Precise orbit determination of QZS-1 with high-fidelity non-gravitational disturbance model

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Background

Precise Orbit Determination

- Precise orbit determination is essential to provide a precise navigation result to users.
- Japanese QZSS also have to provide their precise orbit and clock.
  - JAXA developed orbit and clock analysis tool MADOCA
- In order to provide more precise orbit, orbit disturbance models have to be improved.

Orbital Disturbances in GEO

Disturbances	Order at GEO$[\mathrm{m/s^2}]$
Geopotential	$10^{-1}\sim10^{-12}$
Solid	
Ocean	
Third bodies	10^{-8}
General Relativity Effect	10^{-11}
Solar Radiation Pressure: SRP	10^{-7}
Thermal Radiation Pressure: TRP	$10^{-9}\sim10^{-10}$
Earth Radiation Pressure	10^{-10}
Antenna Thrust	10^{-10}

Gravitational disturbances:
Precise models were already constructed.

Non-gravitational disturbances
Depending on shape, attitude, optical property, and thermal characteristic of each satellite

There are no precise generalized models

Empirical vs Analytical

	Empirical model	Analytical model
Method	• Assume an **empirical** disturbance equation • Estimate parameters with orbits	• Model an analytical formula derived from law of physics
Accuracy	• Acceleration : $10^{-10}\mathrm{m/s^2}$ • Orbit : $1\sim10$ cm	• Acceleration : $10^{-8}\mathrm{m/s^2}$ • Orbit : $10\sim100$ cm
Merit	• Can be expressed simple equation • Can provide better POD accuracy	• Can be modeled without observed data • Can remove systematic error • Can be used for pre-launch analysis

Montenbruck *et al.* [1] showed the analytical box-wing SRP model removes systematic bias error in the empirical model.
The analytical model is focused to improve POD accuracy.

Objectives

- Issues on analytical model
  - Satellite information is not published.
  - Long computational time is needed.
  - Precise TRP model is not considered.
- Objectives of this study
  - Using satellite design info. from providers
    - CAD, Optical properties, Thermal design and analysis
  - Proposing accurate and low calc. cost SRP model
    - PCGT: Pre-Computed Geometry Tensor Method[2]
  - Modeling TRP based on thermal design info.

Non-Gravitational Disturbance Model

- High-fidelity Solar Radiation Pressure(SRP)
- Thermal Radiation Pressure(TRP)

High-fidelity SRP model ~Pre-computed Tensor Method[2]~

Pre-computation Phase

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Geometry Model

Visibility

Approximation

$$\begin{bmatrix} a & b & \cdots & x \\ c & \ddots & & \\ \vdots & & \ddots & \vdots \\ y & & \cdots & z \end{bmatrix}$$

Pre-computed geometry tensor

Calculation Phase

$$\begin{bmatrix} a & b & \cdots & x \\ c & \ddots & & \\ \vdots & & \ddots & \vdots \\ y & & \cdots & z \end{bmatrix}$$

Geometry tensor

⊗

Optical Property

C_s, C_d

⊗

i

Sun direction

SRP force

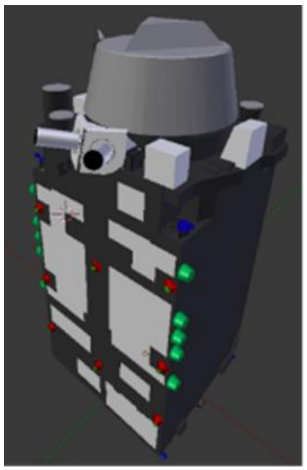
SRP Torque

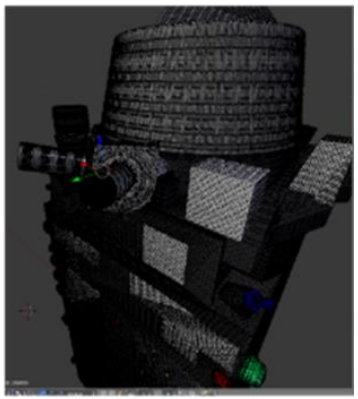
Flight data

Optical Property Estimation

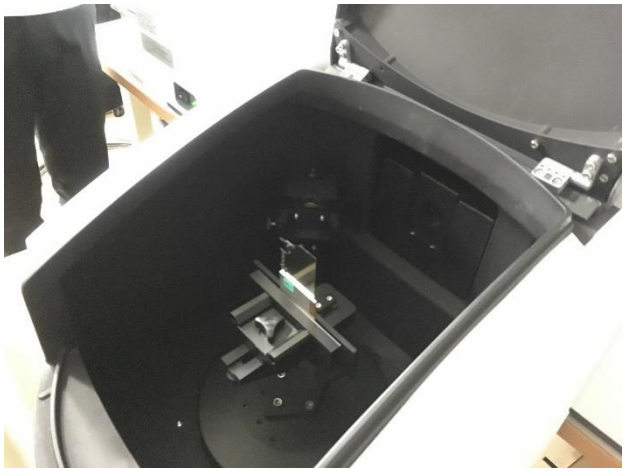
High-fidelity SRP model ~Satellite design information~

- Satellite geometry model based on CAD is used
  - The model is divided 184,000 meshes for self-shadow calculation
  - Pre-computed geometry tensors were generated from this model
- Optical Properties were measured on ground from real materials





184000面分割



Thermal Radiation Pressure(TRP)

- Geometry
  - Assuming Box-Wing shape
- Radiation model
  - Heat flux of each surface is modeled by using thermal design and analysis information with respect to sun direction
- Solar paddle and body-Y plane
  - Heat flux (≒ TRP) is assumed as constant
  - Solar Paddle: $3.7\times 10^{-9}\mathrm{m/s^2}$
  - Body-Y plane: $3 \times 10^{-10}\ \mathrm{m/s^2}$

Thermal Radiation Pressure(TRP)

- Body-X plane
  - Output heat flux is nearly equal to input heat flux since the plane is covered by MLI
  - Parameter c_{MX} expresses efficiency of isolation
    - Estimated by thermal analysis and telemetry data

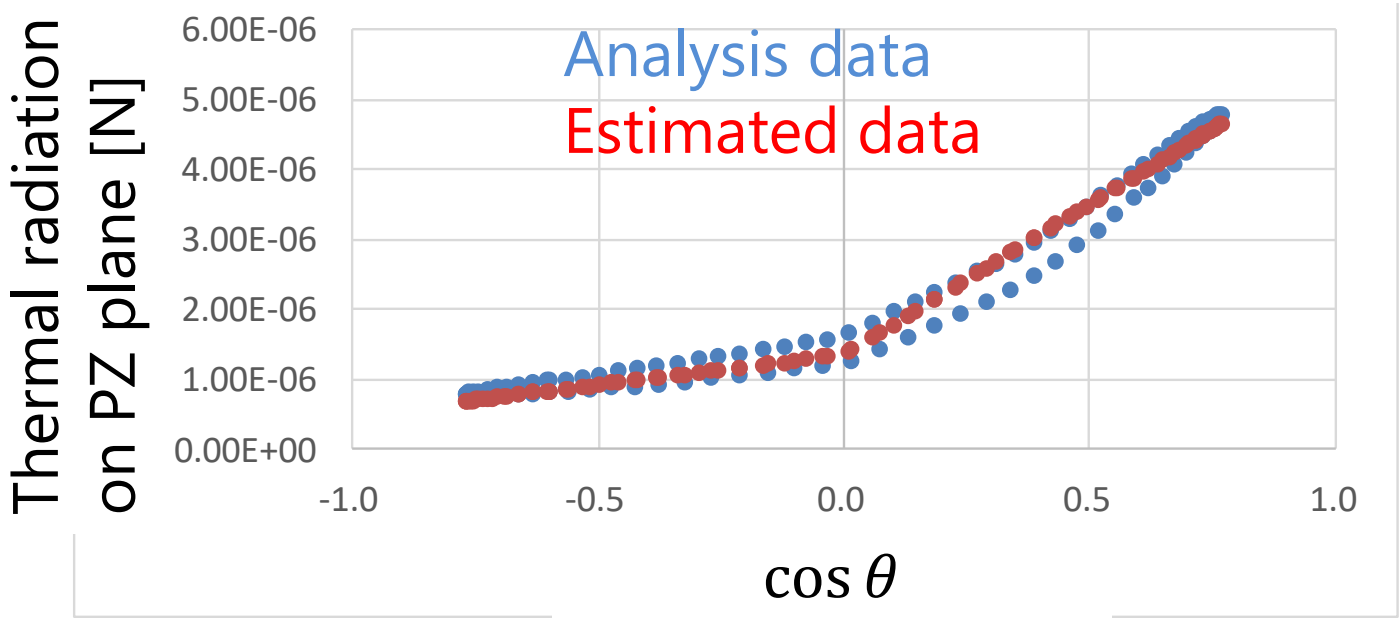
$$P_{\mathrm{MX}} = c_{MX}\left(\frac{1\mathrm{AU}}{r^2}P_{\mathrm{SUN}}\cos\theta\right)\alpha_{\mathrm{MX}}$$

Input Flux

  - Maximum TRP on X-axis reaches $1 \times 10^{-8}\ \mathrm{m/s^2}$

Thermal Radiation Pressure(TRP)

- Body-Z plane
  - Modeling is not easy because the plane has many components (e.g., L-ant, Apogee kick motor etc)
  - The heat flux model is constracted from thermal analysis data



Performance Comparison

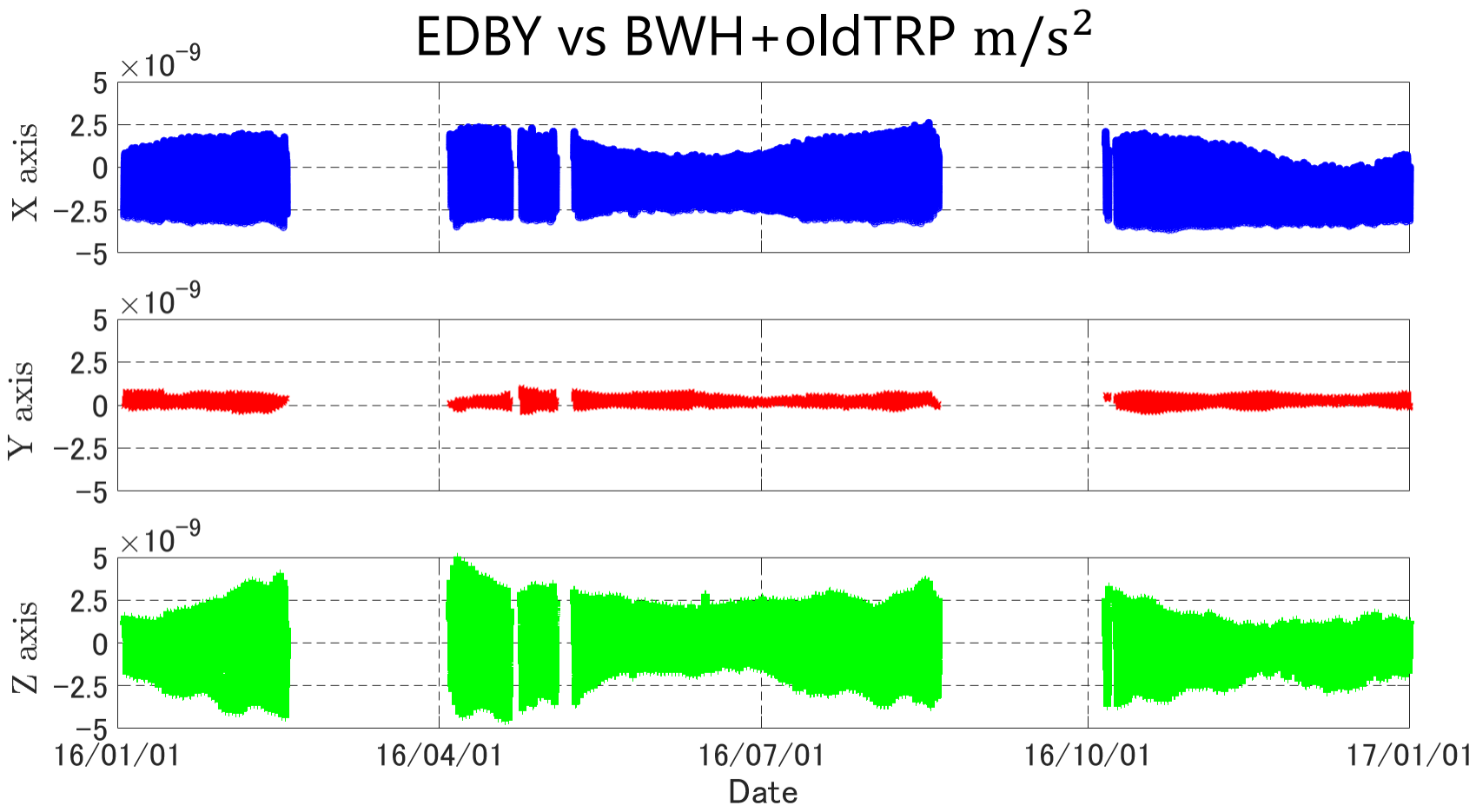
- Comparison of acceleration
- POD result by MADOCA

Experiment Condition

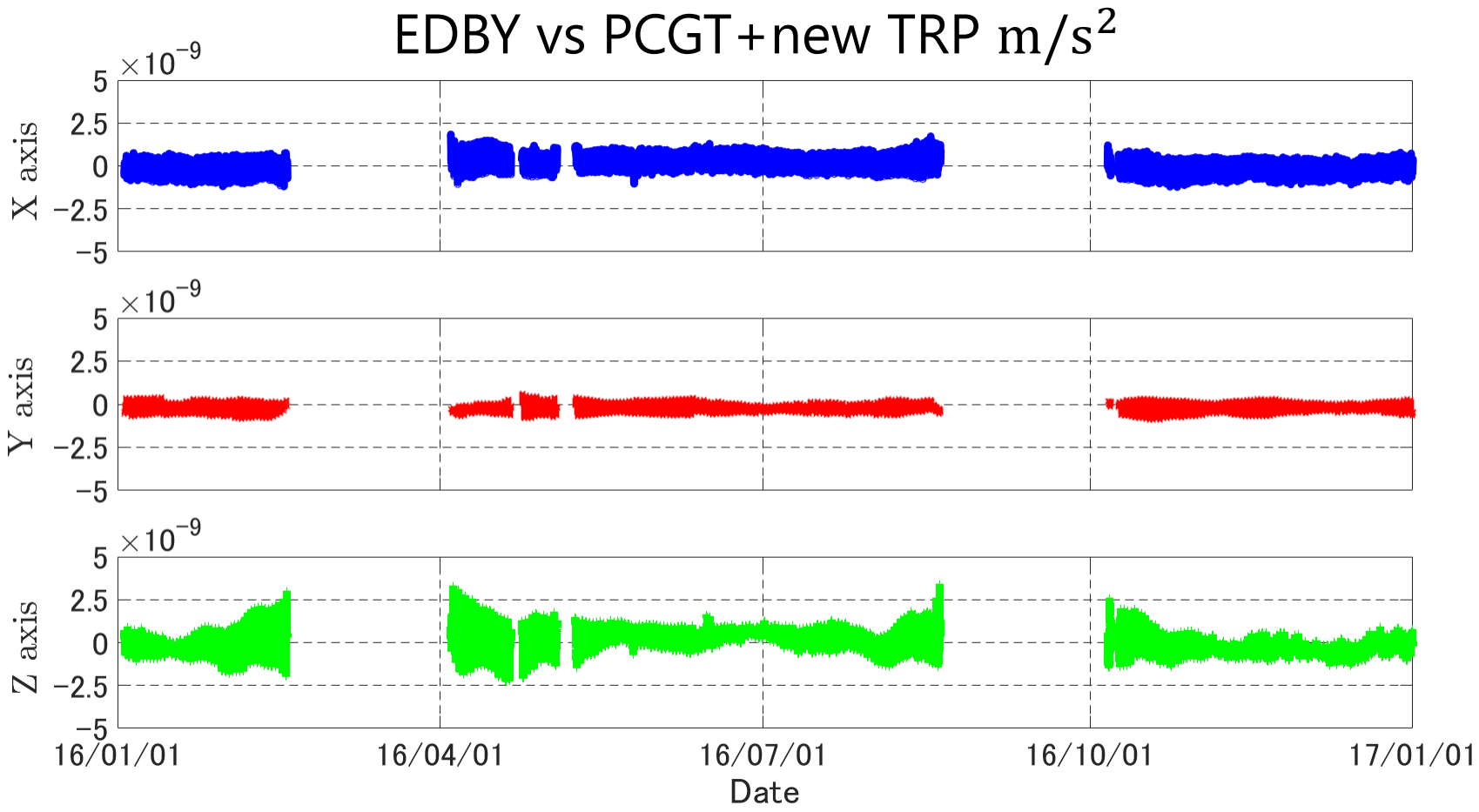
- Precise orbit determination by using MADOCA
- Jan. 1st – Dec. 31st in 2016 *EC(ON) attitude duration is excluded
- 150 ground stations
- Same algorithms and data except for non-gravitational disturbance calculation
- Three non-gravitational disturbance model were used

Model	Type	Est. Params	Self-shadow of SRP	Thermal design info.
EDBY[1]	Empirical	15	-	-
BWH+old TRP[2]	Analytical	0	ignored	Not-used
PCGT+new TRP	Analytical	0	considered	used

Comparison of Acceleration on the body-frame

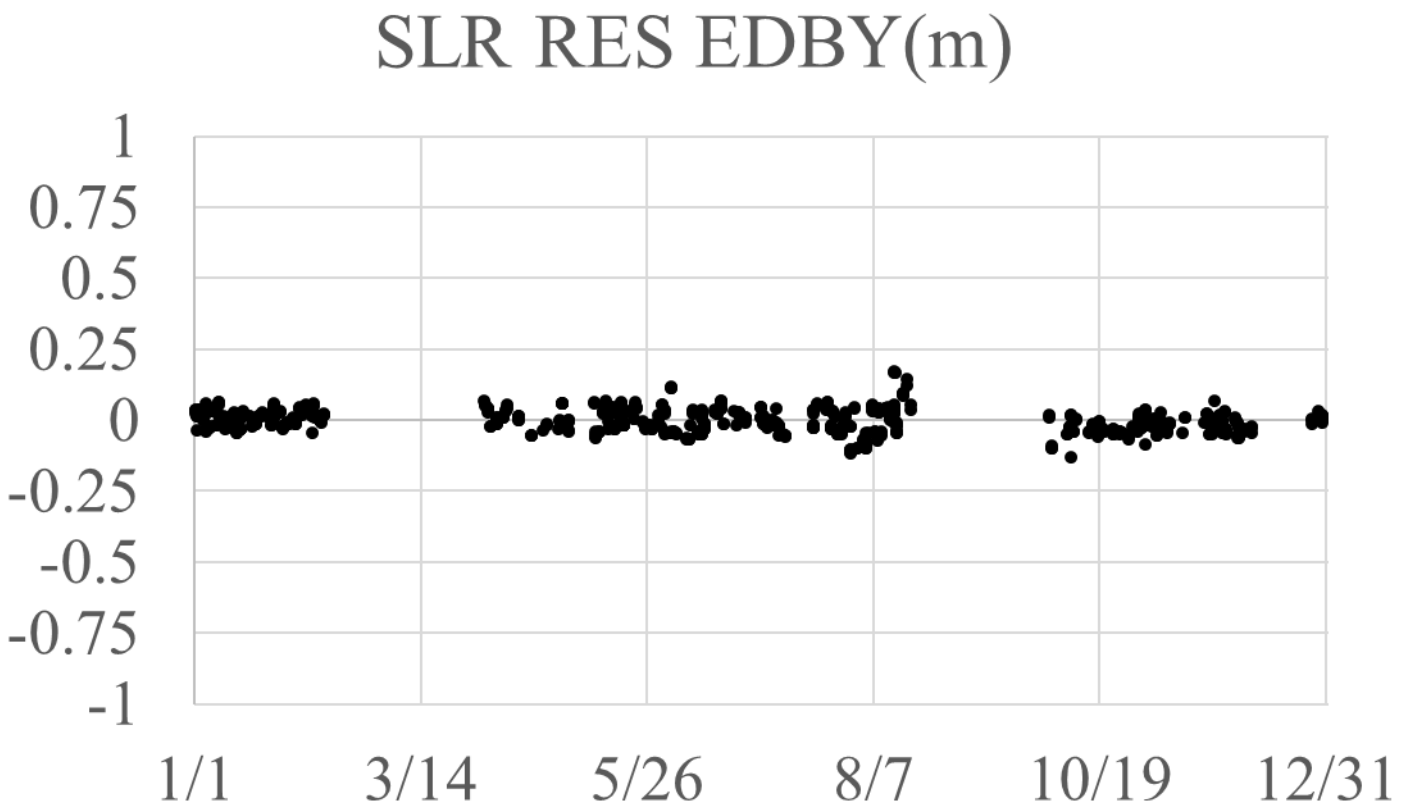


Comparison of Acceleration on the body-frame



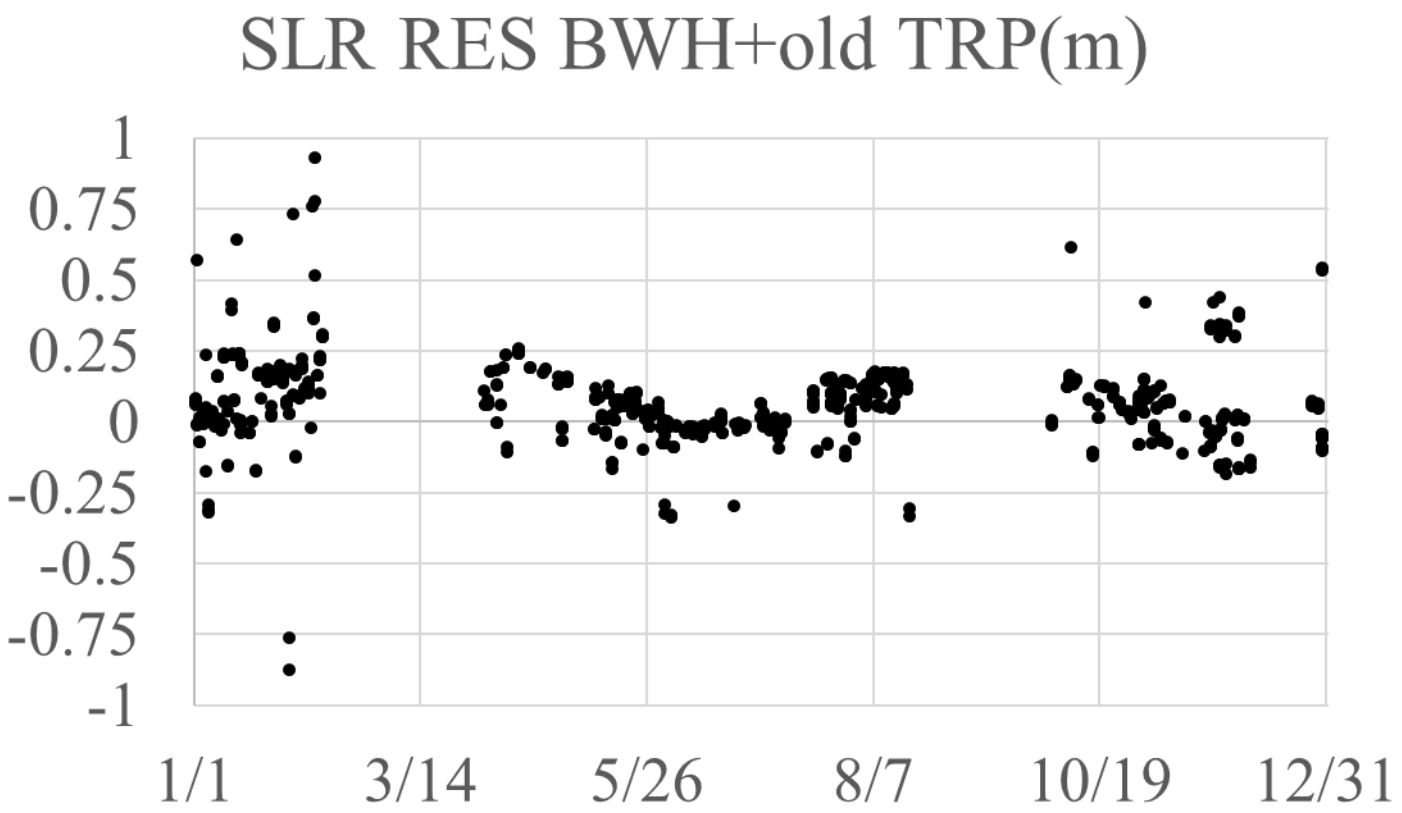
Proposed model is more improved than BWH + old TRP

POD results: SLR residual



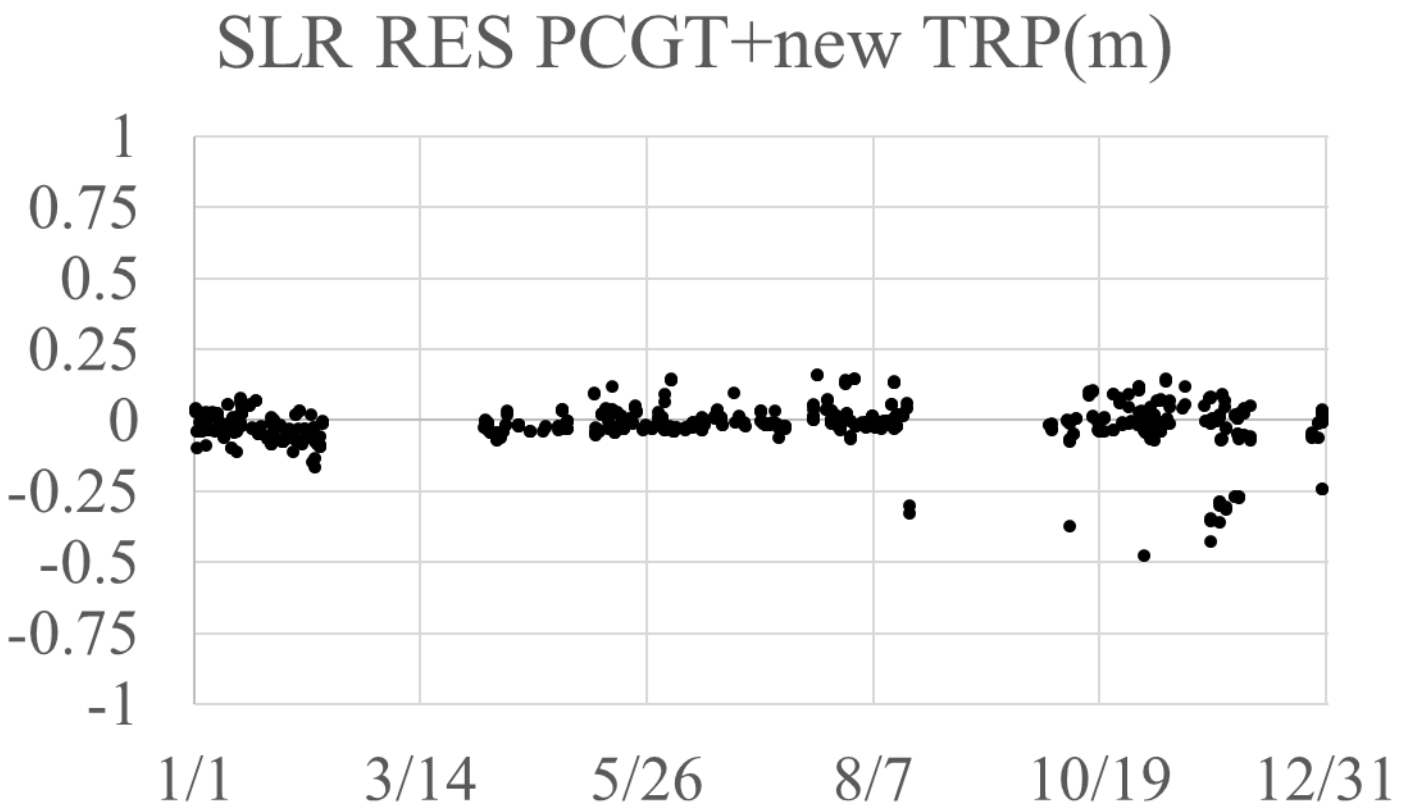
Average: -0.44cm, RMS: 9.6cm

POD results: SLR residual



Average: 7.3cm, RMS: 18.3cm

POD results: SLR residual



Average: -1.2cm, RMS: 11cm

Summary of POD results

			SLR residual		Overlap
Model	**Type**	**Est. Params**	**Average**	**RMS**	**3D RMS**
EDBY	Empirical	15	-0.44 cm	9.7 cm	10.3 cm
BWH + old TRP	Analytical	0	7.3 cm	18.3 cm	66.5 cm
PCGT + new TRP	Analytical	0	-1.2 cm	11.1 cm	36.6 cm

The proposed PCGT + new TRP model reaches 11 cm RMS of SLR residual and 37 cm 3D RMS of overlap **without any parameter estimation** for the non-gravitational disturbance model

Conclusion

- We constructed **high-fidelity analytical** non-gravitational disturbance models by using satellite design information
  - SRP：Geometry from CAD，Measured optical property
  - TRP：Satellite thermal design and analysis info.
- One year POD experiments shows good performance of the proposed model **without parameter estimation**
  - SLR residual : 1 cm average, 11 cm RMS
  - Overlap : 37 cm 3D RMS
- POD result can be improved by combination method with parameter estimation
- The proposed model will be applied for EC mode of QZS-1 and QZS-2, 3, and 4

References

[1] O. Montenbruck, *et al.*, "Enhanced solar radiation pressure modeling for Galileo satellites," Journal of Geodesy, vol. 89, pp. 283-297, 2015.

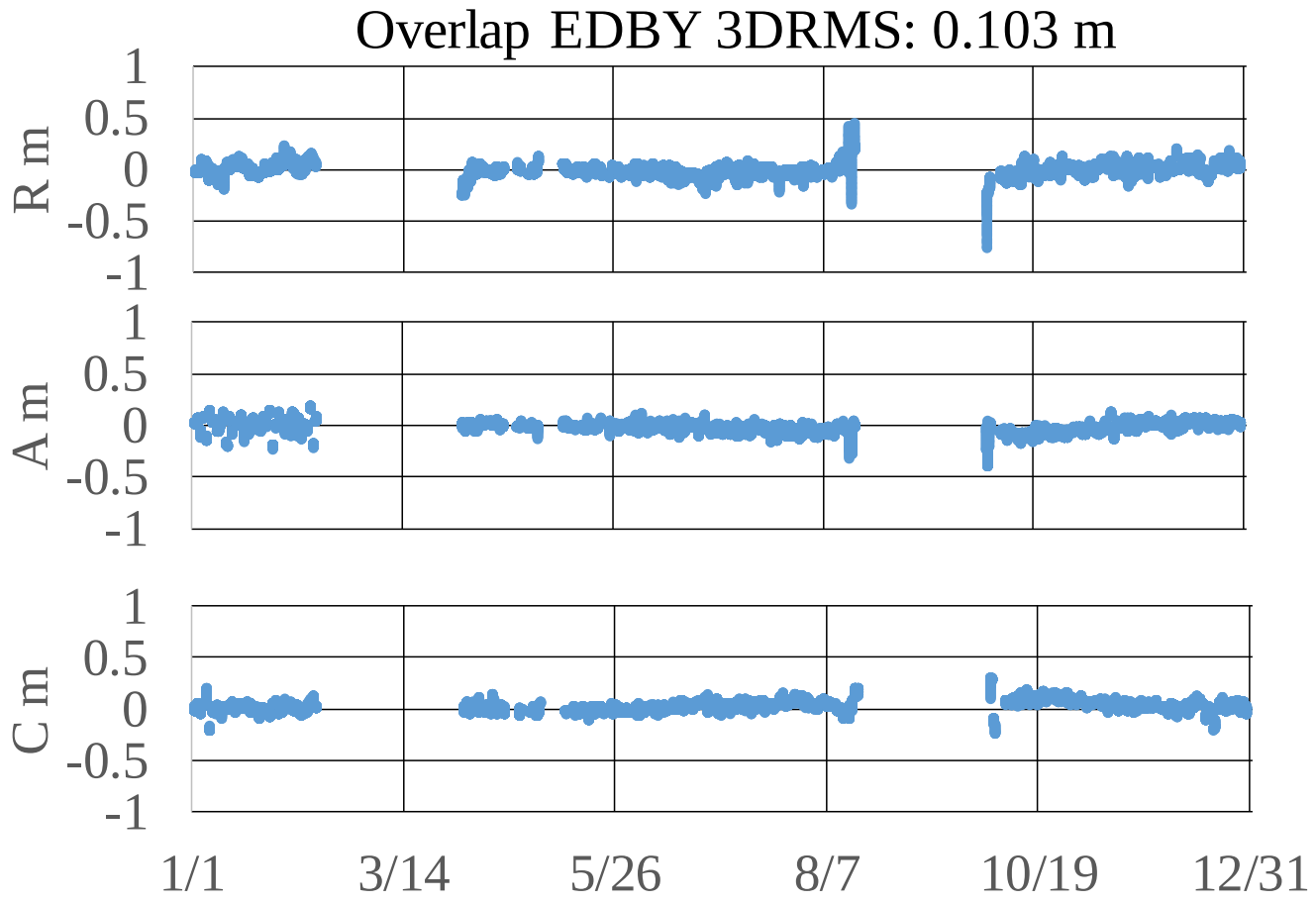
[2] S. Ikari, *et al.*, "A Novel Semi-Analytical Solar Radiation Pressure Model with the Shadow Effects for Spacecraft of Complex Shape," in 26th Space Flight Mechanics Meeting, Napa, 2016.

[3] T. Takasu, *et al.*, "QZSS-1 Precise Orbit Determination by MADOCA," in International Symposium on GNSS, Kyoto, 2015.

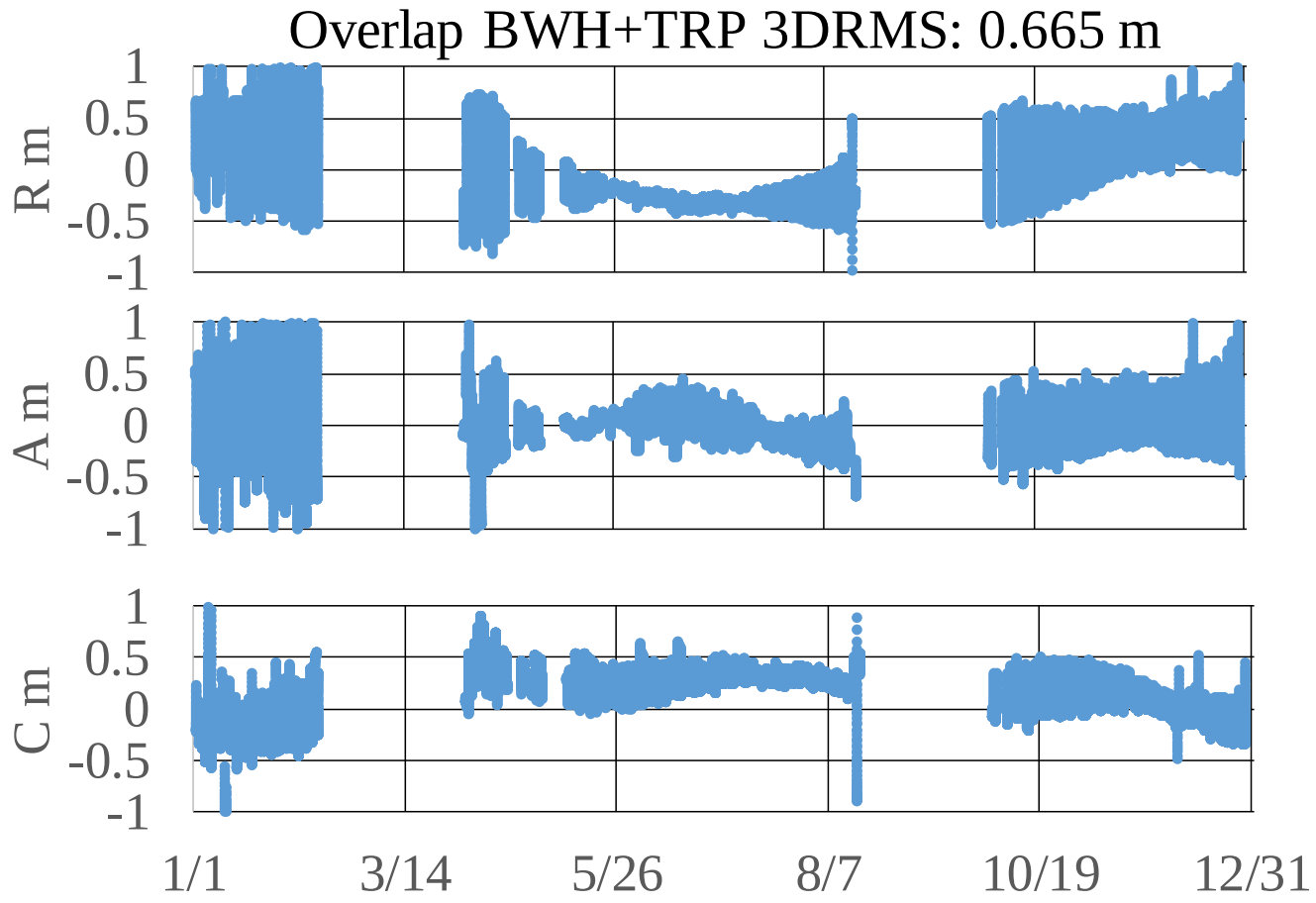
[4] S. Ikari, *et al.*, "Analytical Non-Conservative Disturbance Modeling for QZS-1 Precise Orbit Determination", Proceedings of the ION GNSS+ 2014, 2014

Appendix

POD results: overlap



POD results: overlap



POD results: overlap