大连理工大学
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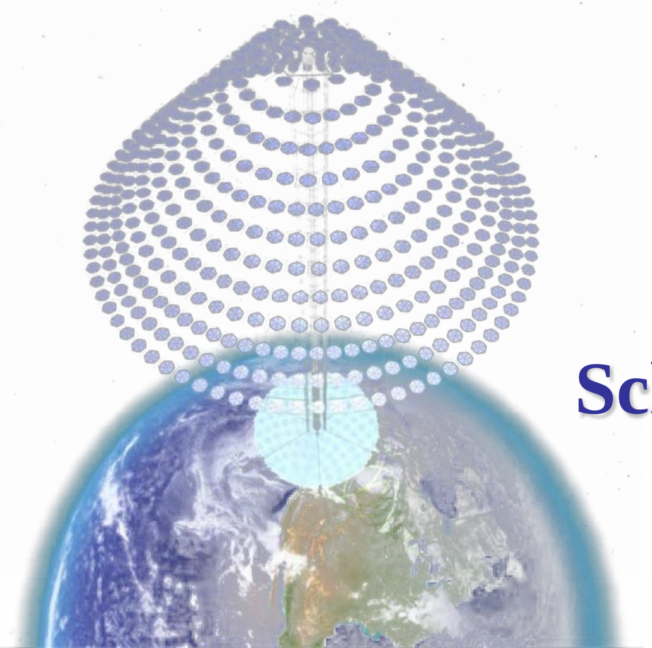
Orbital station keeping control for SPS-ALPHA via electric propulsion and solar pressure



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Team Member Introduction

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Undergraduate students

Advisors

Graduate students

Contents

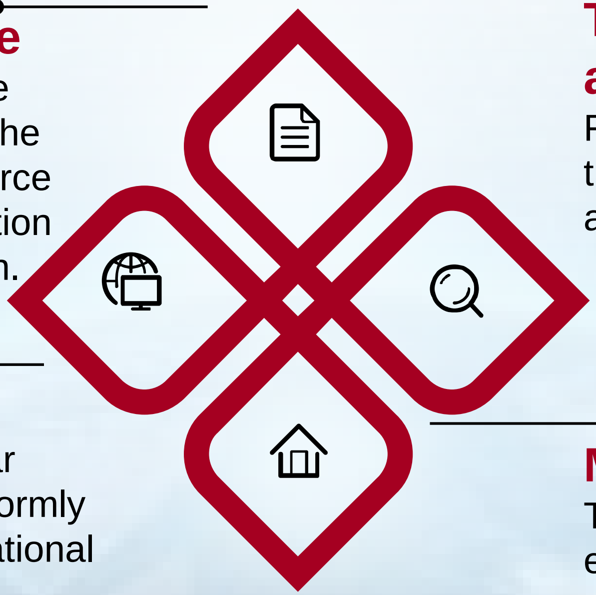
What is our idea

Perturbation Introduction

Major perturbations for SPS on GEO

Solar radiation pressure

Due to the momentum exchange between the solar photons and the SPS, there exist a continuous force acting on the SPS along a direction opposite to that of solar radiation.



Third-body gravitational attraction

For an Earth orbiting satellite, the third-body gravitation are due to the attraction of the Sun and the Moon

terrestrial harmonics

The Earth is actually not a regular sphere, nor does it display a uniformly distributed mass, thus the gravitational field will not be constant. Sphere harmonic series are utilized to represent a more accurate gravitational field. the J2 harmonic term, which represents the oblateness of the Earth's gravity field, is considered as a major perturbation.

Microwave beaming force

The operational SPS sends a high energy beam towards the Earth. This results in a force acting on the SPS. Since we have the microwave beaming acceleration in the opposite direction to the beaming direction

Orbit dynamics analysis

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In a perturbed two-body problem, The orbital shape, orientation varies due to multiple perturbations.

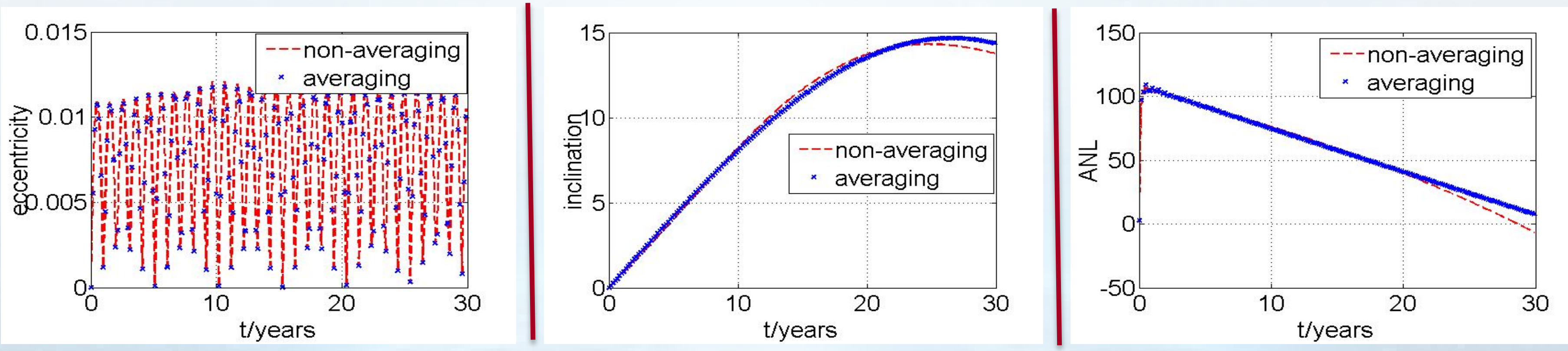

Figure. Integrated effects of the perturbations on eccentricity/inclination/ANL (the results are given by comparison of two methods of dynamical modeling, averaging/non-averaging)

CONCLUSION: in a earth rotating frame, the position of a SPS located on GEO varies with time. Thus, a control tragedy is needed to perform orbital station-keeping.

figures from: **Wen S & Wu S**. the long-term orbit dynamical analysis of a large-scale SPS, 10th Dynamics and Control Congress, Cheng du, China, 2016.

ATMR(area-to-mass ratio) errors seem unignorable since they lead to large changes in SPS orbital parameters, especially in orbital radius and eccentricity.

ATMR	Year 1.5	Error	Year 3	Error
0.286	4.2002	0.0011	4.2186	0.0001
0.296	4.1997	0.0006	4.2186	0.0001
0.306	4.1991	0	4.2185	0
0.316	4.1986	0.0005	4.2185	0
0.326	4.1980	0.0011	4.2184	0.0001

* Unit= 1×10^{4} km

ATMR	Year 1.5	Error	Year 3	Error
0.286	7.6595	-0.5356	1.4317	-0.0991
0.296	7.9273	-0.2678	1.4818	-0.0490
0.306	8.1951	0	1.5308	0
0.316	8.4629	0.2678	1.5817	0.0509
0.326	8.7307	0.5356	1.6316	0.0499

* Unit= 1×10^{-3}

Analysis : (1)ATMR error can perform an approximately linear effect on the orbital elements evolution of SPS;(2) a 3.3% decrease in ATMR value can actually cause orbital radius drifts by about 6 km.

Reversed thinking: by adjusting the ATMR and direction of the reflecting mirror. SRP can utilized to provide thrust and offset other perturbations.

date from :**Wen S & Wu S**, Radice G, Wu Z. Analysis of the influence of area-to-mass ratio error on the orbital motion of a solar power satellite, 67th International Astronautical Congress, Guadalajara, Mexico, 2016， paper no: 31881

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How to Collect the Solar Energy by Rotating the Reflector Modules

Configuration:

Parameters:

reflector: 100 m (hexagon)

offset: 100 m (level)

100 m (vertical)

truss: 13000 m

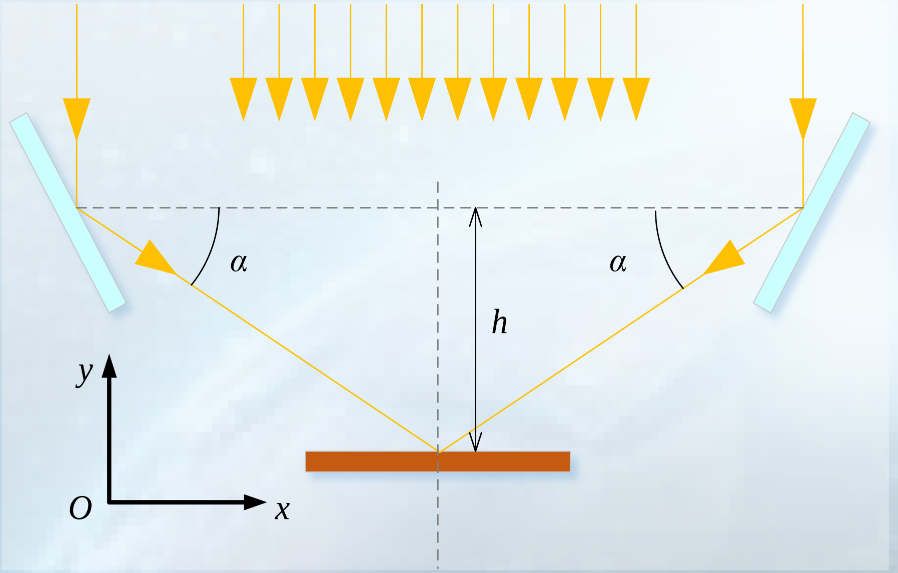
Occlusion:

Critical angles:

①~②:	l(f) r(f)	→		r(f)
②~③:	r(f)	→	l(s)	r(f)
③~④:	l(s) r(f)	→	l(f)	r(f)
④~⑤:	l(f) r(f)	→	l(f)	r(s)
⑤~⑥:	l(f) r(s)	→	l(f)	
⑥~⑦:	l(f)	→	l(f)	r(f)

Note: l: left r: right f: full s:sectional

Ray-tracing:

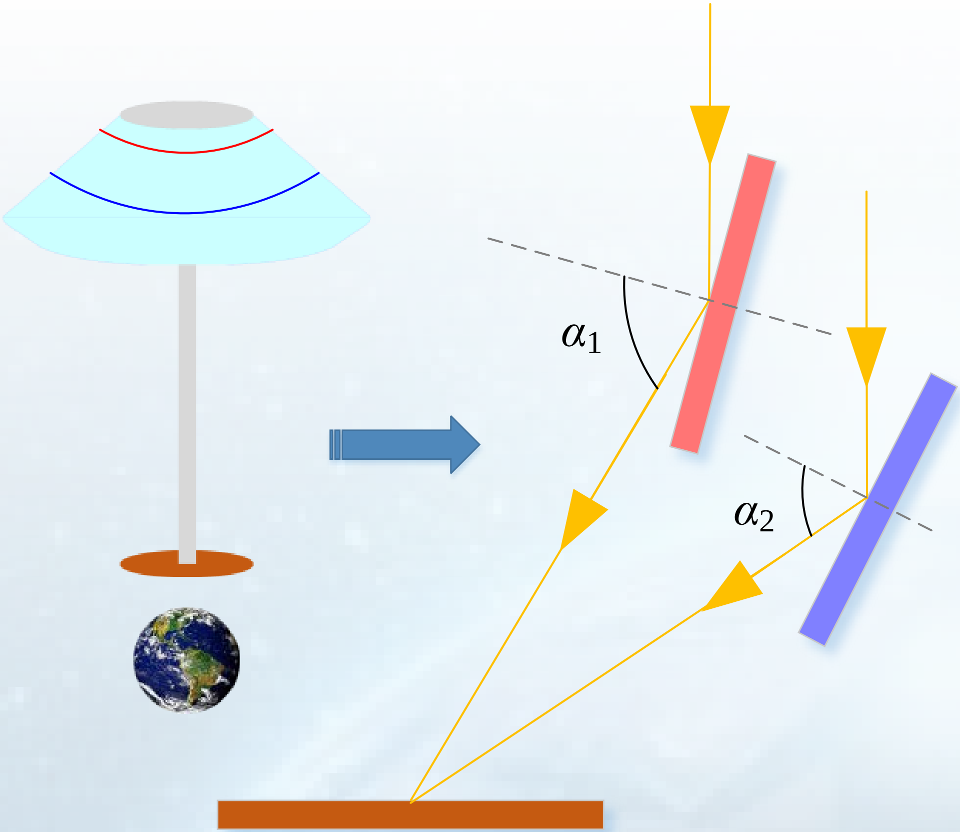


Rotary rule:

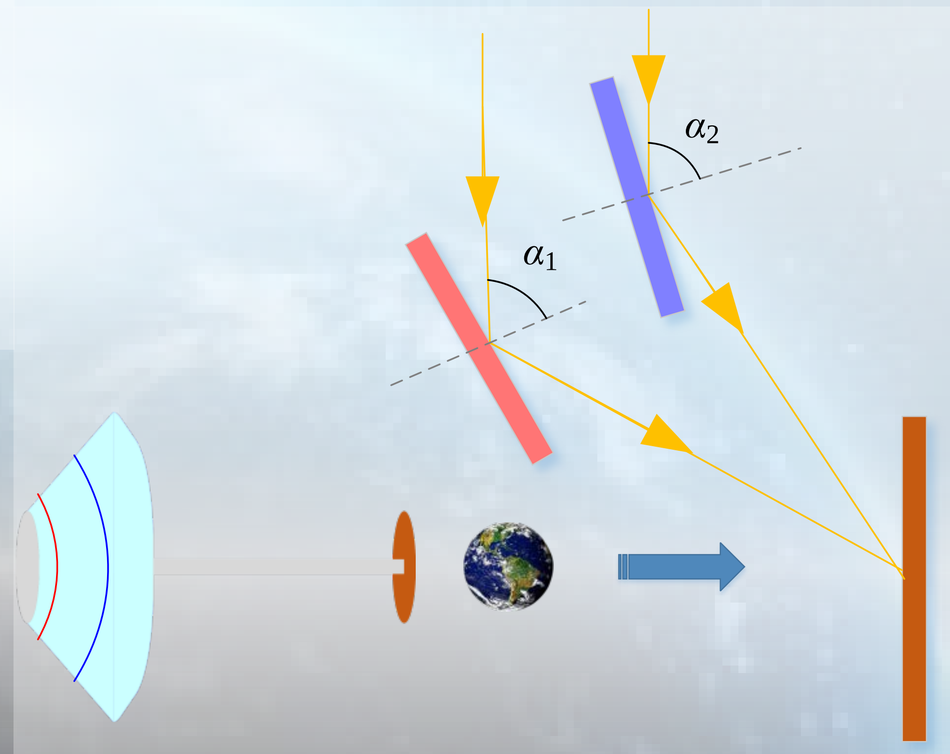
left: $$\frac{270^\circ - \alpha}{2} + \frac{n}{2}t$$

right: $$\frac{90^\circ + \alpha}{2} + \frac{n}{2}t$$

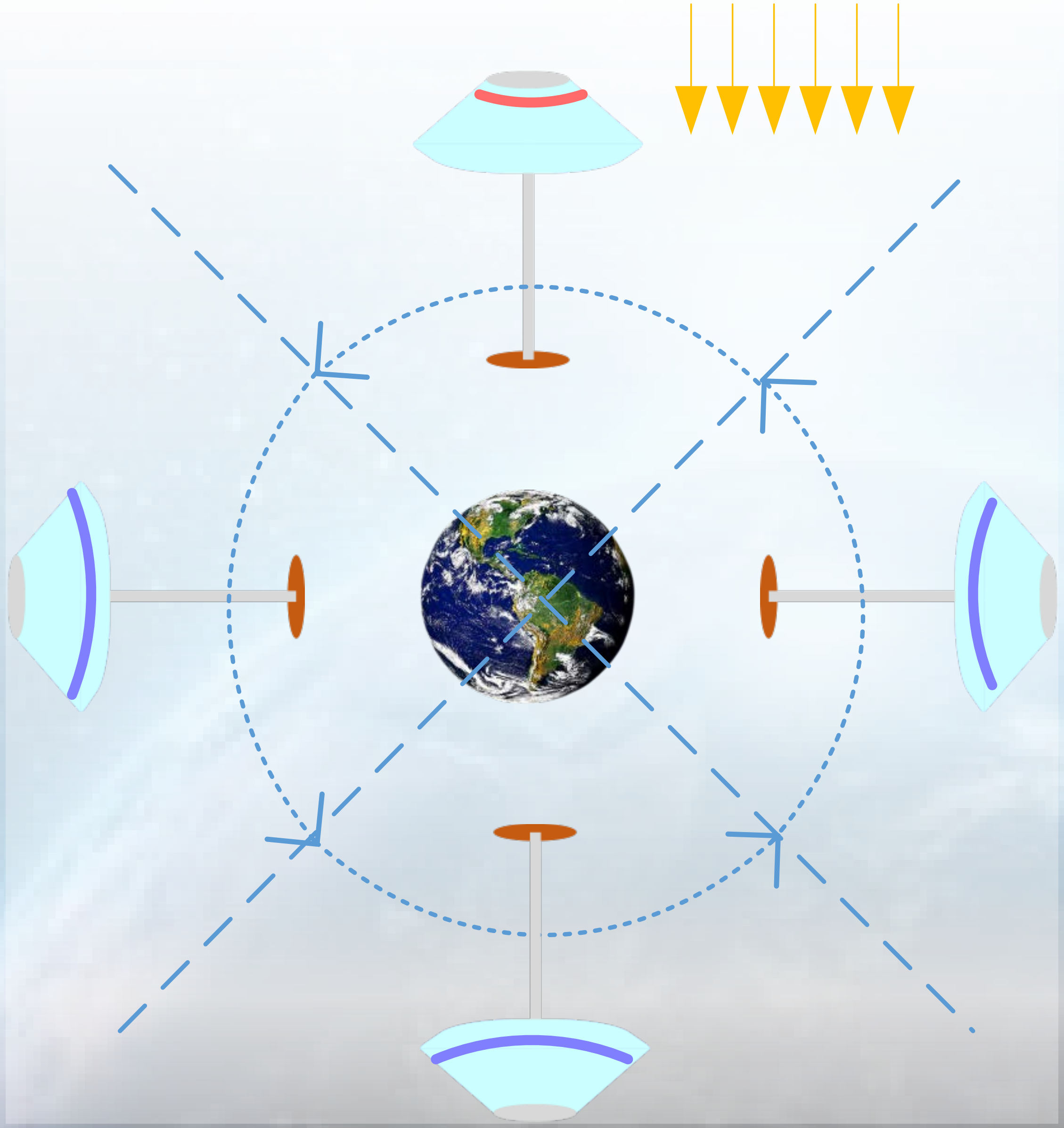
Which Reflectors to be Chosen for Station Keeping



In this case, the effective area of the red reflectors for solar power collection is less than the area of the blue ones. So the red ones are chosen for station keeping.



Oppositely, the effective area of the blue reflectors is less than that of red ones in the right figures. So the blue ones are better choice at this time.



Four districts are divided

- The red line refers to the reflectors close to the center
- The blue lines refer to the reflectors close to the edge

Contents

Influence of Solar Pressure on orbital position of Solar Space Power Station

Other perturbations analysis

Perturbation analysis: describe the perturbating force and it can be dissolved in three directions in a SPS-centered orbital frame

solar radiation pressure

$$\boldsymbol{a}_{\mathrm{SRP}} = P(1+\rho)\left(\frac{A}{m}\right)\frac{\boldsymbol{d}_{\mathrm{s}} - \boldsymbol{r}}{\left|\boldsymbol{d}_{\mathrm{s}} - \boldsymbol{r}\right|^3}$$

terrestrial harmonics

$$\boldsymbol{a}_2 = -\frac{3\mu C_{20}}{2r^4}\left\{\left[1-5(\hat{\boldsymbol{r}}\cdot\hat{\boldsymbol{p}})^2\right]\hat{\boldsymbol{r}} + 2(\hat{\boldsymbol{r}}\cdot\hat{\boldsymbol{p}})\hat{\boldsymbol{p}}\right\}$$

Third-body gravitational attraction

$$\boldsymbol{a}_{\mathrm{p}} = \frac{\mu_{\mathrm{p}}}{d_{\mathrm{p}}^{\,3}}\left[3(\boldsymbol{r}\cdot\hat{\boldsymbol{d}}_{\mathrm{p}})\hat{\boldsymbol{d}}_{\mathrm{p}} - \boldsymbol{r}\right]$$

microwave beaming force

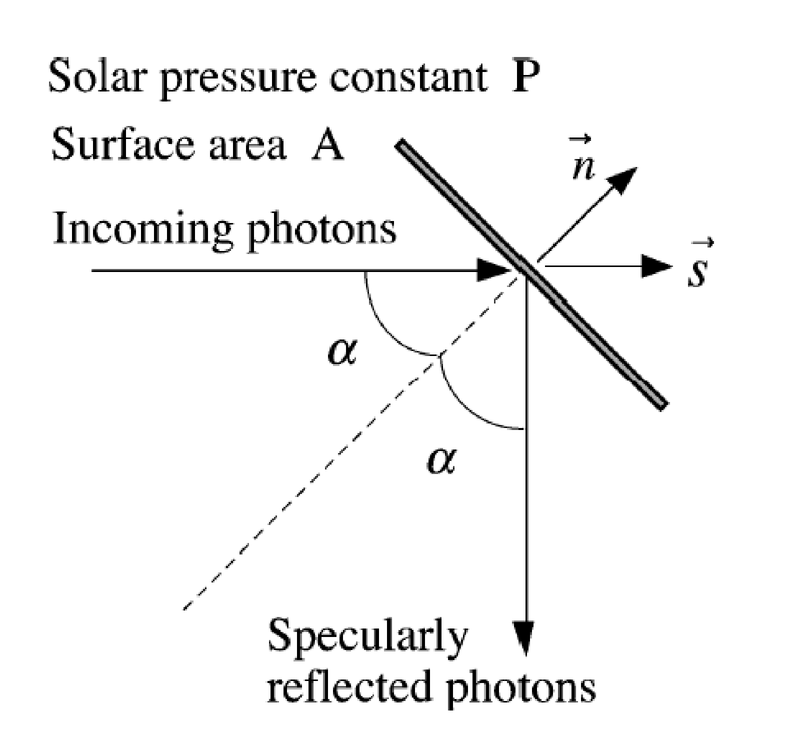
$$\boldsymbol{a}_{\mathrm{c}} = \frac{P}{cm}\hat{\boldsymbol{r}}$$

Magnitude Analysis

Model of Solar Radiation Pressure

The solar radiation pressure forces due to photons impinging on a surface in space, can be expressed:

$$f = PA(\vec{n}\cdot\vec{s})\left\{(\rho_a+\rho_d)\vec{s}+\left[2\rho_s(\vec{n}\cdot\vec{s})+\frac{2}{3}\rho_d\right]\vec{n}\right\}$$



P : nominal solar radiation pressure constant

A : the surface area

$\vec{n}$: a unit vector normal to the surface

$\vec{s}$: a unit vector pointing from the sun to satellite

ρ_s : specularly reflected fraction

ρ_d : diffusely reflected fraction

ρ_a : absorbed fraction

Wie B, Roithmayr C. Integrated orbit, attitude, and structural control system design for space solar power satellites[C]//AIAA Guidance, Navigation, and Control Conference and Exhibit. 2001: 4273.

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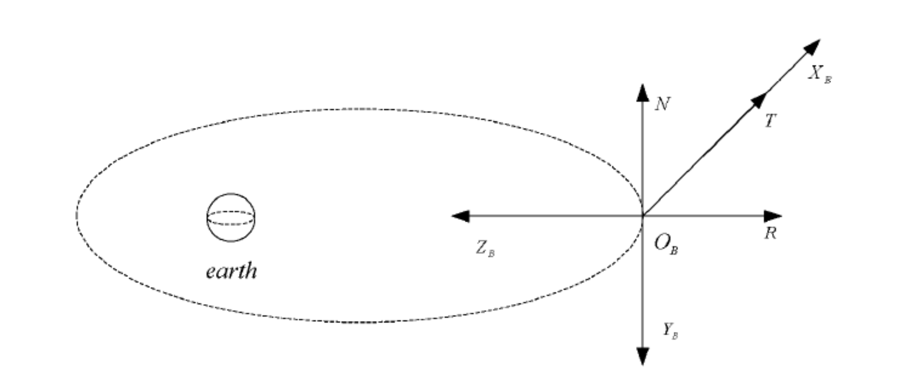
When Reflectors to be Used for Station Keeping to Save Fuel

How to solve station-keeping problem?

Modeling : C-W equation

Linearlized dynamical equation

orbital frame



$$\dot{x} = v_x$$
$$\dot{y} = v_y$$
$$\dot{z} = v_z$$
$$\dot{v}_x = 2\omega v_y + 3\omega^2 x + \frac{F_x}{m} + a_x$$
$$\dot{v}_y = -2\omega v_x + \frac{F_y}{m} + a_y$$
$$\dot{v}_z = -\omega^2 z + \frac{F_z}{m} + a_z$$

$$\Rightarrow \quad \dot{X} = AX + B(u + d)$$

problem definition: a small drift from the desired position. To satisfy least fuel consumption && no thrust limitation.

Problem solving: **LQR** technique is used to perform a rapid maneuver.

How to solve station-keeping problem?

problem definition: a small drift from the desired position. To satisfy least fuel consumption && limitation on the boundry of thrust value.

Problem solving: LQR technique is not proper, and **Gauss pseudo-spectrum && NLP** is used to perform a rapid maneuver.

how to solve it? Scheme is listed as follows:

Step1:Utilise Gauss pseudo-spectrum method and discrete the continuous optimal control problem on several Lagrange point. The initial problem is transferred to a NLP problem.

Step2: Use SNOPT toolbox to solve the NLP problem and get the result of control law which is subject to the constrains in the process of trajectory optimization.

Step3:it is estimated that the control law is a bang-bang control, and we can consider replacing some part of the electrical thrust with solar radiation thrust, thus the SRP can be used to assist station-keeping!

According to the total thrust needed to perform orbital station keeping maneuvers, compute a optimal scheme of mirrors distribution that utilize solar radiation pressure and electric thruster distribution.

Then, the question of orbital station keeping converts into that of optimal distributed location. In order to maximizing solar radiation pressure, the question is expressed as

$$\min \quad J=\sum_{i=1}^{n} T_i$$

$$st. \quad F=\sum_{i=1}^{n} T_i+\sum_{j=1}^{m} f_j\left(\alpha_j\right)$$

$$0 \leq \left\|T_i\right\| \leq T_{\max}$$

$$0 \leq \alpha_i \leq \alpha_{\max}$$

F *is the total thrust needed*

T_i *is the thrust provided by the* i^{th} *electric thruster*

f_i *is the SRP used by the* j^{th} *mirror*

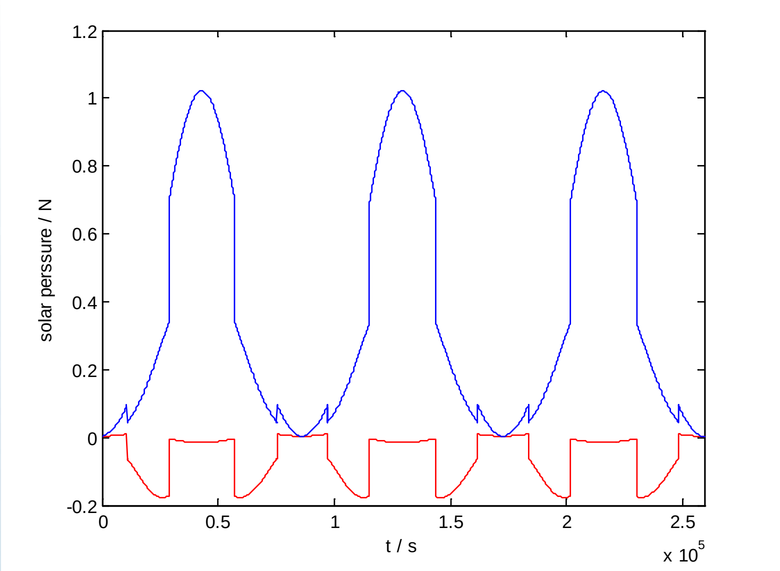
α_i *is the angel between n and s mentioned before*

T_{imax} *is the max thrust allowed*

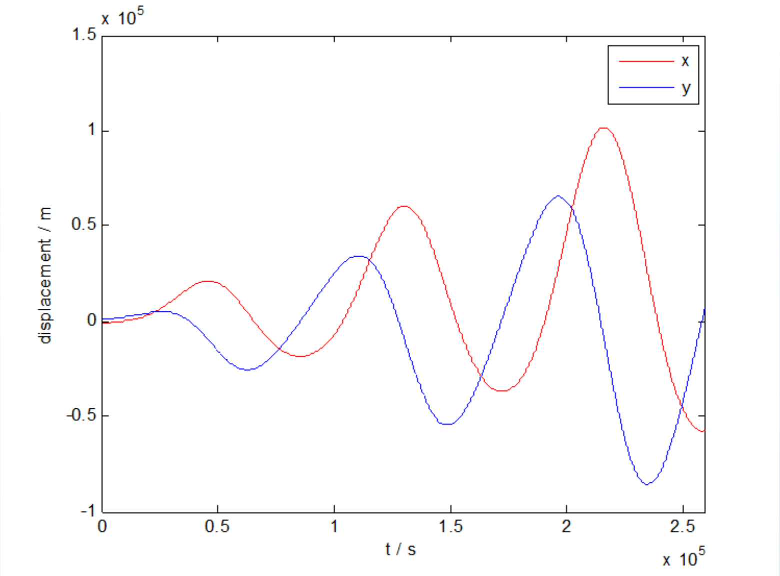
α_{imax} *is the max angel allowed*

Finally, the optimal distributed location(i,j) can be obtained by intelligent algorithm, such as genetic algorithm(GA).

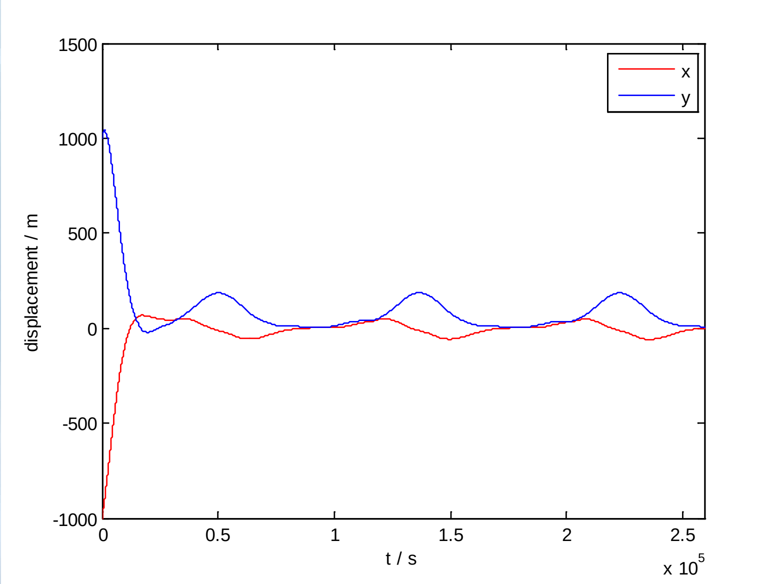
Validation



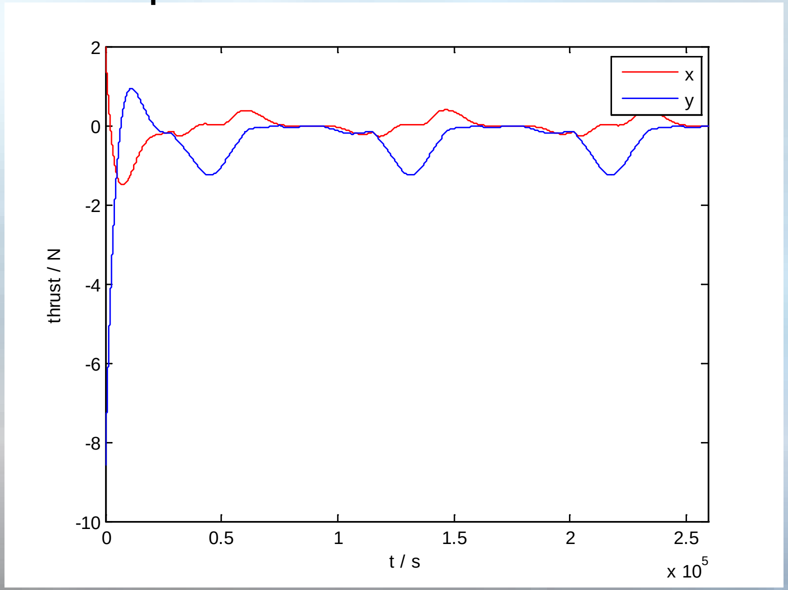
Solar Pressure



Displacement without Control



Displacement under Control



Control Force

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Thank You!