

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

S3MPC STM Annual Performance Report - Year 2018





Mission
Performance
Centre



Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Contract: 4000111836/14/I-LG

Customer:	ESA	Document Ref.:	S3MPC.CLS.APR.004
Contract No.:	4000111836/14/I-LG	Date:	28/02/2019
		Issue:	1.0

Project:			I PERFORMANCE CENTRE (MPC)
	FOR THE COPERNICUS SEN	NTINEL-3 MISSION	
Title:	S3MPC STM Annual Perfo	rmance Report - Year 20	018
Author(s):	STM ESLs		
Approved by:	S. Labroue	Authorized by	J. Bruniquel, Service Manager
Distribution:	ESA, S3MPC		
Accepted by ESA	P. Féménias, ESA TO		
Filename	S3MPC.CLS.APR.004 - i1r0	 - STM Annual Performa	nce Report - Year 2018.docx

Copyright ©2019 - CLS, ECMWF, isardSAT, LEGOS, MSSL, NOVELTIS, PML All rights reserved.

No part of this work may be disclosed to any third party translated, reproduced, copied or disseminated in any form or by any means except as defined in the contract or with the written permission of ACRI-ST

Disclaimer

The work performed in the frame of this contract is carried out with funding by the European Union. The views expressed herein can in no way be taken to reflect the official opinion of either the European Union or the European Space Agency.









S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: iii

Changes Log

Version	Date	Changes
1.0	28/02/2019	First version

List of Changes

Version	Section	Answers to RID	Changes

S CLS

Sentinel-3 MPC

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: iv

Table of content

CI	HANGES	LOG	III
LI	ST OF C	HANGES	III
T	ABLE OF	CONTENT	IV
LI	ST OF F	GURES	VII
LI	ST OF T	ABLES	XX
1	INTI	RODUCTION	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	EXE	CUTIVE SUMMARY	2
	2.1	Sentinel-3 Surface Topography Mission	2
	2.2	SRAL and MWR sensors	2
	2.3	Sea Level	3
	2.4	Winds and Waves	4
	2.5	Land and Sea Ice	5
	2.6	Inland waters	7
3	SRA	L AND MWR MISSION EVENTS	8
4	PRO	CESSING BASELINE STATUS	13
	4.1	Land and Marine Products	13
	4.2	Processing Baseline History	14
	4.2.	1 Summary of Processing Baseline Content	15
	4.2.	2 Model and standard history	16
	4.3	Status of the current Processing Baseline	17
	4.4	List of anomalies in the Processing Baseline	17
5	SEN	SORS STATUS	18
	5.1	SRAL	18
	5.2	MWR	20
	5.2.	1 MWR processing	20
	5.2.	2 MWR Calibration timeline	22
	5.2.	·	
	5.2.	4 MWR Brightness Temperatures monitoring	26
6	SRΔ	TRACKING PERFORMANCES	29



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: v

	6.1	Over Ocean	29
	6.2	Over Land	30
7	PERF	ORMANCE MISSION OVER OCEAN	37
	7.1	Outliers detection	37
	7.1.1	1 Ice detection	37
	7.1.2	2 Outliers detection over ocean	40
	7.2	Monitoring of SRAL parameters	44
	7.2.2	1 Significant Wave Height	44
	7.2.2	2 Backscatter coefficient	47
	7.2.3	3 Dual-Frequency ionospheric correction	50
	7.2.4	4 Off-Nadir angle waveform	57
	7.3	Wet tropospheric correction	61
	7.3.2	1 Along-track analyses	61
	7.3.2	2 Crossover analyses	65
	7.4	Sea Level Performances	67
	7.4.2	1 Along-track analyses	68
	7.4.2	2 Crossovers	71
	7.5	Global Mean Sea Level	78
	7.6	Wind/Wave Performance	79
	7.6.2	1 Backscatter coefficient	80
	7.6.2	2 Altimeter Wind Speed	84
	7.6.3	3 Significant Wave Height	102
	7.7	Investigation : Quality assessment of SAMOSA 2.5 ocean retracker	117
	7.8	Investigation: SARM Sensitivity to the tracker command	119
	7.9	Investigation: SRAL Sensitivity to the Swell Waves	123
	7.10	Investigation: Long term drift	125
	7.10	0.1 SWH long term analysis	125
	7.10	0.2 Range long term analysis	129
	7.10	0.3 Backscatter coefficient long term analysis	132
	7.11	Performance over Coastal areas	134
	7.11	.1 Altimeter characteristics and performances	134
	7.11	2 Comparison with respect to in-situ measurements	138
3	PERF	ORMANCE MISSION OVER SEA ICE	144
	8.1	Freeboard	144
	8.2	Sea Ice Parameters Contributing to Freeboard	
	8.3	Effect of Area Masking and Pole to Pole Processing on Sea Ice Parameters	



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: vi

	8.4	4 4	Availability of Snow Density, Snow Depth and Sea Ice Concentration over Sea Ice	155
9		MISSIC	ON PERFORMANCE OVER LAND ICE	.156
	9.3	1 T	he Effect of SAR Tracking Mode on S3A Land Ice Performance	157
	9.2	2 N	Measurement Precision over Land Ice	158
		9.2.1	Shot-to-shot Precision	159
		9.2.2	Crossover Analysis	162
	9.3	3 N	Measurement Accuracy over Land Ice	167
		9.3.1	Evaluation at Inland Sites	167
		9.3.2	Evaluation at Coastal Sites	169
	9.4	4 10	ce Sheet Rate of Elevation Change from S3A	171
	9.5	5 L	and Ice Parameter Failure Rates	173
	9.6	6 S	lope Correction	182
	9.	7 (Geophysical Correction Availability over Land Ice	183
10)	PERFO	RMANCE MISSION OVER INLAND WATERS	.185
11	L	RANGI	E AND SEA LEVEL ABSOLUTE CALIBRATION	.191
	11	.1 0	Calibration with Crete transponder	191
	11	.2 0	Calibration over Corsica sites	199
12	2	BIAS A	SSESSMENT OF THE DIFFERENT RETRACKERS	.207
	12	1 C	Ocean retracker	207
	12	.2 0	OCOG retracker	207
	12	3 S	ea Ice retracker	210
	12	4 lo	ce margin retracker	210
	12	5 S	ummary	215
13	3	ANNE	K - PROCESSING BASELINE DETAILS	.216
	13	.1 P	Processing Baseline 2.12	216
		13.1.1	Ground processors versions (Instrument Processor Facility)	216
		13.1.2	Prolutions	216
		13.1.3	Fix of anomalies	216
	13	.2 P	Processing Baseline 2.24	217
		13.2.1	Ground processors versions (Instrument Processor Facility)	217
		13.2.2	2 Evolutions	217
		13.2.3	Fix of anomalies	217
	13	.3 P	Processing Baseline 2.27	220
		13.3.1	Ground processors versions (Instrument Processor Facility)	220
		13.3.2	P Evolutions	220



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: vii

13.3.3 Fix of anomalies22	0
13.3.4 Anomalies not solved	1
13.4 Processing Baseline 2.33	5
13.4.1 Ground processors versions (Instrument Processor Facility)	5
13.4.2 Evolutions	5
13.4.3 Fix of anomalies	5
13.4.4 Anomalies not solved	
13.5 Processing Baseline 2.45	
13.5.1 Ground processors versions (Instrument Processor Facility)	
13.5.2 Evolutions	
13.5.3 Fix of anomalies	
13.5.4 Anomalies not solved	
14 ANNEX REFERENCES	3
List of Figures	
List of Figures	
Figure 1 Geographical mask for L2 Land and Marine products coverage: blue is Marine products only	y,
white is Land products only, brown is for regions available in both products1	.3
Figure 2: S3A (left) and S3B (right) Ku band CAL1 SAR Time Delay series1	8
Figure 3: S3A (left) and S3B (right) Ku band CAL1 SAR Integrated and Peak Power series1	9
Figure 4: S3A (left) and S3B (right) Ku band CAL1 SAR PTR width series1	9
Figure 5: S3A (left) and S3B (right) Ku band CAL2 SAR waveforms ripples1	9
Figure 6: Geolocation of S3A MWR measurements in DNB processing2	1
Figure 7: Number of S3A MWR measurements in DNB mode along the year2	1
Figure 8: Geolocation of S3B MWR measurements in DNB mode2	2
Figure 9: Number of S3B MWR measurements in DNB mode along the year2	2
Figure 10: Data gaps in Level 2 products due to MWR calibration before (cycle 26 presented) and after (cycle 28 presented) the calibration timeline update of the 1 st March2	
Figure 11: 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)	
Figure 12: 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)	
Figure 13: 36.5GHz Gain for the 24 th November; Noise injection pulse length around the KREMMS rada facility overflight2	



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: viii



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: ix

Figure 26: Monitoring of the daily averaged percentages of outliers detected by Sentinel-3A and Sentinel-3B sea ice flag (blue and red curves) and AltiKa ice flag (green curve) over Ocean40
Figure 27: 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 2018 and Sentinel-3B (right panel) for June to December 2018
Figure 28: Percentage of outlier detected by the dynamical atmospheric thresholds (left panel) et by the MWR WTC thresholds (right panel). Sentinel-3A is represented in blue, Sentinel-3B in red, Altika in green and Jason-3 in black
Figure 29: 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 2018. Gridded maps of Sentinel-3B SARM (bottom left panel) and P-LRM (bottom right panel) SWH from June to December 201845
Figure 30: 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 (blue curve) SWH46
Figure 31: 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 2018 (top left panel) and for Sentinel-3B from June to December 2018 (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 2018 (bottom left panel) and Sentinel-3B SARM and P-LRM from June to December 2018 (bottom right panel)
Figure 32: 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 2018. Gridded maps of Sentinel-3B SARM (bottom left panel) and P-LRM (bottom right panel) backscatter coefficient from June to December 2018.
Figure 33: 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 (blue curve) backscatter coefficient49
Figure 34: Gridded maps of the collocated backscatter differences between Sentinel-3A SARM and P-LRM from April to December 2018 (top left panel) and between Sentinel-3B SARM and P-LRM from June to December 2018 (top right panel). Gridded map of the absolute value of Sentinel-3A orbital altitude rate computed over cycle 25 (bottom panel).
Figure 35: 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 2018. Gridded maps of Sentinel-3B SARM (bottom left panel) and P-LRM (bottom right panel dual frequency ionospheric correction computed from June to December 201851
Figure 36: Top panels shows the gridded maps of the collocated differences between Sentinel-3A SARM dual frequency ionosphere correction and GIM model for ascending (left panel) and descending (right panel) passes. Bottom panels show the gridded maps of the collocated differences between Jason-3 dual frequency ionosphere correction and GIM model for ascending (left panel) and descending (right panel) passes. The ionosphere corrections derived from altimeter were filtered at 300km53



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: x

Figure 37: Along-track maps of the local hours for ascending (left panels) and descending (right panels) passes, computed over cycle 25 for Sentinel-3A (top panels) and from the 24 th November to the 21 st December 2018 for Sentinel-3B (bottom panels)54
Figure 38: 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 separately55
Figure 39: 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 separately56
Figure 40: Daily monitoring of C-band Sea Level Anomaly without geophysical corrections for Sentinel-3A (blue curve) and Sentinel-3B (red curve) from July to December 201856
Figure 41: Top 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 2018. Middle panels show the same gridded maps for Sentinel-3B from June to December 2018. Bottom panels show the off-nadir angle derived from waveforms for Jason-3 (left panel) and SARAL/AltiKa (right panel) over Sentinel-3A whole mission lifetime58
Figure 42: Daily monitoring of the Sentinel-3A P-LRM (cyan curve), Sentinel-3B P-LRM (orange curve), Jason-3 (black curve) and SARAI/AltiKa (green curve) off-nadir angle derived from waveforms.
Figure 43: 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 th July to the 16 th October 2018. Each map covers 20 days.
Figure 44: Monitoring of MWR (3P) - ECMWF wet tropospheric correction for S3A,S3B, SARAL/AltiKa, Jason3/AMR: mean (left), standard deviation (right)62
Figure 45: Difference of SAR/P-LRM wet tropospheric correction for Sentinel-3A (cycle 26 to 39)63
Figure 46: Difference of SAR/P-LRM wet tropospheric correction for Sentinel-3B (cycle 20)63
Figure 47: Monitoring of 3P and 5P MWR - ECMWF wet tropospheric correction for Sentinel-3A64
Figure 48: Monitoring of 3P and 5P MWR - ECMWF wet tropospheric correction for Sentinel-3A64
Figure 49: Map of the difference 5P - 3P wet tropospheric correction: left: Sentinel-3A (using NTC data; cycle 26 to 39) right: Sentinel-3B (using NTC data; cycle 20)65
Figure 50: Difference of variance of ΔSSH at crossover points for low oceanic variability for Sentinel-3A, SARAL, Jason3: var(ΔSSH with WTC 3P MWR)-var(VSSH with WTC ECMWF) (bottom)66
Figure 51: Difference of variance of SSH at crossover points SAR (left) / P-LRM (right)66



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: xi

Figure 52: Difference of variance of SSH at crossover points for Sentinel-3A, SARAL/AltiKa, Jason3/AMR var(SSH with WTC 5P MWR)-var(SSH with WTC ECMWF)67
Figure 53: Difference of variance of SSH at crossover points SAR (left) / P-LRM (right)67
Figure 54: 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 2018. Gridded maps of Sentinel-3E SARM (bottom left panel) and P-LRM (bottom right panel) SLA computed from June to December 2018.6
Figure 55: Daily monitoring of the Sentinel-3A SARM (blue) and P-LRM (cyan curve), Sentinel-3B SARM (red curve) and P-LRM (orange curve), and Jason-3 (black curve) mean SLA (left panel) and its standard deviation (right panel)
Figure 56: Daily monitoring of the Sentinel-3A SARM (blue) and P-LRM (cyan curve), Sentinel-3B SARM (red curve) and P-LRM (orange curve) mean SLA, over Sentinel-3B mission time period. A constant bias of 1.65cm has been added to Sentinel-3B SARM and of 0.8cm to Sentinel-3B P-LRM. Grey areas represent periods when Sentinel-3B operates in Close Loop.
Figure 57: 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 (green curve).
Figure 58: Gridded maps of SSH differences computed at mono-mission crossovers in SARM (left panels) and in P-LRM (right panels), for Sentinel-3A (top panels) from April 2016 to December 2018, and for Sentinel-3B (bottom panels) from July to December 2018.
Figure 59: 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 60: Gridded maps of SSH differences computed at Sentinel-3A and Jason-3 crossovers (toppoanels) and Sentinel-3B and Jason-3 crossovers (bottom panel), in SARM (left panels) and in P-LRM (right panels).
Figure 61: Cycle per cycle monitoring of the SSH differences computed at Sentinel-3A and Jason-3 crossovers in SARM (blue filled curve) and in P-LRM (cyan curve), and at Sentinel-3B and Jason-3 crossovers in SARM (red filled curve) and in P-LRM (orange curve). The dashed blue and red curves show the evolution of the bias when Jason-3 SSH is computed using an updated SSB (SSB Tran et al. 2012 instead of GDR-D SSB).
Figure 62: 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). Cycle per cycle monitoring of SSH differences (bottom left panel) computed at Sentinel-3B/Sentinel-3A crossovers in SARM (magenta curve) and in Pack (black curve), and its standard deviation (bottom right panel)



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: xii



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: xiii

Figure 73: 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 analysis92
Figure 74: 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) measurements92
Figure 75: Same as Figure 73 but for Sentinel-3B93
Figure 76: 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-3A and Sentinel-3B curves are same as the global curves in Figure 73 and Figure 75, respectively94
Figure 77: 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 period from 13 December 2016 to 12 December 2017. Bias is defined as altimeter - model95
Figure 78: As in Figure 77 but for Sentinel-3B. Note that Sentinel-3B data temporal coverage is from 28 June 2018 till 31 December 2018 which is much less than 1 year yet97
Figure 79: 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 2018 (note that Sentinel-3B data have not covered 1 year yet). Refer to Figure 71 for the meaning of the crosses and the circles as well as the colour coding
Figure 80: 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 analysis101
Figure 81: Same as Figure 80 but for Sentinel-3B101
Figure 82: Sentinel-3A and Sentinel-3B SRAL SWH PDF's over the whole global ocean for the year 2018 (note that Sentinel-3B data have not covered 1 year yet). The corresponding ECMWF wave model (collocated with Sentinel-3A and Sentinel-3B) PDF's are shown for comparison. The 2017 PDF of Sentinel-3A and its model counterpart are also shown. ————————————————————————————————————
Figure 83: Panel (a): Global SWH PDF's from 6 altimeters, including Sentinel-3A and Sentinel-3B SRAL's, for the year 2018 (note that Sentinel-3B data have not covered 1 year yet). The corresponding ECMWF (collocated with each altimeter) PDF's are shown in panel (b) for comparison.————————————————————————————————————
Figure 84: 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
Figure 85: 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 2018 (note that Sentinel-3B data have not covered 1 year yet). 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 71 for the meaning of crosses and the circles



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: xiv

Figure 87: 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 88: Same as Figure 87 but for Sentinel-3B109
Figure 89: Time series of monthly global significant wave height bias defined as altimeter - buoy (top) and standard deviation of the difference (bottom) between SRAL and in-situ measurements110
Figure 90: 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 SRAL (same as the global curves in Figure 87) and the ECMWF model first-guess
Figure 91: 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 2018. Bias is defined as altimeter - model.112
Figure 92: As in Figure 91 but for Sentinel-3B. Note that Sentinel-3B data temporal coverage is from 28 June 2018 till 31 December 2018 which is only half a year114
Figure 93: Difference between SARM Ku band and P-LRM Ku band range wrt P-LRM SWH for Sentinel-3A Samosa 2.3 (dashed blue curve), Sentinel-3A Samosa 2.5 (solid blue curve) and Sentinel-3B Samosa 2.5 (red curve). The curve obtained for the CNES S3 prototype (green curve) is also represented to provide an external reference
Figure 94 Difference between SARM Ku band and PLRM Ku band SWH wrt SWH for Sentinel-3A Samosa 2.3 (dashed blue curve), Sentinel-3A Samosa 2.5 (solid blue curve) and Sentinel-3B Samosa 2.5 (red curve). The curve obtained for the CNES S3 prototype (green curve) is also represented to provide an external reference
Figure 95 Difference between SARM Ku band and P-LRM Ku band backscatter coefficient for Sentinel-3A Samosa 2.3 (left map) and Sentinel-3A Samosa 2.5 (right map).
Figure 96: Top panels show the gridded map of Sentinel-3A collocated backscatter coefficient differences between SARM and P-LRM for ascending (left panel) and descending (right panel) passes. These maps were computed using L2 measurements derived from SAMOSA DPM2.3. Bottom panels shows the corresponding variation of the epoch for ascending (left panel) and descending (right panel) passes
Figure 97: Gridded map of the difference between SARM and P-LRM Sigma0 for Sentinel-3A, over ascending tracks (top left panel) and descending tracks (top right panel). Difference between ascending and descending tracks computed from the above gridded maps of SARM-PLRM SWH difference (bottom panel). These maps were computed using L2 measurements derived from SAMOSA DPM2.5 (currently used version)
Figure 98: Gridded map of the difference between SARM and P-LRM Significant Wave Height for Sentinel-3A (top panels) and Sentinel-3B (bottom panels), over ascending tracks (left panels) and descending tracks (right panels). These maps were computed using L2 measurements derived from SAMOSA DPM2.5 (currently used version). ————————————————————————————————————



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: xv

PLRM SWH difference, for Sentinel-3A (left panel) and Sentinel-3B (right panel). These maps were computed using L2 measurements derived from SAMOSA DPM2.5 (currently used version)122
Figure 102: Polar plot of the SARM (left panel) and P-LRM (right panel) range noises as a function of the mean swell period and as a function of the azimuth angle between swell and track directions. The wave height was fixed between 2 and 3 m
Figure 103: Polar plot of the SWH differences as a function of the mean swell period and the azimuth angle between swell and track direction125
Figure 104: Daily monitoring of the difference between SARM and P-LRM for Sentinel-3A Significant Wave Height (blue curve). Green and red curve show the difference between Sentinel-3A SARM and Jason-3 SWH and the difference between Sentinel-3A P-LRM and Jason-3 SWH, respectively. The slopes indicated in the legend are computed from the 24 th June 2016
Figure 105: Daily monitoring of the difference between SARM and P-LRM for Sentinel-3A Significant Wave Height (blue curve). Green and red curve show the difference between Jason-3 and Sentinel-3A SARM SWH and the difference between Jason-3 and Sentinel-3A P-LRM SWH, respectively. These monitoring is performed for P-LRM SWH between 1.5 and 2.0m. The slopes indicated in the legend are computed from the 24 th June 2016.
Figure 106: Monitoring of SWH difference between Sentinel-3A SARM and PLRM (top panel), between Jason-3 and Sentinel-3A SARM (middle panel), and between Jason-3 and Sentinel-3A P-LRM. The slopes indicated in the legends are computed from the 24 th June 2016.
Figure 107: Daily monitoring of the difference between Sentinel-3A SARM and P-LRM range, over the complete range of SWH (blue curve) and for P-LRM SWH between 2.0 and 2.5 m (red curve). The slopes indicated in the legend are computed from the 24 th June 2016.
Figure 108: Daily monitoring of the difference between Sentinel-3A SARM and P-LRM range, over various intervals of P-LRMSWH. The slopes indicated in the legend are computed from the 24 th June 2016.
Figure 109: Daily monitoring of the difference between Sentinel-3A SARM and P-LRM range (top panel) and the evolution of its drift estimation (bottom panel).
Figure 110:Top panel: Monitoring of the Sea Level Anomaly difference between Sentinel-3A SARM and Jason-3 (green curve) and between Sentinel-3A P-LRM and Jason-3 (red curve). Bottom panel shows their respective drift evolutions
Figure 111: Daily monitoring of the difference between SARM and P-LRM for Sentinel-3A backscatter coefficient (blue curve). Green and red curve show the difference between Sentinel-3A SARM and Jason-3 sigma0 and the difference between Sentinel-3A P-LRM and Jason-3 sigma0, respectively. The slopes indicated in the legend are computed from the 24 th June 2016.
Figure 112: Monitoring of the backscatter coefficient difference between Sentinel-3A SARM and PLRM (top panel), between Jason-3 and Sentinel-3A SARM (middle panel), and between Jason-3 and Sentinel-3A P-LRM. The slopes indicated in the legends are computed from the 24 th June 2016.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: xvi

Figure 114: Percentage of 20Hz missing measurement computed for Sentinel-3A (red curve), SARAL/AltiKa (blue curve) and Jason-3 (green curve) datasets as a function of the distance to the coast. This percentage is computed with respect to their respective high resolution theoretical ground track.136

Figure 118: Area of correlation of the Hub buoy (red circle) based on the four constraints defined in the figure title. S-3 observations collected within the area are expected to be similar to the ones observed at the buoy and thus can be used for the validation. -------140

Figure 119: (Left) Correlation slope for different combinations of buoys and Sentinel-3 tracks as function of distance between the satellite observations and buoy position for SAR observations. (Right) Same as left but for PLRM observations. The figure shows overall agreement (slope 1) between buoy and satellite observations as they get closer to the buoy in SAR mode. A similar trend is not observed in PLRM mode, where the agreement between buoy and satellite observation drastically degrade within 20 km from the coast. The Hub buoy showed in Figures 2 and 3 is not included in the analysis because characteristic of



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: xvii

201801 S3 minus CS2 freeboard

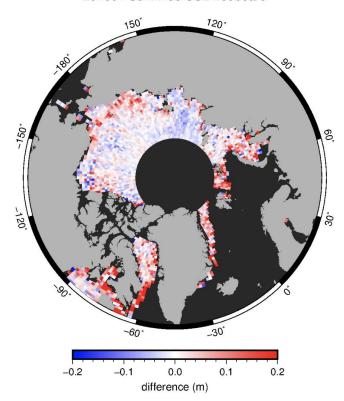


Figure 125: S3-A minus CS2 Freeboard 146

(CPOM Processing)	-146
Figure 126: Comparison of S3A and CS2 Gridded Freeboard (Hamming and Zero Padding applied at L	1)147
Figure 127: Comparison between S3-B and S3-A freeboard during Tandem phase	-147
Figure 128: Number of valid and invalid freeboard measurements over S3A mission life	-148
Figure 129: Number of valid and invalid freeboard measurements over S3B mission life	-149
Figure 130: Typical Arctic map of sea surface height (PB2.33)	- 151



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: xviii

Figure 131: Statistics of Sea Ice Retracker failure in the Arctic over 53A Mission (PB2.33)152
Figure 132: S3A Surface Type Discrimination since start of mission (PB2.33)153
Figure 133: L2 Sea Ice Concentration has zero values around the coastline (PB 2.4x), EUMETSAT plot. 154
Figure 134: S3A SAR Tracking Mode over Ice Sheet Margins (cycles 3-11)157
Figure 135: S3-A Elevation failure rates in Open Loop and Closed Loop cycles over Different Ice Surfaces158
Figure 136: S3A Shot-to-shot Precision over Lake Vostok (6-month period)160
Figure 137: S3A Repeat Measurement Precision over Lake Vostok161
Figure 138: Comparison of measurement precision between S3A (SAR) and ENVISAT (LRM)162
Figure 139: Crossover OCOG Elevation Differences at Lake Vostok Centre (cycle 39, PB2.33)163
Figure 140: Crossover S3A Mission Statistics at Lake Vostok Centre (OCOG Elevation differences) 164
Figure 141: Crossover OCOG Elevation Differences over Antarctic Ice Sheet (S3A cycle 39, S3B cycle 20, PB2.33)165
Figure 142: S3A Mission Statistics of Crossover differences (Antarctic Ice Sheet), OCOG elevation (PB2.33)166
Figure 143: Median absolute cross-over elevation difference (blue dots) and number of cross-overs (blue bars) as a function of surface slope, S3A cycle 12167
Figure 144: Assessment of the accuracy of Sentinel-3A elevation measurements at the Lake Vostok (a,b), Dome C (c,d). The distribution of Sentinel-3 minus IceBridge elevation differences (cyan histograms and axes), and the cumulative distribution of the absolute Sentinel-3 minus IceBridge elevation differences (magenta curves and axes) at each site. ————————————————————————————————————
Figure 145: Sentinel-3A validation statistics for low slope areas based upon comparison to IceBridge airborne altimetry for 3 different retrackers. Elevation differences are calculated as Sentinel- 3A elevation minus IceBridge elevation
Figure 146: Assessment of the accuracy of Sentinel-3A elevation measurements at Dronning Maud Land (e,f) and Wilkes Land (g,h) sites in East Antarctica. The distribution of Sentinel-3 minus IceBridge elevation differences (cyan histograms and axes), and the cumulative distribution of the absolute Sentinel-3 minus IceBridge elevation differences (magenta curves and axes) at each site
Figure 147: Sentinel-3A validation statistics for High Slope Areas based upon comparison to IceBridge airborne altimetry for 3 different retrackers. Elevation differences are calculated as Sentinel- 3A elevation minus IceBridge elevation
Figure 148: Rate of Elevation Change derived from S3A OCOG Elevation (cycles 12-31), (McMillan et al, 2019)172
Figure 149: Antarctica OCOG Elevation Gridded Failure Maps (S3A, S3B, PB2.33)173
Figure 150: Failure rate of elevation_ocog_20_ku (S3A, PB2.33)174
Figure 151: Failure rate of elevation_ocog_20_ku (S3B, PB2.33)175



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: xix

Figure 152: Antarctica ice Sneet Elevation Gridded Fallure Maps (53A, 53B, PB2.33)176
Figure 153: Failure rate of elevation_ocog_20_ku (S3A, PB2.33)177
Figure 154: Failure rate of elevation_ocog_20_ku (S3B, PB2.33)178
Figure 155: Percentage failure of range_ice_20_plrm_ku (S3A, PB2.33)179
Figure 156: S3A SAR ku Slope Correction Magnitude (PB2.33)182
Figure 157: 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 estimated on cycle 21 of Sentinel-3B
Figure 158: Monitoring of the percentage of default values and edited measurements over lakes (here on the sigma0 criteria) for Sentinel-3A (top panels) and Sentinel-3B (bottom panels) computed for both kind of retracking (SAMOSA DPM2.5 and ocog)
Figure 159: Standard deviation of the Sentinel-3A WSH computed over cycle 35 as a function of the lake area (left), of the transect length over lakes sampled (middle), and of the acquisition mode (right) 189
Figure 160: WSH dispersion measured over several Virtual Stations (rivers) crossed by Sentinel-3A and Jason-3 satellites
Figure 161: Monitoring of the Jason-3 and Sentinel-3A WSH over the larke Huron (top panel). Monitoring of the Sentinel-3A WSH derived from ocean retracker and ocog retracker over lake Inarinjarvi
Figure 162 Range Bias Results and Datation Bias Results197
Figure 163 Alignment Results and Stack Noise Results198
Figure 164: 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
Figure 165: 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 202
Figure 166: Sentinel-3A and Sentinel-3B absolute range bias estimates computed by P. Bonnefond (Paris Observatory/SYRTE) and O. Laurain (OCA/Géoazur) in Corsica along the track 741 203
Figure 167: 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 computed204
Figure 168 Range difference: OCOG-Ocean over Arctic in L2 Land products STC Cycle 26208
Figure 169 Backscatter coefficient difference: OCOG-Ocean over Arctic in L2 Land products STC Cycle 26209
Figure 170 Range difference: Ocean-lce margin over Arctic in L2 Land products STC Cycle 26211



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: xx

Figure 171 Range difference: OCOG-Ice margin over Antarctica in L2 Land products STC Cycle 26	212
Figure 172 Backscatter coefficient difference: Ocean-Ice margin over Arctic in L2 Land products	STC
Cycle 26	213
Figure 173 Backscatter coefficient difference: OCOG-Ice margin over Antarctica in L2 Land products	STC
Cycle 26	214

List of Tables

Table 1 History of SRAL and MWR mode changes for Sentinel-3A
Table 2 History of SRAL and MWR mode changes for Sentinel-3B
Table 3: Main Sentinel-3A SRAL and Platform events since the SRAL switch on. The shaded line correspond to a data gap impact on Level-2 products1
table 4: Main Sentinel-3B SRAL and Platform events since the SRAL switch on. The shaded line correspond to a data gap impact on Level-2 products1
Table 5 Model and standard history in L2 products1
Table 6: Characteristics of missions with microwave radiometer2
Table 7: Outliers detection thresholds and corresponding percentages computed over the years 201 and 2018 for Sentinel-3A and from the 11 th July 2018 (in order to consider only SAR mode period) till th end of the year for Sentinel-3B. For Sentinel-3B and Sentinel-3A (year 2018), the percentages have also been calculating removing the days with particular events, i.e. when the percentage of missing DAC of WTC is abnormal (>0.0% for the DAC and >1% for the WTC).
Table 8: Detail of the standard used to compute Sentinel-3A 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



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: xxi

Table 9: Bias of S-3B σ^0 values for different definitions. (Values for bias of S-3A in SAR mode are same as for S-3B in SAR mode.)
Table 10: % Availability of Snow Density, Snow Depth, Sea Ice Concentration over Sea Ice155
Table 11: Results of TRP passes processing193
Table 12: Geophysical Corrections of TRP passes processing196
Table 13 : Sentinel-3A and Sentinel-3B products and parameters used to compute the absolute bias estimates200
Table 14: 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)201
Table 15: Statistics on the Sentinel-3A SAR and PLRM SSH absolute regional bias estimates in Senetosa. 205
Table 16: Statistics on the Sentinel-3A SAR and PLRM SSH absolute regional bias estimates in Ajaccio (PB 2.33 reprocessed dataset)206



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 1

1 Introduction

This document is the Year 2 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 since the start of the mission and of main activities carried out by the S3 Mission Performance Centre. It covers the Sentinel-3A second year of the routine operations phase (started on the 1st of February, 2017) and the Sentinel-3B first months.

It addresses more specifically activities related to the Surface Topography Mission (an equivalent report – S3MPC.ACR.APR.001 – 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).



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 2

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.

2.2 SRAL and MWR sensors

For both satellites, all the SRAL instrumental parameters are indicating a good instrument performance. The instrumental drifts are taken into account in the ground processing and thus are not affecting science data. 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. The CAL1 SAR Ku BAND total power is the only calibration having a decay outside of the expected range at the beginning of the mission, but it does not degrade measurement quality and the drift is becoming more stable. For Sentinel-3B, several small jumps are observed, such a behavior is

GLS

Sentinel-3 MPC

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 3

usually observed during missions beginning of life. A longer time series is needed to observe potential trends or drifts.

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. A jump was observed on the 24th November data in S3A calibration monitoring. Investigations lead to the hypothesis that S3A MWR has probably seen a tracking radar of the KREMMS facility. Beginning of year 2019 a large MWR safing area of 300 km was set around the KREMMS radar facility.

2.3 Sea Level

Since almost 2 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 16th of October 2018 improve 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 3.1 % for Sentinel-3A over the year 2018 and 3.5% for Sentinel-3B. The slight difference could be explained by the several Sentinel-3B modes shift whereas the thresholds were kept fixed. 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 no significant long-term drifts, even if the analysed period is not long enough to have yet good confidence in the capability to detect very small drift
- Sentinel-3 and Jason-3 observe very similar SLA features when considering temporal evolution of global averages but also geographical patterns. Data quality is excellent in both SARM and P-LRM modes.
- 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.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 4

At crossovers Sentinel-3A and Sentinel-3B show a performance similar to Jason-3 mission with a system error of 3.5 cm.

- Orbit quality is excellent for all product latencies (NRT, STC and NTC), even if crossovers analysis with NTC products suggests that the consistency between ascending and descending tracks can be further improved at basin scale.
- 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 -1.5cm² for the diagnosis at crossover points with respect to the model correction.

2.4 Winds and Waves

Since two years, Sentinel-3A SRAL altimeter has been providing excellent wind speed and SWH observations over ocean. Its twin onboard on Sentinel-3B already showed very promising results thanks to the direct comparisons performed during the tandem phase. The analyses performed clearly highlight an over-estimation of 0.5 dB of the Sentinel-3B backscatter. As expected, this has an impact on the Wind Speed calculation. A correction was applied in the Sentinel-3B PB 1.13 deployed on the 6th of December 2018. Then Sentinel-3B Wind Speed quality is excellent (and similar as with Sentinel-3A). 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:

- Global statistics against the model are excellent. The agreement between Sentinel-3A winds and their model counterpart is very good with virtually no bias (except for slight bias at high wind speed values). The standard deviation of the difference (SDD) with respect to the model, which can be used as a proxy to the random error, is about 1.1 m/s. The correlation coefficient is higher than 0.95. These values are similar to those of the other altimeters.
- Global statistics against the buoys are excellent. The bias against in-situ observation for this period is rather small (about 0.1 m/s). The SDD is about 1.4 m/s which is about 17% of the mean. The correlation coefficient is higher than 0.92. These figures are comparable to same statistics emerging from the comparison of wind speeds from other altimeters against in-situ observations.
- 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.
- The PLRM wind speed is now globally unbiased. The SDD with respect to the model improved considerably since Cycle 012. However, it is slightly higher than that of SAR winds (and other altimeters). There is a tendency of PLRM wind speed to degrade slightly in the Northern Hemisphere during the summer months (June to August). This can be only confirmed during the coming years.

Sentinel-3 MPC

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 5

For Sentinel-3B the results are similar as for Sentinel-3A since the 6th 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:

- ❖ The agreement between Sentinel-3A and Sentinel-3B SARM SWH and their model counterpart are very good except for a slight underestimation at SWH values below ∼ 1.5 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, Sentinel-3A and Sentinel-3B overestimate SWH by about 0.14 m. The SDD between the pair is about 0.27 m (or 11% of the mean value) and slightly higher than for other conventional altimeter (with respect to their model counterpart). The correlation coefficient is 0.983 which is quite high. These figures indicate that Sentinel-3A SARM SWH products are what is expected from radar altimeter SWH.
- 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 ~13% 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

2.5 Land and Sea Ice

Sentinel-3A and B 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.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 6

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 2018, significant progress has been made with the development and validation of a specialized L1 IPF processing prototypes for land ice, which will be delivered to ESA in Q1 2019, and used to produce an optimally reprocessed L2 land ice data set from the S3A and S3B operational archives. This will be made available to users alongside the standard operational product. The specification for a specialized L1 sea ice processor (which includes Hamming weighting and zero padding) was developed during 2018 and we expect progress to be made with implementation of this specification and a test data set during 2019.

Whilst separate specialized L1 processing is required for optimal performance over the more complex ice surfaces, work has continued during 2018 to improve the performance of the current L2 operational products over land and sea 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) and sea-ice areas, when tuned to operate with the current ocean optimized L1 input data.

Analysis of land ice performance (stability, precision and accuracy) from the operational product was performed during 2018, which showed that S3A & B in SAR mode have very good performance over the majority of the ice sheets (with slope < 0.1°) as compared with previous pulse-limited missions and good accuracy compared with Operation Ice Bridge validation data. Stability and precision of measurements over a Lake Vostok test site showed ~7cm precision for S3 as compared to ~15cm for ENVISAT over the full mission. Statistics of accuracy comparisons against Operation Icebridge showed that S3 SAR waveforms are not overly sensitive to radar penetration or induced sub-surface scattering from snowpack, and the low dispersion of differences (~10cm) suggest accuracy is not significantly affected by sources of error such as retracker imprecision, radar speckle, slope correction and sub-annual snow pack differences. Overall performance will improve further over the ice sheet margins in 2019 with the implementation of the specialized L1 processor.

For land ice a new updated slope mode ADF was developed for Antarctica and Greenland, derived from a Cryosat-2 DEM and delivered in July 2018. After final validation, this will be used in the next IPF release during 2019. A new L2 parameter for flagging waveform quality over land ice was implemented in PB2.24 and validated during 2018, and in PB2.27 an update to correct an error in the SAR mode slope model algorithm was developed and implemented and a new OCOG elevation parameter requested by users was added. The empirical OCOG (Ice-1) retracker provides a greater measurement density than the standard physical model retracker, but in some areas a lower accuracy. Nevertheless, elevation from

GLS

Sentinel-3 MPC

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 7

the OCOG retracker is available from all previous radar altimetry missions providing a continuity of measurement technique that makes long term multi-mission studies of ice sheet surface elevation change and mass balance possible.

For sea ice a major L2 algorithm upgrade was successfully specified, implemented and validated during 2018 in order to correct an issue with a predominantly negative freeboard (present in all operational cycles processed to date) and to align the sea ice processor specifications with Cryosat Baseline-D. The update, delivered in December 2018, included a new diffuse echo retracker, optimised waveform filtering and outlier removal, and a retracker bias calibration. Final sea ice data quality will only be realized with a specialized L1 processor, which includes Hamming weighting and zero padding.

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 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 percentage of missing measurements is consistent with expectations and drastically reduced thanks to the activation of OL mode acquisition. Sentinel-3B OL mode is activated everywhere between -60° and 60°N and over land surfaces at higher latitudes. The Sentinel-3A OL mode covers a lower area but will be updated and similar to Sentinel-3B scheme. The Sentinel-3B onboard OLTC was updated on the 25th of November 2018. This improved table covers with high precision a larger number of lakes and rivers. It is planned in the coming month to also update the Sentinel-3A onboard OLTC.
- ❖ 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.

CLS COLLECTE LOCALISATION SATELITES

Sentinel-3 MPC

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 8

3 SRAL and MWR Mission events

The Table below gathers the changes related to sensors mode.

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

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 update version V5.0

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

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

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

Sentinel-3 MPC

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 9

Event type	start time	stop time	description
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
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

Sentinel-3 MPC

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 10

Event type	start time	stop time	description
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
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

Sentinel-3 MPC

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 11

Event type	start time	stop time	description
			SRAL Standby Mode
SRAL	2016-03-24 00:52:00	2016-03-24 00:52:36	followed by SAR Open
			Loop
			SRAL Standby Mode
SRAL	2016-03-23 16:30:09	2016-03-23 16:30:45	followed by SAR Open
			Loop
			SRAL Standby Mode
SRAL	2016-03-23 13:38:40	2016-03-23 13:39:16	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
	2010-03-18 11.30.00	2010-03-18 12.03.00	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 shaded lines correspond to a data gap impact on Level-2 products.

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
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



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 12

Event type	start time	stop time	description
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. The shaded lines correspond to a data gap impact on Level-2 products.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 13

4 Processing Baseline Status

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, the Caspian Sea, Great Lakes and Victoria Lake are available in both Marine and Land products.

Marine/Land mask () O,DE+00 Data Min = 0.0E+00, Max = 2.0E+00, Mean = 5.8E 01

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



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 14

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	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 (current)	2.45	1.17

The NTC products have been reprocessed twice:

Reprocessing 1 with Processing Baseline 2.12

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

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.

A third reprocessing is plan during this year 2019.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 15

4.2.1 Summary of Processing Baseline Content

Processing Baseline 2.12 was the processor version used for deriving most of the results presented in this document. 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 Annex. The main impact is for inland waters parameters quality that have been dramatically improved thanks to fixes on OCOG retracker.

Processing Baseline 2.24 represents major achievements and improvements for ocean and coastal areas, sea ice and land ice parameters quality. In addition to the resolution of the anomalies listed in Annex, Processing Baseline 2.24 brings major evolutions of product quality over ocean, coastal sea ice and land ice surfaces. These improvements are detailed in:

https://earth.esa.int/documents/247904/3147059/Sentinel-3-STM-Product-Evolution-Processing-Baseline-2.24

Processing Baseline 2.27 is the version used in operation and for the Reprocessing 2. In addition to some minor anomaly fixes, it brings important improvement to the land ice quality with the inclusion of ice elevation derived from the OCOG retracker and the fix of the SARM slope correction.

For Sentinel-3A, most of the analyses and results presented hereafter are derived from datasets produced with PB 2.27 (2018 reprocessed dataset) and PB 2.33. In addition to the resolution of some minor anomalies in LRM mode and for the dry tropospheric correction, the PB 2.33 evolution 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. Thus the L2 data quality is very similar all along the year 2018.

For Sentinel-3B (SRAL switch on the 8th of May 2018), the PB 1.02 adjusted some calibrations parameters (with a very small impact on the L2 parameters) and the PB1.13 was deployed to account for a bias of 0.5 dB on the backscatter coefficient. Thus, except for this parameter, the impact of PB update is very low on the L2 dataset all along the year 2018.

Recently on the 14th of February 2019, a common (to Sentinel-3A and Sentinel-3B) PB deployment was done. This new PB respectively named 2.45 for Sentinel-3A and 1.17 for Sentinel-3B bring several major improvements, mainly over 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

More details are available in the corresponding Product Notice (or in section 13.5).

C LS

Sentinel-3 MPC

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 16

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.

	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		
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)					
SARM Ocean retracker	SAMOSA 2.3 retracker		SAMOSA 2.5	SAMOSA 2.5 retracker		
Dry troposphere correction	ECMWF model					
Dynamical atmospheric correction	SALP/CNES Mog2D high resolution ocean model					
Radiometer wet troposphere correction	3 parameters correction		3 parameters and 5 parameters corrections			
Model wet troposphere correction	ECMWF model					
Ionospheric 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 2004 FES 2014				
Solid Earth tide correction	Cartwright and Taylor					
Pole tide correction	Wahr					
Mean Sea Surface Solution 1	CNES_CLS_2011 (Referenced to 7 years mean)		CNES-CLS 201 years mean)	.5 (Referenced to 20		
Mean Sea Surface Solution 2	DTU13 (Referenced to 7 years mean)		DTU15 (Refer	enced to 20 years		
SSHA for Ocean	CNES_CLS_2011		DTU15			
SSHA for Sea Ice	CNES_CLS_2011 DTU15		DTU15			
Mean Dynamic Topography	CNES-CLS13 MDT					



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 17

	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		
Geoid	EGM 2008					
Bathymetry	ACE2 model with 30 second resolution					
Surface Slope Model for Land Ice	Derived from RAMP v2 DEM over Antarctica and Bamber 2001 DEM over Greenland					
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 2.45 for Sentinel-3A and 1.17 for Sentinel-3B, deployed on 4 April 2018, 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

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



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 18

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 have a summary, from the beginning of the mission up to the end of 2018, of the main calibration variables that impact 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 2. S3A series shows a notable stabilization in 2018.

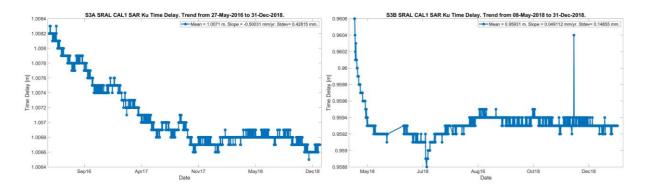


Figure 2: S3A (left) and S3B (right) Ku band CAL1 SAR Time Delay series.

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 Ku band CAL1 SAR mode total (blue line) and maximum (red line) power behaviour along the two missions are plotted in Figure 3. The S3A total power, the one used in the L1b processing, has a drift of close to -0.4 dB/year, a more stable behaviour than the one at the beginning of the mission that was close to -1 dB/year.

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 19

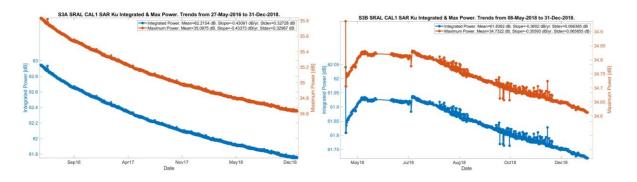


Figure 3: S3A (left) and S3B (right) Ku band CAL1 SAR Integrated and Peak Power series.

The CAL1 PTR width, which impacts the SWH estimations, has a nominal drift of about -0.4mm/year for the S3A mission, three orders of magnitude below its absolute value. The S3A and S3B missions series are depicted in Figure 4. The standard deviation of both missions is similar.

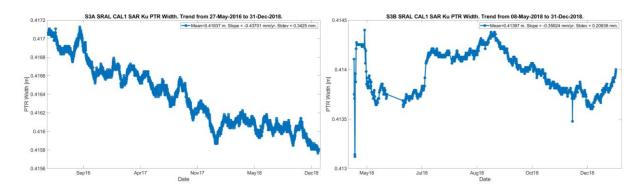


Figure 4: S3A (left) and S3B (right) Ku band CAL1 SAR PTR width series.

Finally, Figure 5 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.

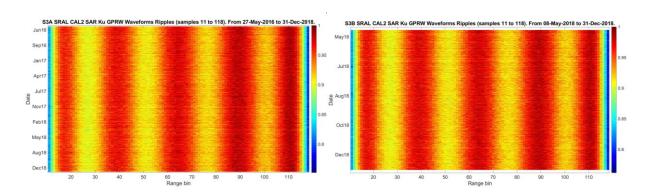


Figure 5: S3A (left) and S3B (right) Ku band CAL2 SAR waveforms ripples.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 20

Summarising, all the parameters of S3A and S3B missions 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. Anyhow, all the parameters are meeting the mission requirements. The CAL1 SAR Ku band total power was the only one having a decay out of the expected at the beginning of the S3A mission, but it is becoming more stable, as depicted in Figure 2 of this section (now the drift is half the one at BOM). The S3B instrument series shown in the figures include the beginning of mission usual excursion, which has been excluded for the S3A mission. In further annual reports, both will be excluded for the sake of a better understanding and prediction of the mission parameters behavior of the routine phase.

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 (Dicke Non-Balanced).

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 6 shows the location of S3A MWR measurements using DNB processing, and Figure 9 the number per day of such measurements along year 2018. Seasonality of the location is shown by Figure 6 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.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 21

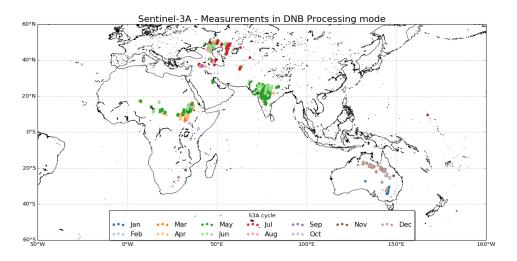


Figure 6: Geolocation of S3A MWR measurements in DNB processing

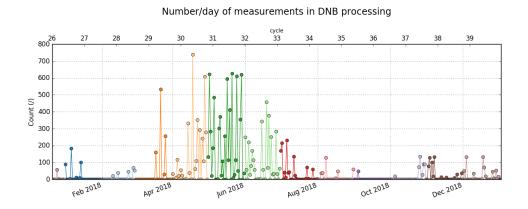


Figure 7: Number of S3A MWR measurements in DNB mode along the year

Figure 8 shows the location of S3B MWR measurements using DNB processing, and Figure 9 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 6th June. Globally, the same behaviour is observed for the two instruments.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 22

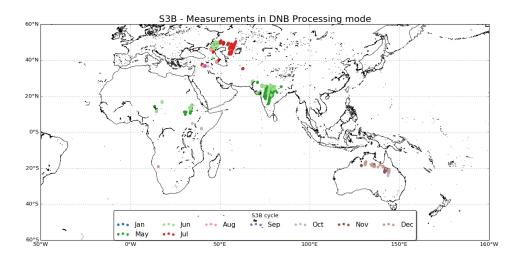


Figure 8: Geolocation of S3B MWR measurements in DNB mode

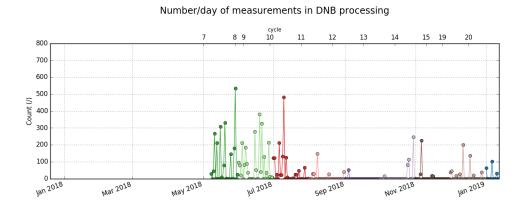


Figure 9: Number of S3B MWR measurements in DNB mode along the year

5.2.2 MWR Calibration timeline

Since the end of the verification phase by industry following MWR switch-on, the MWR was calibrated 3 times per orbit. Each calibration sequence was about 9s long with two modes of calibration: one for the noise injection temperature, one for the receiver gain. After coregistration of MWR pixels in Level2 processing, calibration sequences caused data gaps of brightness temperatures of about 17s. A new calibration timeline was proposed by MPC in order to reduce the length of the calibration sequences and guarantee a full coverage of brightness temperatures at Level2 processing. The new calibration has been implemented on board the 1st March 2018. After this update, calibration sequences are shorter (0.6s) and more frequent (every 30s). Figure 10 shows the impact on data gaps after this update and confirms that, with the new timeline, there is no more data gaps due to MWR calibration sequences.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 23

Data gaps due to MWR calibration in STC Marine Products

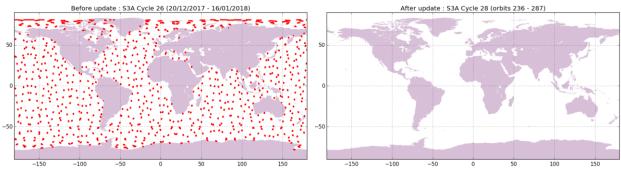


Figure 10: Data gaps in Level 2 products due to MWR calibration before (cycle 26 presented) and after (cycle 28 presented) the calibration timeline update of the 1st March

5.2.3 MWR Calibration parameters

Each calibration parameter is carefully monitored. Figure 11 shows the receiver gain and the noise injection temperature monitoring since march 2016 until end of year 2018, 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 will be addressed later in this section.

The noise injection temperature for 23.8 GHz channel is very slowly decreasing (less than 0.2K over 2017). 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.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

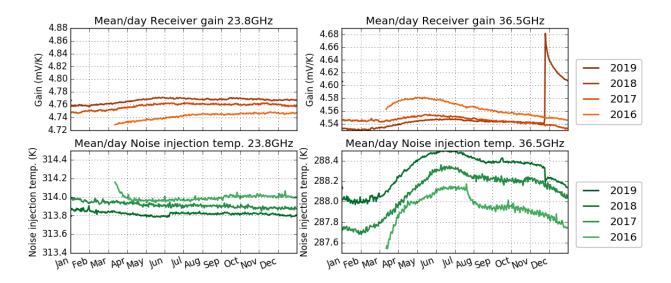


Figure 11: Monitoring of S3A MWR calibration parameters: Receiver gain (top line), Noise injection temperature (bottom line) for both channels: 23.8GHz (left) and 36.5GHz (right)

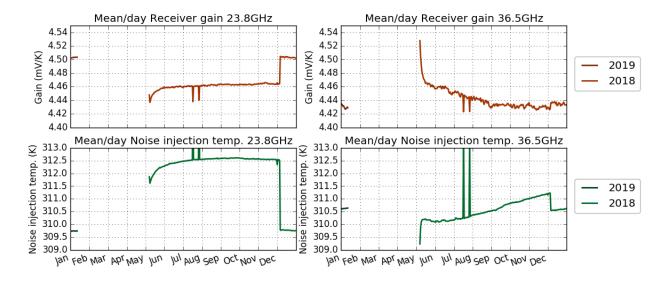


Figure 12: Monitoring of S3A MWR calibration parameters: Receiver gain (top line), Noise injection temperature (bottom line) for both channels: 23.8GHz (left) and 36.5GHz (right)

GLS

Sentinel-3 MPC

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 25

5.2.3.1 S3A - Analyses of 24th November event

The jump observed on 24th November data for S3A caused a change in the calibration parameters. It has been analysed to understand the root cause. As seen with Figure 13 (left panel), the change occurs after overflight of the KREMMS radar facility. Before the safing, a spurious signal is observed on the Noise injection pulse length of this channel (Figure 13; right panel) with DNB measurements just before the safing (pulse length equal to 0). This kind of measurements had never happened over ocean before. It occurred only over land. A closer analysis showed that the S3A MWR has most probably seen a tracking radar of the facility. It caused a stress to the MWR and changed its functional point. The brightness temperatures long term were not impacted by that change.

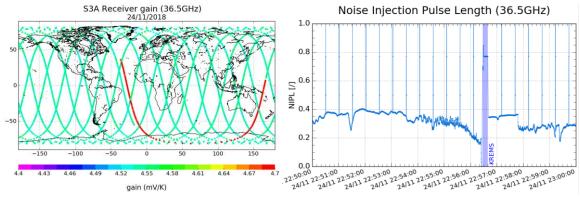


Figure 13: 36.5GHz Gain for the 24th November; Noise injection pulse length around the KREMMS radar facility overflight

The safing zone has been increased up to 300km in order to protect the MWR from other occurrences since 17th January until further investigations. It is shown by Figure 14. With this new area, 12 passes are now impacted by the safing (only 1 before). Further analyses will help the definition of a new safing zone.

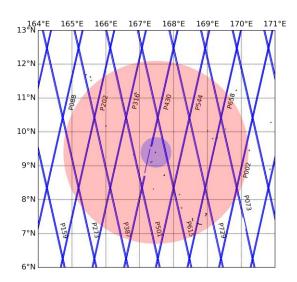


Figure 14: Passes impacted before (50km) and after (300km) the update of the safing area

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 26

5.2.4 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 6.

Table 6: Characteristics of missions with microwave radiometer

					Local time
Mission	Frequen	cies		Inclination	at A/D 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

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.

5.2.4.1 Coldest ocean temperatures

Figure 15 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 6, 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



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 27

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.

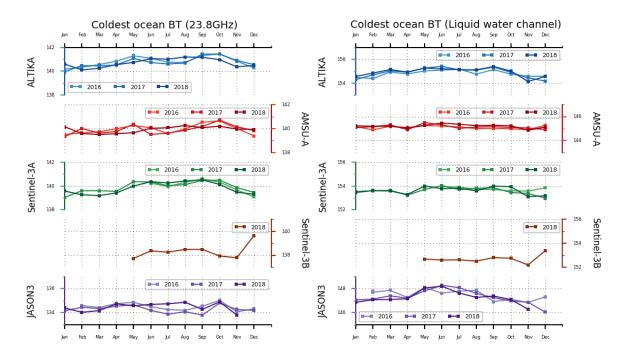


Figure 15: Coldest temperature over ocean for Sentinel-3A, Sentinel-3B, SARAL/AltiKa, Metop02/AMSU-A,

Jason3/AMR for two channels 23.8GHz (left) and 36.5GHz (right)

5.2.4.2 Amazon hottest temperatures

Figure 16 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.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

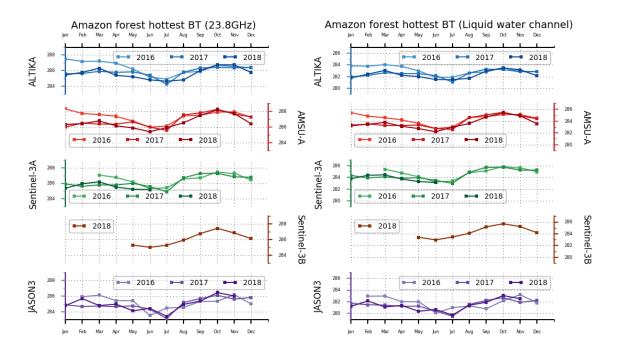


Figure 16: Hottest temperatures over the Amazon forest for Sentinel-3A, SARAL/AltiKa, Metop02/AMSU-A, Jason3/AMR for two channels 23.8GHz (left) and 36.5GHz (right)



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 29

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 17 shows the monitoring of the daily percentage of available measurements from end of December 2016 to beginning of the year 2019. This diagnosis was performed using the water Non-Time-Critical (NTC) Level-2 products. For Sentinel-3A and Sentinel-3B the percentages of available measurement are similar and reach 99.88% which is a good result. Most of the data gaps observed for Sentinel-3A are related to ground segment anomalies (Marine products not available), over this period, only one SRAL anomaly occurred on 1 September 2017. For Sentinel-3B the statistics is computed starting from 23th of November when the satellite reached its final orbit. As for Sentinel-3A the coverage over Ocean is very good and the few events observed (corresponding to lower percentage) are related to ground segment anomalies. Note that for Sentinel-3B, a recent data gap of 20 hours (not plotted hereafter) occurred on the 28th of January. It is related to a SRAL anomaly. The data quality before and after the anomaly has been check and considered as nominal.

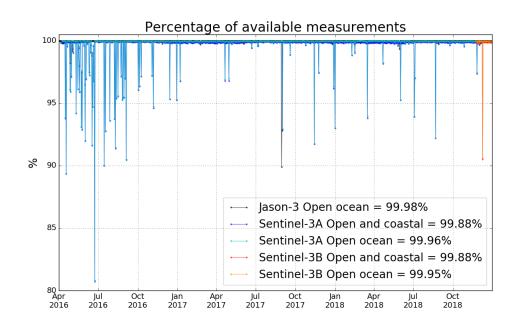


Figure 17: Monitoring of the daily percentage of available measurements for Sentinel-3A over Ocean and coastal area (blue curve), Sentinel-3A over open Ocean (cyan curve), for Sentinel-3B over Ocean and coastal area (red curve), Sentinel-3B over open Ocean (orange curve), and Jason-3 over open Ocean (black curve). This metric is computed with respect to the theoretical track and the theoretical number of measurements expected.

GLS

Sentinel-3 MPC

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 30

6.2 Over Land

While the detection of missing measurements is done at 1 Hz over ocean, the detection needs to be computed using High Rate frequency (20Hz) dataset over land. The location of the missing measurements gives a relevant information about the SRAL altimeter tracking performances. Indeed, if over open Ocean, the delay of the returned signal is easily predictable and quite constant, the surface type and topography variations over land surfaces make the measurement more complicated and challenging.

Over land, there are two different modes for SRAL acquisition: The Open-Loop (OL) and the Closed-Loop (CL) acquisitions. The SRAL acquisition mode is geographically pre-defined following the masks plotted in Figure 18. 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. Sentinel-3B altimeter acquisition mode was switched several times during the commissioning phase (see Table 2). The CL mode activation is global (no OL mode surfaces) whereas when it is operating in OL this is performed following the mask Figure 18 (bottom panel). As far as today, the two acquisition mode masks are different. With the update of the latest OLTC version on Sentinel-3A, it is also planned to use the Sentinel-3B acquisition mode mask. This operation would be performed in March 2019.

Figure 19 top panel shows the geographical distribution of missing measurements within the land level-2 products for Sentinel-3A (top panel) and for Sentinel-3B (bottom panel). When the altimeter operates in OL mode, the number of missing measurements is much lower (close to zero). Thus, for Sentinel-3B, operating in OL between -60° and 60° of latitude north, very few missing measurements are observed. Only few missing passes (ground processing anomaly) and calibration areas (South of Africa, Australia, Gobi desert, Sahara desert, Arabian Peninsula) are observed. Note that these calibration areas are similar for both satellites and for all the cycles. The three portions of track in the Sahara desert are due to the SRAL AutoCal calibrations. Finally, some isolated points are observed in the Ocean, close to the coasts, they are located at the border of the Sentinel-3A water and land products mask. They could be considered as a false alarm since the position of the theoretical first measurement cannot be known precisely.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

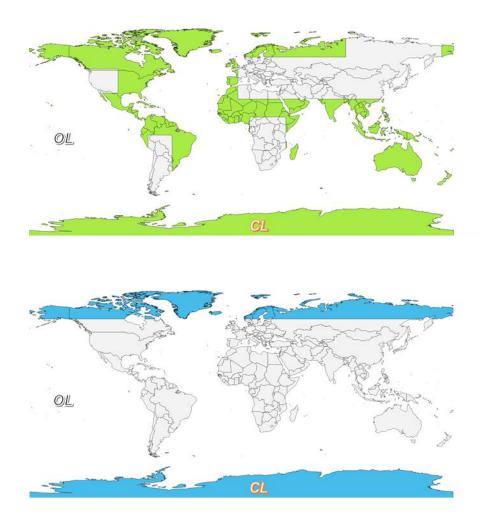


Figure 18: Map of the SRAL tracking mode plotted for Sentinel-3A (top panel) and Sentinel-3B (bottom panel)

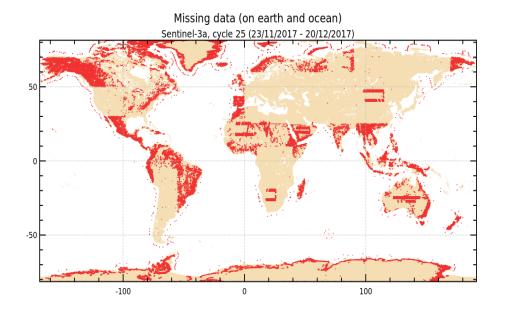


S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019



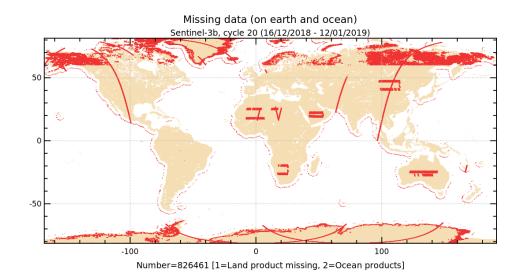


Figure 19: Global map (top panel) of the Sentinel-3A missing measurements for cycle 25 (from 11th of November 2017 to 20th of December 2017). Same map for Sentinel-3B (bottom panel) over the cycle 20 (from 16th of December 2018 to 12th of January 2019).

GLS

Sentinel-3 MPC

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 33

In CL mode, the acquisition of the returned signal mainly depends on the surface topography as illustrated with Sentinel-3A data over Central America, Figure 20. 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. The plot of Sentinel-3B missing measurement over Antarctica (Figure 21) illustrates this behavior. The correlation between surface elevation variations (or surface slopes) and missing measurements is very strong. With more precise estimations of the surface slope such a diagnosis may help to better characterize the limits of the altimeter in CL mode over Land surfaces.

This explain why on the global results plotted on Figure 22, the missing measurements at high latitudes are mainly located over the margins (Antarctica and Greenland) where the variations of the surface altitude are strong.

The map and the along-track plot of the backscatter coefficient over the Antarctica (bottom panels Figure 22) gives information about the surface rugosity and thus about the surface slopes. The sigma0 plotted is derived from the OCOG retracker which is quite robust to retrieve a signal compared to other retrackers, even if less accurate. As this is not a physical retracker the absolute value of the backscatter coefficient differs from the one obtained over Ocean with the SAMOSA ocean retracker. We applied here a -34 dB bias on the OCOG sigma0 to align it on the level of signal usually observed over ocean. The following behaviour is observed:

- Over ocean, the backscatter coefficient (sigma0) is centred on 11 dB.
- Approaching the Antarctica continent, over sea ice surfaces the backscattering energy increased and the sigma0 reaches values higher than 30 dB. It corresponds to flat and very reflective surfaces
- At the borders of the Antarctica continent, over the margins, the amplitude of the measured signal is very low. This region corresponds to very steep areas where are located most of the missing measurements: SRAL altimeter either lost the signal or acquired a very low signal. This behaviour was expected since SRAL sensor was not designed to acquire signal over the margins.
- Finally, over the Antarctica interior, the OCOG backscatter coefficient varies from 5 to 20 dB depending on the type of surface.

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

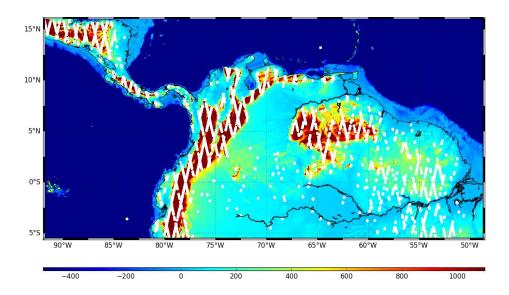


Figure 20: Zoom (bottom panel) over Central and South America of the missing Sentinel-3A measurements (plotted in white) superimposed on a bathymetry grid.

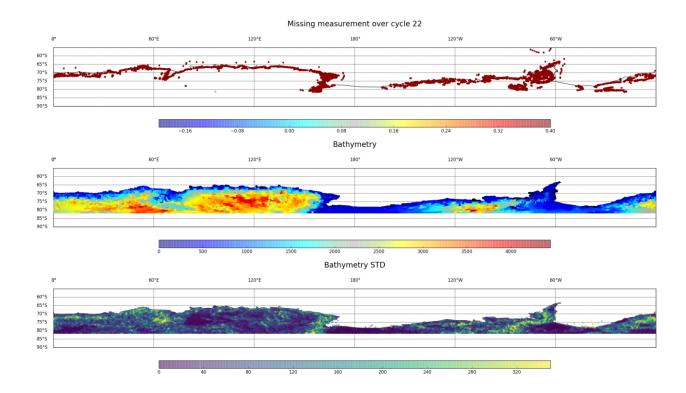


Figure 21: Sentinel-3A (operating in CL mode) missing measurements over Antarctica for cycle 22 (top panel). Bathymetry over Antarctica (middle panel). The standard deviation of the bathymetry (bottom panel) aims at giving an idea of the altitude variations over Antarctica.

S CLS

Sentinel-3 MPC

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 35

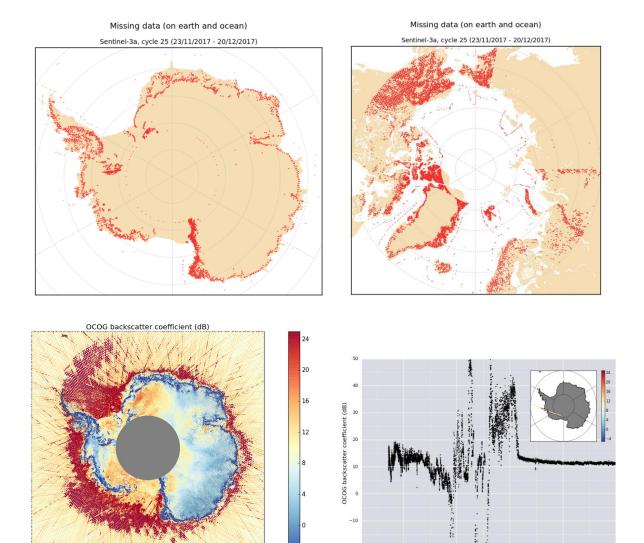


Figure 22: left panels show the Sentinel-3A missing measurements for cycle 25 (from 11th of November 2017 to 20th of December 2017) over Antarctica (left panel) and over the Arctic (right panel) areas. Bottom left panel shows the ocog backscatter coefficient over Antarctica for cycle 25. This variable is derived from both S3A L2 LAND and WATER products. The bottom right panel shows the ocog backscatter coefficient for one pass that cross the Antarctica continent. The along-track profile is derived from both S3A L2 LAND and WATER products.

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 23 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).

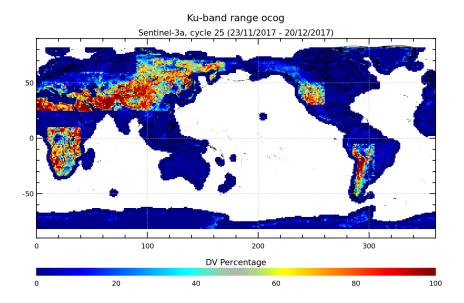


S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019



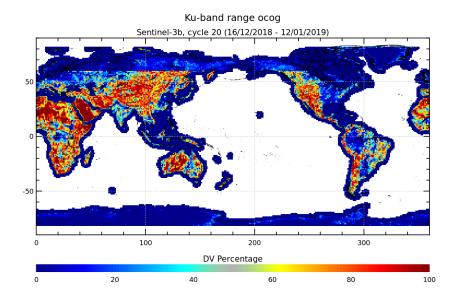


Figure 23: Gridded map of the range ocog Default Value percentage with respect to the available measurements. For Sentinel-3A (top panel) over cycle 25 (from 11th of November 2017 to 20th of December 2017) and for Sentinel-3B (bottom panel) over cycle 20 (from 1-th of December 2018 to 12th of January 2019)



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 37

7 Performance Mission over Ocean

7.1 Outliers detection

The outliers 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 24 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 24 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 is scheduled for the coming months.

960 CLS

Sentinel-3 MPC

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 38

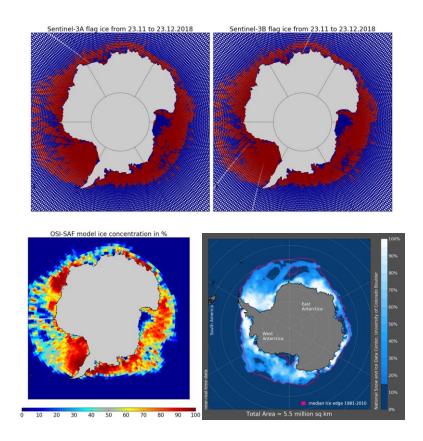


Figure 24: Top panels show Sentinel-3A (left) and Sentinel-3B (right) sea ice flag derived from both L2 LAND and WATER products from 23th November to 23th December 2018. Presence of sea ice corresponds to red, open ocean water is represented in blue. Bottom left panel shows the sea ice concentration 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 25 for Sentinel-3A (top left panel) and for SARAL/AltiKa (top right panel) over the same period from April 2016 to December 2018. 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 25 bottom panel over the whole mission period, i.e. from June to December 2018. Results are slightly different than with Sentinel-3A and SARAL/Altika. This is due to the time period covered by Sentinel-3B. Indeed, the map is average over only one Southern hemisphere winter and no Northern hemisphere winter. It explains the higher percentages of sea ice close to the Antarctic and the lower percentages in the Arctic region compared to Sentinel-3A and SARAL/Altika.

The corresponding global temporal monitoring is plotted in Figure 26. Same temporal variations are observed between Sentinel-3A and Altika with maximums in June-July (Southern hemisphere winter) and in November (Northern hemisphere winter). The percentage of outliers detected by SARAL/AltiKa sea ice flag is slightly higher (2%) than for Sentinel-3A. This could be explained by the algorithm differences, the fact that the Sentinel-3A sea ice detection parametrization is not yet definitely tuned and the difference of sensitivity of the two altimeters to the sea ice impact. Despite a noisier curve for



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 39

Sentinel-3B, Sentinel-3A and 3B are in perfect agreement regarding ice detection from the 11th July 2018, where Sentinel-3B is switch from LRM to SAR mode. During the Sentinel-3B LRM period, here on the plot from 14 June to 11 July 2018, the percentage of measurement edited on ice criteria is abnormally lower. This is explained by the fact that in LRM due to a wrong parametrization of the waveform quality thresholds, the flag sea ice is often set to 5 which corresponds to an unknown surface.

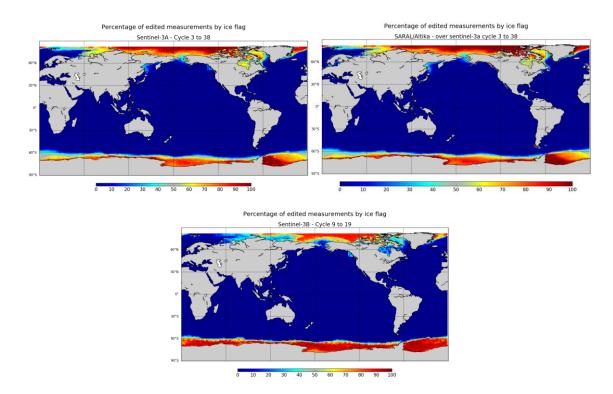


Figure 25: Gridded maps of outlier's percentage detected by sea ice flag for Sentinel-3A (top left panel, from April 2016 to December 2018), SARAL/Altika (top right panel, from April 2016 to December 2018) and Sentinel-3B (bottom panel, from June to December 2018).

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 40

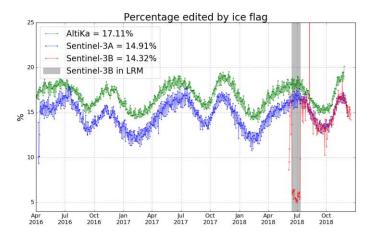


Figure 26: Monitoring of the daily averaged percentages of outliers detected by Sentinel-3A and Sentinel-3B sea ice flag (blue and red curves) and AltiKa ice flag (green curve) over Ocean.

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 7. 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 27 presents the monitoring of the total percentage of corrupted measurements detected over ocean and sea ice (top panel) and the corresponding Sentinel-3A and 3B maps (bottom panels). 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: 18.2 % 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-3B and to a lesser extent for Sentinel-3A. 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 28 shows the monitoring of the percentage of measurements edited on the dynamical atmospheric correction criteria (DAC) (left panel) and on the microwave radiometer Wet Tropospheric Correction criteria (MWR WTC) (right panel).

The dynamical atmospheric correction is derived from the MOG2D model. For Sentinel-3B, the DAC is partially missing on 8 days: the 19th August, on the 9th, 10th, 24th and 25th September and on the 6th, 7th and 31st October 2018. These anomalies are due to ground processing errors in the Marine Centre. Over Sentinel-3A reprocessed period, such anomalies have been addressed and the DAC is correctly provided.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 41

Only one short event occurs on the 12th and 13th July 2018, resulting in a total percentage of edited measurements slightly higher (+1.5%).

Regarding the measurements edited on the radiometer WTC criteria, Figure 28 right 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 25% of edited measurements over the open ocean observed in the map (Figure 27, bottom left panel). This calibration scheme has been changed on the 28th February 2018 to improve Sentinel-3A coverage over ocean. After this date, the average percentage of measurements edited by WTC criteria drops to 0.07%. Sentinel-3B uses the same upgraded calibration scheme as Sentinel-3A. It explains the similar percentages and the absence of 25% pixels on the map (Figure 27, bottom right).
- ❖ Peaky values on 10 days for Sentinel-3A and 20 days for Sentinel-3B. 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. Removing these events, the average percentage of measurements edited by WTC criteria is of 0.02% for Sentinel-3A (after 28th February 2018) and 0.04% for Sentinel-3B, which is lower than for Altika (0.06%) and Jason-3 (0.08%).

Table 7 shows that the percentage of rejected data over ocean (removing ice) is good, with only 3.2% of outliers over 2018 for Sentinel-3A. In 2017, an additional 0.8% of sea level observations were rejected due to the MWR calibrations. After the change in the MWR calibration timeline, the rejected measurements are fully consistent with the same metric observed for Jason-3 (3.3%) and SARAL/AltiKa missions (2.6%). Over the year 2018, special events related to missing DAC or WTC only account for 0.1% of the total rejected measurements.

For Sentinel-3B, the percentage of rejected data over ocean is higher: 5.8% over the beginning of the mission. However, considering nominal operation (i.e. without events on the WTC nor on the DAC), this percentage drops to 3.8%, which is very good considering that Sentinel-3B was not on its final orbit until the 23rd November and it encounters several calibration events during its first months. The percentage of edited data due to the ionosphere correction seems to slightly increase for Sentinel-3B in comparison to Sentinel-3A (+~0.6%). 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 27 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.

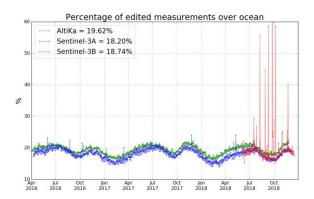


S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019



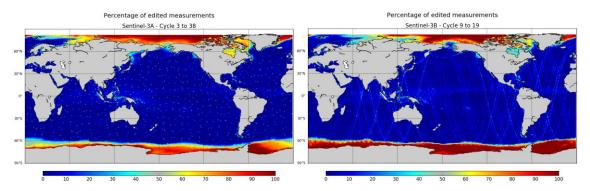
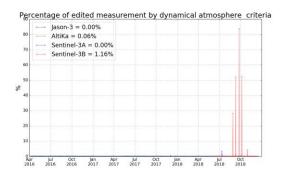


Figure 27: top panel shows Sentinel-3A (blue curve), Sentinel-3B (red curve) and SARAL/AltiKa (green curve) total percentage of outliers over ocean. Bottom panels show the gridded maps of Sentinel-3A (bottom left) from April 2016 to December 2018 and Sentinel-3B (right panel) for June to December 2018.



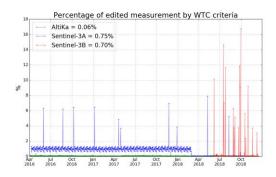


Figure 28: Percentage of outlier detected by the dynamical atmospheric thresholds (left panel) et by the MWR WTC thresholds (right panel). Sentinel-3A is represented in blue, Sentinel-3B in red, Altika in green and Jason-3 in black.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

	Min thresholds	Max thresholds	Mean edited for Sentinel-3A			Mean edited for Sentinel-3B	
Parameter			2017	2018		July to Dec 2018	
			All data	All data	Without events	All data	Without events
Sea Level Anomaly	-2	2	1.74 %	0.92%	0.80%	3.04%	0.86%
Number of range measurement	10	Not applicable	0.07%	0.06%	0.06%	0.12%	0.08%
Standard deviation of range	0	0.12+0.02*SWH	1.41 %	1.33%	1.33%	1.65%	1.58%
Dry tropospheric correction	-2.5	-1.9	0.00 %	0.00%	0.00%	0.00%	0.00%
Dynamical atmospheric correction	-2	2	0.00 %	0.01%	0.00%	1.43%	0.00%
MWR Wet Tropospheric Correction	-0.5	-0.001	1.04 %	0.22%	0.11%	0.78%	0.03%
Sigma0 Standard deviation	0	0.7	2.83 %	2.64%	2.64%	3.17%	3.06%
Altimeter Wind Speed	0	30	0.05 %	0.04%	0.04%	0.22%	0.05%
Dual Frequency ionosphere correction	-0.4	0.04	1.37 %	1.23%	1.21%	2.04%	1.81%
Sea State Bias	-0.5	0	0.05 %	0.04%	0.04%	0.22%	0.05%
Ocean Tide	-5	5	0.01 %	0.01%	0.01%	0.01%	0.01%
Earth Tide	-1	1	0.00 %	0.00%	0.00%	0.00%	0.00%
Pole Tide	-15	15	0.00 %	0.00%	0.00%	0.00%	0.00%
All Together			3.99%	3.19%	3.10%	5,80%	3.76%

Table 7: Outliers detection thresholds and corresponding percentages computed over the years 2017 and 2018 for Sentinel-3A and from the 11th July 2018 (in order to consider only SAR mode period) till the end of the year for Sentinel-3B. For Sentinel-3B and Sentinel-3A (year 2018), the percentages have also been calculating removing the days with particular events, i.e. when the percentage of missing DAC or WTC is abnormal (>0.0% for the DAC and >1% for the WTC).



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 44

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 29 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 months of Sentinel-3B mission, in SARM and in P-LRM (Figure 29 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 under estimated in SARM with respect to P-LRM. Negative estimations over flat sea state are possible due to the level of noise of this parameter.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 45

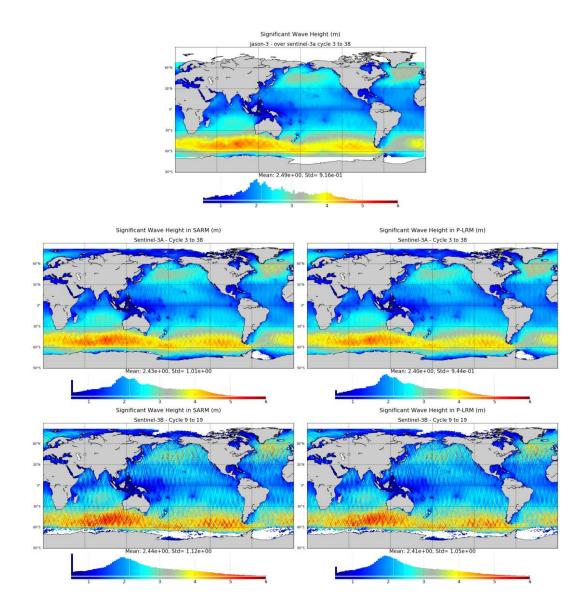


Figure 29: Gridded maps of Jason-3 (top panel), Sentinel-3A SARM (middle left panel) and P-LRM (middle right panel) SWH from April 2016 to December 2018. Gridded maps of Sentinel-3B SARM (bottom left panel) and P-LRM (bottom right panel) SWH from June to December 2018.

The monitoring of the daily averaged SWH (plotted in Figure 30) 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. Thanks to Sentinel-3A reprocessing and to the implementation of SAMOSA 2.5 retracker for SARM observations, SARM SWH mean value have been reduced for Sentinel-3A and 3B complete missions and is now very close to P-LRM and Jason-3 mean values.

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 46

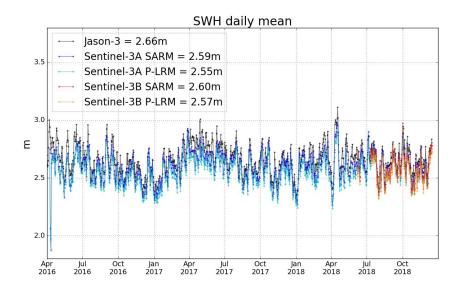


Figure 30: Daily monitoring of the Sentinel-3A SARM (blue curve) P-LRM (cyan curve), Sentinel-3B SARM (red curve) P-LRM (orange curve), and Jason-3 (blue curve) SWH.

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 31). This analysis shows a very good agreement between Jason-3 and Sentinel-3A for both modes, with a mean bias of about 5cm in SARM and about 4cm in P-LRM. No significant dependency is visible when SWH increase for Sentinel-3A P-LRM. However, Sentinel-3A SARM compared to Jason-3 highlights a clear dependency as function of SWH. The differences increase with SWH values from -20cm at SWH equals 0.5m 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-3A 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. For Sentinel-3B, the shorter time period implies noisier curves, but the results are already in very good agreement with the one obtained for Sentinel-3A.

The map plotted in Figure 31 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.

S CLS

Sentinel-3 MPC

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 47

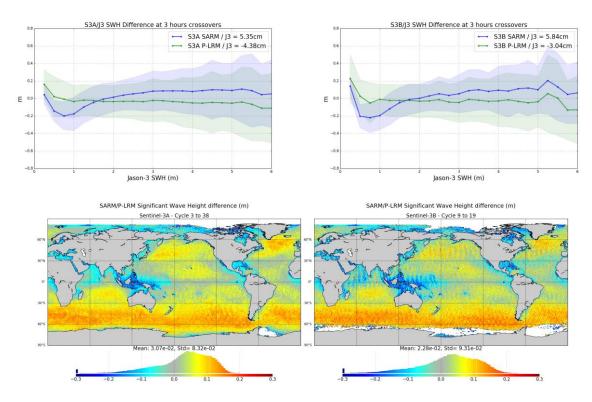


Figure 31: top panels show SWH differences computed at crossovers between SARM and Jason-3 (blue curve) and between P-LRM and Jason-3 (green curve), for Sentinel-3A from April 2016 to December 2018 (top left panel) and for Sentinel-3B from June to December 2018 (top right panel). Bottom panels show the gridded map of collocated SWH differences between Sentinel-3A SARM and P-LRM from April 2016 to December 2018 (bottom left panel) and Sentinel-3B SARM and P-LRM from June to December 2018 (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 32 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. Indeed, the algorithm used to compute the wind speed estimation, the Abdalla's algorithm, is inherited from Envisat mission and thus needs consistent inputs.

CLS

Sentinel-3 MPC

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 48

The same maps have been drawn for Sentinel-3B SARM and P-LRM (Figure 32 bottom panels) over the complete mission period. Despite a different mean value, the same geographical structures are observed than with the other missions.

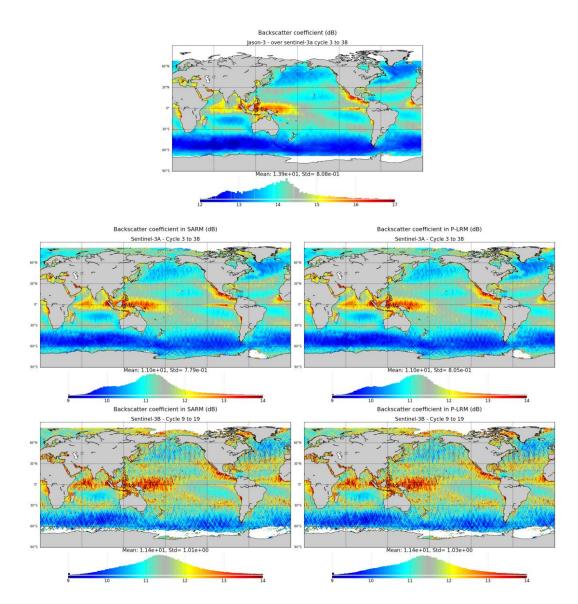


Figure 32: Gridded maps of Jason-3 (top panel), Sentinel-3A SARM (middle left panel) and P-LRM (middle right panel) backscatter coefficient from April 2016 to December 2018. Gridded maps of Sentinel-3B SARM (bottom left panel) and P-LRM (bottom right panel) backscatter coefficient from June to December 2018.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 49

The monitoring of the daily averaged backscatter coefficient (plotted in Figure 33) 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 are consistent between Sentinel-3A and Sentinel-3B modes and between three satellites.

The difference of mean value between Sentinel-3 and Jason-3 is due to a system bias applied on Sentinel-3A to align the sigma0 mean value with the Envisat mean value.

- The system bias on P-LRM data is -2 dB which means that the true bias between Sentinel-3A and Jason-3 is closer to 0.7 dB, Sentinel-3A being lower than Jason-3 sigma0.
- The system bias on SARM data is -18.96 dB which means that the true bias between Sentinel-3A and Jason-3 is closer to 16.2 dB, Sentinel-3A being higher than Jason-3 sigma0.

During the beginning of Sentinel-3B mission, a bias of 0.5dB was observed between Sentinel-3B and Sentinel-A backscatter coefficients. This is not consistent with the parametrization used for the altimeter wind speed calculation. Sentinel-3B sigma0 needs to be aligned to Sentinel-3A (i.e. Envisat) sigma0 in order to provide a correct wind speed. This alignment has been done 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 6th December 2018 for NRT data. The impact is visible on NTC data about 25 days earlier, i.e. on the 11th November 2018, as shown on the daily monitoring on Figure 33. From this date, Sentinel-3A and 3B backscatter coefficients are in line and centred around 11dB.

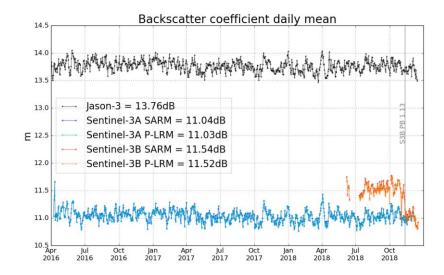


Figure 33: Daily monitoring of the Sentinel-3A SARM (blue curve) P-LRM (cyan curve), Sentinel-3B SARM (red curve) P-LRM (orange curve), and Jason-3 (blue curve) backscatter coefficient.

The co-located differences between Sentinel-3A SARM and P-LRM sigma0 (Figure 34 top left panel), and between Sentinel-3B SARM and P-LRM sigma0 (Figure 34 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



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 50

high latitudes on Sentinel-3A map. Due to the shorter time period, Sentinel-3B map is noisier but the same patterns are already visible. These variations are strongly correlated to the satellites altitude rates, plotted on Figure 34 bottom panel, and not to the satellite altitude as it was the case with SAMOSA 2.3 (see Figure 95).

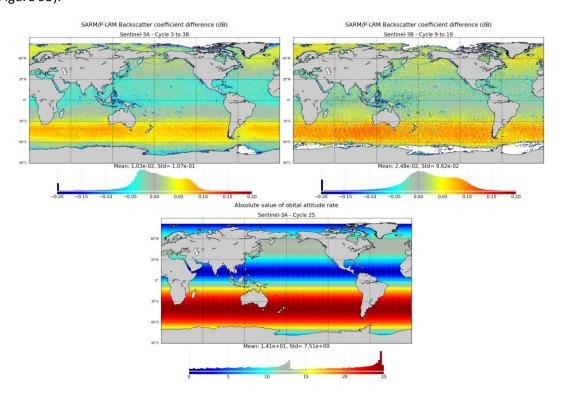


Figure 34: Gridded maps of the collocated backscatter differences between Sentinel-3A SARM and P-LRM from April to December 2018 (top left panel) and between Sentinel-3B SARM and P-LRM from June to December 2018 (top right panel). Gridded map of the absolute value of Sentinel-3A orbital altitude rate 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 35 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). Their level of noise is thus approximatively the 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.

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 51

The four maps obtained for both Sentinel missions and modes are very consistent. Sentinel-3B maps show smaller global mean values in SARM (-0.6cm) and P-LRM (-1cm) compared to Sentinel-3A (-2cm in SARM and -2.3cm in PLRM). The slight discrepancies between SARM and P-LRM ranges (described in Figure 93) 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.

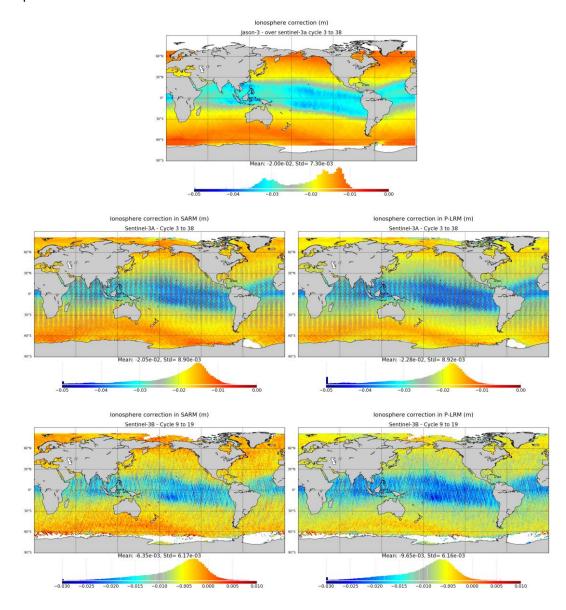


Figure 35: Gridded maps the dual frequency ionospheric correction computed for Jason-3 (top panel), Sentinel-3A SARM (middle left panel) and P-LRM (middle right panel) over the period spanning from April 2016 to December 2018. Gridded maps of Sentinel-3B SARM (bottom left panel) and P-LRM (bottom right panel dual frequency ionospheric correction computed from June to December 2018.

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 52

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 36 shows maps of differences between dual frequency and GIM model ionospheric correction for Jason-3 (top panels), Sentinel-3A (middle panels), and 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 1.6mm for ascending passes and 3.3mm 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 37 shows Sentinel-3A and Sentinel-3B local hours distribution for ascending and descending passes for one cycle (this result is the same whatever the chosen period):

- Sentinel-3A and Sentinel-3B local hours distributions are exactly the same.
- 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.

CLS COLLECTE LOCALISATION SATELITES

Sentinel-3 MPC

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 53

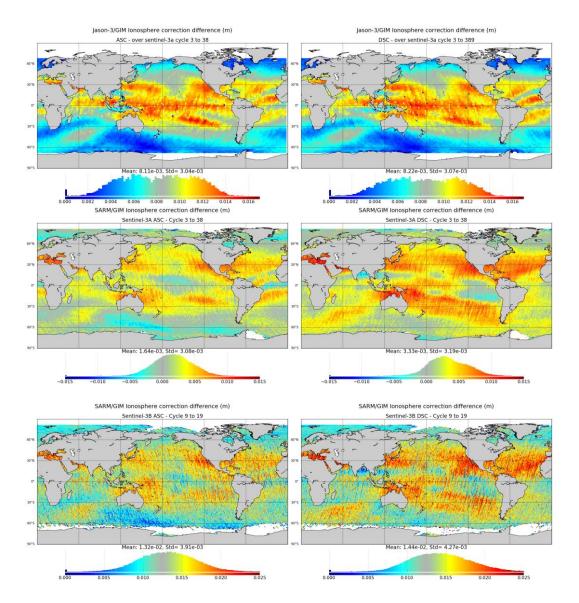


Figure 36: Top panels shows the gridded maps of the collocated differences between Sentinel-3A SARM dual frequency ionosphere correction and GIM model for ascending (left panel) and descending (right panel) passes. Bottom panels show the gridded maps of the collocated differences between Jason-3 dual frequency ionosphere correction and GIM model for ascending (left panel) and descending (right panel) passes. The ionosphere corrections derived from altimeter were filtered at 300km.

CLS

Sentinel-3 MPC

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 54

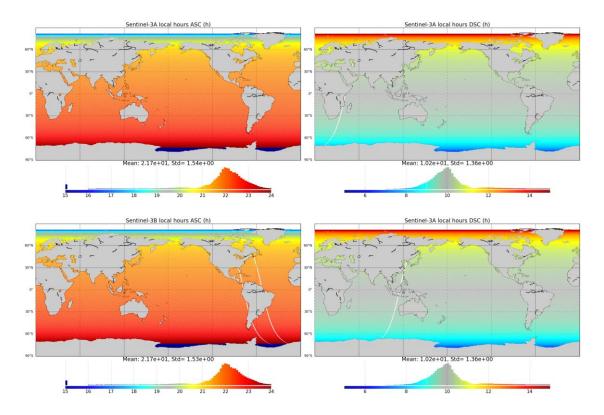


Figure 37: Along-track maps of the local hours for ascending (left panels) and descending (right panels) passes, computed over cycle 25 for Sentinel-3A (top panels) and from the 24th November to the 21st December 2018 for Sentinel-3B (bottom panels).

The monitoring of Sentinel-3A dual frequency and GIM ionosphere corrections and their differences (Figure 38) 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 year 2018, it is centred around 2mm and magnitudes of the variations do not exceed 6mm. The very 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.

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 55

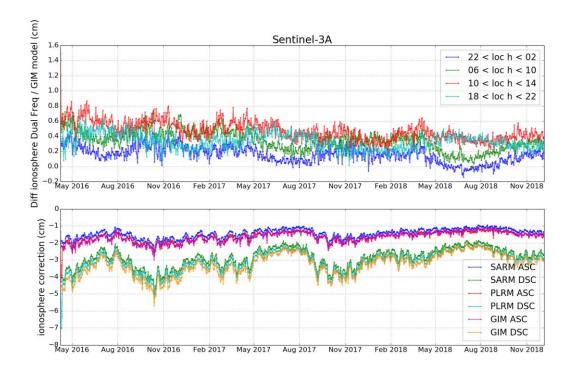


Figure 38: Top panel shows the daily monitoring of the collocated differences between Sentinel-3A SARM dual-frequency ionosphere correction and the GIM model. The Sentinel-3A local hours were split by four hours bins and plotted separately. Bottom panel shows the daily monitoring of the Sentinel-3A SARM, P-LRM dual-frequency ionosphere correction and the collocated GIM model. Ascending and Descending passes were plotted separately.

The same monitoring has been plotted for Sentinel-3B over the beginning of the mission (Figure 39). 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 39 top subplot). These discrepancies are also clearly visible in the monitoring when separating ascending and descending tracks (Figure 39 bottom subplot). 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 40), a constant bias of 8.7cm is observed between Sentinel-3B and Sentinel-3A. This means that Sentinel-3B C-band range is in average 8.7cm 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 35.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 56

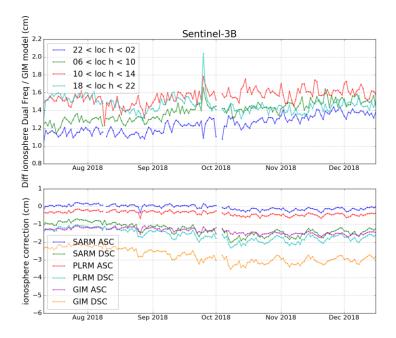


Figure 39: Top panel shows the daily monitoring of the collocated differences between Sentinel-3B SARM dual-frequency ionosphere correction and the GIM model. The Sentinel-3B local hours were split by four hours bins and plotted separately. Bottom panel shows the daily monitoring of the Sentinel-3B SARM, P-LRM dual-frequency ionosphere correction and the collocated GIM model. Ascending and Descending passes were plotted separately.

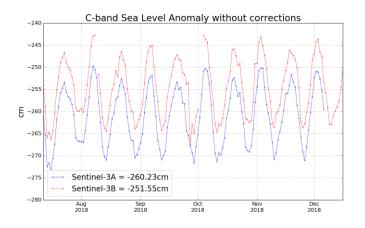


Figure 40: Daily monitoring of C-band Sea Level Anomaly without geophysical corrections for Sentinel-3A (blue curve) and Sentinel-3B (red curve) from July to December 2018.

S CLS

Sentinel-3 MPC

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 57

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 41 presents the maps of mispointing angles derived from Sentinel-3A and 3B waveforms (top and middle left panels), Sentinel-3A and 3B Star-Tracker (top and middle right panels), and from Jason-3 (bottom left panel) and AltiKa (bottom right panel) waveforms. Sentinel-3A (Sentinel-3B) off-nadir angle is biased by -0.006 degrees² (-0.008 degrees²) with respect to the one derived from star-trackers centred on 0 degrees². 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 should be implemented in a future IPF version in 2019. 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 11th 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...). Between SARAL/AltiKa and Jason-3, similar geographical variations are observed, but with a higher dispersion for Jason-3 than for SARAL/AltiKa. This is explained by Jason-3 larger antenna aperture angle: 1.29° against 0.6° for SARAL/AltiKa. For Sentinel-3A and 3B, the map of mispointing derived from P-LRM waveforms is not consistent with the two other missions: 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 and SARAL/AltiKa. 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.

Until the installation of the IPF-SM2 06.10, SRAL calibrations were averaged over one day only. It implied important variability from one day to another on the daily monitoring of Sentinel-3A off-nadir angle derived from P-LRM waveforms. With this IPF version, the calibrations are averaged over 10 days. This upgrade was included in Sentinel-3A reprocessing. Sentinel-3A off-nadir angle shows now temporal variations consistent with Jason-3 and SARAL/AltiKa variations over its complete period (Figure 42). Sentinel-3B off-nadir angle temporal variations are also in agreement.

CLS COLLECTE LOCALISATION SATELITES

Sentinel-3 MPC

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 58

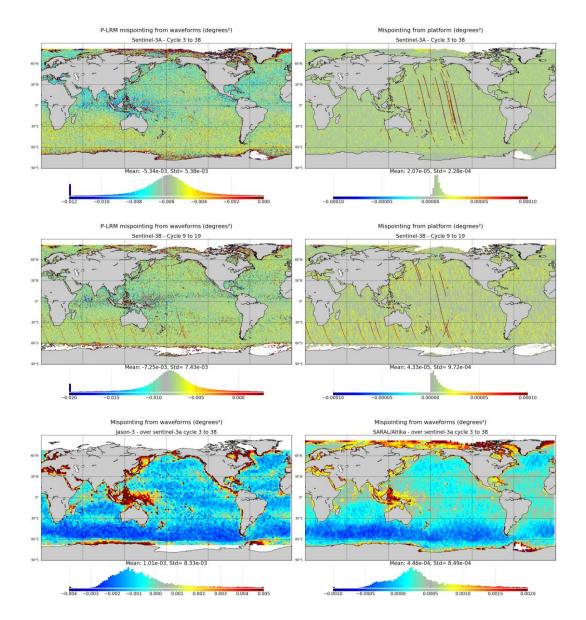


Figure 41: Top panels show the gridded maps of Sentinel-3A off-nadir angle derived from waveforms (left panel) and derived from Star-Trackers (right panel) from April 2016 to December 2018. Middle panels show the same gridded maps for Sentinel-3B from June to December 2018. Bottom panels show the off-nadir angle derived from waveforms for Jason-3 (left panel) and SARAL/AltiKa (right panel) over Sentinel-3A whole mission lifetime.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 59

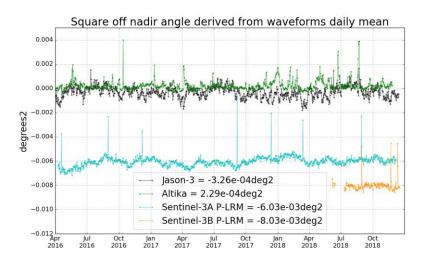


Figure 42: Daily monitoring of the Sentinel-3A P-LRM (cyan curve), Sentinel-3B P-LRM (orange curve), Jason-3 (black curve) and SARAI/AltiKa (green curve) off-nadir angle derived from waveforms.

The study of Sentinel-3A/Sentinel-3B tandem phase allows to detect abnormal behaviour in Sentinel-3A mispointing. Figure 43 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 changes with time: between 30° and 60°N in July 2018 to above 60°N in October 2018. Further analyses performed during the commissioning phase demonstrated that this pattern is related to Sentinel-3A platform. This signal remains very low with 3.10° degrees² of amplitude.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 60

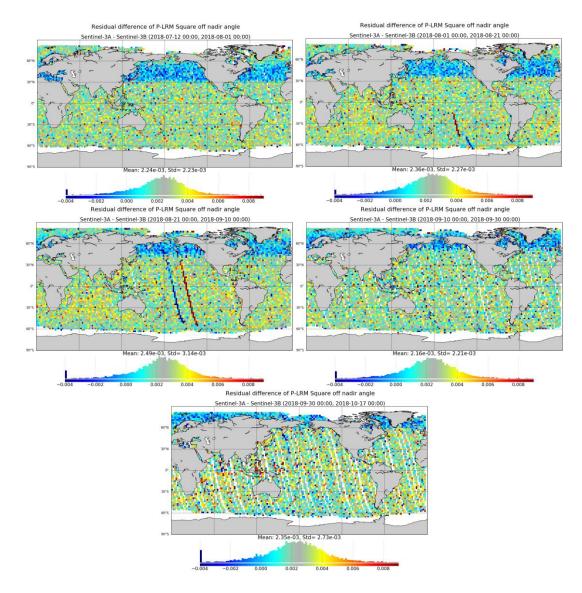


Figure 43: Gridded maps of the residual difference of P-LRM square off nadir angle between Sentinel-3A and Sentinel-3B, on ascending passes only. The five maps cover the entire Sentinel-3A/Sentinel-3B tandem period where Sentinel-3B operate in SAR mode, i.e. from the 11th July to the 16th October 2018. Each map covers 20 days.

900 CLS

Sentinel-3 MPC

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 61

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 γ 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 γ 800.

7.3.1 Along-track analyses

The monitoring of the wet tropospheric correction is performed by comparison of the difference MWR-model of the wet tropospheric correction (Δ wtc) for several instruments. Figure 44 shows this monitoring for Sentinel-3A, Sentinel-3B, SARAL, and Jason-3 with the daily average of the Δ 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 Δ 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 Δ 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 Δ wtc for SARAL and Sentinel-3A Δ 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 Δ 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 Δ wtc is around 0.8mm before the update of the MWR characterisation parameters (6th December) which provided calibrated parameters to the operational processing. After the 6th 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 commissionning phase.

368 315

Sentinel-3 MPC

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 62

The daily Δ 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 Δ 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 Δ 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.

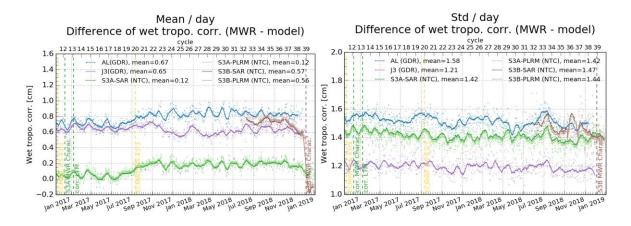


Figure 44: Monitoring of MWR (3P) - ECMWF wet tropospheric correction for S3A,S3B, SARAL/AltiKa,

Jason3/AMR: mean (left), standard deviation (right)

Figure 45 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 (Figure 34) 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.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 63

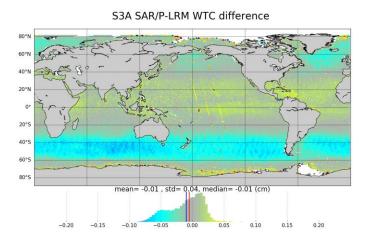


Figure 45: Difference of SAR/P-LRM wet tropospheric correction for Sentinel-3A (cycle 26 to 39)

Figure 46 shows the map of the differences of SAR and P-LRM S3B wet tropospheric corrections for the period covered by cycle 20 of S3B. We used here only the last cycle because it is the only cycle processed with the calibrated MWR parameters. These parameters will influence the brightness temperatures, which are inputs of the retrieval algorithms of the geophysical parameters. 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.

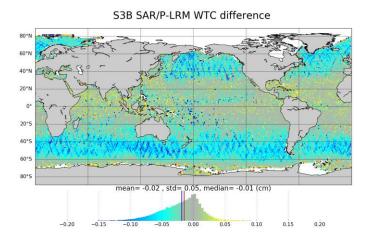


Figure 46: Difference of SAR/P-LRM wet tropospheric correction for Sentinel-3B (cycle 20)

Figure 47 shows the monitoring of **S3A** Δ 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 Δ wtc is the same for almost all the period of study. The standard deviation of 5P Δ wtc is slightly smaller than 3P: for example for P-LRM, standard deviation Δ wtc is around 1.37cm with the 5P algorithm, and 1.43cm 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.

GLS

Sentinel-3 MPC

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 64

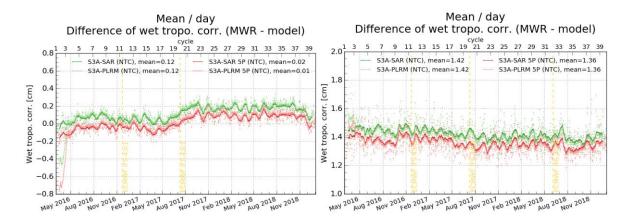


Figure 47: Monitoring of 3P and 5P MWR - ECMWF wet tropospheric correction for Sentinel-3A

Enhanced Retrieval algorithm (5P)

Figure 48 shows the monitoring of **S3B** Δ wtc 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 about 2mm. Secondly, the variations of the daily averaged Δ wtc is the same for almost all the period of study. The standard deviation of 5P Δ wtc is slightly smaller than 3P: for example for P-LRM, standard deviation Δ wtc 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.

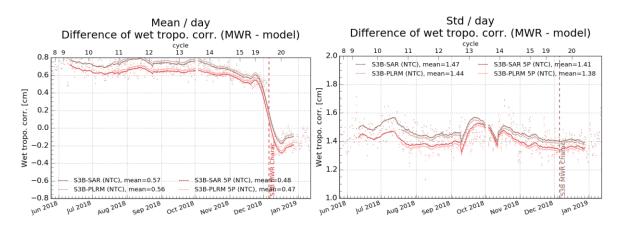


Figure 48: Monitoring of 3P and 5P MWR - ECMWF wet tropospheric correction for Sentinel-3A

Figure 49 shows the map of the difference between 5P and 3P algorithms for Sentinel-3A (left panel) and Sentinel-3B (right panel). For Sentinel-3A, the whole year is considered in this map with the use of data from cycle 26 to 39. For Sentinel-3B, we used only the cycle 20 as explained previously. The S3B map of the difference will be thus noisier than S3A map. As seen before with Figure 47, the average difference is small, less than 1mm, but Figure 49 highlights the geographical impacts of the enhanced algorithm. On this map, we retrieve the signature of the sea surface temperature.

900 CLS

Sentinel-3 MPC

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 65

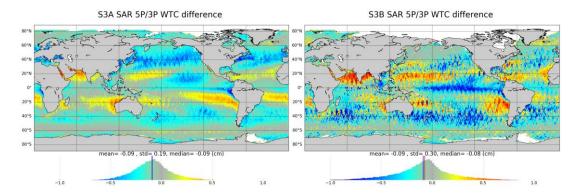


Figure 49: Map of the difference 5P - 3P wet tropospheric correction:

left: Sentinel-3A (using NTC data; cycle 26 to 39)

right: Sentinel-3B (using NTC data; cycle 20)

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:

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

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

We will start by analyzing the wet tropospheric correction retrieved from the classical algorithm (3P) (Figure 50). 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 -2.4cm2, 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 ΔVar (-1.3cm2). Considering Sentinel-3A is a two

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 66

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.

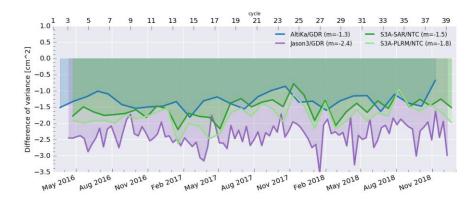


Figure 50: Difference of variance of ΔSSH at crossover points for low oceanic variability for Sentinel-3A, SARAL,

Jason3: var(ΔSSH with WTC 3P MWR)-var(VSSH with WTC ECMWF) (bottom)

Looking at the map of the Δ Var (Figure 51), we can see that we have a global improvement when using MWR correction. The map seems quite noisy for this diagnosis.

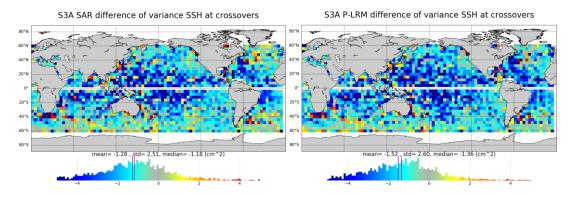


Figure 51: Difference of variance of SSH at crossover points SAR (left) / P-LRM (right)

We perform the same analysis for the enhanced algorithm (5P) again over the lowest oceanic variability areas (Figure 52). Jason-3 with its three channels AMR shows the best improvement with respect to the model correction with an average of -2.4cm2, Sentinel-3A is below with -1.6cm2 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 $\gamma 800$. There is room for improvement for Sentinel-3A as its algorithm is based on simulations.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 67

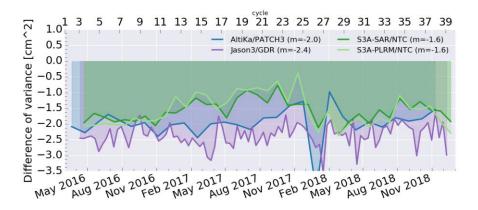


Figure 52: Difference of variance of SSH at crossover points for Sentinel-3A, SARAL/AltiKa, Jason3/AMR: var(SSH with WTC 5P MWR)-var(SSH with WTC ECMWF)

As for the 3P algorithm, the maps of the ΔVar (Figure 53) show a global improvement when using MWR correction.

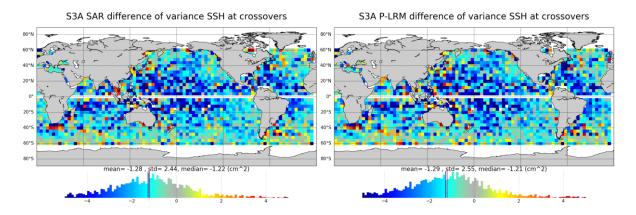


Figure 53: Difference of variance of SSH at crossover points SAR (left) / P-LRM (right)

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:

 $\mathit{SLA} = \mathit{Orbit} - \mathit{Altimeter}\ \mathit{Range} - \sum \mathit{Geophysical}\ \mathit{corrections} - \mathit{Mean}\ \mathit{Sea}\ \mathit{Surface}$

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



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 68

Correction / mission and version	Sentinel-3A			Jason-3
	IPF-SM2 V06.05	IPF-SM2 V06.07	IPF-SM2 V06.10 to V06.14	GDR-D
Dry troposphere correction	ECMWF 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. (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 8: Detail of the standard used to compute Sentinel-3A 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.

7.4.1 Along-track analyses

Figure 54 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. Due to its shorter time coverage, Sentinel-3B shows larger SLA dispersions but the mean values are already really close to Sentinel-3A ones.

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 69

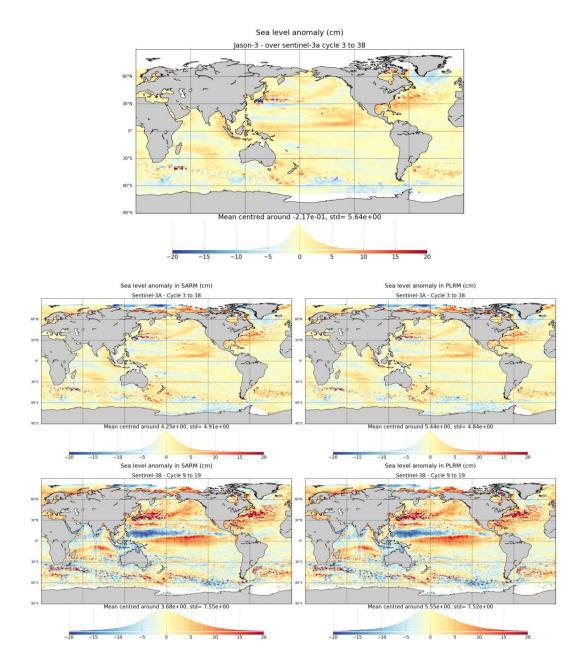


Figure 54: Gridded maps of Jason-3 (top panel), Sentinel-3A SARM (middle left panel), and P-LRM (middle right panel) SLA computed from April 2016 to December 2018. Gridded maps of Sentinel-3B SARM (bottom left panel) and P-LRM (bottom right panel) SLA computed from June to December 2018.

The monitoring of the daily averaged SLA (plotted in Figure 55, 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 whole Sentinel-3A period, the observed temporal variations are consistent between both mission's modes and with Jason-3.

This monitoring of the mean SLA shows several interesting features:



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 70

The bias between Sentinel-3A SARM and PLRM SLA is of 1.1 cm, SARM being lower than P-LRM. The average value of SLA is of 4.4cm in SARM and of 5.5cm in P-LRM.

- Sentinel-3A P-LRM (SARM) bias is of 3.4cm (2.3cm) against Jason-3. Regarding the SLA biases between 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 1.8cm, SARM being lower than P-LRM. It is 0.7cm higher than for Sentinel-3A. The average value of SLA is of 4cm in SARM and of 5.8cm in P-LRM.

Figure 56 shows a zoom of the mean SLA for both Sentinel's mission over Sentinel-3B lifetime. In order to help the comparison, a constant bias of 1.65cm has been added to Sentinel-3B SARM SLA and of 0.8cm to Sentinel-3B P-LRM SLA. This monitoring presents several features:

- During the tandem phase, Sentinel-3A and 3B SLA present the exact same variations, both in SARM and in P-LRM. After the 16th October 2018, Sentinel-3B starts to change its orbit. SLA variations are then less identical but still coherent between the missions.
- When Sentinel-3B operates in Close Loop (grey areas), a small bias is visible between the SARM curves.

The monitoring of the SLA variance (Figure 55 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 PLRM 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.

GLS

Sentinel-3 MPC

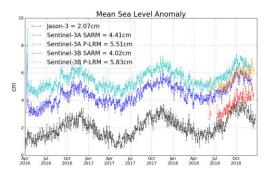
S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 71



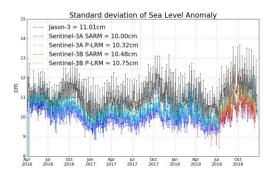


Figure 55: Daily monitoring of the Sentinel-3A SARM (blue) and P-LRM (cyan curve), Sentinel-3B SARM (red curve) and P-LRM (orange curve), and Jason-3 (black curve) mean SLA (left panel) and its standard deviation (right panel).

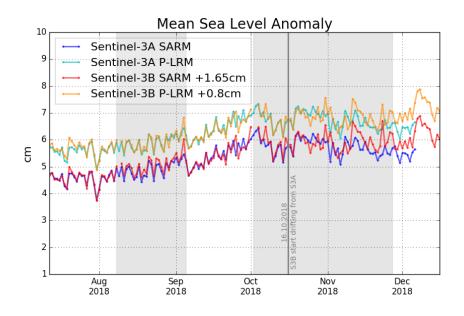


Figure 56: Daily monitoring of the Sentinel-3A SARM (blue) and P-LRM (cyan curve), Sentinel-3B SARM (red curve) and P-LRM (orange curve) mean SLA, over Sentinel-3B mission time period. A constant bias of 1.65cm has been added to Sentinel-3B SARM and of 0.8cm to Sentinel-3B P-LRM. Grey areas represent periods when Sentinel-3B operates in Close Loop.

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

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 72

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 cycle by cycle (Figure 57). The result shows a slight mean bias of 0.4 cm for Sentinel-3A, between ascending and descending passes. This unexpected bias is related to altitude estimation, since performing the same diagnosis with STC altitude gives a mean bias centred in -0.2 cm. For the three missions, temporal variations are observed:

- 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.
- 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.

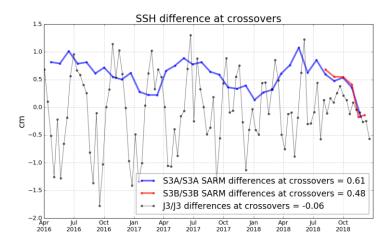


Figure 57: Cycle per cycle monitoring of the SSH differences computed at mono-mission crossovers for Sentinel-3A SARM (blue curve), Sentinel-3B (red curve), and Jason-3 (green curve).

The Sentinel-3A SARM and P-LRM maps of SSH differences at crossovers are plotted in Figure 58 (top panels). Once the global biases of 6.4 mm in SARM and 6.6 mm in P-LRM removed, the SSH differences are low, ranging between -2 and 2 cm. For Sentinel-3A, SARM and P-LRM maps show similar features over the two years of data. Some small discrepancies between modes are still under investigations, namely in a zone in west Australia and in strong wave zones such as the circumpolar.

GLS

Sentinel-3 MPC

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 73

Figure 58 bottom panels present the same metric for Sentinel-3B. As the time period is shorter than for Sentinel-3A, the maps are noisier. However, the same patterns are already visible. A longer time period is required here to validate the coherence between the two missions.

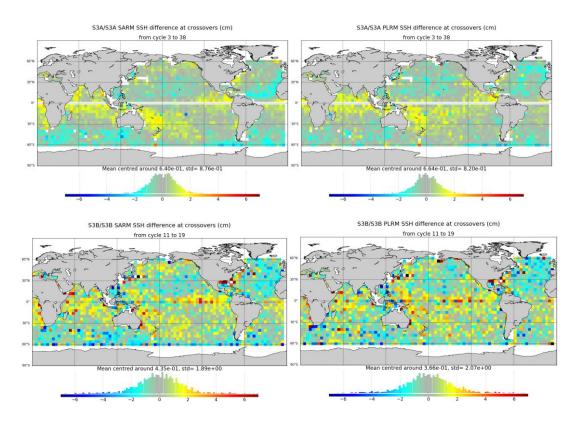


Figure 58: Gridded maps of SSH differences computed at mono-mission crossovers in SARM (left panels) and in P-LRM (right panels), for Sentinel-3A (top panels) from April 2016 to December 2018, and for Sentinel-3B (bottom panels) from July to December 2018.

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 59. 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.

Over its first cycles, Sentinel-3B SSH error is consistent with the one derived from Sentinel-3A. Over Sentinel-3A complete lifetime, the SSH error is slightly higher for Sentinel-3A (3.9 cm) than for Jason-3 (3.5 cm). However, this estimation still includes a natural residual variation of the sea surface height between the two measurements at the crossover location. Computing the mean time 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

GLS

Sentinel-3 MPC

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 74

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.

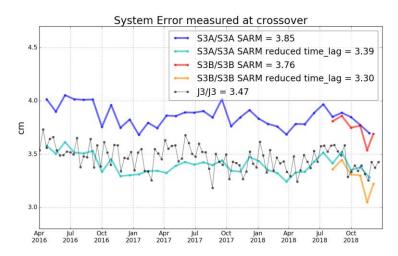


Figure 59: Cycle per cycle monitoring of the system error computed at mono-mission crossovers for Sentinel-3A (blue curve), Sentinel-3B (red curve), and Jason-3 (black curve). The system error is computed through the cyclic SSH differences standard deviation at crossovers and divided by $\sqrt{2}$ because 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 60) shows the differences at crossovers between Jason-3 and Sentinel-3A in SARM (left) and in P-LRM (right). It shows a very good consistency between the two missions with differences ranging between -4 and 2 cm (once the mean bias is removed). However, the discrepancies are less homogeneous in SARM than in P-LRM. 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 which is consistent with the result of Figure 93. In P-LRM, differences are homogenous and very low, a small negative signal is observed between the tropics, the source being still under investigation.

Figure 60 bottom panels show the differences at crossovers between Jason-3 and Sentinel-3B in SARM (left) and in P-LRM (right). Despite the shorter time period, the constituency between the two missions is already very good. The same patterns are observed than for Sentinel-3A, with stronger patterns in SARM.

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 above the histograms of the maps give the global SSH bias between Sentinel-3A and Jason-3: 4.6cm for the SARM, 5.7cm for the P-LRM. These results are consistent with the mean SLA monitoring (Figure 55). Indeed, the MSS is not taken into account in the SSH computation at crossovers but is used in the SLA calculation. Jason-3 uses CNESCLS11 in its SLA whereas Sentinel-3A

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 75

uses CNESCLS15, and the bias between these two MSS is of 2.4cm. Subtracting this bias to the mean differences at crossovers, we obtained values consistent with the mean SLA monitoring.

For Sentinel-3B, the global SSH bias with respect to Jason-3 is: 3.2cm in SARM and 4.9cm in P-LRM.

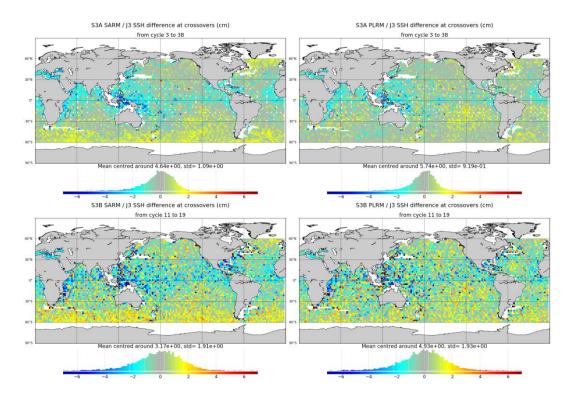


Figure 60: Gridded maps of SSH differences computed at Sentinel-3A and Jason-3 crossovers (top panels) and Sentinel-3B and Jason-3 crossovers (bottom panel), in SARM (left panels) and in P-LRM (right panels).

The following plot (Figure 61) shows the monitoring of the mean bias at crossovers between Sentinel-3A and Jason-3 and between Sentinel-3B and Jason-3. It highlights several features:

- The bias between Sentinel-3A SARM (P-LRM) and Jason-3 equals 4.9cm (5.8cm) which is consistent with previous analyses.
- ❖ The bias between Sentinel-3B SARM (P-LRM) and Jason-3 equals 3.4cm (5cm) which is consistent with previous analyses.
- ❖ When the Jason-3 SSB is updated with the latest version available (Tran et al., 2012), these biases decrease to 2.3cm for Sentinel-3A and to 0.8cm for Sentinel-3B. 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 close to -2.2cm for Sentinel-3B SARM SSH. For Sentinel-3A this result is in agreement with analysis performed using transponder technique since the range bias for Sentinel-3A equals 0.65 cm but for Sentinel-3B we would have expect a SLA absolute bias around 1.5 cm (see section 11.1).



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 76

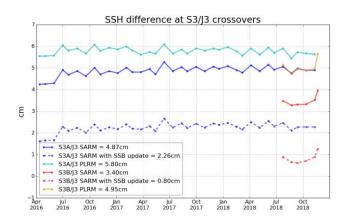


Figure 61: Cycle per cycle monitoring of the SSH differences computed at Sentinel-3A and Jason-3 crossovers in SARM (blue filled curve) and in P-LRM (cyan curve), and at Sentinel-3B and Jason-3 crossovers in SARM (red filled curve) and in P-LRM (orange curve). The dashed blue and red curves show the evolution of the bias when Jason-3 SSH is computed using an updated SSB (SSB Tran et al. 2012 instead of GDR-D SSB).

Figure 62 top panels show the crossovers differences maps between S3A and S3B. Although the results are a noisy (due to the short time period), the geographical discrepancies are relatively smooth, and the patterns are similar to the ones observed on mono-mission maps (Figure 58). The temporal variations of the mean difference (Figure 62 bottom panels) is small (2cm in SARM and 1.1cmcm in P-LRM) and relatively stable in time.

The bias of 2 cm observed between Sentinel-3A and Sentinel-3B in SARM is consistent with analyses performed using the Gavdos transponder. Using transponder method it is found an absolute bias of 0.65 cm for Sentinel-3A range and -1.5 cm for Sentinel-3B range (see section 11.1), which results in 2 cm bias between both altimeters.

The results presented in this section are also in good agreement with in-situ analyses performed at Corsica calibration site.

CLS

Sentinel-3 MPC

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 77

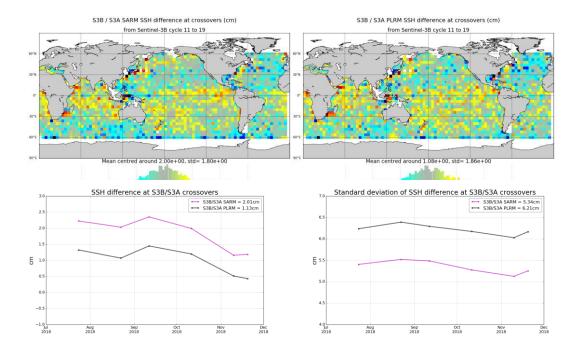


Figure 62: Gridded maps of SSH differences computed at crossovers between Sentinel-3A and Sentinel-3B in SARM (top left panel) and in PLRM (top right panel). Cycle per cycle monitoring of SSH differences (bottom left panel) computed at Sentinel-3B/Sentinel-3A crossovers in SARM (magenta curve) and in P-LRM (black curve), and its standard deviation (bottom right panel).

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 (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 \dot{H} as for instance orbit errors. Therefore, it is called pseudo time tag bias. Figure 63 shows the monitoring of the pseudo datation bias for Sentinel-3A, Sentinel-3B, SARAL/AltiKa and Jason-3 on a cyclic basis. In average Sentinel-3A SARM has higher pseudo time tag bias than AltiKa (respectively 12.7 μ s against 2 μ s), but smaller than Jason-3 in absolute value (-42.5 μ s). Moreover Sentinel-3A pseudo time tag bias presents an annual signal as oserved for the monitoring of the SSH differences between ascending and descending tracks. The amplitude of this annual signal is of about 250 μ s. 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 -150 us).

Over its first cycles, Sentinel-3B pseudo time tag is in good agreement with the one measured for Sentinel-3A, following the same temporal variations.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 78

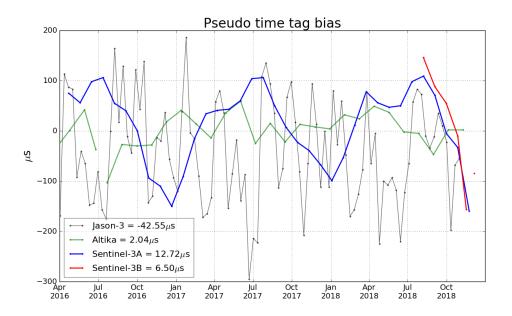


Figure 63: Cycle per cycle monitoring of the pseudo time tag bias for Sentinel-3A (blue curve), Sentinel-3B (red curve), Jason-3 (black curve) and SARAL/AltiKa (green curve). The pseudo time tag biases are computed at mono-mission crossovers.

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. This indicator is computed from the SLA measurements applying then specific methods to estimate precisely the slope and the corresponding uncertainty. These methods are described in Ablain et al. (2017).

The GMSL trend was computed using these processing methods for Sentinel-3A and Jason-3 over the same period. To extend the Sentinel-3A time series and make this analysis more relevant, a homogeneous Sentinel-3A dataset was concatenated from reprocessed and on the fly products. For this dataset, consistent geophysical corrections between both satellites are used. The global trend of 4.16 mm/year measured by Sentinel-3A is relatively consistent with the one derived from the reference time series based on Jason-3 (3.5mm/year). The level of uncertainty is slightly higher for Sentinel-3A, this is mainly explained by the longer repetitive period of the satellite (27 days against 10 days for Jason-3). This result allows to affirm that no significant drift or abnormal behavior is observed on Sentinel-3A sea level.

CLS

Sentinel-3 MPC

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 79

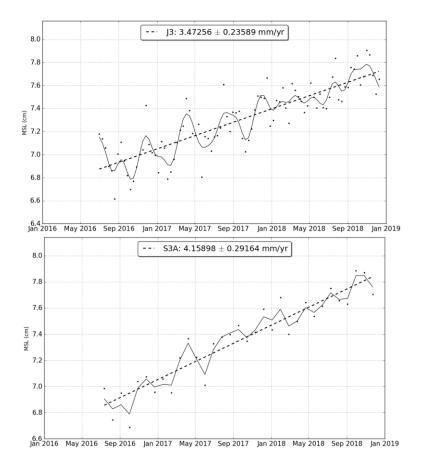


Figure 64: Evolution of the Global Mean Sea Level computed with Jason-3 (top panel) and Sentinel-3A SARM (bottom panel) SLA.

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 in-situ 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

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 80

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 2018 (from 1 January 2018 to 31 December 2018). Both Sentinel-3A and Sentinel-3B products are assessed irrespective of the fact that Sentinel-3B data temporal coverage is limited to the period from late June till end of December 2018 (i.e. about 6 months).

7.6.1 Backscatter coefficient

The ice-free ocean normalised Radar backscatter coefficient (backscatter, σ° 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 SRAL for the year of 2018 is shown in **Figure 65**. However, backscatter from Sentinel-3B shows slightly higher values for the period from 28 June till 31 December 2018. This was a known issue at the time and was corrected as part of Sentinel-3B Processing Baseline 1.13 introduced into operations on 6 December 2018. Sentinel-3A and Sentinel-3B (apart from about 0.5 dB positive bias in case of Sentinel-3B) backscatter PDF compares quite well with those of other Ku-band altimeters as shown in **Figure 66**. This can be clearly seen after applying proper shift of each PDF as shown in the legend of lower panel of **Figure 66**.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 81

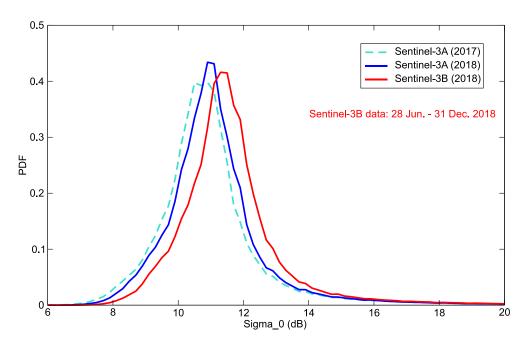


Figure 65: Sentinel-3A and Sentinel-3B SRAL backscatter coefficient PDF's over the whole global ocean for year 2018 (note that Sentinel-3B data have not covered 1 year yet). PDF of Sentinel-3A from 2017 is also shown.

CLS

Sentinel-3 MPC

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 82

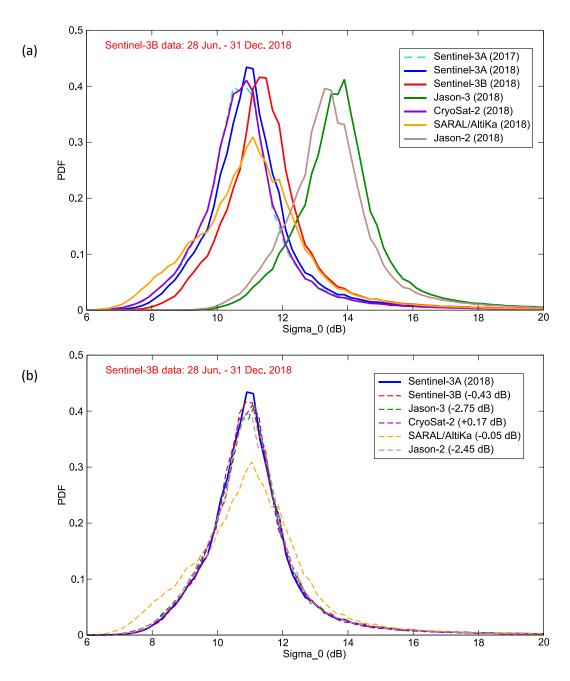


Figure 66: Panel (a): Comparison between backscatter PDF's of various altimeters for year 2018 (note that Sentinel-3B data have not covered 1 year yet). PDF of Sentinel-3A from 2017 is also shown. Panel (b): Better comparison can be carried out when PDF's are shifted to have their peak estimates coincide with that of Sentinel-3A. The amount of shift is given in the legend of panel (b).

The time series of the global (ice-free ocean only) mean and standard deviation (SD) of backscatter coefficients from SRAL of Sentinel-3A are shown in **Figure 67**. 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. Both the mean and the SD of the backscatter are stable (within \sim 0.2 dB) for most of 2017.

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 83

However, there had been a marginal increasing trend in backscatter since late 2017 and continued for about a year. This trend was reversed towards the end of 2018. This increasing trend started a month or two before the implementation of PB 2.24 on 13 December 2017. Although there is no clear connection, it is worthwhile noting that the backscatter coefficient started to be corrected for the radiometer atmospheric correction around that time. On the other hand, the upper panel of **Figure 67** shows a seasonal cycle in the global standard deviation of the backscatter with a peak during August and a trough during January. This in line with the change in storminess in the Northern Hemisphere.

For Sentinel-3B, the backscatter coefficients used to be about 0.5 dB higher than that of Sentinel-3A on average. The implementation of Sentinel-3B PB 1.13 corrected for this and since early December 2018, the backscatter coefficients from both altimeters have been the same. Both altimeters have the same global standard deviation since the beginning and that was not change after PB 1.13.

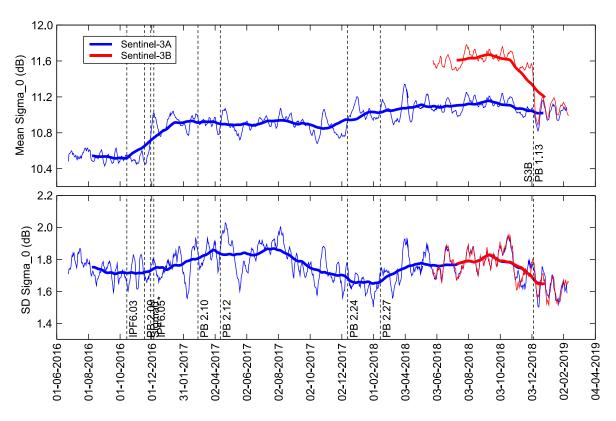


Figure 67: Time series of global mean (top) and standard deviation (bottom) of backscatter coefficient of SRAL Ku-band from both Sentinel-3A and Sentinel-3B after quality control. Mean and SD are computed over a moving time window of 7 days and are shown as thin lines. The 92-day running means are shown 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).



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 84

7.6.2 Altimeter Wind Speed

Figure 68 shows the global wind speed probability density function (PDF) of Sentinel-3A and Sentinel-3B SAR mode for the whole year 2018 (half a year in case of Sentinel-3B). 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. On the other hand, Sentinel-3B underestimates the wind speed for that period when compared to both Sentinel-3A and the ECMWF model.

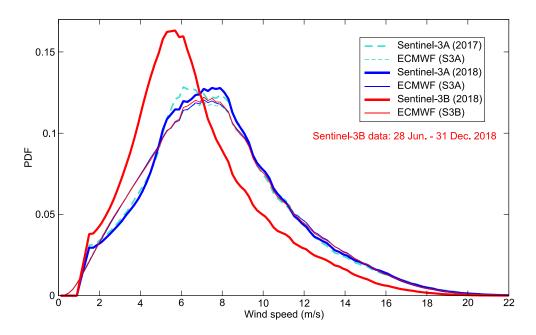


Figure 68: Sentinel-3A and Sentinel-3B SRAL surface wind speed PDF over the whole global ocean for year2018 (note that Sentinel-3B data have not covered 1 year yet). The corresponding ECMWF (collocated with Sentinel-3A and Sentinel-3B) PDF's are shown for comparison. The 2017 PDF's of Sentinel-3A and its model counterpart are also shown.

The deviation between Sentinel-3A PDF and those of the other altimeters are more pronounced as can be seen in the upper panel of **Figure 69**. The PDF's of model colocations with each satellite are shown in the lower panel of **Figure 69**. The deviation among the model PDF's as sampled along the ground track 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).

The time series of the global mean and standard deviation (SD) of the wind speed from Sentinel-3 over a 7-day time window moving by 1 day at a time are shown in the upper and lower panels, respectively, of **Figure 70**. The corresponding time series of the model are also shown for comparison. The global mean



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 85

of Sentinel-3A SAR wind speed is very close to that of the ECMWF model. The processing change in late November 2016 that involved sigma-0 calibration (part of the Processing Baseline, PB 2.09 and IPF 6.05) played the major role to bring Sentinel-3 global mean and standard deviation values closer towards the corresponding model values with a very small difference. However, after the implementation of PB 2.09, Sentinel-3A altimeter showed lower wind speed variability (standard deviation) compared to the ECMWF model. The only exception is for a short period during July each year when the variance of Sentinel-3A and the model winds are almost identical. It is unusual for the instrumental measurements to show lower variability compared to the model. This lower standard deviation continued during 2018. Note that at the scale of the super-observations (~75 km is used for this assessment) one would expect comparable SD values.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 86

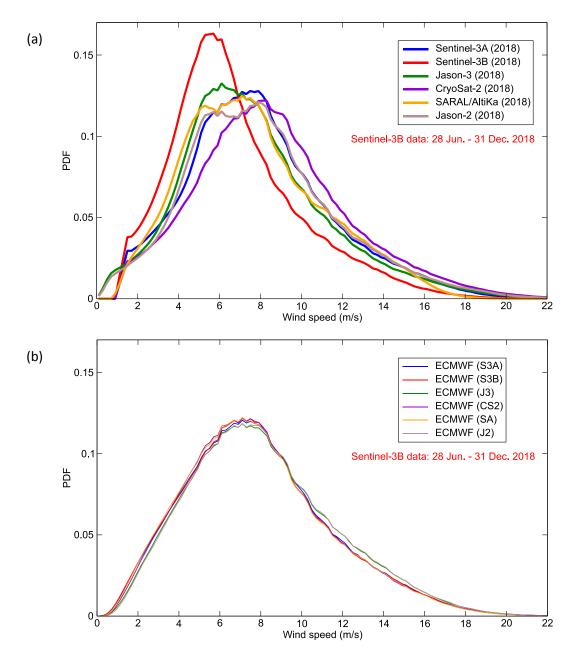


Figure 69: Panel (a): Comparison between wind speed PDF's of various altimeters for year2018 (note that Sentinel-3B data have not covered 1 year yet). PDF of Sentinel-3A from 2017 is also shown. Panel (b): The corresponding ECMWF model PDF's as collocated with the measurements. The abbreviations are as follows: S3A: Sentinel-3A, S3B: Sentinel-3B, J3: Jason-3, CS2: CryoSat-2, SA: SARAL/AltiKa and J2: Jason-2.

CLS

Sentinel-3 MPC

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 87

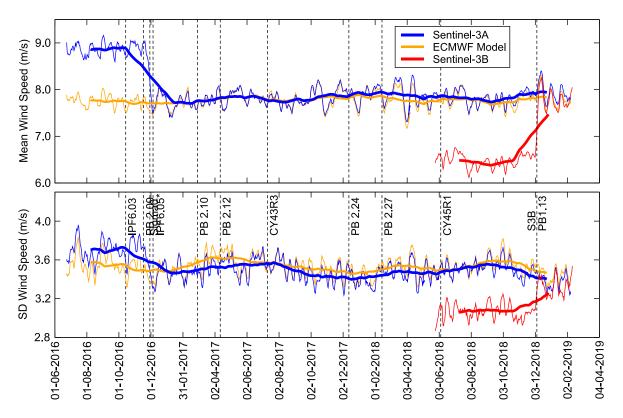


Figure 70: Time series of global mean (top) and standard deviation (bottom) of wind speed from SRAL Ku-band after quality control from both Sentinel-3A and 3B. The collocated model wind speed mean and SD are also shown. Mean and SD are computed over a moving time window of 7 days (shown as thin lines). 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.

Although it is not very clear, there is a marginal decreasing trend in the mean wind speed for about a year from late 2017 till late 2018. Clearly, this a consequence of the marginal increasing trend in the backscatter coefficient. According to **Figure 70**, PB 2.24 has no obvious impact on the wind speed measurements. However, it is possible that the marginal decreasing trend is a apparent trend due to the disruption of a seasonal cycle in the mean wind speed.

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 71** for the whole globe over the whole year of 2018. Panel (a) is for Sentinel-3A while panel (b) is for Sentinel-3B (only for the second half of 2018). The scatter plots in **Figure 71** 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 \times 0.5 m/s of wind speed.

CLS

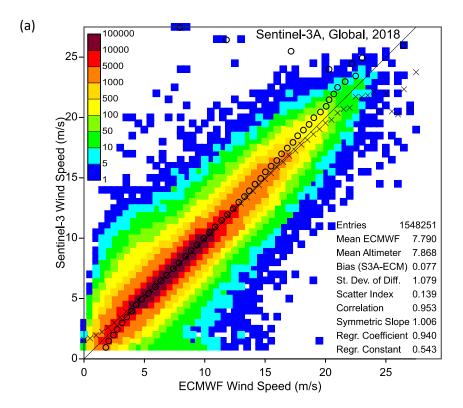
Sentinel-3 MPC

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019



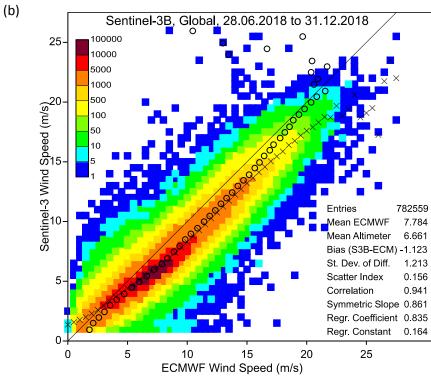


Figure 71: Global comparison of Sentinel-3A and Sentinel-3B, in panels (a) and (b), respectively, SAR surface wind speed against ECMWF model analysis for the year 2018 (Note that Sentinel-3B data have not covered 1 year yet). Number of colocations in each 0.5 m/s x 0.5 m/s 2D bin is color-coded as in 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).



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 89

According to **Figure 71** (a) the agreement between Sentinel-3A winds and their model counterpart 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 1.08 m/s. The correlation coefficient is higher than 0.95. These values are better than the equivalent statistics from the other altimeters.

On the other hand, Sentinel-3B underestimates the wind speed by more than 1 m/s as can be seen from **Figure 71** (b). This is due to the higher backscatter values which prevailed the operational product for more than five months out of the period considered here for validation. The other statistics are within acceptable values. A simple correction to the backscatter coefficient by reducing it by 0.5 dB provided very good altimeter winds (not shown). In any case, Sentinel-3B PB 1.13 corrected this issue.

The comparison against in-situ (mainly buoy) observations for the same period is shown in panels (a) and (b) of **Figure 72** for Sentinel-3A and Sentinel-3B, respectively. Sentinel-3A bias against in-situ observations for this period is rather small (about 0.1 m/s). The SDD is about 1.4 m/s which is about 17% of the mean. The correlation coefficient is higher than 0.92 and can be read from **Figure 72** (a). These figures are similar to the same statistics emerging from the comparison of wind speeds from other altimeters against in-situ observations (not shown). Of course, the in-situ verification in **Figure 72** (b) provides the same results as those provided by the verification against the model. 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 compared to the ECMWF model analysis (AN) are shown in the upper and lower panels, respectively, of **Figure 73**. Since early December 2016, when the processing change known as PB 2.09 / IPF 6.05 which was implemented operationally, the wind speed has been very good as can be seen from **Figure 73**.

The wind speed biases in Northern Hemisphere (NH, area to the north of latitude 20° N), Tropics (the area confined between latitudes 20° N and 20° S) and Southern Hemisphere (SH, area to the south of latitude 20° S) are very small values (well within ± 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 74**. 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 74**) to the NH time series with respect to the model



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 90

(Figure 73). Similar seasonal cycles to those seen in the model comparison (Figure 73) for the NH can be also seen in Figure 74.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

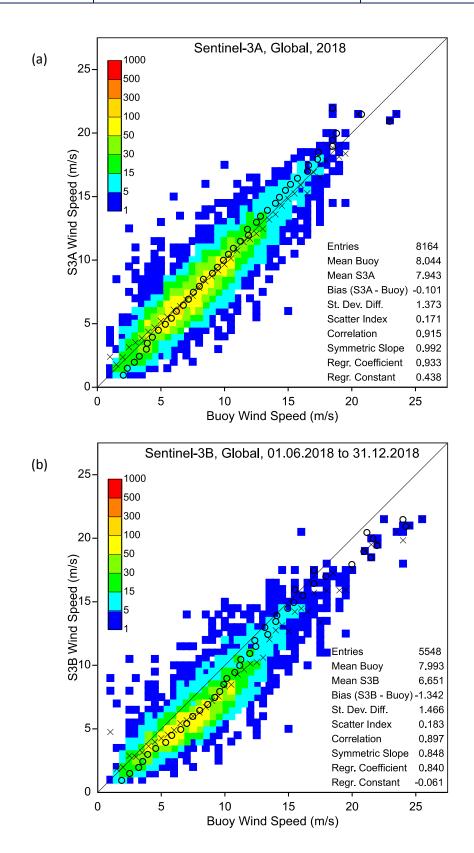


Figure 72: Same as Figure 71 but the comparison is done against in-situ observations (mainly in the NH).

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

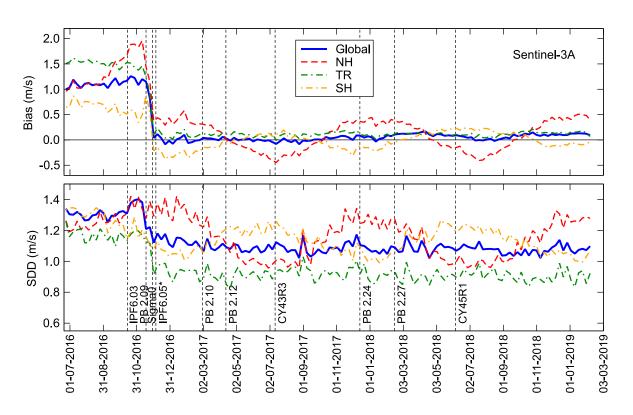


Figure 73: Time series of weekly wind speed bias defined as altimeter - model (top) and standard deviation of the difference (bottom) between Sentinel-3A SRAL Ku-band and ECMWF model analysis.

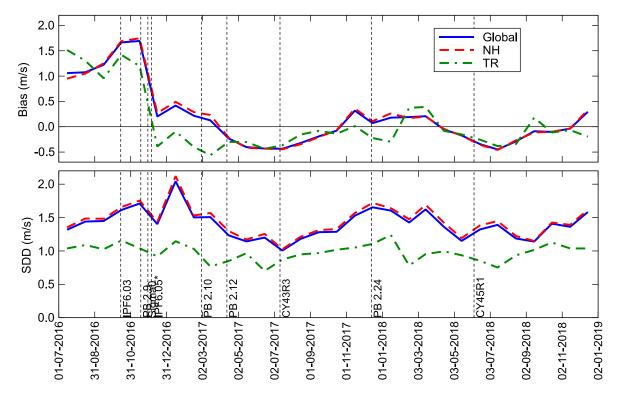


Figure 74: Time series of weekly wind speed bias defined as altimeter - buoy (top) and standard deviation of the difference (bottom) between Sentinel-3A SRAL Ku-band and in-situ (buoy) measurements.

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 93

The time series of the wind speed weekly bias (defined as the altimeter – model) and the SDD of Sentinel-3B compared to the ECMWF model analysis (AN) are shown in the upper and lower panels, respectively, of **Figure 75**. The bias of more than 1 m/s was corrected with the implementation of PB 1.13 introduced operationally in early December 2018. Since then, Sentinel-3B wind speed has been unbiased compared to the model. The time series is still too short to give any information about the trends or seasonality of statistics.

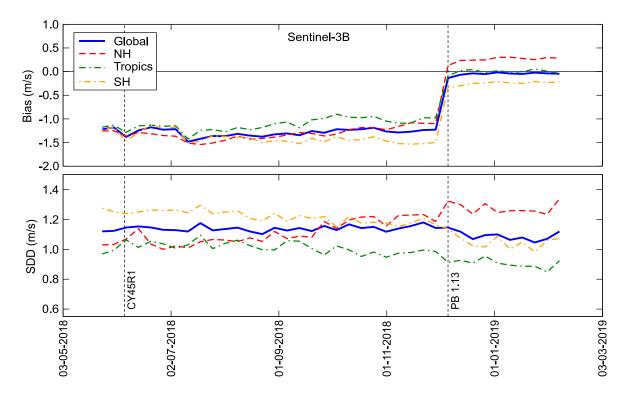


Figure 75: Same as Figure 73 but for Sentinel-3B.

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 76**. It is clear that the wind speed from Sentinel-3A shows the best agreement with the ECMWF model winds. It has the lowest global bias (almost zero) and one of the lowest SDD values. However, there seems to be minor increase in the SDD (possible degradation) during the months of November and December. Sentinel-3B winds also compare very well after the implementation of Sentinel-3B PB 1.13.

Keeping in mind that Jason-3, CryoSat-2, SARAL/AltiKa and Jason-2 are all conventional altimeters (the CryoSat-2 statistics in **Figure 76** are for LRM only), it is possible to conclude that Sentinel-3A SAR wind speed is as good as (if not better than) its counterpart from the conventional altimeters. This statement extends comfortably to include Sentinel-3B after PB 1.13 to be very good as well.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 94

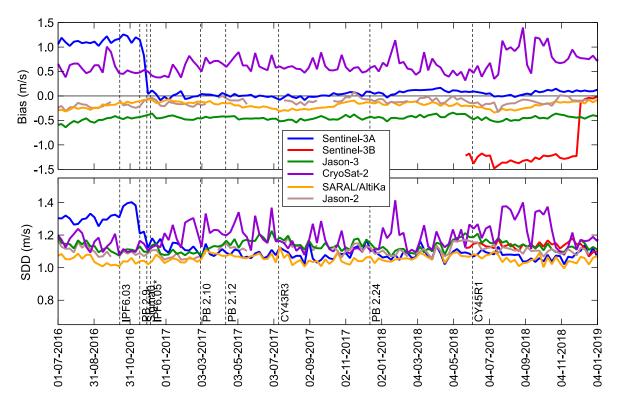


Figure 76: Time series of weekly global wind speed bias defined as altimeter - model (top) and standard deviation of the difference (bottom) between various altimeters (including SRAL) and ECMWF model analysis. Sentinel-3A and Sentinel-3B curves are same as the global curves in Figure 73 and Figure 75, respectively.

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 2018 are shown in **Figure 77** for Sentinel-3A and in **Figure 78** 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. On the other hand, Sentinel-3B biases are rather high and that is a consequence to the high backscatter coefficient before 6 December 2018.

CLS COLLECTE LOCALISATION SATELISTS

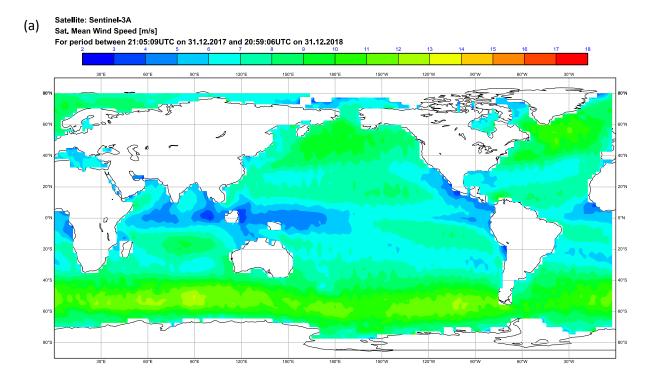
Sentinel-3 MPC

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019



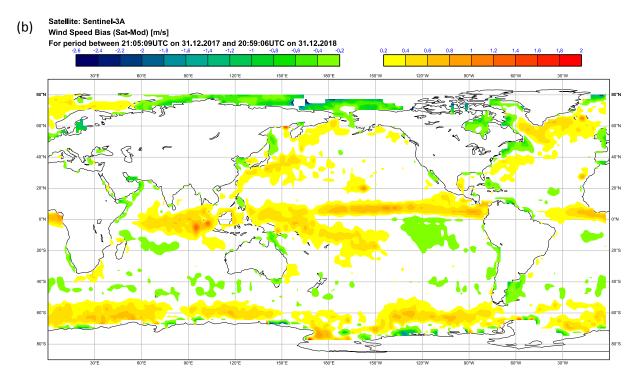


Figure 77: Geographical distribution of mean Sentinel-3 wind speed (a) as well as the bias (b); the SDD (c) and the SI (d) between Sentinel-3 and ECMWF model AN during the period from 13 December 2016 to 12 December 2017. Bias is defined as altimeter - model.

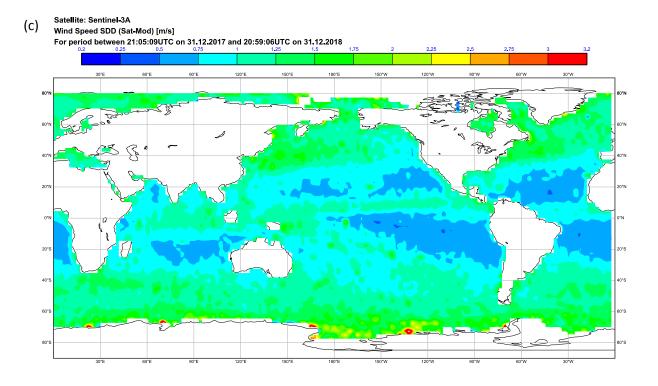


S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019



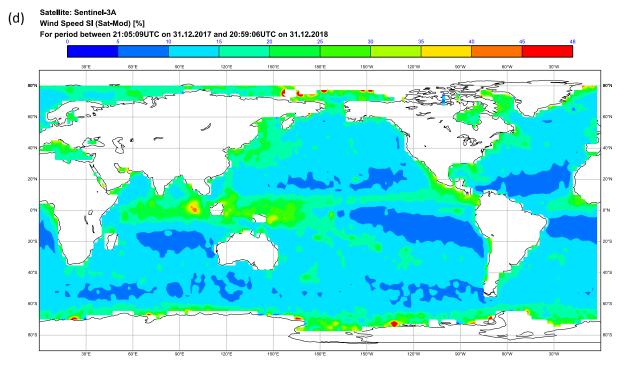


Figure 77: Continued.

CLS COLLECTE LOCALISATION SATELLITES

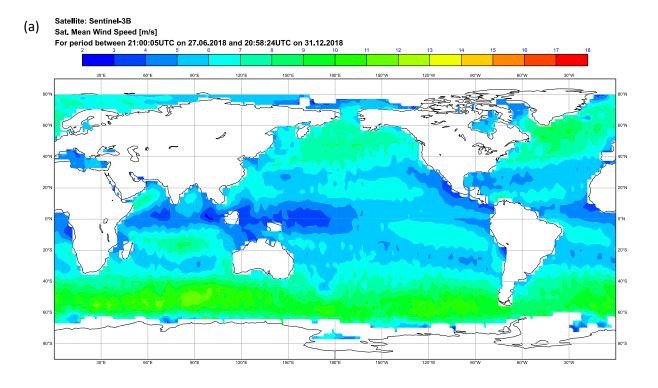
Sentinel-3 MPC

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019



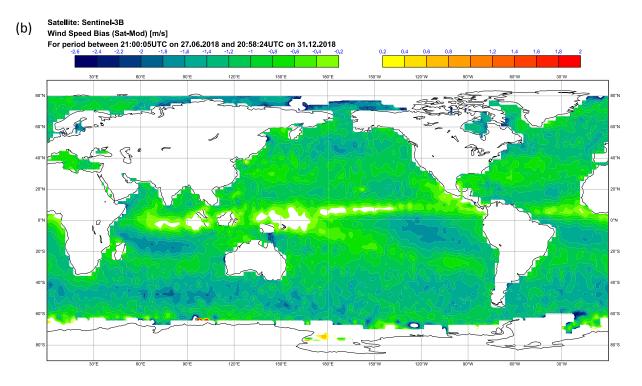


Figure 78: As in Figure 77 but for Sentinel-3B. Note that Sentinel-3B data temporal coverage is from 28 June 2018 till 31 December 2018 which is much less than 1 year yet.

CLS COLLECTE LOCALISATION SATELITES

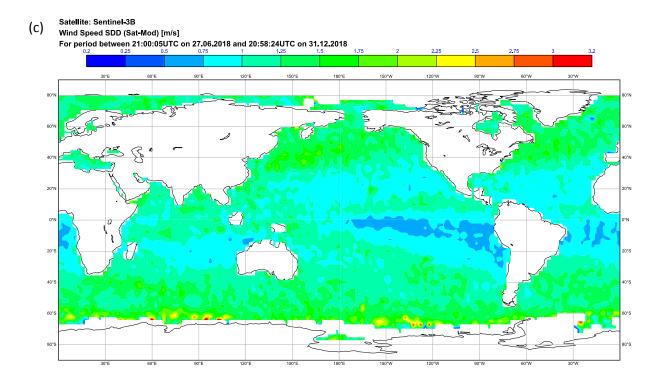
Sentinel-3 MPC

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019



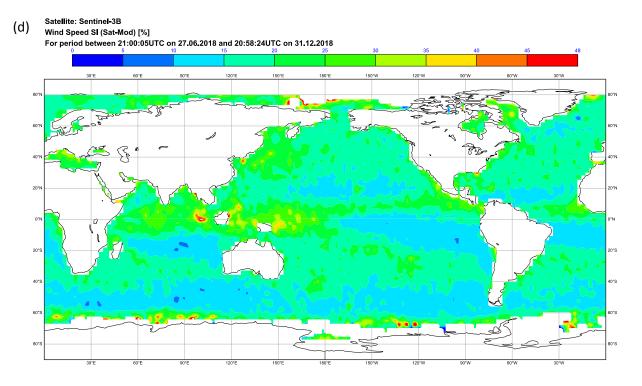


Figure 78: Continued.

GLS

Sentinel-3 MPC

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 99

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 79** for the whole globe over the whole year of 2018. It is clear that the agreement between Sentinel-3A PLRM winds and their model counterpart is very good as can be seen in **Figure 79** (a). Sentinel-3A PLRM is globally unbiased when compared to the model although small regional biases do exist (see for example the upper panel of **Figure 80**). The SDD between Sentinel-3A PLRM wind and the model for the same period is 1.36 m/s (about 17.5% of the mean) which is slightly higher than that of SAR winds (see **Figure 71**). The correlation coefficient of 0.924 is slightly lower than that of the SAR-mode wind comparison (see **Figure 71**).

On the other hand, the comparison between Sentinel-3B PLRM wind speed against the model is shown in **Figure 79** (b). This is mainly the state of the product before the implementation of Sentinel-3B PB 1.13. Similar to Sentinel-3B SAR wind, the PLRM wind shows a bias of about 1 m/s compared to the model. This issue was alleviated with the implementation of Sentinel-3B PB 1.13. However, it is interesting to note that Sentinel-3B PLRM wind product shows lower SDD and higher correlation with respect to the model than the equivalent product from Sentinel-3A irrespective of the bias.

The time series of the weekly bias and the SDD between PLRM wind speed and that of the model are shown in **Figure 80** for Sentinel-3A and in **Figure 81** 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 80** follow seasonal cycles similar to seasonal cycles followed by the corresponding time series of the SAR-model wind speed bias and SDD (**Figure 73**).

Since early September 2018, there has been a noticeable improvement is the Sentinel-3A PLRM wind agreement with the ECMWF model (lower panel of **Figure 80**). The reason for this improvement is not clear and it is now under investigation.

The time series of Sentinel-3B PLRM wind speed bias and SDD with respect to the model shown in **Figure 81** shows the positive impact of Sentinel-3B PB 1.13 in making the PLRM unbiased. It is also introduced a marginal improvement in the SDD values.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

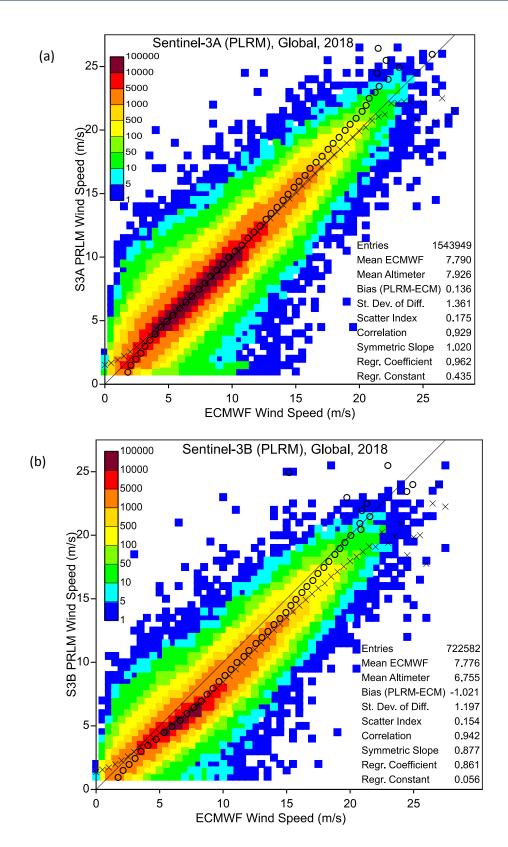


Figure 79: Global comparison of Sentinel-3A and Sentinel-3B, in panels (a) and (b), respectively, PLRM surface wind speed against ECMWF model analysis for the year 2018 (note that Sentinel-3B data have not covered 1 year yet). Refer to Figure 71 for the meaning of the crosses and the circles as well as the colour coding.

CLS

Sentinel-3 MPC

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

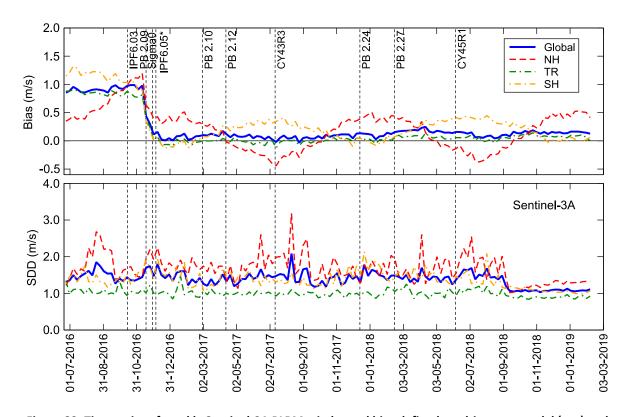


Figure 80: Time series of weekly Sentinel-3A PLRM wind speed bias defined as altimeter - model (top) and standard deviation of the difference (bottom) between SRAL PLRM and ECMWF model analysis.

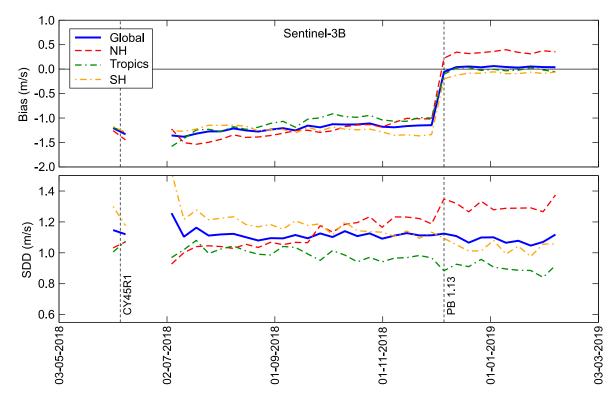


Figure 81: Same as Figure 80 but for Sentinel-3B



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 102

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 82 shows the global SWH PDF of Sentinel-3A for the whole year of 2018 and Sentinel-3B for the six-month period from 28 June till 31 December 2018. For comparison, Figure 82 shows the PDF's of Sentinel-3A for 2017 and the ECMWF model FG SWH collocated with each altimeter/period. Irrespective of the fact that Sentinel-3A data cover a whole year while Sentinel-3B covers only half that period, the PDF's from both altimeters are very close to each other. Both PDF's compare very well with Sentinel-3A PDF of 2017 apart from the enhanced hump at SWH values of less than 1 m. The corresponding model PDF's agree well with their Sentinel-3 counterparts except around the peak of the PDF (at SWH of about 2 m) and at low SWH values (below 1 m).

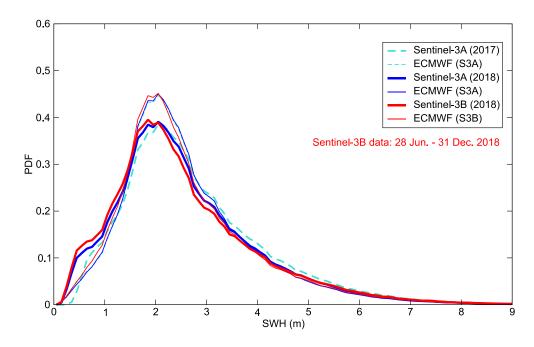


Figure 82: Sentinel-3A and Sentinel-3B SRAL SWH PDF's over the whole global ocean for the year 2018 (note that Sentinel-3B data have not covered 1 year yet). The corresponding ECMWF wave model (collocated with Sentinel-3A and Sentinel-3B) PDF's are shown for comparison. The 2017 PDF of Sentinel-3A and its model counterpart are also shown.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 103

The SWH PDF's from the altimeters on-board Jason-3, CryoSat-2 (only LRM data are used here), SARAL/AltiKa and Jason-2, which are all conventional altimeters or, in the case of CryoSat-2, operating in a conventional mode, are shown in upper panel of **Figure 83** 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 83**. The data used to produce those PDF's cover the whole of 2018 except for Sentinel-3B and its corresponding model (only six months from late June till end of December 2018).

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 and Jason-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 shown in Figure 70 of the last year report. The SWH PDF's between 65°N and 65°S) show marginal differences from those shown in Figure 83 (whole globe). 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 84**. 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 84** suggests that since the implementation of Sentinel-3A PB 2.24 in December 2017, Sentinel-3A mean SWH has reduced and became similar to the model mean value.

Figure 84 suggests that Sentinel-3B global mean and standard deviation is similar to those of Sentinel-3A. The only difference is Sentinel-3B mean SWH is consistently slightly lower than that of Sentinel-3A. As in the case of Sentinel-3A SWH, its global standard deviation is higher than that of the model.

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 85** for the whole globe over the whole year of 2018. 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 85** and other similar wave height scatter plots that appear hereafter) are plotted similar to those of the wind speed (e.g. **Figure 71**) except for the size of the 2-D bin which is $0.25 \text{ m} \times 0.25 \text{ m}$ in the case of SWH. It is clear from **Figure 85** (a) that the agreement between SWH from both Sentinel-3 altimeters and their model counterpart is very good except for a



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 104

slight underestimation at SWH values below $^{\sim}$ 2 m and an overestimation at moderate to high SWH's (above $^{\sim}$ 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 10.7 % of the mean value). The correlation coefficient is 0.983 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.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

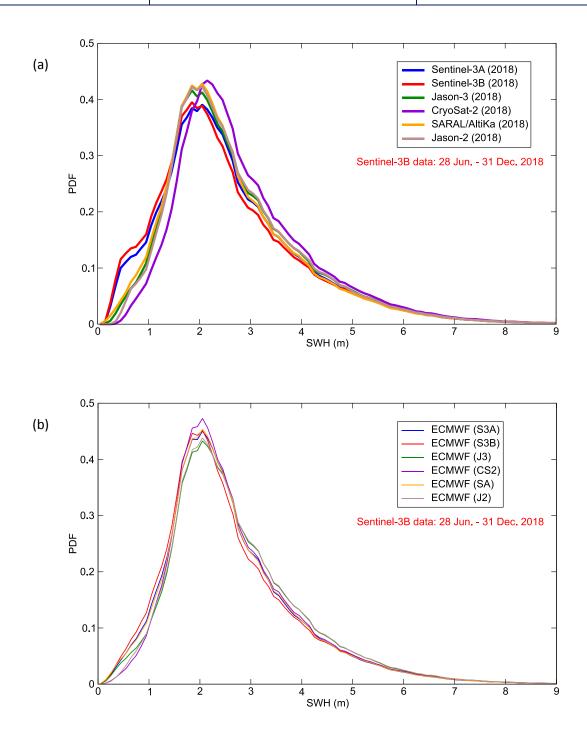


Figure 83: Panel (a): Global SWH PDF's from 6 altimeters, including Sentinel-3A and Sentinel-3B SRAL's, for the year 2018 (note that Sentinel-3B data have not covered 1 year yet). The corresponding ECMWF (collocated with each altimeter) PDF's are shown in panel (b) for comparison.

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 106

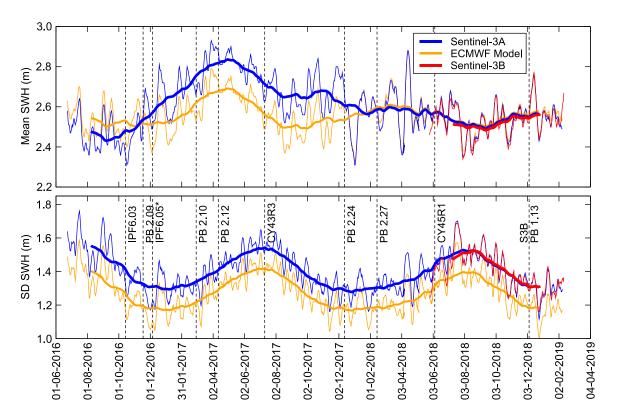


Figure 84: Time series of global mean (top) and standard deviation (bottom) of significant wave height from Sentinel-3A and Sentinel-3B SRAL Ku-band after quality control. The collocated ECMWF model SWH mean and SD are also shown. The mean and SD are computed over a moving time window of 7 days.

The wave height comparison against in-situ (mainly buoy) observations for the whole of 2018 in case of Sentinel-3A and the second half of 2018 for Sentinel-3B is shown in **Figure 86**. SWH from both altimeters is unbiased compared to available in-situ measurements for this period. The SDD (a proxy to the random error) is 0.30 m (~13.4% of the mean) and 0.28 m (~12.6% of the mean) for Sentinel-3A and Sentinel-3B, respectively. 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 87**. Since early December 2017 (Sentinel-3A PB 2.24), Sentinel-3A SWH is 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.

Similarly, the time series of the Sentinel-3B SWH bias and SDD compared to ECMWF model FG are drawn in **Figure 88**. The statistics are consistent with those of Sentinel-3A (**Figure 87**). However, since the length of time series is short, it is difficult to make conclusions apart from the obvious fact that SWH from both altimeters show similar characteristics so far.

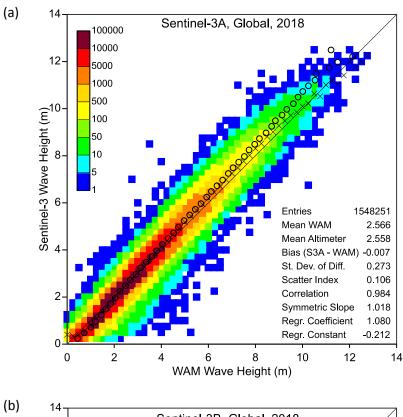


S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019



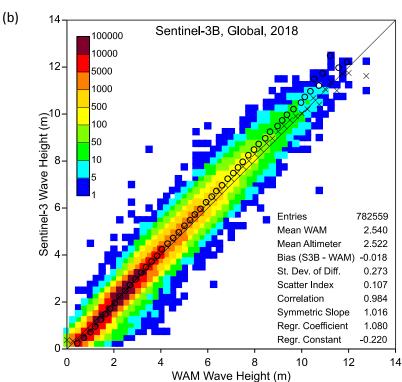


Figure 85: Global comparison of Sentinel-3A and Sentinel-3B, in panels (a) and (b), respectively, SAR SWH against ECMWF model first guess SWH values for the year 2018 (note that Sentinel-3B data have not covered 1 year yet). The number of colocations in each 0.25 m x 0.25 m 2D bin is colour coded as in the legend. Refer to Figure 71 for the meaning of crosses and the circles.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

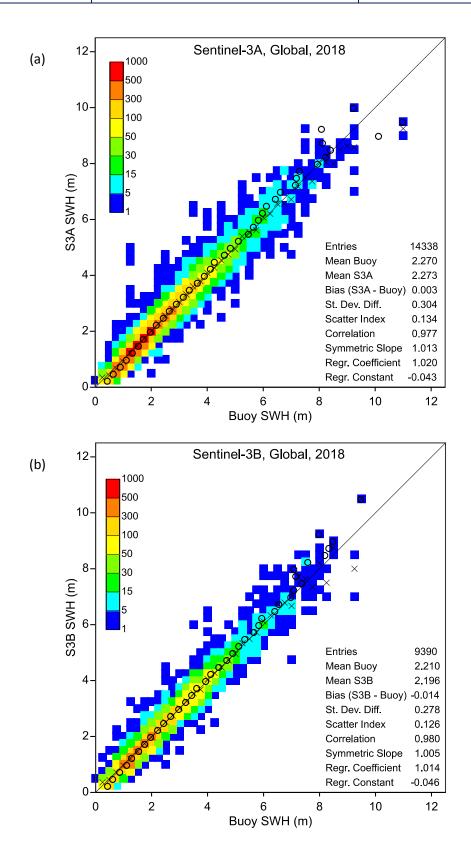


Figure 86: Same as Figure 85 but the comparison is done against in-situ observations (mainly in the NH).



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

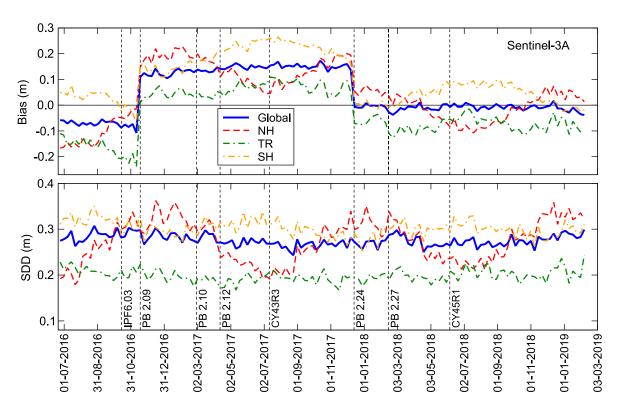


Figure 87: Time series of weekly global significant wave height bias defined as altimeter - model (top) and standard deviation of the difference (bottom) between Sentinel-3A SRAL and ECMWF model first-guess.

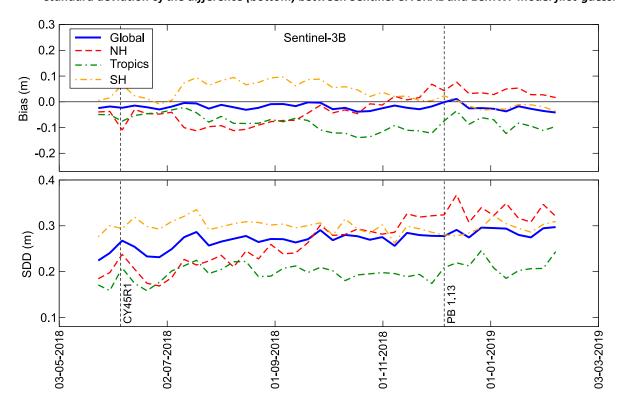


Figure 88: Same as Figure 87 but for Sentinel-3B.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 110

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 89**. 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 87**): Small bias and SDD during the summer (July-August) and higher values during the winter (December-January). Note that before the implementation of Sentinel-3A PB2.24 in early December 2017, Sentinel-3A SWH had a dominantly positive bias (see **Figure 87**).

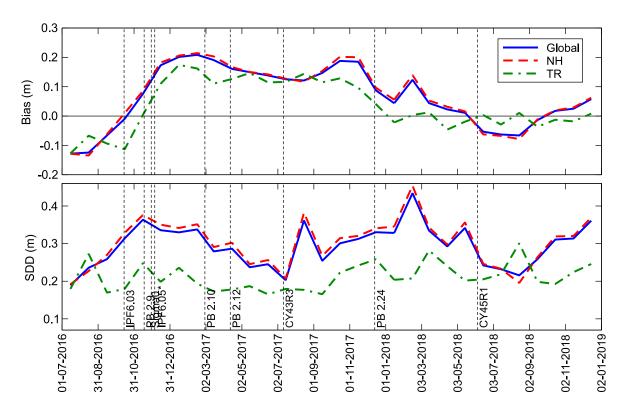


Figure 89: Time series of monthly global significant wave height bias defined as altimeter - buoy (top) and standard deviation of the difference (bottom) between SRAL and in-situ measurements.

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 90**. Since early December 2017 (the implementation of Sentinel-3A PB 2.24), the bias in Sentinel-3A SAR SWH has been one of the lowest among the 6 operational altimeters. Sentinel-3B SWH bias is also very low but tends to be consistently negative and lower than (higher in absolute sense) that of Sentinel-3A.

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



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 111

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 90**.

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 2018 are shown in **Figure 91**. All the four plots look similar to their counterparts from other altimeters (not shown). The equivalent Sentinel-3B maps but for the second half of 2018 are shown in **Figure 92**.

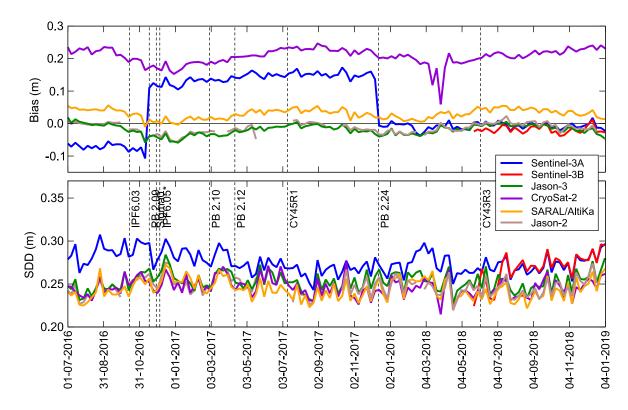


Figure 90: Time series of weekly global significant wave height bias defined as altimeter - model (top) and standard deviation of the difference (bottom) between 5 altimeters including Sentinel-3A SRAL (same as the global curves in Figure 87) and the ECMWF model first-guess.

CLS COLLECTE LOCALISATION SATELLITES

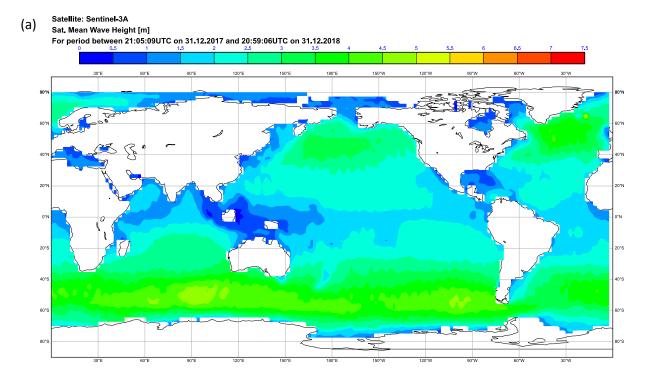
Sentinel-3 MPC

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019



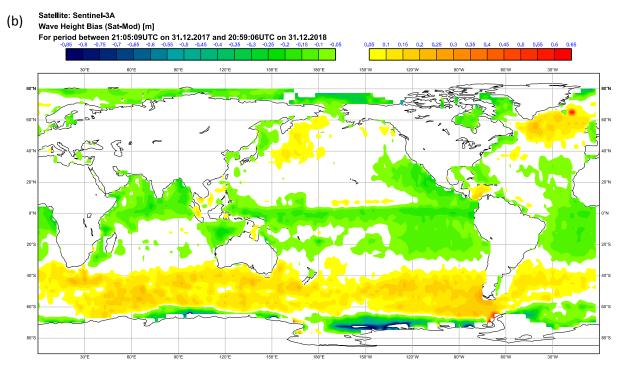


Figure 91: Geographical distribution of mean Sentinel-3A SWH (a) as well as the bias (b); the SDD (c) and the SI (d) between Sentinel-3A and ECMWF model FG during 2018. Bias is defined as altimeter - model.

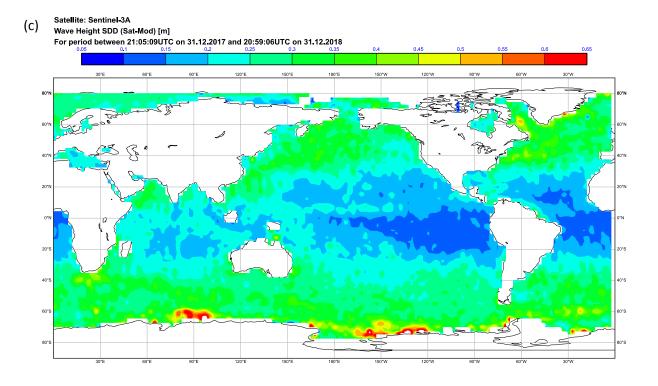


S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019



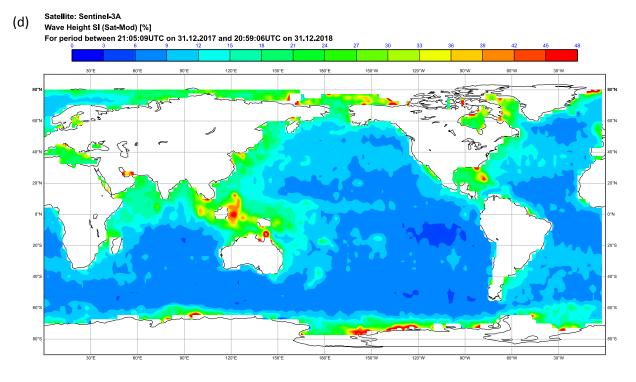


Figure 91: Continued.

CLS COLLECTE LOCALISATION SATELUTES

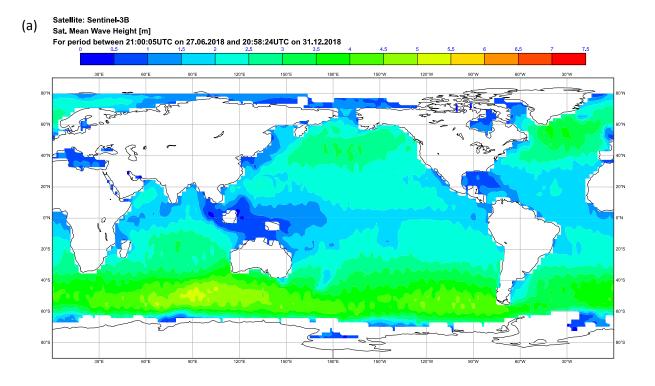
Sentinel-3 MPC

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019



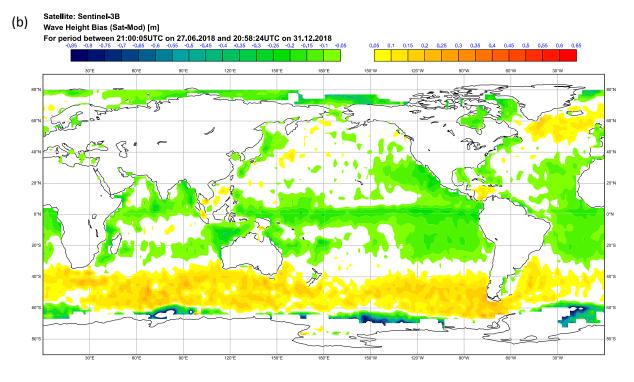


Figure 92: As in Figure 91 but for Sentinel-3B. Note that Sentinel-3B data temporal coverage is from 28 June 2018 till 31 December 2018 which is only half a year.

CLS COLLECTE LOCALISATION SATELISTS

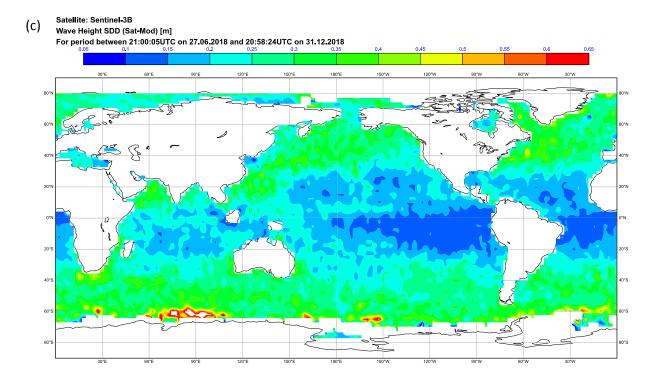
Sentinel-3 MPC

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019



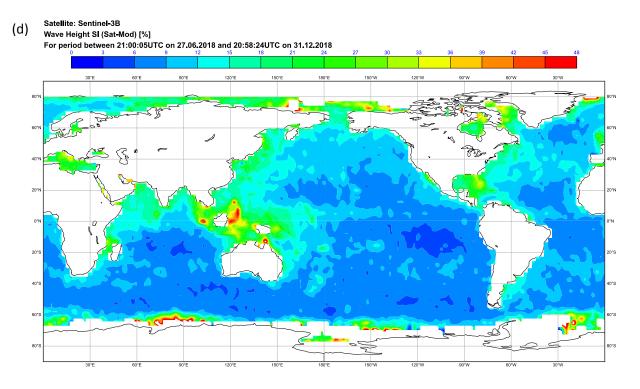


Figure 92: Continued.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 116

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. 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. However, it showed a noticeable improvement in early September 2018 but the reason is not clear so far.

The characteristics of Sentinel-3B wind and wave data are very like those of Sentinel-3A after the implementation of Sentinel-3B PB 1.13 on 6 December 2018 which eliminated the backscatter bias that degraded the wind speed products.

The following points are under close monitoring:

- There seems to be an increasing trend in global mean backscatter (and decreasing trend in wind speed) since the end of 2017. This seems to be reversed starting from September 2018.
- 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 since early September 2018.

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 117

After the implementation of Sentinel-3A processing baseline PB 2.24 (on 13 December 2017) Sentinel-3 SAR significant wave height became virtually unbiased compared to the model and the in-situ measurements. However, SRAL still overestimates high wave heights slightly according to the comparison with the ECMWF model.

❖ The implementation of Sentinel-3A PB 2.27 (on 14 February 2018) caused reduction in small wave heights below ~ 1 m.

7.7 Investigation: Quality assessment of SAMOSA 2.5 ocean retracker

The main achievements brought by the implementation of SAMOSA 2.5 retracker for SARM observations are summarized below. This update of the retracker was implemented during year 2017 the 13th of December within the PB2.24 delivery:

- The SARM range dependency with SWH is decreased as shown on the Figure 93. We observe now a discrepancy reduced to 0.3% SWH for waves greater than 4 m, compared to PLRM. Note that the SSB correction has not yet been tuned for Sentinel-3A and contains Jason-2 SSB solution. With this new version of the retracker, the results are very similar to the ones obtained with the CNES prototype (which is a completely independent processing), except for a constant bias of 1 cm between both processing. Sentinel-3B presents the same dependency as Sentinel-3A, with also a constant bias of 1cm (in line with the CNES prototype).
- The SARM SWH values are decreased by 14 cm in average as shown on the Figure 94, which provides values closer to the PLRM mode, but also to the ECMWF model and to the Jason-3 altimeter (not shown). The dependency with respect to SWH is also improved for the stronger waves greater than 5 m. With this new version of the retracker, the results are also very similar to the ones obtained with the CNES prototype, except for a constant bias of 6 cm between both processing. Sentinel-3B shows results similar to Sentinel-3A.
- ❖ The SARM backscatter coefficient showed an error correlated with the altitude in Samosa 2.3. With Samosa 2.5, this error is reduced to 0.1 dB in the regions where strong radial velocities dominate (between 30S and 60S). This is evidenced when comparing the SARM and PLRM backscatter coefficient for both Processing Baseline versions in the Figure 95. Thus, the SARM wind speed bias (with respect to ECMWF model) was reduced by 0.4 m/s in the region below 50S where the error on the SARM sigma0 was the greater (regions of stronger altitude).



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

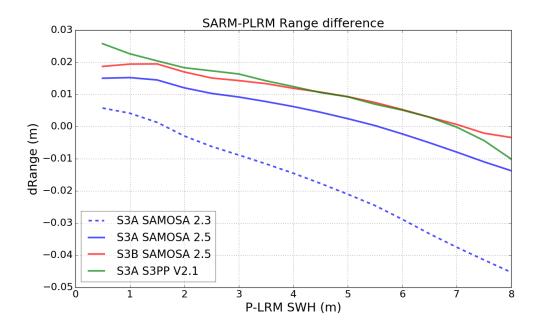


Figure 93: Difference between SARM Ku band and P-LRM Ku band range wrt P-LRM SWH for Sentinel-3A Samosa 2.3 (dashed blue curve), Sentinel-3A Samosa 2.5 (solid blue curve) and Sentinel-3B Samosa 2.5 (red curve). The curve obtained for the CNES S3 prototype (green curve) is also represented to provide an external reference.

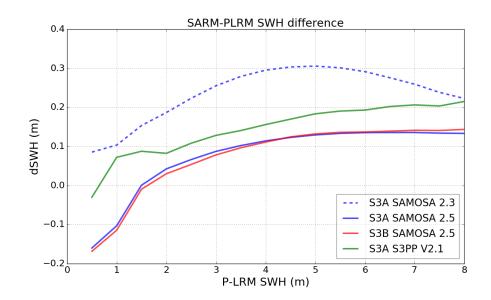


Figure 94 Difference between SARM Ku band and PLRM Ku band SWH wrt SWH for Sentinel-3A Samosa 2.3 (dashed blue curve), Sentinel-3A Samosa 2.5 (solid blue curve) and Sentinel-3B Samosa 2.5 (red curve). The curve obtained for the CNES S3 prototype (green curve) is also represented to provide an external reference.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 119

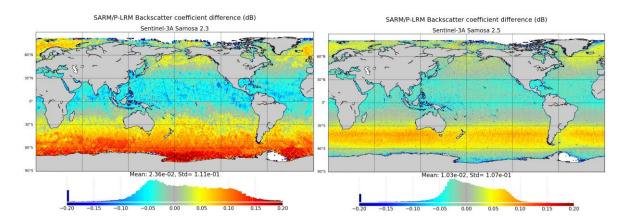


Figure 95 Difference between SARM Ku band and P-LRM Ku band backscatter coefficient for Sentinel-3A Samosa 2.3 (left map) and Sentinel-3A Samosa 2.5 (right map).

7.8 Investigation: SARM Sensitivity to the tracker command

Over ocean, SRAL operates in Open-Loop mode and the tracking command is given by a Digital Elevation Model (DEM) loaded onboard. This model, over ocean, is based on the MSS and does not take into account the effects of the atmosphere on the range and the effects of the tides on the surface elevation. Thus, the echoes positions vary following the difference between the SSH measured and the corresponding MSS. This is not an anomaly and this behavior was expected, it is identical as for other altimetry missions.

However, the SARM model implemented in the IPF SAMOSA DPM 2.3 (from March 2016 to December 2017) was sensitive to this parameter. Figure 96 shows this impact on the backscatter coefficient. Separating ascending and descending tracks on the difference between SARM and P-LRM, different geographical patterns are observed with discrepancies of 0.3 dB compared to P-LRM and with a different signature between ascending and descending maps. These patterns are correlated with the position of the waveform leading edge in the tracking window (Figure 96 bottom panel). Such dependency to the epoch was also found for the range and SWH.

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 120

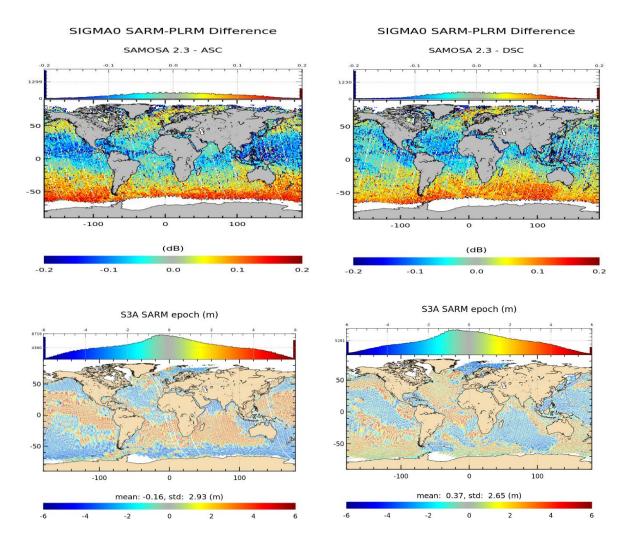


Figure 96: Top panels show the gridded map of Sentinel-3A collocated backscatter coefficient differences between SARM and P-LRM for ascending (left panel) and descending (right panel) passes. These maps were computed using L2 measurements derived from SAMOSA DPM2.3. Bottom panels shows the corresponding variation of the epoch for ascending (left panel) and descending (right panel) passes.

With the implementation of SAMOSA 2.5, the ocean retracker was updated. Thanks to the reprocessing, this version of the retracker is the one used over the complete Sentinel-3A time period. The same analysis on the backscatter coefficient from SAMOSA 2.5 is shown on Figure 98. Ascending and descending tracks maps are now homogenous, as shown on the ascending versus descending difference map (Figure 98 bottom panel). No patterns correlated with the echo centering are visible. This is an expected result of the retracker update. The same results were found for Sentinel-3B backscatter coefficient (not shown).



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 121

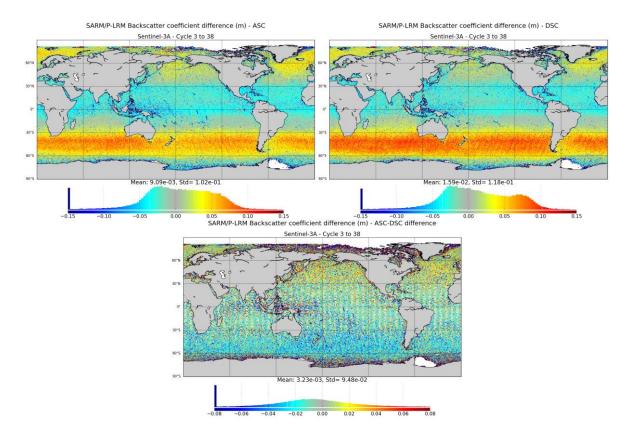


Figure 97: Gridded map of the difference between SARM and P-LRM Sigma0 for Sentinel-3A, over ascending tracks (top left panel) and descending tracks (top right panel). Difference between ascending and descending tracks computed from the above gridded maps of SARM-PLRM SWH difference (bottom panel). These maps were computed using L2 measurements derived from SAMOSA DPM2.5 (currently used version).

Figure 98 shows the results for the Significant Wave Height for both Sentinel-3A and Sentinel-3B. These maps highlight differences between the two track orientations. However, as the SWH estimations are impacted by the sea state (see results in section 7.7) it is hard to say if some of the discrepancies are related to the echo centering. Performing the difference of these two maps (Figure 99) shows clearly the correlation to OLTC patches for Sentinel-3A. Due to the shorter time period, Sentinel-3B difference map is noisier but the correlation to the echo centering is already also visible.

CLS COLLECTE LOCALISATION SATELITES

Sentinel-3 MPC

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

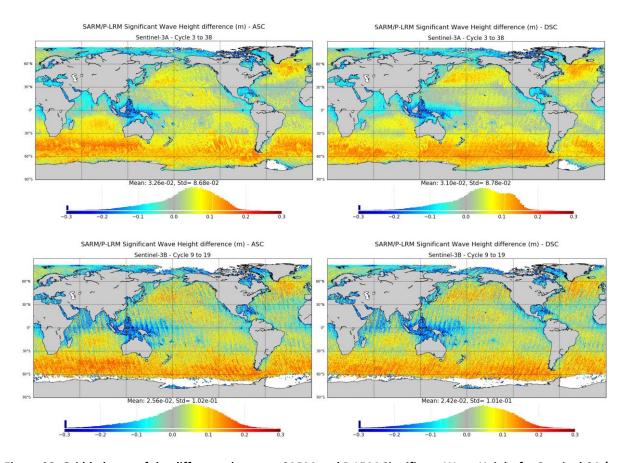


Figure 98: Gridded map of the difference between SARM and P-LRM Significant Wave Height for Sentinel-3A (top panels) and Sentinel-3B (bottom panels), over ascending tracks (left panels) and descending tracks (right panels). These maps were computed using L2 measurements derived from SAMOSA DPM2.5 (currently used version).

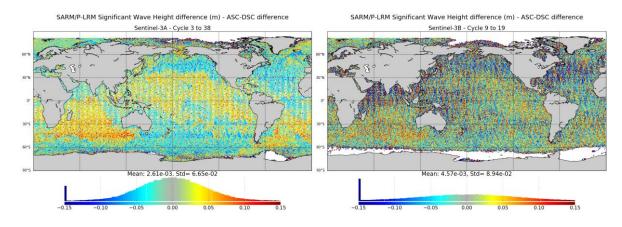


Figure 99: Difference between ascending and descending tracks computed from gridded maps of SARM-PLRM SWH difference, for Sentinel-3A (left panel) and Sentinel-3B (right panel). These maps were computed using L2 measurements derived from SAMOSA DPM2.5 (currently used version).



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 123

7.9 Investigation: SRAL Sensitivity to the Swell Waves

The first evidence of impact of swell on SARM altimetry real data was shown by Aouf and Phalippou in 2015. Trough the comparison between the MFWAM model and the Cryosat-2 SARM SWH, they demonstrated that the altimeter measurements are likely biased by ocean swell, and most noticeably for longest waves and swell fields propagating in a direction parallel to the satellite track. More recently, Moreau et al. (2018) were able to go a bit further in our understanding and explanation of the phenomenon, showing a high correlation between the 20-Hz noise of the altimeter-derived estimates and the swell parameters (namely the period, the swell height and the direction of swell propagation), without however clearly determined errors in SARM estimates due to the restricted number of ocean areas operated in this radar mode.

Unlike Cryosat-2, Sentinel-3A operates in full SARM orbit. This global coverage gives the opportunity to better understand and characterize the specificities of the SARM technique using real data. The impact on biases and noise of the altimeter parameters assessed in this section were computed by using collocation between Sentinel-3A data and WaveWatch3 wave model.

The Figure 100 shows polar plots of the average range noise for wave heights ranged between 2 and 3 m. The radial distance of the plot corresponds to the mean period and the angle of the plot represents the azimuth angle difference between the track and the mean swell direction. A zero angle means the track and the swell are collinear and for 180°, they are anti-collinear. The whole period available (1 year) was used to compute the SARM (left panel) and the P-LRM (right panel) results.

The SARM and P-LRM range noise increase with the mean wave period whatever the azimuth angle between swell and track directions. However, from the lowest to the highest period, the SARM range noise is approximatively twice higher whereas in P-LRM it is only $^{\sim}$ 10% higher. This strong sensitivity of the SARM range noise to the swell long waves is mainly due to the footprint resolution.

The SARM range noise increases faster when the waves propagate in the along-track direction (0° and 180°) than in the across-track direction (90° and 270°). There is a ratio of 12% between range noise in along-track and across-track configurations (for wave periods higher than 6s). Regarding the P-LRM SWH noise, the increase is homogeneous as a function of the angle which means that swell direction has no impact. As for the range noise, this difference of sensitivity to the swell direction between SARM and P-LRM approaches is related to the footprint shape.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 124

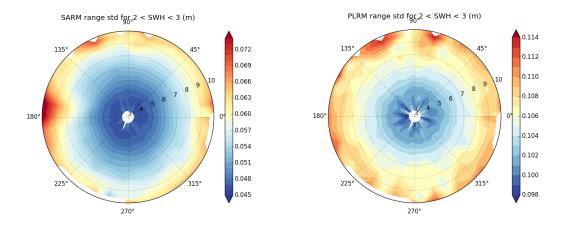


Figure 100: Polar plot of the SARM (left panel) and P-LRM (right panel) range noises as a function of the mean swell period and as a function of the azimuth angle between swell and track directions. The wave height was fixed between 2 and 3 m.

The analyses performed previously demonstrate the sensitivity of the SARM approach to the swell waves characteristics for very short wavelengths below 7 km. Figure 101 shows the polar plots of the difference between SARM and P-LRM SWH at long wavelength for wave heights ranged between 2 and 3 m. The radial distance of the plot corresponds to the mean period and the angle of the plot represents the azimuth angle difference between the track and the mean swell direction. A zero angle means the track and the swell are collinear and for 180°, they are anti-collinear.

It is clear that the bias between SARM and P-LRM SWH decreases while the swell period increases:

- For the lowest swell periods, the SWH bias is around 25 cm, which is consistent with Figure 94.
- For the highest swell periods, the SWH bias decrease to 15 cm.

Thus, it is clear that, at long wavelength, the SARM SWH parameter is sensitive to the swell period. This result confirms the observations made by Abdalla (2017) and Moreau et al. (2018) by comparing the SARM SWH to model outputs. This plot also demonstrates the impact of the relative azimuth angle on the SARM SWH values. When SWH are ranged between 2 and 3 m and the swell mean period equals 8 s, the bias between SARM and P-LRM SWH is around 25 cm when the swell propagation is perpendicular to the satellite direction. In the same SWH and TO2 conditions, it reaches 18 cm if the two directions are parallel.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 125

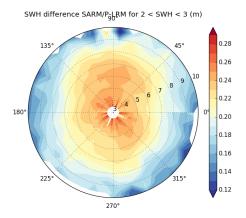


Figure 101: Polar plot of the SWH differences as a function of the mean swell period and the azimuth angle between swell and track direction.

7.10 Investigation: Long term drift

Long term monitoring of the difference between SARM and P-LRM on one hand and between Sentinel-3A and Jason-3 missions allows to detect potential drift on the parameters derived from the altimeter. The following analysis is performed for Sentine-3A SWH, range and backscatter coefficient. As far as today the Sentinel-3B time series is too short for computing relevant statistic.

7.10.1 SWH long term analysis

The daily mean of the difference between Sentinel-3A SARM and P-LRM SWH is presented on Figure 102 (blue curve) over Sentinel-3A complete life time. A selection on the latitude is performed to avoid any impact of the ice: |latitude|<50°. First thing to notice is the important jump of about 4mm on the 24th of June 2016, when the onboard SRAL radar database was updated. In order to be more realistic, the fit used to estimate the drift is performed after this date.

A small drift of 0.08 cm/year is found here. Comparing each mode to Jason-3 (green and red curve), we found 0.6 cm/year drift on SARM SWH and 0.5 cm/year drift on PLRM.

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 126

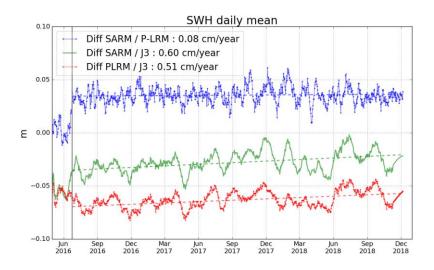


Figure 102: Daily monitoring of the difference between SARM and P-LRM for Sentinel-3A Significant Wave Height (blue curve). Green and red curve show the difference between Sentinel-3A SARM and Jason-3 SWH and the difference between Sentinel-3A P-LRM and Jason-3 SWH, respectively. The slopes indicated in the legend are computed from the 24th June 2016.

Figure 103 shows the same plot but a selection was applied to select only SWH ranged between 1.5 and 2.0 m. For this interval of wave height, the mean differences change. A drift of 0.25 cm/year is observed for Sentinel-3A SARM SWH with respect to Jason-3. On the other hand, no significant drift is observed between Sentinel-3A P-LRM SWH and Jason-3 SWH. Compared to Jason-3 or to PLRM, the SARM SWH exhibits the same bias and the same temporal patterns.

The same metrics over various SWH intervals are presented on Figure 104. It confirms that Sentinel-3A SARM SWH drifts with respect to both P-LRM SWH and Jason-3 SWH significantly depends on the SWH values (Figure 104 top and middle panels).

For Sentinel-3A SARM SWH, the trend is dominated by low SWH. When comparing to Jason-3 (Figure 104 middle panel), the drift is of 0.26 cm/year for SWH lower than 0.5 m and of 0.15 cm/year for SWH between 0.5 and 1m. This highlights the retracker sensitivity to small waves (SWH < 1.5m). Another strong drift of 0.25 cm/year between Sentinel-3A SARM SWH and Jason-3 is observed for SWH between 2.0 and 2.5m.

For Sentinel-3A P-LRM SWH, the drift with respect to Jason-3 is low and does not depends on the SWH values (Figure 104 bottom panel).

With only two years of data, it is difficult to clearly determine a trend. The slopes found here are low and can be impacted by annual signal (visible on low SWH categories for the SARM/P-LRM monitoring). As stated in the previous section 7.9, the SARM SWH at long wavelength is also sensitive to the swell period and direction. As the swell period is usually correlated to the SWH, these effects may have an impact on the monitoring and the drift estimations.

CLS COLLECTE LOCALISATION SATELITES

Sentinel-3 MPC

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 127

Preliminary analyses performed on the uncertainty computation give the following figures:

- Over 8 year time series the uncertainty (at 2 sigma) equals 1.7 cm/year
- Over 2 year (S3A time series) the uncertainty equals 7.5 cm/year

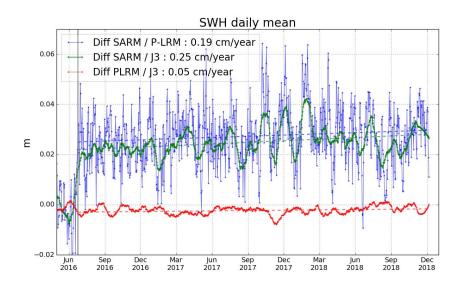
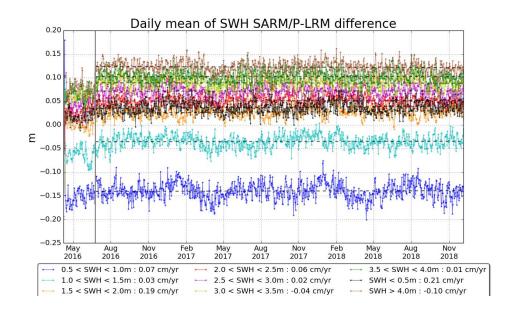


Figure 103: Daily monitoring of the difference between SARM and P-LRM for Sentinel-3A Significant Wave Height (blue curve). Green and red curve show the difference between Jason-3 and Sentinel-3A SARM SWH and the difference between Jason-3 and Sentinel-3A P-LRM SWH, respectively. These monitoring is performed for P-LRM SWH between 1.5 and 2.0m. The slopes indicated in the legend are computed from the 24th June 2016.





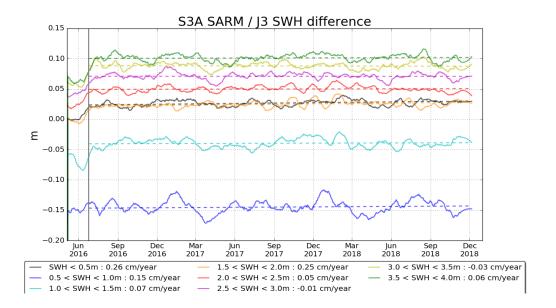
S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 128



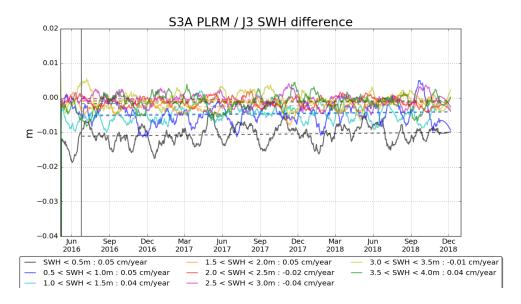


Figure 104: Monitoring of SWH difference between Sentinel-3A SARM and PLRM (top panel), between Jason-3 and Sentinel-3A SARM (middle panel), and between Jason-3 and Sentinel-3A P-LRM. The slopes indicated in the legends are computed from the 24th June 2016.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 129

7.10.2 Range long term analysis

The daily mean of the difference between Sentinel-3A SARM and P-LRM range is presented on Figure 105 (blue curve) over Sentinel-3A complete life time. A selection on the latitude is performed to avoid any impact of the ice: |latitude|<50°. The red curve shows the same metric with a selection on the waves (2.0 < SWH < 2.5m).

A 1 mm/year drift is found between Sentinel-3A SARM and P-LRM ranges. This behaviour does not depend on SWH values, as shown with the red curve and on Figure 106.

However, this drift is not constant in time. On Figure 99, an estimation of the drift evolution is performed. It clearly highlights a stronger drift at the beginning of the mission (up to 3 mm/year). This drift decreases as a function of time until June 2017. After, the drift is stabilized around 0.5 mm/year, and seems to show an annual signal of about 1 mm/year amplitude. A longer time period is required to confirm this assumption.

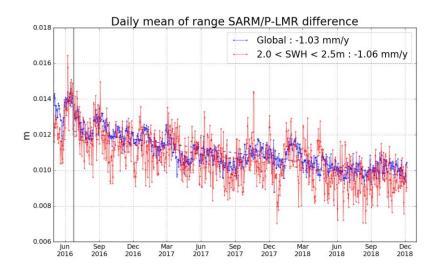


Figure 105: Daily monitoring of the difference between Sentinel-3A SARM and P-LRM range, over the complete range of SWH (blue curve) and for P-LRM SWH between 2.0 and 2.5 m (red curve). The slopes indicated in the legend are computed from the 24th June 2016.

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 130

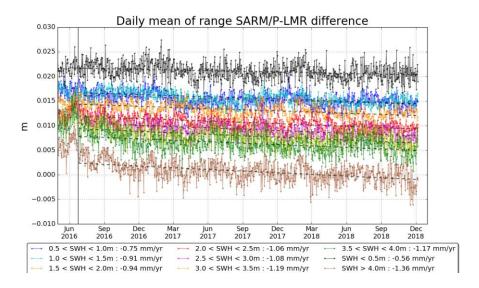


Figure 106: Daily monitoring of the difference between Sentinel-3A SARM and P-LRM range, over various intervals of P-LRMSWH. The slopes indicated in the legend are computed from the 24th June 2016.

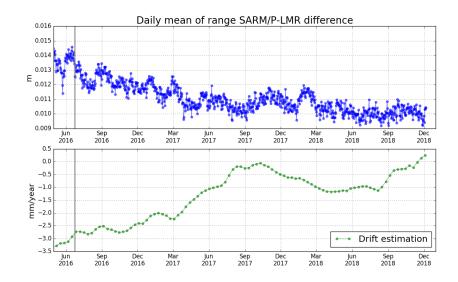


Figure 107: Daily monitoring of the difference between Sentinel-3A SARM and P-LRM range (top panel) and the evolution of its drift estimation (bottom panel).

Figure 108 shows the evolution of Sentinel-3A Sea Level Anomaly with respect to Jason-3. A change of behaviour is observed in June 2017, which is consistent with the above monitoring of range SARM/P-LRM difference.

At the beginning of the mission, the SARM SLA drift with respect to Jason-3 was stronger (up to 5 mm/year) and then decreased with time until June 2017, where it stabilized to a value close to 0. P-LRM



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 131

SLA drift estimation with respect to Jason-3 is more stable in time and does not highlight any strong drift.

From June 2017, the drifts with respect to Jason-3 are consistent for SARM and P-LRM. Another change is visible from September 2018, where both SARM and P-LRM SLA start to drift more from Jason-3. A longer time period is required here to draw conclusions.

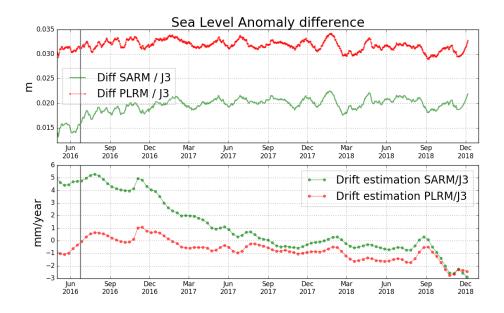


Figure 108:Top panel: Monitoring of the Sea Level Anomaly difference between Sentinel-3A SARM and Jason-3 (green curve) and between Sentinel-3A P-LRM and Jason-3 (red curve). Bottom panel shows their respective drift evolutions.

To conclude, SARM range was drifting until June 2017 with respect to P-LRM and Jason-3 and seems stable after this period. A longer time period is required to fully validate this stability, as the drift seems to evolve at the end of the time series presented here.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 132

7.10.3 Backscatter coefficient long term analysis

The same study was performed for Sentinel-3A backscatter coefficient. Results could be slightly different than those obtained in section 7.6.1 since in this case, the last reprocessing dataset PB2.27 was used and concatenate with operational products derived from 2.33 (very similar PB in term of L2 results over ocean). Figure 109 highlights a small drift of 1.6 10^{-3} dB/year between Sentinel-3A SARM and P-LRM sigma0. When comparing to Jason-3, the drift is higher for Sentinel-3A SARM (4 10^{-3} dB/year) than for Sentinel-3A P-LRM (2.5 10^{-3} dB/year).

Figure 110 shows the same metrics computed for various P-LRM wave selections. Looking at the SARM/P-LRM differences (top panel), no significant drift difference is observed from one wave category to another. The comparisons to Jason-3 present a high noise level. However, we note that the drift for both Sentinel-3A modes with respect to Jason-3 is higher for small waves (SWH < 1.5m) and for waves between 2 and 2.5m. A longer time period is required here to validate this assumption.

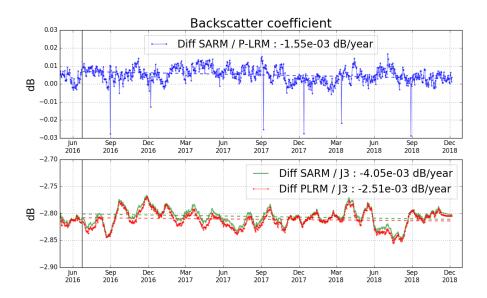


Figure 109: Daily monitoring of the difference between SARM and P-LRM for Sentinel-3A backscatter coefficient (blue curve). Green and red curve show the difference between Sentinel-3A SARM and Jason-3 sigma0 and the difference between Sentinel-3A P-LRM and Jason-3 sigma0, respectively. The slopes indicated in the legend are computed from the 24th June 2016.

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 133

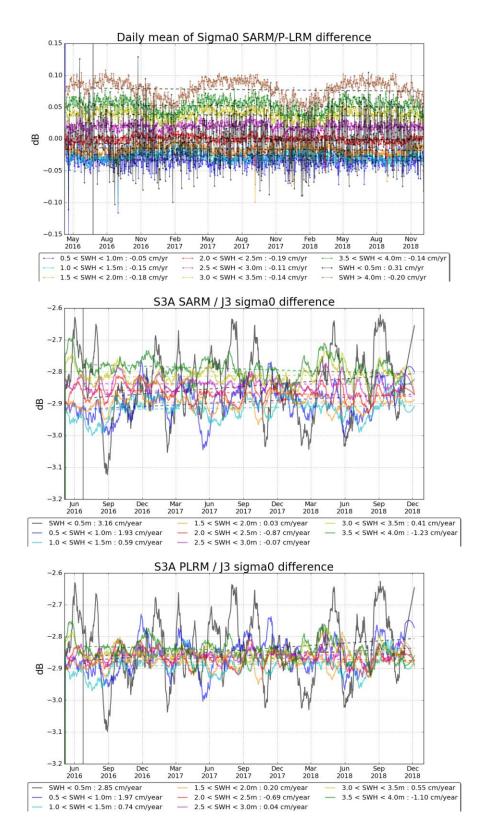


Figure 110: Monitoring of the backscatter coefficient difference between Sentinel-3A SARM and PLRM (top panel), between Jason-3 and Sentinel-3A SARM (middle panel), and between Jason-3 and Sentinel-3A P-LRM.

The slopes indicated in the legends are computed from the 24th June 2016.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 134

7.11 Performance over Coastal areas

7.11.1 Altimeter characteristics and performances

The results presented hereafter are part of the publication Vignudelli et al, 2019 (RD20) under revision. Sentinel-3 analyses were performed in the frame of MPC activities and thus take place in this report to illustrate the specificities of Sentinel-3 radar altimeter with respect to other conventional missions.

Figure 111a) illustrates the percentage of valid measurements computed for three different kinds of Altimeter: Poseidon-2 (Jason-3), Alti-Ka (SARAL/AltiKa) and SRAL (Sentinel-3A) respectively operating in LRM Ku-band, LRM Ka-band and SARM Ku-band. The result shows a clear decrease of the number of valid measurements when the satellites approach to the coast. However, the impact of the land contamination differs for the three altimeters:

- ❖ For Jason-3, the percentage of valid measurement start to decrease around 10 km from the coast. From more than 98% in Open Ocean it reaches only 15% at hundreds of meters to the coast. The value of 10 km roughly corresponds to the radius of the altimeter footprint.
- ❖ For SARAL/altiKa, the decrease is smoother and starts around 6km from the coast. This is explained by the higher resolution of the Ka footprint for which the radius equals 5.7 km in average. Moreover, the antenna gain pattern allows to reduce the energy of the signals the farthest from the nadir (factor 2 for range gates at 4.5 km from nadir) [réf]. For the closest measurements to the coast, 50% of them could be considered as relevant for Sea Level computation.
- ❖ Finally, in the case of Sentinel-3A SARM dataset, the percentage of valid measurements decreases but more slightly than for other altimeters. It is explained by the specific geometry of the SARM footprint with its 300 m of resolution in the along-track direction.

The two polar plots show for SARAL/AltiKa b) and Sentinel-3A c) the percentage of valid SLA measurements as a function of the distance to the coast (radius of the circle) and as a function of the angle formed between the satellite ground track and the coastline (degrees of the circle). For AltiKa, as expected the direction of the satellite with respect to the coastline has no impact on the data quality (the footprint shape is circular). However, for Sentinel-3A SARM datasets an asymmetry is observed. When the satellite ground track is perpendicular to the coastline, the footprint contamination occurs much latter (theoretically at 300 m from the coast). This result would mean that in these specific cases, the SARM range measurements are almost not impacted by the coast.

CLS

Sentinel-3 MPC

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 135

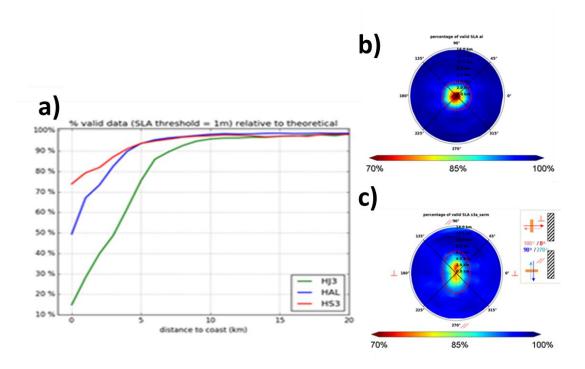


Figure 111: plot a) shows the percentage of 20Hz valid measurement computed for Sentinel-3A (red curve), SARAL/AltiKa (blue curve) and Jason-3 (green curve) datasets as a function of the distance to the coast. For this diagnosis a measurement is considered as valid if the unbiased SLA do not exceed 1 meter. Plots b) and c) shows the percentage of valid measurements for SARAL/AltiKa and Sentinel-3A datasets (respectively b) and c) panels).

The radius of the circle corresponds to the distance of the measurement from the closest coast line. The perimeter of the circle corresponds to the angle formed between the ground track of the satellite and the closest coastline. 0° and 180° angles correspond to a perpendicular approach, whereas 90° and 270° angles correspond to parallel displacement.

In addition to the altimeter signal and antenna characteristics, the tracker performances also play an important role in coastal areas. Figure 112 illustrates the altimeter tracking performances in term of number of available measurements (with respect to the theoretical High-Resolution ground track) derived from different satellites as a function of the distance to the coast. Over the period used to compute these statistics, while SRAL and Poseidon-4 tracker operate in OL mode, the AltiKa tracker is in CL (SARAL/AltiKa geodetic phase). Despite of its smaller footprint, the percentage of missing measurements for AltiKa start to increase at 10 km from the coast while it stays flat for Sentinel-3A and Jason-3. This result means that 3% (respectively 8%) of the time, at 5 km (respectively 0 km) from the coast, AltiKa tracker losses the signal and thus cannot provide Sea Surface measurements.

GLS

Sentinel-3 MPC

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 136

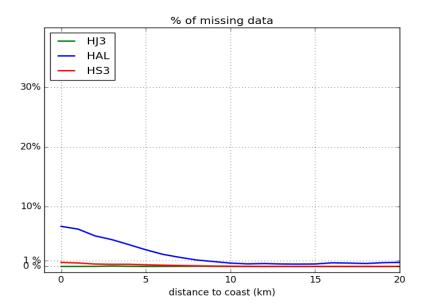


Figure 112: Percentage of 20Hz missing measurement computed for Sentinel-3A (red curve), SARAL/AltiKa (blue curve) and Jason-3 (green curve) datasets as a function of the distance to the coast. This percentage is computed with respect to their respective high resolution theoretical ground track.

Figure 113 aims at describing the impact on the final Sea Surface Height. Global statistics of mean Sea Level Anomaly were computed for Jason-3 (a), AltiKa (b) and Sentinel-3A SARM (c) datasets. First, this analysis shows, in the case of conventional altimetry (a and b plots), an unhooking when the satellites approach to the coast. For Jason-3 it appears at 6 km from the coast with a SLA decrease of 5 cm followed by a strong increase at 4 km. For AltiKa same thing is observed respectively at 4 and 2 km. For both satellites the waveforms are impacted by land backscattered signal (at different distances from the coast because of the different footprint resolutions) which impacts the estimated geophysical parameters since the Brown model dedicated to oceanic waveforms (Brown, 1977) is not suitable to retrack this kind of artefacts. Thanks to the higher resolution in the along-track direction of the Sentinel-3A SARM footprint these variations are not observed

In the case of Sentinel-3A (c) such a variation is not observed. The SLA signal appears flat until hundreds of meters from the coast. Looking more in details the different angle configurations (d) it appears that:

- in the worst case (when Sentinel-3A ground track is parallele to the coast line) the SLA behave similarly as for conventional altimetry (black curve). From 5 to 2 km to the coast a decrease is observed followed by an increase of the SLA.
- in the best configuration (Sentinel-3A ground track perpendicular to the coastline), the SLA slightly increases continuously until the coastline.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 137

Although this result (the gray curve) includes the errors related to the geophysical corrections (as mentioned in the previous section), it gives a first measure of the signal we expect to observe close to the coast when the altimeter footprint is not corrupted by land surfaces. The use of high accuracy regional models combined with the exploitation of optimal Sentinel-3A ground tracks (in perpendicular configuration with respect to the coastline) would allow to compute relevant Sea Surface Height measurements close to the coast.

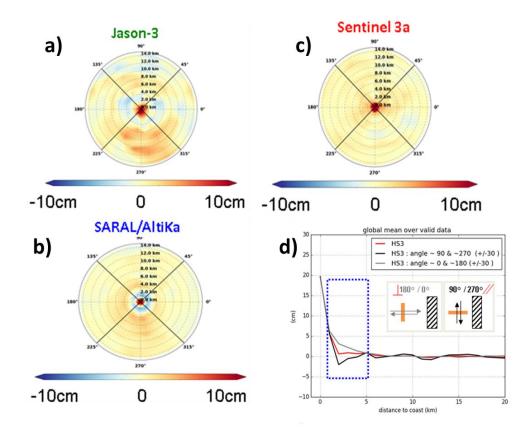


Figure 113:global average of the Sea Level Anomaly derived from Jason-3, SARAL/AltiKa and Sentinel-3A datasets (respectively a), b) and c) panels)For the three first plots, the radius of the circle corresponds to the distance of the measurement from the closest coast line. The perimeter of the circle corresponds to the angle formed between the ground track of the satellite and the closest coastline. 0° and 180° angles correspond to a perpendicular approach, whereas 90° and 270° angles correspond to parallel displacement. Plot d) is a 1-dimension representation of the Sentinel-3A SARM SLA average as a function of the distance to the coast in the global case (red curve) in the optimal case (gray curve) and in the worst case (black curve)

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 138

7.11.2 Comparison with respect to in-situ measurements

This work focused on the validation of S-3 observations in the coastal zone, where S-3 is expected to give a much better performance than most previous instruments. The analysis was based on the Sentinel-3 dataset reprocessed using the PB 2.27 and released in early February. Full resolution (SAR) and pseudo low resolution mode (PLRM) 20-Hz ku-band observations of significant wave height (variables swh_ocean_20_ku and swh_ocean_20_plrm_ku) were analysed from Cycle 002 to 031 (March 2016 to May 2018). These were compared with in-situ observations from 17 meteorological buoys near the coast of southwest England (Figure 114). The buoys are part of the Channel Coastal Observatory (http://www.channelcoast.org) and the Western Channel Observatory (http://www.westernchannelobservatory.org.uk/) and provided time series of 30-minute averages of SWH, direction and period from January 2016 to present.

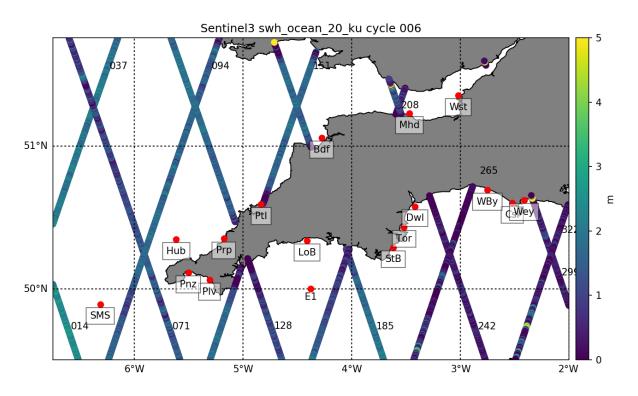


Figure 114: Examples of Sentinel-3 SWH observations in the southwest of the UK. The colour indicates the significant wave height measured during cycle 006. Number of the 12 tracks used in the analysis are displayed. The tracks intersect the complex coastal morphology at different incidence angles providing a broad range of geometrical configurations. The red circles mark the locations of the 17 meteorological buoys which provided insitu observations for the validation. The locations span offshore to inshore providing good coverage of different coastal conditions.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 139

In the last months, our analysis focused on developing an approach to objectively identify the possible combinations of coastal buoy and S-3 track to be used for the validation. In particular, since the satellite tracks are always at a certain distance from the wave buoys, we aimed at identifying whether the observations at a given buoy can be considered representative for a given track or not. To investigate the spatial correlation between the wave properties observed at a buoy location and its surroundings, we used the results from the MetOffice wave watch III model WWIII-AMM7. These consist of hourly wave fields at 7 km spatial resolution from April 2014 to present. The dataset is available from the CMEMS portal (http://marine.copernicus.eu/). For each buoy, the model results were used to compute the linear correlations between closest point to the buoy and rest of model points. Maps of correlation coefficient (r2), root mean square error (RMSE), regression slope and regression intercept such as in Figure 115 were then derived for each buoy.

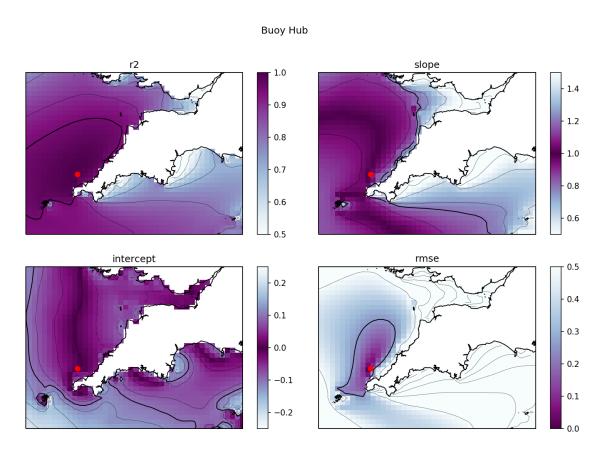


Figure 115: Spatial distribution of correlation coefficient, root mean square error, regression slope and regression intercept between the time series of significant wave height at the Hub buoy (red dot) and the rest of the model domain. The thick black curves identifies the thresholds for each parameter used to define the area of correlation. The data used for the analysis are from the MetOffice WWIII-AMM7 wave model.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 140

The points in the domain where the wave time-series were similar to those observed at the buoy location identified the area of correlation around each buoy (Figure 117). Specifically, such area was defined where the values of all four parameters satisfied the following conditions: r2 equal or larger than 0.95 (good linear relation), slope between 0.8 and 1.2 (linear regression close to the 1:1 curve), intercept between -0.1 and 0.1 (low bias) and rmse lower than 0.25 m/s (small spread around the 1:1 curve).

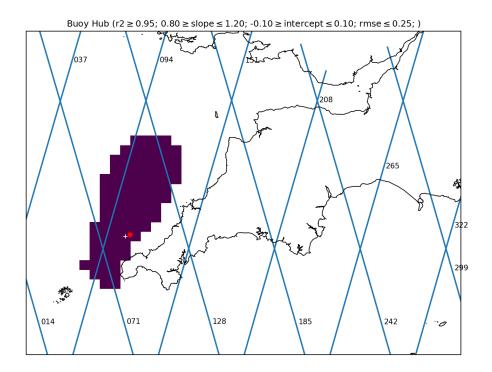


Figure 116: Area of correlation of the Hub buoy (red circle) based on the four constraints defined in the figure title. S-3 observations collected within the area are expected to be similar to the ones observed at the buoy and thus can be used for the validation.

S-3 observations collected within the area of correlation of a given buoy are expected to be similar to the ones observed at the buoy and thus can be used for the validation. The combinations of buoy and satellite tracks obtained with this objective approach, confirmed the ones already identified and used in Figure 116 to assess the improved accuracy of SAR observations with respect to PLRM.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 141

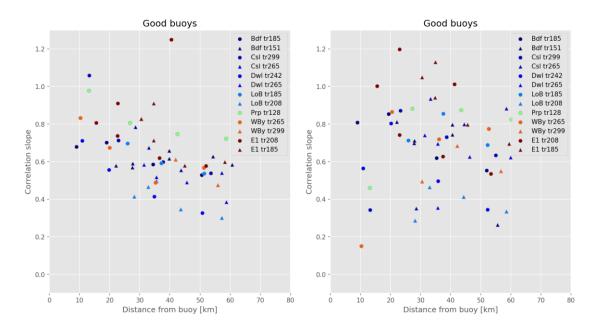


Figure 117: (Left) Correlation slope for different combinations of buoys and Sentinel-3 tracks as function of distance between the satellite observations and buoy position for SAR observations. (Right) Same as left but for PLRM observations. The figure shows overall agreement (slope 1) between buoy and satellite observations as they get closer to the buoy in SAR mode. A similar trend is not observed in PLRM mode, where the agreement between buoy and satellite observation drastically degrade within 20 km from the coast. The Hub buoy showed in Figures 2 and 3 is not included in the analysis because characteristic of open ocean conditions (i.e. wave properties in its surrounding area are not affected by bathymetry or coastline).

Analysis of Tandem data to assess consistency

We have also made a brief analysis of the consistency of data from Sentinel-3A and 3B using near-simultaneous data from their tandem mission. This initial analysis has used data from S-3B cycle 010 (cycle 033 of S-3A), with ~13 days of S-3B operating in LRM and ~13 days in SAR mode (S-3A in SAR mode for full cycle). This period of data allows us to look at any bias between the two satellites, and at the repeatability of data when both are operating in the SAR mode that will be used for constructing the long-term datasets. It also enables us to examine possible differences in output of LRM and SAR issions.

The work reported here concentrates on the products from the ocean retracker. However a cursory examination of the sigma0 values from the OCOG and ice sheet retrackers (which have output over the ocean) reveals an inconsistency in their current calibration (which we believe will be changed in a future IPF). The offsets depend upon whether instrument is in SAR mode or LRM, as shown in Table 9.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 142

	SAR	LRM
OCOG - Ocean	35.15	0.8
Ice sheet-Ocean	36.68	1.8

Table 9: Bias of S-3B σ^0 values for different definitions. (Values for bias of S-3A in SAR mode are same as for S-3B in SAR mode.)

Wave Height data

When both altimeters are operating in SAR mode, and using the same algorithms, there is negligible bias between them (solid curve in Figure 118), whereas the LRM data for S-3B show a positive bias at low wave heights, and a small negative bias at large values. The S.D. of the differences between S-3A and S-3B is consistent with the standard error in the 1 Hz data ($\mathbb{O}_h/V19$) for each instrument (see Figure 118). To assess the independence of the errors, we average the 1 Hz values in groups of 9, which corresponds to $^{\sim}60$ km along-track, similar to the "super-observations" used by Abdalla at ECMWF. This reduces the S.D. of the differences to 40% of that for the 1 Hz values (not shown), which is not quite the factor of three reduction expected if errors were totally uncorrelated.

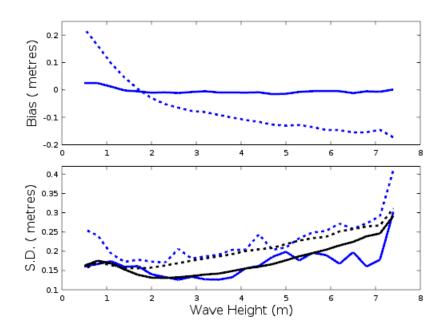


Figure 118: Comparison of 1 Hz wave height records for S-3A and S-3B as a function of wave height. a) Bias (S-3B relative to S-3A), b) Standard Deviation of Difference. (Solid lines for SAR-SAR comparison; dashed lines for LRM-SAR.) Black lines show standard error of the 1 Hz values multiplied by $\sqrt{2}$.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 143

Backscatter data

A comparison of the sigma0 values from the SAR mode data for both S-3A and S-3B shows the latter to be reading high by about 0.55 dB, with a small variation across the range of values (Figure 119). Similarly S-3B's LRM mode sigma0 values are ~0.5 dB higher than S-3A SAR mode over most of the range (up to 16 dB), but with slightly different behaviour at high sigma0 values. As this is the domain where wind speeds are already very low, this non-linear difference should not have a great impact on wind speed climatologies. The S.D. of the difference of the matched 1 Hz values is typically less than 0.2 dB when both instruments are in SAR mode (Figure 119); these values are slightly higher than would be expected from the standard error curves for the 1 Hz estimates (solid black line). There is a greater difference in S.D. of match-ups when S-3B is operating in LRM. This is probably to be expected from an MLE-4 solution including mispointing; we have not yet evaluated the effect of the sigma0 adjustment that was shown to be so effective for the Jason altimeters. Averaging the data in groups of 9 (spatial scale of ~60 km) reduces the S.D. of the LRM-SAR comparison by approximately a factor of 3 (not shown), showing that the cause of the variation is effectively uncorrelated between 1 Hz measurements. It is surprising that the standard error of the 1 Hz LRM values (black dashed line) is the same as for SAR mode.

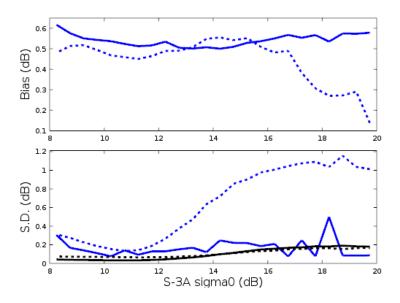


Figure 119: Comparison of 1 Hz sigma0 records for S-3A and S-3B as a function of S-3A σ^0 . a) Bias (S-3B relative to S-3A), b) Standard Deviation of Difference. (Solid lines for SAR-SAR comparison; dashed lines for LRM-SAR.) Black lines show standard error of the 1 Hz values multiplied by $\sqrt{2}$.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 144

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, the first altimetry mission to operate predominantly in this mode over sea ice.

8.1 Freeboard

The primary S3 L2 sea ice parameter is freeboard, and for all operational S3A and S3B products available in 2018 (up to and including PB2.33), there was a known freeboard L2 processor anomaly which results 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. This anomaly was corrected during 2018 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, and delivered in December 2018. The results of a test data set processed with the updated L2 algorithms (PB 2.4x) show that the freeboard now has the expected histogram distribution (peak at +0.17m). The new updated sea ice algorithms will be used in the next product baseline release in 2019.

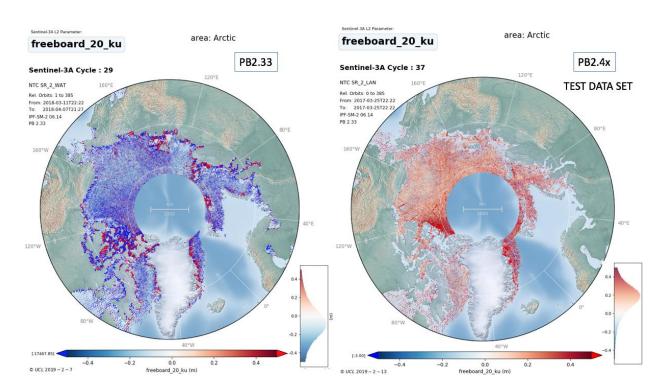


Figure 120: S3A L2 freeboard from PB2.33 (negative anomaly), and PB2.4x TDS (corrected)

The algorithm update also corrects the high values around the coastline shown in PB2.33:

S CLS

Sentinel-3 MPC

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 145

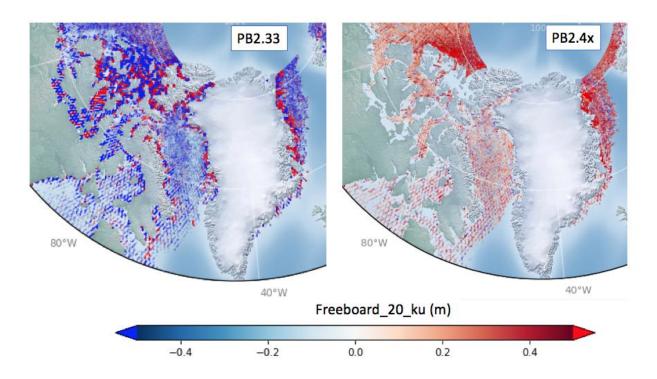


Figure 121: Anomalous high values around coastline corrected in PB2.4x

S3-A L1b IPF data was also processed through a prototype UCL sea ice processor configured with a similar L2 sea ice algorithm specification as the forthcoming IPF update and the gridded freeboard results were compared to Cryosat-2 from the same period. The results indicate similar performance over the majority of the Arctic, but with some areas of higher freeboard noise around the coastline for S3.

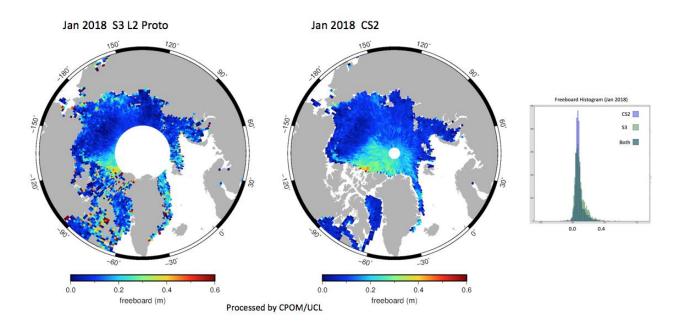


Figure 122: Comparison of S3A and CS2 Gridded Freeboard for January 2018 (CPOM Processing)



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 146

201801 S3 minus CS2 freeboard

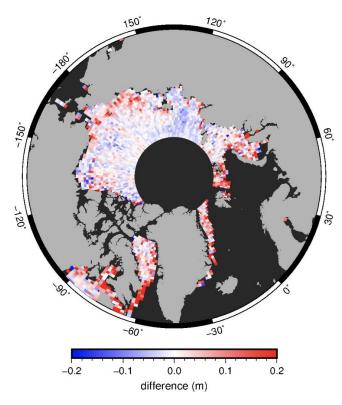


Figure 123: S3-A minus CS2 Freeboard (CPOM Processing)

The current S3 IPF L1 processing is 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.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 147

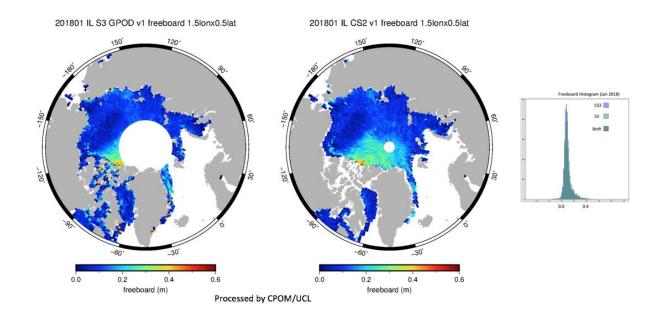


Figure 124: Comparison of S3A and CS2 Gridded Freeboard (Hamming and Zero Padding applied at L1)

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.

S3-B Freeboard Comparison

Sea ice results from S3-B during 2018 were limited as S3-B was launched in April 2018, just before the onset of the Arctic summer (when freeboard cannot be measured accurately due to the presence of melt-ponds in the sea ice). The final cycle of the tandem phase (S3-A cycle 36, S3-B cycle 13), from Sept/Oct 2018 (start of the Arctic winter season) indicate very similar freeboard performance (as processed with the current IPF PB2.33, which has a negative bias).

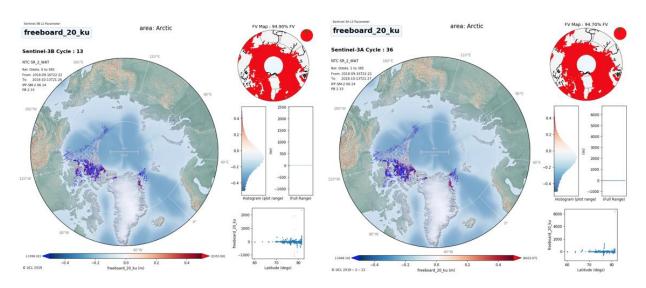


Figure 125: Comparison between S3-B and S3-A freeboard during Tandem phase

CLS

Sentinel-3 MPC

S3MPC STM Annual Performance Report - Year 2018

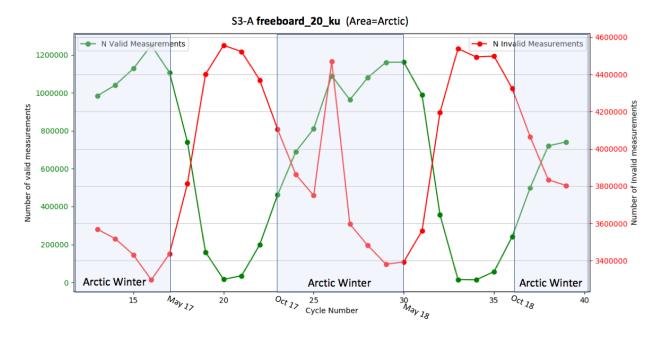
Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 148

Statistics of the number of valid and invalid freeboard measurements (from PB2.33) in the Arctic and Antarctic oceans 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.



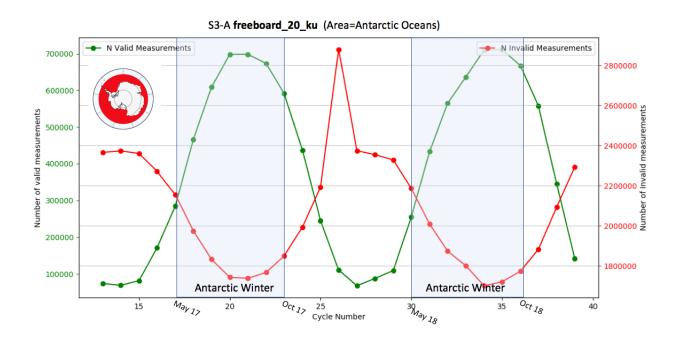


Figure 126: Number of valid and invalid freeboard measurements over S3A mission life



S3MPC STM Annual Performance Report - Year 2018

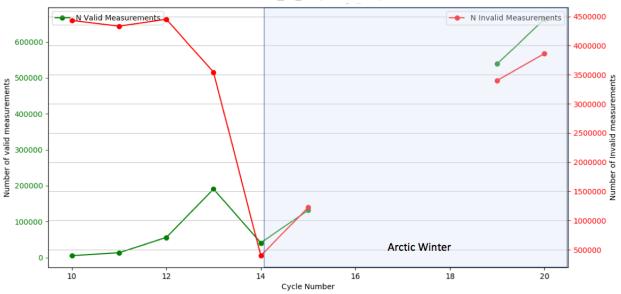
Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 149

S3-B freeboard_20_ku (Area=Arctic)



S3-B freeboard_20_ku (Area=Antarctic Oceans)

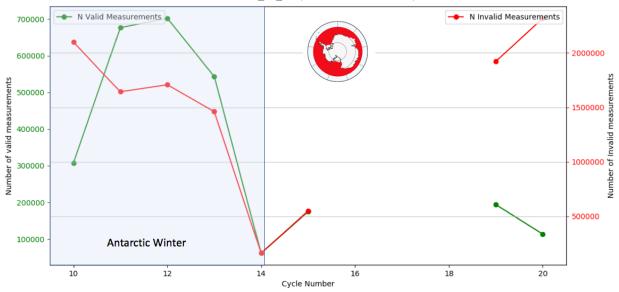


Figure 127: Number of valid and invalid freeboard measurements over S3B mission life



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 150

8.2 Sea Ice Parameters Contributing to Freeboard

Due to the known anomaly resulting in predominantly negative freeboard in all S3A and S3B products up to and including PB2.33, users are recommended not to use freeboard and related sea ice parameters (surface type discriminator, sea ice sea surface height, sea ice SSHA, sea ice interpolated SSHA). These parameters have been processed using an algorithm specification which during S3A commissioning was found to require a significant update to the floe retracker, lead retracker waveform rejection criteria, and additional SSHA filtering and masking. These parameters have been corrected in PB2.4x, the next product baseline in 2019.

Sea Surface Height (Sea Ice Retracker Failure)

In all operational cycles processed to date (PB2.33), areas of sea ice are retracked to calculate sea surface height using a single sea ice physical model retracker. This retracker (which is known to have sub-optimal performance over diffuse echoes) has been replaced with separate retrackers for leads and floes in PB2.4x. An anomaly is also present in PB2.33 relating to an incorrect waveform quality filter applied to lead echoes resulting in higher than expected retracker failure rates.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 151

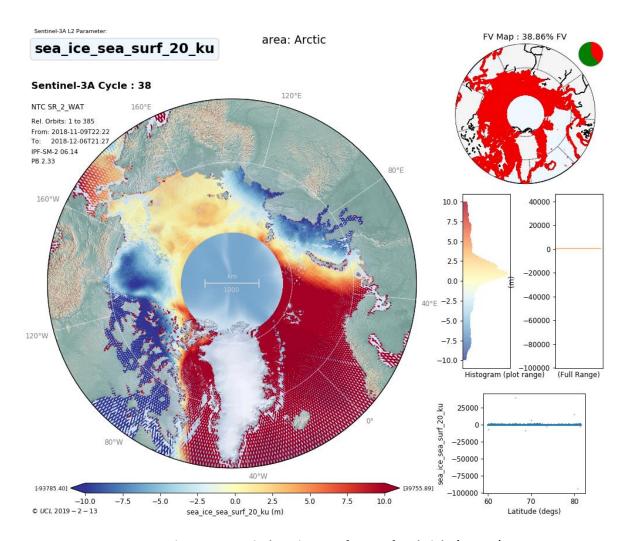


Figure 128: Typical Arctic map of sea surface height (PB2.33)



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 152

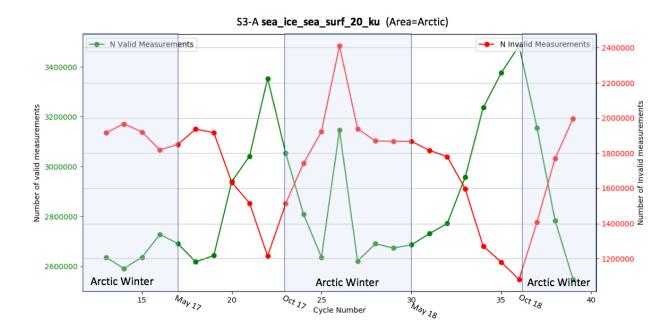


Figure 129: Statistics of Sea Ice Retracker failure in the Arctic over S3A Mission (PB2.33)

The statistics shown relate to PB 2.33 where the retracking and filtering is known to perform poorly. It is likely that the higher retracker failure rates in the winter months are correlated with greater sea ice extent (and more complex waveforms).

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 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).



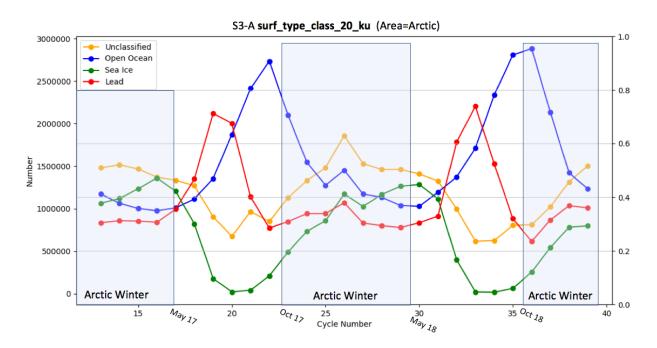
S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 153



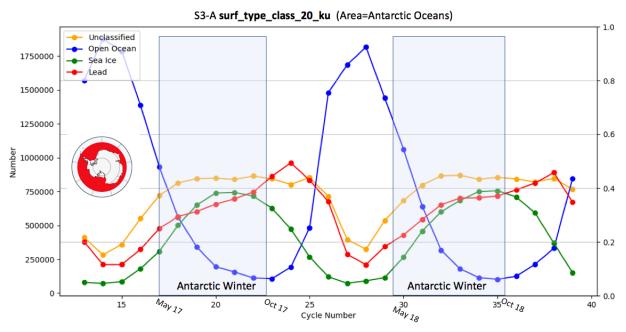


Figure 130: S3A Surface Type Discrimination since start of mission (PB2.33)



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 154

Sea Ice Concentration

In the current IPF (PB2.33) the L2 sea ice concentration parameter is linearly interpolated from contemporaneous dynamic sea ice concentration auxiliary files. The sea ice concentration grid contained within these files do not contain a land mask and sea ice concentration is set to zero over grid cells containing predominantly land surfaces. Linear interpolation of this grid results in low values around the coastline due to the inclusion of surrounding zero value land pixels. 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 users should be aware that the resulting L2 sea ice concentration parameter currently contains false low values around the coastline. In the sea ice algorithm update in 2018 (PB2.4x) the method of interpolation was changed to significantly reduce the extent of false low values around the coastline in line with the method used in Cryosat Baseline-D.

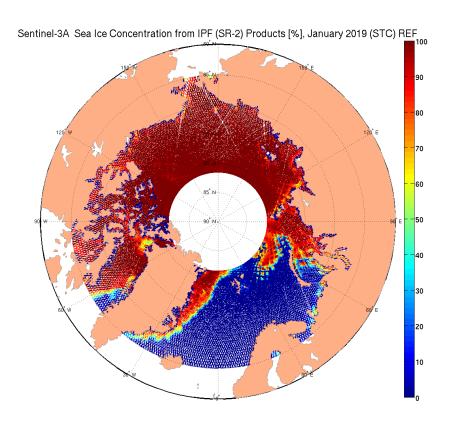


Figure 131: L2 Sea Ice Concentration has zero values around the coastline (PB 2.4x), EUMETSAT plot.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 155

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 seaice 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 (Dec 2018) 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 2018 (PB 2.33), 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 ³	100	100
Snow Density ¹	100	100
Snow Depth	100	100 ²

Table 10: % Availability of Snow Density, Snow Depth, Sea Ice Concentration over Sea Ice

¹Snow Density is set to a single value of 400 Kg/m³ as expected.

² Snow depth over Antarctic sea ice is set to zero as expected.

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



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 156

9 Mission Performance over Land Ice

In this section the mission performance over land ice for S3A and S3B from the operational L2 product (PB2.33) is shown.

Note that the operational L2 product (PB2.33) is 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 the standard IPF L1 processor does not optimally window and centre the waveform over areas of high slope (> 0.3°) such as the ice sheet margins, which can result in truncation or missed echoes. A L1 solution to this issue was prototyped during Q4 2017, and during 2018, significant progress was made with the development and validation of a specialized L1 IPF processing prototypes for land ice, which will be delivered to ESA in Q1 2019, and used to produce an optimally reprocessed L2 land ice data set from the S3A and S3B operational archives. This will be made available to users alongside the standard operational product.

Whilst separate specialized L1 processing is required for optimal performance over the more complex ice surfaces, work has continued during 2018 to improve the performance of the current L2 operational products over land and sea ice surfaces, which are able to produce good results over the majority of the ice sheets (which have low slope), when tuned to operate with the current ocean optimized L1 input data.

Detailed results of S3A land ice performance to date were accepted for publication in the *Cryosphere* in Q1 2019 (*McMillan et al, 2019*).

A large amount of effort during 2018 was spent on commissioning of S3B. Results from the S3B commissioning and tandem phases will not be reproduced here, but will be delivered in a separate dedicated report in Q2 2019. Instead results from S3B operational phase are shown in this report.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 157

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

During the first 11 cycles of the mission, S3A operated in open loop tracking mode (onboard DEM based tracking) over the ice sheet margins.

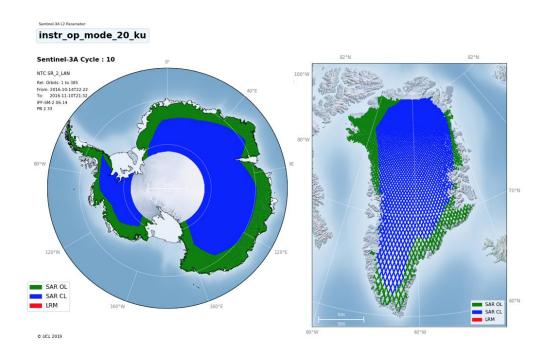


Figure 132: S3A SAR Tracking Mode over Ice Sheet Margins (cycles 3-11)

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 and it is unlikely that these measurements can be fully recovered by future ground processing. It is possible that the new Land Ice specialized L1 processor 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 (PB2.33).



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 158

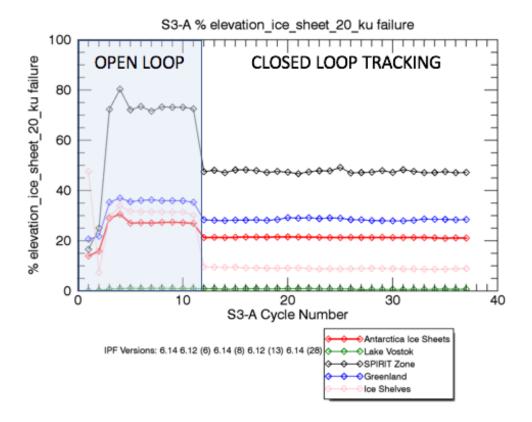


Figure 133: S3-A Elevation failure rates in Open Loop and Closed Loop cycles over Different Ice Surfaces

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*).



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 159

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°) 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.

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).

A typical example of the variability and repeatability of the OCOG elevation measurements of the centre of Lake Vostok over a 6 month period from S3-A cycle 19-25 is shown below, with a median standard deviation from the mean profile of 7cm, and a mean bias to the Cryosat DEMs of 26cm.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

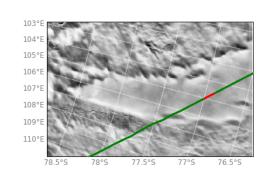
Page: 160

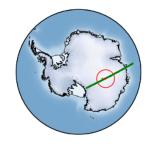
Shot-to-Shot Precision
Reference cycle 25
Previous cycles compared: 7
S3A pass 138 relative orbit 69

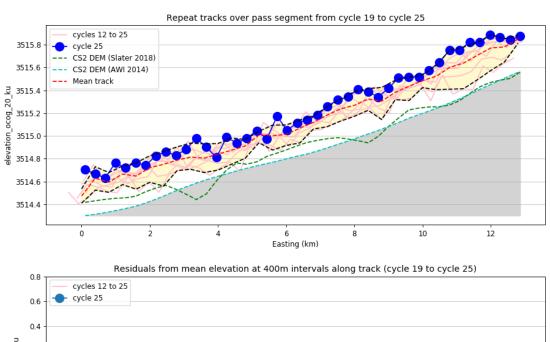
Area: Lake Vostok Centre

S3A L2 Parameter:

elevation_ocog_20_ku







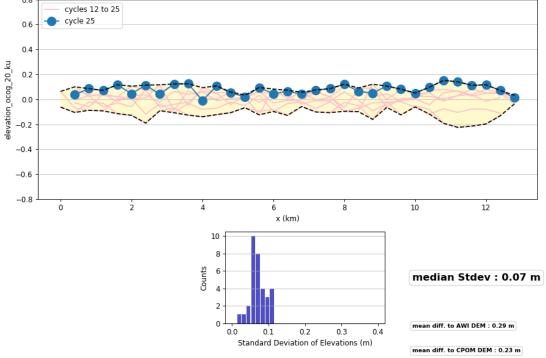


Figure 134: S3A Shot-to-shot Precision over Lake Vostok (6-month period)



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 161

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.

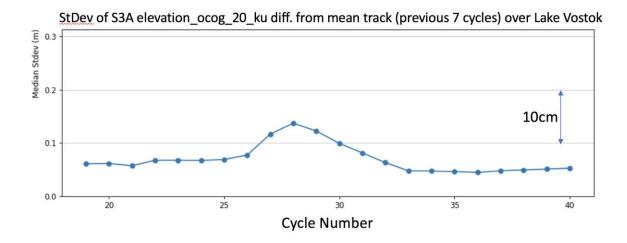


Figure 135: S3A Repeat Measurement Precision over Lake Vostok

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.

GLS

Sentinel-3 MPC

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 162

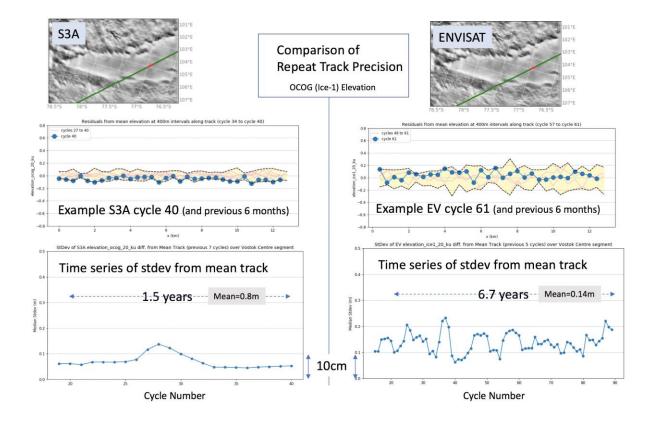


Figure 136: Comparison of measurement precision between S3A (SAR) and ENVISAT (LRM)

From this analysis it appears that S3A (PB2.33) 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.

<u>Crossover Precision over Lake Vostok Centre</u>

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 39), the mean differences was -0.002m, and standard deviation 0.079m. This agrees very well with the previous repeat track precision analysis (0.08m stdev).



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 163

Crossover Differences

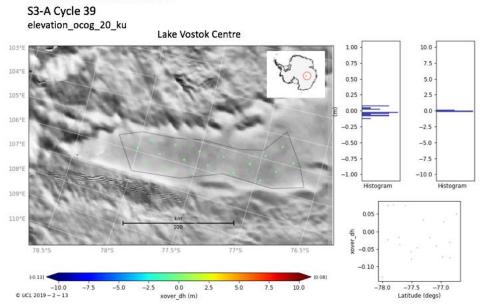
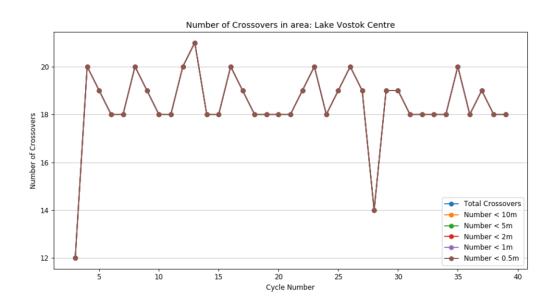


Figure 137: Crossover OCOG Elevation Differences at Lake Vostok Centre (cycle 39, PB2.33)



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 164

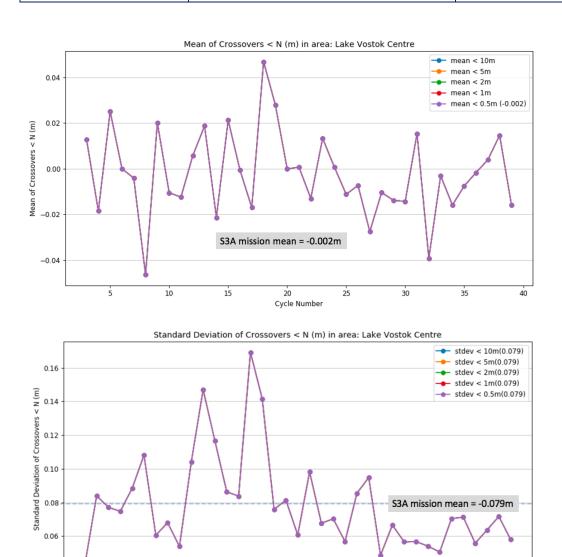


Figure 138: Crossover S3A Mission Statistics at Lake Vostok Centre (OCOG Elevation differences)

Cycle Number

35

For operational cycle 20, S3B had a mean crossover difference over Lake Vostok of 0.009m (S3A mission mean 0.002m), and a standard deviation of 0.066m (S3-A mission mean=0.079m).

Crossover Precision over the Antarctic Ice Sheet

0.04

Crossover differences over the Antarctic ice sheet shows the expected slope dependence, with higher differences over the margins (slope $>0.1^{\circ}$). In these regions, the processes of locating the echoing point within the beam footprint, and of retracking complex multi-peaked waveforms become more challenging.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 165

Cross-overs 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.

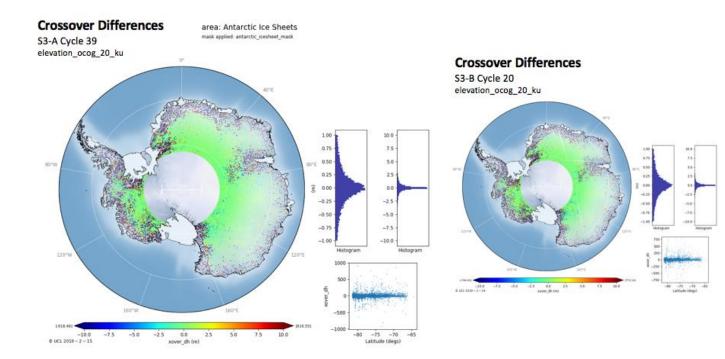
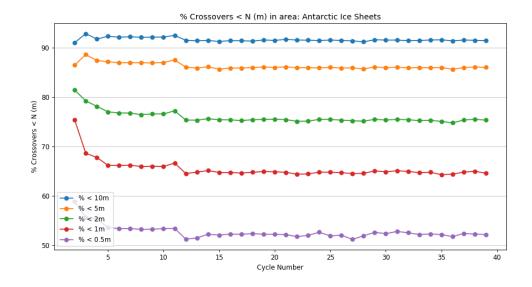


Figure 139: Crossover OCOG Elevation Differences over Antarctic Ice Sheet (S3A cycle 39, S3B cycle 20, PB2.33)





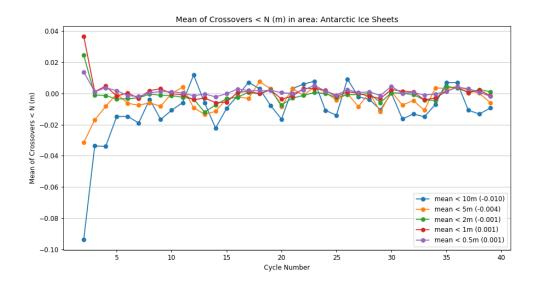
S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 166



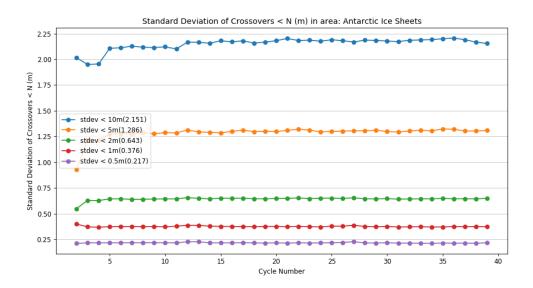


Figure 140: S3A Mission Statistics of Crossover differences (Antarctic Ice Sheet), OCOG elevation (PB2.33)

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.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 167

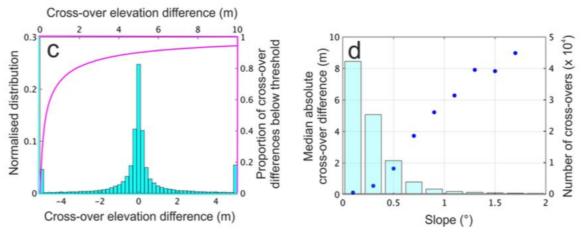


Figure 141: Median absolute cross-over elevation difference (blue dots) and number of cross-overs (blue bars) as a function of surface slope, S3A cycle 12.

9.3 Measurement Accuracy over Land Ice

To conduct an independent evaluation of the accuracy of our Sentinel-3A ice sheet measurements, we used elevation data acquired by the Airborne Topographic Mapper (ATM) and Riegl Laser Altimeter (RLA) instruments carried on Operation IceBridge. Full details of the methods and complete results shown in this section were published in *McMillan et al, 2019. (the Cryosphere)*.

To compute elevation differences between our Sentinel-3A and IceBridge datasets, we identified IceBridge records within a 200-meter search radius of each satellite measurement.

9.3.1 Evaluation at Inland Sites

At the inland sites of Lake Vostok and Dome C, we find very good agreement between the Sentinel-3A and airborne datasets. At Lake Vostok, the median bias between the OCOG elevation and the airborne data is 1 cm, and the MAD dispersion of the differences is 13 cm. At Dome C, the bias is larger (20 cm), but the dispersion of the differences is smaller (6 cm). The differing bias between the two sites was investigated and relates to differences in surface rougness. Comparing the results from the different retrackers, we find variations of approximately 10-30 cm in the median bias, which reflects differences in the algorithms used to select the retracking point on the waveform leading edge. There is nonetheless relatively little difference between retrackers in the MAD of the elevation differences, which is typically of the order of 10 cm in magnitude (Table 3). This is consistent with our previous analysis of the instrument precision above Lake Vostok, and suggests that at these relatively low slope inland sites, uncorrelated sources of error, for example due to imprecision of the retracker, radar speckle, the process of measurement relocation, or small-scale variations in snowpack characteristics, have not significantly affected the SAR altimeter elevation measurements. In total, we find that more than 97 %

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 168

of validation points (OCOG retracker) have an elevation difference of less than 50 cm, and that 70 % (Vostok) and 49 % (Dome C) have a difference of less than 20 cm.

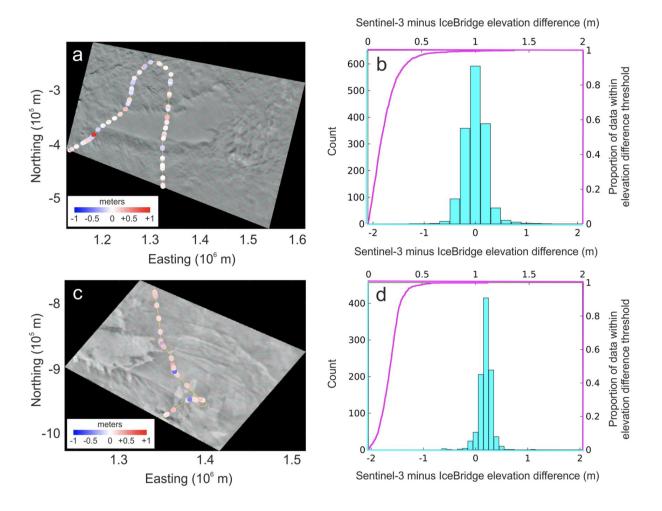


Figure 142: Assessment of the accuracy of Sentinel-3A elevation measurements at the Lake Vostok (a,b), Dome C (c,d). The distribution of Sentinel-3 minus IceBridge elevation differences (cyan histograms and axes), and the cumulative distribution of the absolute Sentinel-3 minus IceBridge elevation differences (magenta curves and axes) at each site.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 169

	Number of measurements	Median elevation difference (m)	Mean elevation difference (m)	Median absolute deviation of elevation differences (m)	Standard deviation of elevation differences (m)	RMS of elevation differences (m)	% points within 0.5 metres of IceBridge elevation	% points within 1 metre of IceBridge elevation	% points within 10 metres of IceBridge elevation
Vostok ¹									
TCOG	1523	0.01	-0.001	0.13	0.22	0.22	97.3	99.5	100.0
TFMRA	1523	-0.15	-0.16	0.13	0.23	0.27	93.8	99.6	100.0
Max. Grad.	1523	-0.25	-0.28	0.16	0.33	0.43	83.5	97.7	100.0
Dome C ²									
TCOG	971	0.20	0.19	0.06	0.12	0.23	98.9	99.9	100.0
TFMRA	971	0.06	0.05	0.06	0.12	0.13	99.5	100	100.0
Max. Grad.	971	-0.08	-0.10	0.10	0.20	0.23	95.8	99.5	100.0

Figure 143: Sentinel-3A validation statistics for low slope areas based upon comparison to IceBridge airborne altimetry for 3 different retrackers. Elevation differences are calculated as Sentinel- 3A elevation minus IceBridge elevation.

9.3.2 Evaluation at Coastal Sites

At the coastal sites of Dronning Maud Land and Wilkes Land the differences between the Sentinel-3A and airborne datasets are, as expected, more widely dispersed than at our inland study locations. At these sites, the more rugged coastal topography can produce complex waveforms, as energy is often returned from several distinct surfaces within the illuminated beam footprint. These factors represent well-established challenges for radar altimetry, both for retracking algorithms and for the procedure of correctly locating the on-the-ground origin of the derived elevation measurement. SAR altimetry, due to its smaller ground footprint, has the potential to be less affected by these topographic influences, and indeed we find that the overall median biases relative to IceBridge remain small, namely 0.03 m and 0.12 m at Dronning Maud Land and Wilkes Land, respectively (OCOG retracking). The magnitude of these biases is comparable to those found at our inland sites, suggesting that for a metric that is robust to outliers, no systematic bias is introduced as large scale topographic complexity increases.

For our coastal sites, the dispersion of the elevation differences relative to IceBridge is larger, as indicated by the MAD values of $0.30 \, \text{m}$ and $0.74 \, \text{m}$ (TCOG retracking) at Dronning Maud Land and Wilkes Land, respectively. Nonetheless, these first results demonstrate that even in these more challenging regions, the MAD precision of SAR elevation measurements is well below 1 meter. At these sites, we find that $^{\sim} 60-85 \, \%$ of the validated satellite elevation measurements (OCOG retracking) are within 1 meter of their airborne counterpart, and 92-98 % are within 10 meters. As is evident from these statistics, and also the standard deviation of the differences, there are a small number of outlying



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 170

measurements that exhibit larger deviations from the airborne validation data. Given that the primary focus of this study is on assessing data quality, we have chosen not to remove these outliers, although we note that for many future applications it may be beneficial to implement filtering procedures to do so. For example, when we consider an Antarctic-wide evaluation, we find that removing Sentinel-3A points that deviate by more than 10 m from our pre-existing DEM achieves a 70% reduction in the standard deviation of the Sentinel-3 minus IceBridge differences. Although a small proportion of outliers still remain even

after this filtering step (~1 % of data deviate by more than 20 m), either because the DEM fails to identify them as outliers or because the IceBridge data themselves are inaccurate, it is evident that a simple post-processing strategy such as this may be beneficial for many glaciological applications.

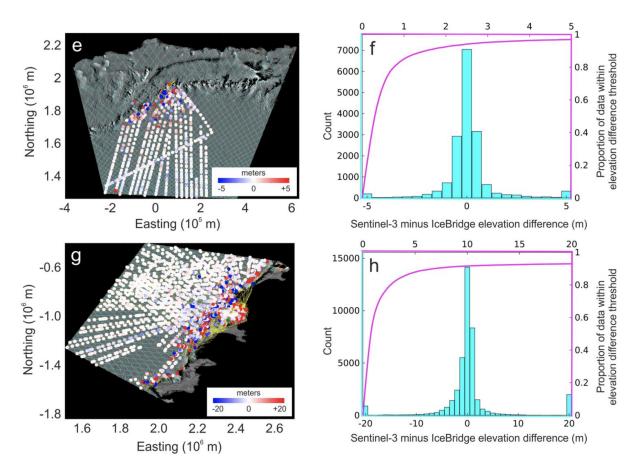


Figure 144: Assessment of the accuracy of Sentinel-3A elevation measurements at Dronning Maud Land (e,f) and Wilkes Land (g,h) sites in East Antarctica. The distribution of Sentinel-3 minus IceBridge elevation differences (cyan histograms and axes), and the cumulative distribution of the absolute Sentinel-3 minus IceBridge elevation differences (magenta curves and axes) at each site.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 171

	Number of measurements	Median elevation difference (m)	Mean elevation difference (m)	Median absolute deviation of elevation differences (m)	Standard deviation of elevation differences (m)	RMS of elevation differences (m)	% points within 0.5 metres of IceBridge elevation	% points within 1 metre of IceBridge elevation	% points within 10 metres of IceBridge elevation
Dronning Maud Land ³									
TCOG	16462	0.03	0.42	0.30	7.30	7.31	68.5	85.0	98.1
TFMRA	16538	-0.11	0.31	0.31	7.39	7.40	66.3	84.4	98.0
Max. Grad.	16538	-0.24	0.13	0.33	7.40	7.40	59.5	81.9	98.0
Wilkes Land ⁴									
TCOG	40400	0.12	1.43	0.74	14.99	15.06	35.0	58.8	91.6
TFMRA	40803	-0.03	1.28	0.75	14.94	14.99	37.3	58.5	91.6
Max. Grad.	40799	-0.20	0.98	0.83	14.96	15.00	35.9	55.2	91.4

Figure 145: Sentinel-3A validation statistics for High Slope Areas based upon comparison to IceBridge airborne altimetry for 3 different retrackers. Elevation differences are calculated as Sentinel- 3A elevation minus IceBridge elevation.

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 all Sentinel-3 data acquired up to and including cycle 32, in order to explore the potential of these data for mapping elevation changes of the Antarctic Ice Sheet. The resulting map is shown below.

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 early 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*).



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 172

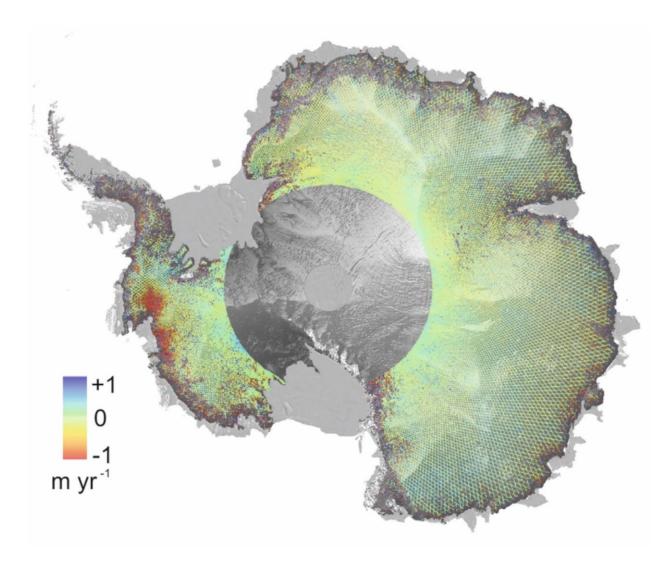


Figure 146: Rate of Elevation Change derived from S3A OCOG Elevation (cycles 12-31), (McMillan et al, 2019).

It is important to note that this result is derived PB2.33, 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 2019.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 173

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. The time series also shows the improvement after the change from open loop to closed loop tracking over the margins. Statistics from LRM mode in cycles 2 and 3 are based on only a small number of orbits available during commissioning.

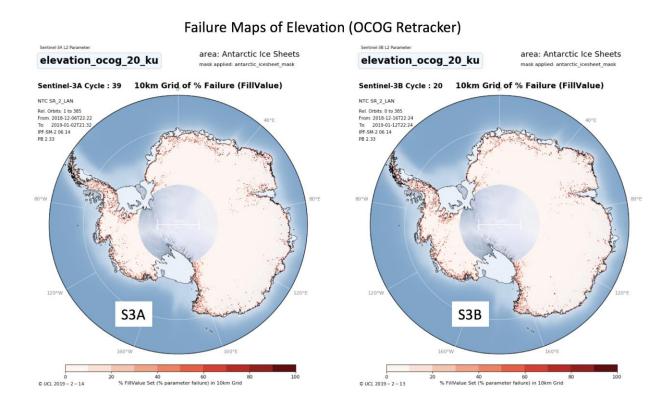


Figure 147: Antarctica OCOG Elevation Gridded Failure Maps (S3A, S3B, PB2.33)



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

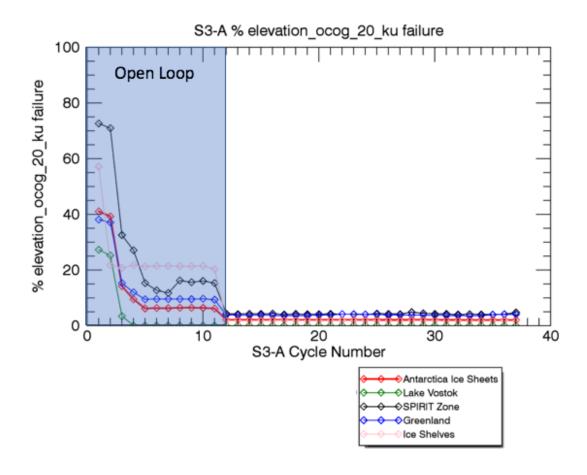


Figure 148: Failure rate of elevation_ocog_20_ku (S3A, PB2.33)



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 175

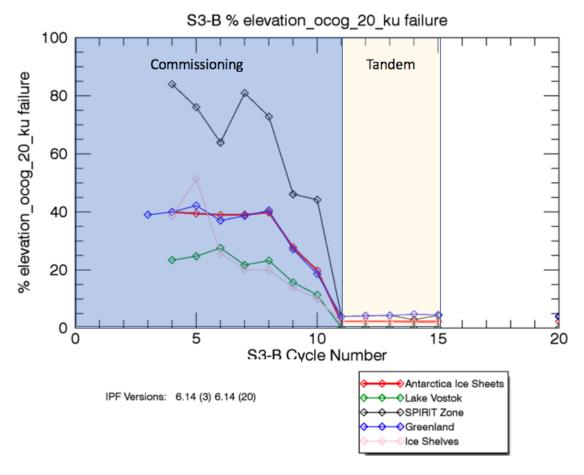


Figure 149: Failure rate of elevation_ocog_20_ku (S3B, PB2.33)

Elevation ice sheet 20 ku

Ice sheet elevation failure is primarily caused by failure of the SAR physcial model Ice Sheet retracker and the waveform quality checks. We expect this failure rate to be sensitive to waveform shape casued 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 ~20%, and Greenland (28%).



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 176

Failure Maps of Elevation (Ice Sheet Retracker)

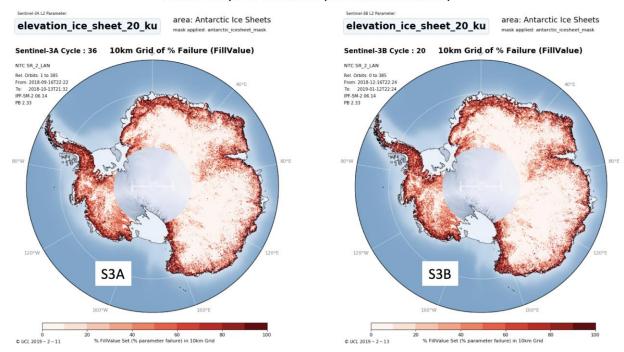


Figure 150: Antarctica Ice Sheet Elevation Gridded Failure Maps (S3A, S3B, PB2.33)

S3B has very similar statistics to S3A over its tandem phase and first operational cycles.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

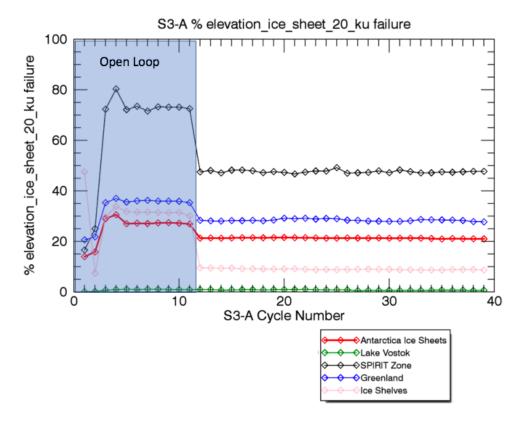


Figure 151: Failure rate of elevation_ocog_20_ku (S3A, PB2.33)



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

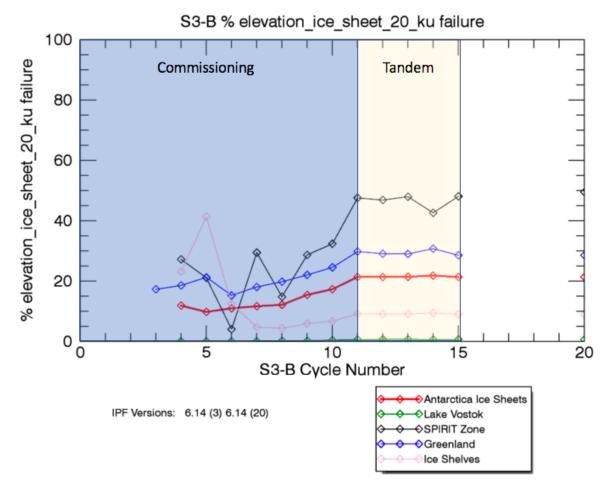


Figure 152: Failure rate of elevation_ocog_20_ku (S3B, PB2.33)



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

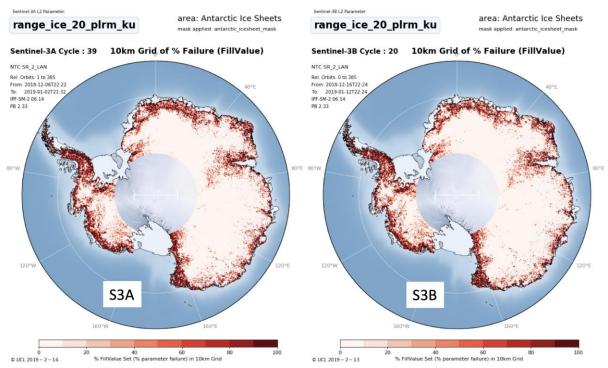
Issue: 1.0

Date: 28/02/2019

Page: 179

Range 20 plrm 20 ku

Failure Maps of PLRM Ice Range Failure



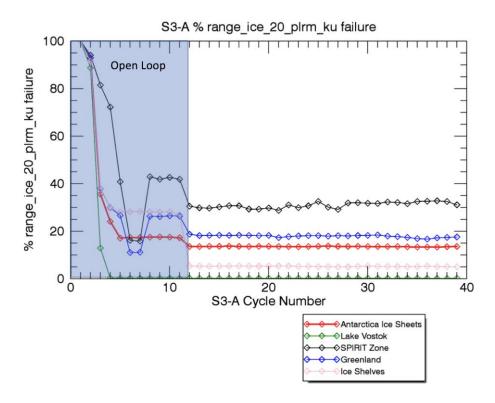


Figure 153: Percentage failure of range_ice_20_plrm_ku (S3A, PB2.33)



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

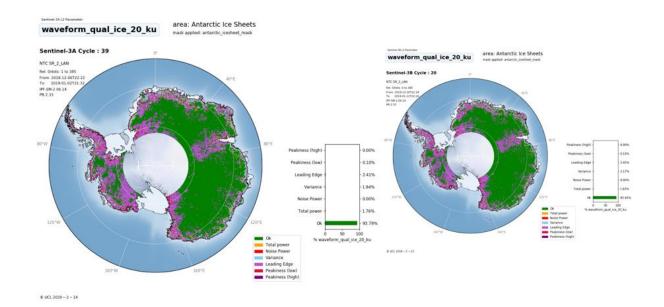
Issue: 1.0

Date: 28/02/2019

Page: 180

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 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 will be corrected in the next IPF release.



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.

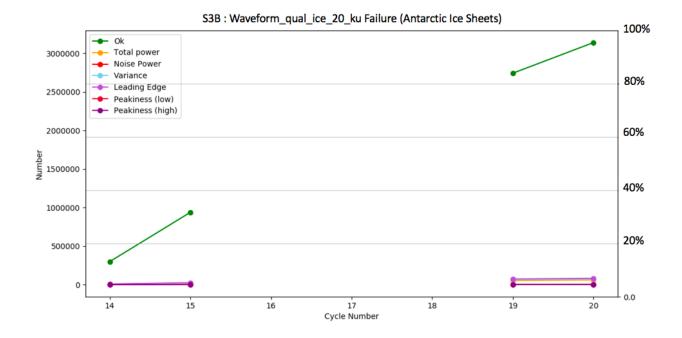


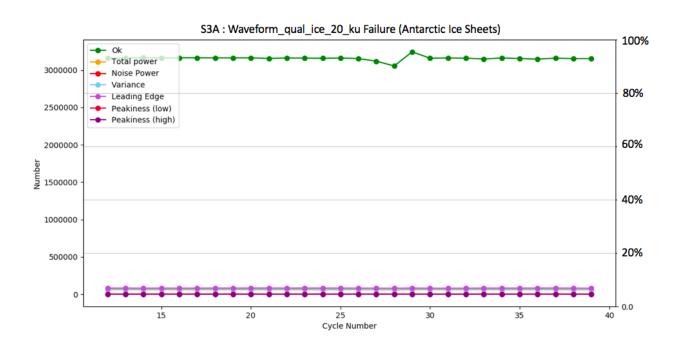
S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019







S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 182

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 the SAR Ice Margin 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.

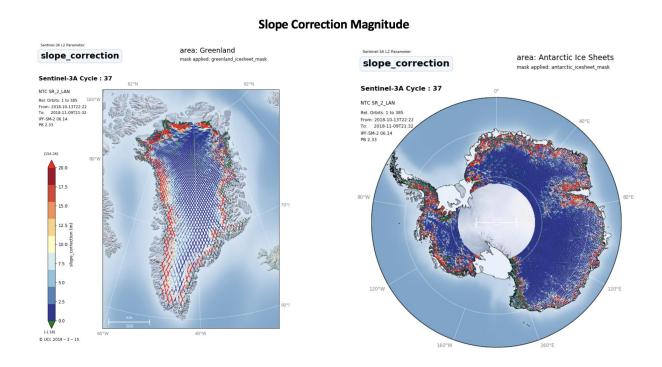


Figure 154: S3A SAR ku Slope Correction Magnitude (PB2.33)

A new updated slope correction derived from a Cryosat-2 DEM (Helm, 2014) will be used in the next IPF release in 2019.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

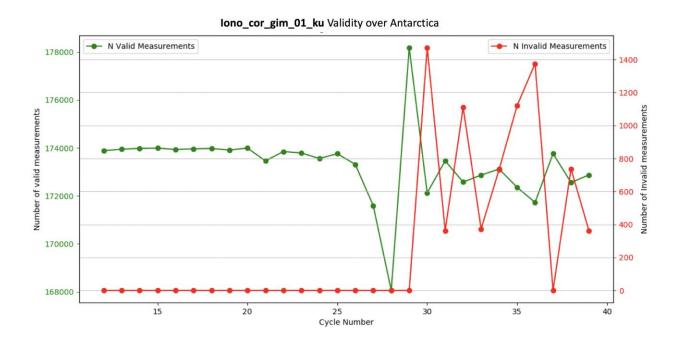
Issue: 1.0

Date: 28/02/2019

Page: 183

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 which had missing orbits since S3A cycle 30 (April 2018).





S3MPC STM Annual Performance Report - Year 2018

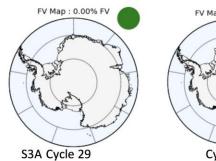
Ref.: S3MPC.CLS.APR.004

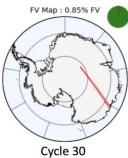
Issue: 1.0

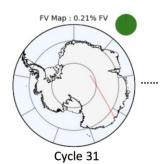
Date: 28/02/2019

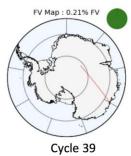
Page: 184

Missing S3 Iono GIM Correction









FV Map : 0.97% FV

S3B Cycle 19



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 185

10 Performance Mission over Inland waters

This section aims at characterizing and describing the SRAL altimeters (3A and 3B) performances over inland waters. Thanks to external data, a pre-selection based on water occurrence probability was performed to keep only measurements over water surfaces. 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.

Even if a first rough selection is performed to select water occurrences, an editing is necessary to remove potential corrupted measurements. The editing criteria defined are twofold. The first technique (editing 1) is based on minimum and maximum thresholds for various parameters. Measurements are edited 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, including the measurements from the last cycle. 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.

Figure 155 shows the statistics of valid and edited measurements for Sentinel-3A and Sentinel-3B over a common period from 12th of January 2018 to 8th of February 2019. Results for both satellites are consistent, slight differences could be explained by the OL mode coverage that is more important for Sentinel-3B (see section 6.2).

Figure 156 shows the stability of the percentage of edited measurement (edited on backscatter threshold criteria). For both satellite the percentage of DV measurements and the percentage of edited measurements are stable. A slightly higher percentage is observed for Sentinel-3B at the beginning of the time series for the ocog retracker. This behaviour is related to an anomaly #15 mentionned in the product notice and in this report in section 13.5.3). 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).



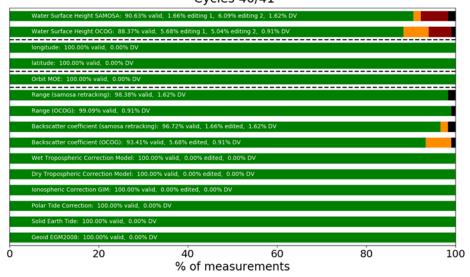
S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Sentinel 3 - A: Valid / edited / DV - L2 Land water data Cycles 40/41



Sentinel 3 - B: Valid / edited / DV - L2 Land water data Cycle 21

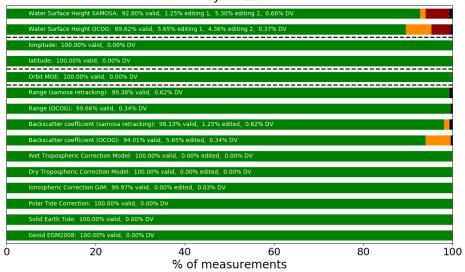


Figure 155: Sentinel-3A (top panel) and Sentinel-3B (bottom panel): Percentage of Valid (green), Edited with technique 1 (orange), Edited with technique 2 (red), and Default Value (black) measurements on the largest lakes worldwide in Open Loop mode. Statistics are provided for all fields necessary to the water surface height estimation with the SAMOSA and the OCOG retracking algorithms. Statistics estimated on cycle 21 of Sentinel-3B.

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 187

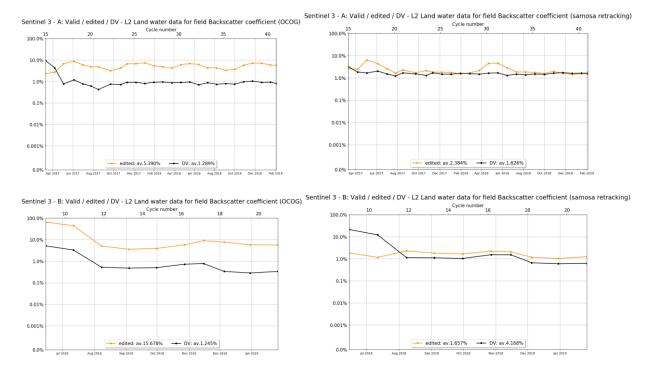


Figure 156: Monitoring of the percentage of default values and edited measurements over lakes (here on the sigma0 criteria) for Sentinel-3A (top panels) and Sentinel-3B (bottom panels) computed for both kind of retracking (SAMOSA DPM2.5 and ocog)

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.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

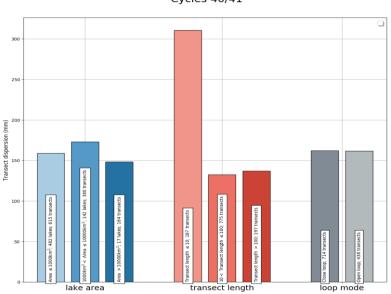
Issue: 1.0

Date: 28/02/2019

Page: 188

Figure 157 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 small lakes and small 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.

The differences between the results for Sentinel-3A and Sentinel-3B are explained by the difference in the regions covered by open loop and close loop tracking commands: Sentinel-3B is currently in open loop mode between 60N and 60S while Sentinel-3A is still operating with several large regions in close loop mode worldwide (see section 6.2). With this latter mode, the altimeter often measures off-nadir echoes which results in a higher dispersion. These results will be more homogeneous between the two satellites when the Sentinel-3A acquisition mask will be similar to the Sentinel-3B one, this operation is planned in March 2019.



Sentinel 3 - A: STD of Water Surface Height OCOG (mm) Cycles 40/41



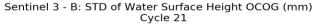
S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 189



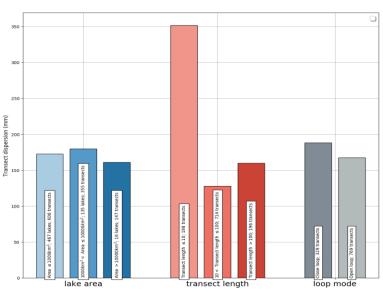


Figure 157: Standard deviation of the Sentinel-3A WSH computed over cycle 35 as a function of the lake area (left), of the transect length over lakes sampled (middle), and of the acquisition mode (right).

To characterize the performances over rivers, the same analysis is performed over Virtual Stations. A virtual station is the intersection between the satellite track and a river. Figure 158 shows the results obtained for Sentinel-3A and Jason-3. In average the dispersion measured for the two satellites are respectively equal to 10 and 15 cm, which are very good results. It demonstrated the higher performances of SARM technique and processing (smaller footprint and lower instrumental noise) with respect to LRM.

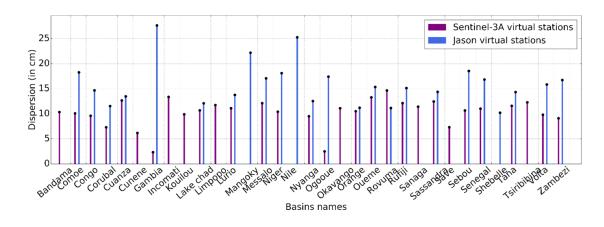


Figure 158: WSH dispersion measured over several Virtual Stations (rivers) crossed by Sentinel-3A and Jason-3 satellites.

GLS

Sentinel-3 MPC

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 190

The long-term monitoring allows to assess stability of the instrument and processing. Comparison of Jason-3 and Sentinel-3A WSH measured over the lake Huron (Figure 159 top panel) shows a very stable and good agreement between the two satellites. The monitoring of Sentinel-3A WSH derived from ocean and ocog retracker (Figure 159, bottom panel) shows really consistent results. A bias of ~30 cm in average is observed which is consistent with previous observations (see section 12.2).

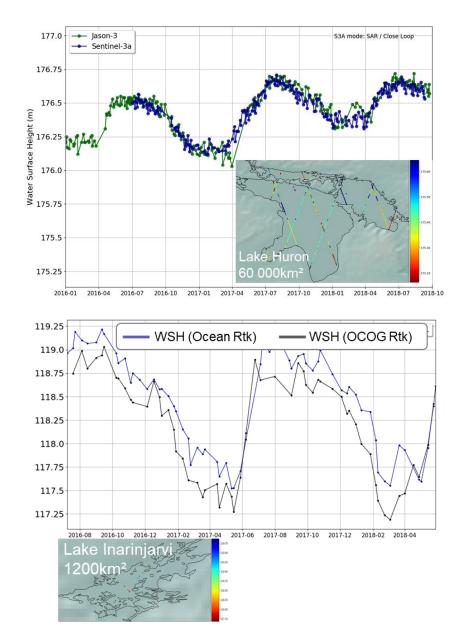


Figure 159: Monitoring of the Jason-3 and Sentinel-3A WSH over the larke Huron (top panel). Monitoring of the Sentinel-3A WSH derived from ocean retracker and ocog retracker over lake Inarinjarvi.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 191

11 Range and Sea Level Absolute calibration

11.1 Calibration with Crete transponder

isardSAT has processed the TRP data from a list of L1A products. S3A Passes with IPF-SR-1 Version 06.13 (cycle 3 to 23) use reprocessed L1A and L2 data provided on the ftp.s3rep.acri-cwa.fr FTP server. S3A Passes from cycle 24 to 39 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. For S3B, cycles 1 to 7 and 15 to 18 have not been included as the satellite was not overflying the TRP.

Table 11, Figure 160 and Figure 161 present the results from the TRP passes processing. The range bias is computed as measured minus theoretical. The results for S3A show a positive measured range, 6.50 mm larger than expected (elevation 6.50 mm shorter than expected), and a datation bias of -184.1 microseconds, both extracted from the minimisation of the RMS between theoretical and measured series. They also show a 0.85 mm stack noise. For S3B, the results show a negative measured range, -15.29 mm smaller than expected (elevation 15.29 mm higher than expected), a datation bias of -199.50 microseconds and a ~0.88 mm stack noise, following the same method. The regression line in Figure 160 shows a S3A range drift of -1.28 mm/year, but it has a very low significance.

960 CLS

Sentinel-3 MPC

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Cycle – Mission	Date	Range bias [mm]	Datation bias [microseconds]	Alignment [mm/beam]	Noise [mm]	IPF-SR-1 Version
3 - S3A	2016/04/09	2.78	-140.07	-0.08	0.81	06.13
4 - S3A	2016/05/06	19.01	-114.60	-0.07	0.78	06.13
5 - S3A	2016/06/02	-3.91	-165.54	-0.09	0.86	06.13
6 - S3A	2016/06/29	0.72	-152.81	-0.06	0.92	06.13
7 - S3A	2016/07/26	-2.86	-152.81	-0.07	1.01	06.13
8 - S3A	2016/08/22	-1.04	-140.07	-0.09	0.81	06.13
9 - S3A	2016/09/18	1.26	-216.48	-0.13	0.71	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	22.34	-127.34	-0.07	0.82	06.13
13 - S3A		Transponde	r not switched on d	ue to heavy sno	W.	
14 - S3A	2017/01/31	26.11	-140.07	-0.09	0.72	06.13
15 - S3A	2017/02/27	1.95	-165.54	-0.10	0.86	06.13
16 - S3A	2017/03/26	-0.24	-216.48	-0.13	0.79	06.13
17 - S3A	2017/04/22	14.70	-165.54	-0.13	1.05	06.13
18 - S3A	2017/05/19	28.66	-127.34	-0.06	1.11	06.13
19 - S3A	2017/06/15	-4.15	-203.74	-0.09	1.28	06.13
20 - S3A	2017/07/12	-15.89	-127.34	-0.09	0.70	06.13
21 - S3A	Tr	ansponder no	ot switched on due	to high tempera	tures.	
22 - S3A	2017/09/04	26.32	-165.54	-0.12	0.69	06.13
23 - S3A	2017/10/01	19.51	-152.81	-0.10	0.70	06.13
24 - S3A	2017/10/28	0.31	-229.21	-0.15	0.92	06.11
25 - S3A	2017/11/24	15.63	-203.74	-0.15	0.83	06.12
26 - S3A	2017/12/21	-1.81	-216.48	-0.14	0.80	06.12
27 - S3A	2018/01/17	10.20	-203.74	-0.14	0.94	06.12
28 - S3A	2018/02/13	13.89	-229.21	-0.15	0.75	06.13
29 - S3A	2018/03/12	-1.69	-203.74	-0.17	0.95	06.14
30 - S3A	2018/04/08	4.78	-229.21	-0.16	0.82	06.14

900 CLS

Sentinel-3 MPC

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 193

Cycle – Mission	Date	Range bias [mm]	Datation bias [microseconds]	Alignment [mm/beam]	Noise [mm]	IPF-SR-1 Version
31 - S3A	2018/05/05	2.01	-241.94	-0.14	0.89	06.14
32 - S3A	2018/06/01	-8.69	-229.21	-0.16	0.93	06.14
8 - S3B	2018/06/01		S3B in LRM mode	, results to be c	omputed	
33 - S3A	2018/06/28	0.39	-216.48	-0.12	0.70	06.14
10- S3B	2018/06/28		S3B in LRM mode	, results to be c	omputed	
34 - S3A	2018/07/25	4.82	-241.94	-0.15	0.82	06.14
11- S3B	2018/07/25		S3B in LRM mode	, results to be c	omputed	
35 - S3A	2018/08/21	-10.35	-216.48	-0.16	0.95	06.14
12 - S3B	2018/08/21	-23.33	-216.48	-0.12	0.84	06.14
36 - S3A	2018/09/17	-1.62	-203.74	-0.15	0.77	06.14
13 - S3B	2018/09/17	-19.00	-191.01	-0.11	1.05	06.14
37 - S3A	2018/10/14	4.84	-216.48	-0.13	0.94	06.14
14 - S3B	2018/10/14	-3.54	-191.01	-0.13	0.76	06.14
38 - S3A	2018/11/10	15.24	-216.48	-0.15	0.69	06.14
39 - S3A	2018/12/07	15.70	-152.81	-0.16	1.13	06.14
19 - S3B	19 - S3B 2018/12/13		good data (issue un	der investigatio	n)	06.14
N	Лean S3A	6.50	-184.10	-0.12	0.85	-
Standar	d Deviation S3A	11.17	38.99	0.03	0.14	-
N	/lean S3B	-15.29	-199.50	-0.12	0.88	-
Standar	d Deviation S3B	10.40	14.70	0.01	0.15	-

Table 11: Results of TRP passes processing

Regarding the geophysical corrections, 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

CLS OLICITE LOCALISATION SATELLITES

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Cycle	Date	Dry Tropo [m]	Wet Tropo [m]	lono [m]	Solid Earth [m]	Geocentric Tide [m]	Ocean Loading [m]
3	2016/04/09	-2.02600	-0.08710	-0.02418	-0.12970	0.00290	0.00310
4	2016/05/06	-2.04220	-0.07140	-0.03489	-0.04410	0.00230	0.01020
5	2016/06/02	-2.05024	-0.12316	-0.03851	0.03480	0.00100	0.00900
6	2016/06/29	-2.05184	-0.11006	-0.02995	-0.00030	-0.00060	0.00250
7	2016/07/26	-2.04933	-0.07117	-0.02432	-0.08820	-0.00260	-0.00200
8	2016/08/22	-2.05343	-0.07527	-0.02265	-0.12310	-0.00380	-0.00140
9	2016/09/18	-2.05799	-0.12541	-0.02411	-0.03270	-0.00470	0.00360
10	2016/10/15	-2.06529	-0.06351	-0.01800	0.13620	-0.00470	0.00680
11	2016/11/11	-2.06734	-0.07036	-0.01639	0.19500	-0.00400	0.00310
12	2016/12/08	-2.07943	-0.01087	-0.01453	0.09160	-0.00270	-0.00300
14	2017/01/31	-2.06552	-0.01138	-0.01913	-0.08110	0.00060	-0.00220
15	2017/02/27	-2.05001	-0.09089	-0.01818	-0.00790	0.00200	0.00310
16	2017/03/26	-2.05115	-0.06735	-0.01618	0.11520	0.00270	0.00520
17	2017/04/22	-2.04841	-0.04449	-0.02672	0.13670	0.00270	0.00160
18	2017/05/19	-2.05320	-0.03910	-0.03295	0.03340	0.00210	-0.00260
19	2017/06/15	-2.05731	-0.07789	-0.02817	-0.08180	0.00080	-0.00230
20	2017/07/12	-2.05252	-0.08288	-0.02232	-0.11870	-0.00080	0.00190
22	2017/09/04	-2.05777	-0.00013	-0.02142	0.02520	-0.00370	0.00900
23	2017/10/01	-2.06119	-0.06361	-0.02128	0.05060	-0.00440	0.00510
24	2017/10/28	-2.03975	-0.12175	-0.01537	0.00120	-0.00440	-0.00040
25	2017/11/24	-2.06119	-0.06461	-0.01486	-0.03940	-0.00340	-0.00270
26	21/12/2017	-2.05275	-0.12315	-0.01603	-0.00760	-0.00160	-0.00150
27	2018/01/17	-2.03678	-0.06282	-0.01587	0.08640	-0.00020	0.00100
28	2018/02/13	-2.04978	-0.04902	-0.01518	0.17020	0.00130	0.00130
29	2018/03/12	-2.04591	-0.11249	-0.01673	0.16230	0.00170	-0.00130
30	2018/04/08	-2.05024	-0.06556	-0.02125	0.05600	0.00160	-0.00350
31	2018/05/05	-2.04203	-0.02587	-0.03728	-0.06510	0.00100	-0.00200
32	2018/06/01	-2.05320	-0.05610	-0.02567	-0.11360	-0.00010	0.00300
33	2018/06/28	-2.04385	-0.06845	-0.02478	-0.07970	-0.00150	0.00810

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Cycle	Date	Dry Tropo [m]	Wet Tropo [m]	Iono [m]	Solid Earth [m]	Geocentric Tide [m]	Ocean Loading [m]
34	2018/07/25	-2.04135	-0.09865	-0.02589	-0.02590	-0.00280	0.00920
35/12	2018/08/21	-2.05320	-0.08720	-0.02164	-0.01370	-0.00350	0.00590
36/13	2018/09/17	-2.05982	-0.08578	-0.01871	-0.04380	-0.00410	0.00100
37/14	2018/10/14	-2.06005	-0.12355	-0.01497	-0.05520	-0.00420	-0.00200
38	2018/11/10	-2.05571	-0.08129	-0.01236	0.01380	-0.00390	-0.00090
39	2018/12/07	-2.05366	-0.01764	-0.01546	0.13660	-0.00290	0.00120

Table 12. The TRP internal delay is 4.954 meters.

Cycle	Date	Dry Tropo [m]	Wet Tropo [m]	lono [m]	Solid Earth [m]	Geocentric Tide [m]	Ocean Loading [m]
3	2016/04/09	-2.02600	-0.08710	-0.02418	-0.12970	0.00290	0.00310
4	2016/05/06	-2.04220	-0.07140	-0.03489	-0.04410	0.00230	0.01020
5	2016/06/02	-2.05024	-0.12316	-0.03851	0.03480	0.00100	0.00900
6	2016/06/29	-2.05184	-0.11006	-0.02995	-0.00030	-0.00060	0.00250
7	2016/07/26	-2.04933	-0.07117	-0.02432	-0.08820	-0.00260	-0.00200
8	2016/08/22	-2.05343	-0.07527	-0.02265	-0.12310	-0.00380	-0.00140
9	2016/09/18	-2.05799	-0.12541	-0.02411	-0.03270	-0.00470	0.00360
10	2016/10/15	-2.06529	-0.06351	-0.01800	0.13620	-0.00470	0.00680
11	2016/11/11	-2.06734	-0.07036	-0.01639	0.19500	-0.00400	0.00310
12	2016/12/08	-2.07943	-0.01087	-0.01453	0.09160	-0.00270	-0.00300
14	2017/01/31	-2.06552	-0.01138	-0.01913	-0.08110	0.00060	-0.00220
15	2017/02/27	-2.05001	-0.09089	-0.01818	-0.00790	0.00200	0.00310
16	2017/03/26	-2.05115	-0.06735	-0.01618	0.11520	0.00270	0.00520
17	2017/04/22	-2.04841	-0.04449	-0.02672	0.13670	0.00270	0.00160
18	2017/05/19	-2.05320	-0.03910	-0.03295	0.03340	0.00210	-0.00260
19	2017/06/15	-2.05731	-0.07789	-0.02817	-0.08180	0.00080	-0.00230
20	2017/07/12	-2.05252	-0.08288	-0.02232	-0.11870	-0.00080	0.00190
22	2017/09/04	-2.05777	-0.00013	-0.02142	0.02520	-0.00370	0.00900



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 196

Cycle	Date	Dry Tropo [m]	Wet Tropo [m]	lono [m]	Solid Earth [m]	Geocentric Tide [m]	Ocean Loading [m]
23	2017/10/01	-2.06119	-0.06361	-0.02128	0.05060	-0.00440	0.00510
24	2017/10/28	-2.03975	-0.12175	-0.01537	0.00120	-0.00440	-0.00040
25	2017/11/24	-2.06119	-0.06461	-0.01486	-0.03940	-0.00340	-0.00270
26	21/12/2017	-2.05275	-0.12315	-0.01603	-0.00760	-0.00160	-0.00150
27	2018/01/17	-2.03678	-0.06282	-0.01587	0.08640	-0.00020	0.00100
28	2018/02/13	-2.04978	-0.04902	-0.01518	0.17020	0.00130	0.00130
29	2018/03/12	-2.04591	-0.11249	-0.01673	0.16230	0.00170	-0.00130
30	2018/04/08	-2.05024	-0.06556	-0.02125	0.05600	0.00160	-0.00350
31	2018/05/05	-2.04203	-0.02587	-0.03728	-0.06510	0.00100	-0.00200
32	2018/06/01	-2.05320	-0.05610	-0.02567	-0.11360	-0.00010	0.00300
33	2018/06/28	-2.04385	-0.06845	-0.02478	-0.07970	-0.00150	0.00810
34	2018/07/25	-2.04135	-0.09865	-0.02589	-0.02590	-0.00280	0.00920
35/12	2018/08/21	-2.05320	-0.08720	-0.02164	-0.01370	-0.00350	0.00590
36/13	2018/09/17	-2.05982	-0.08578	-0.01871	-0.04380	-0.00410	0.00100
37/14	2018/10/14	-2.06005	-0.12355	-0.01497	-0.05520	-0.00420	-0.00200
38	2018/11/10	-2.05571	-0.08129	-0.01236	0.01380	-0.00390	-0.00090
39	2018/12/07	-2.05366	-0.01764	-0.01546	0.13660	-0.00290	0.00120

Table 12: Geophysical Corrections of TRP passes processing



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 197

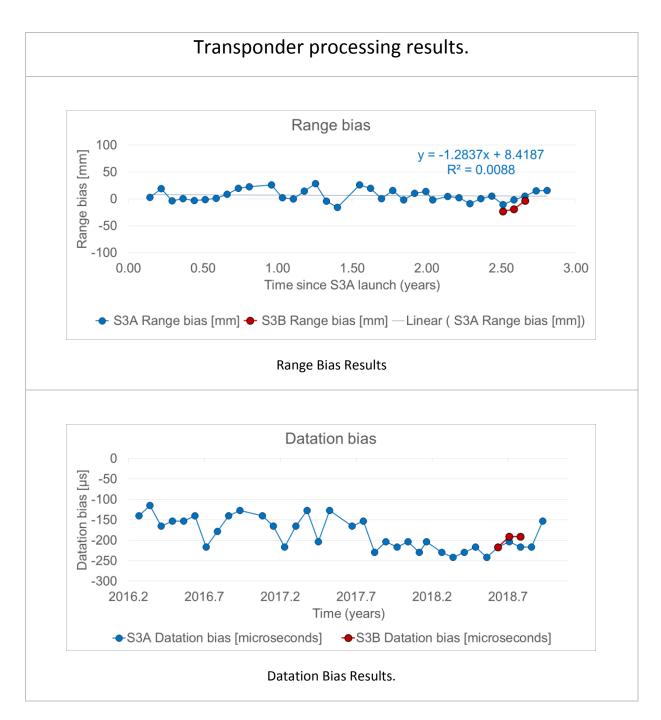


Figure 160 Range Bias Results and Datation Bias Results



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 198

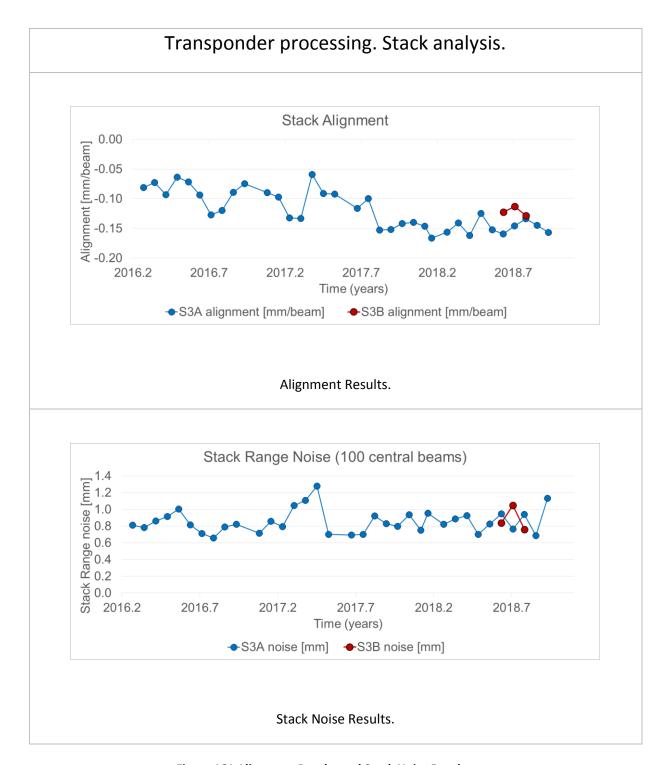


Figure 161 Alignment Results and Stack Noise Results

S CLS

Sentinel-3 MPC

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 199

11.2 Calibration over Corsica sites

Initially developed for monitoring the performance of TOPEX/Poseidon and follow-on Jason legacy satellite altimeters at Senetosa Cape, the calibration/validation site in Corsica was extended to include a new location at Ajaccio. This addition has 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 2018) and recently published in Bonnefond et al, 2018.

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 162, 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. This will also help understand some differences that were observed between the two sites for previous satellite altimetry missions.

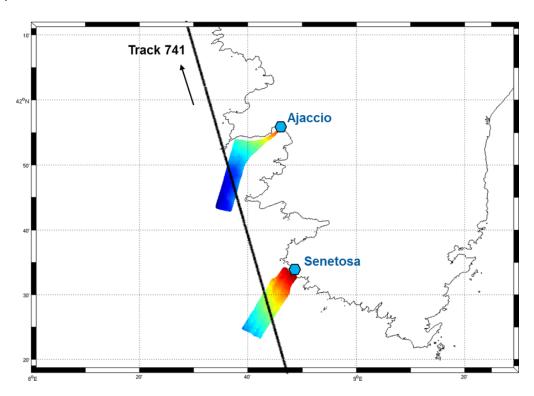


Figure 162: Absolute CALVAL configuration in Corsica. The regions in colours show the two high-resolution mean sea surfaces that were specifically measured to link the calibration sites to the altimetry data

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 200

In particular, systematic bias corrections have been identified in the Ajaccio and Senetosa in situ data, due to some errors in the levelling of the instruments, as was demonstrated by Pascal Bonnefond (OBSPM) at the last OSTST meeting in September 2018:

❖ Ajaccio: SSH_{TG} o_K = SSH_{TG} - 32.8 mm

Senetosa: SSH_{TG_OK} = SSH_{TG} - 24.2 mm

A correction was already applied in Ajaccio in the previous reports and presentations of our results (30 mm instead of 32.8 mm). However, the issue in Senetosa was recently solved and the results presented previously did not account for this bias. This explains the main differences observed in the results in this report, compared to the previous report.

The Sentinel-3A absolute bias estimates were computed in Corsica using the L2 NTC Land products reprocessed with the Processing Baseline 2.33, from cycle 1 to cycle 36 (10/2018). The Sentinel-3B bias estimates were computed with the same products, for cycles 11 to 13 (corresponding to cycles 34 to 36 for Sentinel-3A). Due to the tide gauges data availability, the Sentinel-3B bias estimates were computed only for cycle 11 in Senetosa and for cycles 11 and 13 in Ajaccio. These results will be updated on the fly with the most recent altimetry and in situ data. Table 13 summarizes the products version and the parameters used to compute the bias estimates.

Table 13: Sentinel-3A and Sentinel-3B products and parameters used to compute the absolute bias estimates

Mission	Sentinel-3A	Sentinel-3B				
Period	Cycles 1 to 36 (03/2016 – 10/2018)	Cycles 11 to 13 (08/2018 – 10/2018)				
Product version	NTC Land PB 2.33, from S3 MPC FTP website					
Frequency	20 Hz					
Ionosphere correction	GIM					
Wet troposphere correction	Model (land contamination in radiometer correction)					
Ocean Tide (regional calval only)	FES2014 model on finite element grid (in-house predictions)	/				
TUGOm simulation provided by (regional calval only) LEGOS, available until 12/2017		/				



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 201

1. Direct comparisons in Corsica

As shown in Figure 162, 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 two sites within a few seconds. During the tandem phase, the Sentinel-3B flies on the same orbit with a 30-second shift between the two satellites. This gives 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 14. 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 163 shows the time series of the SSH absolute bias estimates for both missions and both modes, at both calibration sites.

Table 14 : 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).

		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 34)	20 ± 4	23	33	22 ± 5	29	32	
Ajaccio (cycles 1 to 36)	11 ± 4	21	32	28 ± 8	43	31	
Sentinel-3B							
Senetosa (cycle 11)	25	/	1	17	/	1	
Ajaccio (cycles 11 to 13)	13	/	2	75	/	2	

In Senetosa, the S3A SSH bias estimate for cycle 21 was removed from the computation of the mean bias, because of very large bias value linked to very large SWH. For the same reason, the S3A SSH bias estimates for cycles 22 and 29 were removed in Ajaccio. Once these cycles removed from the statistics, the S3A bias estimates on SAR mode are very consistent for both sites (Table 14), 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 SAR mode observations.

The S3A bias estimates computed on the PLRM range are in general noisier than the estimates on the SAR range. The reason why the S3A PLRM SSH bias is very large for cycle 18 in Ajaccio is still unclear. When removing this cycle from the computation of the bias statistics, the new mean is 23 mm with a

CLS

Sentinel-3 MPC

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 202

variability of 36 mm, which is closer to the results in Senetosa. The 2cm difference that was previously observed between the two sites has now disappeared as it corresponded to the 2-cm bias found in the levelling of the Senetosa tide gauges.

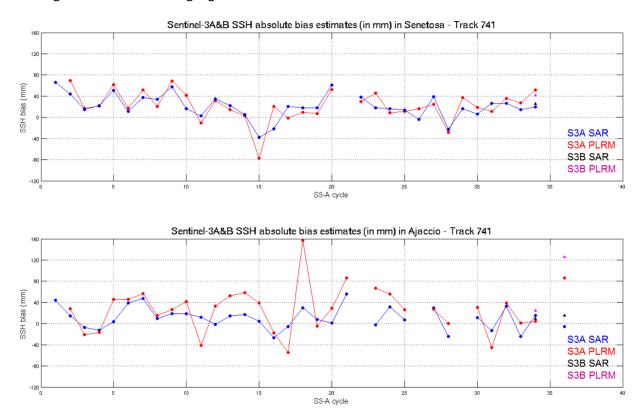


Figure 163: Sentinel-3A and Sentinel-3B absolute bias estimates in Senetosa (upper plot) and Ajaccio (lower plot) on track 741 for the SAR and the PLRM data.

There are not enough cycles of Sentinel-3B measurements to compute statistics on the range bias yet, but Figure 163 shows the very good consistency between the two missions, at both sites and for both types of products (SAR and PLRM). In Senetosa, the S3B range bias estimates for cycle 11 are very close to the S3A bias at the same dates (cycle 34). In Ajaccio, similar results are observed for S3B cycle 11 and S3A cycle 34. For S3B cycle 13 and S3A cycle 36, the dispersion is larger, but the results are still consistent, with a large increase in the PLRM range bias for both missions.

These results are in very good agreement with the Sentinel-3A bias estimates computed by Pascal Bonnefond (Paris Observatory/SYRTE) with his own calval method in Corsica, as shown in Figure 164. In average over the two calibration sites, Pascal Bonnefond obtains a mean bias of $+9 \pm 6$ mm with the SAR products and $+16 \pm 7$ mm with the PLRM products. His first Sentinel-3B bias estimates computed with the STC products are not statistically different from the Sentinel-3A time series, with +4 mm for the first available cycle (LRM mode) and -28 mm for the 2 following cycles (SAR mode).

CLS COLLECTE LOCALISATION SATELITES

Sentinel-3 MPC

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 203

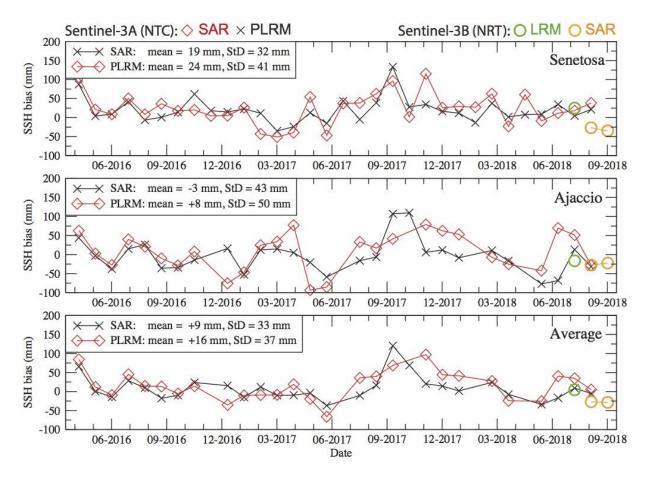


Figure 164: Sentinel-3A and Sentinel-3B absolute range bias estimates computed by P. Bonnefond (Paris Observatory/SYRTE) and O. Laurain (OCA/Géoazur) in Corsica along the track 741.

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 165 (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 165, left). The crossover points used for the computation are shown with green dots in Figure 165 (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 165 (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

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 204

global simulation with the TUGO-m model (ex-MOG2D model). As this DAC solution is only available until December 2017 for now, the offshore bias estimates were computed until cycle 25 for track 741 and cycle 26 for track 044.

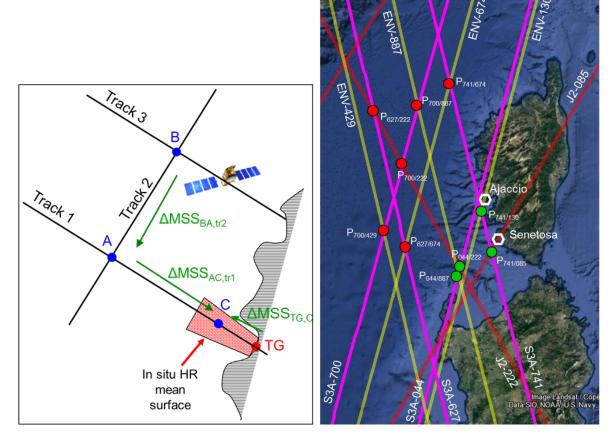


Figure 165: Left: Generic diagram of the regional calibration method. Right: Configuration in Corsica for the Sentinel-3A mission. S3A ground tracks in pink, Jason-2 tracks in red and Envisat tracks in yellow. The green dots show the crossover points where the offshore S3A SSH bias was computed. The red dots show the crossover points where the offshore S3A SSH bias could be potentially computed.

Table 15 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 165, 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 14), 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. 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).



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 205

The results are globally stable, with a small reduction of 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 cycles were 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.

Table 15: Statistics on the Sentinel-3A SAR and PLRM SSH absolute regional bias estimates in Senetosa.

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)	23 ± 5	23	24	21 ± 6	29	23	
Track 741 X J2 085	11 ± 5	26	24	11 ± 7	35	23	
Track 044 X Env 887	21 ± 7	34	25	18 ± 10	50	23	
Track 044 X J2 222	17 ± 6	28	25	20 ± 9	41	23	
Regional mean	18 ± 5	28	25	18 ± 5	39	23	

Table 16 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 165, 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 14), 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. 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).



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 206

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 and under investigation. Part of the explanation may come from the tidal model that is used (FES2014), which has a rather low resolution in the region, compared to the COMAPI regional tidal model that was used by NOVELTIS to compute the regional bias estimates of previous altimetry missions (Jason-2, Envisat, SARAL/Altika...). This will be tested in the near future.

In general, all these results are in 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.

Table 16 : Statistics on the Sentinel-3A SAR and PLRM SSH absolute regional bias estimates in Ajaccio (PB 2.33 reprocessed dataset).

Ajaccio		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.	14 ± 4	20	24	31 ± 9	45	23	
Track 741 (local)	12 ± 4	20	24	27 ± 10	49	25	
Track 741 X Env 130	6 ± 5	23	24	19 ± 12	59	23	
Track 741 X J2 085	36 ± 6	27	24	36 ± 8	39	23	
Track 044 X Env 887	43 ± 7	37	25	41 ± 11	52	23	
Track 044 X J2 222	46 ± 7	33	25	50 ± 9	43	23	
Regional mean	28 ± 18	28	24	34 ± 12	48	23	

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.

The next steps will consist in extending the number of crossover points for the computation of the regional bias estimates. The implementation at the calibration sites in Harvest and Bass Strait will also be finalized. Then the results will be updated on the fly with the most recent altimetry and in situ data.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 207

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 166 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 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.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 208

The backscatter coefficients between both retrackers are also compared on Figure 167. 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. 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 26 (20/12/2017 - 16/01/2018) (x10⁵)-2 RANGE.ALTI-RANGE.ALTI.CORR_OCOG (m)

Figure 166 Range difference: OCOG-Ocean over Arctic in L2 Land products STC Cycle 26

1

-1

-2



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 209

Difference of backscatter coefficient Ocean - Ocog

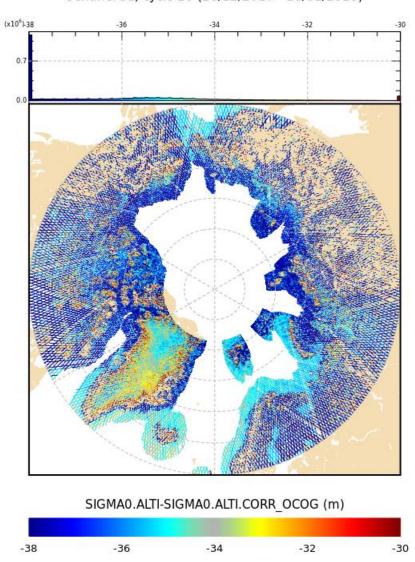


Figure 167 Backscatter coefficient difference: OCOG-Ocean over Arctic in L2 Land products STC Cycle 26



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 210

12.3 Sea Ice retracker

The sea ice retracker in the L2 products is not performing well over the sea ice floes. It has been identified that the diffuse echo retracker (used to correct the range measurements of waveforms discriminated as sea ice floes) needs to be upgraded to a TMFRA retracker, as used in the latest Cryosat baseline-D. Then, the lead and floe retracker bias will be calibrated. Replacement of this retracker is implemented in Sentinel-3A PB 2.45 and Sentinel-3B PB 1.15 deployed in February 2019.

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 168. 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 169 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 170. 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 171 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).



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 211

Difference of range Ocean - ice sheet

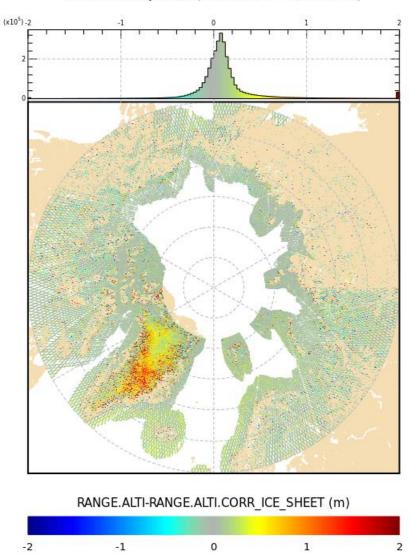


Figure 168 Range difference: Ocean-Ice margin over Arctic in L2 Land products STC Cycle 26



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 212

Difference of range Ocog - Ice sheet

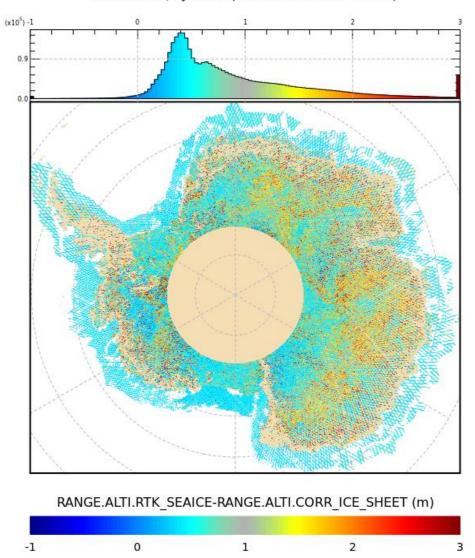


Figure 169 Range difference: OCOG-Ice margin over Antarctica in L2 Land products STC Cycle 26



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 213

ifference of backscatter coefficient Ocean - Ice shee

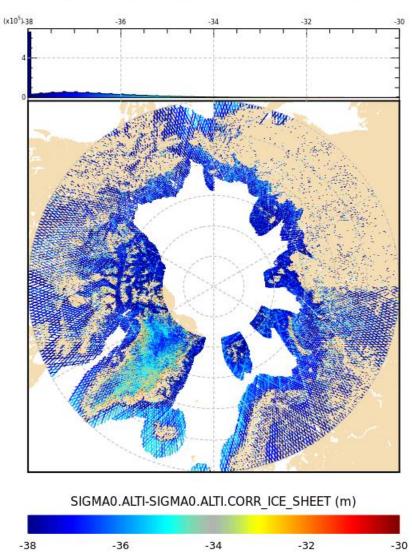


Figure 170 Backscatter coefficient difference: Ocean-Ice margin over Arctic in L2 Land products STC Cycle 26



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 214

Difference of backscatter coefficient Ocog - Ice sheet

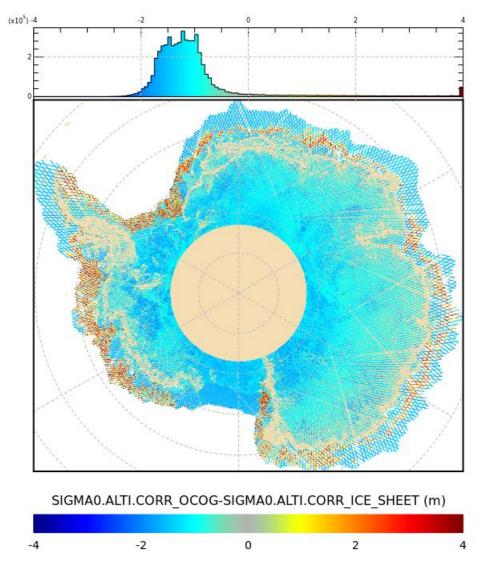


Figure 171 Backscatter coefficient difference: OCOG-Ice margin over Antarctica in L2 Land products STC Cycle 26



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 215

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.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 216

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



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 217

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 : https://earth.esa.int/documents/247904/3147059/Sentinel-3-STM-Product-Evolution-Processing-Baseline-2.24

13.2.3 Fix of anomalies

Anomaly #1 : Duplicated measurements at 10 minutes granule transition in L2 NRT products (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





S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 218

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

Anomaly #3 : Atmospheric attenuation to default values over edges of MWR calibration (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



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 219

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



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 220

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



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 221

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



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 222

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



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 223

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



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 224

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.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 225

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



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 226

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



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 227

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



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 228

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.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 229

13.5 Processing Baseline 2.45

13.5.1 Ground processors versions (Instrument Processor Facility)

SR_1 IPF version: 06.16

MW_1 IPF version: 06.09

SM_2 IPF version: 06.15

13.5.2 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

13.5.3 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.



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 230

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

13.5.4 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



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 231

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



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 232

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

S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 233

14 Annex References

- **RD 1** C. Ruf, 2000: Detection of Calibration Drifts in spaceborne Microwave Radiometers using a Vicarious cold reference, **IEEE Trans. Geosci. Remote Sens., 38, 44-52,** https://doi.org/10.1109/36.823900
- RD 2 S. Brown, C. Ruf, 2005: Determination of an Amazon Hot Reference Target for the on-orbit calibration of Microwave radiometers, Journal of Atmos. Ocean. Techno., 22, 1340-1352, https://doi.org/10.1175/JTECH1769.1
- RD 3 L. Eymard, E. Obligis, N. Tran, F. Karbou, M. Dedieu, 2005: Long term stability of ERS-2 and TOPEX microwave radiometer in-flight calibration, IEEE Trans. Geosci. Remote Sens., 43, 1144-1158, https://doi.org/10.1109/TGRS.2005.846129
- **RD 4** C. Ruf, 2002: Characterization and correction of a drift in calibration of the TOPEX microwave radiometer, **IEEE Trans. Geosci. Remote Sens., 40, 509-511,** https://doi.org/10.1109/36.992824
- RD 5 R. Scharoo, J. Lillibridge, W. Smith, 2004: Cross-calibration and long-term monitoring of the microwave radiometers of ERS, TOPEX, GFO, Jason and Envisat, Marine Geodesy, 27, 279-297, https://doi.org/10.1080/01490410490465265
- RD 6 R. Kroodsma, D. McKague, C. Ruf, 2012: Cross-calibration and long-term monitoring of the microwave radiometers of ERS, TOPEX, GFO, Jason and Envisat, Applied Earth Obs. and Remote Sensing, 5, 1939-1404, https://doi.org/10.1109/JSTARS.2012.2195773
- RD 7 Estimation des dérives et des incertitudes associées pour les radiomètres micro-ondes. Revue des méthodes existantes, SALP-NT-MM-EE-22288
- **RD 8** Brown, S., C. Ruf, S. Keihm, and A. Kitiyakara, "Jason Microwave Radiometer Performance and On-Orbit Calibration," Mar. Geod., vol. 27, no. 1–2, pp. 199–220, 2004.
- **RD 9** Jee, G., H.-B. Lee, Y. H. Kim, J.-K. Chung, and J. Cho (2010), Assessment of GPS global ionosphere maps (GIM) by comparison between CODE GIM and TOPEX/Jason TEC data: Ionospheric perspective, J. Geophys. Res., 115, A10319,
- RD 10 N. Tran, F. Girard-Ardhuin, R. Ezraty, H. Feng and P. Femenias, "Defining a Sea Ice Flag for Envisat Altimetry Mission," in IEEE Geoscience and Remote Sensing Letters, vol. 6, no. 1, pp. 77-81, Jan. 2009. doi: 10.1109/LGRS.2008.2005275
- RD 11 Ablain, M., J. F. Legeais, P. Prandi, M. Marcos, L. Fenoglio-Marc, H. B. Dieng, J. Benveniste, and A. Cazenave (2017), Altimetry-based sea level at global and regional scales, Surv. Geophys., 38, 7—31, doi:10.1007/s10712-016-9389-8.
- RD 12 Pujol, M-I., Schaeffer, P., Faugère, Y., Raynal, M., Dibarboure, G., Picot, N., 2018, Gauging the improvement of recent mean sea surface models: a new approach for identifying and quantifying their errors. Under review, Journal of Geophysical Research.
- RD 13 Tran, N., Labroue, S., Philipps, S., Bronner, E., & Picot, N. (2010). Overview and Update of the Sea State Bias Corrections for the Jason-2, Jason-1 and TOPEX Missions. Marine Geodesy, 33(sup1), 348–362. https://doi.org/10.1080/01490419.2010.487788



S3MPC STM Annual Performance Report - Year 2018

Ref.: S3MPC.CLS.APR.004

Issue: 1.0

Date: 28/02/2019

Page: 234

RD 14 Lauret, O., 2016, Jason-3 validation and cross calibration activities (Annual report 2016) SALP-RP-MA-EA-3060-CLS available from

https://www.aviso.altimetry.fr/fileadmin/documents/calval/validation_report/J3/annual_report_j3_2016 .pdf

RD 15 Roinard, H., 2017, Jason-2 validation and cross calibration activities (Annual report 2017) SALP-RP-MA-EA-23186-CLS available from

http://www.aviso.altimetry.fr/fileadmin/documents/calval/annual_report_****.pdf

- RD 16 Moreau T., Tran N., Aublanc J., Tison C., Le Gac S., Boy F., "Impact of long ocean waves on wave height retrieval from SAR altimetry data", submitted in Adv. Space Res., 2018.
- **RD 17** Abdalla S., 2017. "Wind and Wave Assessment", Expert Support Laboratories Council Meeting, September 2017, Toulouse.
- RD 18 Bonnefond, P.; Laurain, O.; Exertier, P.; Boy, F.; Guinle, T.; Picot, N.; Labroue, S.; Raynal, M.; Donlon, C.; Féménias, P.; Parrinello, T.; Dinardo, S. Calibrating the SAR SSH of Sentinel-3A and CryoSat-2 over the Corsica Facilities. *Remote Sens.* 2018, 10, 92. DOI: 10.3390/rs10010092.
- RD 19 STM ESL, Sentinel-3 STM Yearly Report-Year 1 https://sentinel.esa.int/web/sentinel/user-guides/sentinel-3-altimetry/document-library/-/asset_publisher/ZO9eh5qR8wB9/content/sentinel-3-stm-annual-performance-report-year-1, 2018,05.
- RD 20 Vignudelli et al, 2019, under revision

End of document