

Physical a priori solar radiation pressure models for GNSS satellites with the focus on BDS

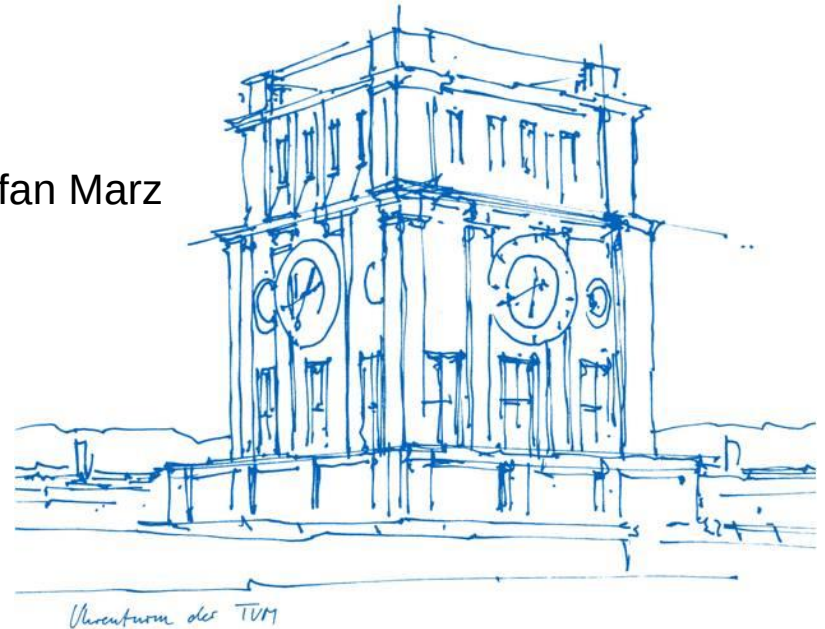
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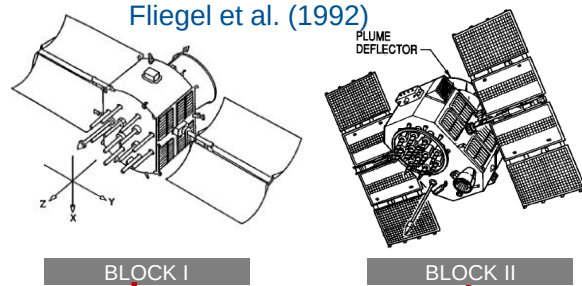
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1. GNSS satellites – metadata information

• GPS



Out of service in 1995

Out of service in 2007

Out of service in 2020

Under service from 1997

Under service from 2005

First satellite in 2010

First satellite in 2019

<https://www.gps.gov>



- Block I, II, IIA and IIR satellites have flat and cylindrical (mainly from antennas) surfaces. Dimensions and optical properties are given by Fliegel et al. (1992) and Fliegel and Gallini (1996). There could be however an aging effect.
- Metadata of Block IIF satellites is not yet officially published.
- Metadata of Block III satellites is published by Steigenberger et al. (2020)

1. GNSS satellites – metadata information

• GLONASS



GLONASS-M



GLONASS-K

Galileo

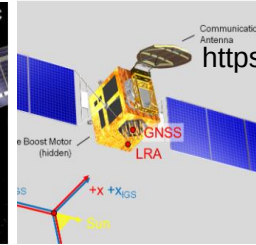


Galileo IOV

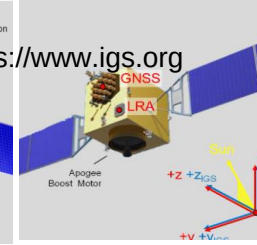


Galileo FOC

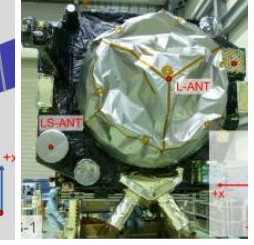
BeiDou-2



BDS-2 GEO

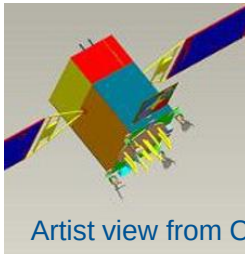


BDS-2 IGSO/MEO



QZSS

• BeiDou-3



BDS3-MEO-CAST



BDS3-MEO-SECM

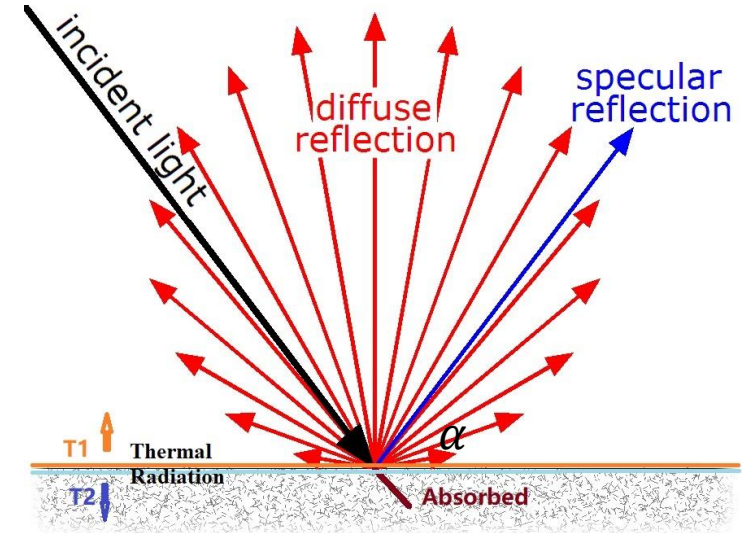
- GLONASS-M satellites have a cylindrical satellite body, metadata of GLONASS satellites is not yet officially published.
- Galileo satellites have an elongated body shape, metadata of Galileo satellites is officially published (<https://www.gsc-europa.eu/>).
- Metadata of BeiDou satellites is officially published, but only one (absorption) of the three optical properties is given (http://www.beidou.gov.cn/yw/gfgg/201912/t20191209_19613.html).
- QZSS satellites have large body size and elongated shape, metadata of QZSS satellites is officially published (<https://www.igs.org/mgex>).

2. Solar radiation pressure (SRP) models

• Analytical model (box-wing)

$$\mathbf{acc} = -\frac{A}{M} \frac{S_0}{c} \cos \theta \left[(\alpha + \delta) \mathbf{e}_D + \left(\frac{\pi}{6} s + \frac{2}{3} (1-s) \right) (\delta + \kappa \alpha) \mathbf{e}_N + \left(\frac{4}{3} s + 2(1-s) \right) \rho \cos \theta \mathbf{e}_N \right]$$

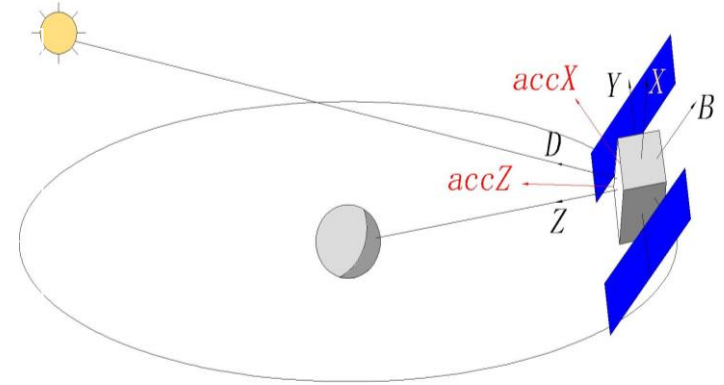
- $\mathbf{acc}$: SRP acceleration
- A : surface area; M : total mass
- S_0 : solar flux; c : vacuum velocity of light
- s : shape factor, from cylindrical (1) to flat (0)
- κ : thermal re-radiation factor, 0 for solar panel (if no detailed information is given) and 1 for satellite body surfaces (if covered by Multilayer Insulation)
- α : fractions of absorbed photons
- δ : fractions of diffusely scattered photons
- ρ : fractions of specularly reflected photons
- $\mathbf{e}_D$ and $\mathbf{e}_N$: Sun direction and surface normal vector
- θ : angle between both vectors



2. Solar radiation pressure (SRP) models

• ECOM/ECOM2 model (in a Sun-oriented DYB frame)

- Nominal yaw steering attitude mode
 - D points toward the Sun
 - Y along the solar panel axis
 - B completes the right-handed system
- Orbit normal attitude mode
 - Y is perpendicular to the orbital plane
 - B is perpendicular to Y and Sun-satellite direction
 - D completes the right-handed system
- 5-parameter ECOM (Beutler et al. (1994), Springer et al. (1999))
 - Three constant parameters (D_0 , Y_0 , B_0) and two first-order Fourier coefficients (BC and BS) in the D, Y, B directions.
- ECOM2 (Arnold et al. (2015))
 - Three constant parameters (D_0 , Y_0 , B_0), two first-order (BC, BS), two second-order (D_2C , D_2S) and two fourth-order (D_4C , D_4S) Fourier coefficients in the D, Y, B directions.



ECOM2 model performs better than ECOM model in satellite orbit determination if a satellite has an elongated shape. Because SRP acceleration show periodical behavior due to the illumination of different surfaces. Higher order Fourier terms can compensate for this behavior fairly well.

2. Solar radiation pressure (SRP) models

- Box-wing + ECOM/ECOM2 model

- Advantage

- Periodical SRP accelerations can be partly or even mostly compensated by the box-wing model
- High order Fourier coefficients in the ECOM2 model might be not needed or at least can be constrained
- With less empirical parameters, correlations between parameters can be greatly reduced
- Estimates of geodetic parameters, for instance the geocenter coordinates and length of day are more free of SRP related errors.

- Consideration

- Metadata of satellites should be known with sufficient accuracy
- Other SRP related perturbations need to be considered as well

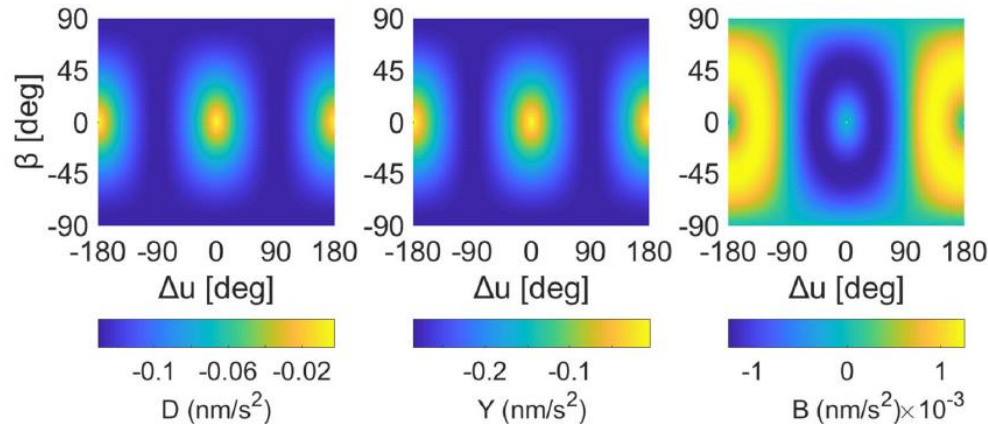
- This contribution

- Estimate satellite surface optical properties based on long time period true GNSS measurements
- Various physical effects such as yaw bias, radiator emission and thermal radiation, are considered in the adjustment

3. Box-wing parameter adjustment considering physical effects

- Yaw bias

- Yaw bias can be caused by a solar sensor bias and is a function of the elongation angle
- Satellite body frame is rotated by the yaw bias around the Z-axis
- It is widely known that GPS Block IIA satellites have an artificial yaw bias of +0.5 deg. However, the impact on SRP acceleration is only about -0.15 nm/s^2 as only δ and ρ cause accelerations in the direction of $\mathbf{e}_N$ (normal vector of satellite surfaces)

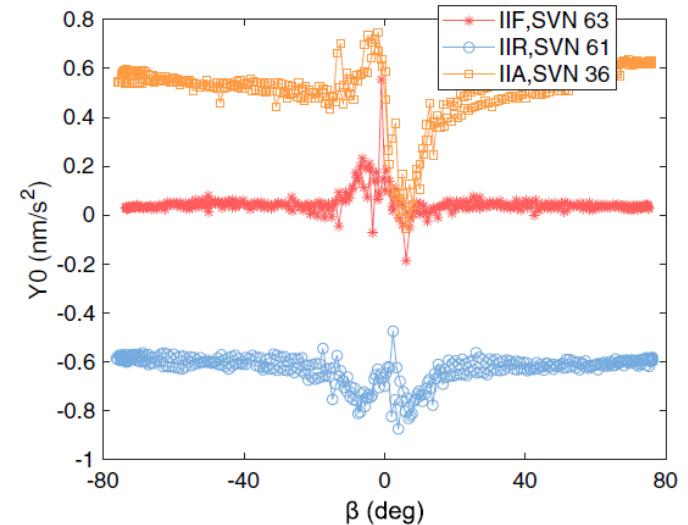


Duan et al. (2021)

3. Box-wing parameter adjustment considering physical effects

- Radiator emission

- Radiator emissions are usually directed by the thermal control system, for instance by louvers, heat pipes and optical solar reflectors. To make radiators more efficient, it is best not to illuminate them. For instance in the $-X$ or $\pm Y$ surfaces.
- The right figure shows the ECOM Y0 estimates over one year as a function of β angle (Sun elevation above orbital plane)
- Consider the yaw bias of $+0.5$ deg for GPS Block IIA satellites, it seems that the radiator emission dominates the Y-bias
- This is the same for Block IIR satellites, while the Block IIF satellites show nearly zero Y0 estimates. The radiator emissions could be balanced on both $\pm Y$ surfaces
- The anomalies inside eclipse seasons indicate that radiator emissions contribute inside shadows as well



Duan et al. (2021)

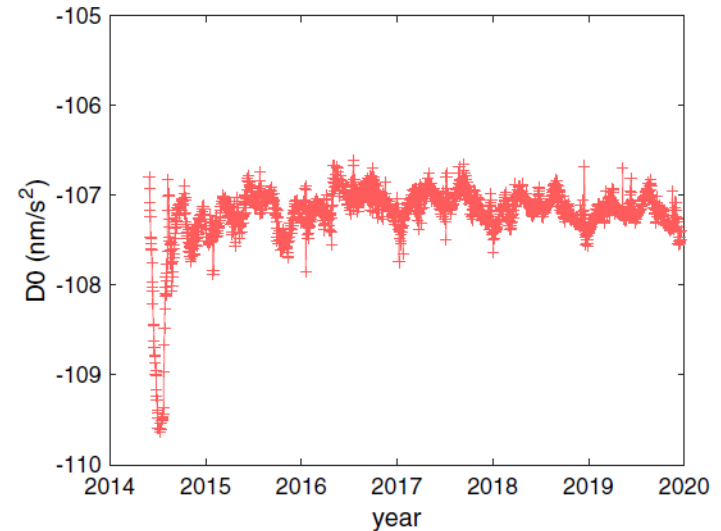
3. Box-wing parameter adjustment considering physical effects

- Outgassing effect

- Soon after arriving in orbit, the satellite is affected by the emission of the gas that is incorporated inside some materials, for instance solar panels, apogee engine, satellite body and Multilayer insulation.
- The right figure shows the ECOM D0 estimates over six years for one GPS Block IIF satellite since it was launched in June 2014
- It is clear that the outgassing effect lasts about half a year after the launch of the satellite. The largest effect reaches up to 2 nm/s²



- All these physical effects are considered in the box-wing parameter adjustment



Duan et al. (2021)

3. Box-wing parameter adjustment considering physical effects

- Box-wing parameter adjustment

- We estimate surface optical properties ($\alpha + \delta$ and ρ) while fixing surface dimensions and total mass of a satellite to the given values, based long time true GNSS measurements.

$$\mathbf{acc} = -\frac{A}{M} \frac{S_0}{c} \cos \theta \left[\boxed{\alpha + \delta} \mathbf{e}_D + \left(\frac{\pi}{6} s + \frac{2}{3} (1-s) \right) (\delta + \kappa \alpha) \mathbf{e}_N + \left(\frac{4}{3} s + 2(1-s) \right) \boxed{\rho} \cos \theta \mathbf{e}_N \right] - \boxed{\mathbf{R}} \mathbf{e}_N$$


Two sets of optical parameters to be estimated for each satellite body surface, Radiator acceleration

- $\alpha + \delta$ and ρ in +X and $\pm Z$ surfaces
- ρ in solar panels to model the thermal radiation effect
- Radiator accelerations in $-X$ and $+Y$ surfaces
- Yaw bias
- Solar panel rotation lag

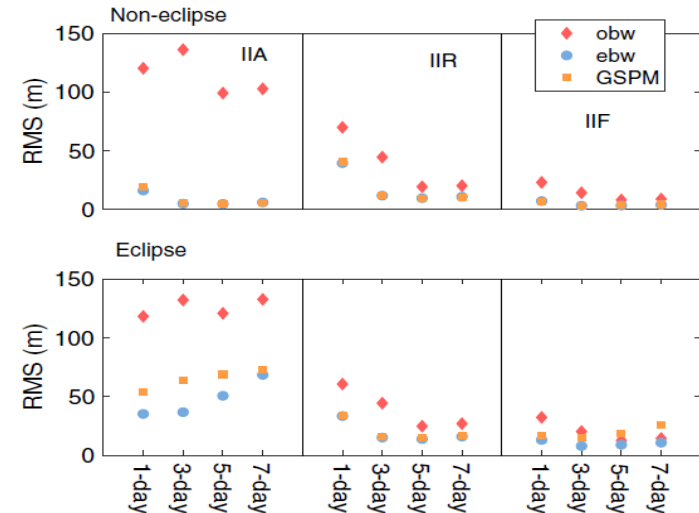


- 1) In total 11 box-wing parameters for each satellite
- 2) Daily normal equations are stacked after pre-eliminating all but the box-wing parameters
- 3) Satellite specific solutions are averaged as Block specific solutions

4. Validation of box-wing parameters

• Orbit prediction (GPS as an example)

- We evaluate box-wing parameters by using an orbit prediction over 5 days. The prediction is based on 1 day, 3 days, 5 days and 7 days of CODE final precise orbit products. Only the constant ECOM Y0 parameter is employed in the orbit fitting
- The predicted orbits of the 5th day are compared to the CODE final orbits of the same day
- The prediction procedure is shifted day-by-day over a time period of 6 months and we compute the mean 3D position RMS of orbit differences
 - obw, original box-wing model
 - ebw, enhanced box-wing model considering all the physical effects (✓ better performance than other two)
 - GSPM, our own estimates of GSPM parameters considering no eclipsing data. Therefore, results inside eclipse seasons are not optimized.

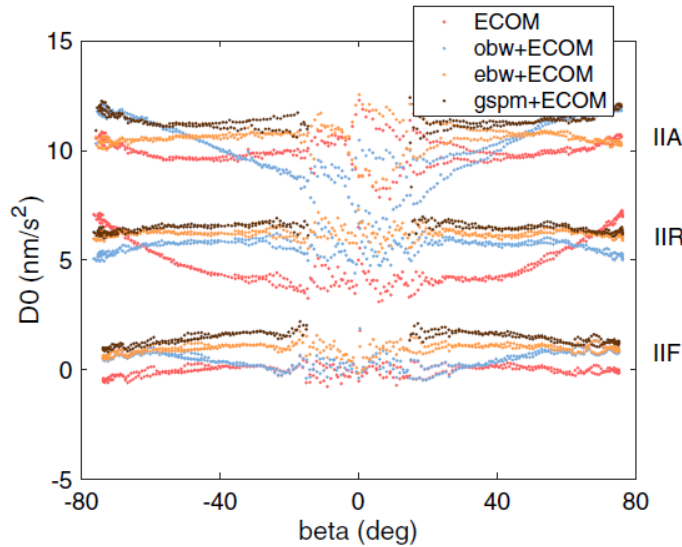


Duan et al. (2021)

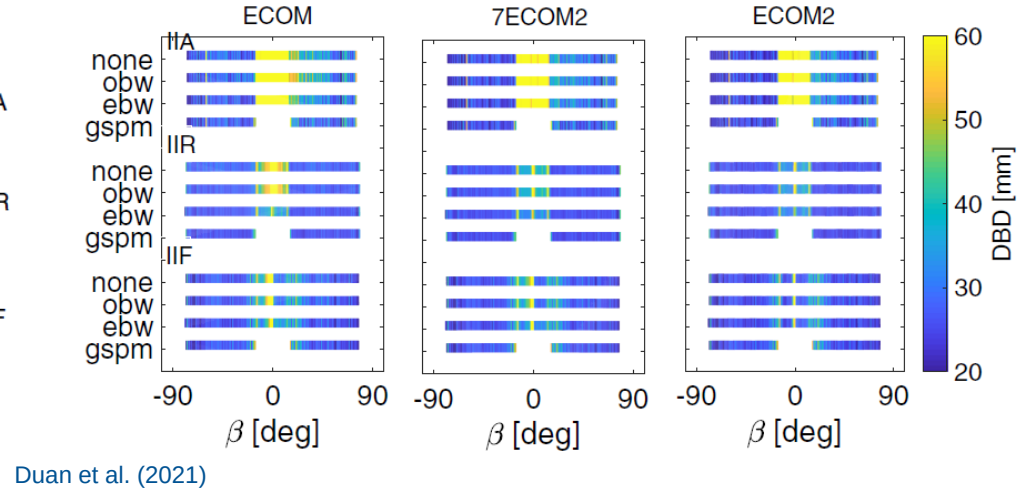
5. Performances in satellite POD

- GPS

ECOM D0 estimates



3D orbit misclosures



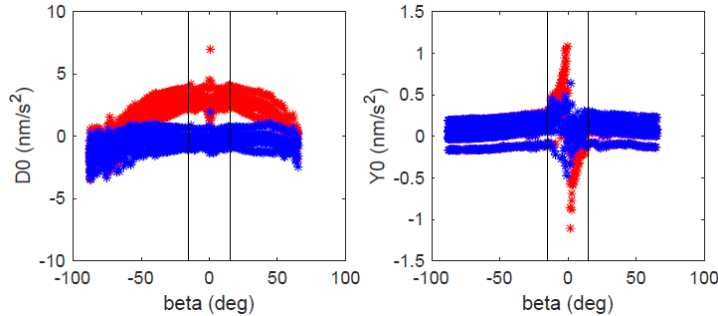
Duan et al. (2021)

- RMS values of ECOM estimates are reduced by 30% compared to results without the a priori model
- The ebw+ECOM model improves orbit misclosures by about 25% and 10% for the eclipsing Block IIR and IIF satellites than the ECOM solutions

5. Performances in satellite POD

• GLONASS

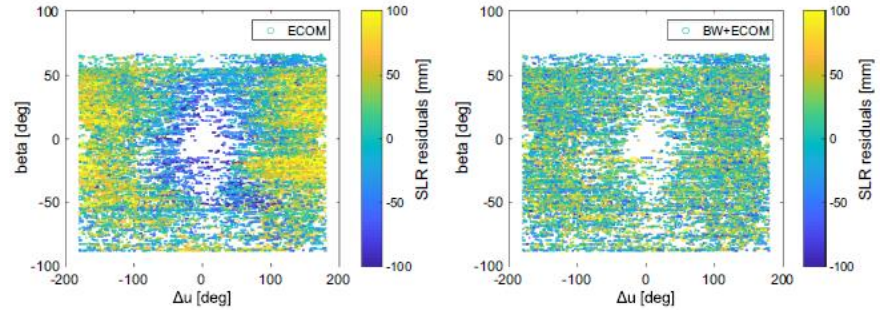
ECOM D0 and Y0 (red--ECOM, blue--BW+ECOM)



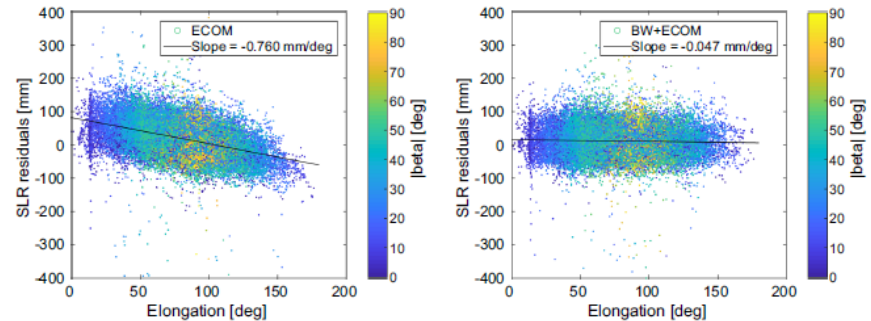
Duan et al. (2020)

- BW+ECOM results in more constant D0 and Y0. Radiator effect causes anomalies in the Y0 during eclipse seasons and this is well solved by the a priori box-wing model.
- Dependencies of SLR residuals on $\beta/\Delta u$ and elongation angle are greatly reduced by using the a priori box-wing model

SLR residuals



Duan et al. (2020)



5. Performances in satellite POD

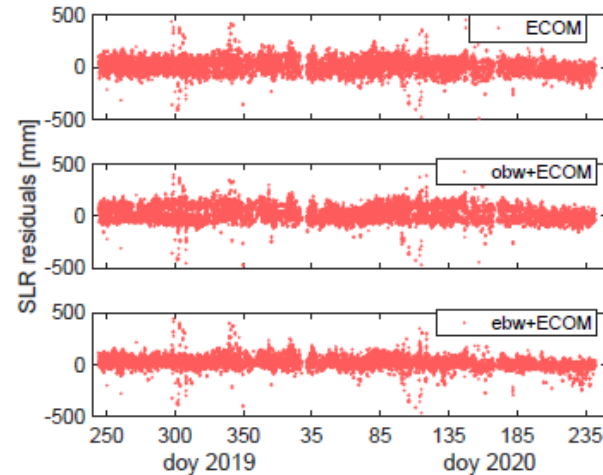
- BeiDou (preliminary results)

- 1) There are clear radiator emissions estimated for BeiDou-3 MEO CAST satellites
- 2) BeiDou-3 MEO CAST satellites seem to have different sub-groups according to our adjustment
- 3) BeiDou-3 MEO SECM satellites show much smaller yaw bias estimates than BeiDou-3 MEO CAST satellites
- 4) Two SECM satellites seem to have higher thermal radiation of solar panels or much smaller mass than the published value

...

- 5) We are preparing a paper for all these details

- The ebw+ECOM model shows clearly better SLR residuals for all the BeiDou-2/3 satellites that have SLR measurements. For instance, the improvement of STD value for BDS3-CAST satellites is about 20%.



6. Summary and conclusion

- Optical parameters of GPS, GLONASS and BeiDou satellites are adjusted considering various physical effects, such as yaw bias, radiator emission, thermal radiation and outgassing effect.
- The radiator emissions for GPS Block IIA and IIR satellites in fact dominate the ECOM Y0 estimates. This radiator effects exist as well inside shadows
- There is a radiator acceleration of about 1 nm/s^2 in the $-X$ surface for GLONASS-M satellites, which corresponds to an emission power of about 430 W
- There are clear radiator emissions estimated for BeiDou-3 MEO CAST satellites
- BeiDou-3 MEO CAST satellites seem to have different sub-groups according to our adjustment
- BeiDou-3 MEO SECM satellites show much smaller yaw bias estimates than BeiDou-3 MEO CAST satellites
- Two SECM satellites seem to have higher thermal radiation of solar panels or much smaller mass than the published value
- ...
- More detailed results about BDS satellites will come soon in a paper

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