The Development of DORIS+SLR and DORIS-only orbits with the New std2400 Standards

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Introduction

- Our primary goal was to develop a new series of orbits to update the std2006_cs21 SLR+DORIS orbits that we had developed for the OSTST.
- The idea was that they would be based entirely on ITRF2020 (that is the SLR and DORIS extensions, SLRF2020, DPOD2020).
- Additional updates have been tested, and include, (1) updated geopotential modelling; (2) updated nonconservative force modelling; (3) GOT5.6 ocean tide model for ocean loading, ocean geopotential, and tidal geocenter modelling.
- We have completed a full set of comparisons with the publically available orbits (e.g. POEF, jpl_igs20).
- We have developed an analysis using SLR data, use of DORIS-only orbits and altimeter crossovers to independently evaluate the radial orbit accuracy of the SLR+DORIS orbits. → ***A by-product is a complete analysis of the radial orbit accuracy of DORIS-only orbits with independent SLR data, for TOPEX, Jasons 1-2-3, Sentinel-6A.***
- The SLR+DORIS orbits are already available at the IDS datacenters (NASA CDDIS and the IGN).

Model summary and comparison (1 of 2)

	Std2006_cs21 (gsfc)	Std2400 (gsfc)	POEF (cnes)	Jpl_igs20 (jpl)
data	SLR+DORIS	SLR+DORIS	**TP: SLR + DORIS, J1 (060807-090126): DORIS. For J1(020115-060807) and J2->S6A: GPS + DORIS**	GPS
technique	Dynamic	Dynamic	Dyn **(TP, J1 060807->)** Red.Dyn **(all others)**	Red. Dyn
Reference frame	SLRF2014/ DPOD2014	SLRF2020/ DPOD2020	SLRF2014/ DPOD2014	ITRF2020/ IGS20
Non-tidal geocenter	ITRF2014	ITRF2020	CNES model	ITRF2020
Tidal geocenter	GOT4.10c	GOT5.5	FES2014/S1+S2 atmos.	N/A
Gravity	GSFC 5x5 + GOCO05s	(1) CNES GRGS_RL05 (2) COSTG-FSM+SLR	CNES_GRGS__ RL04	CNES_GRGS_R L05
Ocean Tide	GOT4.10c	GOT5.6	FES2014	GOT4.8

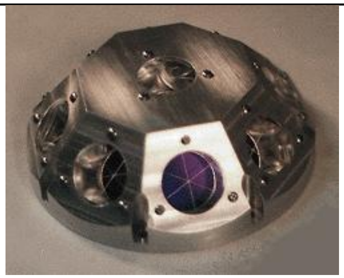
Model summary and comparison (2 of 2)

	Std2006_cs21 (gsfc)	Std2400 (gsfc)	POEF (cnes)	Jpl_igs20 (jpl)
SRP Model	TP: Heritage box-wing J1-J3: tuned box-wing S6A: CNES 6-panel	TP: retuned Heritage box-wing J1-J3 tuned box-wing, S6A: Conrad 12-panel	CNES box-wing	J1-J3: box-wing, S6A: Conrad 12-panel

SLR+DORIS Statistics and Lessons (1 OF 3)
ITRF2014 -vs- ITRF2020

Satellite (tracking span)		Test (std2006_cs21 standards)	DORIS Avg. RMS residuals (mm/s)	SLR Avg. RMS residuals (mm)
TOPEX	(1993.0-2002.0)	ITRF2014	0.5277	16.05
		ITRF2020	0.5276	15.21
	(2002.0-2004.8)	ITRF2014	0.4652	14.92
		ITRF2020	0.4650	13.27
Jason-1	(2002.0-2009.0)	ITRF2014	0.3884	7.86
		ITRF2020	0.3883	7.58
Jason-2	(2008.6-2016.7)	ITRF2014	0.3894	7.05
		ITRF2020	0.3906	7.09
Jason-3	(2016.1-2020.0)	ITRF2014	0.3923	5.90
		ITRF2020	0.3923	5.78
	(2020.0-2023.6)	ITRF2014	0.3906	6.04
		ITRF2020	0.3897	5.94

- TOPEX SLR fits remain high due to Large ring LRA which induces modelling error.
- The LRA's on J1-J3, S6A, allow a more focused return.



SLR+DORIS Statistics and Lessons (2 OF 3)
ITRF2014 -vs- ITRF2020

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- ❑ SLR Network & Reference Frame has improved from 2002 – 2003 (*focus on ITRF2014-only or ITRF2020-only SLR RMS evolution*)

SLR+DORIS Statistics and Lessons (3 OF 3)
ITRF2014 -vs- ITRF2020

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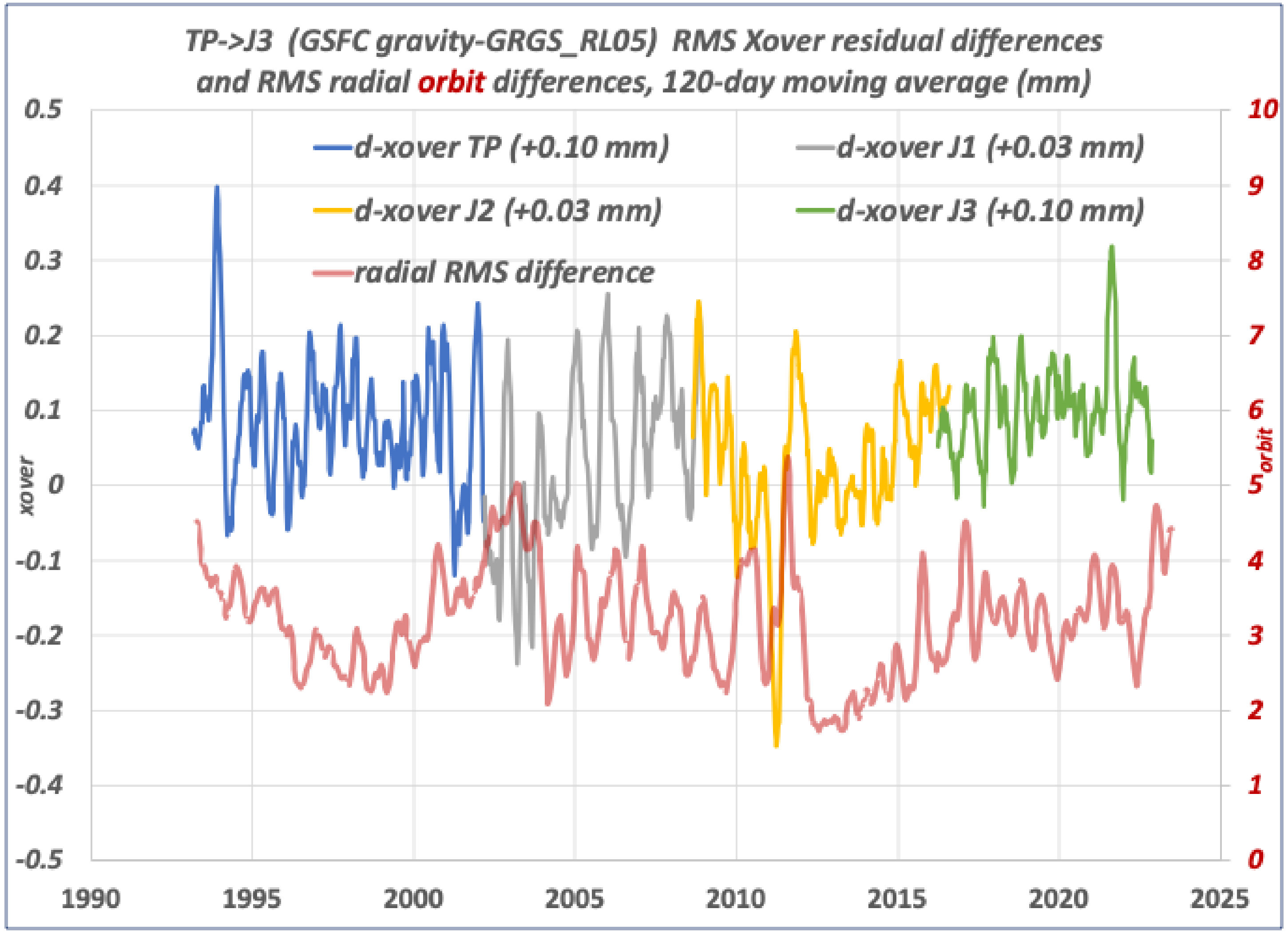
- ITRF2020 (SLRF2020 + DPOD2020) generally an improvement on ITRF2014.

Geopotential Evaluations (1 of 2): grgs_rl05

RMS Altimeter crossover residual differences (GOCO05s + GSFC 5x5 SLR+DORIS TVG, and the GRGS_RL05) smoothed with a 120-day moving average (mm). (***Positive shows improvement***)



Geopotential Evaluations (2 of 2): costg_fsm + SLR

Tests with Jason-3 (2018/0101–2024/0225)

Test	Avg. DORIS residuals (mm/s)	Avg. SLR residuals (mm)	Avg. Altimeter Crossover residuals (cm)	Radial orbit difference with JPL_IGS20 (mm)
Baseline (with ITRF2020)	0.4081	5.92	5.174	5.48
+ GRGS_RL05	0.4080	6.02	5.164	5.27
+ COSTG_FSM	0.4157	5.95	5.165	5.09
+ COSTG_FSM and SLR C_{20} & C_{30}	0.4157	5.95	5.164	5.10
+ COSTG_FSM and SLR 2x2 + C_{30}	0.4157	5.90	5.164	5.05

COSTG-FSM:
Peter H., Meyer U., Lasser M., and Jäggi A., (2022). "2022 COST-G gravity field models for precise orbit determination of Low Earth Orbiting Satellites", *Adv. Space Res., 69(12),* 4155–4168, doi: 10.1016/j.asr.2022.04.005.

For Std2400
This geopotential model applied after launch of Sentinel-6A, for S6A and Jason-3 (COSTG_FSM and SLR 2X2 + C_{30})

SLR:
(1) 5x5 series from Bryant Loomis (NASA GSFC); Moving 4-week solution, 1993– present based on SLR (geodetic) satellites, produced under auspices of GRACE-FO.
(2) available from https://earth.gsfc.nasa.gov/sites/default/files/geo/slr-weekly/gsfc_slr_5x5c61s61.txt

GOT5.5/GOT5.6 tide model

• GOT5.5 & GOT5.6 are the latest in the series of ocean tide models developed using the approach from Schrama and Ray (1994).
• GOT5.5/GOT5.6 replace the GOT4.10c model that was used for the std2006_cs21 set of orbits.
• In our implementation of GOT5, we use Ray and Erofeeva (2014) for the long period tides (e.g. Mm, Mf, Mt, Mq, Sa, Ssa), and a nodal equilibrium tide derived from Ray and Cartwright (1994).
• The GOT5 models are distinguished from the earlier GOT4.10c model by the more extensive set of altimeter data used in its derivation (see Table 2 of Ray, 2025), the improved prior model used in its formulation, and refined processing as described by Ray (2025).
• GOT5.5 explicitly models 16 tidal constituents, while GOT5.6 adds four solutions for third degree tidal constituents.

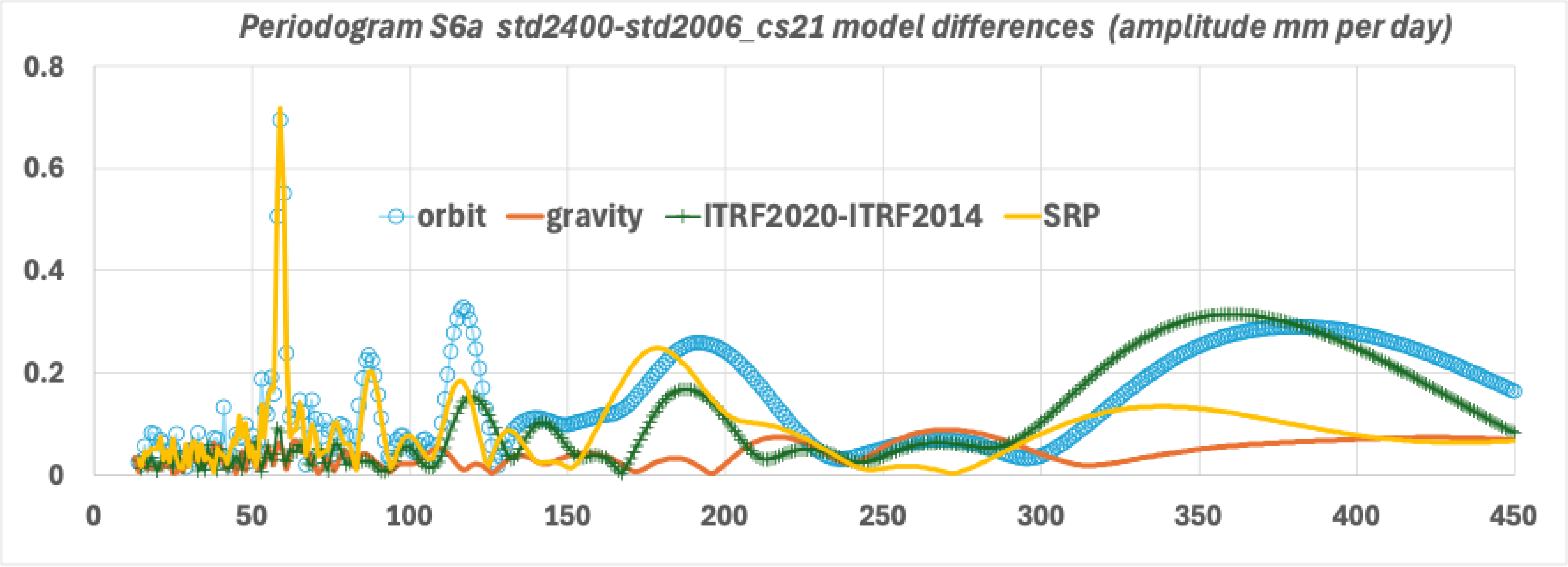
For more information please see the following reference:

Ray R. (2025). "Documentation for Goddard Ocean Tide Solution GOT5: Global Tides from Multimission Satellite Altimetry", NASA TM-20250002085, NASA Goddard Space Flight Center, Greenbelt, Maryland, U.S.A,

https://ntrs.nasa.gov/citations/20250002085

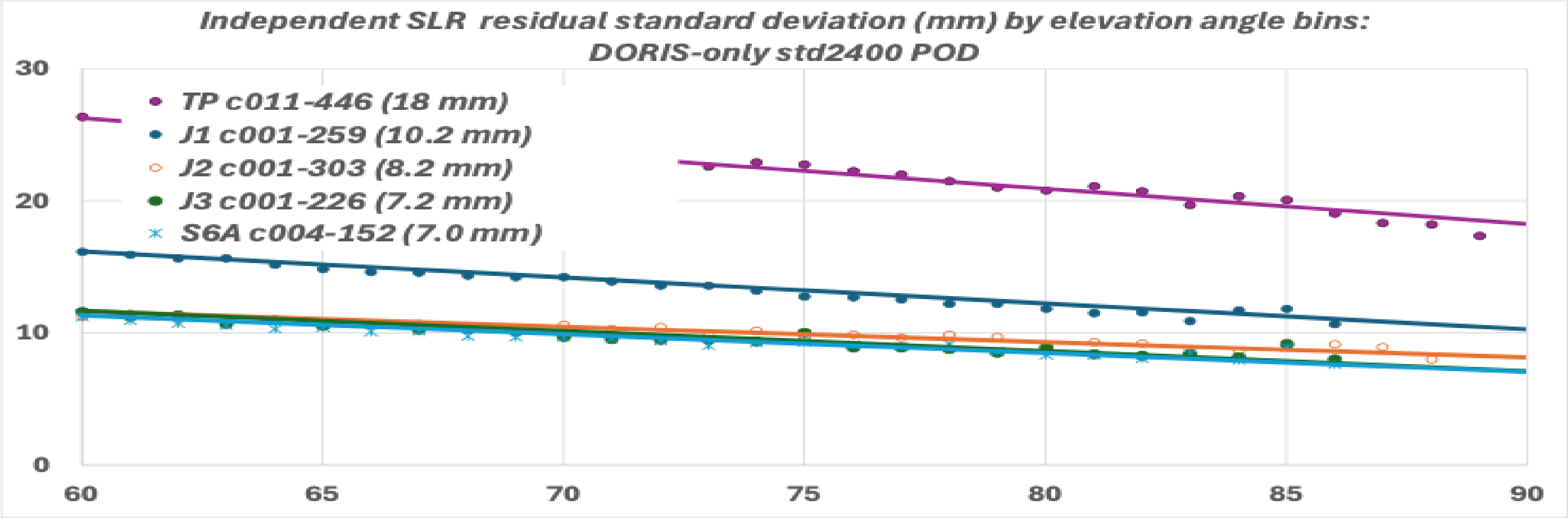
Focus on Sentinel-6A: Spectral Analysis of Orbit Differences

1. Start with orbits that include *all* std2400 standards.
2. Compute permutations, where respectively only the gravity field, only the ITRF, and only the macromodel are computed according to the ”old” (std2006_cs21) standards.
3. Analyze the orbit differences for std2400 – ”subset permutation orbits” via spectral analysis to isolate the impact spectrally of each model change.



Evaluate Radial Orbit Error for DORIS-only orbits with SLR data

1. Compute DORIS-only orbits for all satellites (TOPEX, J1-J2-J3, S6A).
2. Use “external ephemeris” option with GEODYN to evaluate SLR data w.r.t. these DORIS-only orbits
3. Bin the residuals by elevation & compute an SLR residual standard deviation by elevation bin for each satellite, using data from “core” SLR stations.
4. Then we extrapolate the linear fit of these standard deviations to 90° elevation.



Evaluate Radial Orbit Error for SLR+DORIS orbits with Altimeter Crossovers (1)

(1) Evaluate altimeter crossovers for DORIS-only, SLR+DORIS orbits.

$$r_{ESD}^2 = r_{EDonly}^2 + r_{ETVE}^2 + r_{EGCE}^2$$

where r_{ESD} is the SLR+DORIS radial orbit error estimate, r_{EDonly} is the SLR accuracy estimate for the DORIS-only (or non-SLR) orbit, r_{ETVE} is the time-varying error, and r_{EGCE} is the geographically correlated error component.

(2) Evaluate the variance of the altimeter crossover differences RMS.

$$r_{ETVE}^2 = (X_{SD}^2 - X_{non-SLR}^2) / 2.0,$$

where X_{SD}^2 is the Altimeter Crossover variance for the SLR+DORIS orbit, and $X_{non-SLR}^2$ is the altimeter crossover variance for the non-SLR (DORIS-only) orbit

(3) Evaluate the geographically correlated component r_{EGCE}
is computed as the total RMS of the difference of " non-SLR orbit" – std2400 orbit differences computed by 5x5 degree bins.

We estimate the radial orbit error of the SLR+DORIS by bootstrapping with the radial orbit error predicted from the variance of the altimeter crossover differences.

Evaluate Radial Orbit Error for SLR+DORIS orbits with Altimeter Crossovers (2) Examples

Satellite 10-day orbit cycles dates: yymmdd	Orbit	Xover RMS (mm)	SLR est. (mm)	GSFC est. (mm)
Jason-2 cycles 1-303 080712-161004	DORIS std2400	54.109	8.2	---
	std2400	53.997	----	7.8
	std2006_cs21	54.299	----	8.8
	POEF	53.872	7.6	----
	jpl_igs20	53.830	6.9	----
Jason-3 cycles 1-226 160217-220410	DORIS std2400	52.422	7.2	---
	std2400	52.230	----	6.4
	std2006_cs21	52.321	----	6.8
	POEF	52.451	6.4	----
	jpl_igs20	52.149	5.6	----
Sentinel-6A cycles 4-152 201218-250102	DORIS std2400	----	7.0	----
	std2400	55.040	----	6.8
	std2006_cs21	55.260	----	8.0
	POEF	54.867	6.4	----
	jpl_igs20	54.845	5.8	----

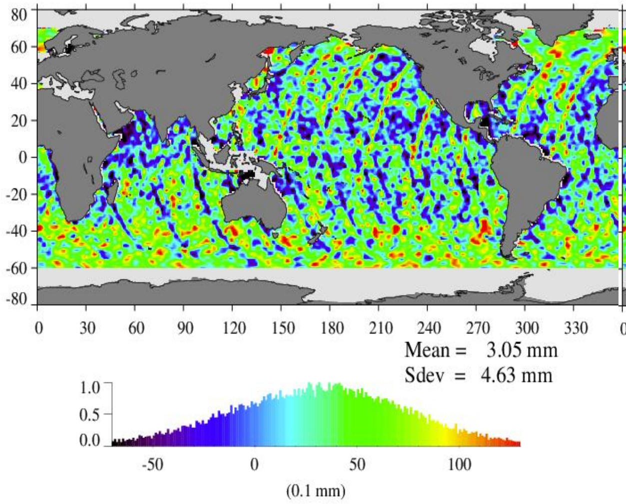
Key points:

(1) We can estimate the radial orbit error of the SLR+DORIS orbits (r_{ESD} or GSFC estimate) by "bootstrapping" from the estimate of the radial error of the DORIS-only orbits using Altimeter Crossovers

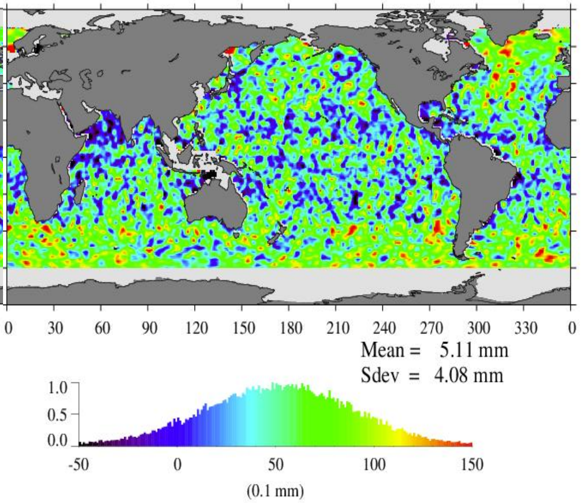
(2) The DORIS-only orbits are very competitive in an aggregate sense with the project orbits based on GPS (especially since there is room for improvements in DORIS modelling … e.g. clocks, troposphere).

Evaluate Sea Surface Height Collinear Residuals for S6A – Jason-3 Tandem Mission (*S6A cycles 32-51)* ***by Orbit***

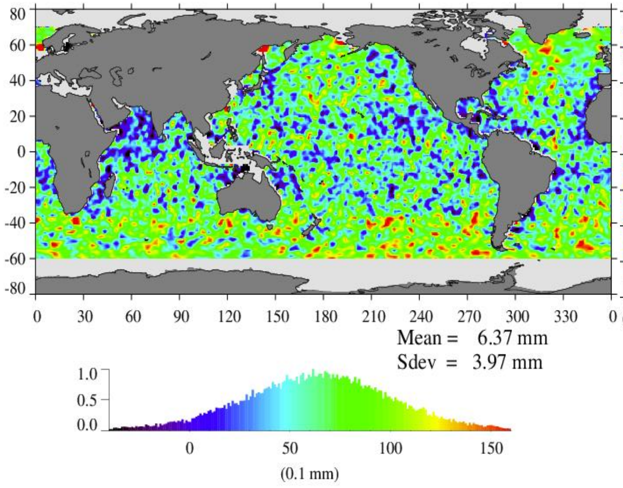
std2006_cs21



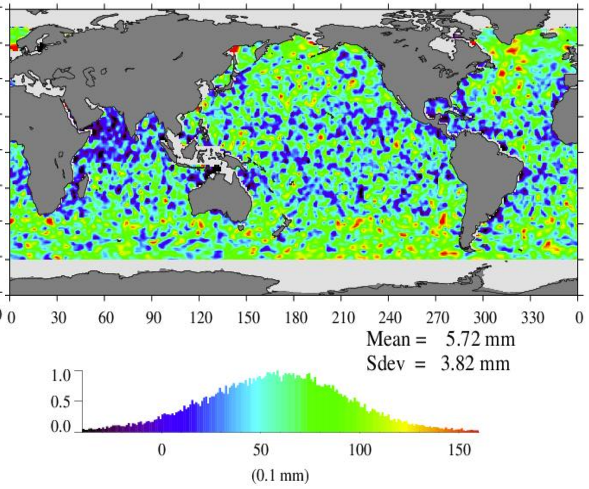
std2400



CNES poef



JPL jpl_igs20



Availability of std2400 orbits

1. Orbits are at the IDS data centers (NASA CDDIS and the IGN).
2. The std2400 orbits were also provided to Remko Scharroo @ eumetsat for ingestion into RADS.
3. Description file (the orbit standards is available:
   https://ids-doris.org/documents/BC/data/std2400_orbit_standards_DORIS+SLR_NASA_GSFC.pdf

3. DOI has been assigned by the International DORIS Service
   10.24400/312072/i01-2025.001 (→ *Thank you, Laurent*)

4. Format of data citation still needs to be finalized.
5. Journal paper that describes the derivation of these orbits has been submitted, and is in review.

The sp3 files have the naming convention: **AAASATVV.bXXDDD.eYYEEE.D_L.sp3.FFF**
AAA = **GSC -- name of analysis center.**
SAT = **TOP, JA1, JA2, JA3, S6A --- Satellite ids**
XXDDD = year and day of year that the orbit file starts.
YYEEE = year and day of year that the orbit file ends.
"D_L" = indicates a DORIS+SLR-based orbit & "_XS" indicated Altimeter Crossover + SLR orbits.
VV = **20, 21** for the std2400 series orbits.
(based on DPOD2020/SLRF2020; GRGS_RL05 to 2021.0, COSTG/FSM after 2021.0;
GOT5.5 to 30x30 for tidal geopotential and ocean loading is used for all orbits).
FFF = File release number:

VV=20: Orbits computed with the grgs_rl05 gravity model
(TOPEX, Jason-1, Jason-2, Jason-3 (through 2020-DOY353)).

VV=21: Orbits computed with the COSTG_FSM + GSFC SLR TVG gravity model (Jason-3 from 2020-DOY352 onwards, and Sentinel-6A) and the GFZ AOD1B RL06 atmosphere-ocean dealiasing model.

Future work

1. Create std2400 orbits for all extended missions (Jason-1).
2. Fill-in any data gaps that are identified that would be important for altimetry users.
3. Prepare a NASA TM on the std2400 orbits to provide extra details that were not included in the journal paper.
4. Start working on next-generation of improvements
   - Jason-3 modelling improvements.
   - Improved DORIS clock modelling for S6A, Jason-3.
   - Improved modelling of troposphere.
   - Correct SLR data problems (Stanford Counter model, pressure errors early in the SLR data history) identified by the Herstmonceux team and the ILRS central Bureau.

Backups

Average RMS radial orbit differences for std2400 orbits

Satellite	POEF (mm)	jpl_igs20 (mm)
TP (930110 – 020115, no GPS)	8.34 ± 1.90	-----
TP (020115 – 041002, no GPS)	8.43 ± 1.86	-----
J1 (020115 – 060807, GPS)	6.30 ± 2.11	6.37 ± 1.83
J1 (020115 – 040625, GPS and DORIS USO #2)	6.88 ± 1.94	6.86 ± 1.77
J1 (040625 – 060807, GPS and DORIS USO #1)	5.63 ± 2.11	5.79 ± 1.74
J1 (060807 – 090126, no GPS and DORIS USO #1)	8.65 ± 2.11	-----
J2 (080712 – 161002, GPS)	6.10 ± 1.47	5.26 ± 1.68
J3 (160217 – 240720*, GPS)	5.90 ± 1.11	4.87 ± 0.93
J3 (160217 – 201217, GPS, std2400)	5.65 ± 1.05	4.75 ± 0.91
J3 (201217 – 240720, GPS, std2400_ext)	6.24 ± 1.10	5.03 ± 0.94
S6A (201217 – 240720, GPS, std2400_ext)	5.79 ± 1.13	4.30 ± 0.84
S6A (201217 – 250103, GPS, std2400_ext)	5.79 ± 1.14	4.32 ± 0.86
* J3 jpl_igs20 orbits available over 160217 – 240720		