GPS-Based Precise Orbit Determination of the Sentinel-6 MF Mission

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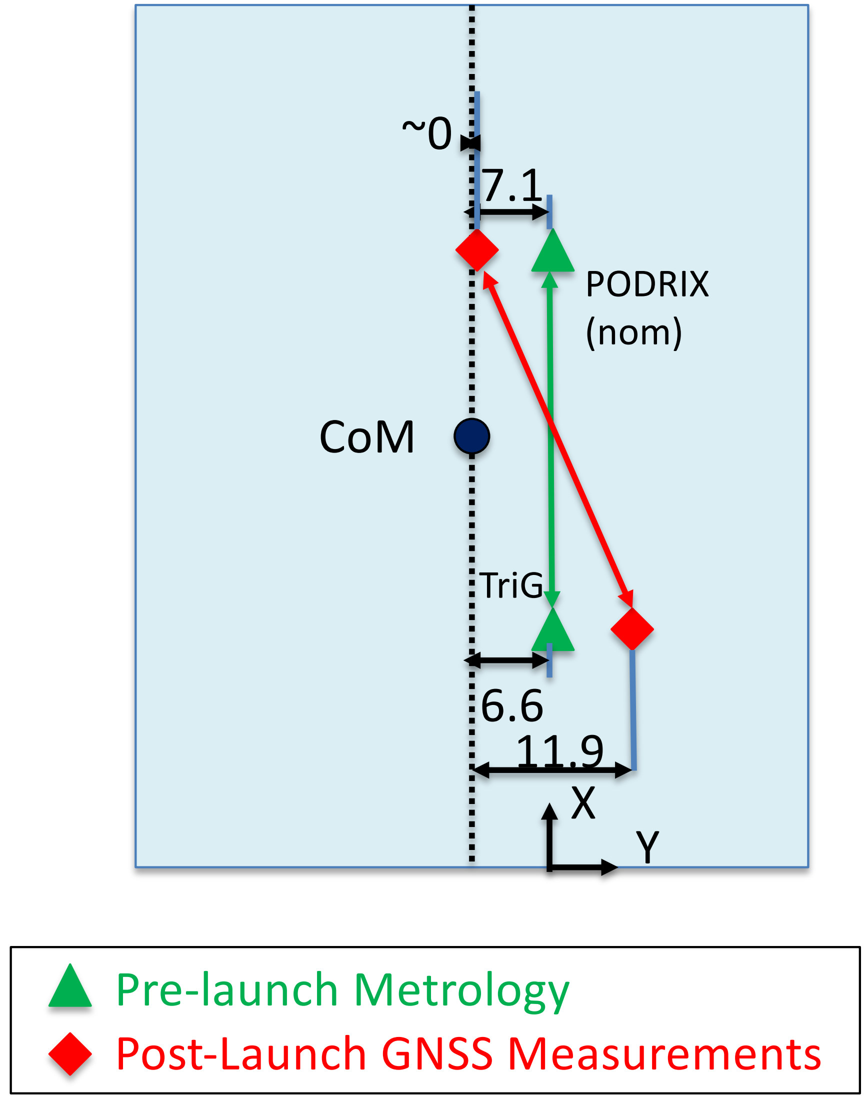
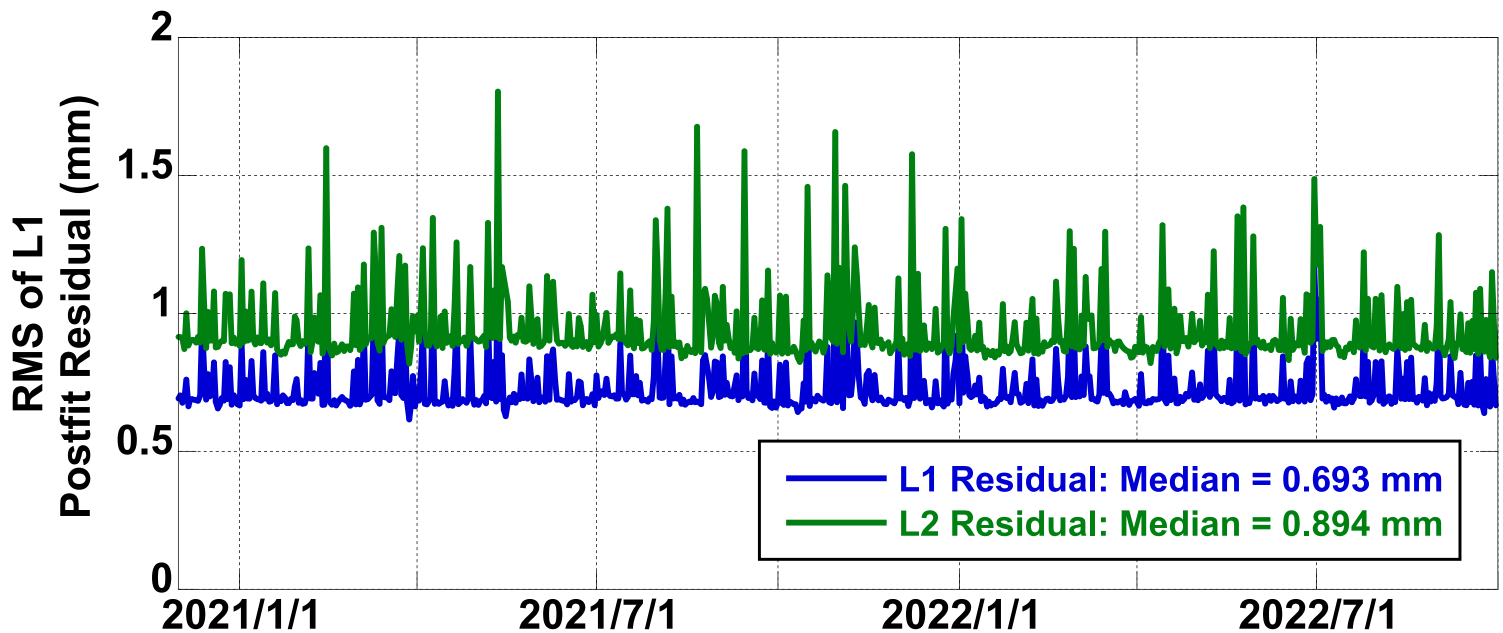
Introduction

- Two active GNSS receivers on S6MF.
  - PODRIX receiver with RUAG antenna.
    - Nominal and redundant.
    - Primary GNSS POD
    - GPS + Galileo
  - TriG receiver with RUAG antenna
    - Single-string.
    - Aimed towards supporting radio occultation measurements, including POD antenna
    - GPS only.
- Provides unique opportunity to validate spacecraft attitude using short baseline GPS solutions.
- Anomalous Y offsets observed for each antenna by multiple groups (e.g., CNES, DLR, JPL).
  - ~-7 mm in body-fixed Y for PODRIX
  - ~+5 mm in body-fixed Y for TriG

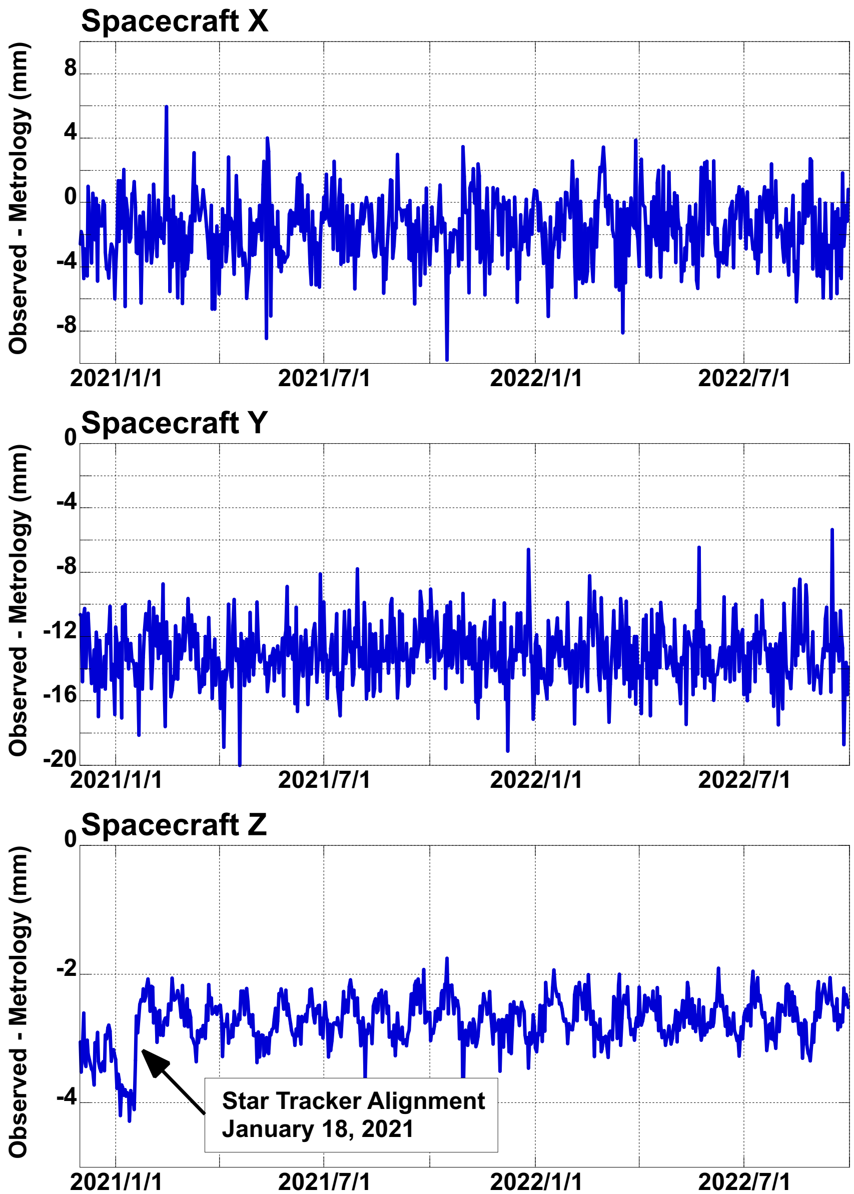


Single-Frequency Short Baseline Solutions Between Two Active GNSS Antennas

- **Daily estimates of baseline vector in s/c body-fixed coordinates**.
  - E.g., Montenbruck (CPOD QWG, 2022)
- GPS 30-sec single-frequency data
  - L1 and L2 processed separately.
- Use data from common lines of sight between each receiver and GPS transmitters.
- Apply pre-launch calibrations for both antennas.
- **Post-fit residuals provide measure of fundamental data noise in each receiver and potential accuracy of baseline solutions.**
  - **L1 Data Noise: < 0.5 mm. (=0.693/sqrt(2))**
  - **L2 Data Noise: < 0.63 mm. (=0.894/sqrt(2))**



L1 Baseline Vector From TriG to PODRIX (Relative to Metrology)



S/C Body Component	Mean (mm)	Std. Dev. (mm)
X	-1.6	2.0
Y	**-13.0**	1.8
Z	-2.7	0.3
Length	-1.6	2.0

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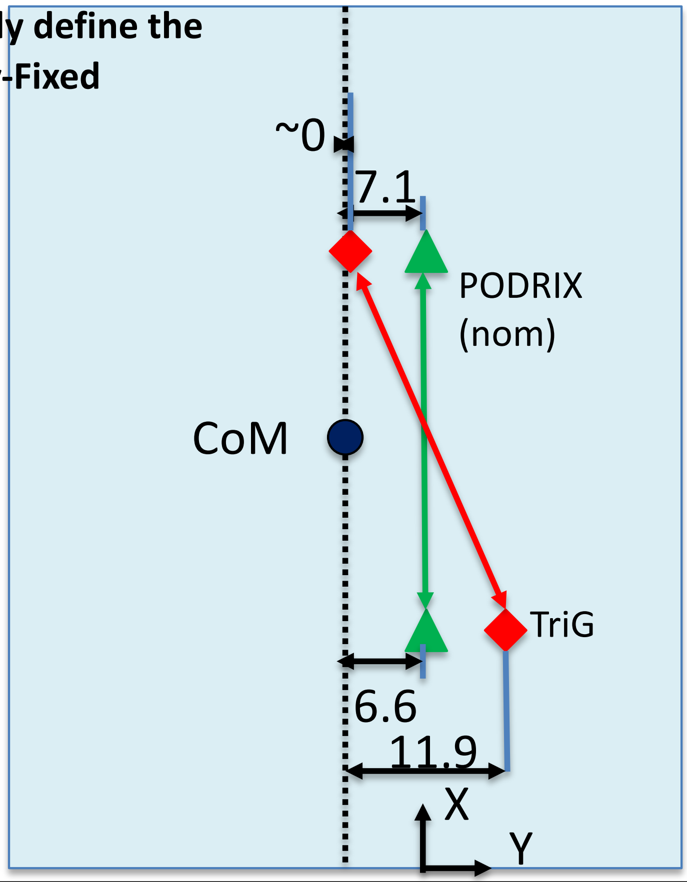
- Beta prime dependence in all components, but otherwise very good repeatability <= 2 mm.
- **Small X-offset:**
  - 1.6 mm => relative time tag of 0.2 microsec
- **Significant 13 mm Y-offset.**
  - **Consistent with observed -7 mm in PODRIX and +5 mm in TriG.**
- **Similar results (< 1 mm) for L2, except in X.**
  - **-9 mm (=> ~= 1.3 microsec relative time tag)**
- **Z component shows sensitivity to star tracker alignment.**

Could GPS Baseline Provide Realization of Body-Fixed Frame?

Body-Fixed Frame

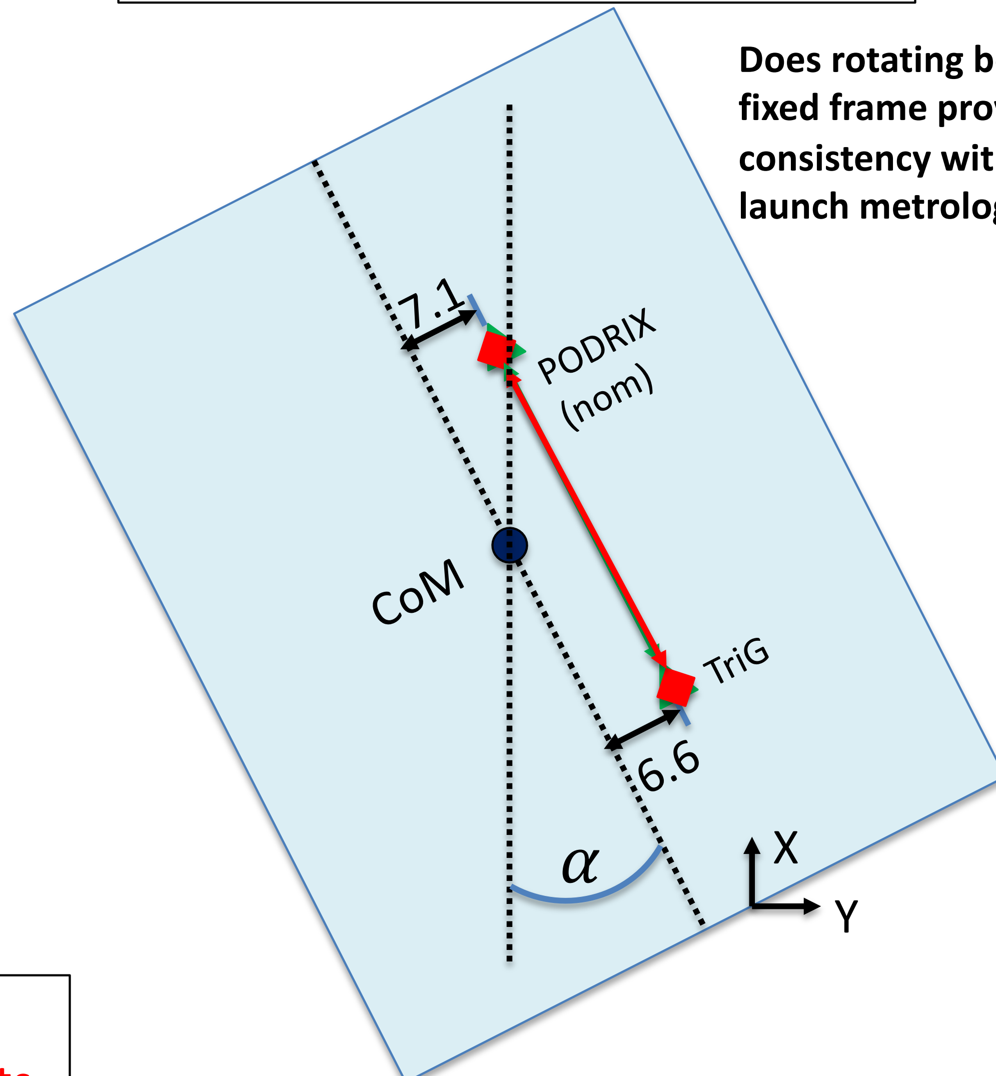
Provided quaternions effectively define the S/C Body-Fixed frame.



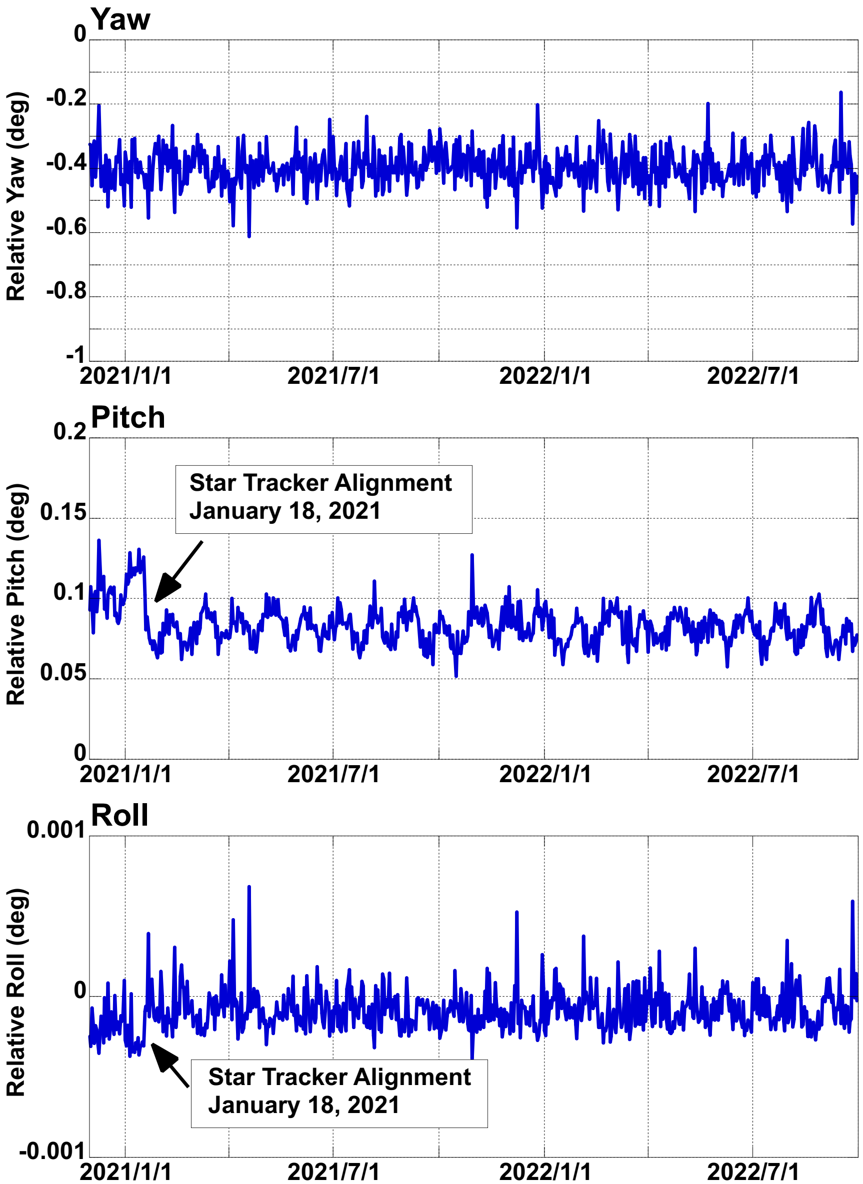
- Pre-launch Metrology
- Post-Launch GNSS Measurements

GPS-Realization of Body-Fixed Frame

Does rotating body-fixed frame provide consistency with pre-launch metrology?



Relative Orientation of L1 GPS-Realization and Star Tracker Body-Fixed Frames



Component	Mean (deg)	Std. Dev. (deg)
Yaw	**-0.398**	**0.054**
Pitch	0.082	0.010
Roll	-9e-5	1e-4

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- 2021-01-18 star tracker alignment evident in relative pitch and roll.
- **Dominated by relative yaw of ~-0.4 degrees.**
  - **Counter-clockwise rotation about spacecraft Z.**
- Similar results for L2.
  - Within 0.03 degrees.

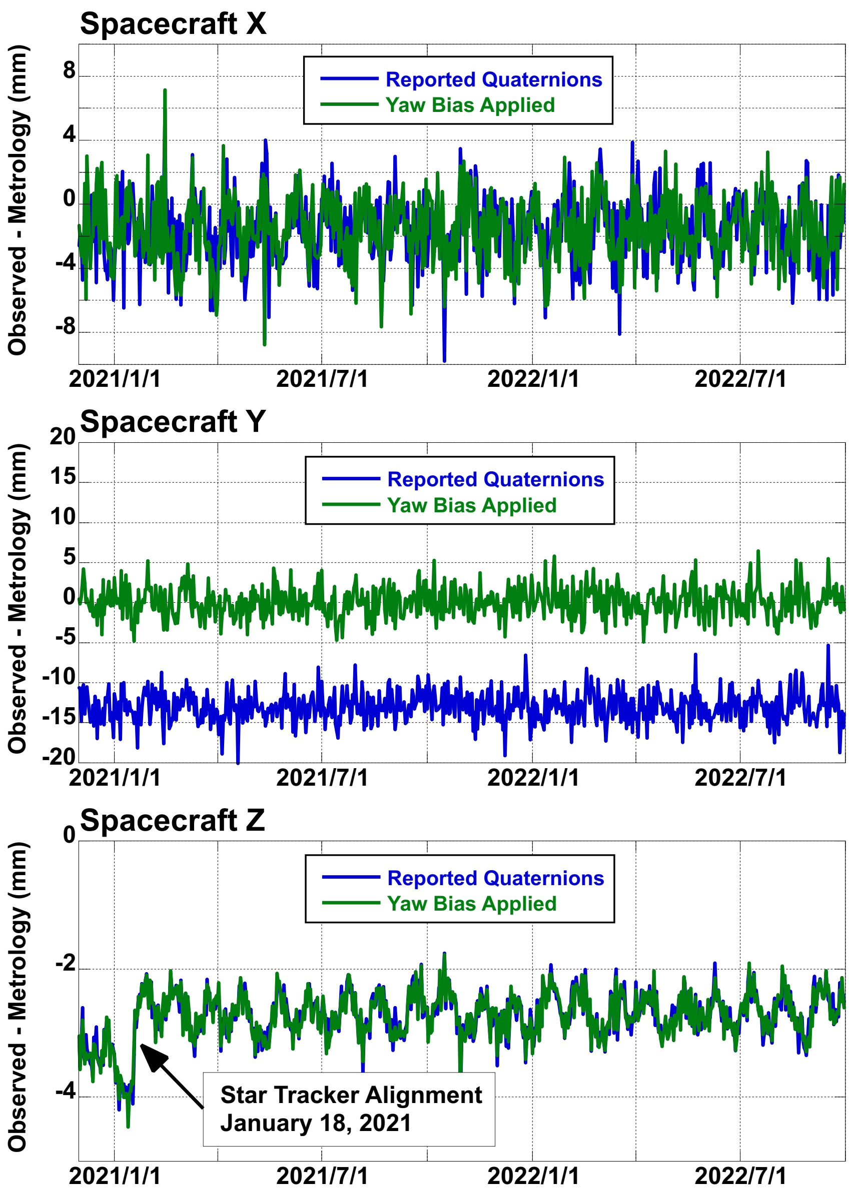
Application of Yaw Bias to Provided Quaternions

- Test recomputing baseline vector after applying relative yaw bias to provided quaternions.

$$M_G = \begin{bmatrix} \cos \propto & \sin \propto & 0 \\ -\sin \propto & \cos \propto & 0 \\ 0 & 0 & 1 \end{bmatrix} M_S$$

  - M_S = Star tracker quaternions
  - M_G = Star tracker quaternions with yaw bias ($\boldsymbol{\alpha}$**=-0.398 degrees**) applied.
- Choose not to apply pitch.
  - Pitch primarily results from relative Z baseline component (-2.7 mm), which could have other contributors, e.g.,
    - Relative antenna calibration.
    - Quaternion time tag error, e.g., 1 second time tag error causes relative pitch of 0.053 degrees.
- Negligible roll, so not applied.

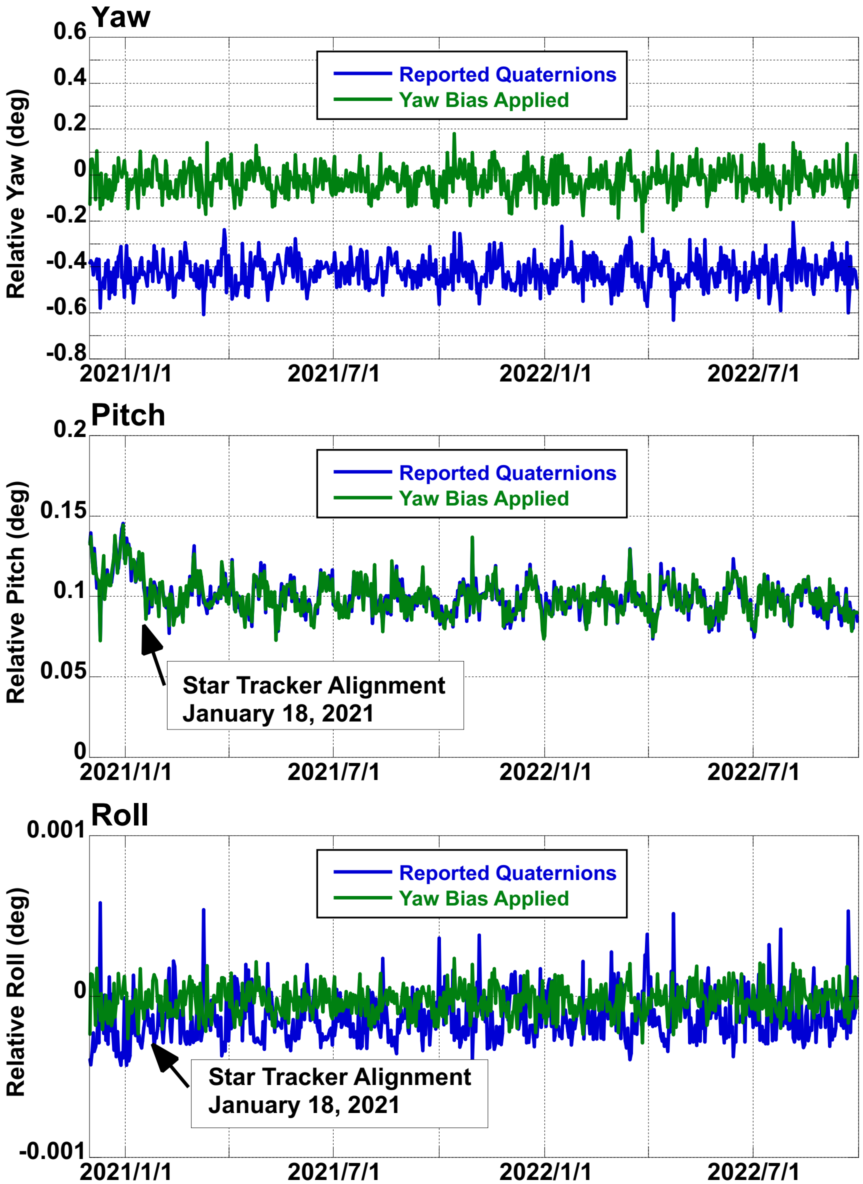
L1 Baseline Vector After Applying Yaw Bias



	Reported Quaternions		Yaw Bias Applied	
Component	Mean (mm)	Std. Dev. (mm)	Mean (mm)	Std. Dev. (mm)
X	-1.6	2.0	-1.6	2.0
Y	**-13.0**	**1.8**	**0.1**	**1.9**
Z	-2.7	0.3	-2.7	0.3
Length	-1.6	2.0	-1.6	2.0

- Expected result with Y component centered around 0.1 mm.
  - Yaw bias primarily derived from Y.
- No impact on X and Z components.

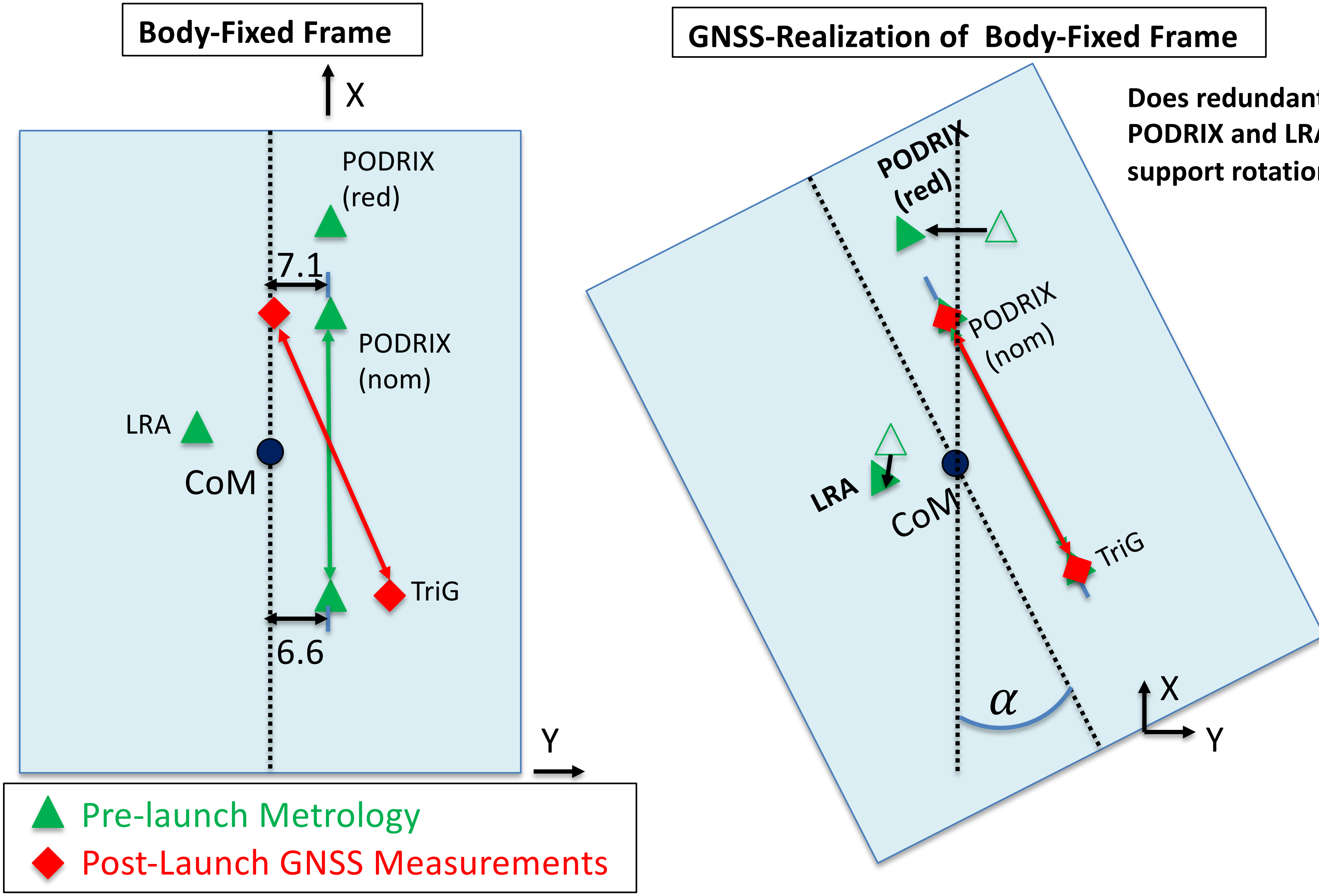
L1 Relative Orientation After Applying Yaw Bias



	Reported Quaternions		Yaw Bias Applied	
Component	Mean (mm)	Std. Dev. (mm)	Mean (mm)	Std. Dev. (mm)
Yaw	**-0.398**	**0.054**	**0.002**	**0.057**
Pitch	0.082	0.010	0.082	0.010
Roll	-9e-5	1e-4	**4e-6**	**7e-5**

- Expected result with mean yaw centered around 0.002 degrees.
- **Applying yaw bias eliminates evidence of star tracker alignment in roll:**
  - **Closer to zero bias.**
  - **Smaller standard deviation.**
- **Similar result with L2**
  - **Mean yaw = 0.020 degrees.**

Rotation Would Also Impact Redundant PODRIX and LRA



Does redundant PODRIX and LRA support rotation?

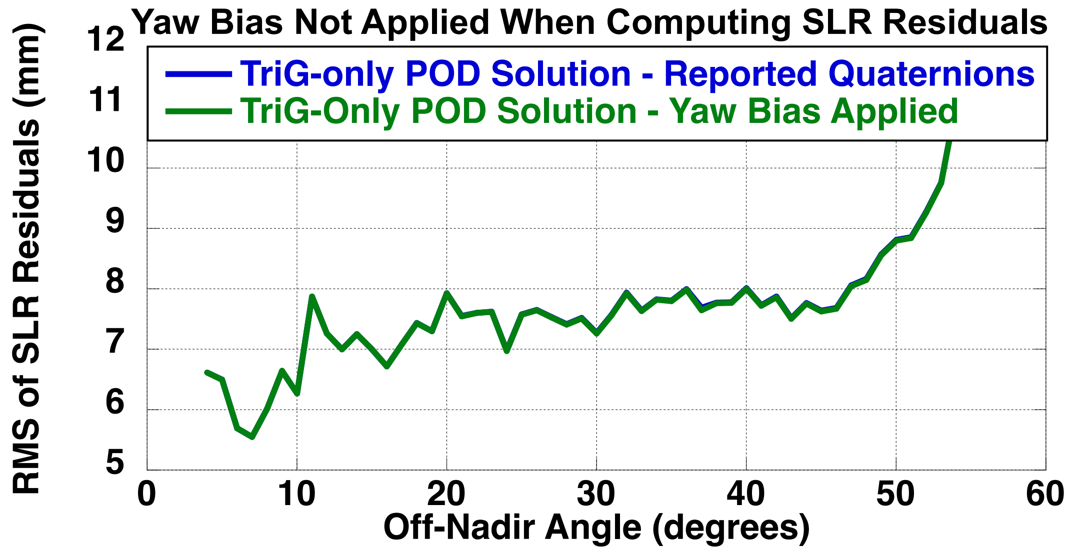
L1 Baseline from Trig to Redundant PODRIX

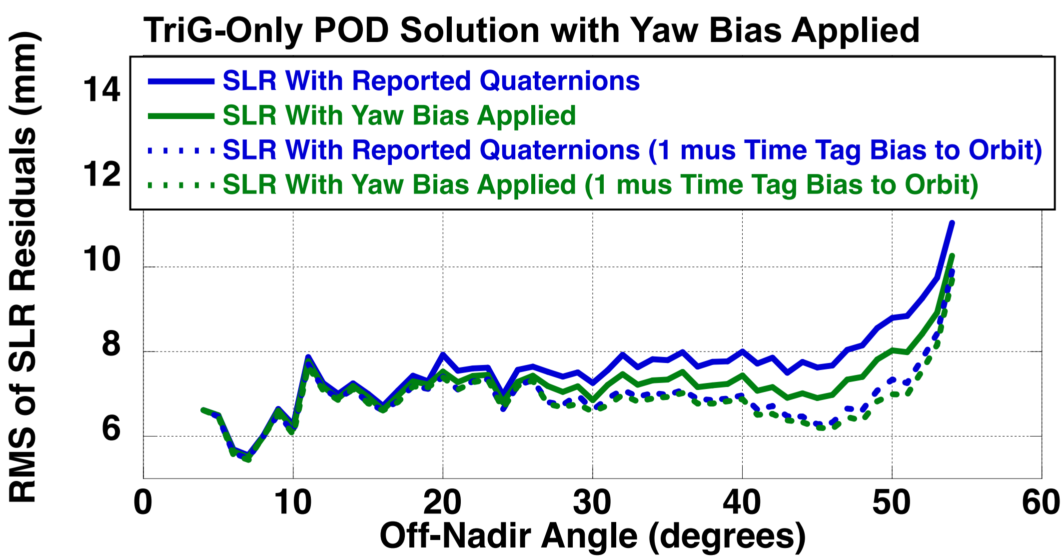
	Reported Quaternions		Yaw Bias Applied	
Component	Mean (mm)	Std. Dev. (mm)	Mean (mm)	Std. Dev. (mm)
X	1.9	1.5	2.5	1.8
Y	**-18.4**	**0.6**	**-1.4**	**0.9**
Z	-4.6	0.2	-4.6	0.2
Length	1.9	1.5	2.4	1.8

- Results using 5 days of data from Jan. 13-17, 2021
  - Full day of GPS tracking.
- Partial GPS coverage on 21 days.

- **Applying -0.4 degree yaw bias significantly reduces Y-component of Trig->PODRIX (red) baseline vector by 17 mm.**
  - **Predicted impact is 15.8 mm.**
- Rotation about s/c Z expected to have larger impact on Y component of redundant PODRIX by ~2.8 mm.
  - E.g., Expect Y-Offset of 9.3 mm in redundant PODRIX and 6.5 mm in nominal PODRIX.
  - Longer lever arm (by 403 mm) between TriG and redundant PODRIX than with nominal PODRIX.

SLR Data

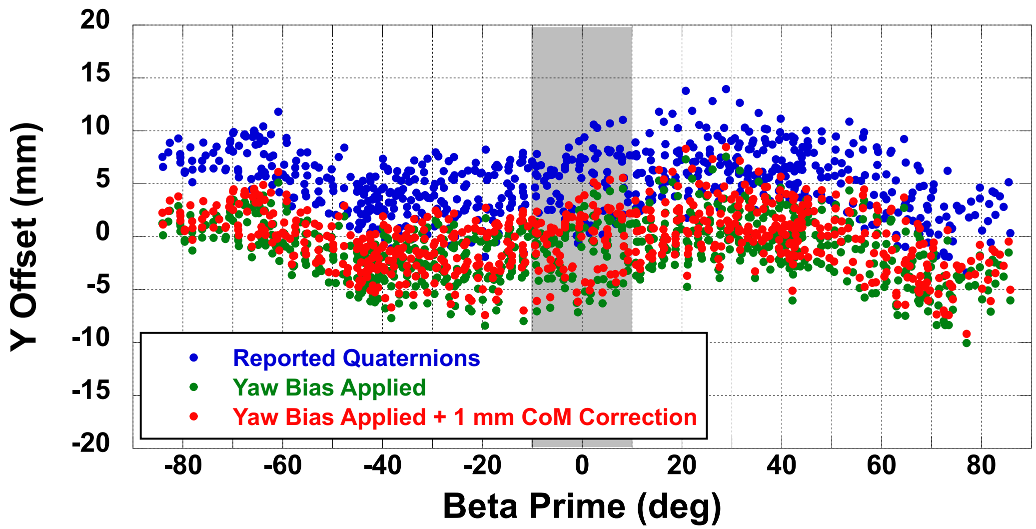




- Trig-Only POD solution is effectively the same when yaw bias applied or not during POD.
  - Use self-consistent in-flight GPS antenna calibration.
  - Reduced dynamics.
- **Lower SLR residuals for off-nadir angles > 20 degrees when yaw bias applied.**
  - **Reduces X and Y offsets to LRA.**
- **1 microsecond TriG time tag bias reduces X offsets to LRA.**
  - 1 microsec ~= 7 mm in X.
- **Yaw + Time tag bias provide additional reduction to LRA offsets.**

Yaw Bias	Time Tag Bias	Body X (mm)	Body Y (mm)
		-8.9	-2.0
✓		-6.2	-1.4
	✓	-2.8	-2.0
✓	✓	**-0.1**	**-1.4**

Center of Mass Correction?



- **Residual Y-Offset in TriG Antenna and LRA reduced to < 1 mm by also adjusting the Center of Mass by 1 mm.**
  - Use Body Y CoM of -6 mm instead of -7 mm.
  - TriG offsets computed from average for -10 deg < Beta < 10 deg.

			SLR Offset		Trig Offset
CoM Correction	Yaw Bias	Time Tag Bias	Body X (mm)	Body Y (mm)	Body Y
			-8.9	-2.0	5.3
	✓		-6.2	-1.4	-1.2
		✓	-2.8	-2.0	5.3
	✓	✓	-0.1	-1.4	-1.2
✓	✓	✓	-0.1	-0.4	-0.2

Conclusion

- Antenna offsets observed in TriG, PODRIX (nominal), PODRIX (redundant), and LRA could be explained **by two possibilities**.
  - **Four independent translations all coincidently consistent** with a single rotation for four different levers arms.
    - Metrology translation error, antenna calibration error, local multipath....in all?
  - **One rotation explaining all four translations**.
    - Star tracker bias or alignment, metrology rotation error, or interpretation of quaternions,…?
    - GPS POD solutions with self-consistent antenna calibration are not impacted by potential rotation error.
- Relative L2 time tag different between TriG and PODRIX of 1-2 microsec.
  - L1 is an order of magnitude smaller
- Care needed to segregate impact of potential rotation error and time tag bias on SLR residuals.
  - Lever arm for GNSS is along X, while lever arm for LRA is along Y.
  - ~1 microsecond relative time tag error between TriG and SLR.
- Perhaps 1 mm error in reported S/C center of mass.

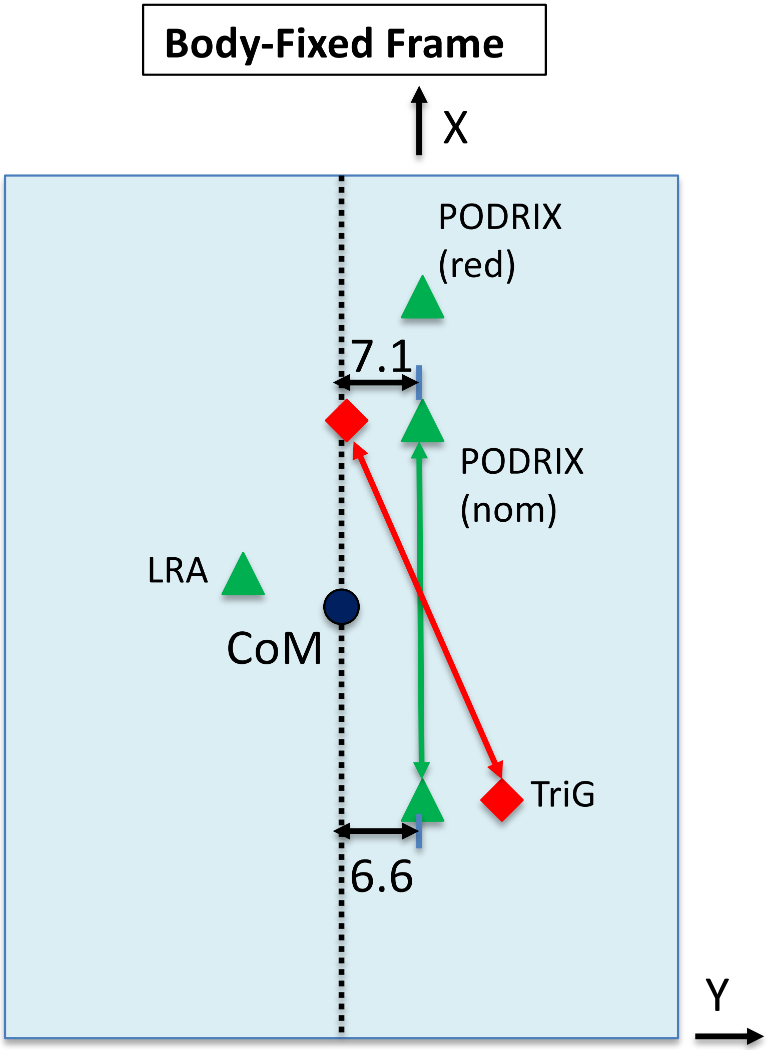
Backup Slides

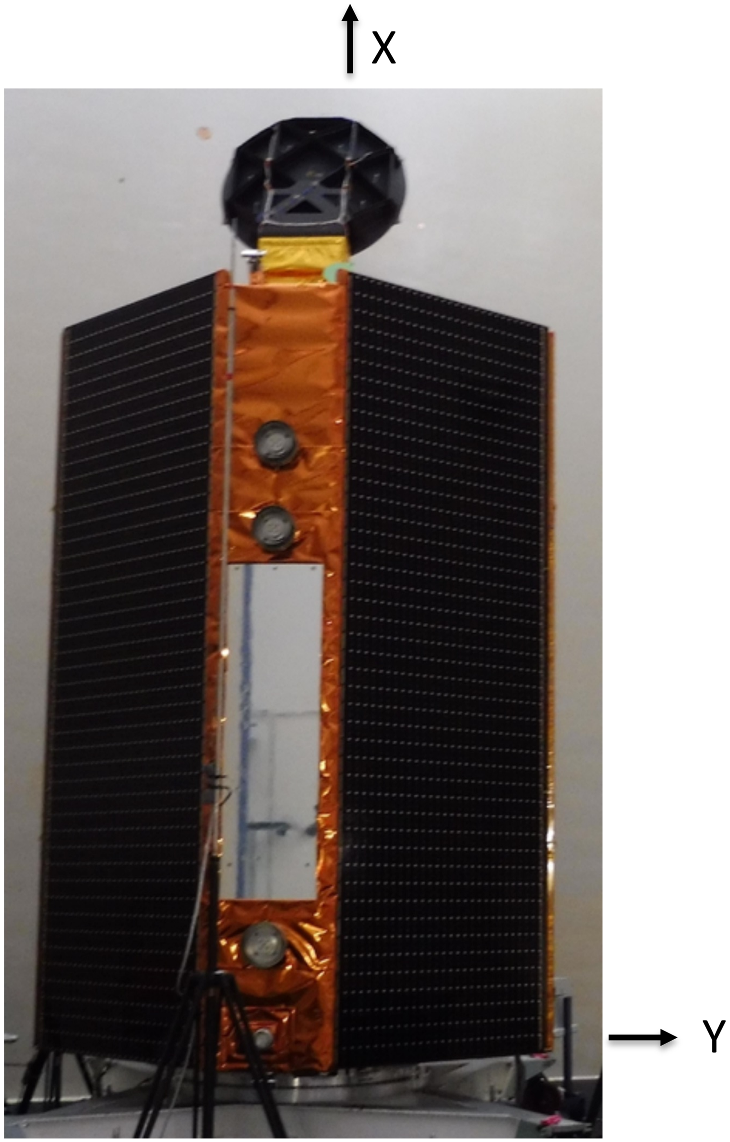
SLR Stations

Station ID	Station Name
7090	Yarragadee, Australia
7105	Greenbelt
7810	Zimmerwald, Switzerland
7825	Mt Stromlo, Australia
7839	Graz, Austria
7840	Herstmonceux, United Kingdom
8834	Wetzell, Germany

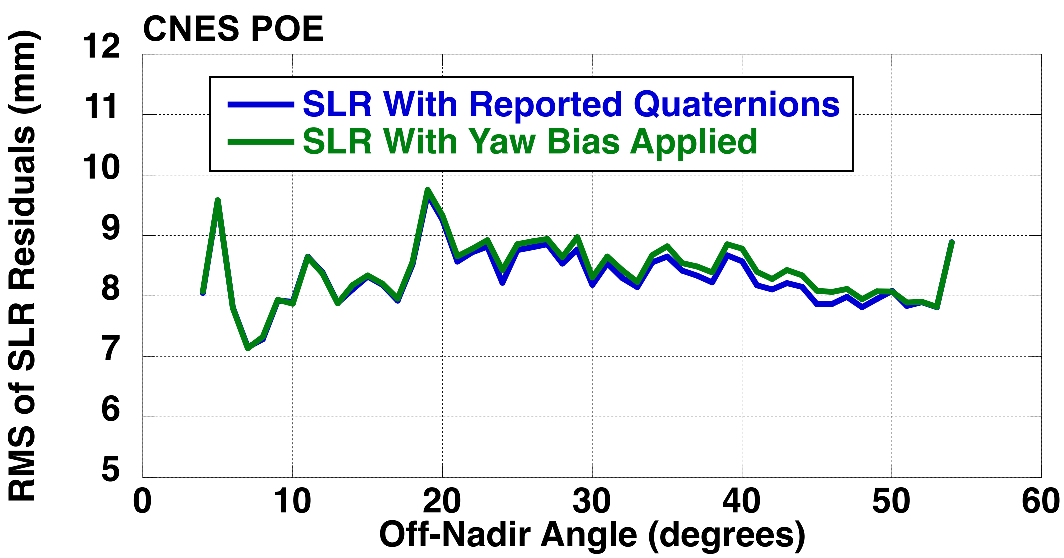
- SLR residuals indicated station biases < 5 mm, low standard deviation of residuals, and large number of observations.

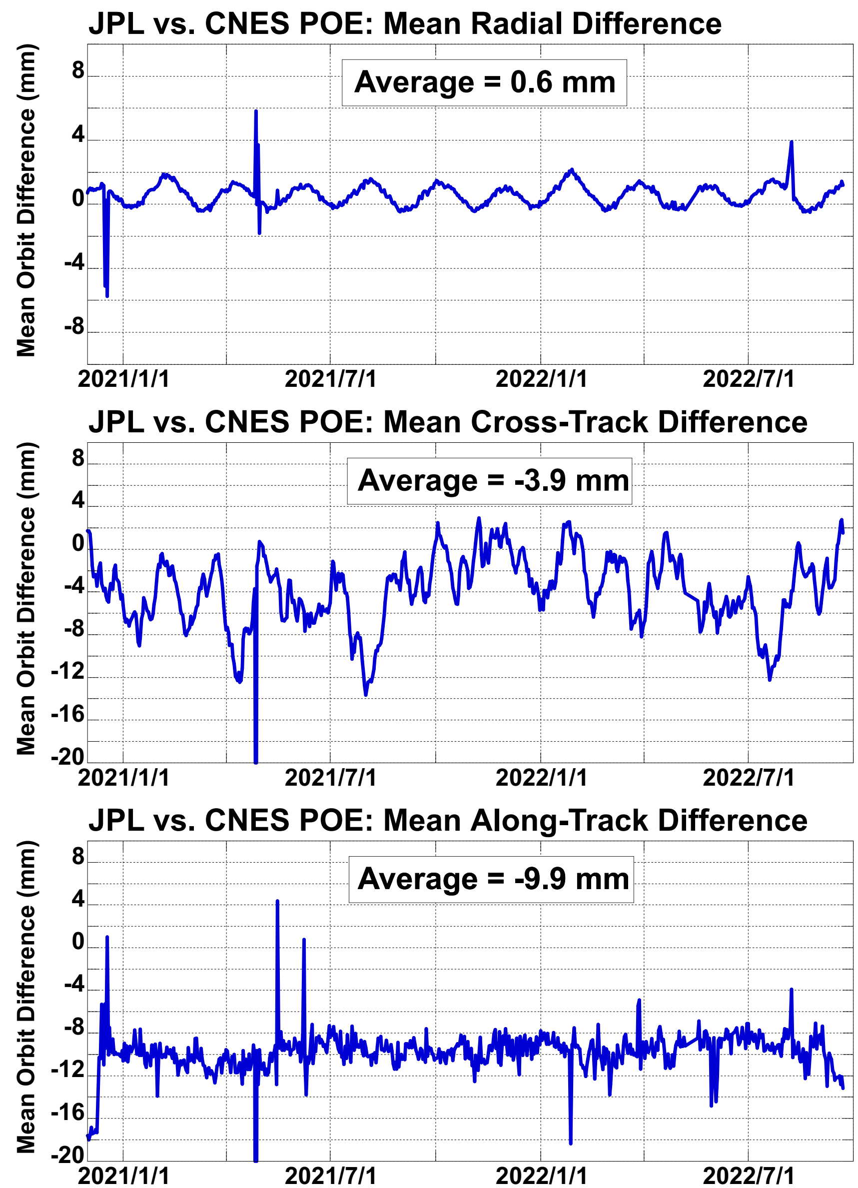
Spacecraft Orientation





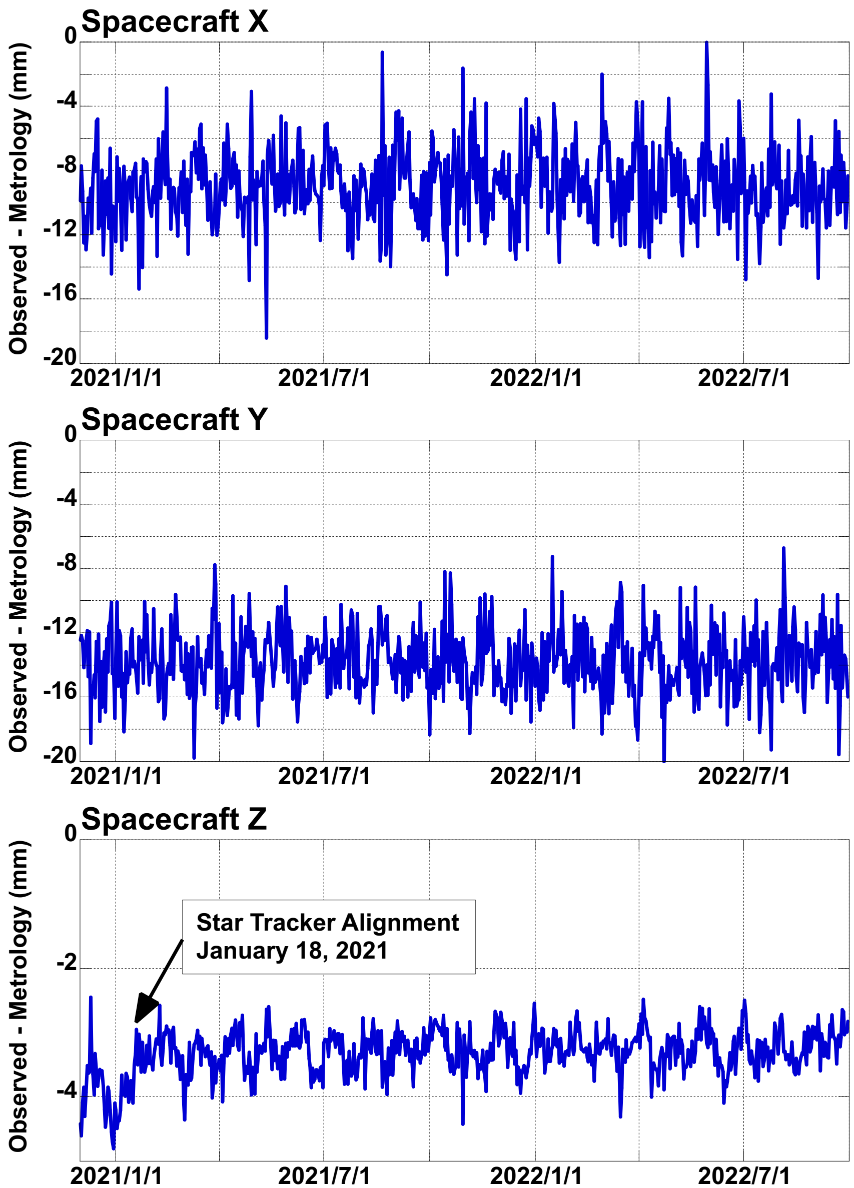
SLR Residuals Using CNES POE





- CNES POE has higher SLR residuals when applying yaw bias.
- Significant relative biases in cross- and along track components.

L2 Baseline Vector From TriG to PODRIX (Relative to Metrology)



Component	Mean (mm)	Std. Dev. (mm)
X	-9.0	2.2
Y	-13.8	1.9
Z	-3.3	0.3
Length	-9.0	2.2

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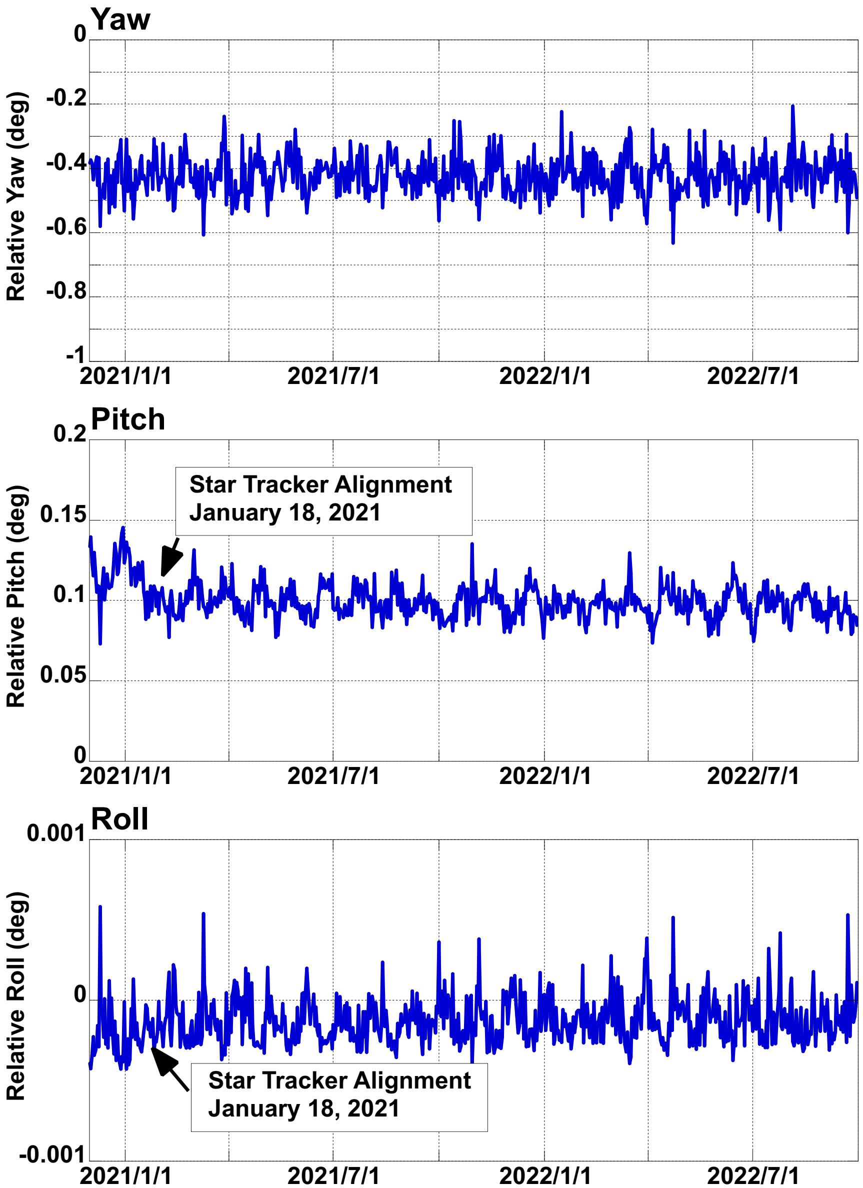
- Baseline length dominated by X component (see backup).
  - 9 mm => relative time tag of 1.3 microsec
  - Order of magnitude larger than L1.
- Beta prime dependence in all components, but otherwise very good repeatability <= 2 mm.
- **Significant 14 mm Y-offset.**
  - **Consistent with -7 mm in PODRIX and + 6 mm in TriG.**
  - **Similar to result from L1.**
- **Z component shows sensitivity to star tracker alignment.**

Relative Orientation of L2 GPS-Realization and Star Tracker Body-Fixed Frames



Component	Mean (deg)	Std. Dev. (deg)
Yaw	-0.423	0.059
Pitch	0.099	0.010
Roll	-1e-4	1e-4

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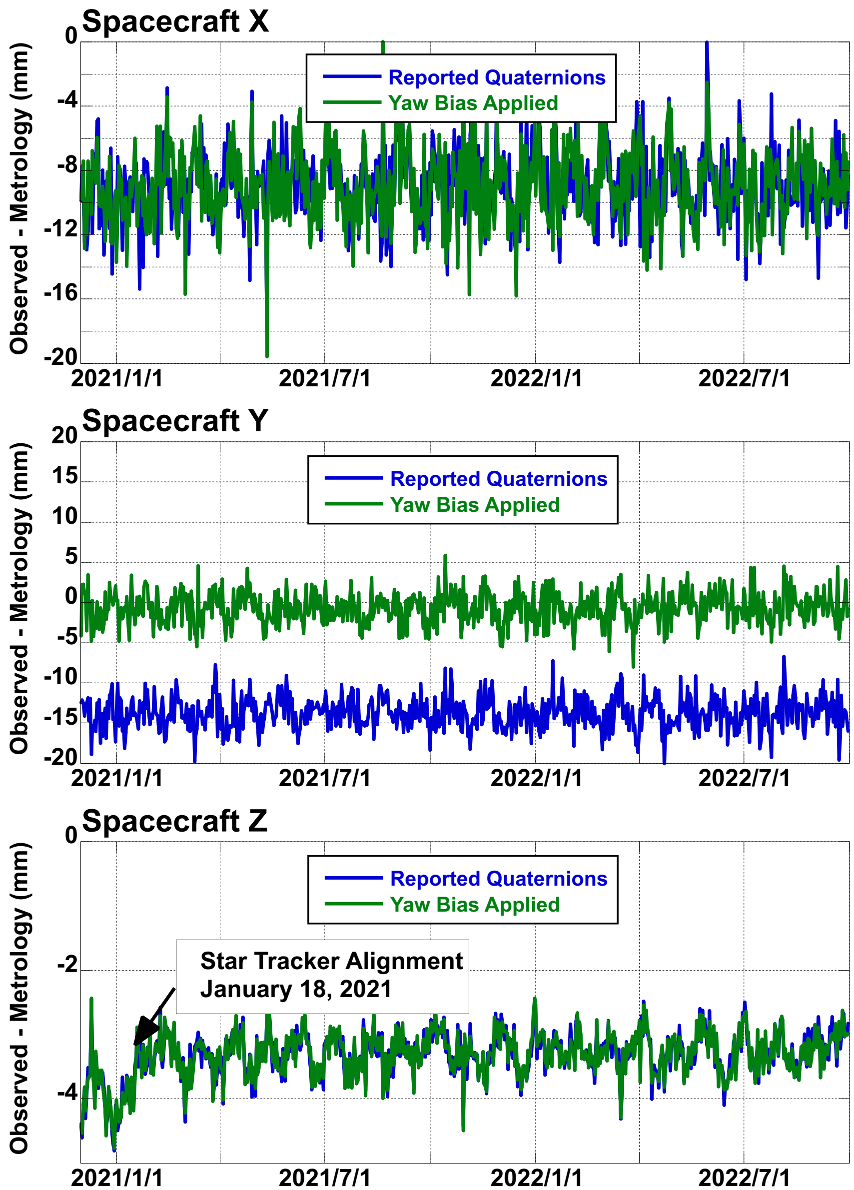
- 2021-01-18 star tracker alignment evident in relative pitch and roll.
- Dominated by relative yaw of ~-0.4 degrees.
  - Counter clockwise rotation about s/c Z.

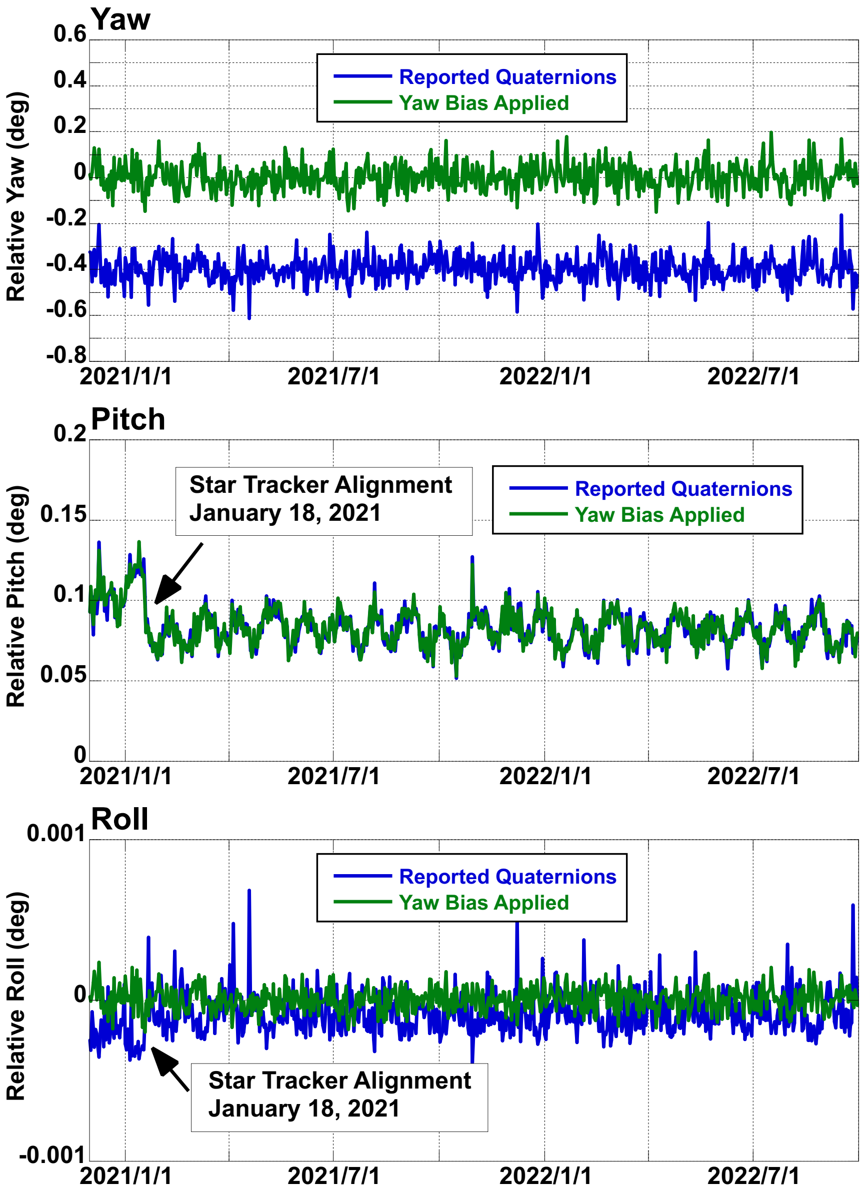
L2 Baseline Vector After Applying Yaw Bias



	Reported Quaternions		Yaw Bias Applied	
Component	Mean (mm)	Std. Dev. (mm)	Mean (mm)	Std. Dev. (mm)
X	-9.0	2.2	-8.9	2.2
Y	-13.8	1.9	-0.7	2.0
Z	-3.3	0.3	-3.3	0.3
Length	-9.0	2.2	-9.0	2.2

- Expected result with Y component centered around -0.7 mm.
  - Yaw bias primarily derived from Y.

L2 Relative Orientation After Applying Yaw Bias



	Reported Quaternions		Yaw Bias Applied	
Component	Mean (mm)	Std. Dev. (mm)	Mean (mm)	Std. Dev. (mm)
Yaw	-0.423	0.059	**-0.021**	0.060
Pitch	0.099	0.010	0.099	0.010
Roll	-1e-4	1e-4	**-3e-5**	**9e-5**

- Expected result with mean yaw centered around -0.02 degrees.
- **Applying yaw bias eliminates evidence of star tracker alignment.**
  - **Closer to zero bias.**
  - **Smaller standard deviation.**

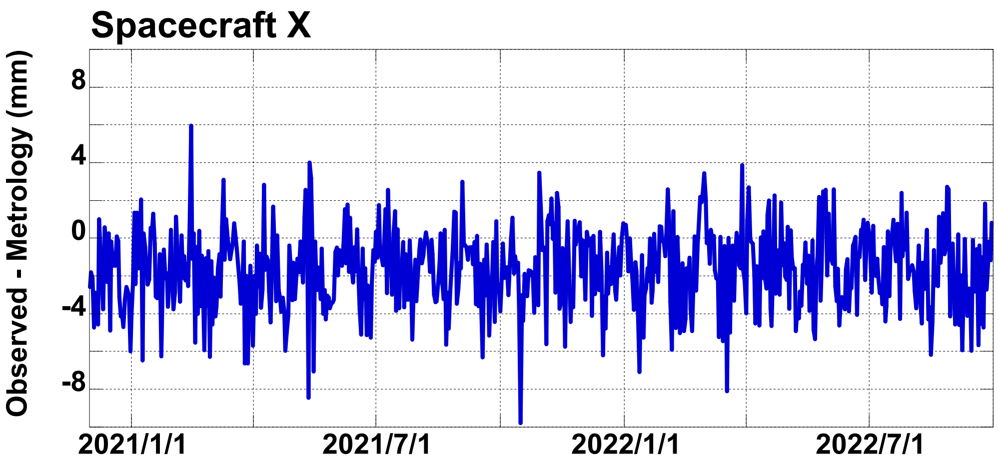
L2 Baseline from Trig to Redundant PODRIX

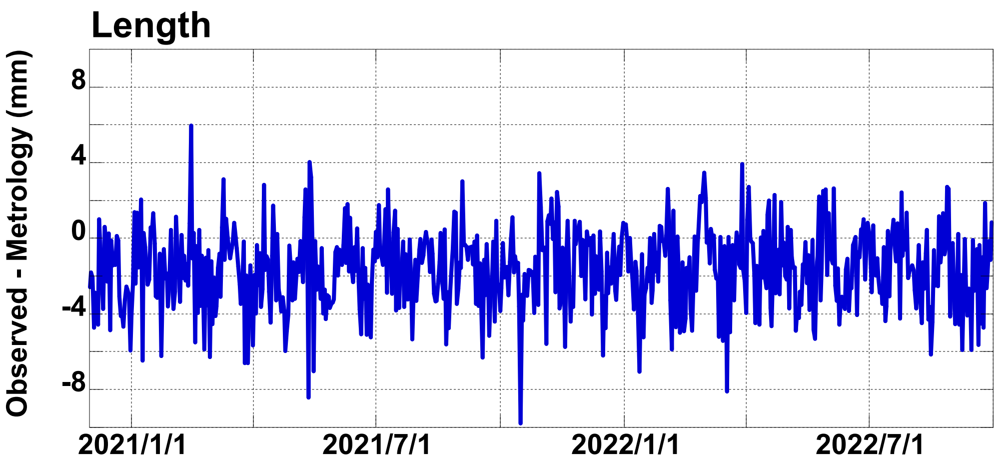
	Reported Quaternions		Yaw Bias Applied	
Component	Mean (mm)	Std. Dev. (mm)	Mean (mm)	Std. Dev. (mm)
X	-14.0	1.0	-13.3	1.1
Y	**-16.4**	**1.8**	**-0.6**	**0.9**
Z	-4.2	0.1	-4.2	0.2
Length	-14.0	1.1	-13.3	1.1

- Results using 5 days of data from Jan. 13-17, 2021
  - Full day of GPS tracking.
- Partial GPS coverage on 21 days.

- **Applying -0.4 degree yaw bias significantly reduces Y-component of baseline vector by 17 mm.**
  - **Predicted impact is 15.8 mm.**
- Rotation about s/c Z expected to have larger impact on Y component of baseline vector from TriG.
  - Longer lever arm (by 403 mm) between TriG and redundant PODRIX than with nominal PODRIX.
- Similar significant offset in X component not observed for L1.
  - Potentially explained by relative time tag bias of 2 microsec.

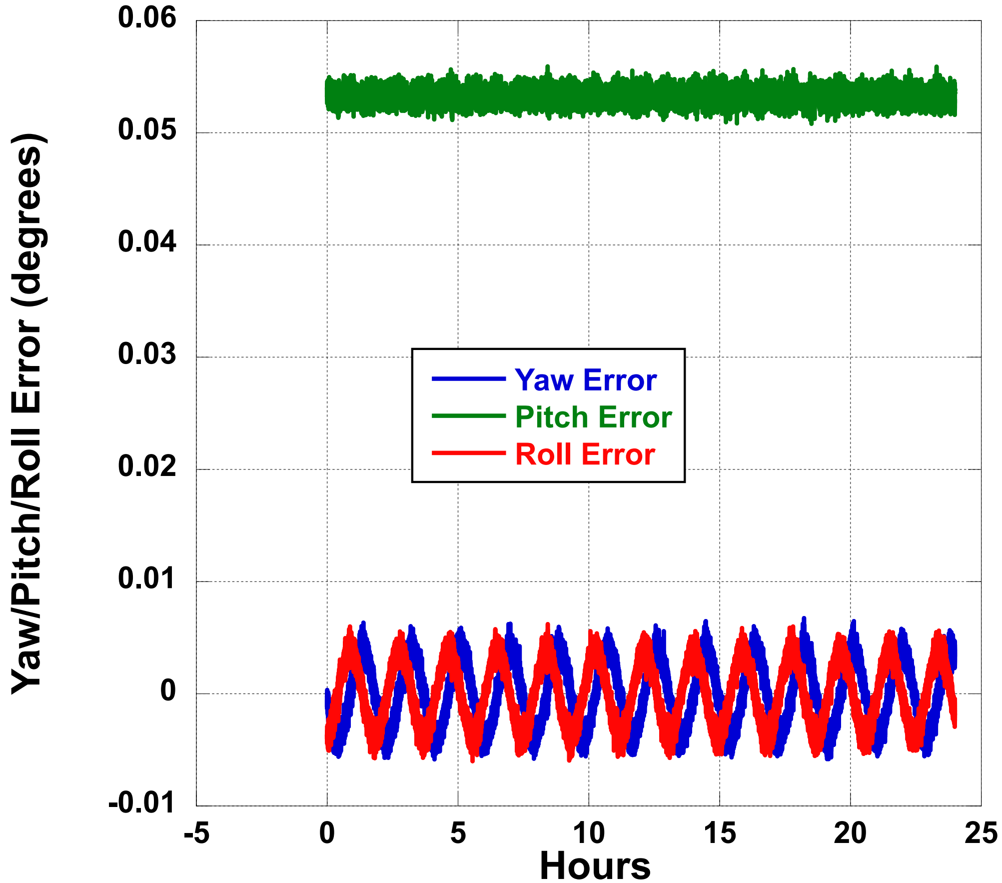
Baseline Length Dominated by X





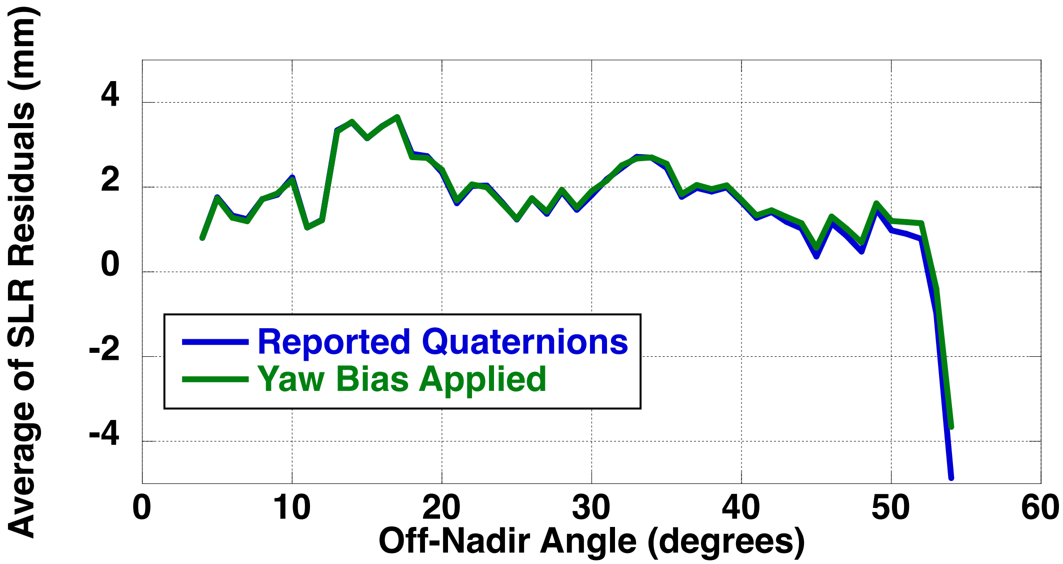
- Baseline length is dominated by the component in spacecraft X direction.

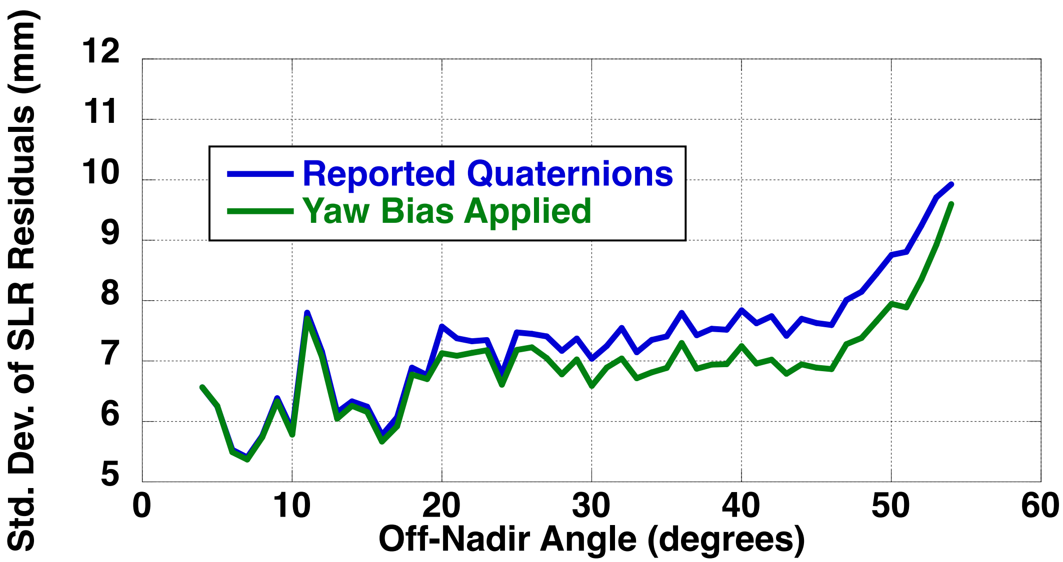
Impact of 1-Second Time Tag Error in Quaternions



- Simulate impact of 1-second time tag error in reported quaternions.
  - Once per revolution error in Yaw and Roll
    - Amplitude = 0.006 degrees
  - Bias error in Pitch of 0.053 degrees.

Yaw Bias Impact on Average and Standard Deviation of SLR Residuals





- No significant impact to average of SLR Residuals.
- Most significant improvement to standard deviation of SLR Residuals at elevations > 20 degrees.