

# An inter-agency comparison of non-gravitational force modeling for Sentinel-3A

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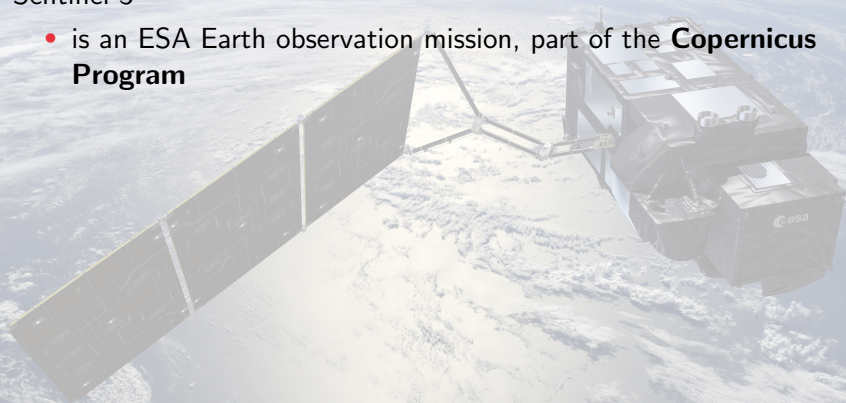
COSPAR Scientific Assembly 2018  
Pasadena, USA  
July 16, 2018

# Introduction – Sentinel-3

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- satellites are equipped with **SAR altimeters** as main topographic instruments for accurate measurements of sea surface topography
- requires precise and accurate orbit information (**requirement: 2-3 cm RMS in radial direction**)
- satellites are equipped with GPS and DORIS receivers and a Laser retro-reflector for **Precise Orbit Determination (POD)**

# Introduction – POD QWG

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- consists of  $\sim 10$  different agencies
- provides orbit solutions obtained with different POD software packages for regular intercomparison

Daniel Arnold: An inter-agency comparison of non-gravitational force modeling for Sentinel-3A  
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- Sophisticated modelling of non-gravitational forces desired for Sentinel-3 to avoid degradation of orbit solutions due to (too many or too loosely constrained) empirical parameters.

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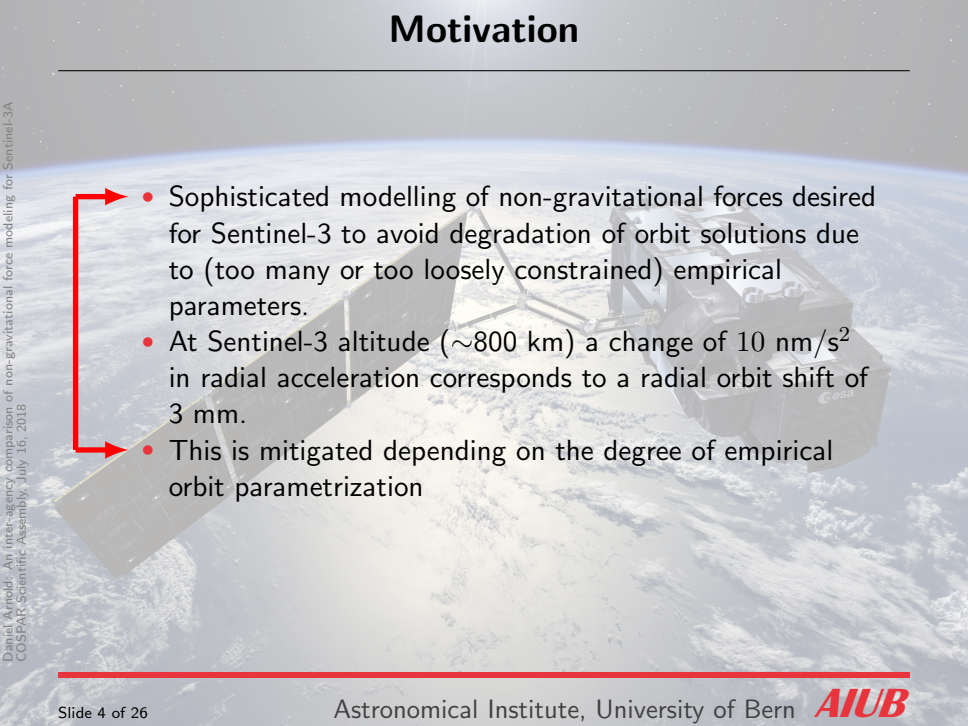
- Sophisticated modelling of non-gravitational forces desired for Sentinel-3 to avoid degradation of orbit solutions due to (too many or too loosely constrained) empirical parameters.
- At Sentinel-3 altitude ( $\sim 800$  km) a change of  $10 \text{ nm/s}^2$  in radial acceleration corresponds to a radial orbit shift of 3 mm.

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# Motivation

**Goal of study:** Compare modeled non-gravitational accelerations for Sentinel-3A (S3A) from different members of the POD QWG. The following groups have participated so far:

Agency	POD Software	
Astronomical Institute, Univ. of Bern	AIUB	Bernese GNSS S/W
Centre National d'Etudes Spatiales	CNES	Zoom
Copernicus POD Service	CPOD	NAPEOS
German Space Operations Center	DLR	GHOST
EUMETSAT	EUM	NAPEOS
Technical University of Munich	TUM	Bernese GNSS S/W

# Methods

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## First comparison:

- Each member used their POD software to compute the following non-gravitational accelerations (w/o estimating scaling factors) along a fixed S3A orbit for the three days 085, 170, and 250 of 2016 in the inertial and satellite-fixed coordinate frames:
  - Direct Solar Radiation Pressure (SRP)
  - Emitted and reflected Planetary Radiation Pressure (PRP)
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- Fit accelerations with linear splines to overcome different and non-uniform sampling of accelerations
- Compare interpolated accelerations at a sampling of 10 s

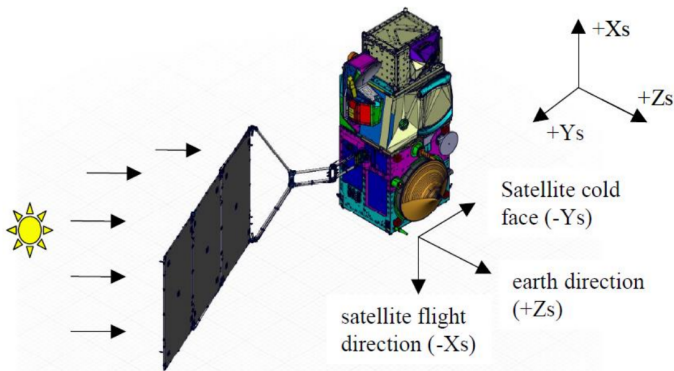
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- Solar panel motion:
  - DLR assumes front panel normal vector into satellite-Sun direction at all times
  - Other groups assume  $+y$  unit vector (rotation axis), panel normal vector and satellite-Sun vector in one plane (optimal orientation)

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- Attitude: CNES used theoretical attitude law, other groups quaternions

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Planetary radiation pressure (visual + IR)

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Aerodynamic accelerations

$\sim 5 \text{ nm/s}^2$

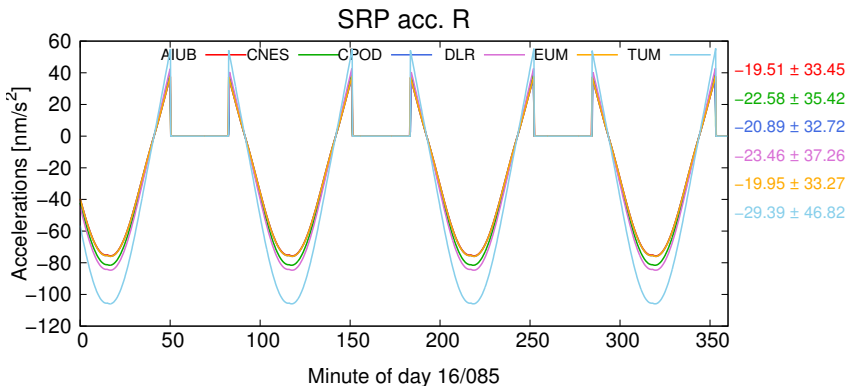
# Solar radiation pressure modeling

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	Earth model	Shadow model	Atm. refr.	Atm. abs.
AIUB	Oblated	Conical	No	No
CNES	Oblated	Conical	Yes	No
CPOD	Spherical	Conical	No	Yes
DLR	Spherical	Conical	No	No
EUM	Spherical	Conical	No	No
TUM	Spherical	Cylindrical	No	No

# Solar radiation pressure

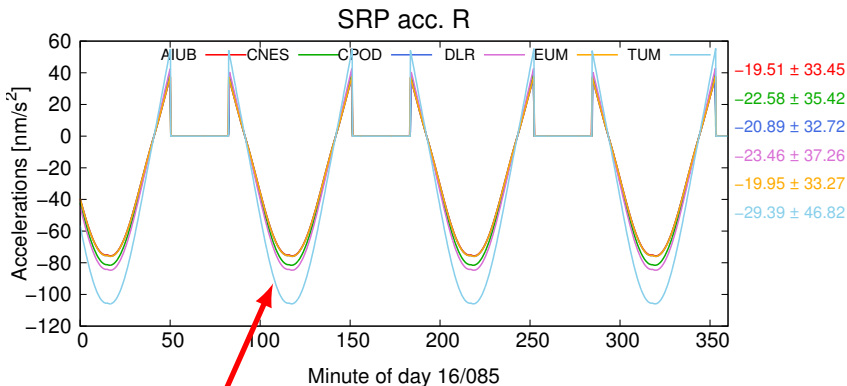
Day 16/085, radial direction (status before May 2018):





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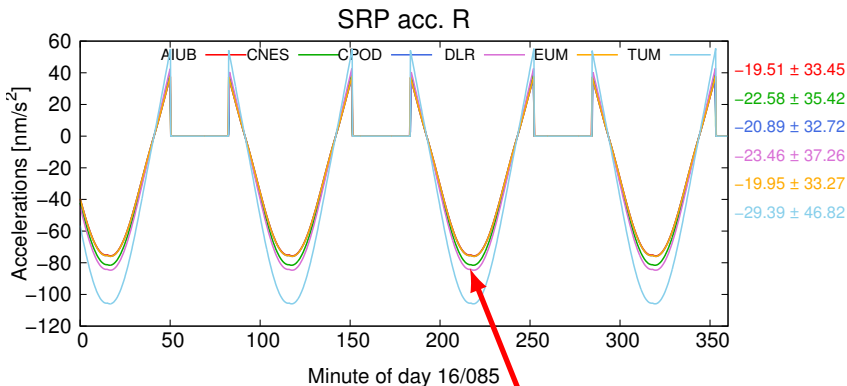
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TUM accelerations show significantly larger amplitudes

# Solar radiation pressure

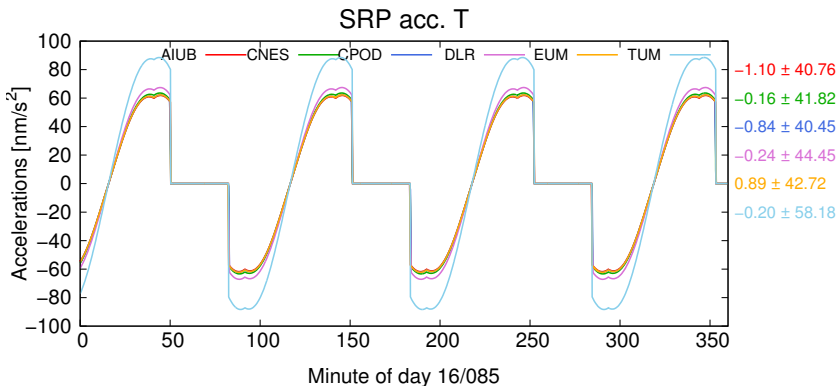
Day 16/085, radial direction (status before May 2018):



CNES and DLR show larger amplitudes (inst. re-emiss.?)

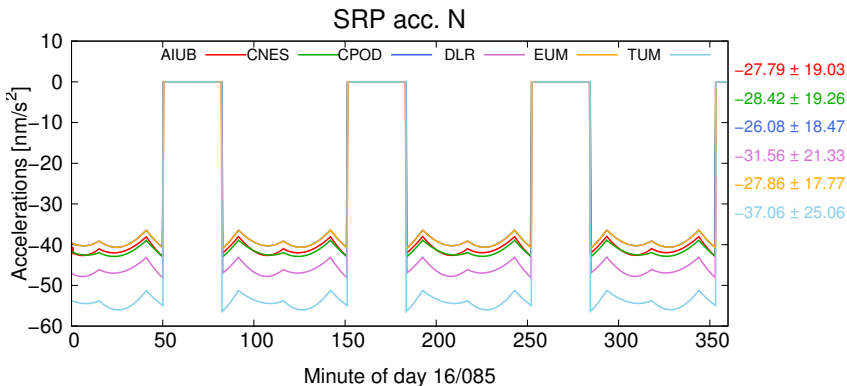
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Day 16/085, along-track direction:



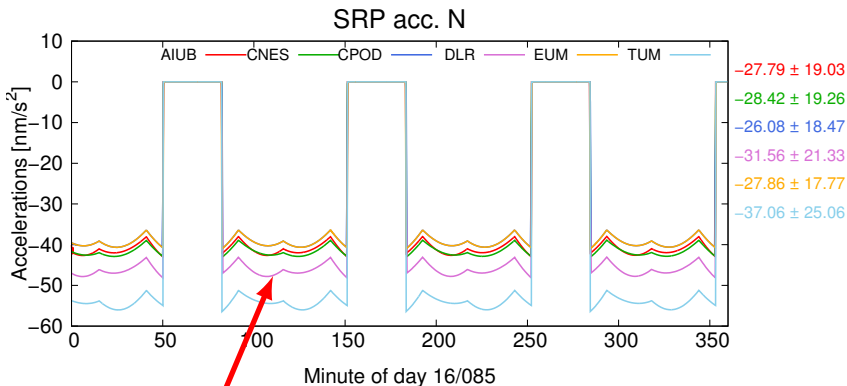
# Solar radiation pressure

Day 16/085, cross-track direction:



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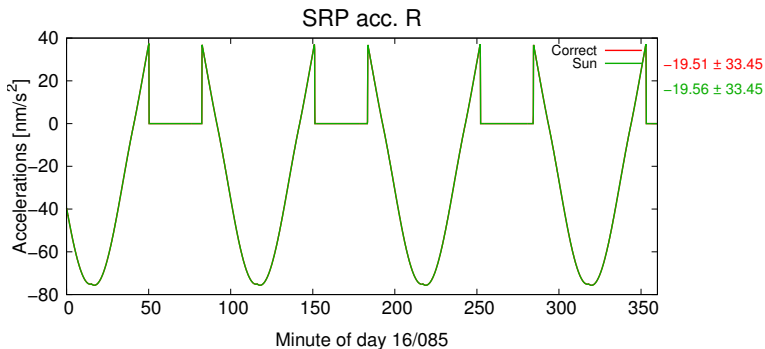
Day 16/085, cross-track direction:



DLR accelerations larger (solar panel orientation?)

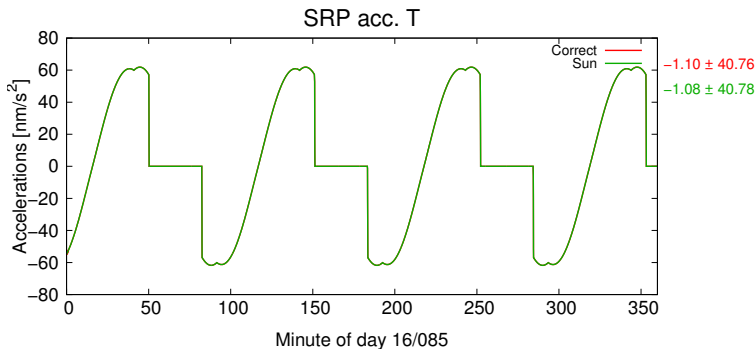
# Solar panel orientation

Impact of solar panel orientation. "Correct": Optimal possible solar panel orientation. "Sun": Solar panel perfectly perpendicular to the Sun direction.



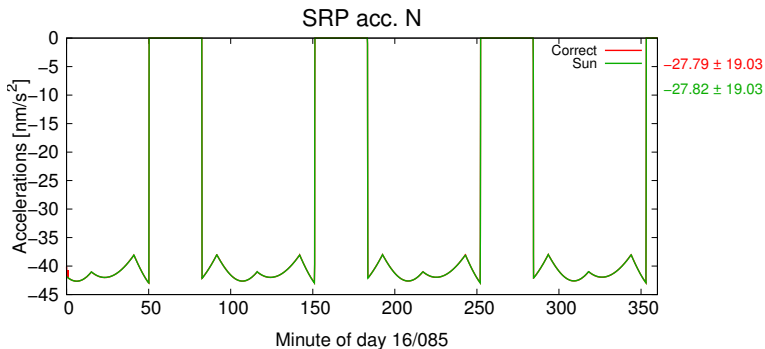
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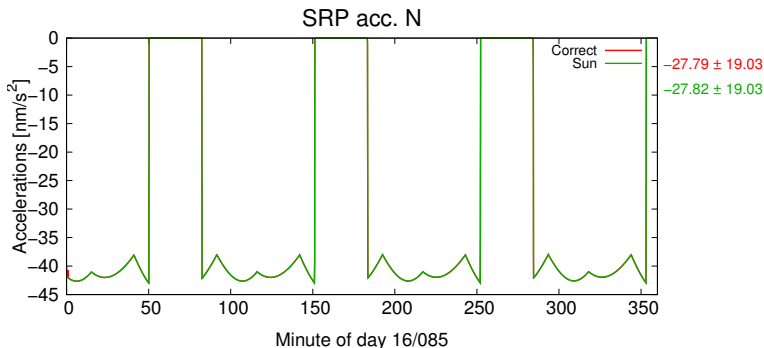
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→ cannot explain the differences of the DLR SRP accelerations

# Instantaneous re-emission

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Acceleration of a flat area element  $A$  due to absorbed ( $\alpha$ ), diffusely reflected ( $\delta$ ) and specularly reflected ( $\rho$ ) radiation:

$$\vec{a}_{\text{RP}} = -\frac{\Phi}{c \cdot m} A \cos \theta \cdot \left[ (\alpha + \delta) \vec{e}_{\text{Sun}} + \frac{2}{3} \delta \vec{n} + 2\rho \cos \theta \vec{n} \right], \quad (1)$$

where

$\Phi$  Solar flux

$c$  Speed of light

$m$  Satellite mass

$\vec{e}_{\text{Sun}}$  Unit vector satellite-Sun

$\vec{n}$  Area normal vector

$\theta$  Angle between  $\vec{e}_{\text{Sun}}$  and  $\vec{n}$ ,

and  $\alpha + \delta + \rho = 1$ .

# Instantaneous re-emission

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If the absorbed radiation is instantaneously re-radiated according to Lambert's law, the following contribution needs to be added:

$$\vec{a}_{\text{RE}} = -\frac{\Phi}{c \cdot m} A \cos \theta \cdot \frac{2}{3} \alpha \vec{n}, \quad (2)$$

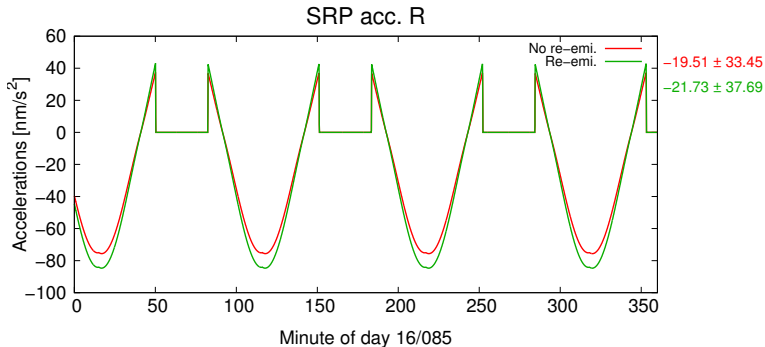
and the total radiation pressure acceleration amounts to

$$\vec{a}_{\text{RP}} = -\frac{\Phi}{c \cdot m} A \cos \theta \cdot \left[ (\alpha + \delta) \left( \vec{e}_{\text{Sun}} + \frac{2}{3} \delta \vec{n} \right) + 2\rho \cos \theta \vec{n} \right]. \quad (3)$$

$$[(\alpha, \delta, \rho) \rightarrow (0, \alpha + \delta, \rho)]$$

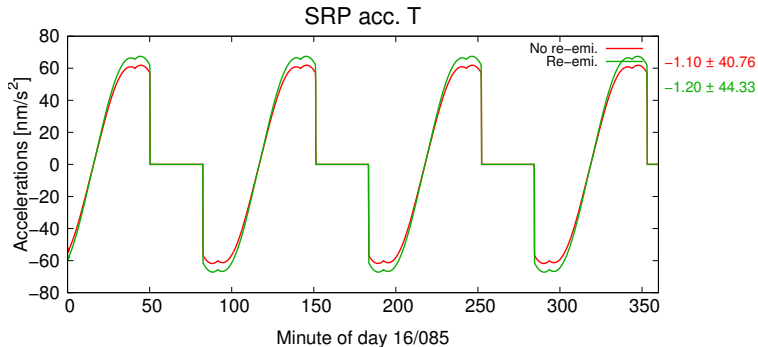
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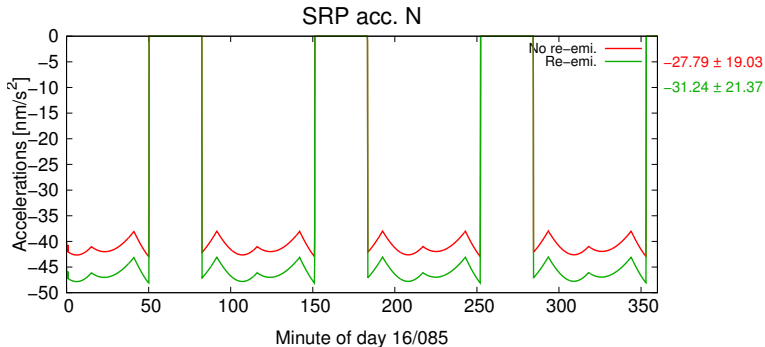
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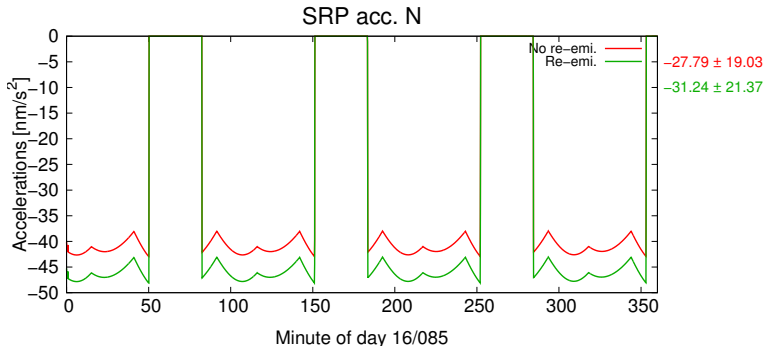
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→ Modeling of instantaneous re-emission is very likely one of the main reasons for the larger DLR accelerations in normal direction. Surprisingly, CNES (which also models inst. re-emission) does not show larger cross-track accelerations.

# Instantaneous re-emission: Updates

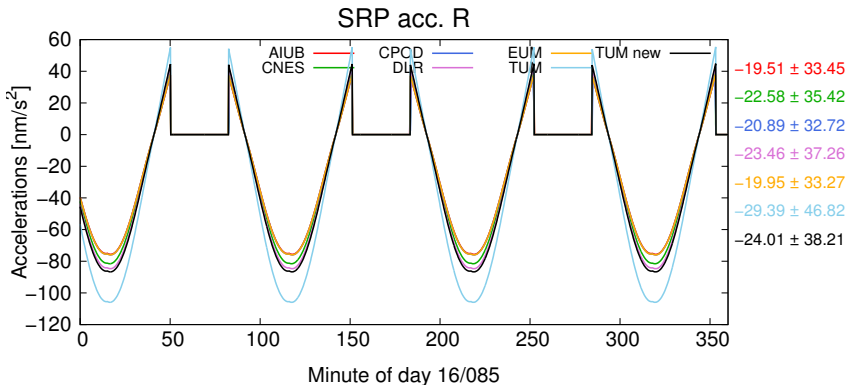
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- Based on these comparisons, TUM found out that they had modeled instantaneous re-emission also for the solar panels.



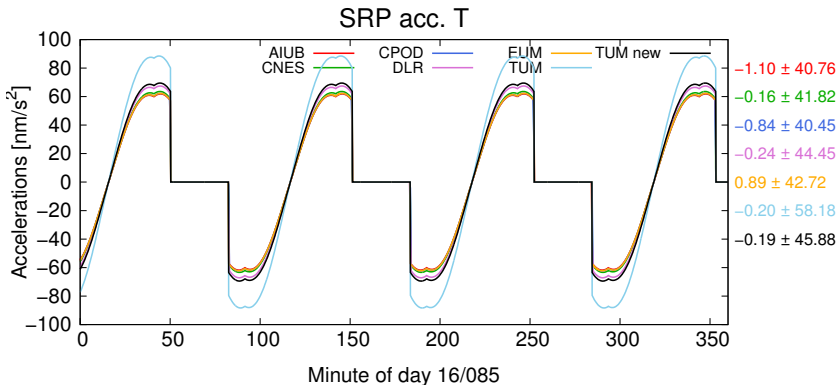
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- Newly provided accelerations now show smaller amplitudes:



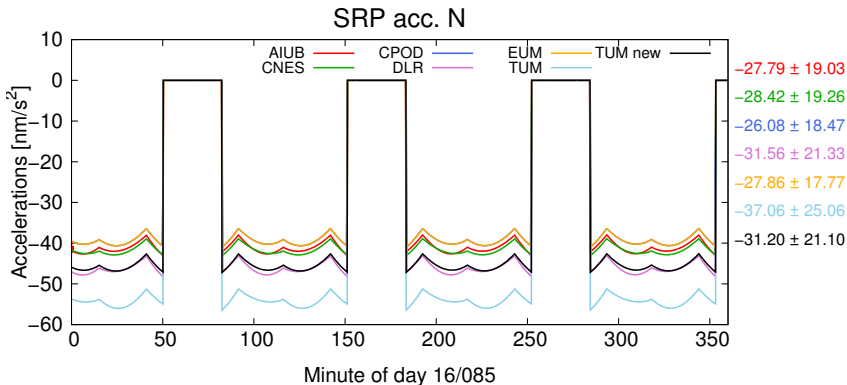
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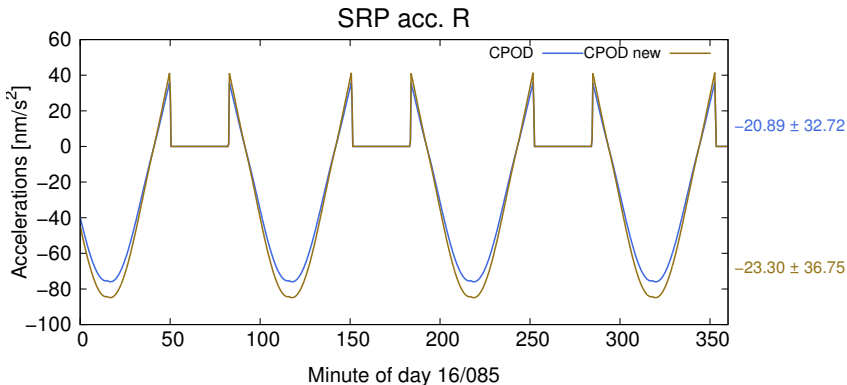
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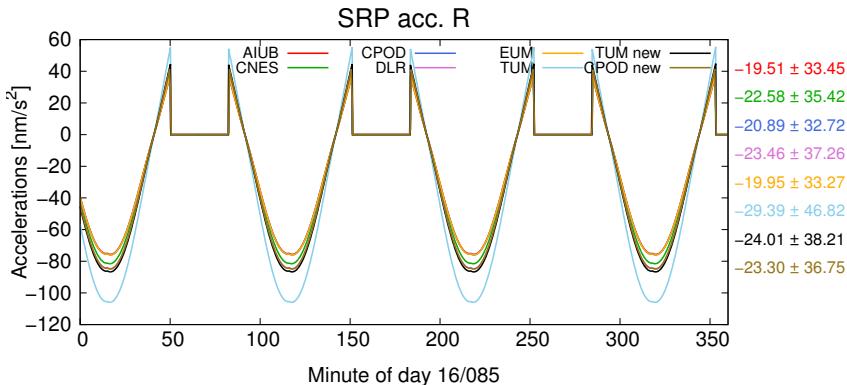
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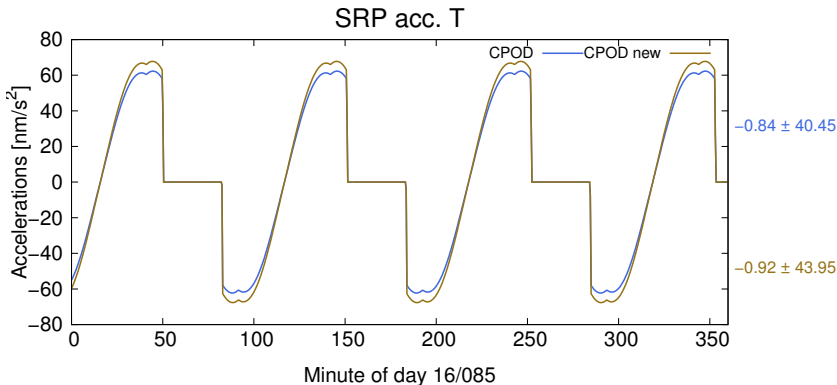
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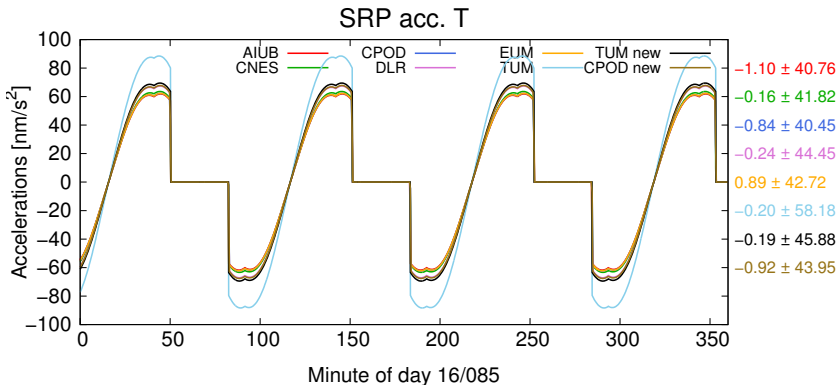
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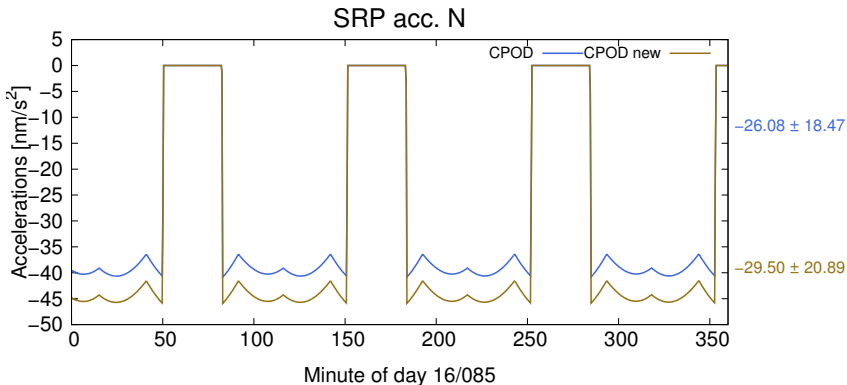
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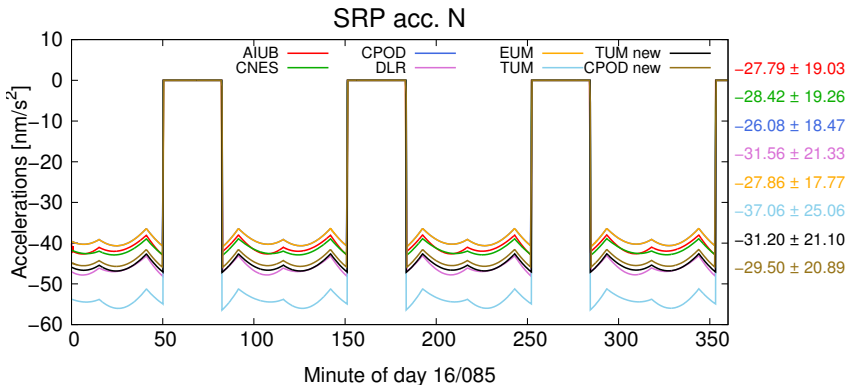
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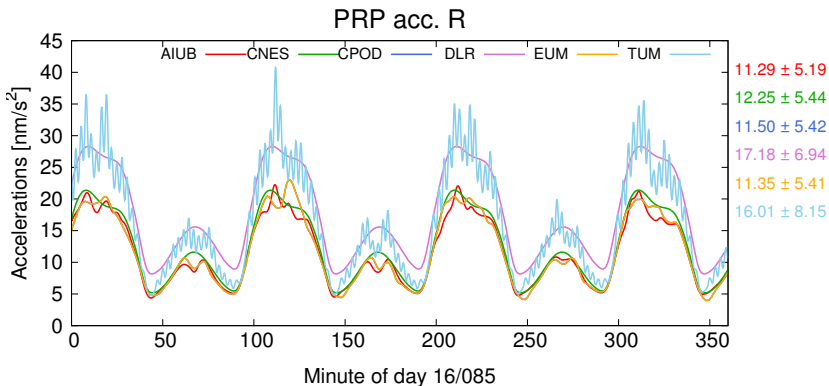
# Planetary radiation pressure modeling

	Earth model	Radiation model
AIUB	Grid $2.5^\circ \times 2.5^\circ$	CERES
CNES	Ring segments	Knocke et al., 1988
CPOD	Grid $5^\circ \times 5^\circ$	CERES
DLR	Ring segments	CERES, approx.
EUM	Grid $5^\circ \times 5^\circ$	CERES
TUM	Grid $10^\circ \times 10^\circ$	CERES

- “Ring segments”: concentric rings with sectors around satellite foot point (3 rings with 4, 8, and 12 sectors for DLR and 15 rings with 15 sectors for CNES).
- “CERES, approx.”: a 2nd order polynomial in latitude and a periodic function in time is used to approximate the CERES grid values.

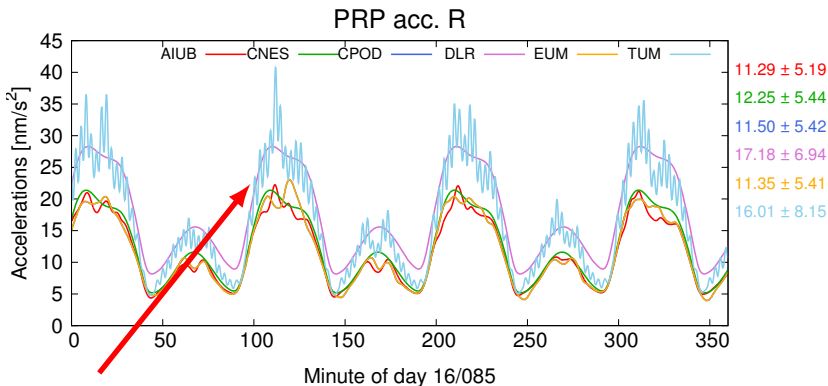
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Day 16/085, radial direction (status before May 2018):



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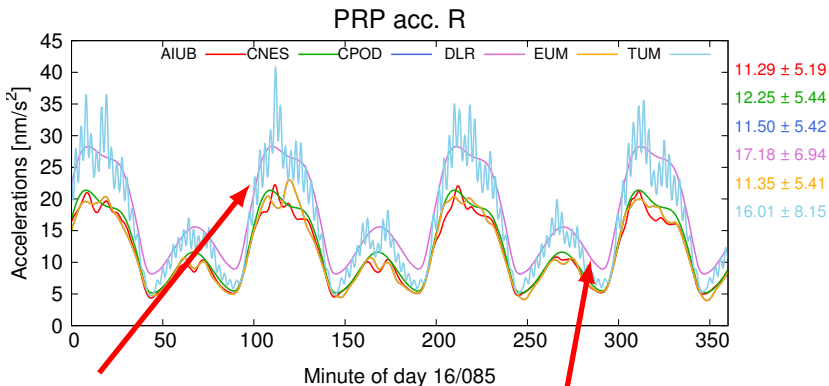
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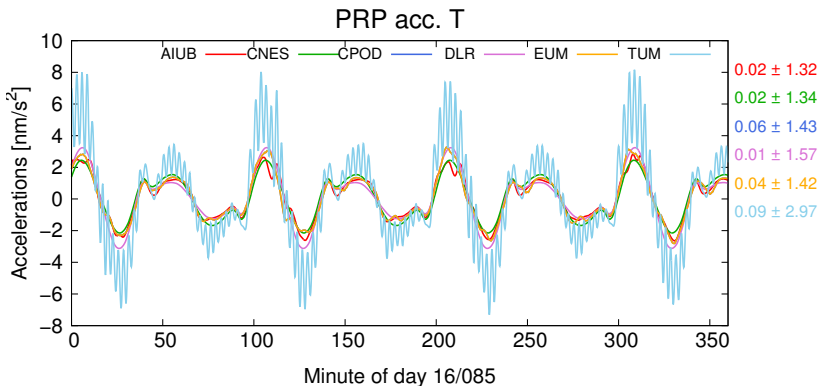


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DLR accelerations show offset

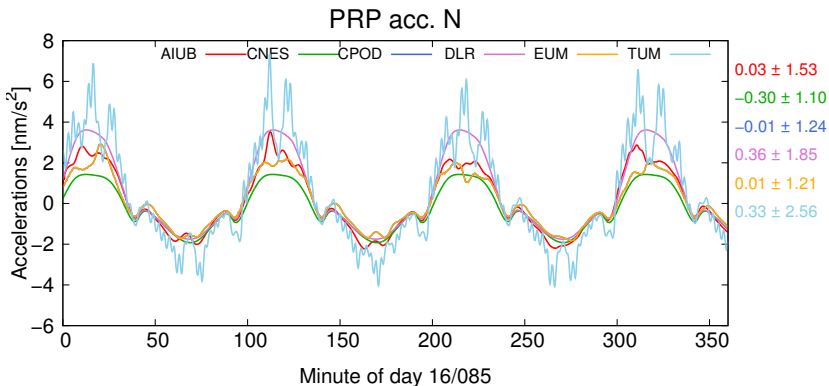
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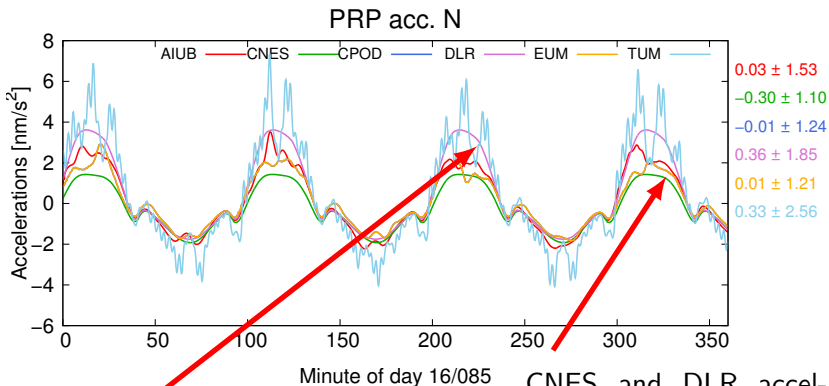
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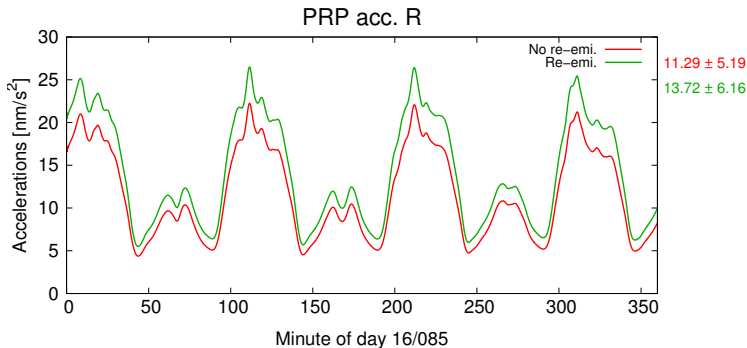


DLR accelerations show larger amplitudes

CNES and DLR accelerations show less fine structure (coarser Earth model)

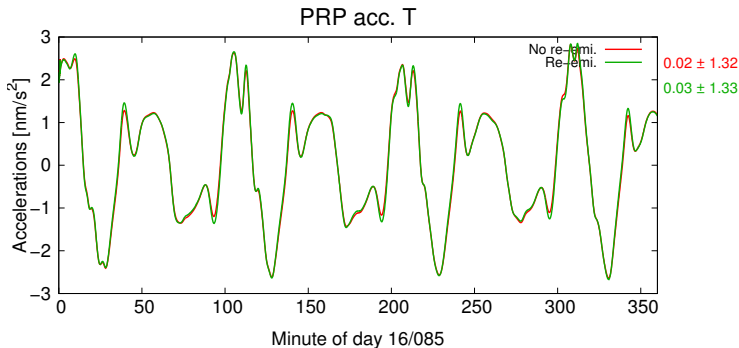
# PRP: Instantaneous re-emission

Impact of instantaneous re-emission:



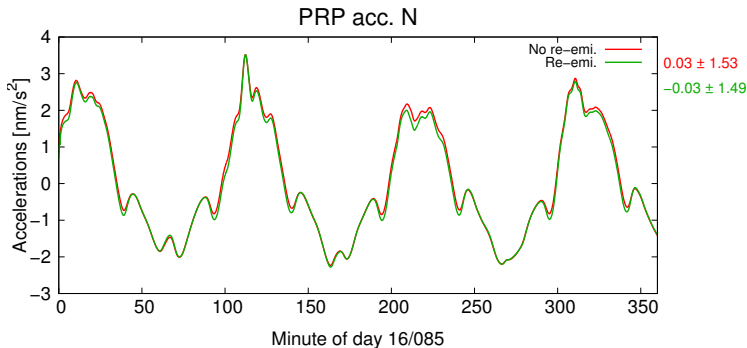
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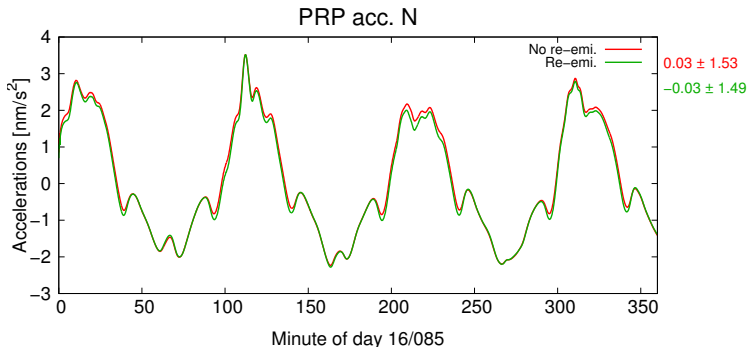
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# PRP: Instantaneous re-emission

Impact of instantaneous re-emission:



→ Modeling of instantaneous re-emission is very likely one of the main reasons for the offset in DLR accelerations in radial direction. Surprisingly, CNES (which also models inst. re-emission) does not show the same acceleration offset in radial direction.

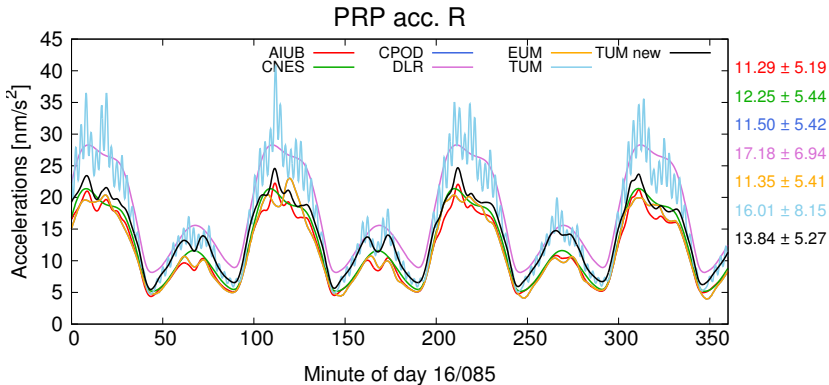
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- TUM is using a grid to model Earth surface, but only one mean direction for PRP. Employed grid resolution of 10 deg seems insufficient.

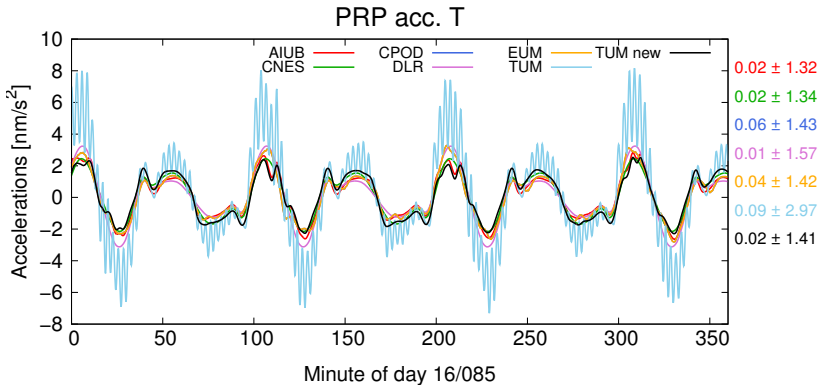
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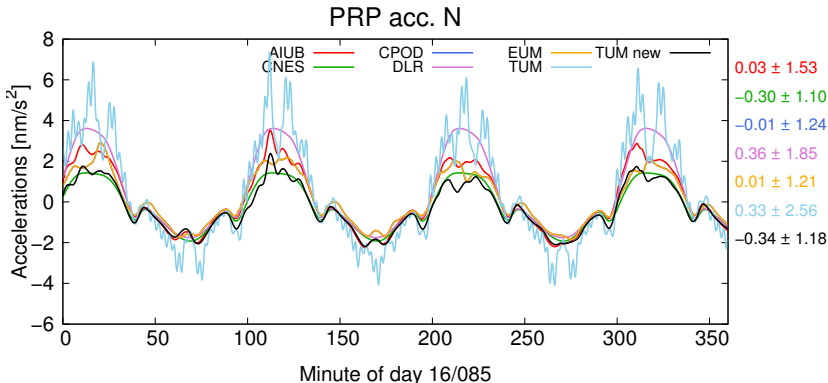
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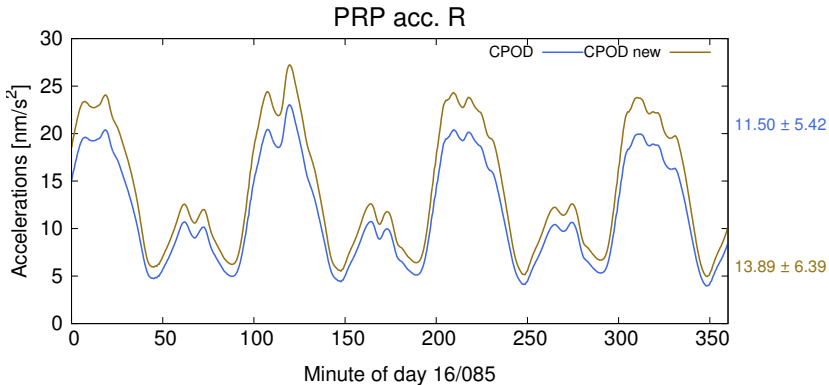
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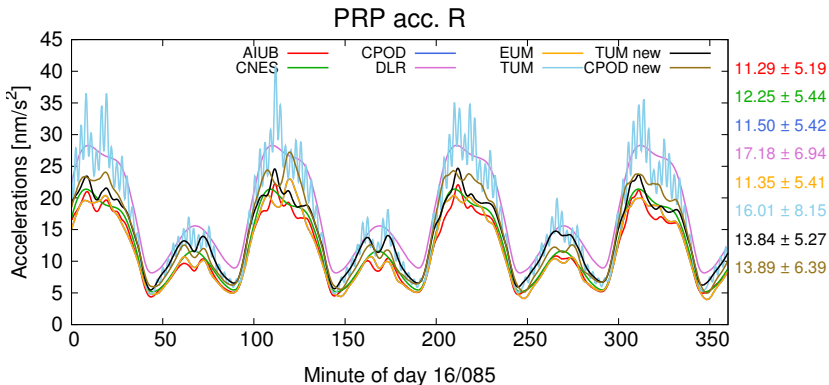
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- CPOD recently updated their radiation pressure modeling to account for instantaneous re-emission



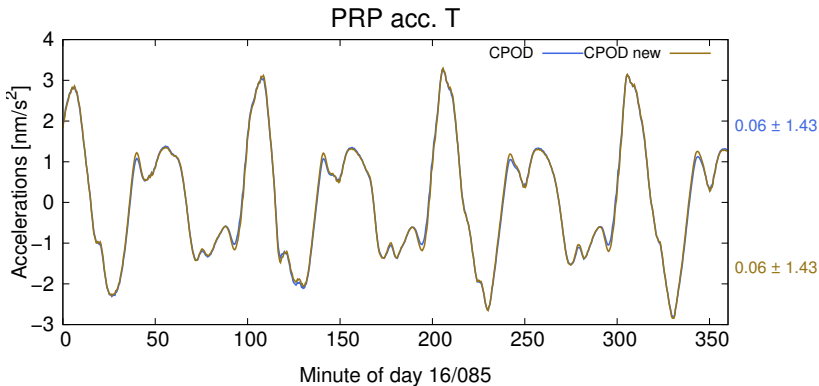
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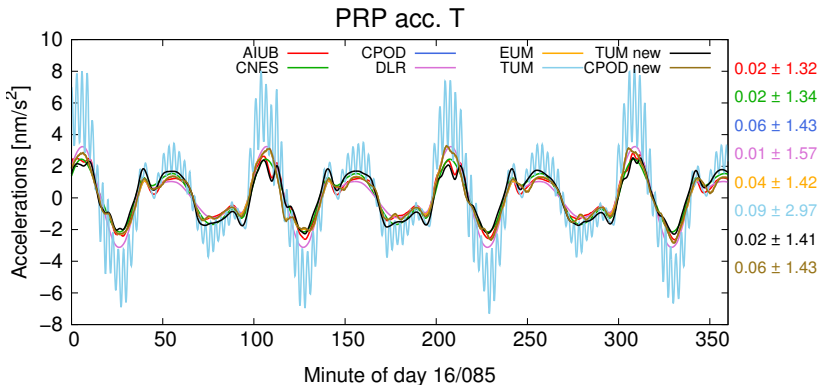
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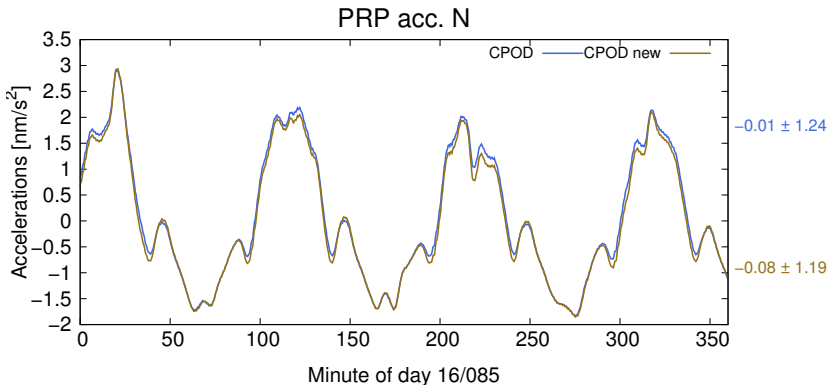
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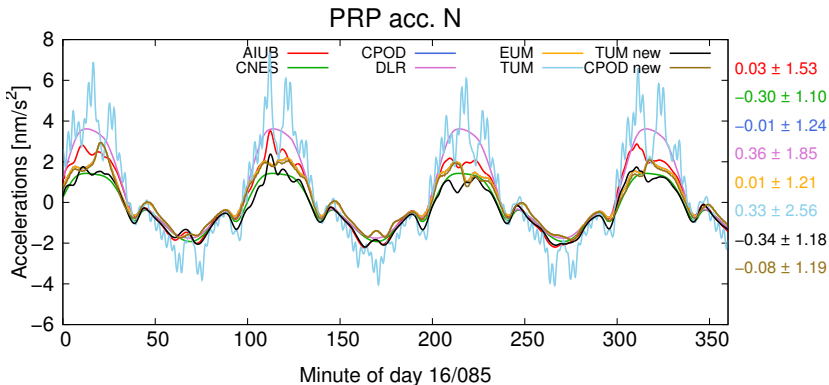
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# Aerodynamic acceleration modeling

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	Density model	Horizontal wind model
AIUB	DTM2013	HWM14
CNES	MSIS-86	None
CPOD	MSISE-90	HWM93
DLR	NRLMSISE-00	None
EUM	MSISE-90	HWM93
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- All groups except EUM and TUM model aerodynamic lift accelerations

# Aerodynamic acceleration modeling

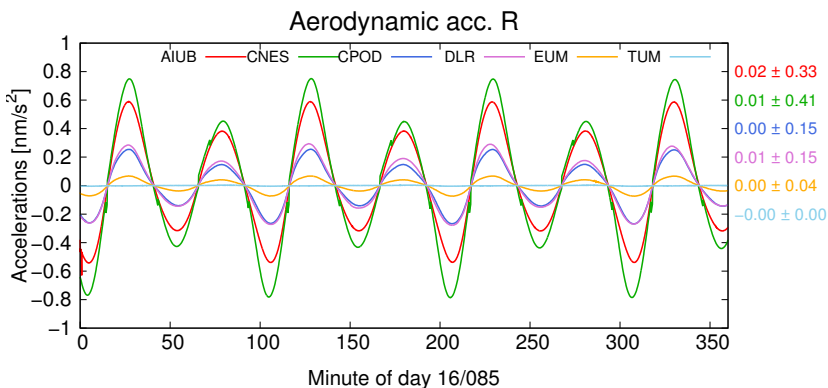
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- All groups except EUM and TUM model aerodynamic lift accelerations
- Aerodynamic accelerations offer largest potential for differences: many different atmospheric models, different proxies, many differences in modeling of gas-surface interaction, ...

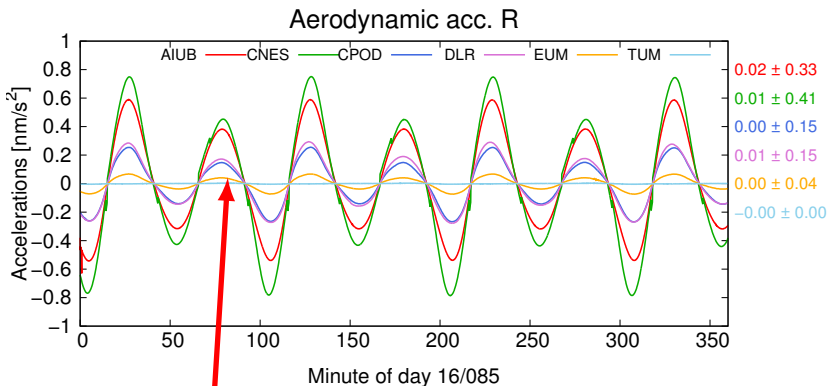
# Aerodynamic accelerations

Day 16/085, radial direction:



# Aerodynamic accelerations

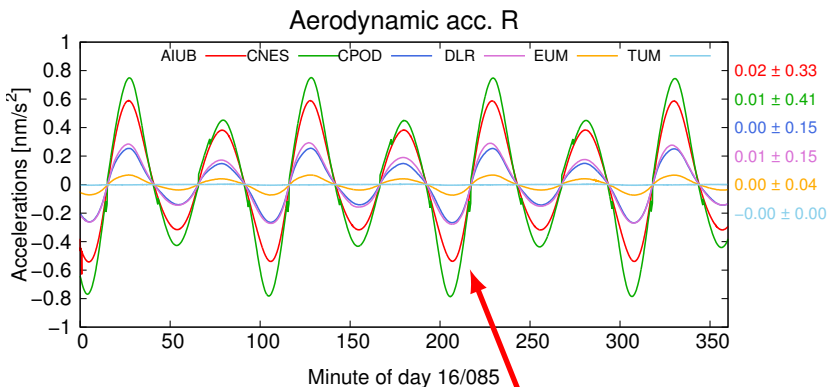
Day 16/085, radial direction:



EUM and TUM do not model lift

# Aerodynamic accelerations

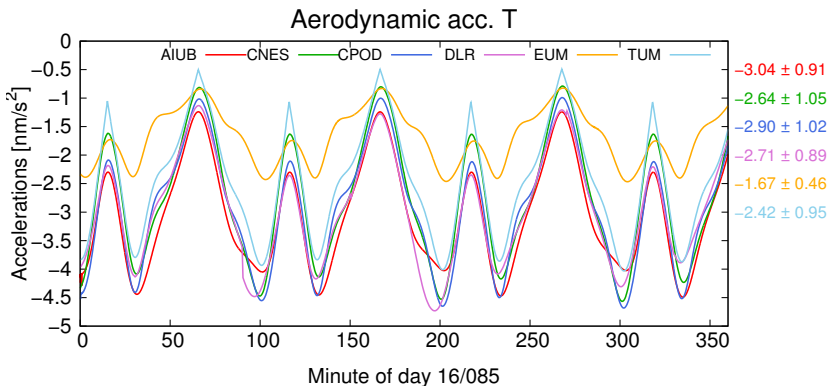
Day 16/085, radial direction:



AIUB and CNES show larger amplitudes (density models?)

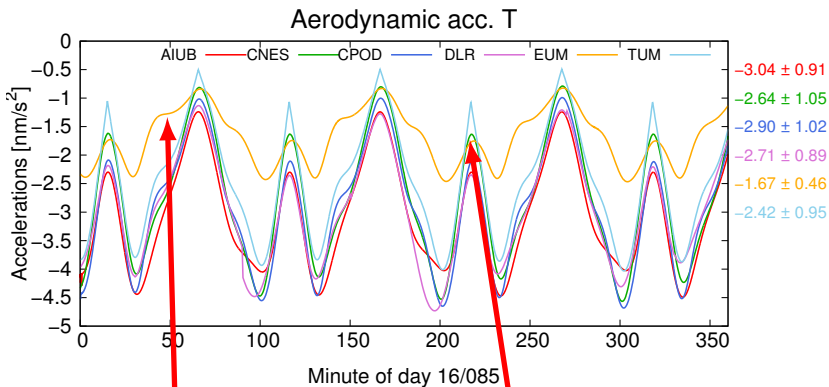
# Aerodynamic accelerations

Day 16/085, along-track direction (largest):



# Aerodynamic accelerations

Day 16/085, along-track direction (largest):

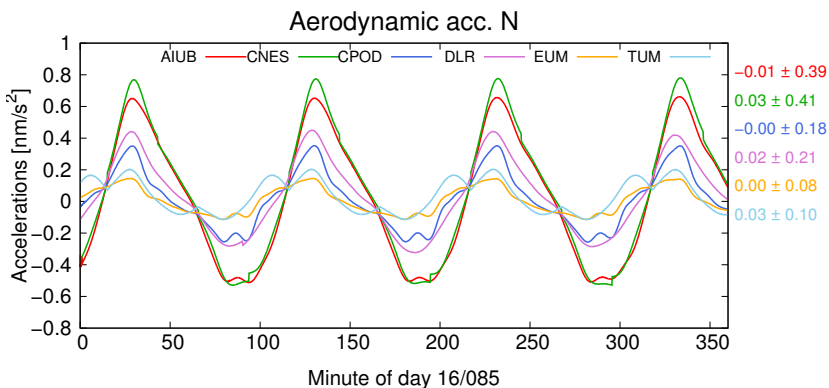


EUM acceleration smaller

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# Aerodynamic accelerations

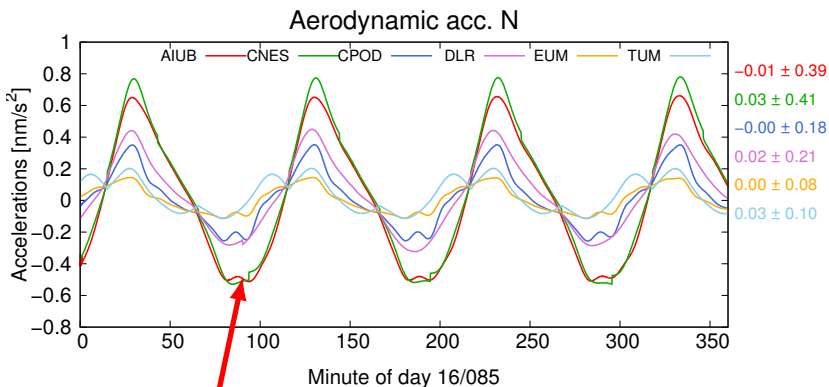
Day 16/085, cross-track direction:





# Aerodynamic accelerations

Day 16/085, cross-track direction:



AIUB and CNES accelerations show larger amplitudes

# Aerodynamic acceleration modeling

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- Further tests needed to better disentangle impact of different density models/wind models
- Even if different groups use the same models, different results are likely (e.g., due to different usage of proxies)
  - Option: Compare densities along an orbit
- For Sentinel-3 the aerodynamic accelerations are rather small.
  - Option: Compare, e.g., for Swarm
- For comparison of different atmospheric models in LEO POD see presentation PSD.1-0008-18 *Non-gravitational forces acting on spacecraft: impact of different atmospheric models on LEO orbits* by V. Girardin, Monday, 16th July 2018, 12:40, R101

# Conclusions

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- Overall, the different agencies of the Copernicus POD QWG agree rather well on the modeled non-gravitational accelerations for Sentinel-3A
- SRP accelerations rather identical (at least up to scaling factor)
- Aerodynamic accelerations rather diverse, but so are the employed models
- Difference between the two employed solar panel orientations not critical
- Instantaneous re-emission explains part of the SRP and PRP differences
- TUM could revise and change their settings to better agree with the other groups

# Outlook

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- Check impact of different radiation data and Earth modelings
- Check impact of different atmospheric models
- For further comparisons of aerodynamic accelerations:
  - Use as unified models as possible (density models, HWM)
  - Compare densities along an orbit
  - Maybe use another LEO with higher aerodynamic accelerations (e.g., Swarm)
- Thermal radiation?



Thank you

Cesa

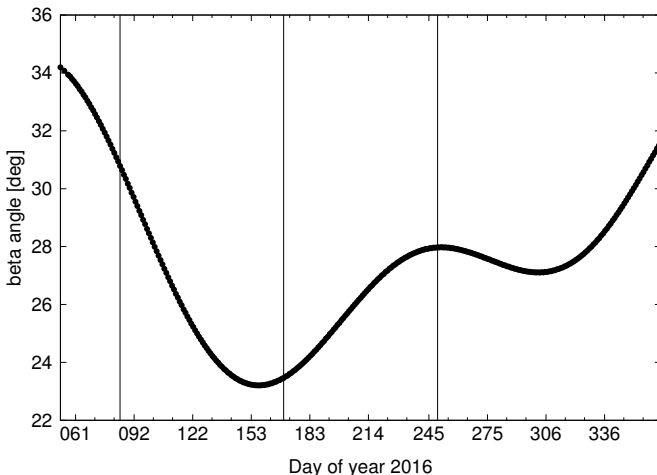
# Environment

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- In 2016 the orbital altitude of S3A was around 800 km

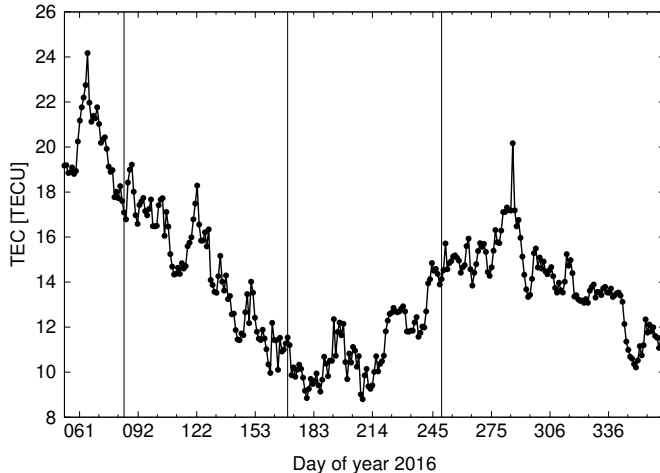
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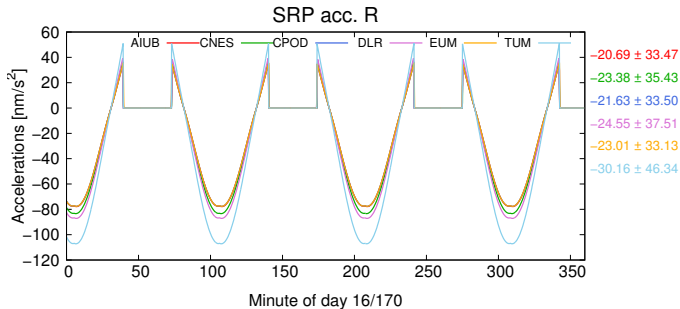
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- TEC:





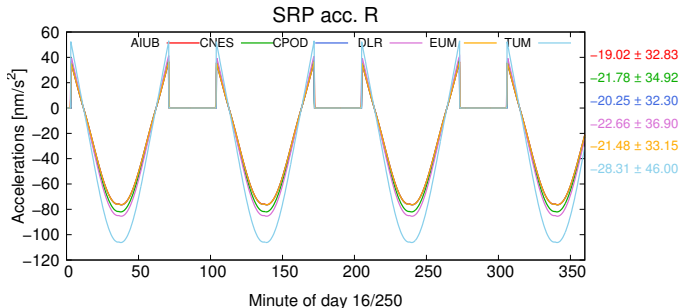
# Solar radiation pressure

Days 16/170 and 16/250:



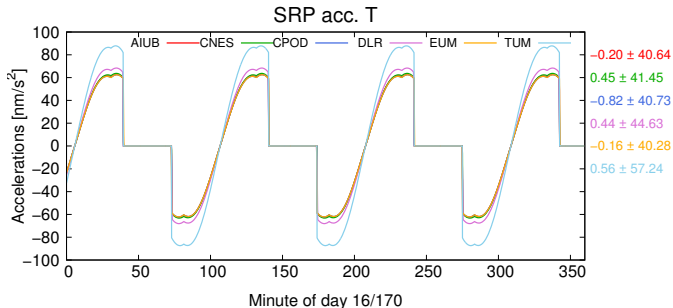
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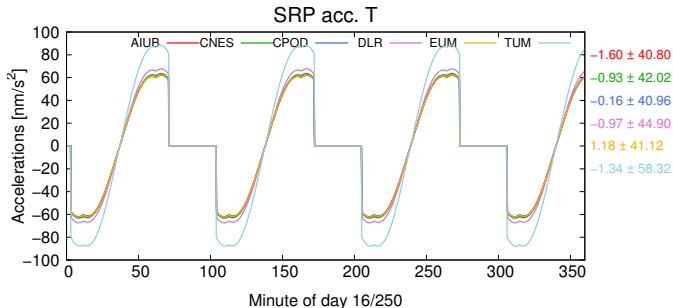
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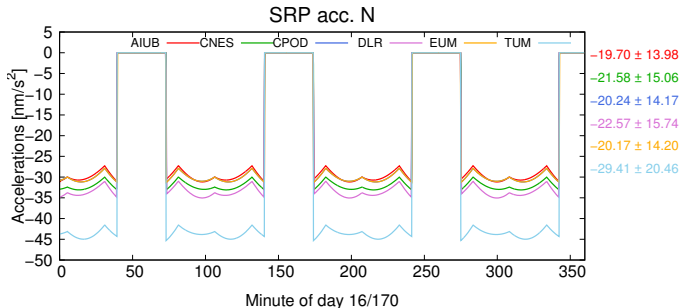
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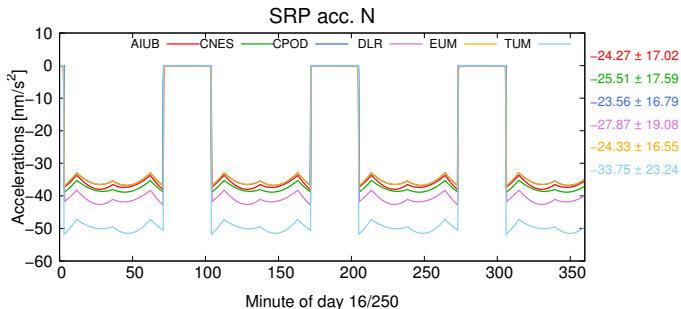
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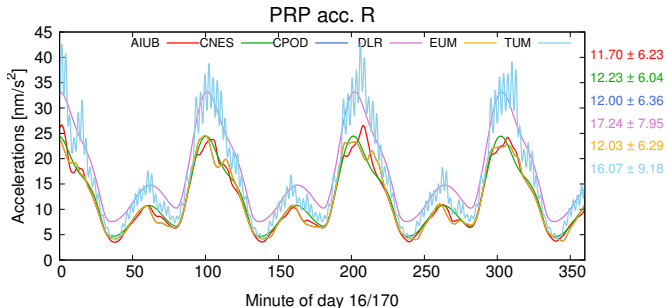
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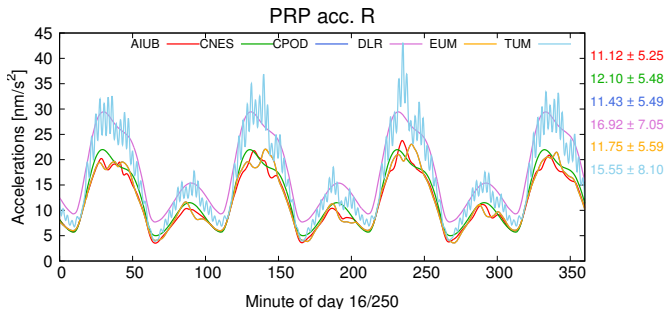
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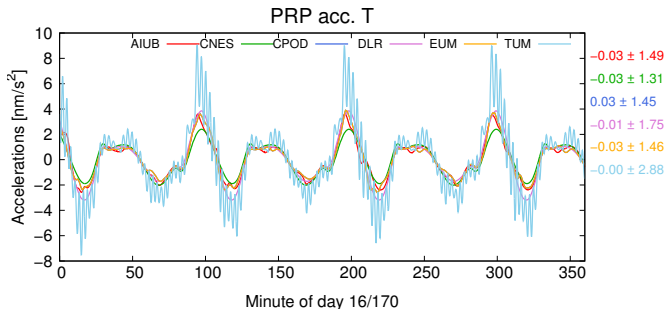
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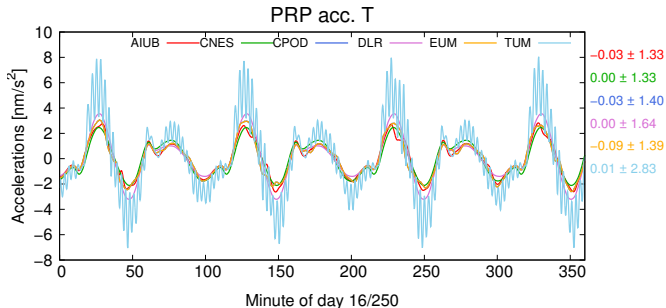
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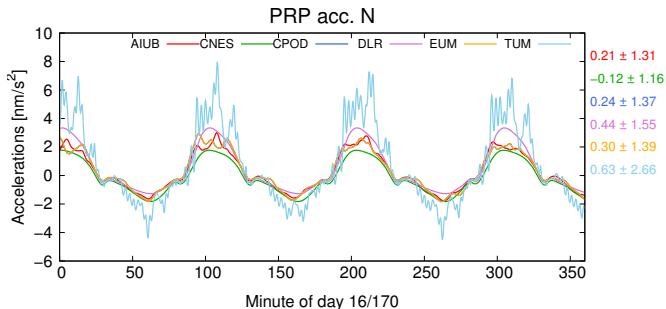
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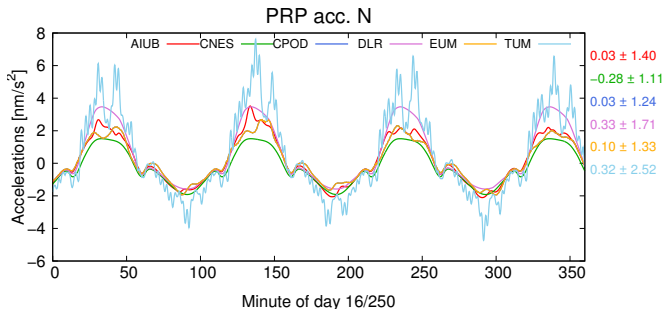
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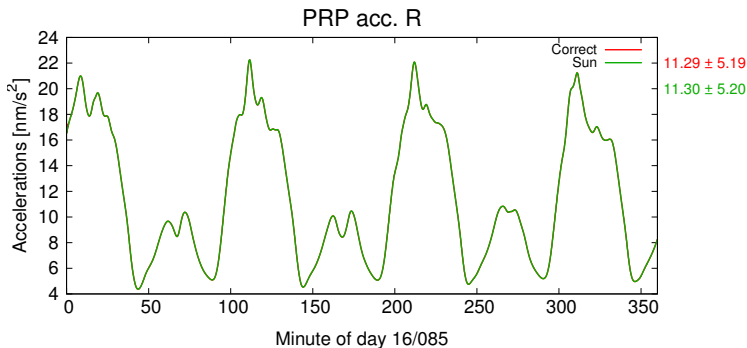
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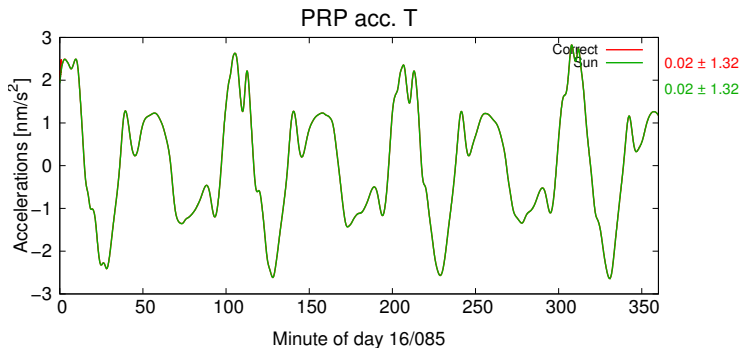
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Impact of solar panel orientation. "Correct": Optimal possible solar panel orientation. "Sun": Solar panel perfectly perpendicular to the Sun direction.



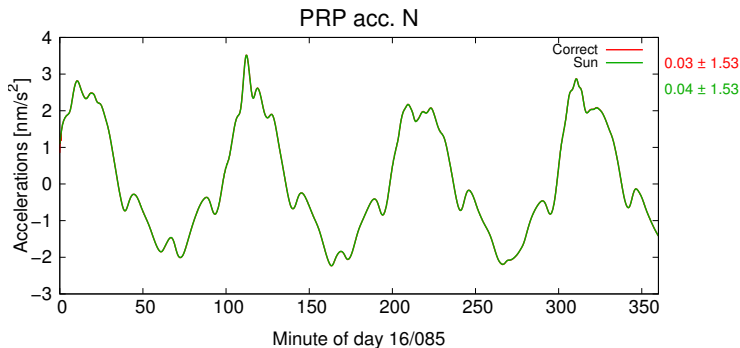
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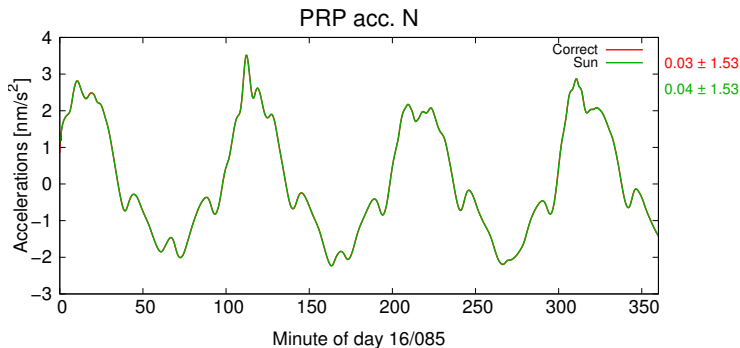
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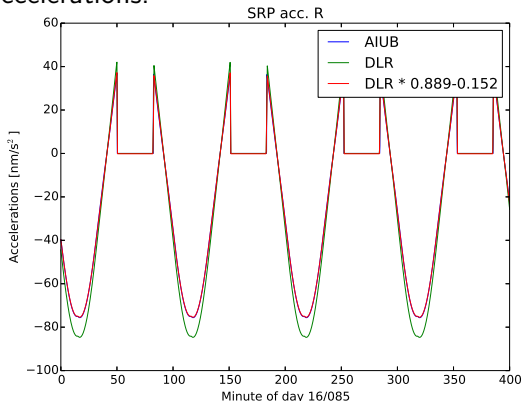


→ Impact negligible (as for SRP)



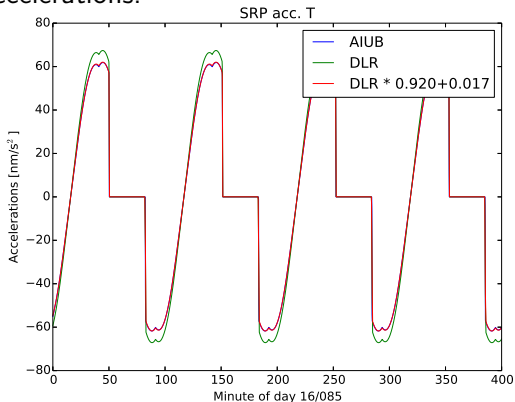
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- E.g., estimate scaling factors and biases to fit accelerations to AIUB accelerations:



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