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Space Glasgow Research Conference

A DEFORMATION MODEL OF FLEXIBLE, HIGH AREA-TO-MASS RATIO DEBRIS FOR ACCURATE PROPAGATION UNDER PERTURBATION

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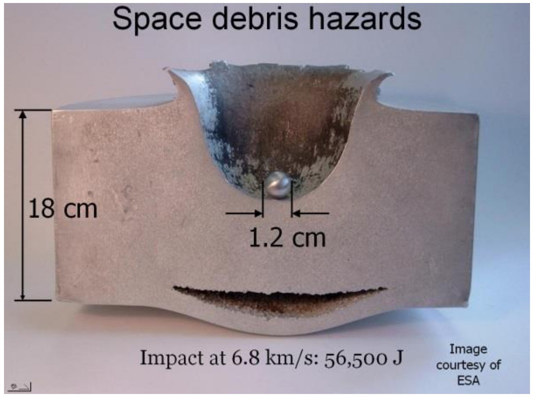
Outline

- Background
- Objective
- The model
- Simulation
- Results
- Conclusion and Future work

Space Debris

Space debris

- Artificial debris and natural debris.
- Orbit with hypervelocity that can threat to active spacecraft leading to catastrophic break-ups generating new space debris
- Need to reduce the number of debris.



Experiment

Gravity movie

Space debris

Discover HAMR objects

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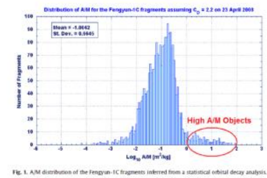
Discovery in 2004 (GEO)

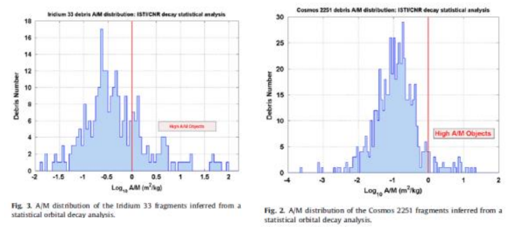
-High area-to-mass ratio (HAMR) objects
-Variations of light curves
-Variations of area-to-mass ratio (AMR)

Collision and explosion

- Fengyun1-C



- Iridium 33 and Cosmos 2251



(Anselmo, L. and C. Pardini, 2010)

Experiment

- Shot micro satellite model

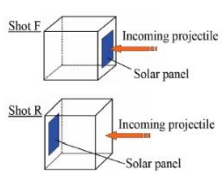


Figure 4 Test Conditions

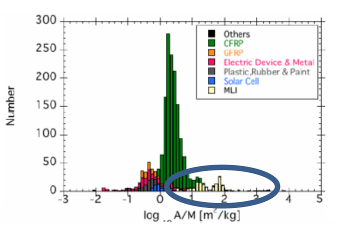


Figure 17 Area-to-Mass Ratio from Shot F

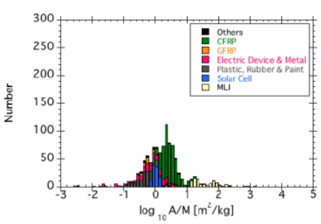
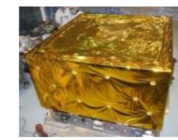


Figure 18 Area-to-Mass Ratio from Shot R

(Murakami, J., et al 2008)

Suspected objects



Multi-layer insulation

Objective

1. **Develop a model of a thin, highly flexible MLI-type membrane, in terms of multi-body dynamics, and solved by using fundamental Newtonian mechanics**

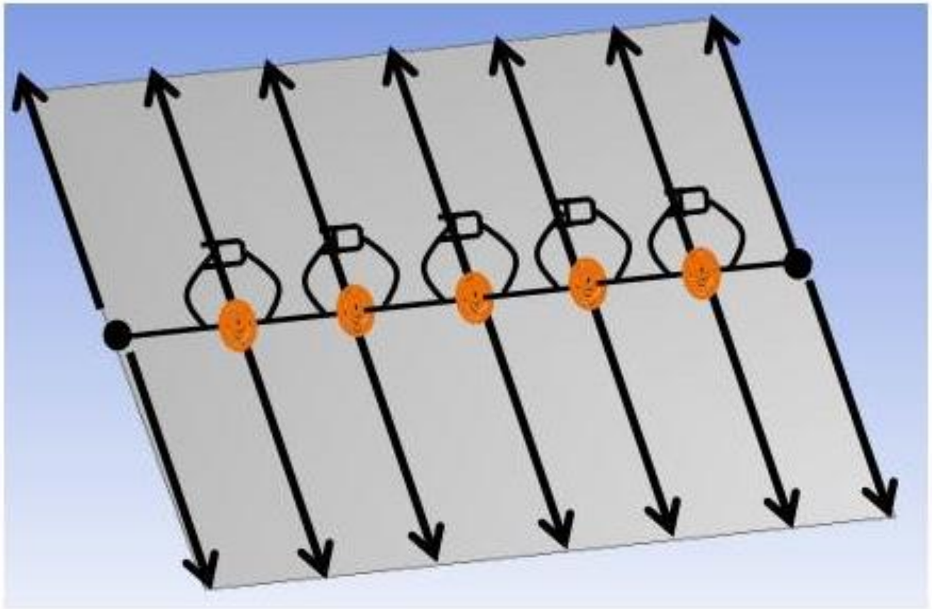
2. **Investigate the orbital dynamics under J2 and the luni-solar third body gravitation and solar radiation pressure (SRP) by comparing with rigid body case**

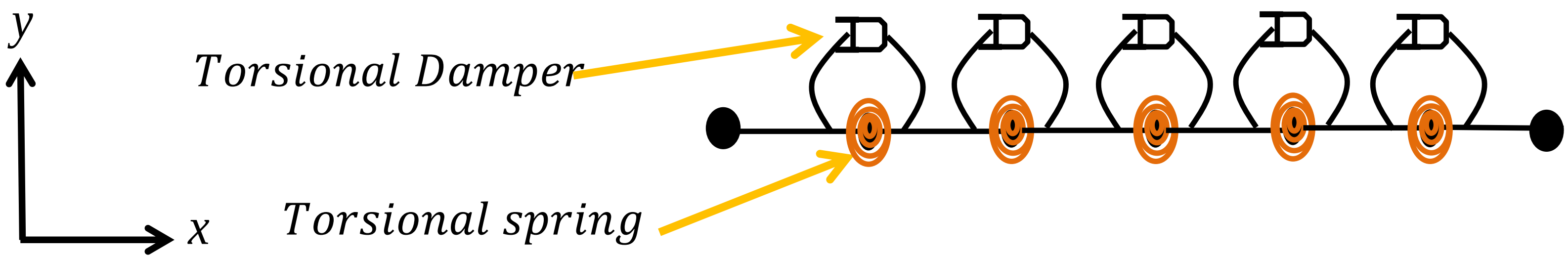
3. **Investigate a self-shadowing effect to the orbital dynamics of flexible debris**

flexible model

The flexible model

Flat plate

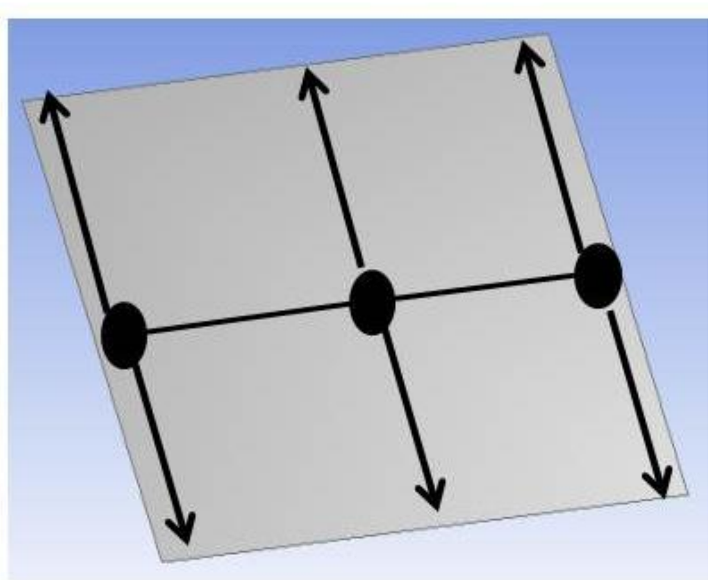




Consider deformation in 2 D of x-y plane

Simplification

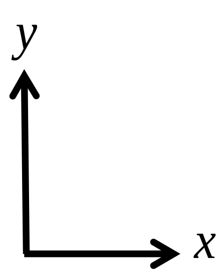
Flat plate

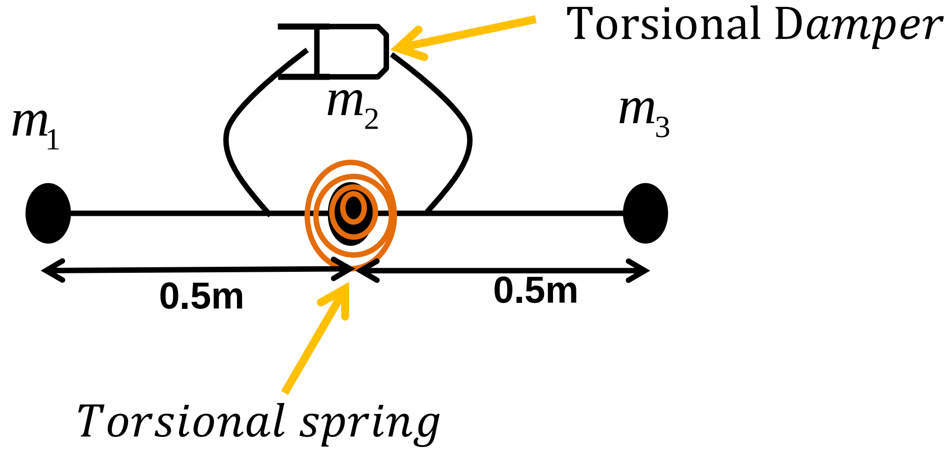


Dimension

1 x 1 square meter

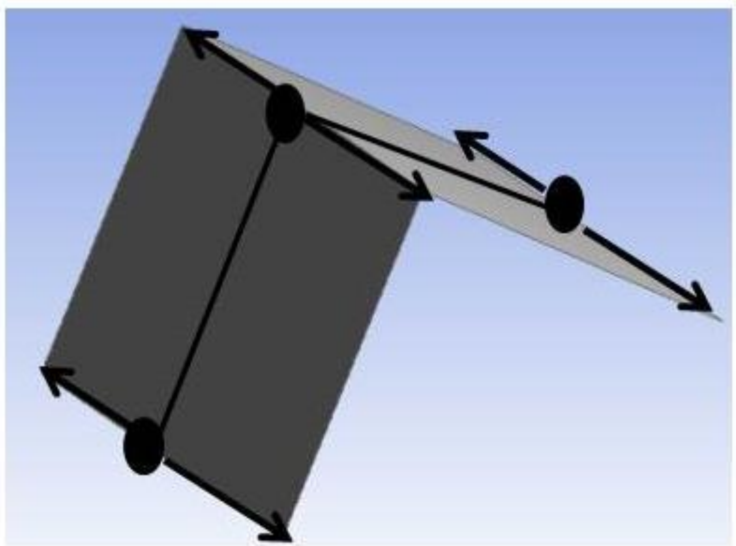
$l_1 = l_2 = 0.5$ (m)

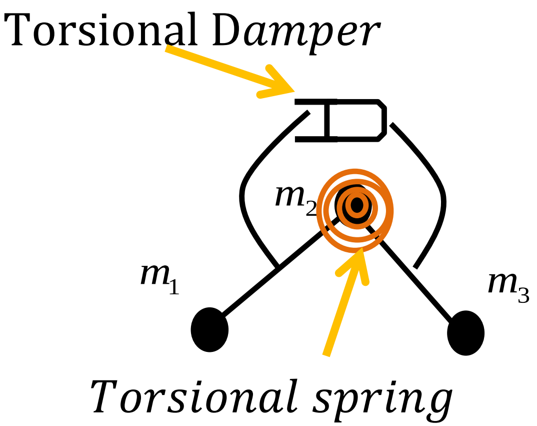


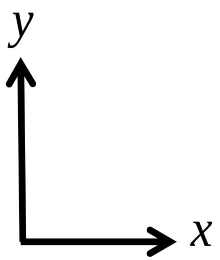


Simplification

Triangular shape





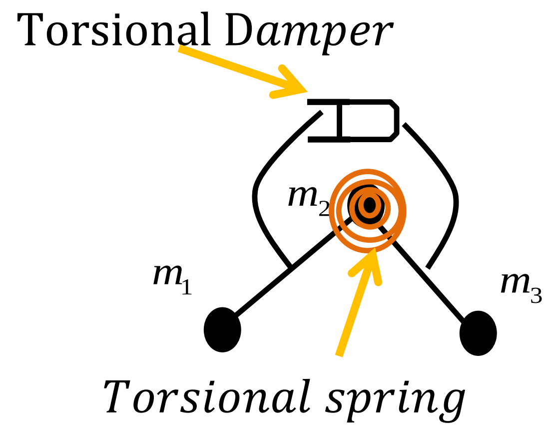


Multibody dynamics

Newtonian equation

$$F_i + T_i + F_{s,i} + F_{d,i} = m_i a_i$$

Where i = mass of each (1,2 and 3)



Spring and damper forces

$$F_s = k_s \theta \qquad F_d = c\,\dot{\theta}$$

$$k_s = \frac{EI}{Length} \qquad c = DF\sqrt{Mk_s}$$

Where
- k_s = rotational spring constant,
- θ = angle of deformation
- $\dot{\theta}$ = angular velocity of the deformation,
- E = young modulus
- I = the moment of inertia of thin plate
- $Length$ = the length of each rod and is
- c = Coefficient of torsion spring (N.m rad^{-1})
- DF = dissipation factor of material
- M = mass of rod (Kg)

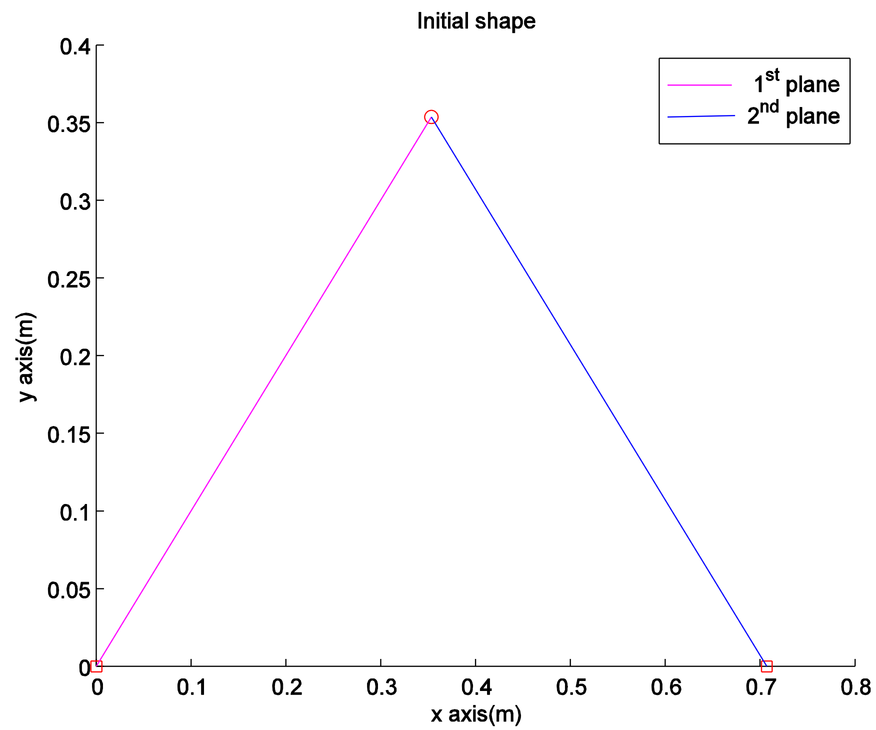
Constrained equation

$$(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2 + (z_{i+1} - z_i)^2 = l_i^2$$

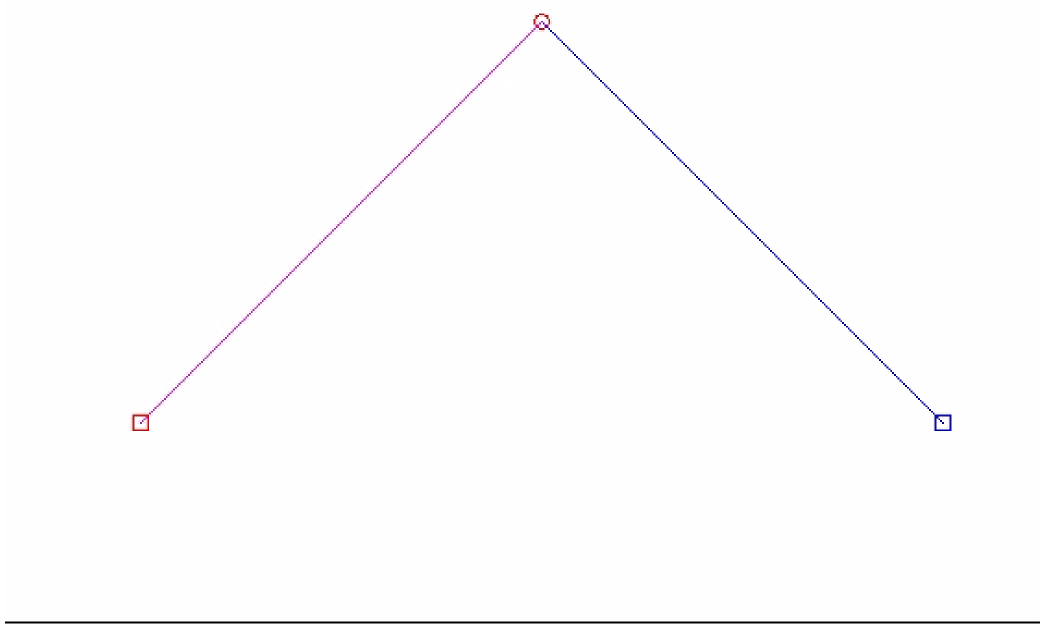
- Length of a rod = 0.5 m

Simulation of the model

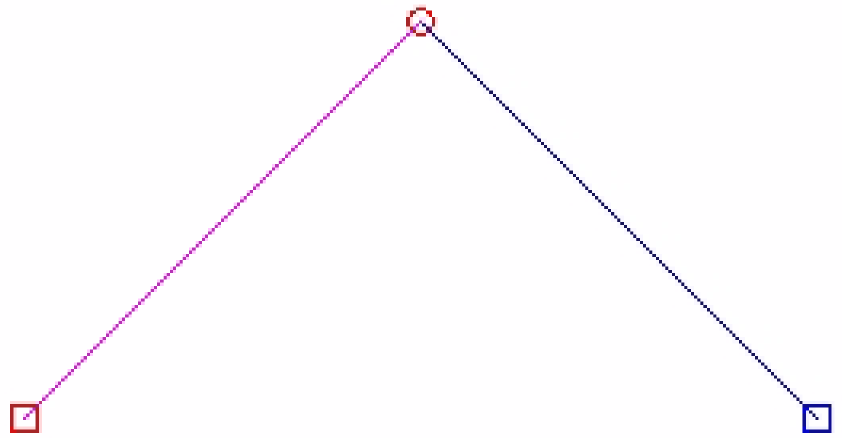
Initial shape to test the model



Validation of spring



The simulation results without external force and damper by activating torsional spring



The simulation with torsional spring and damper

Orbital dynamics and Perturbation

. The modified equinoctial elements

$$\dot{p}_i = \frac{2p}{w}\sqrt{\frac{p}{\mu}}\Delta_{i,t}$$

$$\dot{f}_i = \sqrt{\frac{p}{\mu}}[\Delta_{i,r}\sin L + [(w+1)\cos L + f]\frac{\Delta_{i,t}}{w} - (h\sin L - k\cos L)\frac{g\Delta_{i,n}}{w}]$$

$$\dot{g}_i = \sqrt{\frac{p}{\mu}}[-\Delta_{i,r}\cos L + [(w+1)\cos L + g]\frac{\Delta_{i,t}}{w} - (h\sin L - k\cos L)\frac{f\Delta_{i,n}}{w}]$$

$$\dot{h}_i = \sqrt{\frac{p}{\mu}}\frac{s^2}{2w}\cos L\Delta_{i,n}$$

$$\dot{k}_i = \sqrt{\frac{p}{\mu}}\frac{s^2}{2w}\cos L\Delta_{i,n}$$

$$\dot{L}_i = \sqrt{\mu p}(\frac{w}{p})^2 + \frac{1}{w}\sqrt{\frac{p}{\mu}}(h\sin L - k\cos L)\Delta_{i,n}$$

$$p = a(1-e^2)$$

$$h = \tan(\frac{i}{2})\sin\Omega$$

$$g = e\sin(\omega+\Omega)$$

$$f = e\cos(\omega+\Omega)$$

$$k = \tan(\frac{i}{2})\sin\Omega$$

$$L = \Omega+\omega+\nu$$

Where μ = gravitational constant

Ω = right ascension of ascending node degree

e = eccentricity

ν = true anomaly

a = semi-major axis(km)

ω = argument of perigee

i = Inclination

L = true longitude

p = semi-parameter

J2 Perturbations and Third body

J2 perturbations

$$a_{j2,I} = \frac{\partial R_2}{\partial x_I} = -\frac{3\mu J_2 R_\oplus^2 x_I}{2x^5}(1-\frac{5x_K^2}{x^2})$$

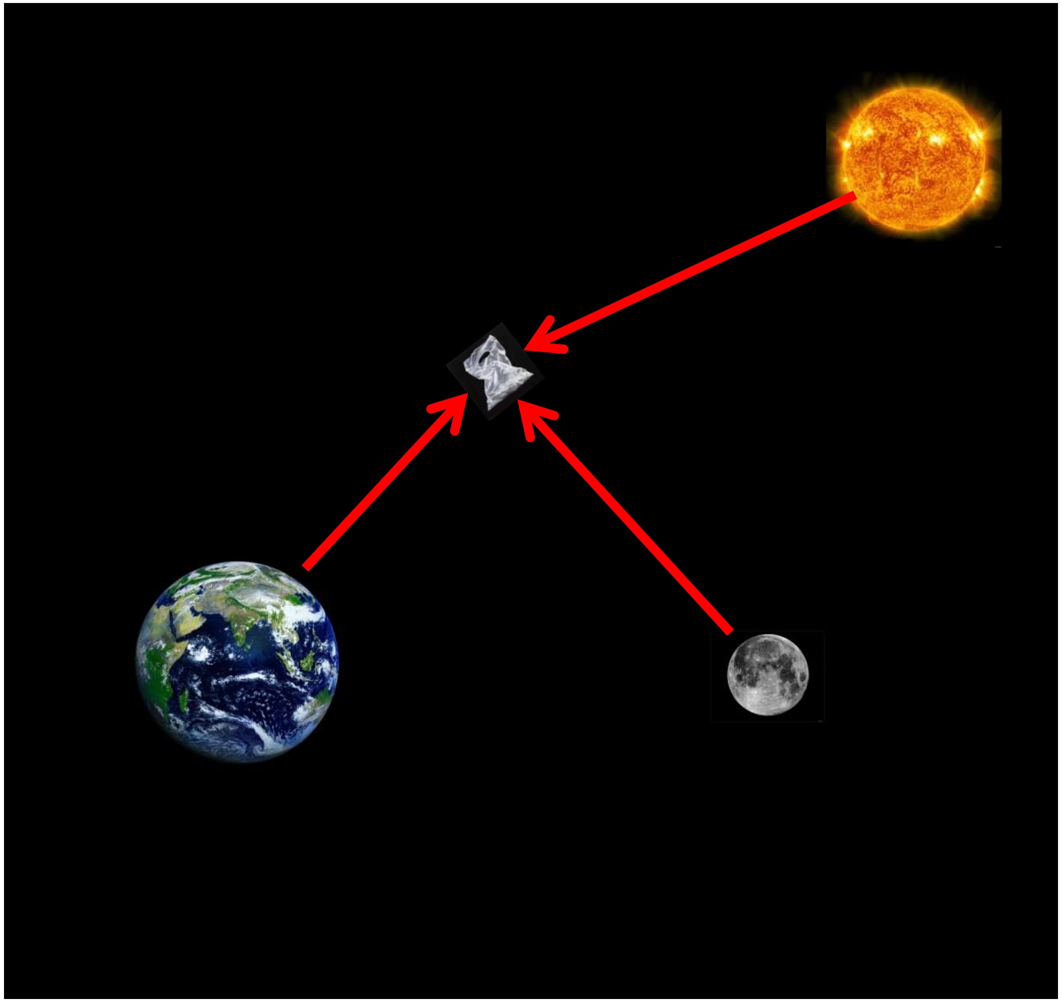
$$a_{j2,J} = \frac{\partial R_2}{\partial x_J} = -\frac{3\mu J_2 R_\oplus^2 x_J}{2x^5}(1-\frac{5x_K^2}{x^2})$$

$$a_{j2,K} = \frac{\partial R_2}{\partial x_K} = -\frac{3\mu J_2 R_\oplus^2 x_K}{2x^5}(3-\frac{5x_K^2}{x^2})$$

The third body

$$\vec{a}_k = -G\sum_{k=1,2} M_k \left[\frac{\vec{x}-\vec{x}_k}{\left|\vec{x}-\vec{x}_k\right|^3} + \frac{\vec{x}_k}{\vec{x}_k^3} \right]$$

Where k = 1 and 2 (Sun and Moon)



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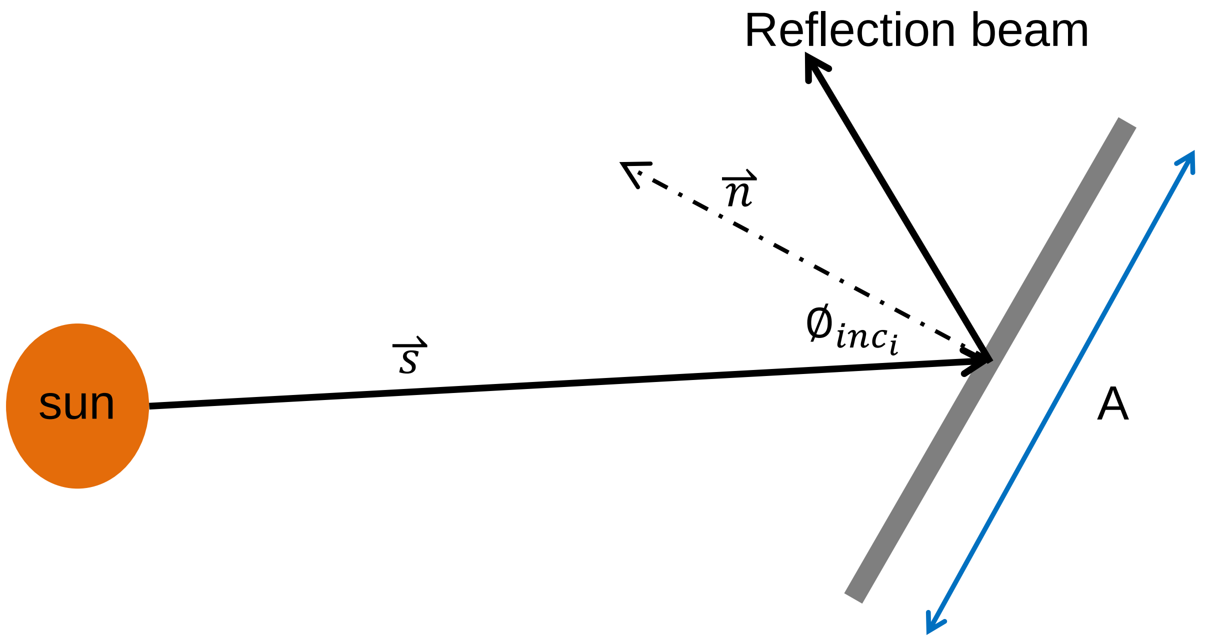
Solar radiation pressure force

$$\vec{F}_{rad} = \sum_{i=1}^{N} \frac{p_{sr} A_i \cos\varnothing}{c} \left\{ 2\left(\frac{C_{Rd_i}}{3} + C_{Rs_i} \cos(\varnothing_{inc_i}) \right) \vec{n} + (1 - C_{Rs_i}) \vec{s} \right\}$$



$\vec{S}_i$ = [1,0,0]

Average solar radiation pressure

Rigid body case

Average SRP force

$$F_{avg} = \frac{1}{4\pi} \int_0^{\pi} \int_0^{2\pi} \vec{F}_{rad,j} \, d\lambda_s \, d\delta_s$$

Equivalent area

$$A_{eq} = \frac{F_{avg}}{P_{SP}(R)}$$

Where

$$P_{SP}(R) = \frac{E}{C} \frac{A_{\oplus}^2}{\left|\vec{x}_i - \vec{x}_{\oplus}\right|^2}$$

Therefore

$$F_{AVG} = -A_{eq} P_{SP}(R) \frac{\vec{x}_i - \vec{x}_{\oplus}}{\left\|\vec{x}_i - \vec{x}_{\oplus}\right\|}$$

Self-shadowing

$$p = l - \frac{d + n \cdot l}{n \cdot (v - l)}(v - l)$$ P

or P = Mv

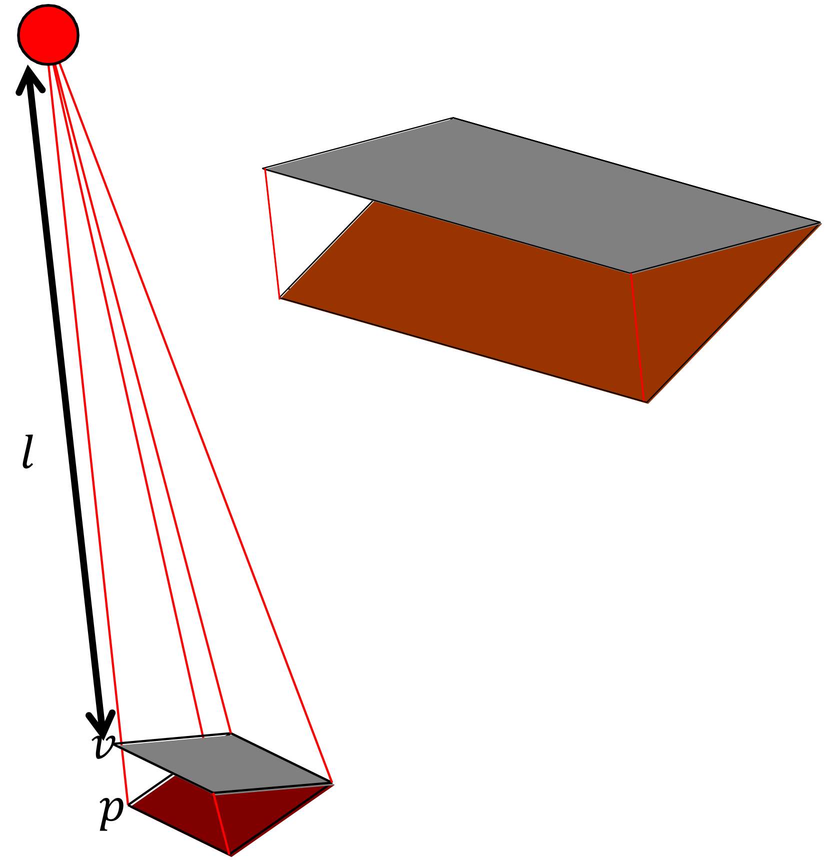
$$M = \begin{bmatrix} n.l + d - l_x n_x & -l_x n_y & -l_x n_z & -l_x d \\ -l_y n_x & n.l + d - l_y n_y & -l_y n_z & -l_y d \\ -l_z n_x & -l_z n_y & n.l + d - l_z n_z & -l_z d \\ -n_x & -n_y & -n_z & n.l \end{bmatrix}$$

Where

p = the projection of vertex v

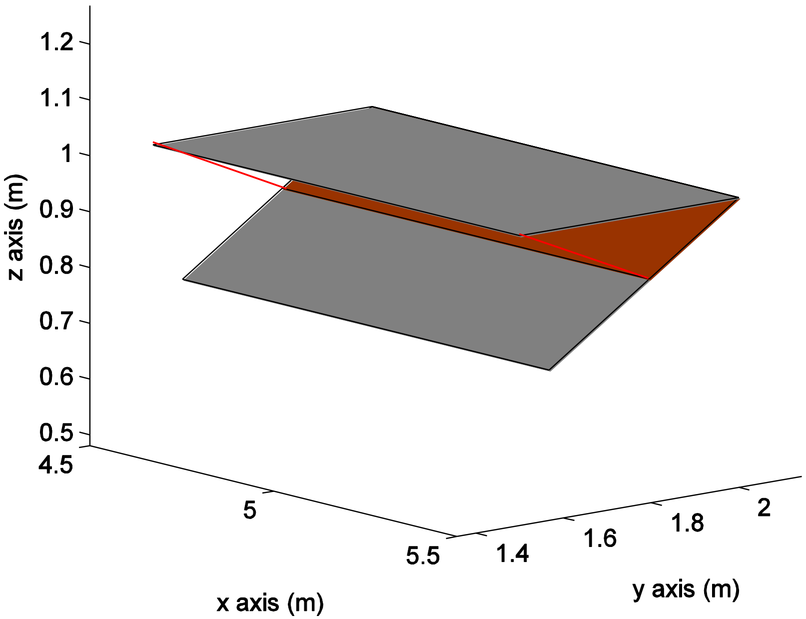
v = Vertex on the plane : $n \cdot x + d = 0$

l = a location of light source

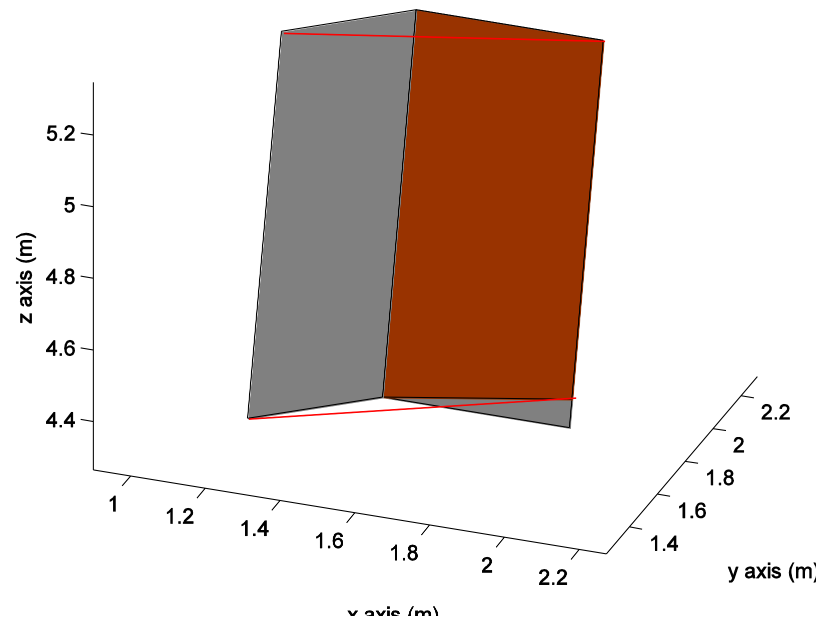


The planar shadow projection , the original technique invented by Blinn [15], allows shadows to be cast on plane surface

Self-shadowing



a) Change position of light source



b) Change the geometry of debris

Simulation

Material properties

Material type		AMR [m2/kg]	Young's Modulus [N/m2]	Cs, Cd, Ca
PET	coated	111.11	8.81×10^9	0.60 0.26 0.14
Kapton	coated	26.30	2.50×10^9	0.60 0.26 0.14
	uncoated	26.30		0.00 0.10 0.90

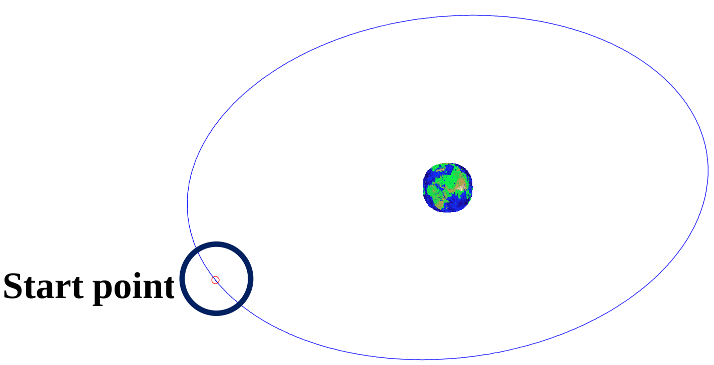
(Sheldahl, *The red book* (2012))

Initial position

Geosynchronous Earth orbit (GEO)

Six element	Value
Semi-major axes(km)	42,164
Mean anomaly(degree)	270°
Argument of perigee(degree)	90°
Ascending node(degree)	60°
Eccentricity	0.0001
Inclination(degree)	5°

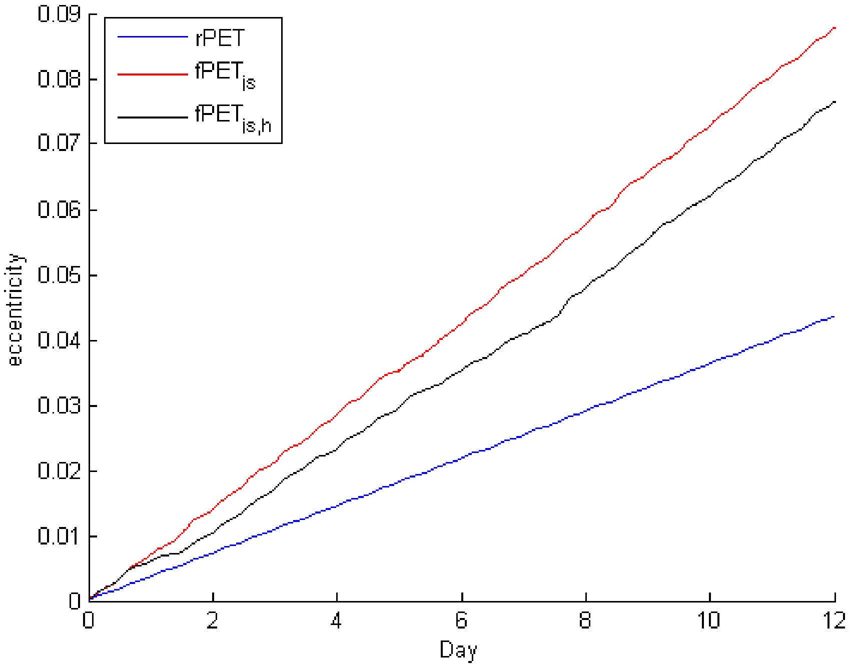
Propagation in 12 days

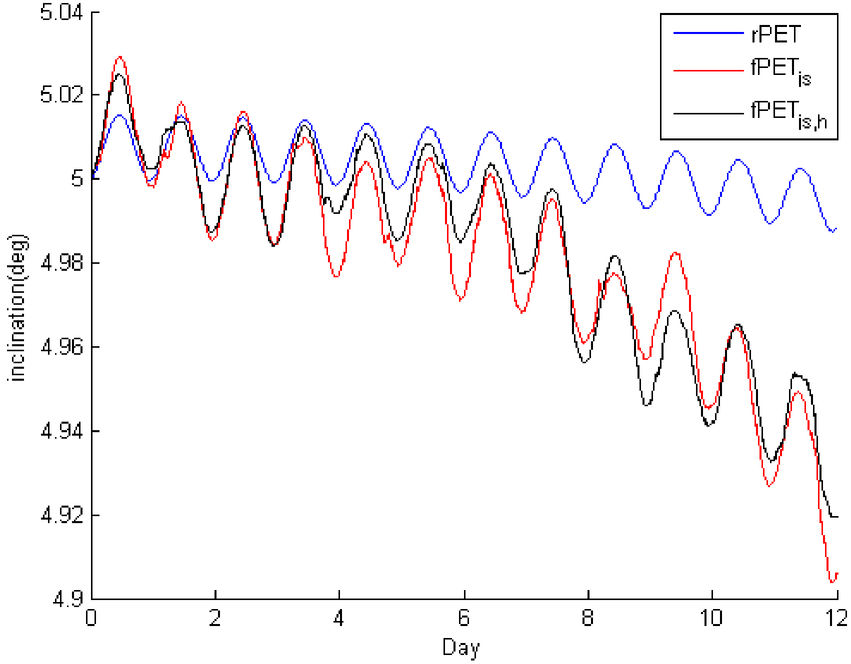


J2 and SRP

Orbital dynamics 12 days

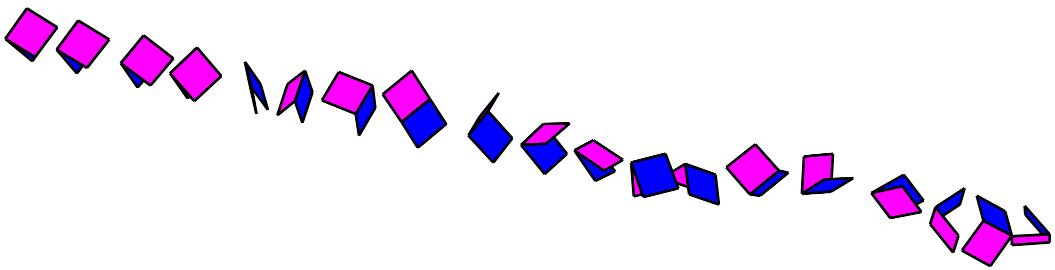
PET

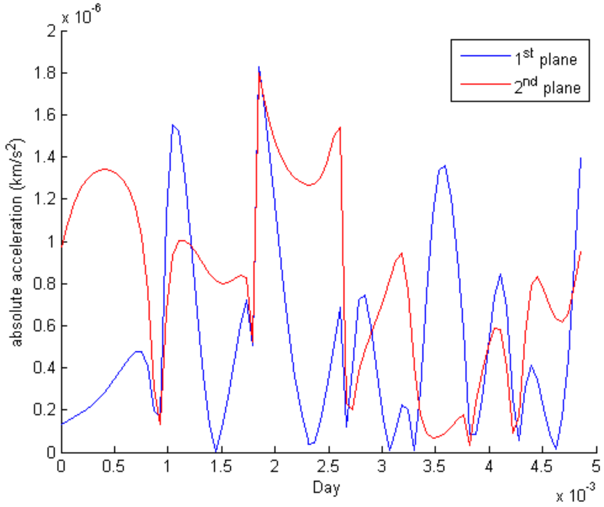


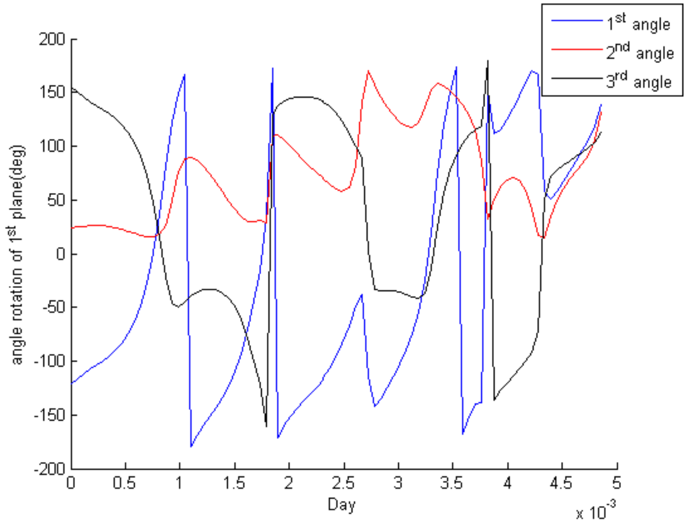


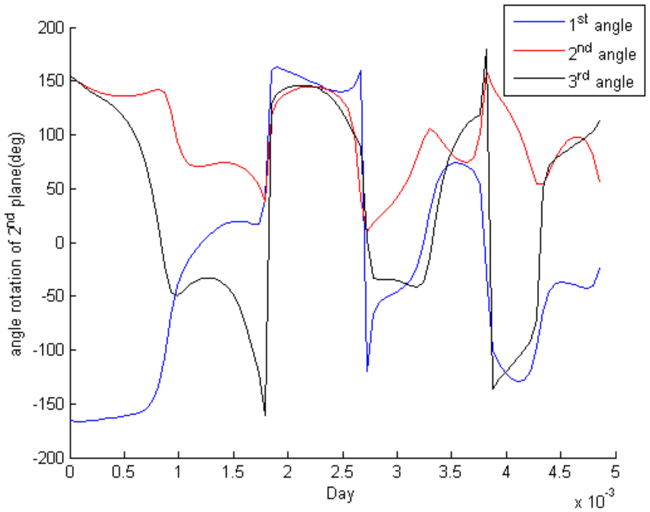
PET without self-shadowing

10 minutes



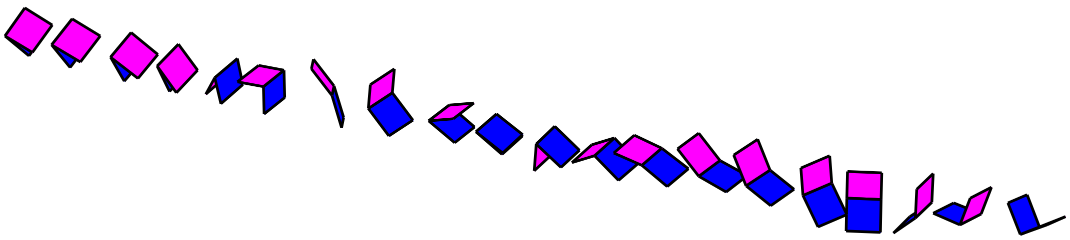


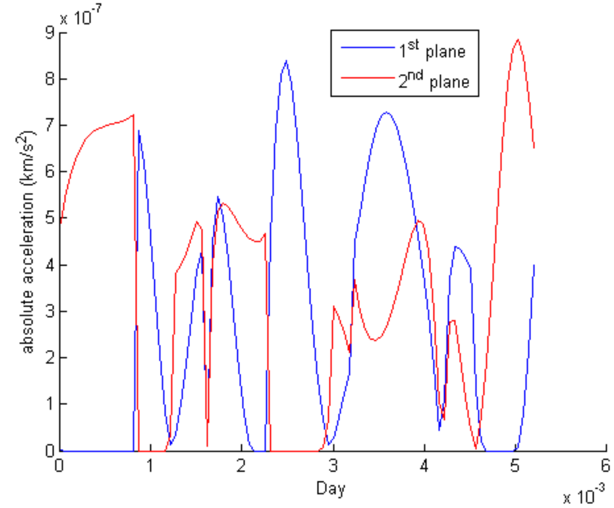


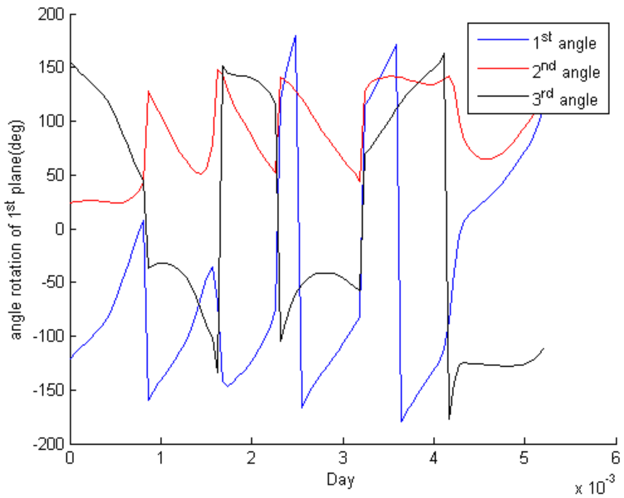


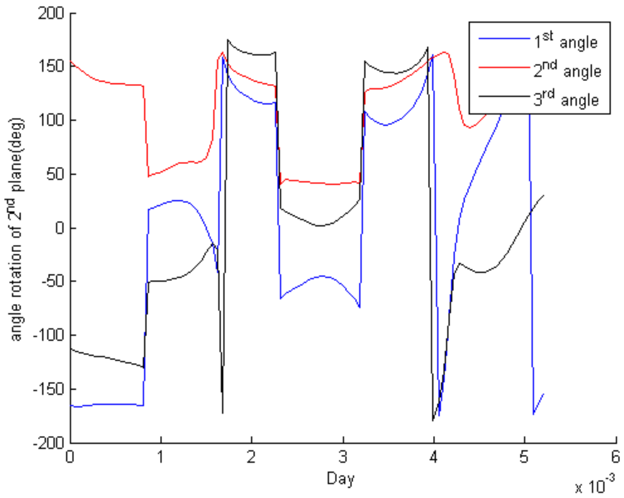
PET with self-shadowing

10 minutes

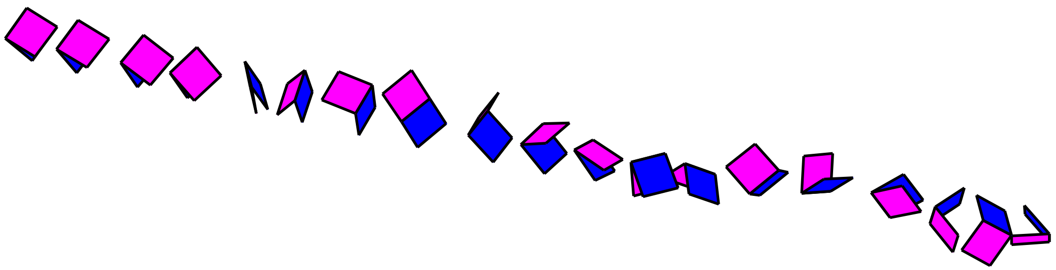




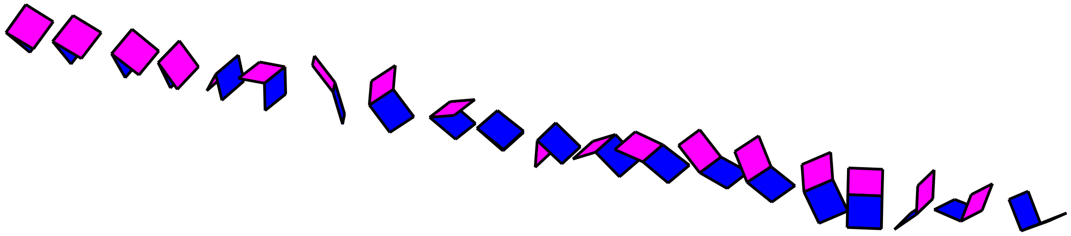




Comparison



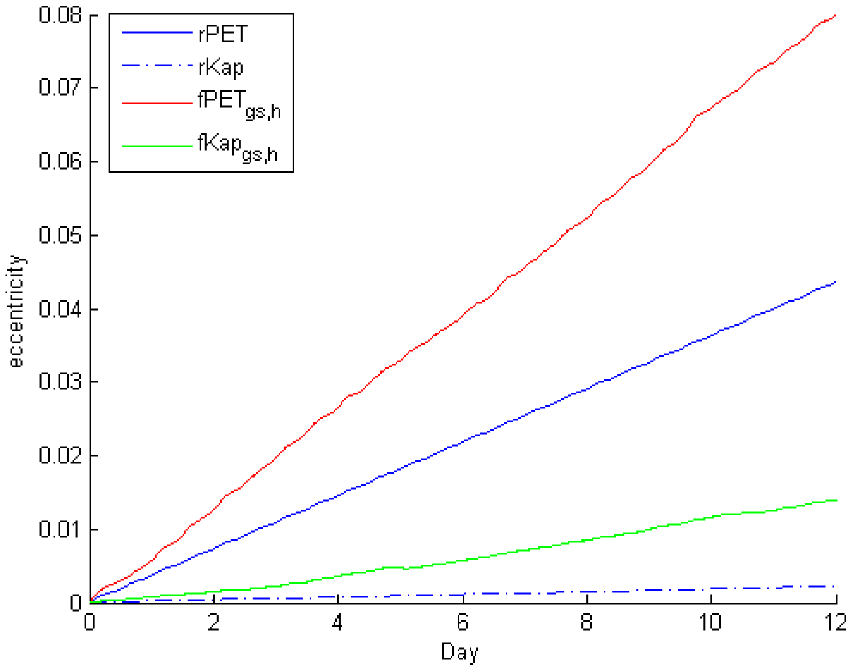
PET without self-shadowing

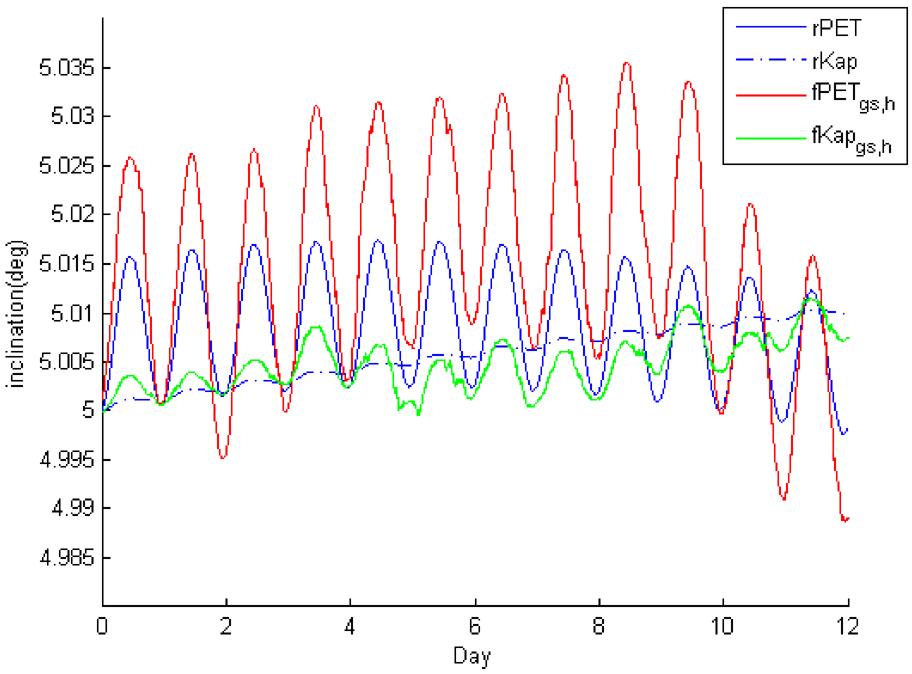


PET with self-shadowing

Orbital dynamics under J2 , third body and SRP

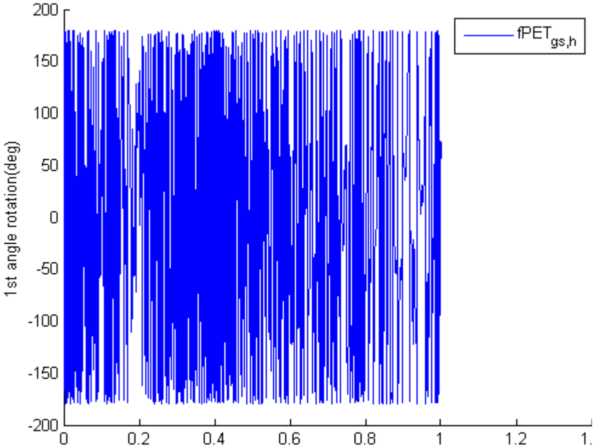
Orbital dynamics 12 days

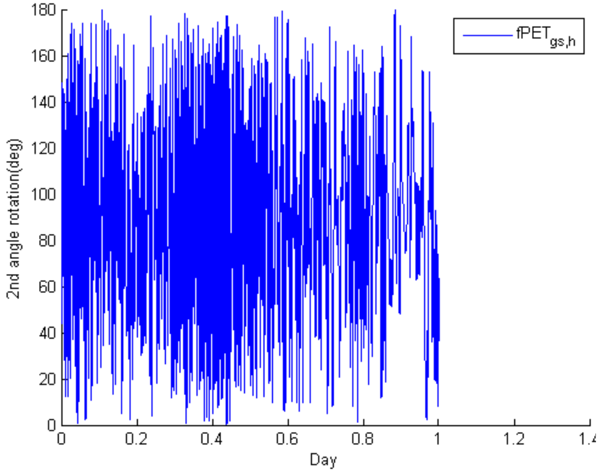


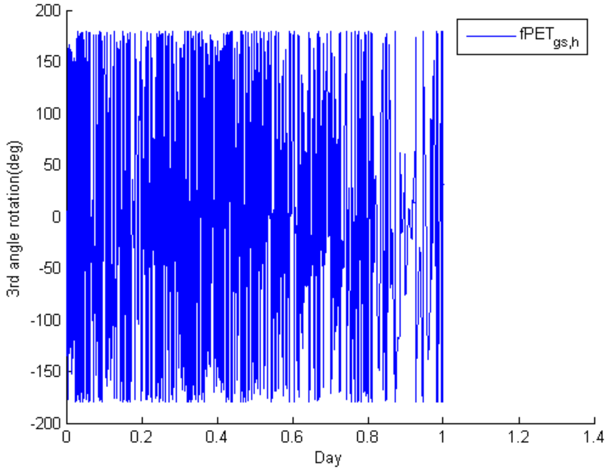


PET Euler angles

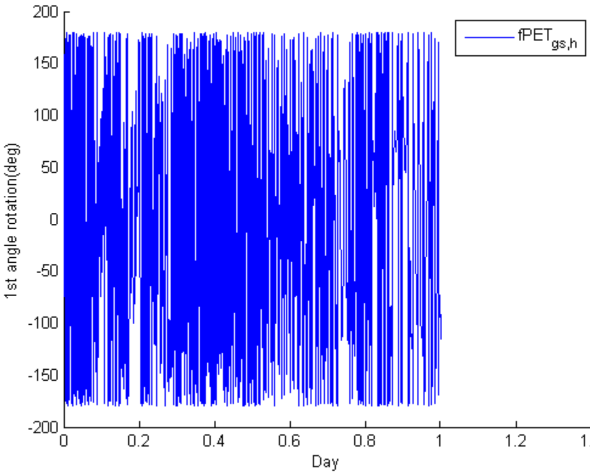
1[st] panel

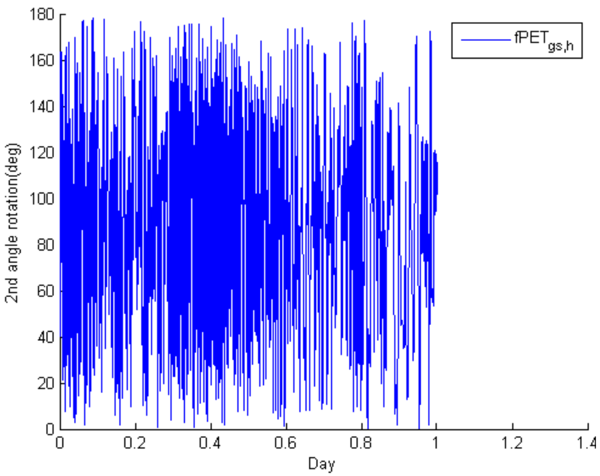


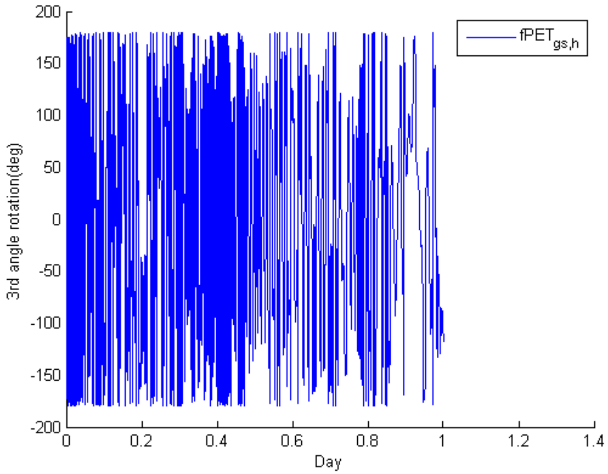




2[nd] panel

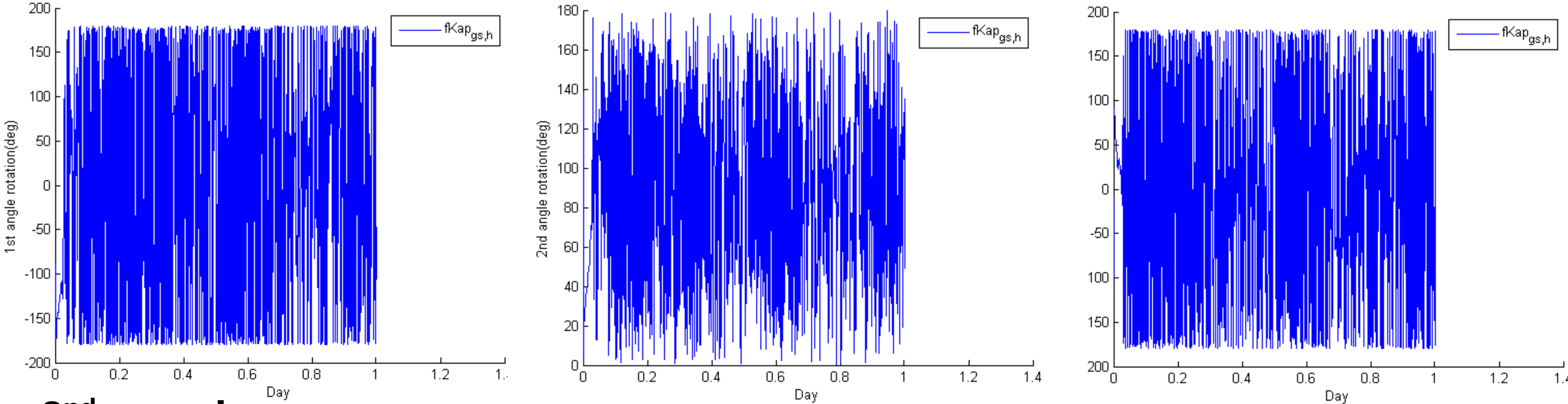




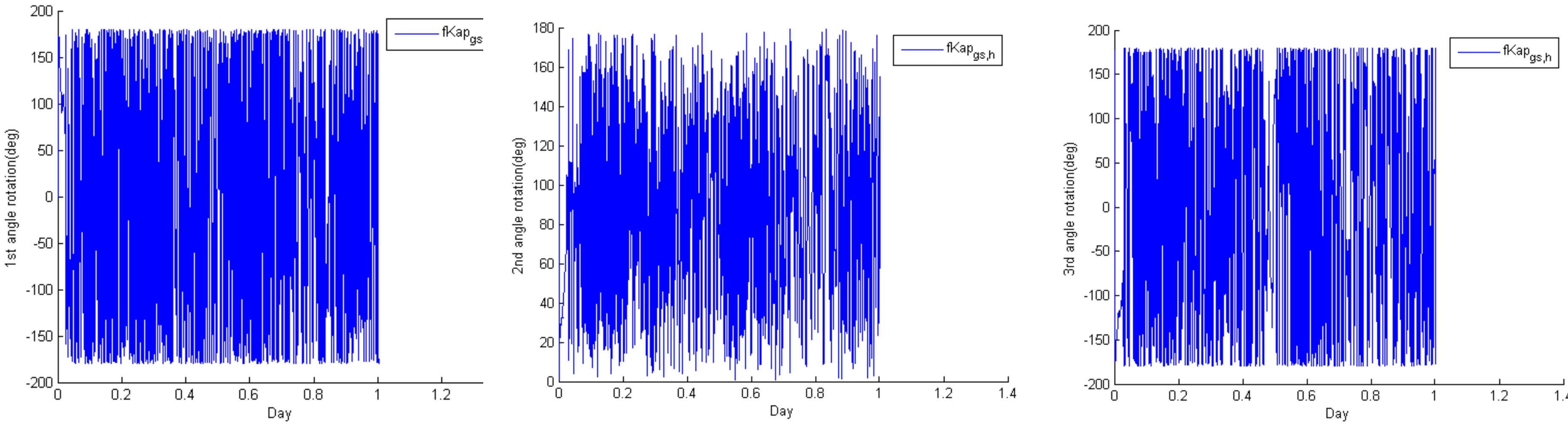


Kapton Euler angles

1st panel



2nd panel



Conclusion

and

Future work

Conclusion

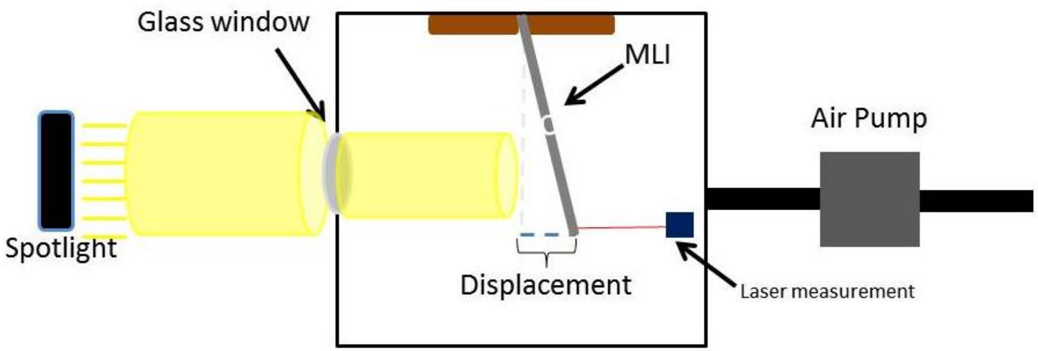
1. **Orbital dynamics of flexible debris is different from that of rigid debris due to the effective area.**

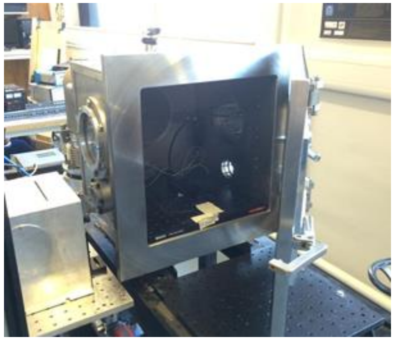
2. **Direct solar radiation pressure is the most effect to the orbital dynamics of HAMR flexible model.**

3. **Self-shadowing effect lead to irregular attitude dynamics and deformation**

Future work

To set the deformation experiment to validate the flexible model





Acknowledge

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Thank you

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