Space vehicle radiation pressure modelling: A demonstration on Galileo satellites in GNSS

Zhen Li

Space Geodesy and Navigation Laboratory

University College London

Shanghai Astronomical Observatory, 19th Feb 2019

Orbit modelling for long-term prediction

Project aims

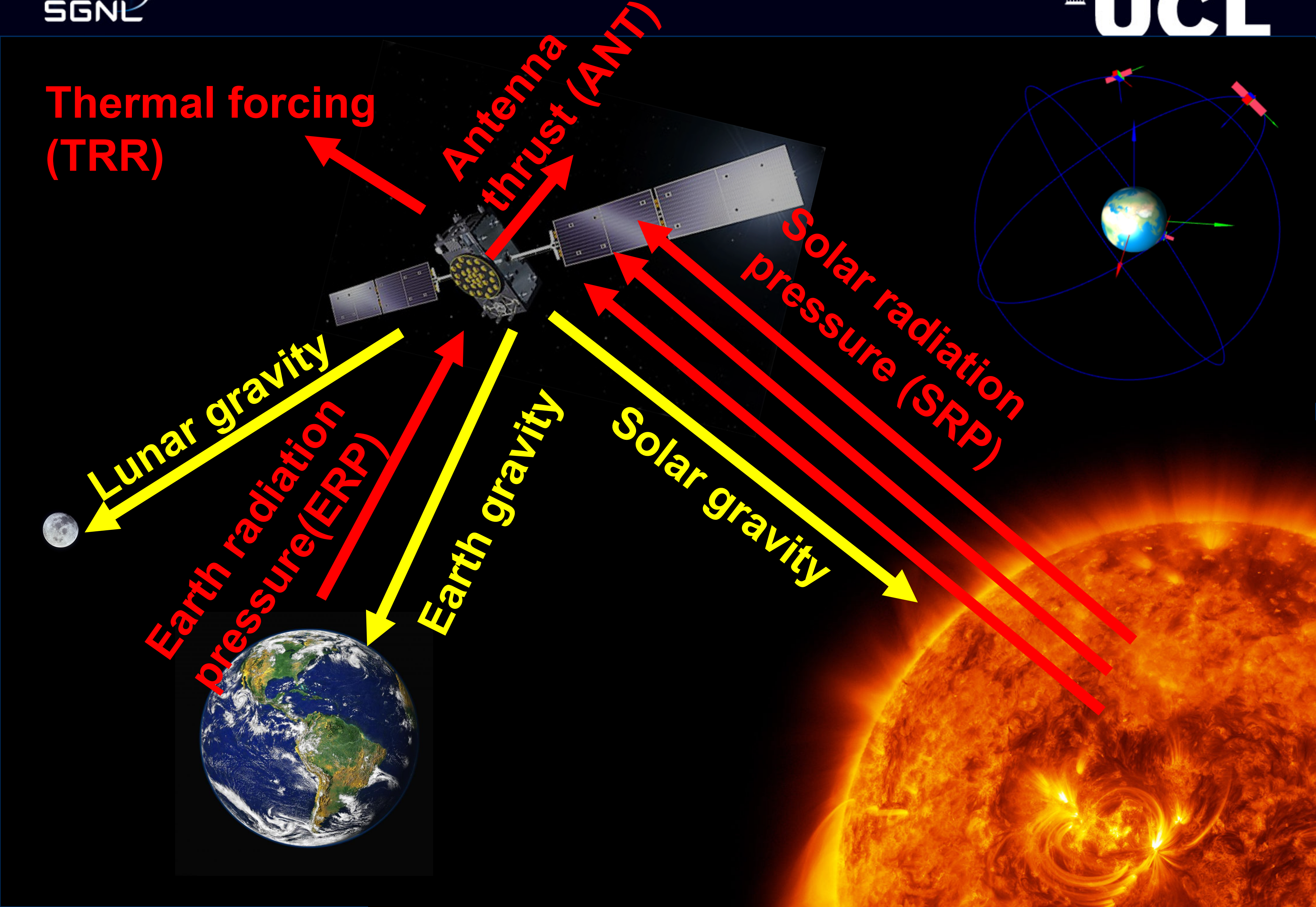
- 1 cm accuracy Galileo precise orbit determination
- 2 cm accuracy orbit prediction over 1 day
- Decimetre level prediction accuracy over 14 days

Orbit modelling for long-term prediction

Two groups

GMV – project management
Positim – orbit prediction/orbit determination analysis
UCL – SRP force modelling

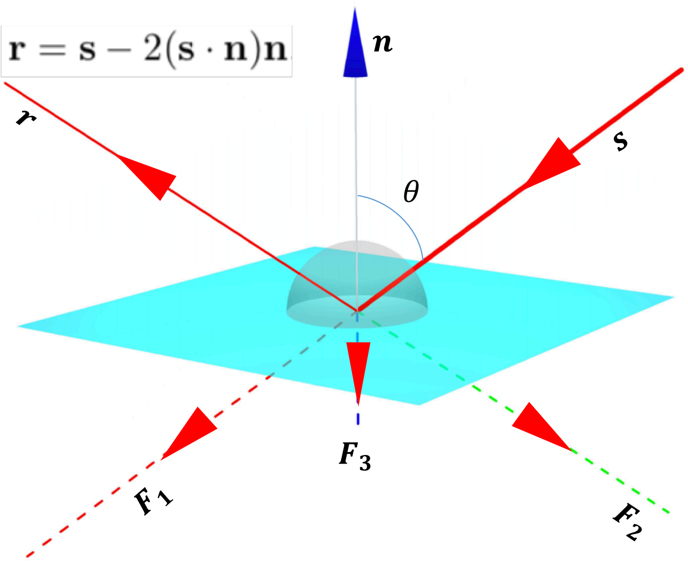
Airbus Defense and Space – prime contractor
University of Bern – sub-contractor for test scenario and accuracy performance validation



Thermal forcing (TRR)
Antenna thrust (ANT)
Solar radiation pressure (SRP)
Lunar gravity
Earth radiation pressure(ERP)
Earth gravity
Solar gravity

Radiation pressure

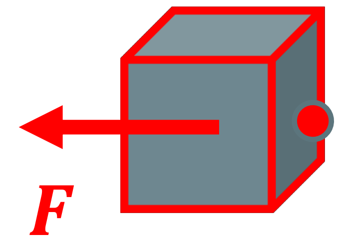
$$\mathbf{r} = \mathbf{s} - 2(\mathbf{s}\cdot\mathbf{n})\mathbf{n}$$



- Momentum of a photon

$$p = \frac{hf}{c}$$

Conservation of momentum



$$\frac{N_f hf}{c}\mathbf{n} + \Delta\mathbf{p}_f = 0$$

$$\mathbf{F} = -\frac{WA}{c}\mathbf{n}$$

$$\frac{N_f hf}{c}\mathbf{s} = \nu_f\mu_f\frac{N_f hf}{c}\mathbf{r} + \frac{2}{3}\nu_f(1-\mu_f)\frac{N_f hf}{c}\mathbf{n} + \Delta\mathbf{p_f}$$

$$\mathbf{F} = \frac{WA\cos\theta}{c}\left\{\mathbf{s} - \nu\mu\mathbf{r} - \frac{2}{3}\nu(1-\mu)\mathbf{n}\right\}$$

Problems in radiation pressure modelling

- Solar radiation flux during eclipse
- Earth radiation flux
- Antenna radiation power
- Thermal radiation flux

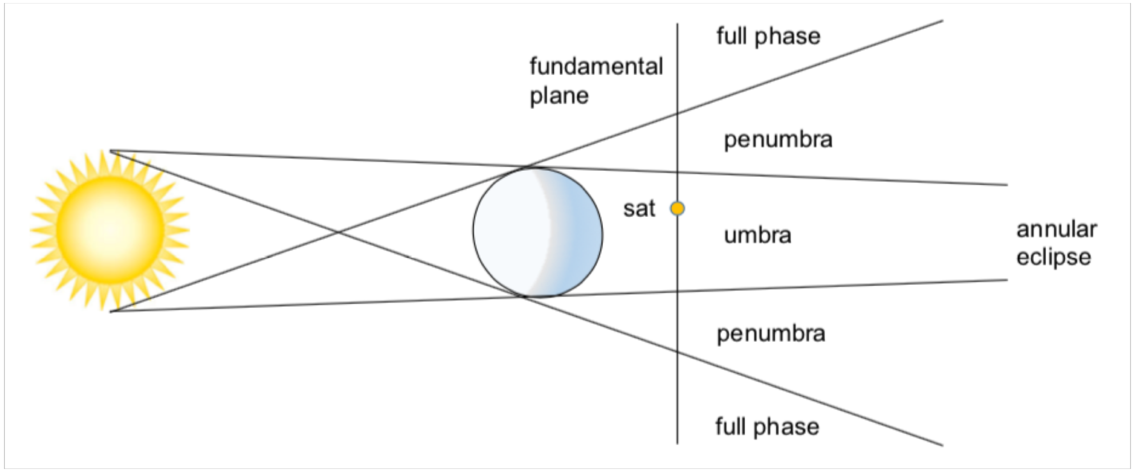
Radiation flux modelling

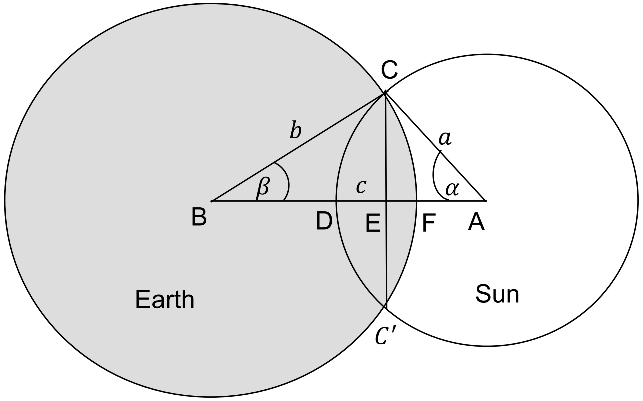
- Satellite attitude
- Interaction between radiation flux and satellite
- Satellite surface optical properties

How flux interacts with satellite's surface

Shadow function modelling (PPM_atm)

A scalar to describe how much solar radiation flux is reduced during penumbra

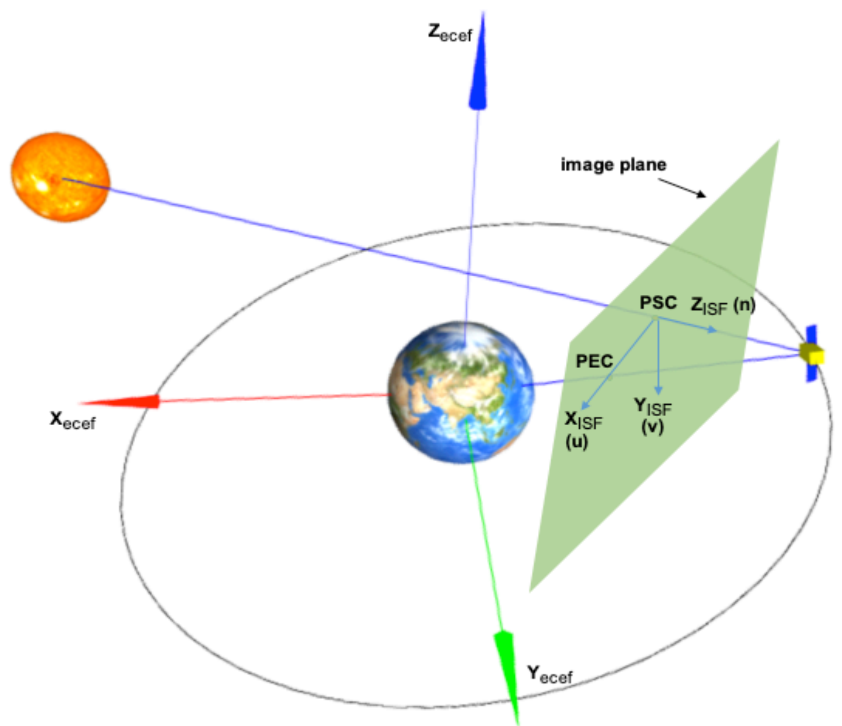


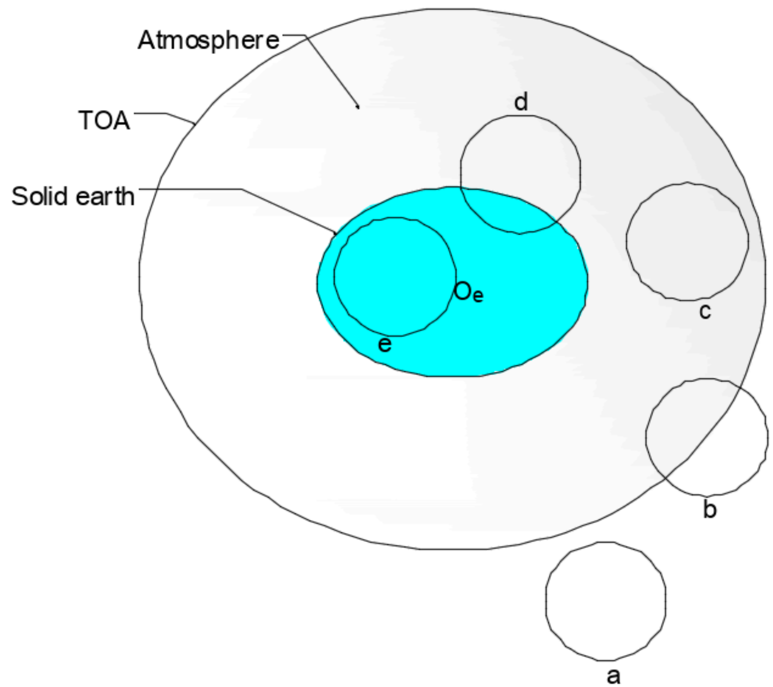


- **Earth's oblateness----Geometrical problem**
- **Atmospheric effects----Physical problem**

Shadow function modelling

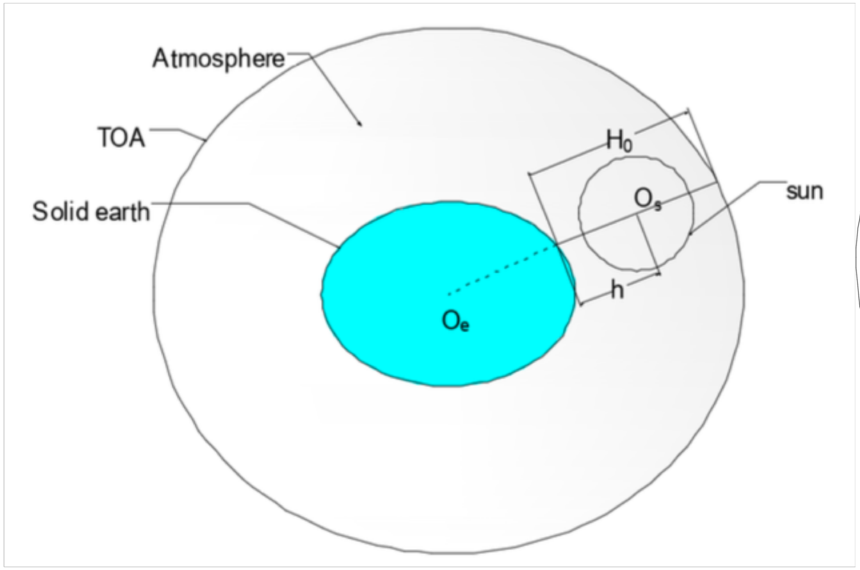
Perspective projection to tackle Earth's oblateness



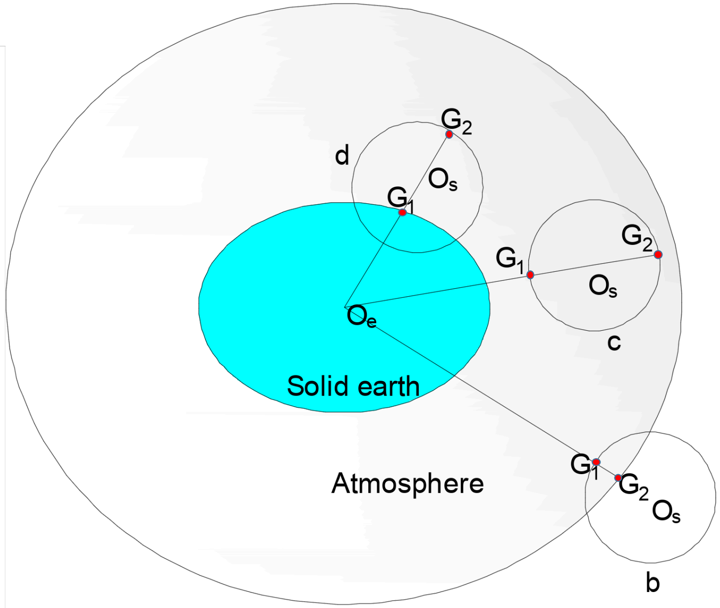


Shadow function modelling

Radiation reduction function to tackle Atmospheric effects



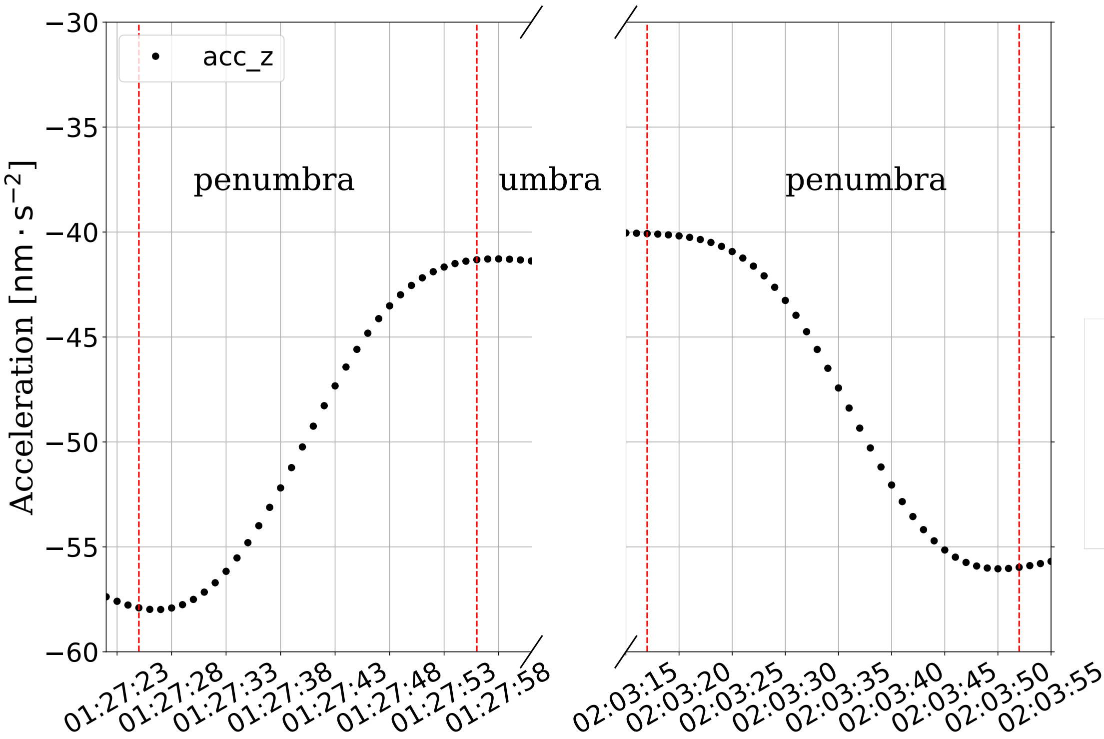
$$f(h) = (\mu_2 - \mu_1)\frac{h}{H_0} + \mu_1$$



$$f(h_G) = \frac{f(h_{G_1}) + f(h_{G_2})}{2}$$

Shadow function modelling----validation

GRACE-A accelerometer observations

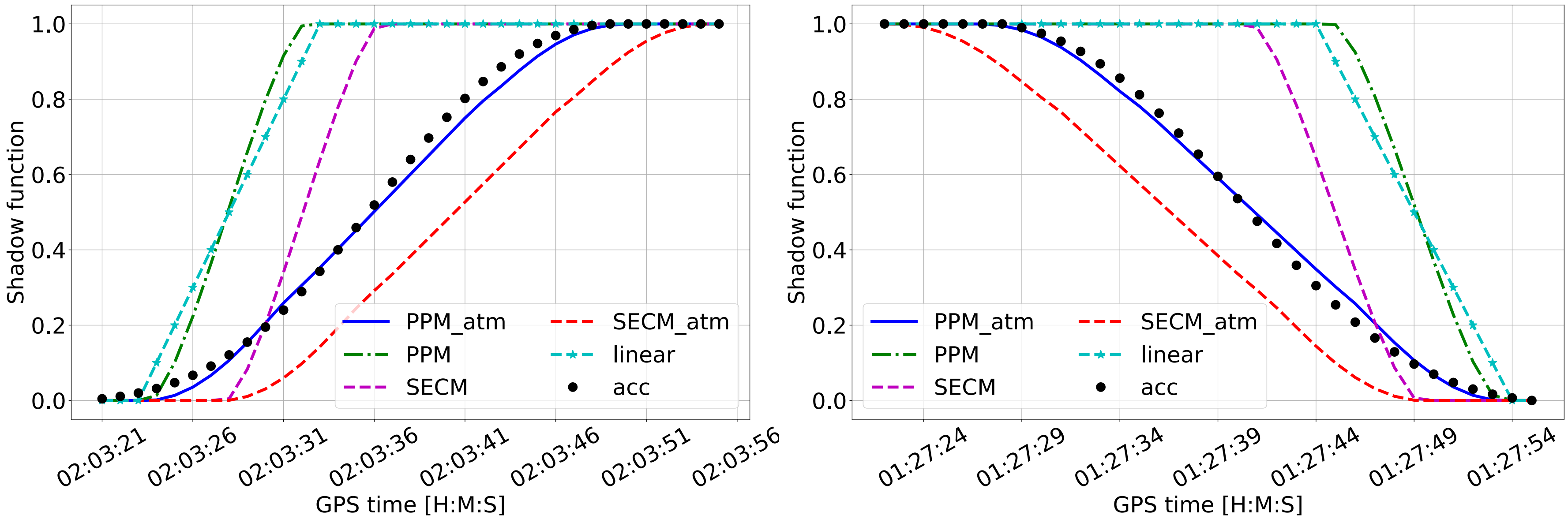


Acceleration derived shadow function $F_{s,acc}$

$$F_{s,acc} = \frac{\zeta_t - \zeta_0}{\zeta_1 - \zeta_0}$$

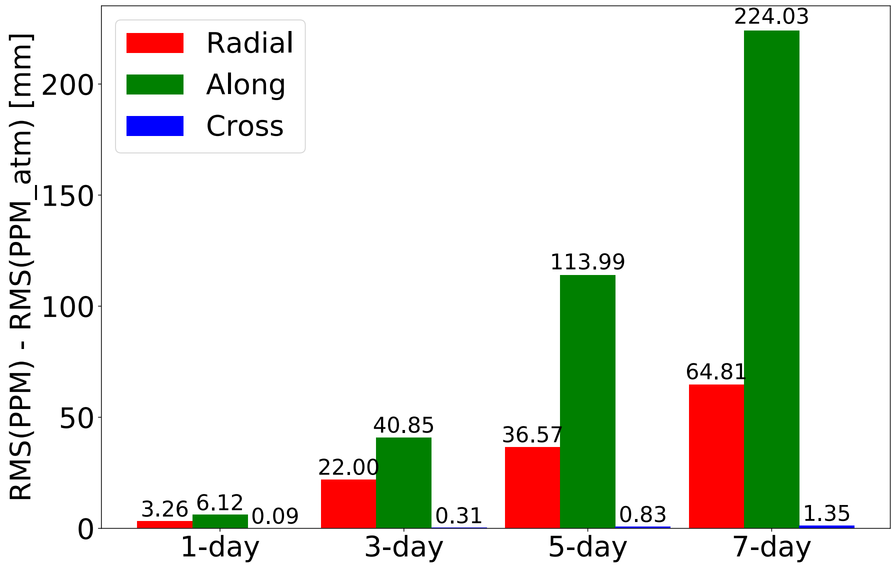
Shadow function modelling----validation

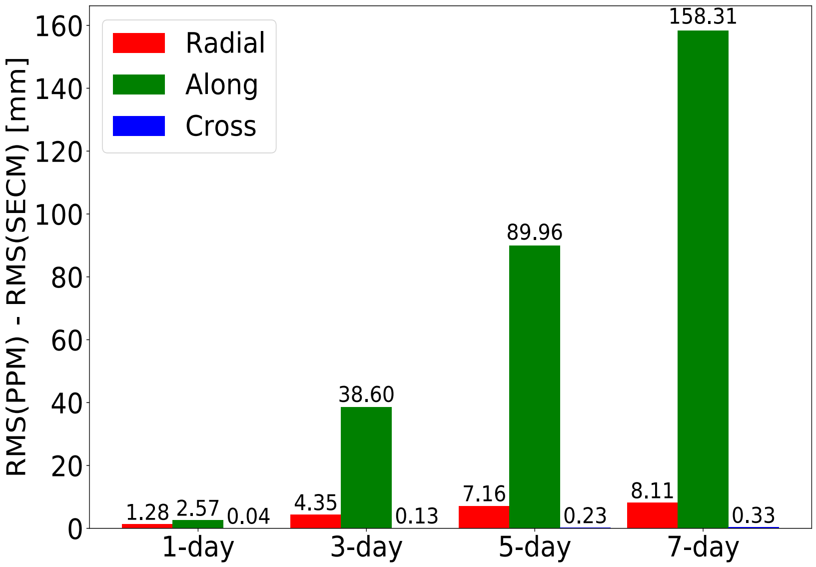
Comparison between different shadow function models



Shadow function modelling----orbit prediction

Galileo IOV satellites orbit prediction





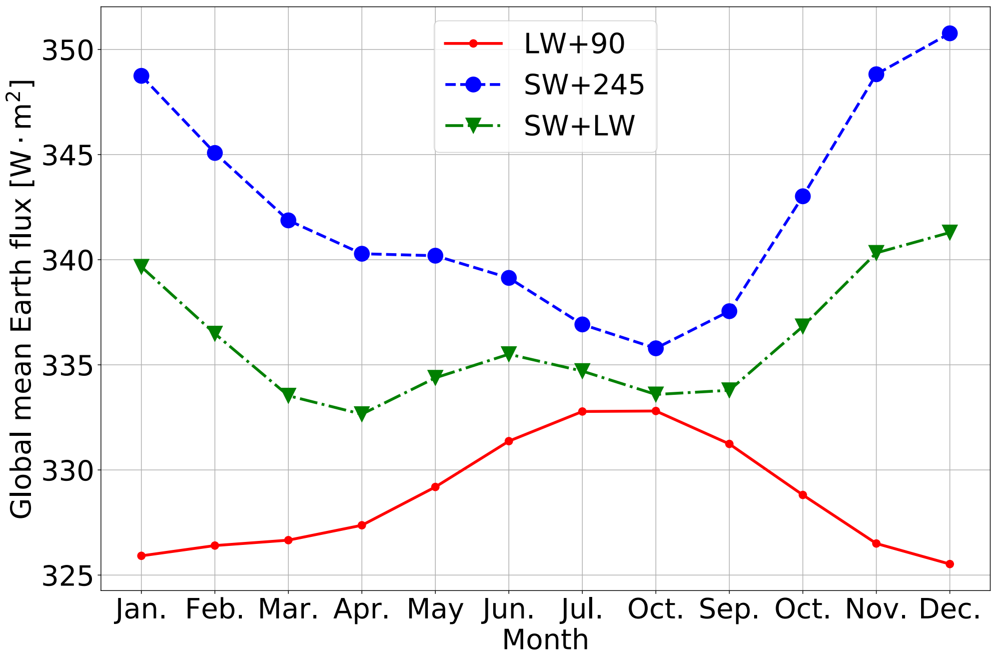
Atmospheric effects

Earth’s oblateness

Impacts are significant for long-term prediction

Earth radiation flux modelling

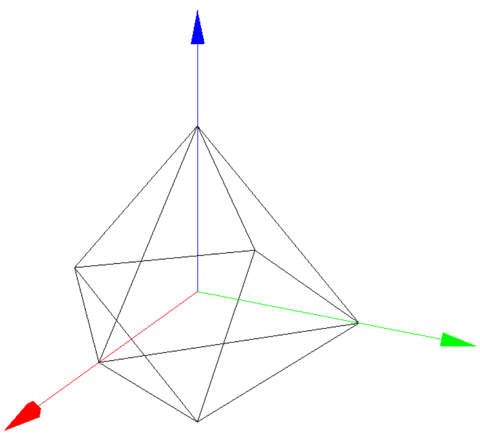
CERES Earth radiation flux observations



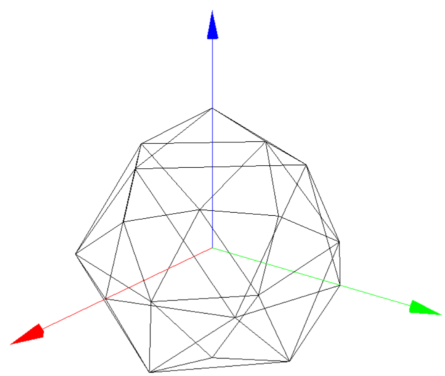
- Based on 1° by 1° grid
- Slow in searching visible area to satellites

Earth radiation flux modelling

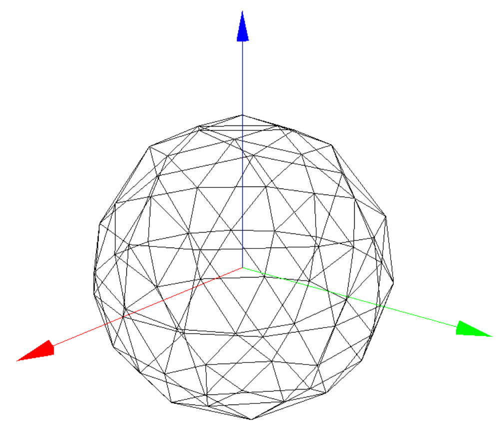
Divide TOA into different levels of triangular mesh



Level 0

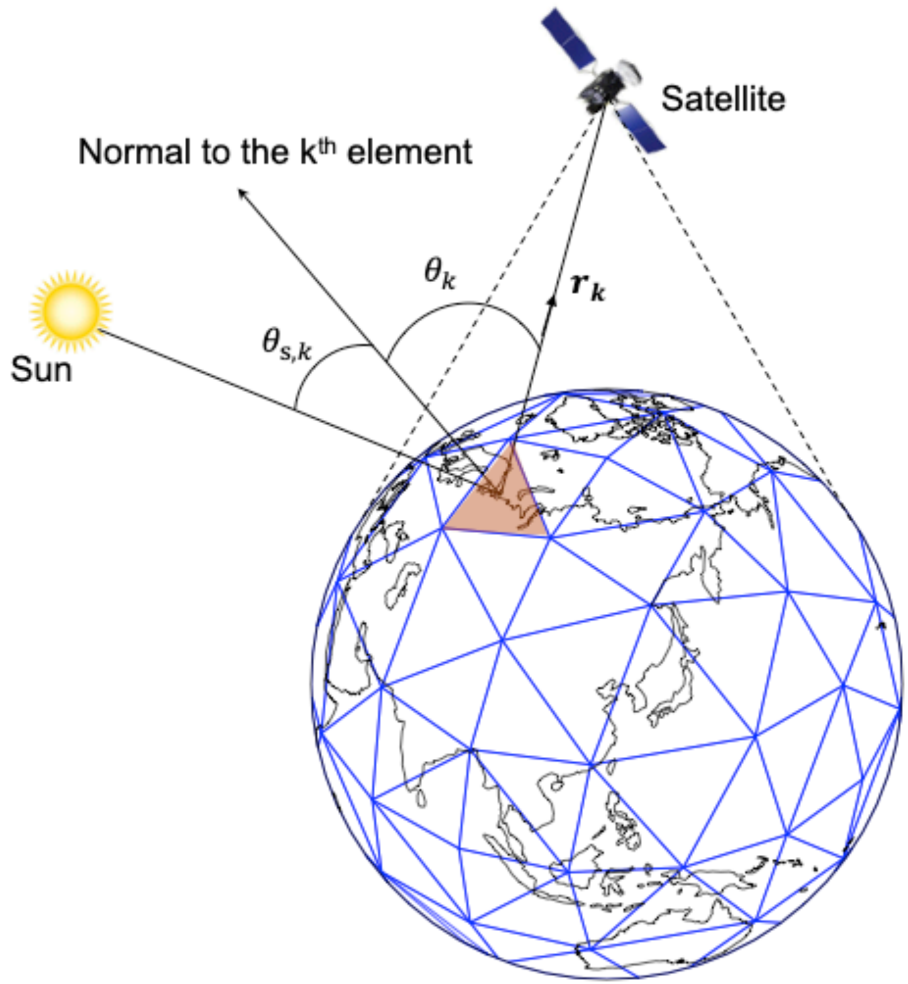


Level 1



Level 2

Earth radiation flux modelling

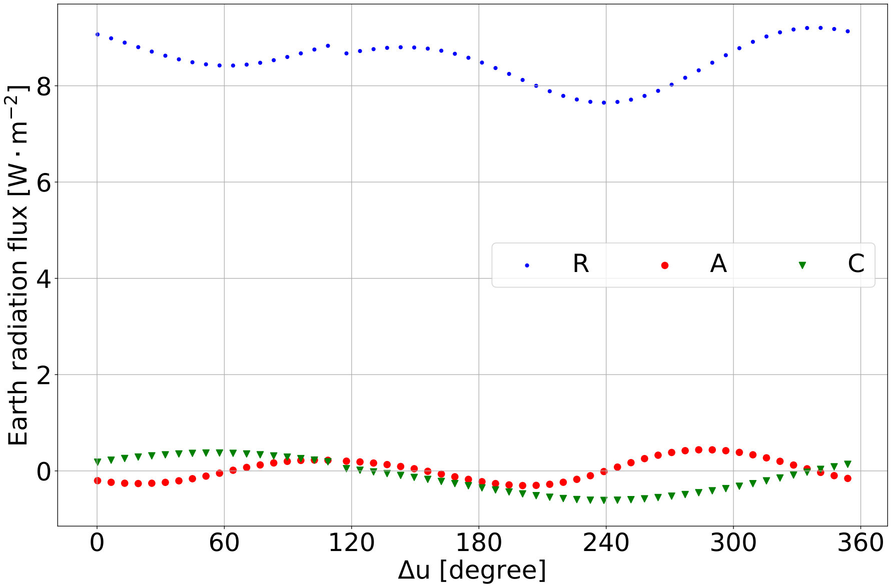


Check the visibility to the satellite

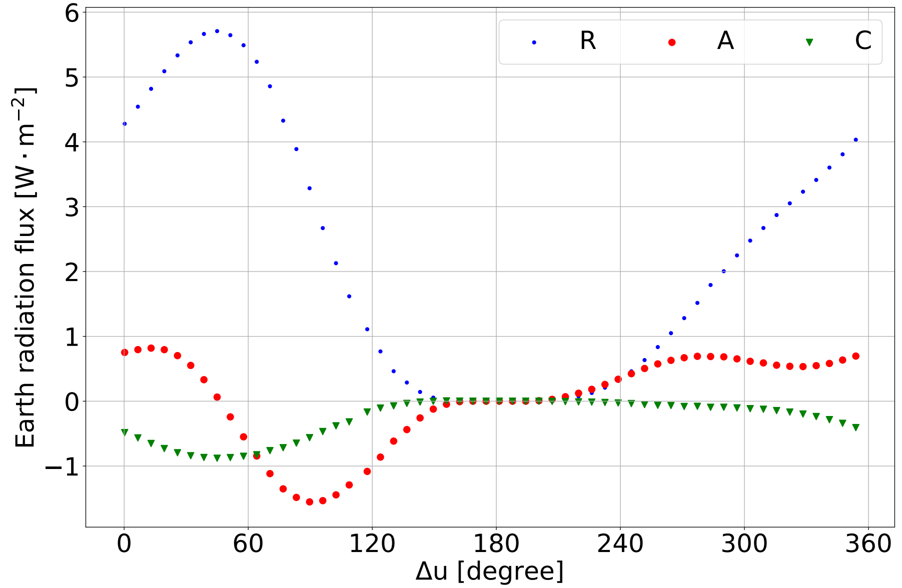
$$\begin{cases} \theta_{s,k} < \dfrac{\pi}{2} & \text{SW+LW} \\ \theta_k < \dfrac{\pi}{2} & \text{Only LW} \end{cases}$$

Earth radiation flux modelling

Earth radiation flux at a Galileo IOV satellite's location



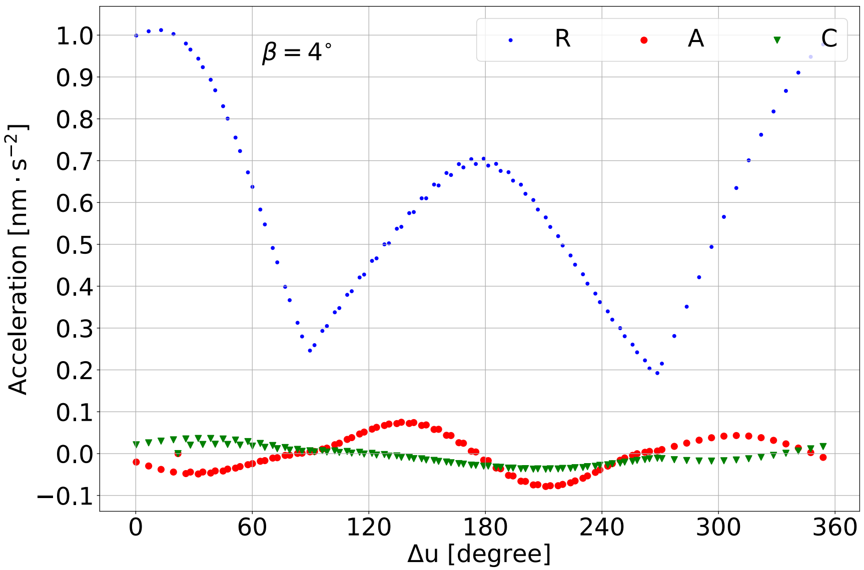
Longwave



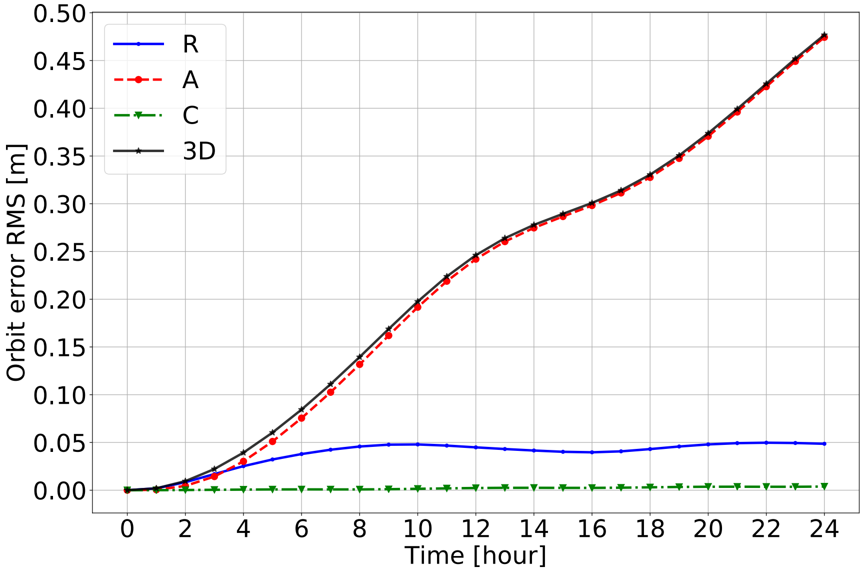
Shortwave

Earth radiation flux modelling

ERP acceleration and impacts to orbit

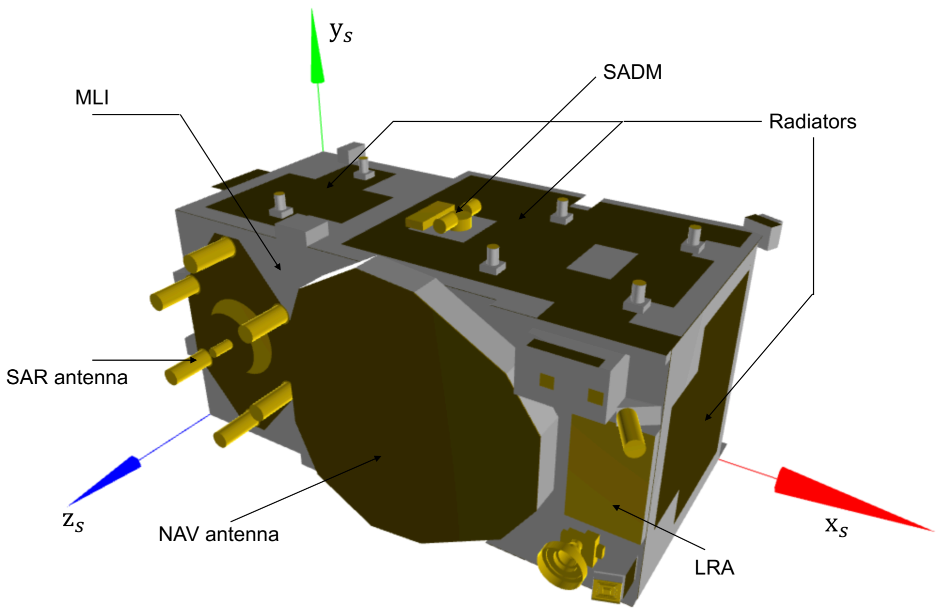


ERP acc

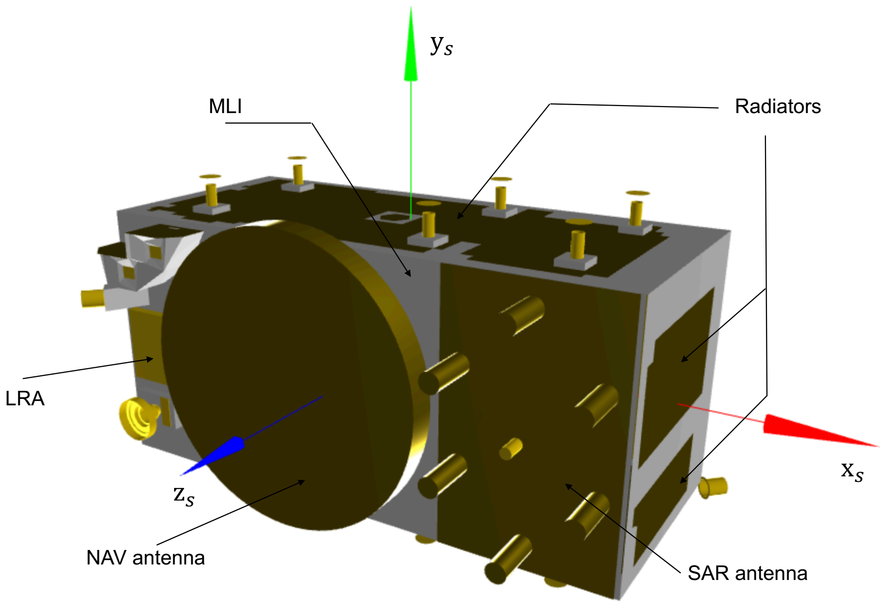


Orbit error RMS

Satellite 3D models and ray tracing

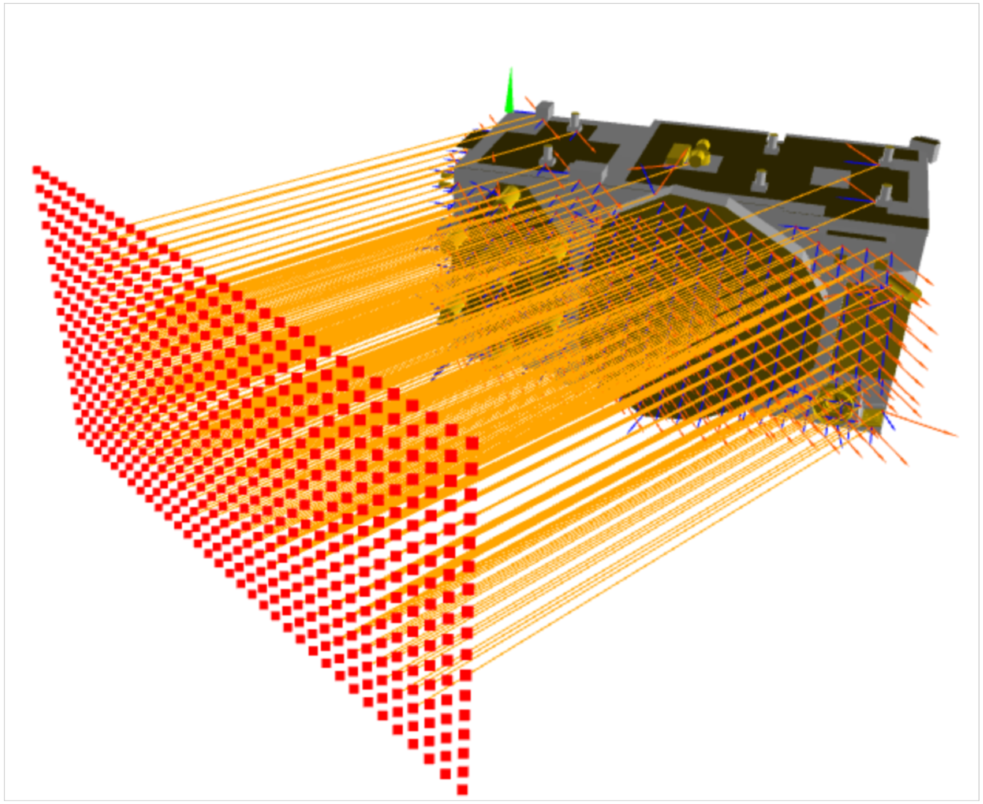


IOV satellite Bus



FOC satellite Bus

Satellite 3D models and ray tracing

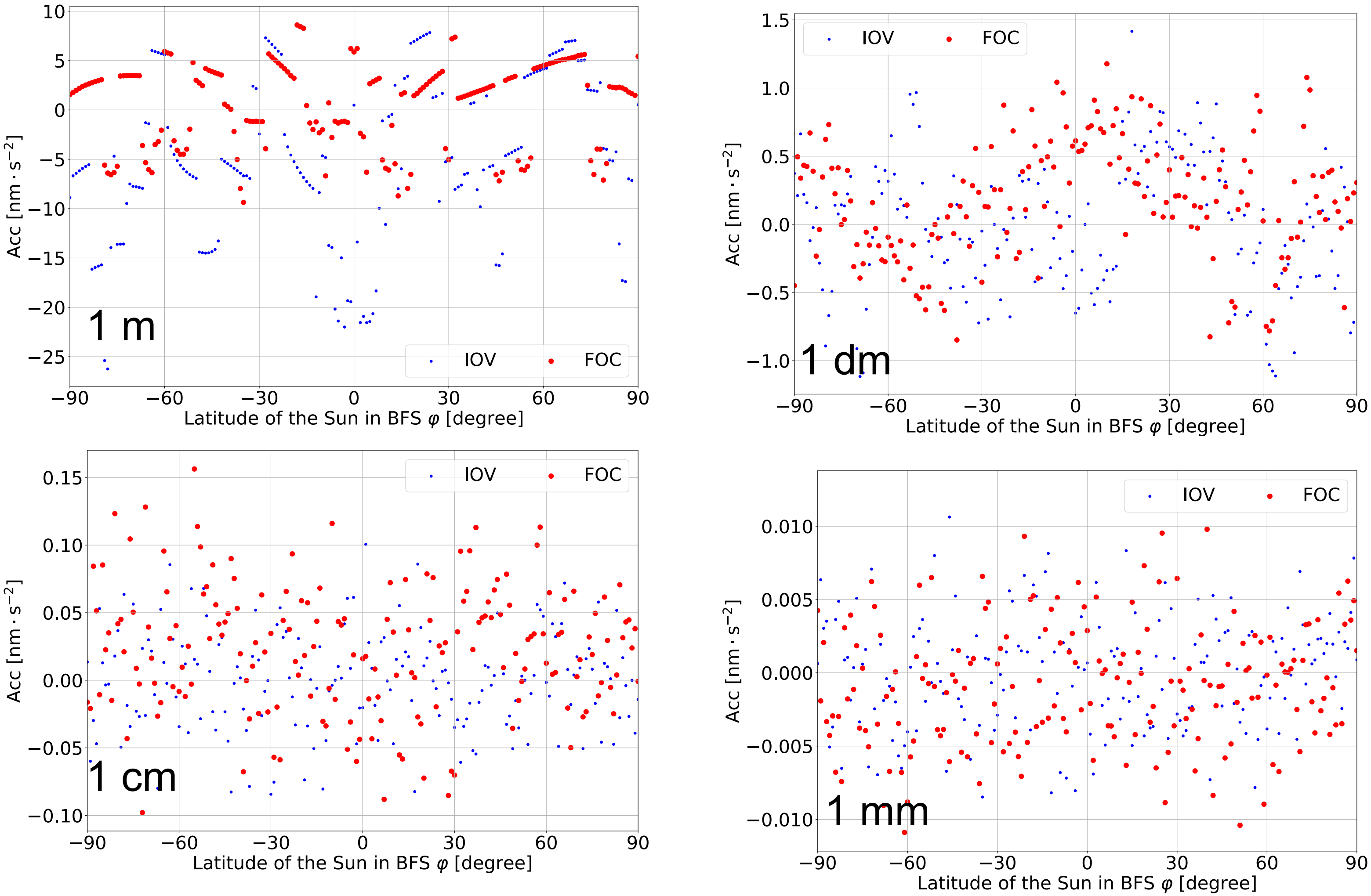


Steps

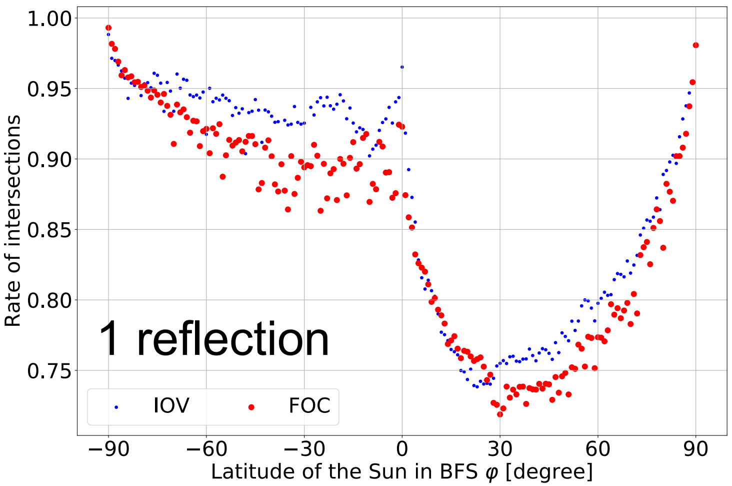
- Generate a pixel array
- Simulate rays
- Compute intersections
- Compute surface normal
- Compute reflection vectors
- Compute force for each intersection and add up

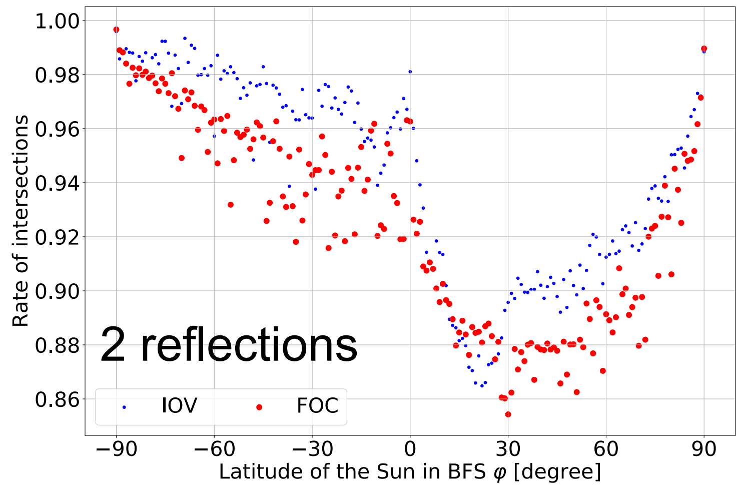
Ray tracing show

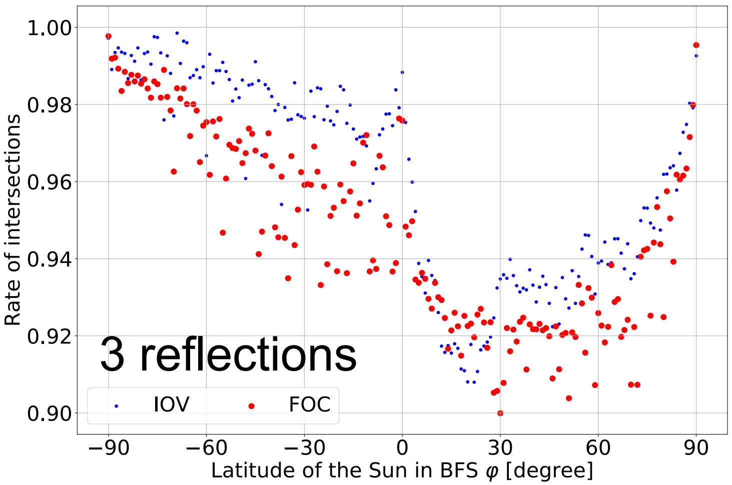
Ray tracing parameters---- pixel size

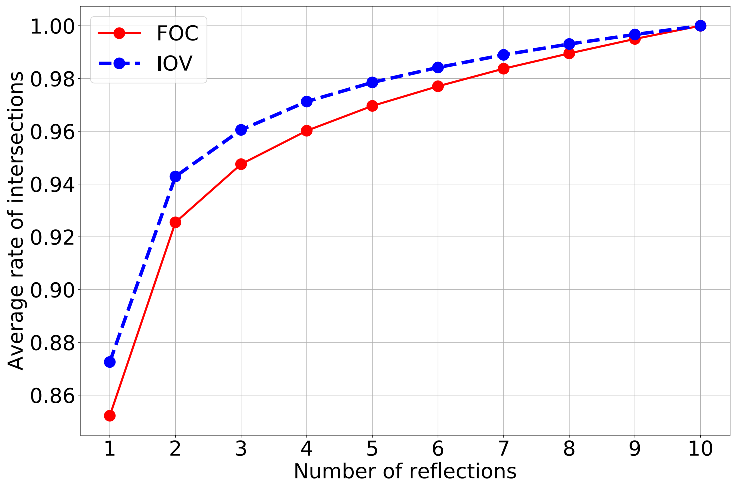


Ray tracing parameters---- maximum reflections

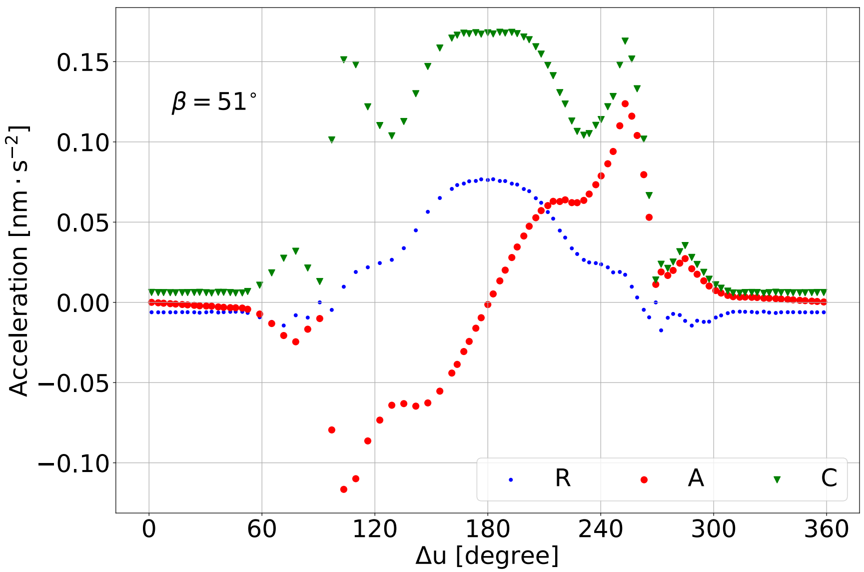


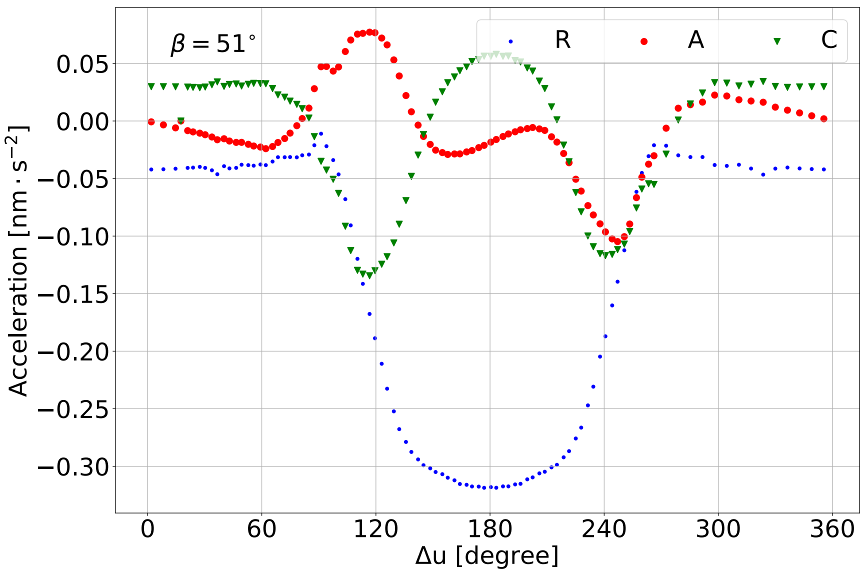






Ray tracing----multiple reflections

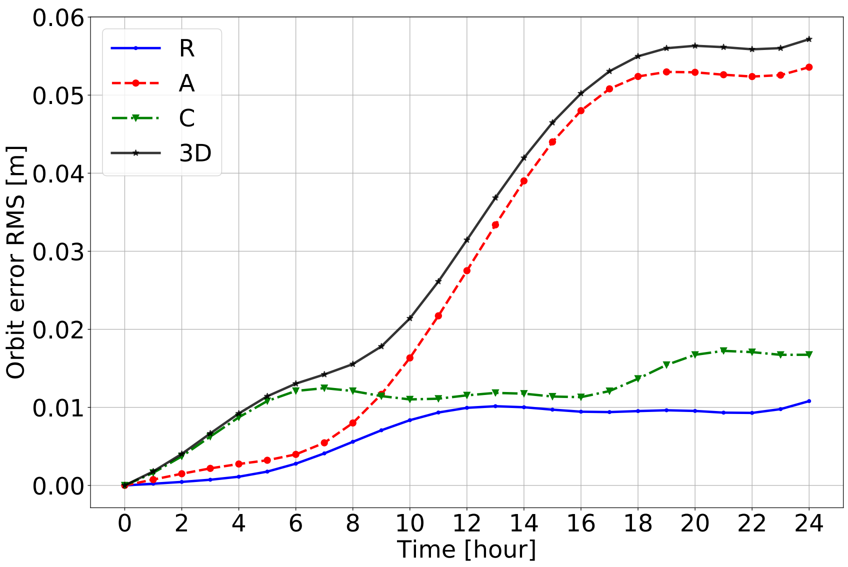




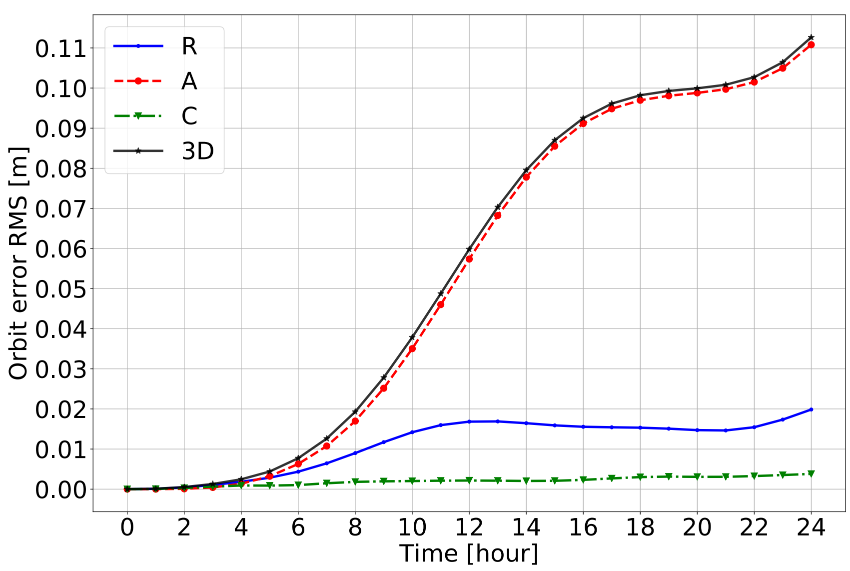
IOV satellite

FOC satellite

Ray tracing----multiple-reflection impacts to orbit



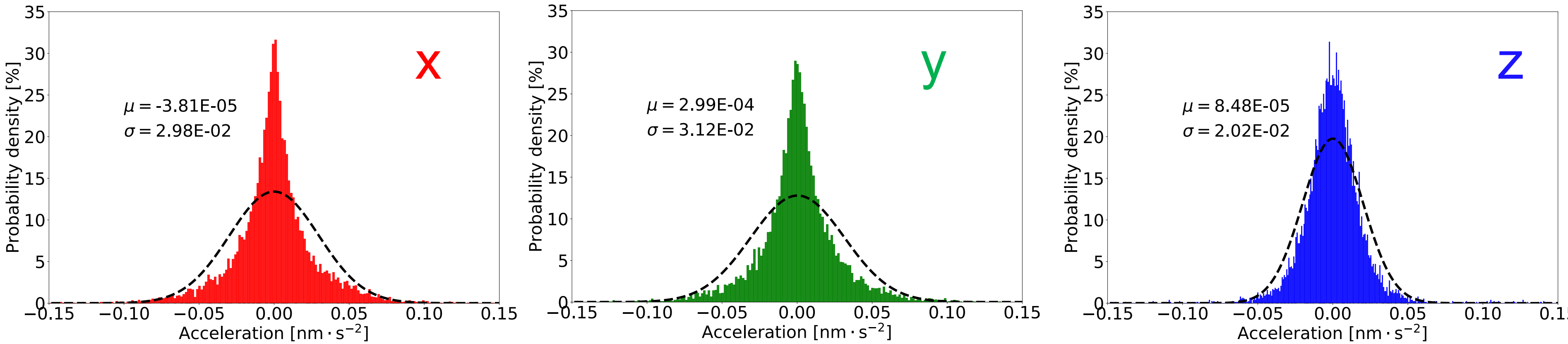
IOV satellite



FOC satellite

Ray tracing---- user algorithm

- Grid files contain all the possible directions of flux to cope with different attitude
- Grid files are pre-computed on high performance computers
- Users only do bilinear interpolation with flux direction



Empirical representation of SRP (DREMT)

Model characteristics

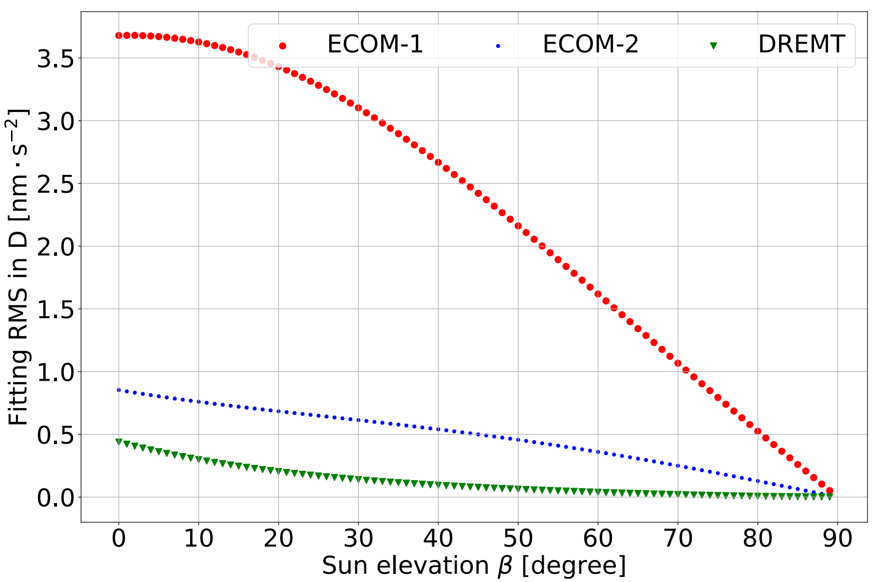
- Nominal attitude
- Box-wing model (SRP+TRR)
- Empirical looking but physics based
- Parameters have physical meanings
- Expressed in DYB and used as simple as ECOM

φ: the latitude of Sun in BFS

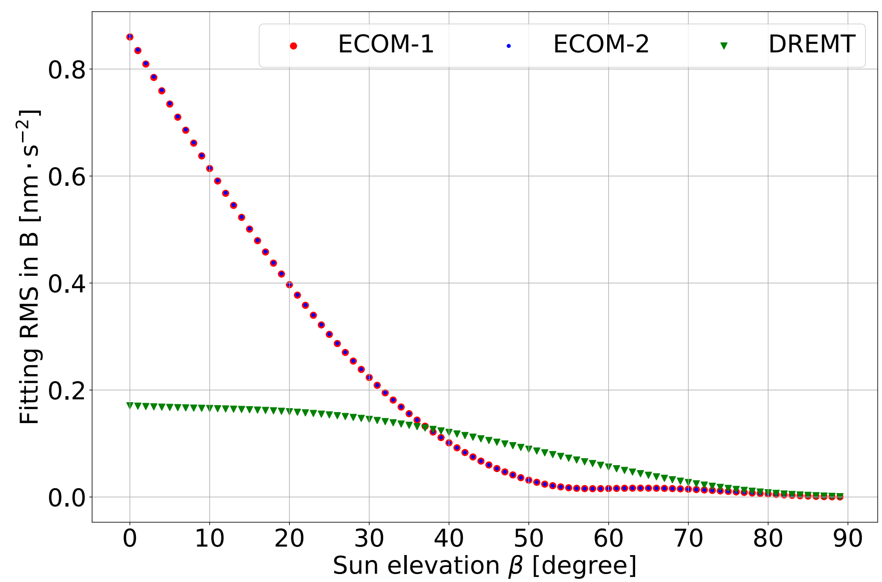
$\Delta\mu$: the angle from the satellite to the Sun in orbital plane

X_1, X_2, X_3, X_4, X_5, X_6: parameters to estimate

Empirical models fitting to ray tracing grids



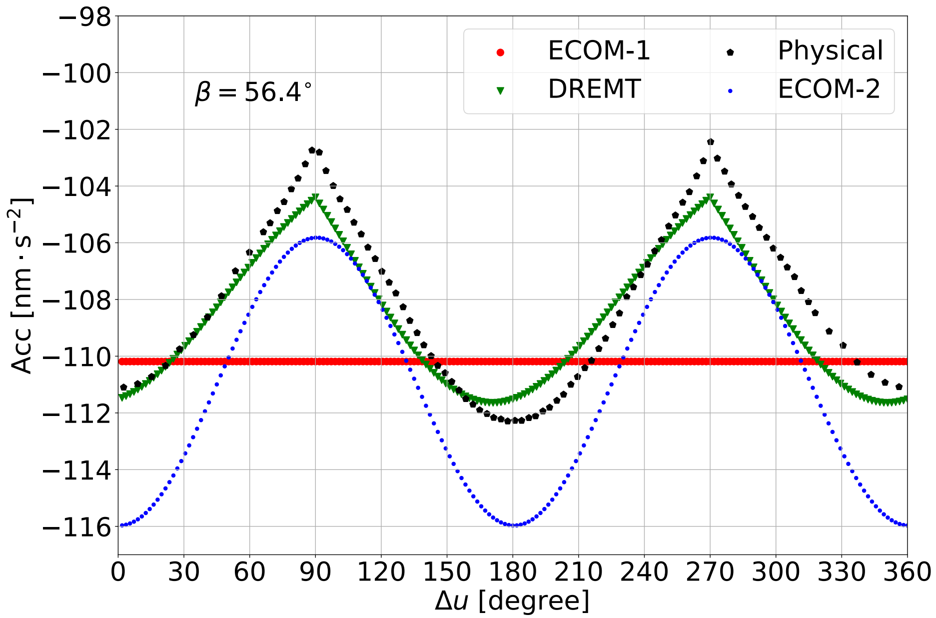
D component



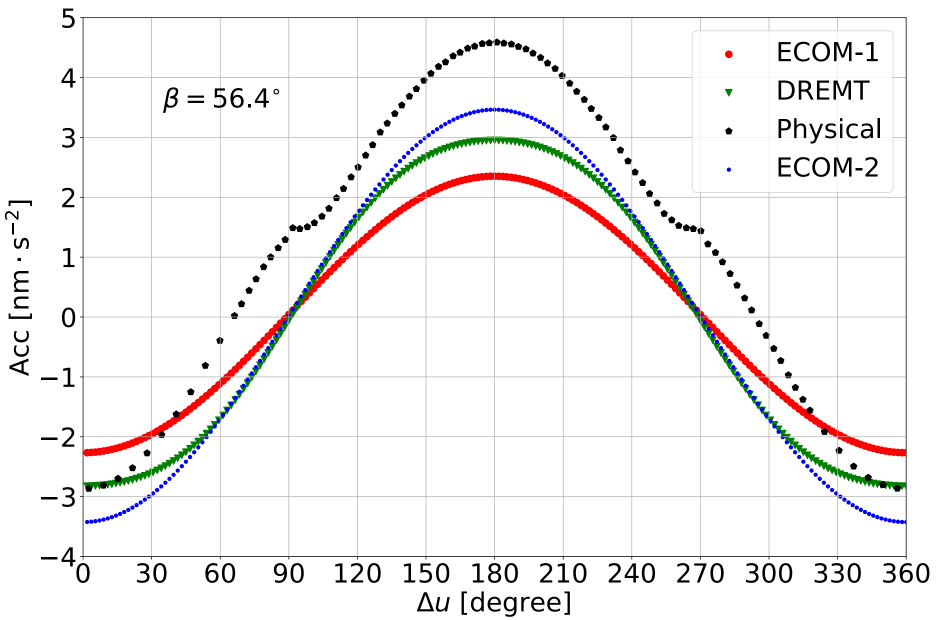
B component

DREMT has less β dependency than ECOM-1 and ECOM-2

Acceleration reconstruction---- high sun elevation

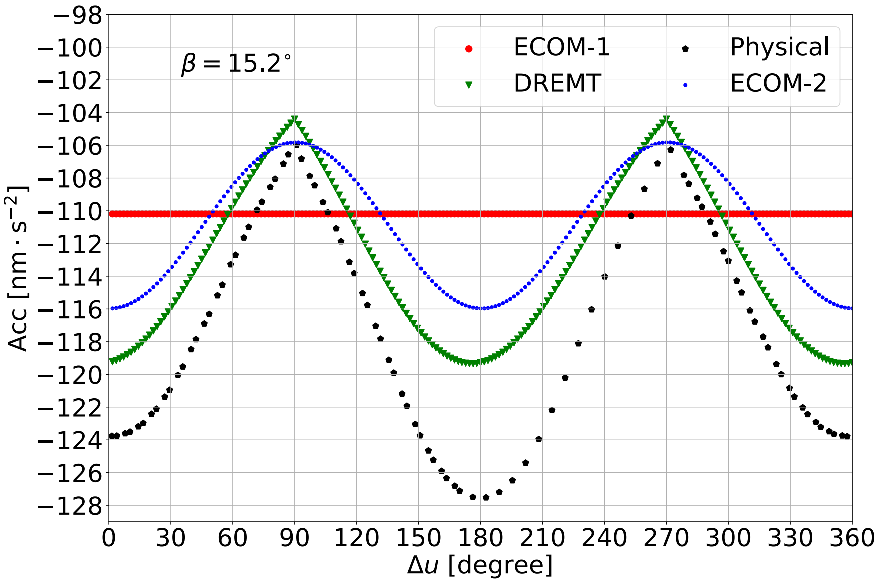


D component

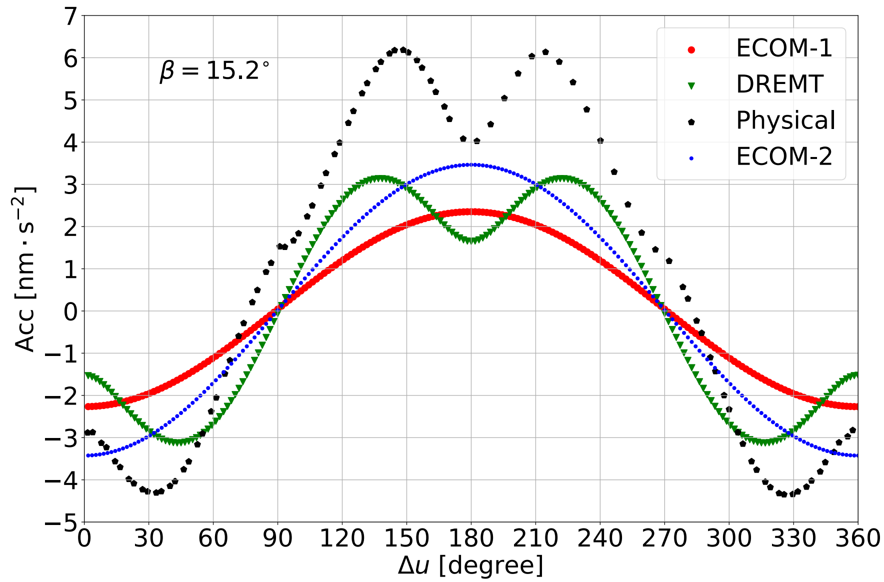


B component

Acceleration reconstruction---- low sun elevation



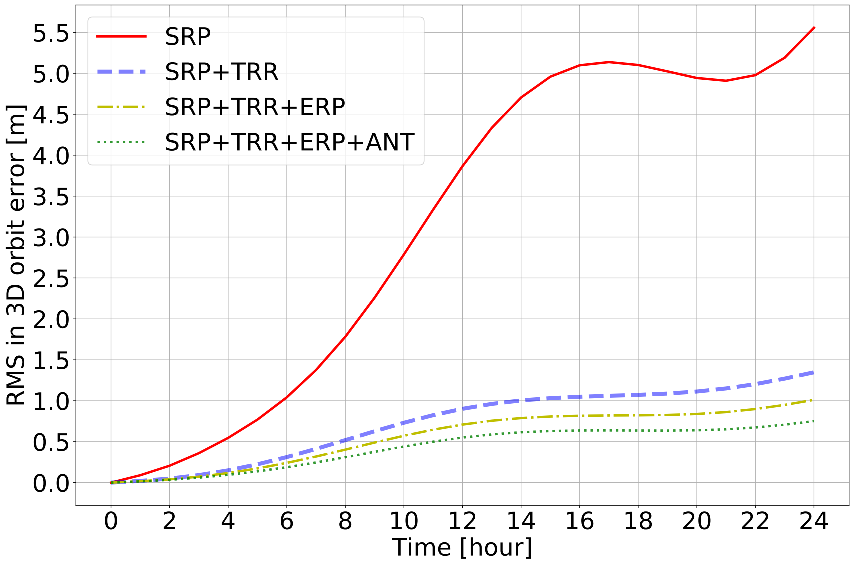
D component



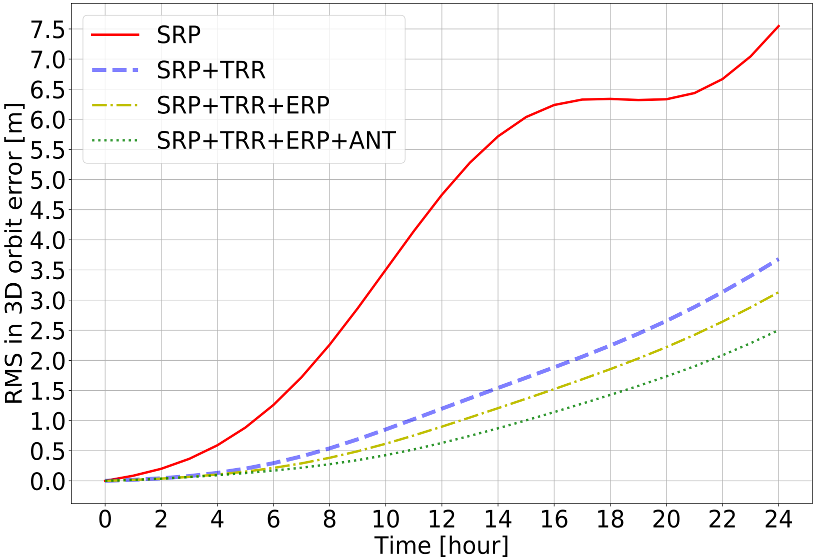
B component

Results----24-hour orbit prediction

with only physical models

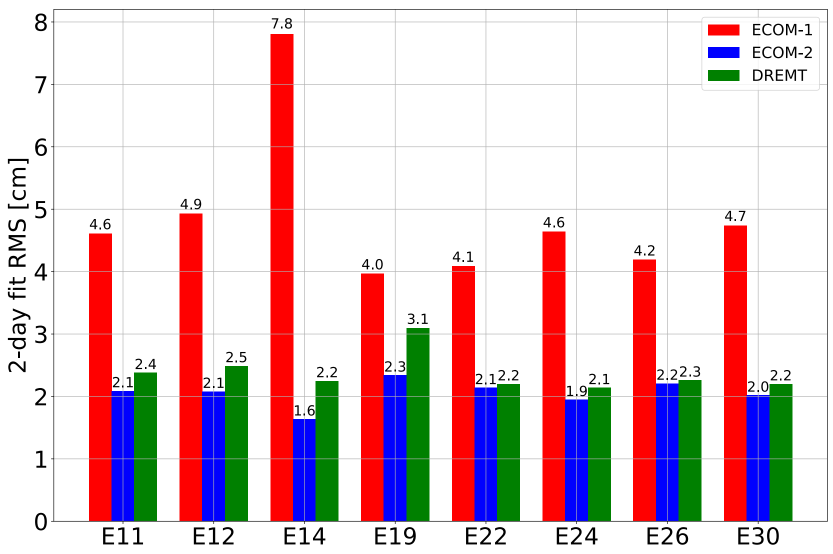


IOV

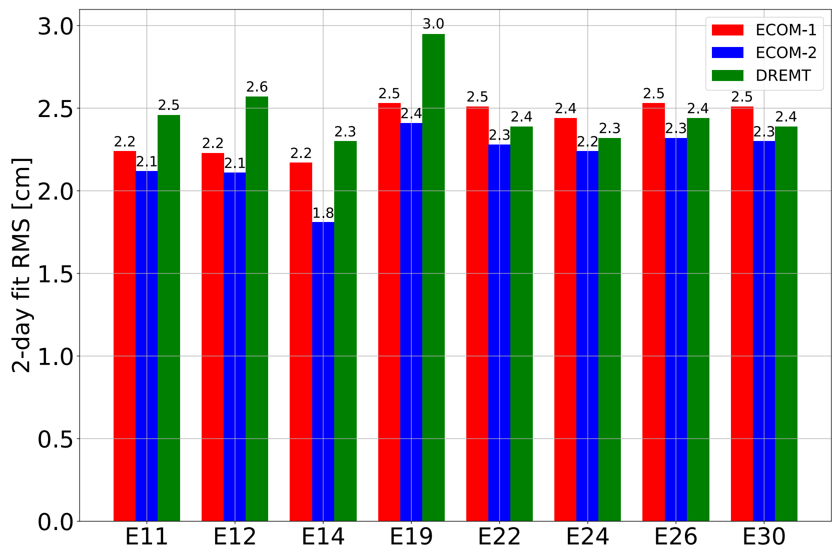


FOC

Results----2-day fit RMS

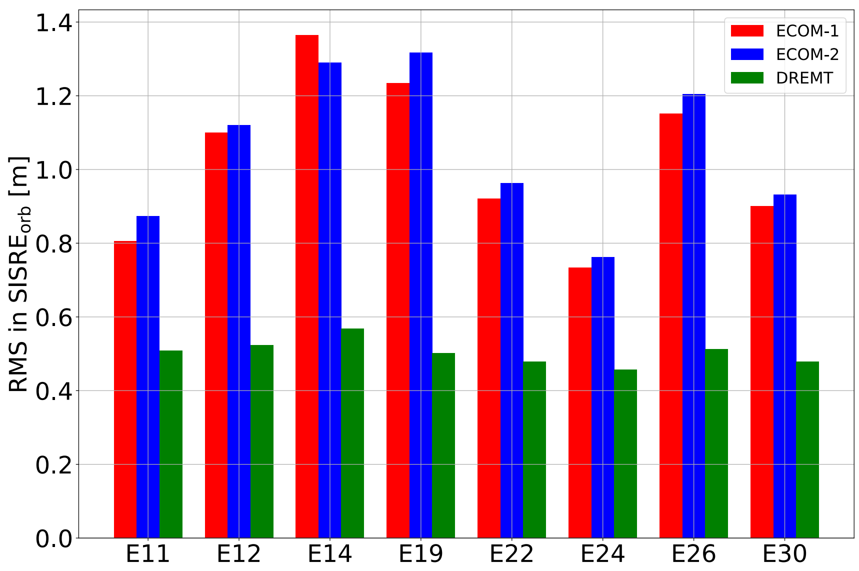


Without physical models

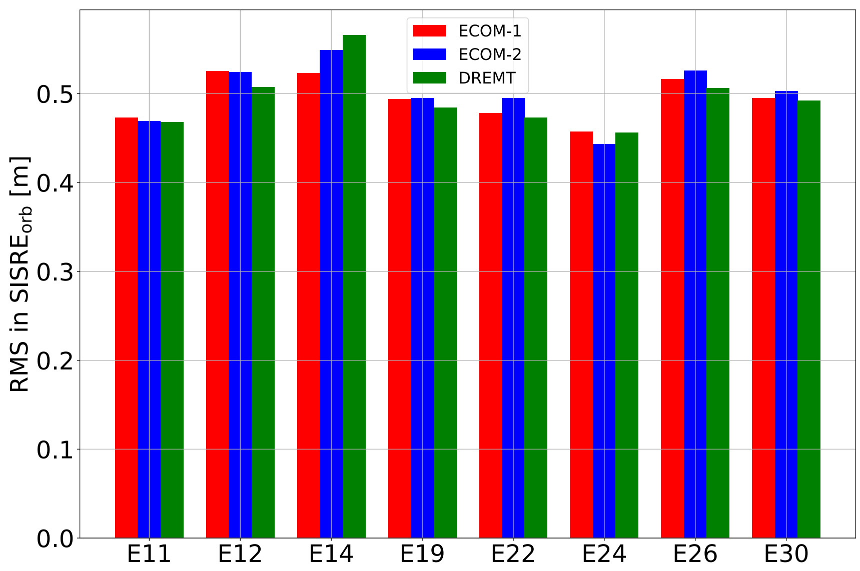


With physical models

Results----7-day orbit prediction

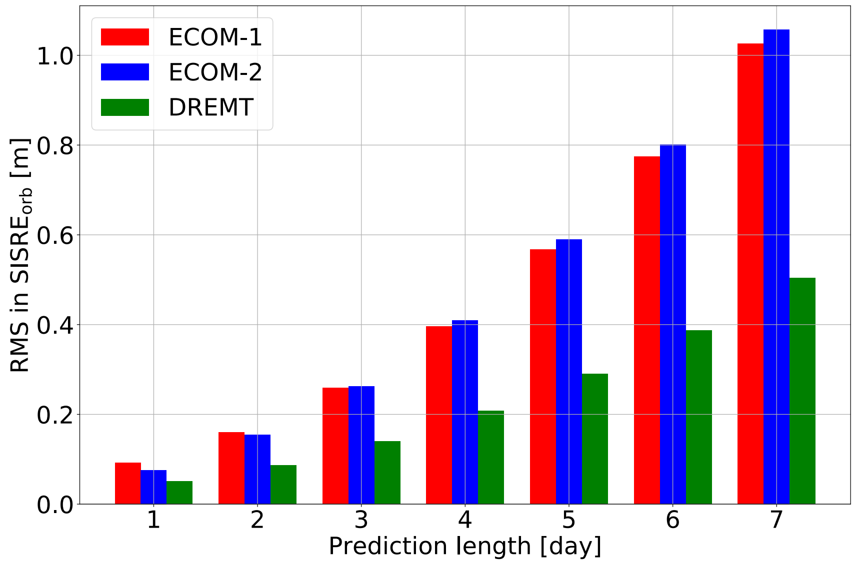


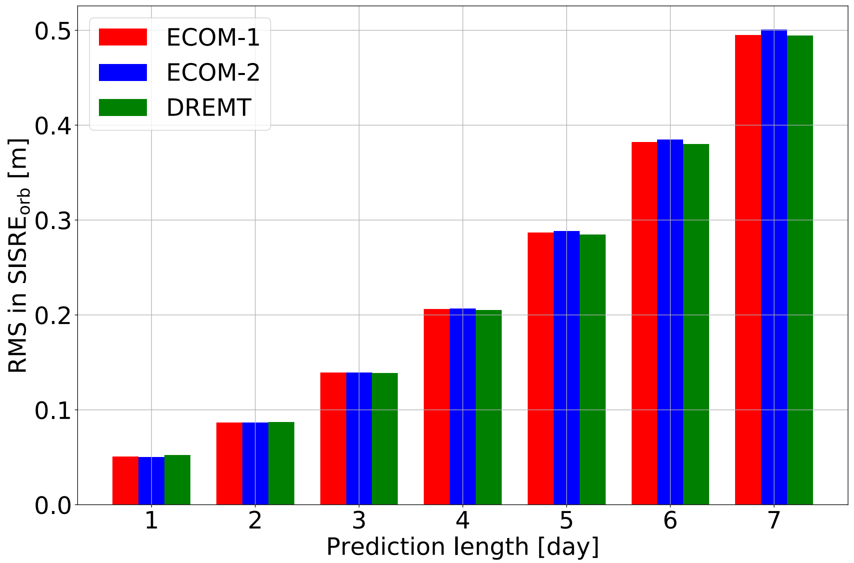
Without physical models



With physical models

Results----7-day orbit prediction

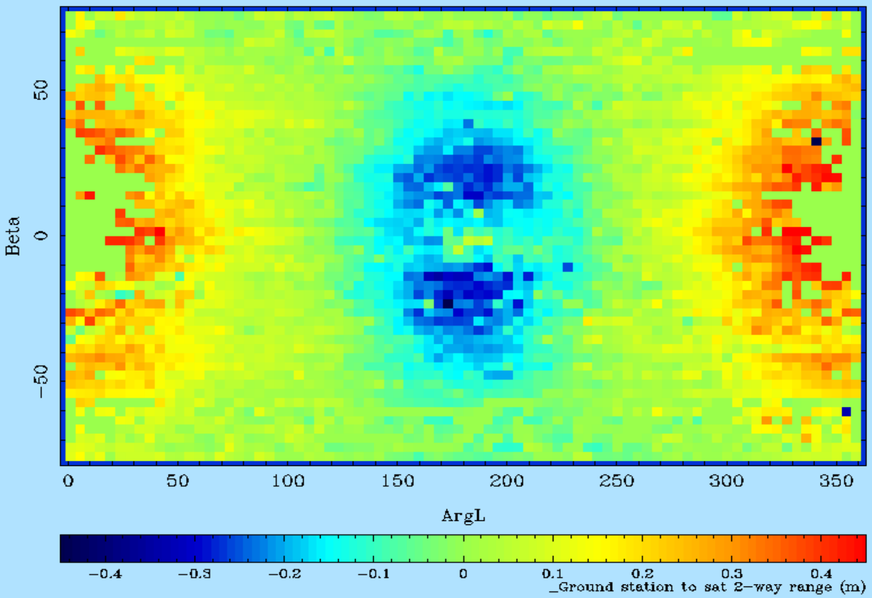


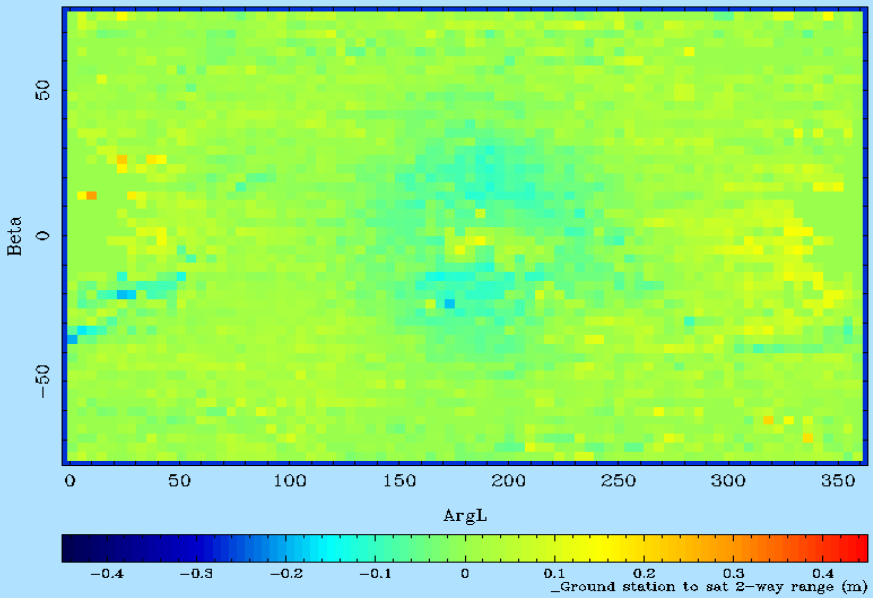


Without physical models

With physical models

SLR Validation:
All IOV and FOC (except eccentric) spacecraft on orbit in 2016





RMS of two-way SLR range residuals improve from 150mm (ECOM) to 50mm (ECOM+UCL)

Conclusions

- RMS prediction error over 24 hours: 4cm in SISRE (whole year 2016)
- After 7 days, orbit prediction accuracy level: 0.28m (radial), 0.31m (across track) and 5.10m (along-track)
- Use of a priori model reduced β dependency of SLR residuals
- A high accuracy shadow function (PPM_atm) is developed
- A physics based empirical model (DREMT) is developed
- UCL models are user friendly and easy to use.

Thank you!