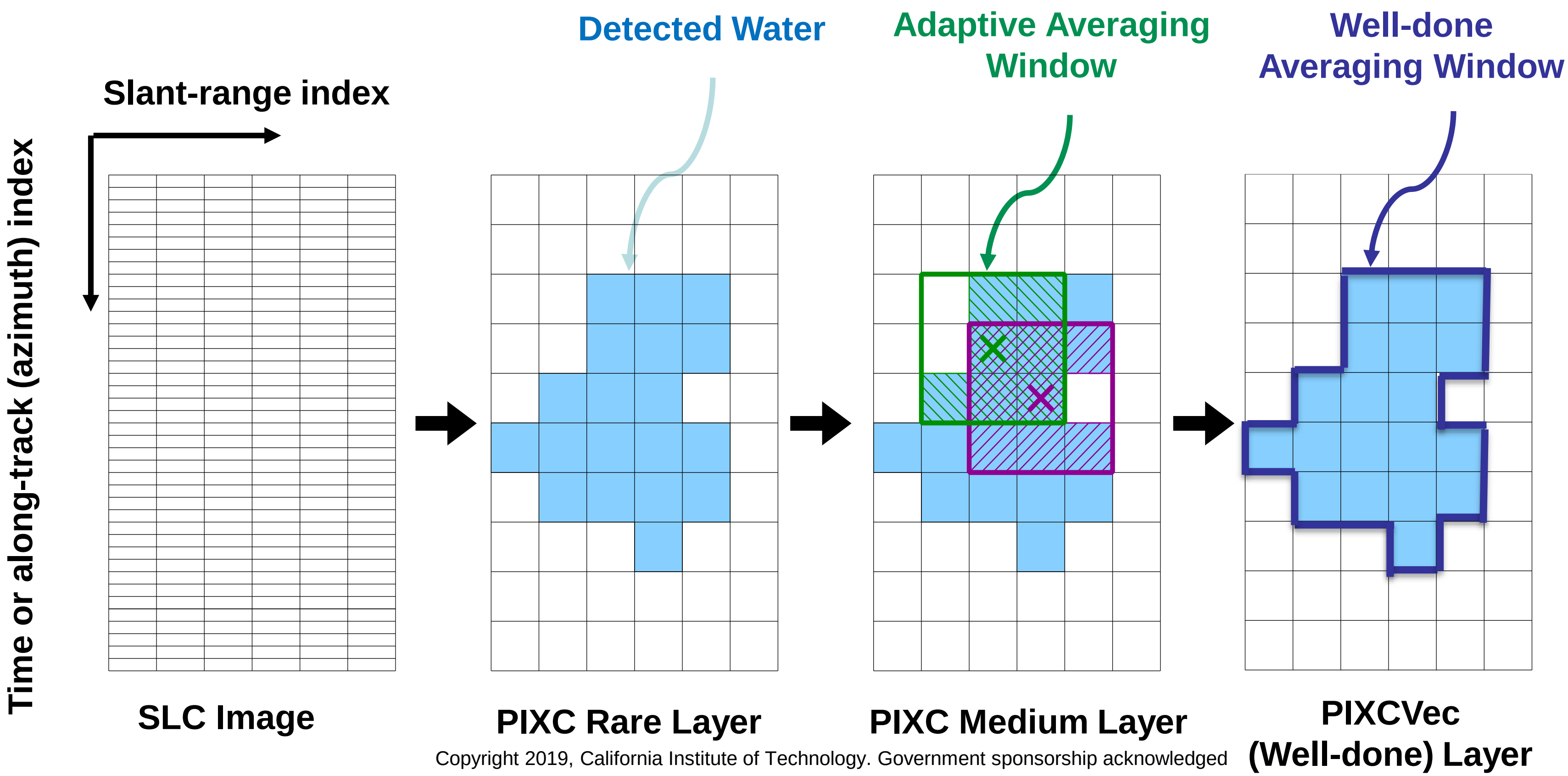






Pixel Cloud Group

- Multiple levels of smoothing
  - Rare and Medium layers on same ‘rare’ slant-plane grid
  - Well-done layer in PIXCVec product (not PIXC), but on same grid
  - Rare and medium variables are in same group with no explicit tags indicating rare or medium



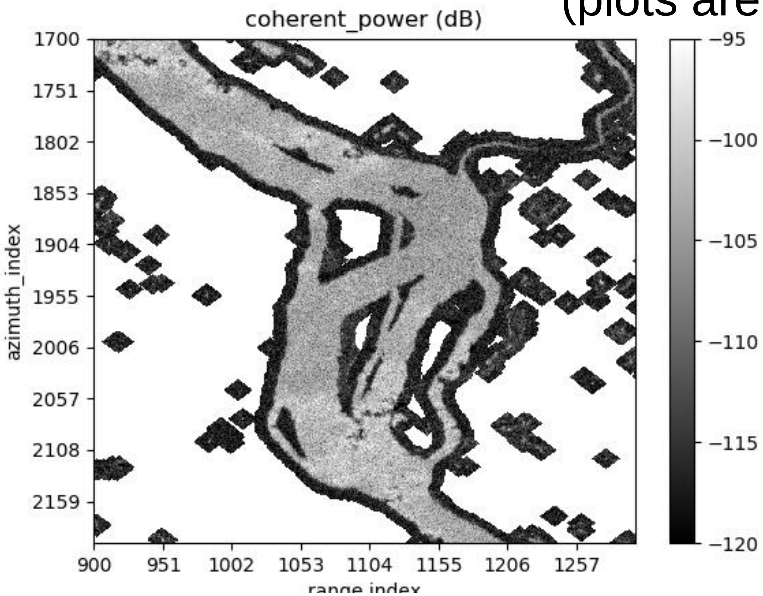
Pixel Cloud Group: Rare Layer

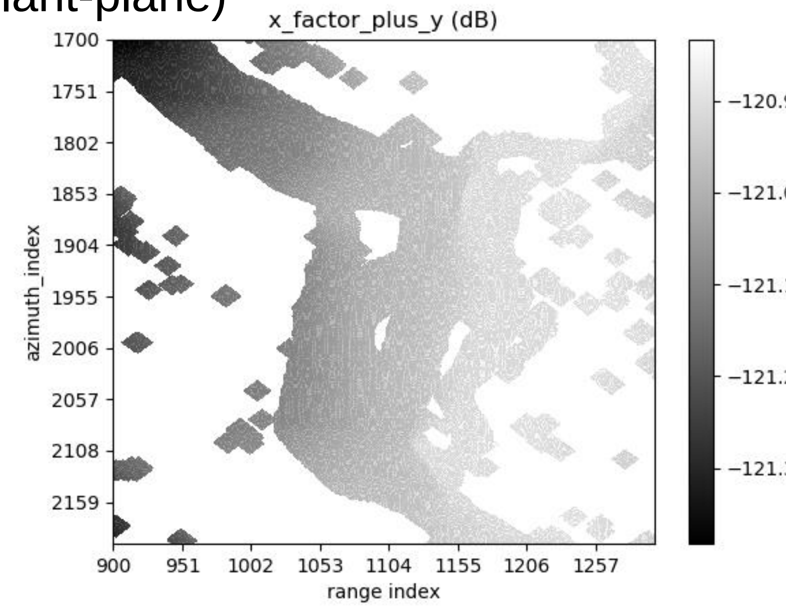
- Rare variables (Note there is no geolocation or height)
  - Grid related items
    - Azimuth and range index
  - Interferometric measurements
    - Interferogram, 2 channel powers, coherent power)
    - Number of rare looks
  - Radiometric calibration terms
    - X-factor for 2 channels
  - Water detection/flag items
    - Classification, water fraction, detection rates, water fraction uncertainty
    - Dark/bright land flags, prior water probability
    - Layover impact

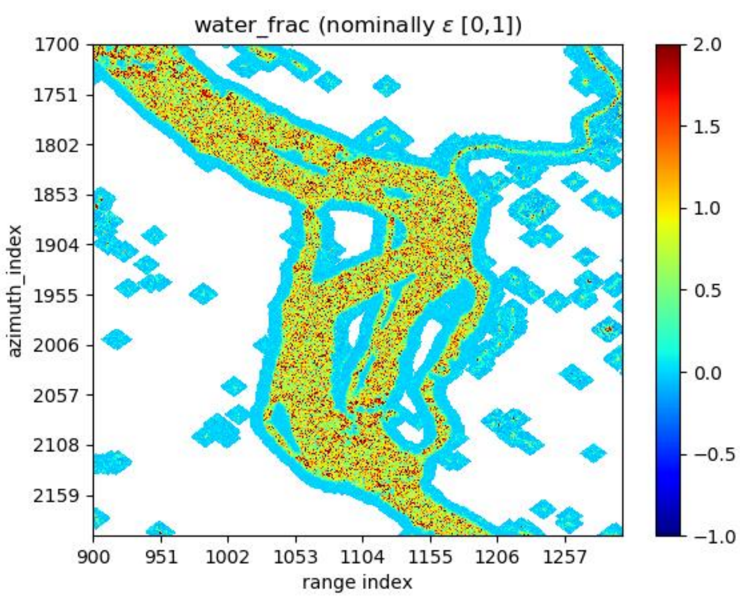
- Philosophy of rare layer is to preserve fine scale information
  - e.g., keep everything needed to redo geolocation and recompute much of the medium layer from rare with offline expert/experimental processing

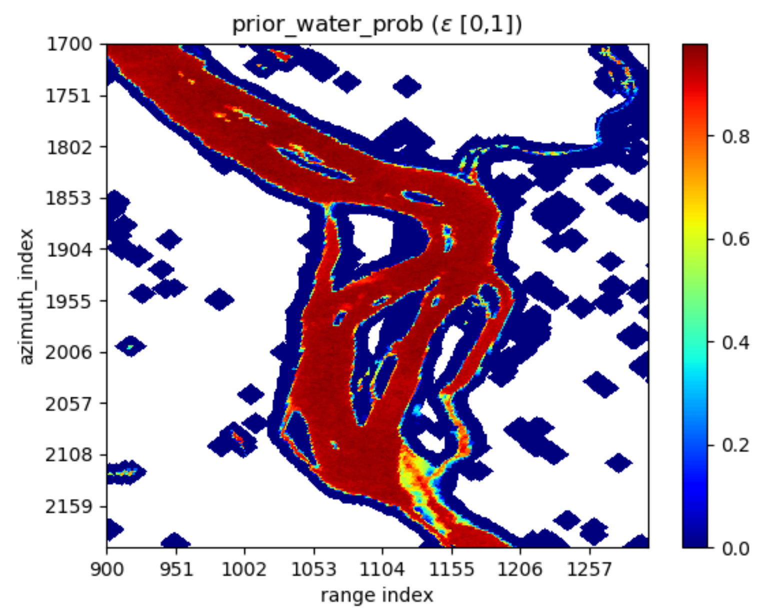
Examples (Rare)

(plots are in slant-plane)







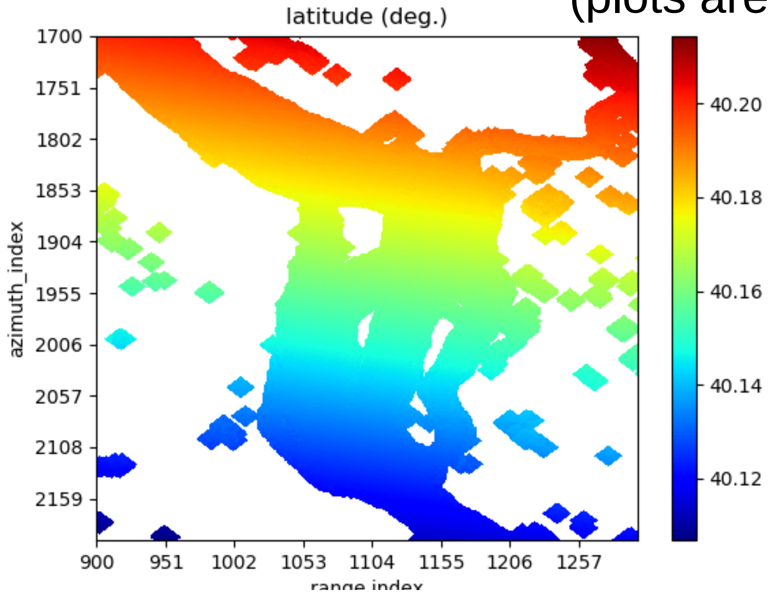


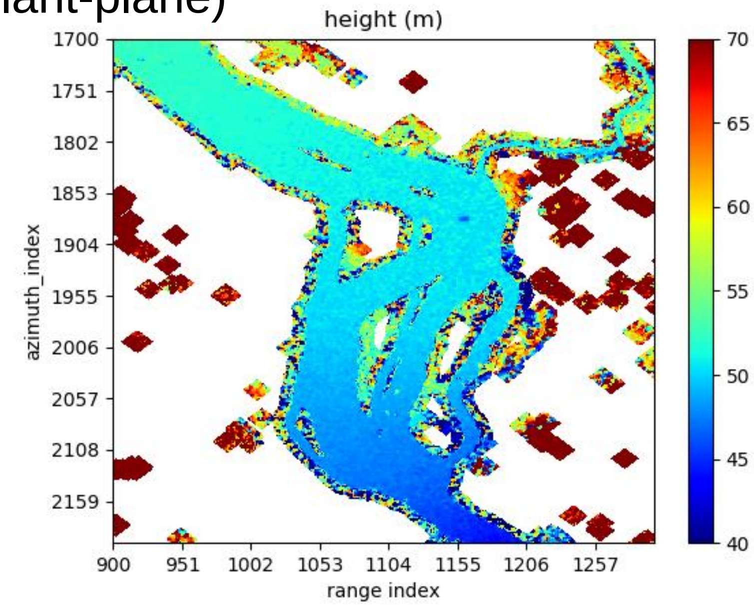
Pixel Cloud Group: Medium Layer

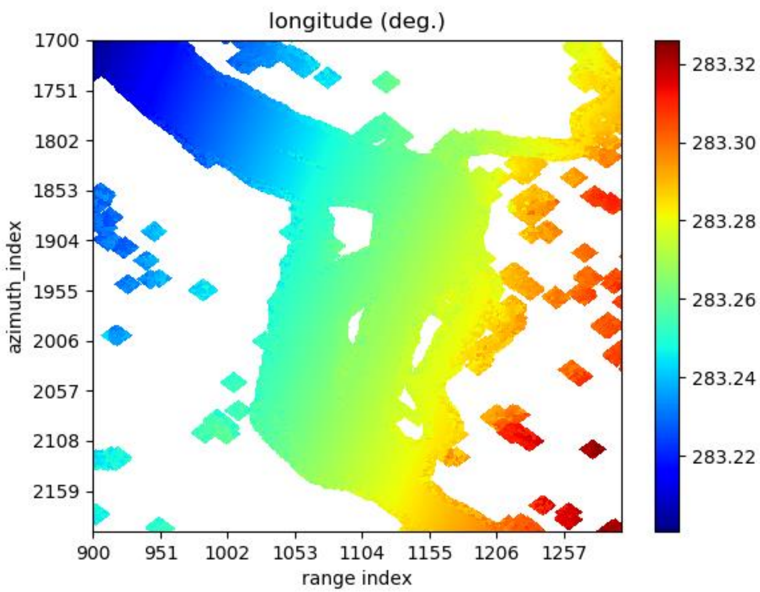
- Medium variables
  - Geolocation related variables
    - Longitude, latitude, height (wrt ref ellipsoid, not geoid like vector prod.)
    - Cross-track position, pixel area (on ground), incidence angle
  - Quality flag
  - Variables needed to compute geolocation/height uncertainty
    - Phase noise standard deviation
    - Geolocation/height sensitivities to phase, roll, baseline, and range
    - Sensitivity of pixel area to height
  - Illumination time for each pixel
  - Phase unwrapping region mask
  - Instrument and geophysical corrections
    - Effective height corrections corresponding to instrument and media delay (wet/dry tropo., iono.) corrections that were applied before geolocation (as range/phase corrections)
    - Other geophysical height references that are not applied: geoid, and Earth tides (solid Earth, load, pole tides)
      - Reported but not applied
    - Geophysical surface type flag

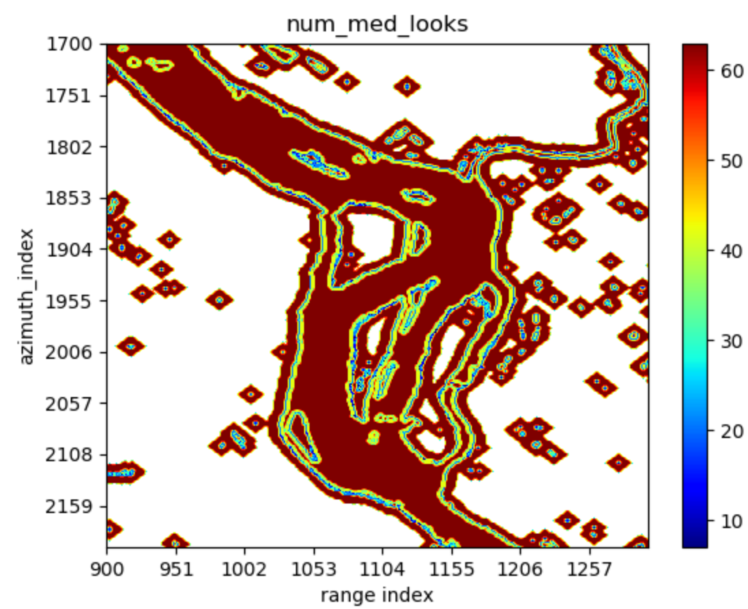
Examples (Medium)

(plots are in slant-plane)









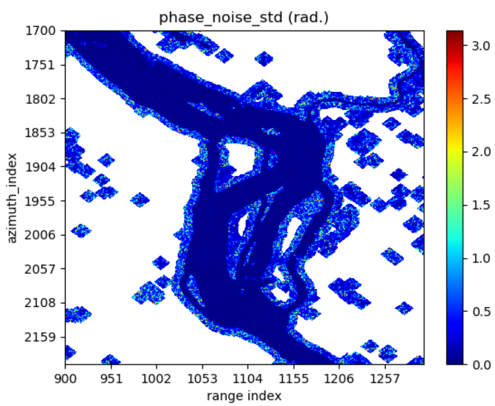
Medium Layer and Uncertainty

- Only the medium layer is geolocated/height reconstructed
- Because of the adaptive averaging, the noise in the medium pixels can be correlated from pixel to pixel
- Uncertainties after aggregation do not simply fall off as 1/sqrt(N)
- PIXC has all the information needed to
  - Optimally aggregate to nodes/lakes/raster bins
  - Estimate height and area uncertainties of the aggregates
    - For the noise- and algorithmic-related components
    - Not necessarily for the systematic components due to errors in the cross-over corrections, or phenomenological uncertainties (existence of layover) etc.
- Optimal aggregation and uncertainty estimation from quantities in the pixel cloud has been implemented and is currently being tested and validated in the context of the rivertile processor

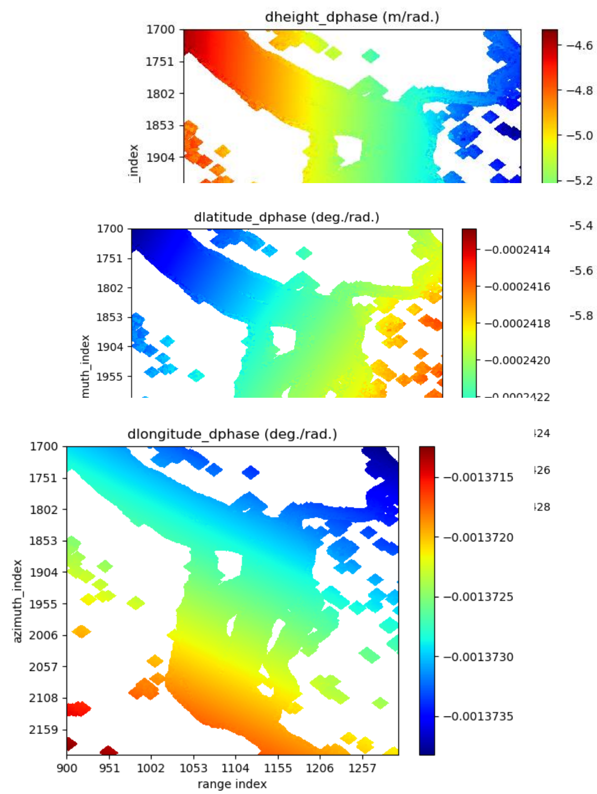
Pixel-wise Height Uncertainties (Random Component)

- Height/lat/lon uncertainties coupled
  - 1-sigma error bars are slanted lines in the 3D plots
  - Computed by phase noise std x |sensitivities|
  - Optimal height aggregation is inverse variance weighting using the height uncertainty

(plots are in slant-plane)



x



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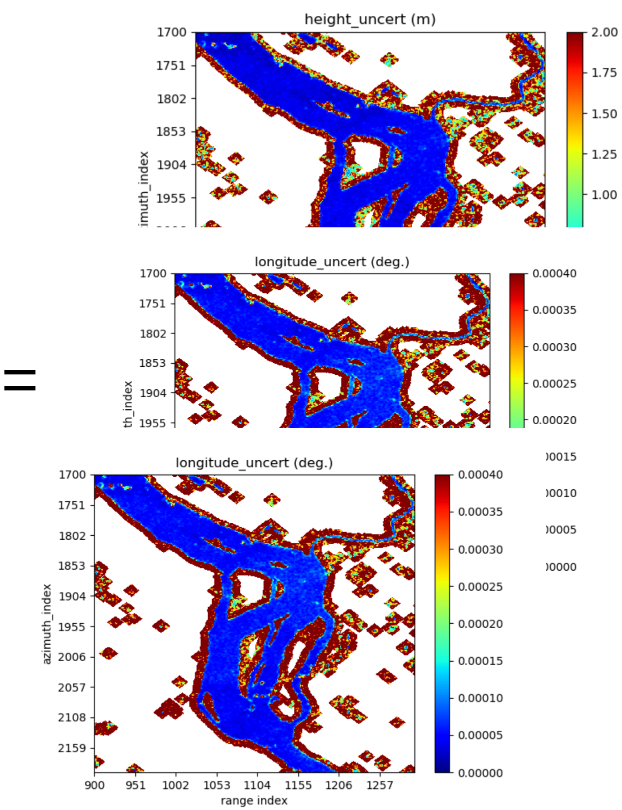
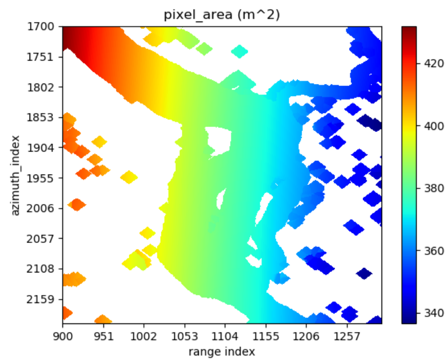
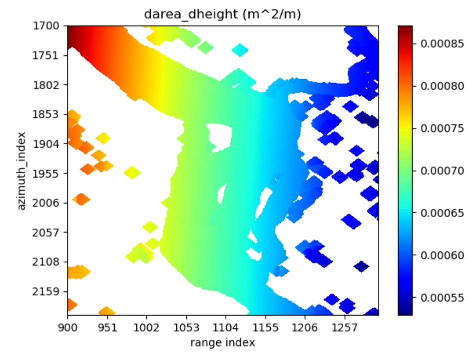


Pixel-wise Area Uncertainties

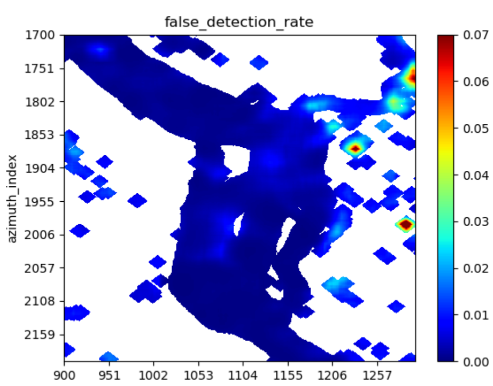
- Estimate of pixel area uncertainty given by sensitivity to height and an estimate of DEM height uncertainty (~10m)
  - This effect is generally negligible

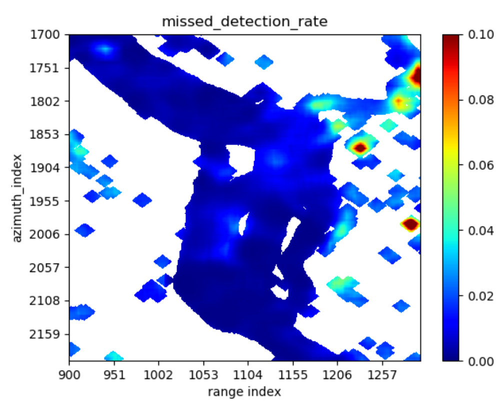
(plots are in slant-plane)

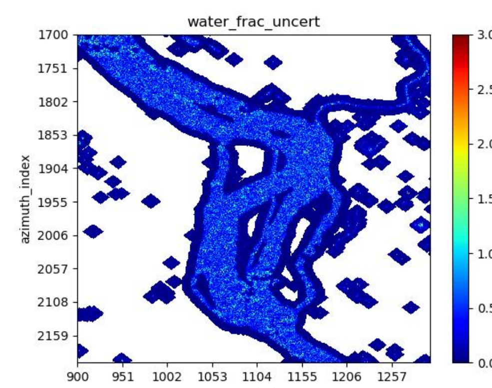




- Estimate of water area of a given pixel needs to incorporate detection errors and/or water fraction uncertainty etc…
  - Majority of error in water area estimates is due to these







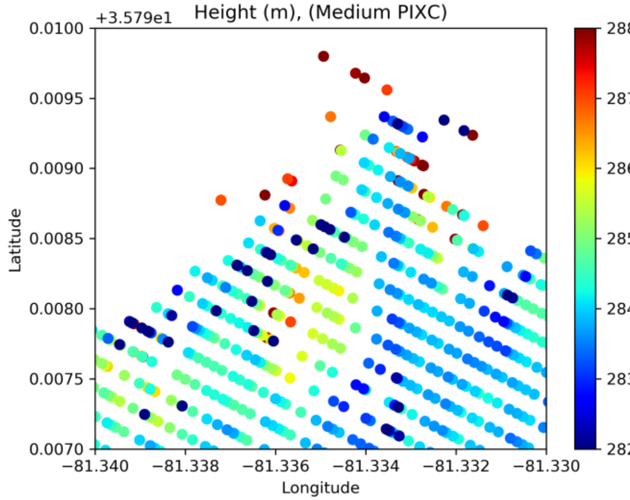
PIXC and PIXCVec: 2 Standard Products

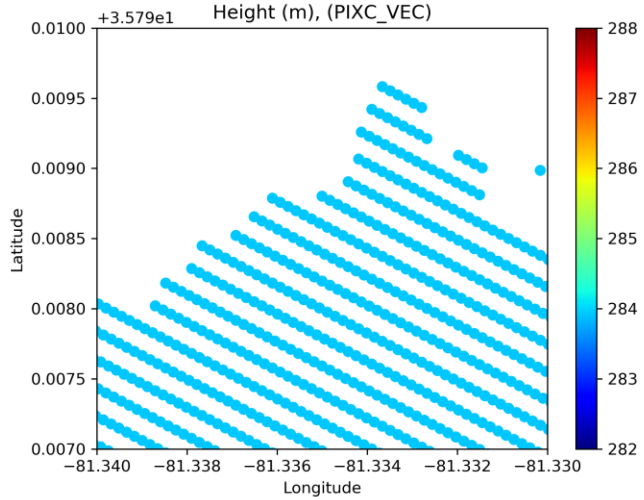
L2_HR_PIXC

- Main PIXC product with1-D list of geolocated radar image grid pixels around water (detected and prior)
- Rare-level interferogram information (4 effective looks)
- Medium-level (~50 looks) geolocated lat/lon/heights and uncertainty estimates
- Water detection and flagging results
- Calibration and sensor info.
- Height references and corrections (included but not applied)

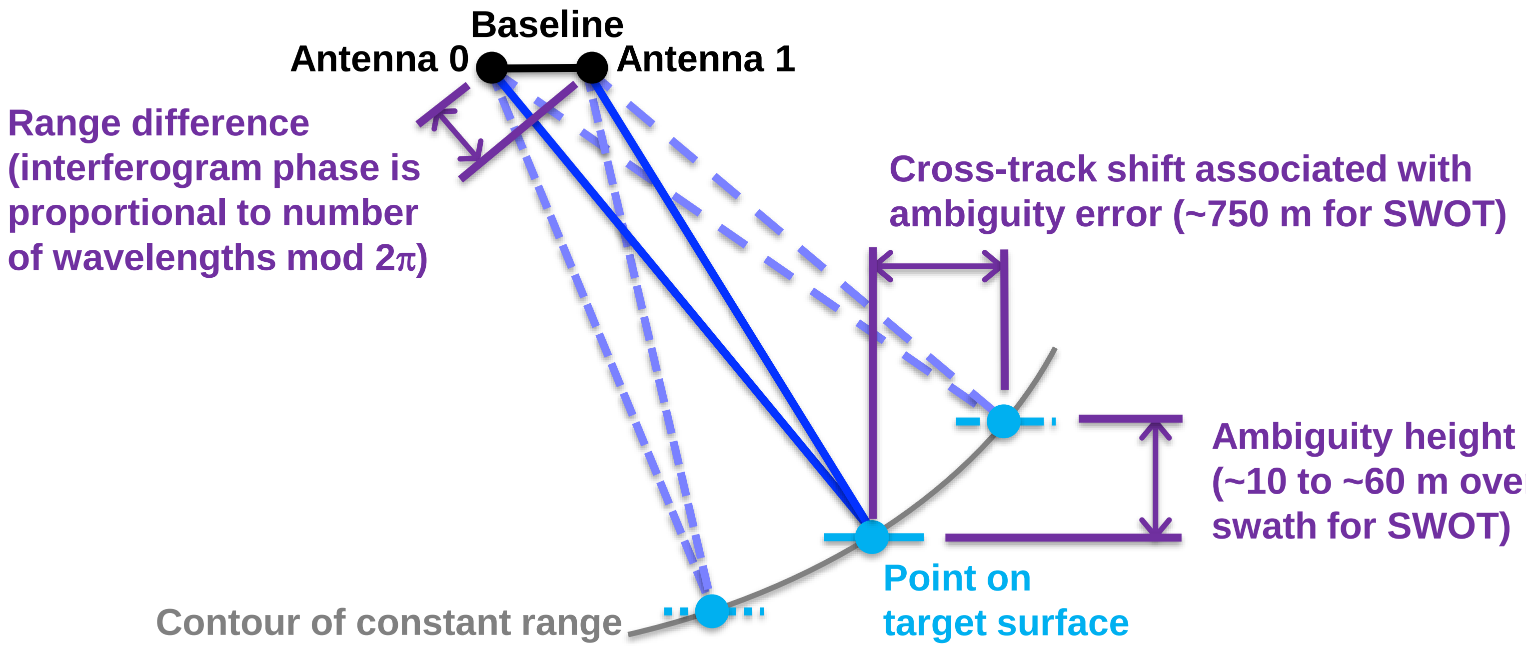
L2_HR_PIXCVec

- Ancillary/overlay product contains info. not available until after river and lake vector level processing
- IDs for each pixel that was attributed to any feature (node, reach, lake, unknown …)
- Height constrained geolocation using aggregated heights at the water feature level (i.e., lat/lon/height for “well-done” level of smoothing)
- Available only after river and lake processors are run (e.g., smooth whole lake to single height)





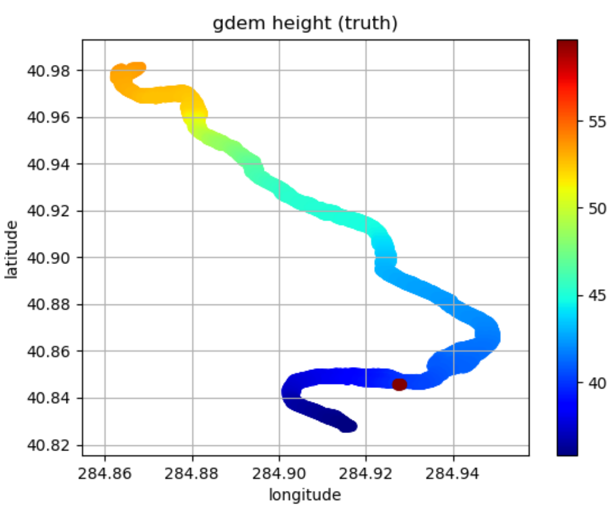
Phase Unwrapping

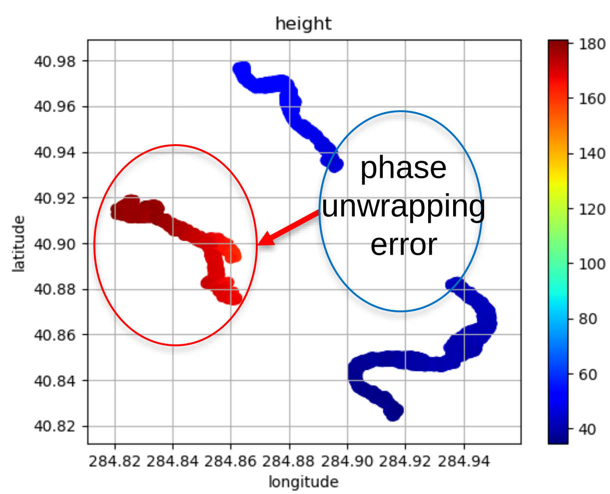


- Interferometric phase is precise measure of difference in range between point on ground and two radar antennas separated by known baseline
- Phase can only determined modulo 2π radians
  - Multiple points in space have same range and interferometric phase; target location is ambiguous
  - Target location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

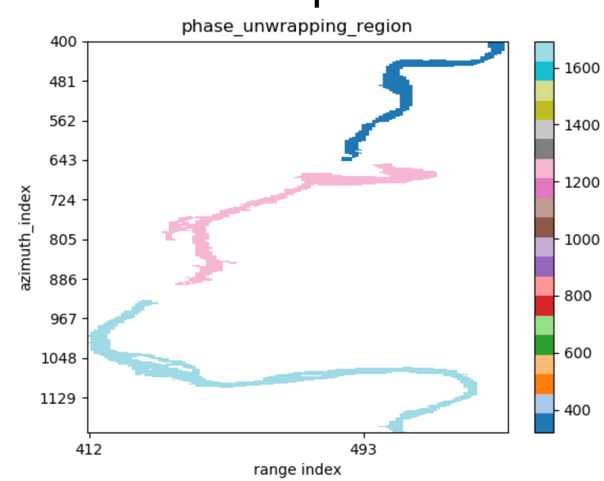
Phase Unwrapping Errors

- Phase is only measured to within a 2-pi ambiguity
- Spatially unwrapped over regions
- For each region, alternative sources are needed to choose which multiple of 2-pi
  - Reference DEM (amb. height ~10m to 60m, near- to far- swath)
  - Prior water mask (1-amb error causes ~750m shift in cross-track location)
- Phase unwrapping errors are rare, but when they happen they can significantly mess up large areas of otherwise good data
  - Whole region is shifted in cross-track and in height (several meters height error and several hundred meters location error)





Slant-plane



Status

- PDD in revision based on Science Team reviewer feedback

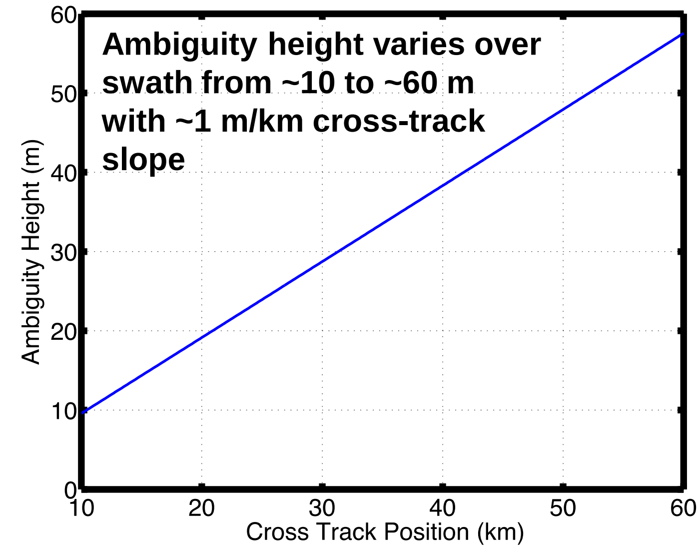
- ATBD drafted, under internal review among ADT subgroup
  - Most algorithms baselined, but many are likely to be revised
    - Water detection fairly stable only minor revisions expected
    - Actively working on phase unwrapping, dark water flagging
    - Bright land flagging algorithm development is starting up
    - Geophysical corrections and phase screen corrections not yet implemented

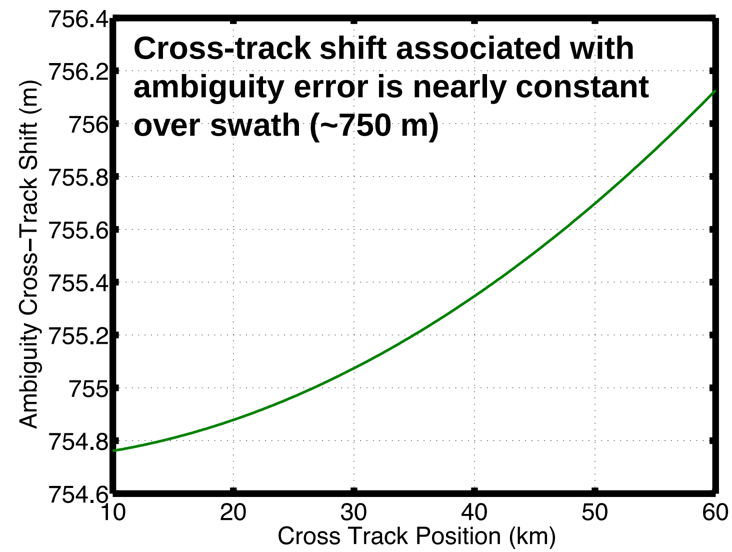
- Example data products will be made available
  - Plan to distribute a PIXC sample product consistent with the river sample products when they are ready

Backup
(from 2018 SWOT Science Team)

Phase Unwrapping Effects and Algorithms

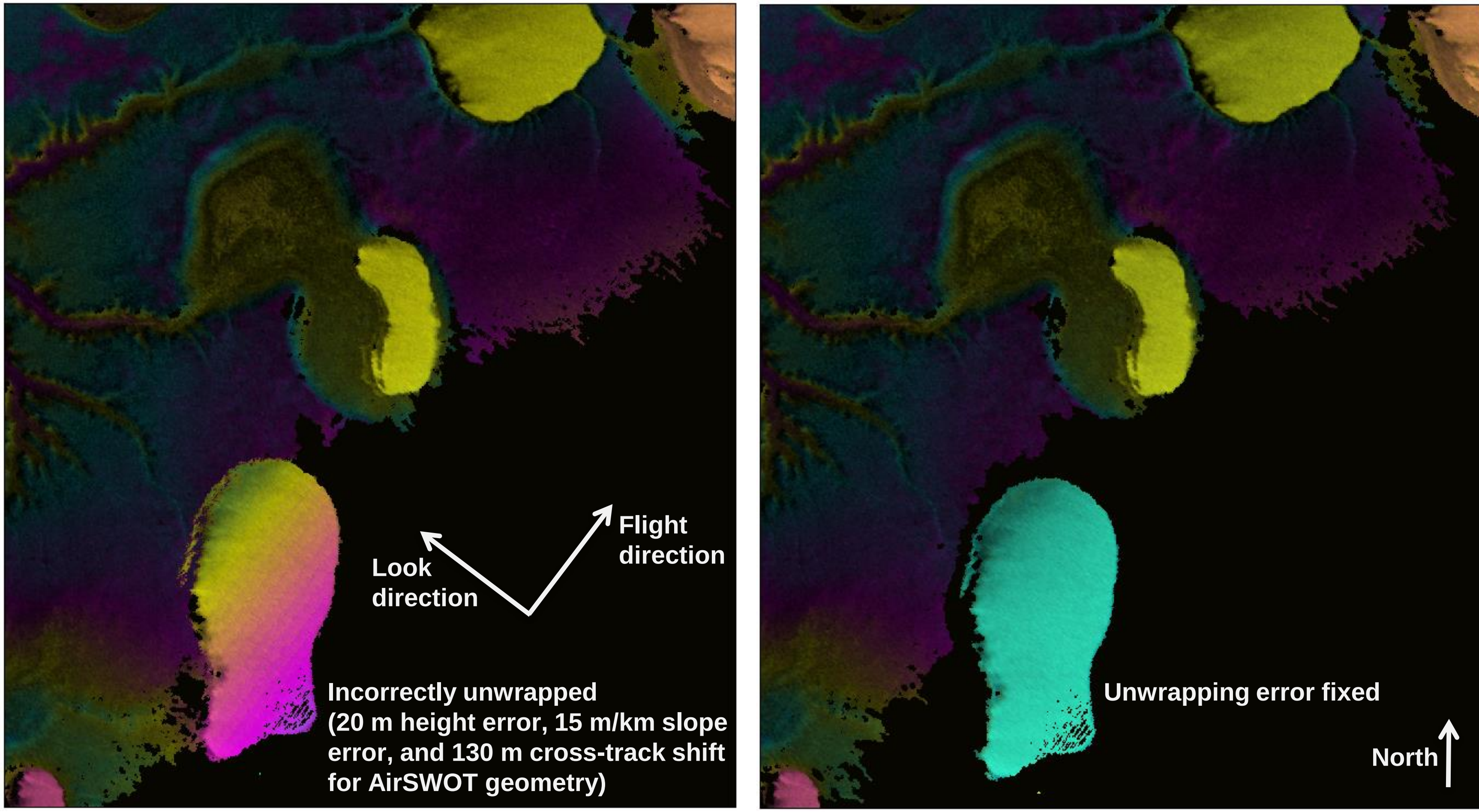
- Many algorithms exist for spatial unwrapping to get regions of pixels that are unwrapped correctly relative to each but not absolutely
- **Absolute ambiguity resolution on region basis is unique challenge for SWOT**
  - Small ambiguity heights require high vertical accuracy for reference DEM
  - Low 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

~4 km



AirSWOT Line 20150615005432
(Near Yukon River, Alaska)

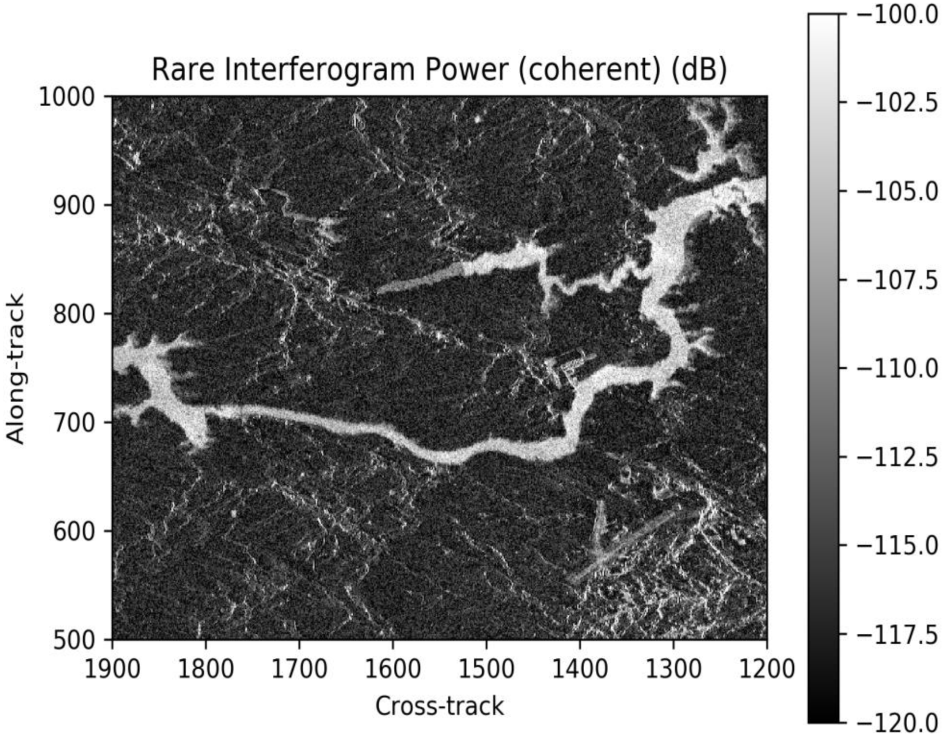
Grayscale represents radar reflectivity

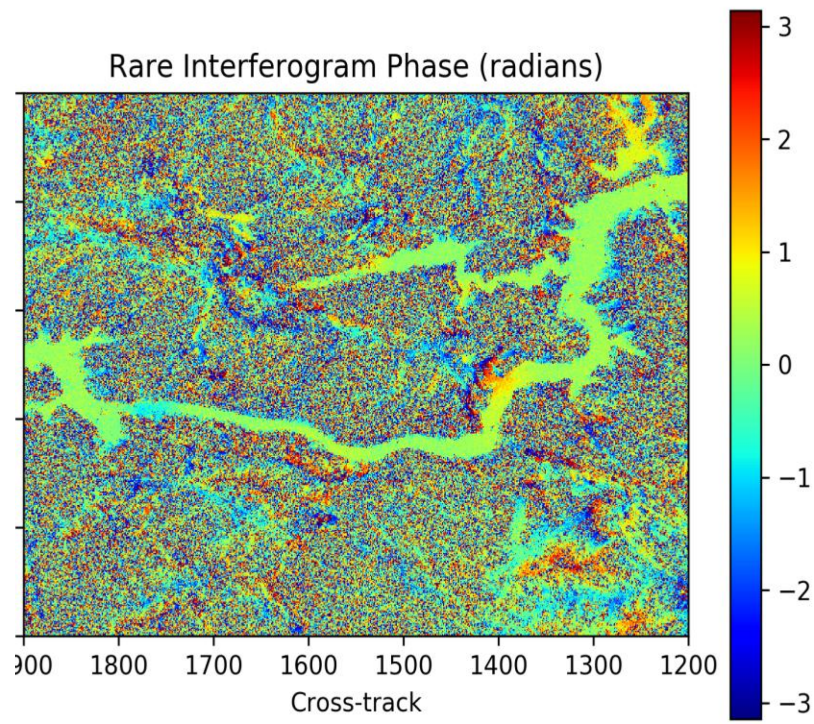
Color represents height (shown with 30 m wrap)

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

Rare Interferogram

- SLC images are interfered and multi-looked (~spatially averaged)

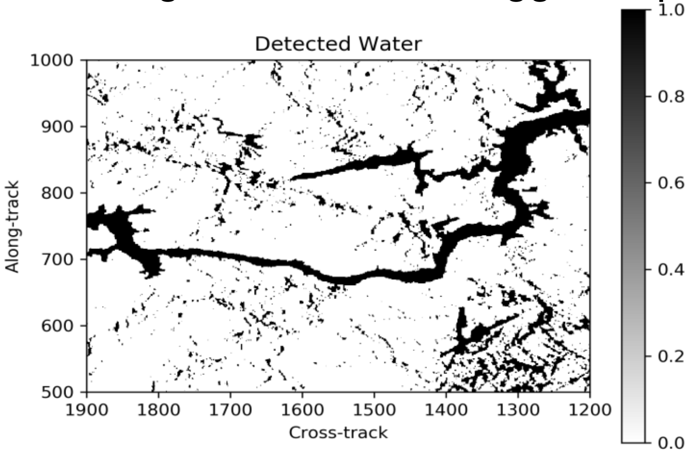


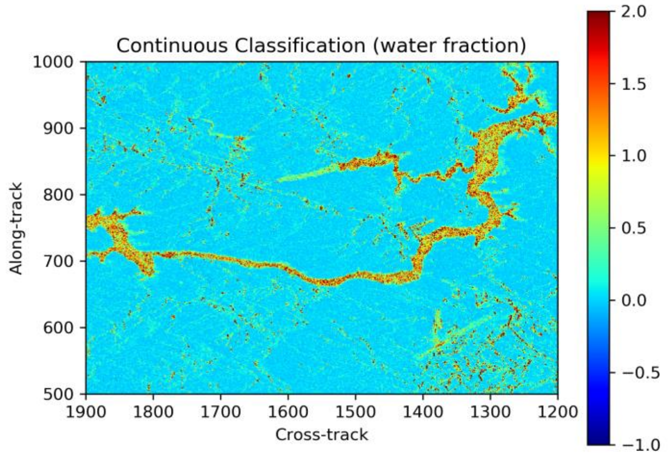


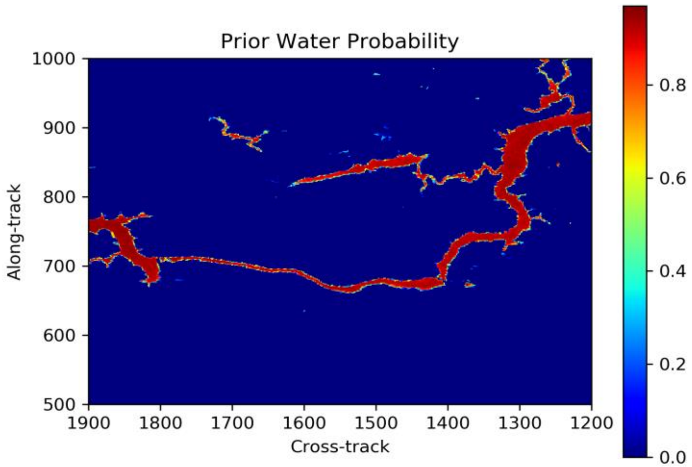
Lake Hickory,
North Carolina

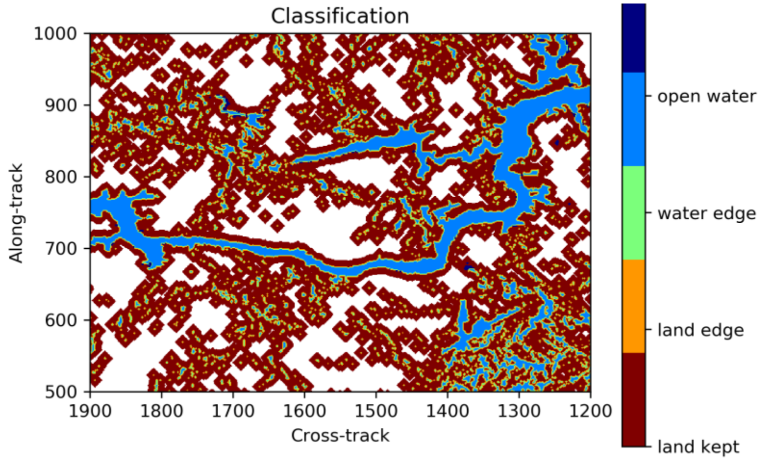
Water Detection

- Power threshold-based binary detection with MRF spatial regularization
- Fractional water estimation
- Dark water flagging base on prior water mask
- Edges/boundaries flagged separately



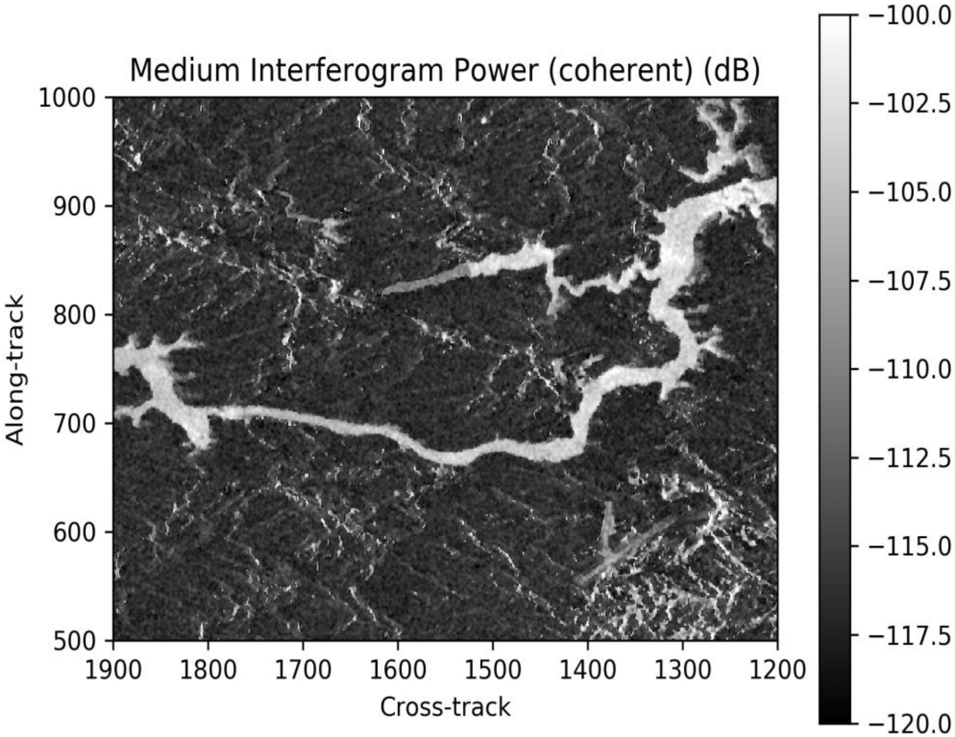


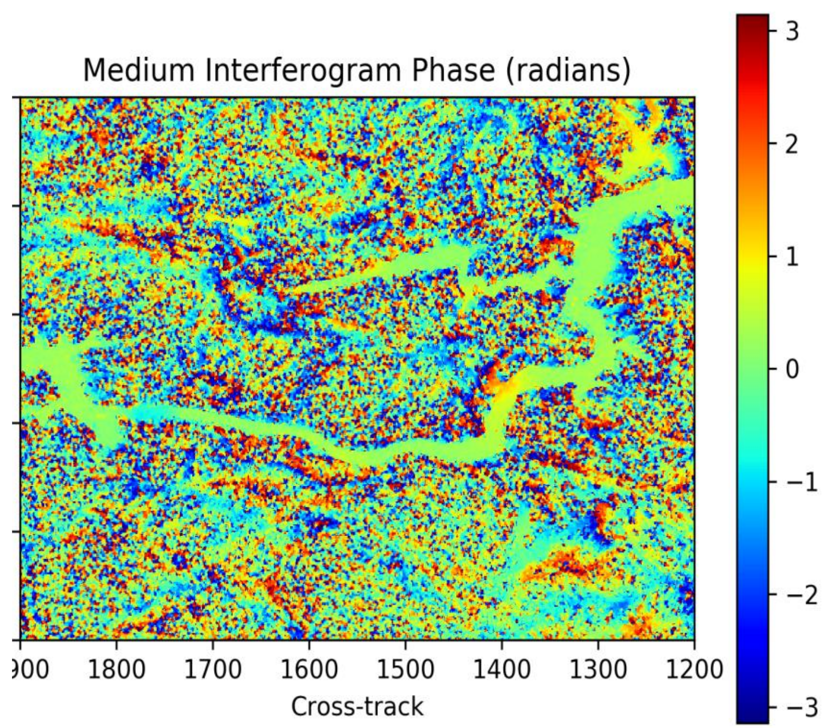




Medium Interferogram

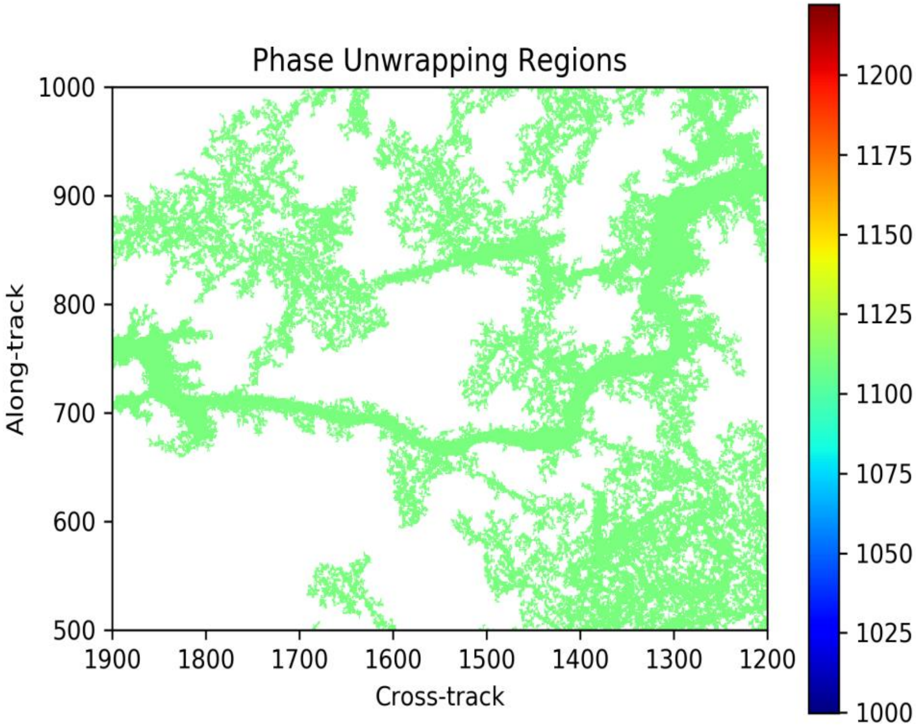
- Interferogram adaptively multi-looked using detected classes

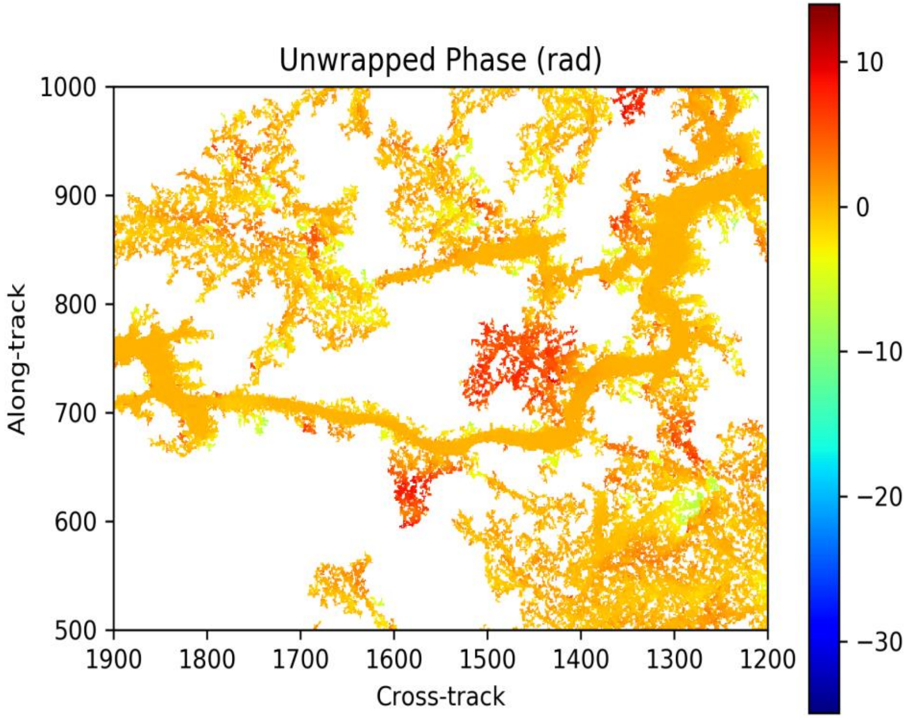




Phase Unwrapping

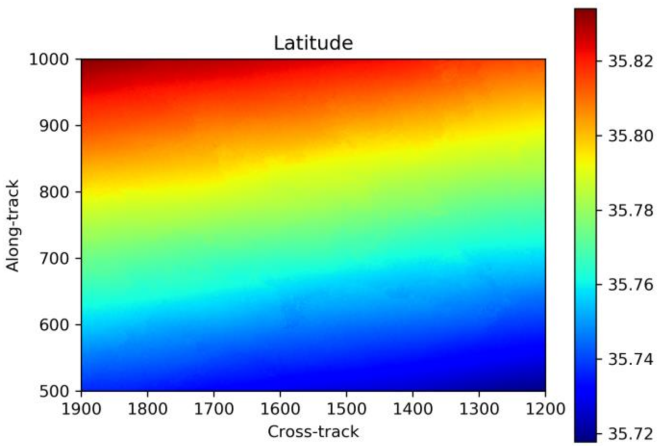
- Spatial phase unwrapping over connected regions
- Ambiguity resolution of each region (using prior DEM and water mask)

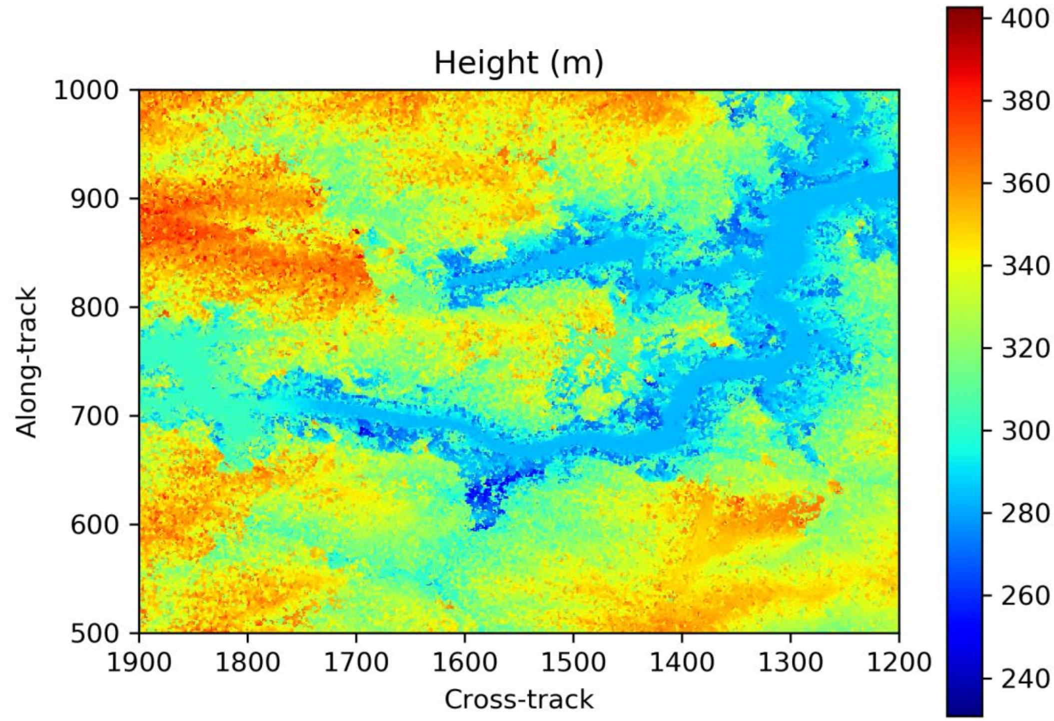


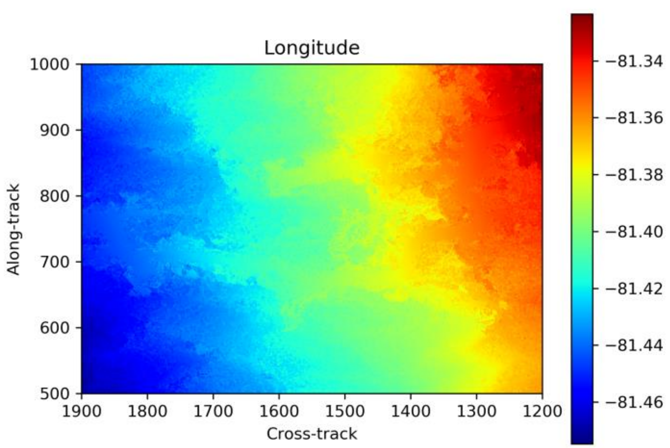


Geolocation

- Absolute phase, range, and doppler (azimuth) converted to lat, lon, height above WGS84 ellipsoid

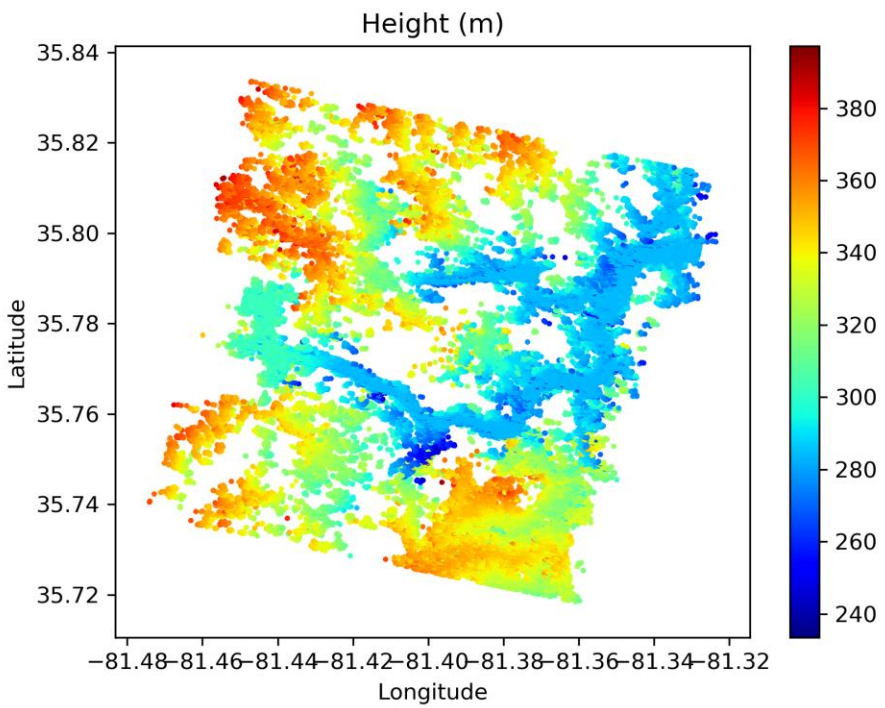


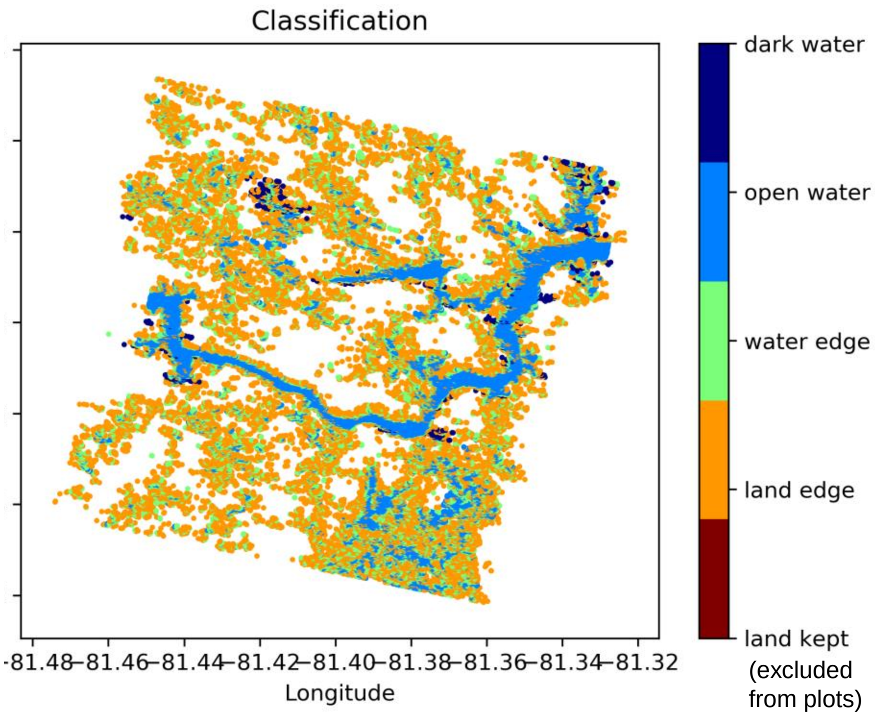




Prune and Create Pixel Cloud

- Exclude pixels not near water (or prior pruning mask)
- Reorder to 1-D list
- Include (but don't apply) height corrections, e.g., geoid, Earth tide…





(excluded from plots)