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Surface Water and Ocean Topography (SWOT) Mission

Validation Meeting

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KaRIn Calibration

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Cal/Val Objectives and Scope

- Basic objectives of Cal/Val[1]:
  - Calibration: Estimate calibration parameters for ground processing based on flight data
  - Error budget validation: Validate measurement performance (“*Does system behave as expected, and if not, what can/should we do?*”)
  - Data product validation: Validate measurement with respect to high-level requirements (“*Does performance meet mission success criteria?*”)
- Cal/Val scope is to fulfill objectives above by:
  - Collecting field data to enable SWOT calibration and validation
  - Performing calibration and validation analyses through comparisons between SWOT measurements and field data (as well as other independent observations)
  - Lead troubleshooting and diagnostic efforts when anomalies related to science performance are encountered

[1] SWOT Cal/Val Plan, Sects. 1.2-1.3

Flavors of "Calibration" for KaRIn

- Dynamic calibration: Time scale = *O*(seconds to minutes)
  - Processing software uses KaRIn internal calibration data to compensate instrument drifts and on-board parameter changes over orbit and repeat cycle automatically
  - Should be transparent to science users
- Crossover calibration: Time scale = *O*(hours to days)
  - Multiple passes of KaRIn data are used to remove instrument drifts at orbital time scales
  - Computed operationally by XOverCal processor
  - Corrections are reported and sometimes applied in products
  - More on this in other talks
- Static calibration: Time scale = *O*(years)
  - Empirical estimation of parameters that are assumed not to vary in time by operational processing software
  - Static calibration estimate are refined periodically, but this is done manually after offline analysis
  - May be updated for discrete changes in flight or ground configuration

Calibration is Joint Between LR and HR

- Static calibration parameters are estimated jointly for LR and HR data products
  - Underlying mechanisms for needing to tune calibration parameters are largely same between LR and HR because both LR and HR rely on same fundamental KaRIn measurement
  - Calibration involves extensive use of LR and HR data over ocean
  - Hydro field data over inland water is *not* used directly for calibration (only for validation)
  - LR and HR products are checked for consistency with each other
  - There are only minor LR-specific or HR-specific calibration parameters to compensate for differences in processing
- Note: Calibration analysis of HR data over ocean used special, offline processing to increase complex averaging (not available in public products) in order to avoid wave-bunching effects

Calibration Status

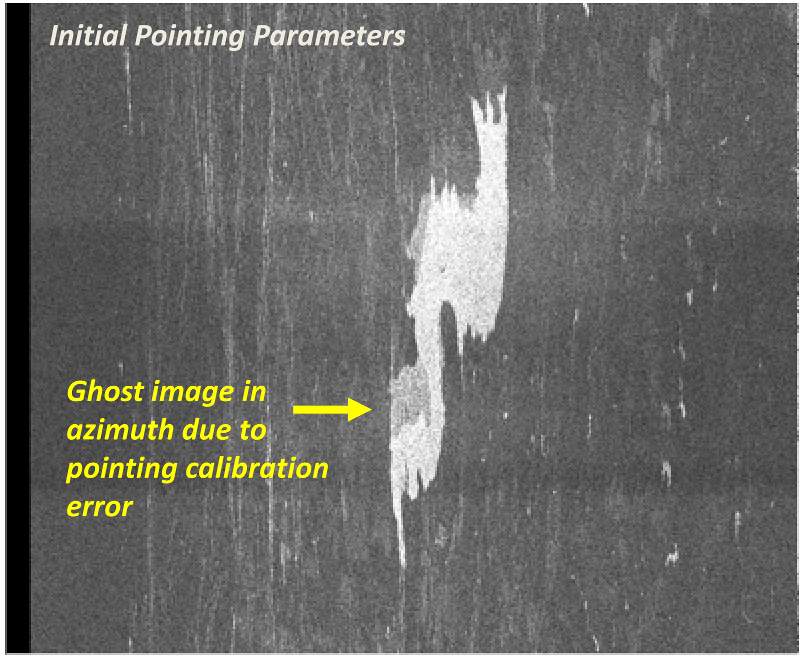
- **KaRIn Calibration has been largely stable since summer 2023**
  - Initial coarse KaRIn calibration (v104) deployed to forward processing 2023-05-16
    - Brings residual KaRIn static height errors from O(20 m) to O(20 cm)
    - Radiometric calibration within O(3 dB)
  - Initial fine KaRIn calibration (v105) deployed to forward processing 2023-06-29
    - Used for Version B (PIB0/beta-pre-validated) data products
    - Brings residual KaRIn static height errors from O(20 cm) to O(2 cm)
  - Refined KaRIn calibration (v106) deployed to forward processing 2023-11-22
    - Currently in use for Version C (PxC0/pre-validated) data products
    - Radiometric calibration adjusted to better balance H+, H-, V+, V- channels and LR vs. HR sigma0
    - No change to height calibration from v105
- Future calibration refinements:
  - Next bulk reprocessing:
    - Fix ~2.5 dB radiometric calibration error that affects sigma0 estimates only
    - Refine phase screens to remove ~ $\pm$4 mm static cross-track height variations
    - Fix ~0.3 HR pixel cross-track geolocation error for H swath
    - Fix ~1.5 cm HR bias relative to LR
  - Other adjustments as needed to compensate for any upstream changes in processing inputs (e.g., attitude reconstruction, ephemeris, KaRIn on-board configuration changes)

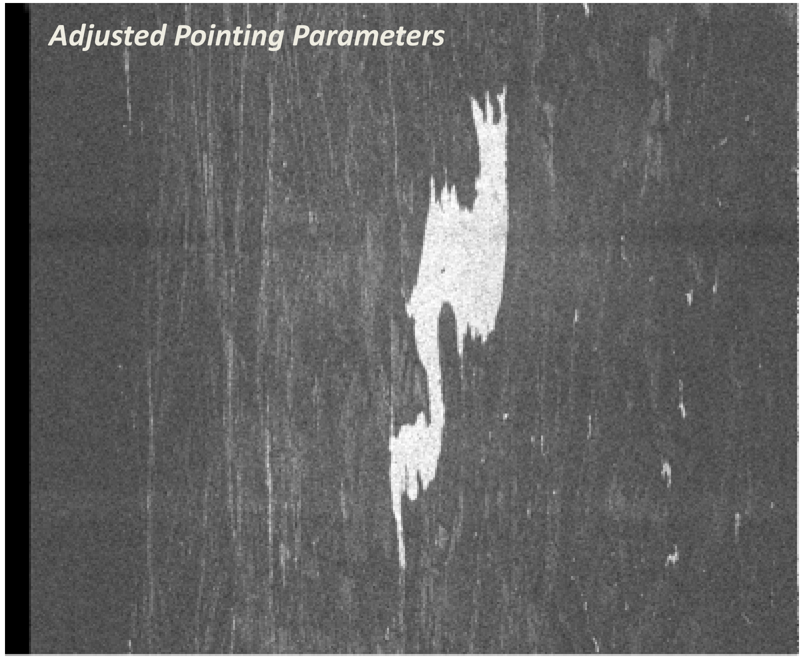
Calibration Sensitivities

- Key calibration parameters:
  - Pointing biases
  - Antenna phase center lever arms and static interferometric phase
  - Channel delays
  - Phase screen
  - Radiometric scale factors
- Methodologies for estimating calibration parameters can introduce dependencies on external information
  - Example: Is it significant that KaRIn agrees with nadir altimeter, or did we simply force them to agree?
  - Relationships are detailed in following slides

KaRIn Pointing Calibration

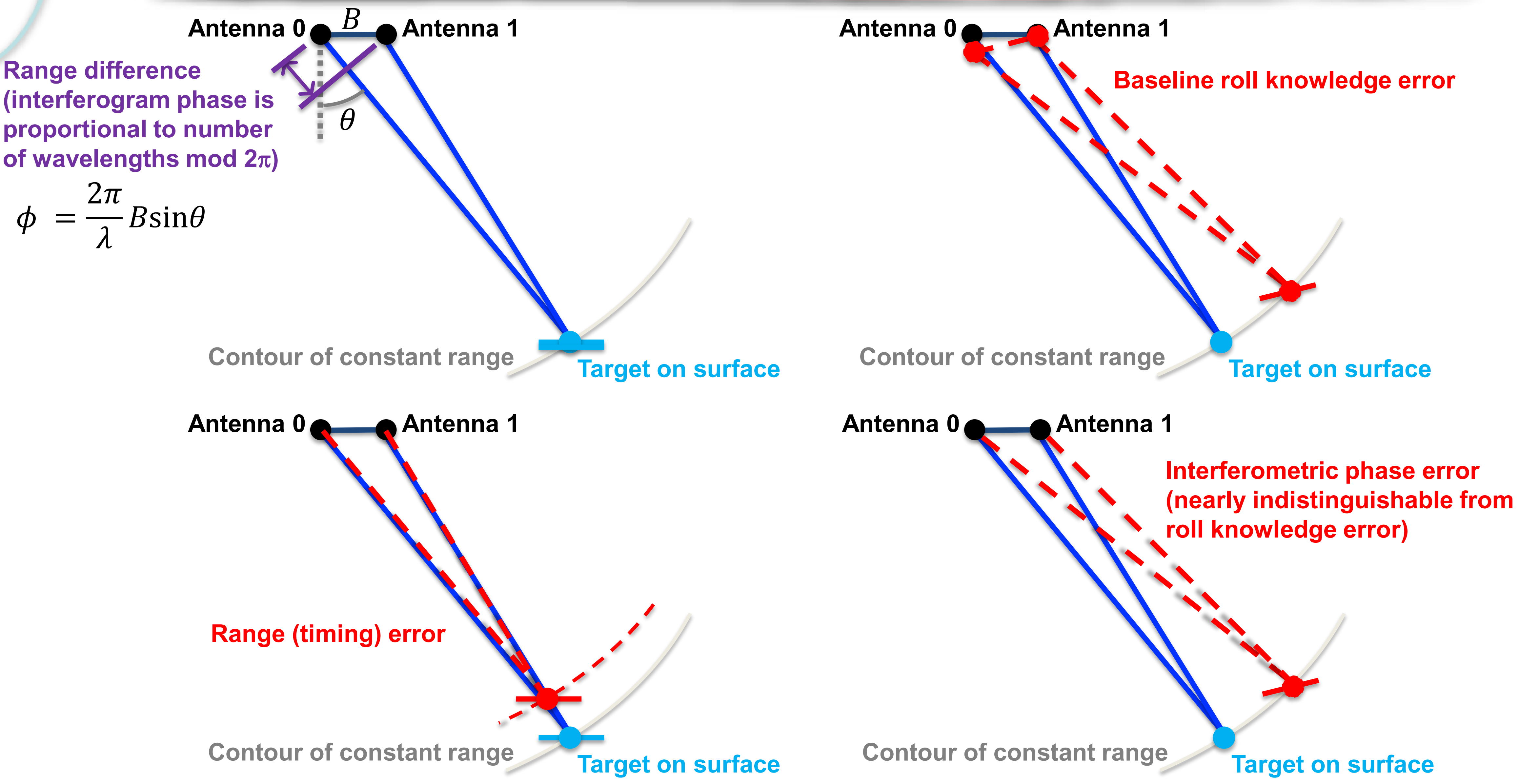
- What it controls: Rotations of four (H+, H-, V+, V-) antenna frames relative to KaRIn frame assumed during ground processing
- What it affects: Variations of height and sigma0 estimates from KaRIn with cross track and with attitude variations
- How it is estimated:
  - Pitch and yaw are estimated by comparison to KaRIn pulse-to-pulse Doppler estimates from KaRIn team
  - Roll is estimated by KaRIn team assuming symmetry of sigma0 vs. incidence angle for left and right sides





Foss Reservoir, Oklahoma, USA

Calibration Error Effects



$$\phi = \frac{2\pi}{\lambda} B \sin\theta$$

Antenna Lever Arms and Static Phase

- What it controls: Translations of antenna phase centers relative to KaRIn frame in 3-D and interferometric phase constant
  - Baseline roll and static phase are nearly equivalent
  - 3-D lever arms control baseline length, baseline roll, baseline yaw, and absolute vertical offset
  - Separate baseline parameters for H and V sides (separate lever arms for H+, H-, V+, V-)
- What it affects: Systematic height vs. cross track trends
  - Static phase and baseline roll (vertical component of lever arms) change gives tilt in height vs. cross track
  - Baseline dilation or length change (cross-track component of lever arms) gives quadratic height vs. cross track
  - Baseline yaw (along-track component of lever arms) is from pre-launch estimates but has negligible impact on products
- How it is estimated:
  - Estimate linear and quadratic height terms vs. cross track by:
    - Comparing observed KaRIn LR heights over ocean to mean sea surface (CNES/CLS 2015 MSS) after extensive along-track averaging (assumes MSS is correct on average)
    - Comparing observed KaRIn LR heights between short-time ocean crossover passes (assumes ocean surface does not change much at swath scales over ~12 hours)
  - Invert linear and quadratic heights to estimate vertical lever arm components and static phase analytically
  - Confirm that HR and LR heights are consistent with each other

Channel Delays

- What it controls: Absolute delay of radar echoes
- What it affects: Absolute height bias of KaRIn measurement before crossover calibration. Also affects cross-track (horizontal) geolocation somewhat.
  - But crossover calibration will update height biases based on LR data
  - Most important factor in calibration is that HR and LR biases are consistent so that crossover calibration estimated from LR data is equally applicable to HR data
- How it is estimated:
  - Tune differential channel delays to optimize interferometric coherence (KaRIn team)
  - Tune common delay coarsely using corner reflector data
  - Tune common delays of KaRIn LR data to agree with SWOT nadir altimeter over long length scales
  - Tune common delays of KaRIn HR data to agree with KaRIn LR data

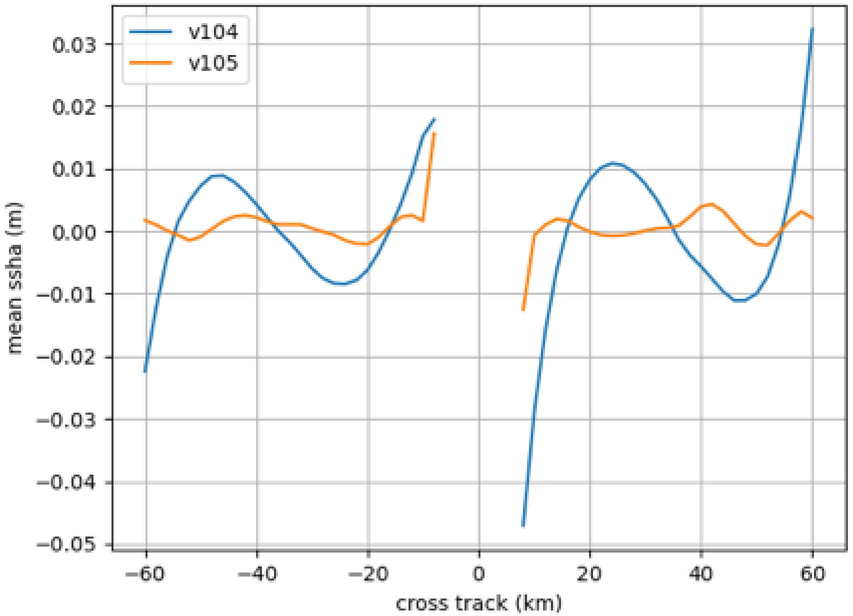
- **Small error in calibrating phase screen term as delay instead of phase gives horizontal geolocation error (cross-track shift) of approximately 0.3 HR pixels for H swath side only**
  - Magnitude of cross-track shift: ~18 m at 10 km cross track, ~3 m at 60 km cross track
  - Will be corrected in next bulk reprocessing
  - No effect for height
  - No effect for V swath side
- **Small residual difference (~1.5 cm) between HR and LR data (unrelated to above)**

Phase Screens

- What it controls: Compensation of systematic interferometric phase variations vs. elevation angle (i.e., across swath for each side)
- What it affects: Arbitrary pattern of height error vs. cross track
  - Phase screen is defined to exclude linear and quadratic empirical terms for cleaner bookkeeping
  - Phase screen has many degrees of freedom, so it is easy to hide other artifacts in phase screen estimate (i.e., unresolved problems can look like time-varying phase screen)
- How it is estimated:
  - Multiple estimation methods are used for both LR and HR due to complexity of phase screen:
    - Comparing observed KaRIn heights over ocean to mean sea surface (CNES/CLS 2015 MSS) after extensive along-track averaging (assumes MSS is correct on average)
    - Comparing observed KaRIn heights between short-time ocean crossover passes (assumes ocean surface does not change much at swath scales over ~12 hours)
    - Comparing observed KaRIn heights to MASS airborne lidar data collected within hours of KaRIn pass (assumes MASS correctly measures SSHA)
  - Confirm that HR and LR estimates are consistent with each other

Phase Screen Estimates

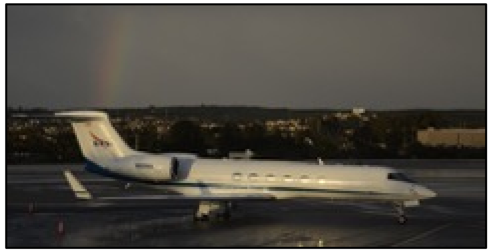
- Phase screen estimation approaches:
  - Compare KaRIn SSHA to MASS SSHA, assuming MASS is truth
    - Agreement to ~1 cm
  - Compare KaRIn SSHA to SSHA from nadir altimeters, assuming nadir altimeter is truth
    - CNES
  - Compare KaRIn SSHA between two crossing passes, assuming little change in SSHA
    - Consistent with other estimates
  - Average KaRIn SSHA in along track, assuming SSHA is zero mean
    - Residuals are below 1 cm
- **Phase screen is very well behaved**
  - Relatively stable and repeatable
  - Magnitude is relatively small
  - Variations have low spatial frequency

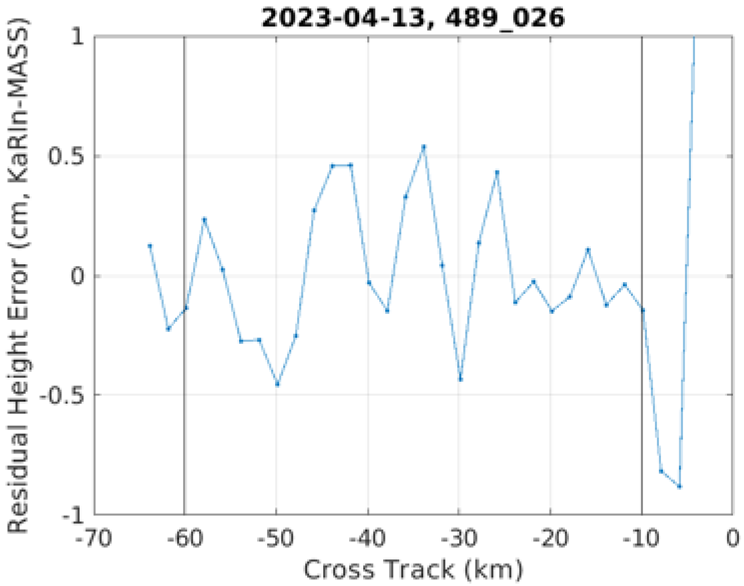


Phase screen residuals from along-track SSHA average after coarse calibration (v104) and fine calibration (v105) for single pass (cycles 563 for v104 and 565 for v105, pass 026)

Phase screen residuals compared to MASS* lidar (H swath, one MASS flight) and one SWOT pass

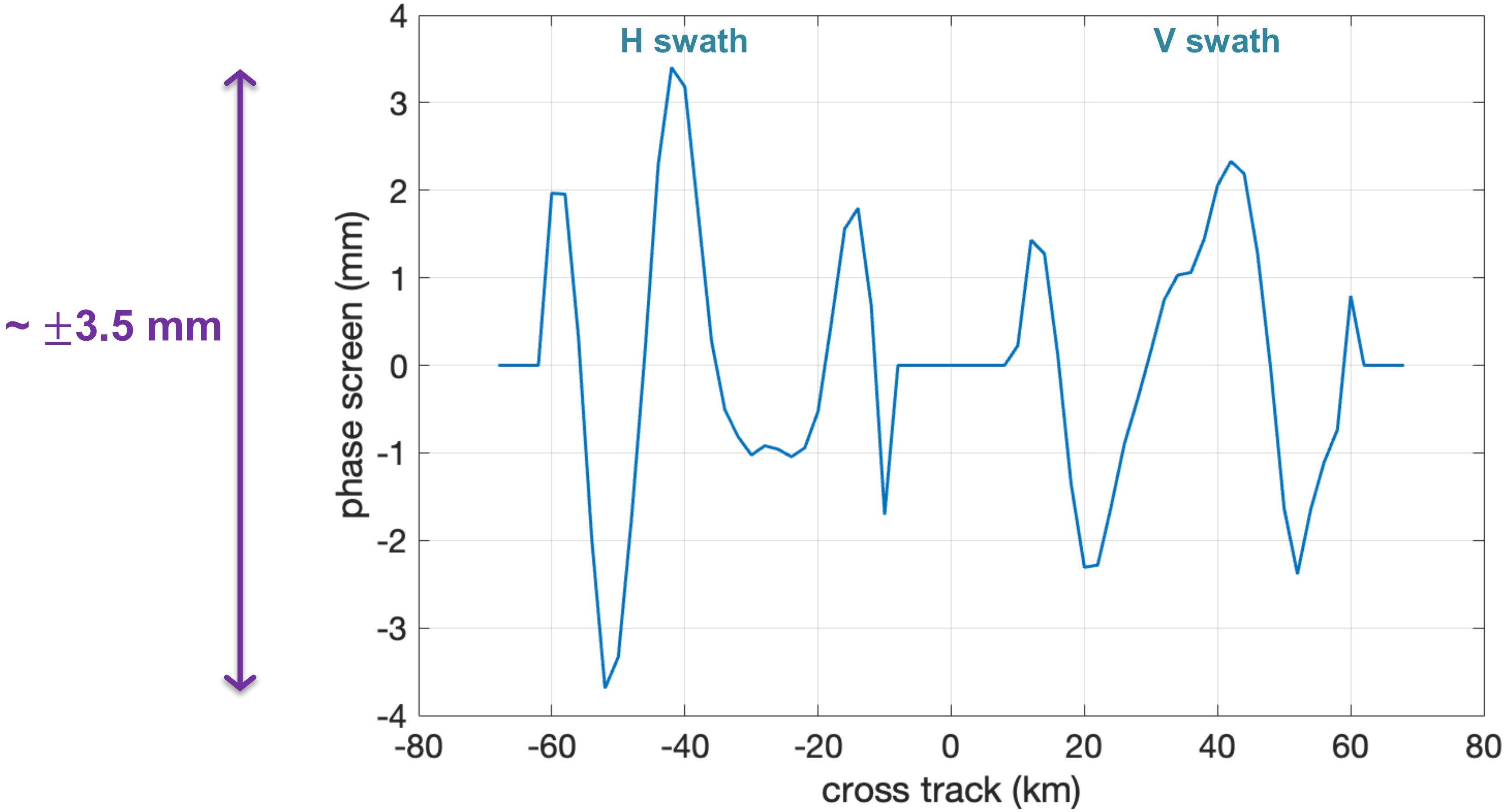
**MASS = Scripps Modular Aerial Sensing System*





Residual Phase Screen

- Residual static cross-track height variation due to phase screen error is small but will be removed in next major version of data products



Pattern shown becomes mirrored horizontally when spacecraft yaw flips

Estimate of residual phase screen obtained after doing lots of along-track averaging of LR SSHA estimates

Radiometric Calibration

- What it controls: Power scaling of KaRIn channels (H+, H-, V+, V-)
- What it affects: Overall scaling of KaRIn sigma0 estimates
  - Tuning of HR water detection parameters depends on radiometric calibration
- How it is estimated:
  - Compare LR sigma0 to geophysical model function (GMF) over ocean and average over lots of data to estimate overall absolute scaling
    - GMF is based on Global Precipitation Mission (GPM) data
    - Comparison is binned by incidence angle and model wind speed (ECMWF)
  - Tune HR to match LR over ocean
  - Adjust individual channels (H+, H-, V+, V-) to give consistent results with each other

- **Error made when computing GPM-based GMF (to which KaRIn was tuned to matched) gives +2.5 dB error in current KaRIn radiometric calibration**
  - Reported sigma0 values are 2.5 dB higher than they should be in current (PxC0) LR and HR products
  - Calibration will be adjusted to remove this error in next (~2025) bulk reprocessing
  - Change will not affect height measurements
  - Other parameters will be adjusted to compensate so there will be no change in HR classification or KaRIn wind speed estimates

Conclusions

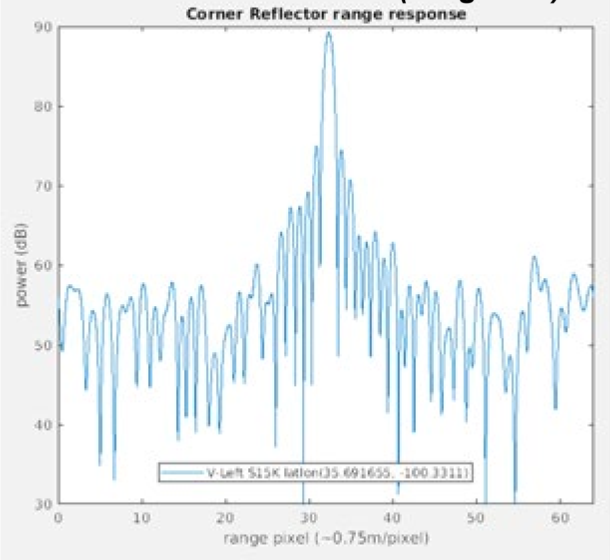
- Initial KaRIn calibration work is complete
  - KaRIn calibration is stable
  - Work to make minor enhancements will continue
- Calibration enhancements are expected for next bulk reprocessing:
  - Correction for 2.5 dB radiometric calibration bias
  - Small [~ $\pm$4 mm] refinements to height calibration, including updated phase screen
  - Correction of 0.3 HR pixel cross-track geolocation error for H swath
  - Correction of 1.5 cm height bias of HR with respect to LR
- **KaRIn data are well enough calibrated for science analyses to proceed**

Backup

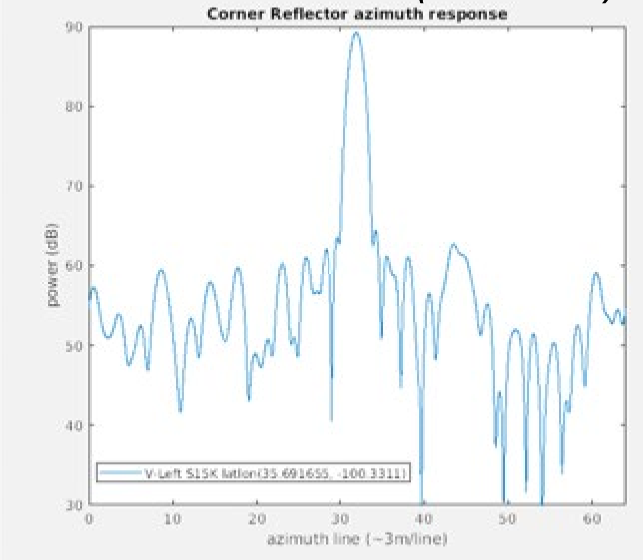
Corner Reflector Data

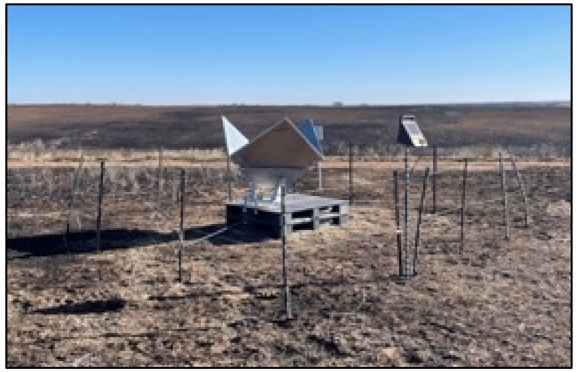
- Corner reflector data show that KaRIn imaging fundamentals are solid
- Corner reflectors were deployed at crossover of calibration orbit and have been taken down now that SWOT is in science orbit

Real data from S15K (range cut)

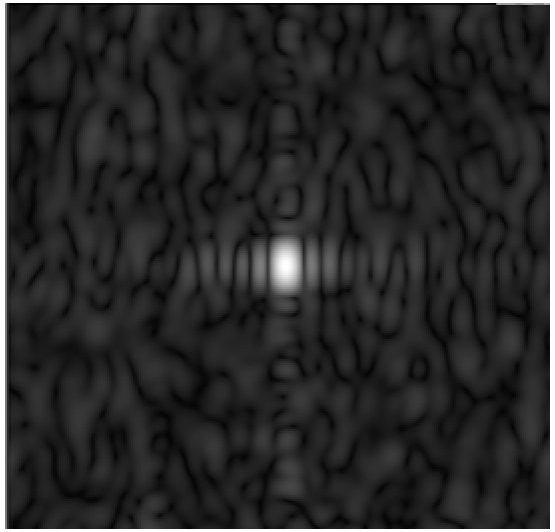


Real data from S15K (azimuth cut)



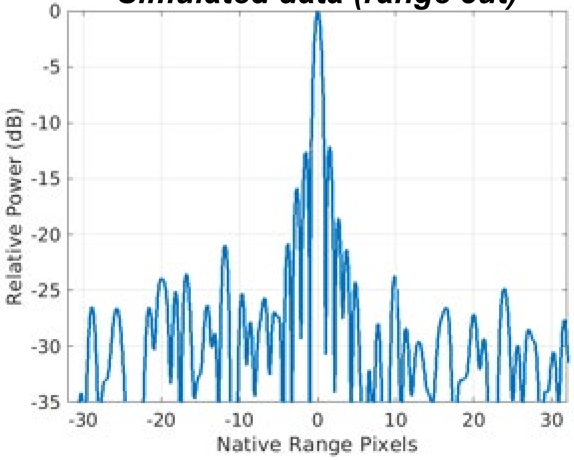


Corner Reflector S11K survived grass fire in early March 2023

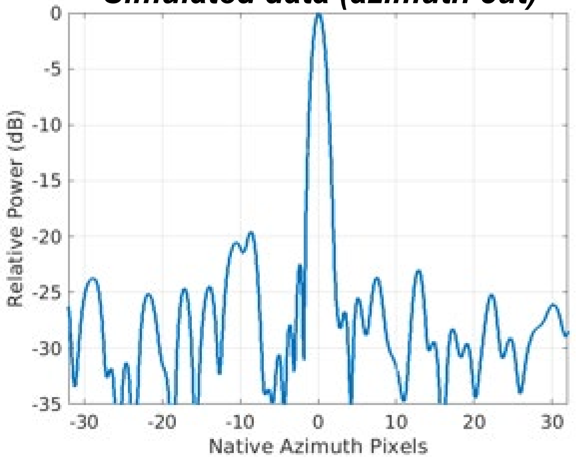


2-D Point target response (PTR) of S15K

Simulated data (range cut)



Simulated data (azimuth cut)



Corner reflector PTRs look great (better than simulation)

Mission Phases/Timeline