

# PREPARATION AND OPERATIONS OF THE MISSION PERFORMANCE CENTRE (MPC) FOR THE COPERNICUS SENTINEL-3 MISSION

## S3MPC STM Annual Performance Report - Year 2019



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S3MPC STM Annual Performance

Report - Year 2019

Ref.: S3MPC.CLS.APR.006 Issue: 1.0 Date: 28/02/2020 Page: iv

#### **Table of content**

Cł	IANGES	LOG	. 111
LI	ST OF CH	IANGES	. 111
T/	ABLE OF	CONTENT	. IV
LI	ST OF FI	GURES	VIII
LI	ST OF TA	BLES	ххі
1	INTR	ODUCTION	1
	1.1	Scope of the document	1
	1.2	Applicable documents	1
	1.3	Reference documents	1
	1.4	Acronyms and abbreviations	1
2	EXEC		2
	2.1	Sentinel-3 Surface Topography Mission	. 2
	2.2	SBAL and MWR sensors	2
	2.3	Sea   evel	3
	2.4	Winds and Waves	4
	2.5	Land and Sea Ice	5
	2.6	Inland waters	6
3	SRAI	AND MWR MISSION EVENTS	8
4	PRO	CESSING BASELINE STATUS AND DATASET DESCRIPTION	.13
	4.1	Land and Marine Products	13
	4.2	Processing Baseline History	14
	4.2.3	Summary of the most recent Processing Baselines content	15
	4.2.2	2 Model and standard history	15
	4.3	Status of the current Processing Baseline	17
	4.4	List of anomalies in the Processing Baseline	17
	4.5	Dataset description	18
5	SENS	ORS STATUS	.19
	5.1	SRAL	19
	5.2	MWR	23
	5.2.2	MWR processing	24
	5.2.	2 MWR Calibration parameters	25
	5.2 5.2.:	<ul> <li>MWR Calibration parameters</li> <li>MWR RFI monitoring</li> </ul>	25 27
	5.2. 5.2. 5.2.	<ul> <li>MWR Calibration parameters</li> <li>MWR RFI monitoring</li> <li>MWR side lobe correction</li> </ul>	25 27 28
	5.2.4 5.2.4 5.2.4 5.2.4	<ul> <li>MWR Calibration parameters</li> <li>MWR RFI monitoring</li> <li>MWR side lobe correction</li> <li>MWR Brightness Temperatures monitoring</li> </ul>	25 27 28 30



## Sentinel-3 MPC S3MPC STM Annual Performance

Report - Year 2019

 Ref.:
 S3MPC.CLS.APR.006

 Issue:
 1.0

 Date:
 28/02/2020

 Page:
 v

e	5.1	Over Ocean	33
6	5.2	Over Land	34
	6.2.2	1 Global analysis	34
	6.2.2	2 Analysis over Antarctica	39
	6.2.3	3 Available measurement and their relevance	43
7	PERF	ORMANCE MISSION OVER OCEAN	.45
7	7.1	Outliers detection	45
	7.1.	1 Ice detection	45
	7.1.2	2 Outliers detection over ocean	48
7	7.2	Monitoring of SRAL parameters	52
	7.2.2	1 Significant Wave Height	52
	7.2.2	2 Backscatter coefficient	55
	7.2.3	3 Dual-Frequency ionospheric correction	59
	7.2.4	4 Off-Nadir angle waveform	65
7	7.3	Wet tropospheric correction	70
	7.3.3	1 Along-track analyses	70
	7.3.2	2 Crossover analyses	74
-	7.4	Sea Level Performances	77
	7.4.3	1 Along-track analyses	78
	7.4.2	2 Crossovers	80
7	7.5	Global Mean Sea Level	88
-	7.6	Wind/Wave Performance	92
	7.6.2	1 Backscatter coefficient	93
	7.6.2	2 Altimeter Wind Speed	96
	7.6.3	3 Significant Wave Height 1	13
-	7.7	Specific investigations 1	128
	7.7.	1 Investigation: Range sensitivity to meridional wind 1	128
	7.7.2	2 Investigation: Estimation of the impact of the PTR shape evolution on the Level-2 estimate 129	es
	7.7.3	3 Investigation on the S3-A SAR GMSL long-term drift 1	136
	7.7.4	Investigation: Assessment and improvement of the Sentinel-3 flag parametrization 1	146
-	7.8	Performance over Coastal areas 1	152
8	PERF	ORMANCE MISSION OVER SEA ICE	153
ξ	3.1	Freeboard 1	153
ξ	3.2	Sea Ice Parameters Contributing to Freeboard1	158
ξ	3.3	Effect of Area Masking and Pole to Pole Processing on Sea Ice Parameters 1	161
ξ	3.4	Availability of Snow Density, Snow Depth and Sea Ice Concentration over Sea Ice	162
9	MISS	SION PERFORMANCE OVER LAND ICE	163



9.1	The Effect of SAR Tracking Mode on S3A Land Ice Performance	163
9.2	Measurement Precision over Land Ice	
9.2	.1 Shot-to-shot Precision	
9.2	.2 Crossover Analysis	167
9.3	Measurement Accuracy over Land Ice	172
9.4	Ice Sheet Rate of Elevation Change from S3A	173
9.5	Land Ice Parameter Failure Rates	175
9.6	Slope Correction	
9.7	Geophysical Correction Availability over Land Ice	182
10 PER	FORMANCE MISSION OVER INLAND WATERS	
10.1	Behaviour of the OLTC (open loop Tracking Command)	
10.	1.1 OLTC content and validation	183
10.	1.2 Advise on the potential Open Loop mode limitations	
10.2	Results from systematic quality assessment over 2019	186
10.	2.1 Default value and potential outliers	186
10.	2.2 Transect dispersion of the 20Hz water level estimates	189
10.3	Validation over Ebro River basin	191
10.4	Comparison of SAR and PLRM performances over inland waters	194
10.	4.1 Coastal contamination	194
10.	4.2 Range Noise (20Hz)	195
11 RAI	NGE AND SEA LEVEL ABSOLUTE CALIBRATION	197
11.1	Calibration with Crete & Svalbard transponders	197
11.2	Calibration in Corsica, Harvest and Bass Strait	207
11.	2.1 Calibration in Corsica	207
11.	2.2 Calibrations in Harvest	219
11.	2.3 Calibrations in Bass Strait	221
12 BIA	S ASSESSMENT OF THE DIFFERENT RETRACKERS	224
12.1	Ocean retracker	224
12.2	OCOG retracker	224
12.3	Sea Ice retracker	226
12.4	Ice margin retracker	227
12.5	Summary	
13 AN	NEX - PROCESSING BASELINE DETAILS	232
13.1	Processing Baseline 2.12	232
13.	1.1 Ground processors versions (Instrument Processor Facility)	232
13.	1.2 Evolutions	232



### Sentinel-3 MPC S3MPC STM Annual Performance

Report - Year 2019

Ref.: S3MPC.CLS.APR.006 Issue: 1.0 Date: 28/02/2020 Page: vii

13.2	Processing Baseline 2.24	233
13.2.	1 Ground processors versions (Instrument Processor Facility)	233
13.2.	2 Evolutions	233
13.2.	3 Fix of anomalies	233
13.3	Processing Baseline 2.27	235
13.3.	1 Ground processors versions (Instrument Processor Facility)	235
13.3.	2 Evolutions	235
13.3.	3 Fix of anomalies	235
13.3.	4 Anomalies not solved	236
13.4	Processing Baseline 2.33	
13.4.	1 Ground processors versions (Instrument Processor Facility)	
13.4.	2 Evolutions	240
13.4.	3 Fix of anomalies	240
13.4.	4 Anomalies not solved	241
13.5	Processing Baseline 1.13 for S3B	243
13.5.	1 Ground processors versions (Instrument Processor Facility)	
13.5.	2 Evolutions	
13.5.	3 Fix of anomalies	244
13.6	Processing Baseline 2.45 for S3A and 1.17 for S3B	244
13.6.	1 Ground processors versions (Instrument Processor Facility)	
13.6.	2 Evolutions	
13.6.	3 Fix of anomalies	244
13.6.	4 Anomalies not solved	246
13.7	Processing Baseline 2.61 for S3A and 1.33 for S3B	247
13.7.	1 Ground processors versions (Instrument Processor Facility)	
13.7.	2 Evolutions	247
13.7.	3 Fix of anomalies	

# 13.7.4 Anomalies not solved 248 14 ANNEX REFERENCES 249



## List of Figures

Figure 1 Geographical mask for L2 Land and Marine products coverage: blue is Marine products only, white is Land products only, brown is for regions available in both products 13
Figure 2: Illustration of the different processing versions used to compute a Sentinel-3A time series based on the most recent PB versions 18
Figure 3: Illustration of the different processing versions used to compute a Sentinel-3B time series based on the most recent PB versions 18
Figure 4: S3A (left) and S3B (right) Ku band CAL1 SAR Time Delay series 19
Figure 5: S3A (left) and S3B (right) Ku band CAL1 SAR Integrated and Peak Power series 20
Figure 6: S3A (left) and S3B (right) Ku band CAL1 SAR PTR width series 20
Figure 7: S3A (left) and S3B (right) Ku band CAL2 SAR waveforms ripples 21
Figure 8: S3A (left) and S3B (right) Ku band AutoCal Power Attenuation Progression 21
Figure 9: S3A and S3B AIR Maximum Position (left) and Maximum Power (right) 22
Figure 10: S3A (top) and S3B (bottom) secondary lobes power drift for the first seven left secondary lobes (left) and the first seven right secondary lobes (right) 23
Figure 11: Geolocation of S3A MWR measurements in DNB processing 24
Figure 12: Number of S3A MWR measurements in DNB mode along the year 24
Figure 13: Geolocation of S3B MWR measurements in DNB mode 25
Figure 14: Number of S3B MWR measurements in DNB mode along the year 25
Figure 15: Monitoring of S3A MWR calibration parameters: Receiver gain (top line), Noise injection temperature (bottom line) for both channels: 23.8GHz (left) and 36.5GHz (right) 26
Figure 16: Monitoring of S3B MWR calibration parameters: Receiver gain (top line), Noise injection temperature (bottom line) for both channels: 23.8GHz (left) and 36.5GHz (right) 26
Figure 17: Definition of the safing area : left for cycle 1 to 39, middle: from cycle 40 to 45, right : since cycle 46 27
Figure 18: Slope (in [1-15km] scales) of brightness temperature spectra for channel 36.5GHz of S3A 28
Figure 19: Sidelobe correction map (Spring) : Top: Version 1; Bottom: Version 2 29
Figure 20: Impact on the brightness temperature of the new sidelobe correction (cycle 31 – spring) 29
Figure 21 Geophysical impact of new sidelobe correction : left: Difference of variance at crossover points; Right: Difference of variance of SLA vs distance from shoreline 30
Figure 22: Coldest temperature over ocean for Sentinel-3A, Sentinel-3B, SARAL/AltiKa, Metop02/AMSU- A, Jason3/AMR for two channels 23.8GHz (left) and 36.5GHz (right) 31
Figure 23: Hottest temperatures over the Amazon forest for Sentinel-3A, SARAL/AltiKa, Metop02/AMSU- A, Jason3/AMR for two channels 23.8GHz (left) and 36.5GHz (right) 32



Figure 25: Map of the SRAL tracking mode plotted for Sentinel-3A (top panel) for OLTC v4.2 until March 1<sup>st</sup> 2019 and Sentinel-3B (bottom panel). Since March 9<sup>th</sup> 2019 the Open Loop tracking command was updated to v5.0 and the OL/CL pattern is similar to S3B (ie OL in between +/- 60° latitude).------ 35

Figure 28: Missing Sentinel-3A measurements (plotted in white) when in Close Loop over this region before cycle 42 superimposed on an elevation grid. ------ 38

Figure 29: Daily monitoring of Sentinel-3A and Sentinel-3B missing measurements over land from January 2018 to December 2019.------ 38

Figure 30: Missing measurements in closed loop for Sentinel-3A cycle 36, from 16 September 2018 to 13 October 2018 (left panel). Slope over Antarctica from REMA DEMA (right panel)------- 39

Figure 31: Histogram of missing points over Antarctica as a function of slope, for Sentinel-3A in closed loop.----- 40

Figure 32: Repeating missing points for closed loop: geographical distribution (top), scatter plot of consecutive missing measurements as a function of slope (bottom right) and histogram (bottom right) 41

Figure 34: Gridded map of the range ocog Default Value percentage with respect to the available measurements. For Sentinel-3A (top panel) over cycle 25 (from 11<sup>th</sup> of November 2017 to 20<sup>th</sup> of December 2017) and for Sentinel-3B (bottom panel) over cycle 20 (from 1-th of December 2018 to 12<sup>th</sup> of January 2019)-------44

Figure 35: Top panels show Sentinel-3A (left) and Sentinel-3B (right) sea ice flag derived from both L2 LAND and WATER products from 23<sup>rd</sup> November to 23<sup>rd</sup> December 2018. Presence of sea ice corresponds to red, open ocean water is represented in blue. Bottom left panel shows the sea ice concentration percentage derived from OSISAF model over the same period. Bottom right panel shows the sea concentration percentage derived from NSIDC model over the month of December 2018. -------46

Figure 36: Gridded maps of outlier's percentage detected by sea ice flag for Sentinel-3A (top left panel, from April 2016 to December 2019), SARAL/AltiKa (top right panel, from April 2016 to December 2019) and Sentinel-3B (bottom panel, from November 2018 to December 2019). ------ 47



Figure 37: Monitoring of the daily averaged percentages of outliers detected by Sentinel-3A (blue curve) and Sentinel-3B (orange curve) sea ice flag and SARAL/AltiKa ice flag (green curve) over ocean. ------ 47

Figure 39: Percentage of outlier detected by the dynamical atmospheric thresholds (top panel) and by the MWR WTC thresholds (bottom panel). Sentinel-3A is represented in blue, Sentinel-3B in orange, and Jason-3 in black.------ 50

Figure 40: Percentage of outlier detected by the MWR WTC thresholds over Sentinel-3A lifetime (top panel). A zoom of the same metrics between March 2018 and December 2019 is shown on the bottom panel, with no ground processing errors considered. Sentinel-3A is represented in blue, Sentinel-3B in orange, and SARAL/Altika in green. -------51

Figure 41: Gridded maps of Jason-3 (top panel), Sentinel-3A SARM (middle left panel) and P-LRM (middle right panel) SWH from April 2016 to December 2019. Gridded maps of Sentinel-3B SARM (bottom left panel) and P-LRM (bottom right panel) SWH from November 2018 to December 2019. ----- 53

Figure 42: Daily monitoring of the Sentinel-3A SARM (blue curve) P-LRM (cyan curve), Sentinel-3B SARM (red curve) P-LRM (orange curve), and Jason-3 (black curve) SWH. ------54

Figure 45: Daily monitoring of the Sentinel-3A SARM (blue curve) P-LRM (cyan curve), Sentinel-3B SARM (red curve) P-LRM (orange curve), and Jason-3 (black curve) backscatter coefficient.----- 58

Figure 47: Gridded maps the dual frequency ionospheric correction computed for Jason-3 (top panel), Sentinel-3A SARM (middle left panel) and P-LRM (middle right panel) over the period spanning from April 2016 to December 2019. Gridded maps of Sentinel-3B SARM (bottom left panel) and P-LRM (bottom right panel) dual frequency ionospheric correction computed from November 2018 to December 2019.----- 60

Figure 48: Gridded maps of the collocated differences between dual frequency ionosphere correction and GIM model for ascending (left panels) and descending (right panels) passes, for Jason-3 (top panels),



SARM Sentinel-3A (middle panels) and Sentinel-3B (bottom panels). The ionosphere corrections derived from altimeter were filtered at 300km.----- 62

Figure 49: Along-track maps of the local hours for ascending (left panels) and descending (right panels) passes, computed from the 6<sup>th</sup> August 2019 to the 2<sup>nd</sup> September 2019 for Sentinel-3A (top panels) and Sentinel-3B (bottom panels). ------62

Figure 50: Top panel shows the daily monitoring of the collocated differences between Sentinel-3A SARM dual-frequency ionosphere correction and the GIM model. The Sentinel-3A local hours were split by four hours bins and plotted separately. Bottom panel shows the daily monitoring of the Sentinel-3A SARM, P-LRM dual-frequency ionosphere correction and the collocated GIM model. Ascending and Descending passes were plotted separately. ------63

Figure 51: Top panel shows the daily monitoring of the collocated differences between Sentinel-3B SARM dual-frequency ionosphere correction and the GIM model. The Sentinel-3B local hours were split by four hours bins and plotted separately. Bottom panel shows the daily monitoring of the Sentinel-3B SARM, P-LRM dual-frequency ionosphere correction and the collocated GIM model. Ascending and Descending passes were plotted separately. ------64

Figure 52: Daily monitoring of C-band Sea Level Anomaly without geophysical corrections for Sentinel-3A (blue curve) and Sentinel-3B (red curve) from November 2018 to December 2019.------ 65

Figure 53: Top panel shows the off-nadir angle derived from waveforms for Jason-3 over Sentinel-3A whole mission lifetime. Middle panels show the gridded maps of Sentinel-3A off-nadir angle derived from waveforms (left panel) and derived from Star-Trackers (right panel) from April 2016 to December 2019. Bottoms panels show the same gridded maps for Sentinel-3B from November 2018 to December 2019.

Figure 54: Daily monitoring of the Sentinel-3A P-LRM (blue curve), Sentinel-3B P-LRM (orange curve), Jason-3 (black curve) and SARAI/AltiKa (green curve) off-nadir angle derived from waveforms ------- 67

Figure 55: Gridded maps of the residual difference of P-LRM square off nadir angle between Sentinel-3A and Sentinel-3B, on ascending passes only. The five maps cover the entire Sentinel-3A/Sentinel-3B tandem period where Sentinel-3B operate in SAR mode, i.e. from the 11<sup>th</sup> July to the 16<sup>th</sup> October 2018. Each map covers 20 days. -------68

Figure 56: Residual difference of P-LRM square off nadir angle between Sentinel-3A and Sentinel-3B, on ascending passes only, averaged in latitude. Computed during the tandem phase over a time period of 20 days centred around the 21<sup>st</sup> June 2018 (summer solstice, left panel) and around the 20<sup>th</sup> September 2018 (autumn equinox, right panel)-------69

Figure 57: Difference of P-LRM square off nadir angle between Sentinel-3A ascending and descending passes, averaged in latitude. Computed over a time period of 60 days around equinox (left panel), summer solstice (middle panel) and winter solstice (right panel).------ 69

Figure 58: Monitoring of MWR (3P) - ECMWF wet tropospheric correction for S3A,S3B, SARAL/AltiKa, Jason3/AMR: mean (left), standard deviation (right)-----71

Figure 59: Difference of SAR/P-LRM wet tropospheric correction for Sentinel-3A (cycle 40 to 53) ------ 72

Figure 60: Difference of SAR/P-LRM wet tropospheric correction for Sentinel-3B (cycle 21 to 33)------72

Figure 61: Monitoring of 3P and 5P MWR - ECMWF wet tropospheric correction for Sentinel-3A ------ 73



Figure 62: Monitoring of 3P and 5P MWR - ECMWF wet tropospheric correction for Sentinel-3A ------ 73

Figure 63: Map of the difference 5P - 3P wet tropospheric correction: left: Sentinel-3A (using NTC data; cycle 40 to 53) right: Sentinel-3B (using NTC data; cycle 21 to 33)------74

Figure 64: Difference of variance of  $\Delta$ SSH at crossover points for low oceanic variability for Sentinel-3A, SARAL, Jason3 : var( $\Delta$ SSH with PLRM WTC 3P MWR )-var(VSSH with WTC ECMWF) (bottom) ------75

Figure 65: Difference of variance of  $\Delta$ SSH at crossover points for low oceanic variability for Sentinel-3A, SARAL, Jason3 : var( $\Delta$ SSH with SAR WTC 3P MWR )-var(VSSH with WTC ECMWF) (bottom)------75

Figure 66: Difference of variance of SSH at crossover points SAR (left) / P-LRM (right) ------ 75

Figure 67: Difference of variance of SSH at crossover points for Sentinel-3A, SARAL/AltiKa, Jason3/AMR: var(SSH with P-LRM WTC 5P MWR)-var(SSH with WTC ECMWF)------76

Figure 68: Difference of variance of SSH at crossover points for Sentinel-3A, Sentinel-3B, SARAL/AltiKa, Jason3/AMR: var(SSH with SAR WTC 5P MWR)-var(SSH with WTC ECMWF)------76

Figure 69: Difference of variance of SSH at crossover points SAR (left) / P-LRM (right) ------ 77

Figure 70: Gridded maps of Jason-3 (top panel), Sentinel-3A SARM (middle left panel), and P-LRM (middle right panel) SLA computed from April 2016 to December 2019. Gridded maps of Sentinel-3B SARM (bottom left panel) and P-LRM (bottom right panel) SLA computed from November 2018 to December 2019. -----78

Figure 71: Daily monitoring of the Sentinel-3A SARM (blue) and P-LRM (cyan), Sentinel-3B SARM (red) and P-LRM (orange), and Jason-3 (black) mean SLA (top panel) and its standard deviation (bottom panel).- 80

Figure 72: Cycle per cycle monitoring of the SSH differences computed at mono-mission crossovers for Sentinel-3A SARM (blue curve), Sentinel-3B (red curve), and Jason-3 (black curve).------ 81

Figure 73: Gridded maps of SSH differences computed at mono-mission crossovers in SARM (left panels) and in P-LRM (right panels), for Sentinel-3A using POE-E orbit from April 2016 to November 2018 (top panels), for Sentinel-3A using POE-F orbit from April 2016 to December 2019 (middle panels), and for Sentinel-3B using POE-F orbit from November 2018 to December 2019 (bottom panels).------ 82

Figure 74: Cycle per cycle monitoring of the system error computed at mono-mission crossovers for Sentinel-3A (blue curve), Sentinel-3B (red curve), and Jason-3 (black curve). The system error is computed through the cyclic SSH differences standard deviation at crossovers and divided by 2 because of the cumulation of ascending and descending errors. The cyan and orange curves show respectively Sentinel-3A and Sentinel-3B SARM system error when the mean time lag at crossovers is consistent with the Jason-3 one.

Figure 75: Gridded maps of SSH differences computed at Sentinel-3A and Jason-3 crossovers (top panels) and Sentinel-3B and Jason-3 crossovers (bottom panel), in SARM (left panels) and in P-LRM (right panels).

Figure 76: Cycle per cycle monitoring of the SSH differences computed at Sentinel-3A and Jason-3 crossovers in SARM (blue curve) and in P-LRM (cyan curve), and at Sentinel-3B and Jason-3 crossovers in SARM (red curve) and in P-LRM (orange curve). Top panel: SSH computed with radiometer Wet Tropospheric Correction, Bottom panel: SSH computed with ECMWF model Wet Tropospheric Correction

----- 85



Figure 77: Daily monitoring of the difference between WTC derived from radiometer and from ECMWF model, for Sentinel-3B SARM and PLRM, over the mission lifetime. ------ 86

Figure 78: Gridded maps of SSH differences computed at crossovers between Sentinel-3A and Sentinel-3B in SARM (top left panel) and in PLRM (top right panel) over Sentinel-3B final orbit. ------ 87

Figure 79: Cycle per cycle monitoring of SSH differences computed at Sentinel-3A/Sentinel-3B crossovers in SARM (blue curve) and in P-LRM (cyan curve). Dash lines represent SSH computed using POE-F orbit solution over the whole period. Left panel: SSH computed with radiometer Wet Tropospheric Correction, Right panel: SSH computed with ECMWF model Wet Tropospheric Correction. ------ 87

Figure 81 - S3-a GMSL trend differences in SAR mode, with Jason-3 and SARAL-AltiKa ------ 90

Figure 82 - S3-a GMSL trend differences in SAR mode, with Jason-2, Jason-3 and SARAL-AltiKa, over the full S3-a/Jason-2 common period------91

Figure 83 - S3-a GMSL trend differences in PLRM, with Jason-3 and SARAL-AltiKa ------ 92

Figure 84: Sentinel-3A and Sentinel-3B SRAL backscatter coefficient PDF's over the whole global ocean for year 2019. PDF of Sentinel-3A from 2018 is also shown. ------94

Figure 85: Panel (a): Comparison between backscatter PDF's of various altimeters for year 2019. Panel (b): Better comparison can be carried out when PDF's are shifted to have their peak estimates coincide with that of Sentinel-3A. The amount of shift is given in the legend of panel (b). ------95

Figure 87: Sentinel-3A and Sentinel-3B SRAL surface wind speed PDF over the whole global ocean for year2019. The corresponding ECMWF (collocated with Sentinel-3A and Sentinel-3B) PDF's are shown for comparison. The 2018 PDF's of Sentinel-3A and its model counterpart are also shown. ------97

Figure 88: Panel (a): Comparison between wind speed PDF's of various altimeters for year2019. Panel (b): The corresponding ECMWF model PDF's as collocated with the measurements. The abbreviations are as follows: S3A: Sentinel-3A, S3B: Sentinel-3B, J3: Jason-3, CS2: CryoSat-2, and SA: SARAL/AltiKa. -------98

Figure 89: Time series of global mean (top) and standard deviation (bottom) of wind speed from SRAL Kuband after quality control from both Sentinel-3A and 3B. The collocated model wind speed mean and SD are also shown. Mean and SD are computed over a moving time window of 7 days (shown as thin lines). The 92-day running means are shown as thick lines. Vertical dashed lines show events which may have impact on the comparison. This includes Sentinel-3 STM Instrument Processing Baseline (PB) changes as well as ECMWF IFS model changes like CY43R3.-------99

Figure 90: Global comparison of Sentinel-3A and Sentinel-3B, in panels (a) and (b), respectively, SAR surface wind speed against ECMWF model analysis for the year 2019. Number of colocations in each 0.5



m/s x 0.5 m/s 2D bin is color-coded as in the legend. The crosses are the means of the bins for given x-axis values (model) while the circles are the means for given y-axis values (Sentinel-3). --------100

Figure 91: Same as Figure 90 but the comparison is done against in-situ observations (mainly in the NH).

Figure 92: Time series of weekly wind speed bias defined as altimeter - model (top) and standard deviation of the difference (bottom) between Sentinel-3A SRAL Ku-band and ECMWF model analysis. -------103

Figure 93: Same as Figure 92 but for Sentinel-3B.-----103

Figure 94: Time series of weekly wind speed bias defined as altimeter - buoy (top) and standard deviation of the difference (bottom) between Sentinel-3A SRAL Ku-band and in-situ (buoy) measurements. ----- 104

Figure 95: Same as Figure 94 but for Sentinel-3B.-----104

Figure 96: Time series of weekly global wind speed bias defined as altimeter - model (top) and standard deviation of the difference (bottom) between various altimeters (including SRAL) and ECMWF model analysis. Sentinel-3B curves are same as the global curves in Figure 93 while those of Sentinel-3A are different than those in Figure 92 since reprocessed data were used before December 2018. -------105

Figure 97: Geographical distribution of mean Sentinel-3 wind speed (a) as well as the bias (b); the SDD (c) and the SI (d) between Sentinel-3 and ECMWF model AN during the whole year of 2019. Bias is defined as altimeter - model.------106

Figure 98: As in Figure 97 but for Sentinel-3B. -----108

Figure 99: Global comparison of Sentinel-3A and Sentinel-3B, in panels (a) and (b), respectively, PLRM surface wind speed against ECMWF model analysis for the year 2019. Refer to Figure 90 for the meaning of the crosses and the circles as well as the colour coding. -------111

Figure 100: Time series of weekly Sentinel-3A PLRM wind speed bias defined as altimeter - model (top) and standard deviation of the difference (bottom) between SRAL PLRM and ECMWF model analysis.-112

Figure 101: Same as Figure 100 but for Sentinel-3B ------112

Figure 102: Sentinel-3A and Sentinel-3B SRAL SWH PDF's over the whole global ocean for the year 2019. The corresponding ECMWF wave model (collocated with Sentinel-3A and Sentinel-3B) PDF's are shown for comparison. The Sentinel-3A PDF's are covered by those of Sentinel-3B. The 2018 PDF of Sentinel-3A and its model counterpart are also shown. ------113

Figure 103: Panel (a): Global SWH PDF's from various altimeters, including Sentinel-3A and Sentinel-3B SRAL's, for the year 2019. The corresponding ECMWF (collocated with each altimeter) PDF's are shown in panel (b) for comparison.-----115

Figure 104: Time series of global mean (top) and standard deviation (bottom) of significant wave height from Sentinel-3A and Sentinel-3B SRAL Ku-band after quality control. The collocated ECMWF model SWH mean and SD are also shown. The mean and SD are computed over a moving time window of 7 days. 116



Figure 106: Same as Figure 105 but the comparison is done against in-situ observations (mainly in the NH). ------118 Figure 107: Time series of weekly global significant wave height bias defined as altimeter - model (top) and standard deviation of the difference (bottom) between Sentinel-3A SRAL and ECMWF model firstguess. ------ 119 Figure 108: Same as Figure 107 but for Sentinel-3B. -----119 Figure 109: Time series of monthly global significant wave height bias defined as altimeter - buoy (top) and standard deviation of the difference (bottom) between Sentinel-3A SRAL and in-situ measurements. ------120 Figure 110: Same as Figure 109 but for Sentinel-3B. -----121 Figure 111: Time series of weekly global significant wave height bias defined as altimeter - model (top) and standard deviation of the difference (bottom) between 5 altimeters including Sentinel-3A and Sentinel-3B SRAL (Sentinel-3A line is different from the global one in Figure 107 since reprocessed data Figure 112: Geographical distribution of mean Sentinel-3A SWH (a) as well as the bias (b); the SDD (c) and the SI (d) between Sentinel-3A and ECMWF model FG during 2019. Bias is defined as altimeter - model. -----123 Figure 113: As in Figure 112 but for Sentinel-3B. -----125 Figure 114: Gridded maps of Sentinel-3A collocated range differences between SARM and P-LRM for ascending (left panel) and descending (right panel) passes, average from April 2016 to December 2018. ------128 Figure 115: Left panel: Difference between Figure 114 maps (ascending – descending). Right panel: Figure 116: Processing scheme implemented to evaluate the PTR drift impact on level 2 estimates---- 130 Figure 117: SWH estimation differences between a PTR at the beginning of the mission and different PTR taken all along the Sentinel-3A/SRAL life -----131 Figure 118: SAMOSA SWH estimate sensitivity to the PTR drift ------132 Figure 119: Range estimation differences between a PTR at the beginning of the mission and different PTR taken all along the Sentinel-3A/SRAL life ------133 Figure 120: SAMOSA Range estimate sensitivity to the PTR drift------133 Figure 121: PLRM SWH estimate sensitivity to the PTR drift ------134 Figure 122: PLRM range estimate sensitivity to the PTR drift -----135 Figure 123 – "Global mean range" difference between S3-a SAR and PLR modes. The slope is obtained Figure 124 – "Global mean ionospheric correction" difference between S3-a SAR and PLR modes. The slope is obtained from a least square fitting method and the uncertainties are the formal ones.------139

Figure 125– "Global mean SSB" difference between S3-a SAR and PLR modes. The slope is obtained from a least square fitting method and the uncertainties are the formal ones. A jump is observed in January



2019 due to an update of the IPF. Data up to S3-a cycle 39 can be used for climate purpose, or one should wait for the new reprocessed data release.-----140

Figure 127- "Global mean ionospheric correction" difference between S3-a SAR and PLR modes. The slope is obtained from a least square fitting method and the uncertainties are the formal ones. -------142

Figure 128 – Daily mean follow-up of the range difference between SAR and PLR modes data from S3-a, as a function of the significant wave height (SWH) derived values. The same order of drift is observed whatever the SWH values is selected.------143

Figure 129 - "Global mean wind speed" of the S3-a SAR and PLR modes, compared to the ECMWF model. The slopes are obtained from a least square fitting method and the uncertainties are the formal ones.

Figure 130 – "Global mean range" difference between S3-a SAR and PLR modes, separated in ascending and descending tracks. The slopes are obtained from a least square fitting method and the uncertainties are the formal ones. ------145

Figure 131 – Difference of the ascending and descending tracks between S3-a SAR and PLRM ranges (red curve), along with the evolution of the meridional wind speed from the ECMWF model. The slopes are obtained from a least square fitting method and the uncertainties are the formal ones. ------146

Figure 132: Sentinel-3A sea ice flag value derived from SARM (left panels) and PLRM (middle panels). OSISAF Ice Type product collocated at Sentinel-3A measurement location (right panels). Top panels show results over Sentinel-3A cycle 15 (Northern winter) over the Arctic region and bottom panels over Sentinel-3A cycle 22 (austral winter) over the Antarctic region.-----147

Figure 134: Seasonal masks for sea ice detection over the Arctic region (top panels) and over the Antarctic region (bottom panels), for Envisat (left panels) and for Sentinel-3 new parametrization (right panels). Blue: winter mask, Red: summer mask.------149

Figure 135: Maps of Sea Level Anomaly for Sentinel-3A SARM cycle 22, over the Artic (left) and Antarctic region (right). The product sea-ice flag is used here to discard data contaminated with ice. ------149

Figure 136: OSISAF Ice Type product collocated at Sentinel-3A measurement location (left panels). Sentinel-3A new sea ice flag value derived from SARM (right panels). Top panels show results over Sentinel-3A cycle 15 (Northern winter) over the Arctic region and bottom panels over Sentinel-3A cycle 22 (austral winter) over the Antarctic region. ------150

Figure 137: Sentinel-3A snow facies type over Greenland in SARM (top panels) and in P-LRM (bottom panels). Left panels represent the actual product flag and right panels the updated version.-----151

Figure 138: Envisat snow facies type flag derived from v3.0 reprocessing (left panel). Sentinel-3A snow facies type over Antarctica in SARM (top panels) and in P-LRM (bottom panels). Middle panels represent the actual product flag and right panels the updated version.-----152



igure 139: S3A L2 freeboard from PB2.33 (negative anomaly), and PB2.4x TDS (corrected)	153
-igure 140: Anomalous high values around coastline corrected in PB2.43	154
Figure 141: Comparison of S3A and CS2 Gridded Freeboard for January 2018	154
Figure 142: S3-A minus CS2 Freeboard (CPOM Processing)	155
igure 143: Comparison of S3A and CS2 Gridded Freeboard (Hamming and Zero Padding applied	at L1) 156
-igure 144: Arctic Freeboard Comparison between S3A and S3B in Mar/Apr 2019	156
igure 145: Number and % of valid freeboard measurements over S3A and S3B mission life	157
	158
igure 147: Statistics of Sea Ice Retracker failure in the Arctic over S3A Mission	159
Figure 148: S3A Surface Type Discrimination since start of mission	159
Figure 149: Invalid 0% sea ice concentration values around coastline in PB2.43	160
Figure 150 : Corrected L2 Sea Ice Concentration, shown over the Arctic Beaufort Sea, available in	2020. 161
Figure 151: S3-A Elevation failure rates in Open Loop and Closed Loop cycles over Different Ice Su	rfaces 164
igure 152: S3A Shot-to-shot Precision over Lake Vostok (6-month period in 2019)	165
-igure 153: S3A Repeat Measurement Precision over Lake Vostok	166
igure 154: Comparison of measurement precision between S3A (SAR) and ENVISAT (LRM)	166
Figure 155: Crossover OCOG Elevation Differences at Lake Vostok Centre (S3A cycle 50, PB2.43)	167
Figure 156 Crossover OCOG Elevation Differences at Lake Vostok Centre (S3B cycle 30, PB2.43)	168
	168
Figure 158: Crossover S3B Mission Statistics at Lake Vostok Centre (OCOG Elevation differences)	169
Figure 159: Crossover OCOG Elevation Differences over Antarctic Ice Sheet (S3A cycle 39, S3B cyc PB2.33)	:le 20, 169
Figure 160: S3A Mission Statistics of Crossover differences (Antarctic Ice Sheet), OCOG elevation (PI	32.43) 171
Figure 161: Median absolute cross-over elevation difference (blue dots) and number of cross-overs pars) as a function of surface slope, S3A	; (blue 171
igure 162: Elevation differences at crossovers between ICESat-2 and S3A over Lake Vostok	172
Figure 163: Crossover differences between ICESat-2 and S3A (OCOG elevation) over Greenland	173
Figure 164: Rate of Elevation Change derived from S3A OCOG Elevation (Dec 2016 to Oct 2019)	174
Figure 165: Antarctica OCOG Elevation Gridded Failure Maps (S3A, S3B, PB2.43)	175
-igure 166: Failure rate of elevation_ocog_20_ku (S3A, PB2.33, PB2.43)	176



Figure 167: Failure rate of elevation_ocog_20_ku (S3B, PB2.43)	176
Figure 168: Antarctica Ice Sheet Elevation Gridded Failure Maps (S3A, S3B, PB2.43)	177
Figure 169: S3A Mission Failure rate of elevation_ice_sheet_20_ku (S3A, PB2.33, PB2.43)	178
Figure 170: S3B Mission Failure rate of elevation_ice_sheet_20_ku (S3B, PB2.33, PB2.43)	178
Figure 171: Percentage failure of range_ice_20_plrm_ku (S3A, PB2.33, PB2.43)	179
Figure 172: S3A/B waveform quality flag map over Antarctica (PB2.43)	180
Figure 173: S3A Mission waveform quality flag statistics over Antarctica (PB2.33,2.43)	180
Figure 174: S3A SAR ku Slope Correction Magnitude (PB2.43)	181
Figure 175: Missing GIM Ionospheric Corrections over Antarctica in 2019	182
Figure 176: River targets for S3A and S3B in the LEGOS hydrology targets database	183
Figure 177: Histograms of the observed sigma0 over the hydrology targets in 2018 and 2019 show improvements brought by the new OLTC	ving the 184
Figure 178: Need to have the waveforms well centered to cope with the variation of the water elevation	surface 185
Figure 179: Histograms of the position of the leading edge that shows that the target heights in t OLTC are good statistically and that it reduces a lot the number or "no data" observed in CL	:he new 185
Figure 180: Sentinel-3A (top panel) and Sentinel-3B (bottom panel): Percentage of Valid (green) with technique 1 (orange), Edited with technique 2 (red), and Default Value (black) measurements largest lakes worldwide in Open Loop mode. Statistics are provided for all fields necessary to the surface height estimation with the SAMOSA and the OCOG retracking algorithms. Statistics con over cycle 33 of Sentinel-3B.	, Edited s on the e water mputed 188
Figure 181: Monitoring of the percentage of default values and edited measurements over lakes backscatter coefficient criteria) for Sentinel-3A (top panels) and Sentinel-3B (bottom panels) confor both kind of retracking (OCOG and SAMOSA).	(on the mputed 188
Figure 182: Standard deviation of the Sentinel-3A (Left) and Sentinel-3B (Right) WSH (computer range derived from OCOG retracking) from 02/12/19 to 29/12/19 as a function of the lake area (the transect length over lakes sampled (middle), and of the acquisition mode (right).	ed with left), of 190

Figure 184 Water bodies covered by Sentinel-3 satellite tracks with all available gauging stations. ----- 191

Figure 185 Water level time series retrieved by ocean retracker and OCOG retracker over two water bodies: Mequinenza Reservoir (left) and Itoiz Reservoir (right).------192

Figure 186 Water level time series retrieved by S3A (+) and S3B (o) over Ribarroja Reservoir. -----193

Figure 187 Water level time series retrieved by S3A (+) and S3B (o) over Mequinenza Reservoir. ------ 194

Figure 188: track over lake IssykKul used to compare S3A data in SAR mode with S3B in LRM during the tandem phase.-----195



Figure 189: Left : Orbit – range value for OCOG (blue) and SAMOSA (green) retrackers for S3A in SAR mod. Left : Orbit – range value for OCOG (blue) and MLE (green) retrackers for S3B in LRM mod-------195

Figure 190: Absolute difference of consecutive orbit – range values of 20Hz points over IssykKul lake (coastal areas excluded) Top : SAR mode (S3A during tandem phase. blue = OCOG range, green = SAMOSA range) Bottom : LRM (S3B during tandem phase. Blue = OCOG range, green = MLE range).------196

Figure 191 Range and Datation Bias Results -----205

Figure 192 Alignment and Stack Noise Results ------ 206

Figure 193: Absolute CALVAL configuration in Corsica. The regions in colours show the two high-resolution mean sea surfaces that were specifically measured to link the calibration sites to the altimetry data--207

Figure 194: Sentinel-3A and Sentinel-3B absolute bias estimates in Senetosa (upper plot) and Ajaccio (lower plot) on track 741 for the SAR and the PLRM data.-----209

Figure 195: Sentinel-3A bias estimates (upper plot), Sentinel-3A averaged SWH (middle plot, 1-std envelop showed with dashed lines) and Sentinel-3A averaged sigma0 (lower plot) in Senetosa.-----210

Figure 196 : Sentinel-3A bias estimates (upper plot), Sentinel-3A averaged SWH (middle plot, 1-std envelop showed with dashed lines) and Sentinel-3A averaged sigma0 (lower plot) in Ajaccio. ------211

Figure 197: Sentinel-3A and Sentinel-3B absolute range bias estimates computed by P. Bonnefond (Paris Observatory/SYRTE) and O. Laurain (OCA) in Corsica along the track 741 (from OSTST 2019).-----212

Figure 198: Left: Generic diagram of the regional calibration method. Right: Configuration in Corsica for the Sentinel-3A mission. S3A ground tracks in pink, Jason-2 tracks in red and Envisat tracks in yellow. The green dots show the crossover points where the offshore S3A SSH bias was computed. The red dots show the crossover points where the offshore S3A SSH bias could be potentially computed. --------214

Figure 199: Unstructured grids of the tidal models in the Corsica region. Left: FES2014 global model. Right: NOVELTIS regional model. ------215

Figure 200 : Offshore Sentinel-3A bias estimates in Corsica for the SAR and PLRM data, with and without ocean dynamics corrections (DAC and FES2014 global tidal model).-----218

Figure 201 : Offshore Sentinel-3A bias estimates in Corsica for the SAR and PLRM data, with and without ocean dynamics corrections (DAC and regional tidal model). -----218

Figure 202 : Configuration of the Sentinel-3A tracks at the Harvest calibration site.-----220 Figure 203: Sentinel-3A absolute bias estimates in Harvest for track 067 (upper plot) and track 710 (lower plot), for the SAR and the PLRM data.------221

Figure 204: Configuration of the Sentinel-3A tracks at the Bass Strait calibration site.-----222

Figure 205 : Sentinel-3A absolute bias estimates in Bass Strait for track 060 (upper plot) and track 247

(lower plot), for the SAR and the PLRM data. -----223

Figure 206 Range difference: OCOG-Ocean over Arctic in L2 Land products STC Cycle 51-----225 Figure 207 Backscatter coefficient difference: OCOG-Ocean over Arctic in L2 Land products STC Cycle 51

------226

Figure 208: Calculation of Sea Ice Retracker Bias for S3A over the Hudson Bay ------227



Figure 212 Backscatter coefficient difference: OCOG-Ice margin over Antarctica in L2 Land products STC
Figure 211 Backscatter coefficient difference: Ocean-Ice margin over Arctic in L2 Land products STC Cycle 51230
Figure 210 Range difference: OCOG-Ice margin over Antarctica in L2 Land products STC Cycle 51 229
Figure 209 Range difference: Ocean-Ice margin over Arctic in L2 Land products STC Cycle 51 228



#### **List of Tables**

Table 1 History of SRAL and MWR mode changes for Sentinel-3A 8
Table 2 History of SRAL and MWR mode changes for Sentinel-3B8
Table 3: Main Sentinel-3A SRAL and Platform events since the SRAL switch on 11
table 4: Main Sentinel-3B SRAL and Platform events since the SRAL switch on 12
Table 5 Model and standard history in L2 products 17
Table 6: List of cycle/Pass with detected interferences       28
Table 7: Characteristics of missions with microwave radiometer 30
Table 8: Missing points statistics over one cycle for the cases of study of missing measurements 42
Table 9: Outliers detection thresholds and corresponding percentages computed over the year 2019 forSentinel-3A and Sentinel-3B.52
Table 10: Backscatter coefficient bias between Sentinel-3A and Sentinel-3B with respect to Jason-3 58
Table 11: Position of the solar exits and entries along the year.         68
Table 12: Detail of the standard used to compute Sentinel-3 and Jason-3 SLA and SSH. For Sentinel-3A, over the year 2018, some of these standards have been updated, thus they are detailed as a function of the IPF-SM2 versions77
Table 13: % Availability of Snow Density, Snow Depth, Sea Ice Concentration over Sea Ice162
Table 14: Results of the water level comparison with in-situ data over the long term monitored reservoirs(June 2016 – December 2019)192
Table 15: Results of the S3B water level comparison with in-situ data (December 2018 – December 2019)        193
Table 16: Results of the S3A and S3B water level comparison with in-situ data (December 2018 – December 2019)194
Table 17: Results of Crete TRP passes processing200
Table 18: Results of Svalbard TRP passes processing201
Table 19: Geophysical Corrections of Crete TRP passes processing203
Table 20: Geophysical Corrections of Svalbard TRP passes processing204
Table 21 : Sentinel-3A and Sentinel-3B products and parameters used to compute the absolute biasestimates208
Table 22 : Statistics on the Sentinel-3A SAR and PLRM SSH absolute bias estimates in Corsica on track 741(PB 2.33 – no tide nor DAC corrections applied)209
Table 23 : Statistics on the Sentinel-3A SAR and PLRM SSH absolute regional bias estimates in Senetosa.        216
Table 24 : Statistics on the Sentinel-3A SAR and PLRM SSH absolute regional bias estimates in Ajaccio (PB         2.33 reprocessed dataset).



S3MPC STM Annual Performance Report - Year 2019 Ref.: S3MPC.CLS.APR.006 Issue: 1.0 Date: 28/02/2020 Page: xxii



## **1** Introduction

This document is the Year 3 (year 2019) Annual Performance Report version of the MPC Altimetry report prepared by the ACRI-ST consortium for the realisation of the "Preparation and Operations of the Mission Performance Centre (MPC) for the Copernicus Sentinel-3 Mission", ESA contract 4000111836/14/I-LG.

#### 1.1 Scope of the document

This document provides a summary of the end-to-end mission performance between the 1<sup>st</sup> of January 2019 until the 31<sup>st</sup> of December 2019 carried out by the S3 Mission Performance Centre during the third year of the routine operations phase.

It addresses more specifically activities related to the Surface Topography Mission (an equivalent report – S3MPC.ACR.APR.005 – is issued to address OPT and general activities).

#### **1.2 Applicable documents**

The full Applicable Documents (AD) ID correspondence is provided in the Configuration Item Data List (S3MPC.ACR.LST.002).

#### 1.3 **Reference documents**

The full Reference Documents (RD) ID correspondence is provided in Configuration Item Data List (S3MPC.ACR.LST.002).

#### 1.4 Acronyms and abbreviations

The definition of the acronyms and abbreviations used in this document is provided in the List of Acronyms and Definitions (S3MPC.ACR.LST.003).



## 2 Executive Summary

#### 2.1 Sentinel-3 Surface Topography Mission

The series of Sentinel satellites mark a major step forward in the collection of Earth Observation data with the commitment to a series of spacecraft and sensors to construct long time series of data suitable for both climate applications and widespread operational use. Each Sentinel mission is based on a constellation of two satellites to fulfil revisit and coverage requirements, providing robust datasets for Copernicus Services.

Sentinel-3A and Sentinel-3B are multi-instrument missions to measure sea-surface topography, sea- and land-surface temperature, ocean colour and land colour with high-end accuracy and reliability. The missions will support ocean forecasting systems, as well as environmental and climate monitoring.

Sentinel-3A was launched on 16 February 2016 and the SRAL and MWR sensors were switched-on 1 March and 29 February 2016 respectively. After 5 months of commissioning, the Routine operations started in July 2016.

After 6 first weeks of acquisition in LRM mode, Sentinel-3A was switched to SAR mode on 12 April 2016 and since then it has operated in SAR mode continuously and over all surfaces, being the first altimetry mission to use this mode at global scale.

When SRAL altimeter operates in SAR mode, an LRM-like processing can be performed to derive waveforms that are close to the standard altimetry (Low Resolution Mode) waveforms but with a higher speckle compared to LRM echoes. This is the so-called Pseudo Low Resolution Mode (P-LRM) and this mode is used as a reference to assess the quality of the SARM measurements.

Sentinel-3B was launched on the 25 April 2018 and SRAL sensor was switched-on on 8 May 2018. On 6 of June 2018 Sentinel-3B reached the Sentinel-3A orbit, 30 seconds ahead this latter one to start the first Sentinel-3 tandem phase. During these 4 months different configurations have been defined to assess the Sentinel-3B instrument performances but also to improve our understanding of the SARM technic and processing. Thus, the Sentinel-3B acquisition was several times switched between CL and OL mode, SRAL also acquired measurements in LRM. The 16<sup>th</sup> of October 2018 Sentinel-3B reach its final orbit, 140° apart from the Sentinel-3A ground track.

#### 2.2 SRAL and MWR sensors

**For both satellites, all the SRAL instrumental parameters are indicating a good instrument performance.** The drift magnitudes are generally bigger than the ones in other ESA altimetry missions such as ENVISAT and CryoSat-2. Anyhow, all the parameters are meeting the mission requirements. Recent studies have demonstrated that the approximations used for accounting for the instrument PTR in the retracking algorithms are not optimal since they do not account for evolution of the total PTR shape. Such errors have an impact on the long term if the instrument behavior is not perfectly stable in time. Several solutions (empirical correction thanks to the PTR center of gravity estimation, numerical retracker,...) are under investigations to account for these effects.



All the MWR instrumental parameters are indicating a good instrument performance. The estimated calibration parameters are slightly drifting but other indicators, such as the vicarious calibrations show a good stability of the brightness temperatures. All the parameters are meeting the mission requirements. Several events of Radio Frequency Interferences (RFI) have been detected over the KREMMS radar facility in the Pacific Ocean. A safe hold mode area has been defined around the island to avoid these contaminations.

A new solution, dedicated to Sentinel-3 MWRs, has been designed to avoid the side lobes contamination on the brightness temperatures measurement. This new, updated ADF improves significantly the measurements quality close to the coasts.

#### 2.3 Sea Level

Since almost 4 years in orbit, Sentinel-3A has been providing high quality sea surface height observations over ocean. After a successful tandem phase dedicated to the instrument validation and calibration, Sentinel-3B, on its definitive ground track since the 16<sup>th</sup> of October 2018 improves the spatial and temporal sampling.

This report summarizes a variety of results, including comparisons with Jason-3 and SARAL/AltiKa data to highlight and quantify the mission performance over ocean. The main points of this performance assessment are summarized below:

- Sentinel-3A and Sentinel-3B provides an excellent coverage of the ocean, with more than 99.9% of measurements available over ocean. Thanks to the new MWR calibration scheme upload on Sentinel-3A on 1 March 2018, the data lost due to MWR calibration are no more observed.
- Data quality and stability is excellent, when specific events (MWR wet tropospheric correction, dynamical atmospheric correction set to Default Value) are removed, the percentage of edited measurements over ocean is below 4% for both satellites. It equals 2.99 % for Sentinel-3A over the year 2019 and 3.3% for Sentinel-3B. The slight difference could be explained by the slight dual frequency ionosphere correction differences between the two datasets. These metrics are consistent with those observed for Jason-3 (3.4%) and SARAL/AltiKa missions (2.6%). Note that this low percentage for Sentinel-3A is excellent considering the larger coverage of the mission at high latitudes compared to Jason-3 mission when sea ice is not present.
- Sea level statistics show a significant long-term drift in SARM whereas no significant drift is detected for P-LRM dataset. Recent investigations demonstrated that the evolution of the Sentinel-3A PTR shape induces a drift ranged between 0.2 and 0.3 mm/yr for both SARM and P-LRM dataset. However, compared to the P-LRM measurement, an additional 1 mm/yr drift is observed in SARM. Several studies are ongoing to understand the origin of this anomaly.
- Absolute bias of sea level in SARM for Sentinel-3A and Sentinel-3B are estimated to be below 2 cm, based on absolute calibration sites and range transponder calibration. Global cross calibration with Jason-3 altimeter also confirm this low value of absolute bias. Results slightly differ depending on the method used (transponder analysis, crossovers, regional absolute calibration...). Differences are under investigation.



- The Sea Surface Height structures observed by Sentinel-3A and -3B are consistent with other altimeters observations. A slight sensitivity to the wind speed direction has been detected on the SARM range parameter. The error induced is very low (sub centimetric).
- At crossovers Sentinel-3A and Sentinel-3B show a performance similar to Jason-3 mission with a system error of 3.5 cm.
- The orbit quality has been significantly improved with the standard-F update in November 2018. This update reduces the mean bias which was observed between ascending and descending passes, as well as the amplitude of the mono-mission crossovers annual signal.
- The time tag bias observed is similar for Sentinel-3A and Sentinel-3B. It is low with a mean value below 150 microseconds which is meeting the requirements.
- MWR Wet tropospheric correction shows a good performance with a standard deviation of 1.4cm for the difference with the model correction (Δwtc), and a variance reduction of -1.5cm<sup>2</sup> for the diagnosis at crossover points with respect to the model correction. Thanks to the update of the side lobe correction ADF, a significant improvement in the coastal areas will be brought with the PB2.61 (S3A) and 1.33 (S3B) deployments, in January 2020.

#### 2.4 Winds and Waves

Since almost four years for Sentinel-3A and two year for Sentinel-3B the SRAL altimeters have been providing excellent wind speed and SWH observations over ocean. The analyses performed during the tandem phase showed that they behave similarly. This report summarizes a variety of results, including comparisons with Jason-3, model and in-situ data to highlight and quantify the mission performance for Wind and Waves. The following conclusions are observed:

- The global mean of Sentinel-3B SAR wind speed is very close to that of the ECMWF model. Sentinel-3A mean is slightly higher than both by about 0.15 m/s. The SD of Sentinel-3A is systematically higher than Sentinel-3B. The model wind speed SD is closer to Sentinel-3A. The differences, however, are not large. While the SARM altimeter mean wind speed, the SDD and SI distributions wrt the model all look similar to their counterparts from other altimeters, the bias between altimeter and model wind speed is rather low almost everywhere. A slightly higher bias is observed for the highest wind speed. This is supposed to be improved in PB 2.61 (S3A) and 1.33 (S3B) deployed in January 2020.
- A small annual signal is observed for the North hemisphere when comparing Sentinel-3 and the ECMWF model.
- A very slight trend is observed on the monitoring of the difference between Sentinel-3A and ECMWF wind speeds, the altimeter wind speed decreasing. This should be further investigated with more homogeneous datasets (avoid the potential impact of IPF and model evolutions)
- Sentinel-3A bias against in-situ observations for this period is rather small (less than 0.1 m/s). Sentinel-3B underestimate wind speed by about 0.2 m/s compared to in-situ observations. The SDD is less than 1.4 m/s which is about 16% of the mean. The correlation coefficients are higher than 0.92. These figures are consistent with the ones obtained with other altimeters.



For Sentinel-3B the results are similar as for Sentinel-3A since the 6<sup>th</sup> of December 2018. Before, the sigma0 is over estimated by 0.5 dB which induced a bias of more than 1m/s on the wind speed calculation. Note that both modes were impacted.

Keeping in mind that Jason-3, CryoSat-2, SARAL/AltiKa and Jason-2 are all conventional altimeters, it is possible to conclude that Sentinel-3A and now Sentinel-3B SARM wind speed are as good as (if not slightly better than) their counterpart from the conventional altimeters.

Since the delivery of PB 2.24 end of 2017, the SWH bias with respect to the model and the in-situ measurements is almost zero. However, some fine tuning of the SAR SWH product is still needed to make it one of the best altimeter SWH products. An excellent agreement is observed between Sentinel-3A and Sentinel-3B in both SARM and P-LRM modes.

The following main conclusions are derived from SWH analyses:

- In general, compared to ECMWF model, SAR SWH from Sentinel-3A and Sentinel-3B is unbiased (global bias is less than 2 cm). The SDD between the altimeter and the model is about 0.27 m (or about 10.2% of the mean value). The correlation coefficient is 0.984 which is quite high. These figures indicate that apart from the underestimation at low wave heights, the quality of Sentinel-3A and Sentinel-3B SAR SWH products is rather high.
- Sentinel-3A and Sentinel-3B SARM SWH are unbiased with respect to in-situ observations. The SDD (a proxy to the random error) is 0.30 m which is ~14% of the mean. The correlation coefficient is 0.98. These numbers indicate that Sentinel-3A and Sentinel-3B SARM SWH products are now very close their counterparts from other altimeters.
- The bias in Sentinel-3A SAR SWH was one of the highest among the 5 operational altimeters between December 2016 (PB 2.09) and December 2017 (PB 2.24). PB 2.24 reduced SRAL SWH bias to almost zero. However, the SDD between Sentinel-3A SAR and the model is the highest among all altimeters irrespective of the various processing changes. Same observation is done for Sentinel-3B. The recent deployment of PB2.61 (S3A) and 1.33 (S3B) in January 2020 is supposed to improve the SARM SWH estimations in low sea state area, this metric is thus expected to be improved in a near future.

#### 2.5 Land and Sea Ice

Sentinel-3A and -3B SRAL altimeters operates in SAR mode over areas of land ice and sea ice and shares a common heritage with Cryosat, the first altimetry mission to operate predominantly in this mode over sea ice. Sentinel-3A was however the first mission to operate in SAR mode over all land ice surfaces and hence the full commissioning of Sentinel-3 missions over land ice required new methods, algorithm tuning, and validation. In comparison, Cryosat operates in LRM mode over the ice sheets, and in SARin interferometric mode over the ice sheet margins.

Sentinel-3 STM currently shares a single ground segment between all surface types (ocean, sea ice, land ice, ice shelves, inland waters, coastal zones) which all have very different properties and processing requirements at each ground processor level. The initial optimization of the Sentinel-3 L1 ground processing was for ocean surfaces (whereas Cryosat was for ice surfaces) and hence the commissioning and tuning of the Sentinel-3 L2 processors for land and sea ice has been a more complex task than a



simple retuning of the Cryosat derived sea ice and land ice L2 algorithms. In particular, for optimal performance over important areas of more complex ice terrain (such as the ice sheet margins and certain types of sea-ice), Sentinel-3 requires a different L1 processing to ocean to provide the specialized L2 processors with the correctly windowed and filtered radar echoes to process over these complex surfaces.

During 2019, progress has been made with the development, tuning and validation of a specialized L1 IPF processing prototype, optimised for land ice, and the development of a full operational land ice thematic processing is expected to be completed by the end of 2020. Initial results from the prototype indicate that it is possible to increase sampling of the ice sheet margins by up to 16%.

Whilst separate specialized L1 processing is required for optimal performance over the more complex ice surfaces, work has continued during 2019 to improve the performance and validation of the current L2 operational products over land ice surfaces, which are able to produce good results as shown in *McMillan et al, 2019*, over the majority of the ice sheets (which have low slope), when tuned to operate with the current ocean optimized L1 input data. A new higher resolution slope model of Antarctica and Greenland was delivered (derived from an updated DEM from CryoSat-2 (Helm, 2014)), a test data set and study performed to validate expected improvements to slope correction. The new slope model will be used operationally in PB 2.61 (from Jan 2020). A new validation study, comparing ICESat-2 ATL-06 elevation data with S3A and S3B at crossover locations over Lake Vostok was performed and showed only a very small mean bias (~ 1cm +/- 6cm) between the two, indicating that S3 SAR is measuring very close to the ice sheet surface, with minimal penetration of the radar echo, and very good accuracy over low slopes.

The requirement for, and the specification of a specialized L1 sea ice processor (which includes the essential L1 steps of Hamming weighting and zero padding) was further developed during 2019 and we expect progress to be made with implementation and testing of this specification during 2020, leading to an operational thematic sea ice product. Without zero padding, specular echoes over sea ice leads can be under sampled, resulting in lower freeboard accuracy and precision. The lack of Hamming weighting can result in contamination of floe echoes by off-nadir leads, which again can affect the accuracy of floe SSHA. A study, published in 2019 (*Lawrence* et al, 2019) showed that S3 can produce the equivalent quality of sea ice freeboard measurements as CryoSat-2 over the whole Arctic region if correctly optimized at L1 and L2.

Due to sea ice conditions in Antarctica, where thin sea ice and snow loading are an issue, producing accurate freeboard measurements from either Sentinel-3A, -3B or Cryosat is still an area of active research. It is currently not possible to measure freeboard from SAR altimetry during the polar summer months (June-Sept in the Arctic) as summer melt creates pooling in the sea ice which makes discrimination between sea ice leads and floe echoes impossible.

#### 2.6 Inland waters

Based on the previous version of IPF, the data quality over inland waters was analysed over the Issykkul Lake which is a calibration site for altimetry. It showed that Sentinel-3A topography observations are very good, with no bias and an improved precision compared to Jason-3 mission (see yearly report #1, **RD19**).



In addition, this report summarizes the recent results obtained over a large number of lakes and rivers at global scales:

- The update of the OLTC performed on 25<sup>th</sup> of November 2018 for Sentinel-3B and 9<sup>th</sup> of March for Sentinel-3A increase significantly the number of small water targets observed. The Sentinel-3A acquisition mask have been updated and is now consistent with the one used for Sentinel-3B : OL mode is used everywhere between -60° and 60°N and over land surfaces at higher latitudes.
- The targets missed by the altimeters over OL mode areas can be added thanks to the following webpage: <u>https://www.altimetry-hydro.eu/</u>
- The transect dispersion measured over lakes could be impacted by geoid high frequency variations. However, the metric compute over rivers shows very good results with, in average, only 10 cm of dispersion against 15 cm for Jason-3.
- The long term monitoring performed over several lakes shows stable performances and no significant trend or drift with respect to Jason-3 results.



## **3** SRAL and MWR Mission events

The Table below gathers the changes related to sensors mode. Note that in addition, both Sentinel-3A and Sentinel-3B are set to safe hold mode (SHM) over the KREMMS radar facility in the Pacific Ocean. More detail about the SHM area is given in 5.2.3

Start time	Stop Time	Event
6 Dec 2016	onward	Switch from Open Loop mode to Closed Loop mode over Antarctica and Greenland margins
19 Dec 2017	onward	Switch from Open Loop mode to Closed Loop mode over Greenwich meridian
1 March 2018	onward	Change of MWR calibration timeline
1 March 2019	9 March 2019	Switch from SARM Open Loop to SARM Close Loop
9 March 2019	onward	OLTC updated to version V5.0
9 March 2019	onward	Switch from SARM Close Loop to SARM Open Loop

Table 1 History of SRAL and MWR mode changes for Sentinel-3A

Start time	Stop Time	Event
6 June 2018	16 Oct 2018	S3A / S3B Tandem Phase (on S3A ground track)
7 June 2018	14 June 2018	Switch from LRM to SARM (Close Loop mode)
14 June 2018	11 July 2018	Switch from SARM to LRM (Close Loop mode)
11 July 2018	8 August 2018	Switch from LRM (Close Loop) to SARM Open Loop
8 August 2018	5 Sept 2018	Switch from SARM Open Loop to SARM Close Loop
5 Sept 2018	2 Oct 2018	Switch from SARM Close Loop to SARM Open Loop
2 Oct 2018	27 Nov 2018	Switch from SARM Open Loop to SARM Close Loop
16 Oct 2018	23 Nov 2019	Sentinel-3B Drifting Phase
23 Nov 2018	onward	Sentinel-3B reach its ground track
27 Nov 2018	onward	OLTC updated version V5.0

Table 2 History of SRAL and MWR mode changes for Sentinel-3B



#### Sentinel-3 MPC S3MPC STM Annual Performance Report - Year 2019

 Ref.:
 S3MPC.CLS.APR.006

 Issue:
 1.0

 Date:
 28/02/2020

 Page:
 9

The Table below gathers the major events that occurred on a	the Sentinel-3A STM payload.
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Event type	start time	stop time	description
Platform	2019-02-27 12:00:00	2019-02-27 12:00:00	in-plane-manoeuvre
Platform	2018-12-19 09:21:00	2018-12-19 09:55:00	out-of-plane-manoeuvre
Platform	2018-11-28 13:38:00	2018-11-28 13:52:00	in-plane-manoeuvre
Platform	2018-08-29 07:38:00	2018-08-29 08:13:00	out-of-plane-manoeuvre
Platform	2018-08-01 08:08:00	2018-08-01 08:22:00	in-plane-manoeuvre
Platform	2018-05-24 08:05:00	2018-05-24 08:19:00	in-plane-manoeuvre
Platform	2018-03-14 08:35:00	2018-03-14 09:10:00	out-of-plane-manoeuvre
MWR	2018-03-01 08:12:00	2018-03-01 10:09:00	instrument-special- operation
Platform	2018-02-28 09:58:00	2018-02-28 10:12:00	in-plane-manoeuvre
Platform	2017-12-13 07:58:00	2017-12-13 08:31:00	out-of-plane-manoeuvre
Platform	2017-11-29 09:13:00	2017-11-29 09:27:00	in-plane-manoeuvre
Platform	2017-09-27 08:01:00	2017-09-27 08:15:00	in-plane-manoeuvre
Platform	2017-09-06 10:15:00	2017-09-06 10:50:00	out-of-plane-manoeuvre
Platform	2017-07-12 09:38:00	2017-07-12 09:50:00	in-plane-manoeuvre
SRAL	2017-06-26 13:20:00	2017-06-26 13:20:00	SRAL OLTC update
Platform	2017-05-23 14:28:00	2017-05-23 14:42:00	in-plane-manoeuvre
Platform	2017-04-27 10:51:00	2017-04-27 11:05:00	in-plane-manoeuvre
Platform	2017-03-15 07:32:00	2017-03-15 08:07:00	out-of-plane-manoeuvre
Platform	2017-02-23 09:33:00	2017-02-23 09:46:00	in-plane-manoeuvre
Platform	2016-12-14 08:36:00	2016-12-14 09:10:00	out-of-plane-manoeuvre
Platform	2016-12-01 07:53:00	2016-12-01 08:06:00	in-plane-manoeuvre
Platform	2016-11-01 11:58:00	2016-11-01 12:11:00	in-plane-manoeuvre
Platform	2016-08-31 07:25:17	2016-08-31 07:33:56	out-of-plane-manoeuvre
Platform	2016-07-21 12:44:58	2016-07-21 12:45:01	in-plane-manoeuvre
SRAL	2016-06-23 08:23:35	2016-06-23 09:32:44	software patch (ASW v2.5)
Platform	2016-06-02 11:13:39	2016-06-02 11:13:52	in-plane-manoeuvre
SRAL	2016-05-29 15:35:13	2016-05-29 15:38:36	SRAL SpW ASIC Anomaly
SRAL	2016-05-25 12:26:15	2016-05-25 14:30:05	Anomaly GS3_SC-23
SRAL	2016-05-24 12:30:00	_	OLTC v4.1 uploaded.
SRAL	2016-05-23 09:32:25	2016-05-24 12:22:25	SAR CL Mode with DEM EEPROM read enabled



# Sentinel-3 MPC **S3MPC STM Annual Performance**

Report - Year 2019

Ref.: S3MPC.CLS.APR.006 Issue: 1.0 Date: 28/02/2020 Page: 10

Event type	start time	stop time	description
SRAL	2016-05-23 08:00:00	2016-05-23 09:32:00	patch of SRAL ASW v2.4
Platform	2016-05-18 08:59:17	-	MHSTR MI patch for pointing issue
SRAL	2016-05-17 15:24:00	2016-05-17 15:28:00	SRAL SpW TRM anomaly
SRAL	2016-05-15 09:28:00	2016-05-15 09:40:00	SRAL SpW TRM anomaly
SRAL	2016-05-15 03:43:00	2016-05-15 04:12:00	SRAL SpW TRM anomaly
SRAL	2016-05-09 10:42:00	2016-05-09 10:43:00	SRAL SpW TRM anomaly
SRAL	2016-05-04 21:44:00	2016-05-04 21:54:00	SRAL SpW TRM anomaly
SRAL	2016-04-29 20:30:00	2016-04-29 21:10:00	SRAL SpW TRM anomaly
SRAL	2016-04-27 12:56:27	2016-04-27 12:57:02	SRAL SpW TRM anomaly
SRAL	2016-04-27 10:57:52	2016-04-27 10:59:20	SRAL SpW TRM anomaly
SRAL	2016-04-20 10:32:30	2016-04-20 10:42:23	SRAL SpW ASIC anomal
SRAL	2016-04-19 18:53:14	2016-04-19 18:56:02	SRAL SpW ASIC anomaly
Platform	2016-04-19 12:03:00	2016-04-19 12:09:44	out-of-plane-manoeuvre
SRAL	2016-04-18 03:43:43	2016-04-18 06:07:14	Altimeter anomaly: bursts #1&4 are missing
SRAL	2016-04-16 19:04:00	2016-04-16 20:34:19	Altimeter anomaly: bursts #1&4 are missing
SRAL	2016-04-15 11:03:03	_	SRAL operating in CL/OL according to the ZDB
Platform	2016-04-13 09:10:56	2016-04-13 10:52:00	in-plane-manoeuvre
SRAL	2016-04-12 09:30:06	2016-04-15 11:03:00	SRAL operating in SAR CL
SRAL	2016-04-11 08:30:00	2016-04-11 09:07:00	Cross cal maneuver
SRAL	2016-04-08 00:00:00	2016-04-08 23:59:00	Activate SRAL SAR_OL Mode for 24 hours
SRAL	2016-04-07 00:00:00	2016-04-07 23:59:00	Activate SRAL SAR_CL and SAR_OL Mode changes
SRAL	2016-04-06 00:00:00	2016-04-06 23:59:00	SRAL SAR_CL Mode for 24 hours.
SRAL	2016-03-30 08:51:14	2016-03-30 08:51:50	SRAL Standby Mode followed by SAR Open Loop
SRAL	2016-03-29 23:56:01	2016-03-29 23:56:37	SRAL Standby Mode followed by SAR Open Loop
SRAL	2016-03-29 17:15:02	2016-03-29 17:15:38	SRAL Standby Mode followed by SAR Open Loop



### Sentinel-3 MPC S3MPC STM Annual Performance Report - Year 2019

 Ref.:
 S3MPC.CLS.APR.006

 Issue:
 1.0

 Date:
 28/02/2020

 Page:
 11

Event type	start time	stop time	description
SRAL	2016-03-29 12:42:26	2016-03-29 12:43:02	SRAL Standby Mode followed by SAR Open Loop
SRAL	2016-03-24 08:06:21	2016-03-24 08:06:57	SRAL Standby Mode followed by SAR Open Loop
SRAL	2016-03-24 00:52:00	2016-03-24 00:52:36	SRAL Standby Mode followed by SAR Open Loop
SRAL	2016-03-23 16:30:09	2016-03-23 16:30:45	SRAL Standby Mode followed by SAR Open Loop
SRAL	2016-03-23 13:38:40	2016-03-23 13:39:16	SRAL Standby Mode followed by SAR Open Loop
Platform	2016-03-23 13:26:28	-	in-plane-manoeuvre
Platform	2016-03-21 11:17:47	2016-03-21 11:22:47	out-of-plane-manoeuvre
SRAL	2016-03-18 11:36:00	2016-03-18 12:03:00	SRAL Cross-Calibration Manoeuvre
Platform	2016-03-13 10:51:55	2016-03-13 10:55:00	in-plane-manoeuvre
SRAL	2016-03-08 10:42:00	2016-03-08 15:36:50	SRAL calibration sequence
Platform	2016-03-07 12:21:24	-	out-of-plane-manoeuvre
Platform	2016-03-02 15:32:56	-	in-plane-manoeuvre
Platform	2016-03-02 12:59:00	-	in-plane-manoeuvre
SRAL	2016-03-01 07:38:00	_	SRAL switch on

#### Table 3: Main Sentinel-3A SRAL and Platform events since the SRAL switch on.

The Table below gathers the major events that occurred on the Sentinel-3B STM payload.

Event type	start time	stop time	description
SRAL	2019-02-15 15:53:00	2019-02-15 15:56:00	instrument-special- operation
SRAL	2019-02-15 14:14:00	2019-02-15 14:20:00	instrument-special- operation
Platform	2019-02-13 09:27:00	2019-02-13 10:00:00	out-of-plane-manoeuvre
SRAL	2019-01-28 17:01:00	2019-01-29 13:21:00	Instrument anomaly
Platform	2018-12-20 08:06:00	2018-12-20 08:43:00	instrument-special- operation



### Sentinel-3 MPC S3MPC STM Annual Performance Report - Year 2019

 Ref.:
 S3MPC.CLS.APR.006

 Issue:
 1.0

 Date:
 28/02/2020

 Page:
 12

Event type	start time	stop time	description
Platform	2018-12-11 08:35:00	2018-12-11 22:23:00	instrument-special- operation (OLCI)
Platform	2018-12-12 13:25:00	2018-12-12 13:57:00	out-of-plane-manoeuvre
SRAL	22-11-2018 09:37:00	22-11-2018 14:08:00	instrument-special- operation
SRAL	07-11-2018 16:00:00	07-11-2018 16:00:00	OLTC update to V2.0
SRAL	06-10-2018 19:04:01	16-10-2018 07:13:06	Expertise calibration
SRAL	04-09-2018 02:24:00	04-09-2018 07:34:00	Expertise calibration
SRAL	25-07-2018 19:59:00	25-07-2018 20:00:00	Expertise calibration
Platform	18-06-2018 08:41:00	18-06-2018 09:10:00	Expertise calibration
SRAL	25-05-2018 17:43:34	25-05-2018 17:48:01	Expertise calibration
SRAL	25-05-2018 06:37:45	25-05-2018 06:42:12	Expertise calibration
Platform	11-05-2018 07:37:21	11-05-2018 08:04:21	Expertise calibration
SRAL	10-05-2018 07:00:00	10-05-2018 12:03:54	Expertise calibration
SRAL	08-05-2018 06:02:05	08-05-2018 06:02:05	Switch on

table 4: Main Sentinel-3B SRAL and Platform events since the SRAL switch on.



## **4** Processing Baseline Status and dataset description

#### 4.1 Land and Marine Products

- Land products that cover all land areas and part of the ocean up to 300 km off the shore (white and brown on the map). This result in gathering all coastal areas, including basins such as the Mediterranean Sea, land ice regions, inland waters and part of the sea ice regions.
- Marine products that cover all ocean and land areas up to 10 km from the shore (blue and brown on the map).

Note that the brown regions on the map stand for regions that are available in both products. Since Processing Baseline 2.24 (December 2017), the Caspian Sea, North American Great Lakes and Victoria Lake are available in both Marine and Land products.



Marine/Land mask

Figure 1 Geographical mask for L2 Land and Marine products coverage: blue is Marine products only, white is Land products only, brown is for regions available in both products



#### 4.2 **Processing Baseline History**

The history of the processing baseline deployed in the Sentinel-3 processing centres is summarized below. All the deployment dates impact NRT and STC products while **the NTC production started on 13 December 2016 with Processing Baseline 2.9**.

Installation Date	IPF Version Level-2	S3A Processing Baseline	S3B Processing Baseline
2016-07-21	SM2 06.02	2.0	-
2016-08-03	SM2 06.03	2.1	-
2016-10-26	SM2 06.05	2.5	-
2016-11-08	SM2 06.05	2.8	-
2016-12-13	SM2 06.05	2.9	-
2017-02-28	SM2 06.06	2.10	-
2017-04-12	SM2 06.07	2.12	-
2017-12-13	SM2 06.10	2.24	-
2018-02-14	SM2 06.12	2.27	-
2018-04-04	SM2 06.14	2.33	1.00
2018-05-17	SM2 06.14	-	1.02
2018-12-06	SM2 06.14	-	1.13
2019-02-14	SM2 06.15	2.45	1.17
2020-01-21	SM2 06.18 (current)	2.61	1.33

The NTC products have been reprocessed three times:

Reprocessing 1 with Processing Baseline 2.12 in 2017

The products span from 16 June 2016 till 15 April 2017. Both Marine and Land L2 products were reprocessed.

Reprocessing 2 with Processing Baseline 2.27 in 2018

The products start since the beginning of the mission and span from 1 March 2016 till 20 January 2018. Both Marine and Land L2 products were reprocessed.

Reprocessing 3 with Processing Baseline 2.61 for Sentinel-3A and 1.33 for Sentinel-3B in 2020

This third reprocessing dataset is not used in this report to describe the Sentinel-3 performances over year 2019.


#### 4.2.1 Summary of the most recent Processing Baselines content

Since the previous annual report, wrote for the year 2018, two new Processing Baselines (PB) have been deployed:

On the 14th of February 2019, the PB 2.45 for S3A and 1.17 for S3B were deployed. The related evolutions brought major improvements, mainly over land ice, sea ice and inland waters surfaces. The most important ones are:

- Freeboard and sea ice sea surface anomaly data quality improved.
- Distance to the coast calculation improved.
- Improvement of the data availability for the sea ice retracker, P-LRM ice2 retracker and C-band ocog retracker
- SAMOSA SARM retracker improved LUT parameters to improve SWH retrieval.

On the 21<sup>st</sup> of January 2020, the PB 2.61 for S3A and 1.33 for S3B were deployed. The main evolutions implemented are the following:

- Improved slope correction over Land ice surfaces (use of Cryosat-2 DEM, Helm 2014)
- Filtering of the dual-frequency ionosphere correction (new fields added in the L2 products)
- SARM Ocean retracker improvement to better estimate the small SWH.
- Extension of the wind speed model table to improve the estimation over the windiest areas
- Update of the Mean Sea Surface solution 2 model (from DTU15 to DTU18)
- Addition of the MWR side lobe correction to improve the WTC path delay in coastal areas.
- A correction performed in the Level-1 processing (consideration of the azimuth compression gain in the sigma0 scaling factor computation) impacts the Level-2 sigma0 parameters derived from land and sea ice retrackers. The ocean retrackers are not impacted (tuning of the global sigma0 system bias in order to constrain the average value around 11dB).
- After the update of the antenna aperture angle for both satellites, the mispointing angle values derived from the waveform are centered around zero degrees<sup>2</sup>.

#### 4.2.2 Model and standard history

Table below summarizes the different models and standards used in the STM Processing baseline. Note that the models and standard are aligned between L2 Land and Marine products.



#### Sentinel-3 MPC

**S3MPC STM Annual Performance** 

Report - Year 2019

 Ref.:
 S3MPC.CLS.APR.006

 Issue:
 1.0

 Date:
 28/02/2020

Page: 16

	Processor Version				
Correction model and standard	IPF-SM2 06.05	IPF-SM2 06.07	IPF-SM2 06.10	IPF-SM2 06.12 to 06.15	IPF-SM2 06.18
Orbit solution	ESA/POD solution for NRT (GPS solution)				
	CNES/SALP solution with POE-E standards for STC (Doris solution until 29 of May 2018 and then Doris+GPS solution) CNES/SALP solution with POE-E standards for NTC (Doris + GPS solution) 9 <sup>th</sup> of November CNES/SALP solution with MOE-F and POE-F standard (Doris + GPS solution)				
SARM Ocean retracker	SAMOSA 2.3	retracker	SAMOSA 2.5 r	etracker	
Dry troposphere correction	ECMWF mod	el			
Dynamical atmospheric correction	SALP/CNES Mog2D high resolution ocean model				
Radiometer wet troposphere correction	3 parameters	s correction	3 parameters	and 5 parameters c	orrections
Model wet troposphere correction	ECMWF model				
lonospheric correction	SALP/CNES maps based on Global Ionosphere TEC Maps from JPL				
Wind Speed model	Abdalla model				
Sea State Bias	Jason-2 Sea State Bias from Tran model (2012)				
Ocean tide correction Solution 1 (including loading tide)	GOT 4.10				
Ocean tide correction Solution 2 (including loading tide)	FES 2004 FES 2014				
Solid Earth tide correction	Cartwright and Taylor				
Pole tide correction	Wahr				
Mean Sea Surface Solution 1	CNES_CLS_2( (Referenced mean)	011 to 7 years	CNES-CLS 2015 (Referenced to 20 years mean)		
Mean Sea Surface Solution 2	DTU13 (Refe years mean)	renced to 7	DTU15 (Refer mean)	enced to 20 years	DTU18 (referenced 20 years)
SSHA for Ocean	CNES_CLS_2	011	DTU15 DTU18		DTU18
SSHA for Sea Ice	CNES_CLS_2011 DTU15 DTU18		DTU18		
Mean Dynamic Topography	CNES-CLS13 MDT				
Geoid	EGM 2008				
Bathymetry	ACE2 model with 30 second resolution				



	Processor Version				
Correction model and standard	IPF-SM2 06.05	IPF-SM2 06.07	IPF-SM2 06.10	IPF-SM2 06.12 to 06.15	IPF-SM2 06.18
Surface Slope Model for Land Ice	Derived from RAMP v2 DEM over Antarctica and Bamber 2001 DEM over Greenland				AWI Cryosat-2 DEM (Helm,2014)
Rain Flag	Envisat model (Tran et al 2008)				
Ice flag	Envisat model (Tran et al 2009)				
ice-sheet snow facies type flag	Envisat model (Tran et al 2008)				

Table 5 Model and standard history in L2 products

### 4.3 **Status of the current Processing Baseline**

The operational processing baseline is 2.61 for Sentinel-3A and 1.33 for Sentinel-3B, deployed on 21 January 2020, in Land and Marine Centres.

### 4.4 List of anomalies in the Processing Baseline

Since June 2016, the details of the anomalies that have been closed through the different Processing Baseline versions are detailed in the different Product Notice documents issued for the SRAL L1 products, L2 Land products. These documents are published for each Processing Baseline and can be found on:

https://sentinel.esa.int/documents/247904/2753172/Sentinel-3-Product-Notice-STM-Level-1 for Marine and Land Level-1 products

https://sentinel.esa.int/documents/247904/2753172/Sentinel-3-Product-Notice-STM-Level-2-Land for Land Level-2 products

https://www.eumetsat.int/website/home/Satellites/CurrentSatellites/Sentinel3/AltimetryServices/inde x.html for Marine Level-2 products



# 4.5 Dataset description

For Sentinel-3A the following figure (Figure 2) summarizes the different product versions concatenated and used to provide a complete time series. Note that the deployment of PB2.33 has a very small impact on the Level-2 data quality as the main evolution aimed at correcting the dry troposphere path delay at the measurement altitude (this field is commonly used for continental surfaces applications) from a 5 mm bias. The dataset is thus homogeneous from the beginning of the mission until February 2019. The main impacts of PB2.45 deployments are described in section 4.2.1.



# Figure 2: Illustration of the different processing versions used to compute a Sentinel-3A time series based on the most recent PB versions

Same illustration is done for Sentinel-3B. Note that, for Marine products, a short preliminary processing was done in 2019 to cover the period from beginning of S3B life to 6<sup>th</sup> of December. This short reprocessing performed in 2019 allows to account for sigma0 0.5 dB bias corrected in PB1.13.



Figure 3: Illustration of the different processing versions used to compute a Sentinel-3B time series based on the most recent PB versions



# **5** Sensors status

#### 5.1 **SRAL**

The SRAL Internal Calibration parameters are regularly measured on-board and have been gathered in order to monitor the performance of the instrument. Here below we first show a summary, from the beginning of the mission up to the end of 2019, of four main calibration variables that impact directly the quality of the final geophysical retrievals for the S3A and S3B missions.

The internal delay is measured on-board, to be then subtracted from the final range in the L1b processing. Hence, it has an additive impact in the SSH. The Ku band CAL1 SAR mode (main operational band and mode) internal delay behaviour along the two missions is shown Figure 4. S3A series shows a notable stabilization from end of 2017.



Figure 4: S3A (left) and S3B (right) Ku band CAL1 SAR Time Delay series.

The calibration signal power variations are used to compensate the science signal sigma0 in the L1b processing. It has mainly an impact in the winds retrievals. The CAL1 SAR Ku total (blue line) and maximum (red line) power behaviour along the two missions are plotted in Figure 5. The S3A and S3B total power, the one used in the L1b processing, have drifts close to -0.4 dB/year. It is, for S3A, a more stable behaviour than the one at the beginning of the mission that was close to -1 dB/year.





Figure 5: S3A (left) and S3B (right) Ku band CAL1 SAR Integrated and Peak Power series.

The CAL1 PTR width, which impacts the SWH estimations, has a nominal drift of close to -0.3 mm/year. Its absolute value of around 0.4 m is three orders of magnitude above its standard deviation. The S3A and S3B missions series are depicted in Figure 6.



Figure 6: S3A (left) and S3B (right) Ku band CAL1 SAR PTR width series.

Figure 7 shows the ripples of the Ku band SAR CAL2 waveforms (the system transfer function) for the two missions, used to correct the science waveform shape for the spectra distortions. The CAL2 signal presents the expected behaviour, with stable slopes and standard deviations along the missions.



40 50 60 70 80 90 100 110 20 30 40 50 60 70 80 90 100 Range bin Range bin

20 30

Nov19

110

Figure 7: S3A (left) and S3B (right) Ku band CAL2 SAR waveforms ripples.

A last instrument calibration variable taken into account in the L1b processing is the Attenuation correction. The delta between the commanded attenuation and the actual value applied is measured for each attenuation step. The progression of this difference along the missions is depicted in Figure 8. Very low variations are observed along the missions, lower than 0.1 dB.



Figure 8: S3A (left) and S3B (right) Ku band AutoCal Power Attenuation Progression.

There are some other characterisations of the instrument that are not used for compensating for them while processing on-ground. Here below we show two of them, which we find especially interesting.

First, the Azimuth Impulse Response (AIR), which is obtained by computing an FFT of the stack waveforms in the azimuth direction. Hence, any anomaly in its shape or drift will mean a potential impact in the stack formation. In Figure 9 we can observe the drifts along the mission of the AIR maximum position and values for the two missions. As expected, the AIR power follows the same behavior as the CAL1 power. The AIR maximum position has for both missions a negative trend, which is very low: -0.22x10<sup>-3</sup> samples/year for S3A and -0.36x10<sup>-3</sup> samples/year for S3B.



Figure 9: S3A and S3B AIR Maximum Position (left) and Maximum Power (right).

Second, the characterization of the secondary lobes of the CAL1 waveform. It is a feature of the PTR shape, which is expected to present a symmetry. For the two missions we can see a dissymmetry (right and left secondary lobes power levels are not equal) and different drifts of these power levels. The different drifts are depicted in Figure 10 for the first seven left and right secondary lobes, for the two missions. The restarts of the instrument can cause a displacement of the operational point of the altimeter, and the secondary lobes power levels suffers jumps just after those events. The worst case is the S3B fourth secondary lobe, which presents a jump up of 0.4 dB after a SRAL restart SMUG event. The analytical physical retracking processing include as one of the convolved terms a modeled CAL1 waveform. If the actual CAL1 waveform shape is not symmetric and stable, it affects the retracking results along the mission.





Figure 10: S3A (top) and S3B (bottom) secondary lobes power drift for the first seven left secondary lobes (left) and the first seven right secondary lobes (right).

Summarising, all the main parameters of S3A and S3B missions involved in the science data processing are indicating a good instrument performance. The drifts are generally bigger than the ones in other ESA altimetry missions such as EnviSat and CryoSat-2, but in the same order of magnitude. All the parameters are meeting the mission requirements. The CAL1 SAR Ku total power was the only one having a not expected decay at the beginning of the S3A mission, but it is becoming more stable, (now the drift is less than half the one at BOM). The two missions instrument series shown in the figures does not include the beginning of mission usual excursion for the sake of a better understanding and prediction of the mission parameters behavior of the routine phase. Some not nominal features as for the two parameters exposed above are not corrected for in the altimeter science data processing, but they have a limited impact.

#### 5.2 **MWR**

The MWR on-board Sentinel-3A/B are noise injection radiometers operating at two frequencies (23.8GHz and 36.5GHz) with a bandwith of 200MHz for both channels. MWR operates as a balanced Dicke radiometer for brightness temperatures lower than the reference load. The balance is achieved by the injection of noise with a noise diode (NIR). For brightness temperatures higher than the reference, the MWR operates in a conventional Dicke mode (**D**icke **N**on-**B**alanced).



Sentinel-3 MPC S3MPC STM Annual Performance Report - Year 2019 
 Ref.:
 S3MPC.CLS.APR.006

 Issue:
 1.0

 Date:
 28/02/2020

 Page:
 24

#### 5.2.1 MWR processing

The transition from one processing to the other will occur depending on the internal temperature of the MWR and the observed temperature. For the 23.8GHz channel, all measurements use the NIR processing. For the 36.5GHz, only a small percentage of measurements over land requires a DNB processing. This behaviour is observed for both S3A and S3B. The measured brightness temperatures depend of the emissivity of the surface, of its temperature, thus a seasonal dependancy in the geolocation of these measurements is observed. Figure 11 shows the location of S3A MWR measurements using DNB processing, and Figure 14 the number per day of such measurements along year 2018. Seasonality of the location is shown by Figure 11 with points closer to the equator in March and April, higher in the North Hemisphere in May, June, July (summer for the North Hemisphere), lower in the South Hemisphere in Australia or South of Africa in December and January (summer in the South Hemisphere). There is much more points using DNB processing from April to July than any other month of the year.







Figure 12: Number of S3A MWR measurements in DNB mode along the year

Figure 13 shows the location of S3B MWR measurements using DNB processing, and Figure 14 the number per day of such measurements along year 2018. The same seasonal variation than S3A is observed over the same areas. The number of points using DNB processing appears to be less for S3B than for S3A during May probably due to the fact that S3B was being moved to the tandem phase orbit which started the 6<sup>th</sup> June. Globally, the same behaviour is observed for the two instruments.









Figure 14: Number of S3B MWR measurements in DNB mode along the year

#### 5.2.2 MWR Calibration parameters

Calibration parameters of each instrument is carefully monitored. Concerning S3A, Figure 15 shows the receiver gain and the noise injection temperature monitoring since march 2016 until end of year 2019, each year being piled on top of the other. The receiver gain for 23.8GHz channel has slightly increased since switch-on. For 2017 and 2018, it seems to follow the same pattern: small increase from January to June, stabilization afterward. For the 36.5GHz receiver gain, it seems to be the opposite: "stabilization" for the earlier months, decreasing from June to December. A significant jump is observed in November 2018 for this channel, also observed on the noise injection temperature. This issue was explained by an interference with KREMS radar facility. The safety area was enlarged following this issue to protect the instrument. A small jump is observed for both channels in February 2019, explained by an update of the ground processor (correction of the gain computation).

The noise injection temperature for 23.8 GHz channel is very slowly decreasing (close to 0.4K since 2016). A small jump (less than 0.1K) is observed in early June with no identified cause so far. For 36.5 GHz



channel, the noise injection temperature is showing a global increase with a seasonal signal. A jump is observed in November 2018 like for the gain of this channel.



Figure 15: Monitoring of S3A MWR calibration parameters: Receiver gain (top line), Noise injection temperature (bottom line) for both channels: 23.8GHz (left) and 36.5GHz (right)

Concerning S3B, Figure 16 shows the receiver gain and the noise injection temperature monitoring since may 2018 until end of year 2019, each year being piled on top of the other. The timeserie shown here is composed of operationnal data only (no reprocessing), meaning that the monitoring will be impacted by changes of characterisation file (for MWR calibration purpose). The signature of this kind of change is a big jump in the calibration parameters such as the one observed in December 2018. The two peaks observed in July 2018 are due to cold sky observations by the MWR. The small jump in February 2019 is due to an IPF correction (same impact that on S3A). In April 2019, the noise diode of the 23.8GHz has shown an increase of its temperature over a period of one day. An internal cause is suspected after analysis of available data.



Figure 16: Monitoring of S3B MWR calibration parameters: Receiver gain (top line), Noise injection temperature (bottom line) for both channels: 23.8GHz (left) and 36.5GHz (right)



#### 5.2.3 MWR RFI monitoring

The Radio Frequence Interference (RFI) that occurred on 24<sup>th</sup> November 2018 around the KREMMS radar facility caused a stress to the MWR and changed its functional point. The calibration parameters were impacted. To avoid other occurrences of these interferences and any additional damage to the instrument, the safing zone has been increased up to 300km on 17<sup>th</sup> January 2019 (Cycle 40). The initial size of the safing area was 50km. After analyses, a new safing area was defined in order to maximize data availability and allow a sufficient protection of the MWR. Safing areas for each period are shown by Figure 17.



Figure 17: Definition of the safing area : left for cycle 1 to 39, middle: from cycle 40 to 45, right : since cycle 46

This event also raised the question of the occurrence of other interference but with a lower intensity. Interferences could degrade the measurement of the MWR by adding a signal to the geophysical signal but be small enough to keep the total signal within geophysical range. This kind of interferences can hard to discriminate. The interference caused by the KREMMS radar facility has a particular signature looking like antenna pattern lobes. They are probably due to the sampling of the tracking radar antenna pattern by the MWR antenna. It was observed that this interference had an impact on the brightness temperature spectra. This observation leads to the development of a specific method for the detection of interferences, based on power spectra of brightness temperatures at MWR sampling rate. Passes are cut in segments of 1000km. The spectrum is computed for each segment and the slope for scales between 15km and 1 km is estimated (Figure 18). With this method, we are able to detect and localize the segments impacted by the interference. Table 6 gives the list of all detected interferences.





Figure 18: Slope (in [1-15km] scales) of brightness temperature spectra for channel 36.5GHz of S3A

Passes	Cycle	Passes	Cycle
2	5, 20, 24	430	38
88	22	458	13
116	15	516	27
202	4,7	544	10, 16, 41
230	44, 51	572	37, 39
316	8,14	658	49
402	30	744	2,



#### 5.2.4 MWR side lobe correction

The sidelobe correction is one of the more important correction for the MWR. It aims to remove the contribution coming from outside the main beam (the so-called side lobe) to the antenna temperature (total measurement from the antenna), to retrieve the brightness temperature (main beam). Since Envisat, the sidelobe correction using seasonal maps for each channel (four maps per channel: spring, summer, fall, winter). The latest version of this correction used for S3A (and S3B) was the correction defined for Envisat. A study funded by ESA/ESTEC has been dedicated to the definition of a correction for Sentinel-3. The antenna patterns of the instruments have been used for the convolution and the method has been reviewed in order to improve the estimation of the sidelobe correction. The antenna pattern apattern apatterns have been dedicated to have interpolation issues. New antenna patterns have been delivered after the end of the study, thus the impact has not been assessed.

The new maps have been computed from Sentinel3A data. A finer resolution is used for the grid. Figure 19 shows the difference for one season (spring) between the previous version and the new one. From this



# Sentinel-3 MPC S3MPC STM Annual Performance Report - Year 2019

 Ref.:
 S3MPC.CLS.APR.006

 Issue:
 1.0

 Date:
 28/02/2020

 Page:
 29

representation, differences are clearly visible in the polar regions due to the huge variability of the sea ice coverage. To observe smaller differences, Figure 20 shows the differences of the brightness temperatures using the two different corrections. One can see that the impact of this new correction is located in the polar regions and the coastal areas.



Figure 19: Sidelobe correction map (Spring) : Top: Version 1; Bottom: Version 2



Figure 20: Impact on the brightness temperature of the new sidelobe correction (cycle 31 – spring)

The assessment was performed also at Level 2 on the wet tropospheric correction and on the SLA. Over ocean, difference of variance of SSH at crossover points is the more relevant diagnostic. On coastal areas, the variance of SLA is used. Figure 21 shows the difference of variance at crossover points (left panel) and the difference of variance of SLA vs the shoreline distance. Over ocean, we can see that there is no impact on the geophysical performances over open ocean, as it was expected. Looking at the coastal areas, however we can see an improvement from 150km from coast with a reduction of the SLA variance. This shows that the new sidelobe correction improved the performances in the coastal areas.

	Sentinel-3 MPC		Ref.:	S3MPC.CLS.APR.006
	S3MPC STM Annual Performance			1.0
CLS	Report - Year 2019		Date:	28/02/2020
COLLECTE LOCALISATION SATELLIFES			Page:	30
			·	
VAR(SSH [WTC newSL]	) - VAR(SSH [WTC OPE])	0.1 VA	R(SLA wtc_etu	) - VAR(SLA wtc_ref)



Figure 21 Geophysical impact of new sidelobe correction : left: Difference of variance at crossover points; Right: Difference of variance of SLA vs distance from shoreline

#### 5.2.5 MWR Brightness Temperatures monitoring

The main difficulty in microwave radiometry is the lack of reference natural target well-known or homogeneous enough that can be used for calibration or monitoring. Thus, the assessment of the MWR brightness temperatures stability is performed using statistical selection over two specific regions of Earth: the coldest temperatures over ocean, the hottest temperature over the Amazon forest. Moreover these methods are applied to several missions for intercomparison: SARAL/AltiKa, Jason3/AMR and Metop02/AMSU-A. The characteristics of these missions is given in Table 7.

					Local time at A/D
Mission	Frequenc	ies		Inclination	node
Metop02/AMSUA		23.8GHz	31.4GHz	98.7°	A 21:30
Jason-3/AMR	18.7GHz	23.8GHz	34GHz	66°	
Sentinel-3A		23.8GHz	36.5GHz	98.65°	D 10:00
Sentinel-3B		23.8GHz	36.5GHz	98.65°	D 10:00
SARAL/AltiKa		23.8GHz	37GHz	98.55°	A 06:00

#### Table 7: Characteristics of missions with microwave radiometer

Following the method proposed by Ruf [RD 1], updated by Eymar [RD 3] and implemented in [RD 7], the coldest ocean temperature is computed by statistic selection over clear sky condition. Ruf has demonstrated how a statistical selection of the coldest BT over ocean allows detecting and monitoring drifts. It is also commonly used for long-term monitoring or cross-calibration as in [RD 4], [RD 5] or [RD 6].



The Amazon forest is the natural body the closest to a black body for microwave radiometry. Thus it is commonly used to assess the calibration of microwave radiometers [RD 2] [RD 3]. The method proposed in these papers have been used as a baseline to propose a new method implemented in [RD 7]. In this new approach, a mask is derived from the evergreen forest class of GlobCover classification over Amazon. The average temperature is computed here over a period of one month for all missions. The same method is applied here.

#### 5.2.5.1 Coldest ocean temperatures

Figure 22 shows the monitoring of the coldest ocean points for both channels, each year of data being piled on top of the other. For the 23.8GHz channel (frequency common to all cited missions), the average coldest ocean temperature is around 140K for AltiKa, AMSU-A, S3A and S3B, while for Jason3 it is around 134.5K due to calibration choices. For the second channel, each mission has a different frequency as shown in Table 7, thus a different average coldest ocean temperature. We retrieve a very similar level for Sentinel-3A and AltiKa due to their very close frequency. One can notice the very good consistency of the 2018 results with respect to previous years results for all missions showing no clear sign of drifts or abnormal events along the period. Sentinel-3B started with temperatures colder than S3A before the inter-calibration. In December, a new ADF was deployed in the operational processing providing calibrated parameters for S3B MWR. This is the reason of the increase of the coldest temperatures for both channels of S3B. With the calibrated parameters, S3B is much closer to S3A.



Figure 22: Coldest temperature over ocean for Sentinel-3A, Sentinel-3B, SARAL/AltiKa, Metop02/AMSU-A, Jason3/AMR for two channels 23.8GHz (left) and 36.5GHz (right)



#### 5.2.5.2 Amazon hottest temperatures

Figure 23 shows the monitoring of the hottest temperatures over the Amazon forest for both channels, each year of data being piled on top of the other. The average hottest temperature is very similar for all four missions for channel 23.8 GHz with a difference of less than 2K. The difference is a little larger for the liquid water channel due to the difference of frequency. One can notice the very good consistency of the 2018 results with respect to previous years results over the same period for all missions. The beginning of 2016 shows a slightly different behaviour due to the strong El Nino event of 2015 which slowly decreased until beginning of 2016. This event affects water vapor content over the Amazon forest. From these results, there is no sign of drifts or abnormal events. Sentinel-3B is very close of S3A in level of hottest brightness temperatures for both channels. The hottest brightness temperatures are not impacted by the update of the MWR characterisation file as expected.



Figure 23: Hottest temperatures over the Amazon forest for Sentinel-3A, SARAL/AltiKa, Metop02/AMSU-A, Jason3/AMR for two channels 23.8GHz (left) and 36.5GHz (right)



# **6** SRAL Tracking performances

The analysis of the percentage of available and missing measurements gives a relevant information about the altimeter performances. It also allows to point out several kinds of events that have an impact on the satellite platform and on the data circulation.

### 6.1 Over Ocean

Figure 24 shows the monitoring of the daily percentage of available measurements over Sentinel-3A lifetime. This diagnosis was performed using the water Non-Time-Critical (NTC) Level-2 products from Sentinel-3A and Sentinel-3B, and a comparison to Jason-3 GDR is performed. For Sentinel-3B, this percentage is computed from the 23<sup>rd</sup> November 2018, i.e. when it reaches its final orbit.

For Sentinel-3A and Sentinel-3B, the percentages of available measurement are similar and is of 99.88%, which is a good result. Most of the data gaps observed for the two Sentinel missions are related to ground segment anomalies (Marine products not available). Note that for Sentinel-3B, a SRAL anomaly occurred on the 28<sup>th</sup> of January, resulting in a data gap of 20 hours. The data quality before and after the anomaly has been check and considered as nominal.

Considering the open ocean only, the results are even better and reach 99.96% of available measurements for both Sentinel-3A and Sentinel-3B.



Figure 24: Monitoring of the daily percentage of available measurements for Sentinel-3A over ocean and coastal area (blue curve), Sentinel-3A over open ocean (cyan curve), for Sentinel-3B over ocean and coastal area (red curve), Sentinel-3B over open ocean (orange curve), and Jason-3 over open ocean (black curve). This metric is computed with respect to the theoretical track and the theoretical number of measurements expected.



# 6.2 Over Land

#### 6.2.1 Global analysis

Data gaps occur when the tracker fails at retrieving the return echo inside the listening window and the satellite enter acquisition mode. No measurements are saved in the product where there should be some. The localization and quantification of these missing measurements give a relevant information about the SRAL altimeter tracking performances. Over ocean, the detection of missing measurements is done at 1 Hz as the delay of the returned signal is easily predictable and quite constant. However, over land, the surface type and topography variations make the measurement more complicated and challenging. Therefore, the detection of missing measurement over land needs to be computed using High Rate frequency (20Hz) dataset.

Over land, two different tracking modes are possible for SRAL acquisition: Open-Loop (OL) and Closed-Loop (CL). Over OL areas, the tracking command is derived from an elevation model (onboard DEM also called OLTC) whereas, over CL areas the tracking window is automatically adjusted as a function of the returned signal. Sentinel-3A altimeter has operated in OL mode since the beginning of the mission. Sentinel-3B altimeter acquisition mode was switched several times during the commissioning phase. The CL mode activation is global (no OL mode surfaces). It is not the case for OL. Indeed, in OL mode, the satellite can still operate in CL in some geographically predefined zones. These acquisition mode masks are presented in Figure 25. Until March 2019, these masks are different between Sentinel-3A and Sentinel-3B. In March 2019, Sentinel-3A OLTC has been updated to the latest version (v5.0) and the same acquisition mode mask is now used for both missions.

Section 10.1 provides more details about the content of the OLTC, and how it is designed and validated for inland water applications.







Figure 25: Map of the SRAL tracking mode plotted for Sentinel-3A (top panel) for OLTC v4.2 until March 1<sup>st</sup> 2019 and Sentinel-3B (bottom panel). Since March 9<sup>th</sup> 2019 the Open Loop tracking command was updated to v5.0 and the OL/CL pattern is similar to S3B (ie OL in between +/- 60° latitude).

Figure 26 shows the geographical distribution of missing measurements within the land level-2 products for Sentinel-3A (top panel) and for Sentinel-3B (bottom panel) during the period corresponding to Sentinel-3A cycle 33. Over this period, Sentinel-3A still operated in both Close Loop and Open Loop (using OLTC v4.2 as detailed in Figure 25) modes, while Sentinel-3B already operated in Open Loop mode between +/-60° of latitude with OLTC v5.0. When the altimeter operates in OL mode, the number of missing measurements is much lower (close to zero) than in Close Loop. Thus, for Sentinel-3B, operating in OL between -60° and 60° of latitude north, very few missing measurements are observed. Only few missing passes (Sentinel-3B suffered of a SRAL Anomaly between 2019/01/28 17:06:46 and 2019/01/29 13:21:15, resulting in the missing tracks highlighted in Figure 26 bottom) and calibration areas (South of Africa, Australia, Gobi desert, Sahara desert, Arabian Peninsula, Sahara) are observed





Sentinel 3 - B: Missing mesurement Cycle 21



Figure 26: Global map (top panel) of the Sentinel-3A missing measurements over land for cycles 40/41 (from 12<sup>th</sup> of January 2019 to 8<sup>th</sup> of February 2019). Same map for Sentinel-3B (bottom panel) over cycle 21 (from 12<sup>th</sup> of January 2019 to 8<sup>th</sup> of February 2019).

As presented in Figure 27, representing the missing measurements over land over a cycle over which both Sentinel-3A and Sentinel-3B are in Open Loop mode with OLTC v5.0, the pattern of the missing measurements is very similar between the two missions. Apart for the calibration areas, the percentage of missing data is close to zero in open loop mode, while it is more important in close loop mode for latitudes higher than 60°.



30 ° N

0

30

60 °

90°-180

150°W

120°W

90 ° W

60 ° W

30 ° W



Sentinel 3 - A: Missing mesurement

Figure 27: Global map (top panel) of the Sentinel-3A missing measurements over land for cycles 52/53 (from 2<sup>nd</sup> of December 2019 to 29<sup>th</sup> of December 2019). Same map for Sentinel-3B (bottom panel) over cycle 33 (from 2<sup>nd</sup> of December 2019 to 29<sup>th</sup> of December 2019).

30 ° E

2

90 ° E

120°E

150°E

180°E

60 ° E

In Close Loop mode, the acquisition of the returned signal mainly depends on the surface topography as illustrated with Sentinel-3A data when it was operating in close loop over Central America before cycle, as illustrated in Figure 28. Most of the missing measurements are located over the highest surface altitudes. In fact, tracker performances are more related to the variations (or slopes) of the surface height than its altitude.





Figure 28: Missing Sentinel-3A measurements (plotted in white) when in Close Loop over this region before cycle 42 superimposed on an elevation grid.

The monitoring of Sentinel-3A and 3B missing measurement percentages is presented in Figure 29 for both OL and CL zones. The two satellites present similar features. In OL, no missing measurements are expected as it is designed in such way that the return signal should always been retrieved by the tracker. The percentages shown here in OL (1.53% for Sentinel-3A and 1.70% for Sentinel-3B) are due to calibration zones and ground processing errors. In CL, the average percentage of missing point is of 7.2% for Sentinel-3A and 6.8% for Sentinel-3B. Since March 2019, the Sentinel-3A daily average dispersion is reduced and become similar to the one observed for Sentinel-3B. This is related to the change of the SRAL acquisition mode mask (Figure 25).



Figure 29: Daily monitoring of Sentinel-3A and Sentinel-3B missing measurements over land from January 2018 to December 2019.



#### 6.2.2 Analysis over Antarctica

In this section, the tracker performances are assessed over Antarctica. This region, and more precisely its margins are of particular interest for the study of the climate change. In this area, the transition between oceanic surface to the continent is particularly complex with strong variations of the surface elevation. The margins were initially acquired in Open Loop, from Sentinel-3A beginning to the 6<sup>th</sup> of December 2016. However, due to a large number of invalid measurements related to the wrong positioning of the tracking window (low precision of the Digital Elevation Models (DEM) over the margins), the acquisition mode was shifted to Close Loop.

Figure 30 shows the location of SRAL 20Hz missing measurements (left panel) and the surface elevation derived from the high-resolution Reference Elevation Model of Antarctica (REMA) DEM (right panel). A clear correlation is observed between detected missing measurements and the surface elevation, as presented in Figure 28. In addition, a circle is observed at the highest latitudes. We indeed detected that for several ascending products the first Level-2 measurements are sometimes missing which is not expected. This behavior is under investigation.



Figure 30: Missing measurements in closed loop for Sentinel-3A cycle 36, from 16 September 2018 to 13 October 2018 (left panel). Slope over Antarctica from REMA DEMA (right panel)

Figure 31 illustrates this relationship between surface slope and missing measurements. Over the strongest slopes sampled, about 25% of the measurements can be missed by the tracker operating in Close Loop mode.



#### Figure 31: Histogram of missing points over Antarctica as a function of slope, for Sentinel-3A in closed loop.

Slope [%]

3

4

2

From this analysis, it has been observed that a missing measurement is normally not isolated. In fact, they come in segments of consecutive missing measurements. The sets of consecutive measurements have been identified and the mean coordinates and a mean slope has been calculated for each group. In Figure 32, the results are summarized. Three main segment sizes are identified:

- below 10 seconds
- between 15 and 20 seconds

5

0+0

- between 35 and 40 seconds

Stronger is surface slope, higher is the probability to lose several consecutive measurements.



Number of consecutive missing points [-]



Figure 32: Repeating missing points for closed loop: geographical distribution (top), scatter plot of consecutive missing measurements as a function of slope (bottom right) and histogram (bottom right)

In order to compare with other altimetry mission, same diagnoses were performed using SARAL/AtliKa dataset. Figure 33 shows similar results. The missing measurements are as expected located on the same areas as for Sentinel-3. The relationship between percentage of missing measurement and surface slope shows the same shape. However, for a given surface slope the percentage of missing measurement is slightly higher for AltiKa: for the strongest surface slope (about 5%), 37% of missing measurement for AltiKa are observed against 25% for Sentinel-3. This can be explained by a higher sensitivity to the surface induced by the AltiKa smaller footprint.



Figure 33: Missing measurements analysis for AltiKa: histogram of slope (top), cartography of consecutive missing points (bottom left) and scatter plot of consecutive missing measurements as a function of slope (bottom right)

Table 8, confirms this observation, as the total percentage of missing measurement over Antarctica is slightly higher than for Sentinel-3A, 3.1 % against 2.3 %.

	Sentinel 3A	SARAL-AltiKa
	Cycle 36 (CL), SAR	Cycle 20 (CL)
	20Hz	40Hz
Missing points rate [%]	2.27 %	3.10 %
Missing points number	90457	240998
Number of points	3984563	7772710

Table 8: Missing points statistics ov	er one cvcle for	r the cases of study	v of missina measurements
			, oj moonig measarement



#### 6.2.3 Available measurement and their relevance

Although the Open-Loop mode allows to record a larger number of measurements over land surfaces, it does not mean that these measurements are all relevant. Indeed, the plot in Figure 34 top panel shows that many Sentinel-3A SRAL measurements acquired over Open-Loop areas have an OCOG range set to Default Value. Thus, in the case of Sentinel-3B operating in OL (bottom panel) all the measurements between -60° and 60° of latitudes are concerned. It occurs when the corresponding waveforms are not meaningful and cannot be properly retracked. As expected, the percentage varies as a function of the surface topography. Over Closed-Loop areas this percentage is artificially lower (above 20%) since there are less acquisitions with this mode (large number of missing measurements).

Over the Antarctica and Greenland margins acquired in Close Loop mode, we can see a high percentage of measurement that cannot be retracked. It means that a signal is acquired by the altimeter but it cannot be converted in a surface elevation. To increase the number of usable measurements, a prototype dedicated to land ice application is under testing. This prototype allows to extend the tracking window in order to better detect the signal returned by the surface.



# Sentinel-3 MPC

## S3MPC STM Annual Performance

Report - Year 2019

 Ref.:
 S3MPC.CLS.APR.006

 Issue:
 1.0

 Date:
 28/02/2020

 Page:
 44



Ku-band range ocog Sentinel-3b, cycle 20 (16/12/2018 - 12/01/2019)



Figure 34: Gridded map of the range ocog Default Value percentage with respect to the available measurements. For Sentinel-3A (top panel) over cycle 25 (from 11<sup>th</sup> of November 2017 to 20<sup>th</sup> of December 2017) and for Sentinel-3B (bottom panel) over cycle 20 (from 1-th of December 2018 to 12<sup>th</sup> of January 2019)



# 7 Performance Mission over Ocean

## 7.1 Outliers detection

The outlier detection or editing step of the Cal/Val process intends to remove any measurement that is considered as erroneous, helping to refine the different metrics that are provided in the other sections dedicated to the performance over ocean. The definition of an erroneous measurement, and of the accepted error level on the final sea level anomaly is of course a tradeoff between accuracy and data coverage. The monitoring of the percentage of valid and edited measurements also gives relevant information about the mission performances.

Editing criteria are used to detect outliers over ocean. This process is divided into 3 main parts:

- removal of all measurements affected by sea-ice.
- removal of all measurements which exceed defined thresholds on different parameters.
- further checks on along-track sla consistency.

For each step of the process, the number of outliers, per track, per day and per cycle is routinely monitored at Cal/Val level. This allows the detection of anomalies through the number of removed data, which could come from instrumental, geophysical or algorithmic changes. The process performed here is dedicated to ocean applications. Data over land are removed using a land/water mask prior to the analysis described in this section.

#### 7.1.1 Ice detection

The ice flag (based on the open\_sea\_ice\_flag field within the products) is used to remove measurements affected by sea ice in the altimeter footprint. This flag is derived from the Tran et al. algorithm developed in 2008 for Envisat mission. This algorithm combines brightness temperatures and backscatter information respectively derived from microwave radiometer and altimeter.

Top panels of Figure 35 show the location of the SRAL outliers detected in the South hemisphere in December 2018 for Sentinel-3A (left) and Sentinel-3B (right). The bottom panels of Figure 35 are derived from external sources. They show the percentage of ice concentration derived from OSISAF (bottom left panel) and from NSIDC (bottom right panel) models over the same period. The location of Sentinel-3A and Sentinel-3B measurements considered as corrupted by sea ice is consistent with the results derived from the two sea ice concentration models. It confirms the relevance of this metric to remove Sentinel-3A and 3B outliers at high latitudes.

Moreover, the accuracy of the Sentinel sea ice detection will be improved since, today, the Tran et al. algorithm is still based on Envisat parameters tuning. A Sentinel-3A dedicated parametrization has been performed and is presented in section 7.7.4. The new parametrization will be implemented in a future Processing Baseline.





Figure 35: Top panels show Sentinel-3A (left) and Sentinel-3B (right) sea ice flag derived from both L2 LAND and WATER products from 23<sup>rd</sup> November to 23<sup>rd</sup> December 2018. Presence of sea ice corresponds to red, open ocean water is represented in blue. Bottom left panel shows the sea ice concentration percentage derived from OSISAF model over the same period. Bottom right panel shows the sea concentration percentage derived from NSIDC model over the month of December 2018.

The percentage of measurements corrupted by sea ice is plotted on Figure 36 for Sentinel-3A (top left panel) and for SARAL/AltiKa (top right panel) over the same period from April 2016 to December 2019. The SARAL/AltiKa is used for these comparisons because both missions have similar high latitude coverage. Once again, there is a good agreement between the sea ice areas detected by both missions.

Sea ice detected by Sentinel-3B is represented on Figure 36 bottom panel over the mission final orbit, i.e. from November 2018 to December 2019. With only one year of data, the sea ice detection patterns and percentages are consistent with Sentinel-3A and SARAL/Altika.

The corresponding global temporal monitoring is plotted on Figure 37. The three missions follow identical temporal variations with maximums in June-July (Southern hemisphere winter) and in November (Northern hemisphere winter). Sentinel-3A and 3B metrics are in perfect agreement. The percentage of outliers detected by SARAL/AltiKa sea ice flag is slightly higher (by 2%) than for Sentinel-3A and 3B. This could be explained by Sentinel-3 sea ice algorithm. Indeed, Sentinel-3 sea ice detection parametrization is based on Envisat's and is not yet definitely tuned for Sentinel-3A and 3B (see section 7.7.4). This can have an impact on the sensitivity to the sea ice.



Figure 36: Gridded maps of outlier's percentage detected by sea ice flag for Sentinel-3A (top left panel, from April 2016 to December 2019), SARAL/AltiKa (top right panel, from April 2016 to December 2019) and Sentinel-3B (bottom panel, from November 2018 to December 2019).



Figure 37: Monitoring of the daily averaged percentages of outliers detected by Sentinel-3A (blue curve) and Sentinel-3B (orange curve) sea ice flag and SARAL/AltiKa ice flag (green curve) over ocean.



#### 7.1.2 Outliers detection over ocean

Once the measurements corrupted by land and sea ice surfaces are identified, the quality of the altimeter retrieved parameters and the geophysical corrections is checked with respect to thresholds. These thresholds and the corresponding percentage of corrupted measurements are detailed in Table 9. For each of the listed parameters, the percentage of outliers detected is closely monitored cycle by cycle, day per day and pass per pass by CLS Cal/Val routines.

Figure 38 presents the monitoring of the total percentage of corrupted measurements detected over ocean and sea ice (top panel) and the corresponding maps for Sentinel-3A and 3B (bottom panels). Due to mispointing events occurring in 2019 for SARAL/AltiKa, the metrics for this satellite are not displayed here over the year 2019. The temporal variations of the percentage of corrupted measurements detected for Sentinel-3A and SARAL/AltiKa are consistent. The averaged percentages are also very close: 18.0 % for Sentinel-3A against 19.6% for SARAL/AltiKa. The two Sentinel missions show equivalent percentages.

This monitoring also highlights some peaky values for Sentinel-3A and 3B. For these days, the increase of corrupted measurements is due to the unavailability of some geophysical corrections. Indeed, the thresholds criteria also allows to detect when a parameter is not defined. Figure 39 shows the monitoring of the percentage of measurements edited on the dynamical atmospheric correction criteria (DAC). Figure 40 presents the same metric on the microwave radiometer Wet Tropospheric Correction criteria (MWR WTC).

The dynamical atmospheric correction is derived from the MOG2D model. This correction is partially missing over few days for Sentinel-3A and 3B. These anomalies are due to ground processing errors in the Marine Centre. Over Sentinel-3A reprocessed period (from April 2016 to December 2017), such anomalies have been addressed and the DAC is correctly provided. Over the next period, four minor events occurred: on the 12<sup>th</sup> and 13<sup>th</sup> July 2018, the 25<sup>th</sup> and 26<sup>th</sup> January 2019, the 26<sup>th</sup> April 2019, and the 11<sup>th</sup> July 2019. For Sentinel-3B, the DAC is partially missing on 5 days over the interleaved orbit: on the 25<sup>th</sup> and 26<sup>th</sup> January 2019, the 26<sup>th</sup> April 2019. Note that most of the events occurred simultaneously for Sentinel-3A and 3B.

Regarding the measurements edited on the radiometer WTC criteria, Figure 40 top panel shows:

- A higher percentage of edited measurement for Sentinel-3A until the end of February 2018: 1 % for Sentinel-3A against 0.06% for SARAL/AltiKa. This higher percentage is explained by the Sentinel-3A MWR calibration pattern (see section 5.2.2 for more details). During MWR calibrations, approximatively 17 seconds 3 times per orbit, the MWR WTC is set to Default Value. This explains both the higher percentage for Sentinel-3A, and regular pixels of partially edited measurements over the open ocean observed in the map (Figure 38, bottom left panel). This calibration scheme has been changed on the 28<sup>th</sup> February 2018 to improve Sentinel-3A coverage over ocean. After this date, the average percentage of measurements edited by WTC criteria drops to 0.02%, which is lower than for AltiKa (0.06%) and Jason-3 (0.07%). Sentinel-3B uses the same upgraded calibration scheme as Sentinel-3A. It explains the similar percentages and the absence of partially edited pixels on the map (Figure 38, bottom right).
- Peaky values on 17 days over Sentinel-3A lifetime and 6 days over Sentinel-3B interleaved orbit. These high percentages of edited measurement are not related to radiometer instrumental



anomalies but to ground processing errors. The microwave radiometer WTC is set to Default Value. In Sentinel-3A reprocessed products, it should be corrected.

Looking more closely at the evolution of the percentage of edited measurements by MWR WTC criteria after the 28<sup>th</sup> February 2018, some small variations are visible in 2019. As shown on Figure 40 bottom panel, these variations are due to the modification of the safety zone over KREMS island. Indeed, when Sentinel-3A or 3B flight over this zone, they entered a Safe Hold Mode and no radiometer data are retrieved. Over 2019, the radius of this safety zone changed twice:

- On the 19<sup>th</sup> January, the radius is changed from 50 km to 300 km, resulting in an increase of 0.07% of the edited measurement by WTC criteria.
- On the 29<sup>th</sup> April, the radius is reduced to 150 km. The percentages of edited measurement due to WTC unavailability drop to 0.03% for Sentinel-3A and to 0.04% for Sentinel-3B.





Figure 38: top panel shows Sentinel-3A (blue curve), Sentinel-3B (red curve) and SARAL/AltiKa (green curve) total percentage of outliers over ocean. Bottom panels show the gridded maps of Sentinel-3A (bottom left) from April 2016 to December 2019 and Sentinel-3B (right panel) for November 2018 to December 2019.





Figure 39: Percentage of outlier detected by the dynamical atmospheric thresholds (top panel) and by the MWR WTC thresholds (bottom panel). Sentinel-3A is represented in blue, Sentinel-3B in orange, and Jason-3 in black.






Figure 40: Percentage of outlier detected by the MWR WTC thresholds over Sentinel-3A lifetime (top panel). A zoom of the same metrics between March 2018 and December 2019 is shown on the bottom panel, with no ground processing errors considered. Sentinel-3A is represented in blue, Sentinel-3B in orange, and SARAL/Altika in green.

Table 9 shows the percentage of rejected data over ocean (removing ice) over the year 2019. These percentages are good, with only 2.9% for Sentinel-3A and 3.31% for Sentinel-3B. It is fully consistent with the same metric observed for Jason-3 (3.3%) and SARAL/AltiKa missions (2.6%). Over the year 2019, special events related to missing DAC or WTC only account for 0.01% of the total rejected measurements for Sentinel-3A and for 0.03% for Sentinel-3B.

The percentage of edited data due to the ionosphere correction is slightly higher for Sentinel-3B than for Sentinel-3A (+~0.4%). This is probably linked to C-band range bias between the two missions (see subsection 7.2.3 for more details).

Regarding the maps of the percentage of total outliers (Figure 38 bottom panels), except the along-track patterns and the isolated pixels described previously, the result at medium and low latitudes mainly highlights the rainiest areas, as usually observed for the altimeters.

Parameters	Min thresholds	Max thresholds	Mean edited for Sentinel-3A	Mean edited for Sentinel-3B
Sea Level Anomaly	-2	2	0.38 %	0.38 %
Number of range measurement	10	Not applicable	0.05 %	0.05 %
Standard deviation of range	0	0.12+0.02*SWH	1.28 %	1.26 %
Dry tropospheric correction	-2.5	-1.9	0.00 %	0.00%
Dynamical atmospheric correction	-2	2	0.00 %	0.00 %
MWR Wet Tropospheric Correction	-0.5	-0.001	0.02 %	0.02 %
Sigma0	5	28	0.12 %	0.12 %

	Sentinel-3 MPC	Ref.:	S3MPC.CLS.APR.006
	S3MPC STM Annual Performance Report - Year 2019	Issue:	1.0
		Date:	28/02/2020
		Page:	52

Parameters	Min thresholds	Max thresholds	Mean edited for Sentinel-3A	Mean edited for Sentinel-3B
Sigma0 Standard deviation	0	0.7	2.57 %	2.52 %
Altimeter Wind Speed	0	30	0.04 %	0.04 %
Dual Frequency ionosphere correction	-0.4	0.04	1.18 %	1.56 %
Sea State Bias	-0.5	0	0.04 %	0.04 %
Ocean Tide	-5	5	0.01%	0.01 %
Earth Tide	-1	1	0.00 %	0.00 %
Pole Tide	-15	15	0.00 %	0.00 %
All Together			2.99 %	3.31 %

Table 9: Outliers detection thresholds and corresponding percentages computed over the year 2019 for Sentinel-3A and Sentinel-3B.

# 7.2 Monitoring of SRAL parameters

#### 7.2.1 Significant Wave Height

The Significant Wave Height (SWH) is a parameter derived from ocean retracking. It corresponds to the average wave height of the highest third of the wave distribution in a given sample period. Moreover, at climatic scales, the study of ocean waves is of great importance to understand the interaction between ocean and atmosphere. The Copernicus Marine Environment Monitoring Service (CMEMS) collects and processes the Sentinel-3A SWH estimations (among others) every day to provide researchers with a long term and homogenous SWH dataset. This section aims at describing the global quality of Sentinel-3A SWH estimations.

Figure 41 middle and top panels show the maps of Sentinel-3A SARM and P-LRM SWH and the one derived from Jason-3 over the same period. Same geographical structures are observed by both Sentinel-3A modes and both satellites: low SWH around Indonesia, in the Mediterranean Sea and in the Gulf of Mexico; high SWH in the band of latitudes around 50°S. The same patterns are visible on the first year of Sentinel-3B on its final orbit, in SARM and in P-LRM (Figure 41 bottom panels).

The corresponding histograms show an important population of very low SWH in SARM (close to 0m) for both Sentinel-3A and -3B. This is explained by the fact that the SARM processing set to 0 m all the SWH negative estimations. This artefact is more frequent in SARM, because the SWH are usually underestimated in SARM with respect to P-LRM. Negative estimations over flat sea state are possible due to the level of noise of this parameter. In the IPF 6.18 deployed in January 2020, the SAMOSA DPM 2.5



SWH fitting routine has been modified in order to improve low SARM SWH estimation. Furthermore, the processing allows now negative value for SARM SWH.





Figure 41: Gridded maps of Jason-3 (top panel), Sentinel-3A SARM (middle left panel) and P-LRM (middle right panel) SWH from April 2016 to December 2019. Gridded maps of Sentinel-3B SARM (bottom left panel) and P-LRM (bottom right panel) SWH from November 2018 to December 2019.

The monitoring of the daily averaged SWH (plotted in Figure 42) allows to detect abnormal events and potential significant drifts. In order to be consistent with Jason-3 global coverage, Sentinel-3A and Sentinel-3B data have been selected below 66° of latitude. The trend and the variations observed are the same for both Sentinel-3A and Sentinel-3B modes and for the three satellites. Sentinel-3A and 3B SWH are in perfect agreement. The mean difference between Sentinel-3 and Jason-3 SWH is reduced since January 2019, with the deployment of PB2.45 (S3A) and PB1.17 (S3B) providing updated SARM Look up Tables (LUT).





Figure 42: Daily monitoring of the Sentinel-3A SARM (blue curve) P-LRM (cyan curve), Sentinel-3B SARM (red curve) P-LRM (orange curve), and Jason-3 (black curve) SWH.

The precise comparison of Sentinel-3A, Sentinel-3B and Jason-3 SWH trough the analysis of histograms and temporal averaging is not an exhaustive metric since the satellite ground tracks are different and the temporal variability of this parameter is very high. Thus, to precisely assess Sentinel-3A an 3B SWH accuracy with respect to other altimetry mission, differences are computed at crossovers for which the time lag between Sentinel-3A (3B) and Jason-3 sampling is lower than 3 hours. From these points, we compute the SWH difference between Sentinel-3A (3B) and Jason-3 as a function of Jason-3 SWH (top panels of Figure 43). The results are similar for Sentinel-3A and Sentinel-3B. This analysis shows a very good agreement between Jason-3 and Sentinel-3A (Sentinel-3B) for both modes, with a mean bias of about 3.5 cm (5.1 cm) in SARM and about 3.1 cm (3.1 cm) in P-LRM. No significant dependency is visible when SWH increase for Sentinel-3 P-LRM. However, Sentinel-3 SARM compared to Jason-3 highlights a clear dependency as function of SWH. The differences increase with SWH values from 20cm at SWH equals 0.75m to -9cm at SWH equals 3m, and then remain stable for higher SWH. This kind of behaviour was already observed from Cryosat-2 SARM, investigations are ongoing to understand the content of SARM observations with respect to conventional altimetry. The good performances obtained with Sentinel-3 P-LRM SWH is an important result. It means that despite its higher level of noise, this processing mode allows to constitute a robust reference at global scales to assess the co-located SARM measurements.

The map plotted in Figure 43 bottom panels illustrates the difference of SWH between Sentinel-3A SARM and P-LRM (bottom left) and Sentinel-3B SARM and P-LRM (bottom right). It confirms the result derived from 3 hours crossover analysis: the SARM SWH estimations, at global scales, vary as a function of the wave height.



Figure 43: top panels show SWH differences computed at crossovers between SARM and Jason-3 (blue curve) and between P-LRM and Jason-3 (green curve), for Sentinel-3A from April 2016 to December 2019 (top left panel) and for Sentinel-3B from November 2018 to December 2019 (top right panel). Bottom panels show the gridded map of collocated SWH differences between Sentinel-3A SARM and P-LRM from April 2016 to December 2019 (bottom left panel) and Sentinel-3B SARM and P-LRM from November 2018 to December 2019 (bottom right panel).

#### 7.2.2 Backscatter coefficient

The backscatter coefficient also called sigma0, is computed from the power of the signal returned by the sampled surface. Over Ocean, it gives an information of the sea surface roughness. Over flat sea surfaces, sigma0 values are high, whereas over strong sea states (with for example high SWH values) sigma0 values are lower. This parameter should be precisely estimated since it is used to compute the wind speed measured by the altimeter. Although the wind direction cannot be provided from altimeter measurements, the wind speed norm is of great importance for climatic applications.

Figure 44 shows the maps of the backscatter coefficient for Jason-3 (top panel), and for Sentinel-3A SARM and P-LRM (middle panels) over the same period. Same geographical structures are observed by both Sentinel-3A modes and both satellites: high values around Indonesia, in the Mediterranean Sea and in the Gulf of Mexico where the sea surface is usually flat; high values in the band of latitudes around 50°S where the SWH are in average higher.

The mean values are different between Sentinel-3A and Jason-3 sigma0. For Sentinel-3A, a bias is applied to the SARM and P-LRM sigma0 values to make them consistent with Envisat sigma0 mean value, i.e



centred around 11 dB. Indeed, the algorithm used to compute the wind speed estimation, Abdalla's algorithm, is inherited from Envisat mission and thus needs consistent inputs. The system biases applied on Sentinel-3A sigma0 is of -18.96 dB in SARM and of -2 dB in P-LRM.

During the beginning of Sentinel-3B mission, its system biases were set to Sentinel-3A values. However, a bias of about 0.5 dB was observed between Sentinel-3B and Sentinel-3A backscatter coefficients, both in SARM and in PLRM (not shown here). Sentinel-3B backscatter coefficient was not in line with the parametrization used for the altimeter wind speed calculation. The alignment was performed in the implementation of Sentinel-3B processing baseline 1.13: the system biases have been changed from - 18.96dB to -19.17dB on SARM data and from -2dB to -2.21dB on P-LRM data. This new processing baseline has been deployed on the 6<sup>th</sup> December 2018 for NRT data. The impact is visible on NTC data about 25 days earlier, i.e. on the 11<sup>th</sup> November 2018. From this date, Sentinel-3A and 3B backscatter coefficients are centred around 11dB, both in SARM and in P-LRM, and present the same geographical structures, as shown on the Figure 44.



# Sentinel-3 MPC S3MPC STM Annual Performance

Report - Year 2019

 Ref.:
 S3MPC.CLS.APR.006

 Issue:
 1.0

 Date:
 28/02/2020

 Page:
 57





Figure 44: Gridded maps of Jason-3 (top panel), Sentinel-3A SARM (middle left panel) and P-LRM (middle right panel) backscatter coefficient from April 2016 to December 2019. Gridded maps of Sentinel-3B SARM (bottom left panel) and P-LRM (bottom right panel) backscatter coefficient from November 2018 to December 2019.

The monitoring of the daily averaged backscatter coefficient (plotted in Figure 45) allows to detect abnormal events and potential significant drifts. In order to be consistent with Jason-3 global coverage, Sentinel-3A and 3B data have been selected below 66° of latitude. The observed temporal variations confirm the perfect agreement between Sentinel-3A and Sentinel-3B (after the change of system biases) and the good consistency with Jason-3.

Considering the system biases applied on Sentinel-3A and Sentinel-3B data, the true biases between Sentinel-3 and Jason-3 are presented in Table 10.





Figure 45: Daily monitoring of the Sentinel-3A SARM (blue curve) P-LRM (cyan curve), Sentinel-3B SARM (red curve) P-LRM (orange curve), and Jason-3 (black curve) backscatter coefficient.

	Jason-3/Sentinel-3 observed bias	Sentinel-3 System bias	Jason-3/Sentinel-3 true bias
J3 / S3A SARM	2.75 dB	-18.96 dB	-16.2 dB
J3 / S3B SARM	2.70 dB	-19.17 dB	-16.4 dB
J3 / S3A P-LRM	2.76 dB	-2.00 dB	+0.8 dB
J3 / S3B P-LRM	2.72 dB	-2.21 dB	+0.5 dB

#### Table 10: Backscatter coefficient bias between Sentinel-3A and Sentinel-3B with respect to Jason-3.

The co-located differences between Sentinel-3A SARM and P-LRM sigma0 (Figure 46 top left panel), and between Sentinel-3B SARM and P-LRM sigma0 (Figure 46 top right panel) highlight patterns that depends on the latitude. The mean difference is centred on 0 dB for both satellites (as already shown on the temporal monitoring). However, negative and positive values are respectively observed at low and high latitudes on both Sentinel-3A and Sentinel-3B maps. These variations are strongly correlated to the satellites altitude rates, plotted on Figure 46 bottom panel, and not to the satellite altitude as it was the case with SAMOSA 2.3 (see in previous S3 STM annual reports).



Figure 46: Gridded maps of the collocated backscatter differences between Sentinel-3A SARM and P-LRM from April to December 2019 (top left panel) and between Sentinel-3B SARM and P-LRM from November 2018 to December 2019 (top right panel). Gridded map of the absolute value of Sentinel-3A orbital altitude rate computed over cycle 25 (bottom panel).

#### 7.2.3 Dual-Frequency ionospheric correction

In addition to the nominal Ku-band transmit frequency, the SRAL altimeter interleaves a C-band signal. The purpose of this second frequency is to provide a collocated ranging measurement to correct for ionospheric path delay in the Ku-band range estimate. Indeed, both Ku and C-band have different sensitivity to the electron content in the atmosphere.

Figure 47 shows the maps of the delay induced by the electron content on the Ku-Band range for Jason-3 (top panel), Sentinel-3A SARM and P-LRM (middle panels), and Sentinel-3B SARM and P-LRM (bottom panels). Note that the fields "iono\_cor\_alt\_01\_ku" and "iono\_cor\_alt\_01\_plrm\_ku" provided in the L2 products are not filtered (this is part of 2019 IPF evolution that has been deployed in January 2020). Their level of noise is thus approximatively the weighted sum of the Ku and C-band range noise. In order to improve the quality of the assessment, the dual-frequency ionosphere correction has been filtered at 300 km.

The four maps obtained for both Sentinel missions and modes are very consistent. Sentinel-3B maps show smaller global mean values in SARM (-0.5cm) and P-LRM (-0.8cm) compared to Sentinel-3A (-2cm in SARM and -2.2cm in PLRM). The slight discrepancies between SARM and P-LRM ranges (described in Figure 114) have a very low impact on the dual frequency ionosphere correction (-5 mm differences in strong SWH



areas). The map derived from Jason-3 altimeter shows similar patterns and magnitude. It has been demonstrated that the ionosphere correction derived from Jason-3 altimeter is 5 mm higher with respect to Jason-2.



Figure 47: Gridded maps the dual frequency ionospheric correction computed for Jason-3 (top panel), Sentinel-3A SARM (middle left panel) and P-LRM (middle right panel) over the period spanning from April 2016 to December 2019. Gridded maps of Sentinel-3B SARM (bottom left panel) and P-LRM (bottom right panel) dual frequency ionospheric correction computed from November 2018 to December 2019.

The delay induced by the electron content can also be derived from the GPS global lonosphere Maps (GIM) model. Jee et al. demonstrated that, although the GIM model is not as accurate as the dual-frequency metric, overall the GIM model is able to reproduce the spatial and temporal variations of the ionosphere. Figure 48 shows maps of differences between dual frequency and GIM model ionospheric correction for Jason-3 (top panels), SARM Sentinel-3A (middle panels), and SARM Sentinel-3B (bottom



panels). Ascending (left panels) and Descending (right panels) passes have been plotted separately. The dual frequency ionosphere derived from Sentinel-3A is, in average, closer to the GIM model (differences centred on 1.7mm for ascending passes and 3.2mm for descending passes) than the one derived from Jason-3 (8 mm bias) and from Sentinel-3B (1.3cm bias for ascending passes and 1.4cm for descending bias). Discrepancies are observed for both Sentinel missions between ascending and descending passes. It is not the case for Jason-3. These differences are related to the local time. Indeed Sentinel-3A and Sentinel-3B are sun-synchronous satellites, which means that for a given latitude and pass orientation, the local time is always the same. Figure 49 shows Sentinel-3A and Sentinel-3B local hours distribution for ascending and descending passes for one cycle (this result does not vary in time):

- Sentinel-3A and Sentinel-3B local hours distributions are identical.
- For ascending passes (left panels) and for latitudes below 70°, the local hours are ranged between 9:00 PM and 01:00 AM. For these local hours, the sun activity and thus the electron content in the atmosphere are lower.
- For descending passes (right panels) and for latitudes below 70°, the local hours are ranged between 8:00AM and 12:00 AM. For these local hours, the sun activity and thus the electron content in the atmosphere are higher.

On the other hand, Jason-3 is not a sun-synchronous satellite and revisits only every 12 cycles (120 days) the same local hours. Day and night hours are thus averaged in both Jason-3 maps, this explain the similarity between Jason-3 ascending and descending passes and the geographical differences with respect to Sentinel-3A and 3B. The patterns are similar between Sentinel-3A and Sentinel-3B difference maps.







Figure 48: Gridded maps of the collocated differences between dual frequency ionosphere correction and GIM model for ascending (left panels) and descending (right panels) passes, for Jason-3 (top panels), SARM Sentinel-3A (middle panels) and Sentinel-3B (bottom panels). The ionosphere corrections derived from altimeter were filtered at 300km.



Figure 49: Along-track maps of the local hours for ascending (left panels) and descending (right panels) passes, computed from the 6<sup>th</sup> August 2019 to the 2<sup>nd</sup> September 2019 for Sentinel-3A (top panels) and Sentinel-3B (bottom panels).

The monitoring of Sentinel-3A dual frequency and GIM ionosphere corrections and their differences (Figure 50) presents a very good and stable agreement between the two solutions. The mean bias is quite stable in time despite a slight slope of about -1mm per year over the first two years of the mission. Over the year 2019, it is centred around 2mm and magnitudes of the variations do not exceed 6mm. The very

	Sentinel-3 MPC	Ref.:	S3MPC.CLS.APR.006
	S3MPC STM Annual Performance Report - Year 2019	Issue:	1.0
		Date:	28/02/2020
		Page:	63

small bias between both corrections is a good way to check that there is no significant bias on the SRAL C-band range. The curves plotted for different bins of local hours highlight slight differences between the months of May and September. For this period, the monitoring of the ionosphere corrections (bottom panel) shows an increase of the range delay and thus of the electron content in the atmosphere. This increase is higher for descending passes (day local hours) than for the ascending passes (night local hours).

Small temporal variations are observed in the two subplots. The main period identified equals to 27 days which corresponds to the solar Dicke cycle. These temporal oscillations could be related to the lowest resolution of the GIM model with respect to the altimeter dual frequency ionosphere correction.



Figure 50: Top panel shows the daily monitoring of the collocated differences between Sentinel-3A SARM dualfrequency ionosphere correction and the GIM model. The Sentinel-3A local hours were split by four hours bins and plotted separately. Bottom panel shows the daily monitoring of the Sentinel-3A SARM, P-LRM dualfrequency ionosphere correction and the collocated GIM model. Ascending and Descending passes were plotted separately.

The same monitoring has been plotted for Sentinel-3B over its final orbit (Figure 51). The differences between Sentinel-3B dual frequency and GIM ionosphere corrections are higher than with Sentinel-3A with a mean bias centred around 1.4cm (Figure 51 top panel). These discrepancies are also clearly visible when separating ascending and descending tracks (Figure 51 bottom panel). Such differences are due to Sentinel-3B C-band range. Indeed, looking at the monitoring of Sea Level Anomaly derived from C-band range and without considering geophysical corrections (Figure 52), a constant bias of 8.8 cm is observed



between Sentinel-3B and Sentinel-3A. This means that Sentinel-3B C-band range is in average 8.8 cm shorter than Sentinel-3A one. A shorter C-band range implies a less negative ionosphere correction, which is consistent with the maps presented on Figure 47.



Figure 51: Top panel shows the daily monitoring of the collocated differences between Sentinel-3B SARM dualfrequency ionosphere correction and the GIM model. The Sentinel-3B local hours were split by four hours bins and plotted separately. Bottom panel shows the daily monitoring of the Sentinel-3B SARM, P-LRM dualfrequency ionosphere correction and the collocated GIM model. Ascending and Descending passes were plotted separately.





Figure 52: Daily monitoring of C-band Sea Level Anomaly without geophysical corrections for Sentinel-3A (blue curve) and Sentinel-3B (red curve) from November 2018 to December 2019.

## 7.2.4 Off-Nadir angle waveform

The off-nadir angle gives an information about the satellite attitude. It can either be the result of real platform mispointing (also seen by the Star-Tracker measurements) or of backscattering properties of the surface measured on the altimeter waveforms.

Figure 53 presents the maps of mispointing angles derived from Sentinel-3A and 3B waveforms (middle and bottom left panels), Sentinel-3A and 3B Star-Tracker (middle and bottom right panels), and from Jason-3 (top panel) waveforms. Sentinel-3A (Sentinel-3B) off-nadir angle is biased by -0.006 degrees<sup>2</sup> (-0.007 degrees<sup>2</sup>) with respect to the one derived from star-trackers centred on 0 degrees<sup>2</sup>. Such a bias could be related to the value used for the antenna aperture angle in the P-LRM processing. More precise values of antenna aperture angle for both Sentinel-3A and 3B have been provided by the commissioning team at Sentinel-3B IOCR. These new values have been implemented in the IPF 6.18, deployed on the 21<sup>st</sup> January 2020.

In SARM, the mispointing information is derived from star-tracker measurement and injected as input of the retracking. The map derived from platform off-nadir angles confirms that Sentinel-3A and 3B pointings are excellent. The along-track effects observed in the Pacific and East Indian Oceans are due to pointing manoeuvres. For Sentinel-3B, some additional events occurred on the 11<sup>th</sup> December 2018: ascending tracks on cycle 19 from half orbit number 613 to 629 present higher mispointing values below 30°S (visible on Sentinel-3B maps). These events are due to specific calibrations part of the OLCI solar diffuser characterisation campaign.

Geographical variations are observed for the waveform mispointing. Indeed, this parameter is estimated trough the waveform trailing edge slope which varies with the surface and the atmosphere perturbations (rain cells attenuation, high SWH, blooms, sea ice...). For Sentinel-3A and 3B, the map of mispointing derived from P-LRM waveforms is not consistent with Jason-3: large scale variations are decreased, and the off-nadir values decrease over calm seas such as in Mediterranean and Indonesian seas, whereas they increase for Jason-3. These differences could be explained by P-LRM waveforms higher level of noise. In P-LRM only 32 individual echoes are averaged to compute the 20Hz waveform, while 91 echoes are used in LRM.

Figure 54 shows that the temporal evolution of Sentinel-3A and -3B waveform mispointing are stable.



# Sentinel-3 MPC

S3MPC STM Annual Performance Report - Year 2019 
 Ref.:
 S3MPC.CLS.APR.006

 Issue:
 1.0

 Date:
 28/02/2020

 Page:
 66

Mispointing from waveforms (degree<sup>2</sup>) - Jason-3, over S3A cycle 3 to 52



<figure>

Figure 53: Top panel shows the off-nadir angle derived from waveforms for Jason-3 over Sentinel-3A whole mission lifetime. Middle panels show the gridded maps of Sentinel-3A off-nadir angle derived from waveforms (left panel) and derived from Star-Trackers (right panel) from April 2016 to December 2019. Bottoms panels show the same gridded maps for Sentinel-3B from November 2018 to December 2019.





Figure 54: Daily monitoring of the Sentinel-3A P-LRM (blue curve), Sentinel-3B P-LRM (orange curve), Jason-3 (black curve) and SARAI/AltiKa (green curve) off-nadir angle derived from waveforms

The study of Sentinel-3A/Sentinel-3B tandem phase has allowed to detect abnormal behaviour in Sentinel-3A mispointing. Figure 55 shows the residual difference between Sentinel-3A and Sentinel-3B of the off-nadir angle derived from waveform, over 20-day period on ascending tracks. These maps are homogeneous except for a band of about 30° latitude wide, visible only on the ascending tracks and not on the descending tracks. The position of this band varies in time: between 30° and 60°N in July 2018 to above 60°N in October 2018. The comparison between ascending and descending tracks demonstrates that this pattern is related to Sentinel-3A platform. This signal remains very low with 3.10<sup>-3</sup> degrees<sup>2</sup> of amplitude, with an impact of only -0.02 dB on Sentinel-3A PLRM backscatter coefficient.

Further analyses were performed to explain this behaviour. They show a possible correlation to the eclipse exit, i.e. when the solar flux is directly directed on the SRAL antenna. Indeed, the eclipse shares several features with the phenomena observed on Sentinel-3A:

- It impacts only ascending tracks,
- Around 30 degrees of amplitude,
- Its position varies along the year. The positions of the eclipse entries and exits are presented on Table 11.

Figure 56 shows the same metrics as the maps displayed on Figure 55 but averaged along the latitudes, for 2018 summer solstice (left panel) and for 2018 autumn equinox (right panel). A good agreement with the eclipse exit is visible even if the peak on the mispointing difference starts slightly earlier than the expected latitude. No clear influence of the eclipse entry is seen.

The tandem phase does not last enough (4 months) to further investigate this hypothesis. The same diagnosis has then been performed on the difference between Sentinel-3A ascending and descending tracks mispointing, over Sentinel-3A complete lifetime. The results (Figure 57) are noisier than previously, and due to sea ice, the number of valid point is not sufficient to detect a clear pattern below 60°S and above 60°N. Thus, such diagnosis does not allow to detect any correlation to winter solstice and equinox eclipse exit or to equinox and summer solstice eclipse entry, given their latitude. Only, a clear correlation to solar eclipse can be seen for summer solstice.



Further investigations are required to fully assess the effect of the eclipse exit and to quantify a possible thermo-elastic effect either from the platform or from the SRAL antenna.

	Winter solstice	Equinox	Summer solstice
Eclipse entry	-35°N	-60°N	-80°N
Eclipse exit	78°N	52°N	30°N





Figure 55: Gridded maps of the residual difference of P-LRM square off nadir angle between Sentinel-3A and Sentinel-3B, on ascending passes only. The five maps cover the entire Sentinel-3A/Sentinel-3B tandem period where Sentinel-3B operate in SAR mode, i.e. from the 11<sup>th</sup> July to the 16<sup>th</sup> October 2018. Each map covers 20 days.

COLLETE LOCALISATION SATELLITES	Sentinel-3 MPC	Ref.:	S3MPC.CLS.APR.006
	S3MPC STM Annual Performance Report - Year 2019	Issue:	1.0
		Date:	28/02/2020
		Page:	69



Figure 56: Residual difference of P-LRM square off nadir angle between Sentinel-3A and Sentinel-3B, on ascending passes only, averaged in latitude. Computed during the tandem phase over a time period of 20 days centred around the 21<sup>st</sup> June 2018 (summer solstice, left panel) and around the 20<sup>th</sup> September 2018 (autumn equinox, right panel)



Figure 57: Difference of P-LRM square off nadir angle between Sentinel-3A ascending and descending passes, averaged in latitude. Computed over a time period of 60 days around equinox (left panel), summer solstice (middle panel) and winter solstice (right panel).



# 7.3 Wet tropospheric correction

The wet tropospheric correction is a parameter retrieved from MWR brightness temperatures and the altimeter backscattering coefficient. It corrects for the radar excess path delay due to the presence of water vapor in the troposphere.

In Sentinel-3A/B processing, two retrieval algorithms based on neural networks are used for the retrieval of the wet tropospheric correction. First the classical three inputs algorithm (annoted 3P) using the two brightness temperatures from the microwave radiometer and the altimeter backscattering coefficient (Sigma0). This type of algorithm is commonly used for European altimetry mission such as Envisat, or AltiKa. Secondly, an enhanced algorithm (annoted 5P) is proposed taking as additional input parameter the sea surface temperature and the atmosphere temperature lapse rate (the so-called  $\gamma$ 800). The sea surface temperature brings additional information from the surface globally over ocean. The atmosphere temperature lapse rate is more useful over specific areas such as upwelling regions where the temperature lapse rate is very specific to these regions. These two additional parameters are provided to the processor by static maps: seasonal maps (one map for each season) for sea surface temperature, one map for  $\gamma$ 800.

## 7.3.1 Along-track analyses

The monitoring of the wet tropospheric correction is performed by comparison of the difference MWRmodel of the wet tropospheric correction ( $\Delta$ wtc) for several instruments. Figure 58 shows this monitoring for Sentinel-3A, Sentinel-3B, SARAL, and Jason-3 with the daily average of the  $\Delta$ wtc on the left panel, and the standard deviation on the right panel. As this monitoring is performed in a long-term perspective, we used delayed-time products: GDR products for SARAL and Jason3, Non Time Critical (NTC) products for Sentinel-3A and Sentinel-3B. To be consistent with Jason-3 coverage, data for the three missions have been selected below 60° of latitude.

#### Classical Retrieval algorithm (3P)

The monitoring of the daily averaged  $\Delta$ wtc allows to detect abnormal events and potential significant drifts. The first conclusion over the full period of study is that a global bias appears between SARAL, Jason3 which have a mean  $\Delta$ wtc around 0.6cm and Sentinel-3A around 0cm. This bias is considered small and more analysis are required to decide if it shall be corrected. One can notice the same variations of  $\Delta$ wtc for SARAL and Sentinel-3A  $\Delta$ wtc: a period with no trend from January to May 2017, followed with a period with a small trend up to October 2017, and finally a period with no trend. Jason3 shows slightly different variations: it is very similar to AltiKa until June2017, then the  $\Delta$ wtc seems to stay at the same level while AltiKa is increasing, and finally a negative trend is observed. These differences of variations are not yet explained. One has also to keep in mind the order of magnitude of these variations: about 2mm. Sentinel-3B level of  $\Delta$ wtc is around 0.8mm before the update of the MWR characterisation parameters (6<sup>th</sup> December) which provided calibrated parameters to the operational processing. After the 6<sup>th</sup> December, Sentinel-3B is coming much closer to S3A with a residual small bias of 1mm. This result was expected from the analyses carried out during the commissioning phase.

The daily  $\Delta$ wtc standard deviation allows to assess the performance of the correction. The instruments used in this study have different configurations. First Jason3 benefits from its three channels radiometer



(18.7GHz, 23.8GHz, 34GHz), providing a correction with a smaller deviation with respect to the model. SARAL is closer to Sentinel-3A/B in this context with its two channels (23.8GHZ, 37GHz). Then the standard deviation for SARAL is the closest reference. But the SARAL GDR products is issued from the so-called "Patch2" algorithms, known to have issues with the Sigma0 in Ka-band in the simulations used for the learning database. Then the difference between SARAL and Sentinel-3A has to be considered carefully. The standard deviation of  $\Delta$ wtc for Sentinel-3A is smaller than for SARAL meaning that we have a better estimation of the correction for Sentinel-3A according to these metrics. Jason-3 shows the best performances with the smallest deviation. Moreover, one can notice that both SAR and P-LRM corrections have very similar performances, as the two curves are almost on top of each other for both mean and standard deviation. Sentinel-3B standard deviation of  $\Delta$ wtc is around 1.47cm, figure mainly driven by the period before the update of the MWR characterisation file. In the last cycle, we can see that S3A and S3B curves are similar.



Figure 58: Monitoring of MWR (3P) - ECMWF wet tropospheric correction for S3A,S3B, SARAL/AltiKa, Jason3/AMR: mean (left), standard deviation (right)

## SAR/P-LRM difference (3P)

Figure 59 shows the map of the differences of SAR and P-LRM S3A wet tropospheric corrections for the period covered by cycle 26 to 39 of S3A, ie one year. The mean difference is very small, lower than 1mm, but it is not homogeneous. Some patterns appear on this map, driven by the differences of Sigma0 that was discussed earlier in this report. The band from -40° to -80° in latitude shows the strongest differences up to -1mm, where the difference of SAR/P-LRM Sigma0 shows its highest values.





Figure 59: Difference of SAR/P-LRM wet tropospheric correction for Sentinel-3A (cycle 40 to 53)

Figure 60 shows the map of the differences of SAR and P-LRM S3B wet tropospheric corrections for the period covered by cycle 21 to 33 of S3B, ie year 2019. The mean difference is very small, lower than 1mm, close to S3A results. The same patterns appear on this map, driven by the differences of Sigma0.



Figure 60: Difference of SAR/P-LRM wet tropospheric correction for Sentinel-3B (cycle 21 to 33)

#### Enhanced Retrieval algorithm (5P) – Comparison to model

Figure 61 shows the monitoring of **S3A**  $\Delta$ wtc for SAR and PLRM wet tropospheric corrections, using both 3P and 5P retrieval algorithms. We used here the full mission reprocessing of 2018 and operational NTC data. First a small bias is observed between 3P and 5P retrievals of about 2mm. Secondly, the variations of the daily averaged  $\Delta$ wtc is the same for almost all the period of study. The standard deviation of 5P  $\Delta$ wtc is slightly smaller than 3P: for example for P-LRM, standard deviation  $\Delta$ wtc is around 1.35cm with the 5P algorithm, and 1.41cm with the 3P algorithm. This indicates that the 5P algorithm improves the retrieval with respect to 3P algorithm. This improvement will have to be quantified by another diagnosis such as the crossover analysis.





0.2

0.0 tropo.

-0.2

-0.6 -0.8

corr.

Wet -0.4

Figure 61: Monitoring of 3P and 5P MWR - ECMWF wet tropospheric correction for Sentinel-3A

2020

Figure 62 shows the monitoring of S3B Awtc for SAR and PLRM wet tropospheric corrections, using both 3P and 5P retrieval algorithms. First a small bias is observed between 3P and 5P retrievals of less than 2mm. Secondly, the variations of the daily averaged  $\Delta$ wtc is the same for almost all the period of study. The standard deviation of 5P Δwtc is slightly smaller than 3P: for example for P-LRM, standard deviation Δwtc is around 1.38cm with the 5P algorithm, and 1.44cm with the 3P algorithm. We retrieve the same differences 3P-5P for S3B than for S3A.



Figure 62: Monitoring of 3P and 5P MWR - ECMWF wet tropospheric correction for Sentinel-3A

#### Comparison of two algorithms (3P - 5P) – Comparison to model

Figure 63 shows the map of the difference between 5P and 3P algorithms for Sentinel-3A (left panel) and Sentinel-3B (right panel). For Sentinel-3A and Sentinel-3B, the whole year is considered in this map with the use of data from cycle 40 to 53, and cycle 21 to 33 respectively. As seen before with Figure 61, the average difference is small, less than 1mm, but Figure 63 highlights the geographical impacts of the enhanced algorithm. On this map, we retrieve the signature of the sea surface temperature.





Figure 63: Map of the difference 5P - 3P wet tropospheric correction: left: Sentinel-3A (using NTC data; cycle 40 to 53) right: Sentinel-3B (using NTC data; cycle 21 to 33)

#### 7.3.2 Crossover analyses

The analysis of difference of variance of SSH at crossover points allows to assess the improvement or degradation of one correction with respect to the other. The SSH difference between the ascending and descending passes is composed of the variation of oceanic signal between the two passages, the measurement errors and estimation errors of the SSH. For a time lag below 10 days, one can consider that the oceanic variability is negligible. Then the SSH difference at crossover points approximates the errors of the corrections applied to the range for the estimation of the SSH. The lower the variance, the better the correction.

The usual reference for such a diagnosis for wet tropospheric correction is the model correction computed using ECMWF analysis. The computation of SSH is detailed on section 7.3. For this study, we compute the difference of variance at cross-over points when using the MWR WTC or the model correction:

 $\Delta Var = Var(\Delta SSH with MWR WTC) - Var(\Delta SSH with model WTC)$ 

When the correction computed using MWR measurements reduces the error on the SSH,  $\Delta$ Var will be negative as the variance of  $\Delta$ SSH using MWR correction will be smaller than the variance of  $\Delta$ SSH when using the model correction. On the opposite when the correction computed using MWR measurements increases the error on the SSH,  $\Delta$ Var will be positive.

We will start by analyzing the wet tropospheric correction retrieved from the classical algorithm (3P) (Figure 64). The analysis is performed here over the lowest oceanic variability areas. Jason-3 with its three channels AMR shows the best improvement with respect to the model correction with an average of - 2.3cm2, Sentinel-3A is below with -1.8 cm2 for P-LRM correction, and finally SARAL using the Patch2 algorithm (see previous explanation) shows the smaller  $\Delta$ Var (-1.3cm2). Considering Sentinel-3A is a two channels radiometer and we analyze here a classical 3P algorithm, these results are good. Sentinel-3B is



not yet presented in this analysis as only one cycle with calibrated parameters is available at the time of writing this report.



Figure 64: Difference of variance of ΔSSH at crossover points for low oceanic variability for Sentinel-3A, SARAL, Jason3 : var(ΔSSH with PLRM WTC 3P MWR )-var(VSSH with WTC ECMWF) (bottom)



Figure 65: Difference of variance of ΔSSH at crossover points for low oceanic variability for Sentinel-3A, SARAL, Jason3 : var(ΔSSH with SAR WTC 3P MWR )-var(VSSH with WTC ECMWF) (bottom)

Looking at the map of the  $\Delta$ Var (Figure 66), we can see that we have a global improvement when using MWR correction.



Figure 66: Difference of variance of SSH at crossover points SAR (left) / P-LRM (right)

COLLECE LOCALISATION SATELLITES	Sentinel-3 MPC	Ref.:	S3MPC.CLS.APR.006
	S3MPC STM Annual Performance Report - Year 2019	Issue:	1.0
		Date:	28/02/2020
		Page:	76

We perform the same analysis for the enhanced algorithm (5P) again over the lowest oceanic variability areas (Figure 67). Jason-3 with its three channels AMR shows the best improvement with respect to the model correction with an average of -2.3cm2, Sentinel-3A is below with -1.9cm2 for P-LRM correction, and finally SARAL using the Patch3 algorithm (see previous explanation) shows similar results. The SARAL Patch3 algorithm is the next version of the retrieval algorithm based on measurements and not simulation, it corrects the issues seen with the previous algorithm and improves the retrieval using SST and y800. There is room for improvement for Sentinel-3A as its algorithm is based on simulations.



Figure 67: Difference of variance of SSH at crossover points for Sentinel-3A, SARAL/AltiKa, Jason3/AMR: var(SSH with P-LRM WTC 5P MWR)-var(SSH with WTC ECMWF)



Figure 68: Difference of variance of SSH at crossover points for Sentinel-3A, Sentinel-3B, SARAL/AltiKa, Jason3/AMR: var(SSH with SAR WTC 5P MWR)-var(SSH with WTC ECMWF)

As for the 3P algorithm, the maps of the  $\Delta$ Var (Figure 69) show a global improvement when using MWR correction.





Figure 69: Difference of variance of SSH at crossover points SAR (left) / P-LRM (right)

# 7.4 Sea Level Performances

The Sea Level Anomaly is the most well-known parameter estimated from altimetry. It corresponds to the elevation of sea surface, with respect to a reference called Mean Sea Surface (MSS), generated by oceanic variability and climatic phenomena (such as Gulf stream current, El Nino, ...). It is computed as follow:

#### $SLA = Orbit - Altimeter Range - \sum Geophysical corrections - Mean Sea Surface$

Where the geophysical corrections and the MSS are listed and described in the following table:

Correction / mission and version	Sentinel-3A		Jason-3	
	IPF-SM2	IPF-SM2	IPF-SM2	GDR-D
	V06.05	V06.07	V06.10 to V06.15	
Dry troposphere correction		ECI	VWF model	
Dynamical atmospheric correction	MOG2D			
Radiometer wet troposphere correction	3 parameters MWR WTC	3 parameters MWR WTC	3 parameters MWR WTC	AMR GDR-D
Ionospheric correction	Dual Frequency altimeter			
Sea State Bias	SSB Tran et al. (2	2012)		Jason-3 GDR D SSB
Ocean tide correction (including loading tide)	GOT 4.8		FES 2014	GOT 4.8
Earth tide height	Cartwright and Taylor			
Pole tide height	Wahr			
Mean Sea Surface	CNES_CLS_2011		CNES_CLS_2015	CNES_CLS_2011

Table 12: Detail of the standard used to compute Sentinel-3 and Jason-3 SLA and SSH. For Sentinel-3A, over the year 2018, some of these standards have been updated, thus they are detailed as a function of the IPF-SM2 versions.



Sentinel-3 MPC S3MPC STM Annual Performance Report - Year 2019 
 Ref.:
 S3MPC.CLS.APR.006

 Issue:
 1.0

 Date:
 28/02/2020

 Page:
 78

### 7.4.1 Along-track analyses

Figure 70 shows the maps of Sentinel-3A and Sentinel-3B SARM and P-LRM SLA and the one derived from Jason-3. Same geographical structures are observed by both Sentinel-3A and 3B modes and by the three satellites. Over the same time period, SLA mean values and their dispersions are slightly different between Sentinel-3A and Jason-3. They cannot be directly compared since Sentinel-3A coverage reaches latitudes around 81° (against 66° for Jason-3), the analysis of the biases between Sentinel-3A and Jason-3 is described in the next section. Despite a shorter time coverage, Sentinel-3B SLA shows dispersion and mean values close to Sentinel-3A ones.





Figure 70: Gridded maps of Jason-3 (top panel), Sentinel-3A SARM (middle left panel), and P-LRM (middle right panel) SLA computed from April 2016 to December 2019. Gridded maps of Sentinel-3B SARM (bottom left panel) and P-LRM (bottom right panel) SLA computed from November 2018 to December 2019.



The monitoring of the daily averaged SLA (plotted in Figure 71, left panel) allows to detect abnormal events and potential significant drifts. In order to be consistent with Jason-3 global coverage, Sentinel-3A and 3B data have been selected below 66° of latitude. Over the complete time period, the Sentinel-3 temporal variations are consistent with respect to Jason-3. Over Sentinel-3B final orbit, Sentinel-3A and - 3B variations are in perfect agreement both in SARM and in P-LRM.

This monitoring of the mean SLA shows several interesting features:

- The bias between Sentinel-3A SARM and PLRM SLA is of 1 cm, SARM being lower than P-LRM. The average value of SLA is of 4.8 cm in SARM and of 5.8 cm in P-LRM.
- Sentinel-3A P-LRM (SARM) bias is of 3.6cm (2.6cm) against Jason-3. Regarding the SLA biases, it is important to notice that:
  - Sentinel-3A SLA computation uses now CNES-CLS15 MSS over the whole mission lifetime whereas the MSS used to compute Jason-3 SLA is still the MSS CNES-CLS11. The Jason-3 MSS CNES-CLS11 is compute over seven years, thus it generates a bias of around 2.4 cm with respect to the MSS computed over twenty years (due to Global Mean Sea Level increase). It means that if we would have computed the Jason-3 metrics with an updated MSS model, all the biases described previously (when comparing Sentinel-3 and Jason-3 SLA) would be reduced by 2.43 cm.
  - The absolute bias is also sensitive to the SSB model used. In this case, the SSB models used in SLA computation are derived from the products. It is discussed in the next section trough crossover analyses
- The bias between Sentinel-3B SARM and PLRM SLA is of 1.7 cm, SARM being lower than P-LRM. It is 0.7cm higher than for Sentinel-3A. The average value of SLA is of 4.5 cm in SARM and of 6.3 cm in P-LRM.

The monitoring of the SLA standard deviation (Figure 71 right panel) allows to detect potential changes in the long-term stability of the altimeter's system performances. The metric between both Sentinel-3A and 3B modes and for the three satellites are consistent. Over the mission lifetime, Sentinel-3B SARM and P-LRM variances are in perfect agreement with Sentinel-3A SARM and PLRM respectively, both in magnitude and in temporal variation.

Sentinel SARM SLA variance is slightly lower than for P-LRM and Jason-3, it could be explained by the range lower level of noise. The difference in MSS versions can also contribute in Jason-3 slightly higher variance. Indeed, Jason-3 uses the MSS CNESCLS11 over all the period assessed while Sentinel-3A and 3B are using MSS CNESCLS15. It has been shown that the latest model is of better quality (Pujol et al., 2018) and induces a lower variance for the SLA.





Figure 71: Daily monitoring of the Sentinel-3A SARM (blue) and P-LRM (cyan), Sentinel-3B SARM (red) and P-LRM (orange), and Jason-3 (black) mean SLA (top panel) and its standard deviation (bottom panel).

#### 7.4.2 Crossovers

The analysis of Sea Surface Height (SSH) computed at mono-mission crossovers allows to assess the consistency between ascending and descending passes. It also provides a robust metric of the system performances. Indeed, it consists on the analysis of the difference between two independent measurements (from ascending and from descending passes) over a same location for which we consider the oceanic signal constant during the time laps. To make this assumption as reliable as possible we applied criteria to select crossovers with a time lag below 10 days and located in the lowest oceanic variability areas.

Note that the MSS is never taken into account in the SSH computation at crossovers. Thus, the differences between Jason-3 and Sentinel-3 MSS models have no impact.

The monitoring of the mean SSH differences at mono-mission crossovers is computed on a cyclic basis (Figure 72). Until November 2018, a mean bias of 0.6 cm is observed between ascending and descending tracks for Sentinel-3A. This unexpected bias is related to altitude estimation. Indeed, from November, the orbit solution has been changed from POE-E to POE-F and the mean SSH bias has dropped to -0.05 cm (and -0.06 cm for Sentinel-3B). Such values can be considered as negligible, meaning that ascending and



descending tracks are now coherent in terms of SSH measurement for both Sentinel-3A and -3B with the use of POE-F orbit solution.

For the three missions, temporal variations are observed:

- Until November 2018, an annual signal of 0.8 cm of amplitude is observed for Sentinel-3A SARM SSH. Note that this signal has been reduced with the use of FES14 ocean tide. Ocean Tide derived from GOT introduced an annual signal of 1.2cm of amplitude. From November 2018, this amplitude has also been reduced to 0.5 cm with the switch to POE-F orbit solution.
- Sentinel-3B crossover difference variations are in perfect agreement with Sentinel-3A.
- A 120 days signal of 2 cm of amplitude is observed for Jason-3 SSH. The explanation of this signal is detailed in the Jason-3 annual report.



Figure 72: Cycle per cycle monitoring of the SSH differences computed at mono-mission crossovers for Sentinel-3A SARM (blue curve), Sentinel-3B (red curve), and Jason-3 (black curve).

The Sentinel-3A and 3B SARM and P-LRM maps of SSH differences at crossovers are plotted in Figure 73. Top panels show the performance using POE-E orbit on Sentinel-3A (until November 2018), while middle and bottom panels present the results using POE-F orbit over Sentinel-3A lifetime and over Sentinel-3B final orbit. POE-F orbit solution over Sentinel-3A complete lifetime have been provided by CNES. This orbit solution is the one used in the IPF 6.18 deployed in January 2020 and is used for the 2020 reprocessing.

Once the global biases removed, the SSH differences are low, ranging between -2 and 2 cm. SARM and P-LRM maps show similar features, with only some small discrepancies between modes that are still under investigations, namely in a zone in west Australia and in strong wave zones such as the circumpolar. For Sentinel-3A, the same patterns are observed between POE-E and POE-F orbits. These patterns are slightly smoother with POE-F orbit, as shown by the smaller dispersion on the histograms bellow the maps, especially in P-LRM. These geographical structures can partly be related to SWH but also to wind (see section 7.7.1 for more details).

Over Sentinel-3B final orbit, POE-F orbit solution is used. As the time period is shorter than for Sentinel-3A, Sentinel-3B maps (Figure 73 Figure 75 bottom panels) are noisier but the same patterns are visible.

COLLETE LICAUSTION STELLIFES	Sentinel-3 MPC	Ref.:	S3MPC.CLS.APR.006
	S3MPC STM Annual Performance Report - Year 2019	Issue:	1.0
		Date:	28/02/2020
		Page:	82







Figure 73: Gridded maps of SSH differences computed at mono-mission crossovers in SARM (left panels) and in P-LRM (right panels), for Sentinel-3A using POE-E orbit from April 2016 to November 2018 (top panels), for Sentinel-3A using POE-F orbit from April 2016 to December 2019 (middle panels), and for Sentinel-3B using POE-F orbit from November 2018 to December 2019 (bottom panels).

As mentioned previously, the crossover analysis also allows to estimate the mission performance at spatial and temporal mesoscales. The monitoring of the systems error is plotted in Figure 74. The global standard deviations computed are the sum of the 2 arc errors (the ascending and the descending), thus the following metrics were divided by  $\sqrt{2}$  (justified since the hypothesis of decorrelation between the measurements. A selection was applied on latitudes to make consistent the global coverage between Sentinel missions and Jason-3. This estimation still includes a natural residual variation of the sea surface height between the two measurements at the crossover location, thus cannot be null.

Sentinel-3B SSH error is in good agreement with the one derived from Sentinel-3A. For both satellites, this error is stable around 3.8 cm, which is slightly higher than for Jason-3 (3.5 cm). Computing the mean time

COLLETE LOCALISATION SATELLITES	Sentinel-3 MPC	Ref.:	S3MPC.CLS.APR.006
	S3MPC STM Annual Performance Report - Year 2019	Issue:	1.0
		Date:	28/02/2020
		Page:	83

lag for the three missions, it was found that the mean delay is larger for Sentinel-3A (4.6 days) and Sentinel-3B (4.5 days) than for Jason-3 (3.3 days). It means that the ocean surface height has more probabilities to change in the case of Sentinel-3A and 3B crossovers, and thus adds more oceanic signal variability in this metric. Applying a specific selection, we reduced Sentinel-3A and 3B mean time lags to make it consistent with Jason-3. The results (cyan and orange curves) show that Sentinel-3A and 3B and Jason-3 performances are now fully comparable and consistent with a mean value of 3.4 cm at global scale.



Figure 74: Cycle per cycle monitoring of the system error computed at mono-mission crossovers for Sentinel-3A (blue curve), Sentinel-3B (red curve), and Jason-3 (black curve). The system error is computed through the cyclic SSH differences standard deviation at crossovers and divided by  $\sqrt{2}$  because of the cumulation of ascending and descending errors. The cyan and orange curves show respectively Sentinel-3A and Sentinel-3B SARM system error when the mean time lag at crossovers is consistent with the Jason-3 one.

The crossover analysis is also a relevant tool to perform cross calibration between two missions. The following plot (Figure 75) shows the differences at crossovers between Jason-3 and Sentinel-3A (top panels) and Sentinel-3B (bottom panels). For this diagnosis, Jason-3 Sea State bias has been updated with the latest version available (Tran et al., 2012).

Despite to the shorter time period for Sentinel-3B, the observed results are similar for both Sentinel missions. A very good consistency is found with respect to Jason-3 with differences ranging between -2 and 2 cm (once the mean bias is removed). However, the discrepancies are less homogeneous in SARM (left panels) than in P-LRM (right panel). In SARM, positive differences are observed in the South and North hemispheres whereas they are mainly negative between the tropics. These geographical patterns are strongly correlated with the SWH signal as illustrated by Figure 112. In P-LRM, differences are homogenous and very low, a small negative signal is observed between the tropics, the source being still under investigation.

These maps do not highlight the same patterns than the maps at mono-mission crossovers. This confirms that these two metrics complete each other to further understand the residual errors that can affect Sentinel-3A and 3B sea level observations.

The mean biases specified on the maps give the global SSH bias between Sentinel-3A and Jason-3: 2 cm for SARM and 3 cm for P-LRM, and between Sentinel-3B and Jason-3: 1.3 cm in SARM and 3 cm in PLRM. If we use here the sea state bias from Jason-3 product, the biases found are consistent with the SLA monitoring (Figure 71).





Figure 75: Gridded maps of SSH differences computed at Sentinel-3A and Jason-3 crossovers (top panels) and Sentinel-3B and Jason-3 crossovers (bottom panel), in SARM (left panels) and in P-LRM (right panels).

The following plot (Figure 76 top panel) shows the monitoring of the mean bias at crossovers between Sentinel-3A and Jason-3 and between Sentinel-3B and Jason-3. Again here, Jason-3 Sea State bias has been updated with the latest version available (Tran et al., 2012). It highlights several features:

The bias between Sentinel-3A SARM (P-LRM) and Jason-3 equals 2.3 cm (3.1 cm). Considering that Jason-3 SSH is biased by 3cm (Jason-3 SSH being too low by 3 cm compared to Jason-2 SSH), we are left with a bias close to -0.7cm for Sentinel-3A SARM SSH and +0.1cm for Sentinel-3A PLRM SSH.

The mean bias between Sentinel-3B SARM (P-LRM) and Jason-3 equals 1.4 cm (2.9 cm). However, this bias is not constant in time. For both SARM and PLRM modes, an increase of about 8 mm occurs in the end of 2018. This increase is linked to the Processing Baseline 1.13 deployed on the 6<sup>th</sup> December 2018 for Sentinel-3B, which aims at re-centring the Sentinel-3B sigma0 around 11 dB and tuned MWR characterization parameters in order to align the brightness temperatures with S3A. As a result, Sentinel-3B wet tropospheric correction (WTC) derived from the radiometer is not fully homogenous along Sentinel-3B lifetime. This is visible on the difference between radiometer and model WTC (Figure 77). As the differences at crossover are computed using the radiometer WTC in the SSH calculation, the diagnosis presented here is impacted by this processing baseline update. Using the model WTC instead (Figure 76 bottom panel), the bias between Sentinel-3B and Jason-3 remains constant over the whole mission. Such variation in Sentinel-3B radiometer WTC should be corrected in the 2020 reprocessing, as homogenous processing will be used over the whole period.



In 2019, the mean bias between Sentinel-3B SARM (P-LRM) and Jason-3 equals 1.6 cm (3.1 cm). Considering that Jason-3 SSH is biased by 3 cm, we are left with a bias close to -1.4cm for Sentinel-3B SARM SSH and +0.1 cm for Sentinel-3B PLRM SSH.

For Sentinel-3A SARM the result is consistent with the transponder analysis presented in section 11.1, as a bias of +0.67 cm is measured on the range, which gives an underestimation of the SSH.

For Sentinel-3B the results slightly differ as a range bias of -0.68 cm is measured thanks to the transponder technique, giving an expected over estimation of the SSH, whereas the crossover method suggests an underestimation of the Sentinel-3B SSH. The SSH comparison between Sentinel-3A and Sentinel-3B is also not consistent. The transponder analysis would suggest that Sentinel-3B SSH estimations are in average higher than Sentinel-3A SSH however, the contrary is observed over Ocean (Figure 71). This inconsistency between the two methods is under investigation.



Figure 76: Cycle per cycle monitoring of the SSH differences computed at Sentinel-3A and Jason-3 crossovers in SARM (blue curve) and in P-LRM (cyan curve), and at Sentinel-3B and Jason-3 crossovers in SARM (red curve) and in P-LRM (orange curve). Top panel: SSH computed with radiometer Wet Tropospheric Correction, Bottom panel: SSH computed with ECMWF model Wet Tropospheric Correction





Figure 77: Daily monitoring of the difference between WTC derived from radiometer and from ECMWF model, for Sentinel-3B SARM and PLRM, over the mission lifetime.

Cross calibration between Sentinel-3A and Sentinal-3B is also performed using crossover analysis between the two missions. Figure 78 shows the SSH differences maps between S3A and S3B. The geographical discrepancies are relatively smooth, ranging between -2cm and 2 cm. The patterns are similar to the ones observed on mono-mission maps (Figure 73). This confirms once again the consistency between the two missions.

The temporal variations of the mean difference are presented in Figure 79 left panel. As for the monomission crossover, this metric is strongly impacted by the orbit solution update from POE-E to POE-F in November 2018 (solid curves). However, using POE-F orbit for both mission and over the complete period (dashed curves) does not fully remove the bias jump observed in the end of 2018. As for the crossover analysis with respect to Jason-3, results are here impact by the deployment of the processing baseline 1.13 for Sentinel-3B and the resulting variation on S3B radiometer WTC. Indeed, Figure 79 right panel shows that using both POE-F orbit solution and WTC derived from ECMWF model completely remove all strong variation in the SSH bias monitoring.

Note that such effect of processing baseline update was not visible on Sentinel-3B mono-mission crossovers. Indeed, the variations on the radiometer WTC are identical for ascending and descending tracks, and therefore cancelled out when computing the difference at the crossover.

Over the year 2019, the mean bias is of 8 mm in SARM and almost null in PLRM. In June 2019, a review of the Sentinel-3A and -3B SCCDB (Satellite Calibration and Characterisation Database) has been performed. In the IPF 6.18 deployed in January 2020, ocean ranges take into account the new recommended values. With these new values, Sentinel-3B range decreases by 9 mm. Hence, with the 2020 reprocessed datasets, we should no longer see SSH bias at crossovers between S3A and S3B in SARM.

As mentioned previously, the biases found are not fully consistent with respect to the transponder analyses as here over ocean, Sentinel-3B SSH estimations are in average lower than the Sentinel-3A ones, whereas this is the contrary with transponder analyses (see section 11.1). This inconsistency between the two methods is under investigation.
COLLETE LOCALISATION SATELLIFES	Sentinel-3 MPC	Ref.:	S3MPC.CLS.APR.006
	S3MPC STM Annual Performance Report - Year 2019	lssue:	1.0
		Date:	28/02/2020
		Page:	87

The regional SSH absolute bias estimation performed over the Corsica CalVal site (see section 11.2) provide a similar result as for the transponder analysis: The Sentinel-3B SSH is higher than the Sentinel-3A SSH.



Figure 78: Gridded maps of SSH differences computed at crossovers between Sentinel-3A and Sentinel-3B in SARM (top left panel) and in PLRM (top right panel) over Sentinel-3B final orbit.



Figure 79: Cycle per cycle monitoring of SSH differences computed at Sentinel-3A/Sentinel-3B crossovers in SARM (blue curve) and in P-LRM (cyan curve). Dash lines represent SSH computed using POE-F orbit solution over the whole period. Left panel: SSH computed with radiometer Wet Tropospheric Correction, Right panel: SSH computed with ECMWF model Wet Tropospheric Correction.

The mono-mission crossover analysis also allows to compute a pseudo time tag bias by computing the regression between SSH differences and orbital altitude rate ( $\dot{H}$ ), also called satellite radial speed:

#### $\Delta$ SSH = $\alpha \dot{H}$

This method allows to estimate the time tag bias, but it can also absorb other errors correlated with H as for instance orbit errors. Therefore, it is called pseudo time tag bias. Figure 80 shows the monitoring of the pseudo datation bias for Sentinel-3A, Sentinel-3B, SARAL/AltiKa and Jason-3 on a cyclic basis. Sentinel-3A and Sentinel-3B pseudo time tags present coherent values and follow the same temporal variations.

In average, Sentinel-3A SARM presents a pseudo time tag of the same order as SARAL/AltiKa in absolute value (respectively 6.8 $\mu$ s and -7.6 $\mu$ s) and smaller than Jason-3 in absolute value (-29.6  $\mu$ s). Moreover Sentinel-3A and Sentinel-3B pseudo time tag bias presents an annual signal as oserved for the monitoring

COLECTE LOCALISATION SATELLIES	Sentinel-3 MPC	Ref.:	S3MPC.CLS.APR.006
	S3MPC STM Annual Performance Report - Year 2019	Issue:	1.0
		Date:	28/02/2020
		Page:	88

of the SSH differences between ascending and descending tracks. The amplitude of this annual signal is of about 250µs. These temporal variations are still under investigations. They are not consistent with the measure of time tag bias performed at Gavdos transponder (where the time tag bias estimation seems more stable around -125 us for Sentinel-3A and -26 us fors Sentinel-3B).



Figure 80: Cycle per cycle monitoring of the pseudo time tag bias for Sentinel-3A (blue curve), Sentinel-3B (orange curve), Jason-3 (black curve) and SARAL/AltiKa (green curve). The pseudo time tag biases are computed at mono-mission crossovers.

## 7.5 Global Mean Sea Level

The Global Mean Sea Level (GMSL) is one of the most important indicators of the climate change. In the past two decades, sea level has been routinely measured from space using satellite altimetry techniques.

Recently, an instrumental drift was detected on the Sentinel-3a (S3-a) data. It has an impact on the estimates of parameters such as waves (SWH) or altimeter distance (Range). Preliminary analyses have demonstrated that the drift of the PTR (Point Target Response) shape, not perfectly accounting for in the retracking algorithms, impacts these parameters in both P-LRM and SAR modes. Its impact on sea level evolution is about -0.3 mm/yr according to preliminary findings. See section 7.7.2 and Poisson et al, OSTST 2019 and Dinardo et al., OSTST 2019). The following results aim at verifying and precisely characterizing this instrumental drift in the evolution of the global mean sea level (GMSL), by analysing it in terms of uncertainties in order to describe its statistical relevance, as well as to discuss on its possible impact on climate studies.

In order to calculate the GMSL S3-a, the same algorithms as for the reference GMSL distributed under AVISO and calculated from TOPEX data, and JASONs have been deployed. For the SAR mode, the reference data used as inputs are the "marine" S3-a mission delayed time L2P products (available under AVISO) available from July 2016 to January 2019. For the PLRM mode, the reference data used are the "marine" NTC L2 data.



The GMSL of the S3-a mission thus calculated is compared with the GMSL of the Jason-2, Jason-3 and SARAL/Altika missions over the periods concomitant to all these missions. This allows us to estimate the relative drifts of the GMSL S3a to all these missions.

Two separate periods were also analysed, as the Jason-2 data are not of sufficient quality to be used over the entire period of S3a:

- The first period S3-a and Jason-3/SARAL-Altika which extends over almost 3 years from the beginning of July 2016. Jason-2 data have not been used during this period.
- The second period S3-a/Jason-2 which extends over a little more than 1 year from the beginning of July 2016 to August 2017. Data from GMSL Altika and Jason-3 have also been used over this period.

On the other hand, comparisons of the GMSL series were made with the tropospheric correction from the radiometer as well as those of the ECMWF models. The use of the model only allows to focus on the instrumental drift related to the altimeter.

Given the relatively short period of the analysis window (~3 years), the precise calculation of uncertainties is crucial to determine whether the observed drifts are statistically significant or not. To do this, the error budget based on the comparison of 2 series of GMSL from two different altimetry missions was established based on the work carried out by Ablain et al. in 2019. From this error budget, the variance-covariance matrix of the errors was calculated, and thus makes it possible to calculate the uncertainties of the different drifts of the GMSL between missions in a realistic way and in controlled confidence intervals.

#### Results on the SAR mode

The results presented in Figure 81 cover the full S3-a period (~3 years). A S3-a GMSL drift is detected by comparison with both SARAL-ALtika (AL) and Jason-3 (J3) missions when the wet tropospheric correction derived from the ECMWF model is applied (on left side) :

- ◆ Δ GMSL S3A-J3 = 1.77 mm/yr ±1.26 mm/yr
- \* Δ GMSL S3A-AL= 2.13 mm/yr ± 1.28 mm/yr





#### Figure 81 - S3-a GMSL trend differences in SAR mode, with Jason-3 and SARAL-AltiKa

The drifts observed are consistent together and are within the 1-sigma confidence interval. This means that no GMSL drift is detected between Jason-3 and SARAL/Altika.

The results presented in Figure 82 are restricted to the common period S3-a/Jason-2. A S3-A GMSL drift is also detected by comparison with Jason-2 (J2), Jason-3 (J3) and SARAL/Altika (AL) when the wet tropospheric correction derived from the ECMWF model is applied (on left side) :

- Δ GMSL S3A-J3 = 3.1 mm/yr ± 2.71 mm/yr
- ☆ Δ GMSL S3A-AL= 5.4 mm/yr ± 2.74 mm/yr
- ◆ Δ GMSL S3A-J2 = 4.8 mm/yr ± 2.63 mm/yr

Although uncertainties are much higher than on the full S3-a period, the S3-a GMSL drift is significant and very likely higher than on the full S3-a period. On the other hand, no significant drift are detected between Jason-2, Jason-3 and SARAL/Altika.

To the right (black curves) of Figure 81 and Figure 82, the same analyses are presented by applying the wet tropospheric correction of on-board microwave radiometers. Results are quite different indicating discrepancies in terms of long-term stability between the different radiometers.





Figure 82 - S3-a GMSL trend differences in SAR mode, with Jason-2, Jason-3 and SARAL-AltiKa, over the full S3-a/Jason-2 common period

#### Results on the PLRM mode

Figure 83 shows the S3-a drift obtained for the PLRM mode with the other altimeter missions, Jason-3 and SARAL/Altika. No significant drifts are detected with any of the two missions, regardless of the wet tropospheric corrections that we used (i.e., radiometer or model):

- \* Δ GMSL S3A-J3 (radiometer) = 0.28 mm/yr  $\pm$  1.31 mm/yr
- Δ GMSL S3A-AL(radiometer)= 0.73 mm/yr ± 1.31 mm/yr
- \* Δ GMSL S3A-J3 (model) = -0.72 mm/yr ± 1.31 mm/yr
- \* Δ GMSL S3A-AL(model)= 0.83 mm/yr ± 1.31 mm/yr

	Sentinel-3 MPC	Ref.:	S3MPC.CLS.APR.006
	S3MPC STM Annual Performance Report - Year 2019	Issue:	1.0
		Date:	28/02/2020
		Page:	92



#### GMSL trend differences on S3A/AL/J3 period (07/2016 to 02/2019)

Figure 83 - S3-a GMSL trend differences in PLRM, with Jason-3 and SARAL-AltiKa

To summarize, a S3-a drift is likely detected in SAR mode by comparison with other altimeter missions. This drift is close to 2.0 mm/yr over the full S3-a period but it is stronger from June 2016 to October 2017. This S3-A drift is significantly higher than the 0.3-0.4 mm/yr expected due the PTR drift (See section 7.7.2 and Poisson et al, OSTST 2019 and Dinardo et al., OSTST 2019).

Such drift is not observed with the PLRM mode of S3-a, at least over the period 07.2016 to 02.2019. when compared to other altimeter missions. This non-drift is statistically significant at 1-sigma.

Further investigations are needed to explain these observations. Part of them are described in Section 7.7.3.1

## 7.6 Wind/Wave Performance

Radar backscatter (sigma0), surface wind speed (WS) and significant wave height (SWH), which are part of Seninel-3 Surface Topography Mission Level 2 Marine Ocean and Sea Ice Areas (SRAL-L2MA) also known as SR\_2\_WAT, are monitored and validated using the procedure used successfully for the validation of the equivalent products from earlier altimeters. The procedure is described in Appendix A of the cyclic reports. The procedure composed of a set of self-consistency checks and comparisons against other sources of data. Model equivalent products from the ECMWF Integrated Forecasting System (IFS) and insitu measurements available in NRT through the Global Telecommunication System (GTS) are used for the validation.



The validation is based on the NRT operational Sentinel-3 Surface Topography Mission Level 2 (S3 STM L2) wind and wave marine products (SR\_2\_WAT) product from both Sentinel-3A and Sentinel-3B. For the time being, the product distributed by EUMETSAT in netCDF through their Online Data Access (ODA) system is used after converting into ASCII format but this will be replaced by the formal BUFR (Binary Universal Form for the Representation of meteorological data) format whenever becomes operationally available. The raw data product is collected for 6-hourly time windows centred at synoptic times (00, 06, 12 and 18 UTC).

The data are then averaged along the track to form super-observations with scales compatible with the model scales of around 75 km. It is worthwhile mentioning that the model scale is typically several ( $4^{8}$ ) model grid spacing. This corresponds to 11 individual (1 Hz) Sentinel-3 observations (7 km each).

To achieve this, the stream of altimeter data is split into short observation sequences each consisting of 11 individual (1-Hz) observations. A quality control procedure is performed on each short sequence. Erratic and suspicious individual observations are removed and the remaining data in each sequence are averaged to form a representative super-observation, providing that the sequence has enough number of "good" individual observations (at least 7). The super-observations are collocated with the model and the in-situ (if applicable) data. The raw altimeter data that pass the quality control and the collocated model and in-situ data are then investigated to derive the conclusions regarding the data quality. The details of the method used for data processing, which is an extension to the method used for ERS-2 RA analysis and described in Abdalla and Hersbach (2004), can be found in Appendix A of the cyclic reports.

This annual assessment of wind and wave products focuses on the year 2019 (from 1 January to 31 December 2019). Both Sentinel-3A and Sentinel-3B wind and wave products are assessed against ECMWF model fields, in-situ measurements and measurements by other altimeters.

## 7.6.1 Backscatter coefficient

The ice-free ocean normalised Radar backscatter coefficient (backscatter,  $\sigma^{\circ}$  or Sigma-0) from Sentinel-3A SR\_2\_WAT product seems to be reasonable and compares well with that from other altimeters. The backscatter global histogram (or the probability density function, PDF) of Sentinel-3A and Sentinel-3B SRAL instruments for the year of 2019 are shown in Figure 84. Both PDF's are almost identical. Both PDF's of 2019 do not deviate much from Sentinel-3A PDF of last year. Sentinel-3A and Sentinel-3B backscatter PDF's compare quite well with those of other Ku-band altimeters as shown in Figure 85. This can be clearly seen after applying proper shift of each PDF as shown in the legend of Figure 85 (b). Of course, the exception is SARAL/AltiKa which is a Ka-band altimeter.



Figure 84: Sentinel-3A and Sentinel-3B SRAL backscatter coefficient PDF's over the whole global ocean for year 2019. PDF of Sentinel-3A from 2018 is also shown.

The time series of the global (ice-free ocean only) mean and standard deviation (SD) of backscatter coefficients from SRAL of Sentinel-3A and Sentinel-3B are shown in Figure 86. The temporal change in the mean and the SD of backscatter of Sentinel-3A SRAL is not much different than the other altimeters (not shown). The plot shows the average of a moving window of 7 days moved by one day at a time to produce smooth plots. To emphasise the long-term changes, 92-day running means are also shown. Both the mean and the SD of the backscatter are stable (within ~ 0.3 dB) for most of 2019. The global mean ocean backscatter values from Sentinel-3A and Sentinel-3B are very close. Sentinel-3B value is slightly higher by about 0.1 dB. This difference started to increase gradually in the second half of the year until it reached about 0.3 dB. The standard deviation of the backscatter from both satellites are very close to each other. However, there are some minor differences. Sentinel-3A showed slightly higher variability (SD) in the first half of the year. This was reversed in the second half. This may be a consequence of the fact that both altimeters do not sample the global ocean at the same time.

Both global backscatters mean and SD from both satellites show a seasonal cycle with peaks during the northern hemispheric summer. The cycle is clearer during 2019 compared to the previous period. The cycle in the mean backscatter is not as clear as the cycle in the SD as can be seen in Figure 86. This in line with the change in storminess in the Northern Hemisphere.





Figure 85: Panel (a): Comparison between backscatter PDF's of various altimeters for year 2019. Panel (b): Better comparison can be carried out when PDF's are shifted to have their peak estimates coincide with that of Sentinel-3A. The amount of shift is given in the legend of panel (b).





Figure 86: Time series of global mean (top) and standard deviation (bottom) of backscatter coefficient of SRAL Ku-band from both Sentinel-3A andSentinel-3B after quality control. Mean and SD are computed over a moving time window of 7 days and are shown as thin lines. The 92-day running means are shown as thick lines. Vertical dashed lines show events which may have impact on the comparison. This includes changes to Sentinel-3 STM Instrument Processing Baseline (PB).

#### 7.6.2 Altimeter Wind Speed

Figure 87 shows the global wind speed probability density function (PDF) of Sentinel-3A and Sentinel-3B SAR mode for the whole year 2019. The PDF's of the ECMWF Integrated Forecast System (IFS) model wind speed collocated with both altimeters during the same period is also shown. Although the PDF of Sentinel-3A wind speed is close to that of the model, there are some deviations especially around the peak of the PDF. Sentinel-3B PDF is slightly more peaked compared to that of Sentinel-3A while PDF's of both altimeters are more peaked than their ECMWF model counterparts.

The deviation between Sentinel-3A and Sentinel-3B PDF's and those of the other altimeters are more pronounced as can be seen in the upper panel of Figure 88. The PDF's of model colocations with each satellite are shown in the lower panel of Figure 88. The deviation among the model PDF's as sampled along the ground tracks of each altimeter (i.e. the colocation with the altimeter super-observations) is not large. This suggests that the wind speed measurements from various altimeters show non-negligible deviations (at least in their PDF distributions).





Figure 87: Sentinel-3A and Sentinel-3B SRAL surface wind speed PDF over the whole global ocean for year2019. The corresponding ECMWF (collocated with Sentinel-3A and Sentinel-3B) PDF's are shown for comparison. The 2018 PDF's of Sentinel-3A and its model counterpart are also shown.

The time series of the global mean and standard deviation (SD) of the wind speed from Sentinel-3A and Sentinel-3B over a 7-day time window moving by 1 day at a time are shown in the upper and lower panels, respectively, of Figure 89. The time series of model collocated with Sentinel-3A is also shown for comparison. The time series of model collocated with Sentinel-3B is not different from the shown one (collocated with Sentinel-3A). To emphasise the long-term changes, 92-day running means are also shown.

According to Figure 89, the global mean of Sentinel-3B SAR wind speed is very close to that of the ECMWF model. Sentinel-3A mean is slightly higher than both by about 0.15 m/s. The SD of Sentinel-3A is systematically higher than Sentinel-3B. The model wind speed SD is closer to Sentinel-3A. The differences, however, are not large.

During 2019, there is a clear seasonal cycle in the global wind speed SD. This cycle shows itself in both Sentinels as well as the model (see Figure 89).





Figure 88: Panel (a): Comparison between wind speed PDF's of various altimeters for year2019. Panel (b): The corresponding ECMWF model PDF's as collocated with the measurements. The abbreviations are as follows: S3A: Sentinel-3A, S3B: Sentinel-3B, J3: Jason-3, CS2: CryoSat-2, and SA: SARAL/AltiKa.





Figure 89: Time series of global mean (top) and standard deviation (bottom) of wind speed from SRAL Ku-band after quality control from both Sentinel-3A and 3B. The collocated model wind speed mean and SD are also shown. Mean and SD are computed over a moving time window of 7 days (shown as thin lines). The 92-day running means are shown as thick lines. Vertical dashed lines show events which may have impact on the comparison. This includes Sentinel-3 STM Instrument Processing Baseline (PB) changes as well as ECMWF IFS model changes like CY43R3.

Collocated pairs of altimeter super-observation and the analysed (AN) ECMWF model wind speeds are plotted in a form of a density scatter plot in Figure 90 for the whole globe over the whole year of 2019. Panel (a) is for Sentinel-3A while panel (b) is for Sentinel-3B. The scatter plots in Figure 90 and other similar wind speed scatter plots that appear hereafter represent two-dimensional (2-D) histograms showing the number of observations in each 2-D bin of 0.5 m/s × 0.5 m/s of wind speed.



 Ref.:
 S3MPC.CLS.APR.006

 Issue:
 1.0

 Date:
 28/02/2020

 Page:
 100



Figure 90: Global comparison of Sentinel-3A and Sentinel-3B, in panels (a) and (b), respectively, SAR surface wind speed against ECMWF model analysis for the year 2019. Number of colocations in each 0.5 m/s x 0.5 m/s 2D bin is color-coded as in the legend. The crosses are the means of the bins for given x-axis values (model) while the circles are the means for given y-axis values (Sentinel-3).



According to Figure 90 the agreement between global Sentinel-3A and Sentinel-3B winds, on one side, and their model counterpart, on the other, is very good with virtually no bias (except for slight bias at high wind speed values). The symmetric slope, which is another measure for the bias is about 1.0. The standard deviation of the difference (SDD) with respect to the model, which can be used as a proxy to the random error, is 1.07 m/s for both altimeters. That value corresponds to a scatter index (SDD normalised by the mean of the model) OF 13.9%. The correlation coefficient is higher than 0.95. The other statistics are shown in the offset of the two panels of Figure 90. These values are better than the equivalent statistics from the other altimeters.

The comparison against in-situ (mainly buoy) observations for the same period is shown in panels (a) and (b) of Figure 91 for Sentinel-3A and Sentinel-3B, respectively. Sentinel-3A bias against in-situ observations for this period is rather small (less than 0.1 m/s). Sentinel-3B underestimate wind speed by about 0.2 m/s compared to in-situ observations. The SDD is less than 1.4 m/s which is about 16% of the mean. The correlation coefficient is higher than 0.92 and can be read from both panels of Figure 91. These figures are similar to the same statistics emerging from the comparison of wind speeds from other altimeters against in-situ observations (not shown). It is important to state that most of in-situ observations are located in the Northern Hemisphere around the American and European coasts.

The time series of the wind speed weekly bias (defined as the altimeter – model) and the standard deviation of the difference (SDD) of Sentinel-3A and Sentinel-3B compared to the ECMWF model analysis (AN) are shown in the upper and lower panels, respectively, of Figure 92 and Figure 93, respectively. Since early December 2016, when the processing baseline PB 2.09 was implemented operationally, Sentinel-3A wind speed has been very good as can be seen from Figure 92. The same happened to Sentinel-3B since early December 2018 with PB 1.13 as can be seen from Figure 93.

The wind speed biases in Northern Hemisphere (NH, area to the north of latitude  $20^{\circ}$ N), Tropics (the area confined between latitudes  $20^{\circ}$ N and  $20^{\circ}$ S) and Southern Hemisphere (SH, area to the south of latitude  $20^{\circ}$ S) are very small values (well within  $\pm 0.5$  m/s). The bias and SDD with respect to the model in the NH and SH follow seasonal cycles which peak during the hemispheric winter and becomes lowest during the summer. The amplitude of the bias seasonal cycle is about 1 m/s and 0.5 m/s in the NH and SH, respectively. On the other hand, the amplitude of the SDD seasonal cycle is about 0.4 m/s and 0.2 m/s in the NH and SH, respectively. The bias and the SDD in the Tropics have been fairly constant since early December 2016.

The time series of the wind speed monthly bias (defined as the altimeter – in situ) and the SDD of Sentinel-3A compared to the in-situ measurements are shown in the upper and lower panels, respectively, of Figure 94. Similar plots for and Sentinel-3B are shown in Figure 95. Similar picture to that of the comparison against the model emerges. Noting that most of the buoy measurements are carried out in the NH, the "global" buoy comparison is nothing but a NH comparison. This is clear when comparing the time series of the bias and the SDD with respect to the in-situ measurements ("global" line in Figure 94) to the NH time series with respect to the model (Figure 92 and Figure 93). Similar seasonal cycles to those seen in the model comparison (Figure 92 and Figure 93) for the NH can be also seen in Figure 94 and Figure 95.



## Sentinel-3 MPC S3MPC STM Annual Performance

Report - Year 2019

 Ref.:
 S3MPC.CLS.APR.006

 Issue:
 1.0

 Date:
 28/02/2020

 Page:
 102



Figure 91: Same as Figure 90 but the comparison is done against in-situ observations (mainly in the NH).





Figure 92: Time series of weekly wind speed bias defined as altimeter - model (top) and standard deviation of the difference (bottom) between Sentinel-3A SRAL Ku-band and ECMWF model analysis.



Figure 93: Same as Figure 92 but for Sentinel-3B.



Figure 94: Time series of weekly wind speed bias defined as altimeter - buoy (top) and standard deviation of the difference (bottom) between Sentinel-3A SRAL Ku-band and in-situ (buoy) measurements.



Figure 95: Same as Figure 94 but for Sentinel-3B.



The time series of the global wind speed weekly bias and SDD of 6 altimeters (including Sentinel-3A and Sentinel-3B) compared to the ECMWF model AN are shown in the upper and lower panels, respectively, of Figure 96. It is clear that during year 2019 the wind speed from Sentinel-3B shows the best agreement with the ECMWF model winds. It has the lowest global bias (almost zero) and one of the lowest SDD values. Sentinel-3A winds are the second best with small bias and a slightly higher SDD.

Keeping in mind that Jason-3, CryoSat-2, SARAL/AltiKa and Jason-2 are all conventional altimeters (the CryoSat-2 statistics in Figure 96 are for LRM only), it is possible to conclude that Sentinel-3A and Sentinel-3B SAR wind speed are as good as (if not better than) their counterparts from the conventional altimeters.



Figure 96: Time series of weekly global wind speed bias defined as altimeter - model (top) and standard deviation of the difference (bottom) between various altimeters (including SRAL) and ECMWF model analysis. Sentinel-3B curves are same as the global curves in Figure 93 while those of Sentinel-3A are different than those in Figure 92 since reprocessed data were used before December 2018.

The geographical distribution of the mean Sentinel-3A and Sentinel-3B wind speed values and the wind speed bias, SDD and scatter index (SI, defined as the SDD divided by the model mean and expressed in percentage) with respect to the ECMWF model averaged over the whole year of 2019 are shown in Figure 97 for Sentinel-3A and in Figure 98 for Sentinel-3B. While the mean Sentinel-3A wind speed, the SDD and SI distributions all look similar to their counterparts from other altimeters (not shown), the bias in panel (b) is rather low almost everywhere.



**S3MPC STM Annual Performance** 

Report - Year 2019

Ref.: S3MPC.CLS.APR.006 Issue: 1.0 28/02/2020 Date: 106 Page:

Satellite: Sentinel-3A (a)

Sat. Mean Wind Speed [m/s]





Figure 97: Geographical distribution of mean Sentinel-3 wind speed (a) as well as the bias (b); the SDD (c) and the SI (d) between Sentinel-3 and ECMWF model AN during the whole year of 2019. Bias is defined as altimeter model.



**S3MPC STM Annual Performance** 

Report - Year 2019

Ref.: S3MPC.CLS.APR.006 Issue: 1.0 28/02/2020 Date: 107 Page:

## (c)



Satellite: Sentinel-3A Wind Speed SI (Sat-Mod) [%] For period between 21:19:26UTC on 31.12.2018 and 20:59:56UTC on 31.12.2019 (d)



Figure 97: Continued.



**S3MPC STM Annual Performance** 

Report - Year 2019

Ref.: S3MPC.CLS.APR.006 Issue: 1.0 28/02/2020 Date: 108 Page:

#### Satellite: Sentinel-3B (a)





Figure 98: As in Figure 97 but for Sentinel-3B.



**S3MPC STM Annual Performance** 

Report - Year 2019

Ref.: S3MPC.CLS.APR.006 Issue: 1.0 28/02/2020 Date: 109 Page:

(c)



Satellite: Sentinel-3B Wind Speed SI (Sat-Mod) [%] For period between 21:03:05UTC on 31.12.2018 and 20:56:58UTC on 31.12.2019 (d) 150°V 60' 120 150°E 180°E



Figure 98: Continued.



Sentinel-3 MPC S3MPC STM Annual Performance Report - Year 2019 
 Ref.:
 S3MPC.CLS.APR.006

 Issue:
 1.0

 Date:
 28/02/2020

 Page:
 110

#### PLRM Wind Speed:

Collocated pairs of Pseudo Low-bit Rate Mode (PLRM) wind speed super-observation and the analysed (AN) ECMWF model wind speeds are plotted in a form of a density scatter plot in Figure 99 for the whole globe over the whole year of 2019. It is clear that the agreement between Sentinel-3A and Sentinel-3B PLRM winds and their model counterparts is very good. Sentinel-3A and Sentinel-3B PLRM winds are globally unbiased (0.19 m/s and 0.07 m/s, for Sentinel-3A and Sentinel-3B, respectively) when compared to the model. However, small regional biases do exist (see for example the upper panel of Figure 100). The SDD between PLRM wind from both Sentinels and the model for the same period is 1.4 m/s (about 18% of the mean) which is slightly higher than that of SAR winds (see Figure 90). The correlation coefficient of 0.925 is slightly lower than that of the SAR-mode wind comparison (see Figure 90).

The time series of the weekly bias and the SDD between PLRM wind speed and that of the model are shown in Figure 100 for Sentinel-3A and in Figure 101 for Sentinel-3B. Sentinel-3A PLRM wind bias with respect to the model is very small. The SDD is rather small but higher than that of SAR wind product with periods of slight deteriorations (in a form of increased SDD values) especially in the NH during the summer period (roughly from June to August). The bias and the SDD time series in the NH and SH shown in Figure 100 follow seasonal cycles similar to seasonal cycles followed by the corresponding time series of the SAR-model wind speed bias and SDD (Figure 92).

There has been a clear drop in the SDD between PLRM wind from both altimeters and the model between early September 2018 and late May 2019 (lower panels of Figure 100 and Figure 101). For the time being there is no explanation for that drop which seems to be artificial.



## Sentinel-3 MPC S3MPC STM Annual Performance

Report - Year 2019

 Ref.:
 S3MPC.CLS.APR.006

 Issue:
 1.0

 Date:
 28/02/2020

 Page:
 111



Figure 99: Global comparison of Sentinel-3A and Sentinel-3B, in panels (a) and (b), respectively, PLRM surface wind speed against ECMWF model analysis for the year 2019. Refer to Figure 90 for the meaning of the crosses and the circles as well as the colour coding.





Figure 100: Time series of weekly Sentinel-3A PLRM wind speed bias defined as altimeter - model (top) and standard deviation of the difference (bottom) between SRAL PLRM and ECMWF model analysis.



Figure 101: Same as Figure 100 but for Sentinel-3B



### 7.6.3 Significant Wave Height

Since the wave model at ECMWF assimilates altimeter significant wave height (SWH) data, the practice is to the model first guess (FG) which is practically a short-term forecast. The analysis model fields, which represent the best available state of the atmosphere, are not suitable for assessing SWH. The use of the FG reduces the impact of error correlation between the model and Sentinel-3 SRAL SWH that may be conveyed through data assimilation.

Figure 102 shows the global SWH PDF of Sentinel-3A and Sentinel-3B for the whole year of 2019. For comparison, Figure 102 shows the PDF's of Sentinel-3A for 2018 and the ECMWF model FG SWH collocated with each altimeter/period. The PDF's from both altimeters are almost identical. Note that 2019 Sentinel-3A PDF's are covered almost totally by the 2019 Sentinel-3B PDF's. Both PDF's compare very well with Sentinel-3A PDF of 2018. Sentinel-3 PDF's differ from their model counterparts around the peak of the distribution (at SWH of about 2 m) where the model shows enhanced peaks. Furthermore, Sentinel-3 PDF's show clear humps at SWH values of less than 1 m.



Figure 102: Sentinel-3A and Sentinel-3B SRAL SWH PDF's over the whole global ocean for the year 2019. The corresponding ECMWF wave model (collocated with Sentinel-3A and Sentinel-3B) PDF's are shown for comparison. The Sentinel-3A PDF's are covered by those of Sentinel-3B. The 2018 PDF of Sentinel-3A and its model counterpart are also shown.

The SWH PDF's from the altimeters on-board Jason-3, CryoSat-2 (only LRM data are used here), and SARAL/AltiKa, which are all conventional altimeters or, in the case of CryoSat-2, operating in a conventional mode, are shown in upper panel of Figure 103 together with the corresponding Sentinel-3A and Sentinel-3B SAR SWH PDF's. The SWH PDF's for model colocations with each altimeter are shown in the lower panel of Figure 103. The data used to produce those PDF's cover the whole of 2019.



The deviation among the model PDF's as sampled along the ground track of each altimeter (i.e. only the model points that are collocated with the altimeter super-observations) is not large. However, the deviation between Sentinel-3A and Sentinel-3B SWH PDF and those of the other altimeters is very clear. Except for that of CryoSat-2, SWH PDF's of the other altimeters are in better agreement with their corresponding model PDF's than those of both Sentinel-3 altimeters. To eliminate the impact of the possible geographical sampling (as Jason-2/3 cannot visit areas beyond latitudes 66°), the PDF's for the global ocean region extending between 65°N and 65°S (which is common for all altimeters considered here) were compared (not shown) and only marginal differences from those shown in Figure 103 (whole globe) cold be seen. This suggests that Sentinel-3A and Sentinel-3B SAR (and CryoSat-2 in LRM) SWH products deviate from those of other altimeters and from their model counterparts.

The time series of the global mean and standard deviation (SD) of the SWH from Sentinel-3A and Sentinel-3B averaged over a 7-day time window moved by 1 day at a time are shown in the upper and lower panels, respectively, of Figure 104. The corresponding time series of the model as collocated with Sentinel-3 are also shown for comparison. Sentinel-3 mean and standard deviation are not much different from those of the model (and the other altimeters). The slightly higher Sentinel-3 SWH standard deviation compared to the model and the other altimeters (not shown) cannot be attributed to the fact that SAR mode has higher resolution compared to the conventional altimetry (LRM). The comparison is done at the scale of the super-observations (about 75 km) and, therefore, the impact of the high frequency variability in the SAR altimetry (below the 1-km scale) is eliminated. Therefore, this enhanced Sentinel-3 SWH variability and higher mean values indicate that fine tuning to SWH retrieval may be needed.

Figure 104 suggests that Sentinel-3B global mean and standard deviation are very close to those of Sentinel-3A. The only difference is Sentinel-3B mean SWH is consistently slightly lower than that of Sentinel-3A.

Collocated pairs of Sentinel-3A and Sentinel-3B altimeter super-observation and the ECMWF model SWH FG are plotted as density scatter plots in Figure 105 for the whole globe over the whole year of 2019. Panel (a) is dedicated to Sentinel-3A (one year) while panel (b) is dedicated to Sentinel-3B (six months only). The SWH scatter plots (Figure 105 and other similar wave height scatter plots that appear hereafter) are plotted similar to those of the wind speed (e.g. Figure 90) except for the size of the 2-D bin which is 0.25 m × 0.25 m in the case of SWH. It is clear from Figure 105 (a) that the agreement between SWH from both Sentinel-3 altimeters and their model counterpart is very good except for a slight underestimation at SWH values below ~ 2 m and an overestimation at moderate to high SWH's (above ~4 m). The underestimation at lower wave heights, although less noticeable, is not noticed in the case of other altimeters.

In general, compared to ECMWF model, SAR SWH from Sentinel-3A and Sentinel-3B is unbiased (global bias is less than 2 cm). The SDD between the altimeter and the model is about 0.27 m (or about 10.2% of the mean value). The correlation coefficient is 0.984 which is quite high. These figures indicate that apart from the underestimation at low wave heights, the quality of Sentinel-3A and Sentinel-3B SAR SWH products is rather high.





Figure 103: Panel (a): Global SWH PDF's from various altimeters, including Sentinel-3A and Sentinel-3B SRAL's, for the year 2019. The corresponding ECMWF (collocated with each altimeter) PDF's are shown in panel (b) for comparison.





Figure 104: Time series of global mean (top) and standard deviation (bottom) of significant wave height from Sentinel-3A and Sentinel-3B SRAL Ku-band after quality control. The collocated ECMWF model SWH mean and SD are also shown. The mean and SD are computed over a moving time window of 7 days.

The wave height comparison against in-situ (mainly buoy) observations for the whole of 2019 for Sentinel-3A and Sentinel-3B are shown in Figure 106. SWH from both altimeters is unbiased compared to available in-situ measurements for this period. The SDD (a proxy to the random error) is 0.34 m (~14.0% of the mean) and 0.30 m (~12.4% of the mean) for Sentinel-3A and Sentinel-3B, respectively. There is a small number of outliers exist especially in Sentinel-3A comparison. The correlation coefficient is about 0.98. These numbers indicate that Sentinel-3A and Sentinel-3B SAR SWH products are very close their counterparts from other altimeters (not shown). It is important to state that most of in-situ observations are located in the Northern Hemisphere around the American and European coasts.

The time series of the SWH bias (altimeter – model) and SDD of Sentinel-3A compared to the ECMWF model FG are shown in the upper and lower panels, respectively, of Figure 107. The corresponding Sentinel-3B plot is shown in Figure 108. Sentinel-3A and Sentinel-3B SWH are globally unbiased compared to ECMWF model FG. However, there is up to 0.10 m mean bias in the extra Tropics with negative bias in the summer (July-August in the Northern Hemisphere, NH, and January-December in the Southern Hemisphere, SH) and positive bias during the hemispheric winter. In the Tropics, negative bias of about 0.05 m dominates. The SDD follows a similar cycle especially in the NH.



## Sentinel-3 MPC S3MPC STM Annual Performance Report - Year 2019

 Ref.:
 S3MPC.CLS.APR.006

 Issue:
 1.0

 Date:
 28/02/2020

 Page:
 117



Figure 105: Global comparison of Sentinel-3A and Sentinel-3B, in panels (a) and (b), respectively, SAR SWH against ECMWF model first-guess SWH values for the year 2019. The number of colocations in each 0.25 m x 0.25 m 2D bin is colour coded as in the legend. Refer to Figure 90 for the meaning of crosses and the circles.



S3MPC STM Annual Performance

Report - Year 2019

 Ref.:
 S3MPC.CLS.APR.006

 Issue:
 1.0

 Date:
 28/02/2020

 Page:
 118



Figure 106: Same as Figure 105 but the comparison is done against in-situ observations (mainly in the NH).





Figure 107: Time series of weekly global significant wave height bias defined as altimeter - model (top) and standard deviation of the difference (bottom) between Sentinel-3A SRAL and ECMWF model first-guess.



Figure 108: Same as Figure 107 but for Sentinel-3B.

	Sentinel-3 MPC	Ref.:	S3MPC.CLS.APR.006
	S3MPC STM Annual Performance Report - Year 2019	Issue:	1.0
		Date:	28/02/2020
		Page:	120

The time series of the SWH monthly bias (defined as the altimeter – in situ) and the SDD of SRAL SAR compared to the in-situ measurements are shown in the upper and lower panels, respectively, of Figure 109. The same plots for Sentinel-3B are shown in Figure 110. With the geographic distribution of the buoy network in mind (limited in number and limited in coverage which is restricted mainly to the Northern Hemispheric coasts), It is possible to see that there is a seasonal cycle in the bias and the SDD like the Northern Hemispheric cycle revealed by the model comparison (Figure 107): Small bias and SDD during the summer (July-August) and higher values during the winter (December-January).



Figure 109: Time series of monthly global significant wave height bias defined as altimeter - buoy (top) and standard deviation of the difference (bottom) between Sentinel-3A SRAL and in-situ measurements.

The time series of the global SWH weekly bias and SDD of 6 altimeters (including Sentinel-3A and Sentinel-3B) compared to the ECMWF model FG are shown in the upper and lower panels, respectively, of Figure 111. Note that Sentinel-3A results before December 2017 are from an earlier reprocessed data set. That explains the difference between During the year 2019, the biases in Sentinel-3A and Sentinel-3B SAR SWH have been the lowest among the 6 operational altimeters.

Note that the improvement in the ECMWF model wave SWH when CY46R1 was implemented in June 2019 is clearly reflected as improvements in comparison statistics in Figure 107, Figure 108 and Figure 111.



Figure 110: Same as Figure 109 but for Sentinel-3B.

Sentinel-3A SAR SWH shows the highest SDD with respect to the model among all altimeters irrespective of the various processing baselines. During the last 6 months of 2018 it was joined by Sentinel-3B at this high SDD. It is worthwhile mentioning that during the single Sentinel-3B cycle when SRAL was configured to operate in LRM mode, the SDD of Sentinel-3B LRM SWH with respect to the model was one of the lowest. This can be seen in Figure 111.

The geographical distribution of the mean Sentinel-3 SWH and the SWH bias, SDD and SI with respect to the ECMWF model FG averaged over the whole year of 2019 are shown in Figure 112. All the four plots look similar to their counterparts from other altimeters (not shown). The equivalent Sentinel-3B maps are shown in Figure 113.



Figure 111: Time series of weekly global significant wave height bias defined as altimeter - model (top) and standard deviation of the difference (bottom) between 5 altimeters including Sentinel-3A and Sentinel-3B SRAL (Sentinel-3A line is different from the global one in Figure 107 since reprocessed data were used before December 2017) and the ECMWF model first-guess.


**S3MPC STM Annual Performance** 

Report - Year 2019

Ref.: S3MPC.CLS.APR.006 Issue: 1.0 28/02/2020 Date: 123 Page:

#### Satellite: Sentinel-3A (a)







Figure 112: Geographical distribution of mean Sentinel-3A SWH (a) as well as the bias (b); the SDD (c) and the SI (d) between Sentinel-3A and ECMWF model FG during 2019. Bias is defined as altimeter - model.



**S3MPC STM Annual Performance** 

Report - Year 2019

Ref.: S3MPC.CLS.APR.006 Issue: 1.0 28/02/2020 Date: Page: 124

# (c)





Figure 112: Continued.



**S3MPC STM Annual Performance** 

Report - Year 2019

Ref.: S3MPC.CLS.APR.006 Issue: 1.0 28/02/2020 Date: Page: 125

#### Satellite: Sentinel-3B (a)







Figure 113: As in Figure 112 but for Sentinel-3B.



**S3MPC STM Annual Performance** 

Report - Year 2019

Ref.: S3MPC.CLS.APR.006 Issue: 1.0 28/02/2020 Date: Page: 126

# (c)





Figure 113: Continued.



#### Summary:

Radar backscatter (sigma0), surface wind speed (WS) and significant wave height (SWH), which are part of Seninel-3 Surface Topography Mission Level 2 Marine Ocean and Sea Ice Areas (SRAL-L2MA) also known as SR\_2\_WAT, from Sentinel-3A have been very good since early December 2017 when PB 2.24 was implemented operationally. Sentinel-3B wind and wave data have also been very good since the implementation of Sentinel-3B PB 1.13 on 6 December 2018.

Validation was carried out against the corresponding parameters from ECMWF Integrated Forecast System (IFS), in-situ measurements and other altimeters. The current quality of SAR wind speed, PLRM wind speed and SWH from Sentinel-3A and Sentinel-3B SRAL can be summarized as being very good and they can be used for practical applications. However, some fine tuning of these products may still be needed to alleviate some of their imperfections:

Sentinel-3A SAR wind speed is globally unbiased compared the wind speeds from the model and the insitu measurements. The standard deviation of the difference (SDD) between SRAL and model wind speeds is one of the lowest among all operational altimeters.

Sentinel-3A PLRM wind speed is also globally unbiased. The SDD with respect to the model is very good although it is not as good as that of SAR wind and suffers from some degradation in June to August.

The following points are under close monitoring:

- There seems to be a seasonal cycle with an increasing trend in global mean backscatter (and decreasing trend in wind speed) since the end of 2017.
- The SAR wind speed is now globally unbiased compared the wind speeds from the model and the other altimeters. The standard deviation of the difference (SDD) between SAR and model wind speeds is as good as that of other altimeters. There is a seasonal cycle in both bias and the SDD between SAR wind and ECMWF model in Northern (minimum in July and maximum in January) and Southern (vice versa) Hemispheres.
- The PLRM wind speed is now globally unbiased. The SDD with respect to the model reduced considerably recently and it is now in line with its counterpart for other altimeter winds. With the removal of the large outliers, the SDD is rather stable. A seasonal signal in the PLRM wind bias with respect to the model like that of SAR wind can be clearly noticed. SDD of PLRM does not show a similar clear signal.
- There has been a clear drop in the SDD between PLRM and model winds between early September 2018 and late May 2019. This drop, which seems to be artificial, has not been explained yet.
- Sentinel-3A SAR significant wave height is virtually unbiased compared to the model and the insitu measurements. However, SRAL slightly overestimates small wave heights (below 1 m).



# 7.7 Specific investigations

This section aims at describing the main investigations performed during this year 2019. Previous studies (swell effect on the estimated parameters, waveform centering analysis, ...) are described in the past annual reports.

### 7.7.1 Investigation: Range sensitivity to meridional wind

The difference between SARM and conventional P-LRM ranges highlights geographical patterns (Figure 114). Weak effects correlated with latitude are visible. Such signature required further investigations as it is possibly related to P-LRM and/or SARM. The patterns visible on these maps are not fully correlated to SWH as expected. Indeed, discrepancies are observed between ascending and descending tracks.

Performing the difference between ascending and descending tracks allows to remove all systematic errors (such as waves) and to highlight SARM/PLRM variations that depend on track orientation. The resulting map is presented on Figure 115 left panel. This map shows twice the value of the actual error, as it accounts for both ascending and descending tracks error. The patterns highlight a strong correlation to the meridional wind (Figure 115 right panel), with value ranging between -1.5 cm and 1 cm. Hence an error of about 1 cm of amplitude on the range. Mono-mission crossover analyses also present the same correlation (Figure 73).

Such result raises the question of a potential impact of the wind depending on the track orientation. It can also be linked to other parameters, such as SWH.

The same diagnosis has been performed on Sentinel-3B dataset and the same correlation to the meridional wind is found. Further analyses are ongoing to evaluate the origin of such a dependency.



Figure 114: Gridded maps of Sentinel-3A collocated range differences between SARM and P-LRM for ascending (left panel) and descending (right panel) passes, average from April 2016 to December 2018.





Figure 115: Left panel: Difference between Figure 114 maps (ascending – descending). Right panel: ECMWF meridional wind speed averaged over the same period.

# 7.7.2 Investigation: Estimation of the impact of the PTR shape evolution on the Level-2 estimates

Since the switch to SAR mode in an operational way, the Impulse response of the Sentinel-3A/SRAL radar altimeter (also called Point Target Response, PTR) is impacted by a drift, see section 5.1. This drift has been firstly detected through a stronger PTR total power decrease compared to other radar altimeters (SARAL/AltiKa, Jason-2 and Jason-3). Then studies leaded in the frame of the Sentinel-3 MPC project on CAL1 analysis have demonstrated that this drift impacts the whole PTR shape and so the radar waveform. Basically, an evolution of the PTR shape (due to instrument ageing or any other sources) doesn't impact altimeter product performances if the PTR evolutions are accounted for in the ground segment.

In the Sentinel-3/SRAL Level-2 processing, the retracking algorithm aims at fiting a waveform model to the radar echo. This model doesn't account for the true PTR but uses a gaussian approximation instead. In consequence, PTR evolutions are not accounted for in the retracker. To manage potential PTR drifts, corrections are computed at Level-1 thanks to the calculation of different parameters using the CAL1 measurements (PTR measurements performed during calibration modes that are regularly performed each day). Unfortunately, these corrections account for total power drifts or linear evolution of the entire PTR but not for dissymmetry evolutions.

In this context, this document aims at characterizing the SAR Sentinel-3A PTR drift and to investigate the potential impact on geophysical estimates in terms of Sea Surface Height (SSH) and Significant Wave Height (SWH).

#### 7.7.2.1 Simulated impacts on SAR Level-2 estimates

In order to evaluate the impact of the Sentinel-3A/SRAL PTR drift on Level-2 SAR geophysical estimates, simulations are performed accounting for the PTR evolution since the altimeter switch on. The simulation scheme is presented in Figure 116: synthetic Sentinel-3A SAR Flat Sea Surface Response (FSSR) are generated using the CNES Sentinel-3 Processing Prototype (S3PP) model generator (based on the CNES AltiDop simulator) and are convoluted to a Gaussian sea height Probability Density Function (PDF) for SWH varying from 1 to 9 meters. Then the simulated SAR echo is convoluted to the true PTR of the Sentinel-3A/SRAL altimeter. 5 PTRs are chosen for this study, picked at different time since the Sentinel-



3A launch. The synthetic SAR waveforms thus generated are noised by speckle noise and retracked using the SAMOSA 2.5 retracker (similar to the PDGS).

Results are studied as a function of the PTR evolution in the following subsections.



Figure 116: Processing scheme implemented to evaluate the PTR drift impact on level 2 estimates

#### 7.7.2.1.1 Impact on SWH

The impact on SWH estimates is investigated by comparing SWH values estimated on synthetic echoes generated using a PTR at the beginning of the mission (28/06/2016) and SWH values estimated on synthetic echoes generated using 4 other PTRs taken at different time during the Sentinel-3A/SRAL life. Results are given in Figure 117 where SWH estimated from different PTRs are compared to SWH estimated from the first PTR (the one measured on the 28/06/2016). A SWH dependency of the bias is clearly visible (variation w.r.t. SWH is close to 1 cm) which is expected as the PTR dissymmetry evolves with time.

To better highlight the SWH drift related to the PTR evolution, values from the 4 curves are averaged between 1 and 4 meters of SWH (main ocean population) in Figure 118 and are plotted as a function of the main lobe width drift which has a linear evolution (cf section 5.1).





Figure 117: SWH estimation differences between a PTR at the beginning of the mission and different PTR taken all along the Sentinel-3A/SRAL life

From Figure 118 we can derive a linear regression allowing to compute the SWH bias as a function of the PTR drift (here we chose to use the PTR main lobe width drift). In this way we can link the PTR drift and the corresponding impact on SWH estimates. The relation between the main lobe width drift and the SWH bias is:

SAR SWH bias  $(m) = 0.0081x + 1.55e^{-4}$ 

with x is the negative value of the main lobe width drift in mm/year.

When combined to the main lobe width drift computed in section 5.1, Figure 6 ( $\sim$ -0.4 mm/year), we can compute the SAR SWH drift related to the PTR drift  $\rightarrow$  SAR SWH drift is about +3.395 mm/year.

As the SAR SWH is an input to the Sea State Bias, the Sea Surface Height will be impacted too through the SSB. Assuming that the SSB correction is about 3% of SWH, we can compute the SAR SSH drift related to the SSB correction  $\rightarrow$  SAR SSH drift related to the SSB is about +0.1 mm/year.

This SWH relation is computed for the whole mission until the written time of this technical note. But it is important to note that the PTR drift is not stable with time (cf Figure 118). The dissymmetry evolution is now lower than at the beginning of the mission. So the SWH drift should be lower if we compute it using the last 200 days. It could be interesting to update this technical note in the future with more data in order to see the decrease of this SWH drift.





Figure 118: SAMOSA SWH estimate sensitivity to the PTR drift

#### 7.7.2.1.2 Impact on SSH

Similarly to the SAMOSA SWH analysis, the impact of the PTR drift on SAMOSA SSH estimates is analysed using the generation and the retracking of synthetic echoes convoluted with true Sentinel-3A/SRAL PTRs. Using the same simulations than in the previous part, the range impact as a function of SWH and for different Sentinel-3A/SRAL PTRs is illustrated in Figure 119. Like the SAMOSA SWH impacts, a SWH dependency is clearly visible and can reach up a variation of 0.2 mm depending on the PTR.

Again, and so as to evaluate the SSH drift as a function of the PTR drift, the curves are averaged between 1 and 4 meters of SWH (main ocean population) and are plotted as a function of the PTR main lobe width drift in Figure 120. From this diagnosis we can derive a linear relation linking the range drift to the PTR drift (through the PTR main lobe width drift):

SAR Range bias  $(m) = -5.03e^{-4}x - 2e^{-5}$ 

with x is the negative value of the main lobe width drift in mm/year.

When combined to the main lobe width drift computed in section 5.1, Figure 6 (~-0.4 mm/year), we can compute the SAR range drift related to the PTR drift  $\rightarrow$  SAR Range drift is about -0.221 mm/year.

The resulting SAR SSH drift combines the direct SAR range drift and the SSB drift computed in 7.7.2.1.1 → SAR SSH drift is about +0.321 mm/year.

This range drift relation is computed for the whole mission until the written time of this technical note. But it is important to note that the PTR drift is not stable with time (cf Figure 118). The dissymmetry evolution is now lower than at the beginning of the mission. So the SSH drift should be lower if we



compute it using the last 200 days. It could be interesting to update this technical note in the future with more data in order to see the decrease of this SSH drift.



Figure 119: Range estimation differences between a PTR at the beginning of the mission and different PTR taken all along the Sentinel-3A/SRAL life



Figure 120: SAMOSA Range estimate sensitivity to the PTR drift



#### 7.7.2.2 Simulated impacts on PLRM Level-2 estimates

In order to evaluate the impact of the Sentinel-3A/SRAL PTR drift on Level-2 PLRM geophysical estimates, simulations are made accounting for the PTR evolution since the altimeter switch on. The simulation scheme follows the one presented in Figure 116 for SAR impacts. But for PLRM, synthetic PLRM waveforms with speckle noise have been generated using the SIMPA simulator (a CNES/CLS simulator used to compute PLRM Look Up Tables). Results are presented in the two following subsections.

#### 7.7.2.2.1 Impact on SWH

The same analysis implemented for SAR mode is now performed on PLRM estimates. The linear regression linking the SWH bias and the PTR drift (it is still the PTR main lobe width drift that is used here) is:

*PLRM SWH bias*  $(m) = 8.27e^{-3}x + 6e^{-5}$ 

with x is the negative value of the main lobe width drift in mm/year.

Using the PTR main lobe width drift computed in section 5.1, Figure 6 (-0.4 mm/year) the PLRM SWH drift can be computed since the beginning of the mission → PLRM SWH drift is about +3.368 mm/year.

Assuming that the SSB correction is about 3% of SWH, we can compute the PLRM SSH drift related to the SSB correction  $\rightarrow$  PLRM SSH drift related to the SSB is about +0.1 mm/year.

Following comments made for impacts on SAR Level-2 estimates, this SWH relation is computed for the whole mission until the written time of this technical note. But the dissymmetry evolution is now lower than at the beginning of the mission. So the SWH drift should be lower if we compute it using the last 200 days. It could be interesting to update this technical note in the future with more data in order to see the decrease of this SWH drift.



Figure 121: PLRM SWH estimate sensitivity to the PTR drift



#### 7.7.2.2.2 Impact on SSH

The linear regression linking the range bias and the PTR drift (it is still the PTR main lobe width drift that is used here) is:

*PLRM Range bias*  $(m) = -6.06e^{-4}x - 3.4e^{-5}$ 

with x is the negative value of the main lobe width drift in mm/year.

When combined to the main lobe width drift computed in section 5.1, Figure 6 ( $\sim$ -0.4 mm/year), we can compute the PLRM range drift related to the PTR drift  $\rightarrow$  PLRM Range drift is about -0.276 mm/year.

The resulting PLRM SSH drift combines the direct range drift and the SSB drift computed in 7.7.2.1.1 → PLRM SSH drift is about +0.376 mm/year.



Figure 122: PLRM range estimate sensitivity to the PTR drift

Following comments made for impacts on SAR Level-2 estimates, this PLRM range relation is computed for the whole mission until the written time of this technical note. But the dissymmetry evolution is now lower than at the beginning of the mission. So the range drift should be lower if we compute it using the last 200 days. It could be interesting to update this technical note in the future with more data in order to see the decrease of this SSH drift.

#### 7.7.2.3 Conclusion

In the ground processing, PTR total power and internal path delay are computed at Level-1 in order to derive corrections to be applied on geophysical estimates to manage potential PTR drifts. Unfortunately, PTR dissymmetry (see section 5.1) is not accounted for and directly impacts geophysical estimates. Basically, and knowing that Level-2 SAR and PLRM retrackers use a Gaussian approximation of the PTR in the echo model to fit the radar waveform, a PTR dissymmetry will induce a bias in the geophysical



estimates. And if the dissymmetry evolves with time, the associated bias will also evolve, resulting in a drift of the geophysical estimates.

It is shown in section 5.1 that the Sentinel-3A/SRAL SAR PTR dissymmetry has strongly evolved during the first 1.5 year of the mission. Since then, the PTR drift seems less important and more stable (more linear). Analyses have been performed to quantify the impact on the geophysical estimates. In SAR mode and directly due to the PTR drift, SAMOSA estimates are potentially impacted by:

- a drift of +3.395 mm/year on the SWH
- a drift of +0.321 mm/year on the SSH (including +0.1 mm/year coming from the SSB)

In PLRM, MLE4 estimates are potentially impacted by:

- a drift of +3.368 mm/year on the SWH
- a drift of +0.376 mm/year on the SSH (including +0.1 mm/year coming from the SSB)

These drifts are not negligible for climatic studies and must be accounted for in the ground processing. Different solutions can be implemented to tackle those drifts, from the implementation of numerical retracking solution accounting for the true PTR of the instrument to the computation of PTR-derived corrections.

Finally, it is important to note that the drift values provided in this technical note are computed since the altimeter switch on, but the evolution of the PTR dissymmetry is not constant at all during the mission. Knowing that the PTR dissymmetry is less important for the last 1.5 year than at the beginning, it could be interesting to update these drift value in the future with more data

#### 7.7.3 Investigation on the S3-A SAR GMSL long-term drift

As presented in Section 7.5, one observes a long-term drift of the Global Mean Sea Level (GMSL) derived with the "marine" S3-a mission delayed time L2P products. This GMSL drift is only observed in the SAR-mode products, the PLRM data showing no statistically significant drift when compared to other missions (i.e., Saral/Altika, Jason-2/3, see Section 7.5).

In this section, we present, in a first part, a detailed analysis of each terms (i.e., altimeter range, instrumental corrections, etc.) used to derive the GMSL. This analysis allows us to pin down the exact origin(s) of the observed drift. In a second part, we present a study on a few geophysical parameters (i.e., waves, wind) and discuss their potential impact on the SAR-mode of S3-a that could be responsible for its drifting behavior.

The conclusions of these analyses are summarized hereafter:

- The range (altimeter distance) of the SAR mode is the only parameters that shows a significant drift over the 2.5-years of the mission (07.2016-01.2019) when compared to the PLRM data. Its drift is estimated to ~0.9 mm/year.
- The total GMSL drift between S3-a SAR and PLRM modes is evaluated to ~1 mm/year, resulting from the range drift only, and its direct impact on the ionospheric correction.



No long-term drifts of the measured parameters such as the waves (and sigma-0), neither the wind, are observed. Time-variations of those two last geophysical parameters hardly explain the observed GMSL drift of the S3-a SAR-mode.

#### 7.7.3.1 Analysis of the GMSL terms long-term evolution

From the results of Section 7.5 one has shown that the PLRM data was not drifting as compared to the reference mission Jason-3, neither to Saral/Altika over the same period as of the SAR data. Here we therefore analyze the difference between the two S3-a modes: SAR and PLRM, in order to understand why the former is drifting but not the latter.

Since the GMSL drift of the SAR data was observed using the wet tropospheric correction from the ECMWF models, the left-over parameters which could be themselves drifting, are:

- The altimeter range
- Therefore, the ionospheric corrections (~0.2\*[range(Ku)-Range(C)])
- The sea state bias

In the following sub-sections, we analyze the long-term behavior of each of the above listed parameters by performing a GMSL equivalent derivation of them (global mean cycle by cycle, weighted by the latitude and the coastal ratio). This allow us to quantify the contribution of each term in the final GMSL. The slope (i.e., potential drift) of the resulting GMSL equivalent is obtained thanks to an ordinary least square fitting method (as for the AVISO GMSL method), and the associated uncertainties are the formal errors of the fitting process.

#### 7.7.3.1.1 Altimeter range

Figure 123 shows the difference of the "global mean range" between SAR and PLRM modes of S3-a over the period ranging from 07.2016 and 01.2019. The derived slope is **0.96+/-0.09 mm/yr** indicating a statistically significant drift of the SAR range parameter over the respective period (once again assuming that the PLRM range is not drifting, based on the analysis shown in Section 7.5)





Figure 123 – "Global mean range" difference between S3-a SAR and PLR modes. The slope is obtained from a least square fitting method and the uncertainties are the formal ones.

#### 7.7.3.1.2 Ionospheric correction

Figure 124 shows the difference of the "global mean ionospheric correction" between SAR and PLRM modes of S3-a over the period 07.2016 and 01.2019. The derived slope is **0.17+/-0.017 mm/yr** indicating a statistically significant drift of the SAR ionospheric correction over the respective period.

This is consistent with the results Section 7.7.3.1.1. Indeed, the ionospheric correction is directly proportional to the altimeter range, of the order of 20% (the ionospheric correction is  $\sim$ 0.2\*[range(Ku)-range(C)]). Consequently, if one understands the range difference between SAR and PLRM modes, one will also explain the difference between the respective ionospheric corrections.





Figure 124 – "Global mean ionospheric correction" difference between S3-a SAR and PLR modes. The slope is obtained from a least square fitting method and the uncertainties are the formal ones.

#### 7.7.3.1.3 Sea State Bias

Figure 125 shows the difference of the "global mean sea state bias" between SAR and PLRM modes of S3-a over the period 07.2016 to 01.2019. The derived slope is **0.11+/-0.03 mm/yr** over this given period. However, one can observe a jump of the last point of the time-series in January 2019.

The observed jump is simultaneous with an update of the IPF SWH Look-Up Tables (LUTs, see section 7.2.1 and 7.6) that impacts the data from S3-a cycle 40 (ending the 29.01.2019). This update created a jump in the SWH derived values, so in the SSB of the NTC L2 products. The observed slopes' difference of SSB is therefore an artificial artifact of this IPF upate.

When excluding this last cycle, stopping at cycle 39 (i.e., 12.2018), the measured slope is of **0.05+/-0.02** *mm/yr* suggesting a good coherence between the SAR and PLRM SSB time-series. We therefore recommand the users to wait for the next reprocessing release to have more coherent data over the full period.





Figure 125– "Global mean SSB" difference between S3-a SAR and PLR modes. The slope is obtained from a least square fitting method and the uncertainties are the formal ones. A jump is observed in January 2019 due to an update of the IPF. Data up to S3-a cycle 39 can be used for climate purpose, or one should wait for the new reprocessed data release.

#### 7.7.3.1.4 Summary of the GMSL drift in SAR mode

Based on the results of the previous sections (7.7.3.1.1 to 7.7.3.1.3) we have shown that the observed GMSL drift of the S3-a SAR mode as compare to its PLRM mode is due, and only due to the altimeter range parameter. The respective drift is estimated to **0.95 mm/yr** (over the period 07.2019 to 01.2019).

The range drift combined with the induced ionospheric correction drift account for a slope difference of **1.12 mm/yr** between SAR and PLRM GMSL time-series. This is consistent with the estimations of the S3- a SAR and PLRM drifts with respect to Jason-3 and Saral/Altika (see Section 7.5).

This observed SAR range drift would therefore explain the observed GMSL drift in the L2P S3-a product.

# 7.7.3.2 Analysis of geophysical parameters long-term evolution and their potential impact on the S3-a SAR range

In this section we investigate the long-term evolution a few potential geophysical sources, e.g., wave and wind, that could create the observed S3-a SAR range drift (see effect on SWH on the crossover comparison



between S3 and J3 in section 7.4.2, as well as the impact of wind speed on SARM range estimate in section 7.7.1). We first check the GSML equivalent long-term evolution of the sigma-0 parameter, as well as the derived waves 'values (noted SWH) and wind. We then present some more details on the potential impact of the wind on the SAR range measurements.

#### 7.7.3.2.1 Long-term evolution of the sigma-0

Figure 126 shows the difference of sigma-0 between the S3-a SAR and PLRM data, derived as one would get the GMSL time-series. The measured slope (from least square fitting) is **1.9+/-0.3 mdB/year**. From Ablain et al., 2012 this difference would create a GMSL drift between the SAR and PLRM modes of **~0.03mm/year** (i.e., 30 mdB/year in sigma-0 is equivalent to 0.375 mm/year in GMSL).

We therefore conclude that the differences observed between the SAR and PLRM derived sigma-0 parameter is not responsible for the observed GMSL drift between the two modes.



Figure 126 - "Global mean sigma-0" difference between S3-a SAR and PLR modes. The slope is obtained from a least square fitting method and the uncertainties are the formal ones.

#### 7.7.3.2.2 Long-term evolution of the significant wave height (SWH)

Figure 127 shows the significant wave height (SWH) between the S3-a SAR and PLRM data, derived as one would get the GMSL time-series. The measured slope (from least square fitting) are **9.6+/-6.7** mm/year and **8.6+/-6.3** mm/year, for the SAR and PLRM modes, respectively. Given the uncertainties (formal



errors) on the measured slopes, there are no significant long-term evolution differences between the SAR and PLRM SWH parameters.



Figure 127- "Global mean ionospheric correction" difference between S3-a SAR and PLR modes. The slope is obtained from a least square fitting method and the uncertainties are the formal ones.

We also investigated the dependence of the SAR range drift as a function of the SWH values. The analysis has been done using the daily mean values of each parameters, rather than a GMSL equivalent, but already gives a good insight on the potential dependence. Indeed, from Figure 128, we find that the drift between SAR and PLRM ranges is of the same order whatever the SWH values, i.e., about 0.9-1.2 mm/year if we exclude the two extreme SWH categories (small and big waves).

We therefore do not observe a direct link between the SWH values and the observed GMSL SAR drift of Sentinel 3-A.





Figure 128 – Daily mean follow-up of the range difference between SAR and PLR modes data from S3-a, as a function of the significant wave height (SWH) derived values. The same order of drift is observed whatever the SWH values is selected.

#### 7.7.3.2.3 Long-term evolution of the wind

We present in Figure 129 the 'Global Mean Wind Speed' evolutions for both the SAR and PLRM modes of S3-A, as well as the 'Global Mean Wind Speed' of the ECMWF model (green curve). The slopes are derived from a least square fitting method and the uncertainties are the formal ones. In this section, we used the L2 S3-A SRAL data from the 06.2016 to 12.2019.

An increase of about 2 cm/s/year is observed over the period 06.2016 to 11.2019 for both SAR and PLRM data, whereas a decrease of about the same order is observed for the ECMWF model. We note that the difference observed between the SAR and PLRM wind is coherent with the sigma-0's differences presented in Section 7.7.3.2.1. From Figure 129, one shows that the S3-A altimeter see a slight increase of the wind (its module) that is not reproduced by the ECMWF model. The potential origins of this discrepancy are not investigated in this report.





Figure 129 - "Global mean wind speed" of the S3-a SAR and PLR modes, compared to the ECMWF model. The slopes are obtained from a least square fitting method and the uncertainties are the formal ones.

As shown in section7.7.1, one suspects the meridional component of the wind to influence the SAR measurements. More precisely, the tracks' orientation (descending or ascending) would create regional differences in the SAR range measurements. We thus investigated the potential link between the evolution of the meridional wind (derived from the ECMWF model) and the SAR vs PLRM range drift.

Figure 130 shows the difference of the "global mean range" between the two modes of S3-A, SAR and PLRM, separated in ascending and descending tracks. A first important observation we can get from this figure is that the range drift is the same regardless of the tracks' orientation, i.e., 0.9 mm/yr. However, one sees strong annual signals appearing for both ascending (light blue curve) and descending (grey curve) tracks, which are respectively in opposite phase.

Consequently, we indeed observe that the tracks' orientation has an impact on the, supposedly, SAR measurement, but that its impact is not responsible for the observed drift between the SAR and PLRM data.



#### S3MPC STM Annual Performance

Report - Year 2019

Ref.: S3MPC.CLS.APR.006 Issue: 1.0 Date: 28/02/2020 Page: 145



Figure 130 – "Global mean range" difference between S3-a SAR and PLR modes, separated in ascending and descending tracks. The slopes are obtained from a least square fitting method and the uncertainties are the formal ones.

In order to confirm the analysis of Figure 130, we compare in Figure 131 the evolution of the ECMWF meridional wind speed along with the difference of the ascending and descending 'Global mean range' difference between SAR and PLRM, i.e., the difference of the grey and the light blue curves of Figure 130. We note the latter quantity 'difference ASC/DSC SAR vs PLRM'.

From Figure 131, one sees that the annual signal of the meridional wind speed is perfectly timed with the difference ASC/DSC SAR vs PLRM. Both quantities are 'perfect' sinusoidal signals with a constant amplitude. In this way, one can clearly connect the evolution of the meridional wind speed with the differences ASC/DSC SAR vs PLRM, but only in term of annual variation and not in terms of long-term drift.

As a conclusion, we do not think with the current analyses that the wind speed long term evolution could be responsible for the observed range drift between the SAR and PLRM modes of S3-A, over the period 06.2016 to 01.2019.





Figure 131 – Difference of the ascending and descending tracks between S3-a SAR and PLRM ranges (red curve), along with the evolution of the meridional wind speed from the ECMWF model. The slopes are obtained from a least square fitting method and the uncertainties are the formal ones.

#### 7.7.4 Investigation: Assessment and improvement of the Sentinel-3 flag parametrization

#### 7.7.4.1 Sea ice flag

The sea ice flag in Sentinel-3A and -3B products (open\_sea\_ice\_flag) is derived from the Tran et al. algorithm developed in 2008 for Envisat mission. This algorithm combines brightness temperatures and backscatter information respectively derived from microwave radiometer and altimeter.

However, this algorithm is not in line with the latest version used for Envisat reprocessed data v3.0 (2012) and is still based on Envisat parameters tuning. It can thus be improved to fit Sentinel-3 specificity and benefits from the progress brought by more recent study. A Sentinel-3 dedicated parametrization has been performed and is presented in this section.

Figure 132 shows the geographic repartition of each ice type detected with Sentinel-3A sea ice flag in SARM and in P-LRM over the Arctic and the Antarctic regions. Strong discrepancies are observed between the two Sentinel-3A modes. Many P-LRM data are tagged as "not evaluated" (green) in both Arctica and Antarctica, indicating that the input data were unavailable.



Maps of OSI-SAF Ice Type product are also presented on Figure 132 (right panels). This data has been collocated at Sentinel-3A measurement location, allowing direct comparison. Over the Arctic region, SARM maps are more similar to those from OSISAF. The histograms on Figure 133 confirm that, over this region, there is a better consistency between SARM and OSI-SAF classifications than between SARM and PLRM results. Note that some SARM measurements are flagged as "Multi-Year Ice" in summer, while it is not possible to do such discrimination (not shown here). Such anomaly will be address in the study bellow.

Over the Antarctic region, OSI-SAF and Sentinel-3A are not in line. OSI-SAF Ice Type product shows one type of sea-ice while Sentinel-3A sea-ice flag detect three types. The Envisat algorithm used for Sentinel-3A has been parametrized over the Arctic region and is then not adapted for the Antarctic region.



Figure 132: Sentinel-3A sea ice flag value derived from SARM (left panels) and PLRM (middle panels). OSISAF Ice Type product collocated at Sentinel-3A measurement location (right panels). Top panels show results over Sentinel-3A cycle 15 (Northern winter) over the Arctic region and bottom panels over Sentinel-3A cycle 22 (austral winter) over the Antarctic region.



10

52

PLRM

48

SAR 2019

52

SAR

Out of Grid

Ambiguous

Coastal data

OW – Open Water

FYI - FirstYearIce

MYI – Multi Year Ice

Figure 133: Histograms of OSISAF Ice Type, Sentinel-3A SARM and P-LRM sea ice flag from the actual product (open\_sea\_ice\_flag), and Sentinel-3 SARM new version of this flag (SAR 2019). Histograms on the left show the values over the Arctic region for Sentinel-3A cycle 15 and histograms on the right show the values over the Antarctic region for Sentinel-3A cycle 22.

45

OSI-SAF

This study focusses on the improvement of the SARM sea ice flag. It follows three steps:

44

39

SAR 2019

1. Update of the cluster tie-point for SARM

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0

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35

OSI-SAF

36

41

SAR

5

41

PLRM

The cluster tie-point allows to identify which class category are observed. This cluster has been computed using Envisat data and only over the Arctic region. A Fuzzy c-means (FCM) clustering method (unsupervised and iterative) has been used to recompute the cluster tie-points coordinates in the 3D space, using Sentinel-3A brightness temperatures and backscatter coefficient values. It has been done separately over the Arctic and the Antarctic regions, in order to account for each region specificities.

Over the Arctic region, four clusters have been identified for SARM Sentinel-3A: Open Water, First Year Ice, Wet Ice and Multi-Year Ice. Over the Antarctic region, only 2 clusters are kept: Open Water and First Year Ice, which is in line with OSI-SAF.

2. Update of the seasonal masks

Seasonal masks are used to avoid false detection of sea-ice in areas where ice has never been observed. One mask for summer and another one for winter are used. Figure 134 left panels present Envisat masks over the Arctic and the Antarctic regions. These masks are currently used for Sentinel-3. The updated versions are presented on the right panels. The zones have been principally extended.

3. Addition of two input parameters

At the boundaries of the ice pack, some SSH data contaminated by sea-ice are not well detected and are thus not edited with this flag information (red patterns surrounding the sea-ice pack limits on Figure 135).

COLLETE LOCALISATION SATELLITES	Sentinel-3 MPC	Ref.:	S3MPC.CLS.APR.006
	S3MPC STM Annual Performance Report - Year 2019	Issue:	1.0
		Date:	28/02/2020
		Page:	149

Such anomalies are due to the combined use of the altimeter and the radiometer data, their differences in footprint size and the proportion of sea-ice in respective footprint. Indeed, due to its smaller size, the altimeter footprint can be completely filled by sea-ice more frequently than the radiometer one. It leads to a higher number of contaminated SSH data that are not well detected with the current algorithm design. The use of both sigma0 standard deviation and OI-Sea State Temperature (NOAA) as additional input parameters has shown to improve the identification of altimeter returns from sea-ice surface. These two parameters have then been added as inputs in order to improve the identification of SSH data contaminated by sea-ice.



Figure 134: Seasonal masks for sea ice detection over the Arctic region (top panels) and over the Antarctic region (bottom panels), for Envisat (left panels) and for Sentinel-3 new parametrization (right panels). Blue: winter mask, Red: summer mask.



Figure 135: Maps of Sea Level Anomaly for Sentinel-3A SARM cycle 22, over the Artic (left) and Antarctic region (right). The product sea-ice flag is used here to discard data contaminated with ice.



Combining these three updates, a new sea-ice flag has been calculated for Sentinel-3A SARM. Results are presented in the fourth histograms in Figure 133 (labelled as "SAR 2019") and on Figure 136. Over the Arctic region, Sentinel-3A new flag shows an improved consistency with OSI-SAF classifications. The percentage of First Year Ice and Multi-Year Ice has increased during winter. In summer (not shown), there is no more Multi Year Ice group as it is impossible to distinguish FYI and MYI because of the presence of snow-melted water on the surface.

Over the Antarctic region, only one ice-type (FYI) is detected in addition to the mixture of type group. This result is more in line with OSISAF results and show the improvement brought by this new algorithm parametrisation.



The new sea-ice flag presented here will be implemented in a future processing baseline.

Figure 136: OSISAF Ice Type product collocated at Sentinel-3A measurement location (left panels). Sentinel-3A new sea ice flag value derived from SARM (right panels). Top panels show results over Sentinel-3A cycle 15 (Northern winter) over the Arctic region and bottom panels over Sentinel-3A cycle 22 (austral winter) over the Antarctic region.

#### 7.7.4.2 Ice-sheet snow facies classification

As for the sea-ice flag, Sentinel-3 snow facies type classification is based on the empirical Envisat algorithm [Tran et al, 2008], based on 2004 GDR\_A data. For this type of classification, no external reference product is available for comparison and validation. The same kind of classification algorithm as for sea-ice for is used in the case of snow facies.



A new classification parametrisation has been performed over Greenland and Antarctica separately and based on Sentinel-3A SARM and P-LRM data, also separately.

Over Greenland (Figure 137), the boundary delimitations around the island have been improved. SARM and P-LRM results present a good consistency.

Over Antarctica (Figure 138), some data are missing on the ice-shelves with the current algorithm. This is due to the surface type flag used as input. A land cover mask allows to gain the missing points. With the new parametrisation, the consistency between SARM and P-LRM has been improved. The snow facies classification is also in better agreement with Envisat v3.0 reprocessed data.



Figure 137: Sentinel-3A snow facies type over Greenland in SARM (top panels) and in P-LRM (bottom panels). Left panels represent the actual product flag and right panels the updated version.





Figure 138: Envisat snow facies type flag derived from v3.0 reprocessing (left panel). Sentinel-3A snow facies type over Antarctica in SARM (top panels) and in P-LRM (bottom panels). Middle panels represent the actual product flag and right panels the updated version.

## 7.8 Performance over Coastal areas

No additional studies have been conducted this year to describe the S3A and S3B performances in coastal areas. The results described in 2018 annual report have been published in two different publication. One in Vignudelli et al, 2019 [RD23] describing the Sentinel-3 altimeter performances with respect to the shoreline distance and the angle measured between the satellite direction and the coast orientation. The other one in Nencioli & Quartly, 2019 [RD24] measuring the correlation between Sentinel-3 SWH parameter and wave height retrieve from buoys.



# 8 Performance Mission over Sea Ice

Sentinel-3A and -3B altimeters operate in SAR mode over areas of sea ice and ocean and shares a common heritage with Cryosat-2, the first altimetry mission to operate predominantly in this mode over sea ice. Here we show the operational mission performance during 2019.

# 8.1 Freeboard

The primary S3 L2 sea ice parameter is freeboard. There was a known freeboard L2 processor anomaly in  $PB \le 2.33$  (to 14<sup>th</sup> Feb 2019), which resulted in incorrect and predominantly negative freeboard. Although negative freeboard is possible due to snow loading, this spread of values has been shown to be to be erroneous when compared with other missions such as CryoSat-2 in SAR mode.

In February 2019, with the release of PB2.43, the freeboard anomaly was corrected with a major L2 algorithm update (new diffuse echo retracker, and optimised waveform filtering and outlier removal), aligned with the sea-ice algorithm specification of Cryosat-2 Baseline-D. The results from PB 2.43, analysed during 2019, with the updated L2 algorithms show that the freeboard now has the expected histogram distribution (peak at +0.17m).



Figure 139: S3A L2 freeboard from PB2.33 (negative anomaly), and PB2.4x TDS (corrected)



The algorithm update also corrects an anomaly where high values were previously found around the coastline in <=PB2.33:



Figure 140: Anomalous high values around coastline corrected in PB2.43

Freeboard was then validated against measurements for the same period from CryoSat-2. The results indicated broadly similar performance over the majority of the central Arctic, but closer to the coastline S3 freeboard has much higher levels of noise.



Figure 141: Comparison of S3A and CS2 Gridded Freeboard for January 2018



This is confirmed by differencing gridded freeboard from S3A and CryoSat-2:

201801 S3 minus CS2 freeboard



Figure 142: S3-A minus CS2 Freeboard (CPOM Processing)

The differences between S3 and CryoSat-2 freeboard can be explained by the known differences in L1 processing. S3's IPF (PB2.43) is currently optimised for ocean surfaces and not sea ice. In particular there is no Hamming weighting or Zero padding applied at L1. As a result of this, specular echoes (over sea ice leads) are under sampled, and echo contamination from off-nadir leads are present. To test the improvement gained from a L1 data set optimised for sea ice, CPOM/UCL obtained cycles of S3A L1 data from GPOD (configured with Hamming and Zero padding applied) and used this as input to the same CPOM L2 sea ice processor. Results are much improved as compared to those processed with the IPF L1b and now share a very similar histogram and gridded freeboard map to Cryosat over their common areas.





Figure 143: Comparison of S3A and CS2 Gridded Freeboard (Hamming and Zero Padding applied at L1)

These results indicate that the optimum S3 performance over sea ice will only be achieved once a specialized L1 IPF processing is performed for sea ice. Detailed results from this study was published in *Lawrence et al, 2019, ASR*.

#### **S3-B Freeboard Comparison**

Unfortunately, the tandem phase between S3A and S3B did not occur during the Arctic winter and hence we cannot do an exact comparison over repeat tracks with near co-temporal sea ice conditions. However, comparing freeboard results for cycles of S3A and S3B in March/April 2019 shows a nearly identical freeboard histogram and parameter validity statistics.



Figure 144: Arctic Freeboard Comparison between S3A and S3B in Mar/Apr 2019

CALLEETE LOCALISATION SATELLITES	Sentinel-3 MPC	Ref.:	S3MPC.CLS.APR.006
	S3MPC STM Annual Performance Report - Year 2019	Issue:	1.0
		Date:	28/02/2020
		Page:	157

Statistics of the number of valid freeboard measurements since start of mission in the Arctic and over the mission lifetime are shown here. As expected during the summer months, the number of valid measurements is at a minimum due to formation of melt-ponds in the sea ice. As expected we see a slight decrease in % validity from PB2.43 onwards, due to the implementation of stricter filtering.





*Figure 145: Number and % of valid freeboard measurements over S3A and S3B mission life* 



# 8.2 Sea Ice Parameters Contributing to Freeboard

Sea ice parameters contributing to the calculation of freeboard were monitored during 2019.

#### Sea Surface Height (Sea Ice Retracker Failure)

In PB2.43 (in operation since Feb 2019) we see a much lower failure rate (2.62%) as compared to PB2.33 (38.86%). This is due to the correction of an anomaly (SIIIMPC-2411) in PB2.33 relating to an incorrect waveform quality filter applied to lead echoes resulting in higher than expected retracker failure rates. In PB2.43 we also see the introduction of dedicated lead and floe retrackers.



Figure 146: Arctic maps of sea surface height (PB2.33 and PB2.43)

Statistics of sea\_ice\_sea\_surf\_20\_ku parameter validity since start of the mission show the expected increase in PB2.43 (IPF 6.15).




Figure 147: Statistics of Sea Ice Retracker failure in the Arctic over S3A Mission

#### Sea Ice Surface Type Discrimination

The surface type discriminator classifies each echo as either a sea ice floe, lead, open ocean or unclassified. As we expect, the number classified as floes (sea ice) has a minimum in the Arctic summer, whereas the number of leads has a maximum in the summer (as melt ponds in the sea ice cause specular reflections).



Figure 148: S3A Surface Type Discrimination since start of mission



Sentinel-3 MPC S3MPC STM Annual Performance Report - Year 2019 
 Ref.:
 S3MPC.CLS.APR.006

 Issue:
 1.0

 Date:
 28/02/2020

 Page:
 160

### Sea Ice Concentration

The L2 sea ice concentration parameter is interpolated from a dynamic sea ice concentration ADF containing a gridded 3 day average. In PB2.33 it was shown that the linear interpolation method used caused contamination of sea ice concentration values from coastline/land areas which contain 0% concentration values. This is actually an intended feature of the sea ice processor (to remove sea ice echoes that may contain land contamination from the freeboard processing), however this does result in an incorrect L2 sea ice concentration value close to the coastline.

In the sea ice algorithm update in PB2.43 the method of interpolation was changed to nearest neighbour, which significantly reduces the extent of false low values around the coastline in line with the method used in Cryosat Baseline-D. However, some incorrect 0% values are still present in PB2.43:



Figure 149: Invalid 0% sea ice concentration values around coastline in PB2.43

This anomaly is scheduled to be corrected in a product baseline in early 2020 using a new land and coastline mask in the associated ADF.



Figure 150 : Corrected L2 Sea Ice Concentration, shown over the Arctic Beaufort Sea, available in 2020.

## 8.3 Effect of Area Masking and Pole to Pole Processing on Sea Ice Parameters

Processing of SR\_2\_LAN (which include some areas of sea ice) and SR\_2\_WAT products for sea ice parameters will not produce the same freeboard result over all areas of sea ice due to the different SSHA interpolation track lengths and area masking used. SR\_2\_LAN products are masked 100km from the coast. A solution to this, which is under investigation by ESA/MPC, is to include all areas of the sea-ice extent in the SR\_2\_LAN product processing mask.

IPF products are processed pole to pole instead of equator to equator as specified in the DPM for SSHA interpolation. This means that tracks will be interpolated over half the Arctic instead of the full Arctic as intended. This has an effect on the interpolated sea surface between leads within 100km of the track cut point. In the sea ice algorithm update (PB2.43) the SLA interpolation algorithm has been adapted and tuned to extrapolate the sea surface to the track end in order to reduce the impact. This anomaly can only be completely solved by equator to equator processing in a specialised IPF sea ice processor.



# 8.4 Availability of Snow Density, Snow Depth and Sea Ice Concentration over Sea Ice

For the product baselines in 2019 (PB 2.33, 2.43), the percentage availability of sea ice concentration, snow depth and snow density data was:

Correction	% Availability Arctic Sea Ice	% Availability Antarctic Sea Ice		
Sea Ice Concentration <sup>3</sup>	100	100		
Snow Density <sup>1</sup>	100	100		
Snow Depth	100	100 <sup>2</sup>		

#### Table 13: % Availability of Snow Density, Snow Depth, Sea Ice Concentration over Sea Ice

<sup>1</sup>Snow Density is set to a single value of 400 Kg/m<sup>3</sup> as expected.

<sup>2</sup> Snow depth over Antarctic sea ice is set to zero as expected.

<sup>3</sup>Sea Ice Concentration is derived from a dynamic 3 day average of sea ice concentration calculated from SSM/I daily brightness temperature data.



# 9 Mission Performance over Land Ice

In this section we show the operational mission performance over land ice for S3A and S3B, up until the end of the 2019 review period.

Note that the operational L2 products in this review period (PB2.33, 2.43) are processed from the standard IPF L1 data which is optimized for ocean surfaces only. Studies during the first 2 years of the S3A mission have shown that this processor does not optimally window and centre the waveform over areas of high slope (>  $0.3^{\circ}$ ) such as the ice sheet margins, which can result in truncation or missed echoes. A L1 solution to this issue has been in prototype development since Q4 2017 and is scheduled for operational use in 2020.

Whilst separate specialized L1 processing is required for optimal performance over the more complex ice surfaces, work has continued during 2019 to improve the performance and validation of the current L2 operational products over land ice surfaces, which are able to produce good results as shown in *McMillan et al, 2019*, over the majority of the ice sheets (which have low slope), when tuned to operate with the current ocean optimized L1 input data. A new higher resolution slope model of Antarctica and Greenland was delivered (derived from an updated DEM from CryoSat-2 (Helm, 2014)), a test data set and study performed to validate expected improvements to slope correction. The new slope model will be used operationally in PB 2.61 (from Jan 2020).

A new validation study, comparing ICESat-2 ATL-06 v001 elevation data with S3A and S3B at crossover locations over Lake Vostok was performed and showed only a very small mean bias ( $\sim$  1cm +/- 6cm) between the two, indicating that S3 SAR is measuring very close to the ice sheet surface, with minimal penetration of the radar echo, and very good accuracy over low slopes.

## 9.1 **The Effect of SAR Tracking Mode on S3A Land Ice Performance**

During 2019, S3A and S3B operated in SAR closed loop mode. It should be noted that during the first 11 cycles of the S3A mission in 2016, S3A operated in open loop tracking mode (onboard DEM based tracking) over the ice sheet margins. SAR open loop mode was found to have significant problems correctly tracking the surface over sloping terrain and this mode was switched to closed loop over the margins in Dec 2016 (cycle 12). As a result measurement density over the margins during cycles 3-11 was severally reduced. It is possible that the new Land Ice specialized L1 processor (2 year test data set available in March 2020) will recover more data during this period as it is able to re-centre echoes at the edge of the extended L0 range window which are missed by the current IPF L1 processor (PB2.43).





Figure 151: S3-A Elevation failure rates in Open Loop and Closed Loop cycles over Different Ice Surfaces

## 9.2 Measurement Precision over Land Ice

To assess the utility of the Sentinel-3 altimeter over ice surfaces, the precision of the SRAL measurements were assessed using the method developed by *McMillan et al., 2019*, by assessing their repeatability in space and time. For this purpose we performed two sets of analysis, (1) an evaluation of repeated profiles that crossed subglacial Lake Vostok, a site that provides a stable and low-slope surface that is well established for validation studies (*Richter et al., 2014; Schröder et al., 2017; Shuman et al., 2006*), and (2) a continent- wide single-cycle cross-over analysis, to evaluate the repeatability of measurements at locations where ascending and descending satellite passes intersect (*Wingham et al., 1998; Zwally et al., 1989*).

### 9.2.1 Shot-to-shot Precision

Repeated altimeter profiles that crossed the ice surface above the Lake Vostok site in East Antarctica were compared in order to assess the SRAL instrument precision. The smooth, flat surface (<  $0.01^{\circ}$ ) above the lake minimises the influence of topography, and allowed us to focus primarily on the performance of the SRAL instrument itself, and specifically to understand the impact of radar speckle, small-scale variations in the firn backscattering properties and the influence of retracker imprecision on the SAR altimeter measurements.



Sentinel-3 MPC S3MPC STM Annual Performance Report - Year 2019 
 Ref.:
 S3MPC.CLS.APR.006

 Issue:
 1.0

 Date:
 28/02/2020

 Page:
 165

For each S3-A cycle we assessed the repeatability of the measurements in space and time by computing the mean elevation profile from the previous 6 months (7 cycles), the residual elevations from the mean profile, and the standard deviations of all elevation measurements within 400 m intervals along-track. We also calculated the interpolated Cryosat-2 DEM elevations along the profile from two separate DEMs (*Slater, 2018,* and *Helm, 2014*).

The variability and repeatability of OCOG elevation measurements of the centre of Lake Vostok over a 6 month period during 2019 from S3-A cycle 46-51 are shown below, with a median standard deviation from the mean profile of 5cm, and a mean bias to the Cryosat DEMs of 31cm.



Figure 152: S3A Shot-to-shot Precision over Lake Vostok (6-month period in 2019)

Repeating the analysis for the precision of measurements of every S3A cycle (compared with the previous 7 cycles) over the full operational mission shows that there is some variability but the mean precision is < 10cm.





Figure 153: S3A Repeat Measurement Precision over Lake Vostok

In comparison, we repeated the same analysis with ENVISAT (GDR v3 product) which has a similar repeat orbit track over Lake Vostok. ENVISAT operated in pulse limited LRM mode.



Figure 154: Comparison of measurement precision between S3A (SAR) and ENVISAT (LRM)



From this analysis it appears that S3A (PB2.43) in SAR mode performs at nearly two times better precision (~8cm mean variability) than ENVISAT GDR v3 (~14cm) over the Lake Vostok test site. In both cases the OCOG (Ice-1) retracked elevation was used.

## 9.2.2 Crossover Analysis

Single-cycle cross-over analysis was used to assess the repeatability of measurements at all ice sheet locations where ascending and descending satellite passes crossed for each S3A and S3B mission cycle. This analysis was performed on both a central Lake Vostok test site (to show precision over a smooth flat ice surface) and on the whole Antarctic ice sheet.

#### **Crossover Precision over Lake Vostok Centre**

For a single cycle, there are a maximum of 21 locations in the centre of Lake Vostok where ascending and descending passes cross. The interpolated elevation (OCOG) difference was calculated at each of these locations, and the statistics analysed for each cycle. Over the whole mission (to S3A cycle 50), the mean differences was -0.003m, and standard deviation 0.081m. This agrees very well with the previous repeat track precision analysis (0.08m stdev).



Figure 155: Crossover OCOG Elevation Differences at Lake Vostok Centre (S3A cycle 50, PB2.43)



#### Sentinel-3 MPC

S3MPC STM Annual Performance

Report - Year 2019

 Ref.:
 S3MPC.CLS.APR.006

 Issue:
 1.0

 Date:
 28/02/2020

 Page:
 168



Figure 156 Crossover OCOG Elevation Differences at Lake Vostok Centre (S3B cycle 30, PB2.43)



Figure 157: Crossover S3A Mission Statistics at Lake Vostok Centre (OCOG Elevation differences)

	Sentinel-3 MPC	Ref.:	S3MPC.CLS.APR.006
	S3MPC STM Annual Performance	Issue:	1.0
CLS	Report - Vear 2019	Date:	28/02/2020
COLLECTE FOCACIONION 241EFEUE2	Report - Tear 2019	Page:	169



Figure 158: Crossover S3B Mission Statistics at Lake Vostok Centre (OCOG Elevation differences)

#### **Crossover Precision over the Antarctic Ice Sheet**

Crossover differences over the Antarctic ice sheet shows the expected slope dependence, with higher differences over the margins (slope >0.1°). In these regions, the processes of locating the echoing point within the beam footprint, and of retracking complex multi-peaked waveforms become more challenging.

Crossovers have a mean difference of < 1 cm in magnitude, and a higher than normal proportion of the differences are clustered around this central value, reflecting the good repeatability of measurements across the low slope interior of the ice sheet.



Figure 159: Crossover OCOG Elevation Differences over Antarctic Ice Sheet (S3A cycle 39, S3B cycle 20, PB2.33)







	Sentinel-3 MPC	Ref.:	S3MPC.CLS.APR.006
	S3MPC STM Annual Performance	Issue:	1.0
CLS	Report - Vear 2019	Date:	28/02/2020
COLLECTE FOCALISATION 24/EFFILE2		Page:	171



Figure 160: S3A Mission Statistics of Crossover differences (Antarctic Ice Sheet), OCOG elevation (PB2.43)

A separate study (*McMillan, 2019*) was undertaken to compare S3A crossover differences as a function of surface slope. For each cycle all the cross-over differences within 0.2° intervals of surface slope were binned, to investigate the relationship between the magnitude of the surface slope and the cross-over elevation precision.



Figure 161: Median absolute cross-over elevation difference (blue dots) and number of cross-overs (blue bars) as a function of surface slope, S3A.



## 9.3 Measurement Accuracy over Land Ice

To conduct an independent evaluation of the accuracy of our Sentinel-3 ice sheet measurements, we used elevation data acquired by the:

- Airborne Topographic Mapper (ATM) and Riegl Laser Altimeter (RLA) instruments carried on Operation IceBridge.
- ICESat-2 ATL-06 v001 elevation data

Results of measurement accuracy versus IceBridge were were published in *McMillan et al, 2019. (the Cryosphere)* and full details included in the 2018 Annual Review. In 2019 we report on a new study comparing S3A and S3B with ICESat-2 elevation measurements (the effective replacement for IceBridge).

Elevation differences at crossover were calculated between ICESat-2 ATL-06 elevations (central beam: gt2r\_h\_li) and S3A elevation\_ocog\_20\_ku. Differences are very small with a mean difference of 1cm and standard deviation of 6cm. This indicates that S3A is measuring to a very similar accuracy and precision to ICESat-2 over ice sheet areas of very low slope. In comparison we repeated the analysis with CryoSat LRM data (difference to ICESat-2) and found that there was a mean difference of 26cm (indicating higher penetration for CS2 LRM).



Figure 162: Elevation differences at crossovers between ICESat-2 and S3A over Lake Vostok

We also calculated the crossover difference between S3A and ICESat-2 over the whole Greenland ice sheet. As expected measurement precision degrades with increased topographic complexity and slope for



# Sentinel-3 MPC S3MPC STM Annual Performance Report - Year 2019

 Ref.:
 S3MPC.CLS.APR.006

 Issue:
 1.0

 Date:
 28/02/2020

 Page:
 173

both S3A and ICESat-2, however we find that 66.3% of measurements have a difference of < 1m, and a mean difference of -0.06m for areas of low slope. For Antarctica we find that 67.57% of measurements have a difference of < 1m, and the mean difference is -0.09m.



Figure 163: Crossover differences between ICESat-2 and S3A (OCOG elevation) over Greenland

# 9.4 Ice Sheet Rate of Elevation Change from S3A

One of the principle uses of altimetry data for climate change studies is to determine changes in ice sheet elevation over time (*Flament & Rémy, 2012; Shepherd et al., 2012; Shepherd & Wingham, 2007; Zwally et al., 2005*). Although the available time span of Sentinel-3A acquisitions is short for detailed glaciological interpretation of any signals, it is nonetheless important to determine whether the precision, accuracy and stability of S3 in SAR mode is sufficient to be able to resolve known signals and modes of glaciological change. We therefore applied a modified model-fit method (*McMillan et al., 2014, 2016*) to almost 3-



years of Sentinel-3A data from Dec 2016 to Oct 2019, in order to explore the potential of these data for mapping elevation changes of the Antarctic Ice Sheet. The resulting map is shown below.



Figure 164: Rate of Elevation Change derived from S3A OCOG Elevation (Dec 2016 to Oct 2019)

Across large parts of the slow-flowing ice sheet interior, the derived rates of elevation change are low. This agrees with numerous recent studies (*Flament & Rémy, 2012; Helm et al., 2014; McMillan et al., 2014*), and provides an indication that the Sentinel-3 instrument and orbital configuration is suitable for mapping changes across the low relief ice sheet interior. Although we believe that the Sentinel-3A record is still too short to perform a detailed, ice sheet-wide, quantitative inter-comparison relative to previously published altimeter datasets, we do find evidence that S3 SAR altimetry is able to map the higher, dynamically-driven, rates of elevation change that are occurring across coastal regions of the ice sheet (*Flament & Rémy, 2012; Helm et al., 2014; McMillan et al., 2014*).



It is important to note that this result is derived from PB2.43, which has a 'ocean optimised' L1 processing (causing some waveform truncation over the margins ) with resulting reduction in accuracy and data density in the high slope land ice margins. A further improvement will be gained using the new specialised land ice L1 processed data set available in 2020.

## 9.5 Land Ice Parameter Failure Rates

Mission lifetime statistics of the failure rate of the main land ice parameters for selected land ice areas (Antarctic Ice Sheet, Greenland, Lake Vostok (low slope), SPIRIT Zone (high slope) are shown in this section. The timeseries of these statistics are a useful indicator of mission lifetime performance and stability.

## Elevation\_ocog\_20\_ku

OCOG elevation failure is primarily caused by failure of the empirical OCOG retracker. We expect this failure rate to be very low (< 5%) for all surfaces as the OCOG retracker has minimal waveform filtering applied and is robust over complex terrain.



Figure 165: Antarctica OCOG Elevation Gridded Failure Maps (S3A, S3B, PB2.43)

Over the review period the %failure of elevation\_ocog\_20\_ku (PB 2.43) over the Antarctic ice sheet remained stable at 3.1% +/- 0.1%, however this represents a step increase of 1.1% failure as compared



to the previous baseline. The most likely cause of this increased failure is the change to the waveform quality flagging in PB2.43 : SIIIMPC-2548 (noise power flag bit fixed), with the additional quality flagging causing higher overall failure. There was also a change made to the OCOG algorithm (SIIIMPC-2564: removal of first and last 12 noise gates to improve inland water performance) which may also effect failure rates.



Figure 166: Failure rate of elevation\_ocog\_20\_ku (S3A, PB2.33, PB2.43)



Figure 167: Failure rate of elevation\_ocog\_20\_ku (S3B, PB2.43)



Sentinel-3 MPC S3MPC STM Annual Performance Report - Year 2019 
 Ref.:
 S3MPC.CLS.APR.006

 Issue:
 1.0

 Date:
 28/02/2020

 Page:
 177

### Elevation\_ice\_sheet\_20\_ku

Ice sheet elevation failure is primarily caused by failure of the SAR physical model ice sheet retracker and its waveform quality checks. We expect this failure rate to be sensitive to waveform shape caused by surface slope and terrain variability. So as expected we see high failure rates over the margins (SPIRIT zone failure ~46%) and low failure in Lake Vostok (<1%), overall Antarctic Ice Sheet failure of ~23%, and Greenland (28%). We again see an increase in failure rate of ~2% between PB2.33 and PB2.43 (due to increased waveform quality checks).



Figure 168: Antarctica Ice Sheet Elevation Gridded Failure Maps (S3A, S3B, PB2.43)





Figure 169: S3A Mission Failure rate of elevation\_ice\_sheet\_20\_ku (S3A, PB2.33, PB2.43)



Figure 170: S3B Mission Failure rate of elevation\_ice\_sheet\_20\_ku (S3B, PB2.33, PB2.43)



# Sentinel-3 MPC S3MPC STM Annual Performance

Report - Year 2019

 Ref.:
 S3MPC.CLS.APR.006

 Issue:
 1.0

 Date:
 28/02/2020

 Page:
 179

#### Range\_ice\_20\_plrm\_20\_ku





Figure 171: Percentage failure of range\_ice\_20\_plrm\_ku (S3A, PB2.33, PB2.43)

#### Waveform\_qual\_ice\_20\_ku

In the product baseline (PB2.24), a new L2 parameter (waveform\_qual\_ice\_20\_ku) was added to indicate the results of a set of waveform quality tests optimized for ice sheet waveforms. Users can test the value of flag bits within this parameter to filter individual measurements or to indicate the reason for parameter failure. In PB2.33 the primary failure is in the leading edge test. This is because of the L1 centered



# Sentinel-3 MPC S3MPC STM Annual Performance Report - Year 2019

 Ref.:
 S3MPC.CLS.APR.006

 Issue:
 1.0

 Date:
 28/02/2020

 Page:
 180

waveform anomaly, which results in the echo moving around the range window over sloping terrain. This will be corrected in the specialised land ice L1 processor. Also in PB2.33 there is an error in the noise test, resulting in zero failure. This was corrected in PB2.43.



Figure 172: S3A/B waveform quality flag map over Antarctica (PB2.43)



Figure 173: S3A Mission waveform quality flag statistics over Antarctica (PB2.33,2.43)



Note that the Ice Sheet Elevation parameter (and associated ice sheet range and sigma0) are already filtered (with a fill value set) from the result of these waveform quality tests. Parameters derived from the Ice-1 (OCOG) retracker are not filtered, but users should use the results of the quality flag as an advisory.

The tests comprise:

- Total power test to detect low power in the echo.
- Noise power test to detect high levels of noise at the start of the echo.
- Variance test to detect unstructured waveforms
- Leading edge detection to check waveform power distribution indicates a leading edge.
- Peakiness test to detect waveforms of too low or high peakiness value.

## 9.6 Slope Correction

A slope correction from a slope model derived from Antarctic (RAMP v2) and Greenland (Bamber 2001) DEMs is applied to 20Hz Ku band elevation over ice sheets to relocate the SAR echo to the point of closest approach across track. Note that no slope correction is performed if both ice retracker fails. The magnitude of the applied slope correction is shown below for a typical S3A cycle. The magnitude (only applied across track) is dependent on the direction of the pass in relation to the local slope.



#### **Slope Correction Magnitude**

Figure 174: S3A SAR ku Slope Correction Magnitude (PB2.43)

A new updated slope correction derived from a Cryosat-2 DEM (Helm, 2014) will be used in the next PB 2.61 released in Q1 2020.



# 9.7 Geophysical Correction Availability over Land Ice

During the S3A and S3B mission there has been generally good availability of geophysical corrections apart from the GIM Ionospheric correction over Antarctica which had missing orbits since S3A cycle 30 (April 2018). This continued until April 2019, after which there was 100% coverage.



Figure 175: Missing GIM Ionospheric Corrections over Antarctica in 2019



# **10 Performance Mission over Inland waters**

# 10.1 Behaviour of the OLTC (open loop Tracking Command)

## **10.1.1 OLTC content and validation**

As previously illustrated in section 6, the aim of the OL mode is to overcome some problems observed over continental surfaces when the altimeter is in CL mode. First, the tracking can be lost when there is a rapid modification of the topography, this implies that the measurements are interrupted. Second, even if the instrument is able to keep tracking, the tracking window can be positioned so that the altimeter is not observing a river but the surrounding topography. Using the OL mode can force the altimeter to observe the river. However, it requires that the knowledge of the water surface elevation is known with an accuracy of about +/- 10 meters.

During the year 2018, we have defined a database of hydrology targets for the Sentinel-3A and 3B altimeters in order to provide this knowledge. We have defined more than 65000 targets that have been used to build the onboard tables used to drive the altimeter tracking (fig.below).



#### Figure 176: River targets for S3A and S3B in the LEGOS hydrology targets database

The OLTC using these new tables were activated

for Sentinel-3B, on November, 27 2018 (cycle 19, pass 219) as soon as it reached its definitive orbit



for Sentinel-3A, on March, 9 2019 (cycle 42, pass 317)

The validation was performed during summer time of the north hemisphere. We compared the results obtained on Sentinel-3A:

- in 2018 (from 31<sup>st</sup> of March to 20<sup>th</sup> of August), in Close Loop mode or using the previous version (4.2) of the OLTC in some areas,
- in 2019 (from 24<sup>th</sup> of March to 6<sup>th</sup> of August), in Open Loop mode using the new version (5.0) of the OLTC everywhere (between 60°N and 60°S)



Distribution of max backscatter over 162888 overpass

*Figure 177: Histograms of the observed sigma0 over the hydrology targets in 2018 and 2019 showing the improvements brought by the new OLTC* 

As high backscatter coefficient (sigma0) is a good proxy for water detection, the Figure 177 shows that the update of the OLTC performed on March 2019 has been successful. Indeed, it shows that the low sigma0 (less than 40 dB) observations from 2018 have disappeared in the 2019 measurements. They have been replaced by high sigma0 observations that can be measured only on calm inland water surfaces. The absolute value of sigma0 is not really important here, what is important is the relative comparison between the two periods. We have chosen periods which are meteorologically similar in order that the observed differences are representative of the change of behavior of the instrument and not a change of the geophysical conditions. Similar results have been obtained on Sentinel-3B.

A second verification that must be performed is the correct centering of the waveforms in the acquisition window. The Figure 178 shows peaky waveforms typically observed over inland waters. The waveform should be approximately centered. If not, the variation of water surface elevation during the hydrological cycle could bring the leading edge outside of the acquisition window and make the measurement unusable.



Figure 178: Need to have the waveforms well centered to cope with the variation of the water surface elevation

The Figure 179 compares the histograms of the position of the leading edge when the altimeter is in Close Loop (left panel) and when it is in Open Loop mode (two right panels). The histograms with the new OLTC are more centered and narrower than with the Close Loop of Sentinel-3. This shows that, statistically, the heights of the targets in the new OLTC are good.



Figure 179: Histograms of the position of the leading edge that shows that the target heights in the new OLTC are good statistically and that it reduces a lot the number or "no data" observed in CL.

We can also observe that the "no data" that were observed with the altimeter in Close Loop mode (caused for example by a loss of tracking) have almost completely disappeared with the new OLTC. This means that with the OLTC, when a temporal series of water levels is available, there is a high probability that it will be complete (provides a measurement for each cycle). This is a big advantage with respect to the Close Loop mode for which the altimeter could always loose the tracking depending of the history of the return power before arriving over the target.

From a more qualitative point of view we have received many good feedbacks from users (especially those working in mountainous areas). We also received a few feedbacks from users complaining that some reservoirs where not observed. The root cause for this is that these reservoirs were not included in the waterbodies database that we used. These feedbacks will be taken into account in the next generation of the database for the Sentinel-3A and 3B OLTC (due in spring 2020).



## **10.1.2** Advise on the potential Open Loop mode limitations

As the Open Loop consign is interpolated between the points on which it was defined (points in Figure 176) the consign might not be adapted to track water bodies not present in the consign database. Users are encouraged to check if their rivers, lakes of interest are correctly sampled by the Sentinel-3 alimeters and if this is not the case to provide there feedbacks and targets characteristics on : <u>https://www.altimetry-hydro.eu/</u>. These feedbacks are taken into account to generate the next versions of the database for the Sentinel-3A and 3B OLTC (next one is due in spring 2020).

## **10.2 Results from systematic quality assessment over 2019**

This section aims at characterizing and describing the SRAL altimeters (3A and 3B) performances over inland waters. Thanks to external data (Global Lakes and Wetlands Database), a pre-selection based on water occurrence probability was performed to ensure only keeping measurements over water surfaces: data over the largest 700 lakes worldwide are extracted to assess the products quality. Some of the diagnoses presented illustrate the monitoring performed over a specific cycle, others show the stability of the performances as a function of the time.

## **10.2.1** Default value and potential outliers

#### 10.2.1.1 Method

Even though a first selection is performed to select data over water areas, an editing is performed to determine potentially corrupted measurements. The editing criteria defined are twofold. The first technique (editing 1) is based on minimum and maximum thresholds for various parameters. For a given 20Hz data point, the measurement is flagged if at least one parameter is found to be outside those thresholds. The second technique (editing 2) is based on a statistical analysis of the water surface height evolution in time: the water surface height time series is estimated for each lake, averaging the 20Hz measurements from each transect (intersection of the ground track with the water body). Then the time series is low pass filtered and subtracted to the original time series. The outliers are identified as the values outside a +/- 3 sigma range of this residual. The percentage of outliers with both techniques is expected to remain similar for Sentinel-3A and Sentinel-3B and consistent throughout the missions.

### 10.2.1.2 Results

The statistics of valid and edited measurements for Sentinel-3A and Sentinel-3B are monitored over each cycle. An example over the common period from 2<sup>nd</sup> of December 2019 to 29<sup>th</sup> of December 2019 is presented in Figure 180. Results for both satellites are consistent, in particular the statistics of the retracking derived parameters (backscatter coefficient, range).

Statistics presented in Figure 180 are also monitored in between the different cycles. Figure 181 shows the stability of the percentage of Sigma0 default values and edited measurement (this editing criterion consists in a minimum threshold of 40 and 7dB on the backscatter coefficients OCOG and SAMOSA respectively). At the beginning of the Sentinel-3B timeseries, higher default values percentages are



noticed (cycles 9 and 10), this is explained by the Low Resolution Mode in which S3B operated during theses cyclces. The higher level of edited values for sigma0 OCOG over cycles 9 and 10 (bottom left plot) are due to an anomaly on sigma0 OCOG in LRM, which was later corrected in IPF version 6.15. Since the end of cycle 10, S3B is operating in SAR mod. The drop in the number of sigma0 default values for both SAMOSA and OCOG retrackers since December 2018 is explained by the switch of S3B from close to Open Loop mode in between latitudes +/- 60 ° on November 27<sup>th</sup> 2018.

Similar improvement in the percentage of default values for sigma0 OCOG and SAMOSA is observed for Sentinel-3A in March 2019 (Figure 181 top plots). It corresponds to the Open Loop Tracking Command update from v4.2 to v5.0 onboard S3A. This OLTC upload occurred from February 28<sup>th</sup> 2019 to March 9<sup>th</sup> 2019. Prior to this upload S3A was operating in both close loop and open loop modes on some patches over land (see Figure 25), while it now fully operates in open loop mode over land between +/- 60° of latitude since OLTC v5.0 update.

These statistics are performed over lakes, where both ocean and ocog retracking are quite similar. Slight differences observed consist in more DV values observed for ocean retracking (ocog retracker less sensitive to corrupted waveforms) but more edited values for the ocog retracker (the corrupted waveforms are retracked but the estimated parameters could be wrong).



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Sentinel 3 - B: Valid / edited / DV - L2 Land water data Cycle 33



Figure 180: Sentinel-3A (top panel) and Sentinel-3B (bottom panel): Percentage of Valid (green), Edited with technique 1 (orange), Edited with technique 2 (red), and Default Value (black) measurements on the largest lakes worldwide in Open Loop mode. Statistics are provided for all fields necessary to the water surface height estimation with the SAMOSA and the OCOG retracking algorithms. Statistics computed over cycle 33 of Sentinel-3B.



Figure 181: Monitoring of the percentage of default values and edited measurements over lakes (on the backscatter coefficient criteria) for Sentinel-3A (top panels) and Sentinel-3B (bottom panels) computed for both kind of retracking (OCOG and SAMOSA).



### 10.2.2 Transect dispersion of the 20Hz water level estimates

The along-track analysis of Water Surface Height is necessary to monitor the performance of the product, mainly in terms of:

- its capability to measure Nadir water echoes without the contamination of off-nadir echogenic targets (mostly on small lakes and banks)
- the resolution and precision of the geoid model

The dispersion is estimated for the water surface height on each transect. A transect is defined as the union of the intersection of a single ground-track with a lake delineation. In many cases, there are several intersections of the same track with one lake (presence of islands, concave shapes...etc) and the union of these intersections defines the transect.

The dispersion contains both the performance of the altimeter itself but also of each correction and particularly the geoid that contains errors of 20cm in average. However, geoid errors are generally constant from one cycle to another for one transect, modulo in the cross-track drift of the orbit (specification: lower than 1km w.r.t the theoretical ground track in 95% cases). The transect dispersion must thus be considered as a relative level that is designed to be compared between two cycles, for the same transect. However, the global statistics calculated with this metric provides an overview of the performance of the product.

Figure 182 shows the repartition of the Water Surface Height transects dispersion for several classes: lake area, transect length and open loop or close loop mode. The dispersion is expected to be significantly larger on short transects, mainly because the number of samples within the transects is low and proportionally more contaminated by non-water off-Nadir surfaces. On larger transects, the dispersion provides a better knowledge of the performance of the product and is expected to be below 15cm in open loop mode. This dispersion is however significantly driven by the geoid errors. As expected, both missions present similar statistics.



	Sentinel-3 MPC	Ref.:	S3MPC.CLS.APR.006
	S3MPC STM Annual Performance	Issue:	1.0
CLS		Date:	28/02/2020
COLLECTE LOCALISATION SATELLITES	Report - Teal 2019	Page:	190

Figure 182: Standard deviation of the Sentinel-3A (Left) and Sentinel-3B (Right) WSH (computed with range derived from OCOG retracking) from 02/12/19to 29/12/19 as a function of the lake area (left), of the transect length over lakes sampled (middle), and of the acquisition mode (right).

In Figure 1830, the median value of each transect is estimated and represented in time for Sentinel-3A (blue lines) and Sentinel-3B (red lines). The long-term water surface height variation is consistent between the two altimeters. It suggests no drift or jumps in the product. The biases between the transects result mainly from the geoid errors. As Sentinel-3B was shifted from its tandem orbit with Sentinel-3A to its final orbit, there are some single points for some tracks numbers in October-November 2018.



Figure 183 : Time series of Water Surface Height (m) on Lake Issyk-kul for the Sentinel-3A transects (blue lines) and Sentinel-3B transects (red lines), OCOG retracker.



## 10.3 Validation over Ebro River basin

isardSAT has validated S3A and S3B L2 data with in-situ measurements over all possible inland water bodies within the Ebro River basin. When possible, results from S3A and S3B have been also intercompared.

The Ebro basin is located in Iberian Peninsula within longitudes 4.5° W, 2° E and latitudes 40° N, 43° N. Over the western part of the basin, S3A was in CL tracking mode until March 9<sup>th</sup>, 2019, and changed to OL afterwards with the update of the DEM to v5 (see previous sections). The eastern part of the basin has always been in OL tracking mode.

Water bodies in Ebro River basin have different sizes with width ranging from 130 m to 4.5 km. Pyrenees mountains (with heights over 3000m) are located in the north east part of the basin making range measurements challenging over some reservoirs (e.g. Cavallers, Irabia). In situ validation data for all reservoirs comes from the Automatic Hydrological Information System (SAIH Ebro).



Figure 184 Water bodies covered by Sentinel-3 satellite tracks with all available gauging stations.

Both Sentinel-3 L2 ocean retracker and OCOG retracker have been used to calculate water levels from L2 products together with L2 geophysical corrections (including the wet troposphere, dry troposphere, ionosphere, solid earth tide, geocentric pole tide and ocean loading tide) and the geoid correction. The time series of the water levels are calculated using a strict water mask polygon. The water levels of the altimeter footprints within the mask are considered, selected and averaged for each date.

Three reservoirs have been monitored for a long-time period with S3A. These are: Sotonera, Ebro and Ribarroja reservoir. Results for the different reservoirs are shown in Table 14. Results show in general a good agreement between water levels derived from S3A L2 and in-situ.



No accuracy changes were observed with the update of the OLTC DEM. Two reservoirs are not tracked with DEM v4.2 nor with DEM v5. These are: Cavallers and San Salvador. The correct coordinates for Cavallers and San Salvador reservoirs were introduced in <u>https://www.altimetry-hydro.eu/</u> by August 2018.

Reservoir	Width	Average slope (5 km)	Track	Tracking mode	RMSE / ubRMSE [m]	
					Level-2 ocean	Level-2 OCOG
Ebro	1.8 km	4%	S3A 014	$CL \rightarrow OL$	3.6 / 3.4	2.2 / 2.1
Sotonera	4.5 km	3%	S3A 222	$CL \rightarrow OL$	1.3 / 0.90	1.15 / 0.62
Ribarroja	400 m	24%	S3A 242	OL	0.80 / 0.54	0.80 / 0.57
Cavallers	800 m	27%	S3A 299	OL	Off-track	
San Salvador	1.2 km	4.5%	S3A 242	OL	Off-track	

 Table 14: Results of the water level comparison with in-situ data over the long term monitored reservoirs (June 2016 –December 2019).

With the update of the OLTC DEM to v5 we were able to obtain valid measurements over Mequinenza reservoir. However we have lost track over two reservoirs that were previously in CL: Itoiz reservoir (as shown in Figure 185) and Irabia reservoir. The correct coordinates for Itoiz and Irabia reservoirs have been introduced in <u>https://www.altimetry-hydro.eu/</u> by February 2020.



Figure 185 Water level time series retrieved by ocean retracker and OCOG retracker over two water bodies: Mequinenza Reservoir (left) and Itoiz Reservoir (right).

	Sentinel-3 MPC	Ref.:	S3MPC.CLS.APR.006
	S3MPC STM Annual Performance	lssue:	1.0
CLS	Poport Voor 2019	Date:	28/02/2020
COLLECTE LOCALISATION SATELLITES	Report - Teal 2019	Page:	193

Since S3B measurements are available, we are able to monitor 3 new reservoirs (Ullibarri, Canelles and Santa Ana). The comparison results with in-situ data are shown in Table 15.

Reservoir	Width	Average slope (5 km)	Track	Tracking	RMSE / ubRMSE [m]	
				mode	Level-2 ocean	Level-2 OCOG
Ullibarri	260 m	8%	S3B 128	OL	2.89 / 2.88	0.89 / 0.13
Canelles	260 m	26%	S3B 299	OL	1.96 / 1.8	2.05 / 1.83
Santa Ana	300 m- 1.8 km	17%	S3B 299	OL	0.89 / 0.65	1.05 / 0.66

Table 15: Results of the S3B water level comparison with in-situ data (December 2018 – December 2019)

With availability of S3B data, we are also able to validate both missions measurements over 2 reservoirs (Ribarroja and Mequinenza). Figure 186 and Figure 187 show the comparison of S3A and S3B water levels over Ribarroja and Mequinenza respectively. Note that S3B passes are closer to the in-situ measuring point, which could explain the slightly better comparison with in-situ data.



Figure 186 Water level time series retrieved by S3A (+) and S3B (o) over Ribarroja Reservoir.



Figure 187 Water level time series retrieved by S3A (+) and S3B (o) over Mequinenza Reservoir.

Reservoir	Width	Average slope (5 km)	Track	Tracking	RMSE / ubRMSE [m]		
				mode	Level-2 ocean	Level-2 OCOG	
Ribarroja	400 m	24%	S3A 242	OL	S3A 1.17 / 0.78	1.15 / 0.83	
			S3B 336		S3B 0.43 / 0.20	0.52 / 0.21	
Mequinenza	600 m	3.5%	S3A 279	OL	S3A 2.32 / 1.69	1.58 / 1.06	
			S3B 242		S3B 0.64 / 1.19	0.78/ 1.22	

#### Table 16: Results of the S3A and S3B water level comparison with in-situ data (December 2018 – December 2019)

In summary, the accuracy of both S3A and S3B over small water bodies such as here considered is good. Better results (in the decimetre range) over in-land water bodies can be obtained when filtering the waveform to consider only the portion return from nadir as in Gao et al. 2019 [RD24].

## **10.4 Comparison of SAR and PLRM performances over inland waters**

During the 14<sup>th</sup> June 2018 to 11<sup>th</sup> June 2018 period, S3A operated in SAR mod and S3B in LRM while both instruments were in their tandem. This configuration provides an opportunity to compare both acquisition mods.

### **10.4.1** Coastal contamination

The orbit-range quantity is compared along a track across the IssykKul lake. As presented in Figure 189, the coastal contamination (red ellipses) is higher in LRM than in SAR mod. This is explained by the smaller SAR footprint that reduces the extend of land contamination.




Figure 188: track over lake IssykKul used to compare S3A data in SAR mode with S3B in LRM during the tandem phase.



Figure 189: Left : Orbit – range value for OCOG (blue) and SAMOSA (green) retrackers for S3A in SAR mod. Left : Orbit – range value for OCOG (blue) and MLE (green) retrackers for S3B in LRM mod

### 10.4.2 Range Noise (20Hz)

The difference between the orbit-range quantities for two consecutive 20Hz measurements is an indicator on the noise associated to range estimates. As presented in Figure 190, consecutive measurements noise is smaller in SAR mod (5.3 and 5.6 cm for respectively SAMOSA and OCOG) than in LRM (9.4 and 8.1 cm for respectively SAMOSA and OCOG). This result obtained on the IssykKul lake, which is quite extended (transect length is longer than 50km), is consistent with the behavior over oceans.





Figure 190: Absolute difference of consecutive orbit – range values of 20Hz points over IssykKul lake (coastal areas excluded) Top : SAR mode (S3A during tandem phase. blue = OCOG range, green = SAMOSA range) Bottom : LRM (S3B during tandem phase. Blue = OCOG range, green = MLE range).



# **11 Range and Sea Level Absolute calibration**

# 11.1 Calibration with Crete & Svalbard transponders

isardSAT has processed the TRP data from a list of L1A products. Passes with IPF-SR-1 Version 06.13 (cycle 3 to 23) use reprocessed L1A and L2 data provided on the acri-cwa FTP server. Passes from cycle 24 to 53 increase in IPF-SR-1 Version as newer ones become available, up to Version 06.14 for the most recent passes.

The range bias results are of the order of millimetres. The datation bias is of the order of hundreds of microseconds.

For S3A, the passes on cycles 13 and 21 have not been analysed because the transponder was not switched on due to extreme climate conditions and pass on cycle 48 and 50 have not been analysed due to maintenance work. For S3B, cycles 1 to 7 and 15 to 18 have not been included as the satellite was not overflying the TRP. The TRP was not switched on due to extreme snow event for cycle 20.

Table 17 and Table 18 depicts the series of TRP processing results for the two missions and the two transponders, including range, datation, stack alignment and stack range noise.

Table 17 presents the results from the Crete TRP passes processing. The range bias is computed as measured minus theoretical. The results for S3A show a positive measured range, 6.79 mm larger than expected (elevation 6.79 mm shorter than expected), and a datation bias of -125.95 microseconds, both extracted from the minimisation of the RMS between theoretical and measured series. They also show a 0.81 mm stack noise. For S3B, the results show a negative measured range, 6.80 mm smaller than expected (elevation 6.80 mm higher than expected), and a datation bias of -26.22 microseconds, both extracted from the minimisation of the RMS between theoretical and measured series. They also show a 0.82 mm stack noise. It is interesting to note that for S3B these are the first 14 successful acquisitions in the new orbit (previous passes were in tandem orbit following S3A). The new results for cycles [21-34] show that the datation bias and the stack alignment has been reduced from -114.60 microseconds to residual values for cycles [21-34]. More passes will be needed to conclude something.

The regression line in Figure 191 (TOP) shows a drift of -0.57 mm/year, but it has a very low significance.

Table 18 presents the results from the TRP passes over Svalbard. The results for S3B show a negative bias range, 62.04 mm smaller range than expected (elevation 62.04 mm higher than expected), and a datation bias of -48.10 microseconds, both extracted from the minimisation of the RMS between theoretical and measured series. They also show a 7.17 mm stack noise (we have less than 1 mm with S3A/B over Crete and 7.4 mm with CryoSat-2 over Svalbard). For S3A, the results show a negative measured range, 119.58 mm smaller than expected (elevation 119.58 mm higher than expected), and a datation bias of -84.41 microseconds, both extracted from the minimisation of the RMS between theoretical and measured series. They also show a 15.88 mm stack noise.

We have added a new correction, applied to the range measurements. That correction takes into account only the vertical effect of the plate motion. From April 2011 (Svalbard TRP location date), and based in the Ny-Ålesund GPS station data, the range results are corrected by 8.331 mm/year.



# Sentinel-3 MPC S3MPC STM Annual Performance Report - Year 2019

 Ref.:
 S3MPC.CLS.APR.006

 Issue:
 1.0

 Date:
 28/02/2020

 Page:
 198

In the same way, the Crete plate motion is monitored with the TUC2 GPS station, located in the Technical University of Crete. It belongs to the same network of GPS stations as NYA1. Additionally to it, a differential GPS instrument installed in the TRP site is also checking the terrain movements. Both show that the site is stable so this correction has not been included in the Crete analysis.

Cycle – Mission	Date	Range bias [mm]	Datation bias [microseconds ]	Alignment [mm/beam ]	Noise [mm]	IPF-SR-1 Version
3 - S3A	2016/04/09	2.48	-127.34	0.07	0.41	06.13
4 - S3A	2016/05/06	18.84	-114.60	0.06	0.41	06.13
5 - S3A	2016/06/02	-3.91	-165.54	0.09	0.86	06.13
6 - S3A	2016/06/29	1.09	-152.81	0.06	0.93	06.13
7 - S3A	2016/07/26	-2.78	-152.81	0.07	1.02	06.13
8 - S3A	2016/08/22	-0.29	-127.34	0.09	0.80	06.13
9 - S3A	2016/09/18	2.47	-114.60	0.04	0.73	06.13
10 - S3A	2016/10/15	8.83	-178.27	0.12	0.66	06.13
11 - S3A	2016/11/11	19.89	-140.07	0.09	0.79	06.13
12 - S3A	2016/12/08	22.47	-127.34	0.07	0.80	06.13
13 - S3A	Transponder not switched on due to heavy snow.					
14 - S3A	2017/01/31	26.38	-114.60	0.07	0.73	06.13
15 - S3A	2017/02/27	2.49	-127.34	0.07	0.87	06.13
16 - S3A	2017/03/26	0.51	-127.34	0.06	0.84	06.13
17 - S3A	2017/04/22	13.61	-140.07	0.08	0.41	06.13
18 - S3A	2017/05/19	28.20	-127.34	0.06	1.15	06.13
19 - S3A	2017/06/15	-4.72	-165.54	0.07	1.18	06.13
20 - S3A	2017/07/12	-16.89	-114.60	0.08	0.71	06.13
21 - S3A		Transponder no	ot switched on due t	o high temperat	ures.	
22 - S3A	2017/09/04	19.37	-127.34	0.07	0.68	06.13
23 - S3A	2017/10/01	11.85	-114.60	0.07	0.68	06.13
24 - S3A	2017/10/28	1.30	-127.34	0.07	0.96	06.11
25 - S3A	2017/11/24	18.22	-101.87	0.07	0.79	06.12
26 - S3A	2017/12/21	-2.41	-114.60	0.06	0.68	06.12
27 - S3A	2018/01/17	11.56	-101.87	0.06	0.94	06.12
28 - S3A	2018/02/13	15.27	-127.34	0.06	0.74	06.13



**S3MPC STM Annual Performance** 

Report - Year 2019

 Ref.:
 S3MPC.CLS.APR.006

 Issue:
 1.0

 Date:
 28/02/2020

 Page:
 199

Cycle – Mission	Date	Range bias [mm]	Datation bias [microseconds ]	Alignment [mm/beam ]	Noise [mm]	IPF-SR-1 Version
29 - S3A	2018/03/12	-0.38	-101.87	0.09	1.00	06.14
30 - S3A	2018/04/08	6.25	-127.34	0.08	0.83	06.14
31 - S3A	2018/05/05	3.59	-140.07	0.06	0.88	06.14
32 - S3A	2018/06/01	-7.61	-127.34	0.09	0.91	06.14
8 - S3B	2018/06/01		S3B in LRM mod	e, results to be o	computed	
33 - S3A	2018/06/28	1.72	-101.87	0.04	0.72	06.14
10 - S3B	2018/06/28		S3B in LRM mod	e, results to be o	computed	
34 - S3A	2018/07/25	6.18	-140.07	0.07	0.87	06.14
11 - S3B	2018/07/25		S3B in LRM mod	e, results to be o	computed	
35 - S3A	2018/08/21	-9.00	-114.60	0.07	0.99	06.14
12 - S3B	2018/08/21	-20.38	-114.60	0.04	0.86	06.14
36 - S3A	2018/09/17	-0.72	-114.60	0.07	0.79	06.14
13 - S3B	2018/09/17	-12.60	-89.14	0.03	0.97	06.14
37 - S3A	2018/10/14	5.89	-114.60	0.05	0.93	06.14
14 - S3B	2018/10/14	-0.83	-89.14	0.05	0.75	06.14
38 - S3A	2018/11/10	15.85	-127.34	0.07	0.82	06.14
39 - S3A	2018/12/07	16.72	-50.94	0.08	1.13	06.14
40 - S3A	2019/01/03	11.93	-114.60	0.06	0.80	06.14
20 - S3B	2018/01/09	Transpo	onder not switched c	on due to heavy	snow	06.14
41 - S3A	2019/01/30	27.00	-140.07	0.07	0.76	06.14
21 - S3B	2019/02/05	10.29	-25.47	0.02	0.69	06.14
42 - S3A	2019/02/26	-10.21	-140.07	0.09	0.79	06.14
22 - S3B	2019/03/04	17.18	0.00	0.02	0.90	06.14
43 - S3A	2019/03/25	-7.42	-127.43	0.06	0.90	06.14
23 - S3B	2019/03/31	-24.49	-12.73	0.02	0.79	06.14
44 - S3A	2019/04/21	-1.03	-114.60	0.07	0.77	06.14
24 - S3B	2019/04/27	-13.57	-12.73	0.01	0.84	06.14
45 - S3A	2019/05/18	3.50	-140.07	0.08	0.85	06.14
25 - S3B	2019/05/24	-5.47	-12.73	0.00	0.84	06.14



S3MPC STM Annual Performance

Report - Year 2019

 Ref.:
 S3MPC.CLS.APR.006

 Issue:
 1.0

 Date:
 28/02/2020

 Page:
 200

Cycle – Mission	Date	Range bias [mm]	Datation bias [microseconds ]	Alignment [mm/beam ]	Noise [mm]	IPF-SR-1 Version
46 - S3A	2019/06/14	-7.70	-140.07	0.08	0.78	06.14
26 - S3B	2019/06/20	-9.07	-25.47	0.02	0.92	06.14
47 - S3A	2019/07/11	9.16	-152.81	0.06	0.85	06.14
27 - S3B	2019/07/17	-20.26	-12.73	0.01	0.79	06.14
48 - S3A	2019/08/07	Transpond	ler not switched on o	due to maintena	ce work	06.14
28 - S3B	2019/08/13	-25.82	-12.73	0.02	0.84	06.14
49 - S3A	2019/09/03	4.55	-114.60	0.06	0.80	06.14
29 - S3B	2019/09/09	-19.44	0.00	0.02	0.84	06.14
50 - S3A	2019/09/30	Transpond	ler not switched on o	due to maintena	ce work	06.14
30 - S3B	2019/10/06	-11.08	-12.73	0.01	0.67	06.14
51 – S3A	2019/10/27	4.08	-140.07	0.07	0.75	06.14
31 - S3B	2019/11/02	-4.55	0.00	0.01	0.96	06.14
52 – S3A	2019/11/23	23.17	-127.34	0.08	0.67	06.14
32 - S3B	2019/11/29	0.58	0.00	0.02	0.94	06.14
53– S3A	2019/12/20	19.17	-114.60	0.07	0.65	06.14
33 - S3B	2019/12/26	13.91	-12.73	0.02	0.67	06.14
34 - S3B	2020/01/22	9.93	-12.73	0.01	0.73	06.14
N	lean S3A	6.79	-125.95	0.07	0.81	-
Standar	d Deviation S3A	10.92	19.95	0.01	0.16	-
N	lean S3B	-6.80	-26.22	0.02	0.82	-
Standard Deviation S3B 13.64		35.29	0.01	0.09	-	

Table 17: Results of Crete TRP passes processing



S3MPC STM Annual Performance

Report - Year 2019

 Ref.:
 S3MPC.CLS.APR.006

 Issue:
 1.0

 Date:
 28/02/2020

 Page:
 201

Cycle – Mission	Date	Range bias [mm]	Datation bias [microseconds ]	Alignment [mm/beam ]	Noise [mm]	IPF-SR-1 Version
26 - S3B	2019/06/14	-48.26	-50.93	-0.04	17.05	06.14
46 - S3A	2019/06/29	-121.97	-114.60	0.04	31.42	06.14
27 - S3B	2019/07/11	-56.05	-50.93	0.02	8.97	06.14
47 - S3A	2019/07/26	-152.91	-38.20	0.05	12.05	06.14
28 - S3B	2019/08/07	-71.35	-25.47	0.03	6.48	06.14
48 - S3A	2019/08/22	-109.83	-114.60	0.08	35.52	06.14
29 - S3B	2019/09/03	-97.96	-25.47	0.03	3.36	06.14
49 - S3A	2019/09/18	-151.55	-76.40	0.08	7.70	06.14
30 - S3B	2019/09/30	-90.42	-50.93	0.04	4.70	06.14
50 - S3A	2019/10/15	-96.85	-101.87	0.08	7.17	06.14
31 - S3B	2019/10/27	-33.86	-114.60	0.06	4.27	06.14
51 - S3A	2019/11/11	-77.71	-63.67	0.07	8.93	06.14
32 - S3B	2019/11/23	-50.83	-25.47	0.01	7.69	06.14
52 - S3A	2019/12/08	-67.80	-127.34	0.12	13.96	06.14
33 - S3B	2019/12/20	-69.52	-12.73	0.01	6.20	06.14
53 - S3A	2020/01/04	-178.07	-38.20	0.04	10.29	06.14
34 - S3B	2020/01/16	-40.09	-76.40	0.06	5.70	06.14
N	lean S3A	-119.58	-84.41	0.07	15.88	-
Standar	d Deviation S3A	38.74	35.37	0.03	11.13	-
N	lean S3B	-62.04	-48.10	0.02	7.17	-
Standar	d Deviation S3B	21.98	31.69	0.03	4.12	-

Table 18:	Results of	<sup>r</sup> Svalbard	TRP	passes	processing
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Regarding the geophysical corrections, for the Crete measurements the ionospheric and wet/dry tropospheric corrections were extracted from the transponder auxiliary files provided by the MPC team.

Then, the solid earth, geocentric tide and ocean loading corrections are selected from the L2 products. A table with the Geophysical corrections used is shown in Table 19. The TRP internal delay is 4.954 meters.



**S3MPC STM Annual Performance** 

Report - Year 2019

 Ref.:
 S3MPC.CLS.APR.006

 Issue:
 1.0

 Date:
 28/02/2020

 Page:
 202

Cycle A-S3A B-S3B	Date	Wet Tropo [m]	Dry Tropo [m]	lono [m]	Solid Earth [m]	Geocentric Tide [m]	Ocean Loading [m]
ЗA	2016/04/09	-0.09	-2.03	-0.02	-0.13	0.003	0.003
4A	2016/05/06	-0.07	-2.04	-0.03	-0.04	0.003	0.010
5A	2016/06/02	-0.12	-2.05	-0.04	0.03	0.001	0.009
6A	2016/06/29	-0.11	-2.05	-0.03	0.00	-0.001	0.003
7A	2016/07/26	-0.07	-2.05	-0.02	-0.09	-0.003	-0.002
8A	2016/08/22	-0.08	-2.05	-0.02	-0.12	-0.004	0.003
9A	2016/09/18	-0.13	-2.06	-0.02	-0.03	-0.005	0.004
10A	2016/10/15	-0.06	-2.07	-0.02	0.14	-0.005	0.007
11A	2016/11/11	-0.07	-2.07	-0.02	0.20	-0.004	0.003
12A	2016/12/08	-0.01	-2.08	-0.01	0.09	-0.003	-0.003
14A	2017/01/31	-0.01	-2.07	-0.02	-0.08	0.000	-0.002
15A	2017/02/27	-0.09	-2.05	-0.02	-0.01	0.001	0.003
16A	2017/03/26	-0.07	-2.05	-0.02	0.12	0.002	0.005
17A	2017/04/22	-0.04	-2.05	-0.03	0.14	0.002	0.002
18A	2017/05/19	-0.04	-2.05	-0.03	0.03	0.001	-0.003
19A	2017/06/15	-0.08	-2.06	-0.03	-0.08	0.000	-0.002
20A	2017/07/12	-0.08	-2.05	-0.02	-0.12	-0.002	0.002
22A	2017/09/04	0.00	-2.06	-0.02	0.03	-0.005	0.009
23A	2017/10/01	-0.06	-2.06	-0.02	0.05	-0.005	0.005
24A	2017/10/28	-0.12	-2.04	-0.02	0.00	-0.004	0.000
25A	2017/11/24	-0.06	-2.06	-0.01	-0.04	-0.003	-0.003
26A	2017/12/21	-0.12	-2.05	-0.02	-0.01	-0.002	-0.002
27A	2018/01/17	-0.06	-2.04	-0.02	0.09	0.000	0.001
28A	2018/02/13	-0.05	-2.05	-0.02	0.17	0.001	0.001
29A	2018/03/12	-0.11	-2.05	-0.02	0.16	0.002	-0.001
30A	2018/04/08	-0.07	-2.05	-0.02	0.06	0.002	-0.004
31A	2018/05/05	-0.03	-2.04	-0.04	-0.07	0.001	-0.002
32A	2018/06/01	-0.06	-2.05	-0.03	-0.11	0.000	0.003
33A	2018/06/28	-0.07	-2.04	-0.02	-0.08	-0.002	0.008
34A	2018/07/25	-0.10	-2.04	-0.03	-0.03	-0.003	0.009



S3MPC STM Annual Performance

Report - Year 2019

 Ref.:
 S3MPC.CLS.APR.006

 Issue:
 1.0

 Date:
 28/02/2020

 Page:
 203

Cycle A-S3A B-S3B	Date	Wet Tropo [m]	Dry Tropo [m]	lono [m]	Solid Earth [m]	Geocentric Tide [m]	Ocean Loading [m]
35A/12B	2018/08/21	-0.09	-2.05	-0.02	-0.01	-0.004	0.006
36A/13B	2018/09/17	-0.09	-2.06	-0.02	-0.04	-0.004	0.001
37A/14B	2018/10/14	-0.12	-2.06	-0.01	-0.06	-0.004	-0.002
38A	2018/11/10	-0.08	-2.06	-0.01	0.01	-0.004	-0.001
39A	2018/12/07	-0.02	-2.05	-0.02	0.14	-0.003	0.001
40A	2019/01/03	-0.05	-2.04	-0.02	0.21	-0.001	0.001
41A	2019/01/30	-0.04	-2.03	-0.02	0.18	0.000	-0.003
21B	2019/02/05	-0.04	-2.04	-0.02	-0.02	0.000	0.009
42A	2019/02/26	-0.04	-2.04	-0.02	0.06	0.001	-0.005
22B	2019/03/04	-0.05	-2.05	-0.03	0.03	0.001	0.008
43A	2019/03/25	-0.04	-2.04	-0.02	-0.08	0.001	-0.003
23B	2019/03/31	-0.05	-2.04	-0.03	0.03	0.001	0.003
44A	2019/04/21	-0.06	-2.06	-0.02	-0.12	0.001	0.004
24B	2019/04/27	-0.06	-2.05	-0.03	-0.02	0.001	-0.001
45A	2019/05/18	-0.08	-2.05	-0.02	-0.05	0.000	0.009
25B	2019/05/24	-0.05	-2.05	-0.02	0.02	0.000	-0.003
46A	2019/06/14	-0.09	-2.05	-0.03	0.00	-0.001	0.009
26B	2019/06/20	-0.09	-2.05	-0.03	0.06	-0.001	-0.000
47A	2019/07/11	-0.04	-2.04	-0.02	-0.01	-0.002	0.004
27B	2019/07/17	-0.16	-2.03	-0.03	0.17	-0.002	0.000
28B	2019/08/13	-0.07	-2.04	-0.03	0.22	-0.004	-0.000
49A	2019/09/03	-0.13	-2.05	-0.02	-0.11	-0.004	-0.002
29B	2019/09/09	-0.09	-2.05	-0.02	0.16	-0.004	-0.003
30B	2019/10/06	-0.08	-2.05	-0.03	0.03	-0.004	-0.004
51A	2019/10/27	-0.03	-2.05	-0.01	0.15	-0.004	0.006
31B	2019/11/02	-0.11	-2.05	-0.03	-0.08	-0.003	0.000
52A	2019/11/23	-0.10	-2.05	-0.02	0.21	-0.003	0.003
32B	2019/11/29	-0.07	-2.05	-0.02	-0.10	-0.002	0.007
53A	2019/12/20	-0.04	-2.06	-0.02	0.11	-0.001	-0.003
33B	2019/12/26	-0.03	-2.04	-0.02	-0.05	-0.001	0.011
34B	2020/01/22	-0.03	-2.07	-0.02	-0.02	0.000	0.001

Table 19: Geophysical Corrections of Crete TRP passes processing



For the Svalbard transponder, the ionospheric and wet/dry tropospheric, the solid earth, geocentric tide and ocean loading corrections are selected from the L2 products. A table with the Geophysical corrections used is shown in Table 20. The TRP internal delay is 9.88 meters.

Cycle A-S3A B-S3B	Date	Wet Tropo [m]	Dry Tropo [m]	lono [m]	Solid Earth [m]	Geocentric Tide [m]	Ocean Loading [m]
26B	2019/06/14	-0.09	-2.31	-0.02	-0.03	-0.001	0.001
46A	2019/06/29	-0.16	-2.31	-0.02	0.03	-0.002	-0.002
27B	2019/07/11	-0.11	-2.31	-0.02	-0.03	-0.001	0.000
47A	2019/07/26	-0.20	-2.33	-0.02	0.01	-0.003	0.009
28B	2019/08/07	-0.12	-2.32	0.01	-0.04	-0.004	-0.004
48A	2019/08/22	-0.14	-2.31	-0.02	-0.01	-0.004	0.009
29B	2019/09/03	-0.11	-2.31	-0.01	-0.05	-0.004	-0.003
49A	2019/09/18	-0.16	-2.33	-0.02	-0.03	-0.004	0.002
30B	2019/09/30	-0.09	-2.33	-0.01	-0.05	-0.004	0.006
50A	2019/10/15	-0.11	-2.32	-0.02	-0.03	-0.004	-0.006
31B	2019/10/27	-0.04	-2.32	-0.01	-0.04	-0.003	0.009
51A	2019/11/11	-0.08	-2.31	-0.02	-0.03	-0.003	-0.009
32B	2019/11/23	-0.07	-2.32	-0.01	-0.02	-0.003	0.000
52A	2019/12/08	-0.05	-2.27	-0.01	-0.03	-0.002	-0.004
33B	2019/12/20	-0.05	-2.32	-0.00	-0.01	-0.001	-0.010
53A	2020/01/04	-0.13	-2.30	-0.01	-0.03	-0.001	0.003
34B	2019/12/20	-0.02	-2.31	-0.00	-0.02	-0.000	-0.014

Table 20: Geophysical Corrections of Svalbard TRP passes processing



**S3MPC STM Annual Performance** 

Report - Year 2019

Ref.: S3MPC.CLS.APR.006 Issue: 1.0 Date: 28/02/2020 Page: 205



Figure 191 Range and Datation Bias Results



**S3MPC STM Annual Performance** 

Report - Year 2019

Ref.: S3MPC.CLS.APR.006 Issue: 1.0 Date: 28/02/2020 Page: 206



Figure 192 Alignment and Stack Noise Results



# 11.2 Calibration in Corsica, Harvest and Bass Strait

### **11.2.1** Calibration in Corsica

The Corsica calibration/validation site was initially implemented in Senetosa to monitor the performance of TOPEX/Poseidon and the follow-on Jason legacy satellite altimeters. The Corsica site was extended to Ajaccio a few years ago, which enabled to monitor Envisat and ERS missions, CryoSat-2 and, more recently, the SARAL/AltiKa mission and Sentinel 3A&B satellites.

The maintenance of the facilities is mainly funded by CNES and operations, data retrieval and analysis are performed by the Observatoire de Paris (OBSPM/SYRTE) and the Observatoire de la Côte d'Azur (OCA/Géoazur). Results of the Sentinel-3A&B SSH absolute calibration have been regularly presented (e.g. OSTST meeting 2019) and recently published in Bonnefond et al, 2018 & 2019.

In situ data, geodetic datum and all necessary information are shared with NOVELTIS for the extension of the absolute calibration through a regional method. The absolute bias estimates were computed by NOVELTIS for the Sentinel-3A and Sentinel-3B altimetry missions during their tandem phase at the Corsica calibration site, in Ajaccio and Senetosa.

As shown in Figure 193, the Sentinel-3A configuration in Corsica is of particular interest, as the same track (741) flies close to both tide gauges in Ajaccio and Senetosa, which gives the opportunity to estimate the absolute bias of the altimeter range at the two sites within a few seconds.



Figure 193: Absolute CALVAL configuration in Corsica. The regions in colours show the two high-resolution mean sea surfaces that were specifically measured to link the calibration sites to the altimetry data



The Sentinel-3A absolute bias estimates were computed using the L2 NTC Land products reprocessed with the Processing Baselines 2.33 to 2.45, from cycle 1 to cycle 49 (09/2019).

The Sentinel-3B bias estimates were computed with the same products (Processing Baselines 1.0 to 1.17) for cycles 9 to 13 (tandem phase period, corresponding to cycles 32 to 36 for Sentinel-3A).

Table 21 summarizes the products version and the parameters used to compute the bias estimates.

Table 21 : Sentinei-3A ana	i Sentinei-3B products and	a parameters usea	a to compute the absolute blas est	imates

Mission	Sentinel-3A	Sentinel-3B			
Period	Cycles 1 to 41 (03/2016 – 02/2019)	Cycles 9 to 13 (06/2018 – 10/2018)			
Product version	From S3 MPC FTP & ESA Scihub PB 2.33 – PB 2.45	From S3 MPC FTP, Tandem phase PB 1.0 – PB 1.17			
Frequency	20	) Hz			
lonosphere correction	GIM				
Wet troposphere correction	Model i Radiometer in Harv	in Corsica vest and in Bass Strait			
Ocean Tide (regional calval only)	Regional model on finite element grid (in-house predictions)	/			
DAC (regional calval only)	TUGOm simulation provided by LEGOS, available until 12/2017	/			

### 11.2.1.1 Direct comparisons in Corsica

As shown in Figure 193, the Sentinel-3A configuration in Corsica is of particular interest, as the same track (741) flies close to both calibration sites, in Ajaccio and Senetosa, which gives the opportunity to estimate the absolute bias of the altimeter range at the two sites within a few seconds. During the tandem phase, Sentinel-3B flew on the same orbit with a 30-second shift between the two satellites. This gave the opportunity to compare the SSH measurements of both satellites at the two calibration sites in Corsica within a very short timeframe.

The computation of the bias estimates was performed both for the SAR data and the PLRM data and the results are given in Table 22. In this configuration, no tide nor DAC corrections were applied to the altimetry and tide gauge sea surface heights. S3A cycle 1 is in LRM mode but the bias estimate for this cycle was included in the time series of the SAR mode bias estimates. In PLRM mode, the range data for S3A cycle 1 are not available, as expected. Figure 194 shows the time series of the SSH absolute bias estimates for both missions and both modes, at both calibration sites.



# Table 22 : Statistics on the Sentinel-3A SAR and PLRM SSH absolute bias estimates in Corsica on track 741 (PB2.33 – no tide nor DAC corrections applied).

		SAR			PLRM		
Absolute bias estimates in Corsica	Mean (mm)	Standard deviation (mm)	Number of cycles	Mean (mm)	Standard deviation (mm)	Number of cycles	
Sentinel-3A							
Senetosa (cycles 1 to 47)	22 ± 4	22	45	25 ± 4	25	44	
Ajaccio (cycles 1 to 47)	9 ± 3	19	42	27 ± 6	41	40	
Sentinel-3B							
Senetosa (cycles 9 to 13) [Sentinel-3A on same period]	39 [24]	/	5	48 [29]	/	4	
<b>Ajaccio</b> (cycles 9 to 13) [Sentinel-3A on same period]	27 [11]	/	5	49 [26]	/	4	

Sentinel-3A&B SSH absolute bias estimates (in mm) in Senetosa - Track 741





Figure 194: Sentinel-3A and Sentinel-3B absolute bias estimates in Senetosa (upper plot) and Ajaccio (lower plot) on track 741 for the SAR and the PLRM data.



Some in-depth analyses of the altimeter waves and sigma0 estimates in the area of the range bias computation were performed and led to the removal of some cycles from the mean bias estimates.

For each cycle in Senetosa, Figure 195 shows the Sentinel-3A bias estimates and the corresponding Sentinel-3A SWH and sigma0. Considering these plots, the Sentinel-3A SSH bias estimate for cycle 21 was removed from the computation of the mean bias for both the SAR and the PLRM data because of very large bias values linked with strong wave conditions (SWH > 3.5 m) in the comparison area. Cycle 42 was also removed from the SAR bias estimates as it corresponds to some sigma bloom event (large sigma0 value and very low waves). The statistics in Table 22 were computed after removing these cycles.

This figure also shows that the SWH is quite large for some cycles (10 and 40) but not linked with large bias estimates. Although these cycles are questionable, they were not removed from the mean bias computation.



Figure 195: Sentinel-3A bias estimates (upper plot), Sentinel-3A averaged SWH (middle plot, 1-std envelop showed with dashed lines) and Sentinel-3A averaged sigma0 (lower plot) in Senetosa.

Figure 196 shows the diagnostics on the SWH and the sigma0 for the Sentinel-3A bias estimates in Ajaccio.

There is no bias estimate for Sentinel-3A cycle 26 due to the unavailability of the in situ data.

The following cycles were removed from the computation of the mean bias for the Sentinel-3A SAR data in Ajaccio:

- Cycle 21: strong waves (SWH > 3.5 m) in the comparison area ;
- Cycle 22: very low waves (SWH < 0.5 m) in the comparison area, with some sigma bloom ;</p>
- Cycles 29 and 42: not enough altimetry points to estimate the bias in the comparison area.



For the Sentinel-3A PLRM data, the following cycles were removed from the mean bias computation:

- Cycle 18: waves very low in the whole comparison area and jumps in the sigma0 values ;
- Cycle 21: strong waves (SWH > 3.5 m) in the comparison area;
- Cycles 22, 29 and 42: not enough altimetry points to estimate the bias in the comparison area.

The statistics in Table 22 were computed after removing these cycles.

Like in Senetosa, the SWH is quite large for some cycles (10 and 40) but not linked with large bias estimates. Although these cycles are questionable, they were not removed from the mean bias computation. Cycle 47 for the PLRM data also shows a large bias value but no explanation was found yet.



Figure 196 : Sentinel-3A bias estimates (upper plot), Sentinel-3A averaged SWH (middle plot, 1-std envelop showed with dashed lines) and Sentinel-3A averaged sigma0 (lower plot) in Ajaccio.

The Sentinel-3A bias estimates on SAR mode are still very consistent for both sites (Table 22), within 1 cm. In general, the largest bias values are linked with large SWH, as the SSB correction available in the products is not optimal for the SAR mode observations.

The Sentinel-3A bias estimates computed on the PLRM range are in general noisier than the estimates on the SAR range, as expected.

There were not enough cycles of Sentinel-3B measurements during the tandem phase to compute robust statistics on the range bias, but Figure 194 shows the very good consistency between the two missions, at both sites and for both types of products (SAR and PLRM).



The difference between the Sentinel-3A and the Sentinel-3B biases are a bit larger for the PLRM data at both sites, with a mean difference of about 2 cm. The analysis of the parameters of the Sentinel-3B cycles (SWH and sigma0) does not lead to any clear explanation to these discrepancies for now.

For Sentinel-3A, the results are quite consistent with the bias estimates obtained by Pascal Bonnefond (Paris Observatory/SYRTE) and Olivier Laurain (OCA/Géoazur) with their own method applied in Corsica, as showed in Figure 197.

However, it should be noticed that the Sentinel-3B bias estimates obtained with NOVELTIS's method are generally larger (more positive) than the Sentinel-3A bias estimates in these results. This may not be aligned with some other calibration results, in particular with the results obtained at the transponder in Crete, where the Sentinel-3B range measurements appear to be longer than the Sentinel-3A range measurements (so the S3B SSH is shorter and the S3B bias is smaller as bias = SSH<sub>alti</sub> – SSH<sub>ref</sub>, "ref" being the reference dataset, ie the tide gauge data or the transponder reference). This is also different from the results obtained by Pascal Bonnefond and Olivier Laurain with their own calval method on the same cycles in Corsica (Figure 197). However, the comparison of the Sentinel-3A and Sentinel-3B SSH at 20 Hz in the comparison area considered when using NOVELTIS method generally shows longer S3B SSH for these cycles, which leads to larger bias estimates. This may be a local effect or may be due to the processing of the altimetry data in the various methods. Some further comparisons with P. Bonnefond's results will be performed to better understand these differences.



Figure 197: Sentinel-3A and Sentinel-3B absolute range bias estimates computed by P. Bonnefond (Paris Observatory/SYRTE) and O. Laurain (OCA) in Corsica along the track 741 (from OSTST 2019).



### 11.2.1.2 Regional calval in Corsica

In order to increase the number of the Sentinel-3A SSH bias estimates around the calibration sites in Corsica, offshore bias estimates were computed, using the regional calibration technique described in Figure 198 (left). The offshore crossover points between the Sentinel-3A mission and the Jason-2 and Envisat missions (nominal orbits) were considered. Along-track mean sea surface profiles computed along the Jason-2 and Envisat tracks were used to link the Sentinel-3A SSH observations offshore to the tide gauges observations. The catamaran high resolution mean sea surfaces measured by OCA at Ajaccio and Senetosa were used to link the altimetry and the tide gauge observations at the comparison point (point C in Figure 198, left). The crossover points used for the computation are shown with green dots in Figure 198 (right). In the future, the number of crossover points will be increased for the estimation of the SSH bias, also considering some of the red dots in Figure 198 (right).

The tide and the atmospheric corrections were applied to the altimetry and tide gauge SSH in order to take into account the differences in the ocean dynamics between the offshore altimeter crossover points and the tide gauge stations at the coast. In order to apply the same corrections to the altimetry and to the tide gauge SSH, the tide and DAC corrections were computed specifically, using the FES2014 global tidal model on its native finite element grid and a DAC solution provided by LEGOS and based on a global simulation with the TUGO-m model (ex-MOG2D model). As this DAC solution is only available until December 2017 for now, the Sentinel-3A offshore bias estimates were computed until cycle 25 for track 741 and cycle 26 for track 044.

COLLETE LIDAUSATION SATELLITES	Sentinel-3 MPC	Ref.:	S3MPC.CLS.APR.006
	S3MPC STM Annual Performance	Issue:	1.0
	Deport Veer 2010	Date:	28/02/2020
	Report - Tear 2019	Page:	214
		•	



Figure 198: Left: Generic diagram of the regional calibration method. Right: Configuration in Corsica for the Sentinel-3A mission. S3A ground tracks in pink, Jason-2 tracks in red and Envisat tracks in yellow. The green dots show the crossover points where the offshore S3A SSH bias was computed. The red dots show the crossover points where the offshore S3A SSH bias could be potentially computed.

For the tide correction, the results obtained with the FES2014 global tidal model on its native finite element grid were very noisy, especially in Ajaccio (cf. STM Annual Performance Report –  $2^{nd}$  year). A regional model implemented by NOVELTIS several years ago, with a high-resolution grid in the Corsica region, was used in a second step (Figure 199).





Figure 199: Unstructured grids of the tidal models in the Corsica region. Left: FES2014 global model. Right: NOVELTIS regional model.

Table 23 gives the Sentinel-3A SSH regional bias estimates in Senetosa, both for the SAR and the PLRM products. Three crossover points were considered, between the S3A track 741 and the Jason-2 track 085, and between the S3A track 044 and the Envisat track 887 and the Jason-2 track 222 respectively (see green dots in Figure 198, right).

The first line in the table gives the results obtained with the local calibration method, i.e. the direct comparison between the S3A SSH and the Senetosa tide gauge SSH on track 741, when no ocean dynamics correction is applied (same configuration as in Table 22), but over the period of availability of the DAC correction (cycles 1 to 26), for comparison with the following lines. The second line shows the results of the direct comparison on track 741 when using the ocean dynamics corrections (DAC and regional tidal model). For all the other lines (crossover points), the ocean dynamics corrections were also applied. The regional mean is the average of all the estimates (local and offshore).

The results are globally stable, with a slight increase in the bias estimates variability when applying the ocean dynamics corrections (comparison between lines 1 and 2 in the table). Cycle 21 was removed from the mean bias estimates for track 741 (both for local comparison as previously, and for the computation at the crossover point with the Jason-2 track 085). In the PLRM product, cycle 1 is not available (measured in LRM mode) for track 741, which explains the difference in the total number of cycles between the two products. For track 044, no cycle was removed due to large bias values. However, one can notice that the variability of the bias estimates is larger at the crossover point with the Envisat track 887. In the SAR product, this is mainly explained by rather strong bias values for cycles 4 and 14. In the PLRM product, this is intensified by the strong bias value on cycle 13.



The Sentinel-3A regional bias in Senetosa is quite consistent with the local estimates, both in terms of mean and variability.

Senetosa	SAR			PLRM			
PB 2.33 (MPC S3) cycles 1 – 26	Mean (mm)	Standard deviation (mm)	Number of cycles	Mean (mm)	Standard deviation (mm)	Number of cycles	
Track 741 (local) no ocean dyn. corr.	23 ± 5	24	24	22 ± 6	31	23	
Track 741 (local)	22 ± 5	26	24	20 ± 7	33	23	
Track 741 X J2 085	10 ± 6	31	24	10 ± 8	38	23	
Track 044 X Env 887	20 ± 7	33	25	17 ± 10	18	23	
Track 044 X J2 222	16 ± 5	27	25	18 ± 8	40	23	
Regional mean	17 ± 6	29	25	16 ± 8	40	23	

Table 23 : Statistics on the Sentinel-3A SAR and PLRM SSH absolute regional bias estimates in Senetosa.

Table 24 gives the S3A SSH regional bias estimates in Ajaccio, both for the SAR and the PLRM data. Four crossover points are considered, between the S3A track 741 and the Envisat track 130 and the Jason-2 track 085, and between the S3A track 044 and the Envisat track 887 and the Jason-2 track 222, respectively (see green dots in Figure 198, right).

The first line in the table gives the results obtained with the local calibration method, i.e. the direct comparison between the S3A SSH and the Ajaccio tide gauge SSH on track 741, when no ocean dynamics correction is applied (same configuration as in Table 22), but over the period of availability of the DAC correction (cycles 1 to 26), for comparison with the following lines. The second line shows the results of the direct comparison on track 741 when using the ocean dynamics corrections (DAC and regional tidal model). For all the other lines (crossover points), the ocean dynamics corrections were also applied. The regional mean is the average of all the estimates (local and offshore).



# Table 24 : Statistics on the Sentinel-3A SAR and PLRM SSH absolute regional bias estimates in Ajaccio (PB 2.33 reprocessed dataset).

Ajaccio PB 2.33 (MPC S3) cycles 1 – 26	SAR			PLRM			
	Mean (mm)	Standard deviation (mm)	Number of cycles	Mean (mm)	Standard deviation (mm)	Number of cycles	
Track 741 (local) no ocean dyn. corr.	14 ± 4	20	24	31 ± 9	45	23	
Track 741 (local)	10 ± 5	23	24	26 ± 11	51	25	
Track 741 X Env 130	5 ± 6	28	24	18 ± 13	61	23	
Track 741 X J2 085	35 ± 6	31	24	35 ± 9	41	23	
Track 044 X Env 887	41 ± 7	36	25	39 ± 10	50	23	
Track 044 X J2 222	44 ± 6	32	25	48 ± 9	41	23	
Regional mean	27 ± 6	30	24	33 ± 10	49	23	

The Sentinel-3A offshore bias estimates in Ajaccio are more variable, from one crossover to the other, than in Senetosa, both for SAR and PLRM products. Indeed the variability of the mean bias estimates is 5 mm at Senetosa, both for SAR and PLRM products, while it reaches 12 mm for PLRM and even 18 mm for SAR in Ajaccio. This is generally due to a few cycles in the time series, but the reason why they show such large biases is still unclear.

The same kind of results is obtained whatever the tidal model, as shown in Figure 200 using the FES2014 global tidal correction and in Figure 201 using NOVELTIS regional tidal model correction. Some tests were done when applying only the tidal corrections (and not the DAC), with similar results. When only the DAC is applied (no tide correction), the results are more stable and close to those obtained with no correction at all. This means that the tide correction is responsible for this additional variability in the results in Ajaccio, whatever the tidal model used as correction.





Figure 200 : Offshore Sentinel-3A bias estimates in Corsica for the SAR and PLRM data, with and without ocean dynamics corrections (DAC and FES2014 global tidal model).



Figure 201 : Offshore Sentinel-3A bias estimates in Corsica for the SAR and PLRM data, with and without ocean dynamics corrections (DAC and regional tidal model).

This kind of results was already observed previously, for the Jason-1, Envisat, Jason-2 and SARAL/AltiKa missions. Unlike the Senetosa tide gauges, the Ajaccio tide gauge is located in the very sheltered harbour, while the altimetry measurements are made in open ocean conditions. As a consequence, the Ajaccio tide gauge sees a more complex tidal signal than the open ocean altimetry, with more non-linear tidal components and resonance effects.

A comparison was performed between the tidal models (global and regional) and the tidal signal extracted from the tide gauge SSH time series at Senetosa and Ajaccio. A harmonic analysis was used to extract the tidal signal from the in situ SSH time series. The vector differences (considering the amplitude and the phase lag) between the models and the tide gauge observations were computed for the main tidal



components (M2, K1, O1 and S2) in the area. None of these differences are in the order of the 2-cm difference that is observed in the bias estimates in Ajaccio.

When considering more tidal components, including non-linear ones, to compute the tidal elevations in Ajaccio, either from the models or from the harmonic analysis, differences of more than 2 cm are observed between the tidal predictions, which confirms that the Ajaccio tide gauge sees different tides than what is currently in the models. However, the tidal signal from the harmonic analysis tends to be larger than the tidal signal from the models, which means that, when applied, this tidal correction removes more signal from the tide gauge, resulting in smaller in situ SSH and even-larger altimeter bias estimates.

For now, the conclusion of these analyses is that the Ajaccio site is not very well adapted for the offshore regional calibration, although located in a region with relatively small tidal signals.

Except for this specific issue in Ajaccio, all these results are, in general, in rather good agreement with the global calval analysis, the local calval analysis (P. Bonnefond in Corsica) and the Crete transponder results. The bias estimates is close to 2 cm in SAR mode, with a variability of about 2.5 cm. In PLRM mode, the variability is about 1.5 cm higher, which is expected.

However, these results are still very dependent on the quality of the SSB correction that is provided in the products. Several cycles are removed from the bias estimate computation because of very strong SWH events which are not accurately managed in the current SSB correction. As a consequence, there is a strong need for a dedicated SAR SSB correction.

### **11.2.2 Calibrations in Harvest**

Absolute bias estimates were computed by NOVELTIS for the Sentinel-3A altimetry mission at the Harvest calibration site.

In situ data, geodetic datum and all necessary information are shared by NASA/JPL with NOVELTIS.

The Harvest calibration site has been operated by NASA/JPL since the Topex/Poseidon era. It is located right below the TP/Jason track 043. The site is equipped with tide gauge and GPS instruments (Figure 202). A buoy has also been deployed to measure the height of the waves as the sea is often very rough in this region, with common wave heights of 2-3 m. JPL corrects the tide gauge SSH for the waves effect using this buoy measurements.

These in situ data were provided to NOVELTIS until the 31/08/2019.

Two Sentinel-3A tracks (067 and 710) cross nearby, at about 18 km from the Harvest platform. NOVELTIS computed direct absolute bias estimates for these two tracks and the results and time series are showed in Figure 203. The bias estimates are quite consistent for both tracks, in terms of mean. The variability of the bias estimates is 6 mm higher on the descending track (710). On average, the bias estimates are 7 mm higher for the PLRM data than for the SAR data.

It should be noticed that the tide and the DAC corrections were not applied in this computation. It may have an impact as the Sentinel-3A tracks are 18 km off the calibration site, in a region where the ocean dynamics is not negligible. The next step is to apply these corrections in the computation.



These results have to be compared with the bias estimates computed by Bruce Haines from NASA/JPL with his own method, when they are available.



*Figure 202 : Configuration of the Sentinel-3A tracks at the Harvest calibration site.* 





Figure 203: Sentinel-3A absolute bias estimates in Harvest for track 067 (upper plot) and track 710 (lower plot), for the SAR and the PLRM data.

25

Sentinel-3A cycle number

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35

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15

### 11.2.3 Calibrations in Bass Strait

5

10

-20 --40 --60 -

Absolute bias estimates were computed by NOVELTIS for the Sentinel-3A altimetry mission at the Bass Strait calibration site.

In situ data, geodetic datum and all necessary information are shared by the University of Tasmania with NOVELTIS.

The Bass Strait calibration site was first implemented to monitor the Jason altimeters series. Given that the Sentinel-3A&B satellites do not fly directly over the initial calibration site, the University of Tasmania has deployed a mooring at the location of the crossover point between the Sentinel-3A tracks 060 and 247 in the Bass Strait, as showed in Figure 204.

This mooring data were provided to NOVELTIS until the 21/08/2018 (cycle 34 of Sentinel-3A).

NOVELTIS computed the absolute bias estimates for these two tracks and the results and time series are showed in Figure 205. The bias estimates are quite consistent for both tracks, in terms of mean and variability. The results are also very close for the SAR and the PLRM data. These bias estimates are in very good agreement with the values obtained by Christopher Watson from the University of Tasmania, using his own method, as shown at the OSTST meeting in October 2019.

When comparing the results at the three sites, one can notice the good agreement between Corsica (Senetosa) and Bass Strait, with bias estimates of about 2 cm for Sentinel-3A. In Harvest, the bias



estimates are a bit lower (close to 0) but some further computations are needed at this site, including the ocean dynamics corrections.



Figure 204: Configuration of the Sentinel-3A tracks at the Bass Strait calibration site.







Figure 205 : Sentinel-3A absolute bias estimates in Bass Strait for track 060 (upper plot) and track 247 (lower plot), for the SAR and the PLRM data.



# **12** Bias assessment of the different retrackers

There are several SARM retrackers provided in the L2 products that are specifically designed to be used for the different surfaces.

- Ocean retracker derived from SAMOSA model that is meaningful over open ocean and coastal areas.
- OCOG (ICE 1) retracker which is traditionally used over inland water because it is quite robust. It can also be used over land ice for the same reason but is expected to provide a lower accuracy.
- Sea ice retracker which is an empirical retracker designed for sea ice
- Ice margin retracker which is a physical ice sheet model designed for land ice

The aim of this section is to highlight any mean absolute bias that could be identified on all these retrackers.

### 12.1 Ocean retracker

There have been several assessments for the range derived over ocean that are detailed in this document. Several figures are found to be below 2 cm for the ocean retracker, which is a small bias, almost negligible.

For the Ku band sigma0 estimated by the ocean retracker, a system bias of 18.9 dB is applied in the L2 ground processor to align it to a mean value of 11 dB over ocean. This means that the Ku-band SARM sigma0 is too strong, but there are some evolutions to be implemented in the future ground processing versions to get a level closer to the ocean mean value without any system bias applied

# 12.2 OCOG retracker

The estimation of a range bias for this retracker is quite difficult since it is an empirical retracker and, by design, the bias will depend on the waveforms shape and therefore on the surface (ocean, inland waters, sea ice, land ice echoes). Figure 206 shows that the difference between the Ocean and OCOG range varies a lot depending on the considered surface. We can observe a bias of 40-50 cm over ocean because this retracker is not meant to be accurate over this surface, while both retrackers agree below 20 cm over regions where sea ice dominate. Over Greenland, such a difference is not meaningful since the ocean SAMOSA model is not defined to work over land ice.

Nevertheless, calibration of the OCOG range over the Issykkul Lake found a bias of +28 cm (see previous annual report section 10, RD 19), which is in agreement with the bias observed with this retracker for other altimetry missions. We can therefore conclude that there is no bias identified for the OCOG range.

The backscatter coefficients between both retrackers are also compared on Figure 207. It shows a large bias for the OCOG sigma0. Values are close to -35 dB over ocean which means that the mean OCOG sigma0 is close to 46 dB. This bias is expected to be reduce with the deployment of PB2.61 (S3A) and 1.33 (S3B) in January 2020. Despite this strong absolute bias, we also note variations with several dB magnitude depending on the considered surface.



#### Difference of range Ocean - Ocog

Sentinel-3a, cycle 51 (26/10/2019 - 22/11/2019)



Figure 206 Range difference: OCOG-Ocean over Arctic in L2 Land products STC Cycle 51



# 

Difference of backscatter coefficient Ocean - Ocog

Figure 207 Backscatter coefficient difference: OCOG-Ocean over Arctic in L2 Land products STC Cycle 51

### 12.3 Sea Ice retracker

In PB2.43 a major evolution of the L2 sea ice algorithms included a new sea ice TFRM retracker which operates on sea ice floes. A separate sea ice physical model retracker is used over sea ice leads. It is known that the use of two different sea ice retrackers introduces a retracker bias as detailed for CryoSat in *Tilling et al, 2018*.

During 2019, MSSL estimated this bias for S3A and S3B. Data from the Hudson Bay area was analysed to locate tracks where very thin sea ice was present. This provides diffuse returns that will be retracked with the sea ice floe retracker at the same height as specular returns from leads, therefore any difference in measured height is the bias between the retracking methods. Bias values were estimated from a number of tracks, averaged, and supplied for use in the processing configuration. This work will need to be redone when the L1 processing is changed to perform zero padding and Hamming weighting, which is necessary to improve the quality of the sea ice retrievals. The bias was calculated as -17.89cm. This compares to a -16.2cm bias calculated for CryoSat-2 by *Tilling et al*, *2018*, however due to the lack

COLLECTE LOCALISATION SATELLIFIS	Sentinel-3 MPC	Ref.:	S3MPC.CLS.APR.006	
	S3MPC STM Annual Performance	Issue:	1.0	
	Report - Year 2019	Date:	28/02/2020	
		Page:	227	

of zero padding in S3 data there is an error in the lead measurements which is twice as large as that measured for CryoSat-2.



# Mean S3A bias calculated as -17.89cm Recommend same bias for S3B

Figure 208: Calculation of Sea Ice Retracker Bias for S3A over the Hudson Bay

# 12.4 Ice margin retracker

In order to assess possible residual bias on ice margin range, we compared this retracker output to the ocean range and to the OCOG range over land ice.

Surprisingly, the difference between ice margin range and ocean range is close to zero over almost all surfaces as shown by Figure 209. Over ocean and sea ice, the difference varies between 10 and 20 cm. This could suggest that there is no significant bias on the ice sheet range, given that the ocean range has almost no bias. This must be further confirmed by comparison of elevation data over land ice with external sources, since this is the surface where this retracker is relevant.



Figure 210 also displays the map over Antarctica of the difference between OCOG and ice margin range. This comparison is more meaningful since both retrackers are supposed to retrieve a good signal over land ice. The difference shows variations between the retrackers that vary between 50 cm and 2 m, but no clear mean bias can be found between both retrackers. As explained in section 9, values are not defined everywhere, due to the large amount of failure of the ice margin retracker.

The backscatter coefficients between both retrackers are also compared on Figure 211. It shows a large bias for the OCOG sigma0. Values are close to -36 dB over ocean which means that the mean OCOG sigma0 is close to 47 dB. Despite this strong absolute bias, we also note variations with several dB magnitude depending on the considered surface.

Figure 212 also displays the map over Antarctica of the difference between OCOG and ice margin backscatter coefficient. In this case values are very close with a bias varying mainly between -1 and -2 dB, OCOG sigma0 being lower than the ice margin one. As for the range, values are not defined everywhere, due to the large amount of failure of the ice margin retracker. The values are different over the sea ice areas where we observe larger and positive differences (+4 dB).



Difference of range Ocean - ice sheet

Sentinel-3a, cycle 51 (26/10/2019 - 22/11/2019)

Figure 209 Range difference: Ocean-Ice margin over Arctic in L2 Land products STC Cycle 51





Difference of range Ocog - Ice sheet

Figure 210 Range difference: OCOG-Ice margin over Antarctica in L2 Land products STC Cycle 51





ifference of backscatter coefficient Ocean - Ice shee

Figure 211 Backscatter coefficient difference: Ocean-Ice margin over Arctic in L2 Land products STC Cycle 51




#### Difference of backscatter coefficient Ocog - Ice sheet

Figure 212 Backscatter coefficient difference: OCOG-Ice margin over Antarctica in L2 Land products STC Cycle 51

## 12.5 Summary

There is no absolute bias identified on the range parameters estimated by the different retrackers. Nevertheless, there are strong absolute biases present on the backscatter coefficients. Values are very close between OCOG and Ice margin retracker (35 and 35 dB wrt a mean value of 11 dB over ocean) while the Ocean retracker has a smaller bias (19 dB). There will be some evolutions to be implemented in the future ground processing versions to get a level closer to the ocean mean value without any system bias applied.



# **13 Annex - Processing Baseline Details**

# 13.1 Processing Baseline 2.12

## **13.1.1** Ground processors versions (Instrument Processor Facility)

- SR\_1 IPF version: 06.11
- MW\_1 IPF version: 06.03
- SM\_2 IPF version: 06.07

## 13.1.2 Evolutions

There is no evolution of algorithm nor model coming from Processing Baseline 2.12. The content is completely described by the list of the anomaly fixes detailed in the following sections.

## 13.1.3 Fix of anomalies

#### Anomaly #4 : Error in bathymetry parameter (S3MPC-1078)

- The bathymetry parameter has some error at the crossing of the Greenwich meridian. The bathymetry is set to zero between 0° and 20°E for some specific latitudes.
- All versions up to and including 06.06 are impacted
- Fixed in version 06.07

## Anomaly #12 : High level of retracker failure over in-land waters (S3MPC-1064)

- The OCOG ice retracker shows higher percentage of failure than the ocean retracker over rivers and lakes. Further tuning of the S3 retracker or waveform rejection algorithms is required. Note that only a few targets have been assessed so far by the validation team so the percentage of failure can be different for the different water bodies.
- All versions up to and including 06.06 are impacted
- Fixed in version 06.07

#### Anomaly #13 : Error in the OCOG retracker (S3MPC-1478)

- The threshold value used in the OCOG retracker is not adapted to Ku band. The effect is an error on the range values which varies depending on the waveform shape. For waveforms close to ocean waveforms, a bias of 80 cm is observed (calibration done over the Lake Issykkul).
- All versions up to and including 06.06 are impacted
- Fixed in version 06.07

#### Anomaly #14 : GIM ionospheric correction not calculated for STC products (S3MPC-1468)

The model GIM ionospheric correction is not calculated for STC products, therefore the field is set to default value. Note that the correction is available in NRT and NTC products.



- All versions up to and including 06.06 are impacted
- Fixed in version 06.07

# 13.2 Processing Baseline 2.24

- **13.2.1** Ground processors versions (Instrument Processor Facility)
  - SR\_1 IPF version: 06.12
  - MW\_1 IPF version: 06.04
  - SM\_2 IPF version: 06.10

## 13.2.2 Evolutions

In addition to the resolution of the anomalies listed in the following section, Processing Baseline 2.24 brings major evolutions of product quality over ocean, coastal sea ice and land ice surfaces. These improvements are detailed in : <u>https://earth.esa.int/documents/247904/3147059/Sentinel-3-STM-Product-Evolution-Processing-Baseline-2.24</u>

## 13.2.3 Fix of anomalies

## <u>Anomaly #1 : Duplicated measurements at 10 minutes granule transition in L2 NRT products</u> (S3MPC-926)

- There are duplicates of 1 Hz measurements (same 1 Hz time tag) between consecutive granules. At granules transition, the last 1 Hz measurement and the first 1 Hz measurement of the following granule may have the same datation. In some cases, 1 Hz range values might be set to default values because there are not enough 20 Hz observations within the granule to compute the 1 Hz range. Note that the 20 Hz parameters (range, SWH and Sigma0) are not affected.
- Fixed in version 06.10

## Anomaly #2 : Overflow of the Ku band atmospheric attenuation in the L2 products (S3MPC-1076)

- The atmospheric attenuation in Ku band is set to default values in the products when value exceeds 1.27 dB. Note that for these measurements the wind speed is well calculated.
- Fixed in version 06.10



## <u>Anomaly #3 : Atmospheric attenuation to default values over edges of MWR calibration</u> (S3MPC-1077)

- The atmospheric attenuation on Ku band and C band is set to defaults values for sporadic points located in the fringe of the MWR calibration sequences. These isolated 1 Hz values can be found over open-ocean. As a consequence, wind speed, sea state bias, dual frequency ionospheric correction and SSHA parameters are set to default value.
- Fixed in version 06.10

# Anomaly #4 : SAR backscatter coefficient has an error correlated with radial velocity (S3MPC-1251)

- The SAR Ku band sigma0 from ocean/coastal retracker (sig0\_ocean\_01\_ku) shows an error correlated with radial velocities above 20 m/s. The maximum magnitude of the error is estimated to 0.2 dB for the stronger velocities (25m/s).
- Fixed in version 06.10

## Anomaly #5 : Error in the manoeuvre flag (EUM/Sen3/AR/2268)

- There is an inconsistency between the product specifications (S3IPF PDS 003 -i1r7- Product Data Format Specification - SRAL-MWR) and the effective values in the products of the manoeuvre presence flag (values set to 4 or 5 instead of 0 and 1 as specified in the documentation.
- Fixed in version 06.10

## Anomaly #6 : Error in Inverse Barometer correction (S3MPC-1253)

- There is a bias of 1 cm over open-ocean on the inverse barometer correction. Note that this error has no impact in STC and NTC products on the sum of the 2 fields used in the SSHA calculation (inverted barometer height correction (inv\_bar\_cor) + high frequency fluctuations of the sea surface topography (hf\_fluct\_cor)).
- Fixed in version 06.10

## Anomaly #7 : High level of retracker failure in continental ice sheets (S3MPC-1014)

- Over the inland ice sheets of Antarctica and Greenland there are much higher levels of the ice sheet retracker failure than found in previous missions (ie CryoSat LRM or Envisat RA2) over sloping surfaces. The anomaly on the SAR ice margin retracker also impacts the slope correction which is set to FillValue in a high number of occurrences.
- Improvement is observed with version 06.10 reducing the loss to 20% of the data set over Antarctica. Further tuning of the SRAL L1 processing is required to insure full consistency between L1 processing and L2 ice sheet retracker, so that the expected level of ice sheet retracker coverage is finally met. Meanwhile, users are advised to use the OCOG retracker to exploit a data set with the expected coverage over land ice.
- All versions up to and including 06.10 are impacted



## Anomaly #8 : Sea Ice discrimination identifying too many floes (S3MPC-1013)

- A comparison of Arctic sea ice discrimination statistics during October 2016 between Sentinel-3A and CryoSat shows that S3 processing is identifying four times more floes to leads than CryoSat's discriminator than would be expected during this period. Sentinel-3A discrimination requires further tuning.
- Fixed in version 06.10

#### Anomaly #9 : Large negative values in elevation over ice sheet (S3MPC-1020)

- Elevation values over ice sheet (elevation\_ice\_sheet\_20\_ku) are occasionally set to large negative values (in the order of -214680m). It varies and is not the FillValue of the field. This happens particularly in the areas of ice shelves just off the coast and appears to be isolated points along the track. It does not seem to occur in the interior ice sheets or in the ocean.
- Fixed in version 06.10

## 13.3 Processing Baseline 2.27

#### 13.3.1 Ground processors versions (Instrument Processor Facility)

- SR\_1 IPF version: 06.13
- MW\_1 IPF version: 06.04
- SM\_2 IPF version: 06.12

## 13.3.2 Evolutions

In addition to the resolution of the anomalies listed in the following section, Processing Baseline 2.27 improves product quality over the land ice with the inclusion of a new parameter in the L2 products, as recommended by the S3VT meeting in March 2017: elevation field derived from the OCOG retracker that provides a better coverage compared to the elevation derived from the ice sheet retracker that was already provided in the products.

#### 13.3.3 Fix of anomalies

#### Anomaly #15 : Wrong values of ssha over sea ice (S3MPC-2067 and S3MPC-2271)

- The ssha parameter over sea ice (sea\_ice\_ssha, int\_ sea\_ice\_ssha) exhibits large values of 3.27 m when the GIM ionospheric correction is set to default value. The anomaly on the ssha field is due to bad handling of the default value into the ssha calculation.
- Fixed in version 06.12



#### Anomaly #16 : SAR mode slope correction relocates echo position incorrectly (S3MPC-2074)

- SAR mode slope correction relocates echo position incorrectly down slope and not across track. Note that for LRM slope correction relocates echo in correct direction.
- Fixed in version 06.12

#### Anomaly #18 : Numerical Overflow for the Waveform MQE Parameter (S3MPC-2027)

- There is an overflow for the waveform Mean Quadratic Error between the waveform and the model used for the ocean retracker (mqe\_ocean\_20\_ku) in the products. This results in field padded to default value over sea ice in Antarctica and Arctic and sporadically over open ocean.
- Fixed in version 06.12

#### Anomaly #19: Numerical Overflow for the peakiness parameter (S3MPC-2028)

- There is an overflow for the peakiness parameters (peakiness\_2\_20\_ku, peakiness\_2\_20\_c, peakiness\_1\_20\_plrm\_ku) in the products. This results in fields padded to default value over sea ice in Antarctica and Arctic where peaky waveforms can happen.
- Fixed in version 06.12

#### 13.3.4 Anomalies not solved

The following list summarizes the anomalies that still affect the products with the Processing Baseline 2.27:

#### Anomaly #7 : High level of retracker failure in continental ice sheets (S3MPC-1014)

- Over the inland ice sheets of Antarctica and Greenland there are much higher levels of the ice sheet retracker failure than found in previous missions (ie CryoSat LRM or Envisat RA2) over sloping surfaces. The anomaly on the SAR ice margin retracker also impacts the slope correction which is set to FillValue in a high number of occurrences.
- Improvement is observed since version 06.10 reducing the loss to 20% of the data set over Antarctica. Further tuning of the SRAL L1 processing is required to insure full consistency between L1 processing and L2 ice sheet retracker, so that the expected level of ice sheet retracker coverage is finally met. Meanwhile, users are advised to use the OCOG retracker to exploit a data set with the expected coverage over land ice (loss of only 2% of data).
- All versions up to and including 06.12 are impacted

#### Anomaly #10 : Dry tropospheric correction residual error over land (S3MPC-1518)

- The dry tropospheric correction at the measurement altitude (mod\_dry\_tropo\_cor\_meas\_altitude\_01) exhibits some residual error correlated to the topography. The error has a magnitude of a few millimetres.
- All versions up to and including 06.12 are impacted



## Anomaly #11 : Quantization of the distance to coast (S3MPC-1519)

- The distance to coast at 1 Hz and at 20 Hz exhibits some quantization. The effect is larger at 20 Hz for which the value is constant over several 20 Hz measurements.
- All versions up to and including 06.12 are impacted

## Anomaly #12 : Degraded quality of atmospheric attenuation over coastal areas (S3MPC-1934)

- The MWR atmospheric attenuation was improved over coastal zone except for some specific cases over coastal areas, for which the attenuation is negative (-0.3 dB). This anomaly affects only 0.25% of the ocean measurements and occurs when backscatter coefficient exceeds 18 dB.
- This anomaly was introduced in version 06.10 and all versions up to and including 06.12 are impacted

## Anomaly #13 : GIM ionospheric to default value (S3MPC-2030)

- The GIM ionospheric correction is systematically set to default values for portions of tracks that are closed to midnight. Therefore, parameters related to the topography observations are impacted (sea\_ice\_ssha, int\_ sea\_ice\_ssha).
- Fixed in version 06.10 for STC products.
- All versions up to and including 06.12 are impacted for NTC products. The impact is that ssha, sea\_ice\_ssha and int\_ sea\_ice\_ssha parameters exhibit too large values.
- All versions up to and including 06.12 are impacted for NTC products. Since IPF version 06.12, the impact is that sea\_ice\_ssha and int\_sea\_ice\_ssha parameters are calculated without the GIM ionospheric correction.
- The reprocessed products with IPF 06.10 are not affected by this anomaly.

## Anomaly #14 : L2 sea ice freeboard (freeboard 20 ku) is predominantly negative (S3MPC-2244)

- The freeboard parameter exhibits a mean value centred around -30 cm which is not expected. It is mainly due to the retracker used for the diffuse echoes which is not optimal to properly retrack the double peak waveforms that are characteristics over floes.
- All versions up to and including 06.12 are impacted

## Anomaly #20 : Sea ice lead echoes incorrectly filtered by waveform quality check (S3MPC-2409, S3MPC-2411)

The sea ice retracker exhibits a much higher level of failure compared to the other retrackers (ocean, OCOG and ice sheet retrackers), due to the use of a quality check applied on the



waveforms. This results in the sea ice retracking not being applied to waveforms for observations that are associated to leads and sea ice, leads being the dominant population where the retracker is not activated. This anomaly will be corrected in future STM Processing Baseline.

All versions up to and including 06.12 are impacted.

# Anomaly #21 : 5 millimeter bias between zero-altitude dry tropo correction and measured dry tropo correction (S3MPC-2338)

- The dry tropospheric correction (mod\_dry\_tropo\_meas\_altitude\_01) exhibits a bias over all surfaces (ocean and land). It is close to 5 millimeters over ocean (including coastal areas) and less than 5 millimeters over land. This anomaly will be corrected in future STM Processing Baseline.
- All versions up to and including 06.12 are impacted.

#### Anomaly #22 : Discrimination flag set to ocean over land (S3MPC-2412)

- The discrimination flag (surf\_type\_class\_20\_ku) which is designed for sea ice is set to ocean over land surfaces.
- All versions up to and including 06.12 are impacted.

#### Anomaly #23 : Wrong values of interpolated sea\_ice\_ssha over ocean (S3MPC-2413)

- Values of interpolated ssha for sea ice (int\_ sea\_ice\_ssha) show stronger magnitude than the original sea\_ice\_ssha parameter, over transition zones between ocean and land areas.
- All versions up to and including 06.12 are impacted.

#### Anomaly #24 : Ice concentration set to zero over land (S3MPC-2417)

- Sea\_ice\_concentration\_20\_ku is set to zero percent over land but it does not affect the quality of the sea ice parameters using this parameter.
- All versions up to and including 06.12 are impacted

#### Anomaly #25 : Ice2 PLRM retracker not defined over the ice shelves (S3MPC-2415)

- The parameters estimated by the Ice2 retracker on PLRM waveforms (range\_ice\_20\_plrm\_ku and sig0\_ice\_20\_plrm\_ku) are not defined over the ice shelves.
- All versions up to and including 06.12 are impacted.



#### Anomaly #26 : SRAL L2 NRT products with zero duration (S3MPC-2340)

- There are some products generated with a duration less than 1 second, with only a few 20 Hz records inside the product. Note that this anomaly only affects the NRT products.
- All versions up to and including 06.12 are impacted.

#### Anomaly #27 : Partial coverage for OCOG retracker in C-band (S3MPC-2365)

- The output of the OCOG retracker in C-band (range\_ocog\_20\_c and sig0\_ocog\_20\_c parameters) are very frequently set to fill values, whatever the surface.
- All versions up to and including 06.12 are impacted.



# 13.4 Processing Baseline 2.33

13.4.1 Ground processors versions (Instrument Processor Facility)

- SR\_1 IPF version: 06.14
- MW\_1 IPF version: 06.07
- SM\_2 IPF version: 06.14

## 13.4.2 Evolutions

In addition to the resolution of the anomalies listed in the following section, the evolution in Processing Baseline 2.33 deals with the inclusion of the SRAL acquisitions measurements in the SRAL Level 1 products and the evolution needed in the Level 2 ground processor to manage the new MWR calibration timeline.

## **13.4.3** Fix of anomalies

# Anomaly #8 : 5 millimeter bias between zero-altitude dry tropo correction and measured dry tropo correction (S3MPC-2338)

- The dry tropospheric correction (mod\_dry\_tropo\_meas\_altitude\_01) exhibits a bias over all surfaces (ocean and land). It is close to 5 millimeters over ocean (including coastal areas) and less than 5 millimeters over land. This anomaly will be corrected in future STM Processing Baseline.
- Fixed in version 06.14

## Anomaly #13 : SRAL L2 NRT products with zero duration (S3MPC-2340)

- There are some products generated with a duration less than 1 second, with only a few 20 Hz records inside the product. Note that this anomaly only affects the NRT products.
- Fixed in version 06.14

## Anomaly #16 : the field "ssha 20 ku" is always set to Fill Value in LRM mode (S3MPC-2469)

- The field ssha\_20\_ku is set to Fill Value when the SRAL altimeter operates in LRM mode.
- Fixed in version 06.14

# Anomaly #17 : the field "elevation ice sheet 20 ku" is set very often to Fill Value in LRM mode (S3MPC-2477)

- The field elevation\_ice\_sheet\_20\_ku is set to Fill Value for some measurements over Greenland and Antarctica when the SRAL altimeter operates in LRM mode (before 12 April 2016).
- Fixed in version 06.14



## Anomaly #18 : the field "elevation ocog 20 ku" is set to Fill Value in LRM mode (S3MPC-2478)

- The field elevation\_ocog\_20\_ku is set to Fill Value for some measurements over Greenland and Antarctica when the SRAL altimeter operates in LRM mode (before 12 April 2016).
- Fixed in version 06.14

## 13.4.4 Anomalies not solved

The following list summarizes the anomalies that still affect the products with the Processing Baseline 2.33:

## Anomaly #1 : High level of retracker failure in continental ice sheets (S3MPC-1014)

- Over the inland ice sheets of Antarctica and Greenland there are much higher levels of the ice sheet retracker failure than found in previous missions (ie CryoSat LRM or Envisat RA2) over sloping surfaces. The anomaly on the SAR ice margin retracker also impacts the slope correction which is set to FillValue in a high number of occurrences.
- Improvement is observed since version 06.10 reducing the loss to 20% of the data set over Antarctica. Further tuning of the SRAL L1 processing is required to insure full consistency between L1 processing and L2 ice sheet retracker, so that the expected level of ice sheet retracker coverage is finally met. Meanwhile, users are advised to use the OCOG retracker to exploit a data set with the expected coverage over land ice (loss of only 2% of data).
- All versions up to and including 06.14 are impacted

## Anomaly #2 : Dry tropospheric correction residual error over land (S3MPC-1518)

- The dry tropospheric correction at the measurement altitude (mod\_dry\_tropo\_cor\_meas\_altitude\_01) exhibits some residual error correlated to the topography. The error has a magnitude of a few millimetres.
- All versions up to and including 06.14 are impacted

## Anomaly #3 : Quantization of the distance to coast (S3MPC-1519)

- The distance to coast at 1 Hz and at 20 Hz exhibits some quantization. The effect is larger at 20 Hz for which the value is constant over several 20 Hz measurements.
- All versions up to and including 06.14 are impacted

## Anomaly #4 : Degraded quality of atmospheric attenuation over coastal areas (S3MPC-1934)

The MWR atmospheric attenuation was improved over coastal zone except for some specific cases over coastal areas, for which the attenuation is negative (-0.3 dB). This anomaly affects only 0.25% of the ocean measurements and occurs when backscatter coefficient exceeds 18 dB.



This anomaly was introduced in version 06.10 and all versions up to and including 06.14 are impacted

## Anomaly #5 : GIM ionospheric to default value (S3MPC-2030)

- The GIM ionospheric correction is sometimes set to default values for portions of tracks that are closed to midnight. Therefore, parameters related to the topography observations are impacted (sea\_ice\_ssha, int\_ sea\_ice\_ssha).
- All versions up to and including 06.14 are impacted for STC and NTC products.
- Since IPF version 06.12, the impact is that sea\_ice\_ssha and int\_sea\_ice\_ssha parameters are calculated without the GIM ionospheric correction.
- The reprocessed products with IPF 06.12 are not affected by this anomaly.

## Anomaly #6 : L2 sea ice freeboard (freeboard 20 ku) is predominantly negative (S3MPC-2244)

- The freeboard parameter exhibits a mean value centred around -30 cm which is not expected. It is mainly due to the retracker used for the diffuse echoes which is not optimal to properly retrack the double peak waveforms that are characteristics over floes.
- All versions up to and including 06.14 are impacted

## Anomaly #7 : Sea ice lead echoes incorrectly filtered by waveform quality check (S3MPC-2409, S3MPC-2411)

- The sea ice retracker exhibits a much higher level of failure compared to the other retrackers (ocean, OCOG and ice sheet retrackers), due to the use of a quality check applied on the waveforms. This results in the sea ice retracking not being applied to waveforms for observations that are associated to leads and sea ice, leads being the dominant population where the retracker is not activated. This anomaly will be corrected in future STM Processing Baseline.
- All versions up to and including 06.14 are impacted.

## Anomaly #9 : Discrimination flag set to ocean over land (S3MPC-2412)

- The discrimination flag (surf\_type\_class\_20\_ku) which is designed for sea ice is set to ocean over land surfaces.
- All versions up to and including 06.14 are impacted.



#### Anomaly #10: Wrong values of interpolated sea ice ssha over ocean (S3MPC-2413)

- Values of interpolated ssha for sea ice (int\_ sea\_ice\_ssha) show stronger magnitude than the original sea\_ice\_ssha parameter, over transition zones between ocean and land areas.
- All versions up to and including 06.14 are impacted.

#### Anomaly #11 : Ice concentration set to zero over land (S3MPC-2417)

- Sea\_ice\_concentration\_20\_ku is set to zero percent over land but it does not affect the quality of the sea ice parameters using this parameter.
- All versions up to and including 06.42 are impacted

#### Anomaly #12 : Ice2 PLRM retracker not defined over the ice shelves (S3MPC-2415)

- The parameters estimated by the Ice2 retracker on PLRM waveforms (range\_ice\_20\_plrm\_ku and sig0\_ice\_20\_plrm\_ku) are not defined over the ice shelves.
- All versions up to and including 06.14 are impacted.

#### Anomaly #14 : Partial coverage for OCOG retracker in C-band (S3MPC-2365)

- The output of the OCOG retracker in C-band (range\_ocog\_20\_c and sig0\_ocog\_20\_c parameters) are very frequently set to fill values, whatever the surface.
- All versions up to and including 06.14 are impacted.

#### Anomaly #15 : Partial coverage for OCOG retracker in LRM mode (S3MPC-2564)

- The output of the OCOG retracker in Ku-band in LRM mode (range\_ocog\_20\_ku and sig0\_ocog\_20\_ku parameters) are very frequently set to fill values, whatever the surface.
- All versions up to and including 06.14 are impacted.

## 13.5 Processing Baseline 1.13 for S3B

#### **13.5.1** Ground processors versions (Instrument Processor Facility)

- SR\_1 IPF version: 06.14
- MW\_1 IPF version: 06.07
- SM\_2 IPF version: 06.14



## 13.5.2 Evolutions

This Processing Baseline was dedicated to the correction of the Sentinel-3B sigma0 bias of +0.5dB related to SRAL instrumental parametrization. The IPF version are similar as for the previous PB 2.33, only L2 ADFs were updated with new SRAL and MWR characterization parameters.

## 13.5.3 Fix of anomalies

The +0.5dB bias observed on Sentinel-3B is corrected, the mean value is thus consistent with Sentinel-3A.

The wet troposphere path delay derived from Sentinel-3A and Sentinel-3B MWRs are now consistent.

# 13.6 Processing Baseline 2.45 for S3A and 1.17 for S3B

## **13.6.1** Ground processors versions (Instrument Processor Facility)

- SR\_1 IPF version: 06.16
- MW\_1 IPF version: 06.09
- SM\_2 IPF version: 06.15

## 13.6.2 Evolutions

In addition to the resolution of the anomalies listed in the following section, the evolution in Processing Baseline 2.45 (S3A) and 1.15 (S3B) deals with the inclusion of several evolutions and corrections that aimed at improving parameters dedicated to land ice and sea ice surfaces

## 13.6.3 Fix of anomalies

## Anomaly #3: Quantization of the distance to coast (S3MPC-1519)

- The distance to coast at 1 Hz and at 20 Hz exhibits some quantization. The effect is larger at 20 Hz for which the value is constant over several 20 Hz measurements.
- Fixed in version 06.15

#### Anomaly #6: L2 sea ice freeboard (freeboard\_20\_ku) is predominantly negative (S3MPC-2244)

- The freeboard parameter exhibits a mean value centred around -30 cm which is not expected. It is mainly due to the retracker used for the diffuse echoes which is not optimal to properly retrack the double peak waveforms that are characteristics over floes.
- Fixed in version 06.15



## Anomaly #6: L2 sea ice freeboard (freeboard 20 ku) is predominantly negative (S3MPC-2244)

- The freeboard parameter exhibits a mean value centred around -30 cm which is not expected. It is mainly due to the retracker used for the diffuse echoes which is not optimal to properly retrack the double peak waveforms that are characteristics over floes.
- Fixed in version 06.15

# Anomaly #7: Sea ice lead echoes incorrectly filtered by waveform quality check (S3MPC-2409, S3MPC-2411)

- The sea ice retracker exhibits a much higher level of failure compared to the other retrackers (ocean, OCOG and ice sheet retrackers), due to the use of a quality check applied on the waveforms. This results in the sea ice retracking not being applied to waveforms for observations that are associated to leads and sea ice, leads being the dominant population where the retracker is not activated.
- Fixed in version 06.15

#### Anomaly #9: Discrimination flag set to ocean over land (S3MPC-2412)

- The discrimination flag (surf\_type\_class\_20\_ku) which is designed for sea ice is set to ocean over land surfaces.
- Fixed in version 06.15

#### Anomaly #10: Wrong values of interpolated sea ice ssha over ocean (S3MPC-2413)

- Values of interpolated ssha for sea ice (int\_ sea\_ice\_ssha) show stronger magnitude than the original sea\_ice\_ssha parameter, over transition zones between ocean and land areas.
- This anomaly is corrected in version 06.15. All versions up to and including 06.14 are impacted.

#### Anomaly #11: Ice concentration set to zero over land (S3MPC-2417)

- Sea\_ice\_concentration\_20\_ku is set to zero percent over land but it does not affect the quality of the sea ice parameters using this parameter.
- Fixed in version 06.15

#### Anomaly #14: Partial coverage for OCOG retracker in C-band (S3MPC-2365)

- The output of the OCOG retracker in C-band (range\_ocog\_20\_c and sig0\_ocog\_20\_c parameters) are very frequently set to fill values, whatever the surface.
- Fixed in version 06.15

#### Anomaly #15: Partial coverage for OCOG retracker in LRM mode (S3MPC-2564)

- The output of the OCOG retracker in Ku-band in LRM mode (range\_ocog\_20\_ku and sig0\_ocog\_20\_ku parameters) are very frequently set to fill values, whatever the surface.
- Fixed in version 06.15



## 13.6.4 Anomalies not solved

## Anomaly #1: High level of retracker failure in continental ice sheets (S3MPC-1014)

- Over the inland ice sheets of Antarctica and Greenland there are much higher levels of the ice sheet retracker failure than found in previous missions (i.e. CryoSat LRM or Envisat RA2) over sloping surfaces. The anomaly on the SAR ice margin retracker also impacts the slope correction, which is set to FillValue in a high number of occurrences.
- Improvement is observed since version 06.10 reducing the loss to 20% of the data set over Antarctica. Further tuning of the SRAL L1 processing is required to insure full consistency between L1 processing and L2 ice sheet retracker, so that the expected level of ice sheet retracker coverage is finally met. Meanwhile, users are advised to use the OCOG retracker to exploit a data set with the expected coverage over land ice (loss of only 2% of data).
- All versions up to and including 06.15 are impacted

## Anomaly #4: Degraded quality of atmospheric attenuation over coastal areas (S3MPC-1934)

- The MWR atmospheric attenuation was improved over coastal zone except for some specific cases over coastal areas, for which the attenuation is negative (-0.3 dB). This anomaly affects only 0.25% of the ocean measurements and occurs when backscatter coefficient exceeds 18 dB.
- This anomaly was introduced in version 06.10 and all versions up to and including 06.15 are impacted

## Anomaly #5: GIM ionospheric to default value (S3MPC-2030)

- The GIM ionospheric correction is sometimes set to default values for portions of tracks that are close to midnight. Therefore, parameters related to the topography observations are impacted (sea\_ice\_ssha, int\_ sea\_ice\_ssha).
- All versions up to and including 06.15 are impacted for STC and NTC products.
- Since IPF version 06.12, the impact is that sea\_ice\_ssha and int\_sea\_ice\_ssha parameters are calculated without the GIM ionospheric correction.
- The reprocessed products with IPF 06.12 are not affected by this anomaly.

## Anomaly #12: Ice2 PLRM retracker not defined over the ice shelves (S3MPC-2415)

- The parameters estimated by the Ice2 retracker on PLRM waveforms (range\_ice\_20\_plrm\_ku and sig0\_ice\_20\_plrm\_ku) are not defined over the ice shelves.
- All versions up to and including 06.15 are impacted.

## Anomaly #16: Global attribute "pass\_number" wrong information (S3MPC-3263)

- In the global attribute of the product, the first pass of a cycle is labeled as 771 instead of 1
- All versions up to and including 06.15 are impacted.

## Anomaly #17: P-LRM Sea Surface Height is computed using SARM Sea State Bias (S3MPC-3284)

- The fields "ssha\_01\_plrm\_ku" and "ssha\_20\_plrm\_ku" are computed using a Sea State Bias derived from SARM processing.
- All versions up to and including 06.15 are impacted



## Anomaly #18: Degraded quality of SWH below 1 meter (S3MPC-3284)

- The analysis of SWH distribution shows an unusual high number of values, for low SWH, below 1 meter. Both SARM and P-LRM processing are concerned.
- All versions up to and including 06.15 are impacted

# 13.7 **Processing Baseline 2.61 for S3A and 1.33 for S3B**

## 13.7.1 Ground processors versions (Instrument Processor Facility)

- SR\_1 IPF version: 06.16
- MW\_1 IPF version: 06.09
- SM\_2 IPF version: 06.15

#### 13.7.2 Evolutions

In addition to the resolution of the anomalies listed in the following section, the evolution in Processing Baseline 2.61 (S3A) and 1.33 (S3B) deals with the inclusion of several evolutions and corrections that aimed at improving parameters dedicated to ocean and land ice surfaces.

## 13.7.3 Fix of anomalies

#### Anomaly #4: Global attribute "pass number" wrong information (S3MPC-3263)

- In the global attribute of the product, the first pass of a cycle is labeled as 771 instead of 1
- Fixed in version 06.18

#### Anomaly #5: P-LRM Sea Surface Height is computed using SARM Sea State Bias (S3MPC-3284)

- The fields "ssha\_01\_plrm\_ku" and "ssha\_20\_plrm\_ku" are computed using a Sea State Bias derived from SARM processing.
- All versions up to and including 06.15 are impacted.
- Fixed in version 06.18

#### Anomaly #6: Degraded quality of SWH below 1 meter (S3MPC-3476)

- The analysis of SWH distribution shows an unusual high number of values, for low SWH, below 1 meter. Both SARM and P-LRM processing are concerned.
- All versions up to and including 06.15 are impacted.
- Fixed in version 06.18



## 13.7.4 Anomalies not solved

## Anomaly #1: High level of retracker failure in continental ice sheets (S3MPC-1014)

- Over the inland ice sheets of Antarctica and Greenland there are much higher levels of the ice sheet retracker failure than found in previous missions (i.e. CryoSat LRM or Envisat RA2) over sloping surfaces. The anomaly on the SAR ice margin retracker also impacts the slope correction, which is set to FillValue in a high number of occurrences.
- Improvement is observed since version 06.10 reducing the loss to 20% of the data set over Antarctica. Further tuning of the SRAL L1 processing is required to insure full consistency between L1 processing and L2 ice sheet retracker, so that the expected level of ice sheet retracker coverage is finally met. Meanwhile, users are advised to use the OCOG retracker to exploit a data set with the expected coverage over land ice (loss of only 2% of data).
- All versions up to and including 06.18 are impacted

#### Anomaly #2: Degraded quality of atmospheric attenuation over coastal areas (S3MPC-1934)

- The MWR atmospheric attenuation was improved over coastal zone except for some specific cases over coastal areas, for which the attenuation is negative (-0.3 dB). This anomaly affects only 0.25% of the ocean measurements and occurs when backscatter coefficient exceeds 18 dB.
- This anomaly was introduced in version 06.10 and all versions up to and including 06.18 are impacted.

## Anomaly #3: GIM ionospheric to default value (S3MPC-2030)

- The GIM ionospheric correction is sometimes set to default values for portions of tracks that are close to midnight. Therefore, parameters related to the topography observations are impacted (sea\_ice\_ssha, int\_sea\_ice\_ssha).
- All versions up to and including 06.18 are impacted for STC and NTC products.
- Since IPF version 06.12, the impact is that sea\_ice\_ssha and int\_sea\_ice\_ssha parameters are calculated without the GIM ionospheric correction.
- This anomaly only impacts the operational products, the reprocessed products (spring 2018 reprocessing campaign and 2019/2020 reprocessing campaign) are not affected by this anomaly.



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 Page:
 251

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