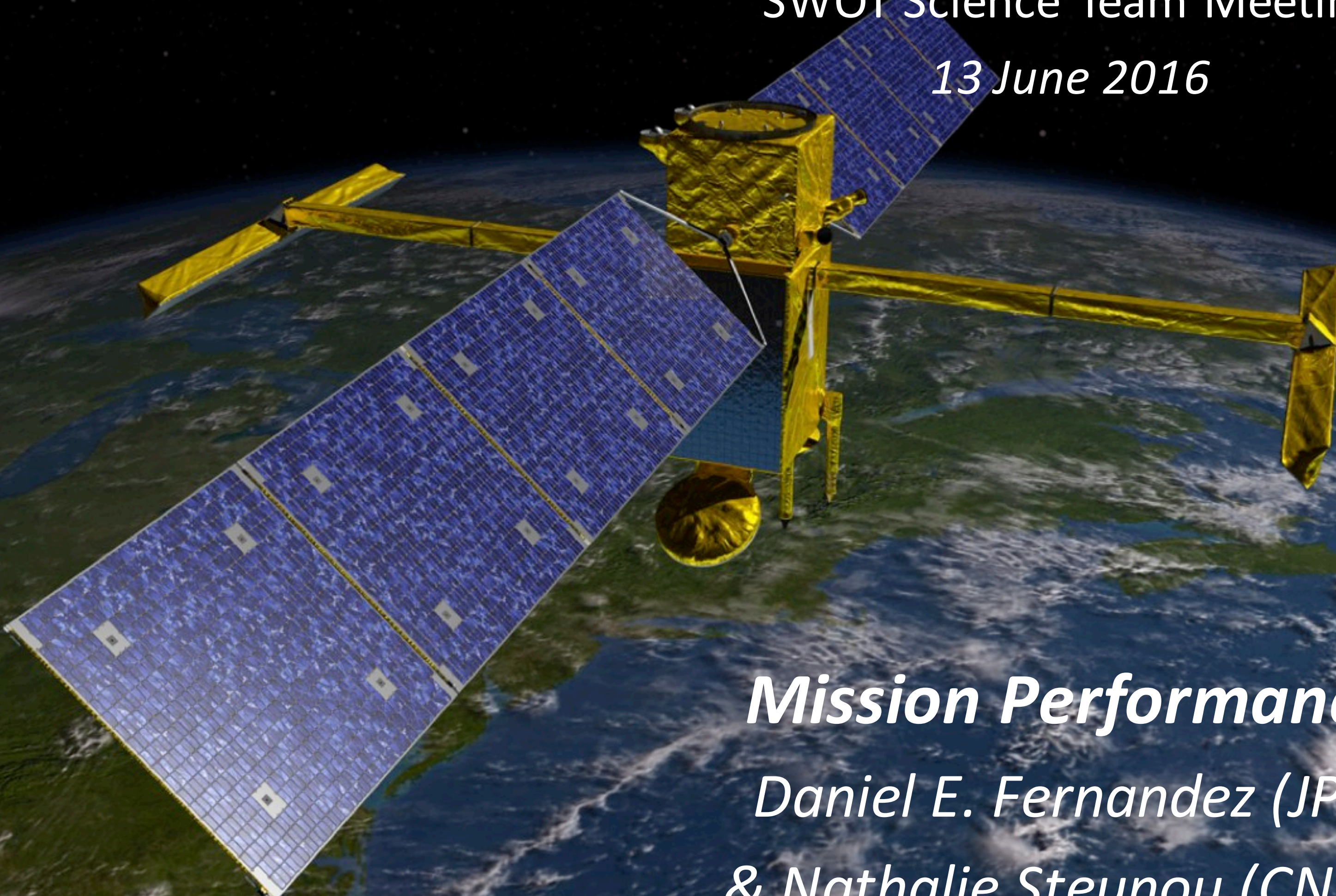
National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Surface Water and Ocean Topography (SWOT) Mission

SWOT Science Team Meeting

13 June 2016



Mission Performance

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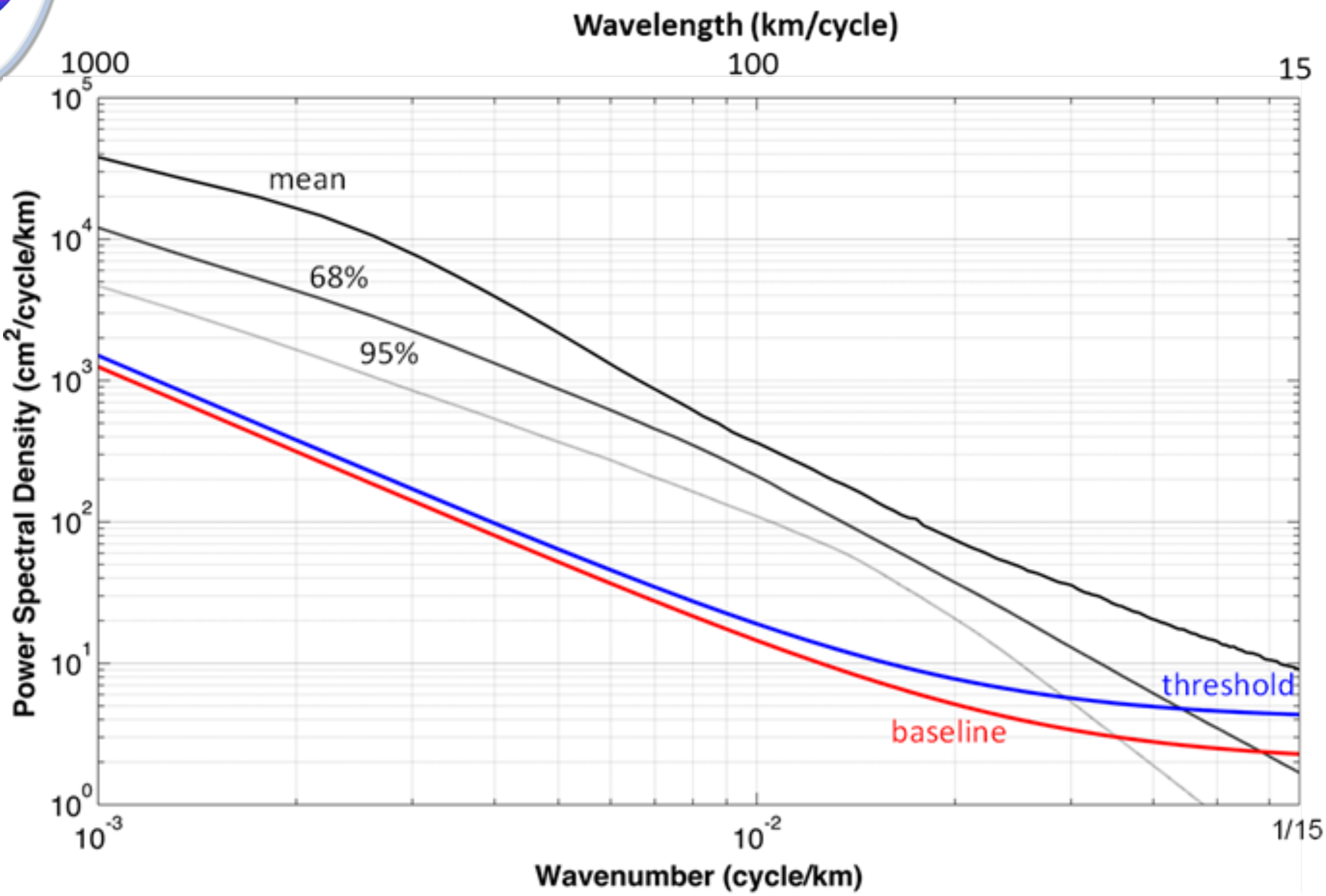
Introduction

- Mission Performance Engineering is responsible for developing and maintaining the mission performance error budget, tracking the performance estimates (CBEs) through the mission development, and developing and executing the pre-launch end-to-end performance Verification & Validation.
  - The SWOT error budget is documented in the SWOT Mission Error Budget Document, JPL D-79084.
    - Available at http://swot.jpl.nasa.gov/science/resources/
    - Describes the measurement, and documents the entire derivation and flow-down of the error budget.
    - Presented at various project reviews (SRR/MDR), and presented during past SDT meetings.
    - Being updated to include updates/evolutions.

Ocean SSH Requirement <1,000 km



The fundamental topographic measurement is provided by KaRIn, as a swath measurement

Ocean Error Budget Drivers

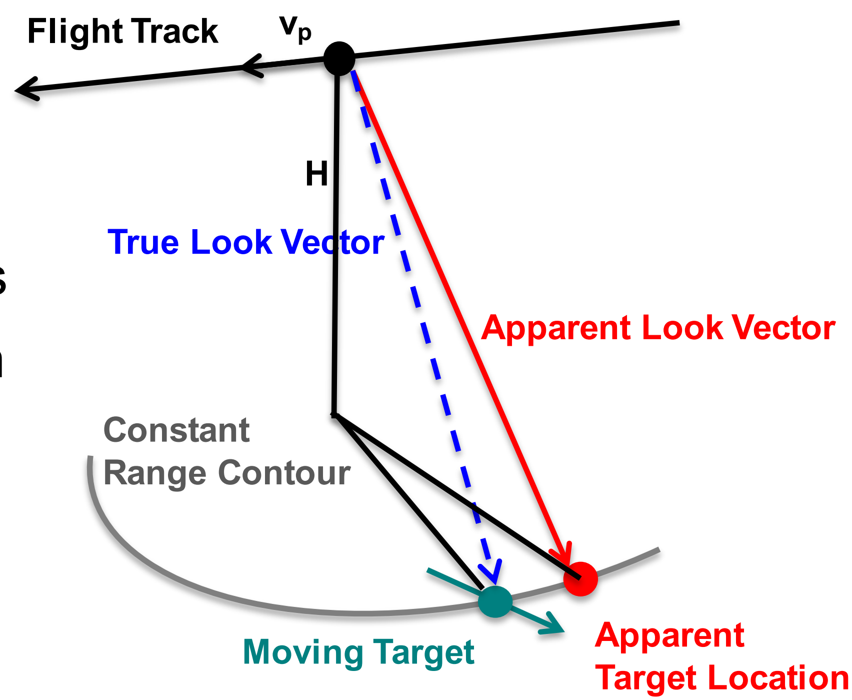
- Ocean SSH requirements apply over short time scales (1,000 km or ~2.6 min) and are described as a PSD.
  - Drives overall stability of the flight system over these time scales
  - Drives a minimum signal-to-noise ratio in the KaRIn measurement
  - Also need to consider other error contributors:
    - POD: radial height errors
    - Media effects, causing propagation delays of the EM signal: wet tropo, dry tropo, ionosphere
    - Sea-State Bias: different scattering from troughs and peaks of the waves bias the measured height
    - Wave effects (volumetric decorrelations, surf-board effect, motion errors)
- Ocean SSH RMS requirements (long wavelength) à la Jason
  - Similar to the Jason series of altimeters.

Ocean Interferometric Top-Level Error Budget

- **Systematic interferometric errors:** not zero mean, but not-destructive in nature; could be corrected in theory if adequate knowledge existed.
  - Baseline roll drift (KaRIn includes a dedicated gyro)
  - Relative phase drift
  - Baseline dilation drift
  - System timing (group delay) drift
  - Disturbances
  - Orbit error (platform radial height) drift
  - Angular biases
  - Surface motion errors (new at PDR)
- **Random interferometric errors:** zero mean and uncorrelated in space and time; destructive in nature, cannot be overcome after signals are acquired.
  - Noise (system thermal noise/speckle)
  - Geometric and angular decorrelations
  - Wave effects: wave (volumetric) decorrelation, and surf-board effect
- **Media and sea-state errors:** related to target and echo path characteristics, expected to be temporally and spatially correlated, at least on local scales.
  - SSB: Sea State Bias (different scattering from troughs and peaks of the waves bias the measured height).
  - Wet and dry troposphere (propagation delay of the EM signal)
  - Ionosphere (propagation delay of the EM signal)

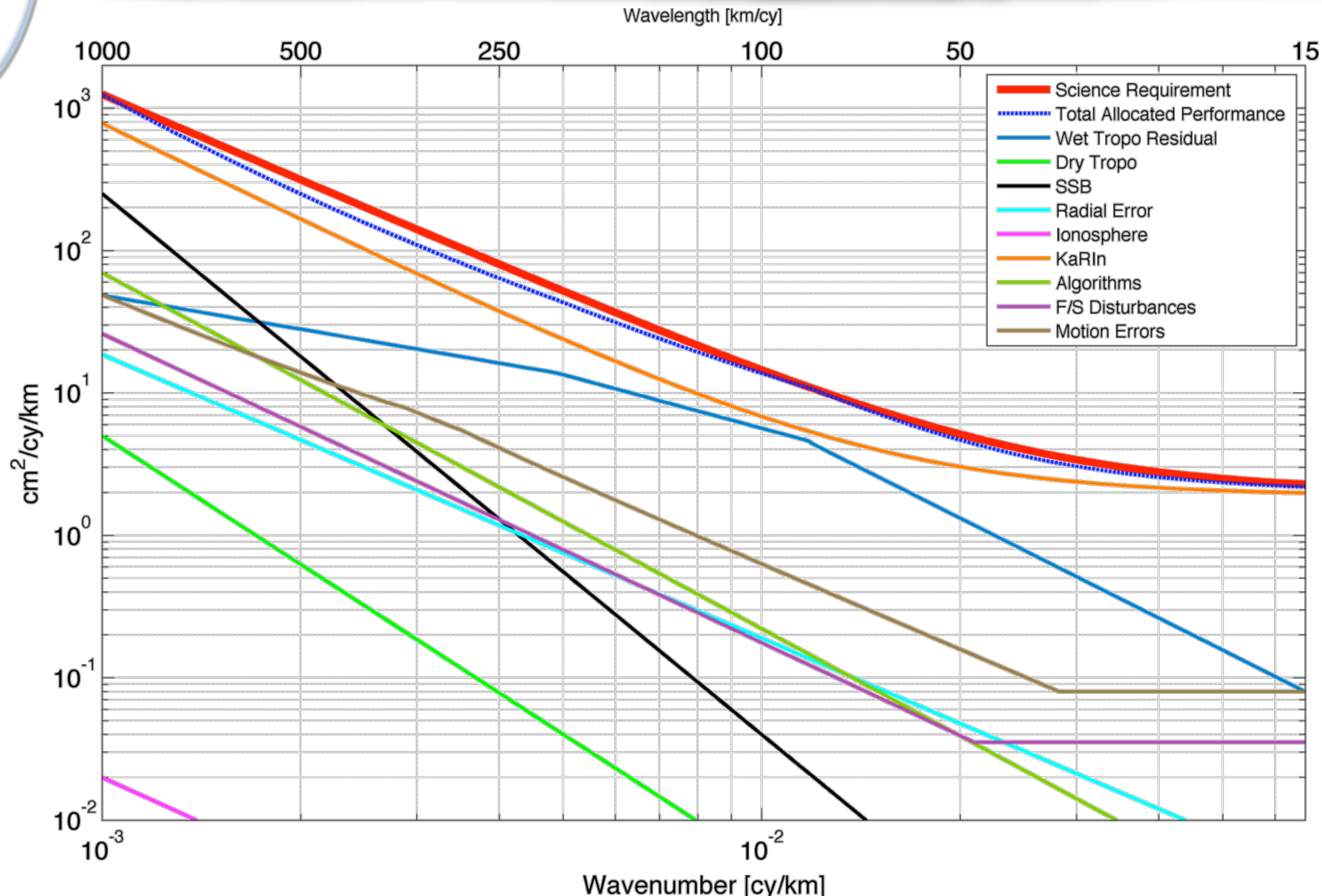
Velocity Effects on Interferometric Height

- Target motion causes errors in the interferometric height estimate
  - This is a well known effect: moving targets appear shifted in SAR images
  - Without knowledge of (and correction for) the target motion, the difference in interferometric phase between targets at the true and apparent target positions becomes an error in the interferometric measurement.



- Motion errors are a recent development
  - Emerged as a result of recent AirSWOT observations and data analysis
  - For SWOT, the pointing control error is sufficiently small to ensure that velocity errors are small and can be absorbed with a portion of the existing unallocated margins.

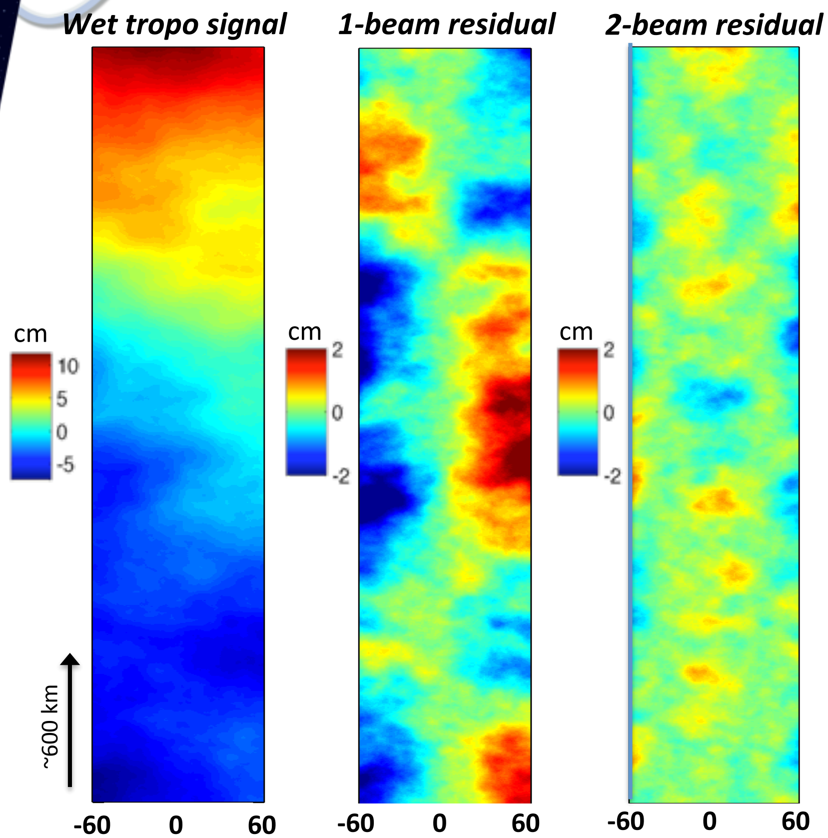
Ocean Top-Level Error Budget Allocations



The conversion from wavelength to sampling time is $T_s = \frac{\lambda_{ocean}}{v_{ground}} = \frac{\lambda_{ocean}}{6.5\ km/s}$

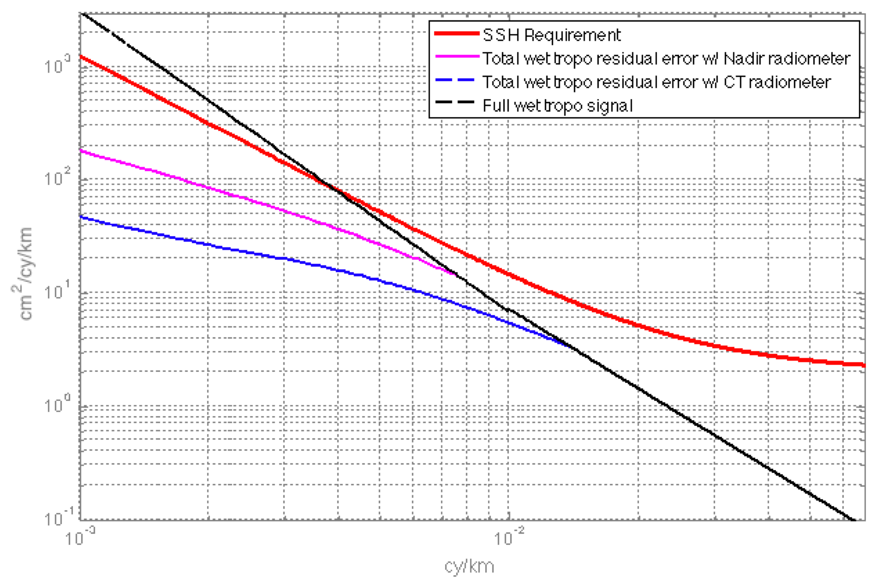
Ocean Wet Tropo Errors

Since MDR, the implementation of the cross-track radiometer has been confirmed.



- A nadir only radiometer correction leaves cross-track slopes resulting in 100-km scale cm-level PD error structures at the swath edges.
- For many regions of the globe, the mean eddy amplitude is on the order of about 5 cm, which is at about the same level of the larger edge of swath PD error structures from the nadir only radiometer correction
- A two-beam (cross-track) radiometer is able to remove a linear slope.

Spectrally, the cross-track radiometer is able to significantly reduce the wet tropo error for wavelengths >~80 km.



Ocean SSH Long Wavelength Error Budget

Ocean Error Component > 1,000 km	**Error [cm]**
Ionosphere signal	0.5
Sea-State Bias residual (1% of SWH)	2
Dry Troposphere signal	0.7
Wet Troposphere residual	1.2
Radial Error	1.6
Altimeter Noise	1.7
Total (RSS) Sea Surface Height Error	**3.4**

- Contrary to the error budget for SSH<1000 km, the nadir altimeter requires well-established model corrections to meet the media error allocations.
- Note the wet tropo error performance is slightly degraded (mm scale) for the nadir altimeter due to the implementation of a cross-track radiometer, but it is small and does not impact the feasibility of meeting the requirement.

Hydrology Error Budget

- The process of establishing the error budget for hydrology follows the same methodology as that of the ocean
  - Error sources are broken down in to media, systematic, and random
- Height error requirements (that apply for all time scales)
  - Relies on correcting long-term drifts using the KaRIn data itself (via cross-overs) such that the flight system does not have to be itself absolutely stable for the duration of the mission.
    - Extends (less stringent) stability for time scales up to ~30 min
  - POD and media effects (corrected via models).
- Slope error requirements (that apply for all time scales)
  - An extension of the above, as a derivative of the heights.
  - As a derivative, most of the error comes from the white noise.
- We need to detect water with a certain accuracy
  - Relies on the fact that water is brighter than land to be able to separate them. Actual limiting contrast is water-to-noise.
- Meeting these requirements requires achieving a certain signal-to-noise in the measurement, but not beyond what's required for SSH

Evolutions since MDR

- Since the MDR, the trade-off in the Land and Ocean resolutions of the onboard processed products has been finalized.
  - MDR baseline was to generate complex interferograms and SAR images with 1 km^2 pixels at 1 km posting, and a pre-sum factor of 2 for land.
  - Project constraints primarily imposed by data volume, required slight increase in the pre-sum factor for land to allow improving the ocean resolution.
- Following the recommendation of the SDT after the July'15 meeting, the baseline has since changed to:
  - Complex interferogram and both SAR images per swath at 500 m x 500 m pixels and 250 m posting.
  - Pre-sum factor of 2.1 (baseline), with an option for a second pre-sum factor of 2.4 available.

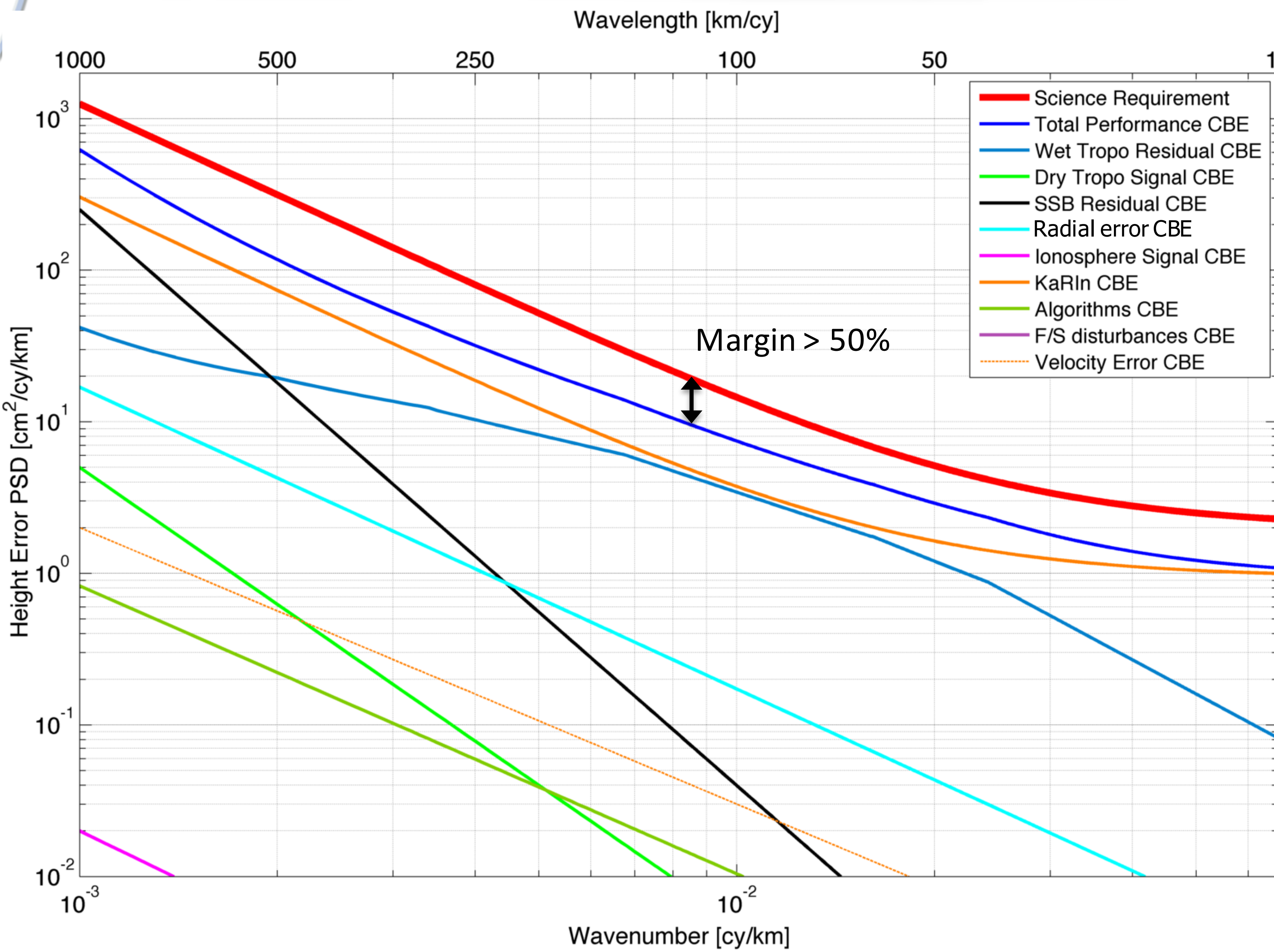
Hydrology Height/Slope Error Budget

Hydrology Error Component	Height Error [cm]	Slope Error [urad]	Basis/Comments
Ionosphere signal	0.8	0.1	RMS of full signal for maximum solar activity using IONEX model
Dry troposphere Signal	0.7	0.1	RMS after correction with models, based on Jason heritage
Wet Troposphere Signal	4.0	1.5	Model-based correction
Radial Error	1.62	0.5	Radial Error RMS
KaRIn Random and Systematic Errors after Cross-Over Correction	8.9	15.5	Includes cross-over correction residual
KaRIn Random	(4.4)	15.3	Height: 1km^2 avg. area of water-only pixels; slope: 10 km downstream of a 100 m river.
KaRIn Systematic cross-track errors after cross-over correction	(7.4)	(1.7)	RMS cross-track slopes for the entire along-track land pass.
KaRIn Systematic along-track height bias error	(1.5)	(0.08)	RMS timing and dilation along-track height errors down to 0 Hz.
High Frequency errors	(1.15)	(0.5)	RMS of systematic errors > 6.5 Hz
(Unallocated margin, RSS)	1.23	1.75	
Motion errors	0.8	1.6	Surface velocities of 2.6 m/s (1-sigma)
Total Allocation (RSS)	**9.98**	**15.7**	**Total error, as allocated**
Unallocated margin (RSS)	0.65	6.6	
Total (RSS) Error	**10**	**17**	**Requirement**

Basis of Ocean <1,000 km performance CBE

- CBEs of Dry tropo, SSB, etc. errors are based on analysis of data and well established models.
  - Original allocations were based on envelopes of earlier estimates.
  - Re-validated both by JPL and CNES teams.
  - CBEs are consistent with the allocations, with a little bit of margin.
- Wet troposphere residual error is based on AMR instrument and Wet tropo algorithm residual error CBEs.
- Radial error is based on analysis of other missions, and considering high frequency (<1,000 km) gravity effects and surface forces.
- KaRIn Random and Systematic Errors: based on phase B hardware test measurement results, STOP (Structural Thermal Optical) end-to-end analysis for in-flight temperatures and deformations of external structures.
- Algorithm Errors: based on analysis and simulation with prototype algorithms.
- S/C Pointing & Disturbances: based on preliminary analysis as part of the work leading to the S/C PDR.

SSH < 1,000 km CBE Roll-up



Ocean SSH Long Wavelength CBE

Ocean Error Component	Height Error CBE [cm]	Comments
Ionosphere signal	0.2	Based on Jason heritage Ku/C ionospheric residual error after filtering
Dry troposphere residual	0.7	RMS after correction with models, based on Jason heritage
Wet Troposphere residual	0.67	Based on AMR and Wet tropo algorithm analysis. Includes sampling error (0.35 cm), instrument error (0.4 cm), and retrieval (0.4 cm)
Radial Error	1.6	Jason heritage is ~ 1 cm. Preliminary analysis of CoM variation of F/S.
Sea State Bias residual	2.0	Based on Jason heritage.
Altimeter noise	1.52	Based on Jason heritage, including addition of 2.3 mm for antenna phase center variation (variable part estimated from PL module analysis)
Total (RSS)	**3.13**	
Requirement	**3.4**	

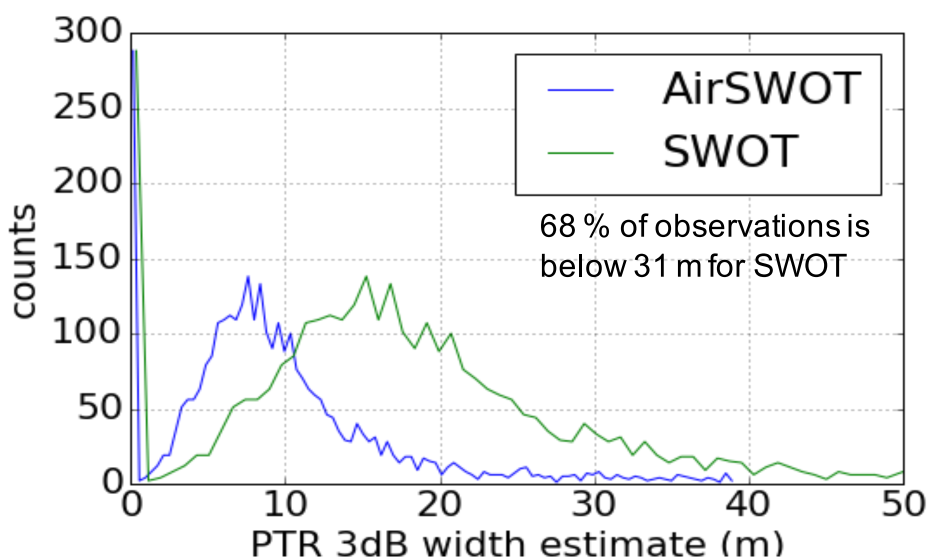
CBE is near the requirement value but this measurement has a lot of heritage

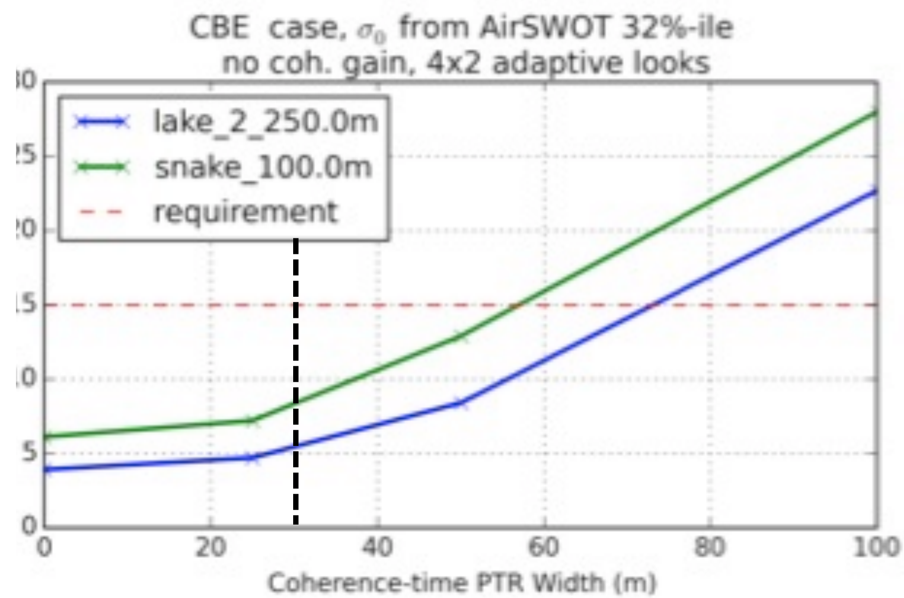
Hydrology Height/Slope CBE

Hydrology Error Component	Height Error [cm]	Slope Error [urad]	Comments
Ionosphere residual	0.8	0.1	RMS of full signal for maximum solar activity using IONEX model
Dry troposphere residual	0.7	0.1	RMS after correction with models, based on Jason heritage
Wet Troposphere residual	1.0	1.5	Model-based correction.
Radial Error	1.6	0.02	Radial Error (POD+CoM to Phase Center radial) RMS
KaRIn Random and Systematic Errors after Cross-Over Correction	6.9	8.5	KaRIn roll-up, after cross-over correction
KaRIn Random	2.4	8.32	Based on measurement KaRIn test data & STOP analysis
KaRIn Systematic cross-track errors after cross-over correction	6.33	1.62	Operational Calibration analysis of residual error
KaRIn Systematic along-track height bias error	1.5	0.08	Based on measurement KaRIn test data & STOP analysis
High Frequency errors	0.045	<0.01	S/C disturbance analysis
Motion Errors	0.4	0.8	Based on analysis of river motion data
Total (RSS)	**7.2**	**8.7**	
Requirement	**10**	**17**	
Margin	**28%**	**49%**	

Classification CBE

- Analysis for 100 m rivers and (250 m)^2 lakes shows compliance to requirement of 15% in area accuracy.
  - Based on analysis and simulation of lakes & river scenes reviewed during the Measurement System Review
- Current classification error CBE is 8%
  - Based on simulated scenes using sigma0's and PTR width observations consistent with AirSWOT's observations (no coherent gain assumed): 6% for (250 m)^2 lakes and 8% for 100 m wide rivers





Measurement Review

- A review of the SWOT measurement system was held on February 16 – 17, 2016.
  - Scope was to review the Error Budget and performance CBEs, Algorithms and Cal/Val development plans to assess the maturity to support the project PDR
- A significant portion of the review was also devoted to present out current understanding of the phenomenological aspects relevant for SWOT.
  - The results presented represent the culmination of a very significant effort conducted by the project to advance our understanding of key phenomenology
    - Examined all available sources of phenomenological information: GPM, AirSWOT, Umass Scatterometer, and others
    - Overall, error budget assumptions on phenomenology appear consistent with experimental observations and theory.
    - Residual risk of unexpected phenomenology is inherent given revolutionary nature of SWOT measurement; captured as mission concern in the project's risk list.
  - Efforts to reduce unanticipated phenomenology will continue through launch
    - Plans are in place to continue exploiting available datasets, acquire additional ones, and continue efforts in modeling, analysis and simulations.
    - Error budgeting process will incorporate new phenomenology results as they become available, similar to updates for hardware-related CBEs, etc.

Summary

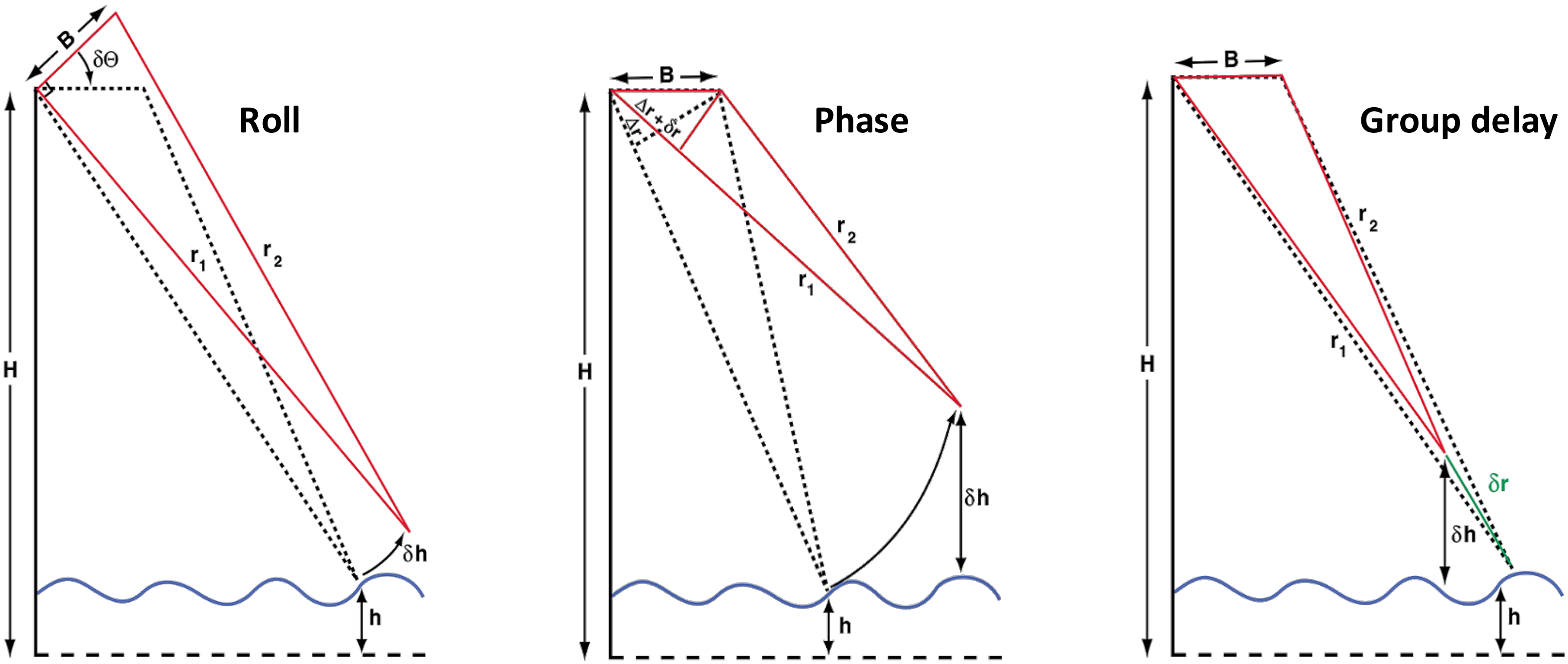
- Mission Performance also completed a rigorous set of reviews culminating in the Measurement System Review (February), and the Project PDR (April).
  - Tracked evolutions since MDR of the SWOT mission error budget
  - Motion errors are new addition.
- Phase B analyses show that Mission performance requirements are met with adequate level of margin
  - ~50% margin in SSH < 1,000 km
  - Ocean long wavelength requirement CBE is near the requirement value but the Nadir Altimeter-based measurement has a lot of heritage
  - Hydrology height/slope performance CBEs show margins of ~30 % and ~ 50%, respectively.
  - Classification performance CBE of 8% vs. 15% requirement
- Extensive efforts conducted since MDR to characterize phenomenology, and plans are in place to continue characterization through launch.

Backup

Primary Sources of Systematic Errors

The primary sources of systematic errors are due to drifts in roll, phase, baseline, and group delay.

$$\delta h_{roll} \approx C\left(1+\frac{H}{R_E}\right)\delta\theta_r \qquad \delta h_{phase} \approx \frac{C}{kB}\left(1+\frac{H}{R_E}\right)\delta\phi \qquad \delta h_B \approx -\frac{C^2}{HB}\left(1+\frac{H}{R_E}\right)\delta B \qquad \delta h_{gd} \approx \frac{c}{2}\cos(\theta)\delta t$$



1 asec roll = ~20 cm height error at center of swath

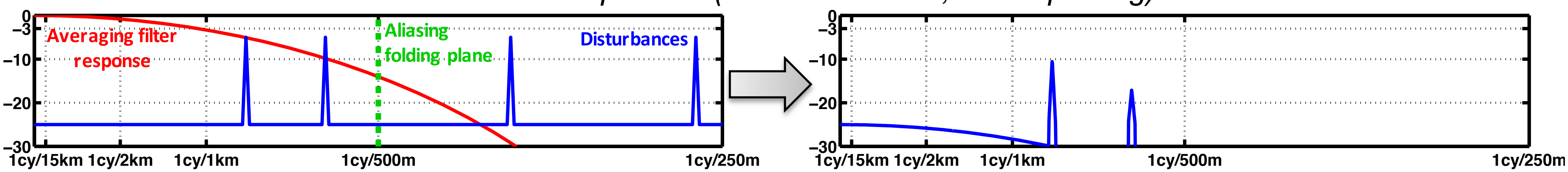
0.1 deg phase = ~1 cm height error at center of swath

100 ps = ~1.5 cm height error at center of swath

Disturbances

- Disturbance errors are also controlled
  - Induced by reaction wheels and solar array motions (only moving parts in the F/S)
  - Disturbance PSD requirement, together with the requirement of the fundamental deployed frequency of the system prevents excitation of non-rigid body motions that could impact the ocean PSD requirement;

Ocean OBP product (500m resolution, 250m posting)

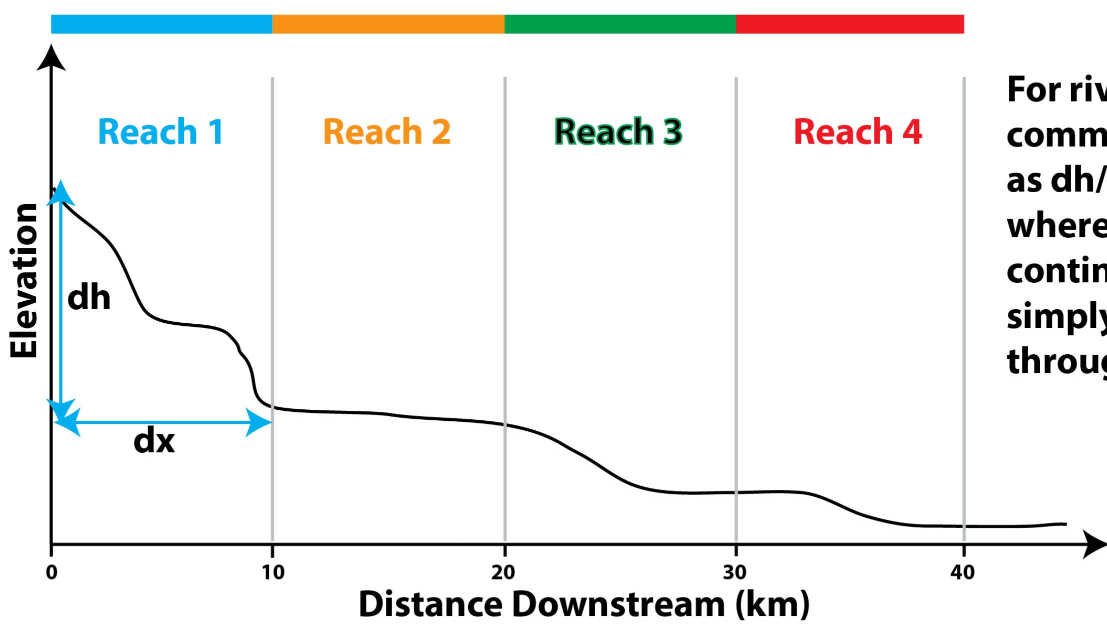


No spurs below 1cy/1km. Above 1cy/1km, spurs are greatly attenuated above folding plane, and can be removed in ground processing in generating the final resolution product.

  - Disturbance RMS requirement above 6.5 Hz limits high-frequency errors for hydrology

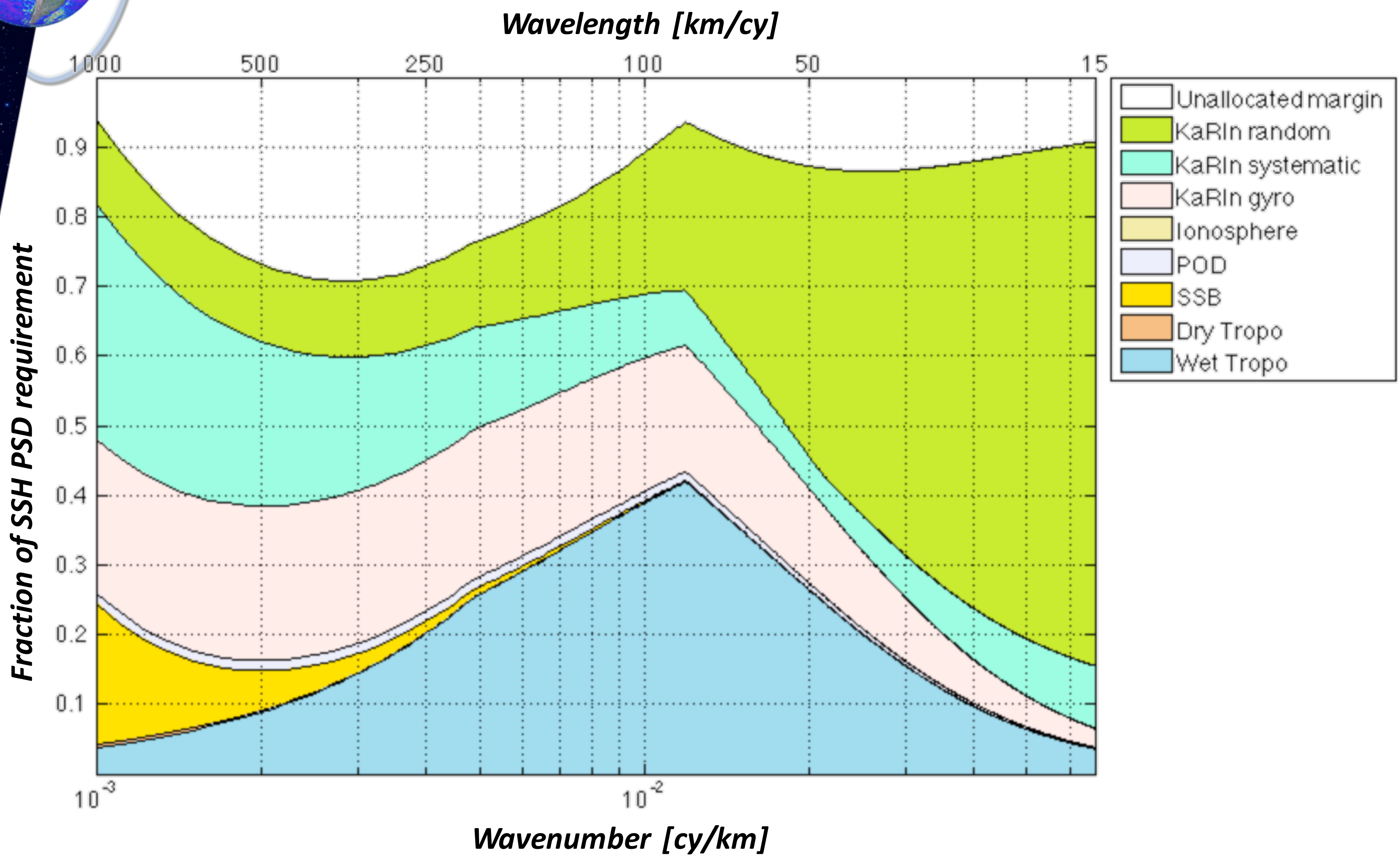
Evolutions since MDR

- Wetlands are now specified for characterization only.
- The slope requirement changed from 10 urad to 17 urad to account for a definition of slope that uses reaches with hard boundaries, rather than weighting functions with overlapping reaches.
  - No change in the assumption of the measurement noise: using a rectangular window of 10 km reduces the number of points available, and therefore the effective length over which the slope estimation is performed, resulting in an increased estimation error.



For rivers, slope is commonly calculated as dh/dx or, in cases where there is continuous data, simply fitting a line through that data.

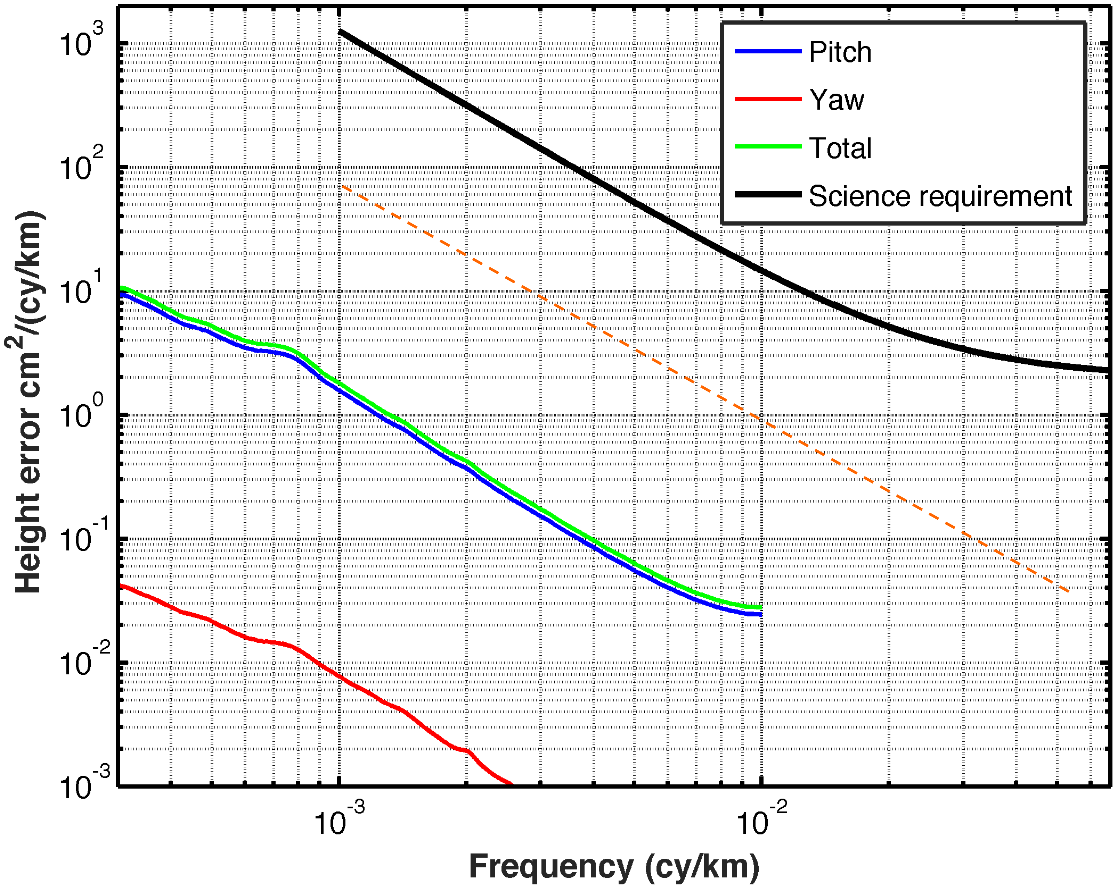
Ocean Error Budget Contributions: What Matters?



Radial Velocity Error CBE

The overall pointing control error CBE (S/C + KaRIn) has been used to derive the CBE of the impact of radial velocities on the height errors.

- Includes tilt and hydrodynamic (3% & 240 deg) modulations



Error CBE is ~1 order of magnitude lower than the envelope, and ~2 orders of magnitude below the SSH requirement.

Ocean Global Performance

Thermal noise + Surfboard only