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CryoSat Long-Term Ocean Data Analysis and Validation: final words on GOP Baseline-C

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Baseline-C … what we did …

- Long-term analysis and validation of the CryoSat-2 Level-2 Baseline-C (BLC) 1-Hz altimeter Geophysical Ocean Product (GOP)
  - Assess quality, consistency and stability of GOP parameters and corrections
  - Comparing GOP with concurrent altimetry in RADS
  - Comparing GOP with concurrent in situ data
- We wrote the final report for ESA, wrote a paper (under review*at *Rem. Sens.*), and wrote a contract change proposal for future Baselines
- Here we present highlights from the report/paper

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Baseline-C conclusions

- More than 12 years worth of CryoSat-2 GOP Baseline-C data compare well with Jason-2 and Jason-3 and are perfectly suited for oceanographic applications
- They also compare well with Sentinel-3A/B, SARAL and Sentinel-6A, and the CryoSat platform is going strong showing no sign of any deterioration
- CryoSat-2 GOP has a slowly increasing timing error of avg. 0.367 ms which when applied totally removes the found ascending/descending bias of 0.9 cm
- CryoSat-2 GOP corrections deviate from RADS generated corrections like pole tide, ocean tide FES14, MSS DTU15, and GIM IONO: patterns reveal possible errors or different implementations, though none of these deviations contribute to any trend
- CryoSat-2 GOP has an absolute range bias of −2.9 cm and no apparent drift
- We find a SAR-LRM bias of 1.4 cm, of which 0.9 cm can be attributed to the asc/des bias. The other 0.5 cm is due to a SAR-LRM SSB bias which in turn is due to a SAR-LRM SWH bias of 10.5 cm: the latter likely originates from a re-tracker bias
- CryoSat-2 GOP has an R=0.82, sd=5.7 cm and drift of 0.17 mm/yr (GIA applied) w.r.t. 309 selected PSMSL tide gauges over the timespan 2010–2022, showing off the altimeter platform's perfect stability

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Baseline-C final words

We end with our final words on CryoSat GOP Baseline-C:

- Baseline-C data's quality, continuity, and reference is exceptionally good and stable over time and no proof of any deterioration or platform aging has been found thus far
- Any improvements for successor Baselines should come from
  - SSB optimisation
  - Improving ionosphere correction
  - Improving pole tide correction
  - Removing any (calibrated) remaining timing bias

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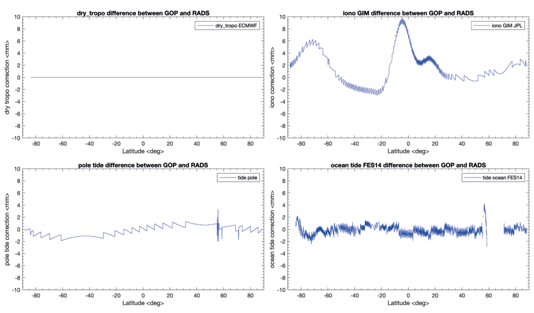
*) Meanwhile published: Naeije, M.; Di Bella, A.; Geminale, T.; Visser, P. CryoSat Long-Term Ocean Data Analysis and Validation: Final Words on GOP Baseline-C.Remote Sens. 2023, 15, 5420. https://doi.org/10.3390/rs15225420

Corrections GOP−RADS pass 840 (34)

- 1 Hz P2P GOP BLC corrections minus *RADSified* corrections: Mostly within 1 mm like the one for dry tropo
- The GIM ionosphere correction stands out: RADS and GOP differ in how the GNSS TEC maps are processed. It is yet undecisive which solution is better
- Also the pole tide and FES ocean tide corrections raise concern with their zigzag patterns



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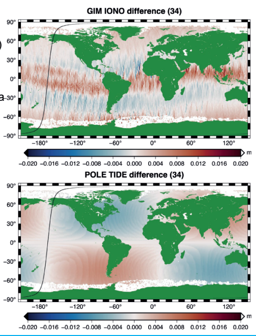
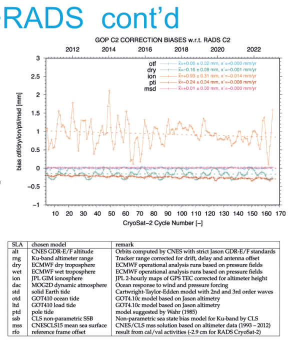
Corrections GOP−RADS cont'd

- Geographic maps of the GOP−RADS differences (cycle 34)
- The GIM iono shows the signature of the magnetic equator
- The pole tide shows a low harmonic east-west pattern
- Over time, the corr. differences do not contribute to a significant mean (<1mm) or trend (<0.014 mm/yr: top right panel)
- The table gives the GOP parameters chosen in our analyses





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CryoSat-2 crossovers analysis

- We cross GOP passes (CG: cycles 4–165) with Jason-2 (J2:75–303), Jason-3 (J3:0–227), Sentinel-3A (3A:1–94), Sentinel-3B (3B:19–75), SARAL (SAa:1–35), SARAL (SAb:36–104), Sentinel 6-A (6A:4-81) and RADS CryoSat-2 (C2:4–165)
- Maximum crossover time difference is 2 days to have not too much changes in the dynamically varying sea level: less days would not leave enough crossovers
- Increased ocean surface variability is bypassed by a crossover difference edit criterion of 2×sd (95% confidence level)
- To exclude sea ice areas the analyses are limited between 70° S and 70° N. This also excludes the high number of crossovers in the polar regions
- CryoSat-2 compared with Jason 2 (crossover or XO difference CG – J2) gives range bias referenced to Jason-2 but as both have their height data referenced to the TOPEX reference ellipsoid and for Jason-2 already a calibrated range bias is applied, the actual XO or range difference is consequently referenced to TOPEX and can be considered the absolute bias

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Crossover difference statistics

- Crossover statistics from the dual-XOs analyses (top) and single-XOs (bottom)
- GOP BLC is of similar quality as the Jasons, the Sentinels, and both SARAL phases
- The avg. SLA range bias is −2.9 cm, an improvement of 3.4 cm over Baseline-B
- Overall 3.7 cm sd of GOP XO diffs, which is on par with the Jasons
- We see improvements in wind speed and swh
- We do notice a non-zero SLA mean in CG/C2's single-XOs

w.r.t.	SLA [m]		SWH [m]		σ^0 [dB]		WIND [m/s]		SSB [m]		XOs [no.]
	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	
C2	−0.029	0.035	0.000	0.710	0.001	1.585	−0.003	2.770	−0.000	0.032	343365
J2a	−0.029	0.037	0.002	1.006	−0.257	1.451	0.167	3.321	−0.038	0.038	1133727
J2b	−0.028	0.036	0.008	0.998	−0.249	1.485	0.143	3.545	−0.037	0.038	116963
J2c	−0.029	0.037	0.001	1.006	−0.232	1.487	0.073	3.593	−0.038	0.038	177958
J2d	−0.029	0.037	0.008	1.008	−0.254	1.490	0.124	3.520	−0.038	0.038	160395
J3a	−0.029	0.037	0.010	1.015	−2.863	1.521	−0.011	3.605	−0.018	0.038	1286827
J3b	−0.026	0.039	0.021	1.021	−2.850	1.500	−0.064	3.563	−0.019	0.038	135512
3A	−0.029	0.037	−0.093	0.952	−0.128	1.517	−0.148	3.275	−0.008	0.036	620735
3Ba	−0.033	0.039	−0.076	0.957	−0.173	1.547	−0.051	3.199	−0.007	0.036	31053
3Bb	−0.028	0.037	−0.099	0.953	−0.187	1.513	0.032	3.238	−0.008	0.036	375064
SAa	−0.027	0.037	−0.002	0.945	−0.043	1.634	0.115	3.175	−0.053	0.037	288403
SAb	−0.023	0.037	0.010	0.936	−0.131	1.635	0.323	3.146	−0.054	0.037	329370
6A	−0.018	0.038	0.023	1.017	−1.641	1.484	0.019	3.574	−0.019	0.038	428821
avg	−0.029	0.037	-	-	-	-	-	-	-	-	-
	SLA [m]		SWH [m]		σ^0 [dB]		WIND [m/s]		SSB [m]		XOs [no.]
	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	
CG	−0.007	0.035	−0.000	0.715	−0.005	1.591	−0.013	2.788	0.000	0.032	179905
C2	−0.007	0.035	0.002	0.710	−0.003	1.586	−0.014	2.765	0.000	0.032	128201
J2a	−0.000	0.034	−0.003	0.981	0.003	1.440	−0.006	3.440	0.000	0.032	522648
J2b	0.000	0.033	−0.001	0.978	0.003	1.470	−0.002	3.482	0.000	0.032	51426
J2c	0.001	0.034	−0.004	0.983	−0.008	1.464	0.018	3.511	0.000	0.032	80525
J2d	0.001	0.035	0.004	0.982	0.008	1.490	−0.010	3.448	−0.000	0.031	71546
J3a	0.000	0.035	0.001	1.006	0.004	1.571	−0.003	3.623	0.000	0.034	609933
J3b	0.000	0.038	0.002	1.003	−0.003	1.553	0.014	3.632	−0.000	0.034	74187
3A	0.003	0.034	−0.008	0.958	0.015	1.636	−0.021	3.219	0.000	0.032	340851
3Ba	0.003	0.034	−0.009	0.927	0.012	1.700	−0.024	3.051	0.000	0.030	16685
3Bb	0.003	0.034	−0.001	0.957	0.015	1.617	−0.019	3.153	0.000	0.034	208379
SAa	0.002	0.033	0.001	0.930	−0.012	1.770	0.034	2.948	−0.000	0.022	158932
SAb	0.003	0.034	0.003	0.919	−0.005	1.757	0.026	2.905	−0.000	0.022	276546
6A	0.000	0.035	0.001	1.008	0.001	1.534	0.007	3.605	−0.000	0.034	210622

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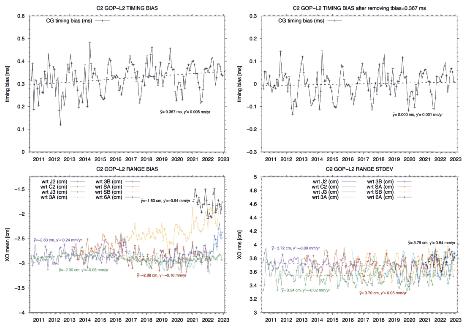
Evolution of biases over time

- The timing bias has an avg. of 0.367 ms that slightly rises
- The BLC absolute bias is established at −2.9 cm, and the drift w.r.t. Jasons at 0.07 mm/yr, making it excellently stable and significantly better than the SLA ECV constraint of 0.5 mm/yr and on par with todays uncertainties in sea level trend estimates
- The dual-XO rms is steady around 3.7 cm
- What happens w.r.t. Sentinel-3 after 2022?



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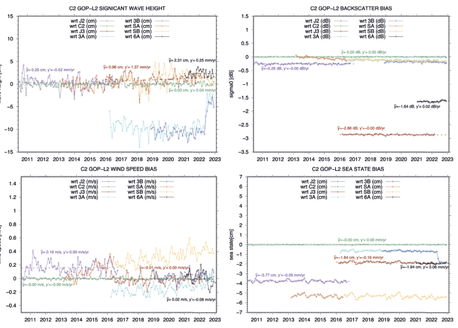
Evolution of biases cont'd

- All the mean biases confirm the earlier figures and tables
- There are jumps in sigma0 and wind speed switching from J2 to J3: this is discounted for in the tailored J2/J3 SSBs
- The same is true for the offset in SWH in 3A and 3B, though the rising at mid 2022 is unforeseen and seems related to the rise in SLA range bias around 2022
- With the help of GOP BLC we found a -1.1 cm absolute range bias for Sentinel-6A



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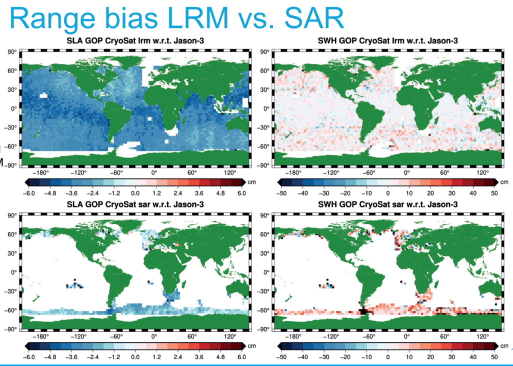
Range bias LRM vs. SAR

- Geographic range bias plots (mean XO diffs) for LRM (top) and SARM (bottom)
- The LRM solutions are close to plots where LRM was combined with SARM
- The blue in the SARM patches is lighter for SLA (bottom left), whereas for SWH darker red (bottom right), so we can conclude that both SLA and SWH have biases between LRM and SARM; we call these mode biases



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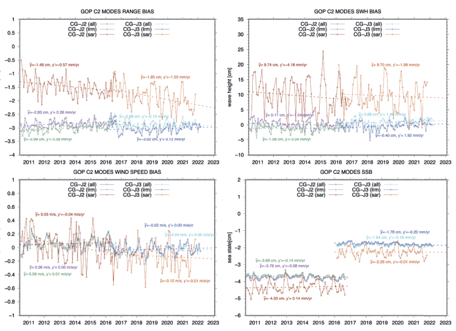
Evolution of biases: SAR vs. LRM

- Bias plots for SARM and LRM separately for range, SWH, wind speed and SSB
- Compared to J2 and J3, GOP BLC has a SAR-LRM range bias difference average of approx. −1.4 cm
- The SWH SAR-LRM difference is approx. 10.5 cm, whereas the windspeed SAR-LRM difference is negligible
- The BLC non-tailored SSB translates this SWH bias to −0.5 cm bias diff in the SLA … which leaves 0.9 cm bias unexplained …



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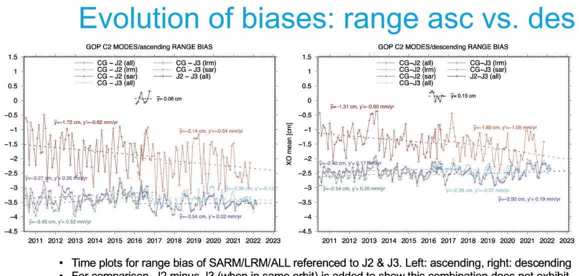
Evolution of biases: range asc vs. des



- Time plots for range bias of SARM/LRM/ALL referenced to J2 & J3. Left: ascending, right: descending
- For comparison, J2 minus J3 (when in same orbit) is added to show this combination does not exhibit an asc/des bias difference: ascending minus descending is within 1 mm (black curves)
- The strange behaviour of the dark and light brown (SAR) lines (obvious trend and less asc/des difference) is not fully understood but could come from the limited and changing coverage of SARM
- So, only looking at LRM: the ascending range bias is about −3.45 cm, whereas the descending range bias is about −2.54 cm (green curves, lrm), a noteworthy difference of approx. 0.9 cm (cf. slide 11)

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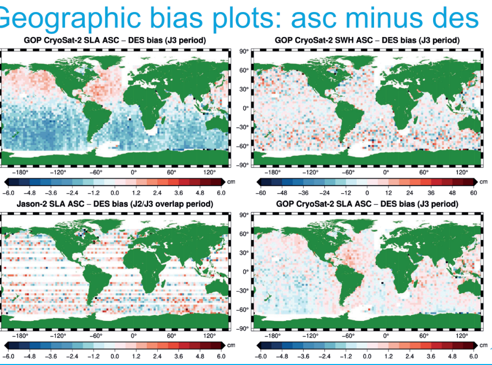
Geographic bias plots: asc minus des

- Top: asc minus des range (left) and SWH (right) bias difference of BLC w.r.t. J3
- Subtracting des from asc cancels out J3, as if we were doing a single XO analysis on CryoSat, but now with full global coverage
- Obviously, the SWH does not show any sign of asc/des bias, and J2 w.r.t. J3 also not (bottom left)
- The north-south bias pattern in SLA bias disappears if we apply the 0.367 ms timing bias (bottom right)



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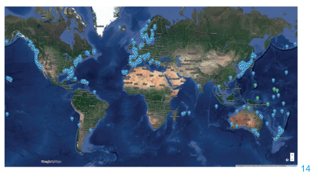
CryoSat-2 tide gauge comparison

- To compare tide gauge (TG) data with altimeter data, all standard corrections are applied to GOP BLC (CG) and J2/J3/6A (REF): incl. GOT410 total ocean tide, CNESCLS15 MSS and the high frequency part of DAC
- The altimetric SLA is gridded to monthly solutions: Gaussian distance-weighted gridding: σ = 0.75°, cut-off 3σ, spacing 0.25° and then interpolated to the TG locations with bicubic grdtrack routine from GMT
- PSMSL TGs have been selected from 2010 – 2022: this reduces the data set from 1573 gauges to 565
- Next, only TGs are considered with correlation with altimetric SLA R > 0.5, sd σ < 12 cm, and SLA – TG absolute slope < 6 mm/yr. Excluding TG with large data gaps further reduces the set to 309 TGs (see map)
- For CG and REF the table gives the mean correlation, standard deviation, and tilt (ICE-5G GIA corrected) with respect to the tide gauges
- The 0.17 mm/yr tilt between TG and CG, shows that BLC is perfectly stable and suited to be an ECV

	Correlation [-]	st. dev. [cm]	tilt [mm/yr]
CG − TG	0.82	5.7	0.17
REF − TG	0.84	4.9	−0.11
mean GIA			−0.27



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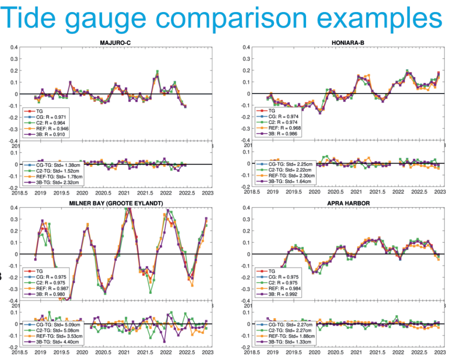
Tide gauge comparison examples

- Recent SLA vs tide gauges: four best (R) TGs with CG (GOP BLC), REF, C2, and 3B
- Each of the curves follow the TG data closely and in fact we do not see any deterioration after mid 2022, even not in 3B but be aware that we look here at decimetre level, not centimetre
- On several occasions GOP BLC and REF fall short in the TG comparison towards Sentinel-3B, making 3B a bit more suited for local oceanography



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