CryoSat-2 for enhanced sea-ice thickness and ocean observations in Antarctica

Project Overview

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and the CS+AO Consortium

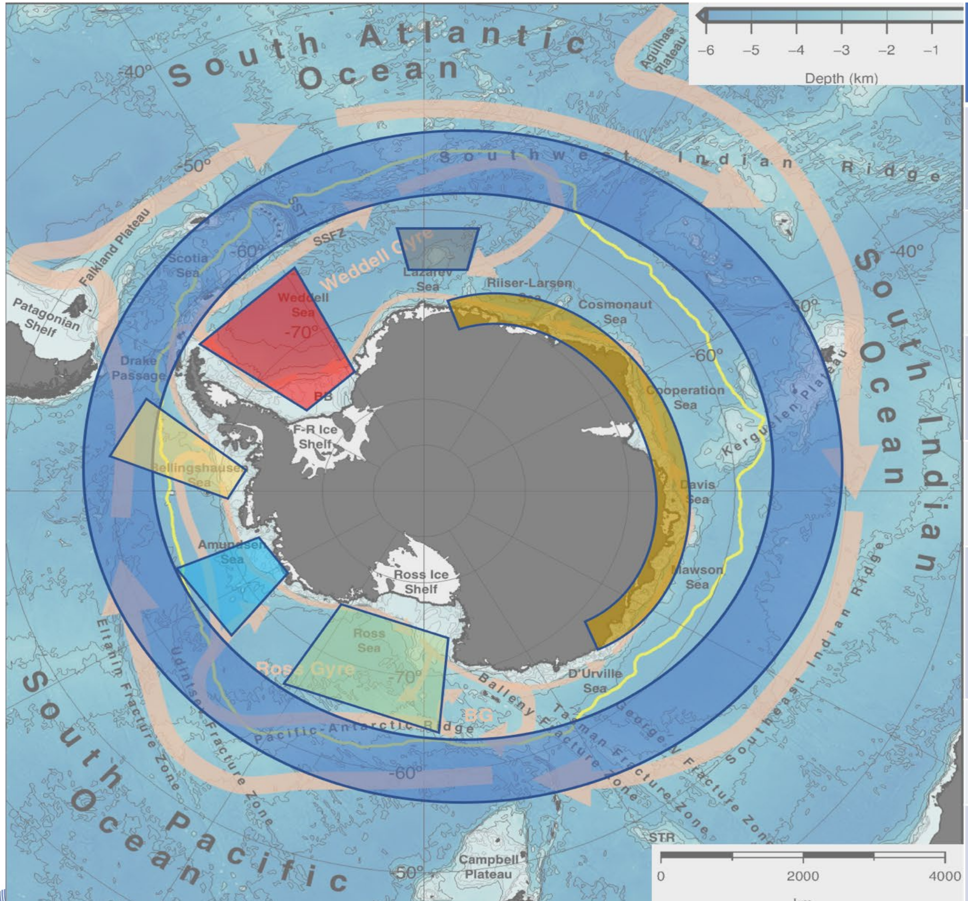
Objectives 1

1. Investigate novel methods to improve SI freeboard, SIT, ocean topography & currents in Antarctic ocean, using CS SAR, SARin and other satellites
2. Design a new algorithm for retrieving improved SI freeboard + thickness in Antarctica, that could be implemented in CS-PDS
3. Novel methods to get SSH and currents in polynyas and leads from CS2, to analyse variability of the ocean dynamics. Assess impacts of ocean dynamics on transport of floating sea-ice.
4. Deliver experimental dataset covering points 2/3 for the full Antarctic region and full mission lifetime.
5. Perform scientific assessment of the main changes and dynamics of sea-ice and ocean mesoscale and large scale circulation in Antarctica demonstrating the scientific value of the new products.

Objectives 2

- Develop, inter-compare and validate multiple approaches to sea surface height and sea ice thickness retrieval on Antarctic sea ice. Approaches to be considered are:
  - Novel LRM/SAR/SARIN methods for leads, polynyas, open ocean and sea ice classification
  - Along-track processors over leads, polynyas and open ocean for sea surface estimation
  - Along-track processors over sea ice floes for sea ice thickness estimation
  - Pan-Antarctic gridded products of dynamic ocean topography and geostrophic currents (along with secondary products: EKE, upwelling, etc…)
  - Pan-Antarctic gridded products of sea ice thickness
  - Preliminary inter-comparison of along-track and gridded products developed in steps b-e
  - Validation over selected tracks and key regions against in-situ and airborne data.

Candidate test areas



Regions	Science questions	Data availability / CS2 challenges
Sea ice – Ocean edge	Up- or Down-welling Jet formation AAIW formation	LRM/SAR boundady AVISO overlap
Weddell Sea	MYI formation AABW formation Weddell Gyre Continental shelves	Thicker sea ice / snow Snow buoy data Flooding Snow-ice formation
Belligshausen Sea	ACC proximity Thinning ice shelves Continental shelves	OIB availability
Amundsen Sea	Thinning ice shelves Continental shelves Amundsen Sea Low	Tide gauges available Moorings available CS2 SSH validation
Ross Sea	Spin up / down of gyre AABW formation Continental shelves Polynyas Coastal currents	Tide gauges available Gliders deployed Geoid bias FYI AMSRE / SMOS
Indian/Pacific sector	ACC proximity Coastal current	Data paucity AVISO overlap Geoid bias
Weddell polynya	Unknown formation Upwelling location	Regular cruises SAR mode polynya

Tasks (High-level view)

WP 1
Scientific Requirements Consolidation
Lead: UCL-CPOM
Contributor: DTU, ShepSp

WP 2
Dataset Collection
Lead: ShepSp
Contributors: MSSL, NOCS, IPSL

WP 3
Along-track Product Development and Validation
Lead: CLS, dept: iSAT
Contributors: All

WP 4
Gridded Product Development and Validation
Lead: DTU, dept: LEGOS
Contributor: All

WP 5
Data Set Generation and Impact Assessment
Lead: UCL-MSSL
Contributor: UCL, CSL, DTU, IPSL MERCATOR, NOCS,

WP 6
Scientific Roadmap
Lead: UCL-CPOM
Contributors: ShepSp, DTU

WP 7 Management ***Lead: UCL-MSSL***

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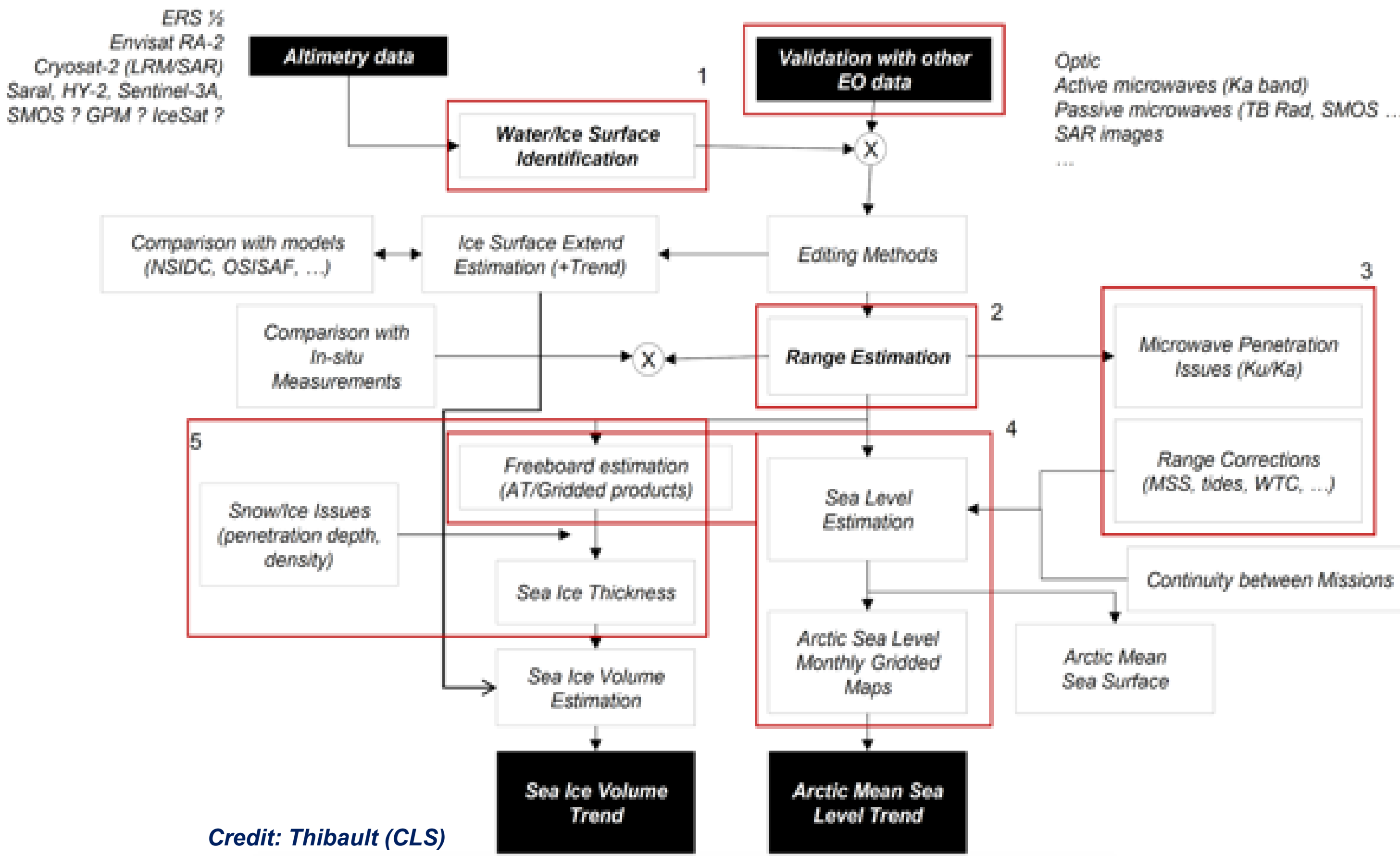
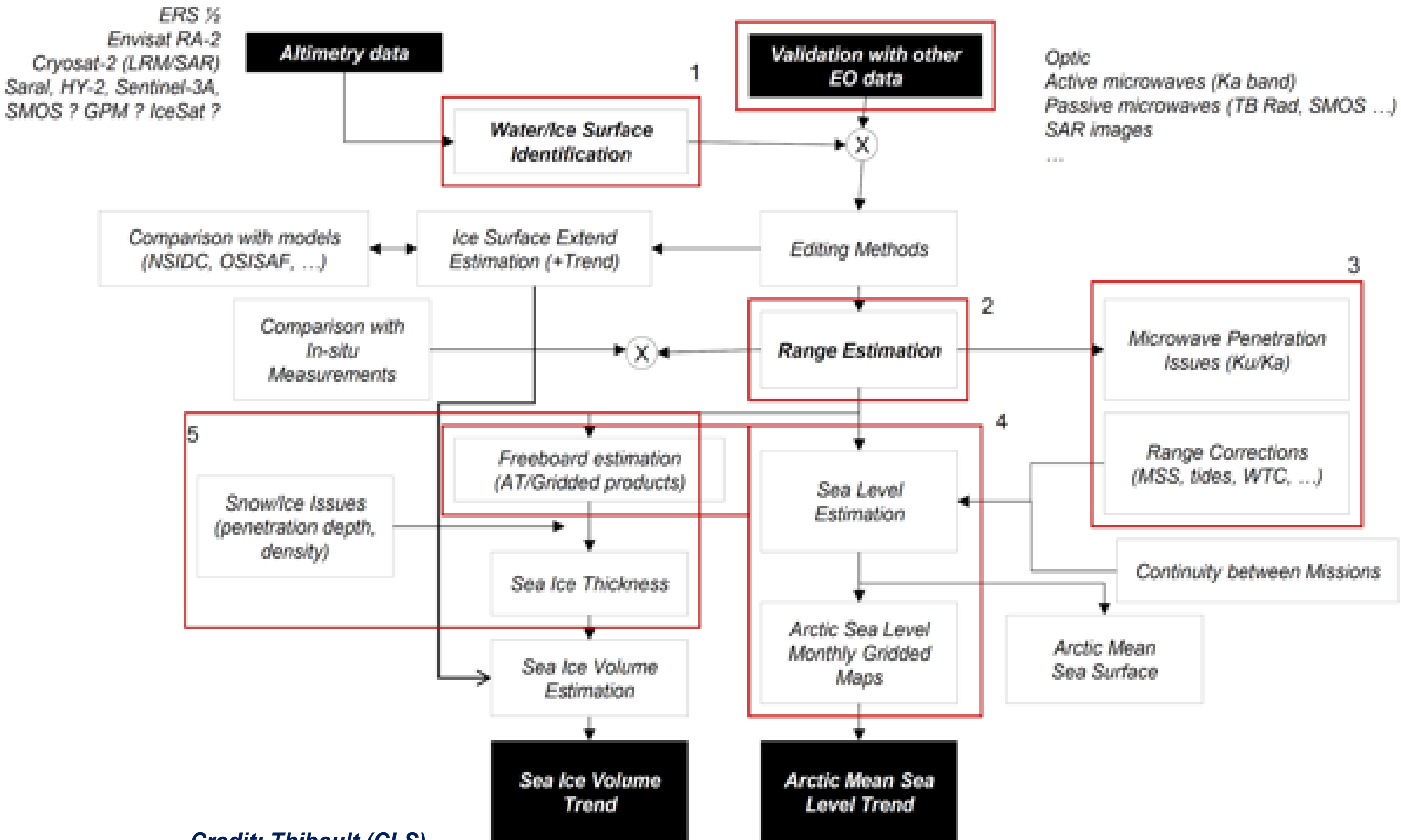
WP 7 Management ***Lead: UCL-MSSL***

Radar Processing Chain

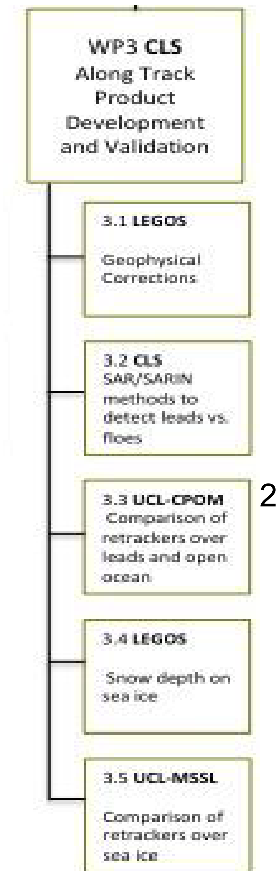


Credit: Thibault (CLS)

WP3: along-track



Credit: Thibault (CLS)



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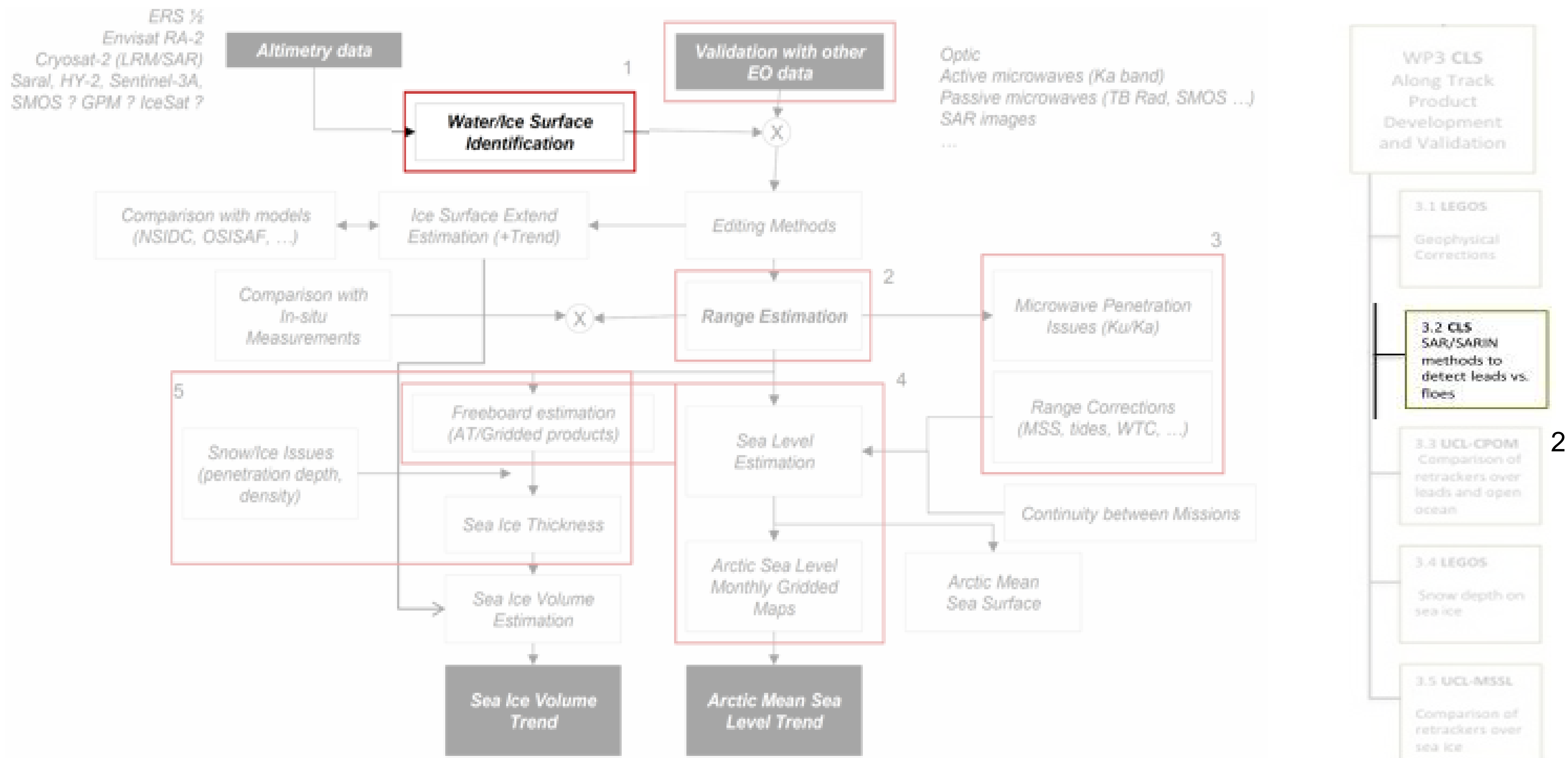
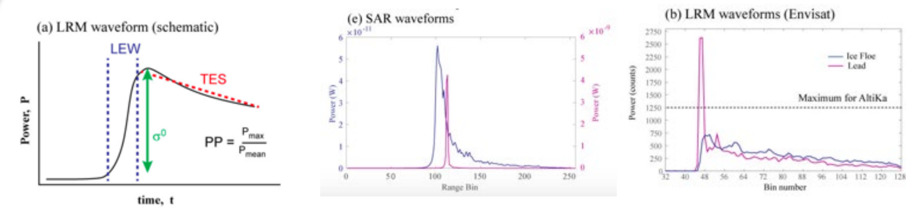


Waveform discrimination

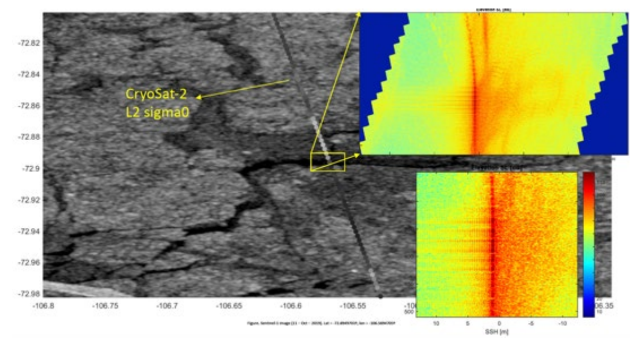
Group	Method	Operational	Reference
CLS	Neural Network (SAR and SARin L1b)	Prototype: Yes Pan-Arctic: Yes Pan-Antarctic: Yes	Thibaut et al (2010) Poisson et al (2018) Longepe et al, in prep
LEGOS	Peakiness (L1b)/RIP(L1a)	Prototype:Yes/Yes Pan-Arctic: Yes/No Pan-Antarctic: No/No	Guerreiro et al (2017) Fleury et al (2017)
MSSL	Echo shape (skewness, etc) (L1b)	Prototype: Yes Pan-Arctic: Yes Pan-Antarctic: No	Laxon et. al. (1987)
isardSAT	Fully Focused SAR (L1a)/ Off-nadir SARIN (L1b)	Prototype: Yes/Yes Pan-Arctic: No/No Pan-Antarctic: No/No	Rey et al. (2015) Passaro et al. (2017)
DTU	Peakiness + backscatter (L1b)	Prototype: Yes Pan-Arctic: Yes Pan-Antarctic: No	Jain et al., (2015)



Credit: Quartly et al (2019)

- Class 1: Oceanic shape, mainly found in open ocean but also over rough sea ice (MYI with a lot of ridges)
- Class 2: Peaky shape and only peaky shape → sea ice leads/polynya
- Class 3: Multi-peak shape → multi specular returns (multi-leads) or very disturbed surfaces in the radar footprint
- Class 4: Specular return with a trailing edge → high reflective sea ice (FYI)
- Class 5: Diffuse waveform with a peak in the trailing edge → Sea ice with off-nadir specular return (leads or high reflective sea ice)
- Class 5: Diffuse WFs with a peak on the leading edge or with a steep trailing edge → sea ice with an average roughness (MYI)
- Class 20: Oceanic shape with a peak in the thermal noise part of with a peak close to the leading edge → only found in the ocean (potential effect of zero-padding)

Credit: CLS



Credit: IsardSat

Waveform discrimination

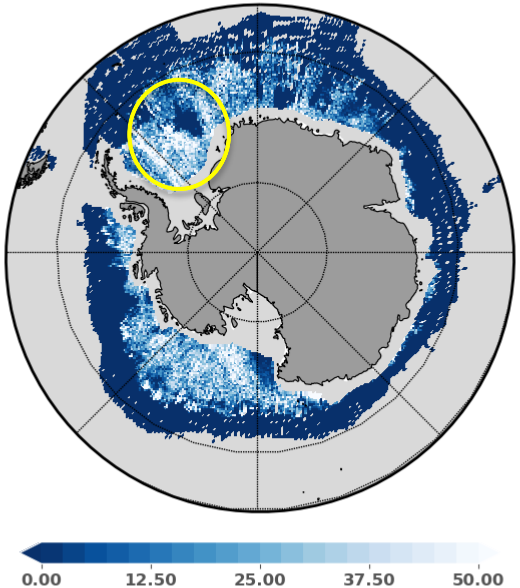
CS-2
Baseline D
Ice

Density Maps (Floes)

* SAR
* SARIn

Cryosat-2: MSSL discrimination

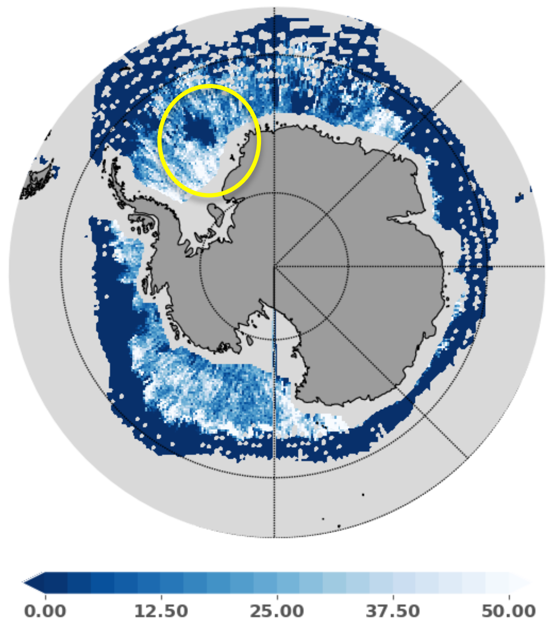
2019-11-1 to 2019-11-30



Sea ice fraction, mean=9.346, std=16.039 (%)

Cryosat-2: CLS discrimination

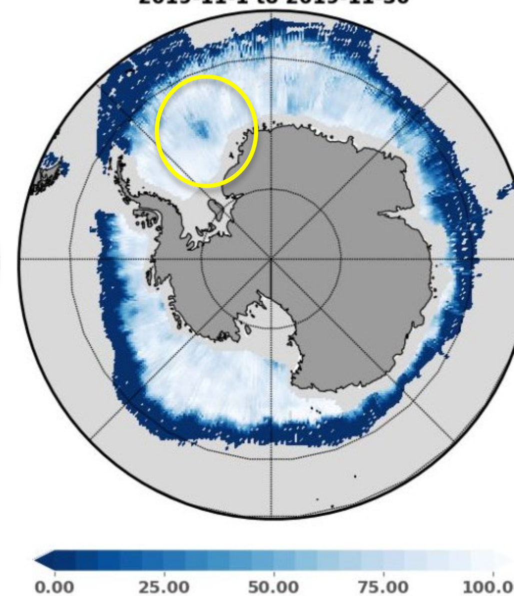
2019-11-1 to 2019-11-30



Sea ice fraction, mean=10.402, std=16.540 (%)

Cryosat-2: NSIDC

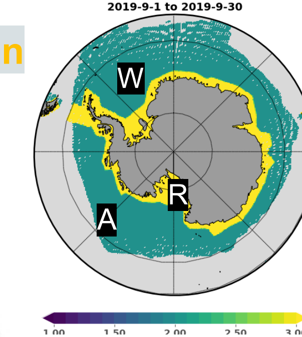
2019-11-1 to 2019-11-30



Sea Ice frac, mean=42.607, std=39.169 (%)

Cryosat-2: Baseline

2019-9-1 to 2019-9-30

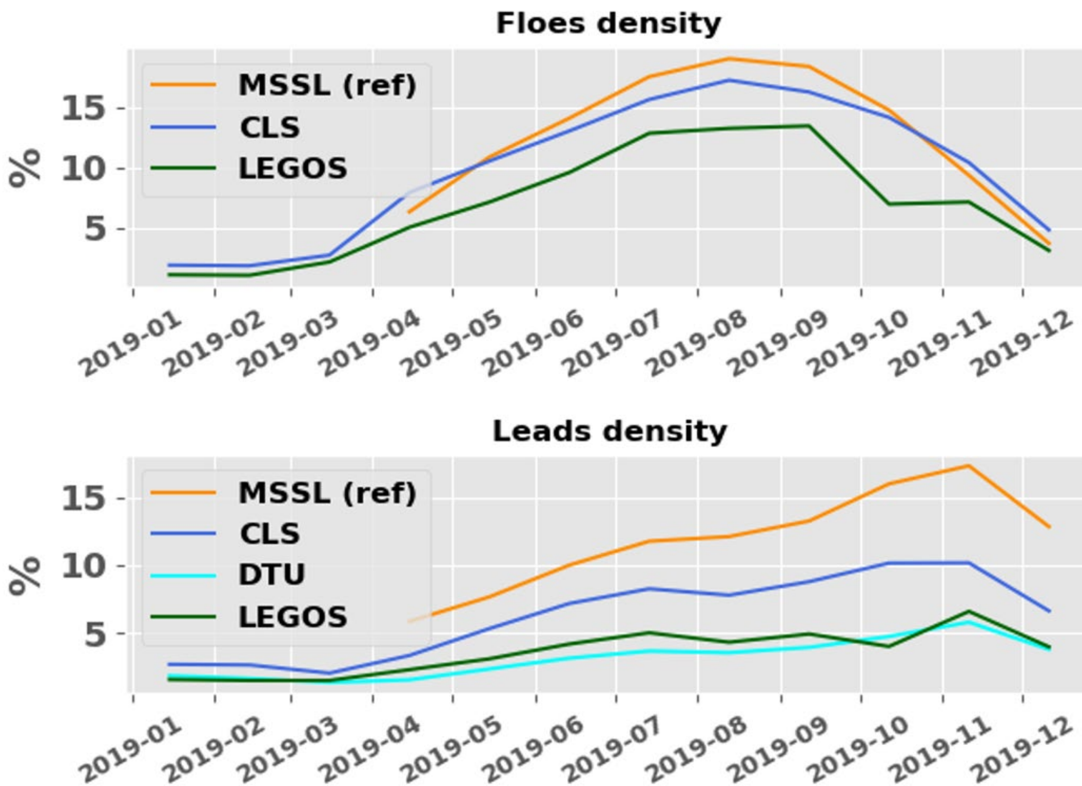


CS-2 Modes

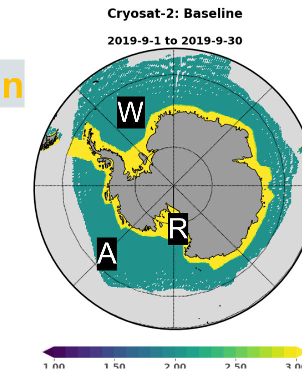
Waveform discrimination

CS-2
Baseline D
Ice

Density Maps (Leads)

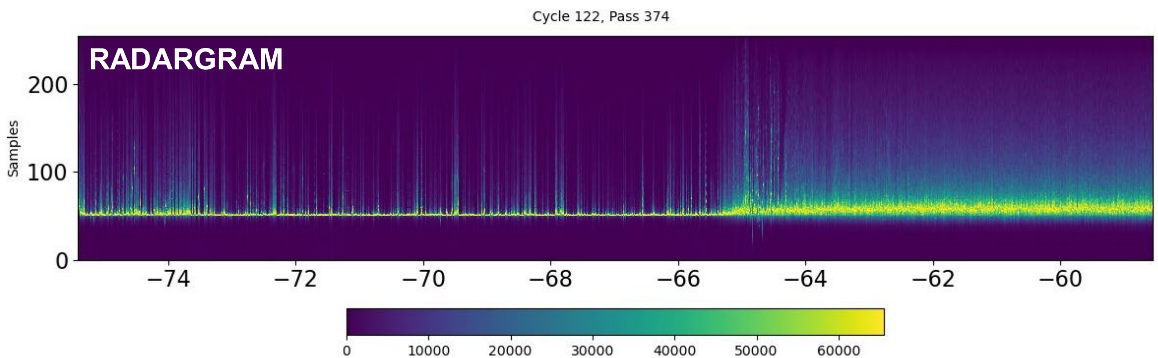


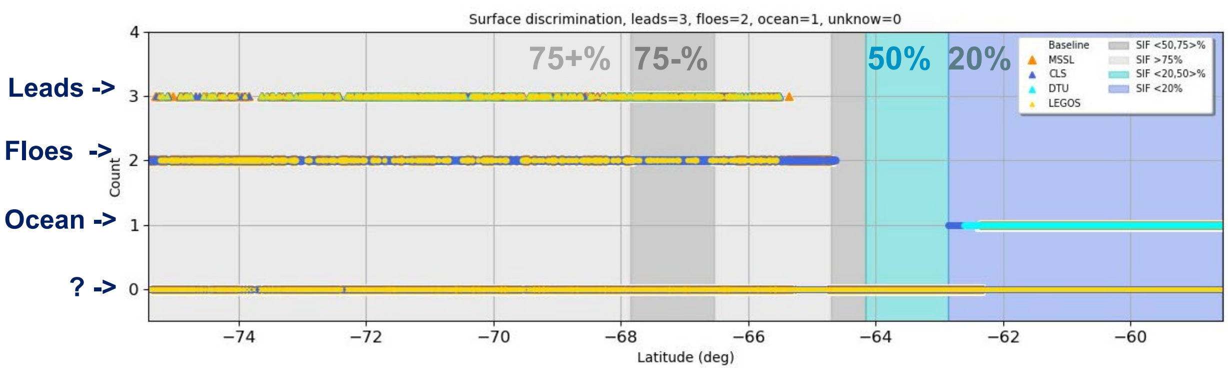
* SAR
* SARIn



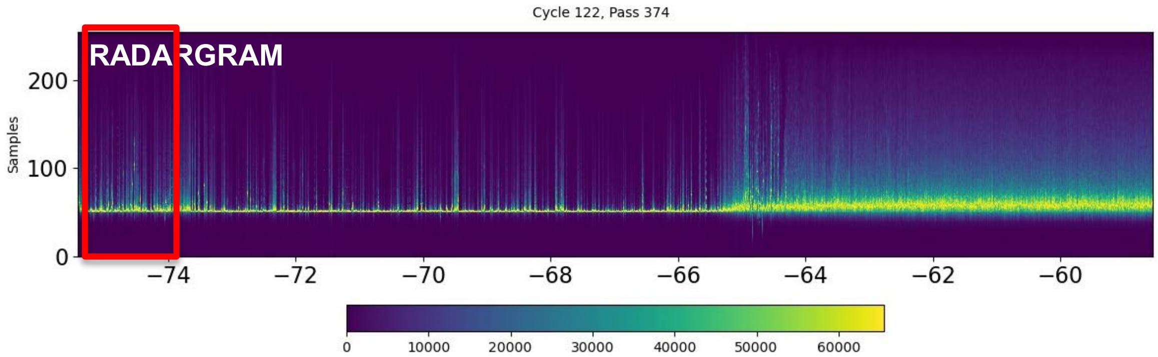
CS-2 Modes

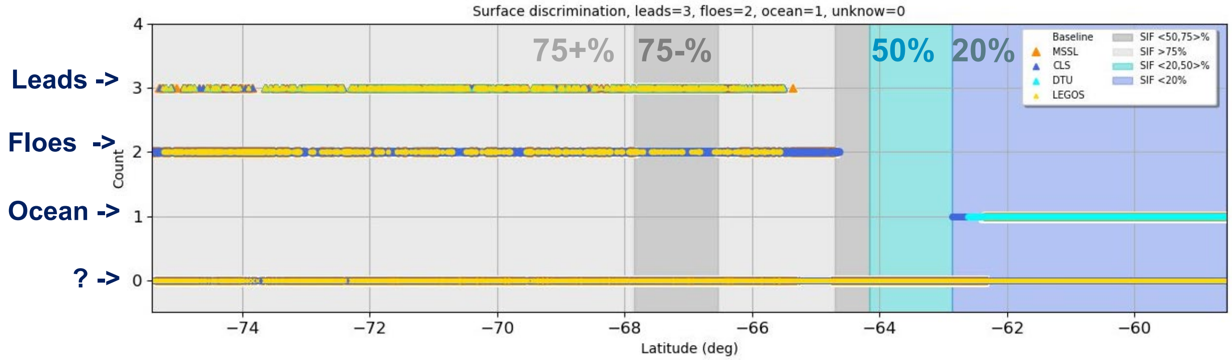
Waveform discrimination



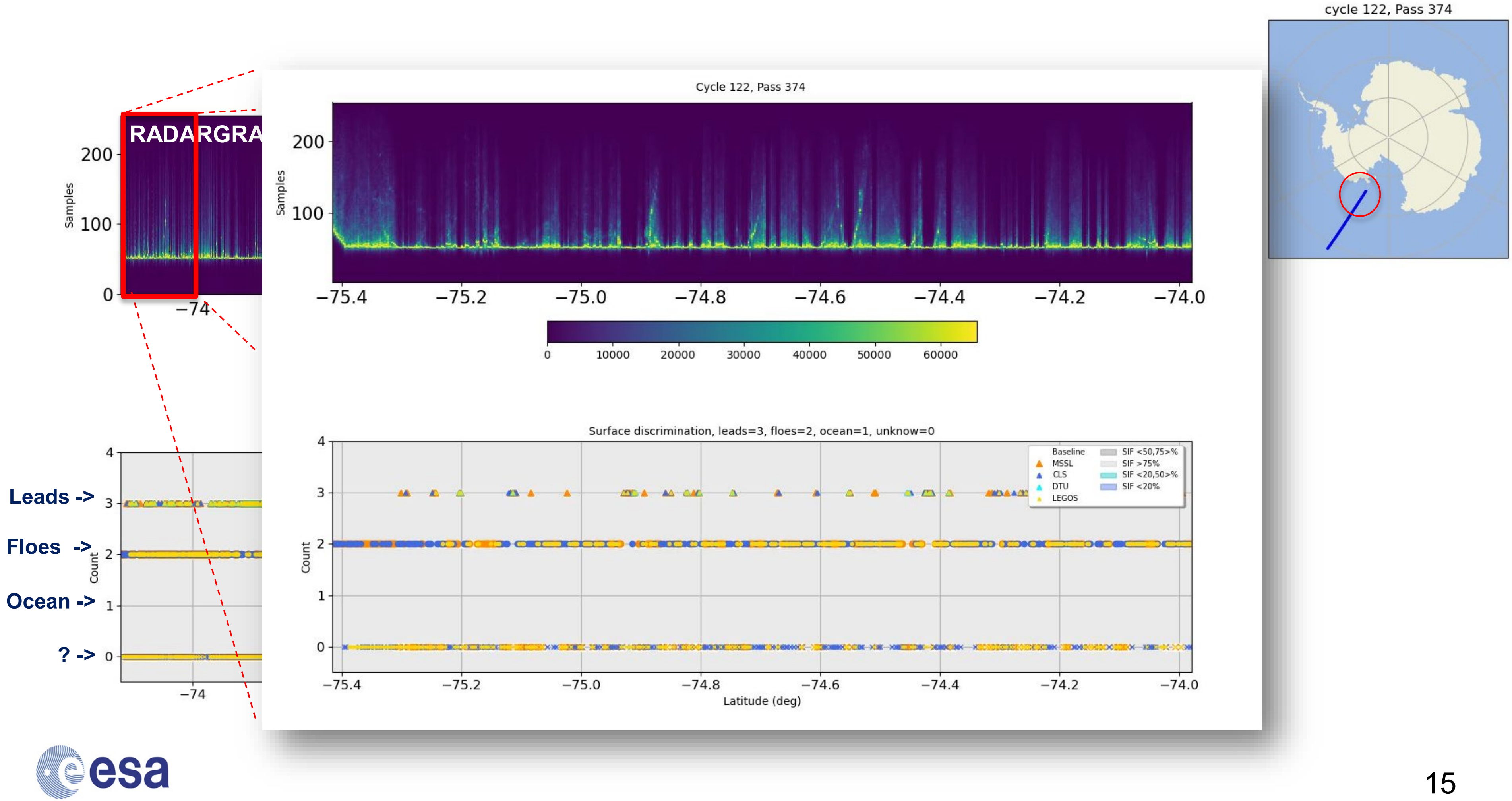


Waveform discrimination



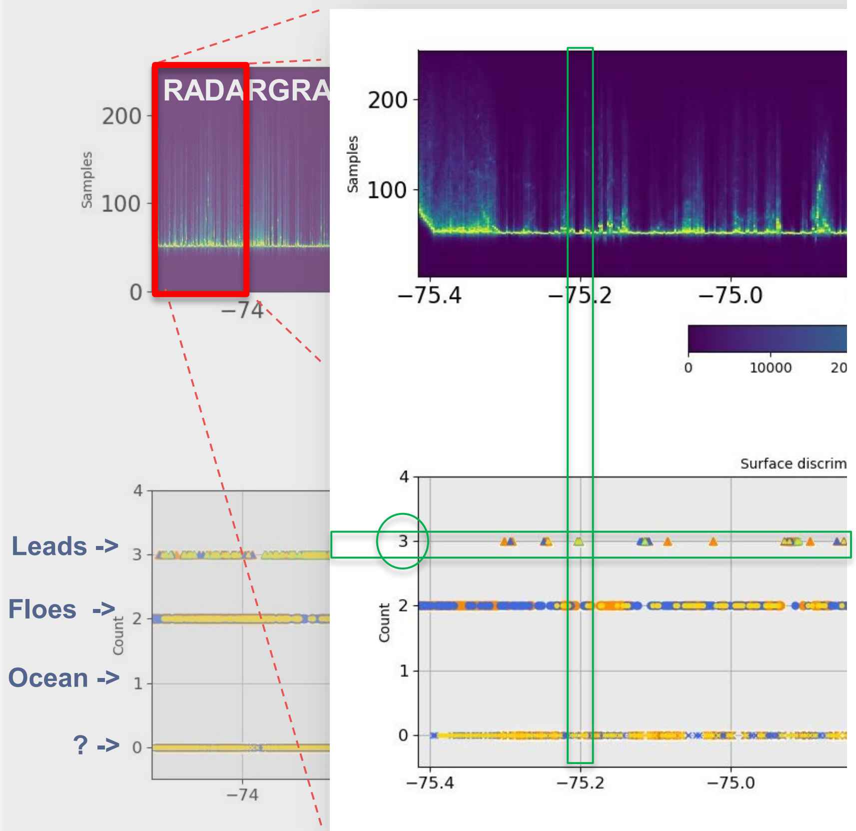


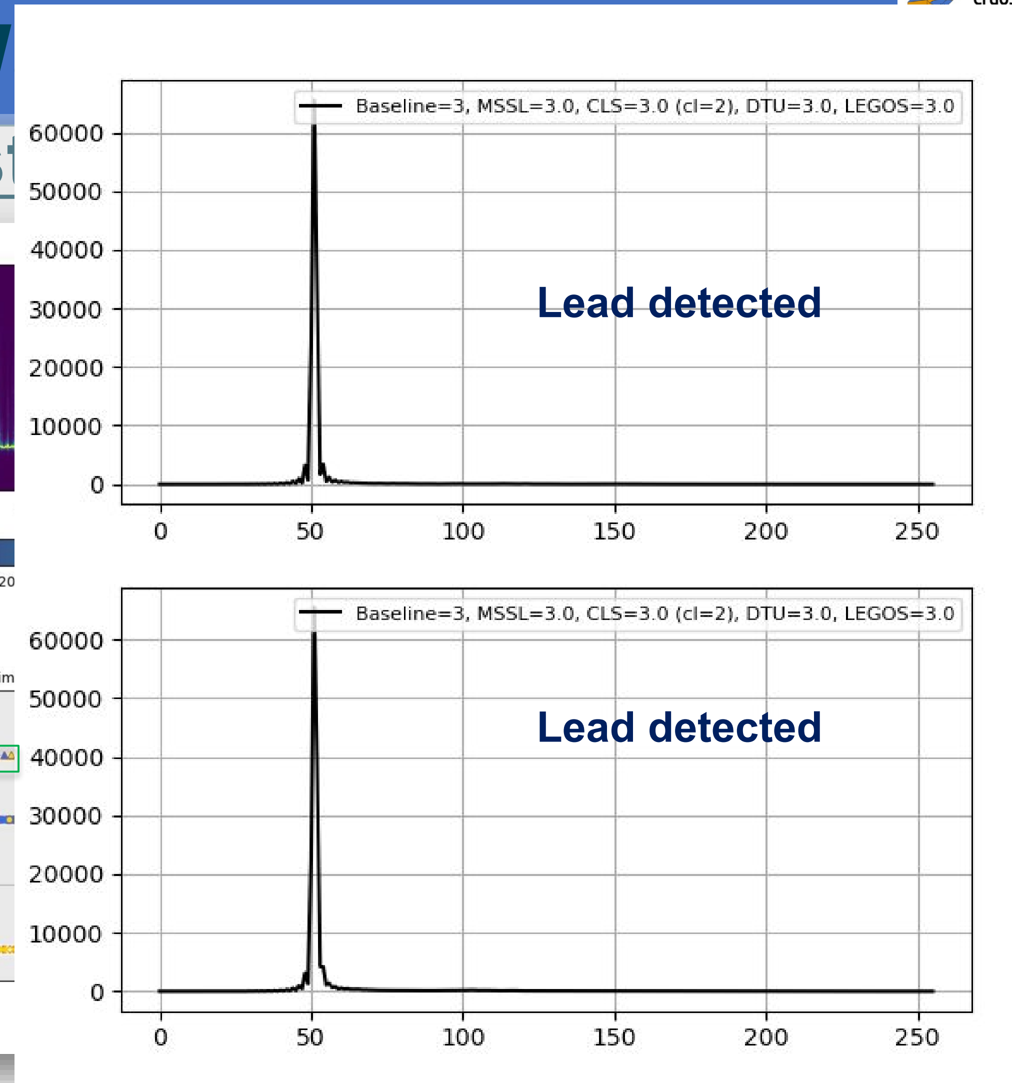
Waveform discrimination



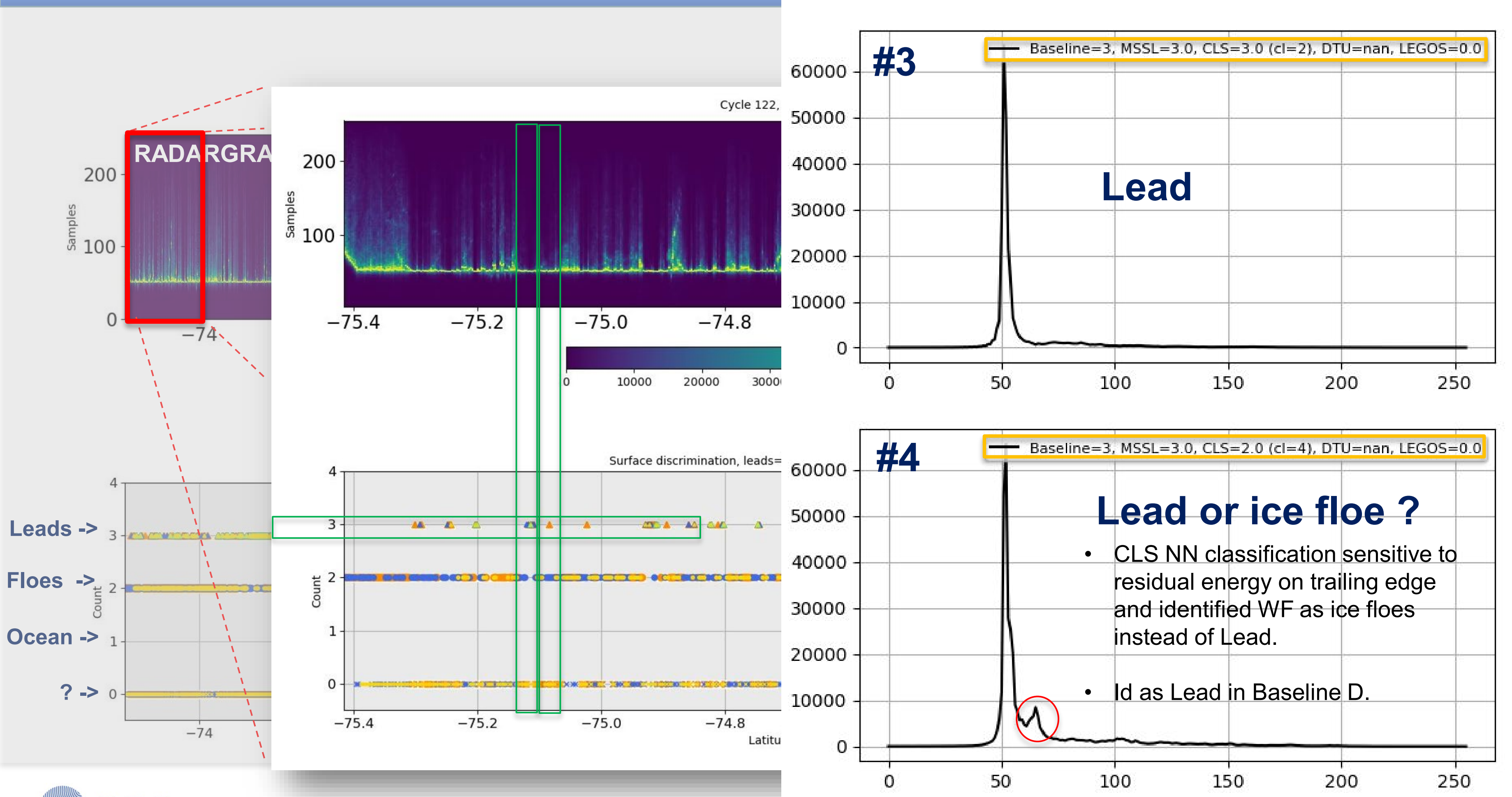
CryoSat+ Antarctic Ocean

Along-track: Case st

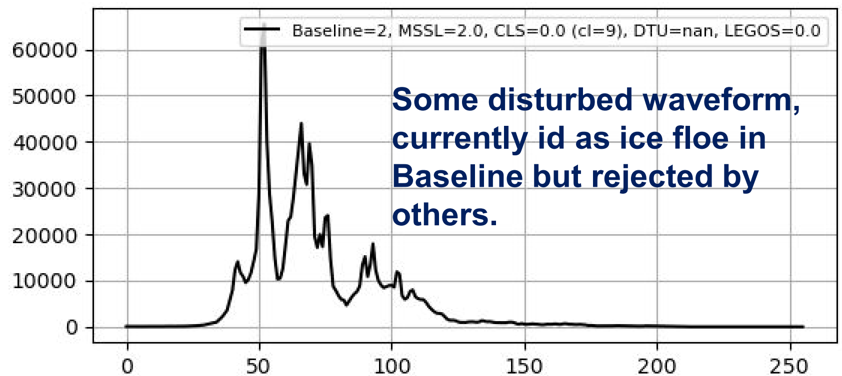


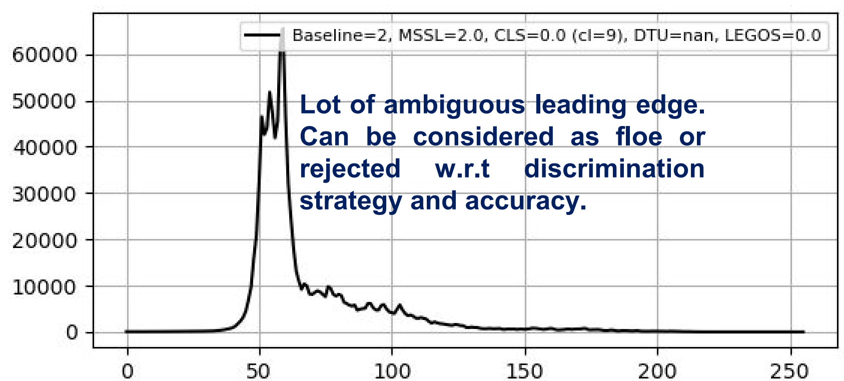


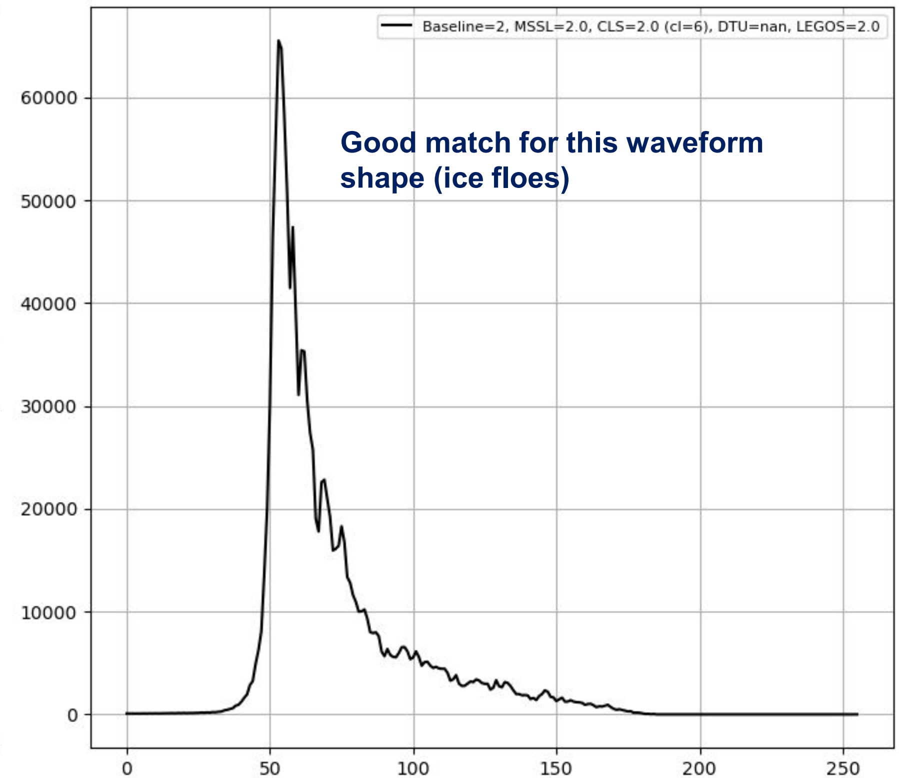
Waveform discrimination



Waveform discrimination







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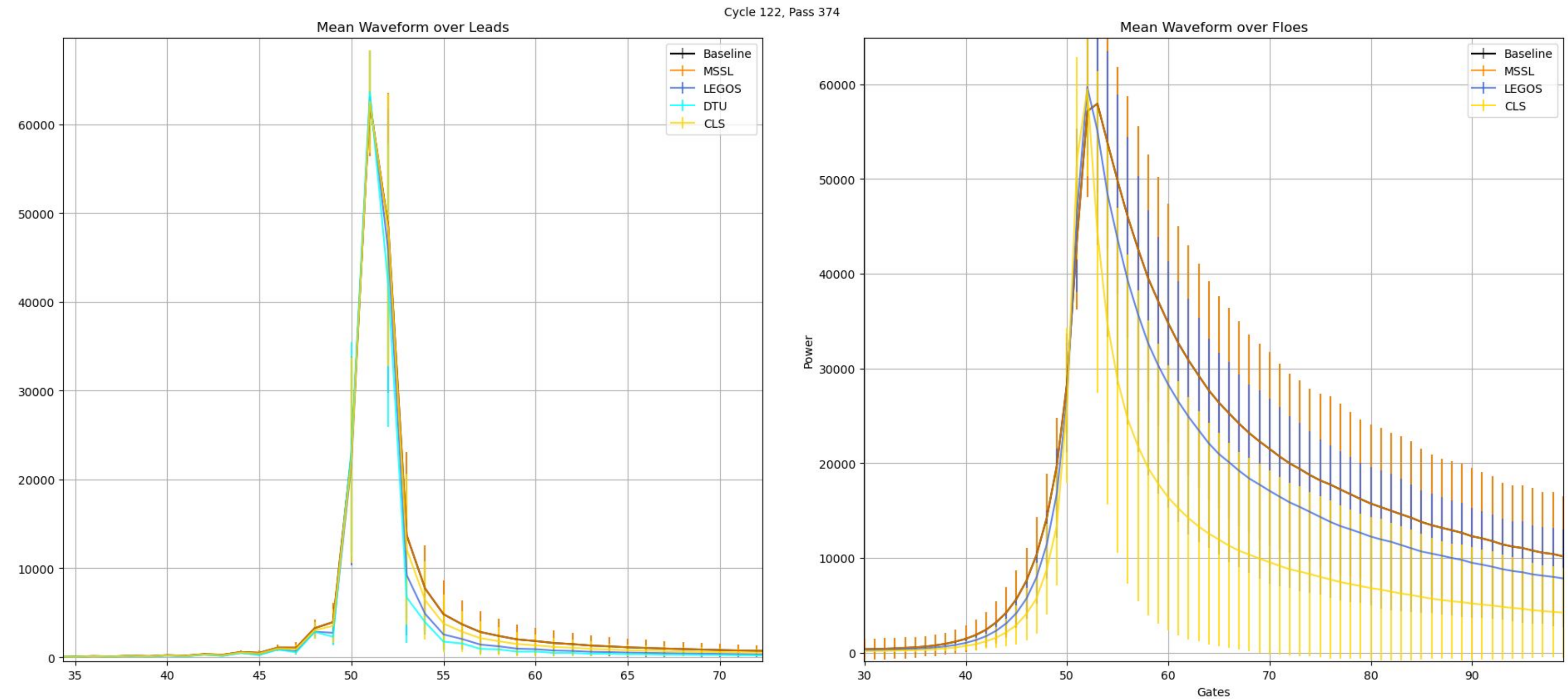


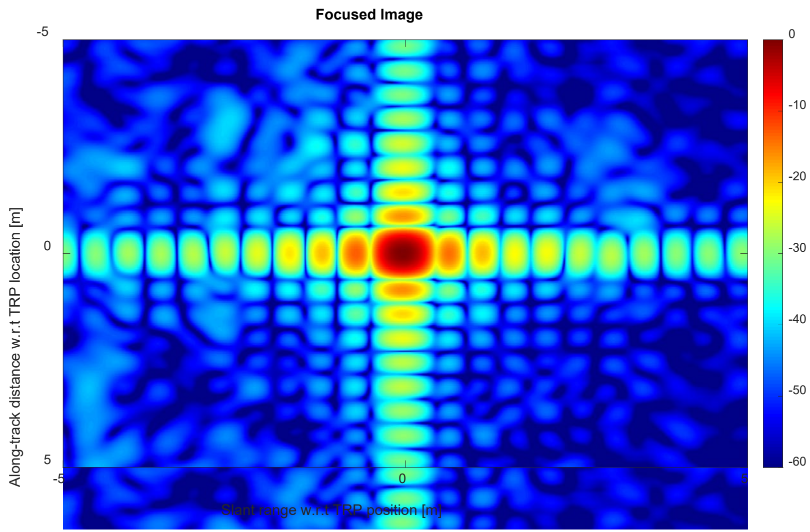
Waveform discrimination

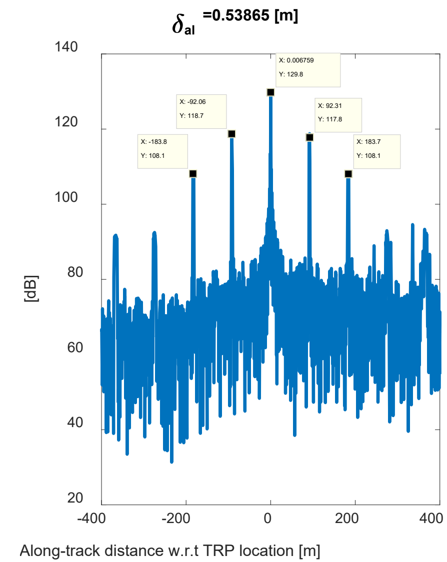
Next:

- Looking for CS-2 « ground truth »
- Comparison with FFSAR (IsardSat)

FFSAR Lead detector

- Lead detection approach
  - CS2 presents replica patterns with grating lobes spaced +/-92m
    - Caused by closed-burst operation
    - If along-track lead size is <than replica spacing, replicas may be disentangled from main signal.



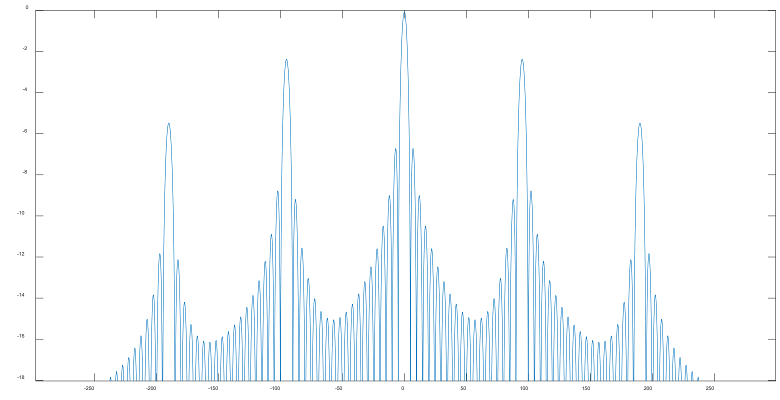


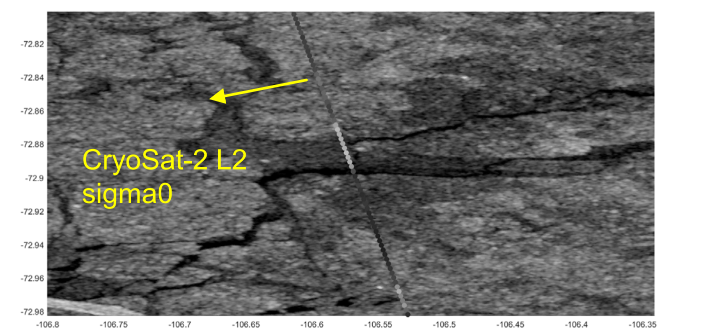
Credit: IsardSat

FFSAR Lead detector

- Modeled sinc signal approach:

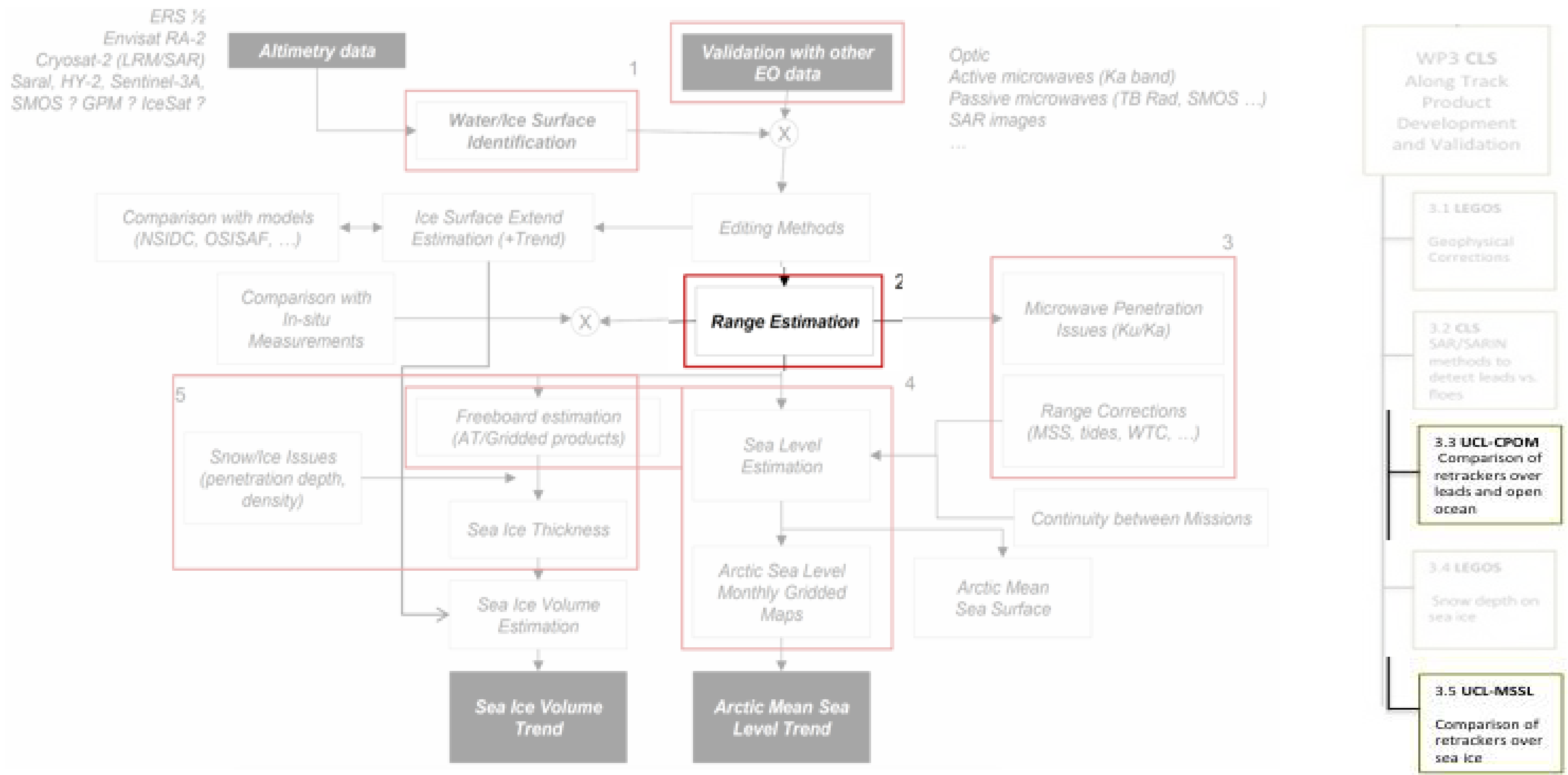
  - Using correlation with a modeled sinc function help us to <u>detect the position of the leads</u>.
  - We have to determine a proper bandwidth threshold for leads narrower than 92 meters.
  - We may be able to estimate leads wider than 92 meters with a resolution of 92 meters.
  - On going development





Credit: IsardSat

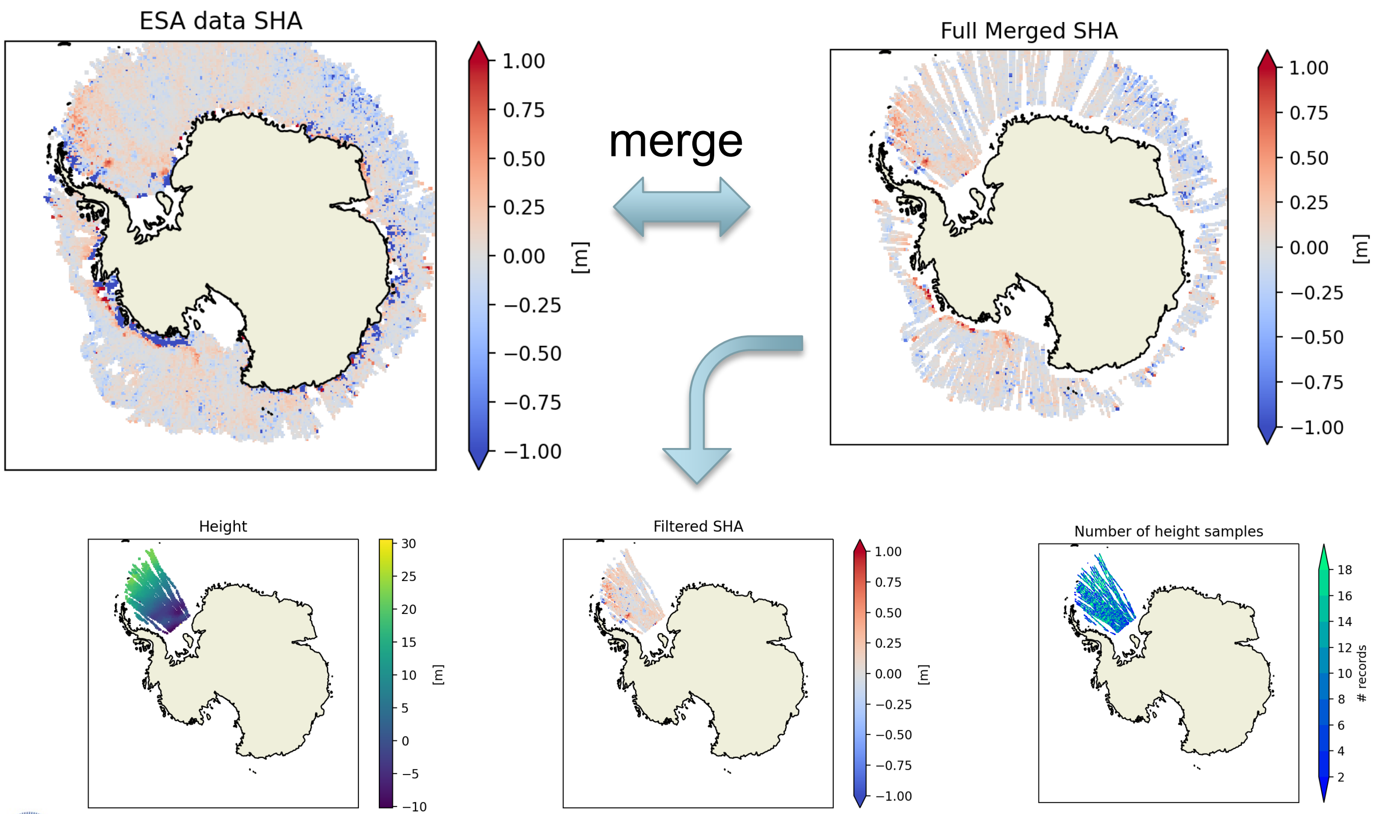
WP3: along-track



WP3: along-track

Group	Retracker	Operational	Reference
CLS	Physical on LRM, SAR or SARin multilooked echoes	Prototype: Yes Pan-Arctic: Yes Pan-Antarctic: Yes	Poisson et al (2018) in LRM Thibaut et al (2017) in SAR/SARin
DTU	Threshold	Prototype: Yes Pan-Arctic: Yes Pan-Antarctic: Yes	Skourup et al. (2017)
CPOM	Threshold/Physical	Prototype: Yes/Yes Pan-Arctic: Yes/No Pan-Antarctic: Yes/No	Tilling et al. (2017) / Wingham et al. (2018) Armitage et al. (2016)
LEGOS	Threshold/Physical	Prototype: Yes Pan-Arctic: Yes Pan-Antarctic:Yes	Guerreiro et al. (2017) Fleury et al. (2017)
MSSL	Threshold/Model	Prototype: Yes Pan-Arctic: Yes Pan-Antarctic: No	Tilling et. al. (2017) Giles et. al. (2007)
isardSAT	Physical	Prototype: Yes Pan-Arctic: Yes Pan-Antarctic: No	Ray et al., (2015)

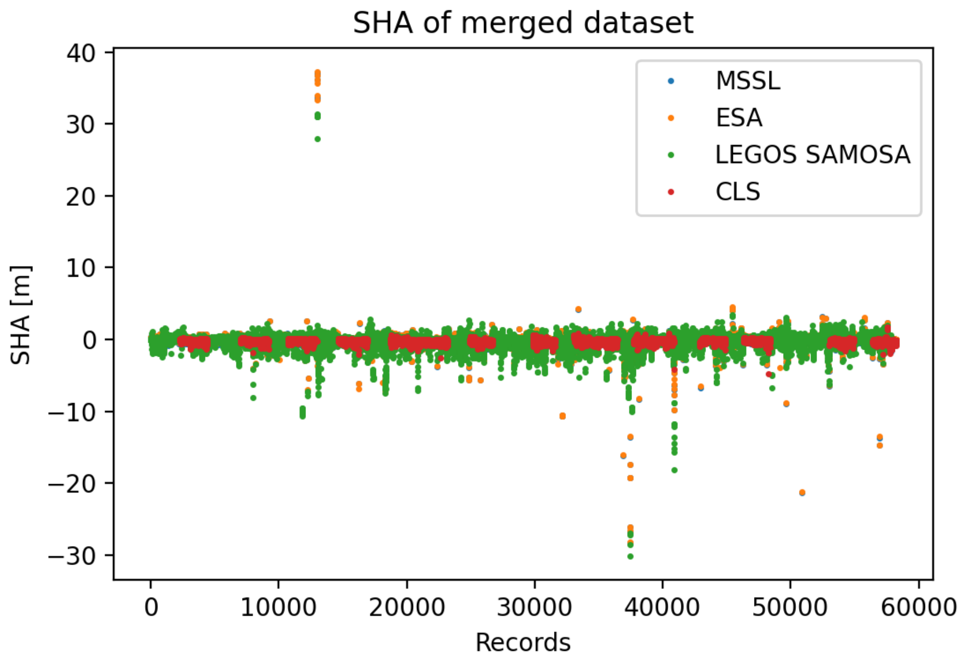
Ingestion, alignment and ROI filtering

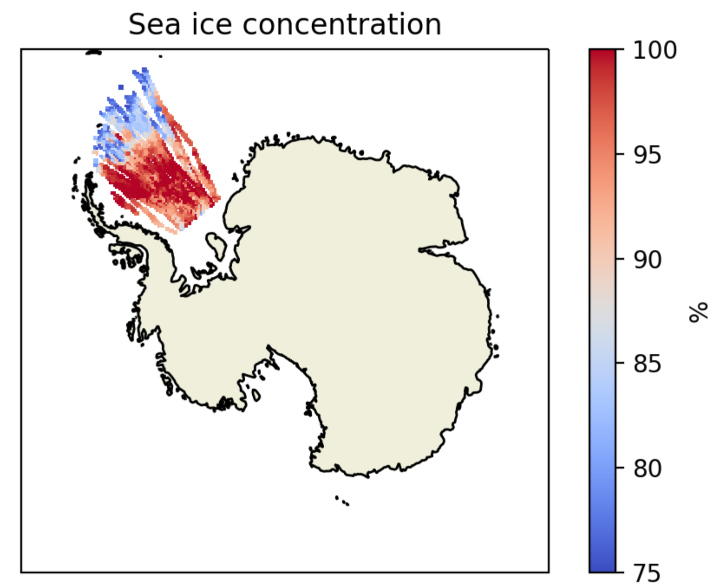


- Filtering performed by lat/lon box to get a region of interest
- Remaining measurement count on a 10km grid shows variation in density

Credit: MSSL

Floe Retracking

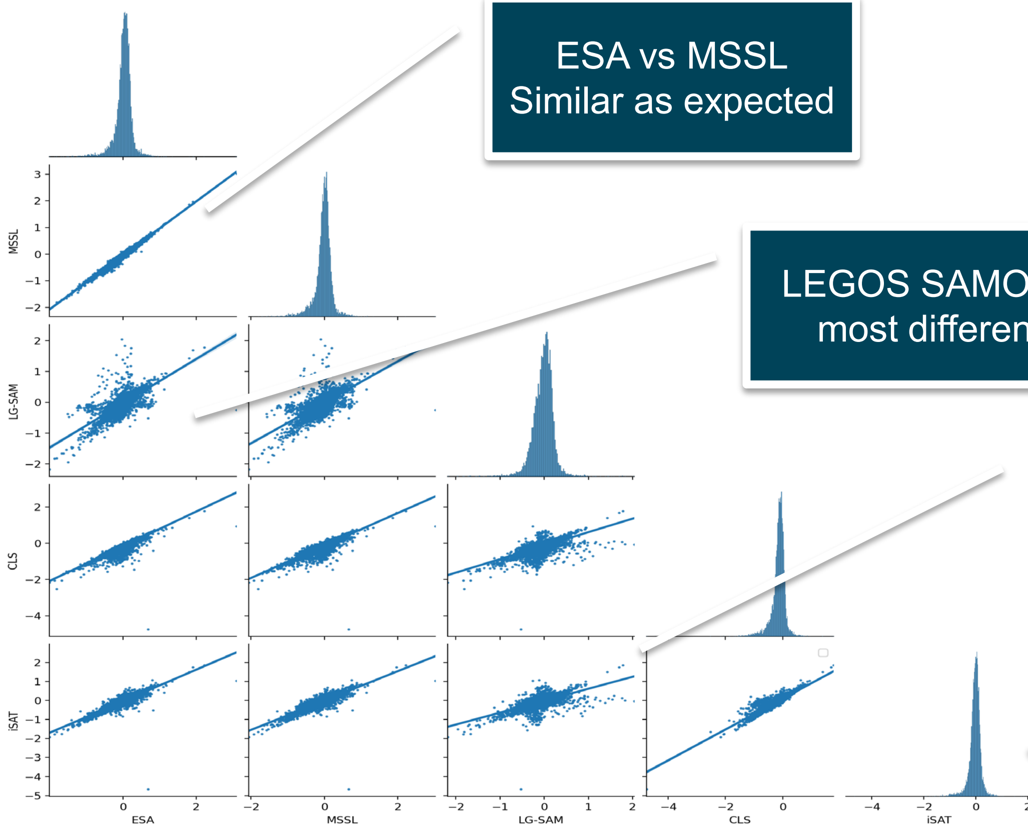




- Level of variation similar between ESA, MSSL, LEGOS
- CLS variation is smaller, but parameter is set to ‘not-a-number’ more frequently
  - Is filtering out anomalous waveforms
- Outlier SHA values can be caused by anomalous waveforms or land in the footprint
  - Other data has no QA filter to allow maximum # records for comparison

Credit: MSSL

CryoSat+ Antarctic Ocean **Floe Retracking**



ESA vs MSSL
Similar as expected

LEGOS SAMOSA
most different

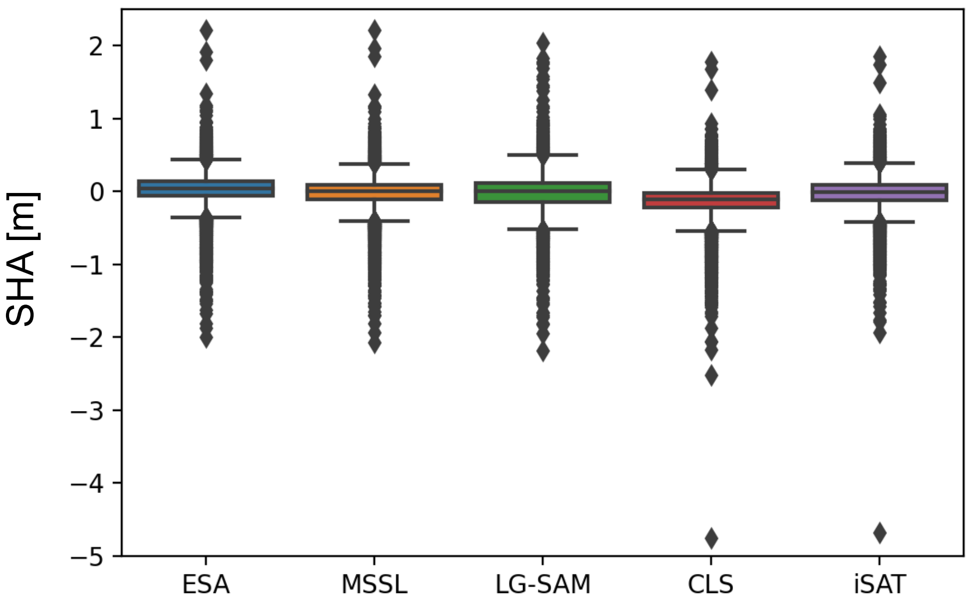
LEGOS comparisons have records where one is ~0 and the other isn't

iSAT histogram is cleaner and tighter, but plot scale magnifies this effect

From now onwards, just co-located measurements where a measurement from EVERY dataset is available.

Credit: MSSL

Floe Retracking



- Results similar
- isardSAT has lowest standard deviation
- True SHA distribution not known
- LEGOS spread more symmetrical
- isardSAT possibly best?

	ESA	MSSL	LG-SAM	CLS	iSAT
mean	0.019	-0.030	-0.023	-0.148	-0.028
std	0.232	0.240	0.235	0.251	0.224
min	-1.998	-2.066	-2.181	-4.747	-4.671
25%	-0.062	-0.107	-0.141	-0.225	-0.115
50%	0.044	-0.001	-0.001	-0.109	-0.006
75%	0.136	0.089	0.114	-0.015	0.089
max	3.092	3.020	2.041	1.774	1.858

Credit: MSSL

Summary

- ESA – MSSL results almost identical (as expected)
- CLS result similar to ESA.
  - Needs a bias correction or matched MSS
- LEGOS SAMOSA most different comparing record to record but produces almost identical histogram
  - Retracks more data than CLS
  - Low correlation with current ESA data
- Conclusions
  - LEGOS SAMOSA has good coverage and histogram shape
  - If CLS coverage is sufficient to produce good gridded freeboard coverage, worth exploring further
  - If isardSAT lower SD due to avoiding noise, best result as it also has good coverage

Credit: MSSL

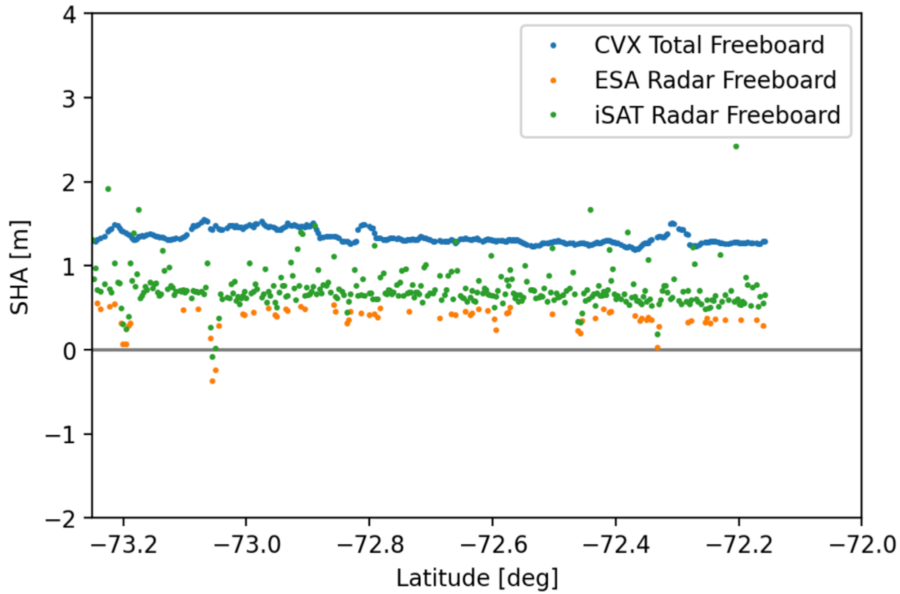
Underflight comparisons

- Only way to get a direct comparison of retracker results against reality is to use underflight ground truth (or very recent Cryo2Ice data)
  - Very limited data in Antarctica
- Also need to remove snow data to compare ALS freeboard with radar freeboard
  - 2010 track not covered by snow data
- Recently obtained data from 2017-2018
  - Snow data available
  - All groups running retracking for these additional tracks
    - Currently looking at data from ESA and isardSAT
- Also looking at comparisons with collocated L1b OIB data

Credit: MSSL

Floe Retracking

First partial along track results

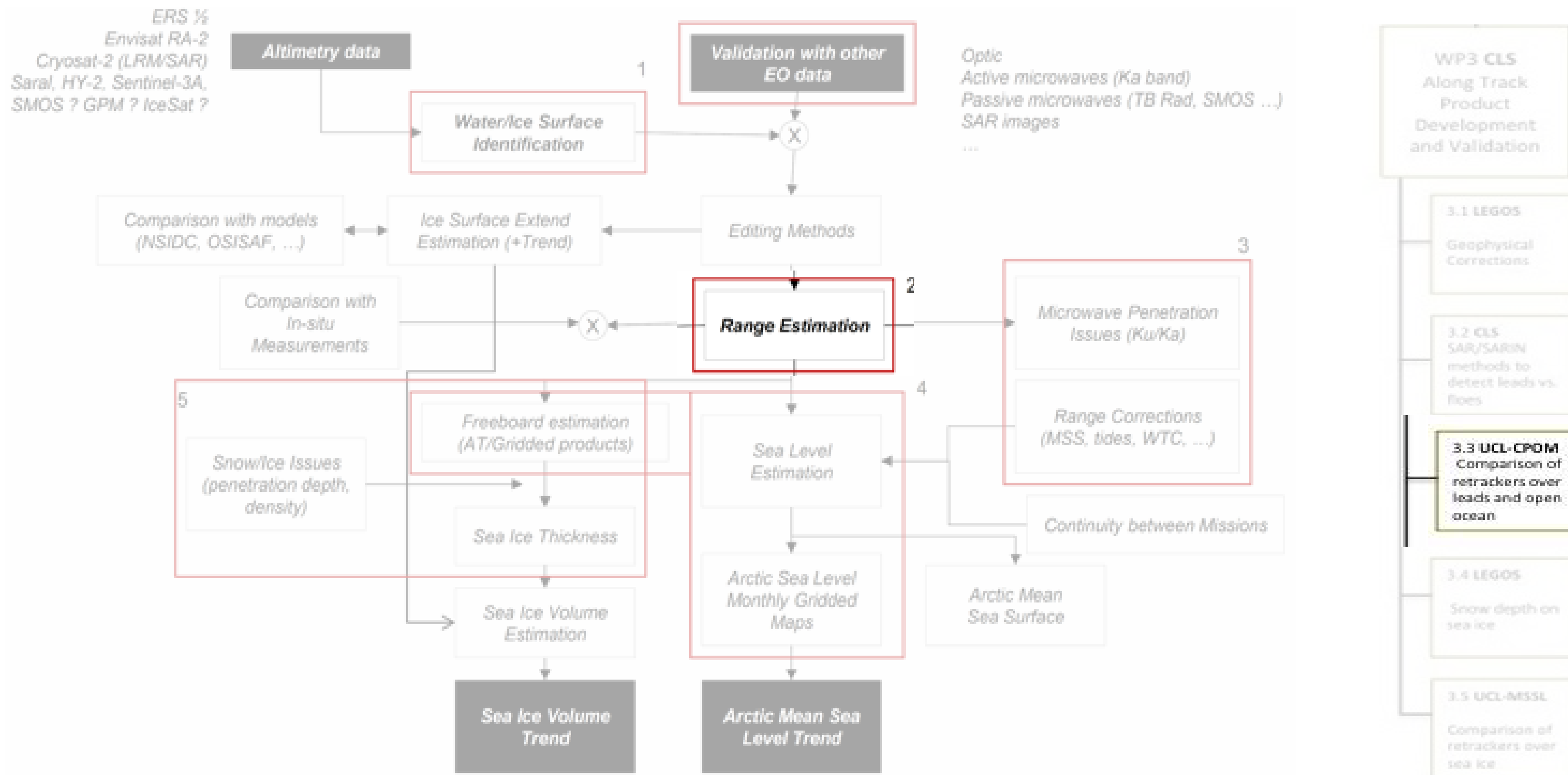


Track
ALS_CRYOVEX_DTU_20171230.frb

- ALS data resampled to Cryosat doppler footprints (mean value within footprint)
  - Reduce noise and represent the surface as Cryosat detects it
- Snow depth needs to be removed from ALS heights (will lower height)
- Snow delay needs to be applied to CS2 heights (will increase height)
- In the process of checking common use of MSS models and geo corrections

Credit: MSSL

CryoSat+ Antarctic Ocean WP3: along-track

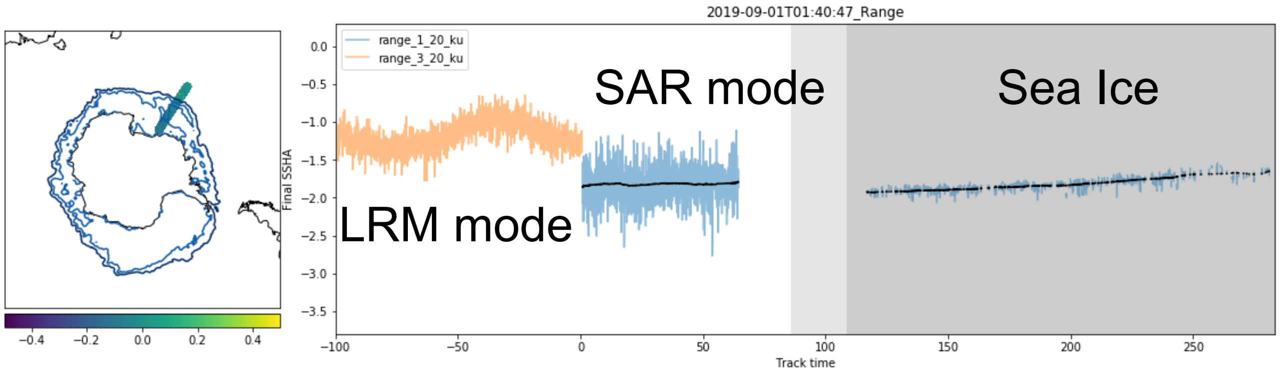


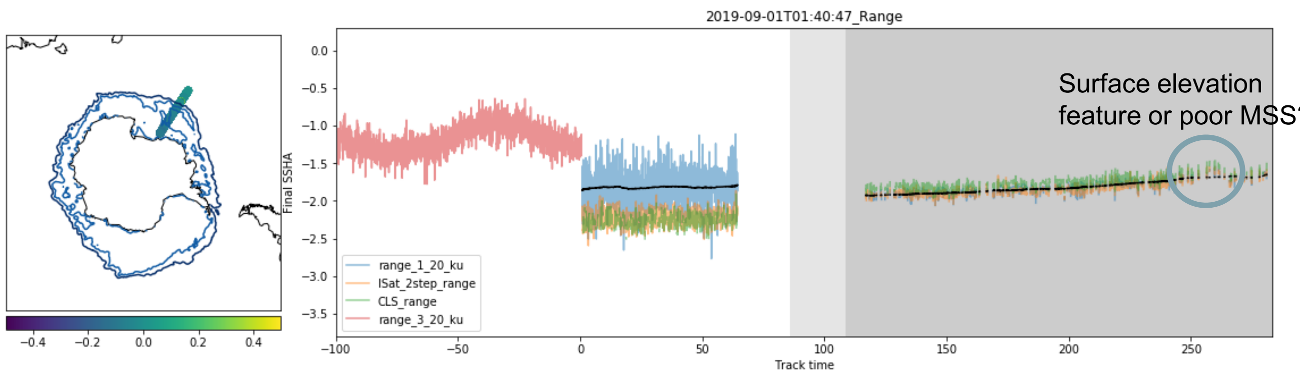
Lead/ocean retracking

Open ocean surface elevation from CryoSat2

- Radar echoes from the ocean surface have been analysed by:
  - DTU (3 methods), MSSL, CLS, IsardSat, LEGOS (3 GPOD methods)
- In SAR mode ocean surface is considered in both leads and open ocean
- The leads are classified in the existing ESA L2 data (Baseline D)
- CLS provides an alternative classification method

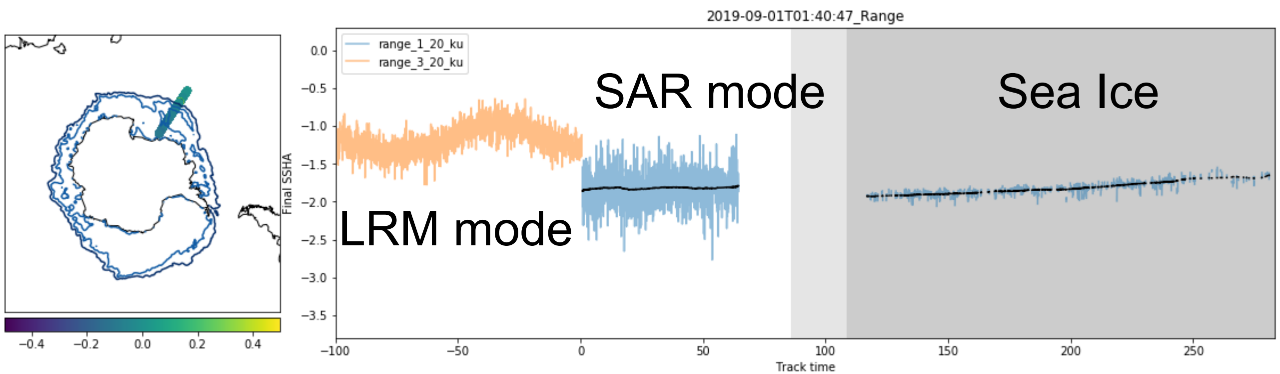
Lead/ocean retracking

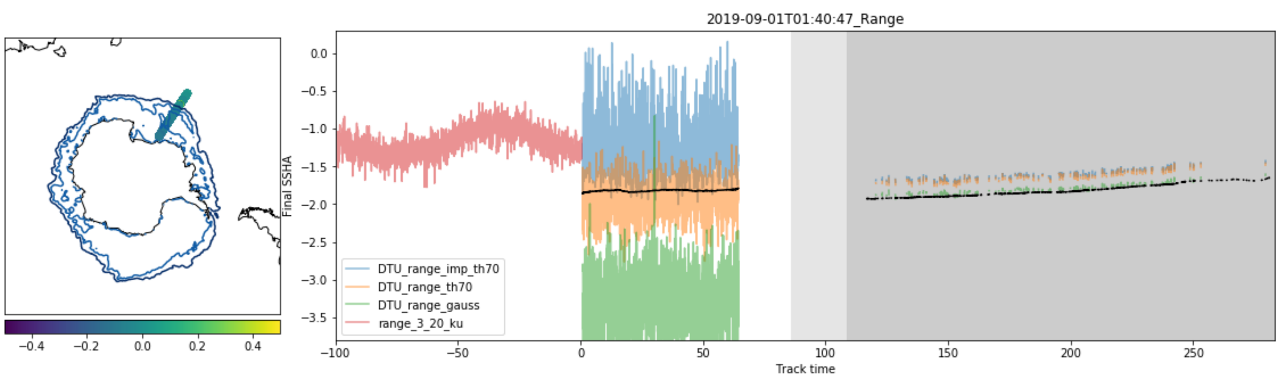




- The CLS and IsardSat physical retrackers are compared
- They have similar lead elevations to L2
- The ocean elevations are lower with less spread for this track

Lead/ocean retracking

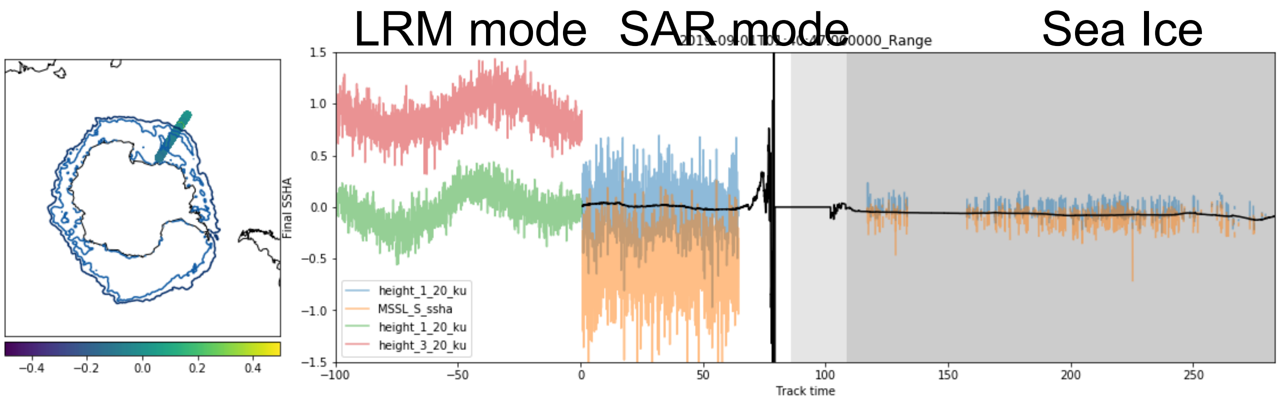


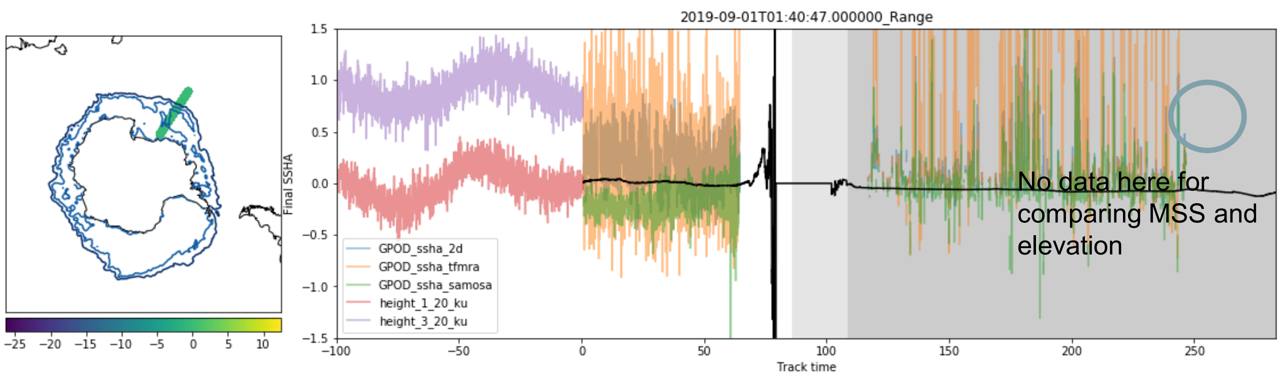


- The DTU retrackers are compared, th70, imp_th70, and gaussian
- All supplied DTU data has less coverage than L2
- In leads the gaussian is closest to L2
- In the open ocean DTU retrackers have a large spread, th70 closest to existing L2

Lead/ocean retracking

Along track analysis including corrections

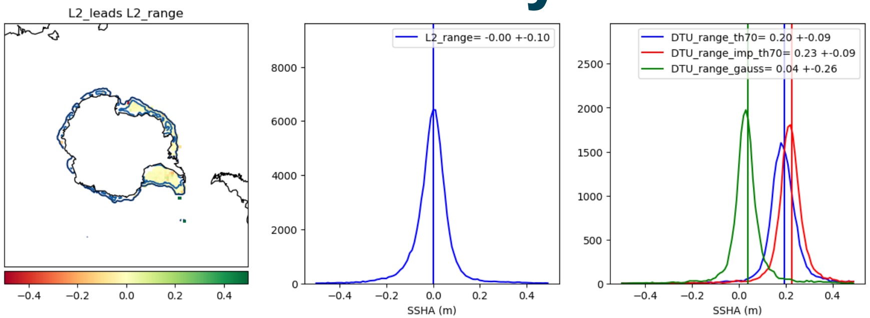


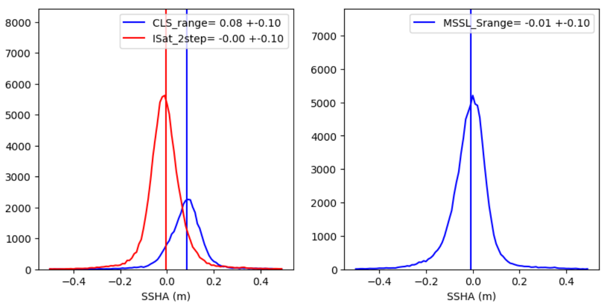


- GPOS SSHA anomalies are all very noisy for leads
- The samosa retracker performs well for open ocean

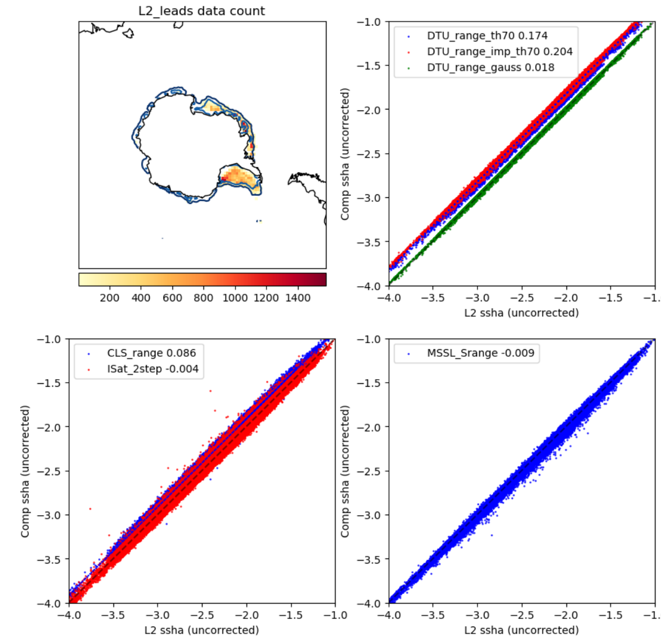
Lead/ocean retracking

Whole month analysis





- 283 separate tracks
- 80K coincident retrievals



L2_leads Data	L2_range	DTU_range_th70	DTU_range_imp_th70	DTU_range_gauss	CLS_range	ISat_2step	MSSL_Srange
Mean	-2.306	-2.151	-2.120	-2.306	-2.168	-2.310	-2.314
Std	0.497	0.524	0.524	0.578	0.497	0.499	0.500
Bias	0.000	0.174	0.204	0.018	0.086	-0.004	-0.009

Lead/ocean retracking

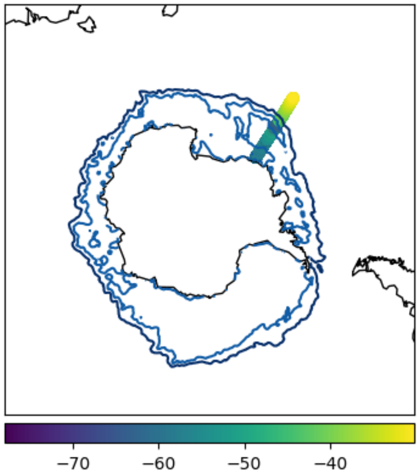
Summary

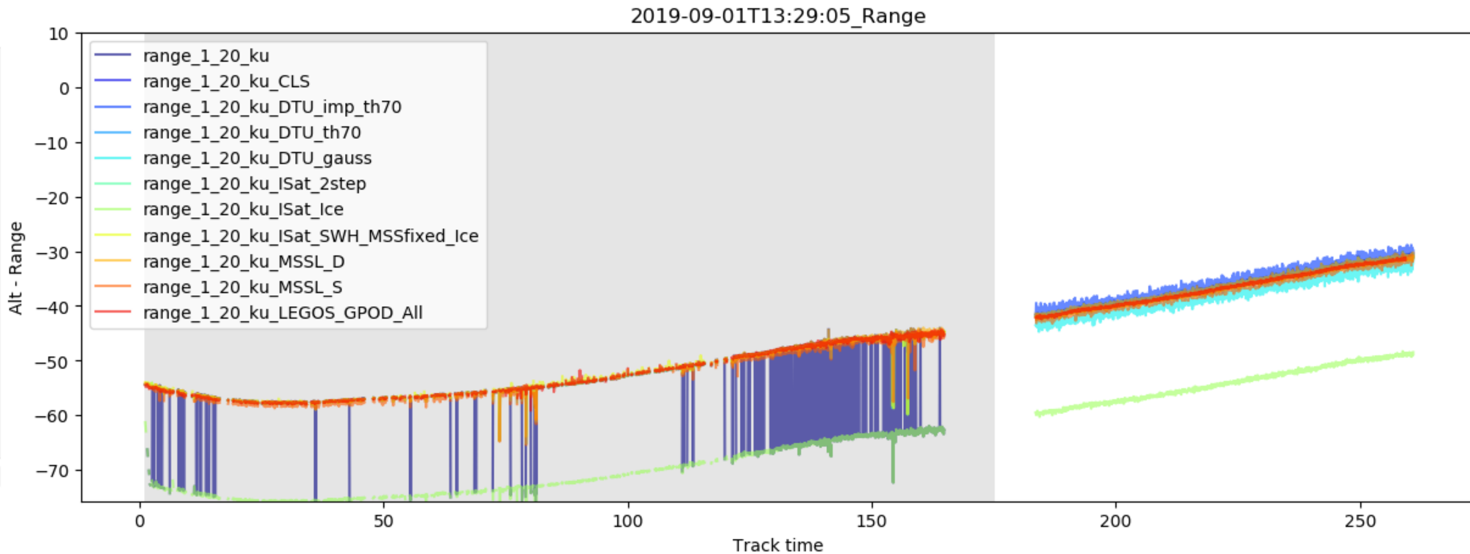
- DTU - gauss performs well in leads
- DTU - th70 performs well in the open ocean
- CLS and IsardSat retrackers perform similarly, with IsardSat with the lower spread
- MSSL-Specular is similar to current L2

- CLS lead classification greatly reduces the amount of data
  - But potentially may remove many erroneous sea ice floe elevations

- Further analysis will be performed

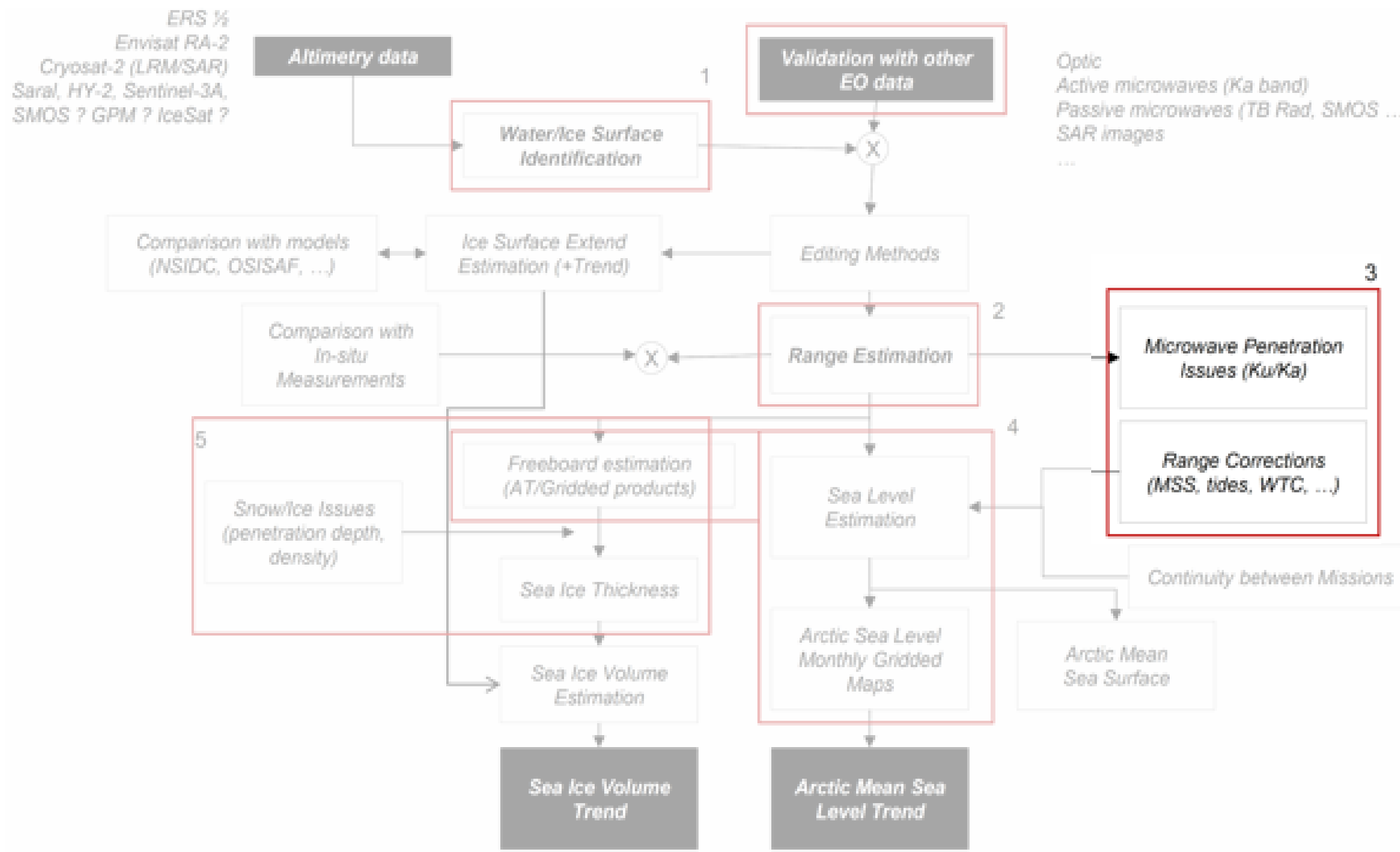
Merged along-track product

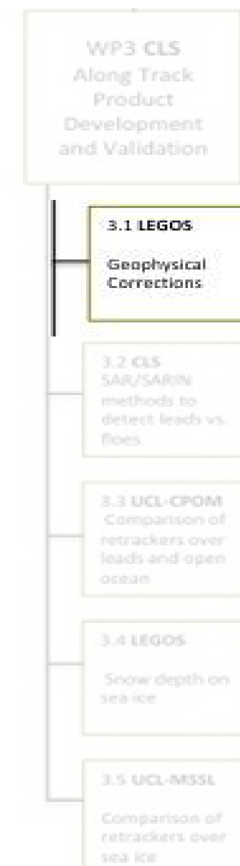




- ➢ Input for gridded product (WP4)

WP3: along-track





Geophysical corrections

3 criteria to evaluate the impact of a geophysical correction:

1. it should reduce the standard deviation of the SLA
2. it should aim the mean SLA close to zero
3. it should improve the continuity of the SLA among the ice relatively to the best SLA solutions over open ocean

Geopgysical corrections

- Referenced SLA : SLA computed by LEGOS using SAMOSA+ ranges:

  ssa_median_20hz - sea_state_bias_20hz
- We change one by one the evaluated correction, starting by the correction type that have the bigger impact.
- We compute the mean and the std of the SLA

  The smaller is the STD(SLA) the better is the correction
- For each correction type, we keep the solution with the lower std before considering the next correction type.
- Three correction types considered: MSS, Ocean Tide, DAC:

SLA (m)	mean	std	order
No MSS corr	-7.2636	29.1299	1st
No_TIDE corr	0.020	0.232	2nd
No_DAC corr	0.235	0.163	3rd

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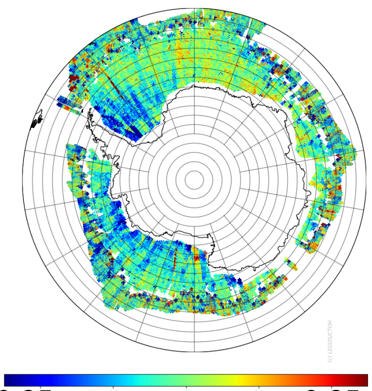
Geopgysical correction

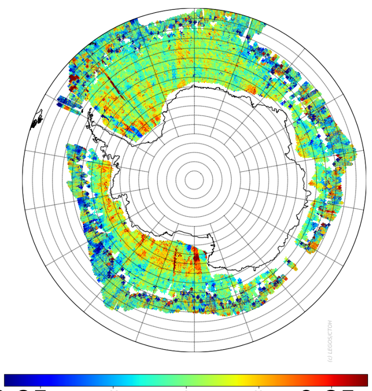
SLA for Cycle 121 20190721-20190819

MSS_DTU15



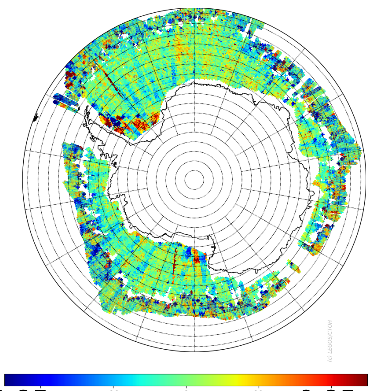
SLA MSS_DTU15 (cm)	
mean	std
-3.3	11.7

MSS_DTU18



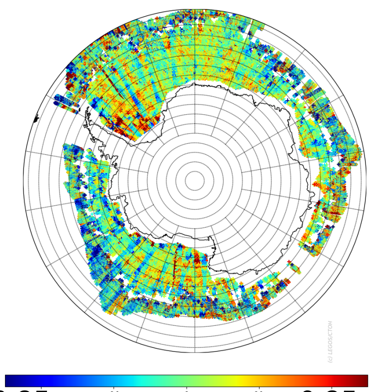
SLA MSS_DTU18 (cm)	
mean	std
-1.9	11.7

MSS_CLS15



SLA MSS_CLS15 (cm)	
mean	std
-2.5	21.0

MSS_ESAD

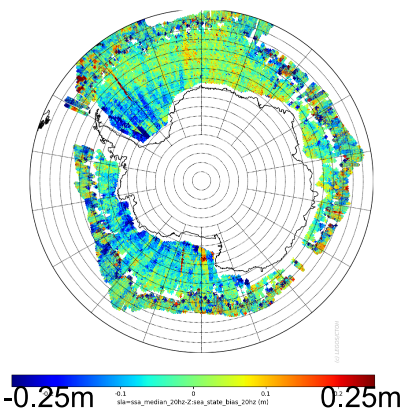


SLA MSS_ESAD (cm)	
mean	std
-0.07	22.1

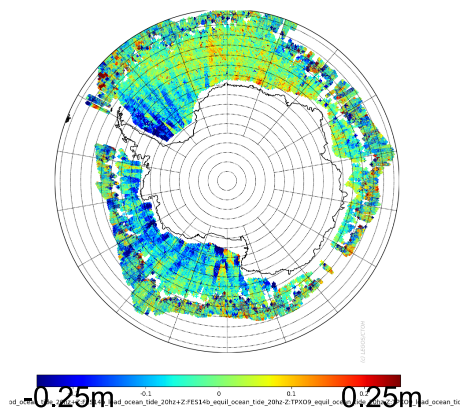
CryoSat+ Antarctic Ocean **Geopgysical correction**

SLA for Cycle 121 20190721-20190819

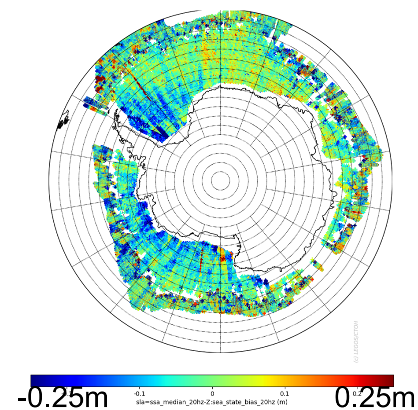
FES14



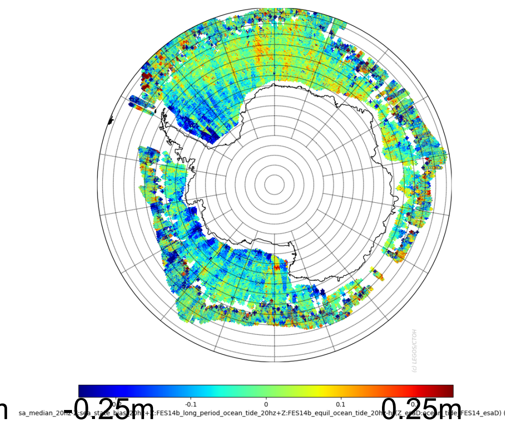
TPX09



GDR_D



LEGOS



SLA (cm) FES14	
mean	std
-3.2	10.3

SLA (cm) TPX09	
mean	std
-2.8	10.3

SLA (cm) GDR_D	
mean	std
-3.3	10.3

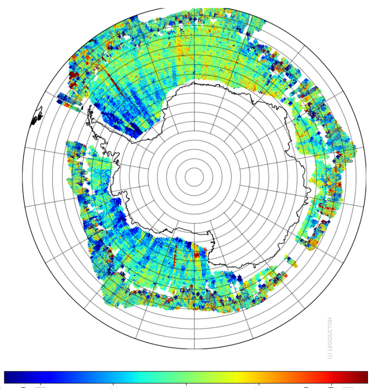
SLA (cm) LEGOS	
mean	std
-3.2	10.4

Low impact of the Ocean Tide Solution

Geopgysical correction

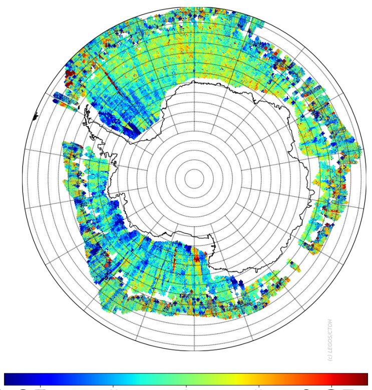
SLA for Cycle 121 20190721-20190819

IB-GPOD



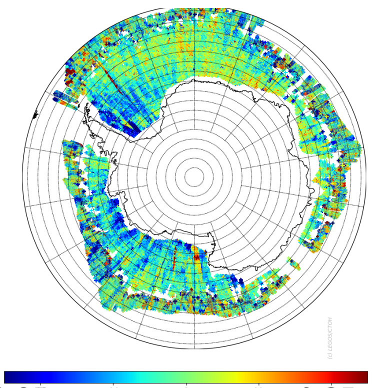
SLA (cm) DAC GPOD	
mean	std
-3.3	11.7

DAC_GDR_D



SLA (cm) DAC GDR_D	
mean	std
-3.3	12.0

DAC_LEGOS



SLA (cm) DAC LEGOS	
mean	std
-3.3	11.9

Low impact of the IB/DAC Solution

Geopgysical correction

	SLA (m)	cycle 119 20190524-20190622		cycle 121 20190721-20190819		cycle 124 20191016-20191114		2015-2019 gridded	
		mean	std	mean	std	mean	std	mean	std
MSS	*NO_MSS*	*-7.2636*	*29.1299*						
	DTU15	-0.032	**0.103**	-0.033	0.117	-0.001	0.112	-0.010	0.029
	DTU18	-0.016	0.107	-0.019	0.117	0.017	0.114		
	CLS15	-0.023	0.143	-0.025	0.210	0.008	0.150	0.000	0.189
	GDR_D	-0.005	0.159	-0.007	0.221	0.027	0.165		
TIDE	*NO_TIDE*	*0.020*	*0.232*						
	FES14	-0.032	0.103	-0.033	0.117	-0.001	0.112		
	TPX09	-0.028	0.103	-0.033	0.117	-0.006	0.114		
	OT_GDR_D	-0.033	0.103	-0.033	0.116	-0.005	0.114		
	OT_LEGOS	-0.032	0.104	-0.033	0.117	-0.007	0.114		
DAC	*NO_DAC*	*0.235*	*0.163*						
	IB_GPOD	-0.032	0.103	-0.033	0.117	-0.001	0.112		
	IB_GDR_D	-0.032	0.104	-0.033	0.120	-0.001	0.116		
	IB_LEGOS	-0.033	0.104	-0.033	0.119				

Green: the lower std

If the MSS is not improved, the other corrections are negligible (cannot go bellow 10.3 cm STD)

esa

Geopgysical correction

Conclusion

- 3 correction types considered: MSS, ocean tide, DAC
- MSS: 4 models, Tide: 4 models, DAC: 3 models
- The MSS has the larger impact
- MSS_DTU15 seems to be for now the best solution, but still margins of improvement for a better continuity between open ocean and sea ice
- For now Ocean Tides and DAC have small impacts but they can get very sensitive with the improvement of MSS and retracker

Scientific Roadmap

1. Critical analysis of work done, c.f. project objectives
2. Identify additional work and development towards achieving better sea ice thickness /sea surface height /geostrophic current information in the Southern Ocean. Identify observational/operational gaps, that could be addressed by novel future data development/campaigns/missions.
3. Potential for integrating data into current observational and modelling work/understanding
4. Define a scientific agenda for the project 2019-2023. Coordinate with other relevant projects/initiatives (EC/national) that may be relevant for the project development.
5. Define a plan for transition between scientific and operation activities.

Tasks (High-level view)

cryosat+ Antarctic Ocean

<u>WP 1</u>
Scientific Requirements Consolidation
Lead: UCL-CPOM
Contributor: DTU, ShepSp

<u>WP 2</u>
Dataset Collection
Lead: ShepSp
Contributors: MSSL, NOCS, IPSL

<u>WP 3</u>
Along-track Product Development and Validation
Lead: CLS, dept: iSAT
Contributors: All

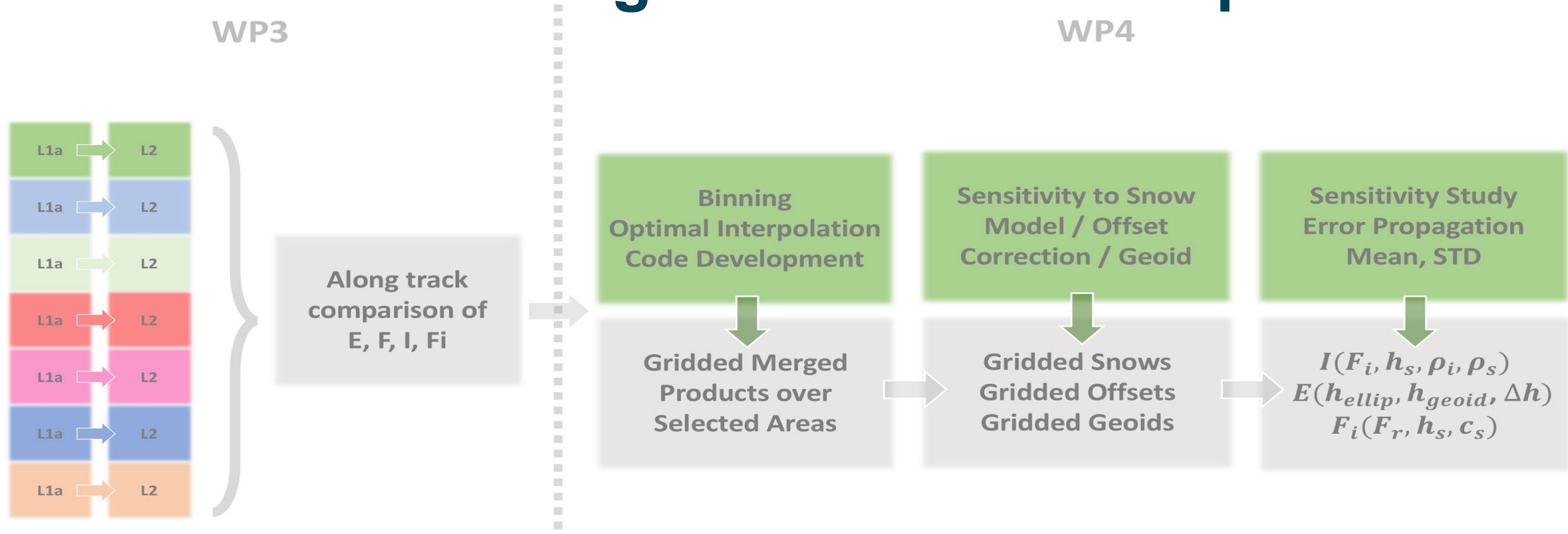
<u>WP 4</u>
Gridded Product Development and Validation
Lead: DTU, dept: LEGOS
Contributor: All

<u>WP 5</u>
Data Set Generation and Impact Assessment
Lead: UCL-MSSL
Contributor: UCL, CSL, DTU, IPSL MERCATOR, NOCS,

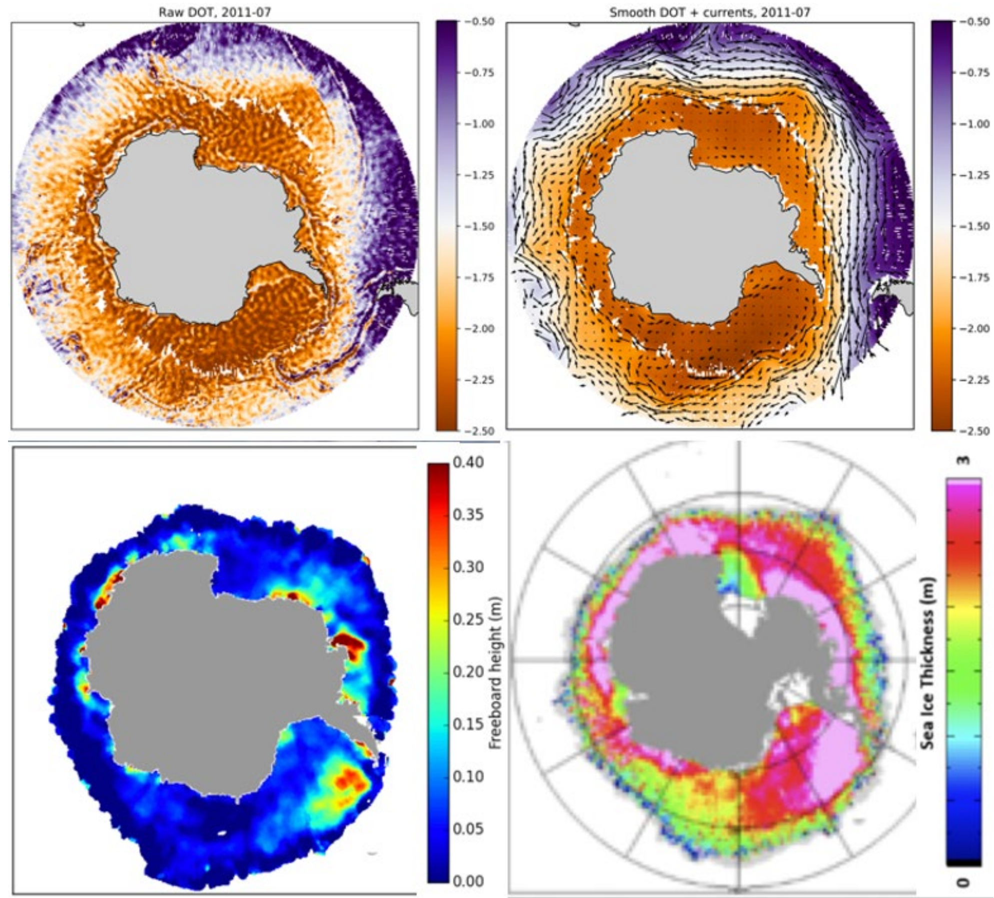
<u>WP 6</u>
Scientific Roadmap
Lead: UCL-CPOM
Contributors: ShepSp, DTU

<u>WP 7</u> Management ***Lead: UCL-MSSL***

Higher-level Gridded products



Towards gridded products



Credit: UCL

Credit: LEGOS

Credit: Leeds

CryoSat+ Antarctic Ocean

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