Impact of satellite yaw attitude regime on in-flight calibration of low-Earth orbiter GPS antenna phase center

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Motivation and Background

- Antenna calibration is critical for high-precision GNSS-based precise orbit determination (POD).
  - Simple Phase Center Offset (PCO), or 3-D vector to best-fit sphere is one approach.
  - Phase Center Variations (PCVs) as function of elevation and azimuth proves to be better.
- In-flight calibration of Jason-series has benefited from yaw-steering.
  - Improves coverage and sampling, especially to decouple along-track PCO from clock.
- In-flight calibration of Sentinel-6 A/B and SWOT poses challenges, as both will be flying in fixed yaw only.
- Sentinel-3 A/B satellites already flying in fixed-yaw mode.
  - Can be used to develop and test approaches for Sentinel-6 and SWOT.

Estimation of Jason-3 PCO
Yaw-Steering vs Yaw-Fixed Phases

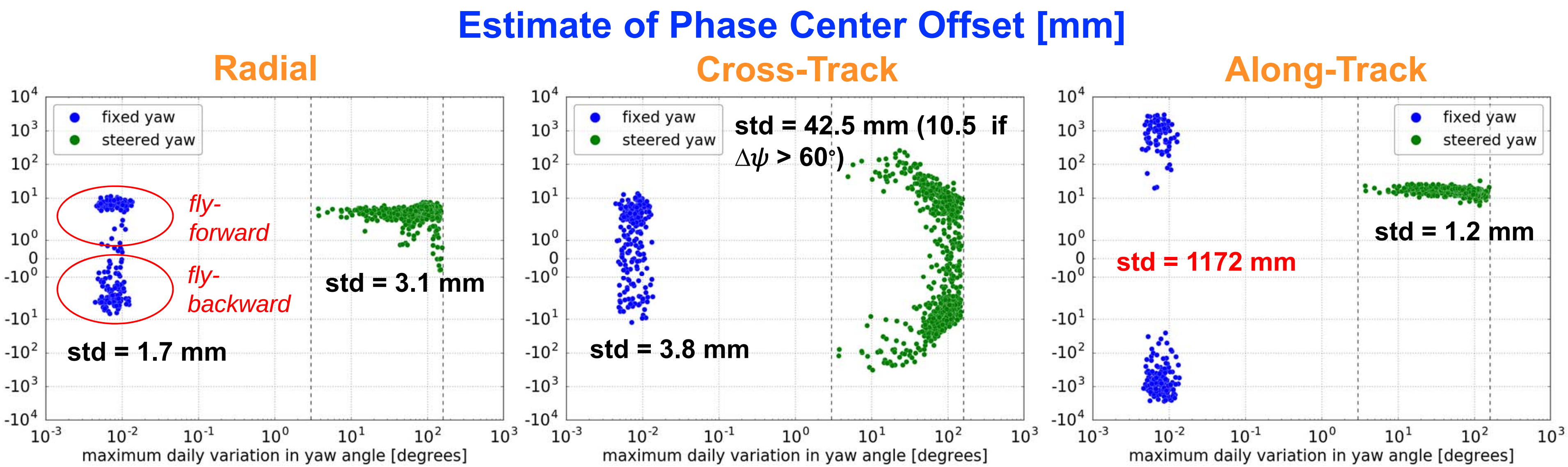
- Estimates shown as **function of maximum daily yaw angle variations**

<u>Yaw-Steering case</u>: 787 days included

- PCO well-determined in all 3 directions (provided max $\Delta\psi > 60^\circ$ in cross-track)

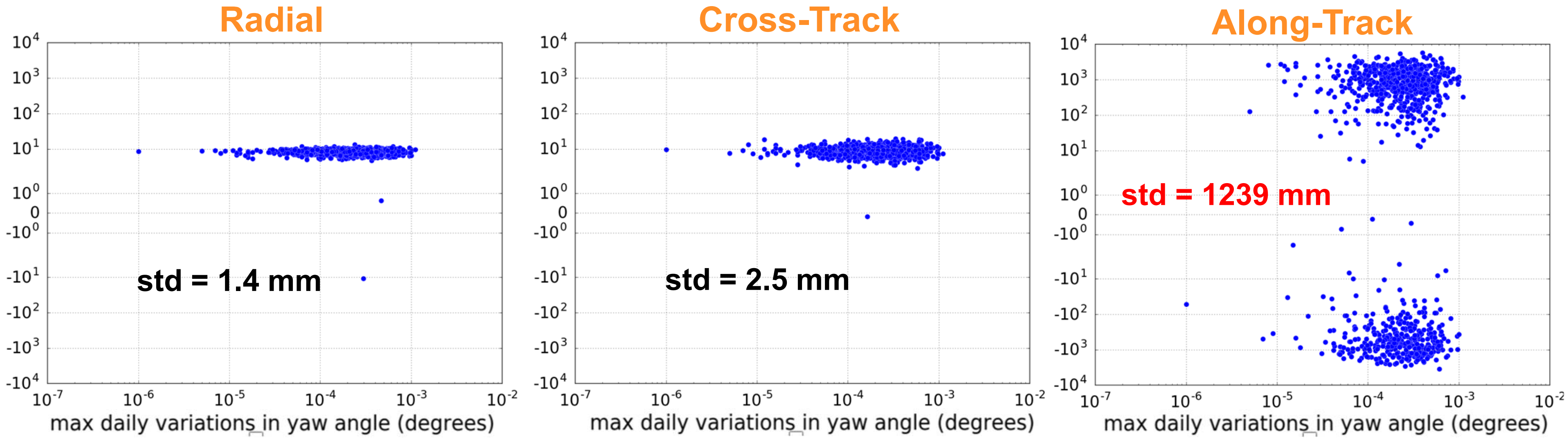
<u>Yaw-Fixed case</u>: 242 days included (AMR calibration days excluded)

- **Along-track poorly observable**; cross-track and radial components well determined
- Unexplained **fly-forward/fly-backward discrepancy in radial direction** (also visible to lesser extent in cross-track direction in steered yaw)

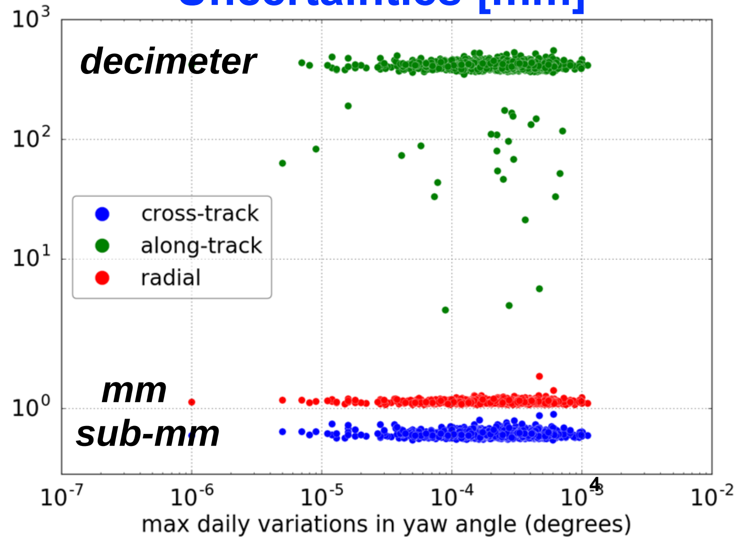


Estimation of Sentinel-3A PCO
(Sun-synchronous orbit, fixed-yaw attitude law)

Estimates of Phase Center Offset [mm]



Uncertainties [mm]



- PCO best determined in orbit transverse and radial directions (based on scatter in estimates and formal errors).
- Along-track component poorly determined.
- **Consistent with observations made for Jason-3 fixed-yaw attitude regime**

Overview of Antenna Calibrations Discussed

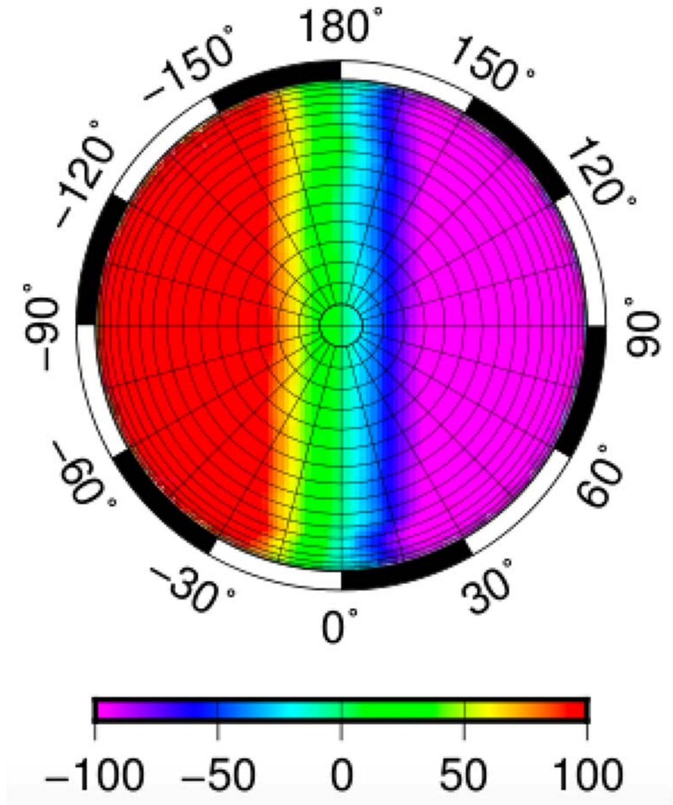
Calibration type	Description
PCO	Pre-launch estimate of phase center offset from mission project documents
PRELAUNCH	Pre-launch calibration of GPS antennas. • Jason-3: available • Sentinel-3 A/B: apply pre-launch calibration of the **Sentinel-6 RO-POD antenna**
INFLIGHT	Sum total of prelaunch and correction computed using in-flight data. • Jason-3: 1310 days (Feb 13, 2016 to Sep 14., 2019) • Sentinel-3A: 1316 days (Feb 23, 2016 to Sep 30, 2019) • Sentinel-3B: 517 days (May 1, 2018 to Sep 30 2019) • **Sentinel-3 A/B has along-track PCO correction constrained to 0**

Mitigation of Unobservability by Means of Constraint
Sentinel-3A example

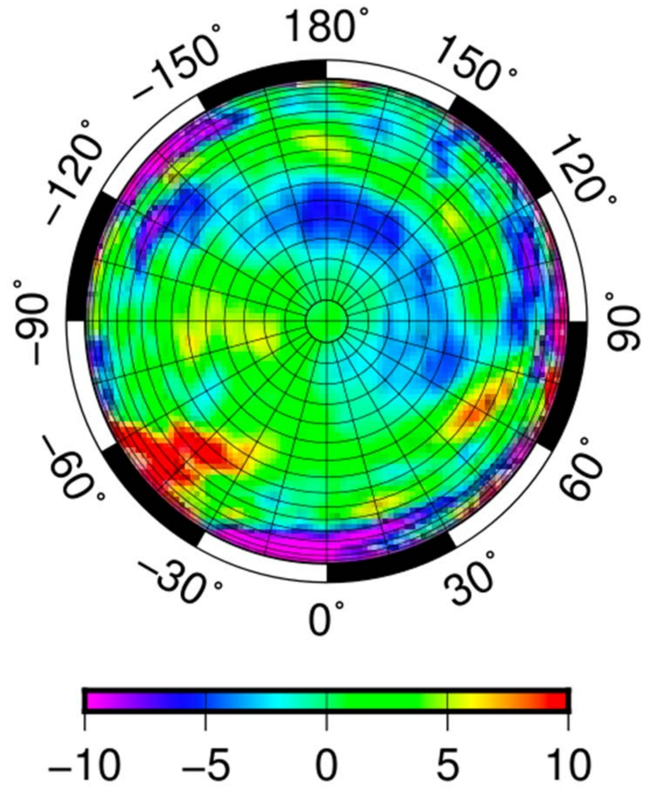
- In-Flight calibration of S3A antenna without constraints results with large (~300 mm) estimated PCO in along-track direction.

Even when satellite is flying in fixed-yaw, calibration correction can be achieved.

Unconstrained correction to prelaunch calibration



Correction to prelaunch calibration after constraining PCO in along-track direction



mm

Antenna Calibration Corrections

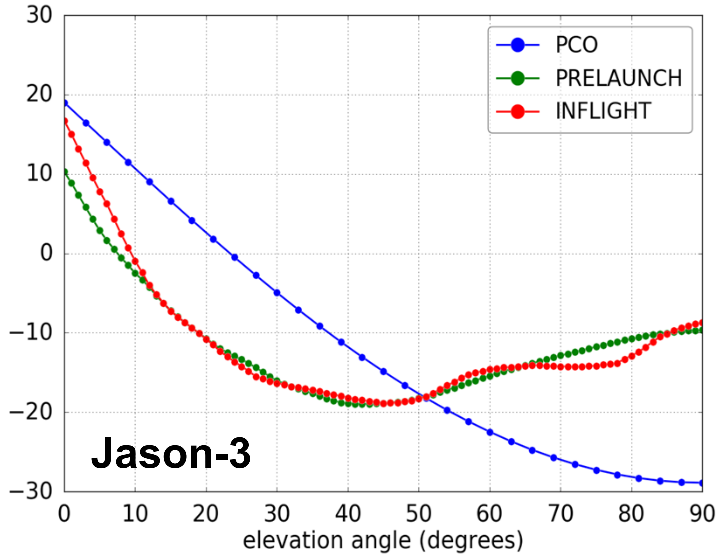
- Prelaunch calibrations contain PCO and PCV information.

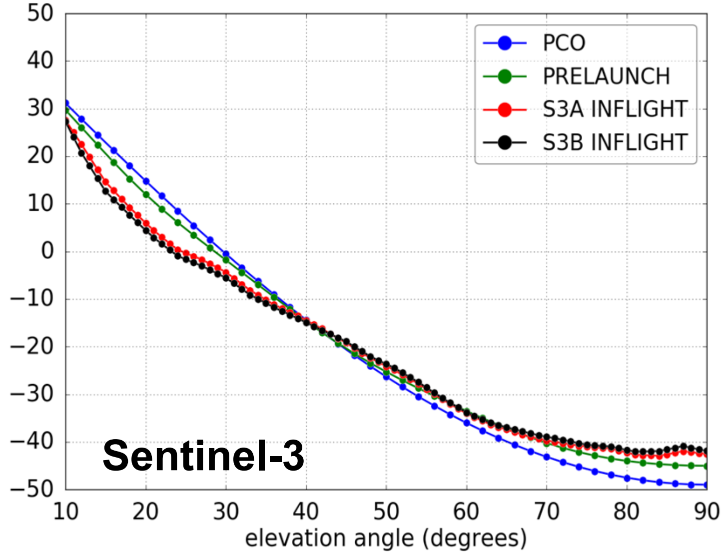
→Add value relative to prelaunch PCO

- Significant departure of pre-launch calibration from prelaunch PCO for JA3

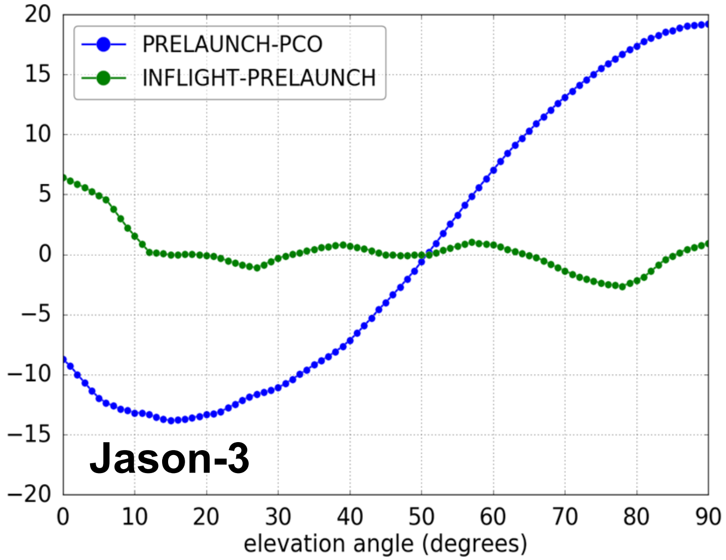
- Seemingly small corrections (e.g. estimated from in-flight data) can dramatically impact quality of LEO POD solutions.

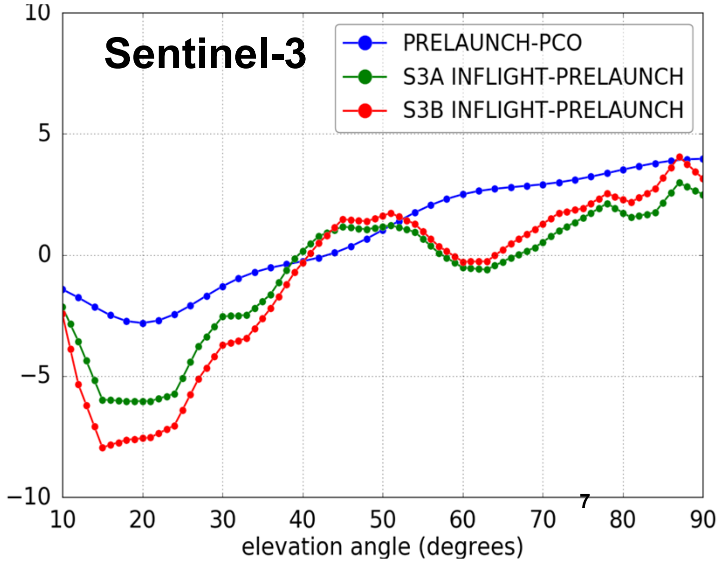
Azimuth-averages of CALIBRATIONS [mm]





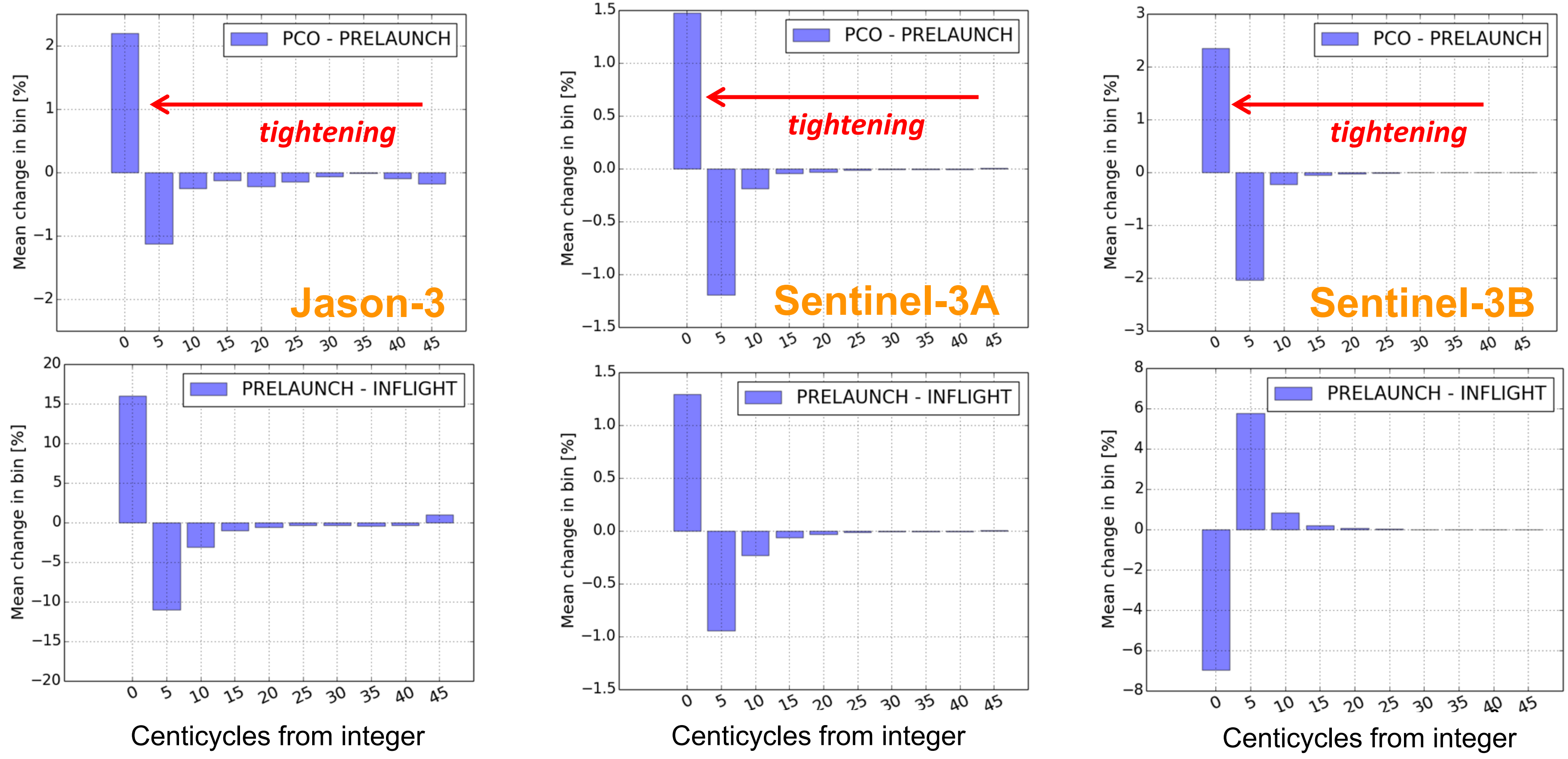
Azimuth-averages of CALIBRATION **DIFFERENCES** [mm]



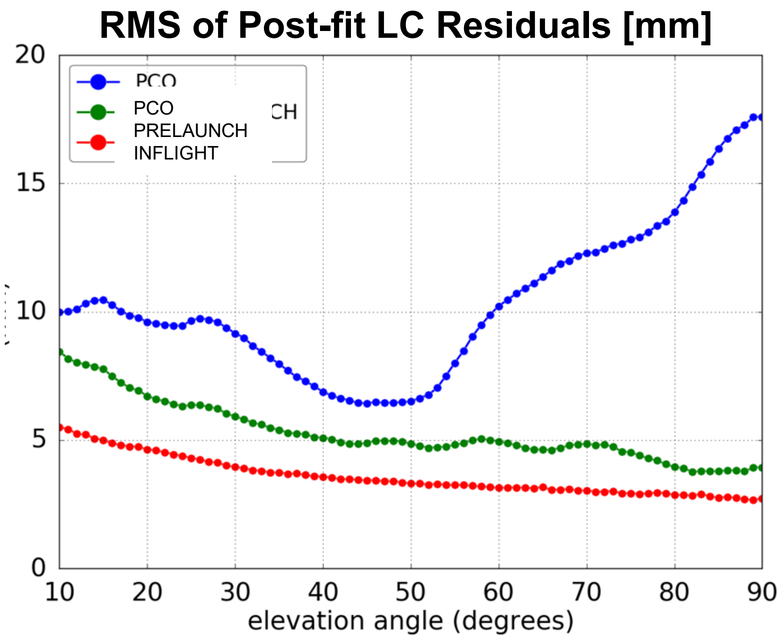


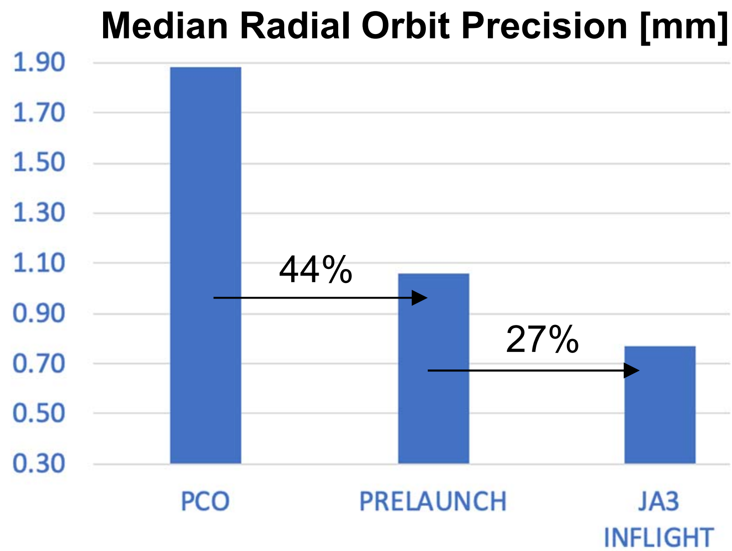
Measurement Model Improvement

– Improvement in **resolution of phase ambiguities = better measurement modeling**
– Overall tightening of the histograms closer to integer for solutions
  - For all 3 satellites when **using prelaunch calibration relative to PCO model**.
  - Additional improvement when **using inflight vs. prelaunch**: significantly larger for JA3, equal for S3A, marginal for S3B

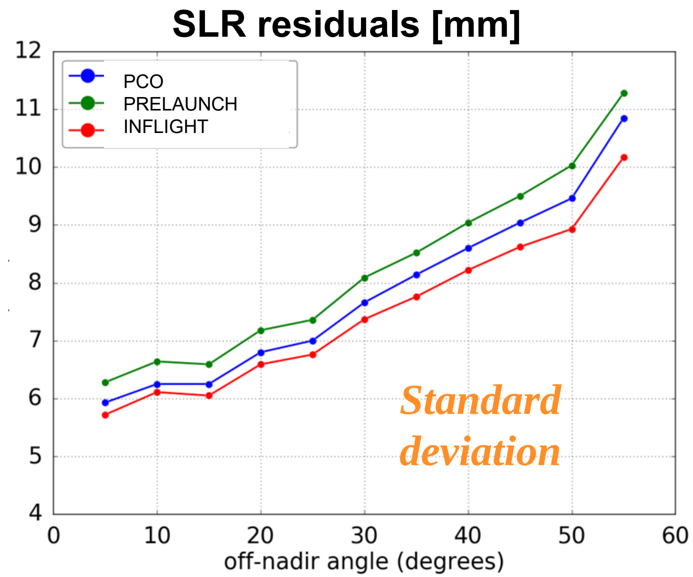


POD Performance Assessment: Jason-3



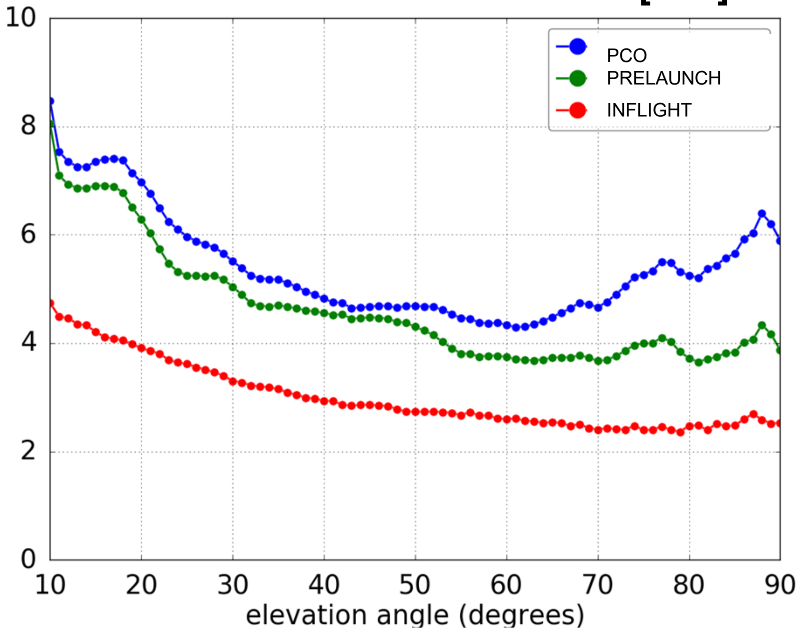


- use of prelaunch or inflight calibration yields better fit at all elevation angles
- dramatic improvement of data fit for elevations > 50°
- radial orbit precision gradually improves when using prelaunch and corrected prelaunch calibrations
- SLR residuals show orbit radial accuracy:
    - improves when using inflight calibration
    - worsens when using prelaunch calibration

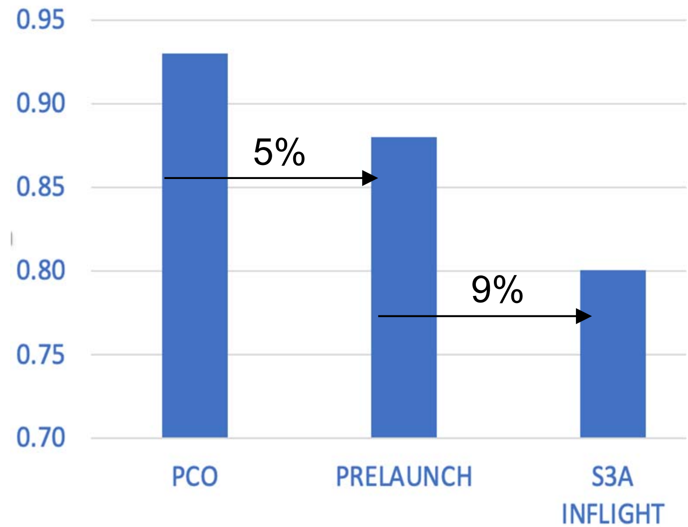


POD Performance Assessment: Sentinel-3A

RMS of Post-fit LC Residuals [mm]

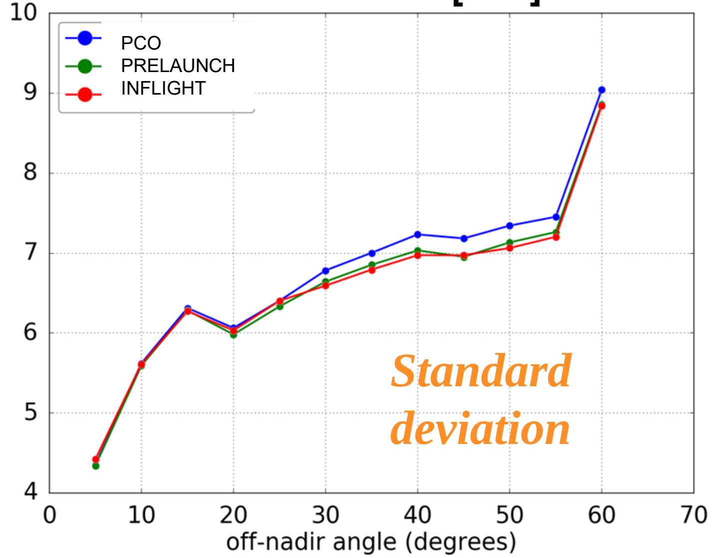


Median Radial Orbit Precision [mm]

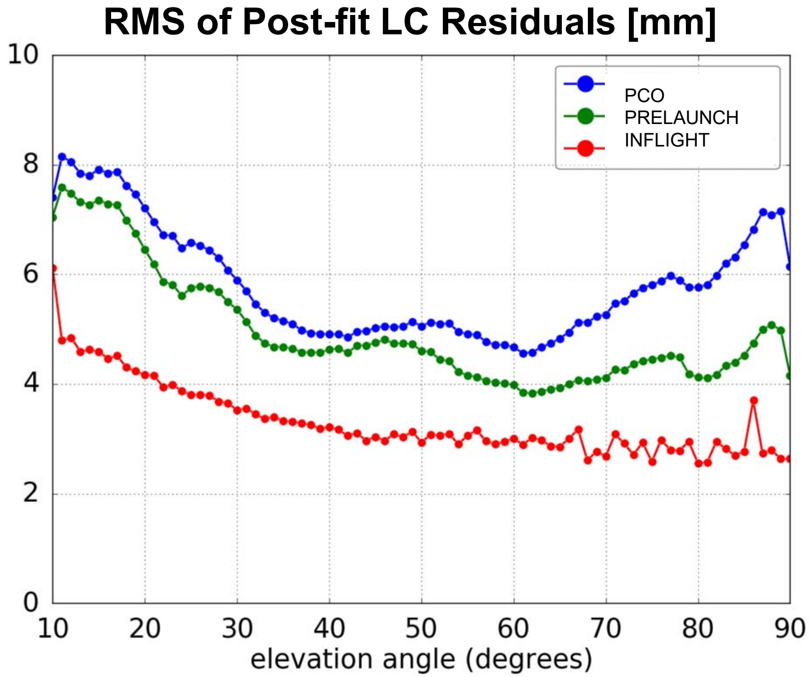


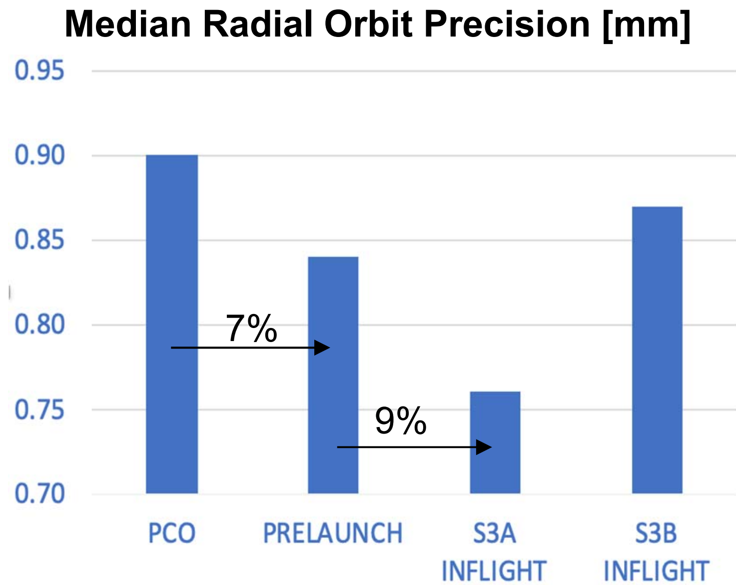
- Improved performance seen for all 3 metrics:
  - when using prelaunch calibration relative to PCO model
  - when applying corrections estimated from in-flight data to prelaunch calibration
- Similar to JA3, impact on data fit of using prelaunch over PCO increases for elev. > 50°

SLR residuals [mm]

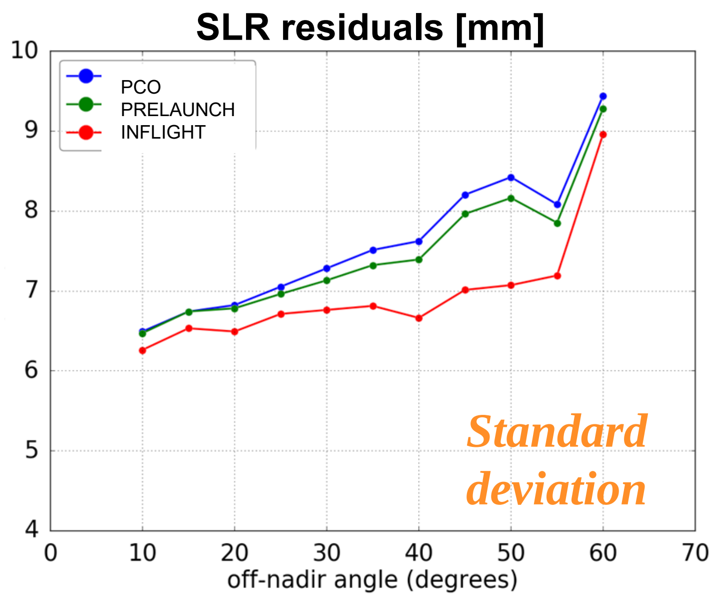


POD Performance Assessment: Sentinel-3B





- Impact of in-flight correction on orbit accuracy is largest at higher off-nadir angles (lower elevation angles).
- S3B orbit precision better when applying S3A inflight calibration than when applying S3B inflight calibration.



Conclusion

- **Recommend use of full antenna calibration (PCO+PCV) over use of PCO vector only**
  - Demonstrated benefit of using prelaunch calibration over simple PCO model,
  - Shown added benefit of applying corrections estimated from in-flight data to prelaunch calibration

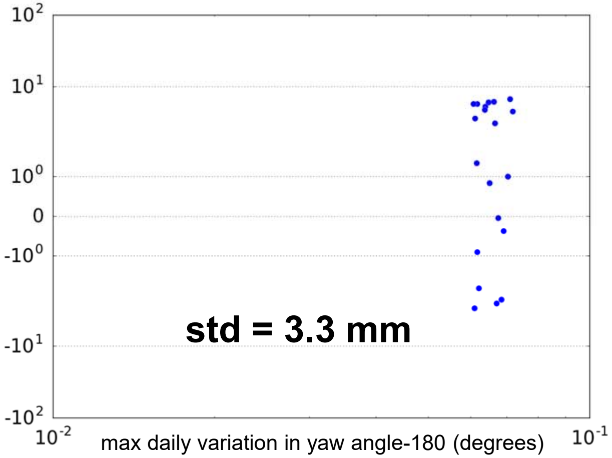
- Challenges associated with poor observability of PCO vector in satellite's direction of motion when flying in fixed-yaw can be mitigated in 2 ways:
    - use **prelaunch** antenna calibration,
    - **constrain along-track component of PCO** to prelaunch calibration value when estimating correction to a priori antenna calibration

Backup Slides

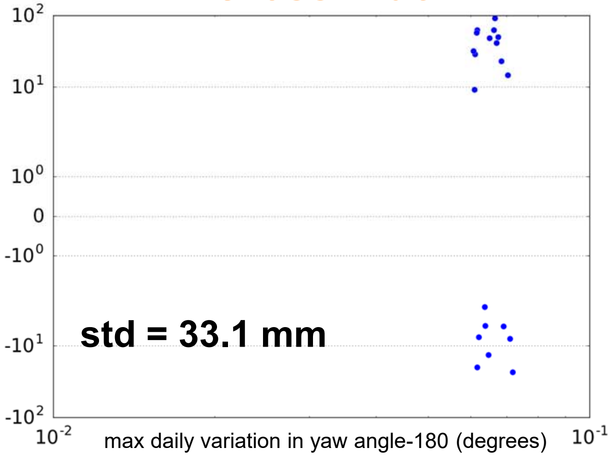
Yaw Flip Events

Estimate of Phase Center Offset [mm]

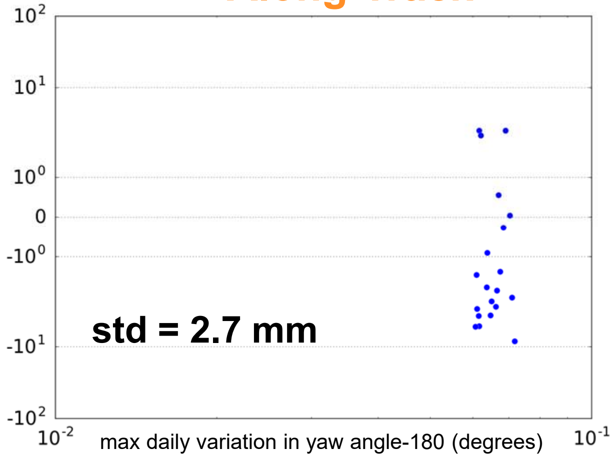
Radial



Cross-Track

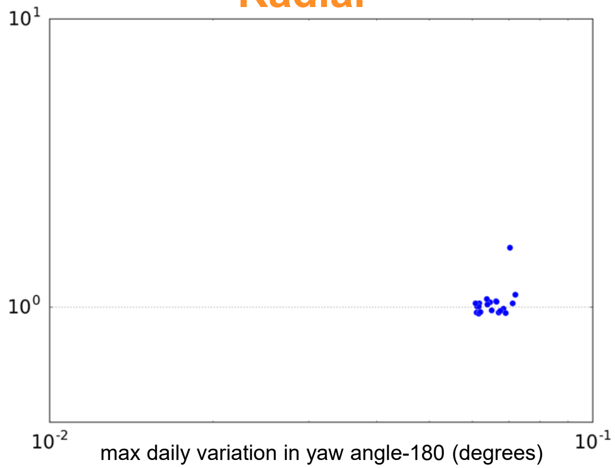


Along-Track

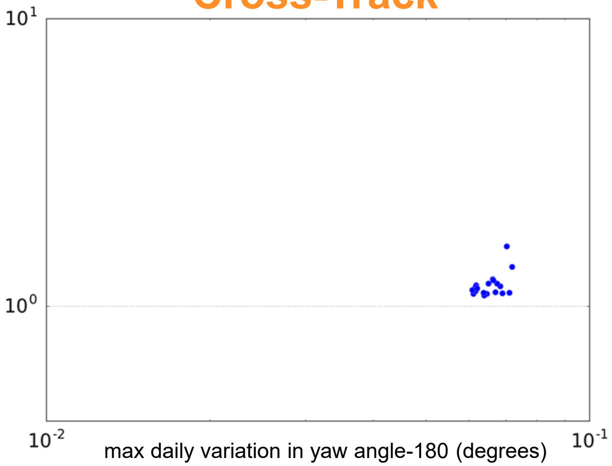


Formal Error of Phase Center Offset Estimates [mm]

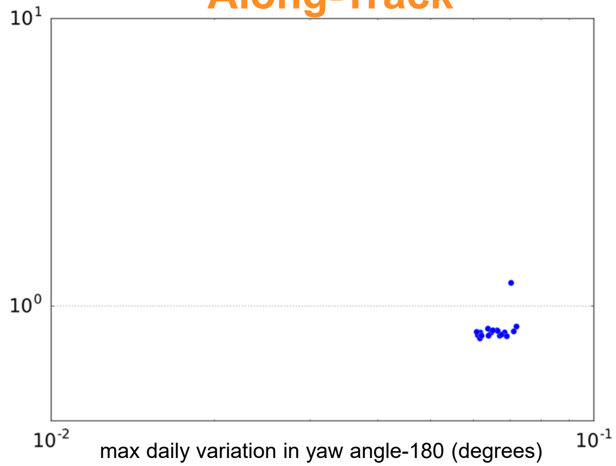
Radial



Cross-Track



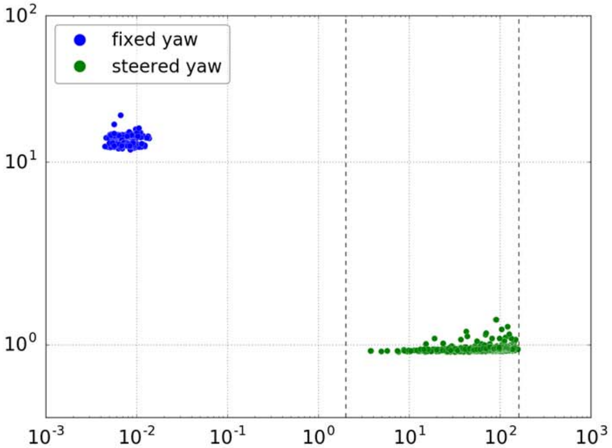
Along-Track



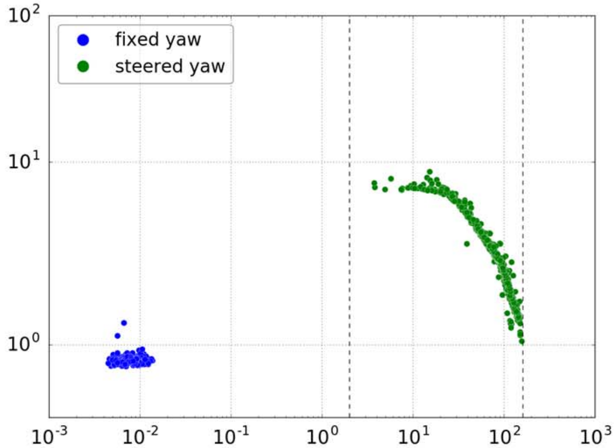
Jason-3 Formal Errors
Yaw-Fixed vs Yaw Steering

Formal Errors of Phase Center Offset Estimates [mm]

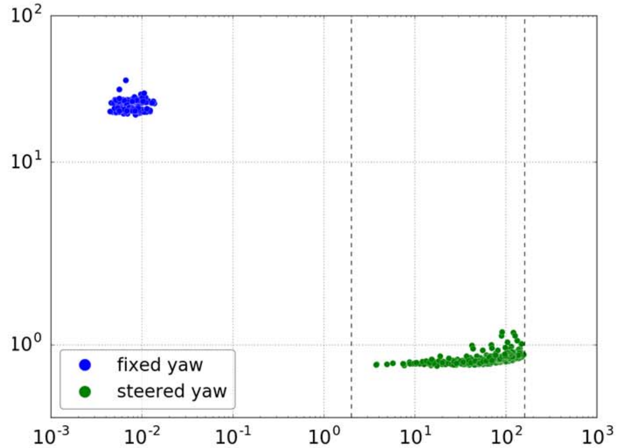
Radial



Cross-Track



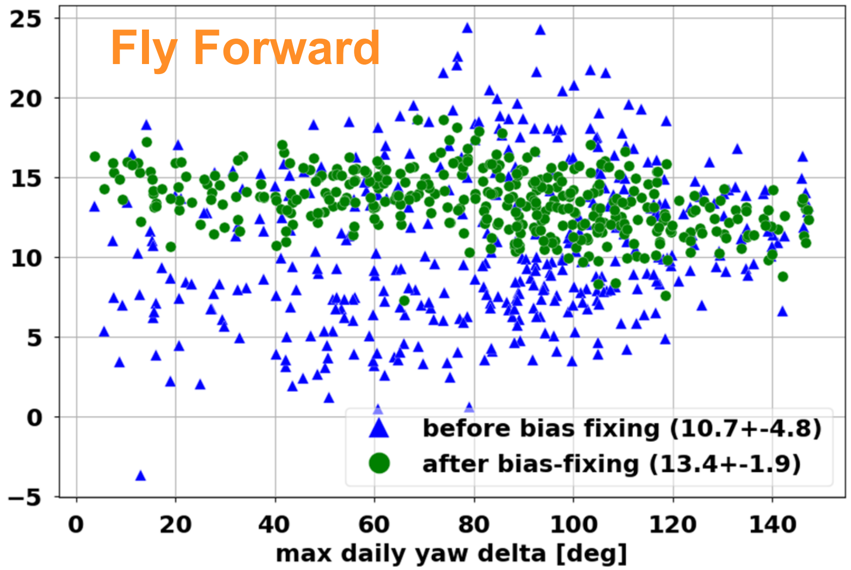
Along-Track

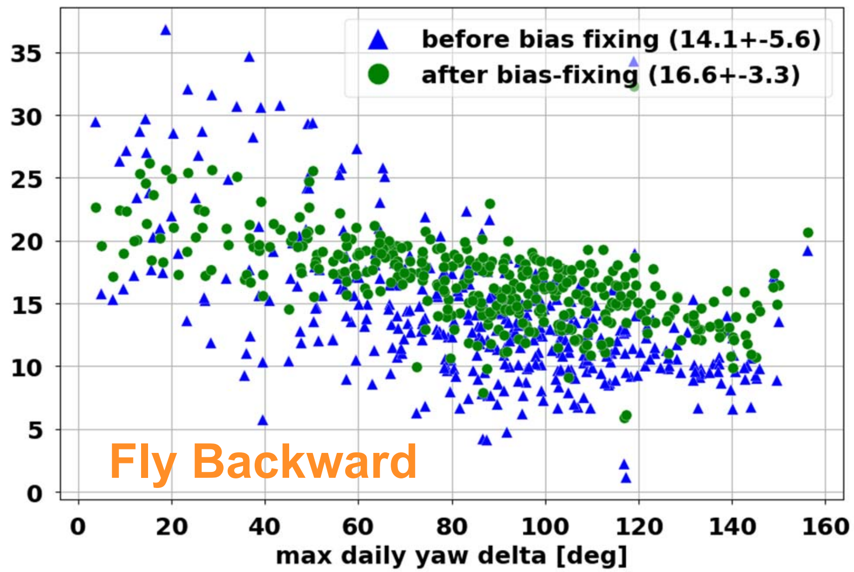


Impact of Ambiguity Resolution on PCO Determination

- Bias fixing reduces the scatter in the PCO estimates, esp. along-track
- Formal errors are reduced in all 3 directions after ambiguities are resolved.

Estimates of Phase Center Offset in Along-Track Direction during Steered Yaw Phases [mm]





Ambiguity resolution has impact on estimated value of PCO, esp. along-track

	X [mm] σ_X [mm]	Y [mm] σ_Y [mm]	Z [mm] σ_Z [mm]
Before bias fixing	12.7 0.08	0.5 0.12	-0.23 0.04
After bias fixing	15.6 0.03	-1.2 0.03	0.8 0.03

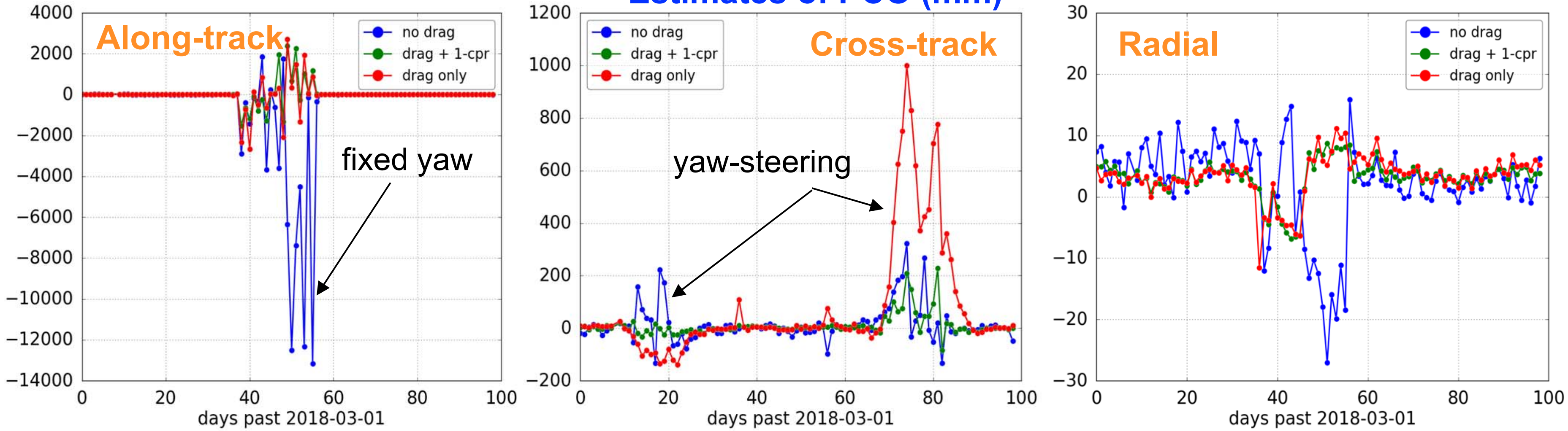
Sensitivity of PCO Determination to Dynamic Parameterization

- 30-hour-long solutions, centered on 12PM, dynamic orbits , 0º elevation cut-off
- Various dynamics parameterizations tested

✓ = estimate as good as baseline ; ✗ = estimate degraded relative to baseline

	Along-track (L)	Cross-track (C)	Radial (H)
drag + 1-cpr along H/L	JPL's operational strategy (baseline)		
drag only	✓	✗	✓
1-cpr along H/L (no drag)	✗	✗	✗
drag + const. acc. H/C/L	✗	✗	✗
drag + 1cpr along H/L + const. acc. H/C/L	✓	✗	✗

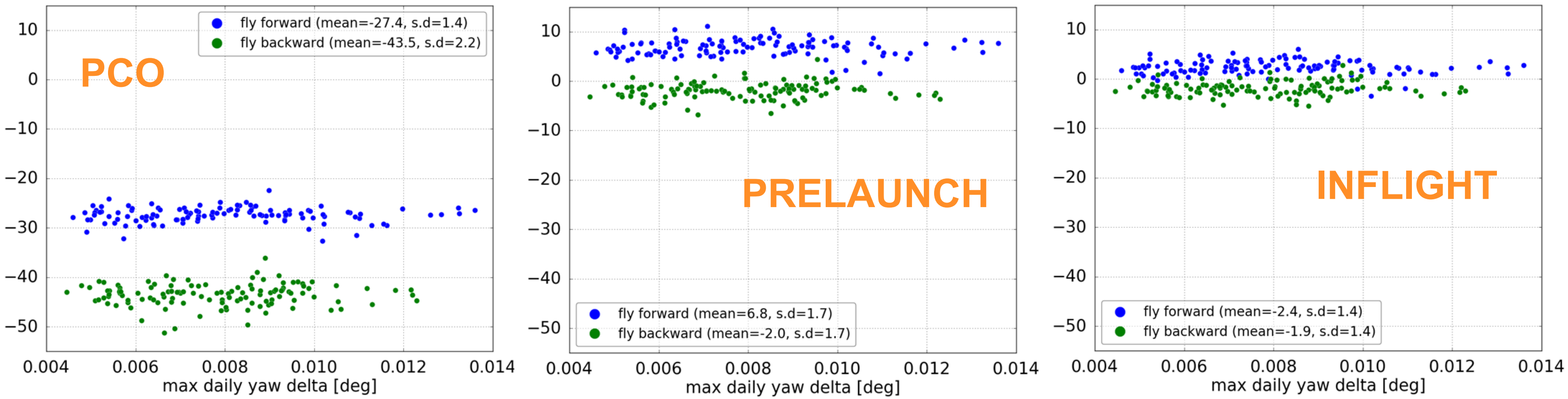
Estimates of PCO (mm)



Sensitivity of PCO Determination to A Priori Antenna Calibration

- Overall reduction in scatter for 3 components for different attitude regimes when:
  - Using prelaunch calibration over PCO calibration
  - Using post-launch estimated correction to prelaunch calibration
- Conspicuous reduction of (unexplained) bias between fly-forward and fly-backward estimates of the PCO; e.g. in the radial direction when s/c flying in fixed-yaw

Estimates of Radial Component of Phase Center Offset in Fixed Yaw Mode [mm]

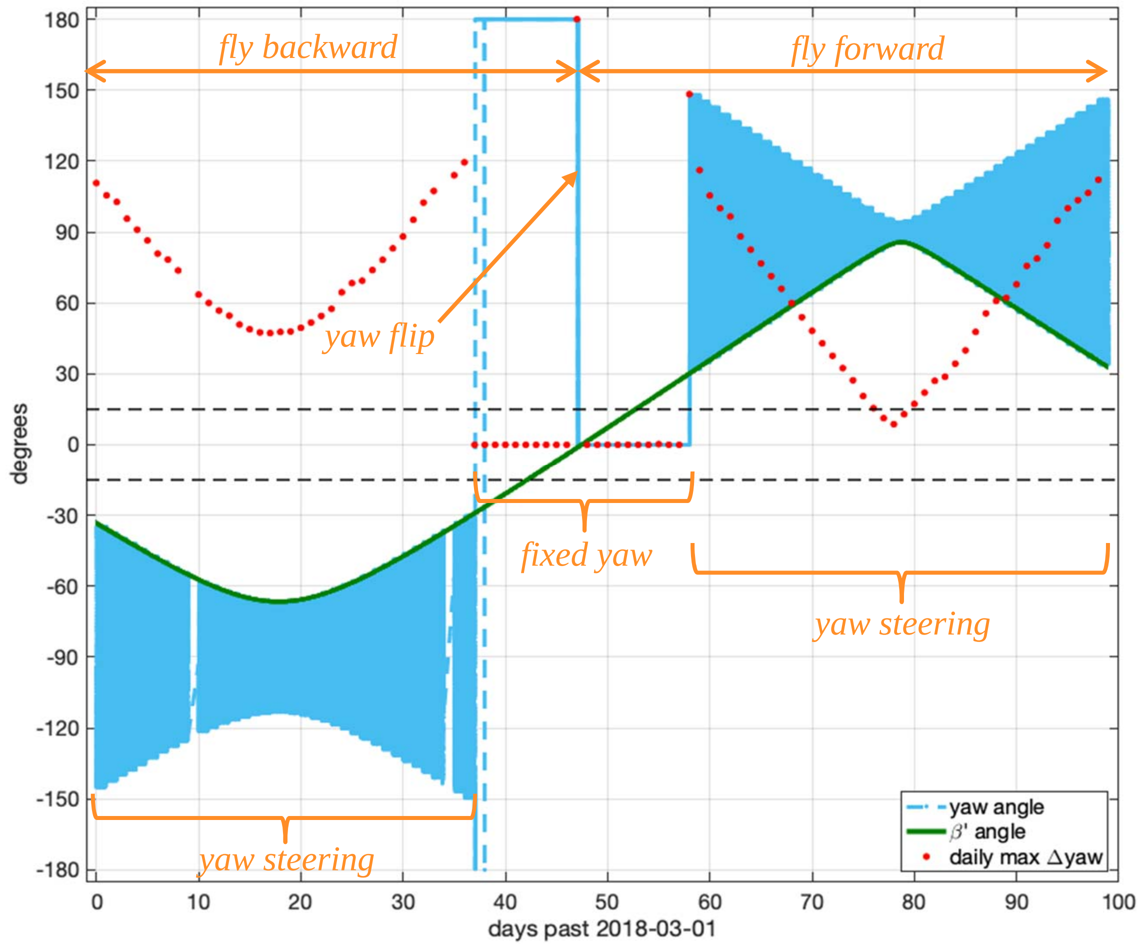


Jason-3 attitude sequence

<u>Attitude laws for Jason-3:</u>

- $|\beta'|>15^o$: yaw steering mode
- $|\beta'|\leq 15^o$: fixed yaw mode
- $\beta'=0^o$: yaw flip (180º yaw variation)

s/c alternates between:
fly-forward (FF) and
fly-backward (FB)
between yaw flip events.



Jason-3 SLR Residuals