GPS-based dynamic orbit determination for low Earth orbit satellites

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Outline

- Background and motivation
- Bernese reduced-dynamic and dynamic orbit determinations
- Internal consistency check
- External orbit validations
- Conclusions

Background: Low Earth Orbit (LEO) satellites

- LEO satellites are widely used for space geodesy research necessitating high precision orbits
- GPS-based Precise Orbit Determinations (PODs) can generate the state-of-the-art orbits

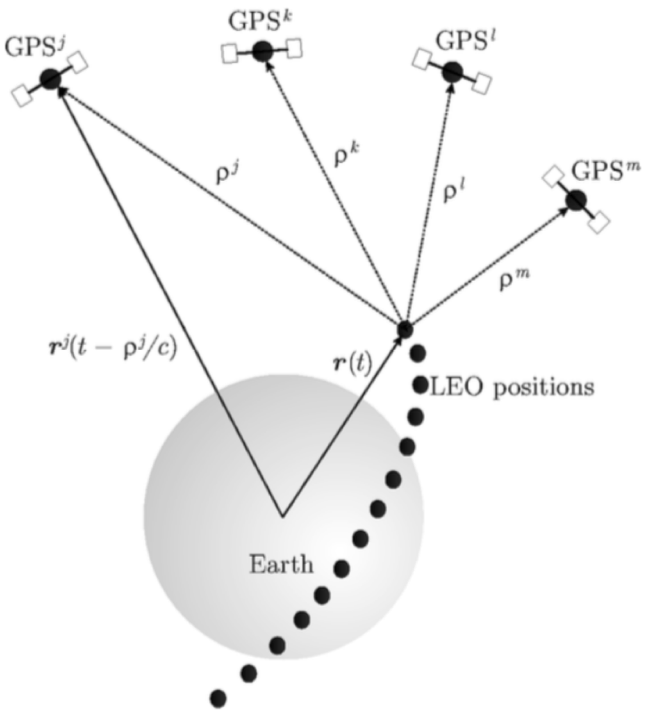
Selected LEO satellite missions and POD strategies in this research

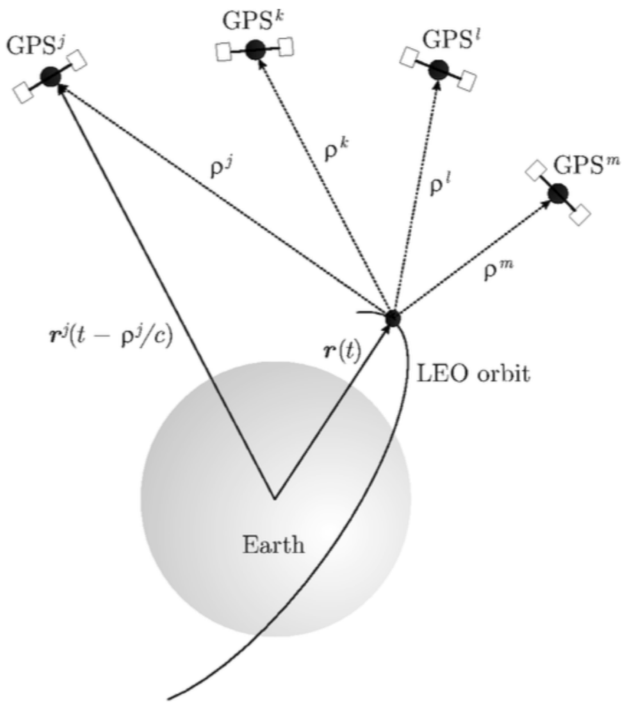
Missions	Launch	Altitude [km]	Operator	Mission type	POD strategy	Best precisions
Swarm-A/B/C	2013	550-450	ESA	Magnetic field	GPS/SLR	~2cm
Sentinel-1A/B	2014/2016	700	ESA	Radar imaging	GPS	~2cm
Sentinel-2A/B	2015/2017	800	ESA	Optical imaging	GPS	~2cm
Sentinel-3A/B	2016/2018	800	ESA/EUMETSAT	Oceanography	GPS/SLR/DORIS	~1-2cm
Jason-3	2016	1350	NSAS/EUMETSAT/CNES/NOAA	Oceanography	GPS/SLR/DORIS	~1-2cm
GRACE-FO-C/D	2018	500	NASA/DLR	Gravity field	GPS/SLR/KBR/LRI	~1-2cm

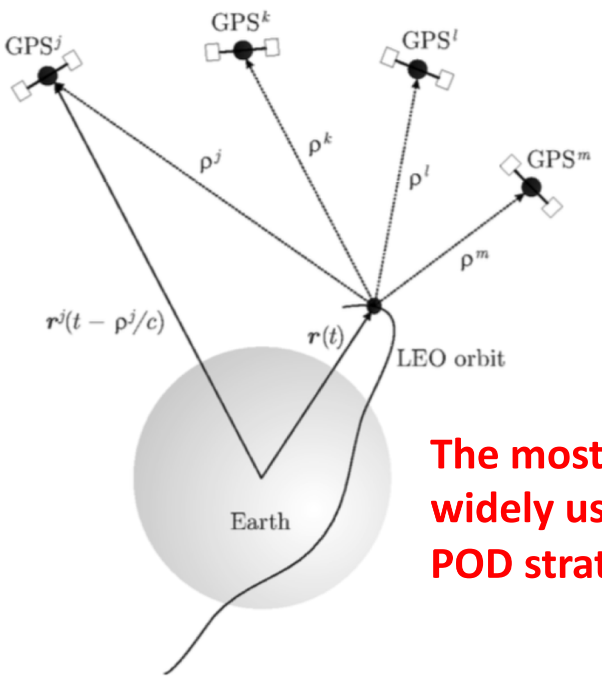
Background: satellite data sets

- Satellites flying at different orbit altitudes, experiencing different in-flight perturbations, e.g., atmospheric force
- Time span: September 2020, DOY: 245-274
- Input: Satellite metadata, GPS data (**single-receiver integer ambiguity-fixed observations**, antenna patterns), attitude nominal law/quaternions, etc.
- Software: Bernese GNSS Software (version 5.3)

Motivation: traditional POD solutions







The most widely used POD strategies!

Kinematic

- Discrete epochs
- Fully independent of force models

Dynamic

- Consecutive orbits
- Fully dependent of force models
- No 'real' perfect dynamic POD

Reduced-dynamic

- Consecutive orbits
- Dependent of reduced force models and additional empirical parameters

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Motivation

- A classical reduced-dynamic GPS-based POD strategy for LEO satellites necessitates the estimates of **numerous empirical parameters**, to compensate a limited explicit modelling of satellite dynamics. **Often, it generates the highest quality satellite orbits!**

- A more dynamic strategy, estimating **significantly fewer empirical parameters**, allows for force modeling sensitivity analyses and evaluating potential errors in the adopted GPS antenna reference points or phase center offsets, etc. But, it normally obtains worse satellite orbits than the reduced-dynamic strategy.

- **Can we get precise dynamic orbit while maintaining its high sensitivity to force models and geometric offsets?**

Bernese reduced-dynamic and dynamic POD

- Equation of motion of typical Bernese reduced-dynamic POD

$$\ddot{\vec{r}} = -GM\frac{\vec{r}}{r^3} + \vec{f}\left(t, \vec{r}, \dot{\vec{r}}, Q_1, \ldots, Q_d, P_1, \ldots, P_s\right)$$

GM: gravitational constant times mass of the Earth
r : geocentric position vector of the satellite center of mass
t : epoch
f : satellite accelerations consist of gravitational and non-gravitational perturbations
Q: empirical parameters, e.g., force scale factors
P: pseudo-stochastic parameters, e.g., piece-wise constant accelerations
d,*s*: number of parameters, *s* is often much larger than *d*

- Bernese dynamic POD

$$\ddot{\vec{r}} = -GM\frac{\vec{r}}{r^3} + \vec{f}\left(t, \vec{r}, \dot{\vec{r}}, Q_1, \ldots, Q_d, \cancel{P_1, \ldots, P_s}\right)$$

Estimate minimum dynamic and pseudo-stochastic empirical parameters!

Bernese reduced-dynamic and dynamic POD

Satellite dynamic and pseudo-stochastic parameterization for 24-hrs POD solutions

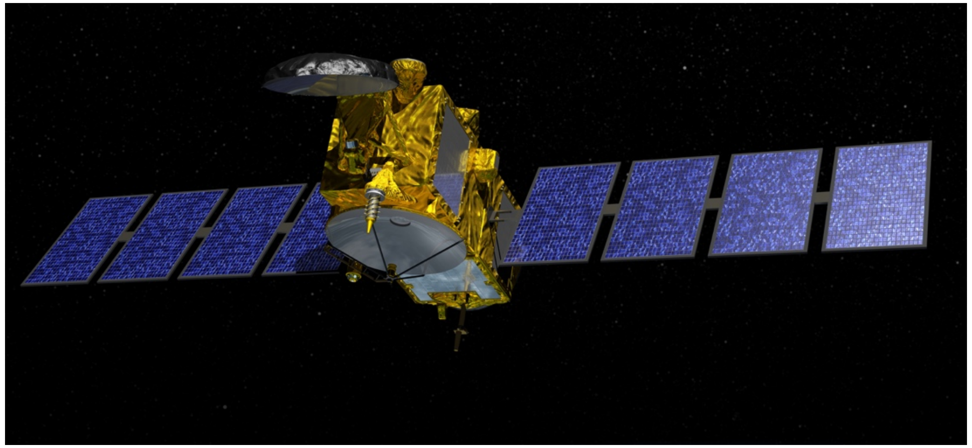
Forces and Paras.	Kinematic (KN)	Reduced-dynamic (NG)*	Dynamic (DN)
Grav. forces	No	Earth solid, ocean and atmosphere gravity, third-body, relativity, etc.	The same
Non-grav. forces	No	Atmospheric force (AF), Sun/Earth radiation pressure (SRP/ERP)	The same
Non-grav. scale factors	No	1 AF, 1 SRP	12 (SWA, SWB, GFO) / 1 (SEN-1/2/3) / 0 (JA3) AF
Constant acc.	No	No	No
1/rev. acc.	No	No	12*4 (every 1 hrs, sine/cosine, alo/cro)
Piece-wise cons. acc.	No	720 (every 6 mins, rad/alo/cro)	No

A significant reduction of the estimated dynamic and pseudo-stochastic empirical parameters!

* For detailed modeling of satellite force models please refer to: Mao, X., Arnold, D., Girardin, V., Villiger, A. and Jäggi, A., 2021. Dynamic GPS-based LEO orbit determination with 1 cm precision using the Bernese GNSS Software. *Advances in space research*, *67*(2), pp.788-805.

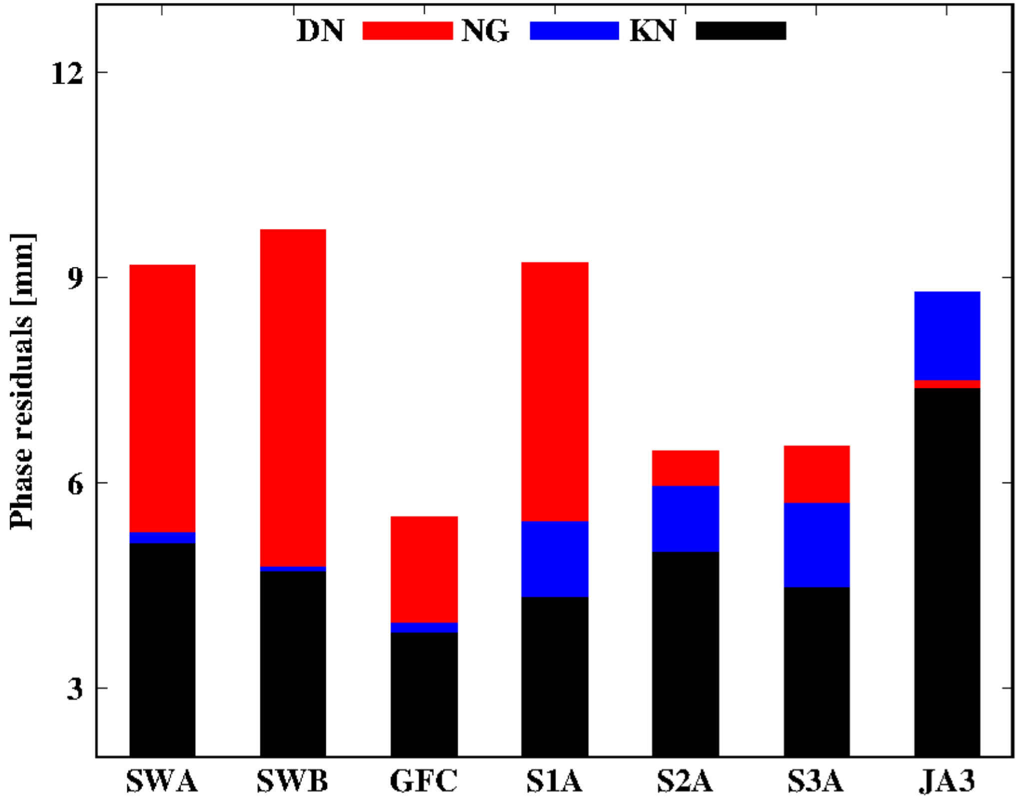
Bernese reduced-dynamic and dynamic POD

- The setup of dynamic parameterization mostly depends on the altitudes
- Solar radiation pressure is modeled however not scaled by estimated factors
- For special case like Jason-3, which experienced 4 totally different and challenging types of attitude modes in this month, we need to double the use of 1/rev. periodic accelerations, i.e., 24 groups
  - Sep.1-Sep.6: Yaw-steering forwards
  - Sep.6.Sep.16: Fixed-yaw forwards
  - Sep16-Sep.27:Fixed-yaw backwards
  - Sep.27-Sep.30:Yaw-steering backwards



* For detailed information about Jason-3 POD please refer to: Kobel, C., Arnold, D., and Jäggi, A.: Impact of different attitude modes on Jason-3 precise orbit determination and antenna phase center modeling, EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-4831.

Internal consistency check: carrier-phase residuals

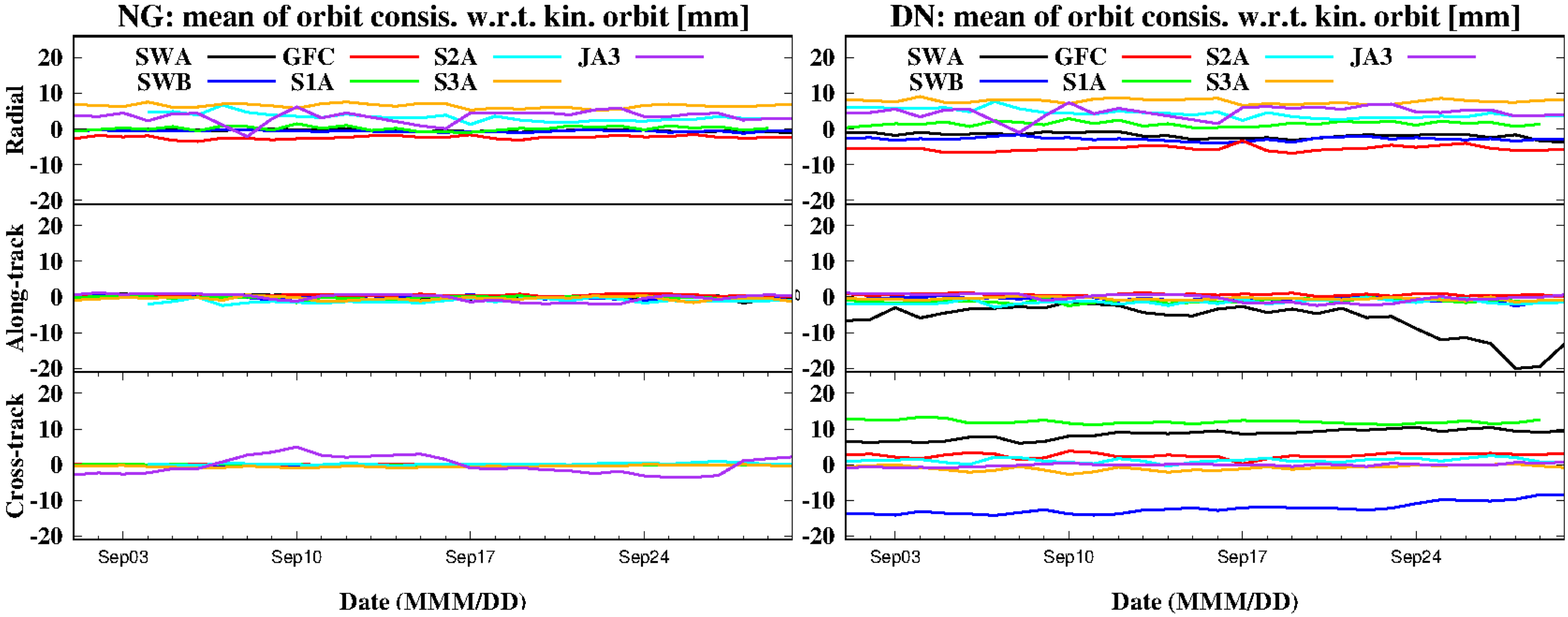


GPS carrier-phase observation residuals for the three POD solutions

A few days are removed in analyses due to satellite maneuvers and data gaps, etc.

1. The kinematic POD solutions always show the smallest residuals due to the largest number of estimated parameters, e.g., epoch-wise 3-dimentional coordinates.
2. The dynamic solutions ought to show the largest residuals due to the least estimated parameters. But surprisingly the Jason-3 dynamic solution shows smaller residuals than the reduced-dynamic solution, this needs further investigations.

Internal consistency check: orbit comparison



1. Dynamic POD and orbit comparisons indicate potential geometry bias more easily particularly in the cross-track direction.
2. It might be necessary to apply PCO/ARP corrections in the radial or the ‘Up’(NEU reference) direction for different satellites.

Internal consistency check: orbit comparison

As Dr. Montenbruck has recommended* that there should be a 1-cm correction to the CoG of the Sentinel-3A satellite in the **cross-track direction**, and we have implemented this. What will happen if we do not apply this correction? Can a dynamic POD indicates this 1-cm bias more easily?

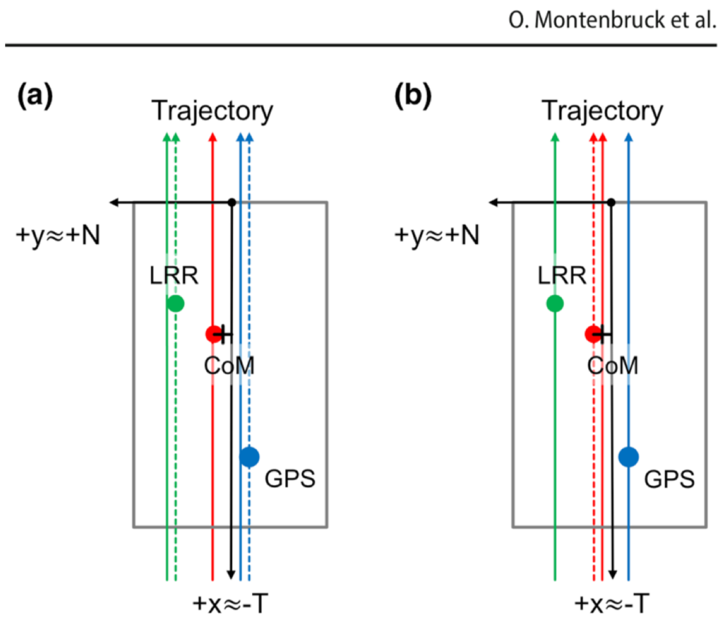
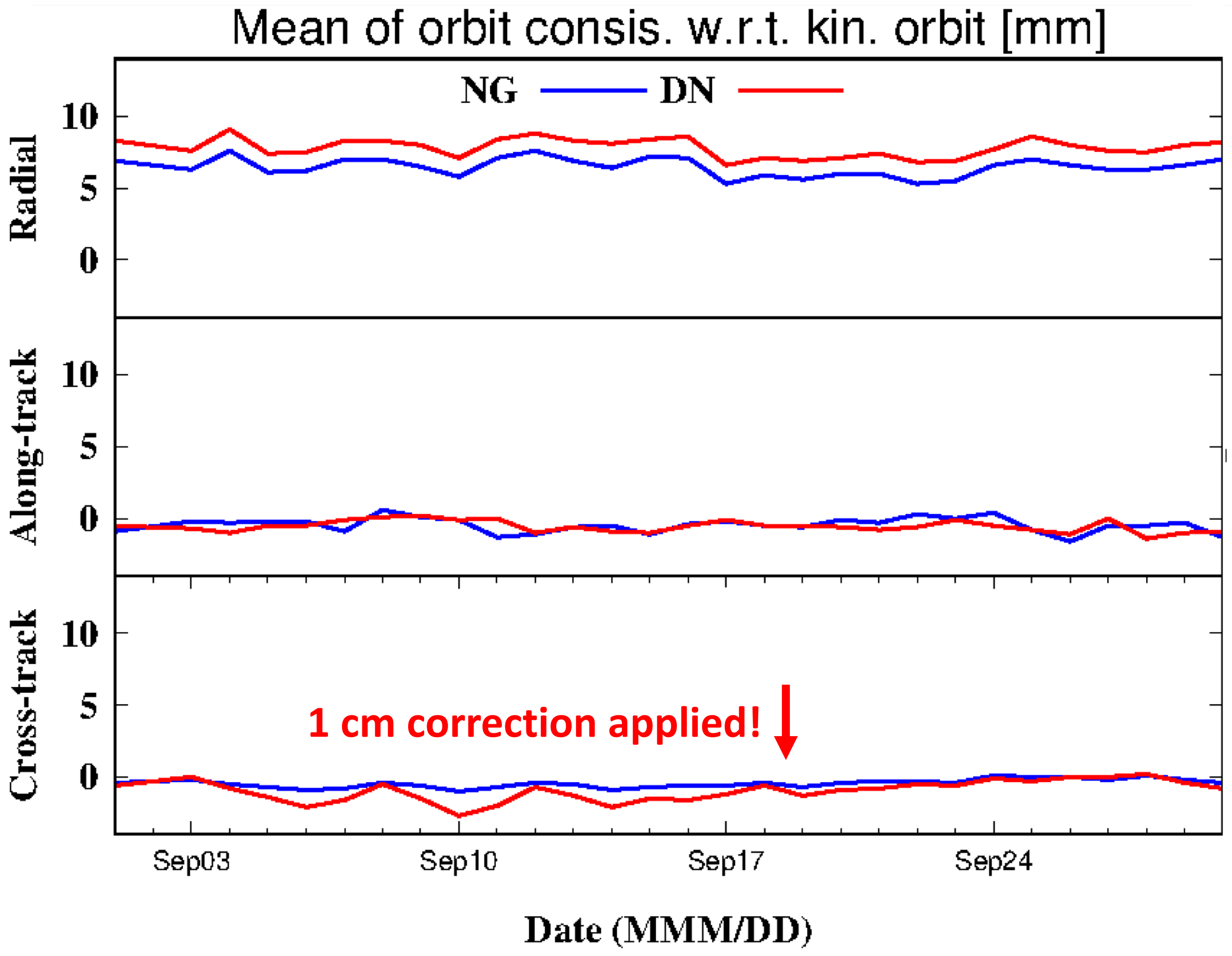
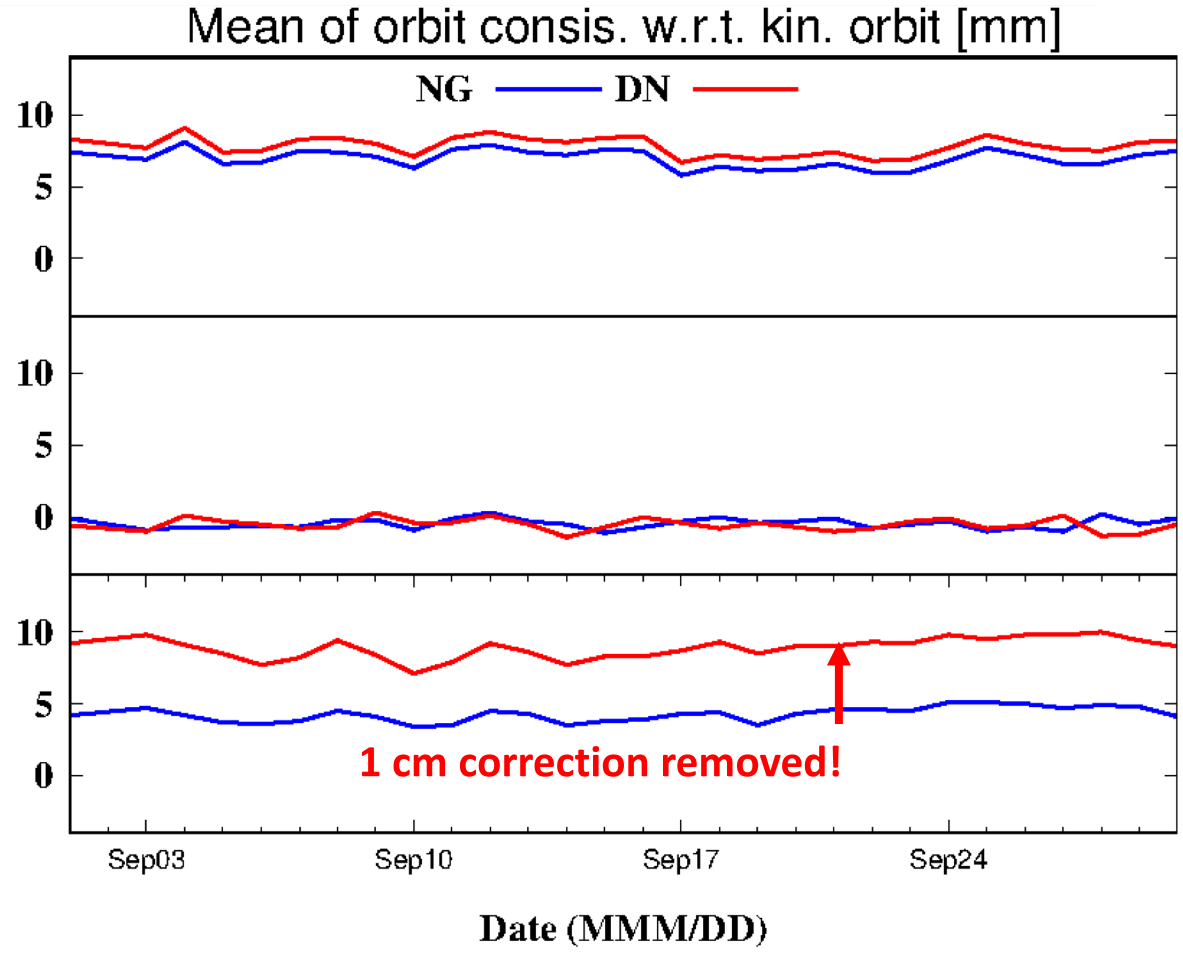


Fig. 6 Impact of an erroneous CoM location in the spacecraft body frame on float ambiguity POD (**a**) and ambiguity-fixed POD (**b**). The true center-of-mass in the schematic drawing of the Sentinel-3A satellite (as seen from above) is marked by a black cross, while the position reported by the spacecraft operator is indicated by a red dot. The blue and green dots show the location of the main GPS antenna and the laser retroreflector, respectively. Solid lines indicate the true trajectories, while dashed lines describe computed trajectories based on nominal offset values

* For detailed information about 1-cm correction to Sentinel-3A please refer to: Montenbruck, O., Hackel, S., & Jäggi, A. (2018). Precise orbit determination of the Sentinel-3A altimetry satellite using ambiguity-fixed GPS carrier phase observations. Journal of geodesy, 92(7), 711-726.

Internal consistency check: orbit comparison





1. We should apply this 1-cm correction!
2. Apparently, after the removal of this 1-cm, a dynamic POD recovers more of it because it is very sensitive to geometry bias.

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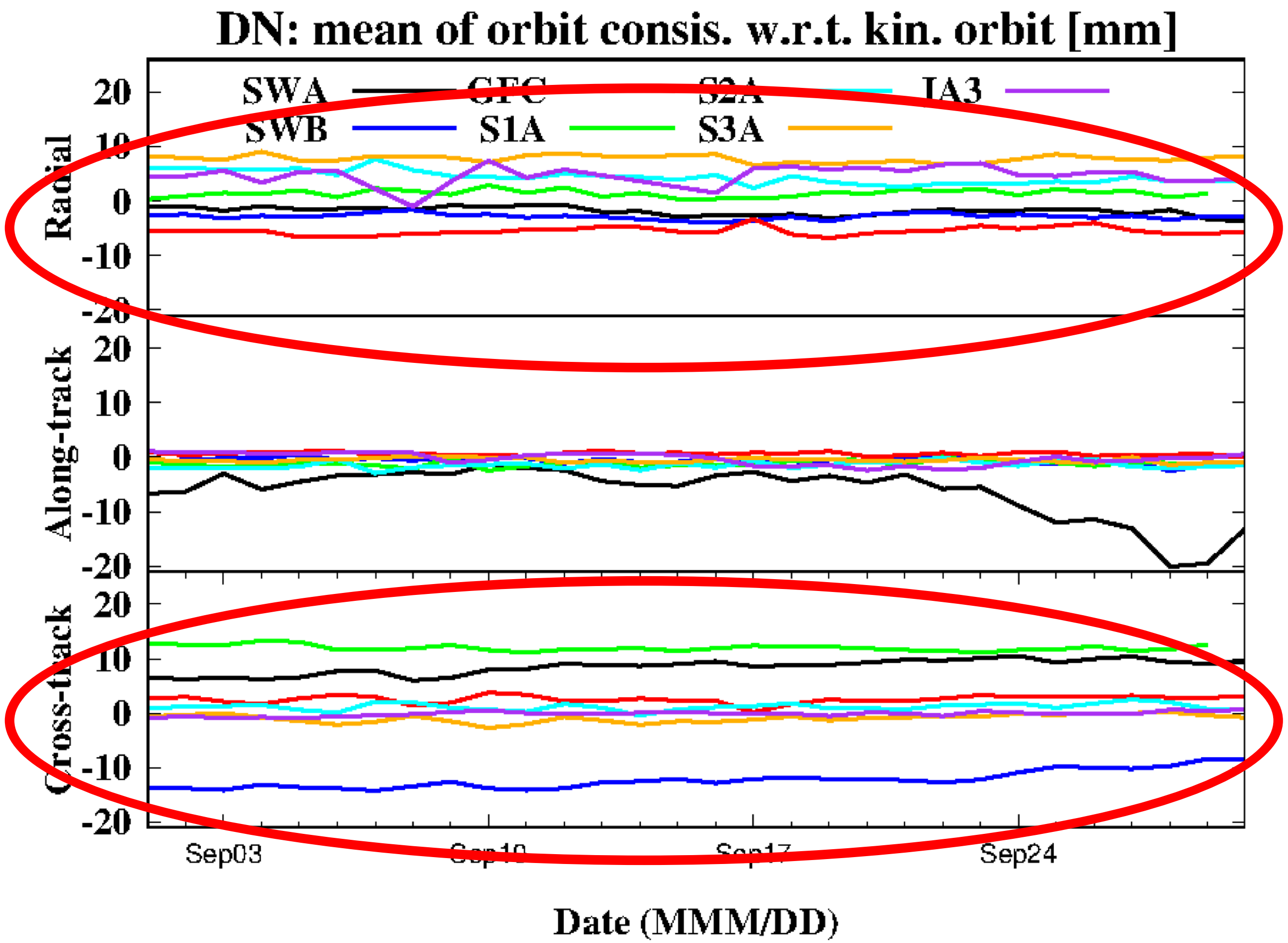
Internal consistency check: orbit comparison



Levels up to 15 mm!

1. Probably we should apply corrections to not only Sentinel-3A!
2. A dynamic POD strategy can be used as a tool to indicate geometry offsets!

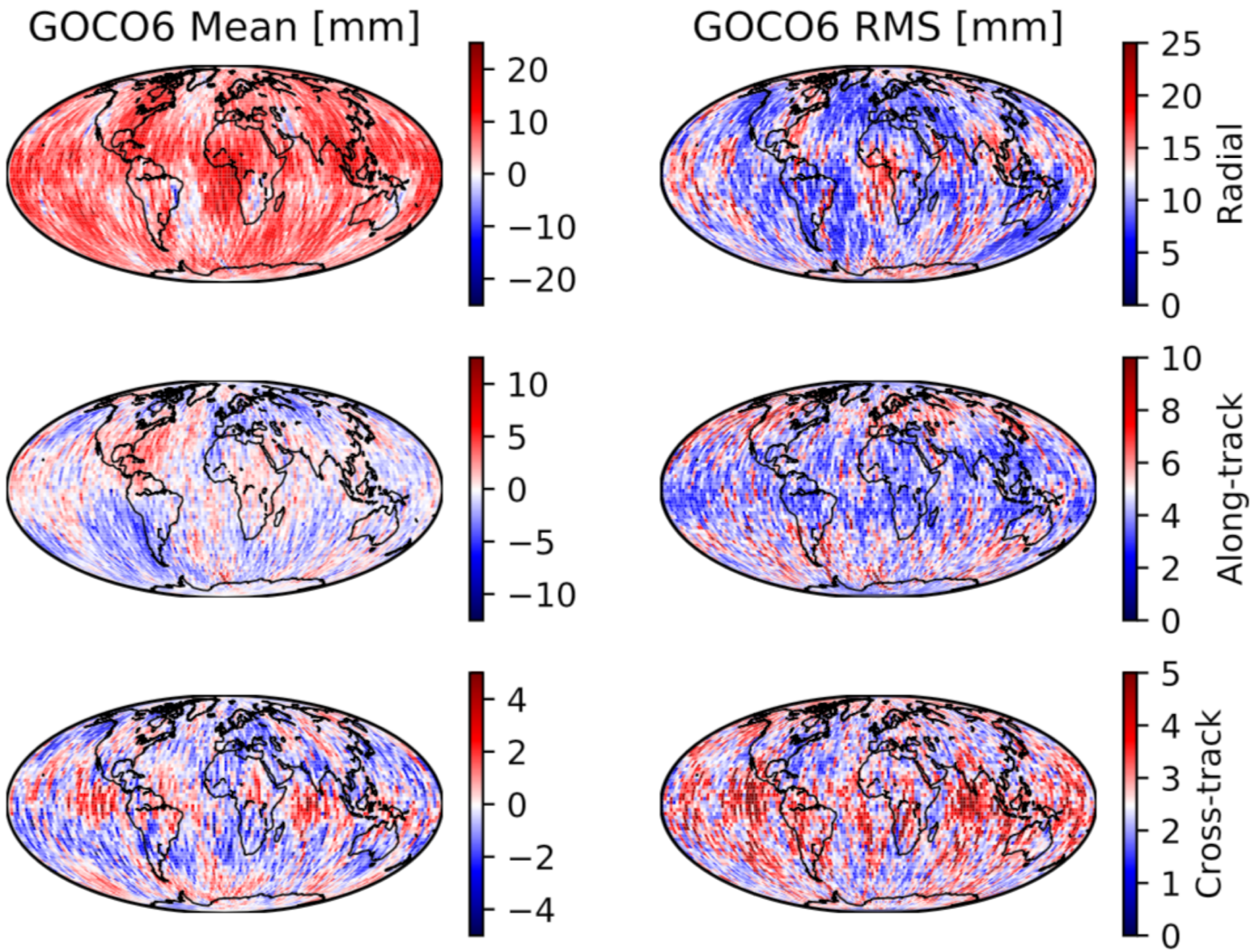
External orbit validations: satellite laser ranging

Satellite	Mean [mm]			STD [mm]		
	KN	NG	DN	KN	NG	DN
Swarm-A	2.96	3.03	**0.21**	9.84	8.50	12.11
Swarm-B	2.24	2.00	**-1.32**	9.24	8.42	11.21
Grace-FO-C	6.91	5.97	**2.80**	13.65	9.71	9.86
Sentinel-3A	-3.82	0.48	**0.30**	11.00	8.69	10.94
Jason-3	-5.90	-3.52	**-2.90**	14.95	11.86	12.08

Mean and STD statistics of SLR validation residuals in the line-of-sight direction for the 5 satellites equipped with laser retro-reflector array.
(10 selected SLR stations, elevation cut-off angle: 10 deg, outlier screening: 200 mm, selected period: September, 2020. unit: [mm].)

1. It is not surprised to see downgraded quality for dynamic orbits due to smaller number of estimated parameters and more challenging in-flight environment for LEO satellites, in particular for Swarm.
2. However in general the precisions of dynamic orbits are still at a level of 1-cm (**all with smaller mean**) when validated by the independent SLR measurements. They are still reasonably good for most of the space geodesy applications.

External orbit validations: sensitivity to dynamic models



Geographical distribution of orbit consistency residuals between the dynamic orbit and the kinematic orbit for an example satellite Sentinel-3A. The large mean in radial direction indicates potential errors in PCO/CoM. The distributions in the other two directions hint variation features associated with Earth gravity field and/or other models.

Conclusions

1. The dynamic POD strategy uses significantly fewer estimated empirical parameters however still obtains reasonably good orbits.
2. The dynamic orbit allows for better force modeling sensitivity analyses and evaluating potential errors in the adopted GPS antenna reference points or phase center offsets, etc.
3. For different LEO satellites the dynamic POD strategy has to be tailored to fit into specific in-flight environment, e.g., heavy atmospheric perturbation at low orbits.
4. The dynamic orbit solutions are sensitive to the different supporting models, e.g., gravity field. It might be used as an independent validation tool for these models.

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-Precise orbit determination solutions from the Bernese GNSS software

1.Selected space geodesy missions:

Satellites	Alt. [km]	POD tools
Swarm-A	440	**GPS/SLR**
Swarm-B	500	**GPS/SLR**
GraceFO-C	500	**GPS/SLR**/KBR
Sentinel-1A	700	**GPS**
Sentinel-2A	800	**GPS**
Sentinel-3A	800	**GPS/SLR**/DORIS
Jason-3	1350	**GPS/SLR**

2.POD input (Sep. 2020):

Satellite metadata
Ambiguity-fixed GPS observations
GPS products
Quaternions
…

3. Estimate min. dynamic and empirical paras.:

From reduced-dynamic:
1 Solar radiation pressure scale factor
1 Atmospheric force (AF) scale factor
720 piece-wise constant accelerations
…

To dynamic:
0-12 AF scl. factors based on altitudes
12 once-per-rev along-track/cross-track accelerations in sine/cosine items
…

A reduction of more than 90%!

4. Still high POD performance:

a. 1-cm level orbit precision validated by satellite laser ranging,
b. 1-cm level orbit consistency with kinematic orbits,
for particularly high-flying sats.

5. Open room for:

a. Least constraints for computing more dynamic orbits
b. High sensitivity to geometry bias, e.g., center-of-mass

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