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.
Gravitational disturbances:
Precise models were already constructed.

<table>
<thead>
<tr>
<th>Disturbances</th>
<th>Order at GEO $[\text{m/s}^2]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geopotential</td>
<td>$10^{-1} \sim 10^{-12}$</td>
</tr>
<tr>
<td>Solid Earth Tide</td>
<td>$10^{-9}$</td>
</tr>
<tr>
<td>Ocean Tide</td>
<td>$10^{-9}$</td>
</tr>
<tr>
<td>Third bodies</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>General Relativity Effect</td>
<td>$10^{-11}$</td>
</tr>
<tr>
<td>Solar Radiation Pressure: SRP</td>
<td>$10^{-7}$</td>
</tr>
<tr>
<td>Thermal Radiation Pressure: TRP</td>
<td>$10^{-9} \sim 10^{-10}$</td>
</tr>
<tr>
<td>Earth Radiation Pressure</td>
<td>$10^{-10}$</td>
</tr>
<tr>
<td>Antenna Thrust</td>
<td>$10^{-10}$</td>
</tr>
</tbody>
</table>

Non-gravitational disturbances

Depending on shape, attitude, optical property, and thermal characteristic of each satellite

There are no precise generalized models
## Empirical vs Analytical

<table>
<thead>
<tr>
<th>Method</th>
<th>Empirical model</th>
<th>Analytical model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>• Assume an <strong>empirical</strong> disturbance equation</td>
<td>• Model an analytical formula derived from law of physics</td>
</tr>
<tr>
<td></td>
<td>• Estimate parameters with orbits</td>
<td></td>
</tr>
<tr>
<td>Accuracy</td>
<td>• Acceleration: $10^{-10}$ m/s$^2$</td>
<td>• Acceleration: $10^{-8}$ m/s$^2$</td>
</tr>
<tr>
<td></td>
<td>• Orbit: 1~10 cm</td>
<td>• Orbit: 10~100 cm</td>
</tr>
<tr>
<td>Merit</td>
<td>• Can be expressed simple equation</td>
<td>• Can be modeled without observed data</td>
</tr>
<tr>
<td></td>
<td>• Can provide better POD accuracy</td>
<td>• Can remove systematic error</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Can be used for pre-launch analysis</td>
</tr>
</tbody>
</table>

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

Visualization

Calculation Phase

Geometry tensor

Optical Property
$C_s, C_d$

SRP force

SRP Torque

Flight data

Optical Property Estimation

Pre-computed geometry tensor

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Geometry Model

© CAO

Geometry tensor

Optical Property
$C_s, C_d$

Sun direction

Flight data

Optical Property Estimation
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
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: $3.7 \times 10^{-9} \text{m/s}^2$
  - Body-Y plane: $3 \times 10^{-10} \text{m/s}^2$
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
    
        \[ P_{MX} = c_{MX} \left( \frac{1\text{AU}}{r^2} P_{\text{SUN}} \cos \theta \right) \alpha_{MX} \]

    - Input Flux

- Maximum TRP on X-axis reaches $1 \times 10^{-8}$ 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 constructed from thermal analysis data

![Graph showing thermal radiation pressure on PZ plane](https://via.placeholder.com/150)

- Thermal radiation on PZ plane [N]
- Analysis data
- Estimated data
- cos θ
Performance Comparison

- Comparison of acceleration
- POD result by MADOCA
Experiment Condition

- Precise orbit determination by using MADOCA
- Jan. 1\textsuperscript{st} – Dec. 31\textsuperscript{st} 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

<table>
<thead>
<tr>
<th>Model</th>
<th>Type</th>
<th>Est. Params</th>
<th>Self-shadow of SRP</th>
<th>Thermal design info.</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDBY\textsuperscript{[1]}</td>
<td>Empirical</td>
<td>15</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>BWH+old TRP\textsuperscript{[2]}</td>
<td>Analytical</td>
<td>0</td>
<td>ignored</td>
<td>Not-used</td>
</tr>
<tr>
<td>PCGT+new TRP</td>
<td>Analytical</td>
<td>0</td>
<td>considered</td>
<td>used</td>
</tr>
</tbody>
</table>
Comparison of Acceleration on the body-frame

EDBY vs BWH+oldTRP m/s²

X axis

Y axis

Z axis

Date

16/01/01  16/04/01  16/07/01  16/10/01  17/01/01
Comparison of Acceleration on the body-frame

EDBY vs PCGT+new TRP $\text{m/s}^2$

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

<table>
<thead>
<tr>
<th>Model</th>
<th>Type</th>
<th>Est. Params</th>
<th>SLR residual</th>
<th>Overlap</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Average</td>
<td>RMS</td>
<td>3D RMS</td>
</tr>
<tr>
<td>EDBY</td>
<td>Empirical</td>
<td>-0.44 cm</td>
<td>9.7 cm</td>
<td>10.3 cm</td>
</tr>
<tr>
<td>BWH + old TRP</td>
<td>Analytical</td>
<td>7.3 cm</td>
<td>18.3 cm</td>
<td>66.5 cm</td>
</tr>
<tr>
<td>PCGT + new TRP</td>
<td>Analytical</td>
<td>-1.2 cm</td>
<td>11.1 cm</td>
<td>36.6 cm</td>
</tr>
</tbody>
</table>

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


Appendix
POD results: overlap

Overlap EDBY 3DRMS: 0.103 m
POD results: overlap

Overlap BWH+TRP 3DRMS: 0.665 m
POD results: overlap

Overlap Pre-computed Tensor 3DRMS: 0.366 m