Level-2 and Level-3 data-driven calibration

G.Dibarboure (CNES), C.Ubelmann (DATLAS)
B.Flamant, F.Briol, G.Brachet, Y.Faugère, O.Vergara (CLS)

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Introduction and context

- Why do we need XCAL and how does it work ? (pres. Gerald)

SWOT's pre-launch status

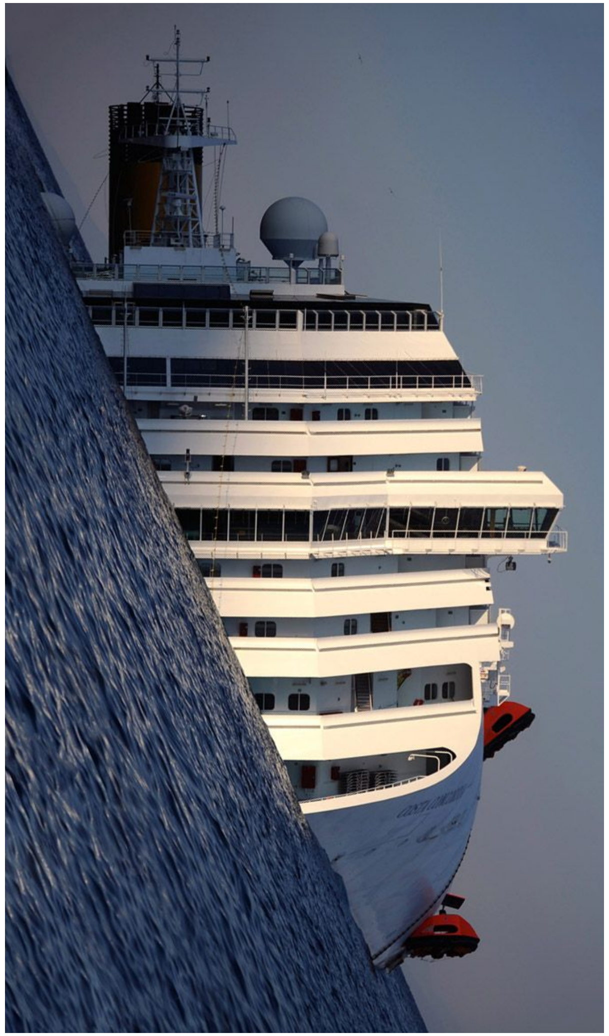
- Project Level-2 algorithms and performance (pres. Benjamin)
- Research Level-3 algorithms and performance (pres. Clement)

Summary and conclusions


Why do we need data-driven calibration?

The short answer is…

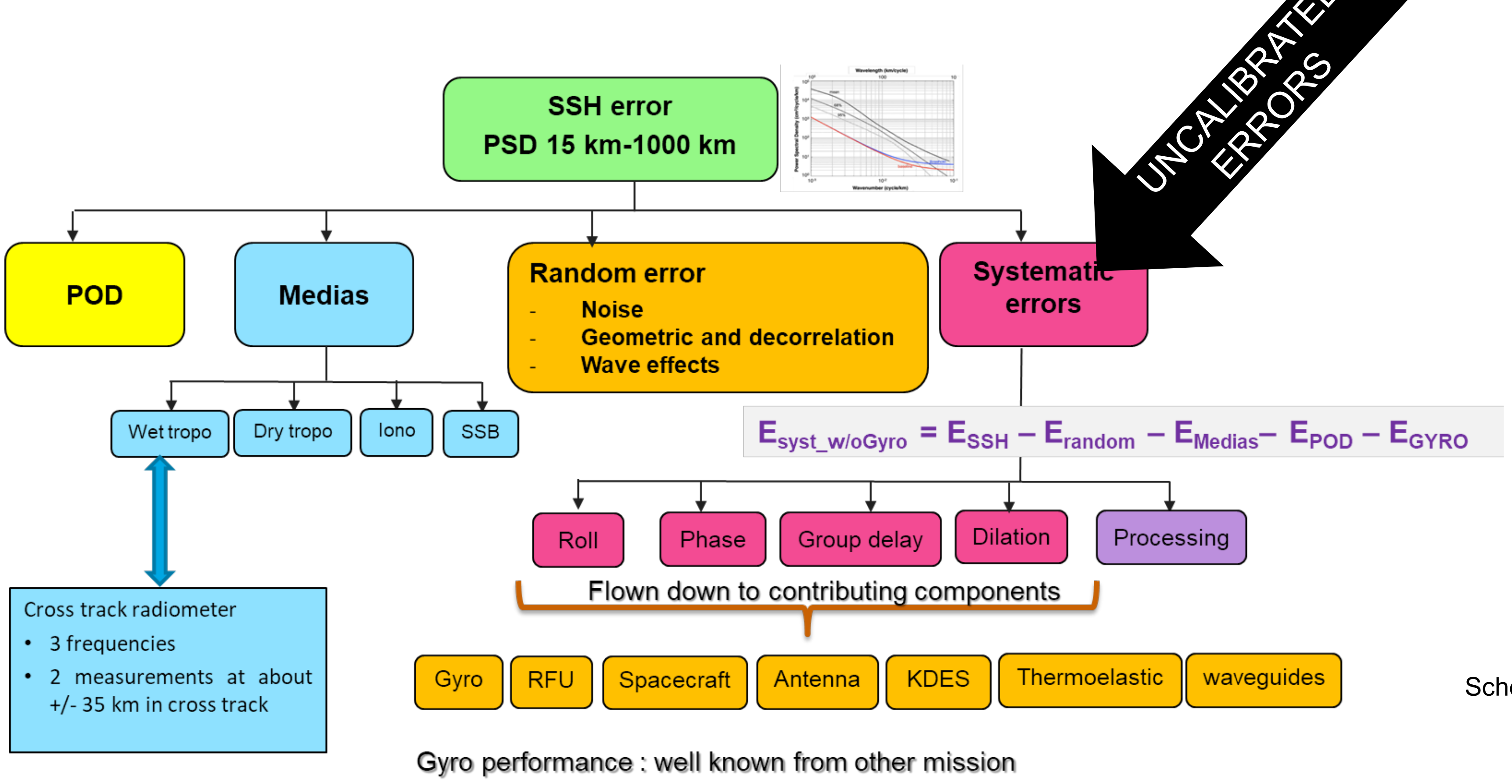
…because you don't want the ocean topography to look like this [1]



…and neither do hydrologists for inland water heights and slopes

[1] This is grossly exaggerated. Phew! Actual numbers in the next slides.

Starting point: the uncalibrated systematic errors



Schematics courtesy of N.Steunou

To summarize:

- The total uncalibrated systematic error is the sum of two simulations from the Project (updated in 2021)
  1. Attitude Knowledge Error Simulations (sensors + processing error, tagged as AOCS error)
  2. Instrument Model Simulations (in this talk, tagged as STOP21)
- Can be approximated as the sum of three error types : offset, linear & quadratic in the cross-track direction

3 examples of KaRIN's systematic errors

Antenna roll angle is not perfect?
Phase error in processing?

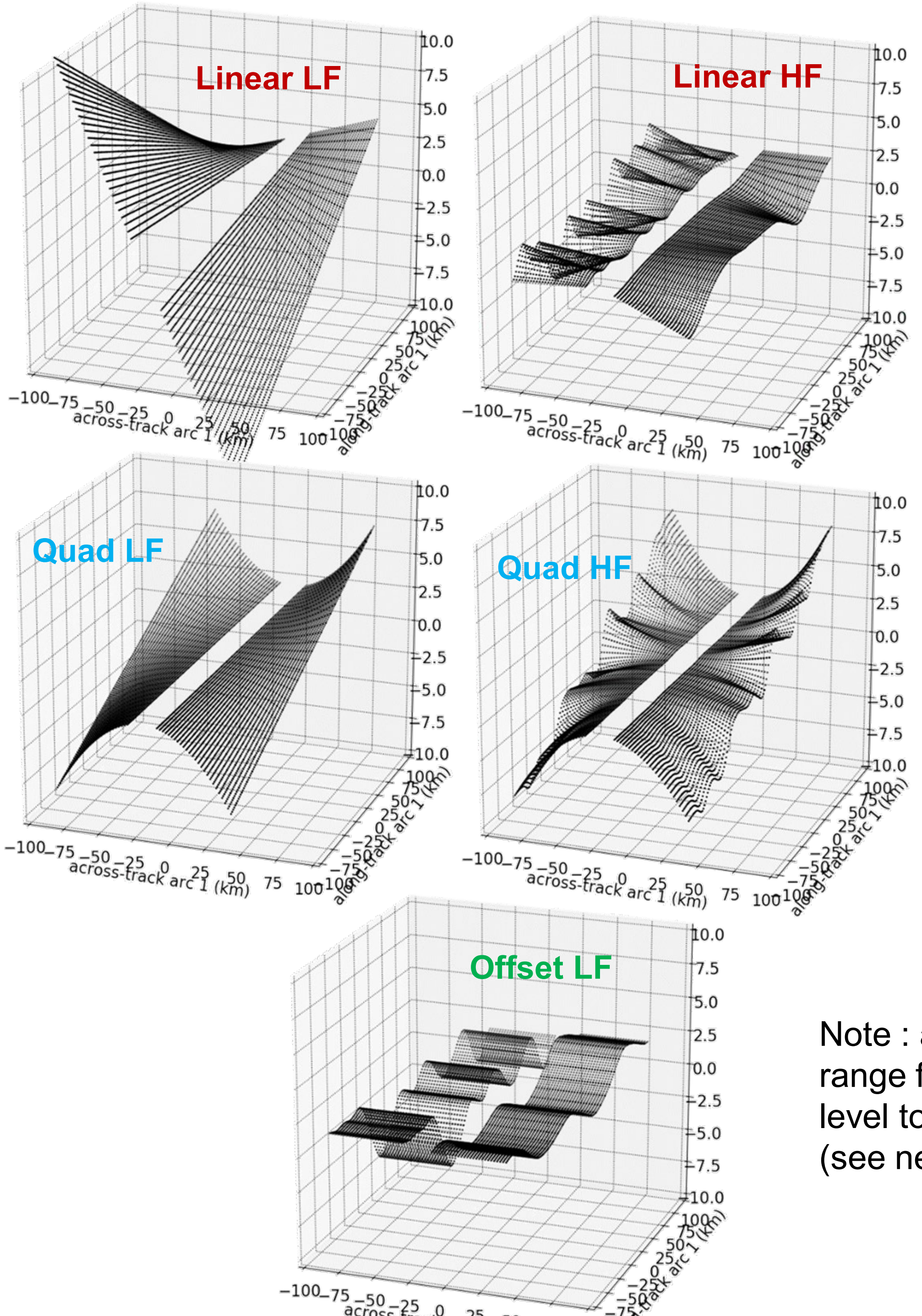
➡ Linear cross-track topography

Baseline length is not perfect?

➡ Quadratic cross-track topography

Range timing bias in KaRIN?

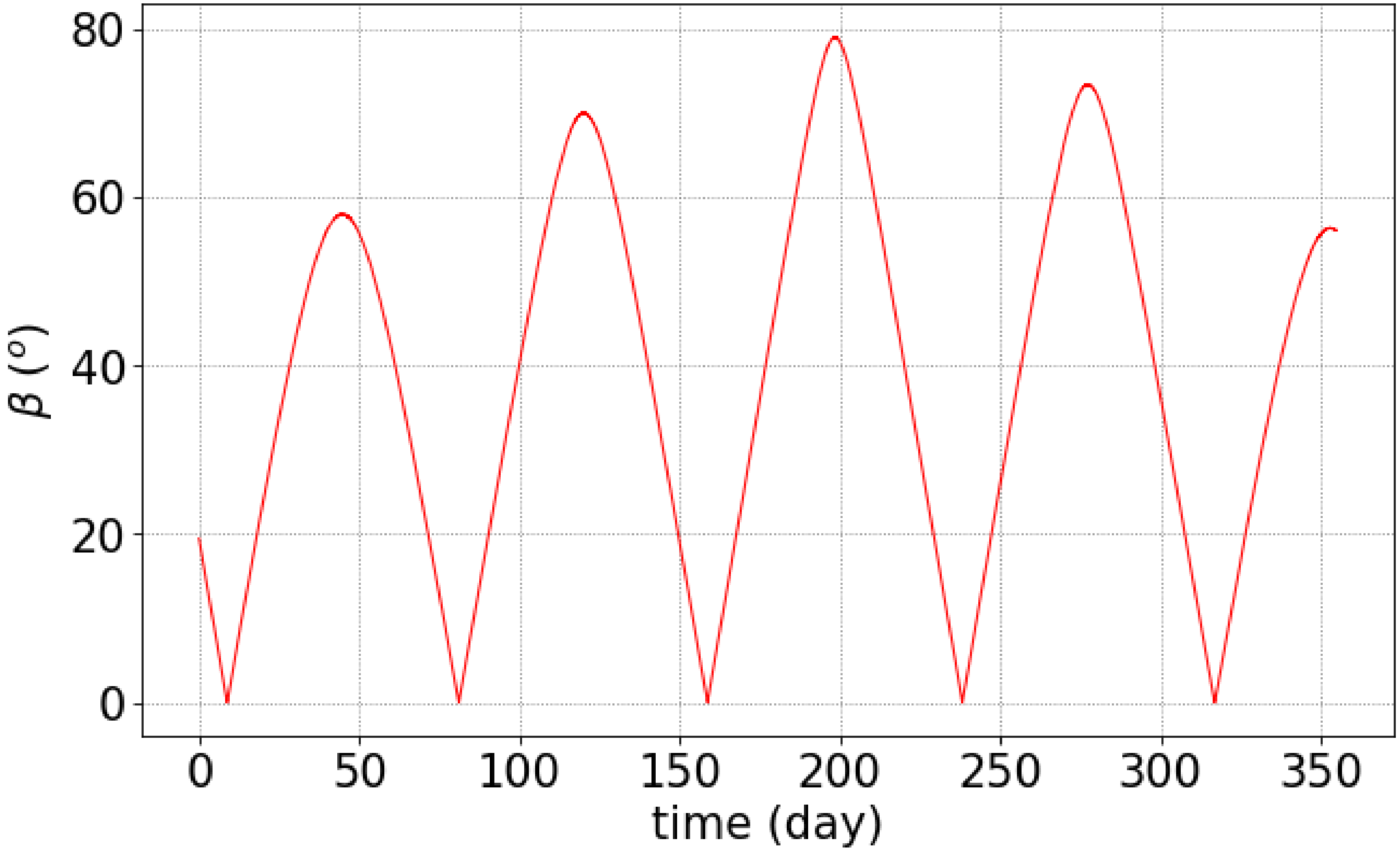
➡ Time-varying offset topography



Note : actual Z scales range from millimeter-level to meter-level (see next slides)

SWOT's orbit beta angle (not sun-synchronous)

The beta angle (angle between the Sun and the orbit plane) control the thermal conditions affecting the instrument, the AOCS sensors, and the platform along the orbital circle (e.g. modulation of TED).

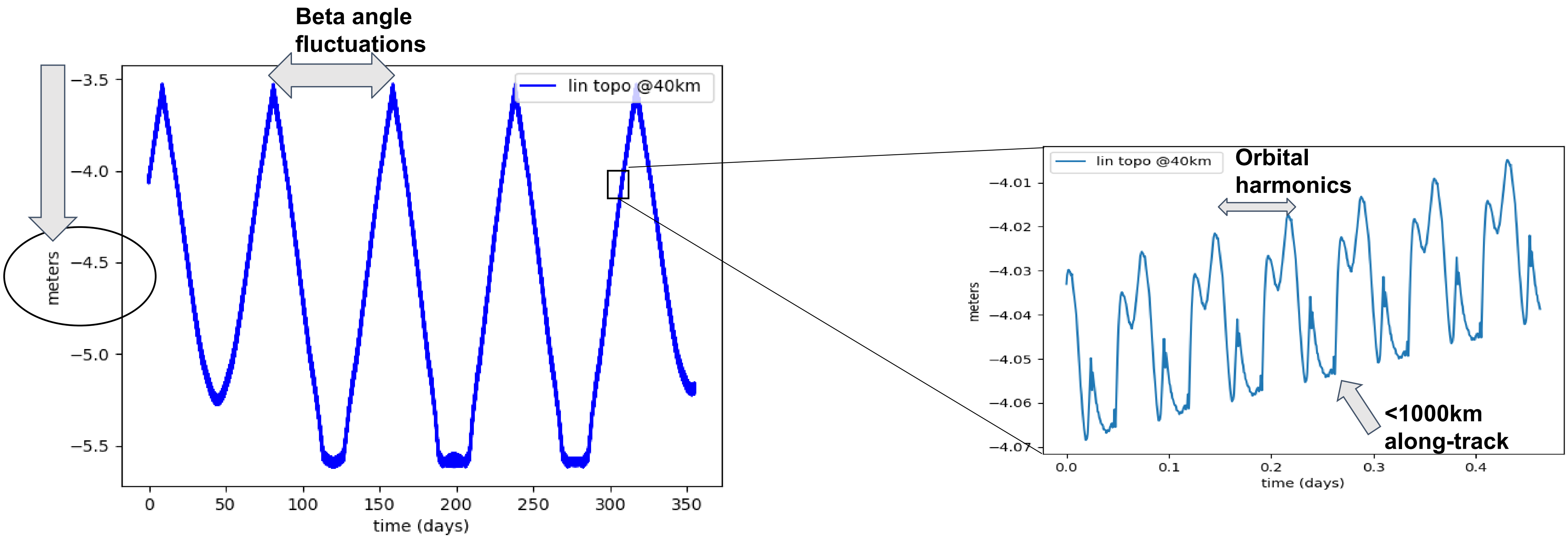


Instrument Model Error (STOP21)

Here: linear component, i.e. roll+phase error

4 temporal scales :
- non-zero mean (>1-year),
- month/season (beta angle)
- rev (and sub-harmonics)
- 150s or 1000km along-track for HF eclipses

Stationary anomaly



STOP21 data courtesy of E.Peral

Why do we need a data-driven calibration algorithm?

SWOT Requirements

- 7.4 cm RMS for Inland Waters (allocation for XCAL residuals) and 1.7 µrad for river slopes
- 15-1000 km spectral allocations (13 dB below 1-sigma SLA spectrum)

STOP21 uncalibrated errors

RMS of systematic errors from STOP 2021	**Components**	Stationary (>1-year)	Seasonnal (**β** variations)	Orbital harmonics (and sub-harmonics)	Broadband spectrum <1000km
	Offset	**300 cm**	1 cm	0.5 cm	<0.1 cm
	Linear	**500 cm**	**200 cm**	**8 cm**	<0.1 cm
	Quadratic	**20 cm**	2 cm (excursions)	1 cm	<0.1 cm
	Residual	<1 cm	<0.1cm	<0.1cm	<0.1 cm

Stationary: Should be corrected by phase screen. Residuals could be handled by Xcal

Seasonnal: Must be handled by Xcal

Orbital harmonics: Must be handled by Xcal with proper harmonic filter (not mandatory for STOP, mandatory for AOCS roll)

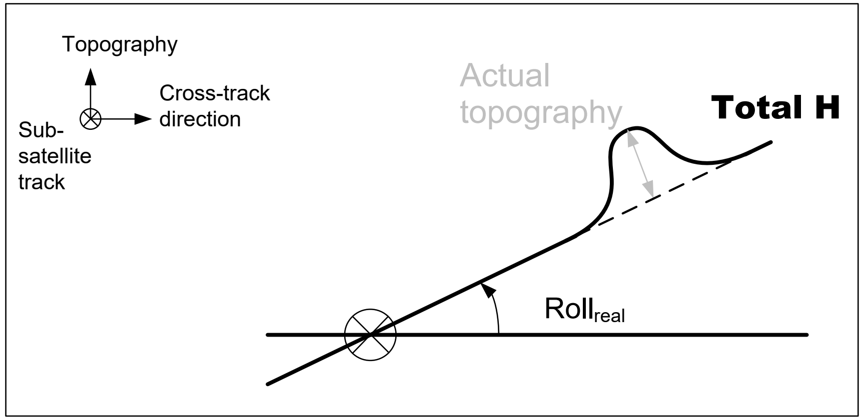
Broadband spectrum: No L2 xcal required for hydrology Dedicated L3 calibrations over Oceans (XCAL is a risk reduction algorithm, research grade, improves Gyro (roll))

Data-driven calibration principle

Roll estimation in a nutshell

H_{real} is what SWOT wants to observe
α is the roll unknown
ε is the random error (roll excluded)
d is the cross-track distance

$$H_{obs} = H_{real} + \varepsilon + \alpha(t) * d$$



Cross-track linear signature of roll

Can be observed from topography (or phase)

➡ Adjust the cross-track slope every line of a KaRIN image

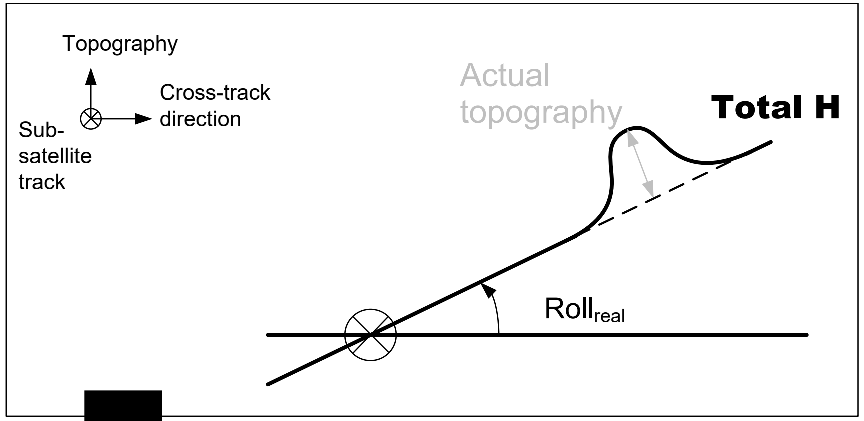
Do the same for other errors (bias, quadratic model…)

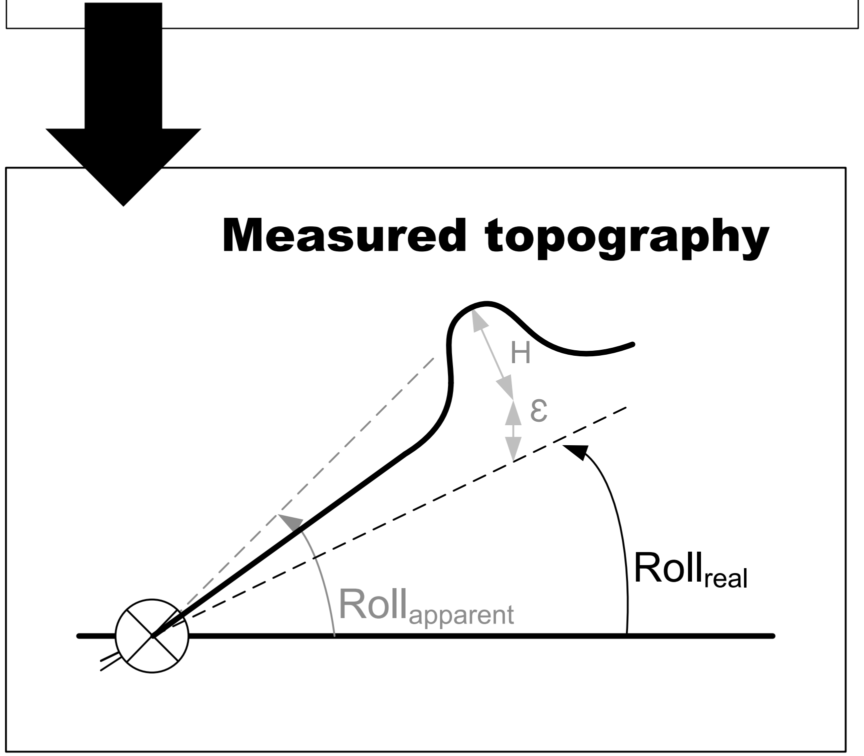
Pitfall of data-driven calibration

- SWOT has a narrow field of view (120 km)
- H_{real} can have a non-zero cross-track slope (not orthogonal with roll signature)

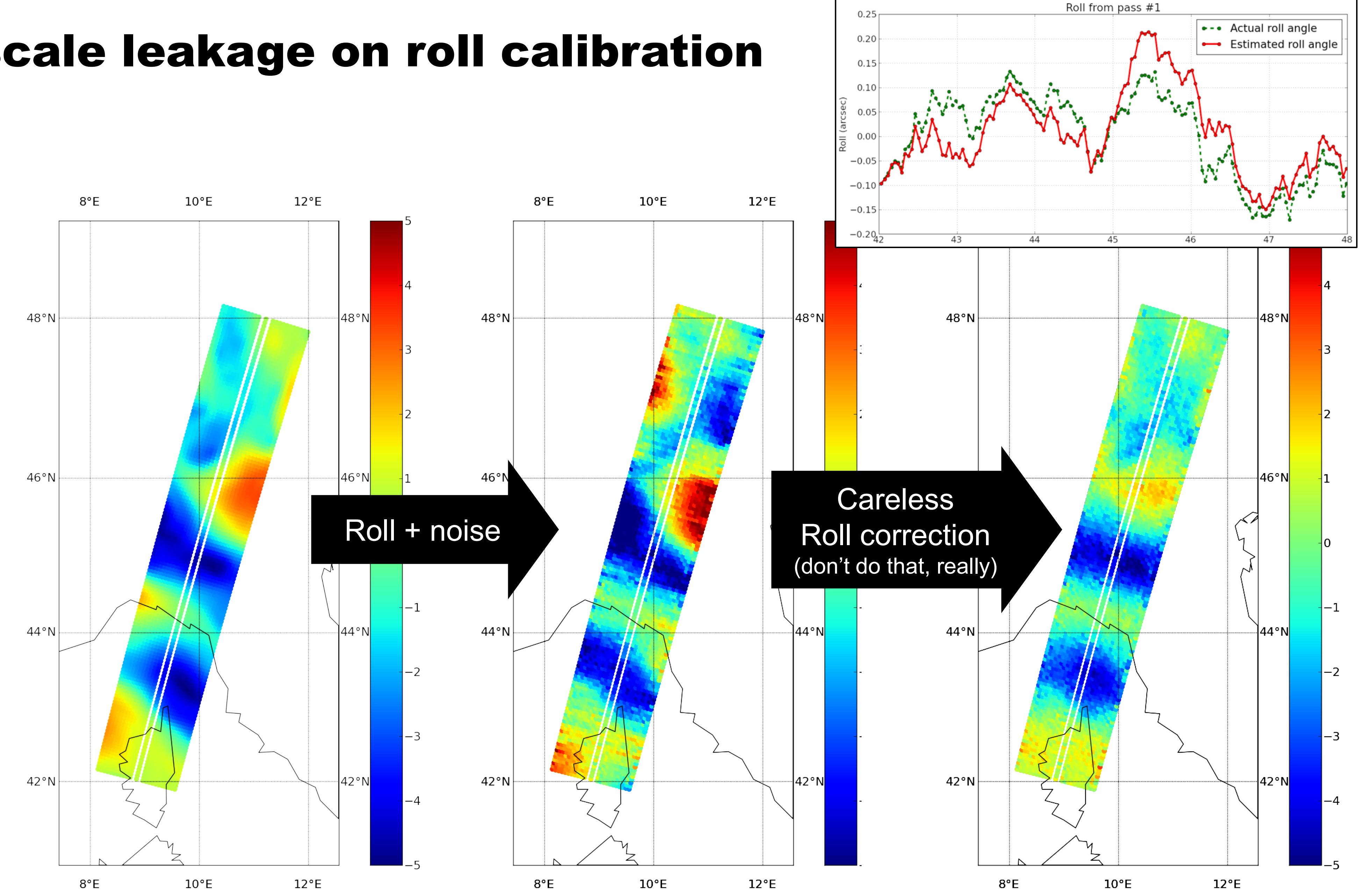
➡ **Any 120 km slope is "seen" as roll and <u>removed</u> from the image**

- E.g. mesoscale gradient killed (very bad)





Mesoscale leakage on roll calibration



Roll removed <u>BUT</u> cross-track gradient from mesoscale destroyed as well

The practical challenge of data-driven calibration methods

The challenge is not to remove systematic errors, but to isolate them from the true ocean topography

Mitigation methods from Dibarboure & Ubelmann (2014)

1. Use image-to-image difference to cancel out slow ocean/geophysics variability
2. Use external H_{real} first guess from nadir altimeter(s) to cancel out large scale variability
3. Use statistical knowledge of oceanic variability spectrum / covariance
4. Use statistical knowledge of uncalibrated errors (measurable in Cal/Val, Ubelmann et al, 2017)

Level-2 crossovers

Level-3 multimission

Level-3 research grade « optimal » inversions

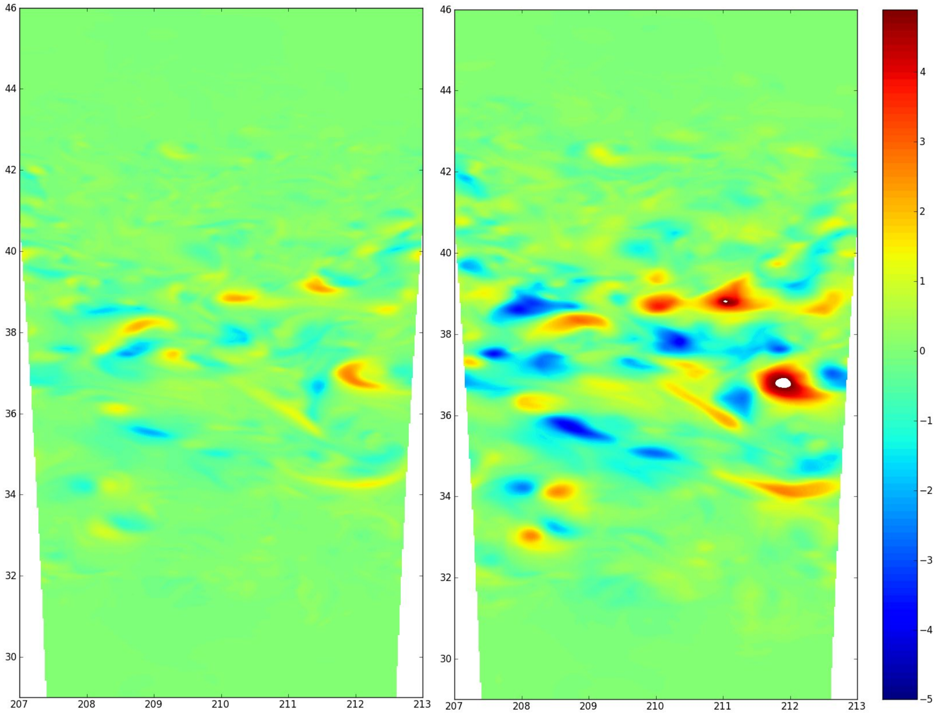
Mitigation method #1: image-to-image difference and high-frequency

Short δT = less variability which can be misinterpreted as roll

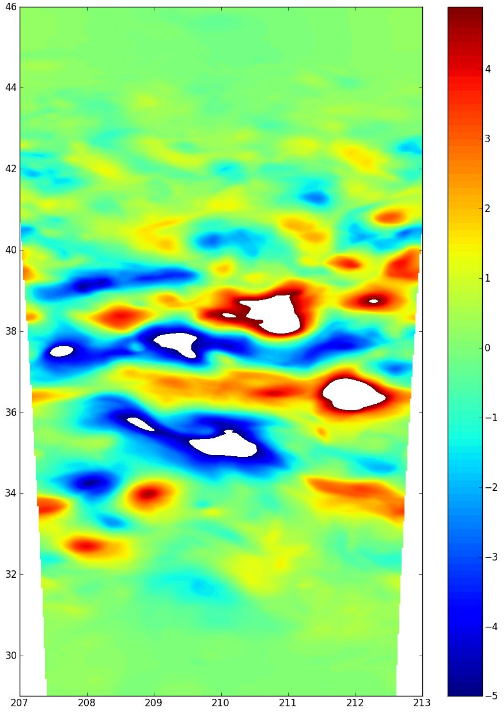
Short δT = smaller structures (less ambiguity with roll over 120 km)

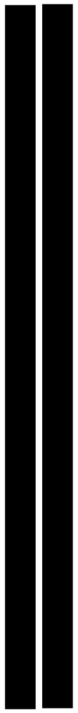
1-day δT

3-day δT



Full variability





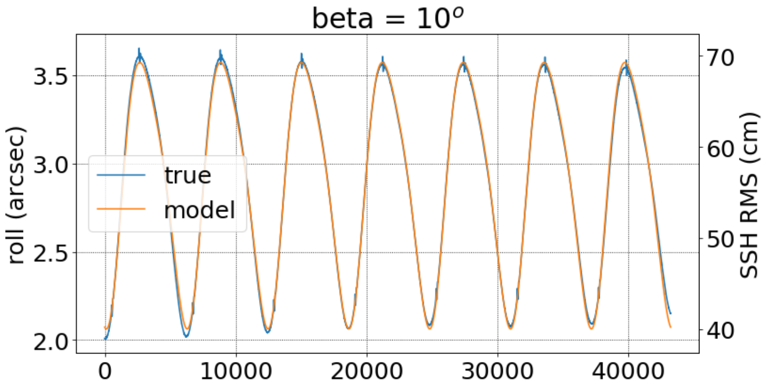
SWOT geometry for scale

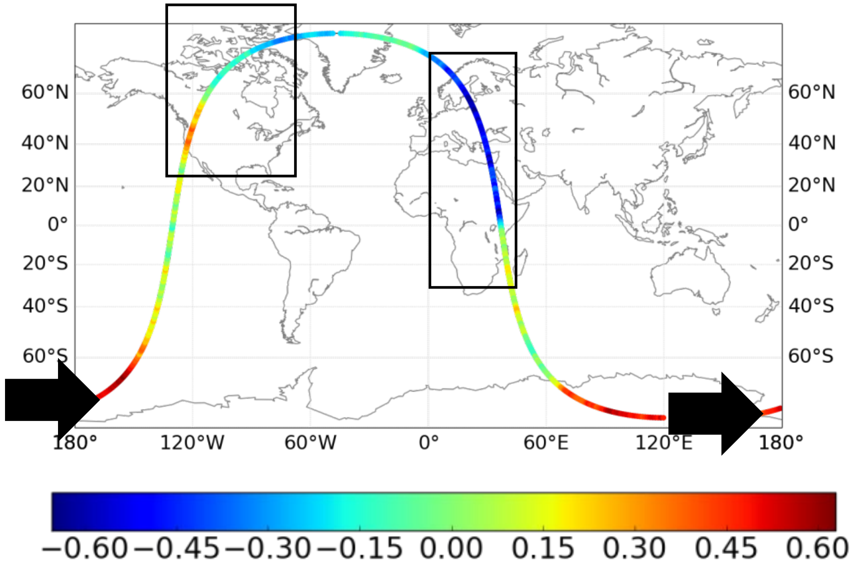
Model outputs from Klein et al (2008) incl. rapid submesoscale

Level-2 algorithms and performance

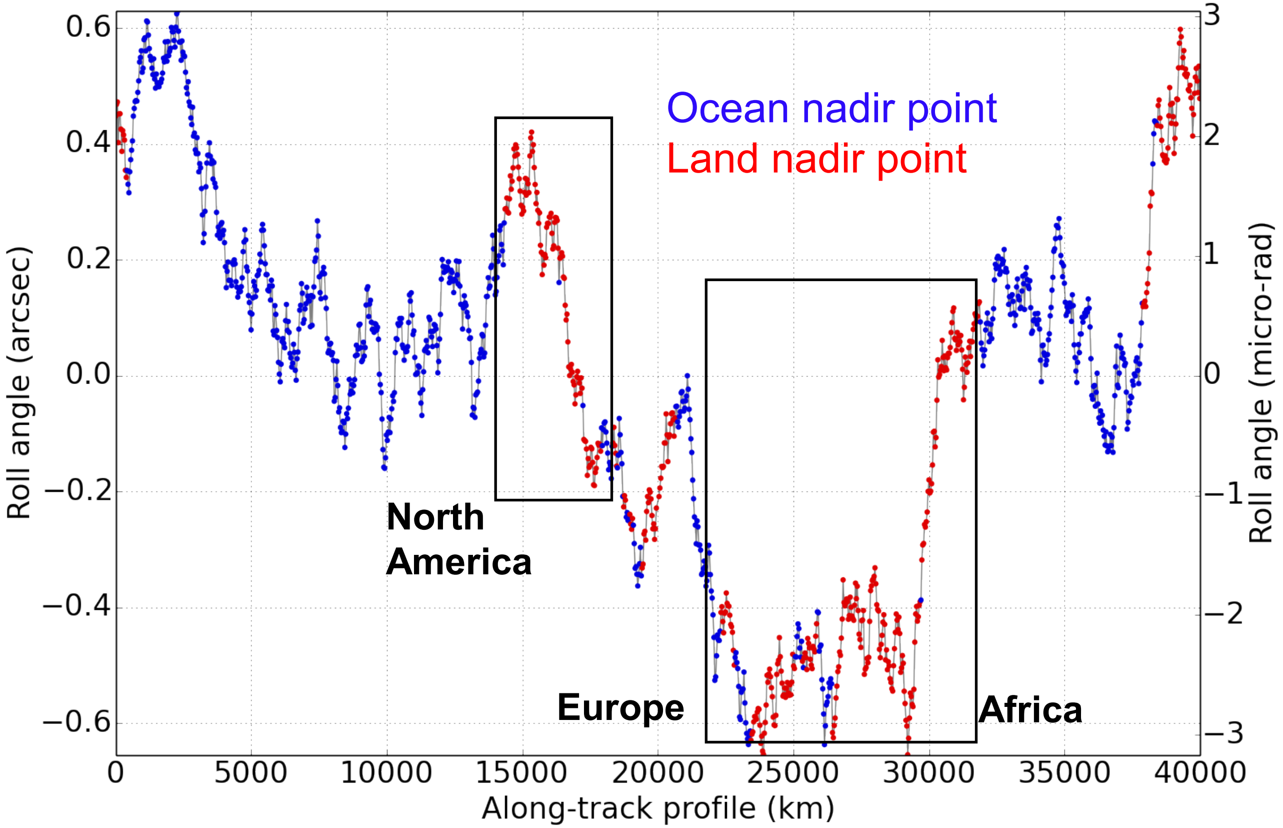
Example for one revolution

Orbital harmonics derived from attitude retrieval error simulation



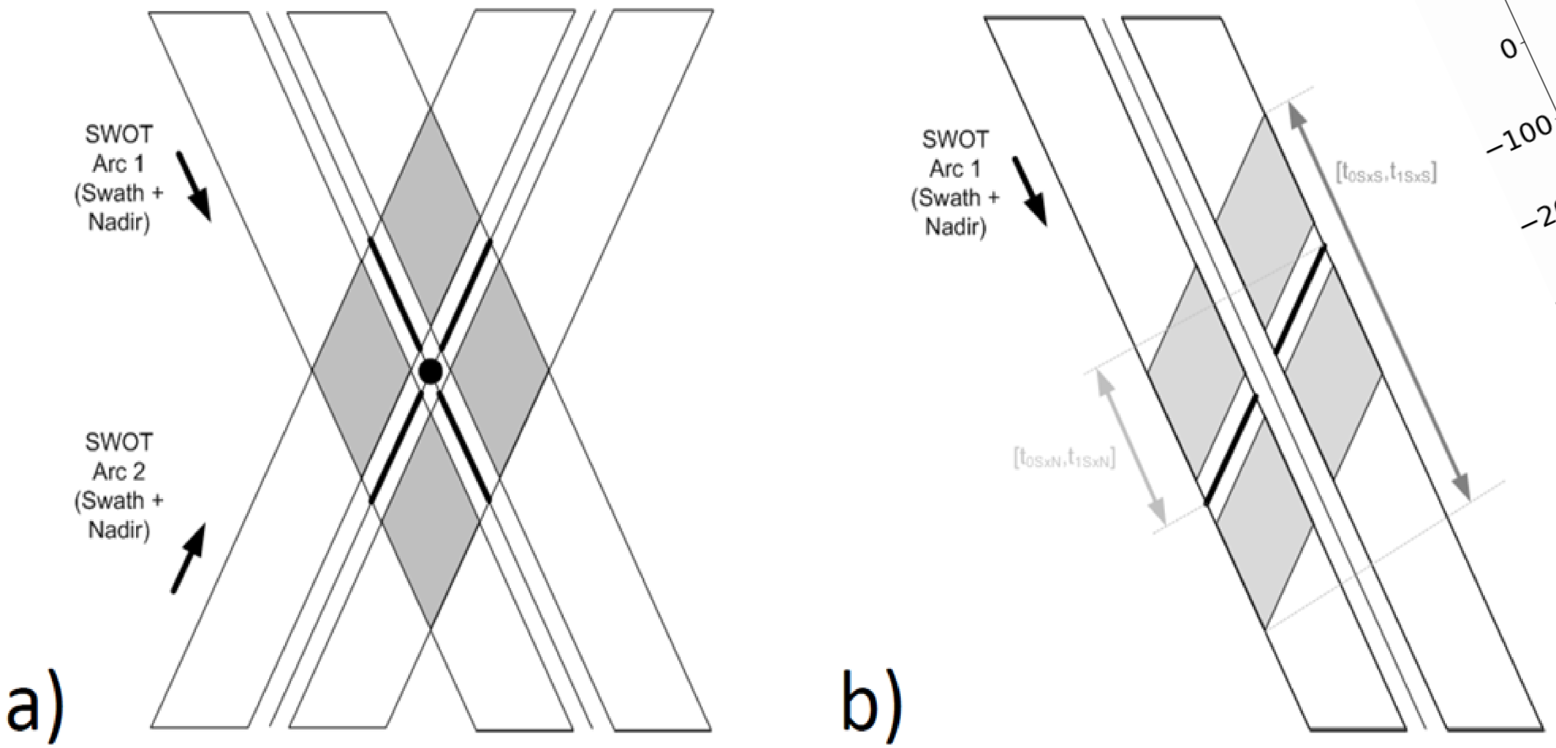


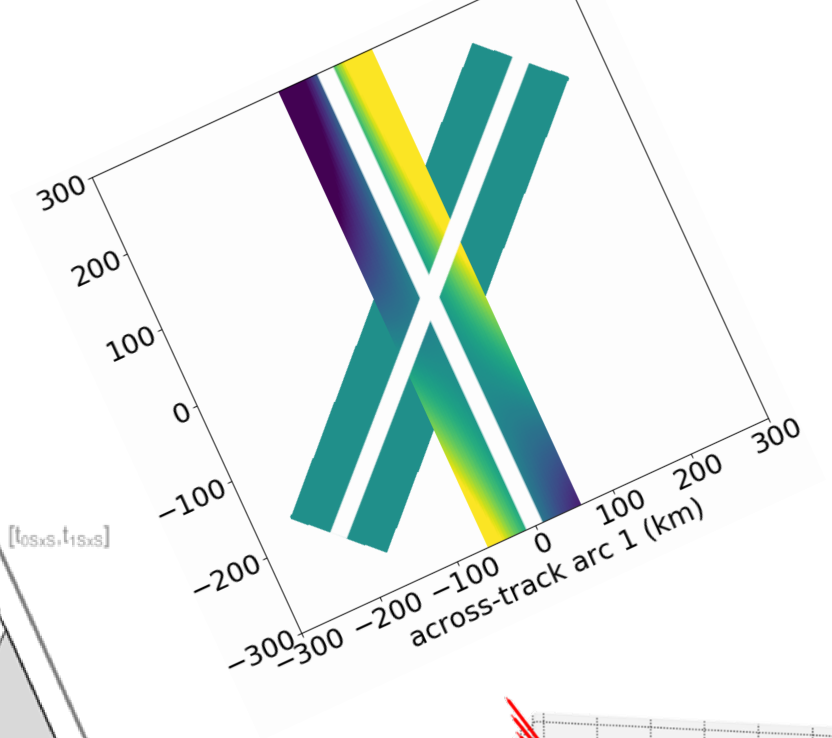
Broadband error from gyro/phase/etc (STOP21)

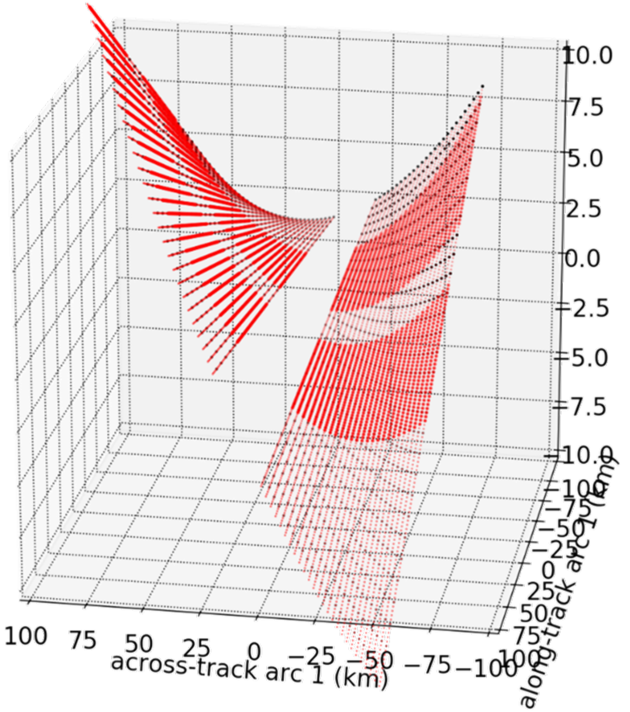


Combination of slow and rapid changes (K^{-2} gyro/phase requirement) + orbital sub harmonics

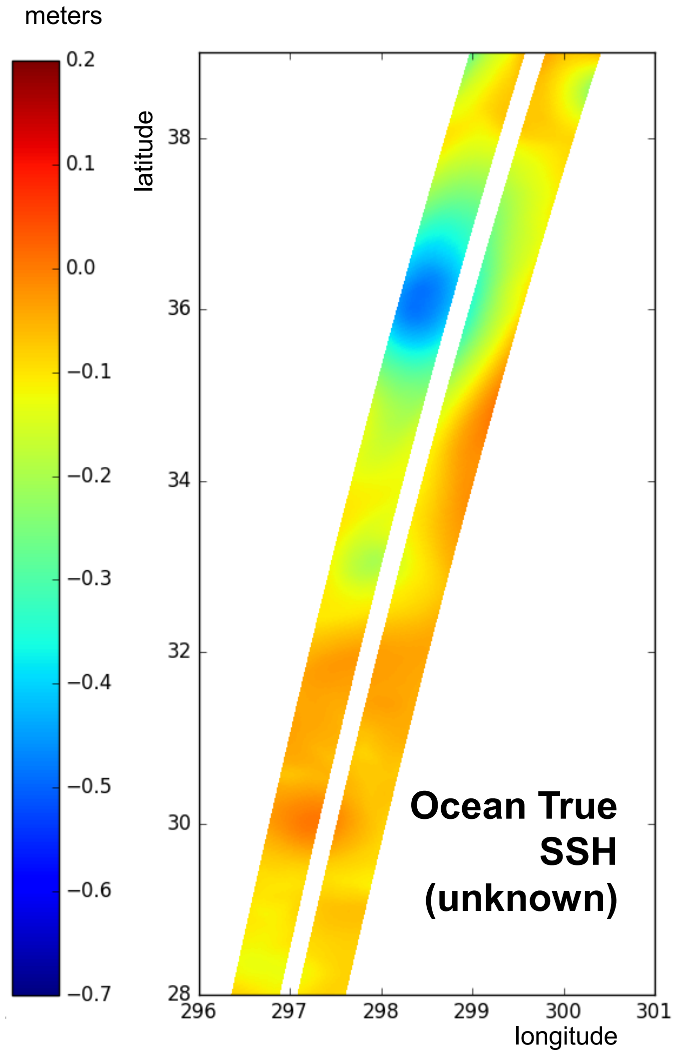
Crossover principle (1/2)

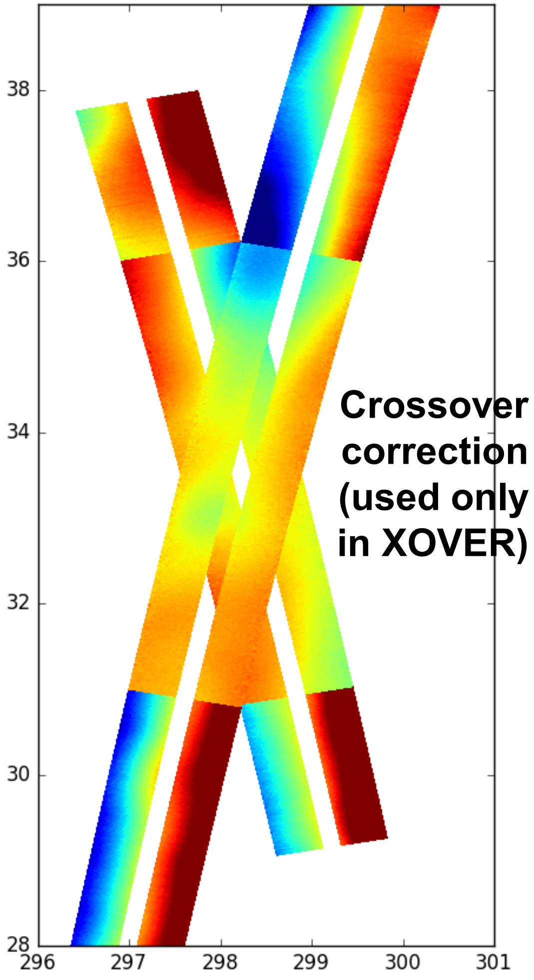




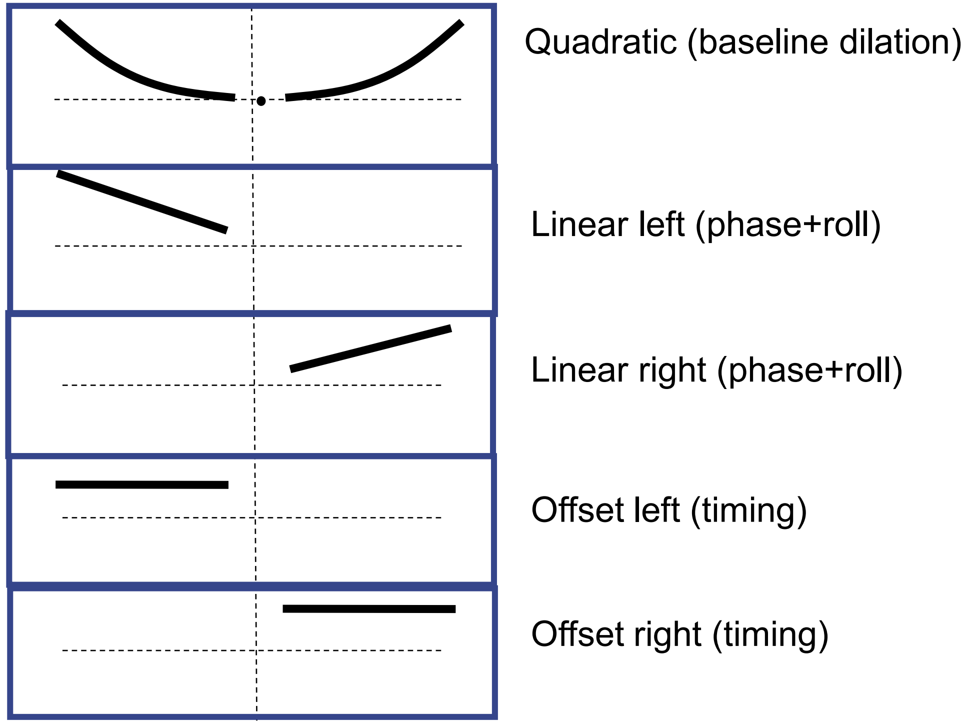


Crossover principle (2/2)





Inverted parameters :



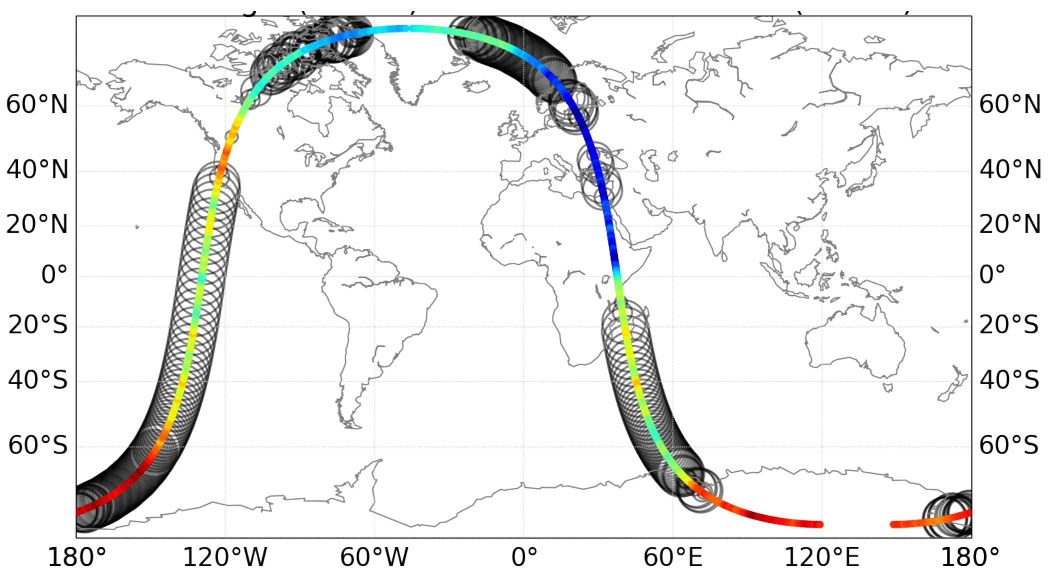
This diamond (or calibration zone) now benefits from a local correction

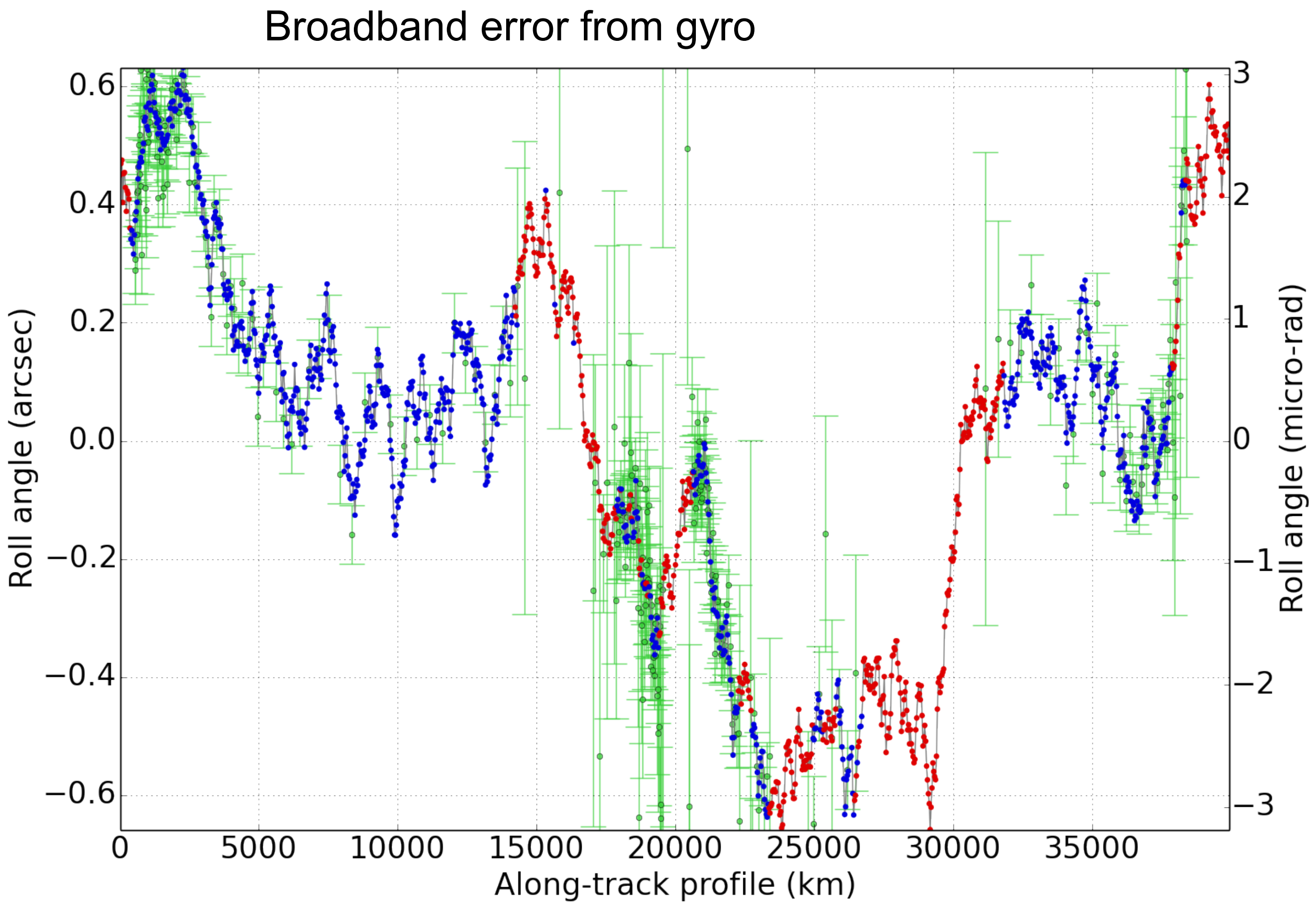
STEP1 - Inverse ocean XOVER diamonds (2/2)

Ocean **XOVER zones**

Green dot
& error bars

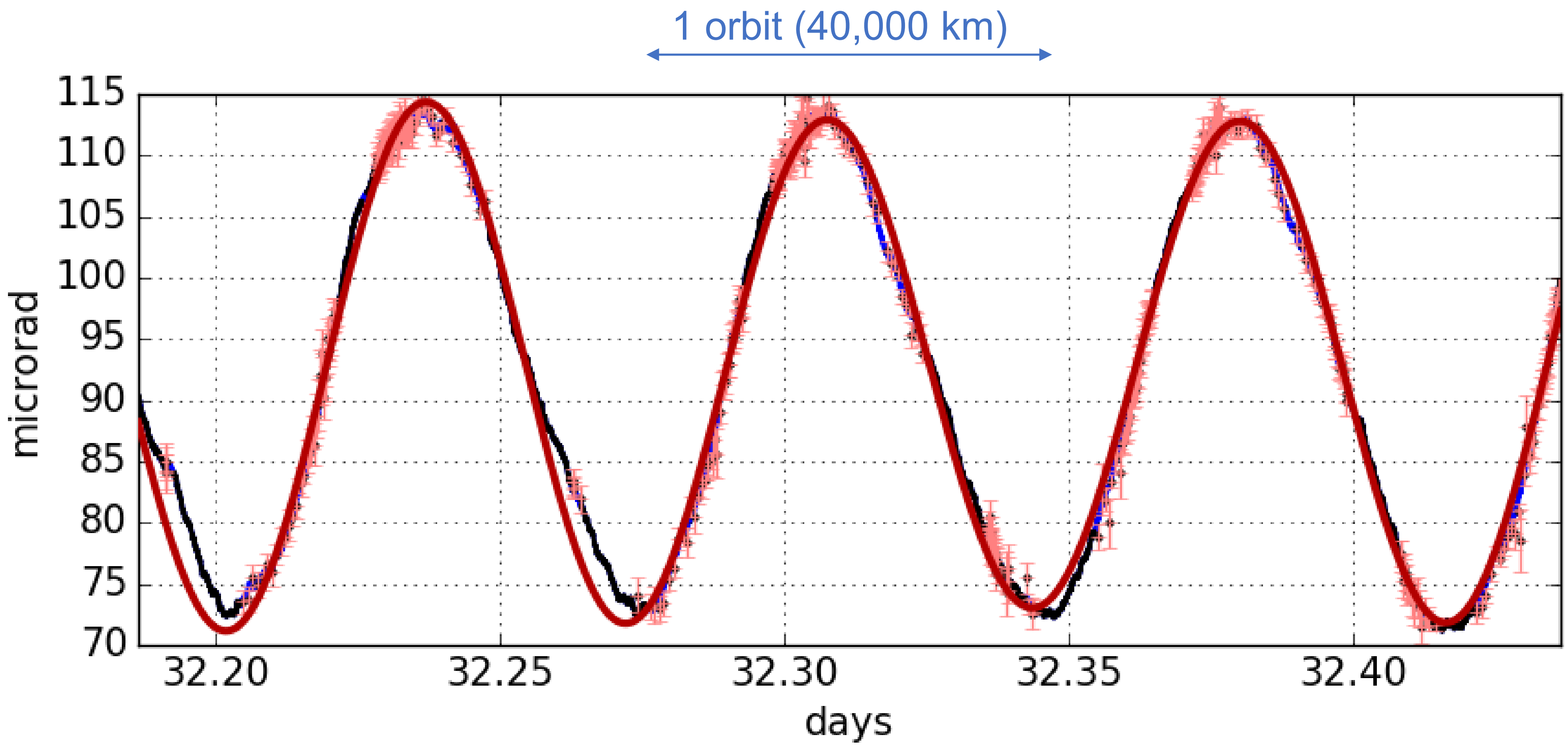
Black circles





- Roll is well observed in the open ocean
- No data for long inland segments

STEP2a - Interpolate orbital harmonics



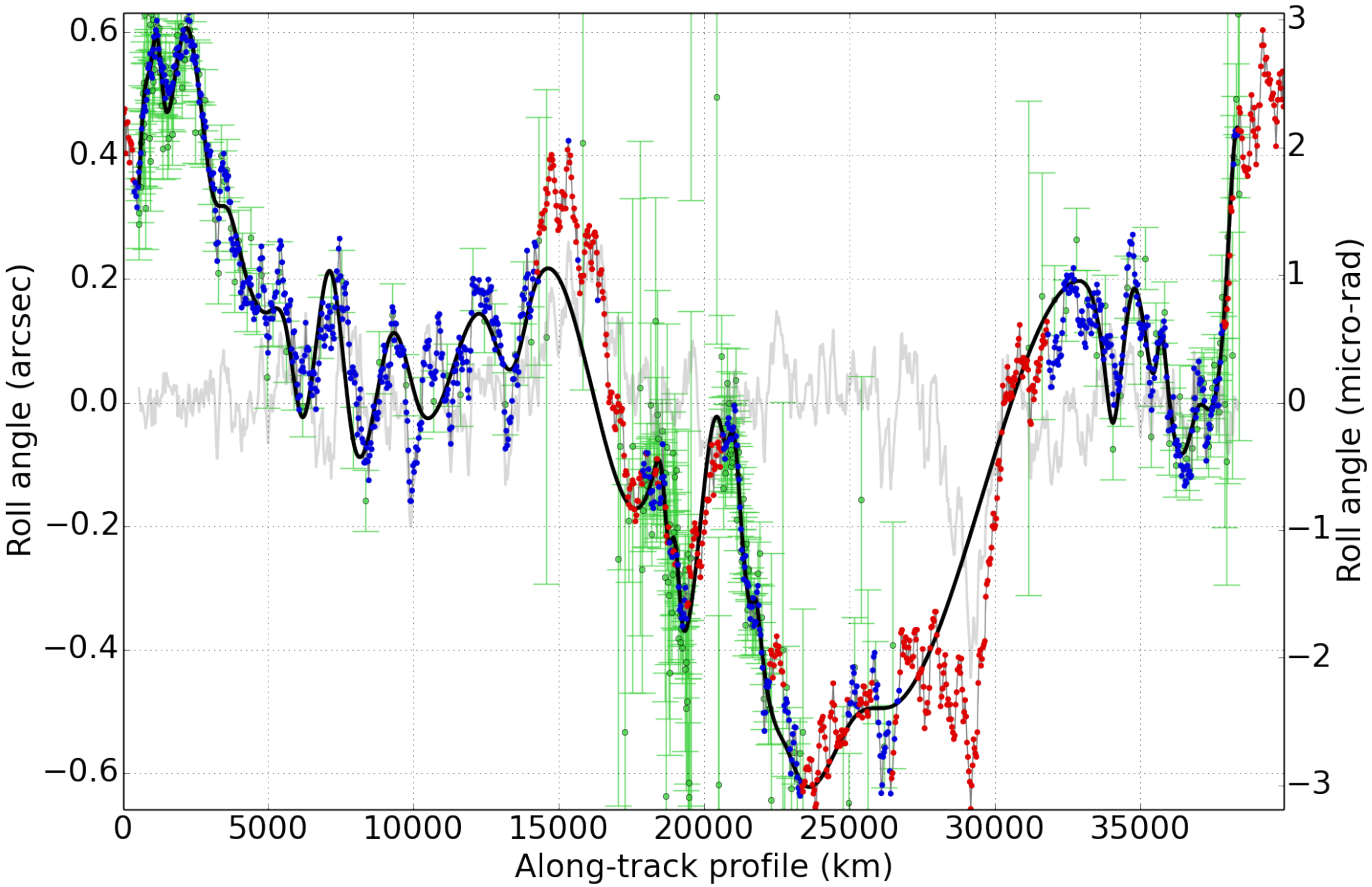
- - True (unknown) slope **overland**, **over ocean**

Ⅰ **Estimation and uncertainty* for all valid ocean crossover** **(Ice and thermal-snap (2min/eclipse) rejected)**

— **8 passes orbital fit**

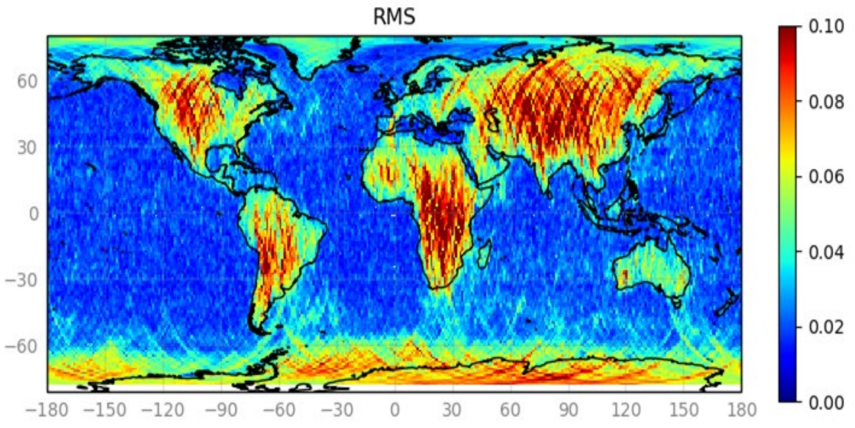
STEP2b - Interpolate broadband residual

- Interpolated correction (black, thick) and residual (gray, thin)
- Slow signals are well captured everywhere
- Inland error is substantially reduced
- Uncorrected residuals due to rapid roll events occurring inland
- Level-2 correction is suboptimal over the ocean (xcal is too smooth) because the algorithm is designed for the hydrology requirements



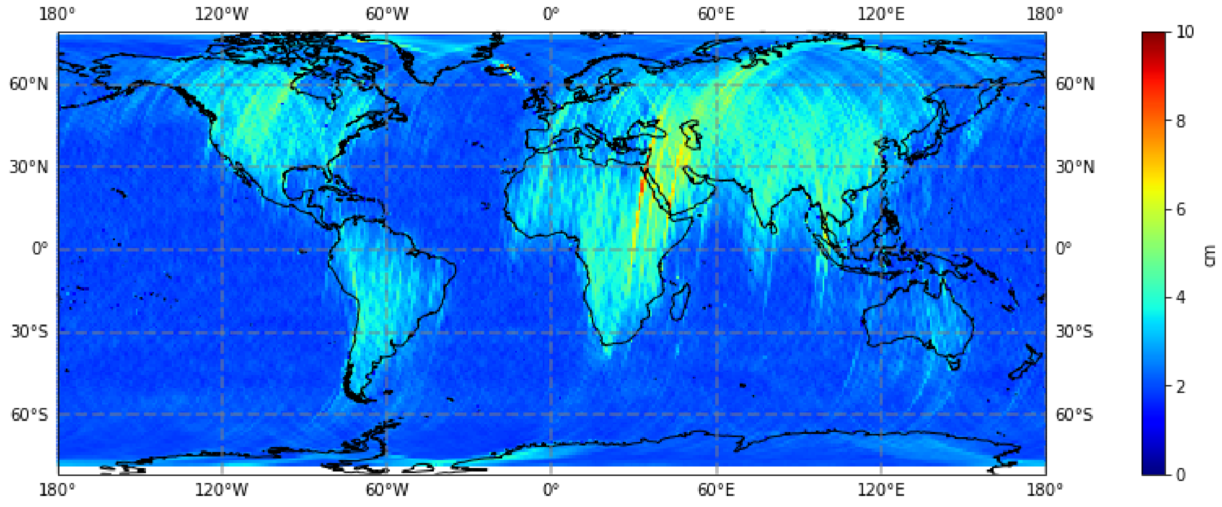
Global Level-2 performance (pre-launch)

Spectral error allocations (worst case uncalibrated input scenario, especially AOCS at large scale)



Open-Ocean std : 2.30 cm
Land std : 6.37 cm

Current Best Estimate Scenario (CBE, revised 2021)



Open-Ocean std : 2.30 cm
Land std : 3.43 cm

Good margins with respect to SWOT inland requirements

	CBE	Allocations	Requirements
Global inland water-level RMS :	3.4 cm	6.4 cm	7.4 cm
Global inland water slope:	0.8 µrad	1.4 µrad	1.7 µrad

The global performance for hydrology is dominated by the interpolation error over (very) long inland segments with no crossover

No requirement for the ocean

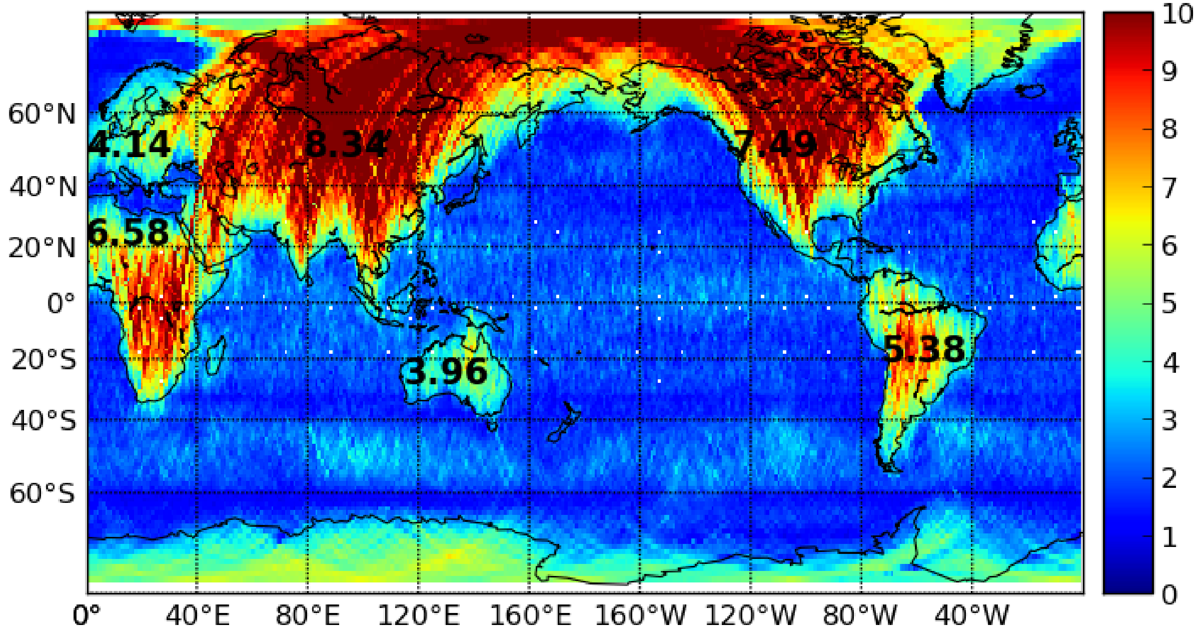
(but you might want to use the XCAL anyway)

	Calibrated	Not calibrated
Global ocean SSH error RMS :	2.3 cm	10-200 cm

The global performance for oceanography is dominated leakage of ocean variability and the interpolator (designed for hydrology reqs)

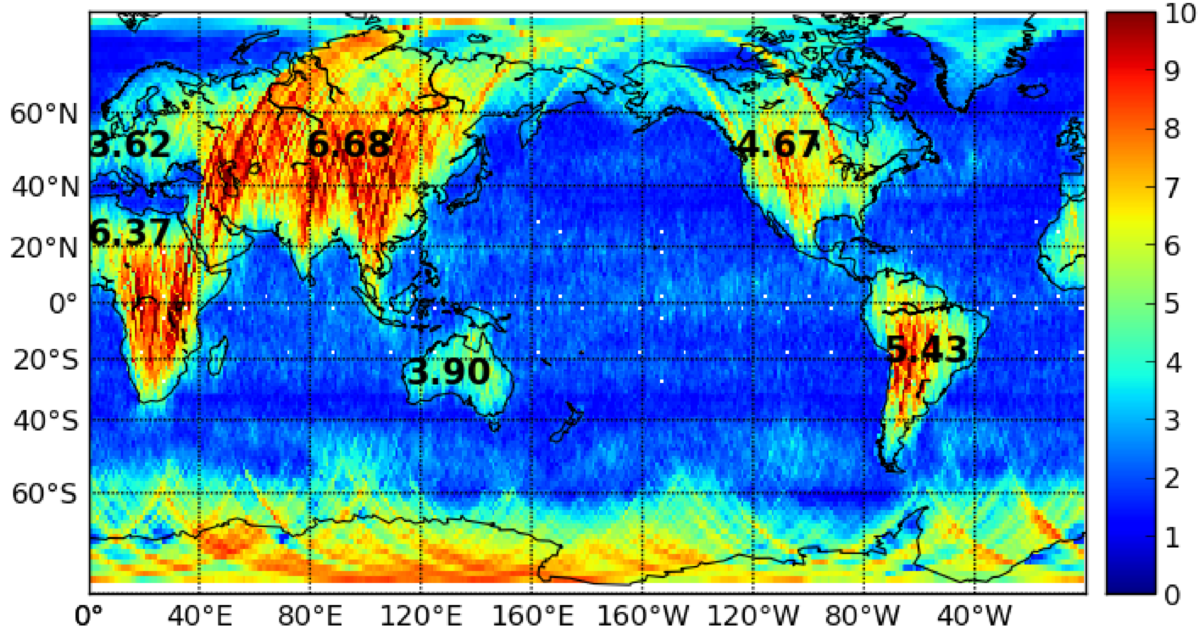
Seasonal variability because sea-ice crossovers cannot be used

Jan-Feb-Mar



Inland RMS: 6.85cm

Jul-Aug-Sep

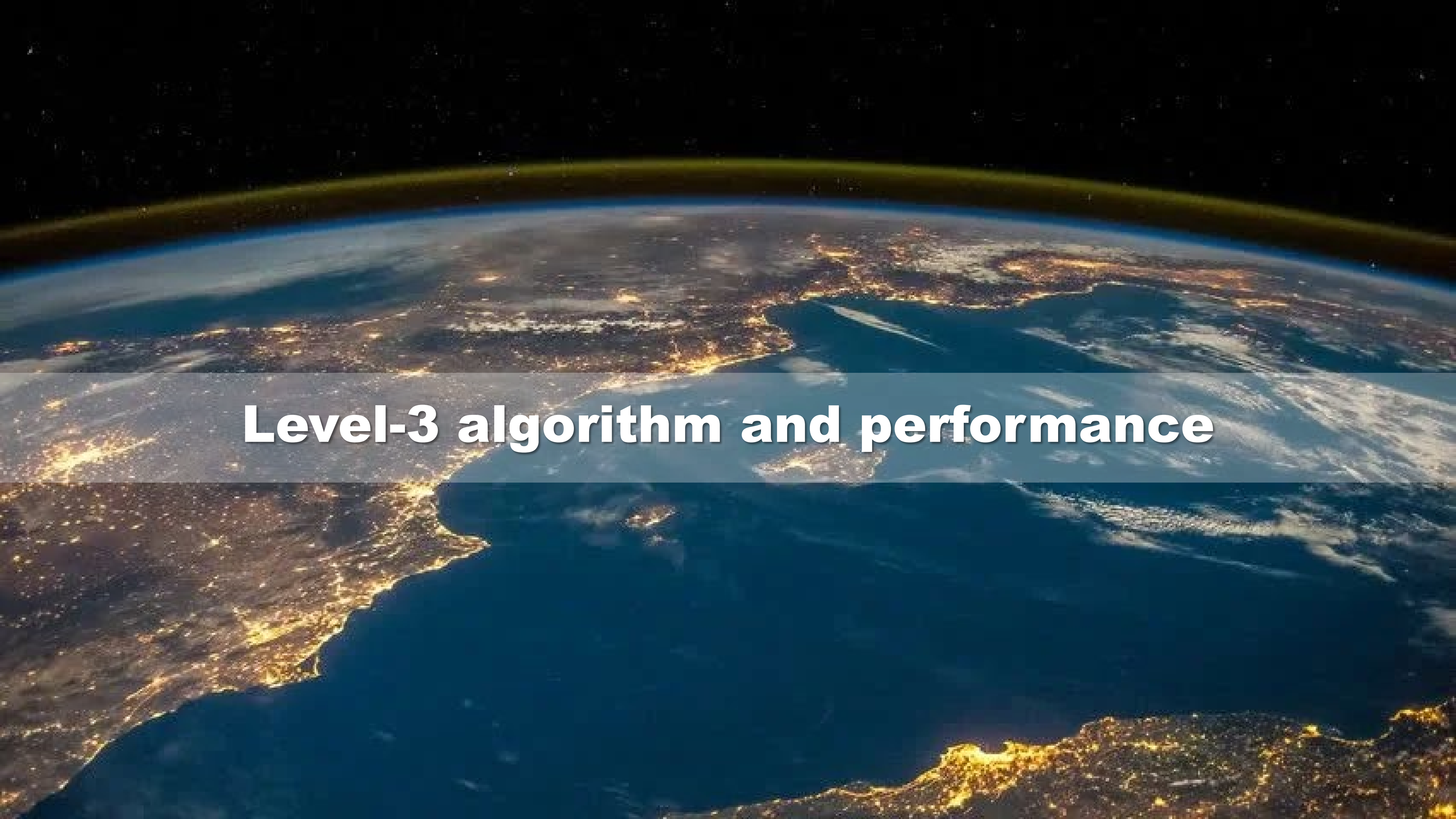


Inland RMS: 5.58cm

- Strong seasonal variability
- Sea-ice bridges very long inland arcs with no ocean crossover : very high errors
- Non-freezing Norwegian sea helps Europe

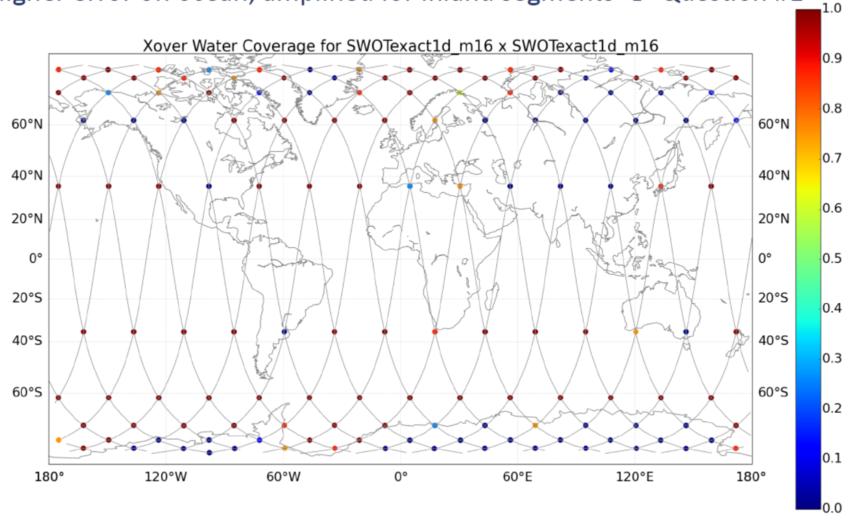
➡ Calibration performance is strongly affected by long arcs with frozen seas (main target if more margins are needed)

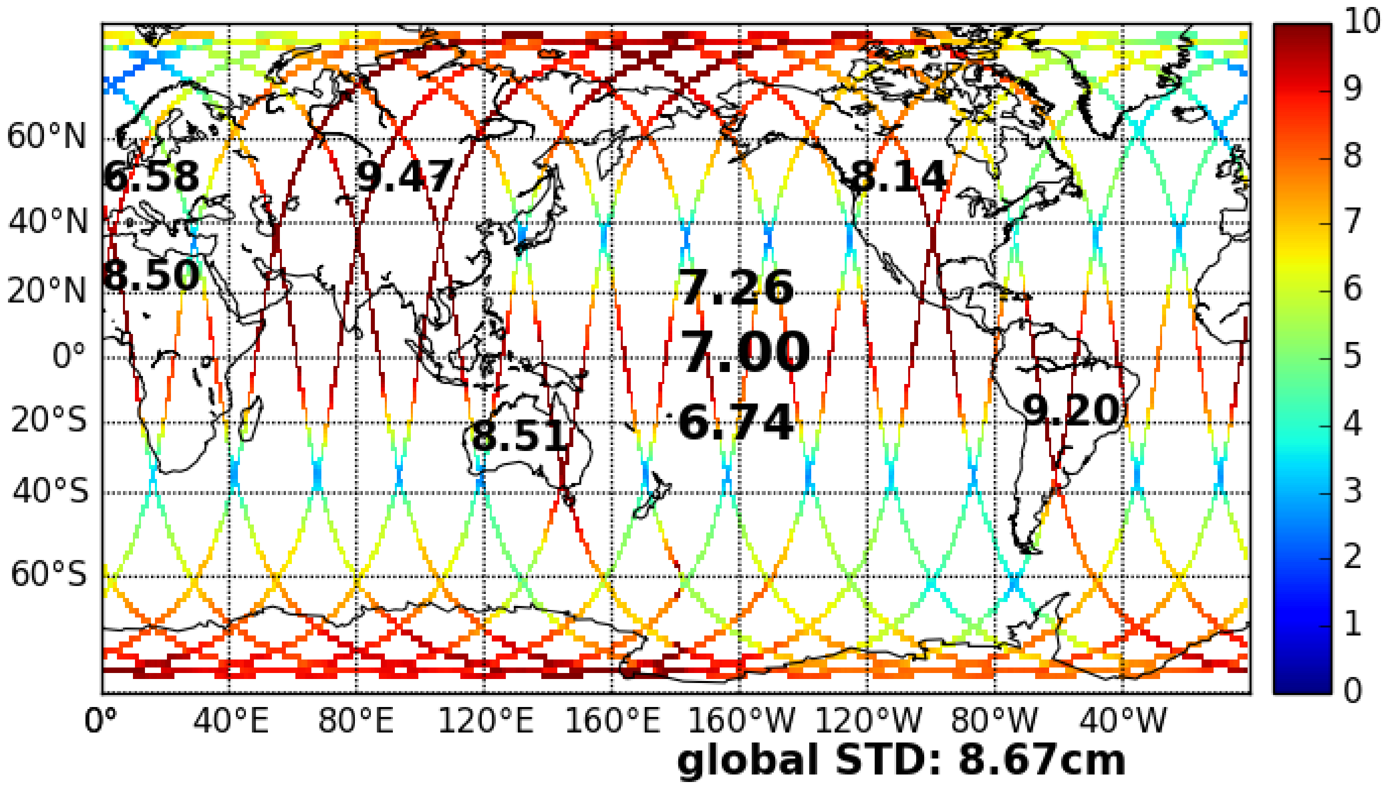
Level-3 algorithm and performance



Starting point: the XCAL performance for the 1-day orbit

Baseline orbit = 28 passes per cycle
Approx 10 ocean XOVERs per pass (nothing between 33°N / 33°S)
Higher error on ocean, amplified for inland segments ➔ Question #1





1-day orbit : Direct, Colinear and Hybrid algorithms

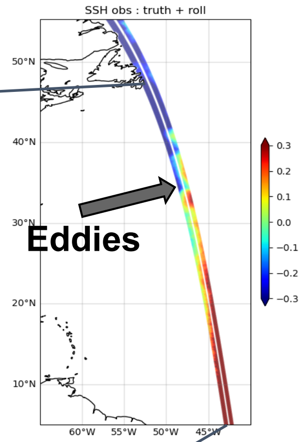
More sophisticated XCAL is needed

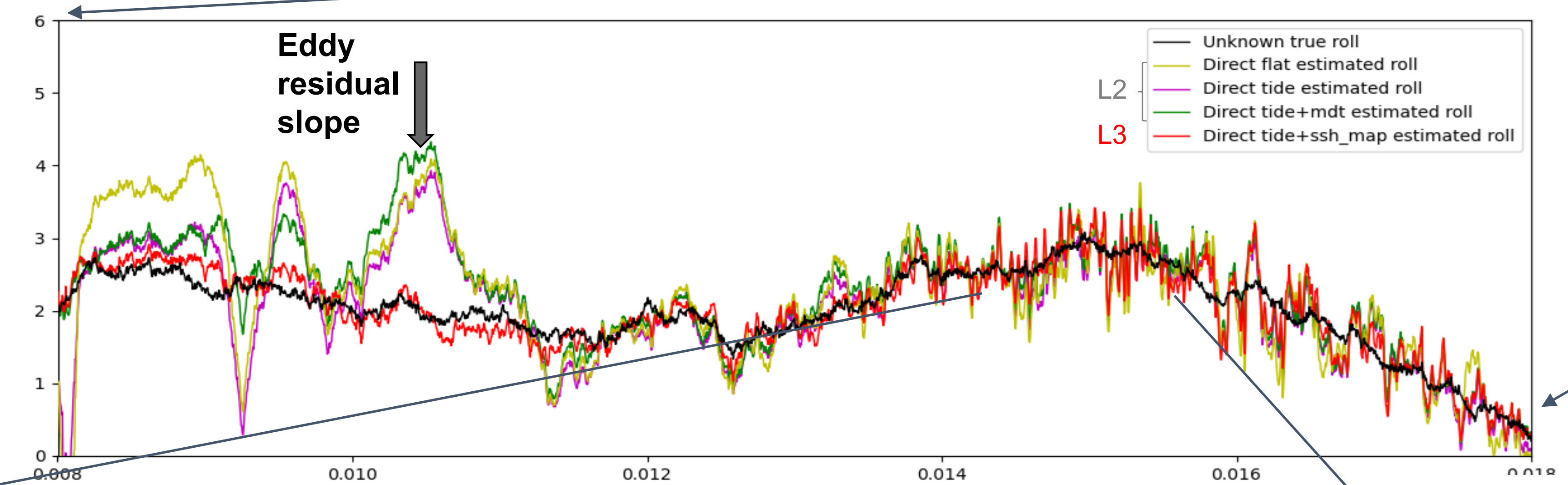
- Direct method works well on all orbits but for low frequency roll only
  (leakage of small mesoscale not resolved by nadir constellation + internal tides in XCAL correction)
- Colinear method is a partial replacement of the XOVER for the 1-day orbit
  (good for higher frequency roll but correction is strongly biased because of the aligned geometry)
- Hybrid method merges Direct + Colinear to get the best of both worlds

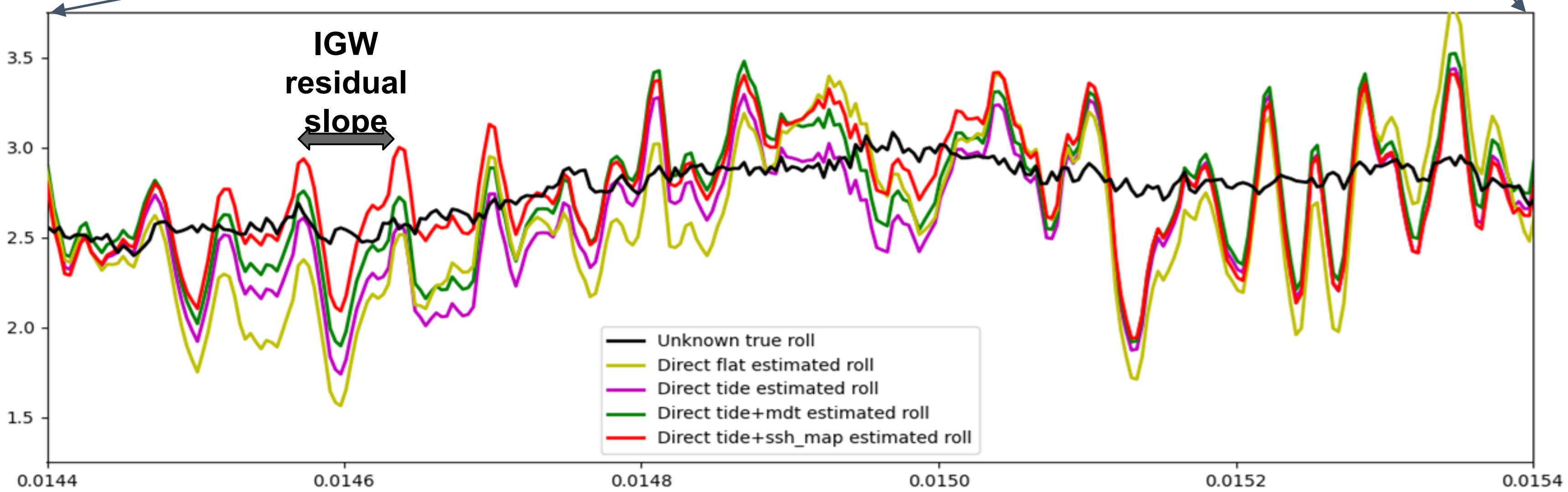
But these algorithms are more fragile and complex

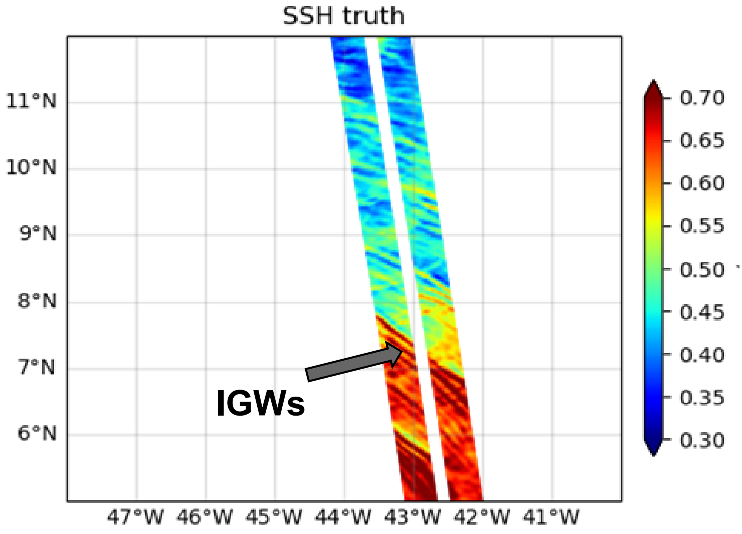
- Multi-mission by design (dependency to other missions which is not acceptable in ground segment)
- Parameterization is complex on flight data (ocean decorrelation, uncalibrated error spectra, etc.)
- For SWOT: only implemented in a research-grade Level-3 (demonstration CMEMS processor)

Example: Direct method



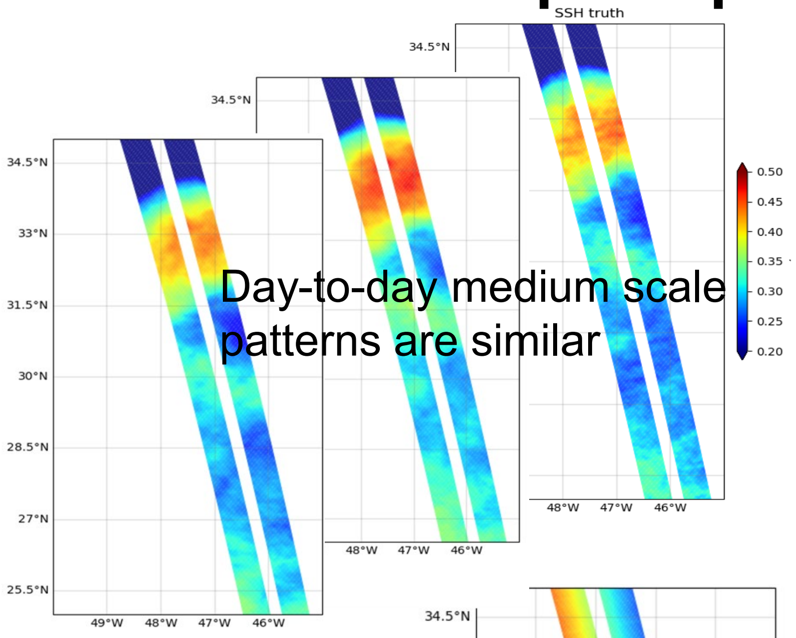




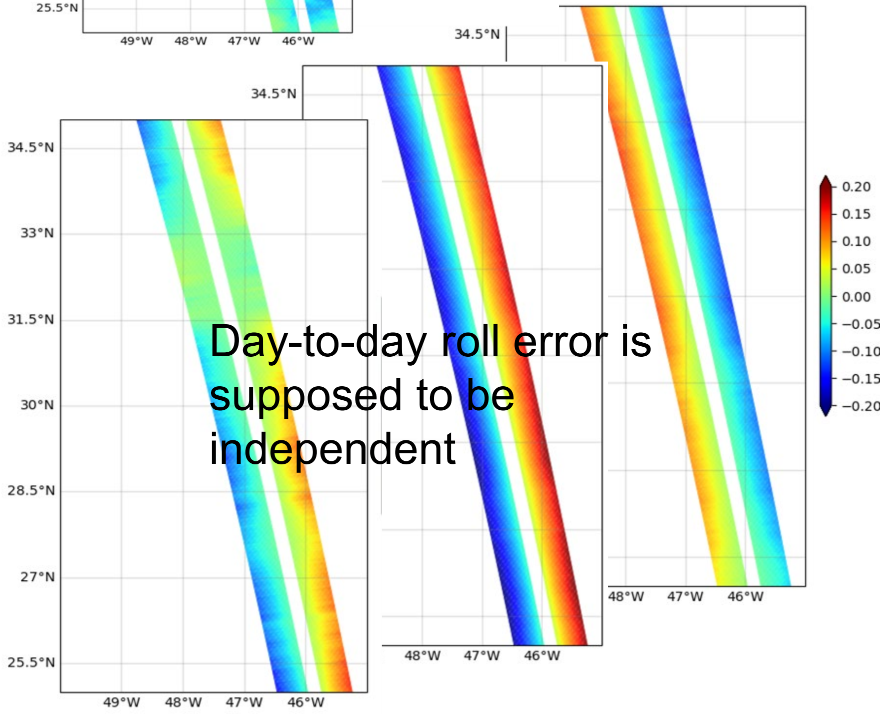


- As expected, **the correction is efficient at large scales**
- Using an **multi-mission first guess** (4+ nadir altimeters) is essential to take out the large eddies
- Unresolved wave patterns leak on the roll estimations ➔ this method should not be used alone

Colinear method : principle for 1-day orbit

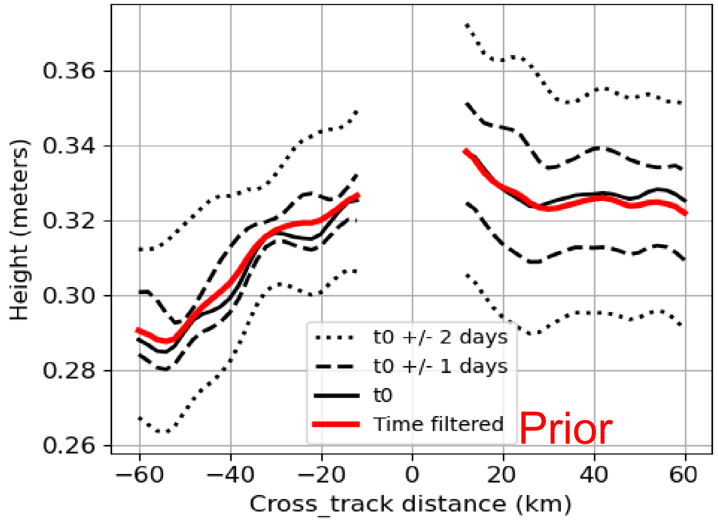


Day-to-day medium scale patterns are similar

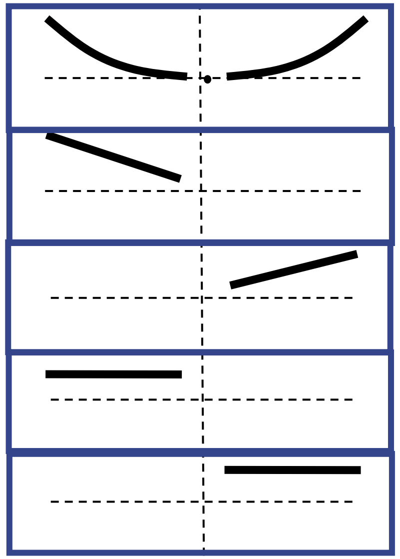


Day-to-day roll error is supposed to be independent

Same implementation as Direct, but Prior is the time-filtered observations



Inverted parameters :



Quadratic (baseline dilation)

Linear left (phase+roll)

Linear right (phase+roll)

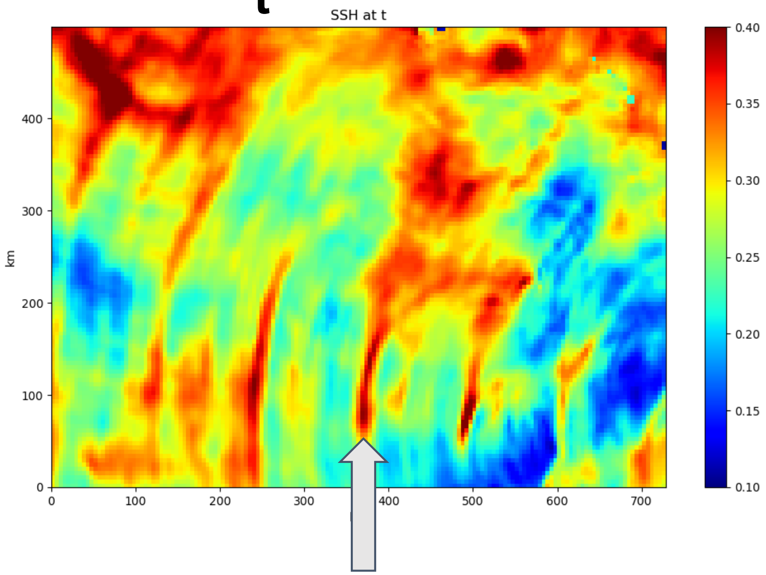
Offset left (timing)

Offset right (timing)

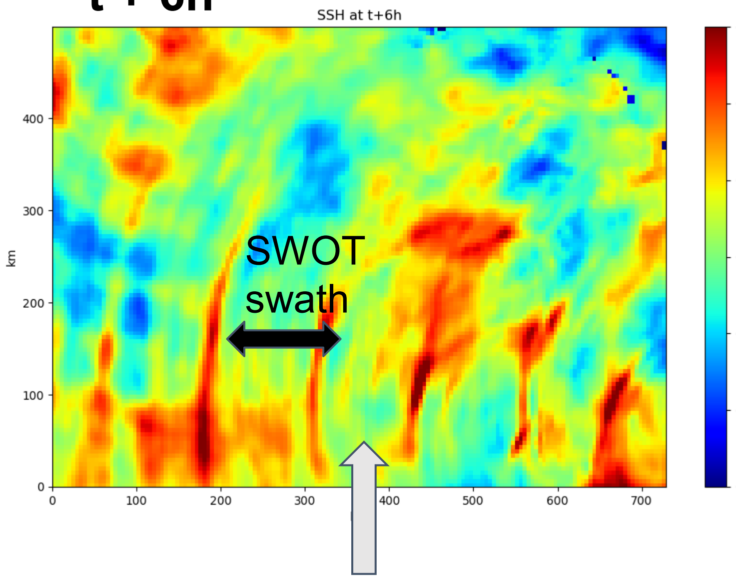
The collinear method is less sensitive than Direct to IGWs

Both methods are based on comparisons with signals at longer time-scales than IGW period, **BUT @12h :**

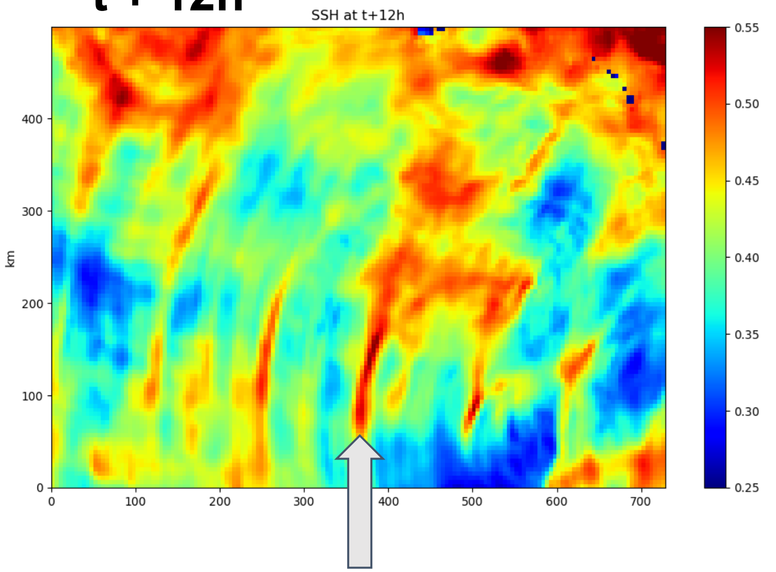
t



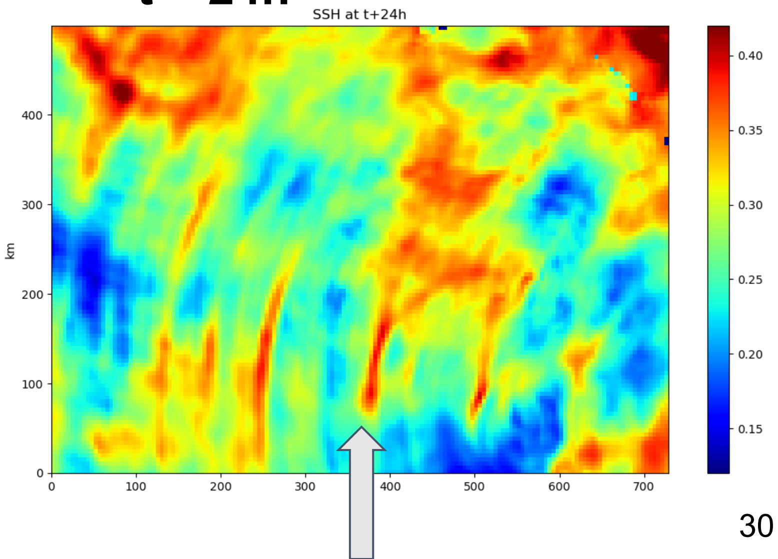
t + 6h



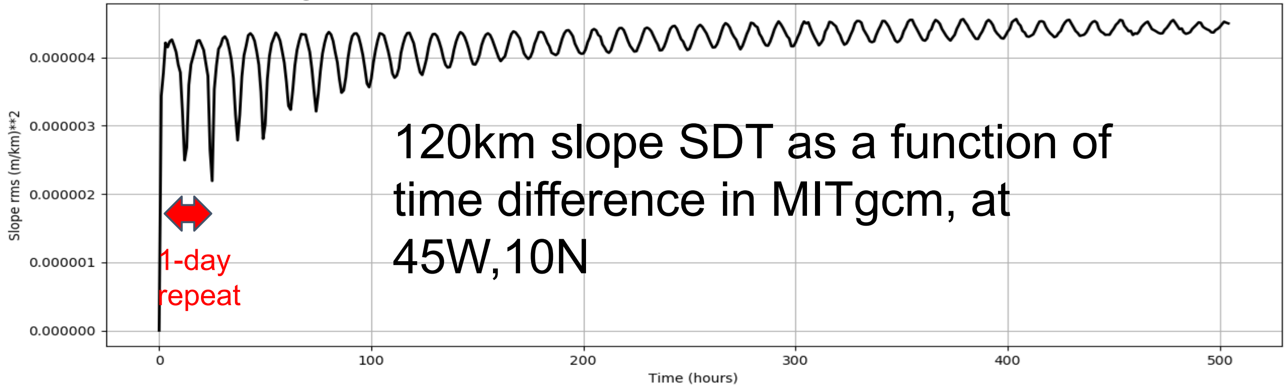
t + 12h



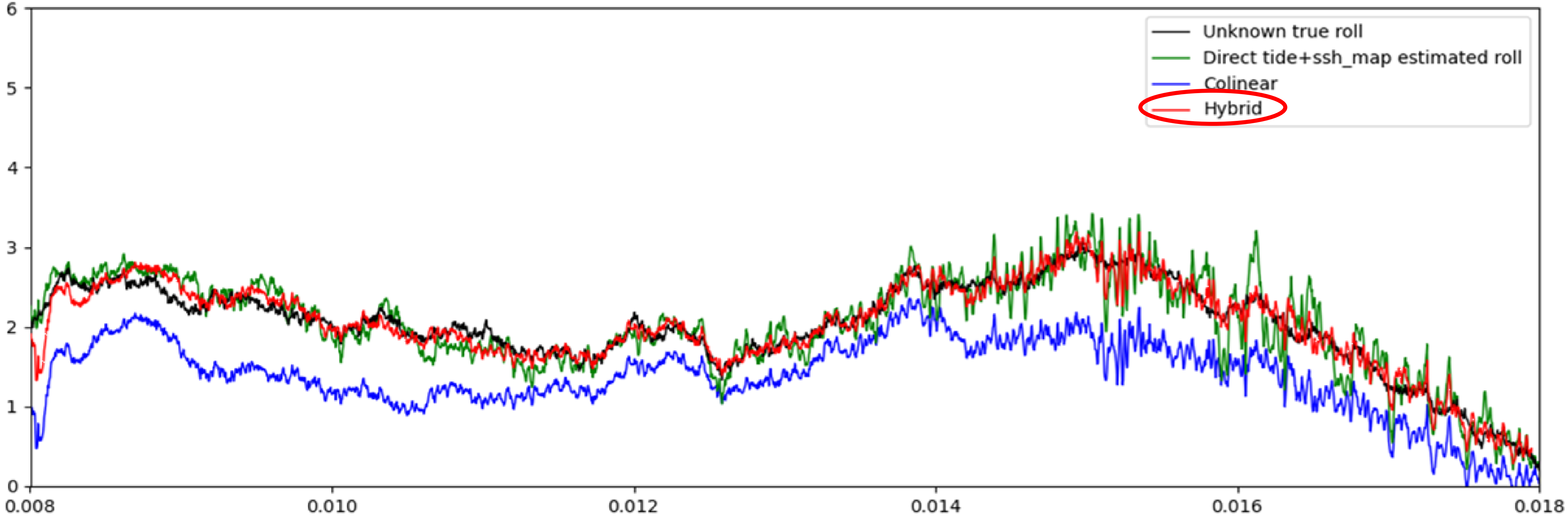
t + 24h



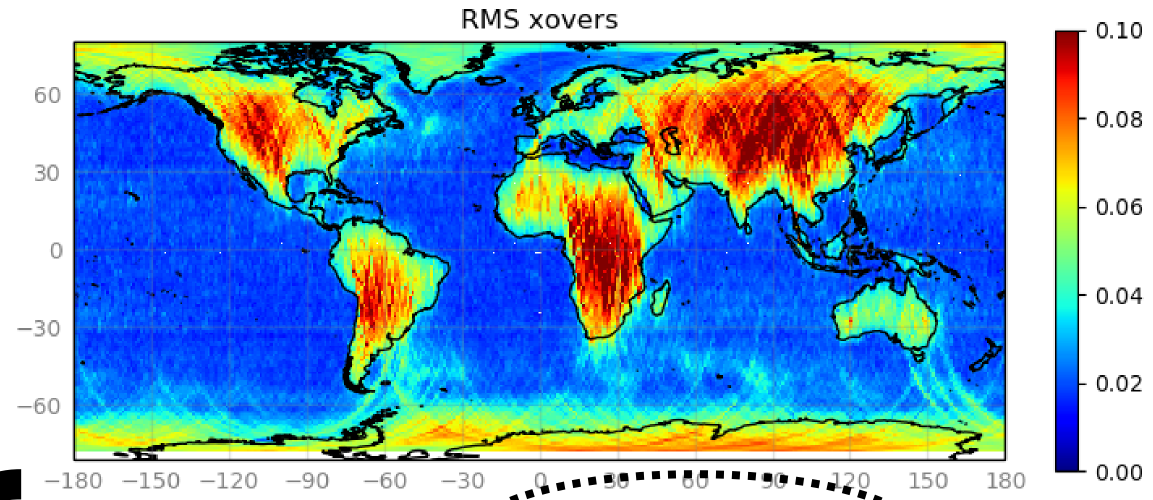
Repeat_fast_sampling = 23.84h



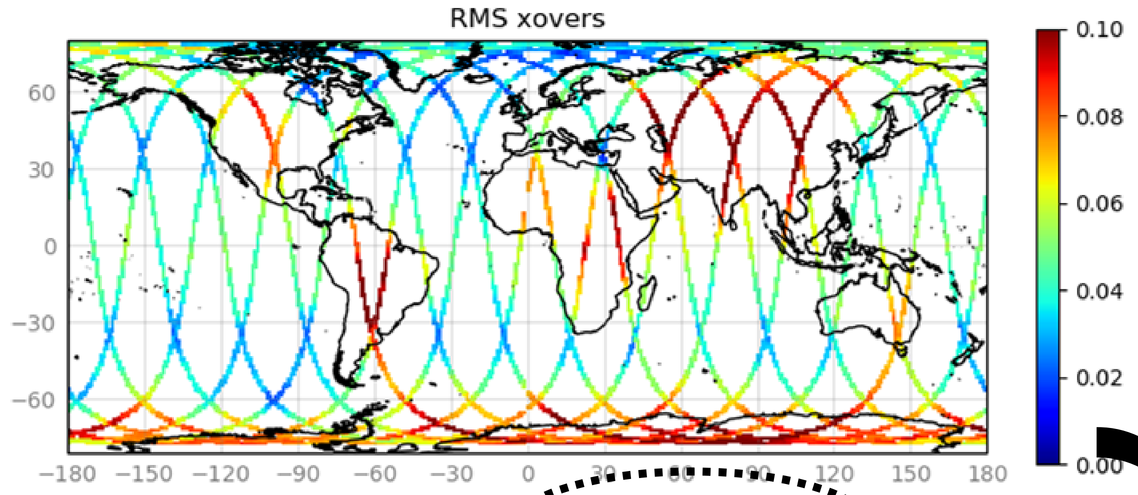
Comparison of DIRECT, COLINEAR and HYBRID inversions



Performance comparison (pre-launch, ongoing work)



Open-Ocean std : 2.16 cm
Land std : 6.51 cm



Open-Ocean std : 4.56 cm
Land std : 7.57 cm

75% variance reduction (ocean)
15% variance reduction (inland)

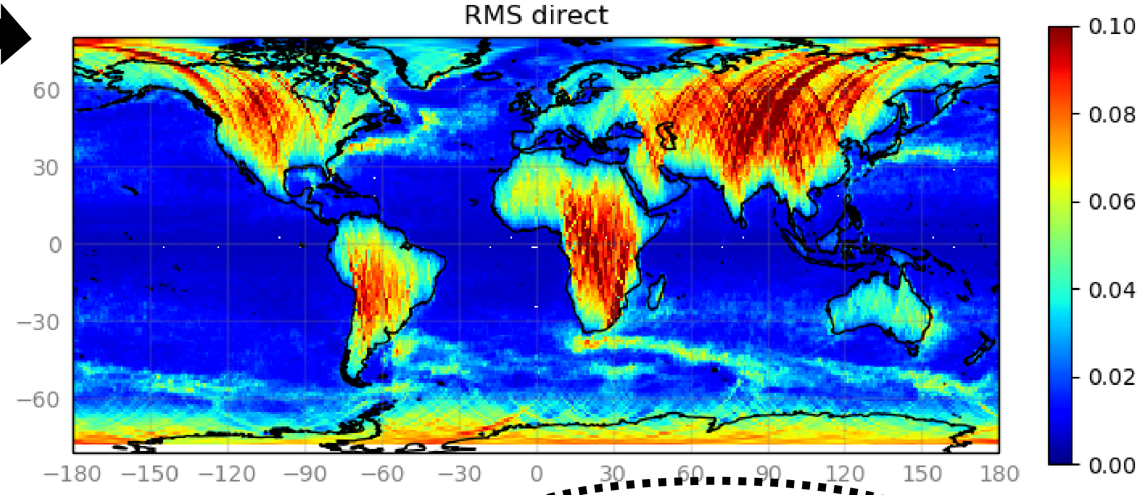
21-day

Level-2

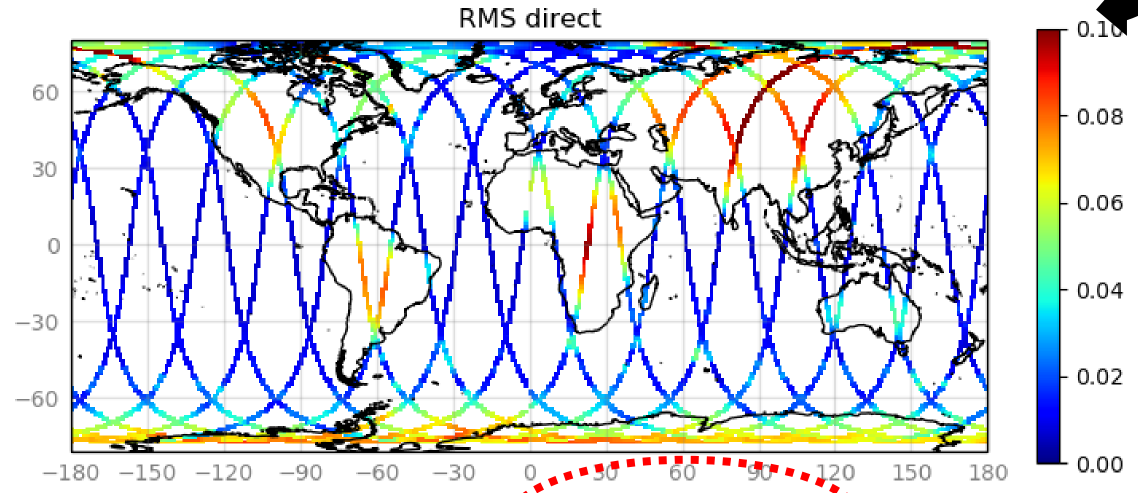
Level-3

1-day orbit

85% variance reduction (ocean)
40% variance reduction (inland)



Open-Ocean std : 1.31 cm
Land std : 6.08 cm



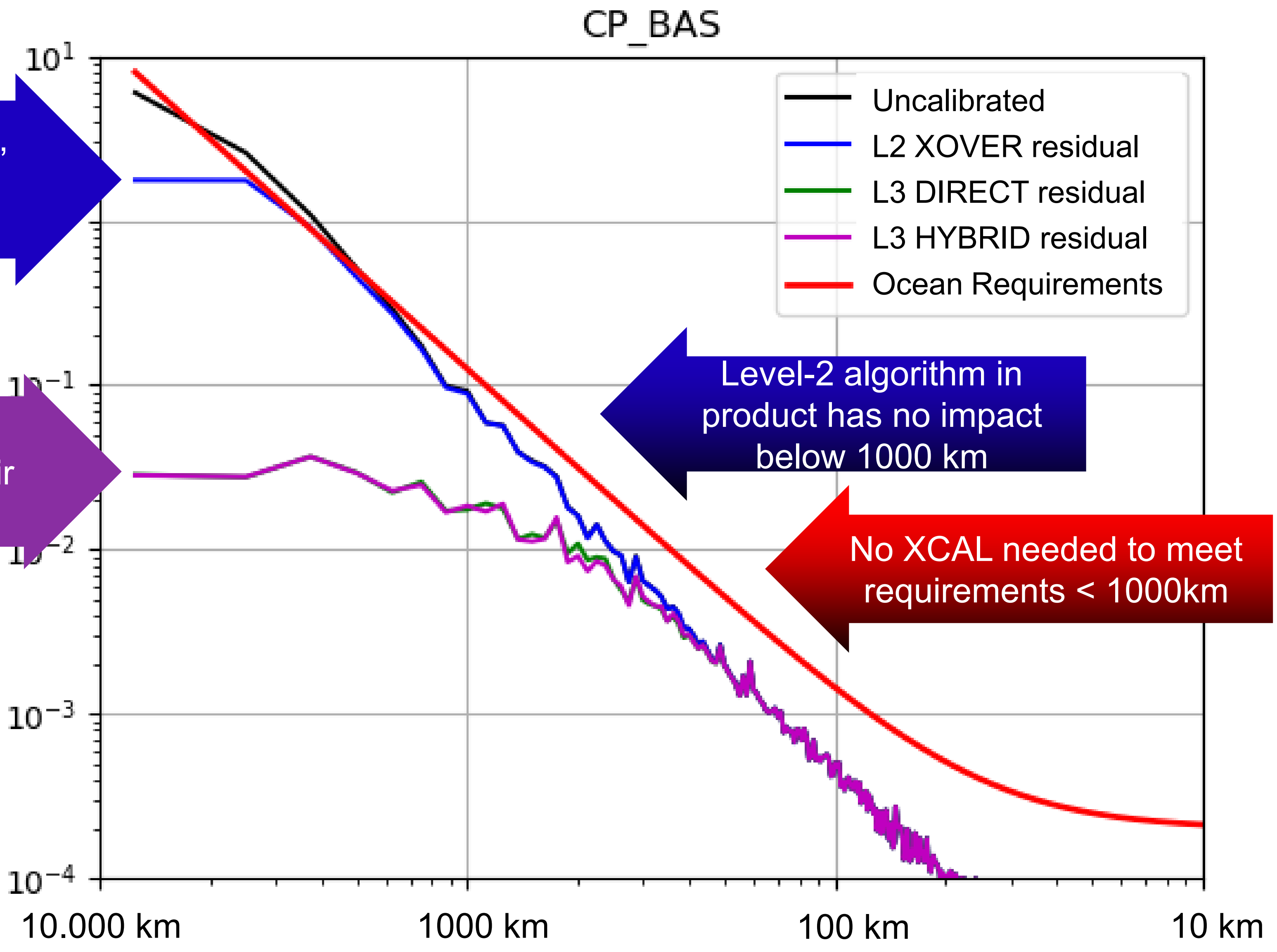
Hydrology
requirements are met

Open-Ocean std : 1.10 cm
Land std : 5.86 cm

Spectral performance of the L3 algorithm (1-day orbit)

Long distance between XOVERs, little improvement of Level-2 correction below 3000-4000 km

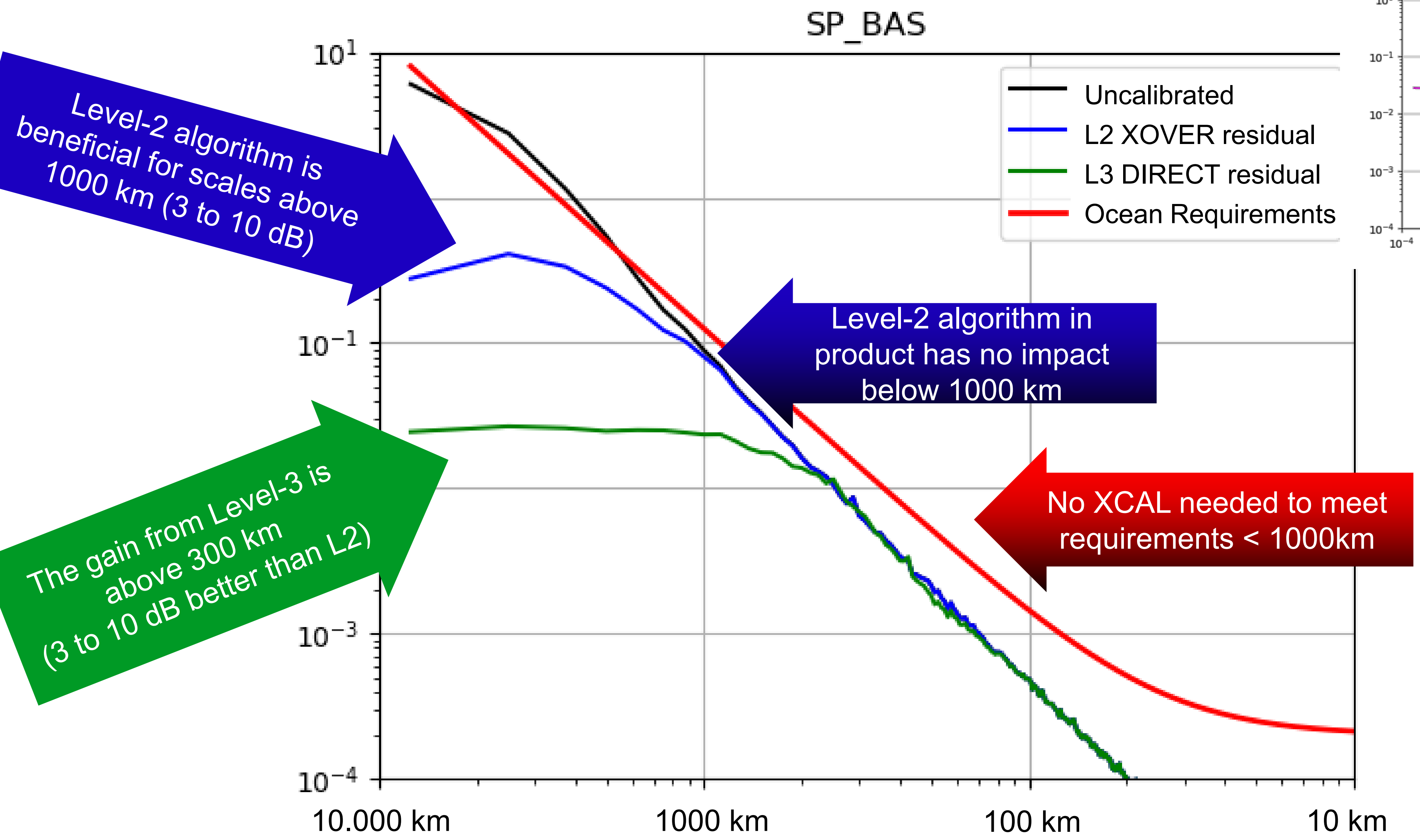
The gain from hybrid Level-3 is above 300 km (controlled by nadir constellation)



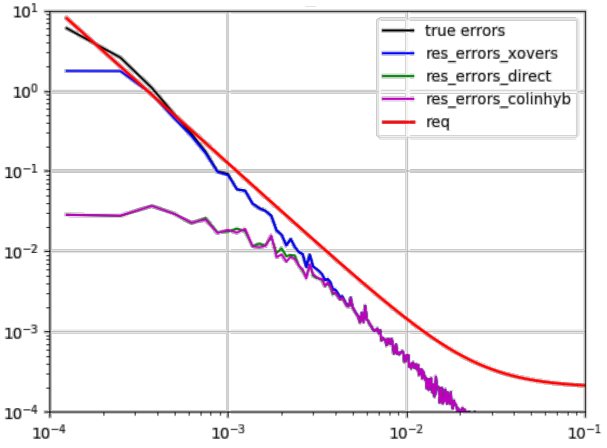
Level-2 algorithm in product has no impact below 1000 km

No XCAL needed to meet requirements < 1000km

Spectral performance of the L3 algorithm (21-day orbit)



1-day orbit for reference




Conclusion

Conclusion: where do we stand before launch?

- The challenge is to isolate uncalibrated errors from ocean content
  - ❖ XCAL should not alter ocean signals for oceanographers (i.e. do less xcal error than uncalibrated SSH)
  - ❖ XCAL should not project ocean variability onto hydrology products
- A two-sided algorithm activity
  - ❖ SWOT Operational L2 Processor: to secure a big component of the hydrology error budget
  - ❖ SWOT Science Team L3 Research Processor
    - for the 1-day orbit (not enough crossover for the standard XCAL)
    - to provide the best research-grade ocean products
- Other groups exploring alternative calibrations (e.g. IMT Atlantique, IGE, Wuhan University)
- Performance updated with high resolution ocean models & new simulations from the Project
  - ❖ Current Best Estimate (CBE) is 3.4 cm RMS for hydrology (50% margins for requirements)
  - ❖ No requirement for the ocean (Level-2 XCAL is not needed nor efficient up to 1000 km)
  - ❖ The L2 and L3 XCAL should be beneficial above 1000 km (uncalibrated error is tens of cm, calibrated is 1-2 cm)
- Question for the ST: should we update the scientific simulator or the simulated products ?

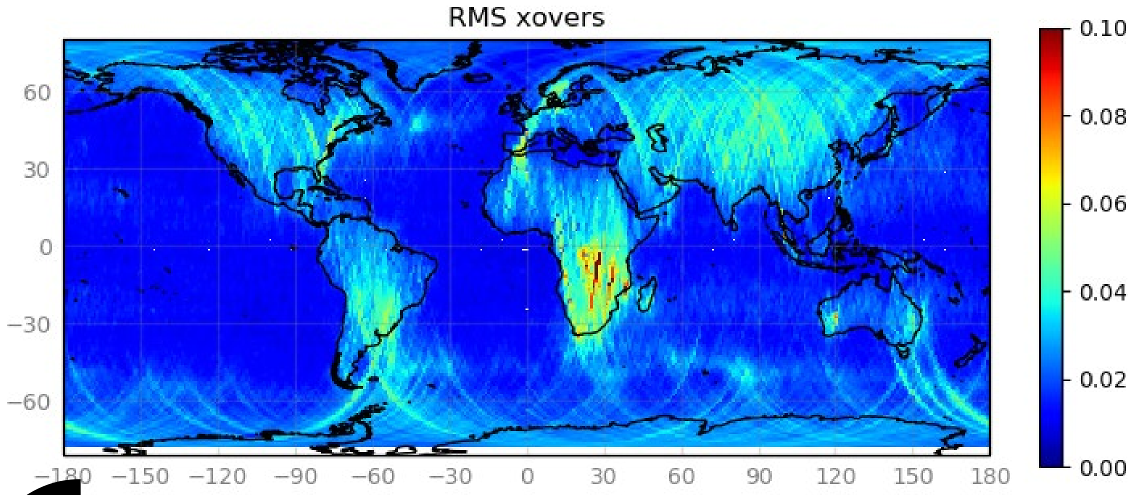
Level-2 and Level-3 data-driven calibration

G.Dibarboure (CNES), C.Ubelmann (DATLAS)
B.Flamant, F.Briol, G.Brachet, Y.Faugère, O.Vergara (CLS)

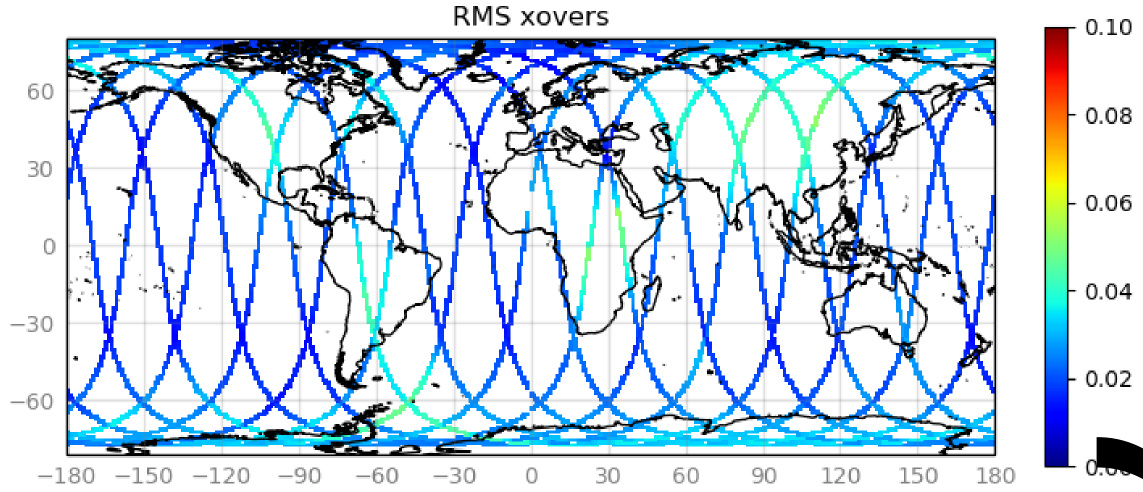
cnes CLS datlas


BACKUP SLIDES

CBE21 scenario: Level-2 and Level-3 performance



Open-Ocean std : 1.51 cm
Land std : 3.12 cm



Open-Ocean std : 1.96 cm
Land std : 3.10 cm

60% variance reduction (ocean)
20% variance reduction (inland)

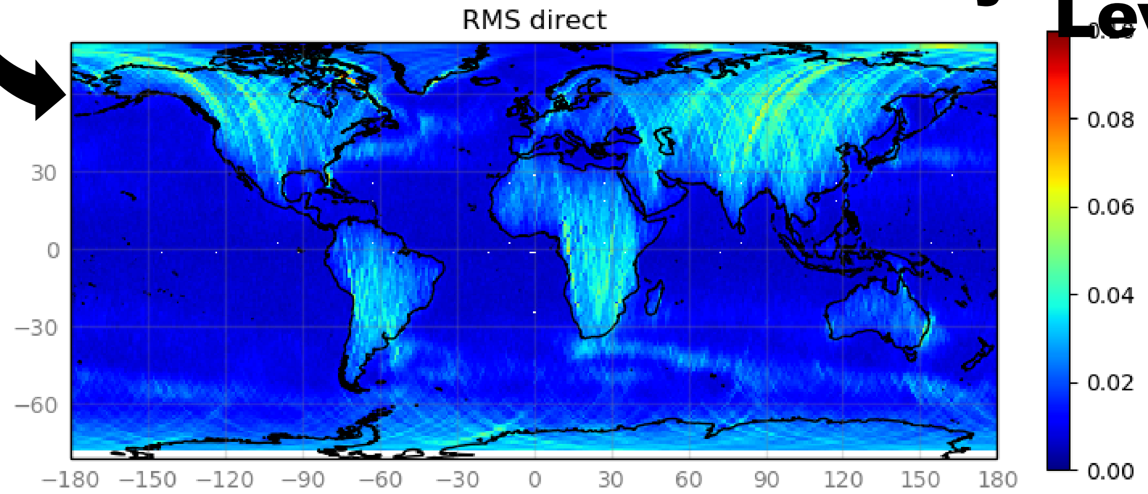
21-day

Level-2

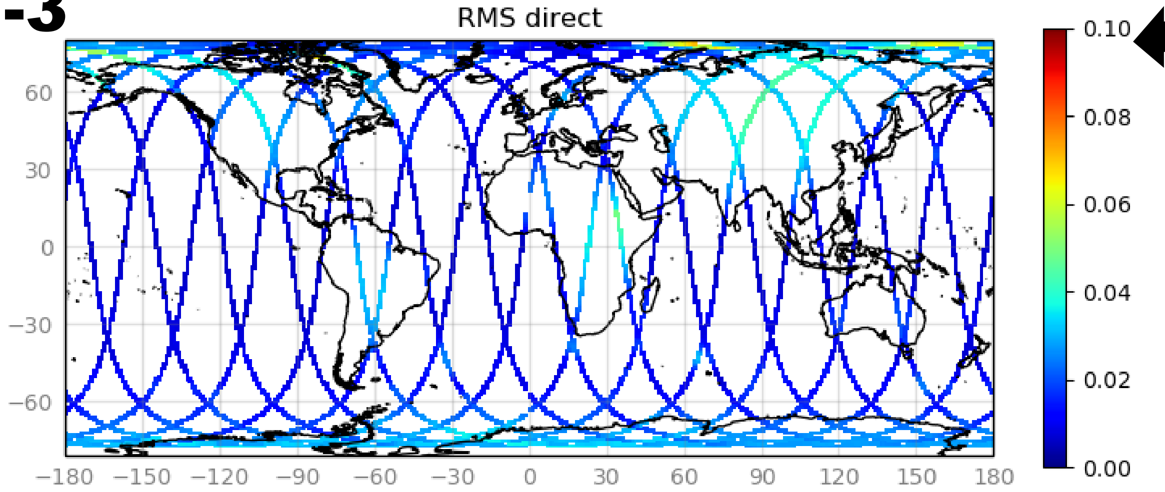
Level-3

1-day orbit

80% variance reduction (ocean)
20% variance reduction (inland)



Open-Ocean std : 0.93 cm
Land std : 2.77 cm



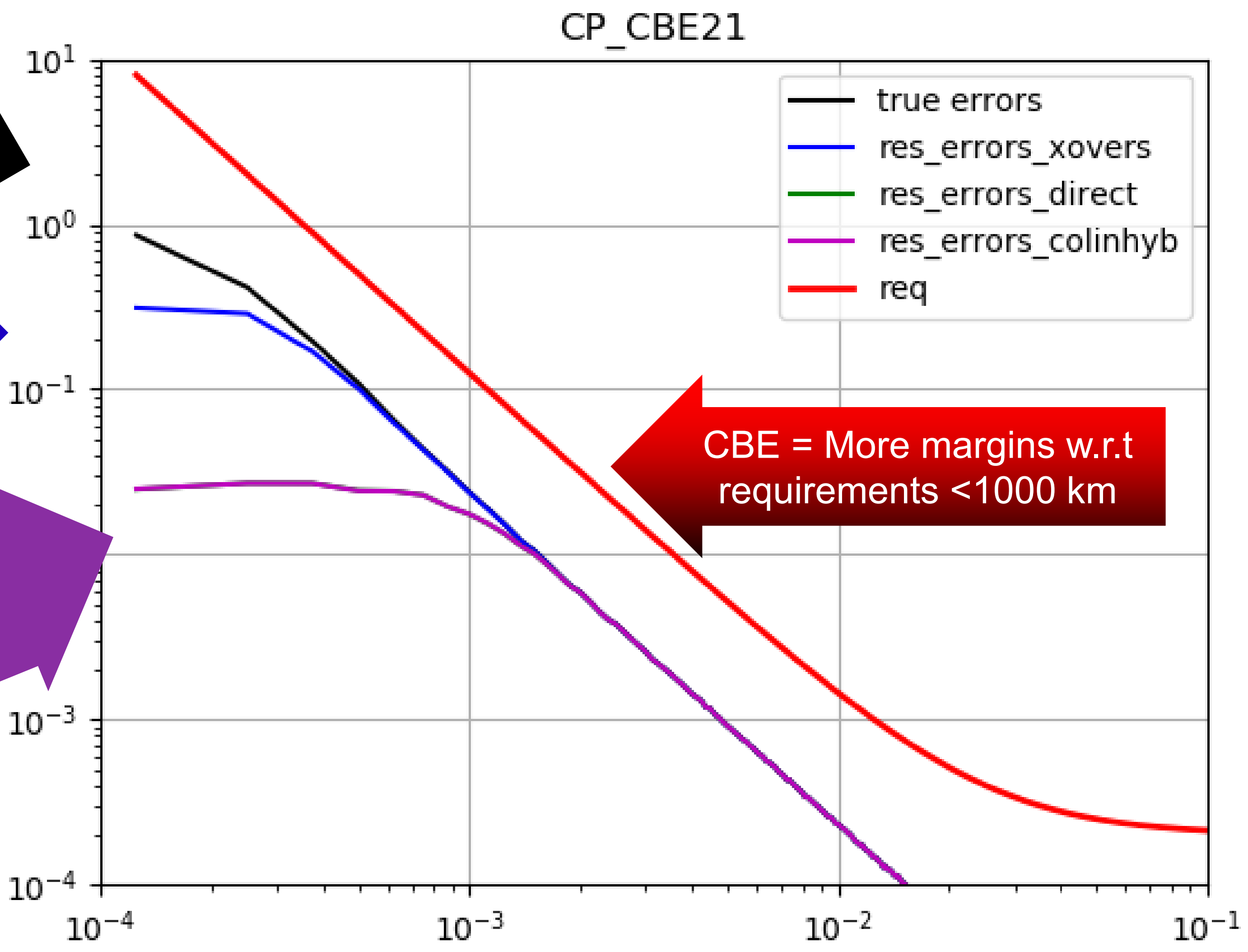
Open-Ocean std : 0.89 cm
Land std : 2.73 cm

CBE21 scenario: Spectral view of the 1-day orbit

Much less uncalibrated error at scales above 1000 km

Long distance between XOVERs, little improvement of Level-2 correction below 3000-4000 km (like in baseline scenario)

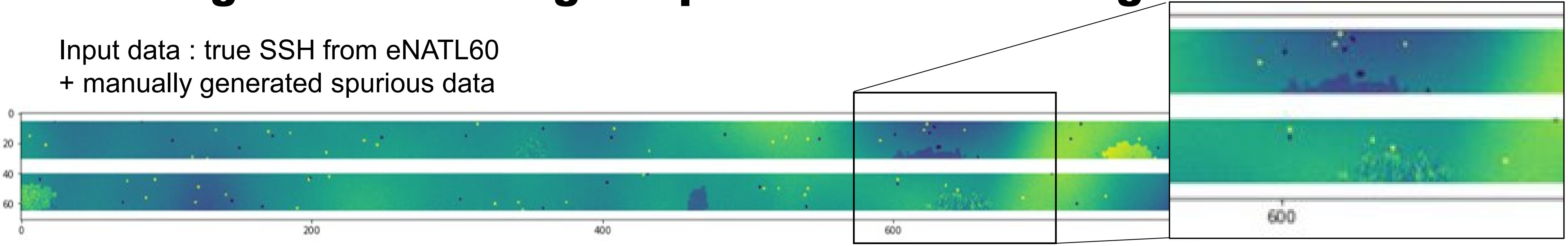
The gain from hybrid Level-3 is above 700 km (because the uncalibrated error is smaller in CBE, i.e. harder to separate from the ocean)



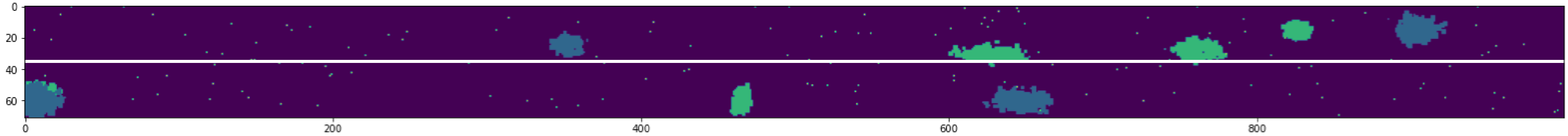
CBE = More margins w.r.t requirements <1000 km

Level-3 algorithm : editing of spurious data and regions

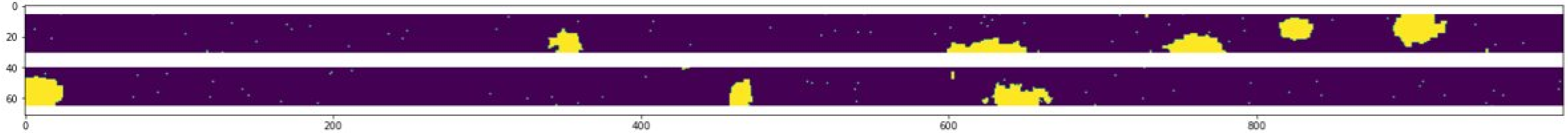
Input data : true SSH from eNATL60
+ manually generated spurious data



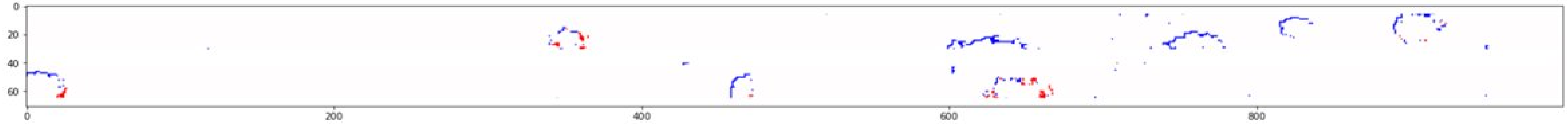
Truth: spurious regions we are looking for (spurious points in blue, biased regions in cyan, very noisy regions in green)



Output : suspected anomalies flagged in yellow



Editing errors (blue is false alarm, red is undetected anomaly)



First run on 3 days of KaRIN data :

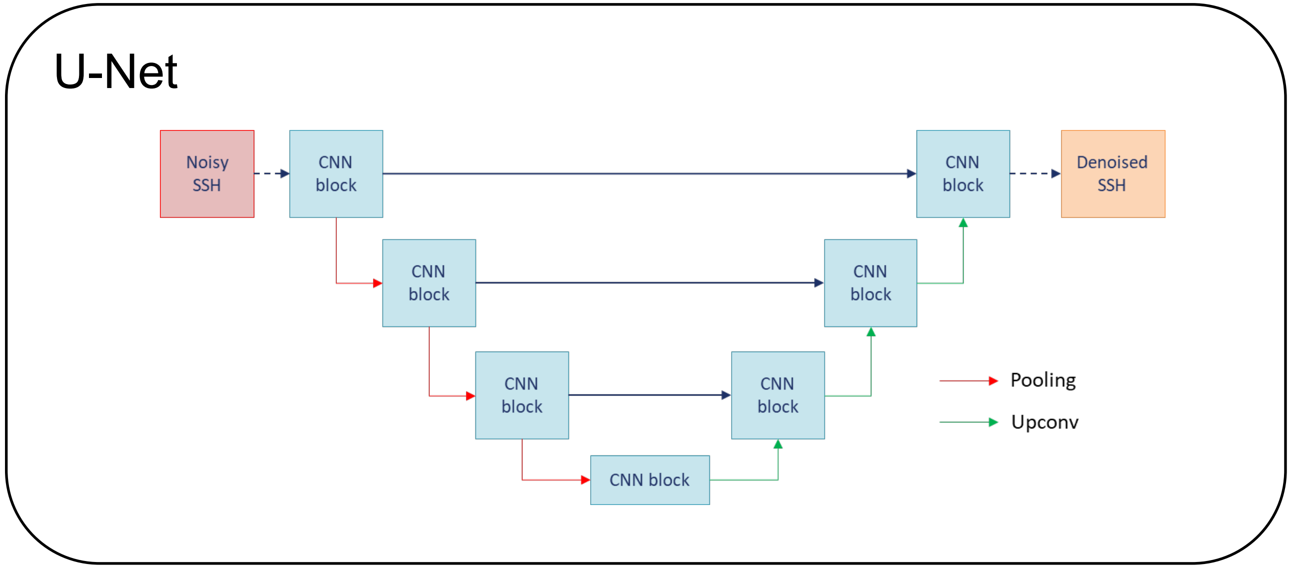
Corrected flagging : 98 %

False alarms : 1.27 %
Misses : 0.41 %

HK score : 0.93
Computing time : 22 s

Courtesy of A.Treboutte

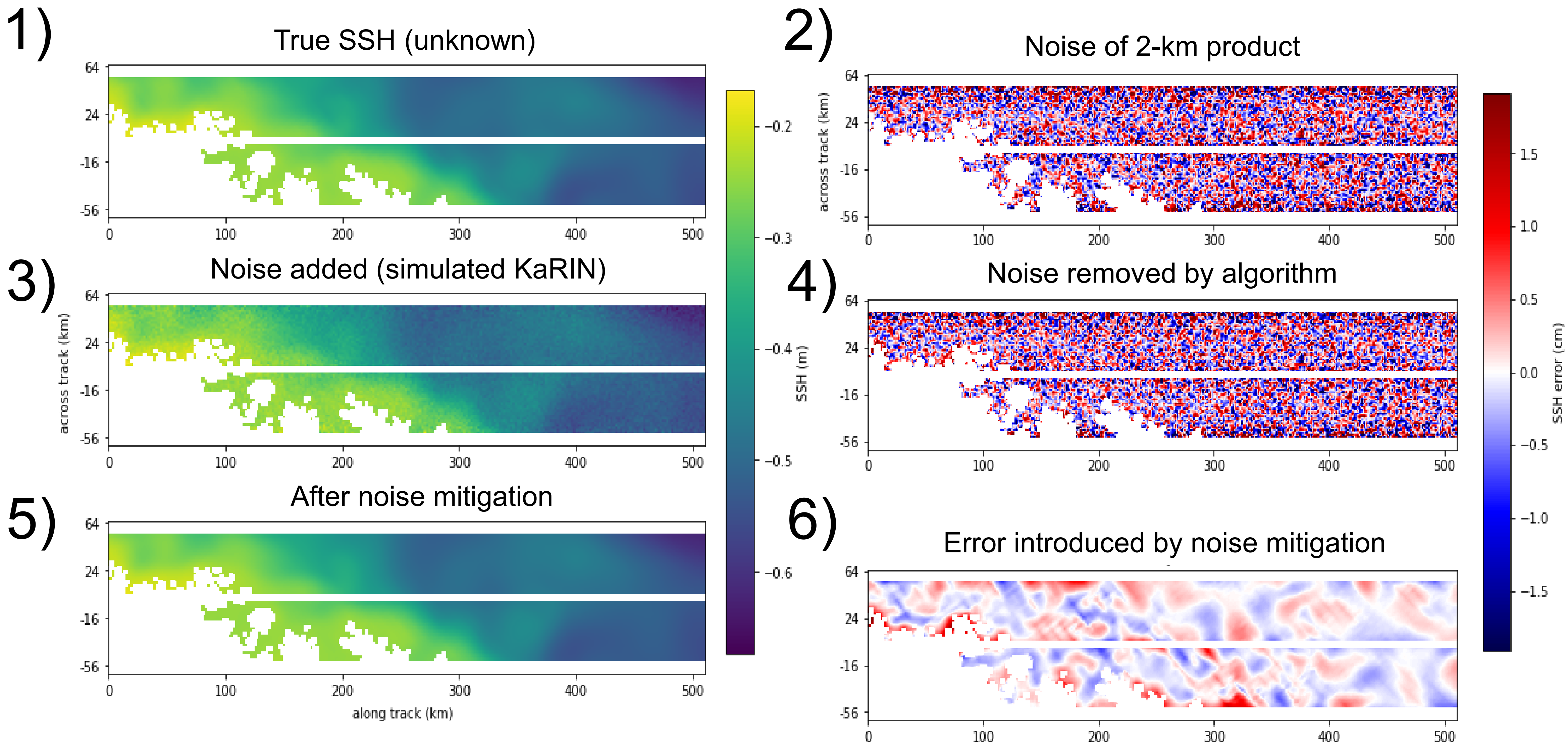
Level-3 algorithm : AI-based noise mitigation with U-Net



- U-Net was trained on 1-year of simulated KaRIN data with eNATL60 as « ocean truth »
- Evaluation at global scale on MITgcm and GLORYS models (read: independent from training)

Courtesy of A.Treboutte

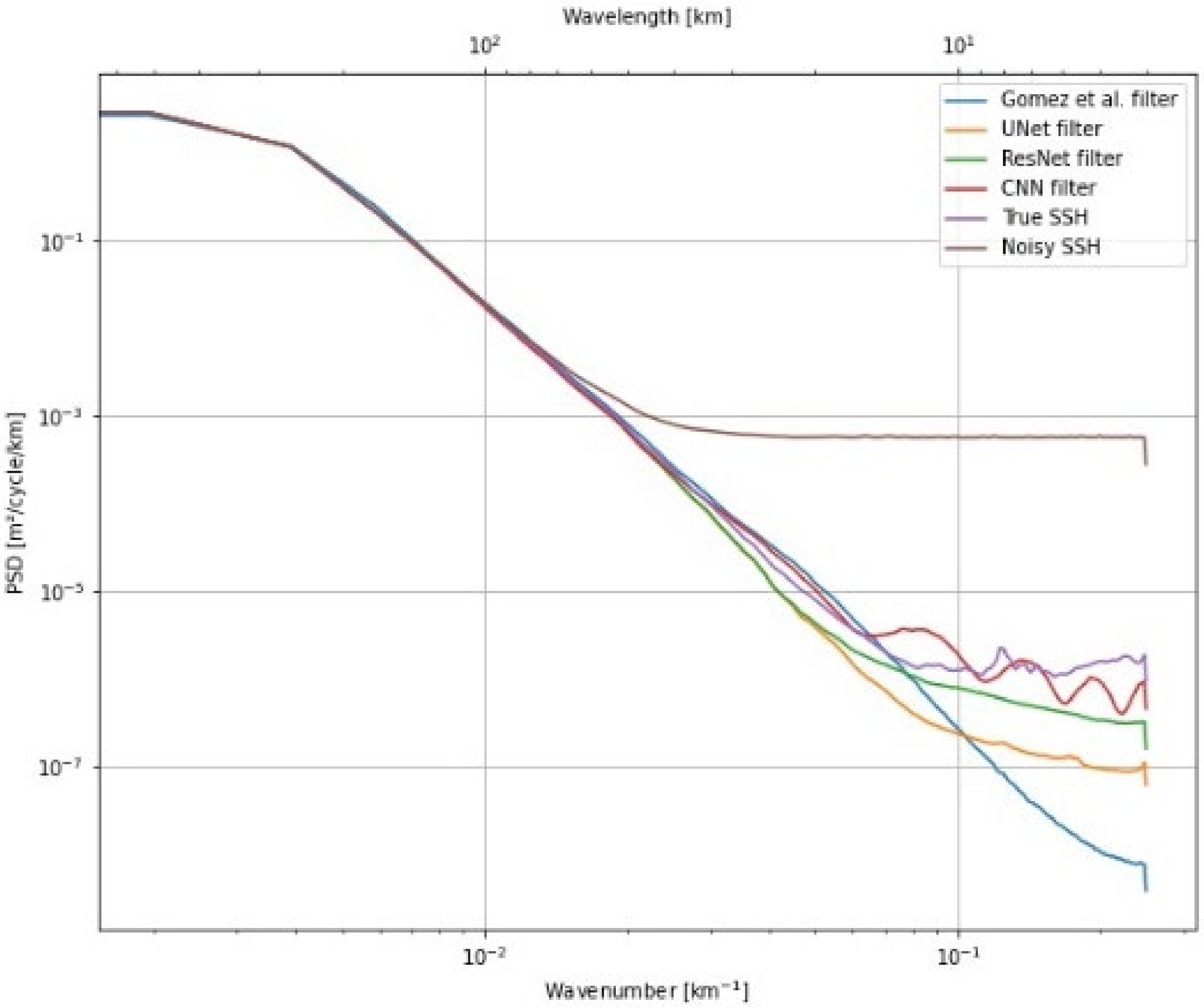
Noise mitigation: results (1/2)



- Residual error : 2 mm RMS global ocean (before removal : 2 – 5 cm RMS noire or more depending on local waves)
- Yields better results than other noise removal techniques (second best is from Gomez & al.)

Courtesy of A.Treboutte

Noise mitigation: results (2/2)

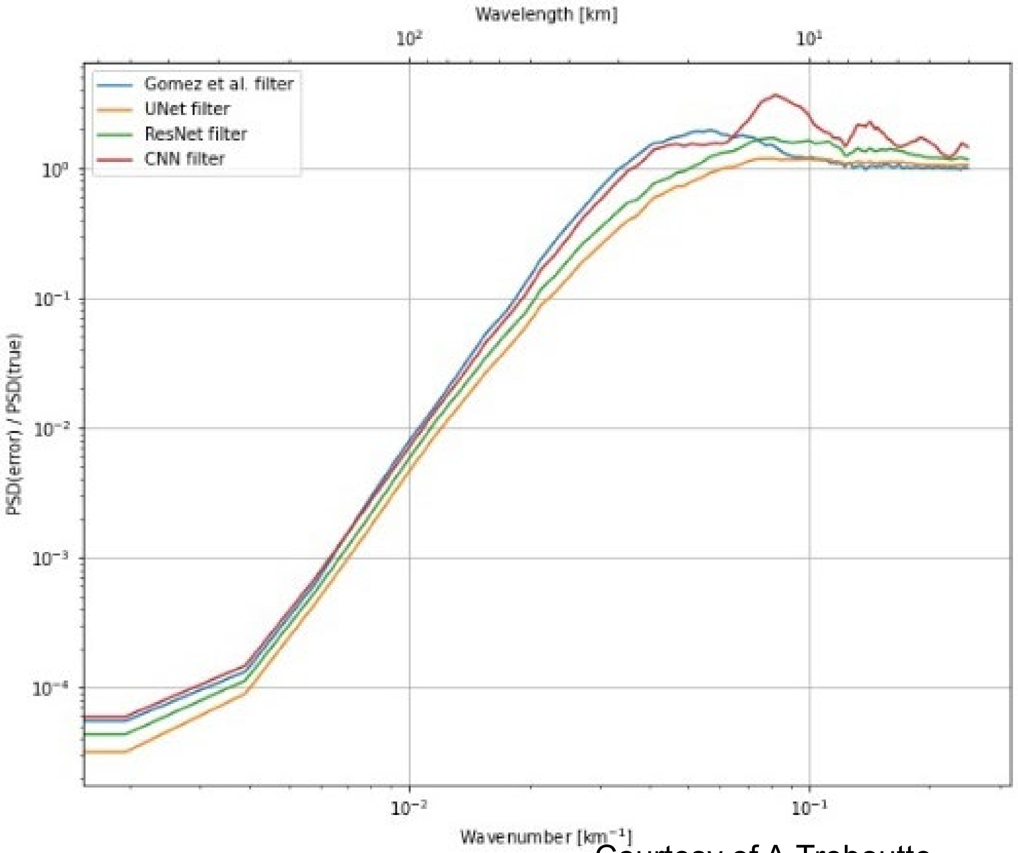


Note : global spectrum, incl. high waves, no 7.5 km cross-track averaging as opposed to the SWOT Scientific Requirement Document, hence a higher noise floor before mitigation

Effective observability scale
(global, incl. waves up to 10 m or more)

	SNR = 1
Gomez et al. filter	28 km
CNN	27 km
ResNet	20 km
U-Net	16 km

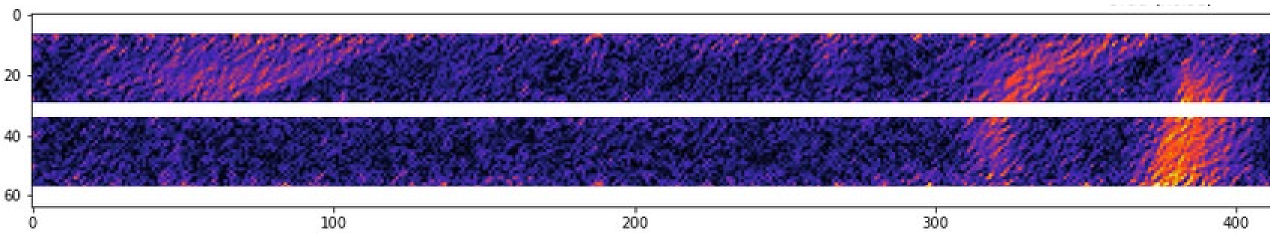
Error PSD / True PSD



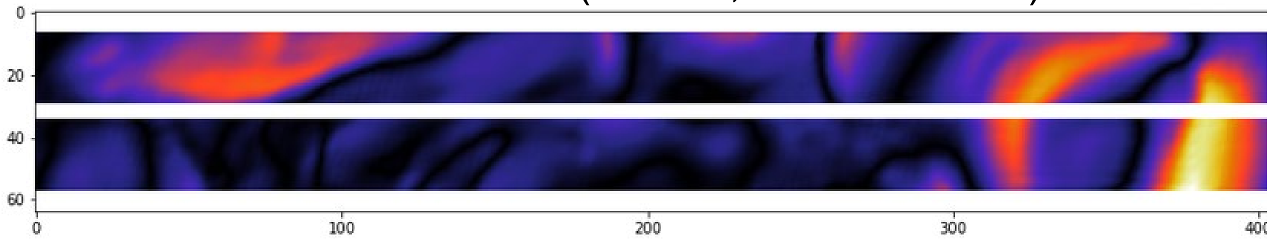
Courtesy of A.Treboutte

The value of noise mitigation (as opposed to kernel filtering)

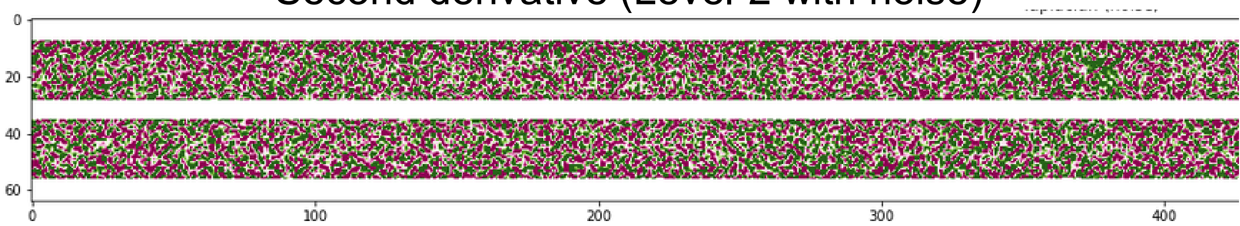
First derivative (Level-2 with noise)



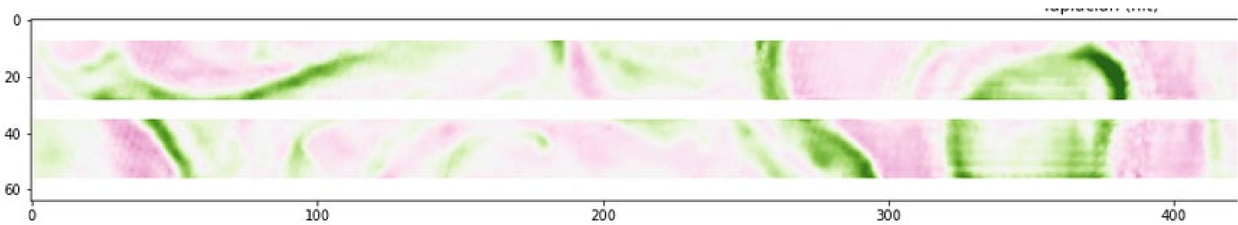
First derivative (Level-3, noise removed)



Second derivative (Level-2 with noise)

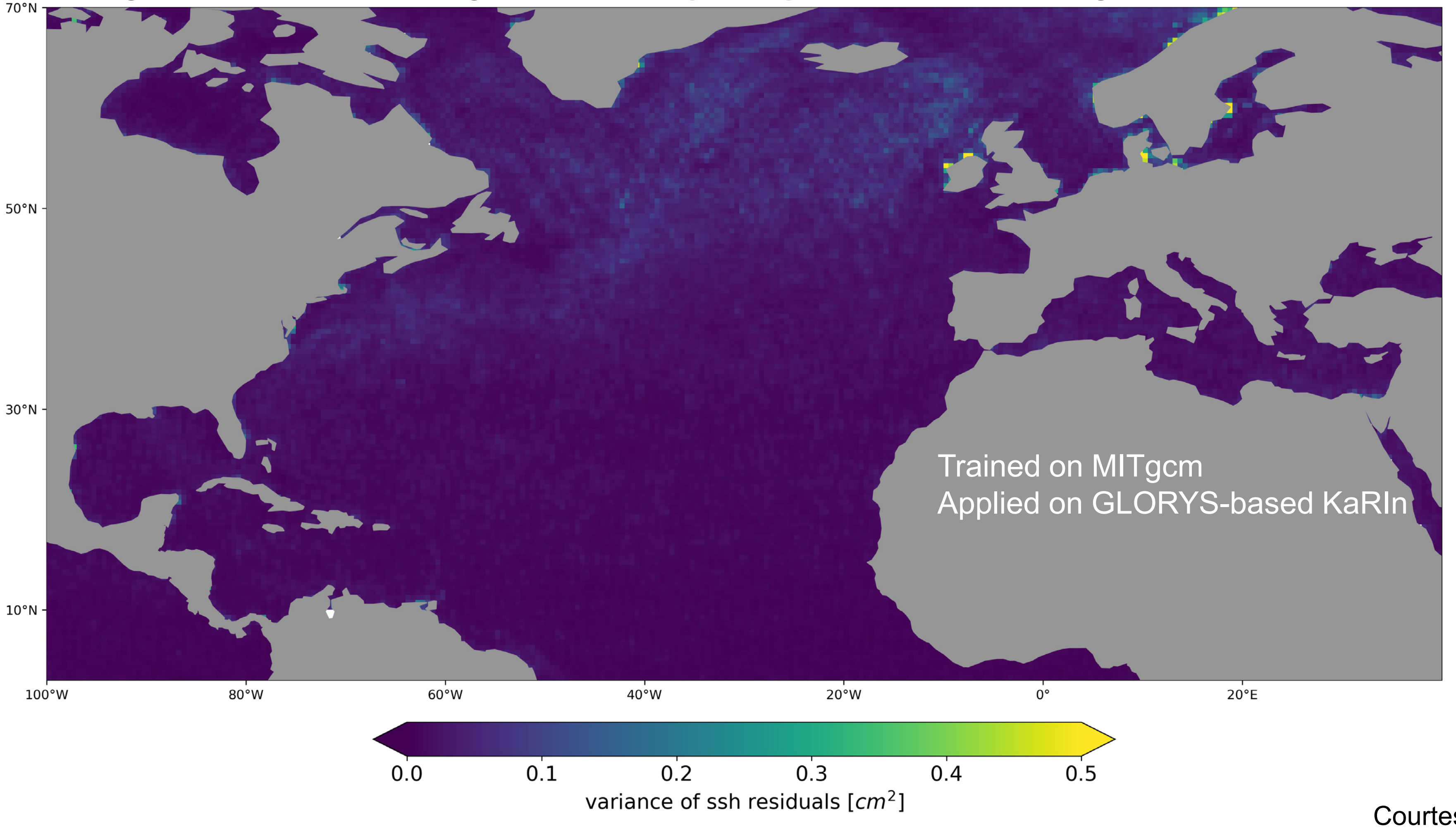


Second derivative (Level-3, noise removed)



Noise mitigation: residual error after noise removal

- Generally less than 0.1 cm² or error variance after noise mitigation
- Modulation of noise by waves is slightly visible up to 0.2 cm²
- Very limited coastal artifacts of the noise removal algorithms (as opposed to all other techniques)
- No regional tuning required, training can be updated based on in-flight CalVal performance of KaRIn



Courtesy of A.Treboutte