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帯電衛星によるスペースデブリの軌道変換

Orbital change of space debris using the charged satellite

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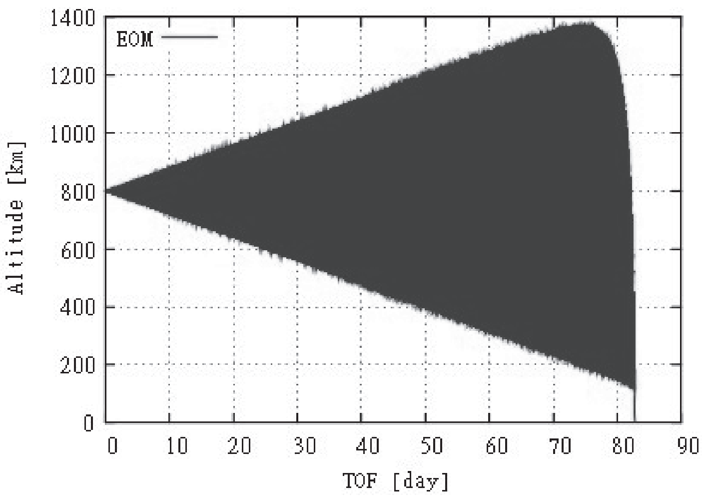
打ち上げで使用したロケット・スペースシャトルの破片や運用を終了して地球の周囲を浮遊している人工衛星等の宇宙ゴミ(スペースデブリ)は増え続けており、近年、能動的なデブリ除去の検討が盛んに行われている。デブリを除去する方法には、例えば、除去衛星を打ち上げてデブリを捕獲し、デブリの軌道を変更させて地球大気圏に突入させる方法がある。しかし、従来から人工衛星で使われているガスジェットを使ってデブリの軌道を変更させるには多量の推進剤が必要となる。そこで本研究では、帯電衛星によるデブリの軌道変換手法を提案する。一般に、宇宙プラズマによる生じる人工衛星の帯電は回避すべき現象であるが、この帯電を能動的に制御してデブリ除去に応用し、帯電衛星と地磁場が干渉して生じるローレンツ力を推力とすることで、推進剤無しでデブリの軌道を変換して大気圏に落下させる手法について検討を行った。

The number of the space debris is increasing every year. Thus, space debris has been a serious environmental problem. This study proposes the way of the orbital change of space debris using the charged satellite which generates a thrust without propellant by utilizing interactions between the charge of the satellite and the Earth's magnetic field.



帯電衛星による軌道変換

5th Workshop of Space Debris
January 22-23, 2013 @ JAXA Chofu

帯電衛星によるスペースデブリの軌道変換

Orbital Change of Space Debris Using the Charged Satellite

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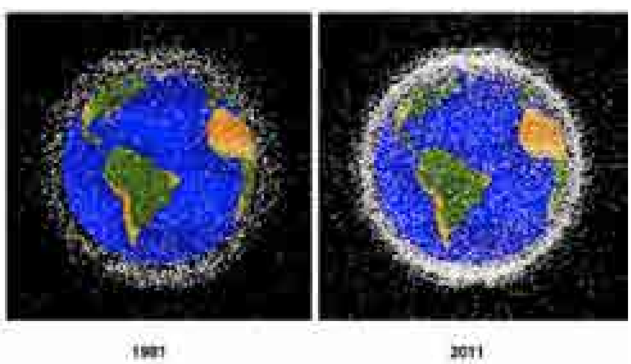
Background

Issue

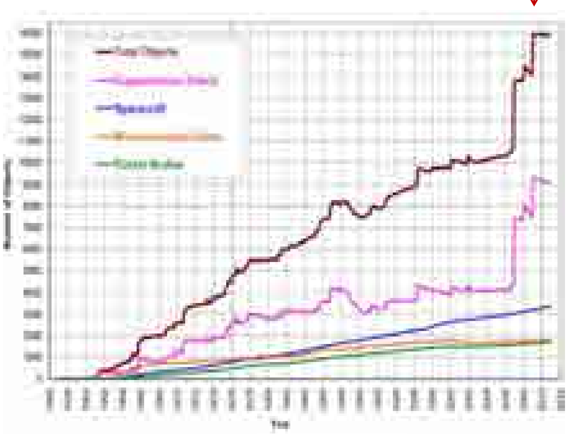
Increasing the Number of Space Debris
(spent rocket fragments and defunct satellites)

Huge problem for space exploration



(NASA)

As of July, 2011
About 16000



(NASA)

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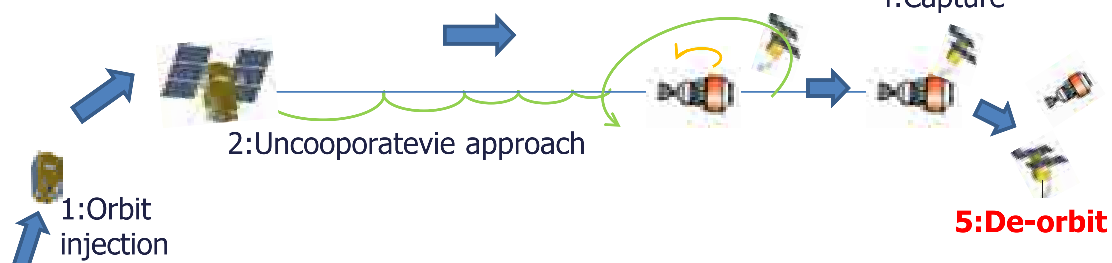
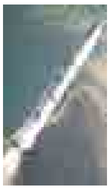
Active Debris Removal

Removal satellite




Launch

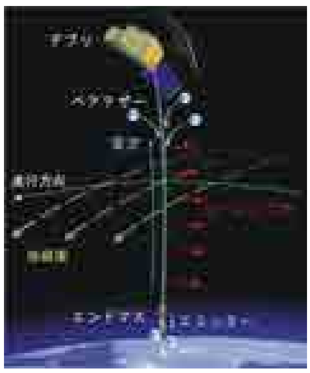
Using a removal satellite,
space debris is captured and is dropped into the Earth's atmosphere by changing its orbit !

Orbital Change

Method

<Chemical Engine>
- ○ Matured technology
- × Large amount of propellant
- × Fix with debris

<ElectroDynamic Tether (EDT)>
- ○ No propellant
- × Extending the tether



Propose

Orbital Change by Charged Satellite (CS)

New method of debris removal using a charged satellite

<Charged satellite>

× Natural charging on satellite due to space plasma should avoid

Generate a large charge on a satellite by ion and electron emitters passively

↓

Control the orbit utilizing the Lorentz force that is obtained
as the Charged Satellite travels through the Earth’s magnetic field

- ○ No propellant
- ○ Small system (ion and electron emitters)
- × Not matured technology

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Objective

To investigate the orbital change of space debris using charged satellite

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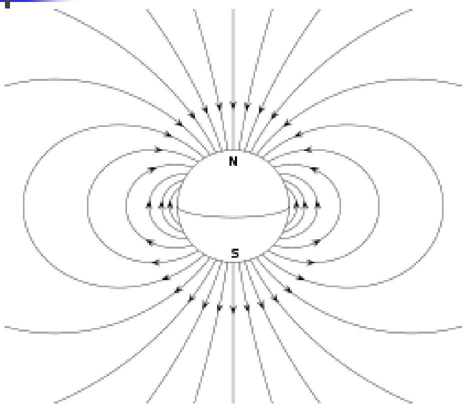
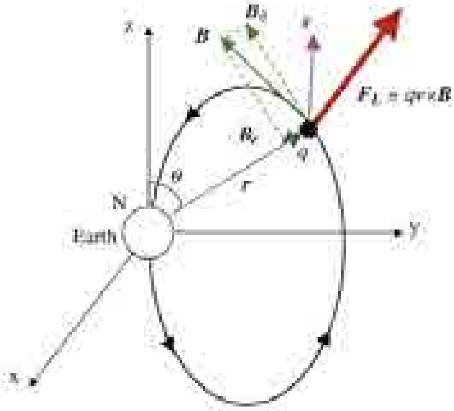
Assumption

Model



Dipolar Approximation
(Not tilted, Rotating with Earth)

$$\mathbf{B} = (B_0/r^3)\left(2\cos\theta\hat{\mathbf{r}} + \sin\theta\hat{\boldsymbol{\theta}}\right)$$



$$\mathbf{F}_L = q(\mathbf{v} - \omega_E \times \mathbf{r}) \times \mathbf{B}$$

Equations of Motion: $\mathbf{a} = \mathbf{F}/m = -\dfrac{\mu}{r^3}\mathbf{r} + \dfrac{q}{m}(\mathbf{v} - \omega_E\hat{\mathbf{n}} \times \mathbf{r}) \times \mathbf{B}$

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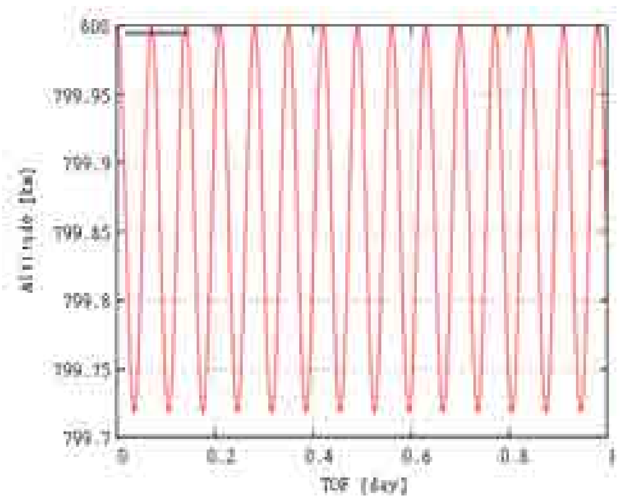
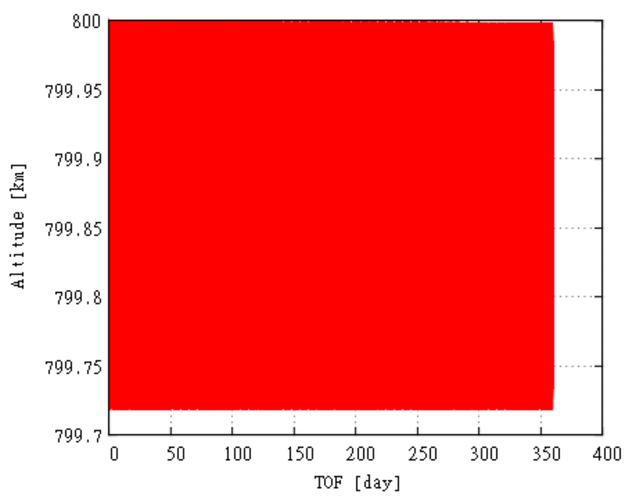
Characteristic of Orbit Change

By Charged Satellite

Initial condition : 800 x 800 km, Inclination = 0 deg (Mass = 500+500 kg)
Charge = -1 C （feasible [Peck]）





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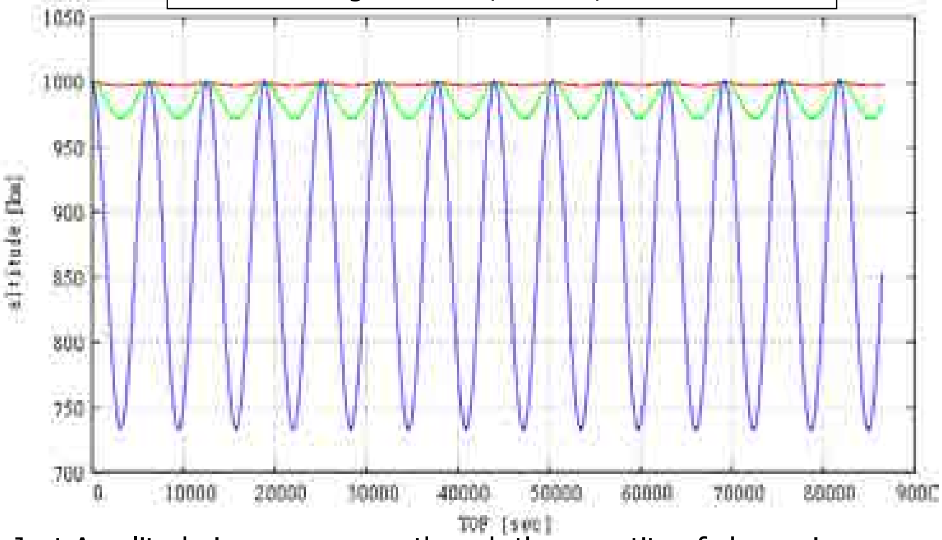
Characteristic of Orbit Change

Sensitive Analysis of Charge Amount

Initial condition：1000 x 1000 km, Inclination = 0 deg (Mass = 1000 kg)

Charge = -10 C, -100 C, -1000 C



Just Amplitude increases even though the quantity of charge increases.
(The quantity is not practical)

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What if Controlling the Charge?

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Linearized Equation of Motion

Control the charge amount periodically

Charge control (periodic) $q = q_0 \sin\omega t$

Conservation of angular momentum $\left[L = mr^2\dot{\theta} \rightarrow \dot{\theta} = \frac{L}{mr^2} \right]$

Equation of Motion (Radial component; No Earth's atmosphere and no inclination)

$$f(r) = \ddot{r} = r\dot{\theta}^2 - \frac{\mu}{r^2} + \frac{B_0}{m}\left(\frac{R_E}{r}\right)^3 (\dot{\theta} - \omega_E) r q_0 \sin\omega_0 t = \frac{L^2}{m^2 r^3} - \frac{\mu}{r^2} + \frac{B_0 L {R_E}^3}{m^2}\left(\frac{1}{r^4} - \frac{m\omega_E}{r^2}\right) q_0 \sin\omega t$$

Linearized around initial altitude, r0

$$f(r_0 + \Delta r) = \ddot{r_0} + \Delta\ddot{r} = \Delta\ddot{r} \approx f(r_0) + \left.\frac{\partial f}{\partial r}\right|_{r_0} \Delta r$$

$$= \left[\frac{L_0^2}{m^2 r_0^3} - \frac{\mu}{r_0^2}\right] + \left[\frac{B_0 L {R_E}^3}{m^2}\left(\frac{1}{r_0^4} - \frac{m\omega_E}{r_0^2}\right) q_0 \sin\omega t\right] + \left\{\left[-3\frac{L^2}{m^2 r^4} + 2\frac{\mu}{r^3}\right] + \left[\frac{B_0 L {R_E}^3}{m^2}\left(-\frac{4}{r^5} + 2\frac{m\omega_E}{r^3}\right) q_0 \sin\omega t\right]\right\} \Delta r$$

$$= 0 + q_1 \sin\omega t + \{-\omega_0^2 + q_2 \sin\omega t\}\Delta r$$

$(\because \omega_0^2 \gg q_2)$

$\therefore \quad \Delta\ddot{r} + \omega_0^2 \Delta r = q_1 \sin\omega t \quad \cdots①$ Forced Oscillation!

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Resonance is occurred!

with charge control period = orbital period

General and particular solution $\Delta r = C_1 \cos\omega_0 t + C_2 \sin\omega_0 t + \frac{q_1}{\omega_0^2 - \omega^2} \sin\omega t$

From initial cond. $\Delta r(0) = C_1 = 0$ $\quad \Delta\dot{r}(0) = C_2\omega_0 = \frac{\omega q_1}{\omega_0^2 - \omega^2} = 0$ $\quad \therefore C_2 = -\frac{\omega}{\omega_0}\frac{q_1}{\omega_0^2 - \omega^2}$

$$\Delta r = \frac{q_1}{\omega_0^2 - \omega^2}\left(\sin\omega t - \frac{\omega}{\omega_0}\sin\omega_0 t\right)$$

$\omega \rightarrow \omega_0$

$$\Delta r = \frac{q_1}{2\omega_0}\left(-t\cos\omega_0 t + \frac{1}{\omega_0}\sin\omega_0 t\right)$$

Secular term --> Resonance is occurred!

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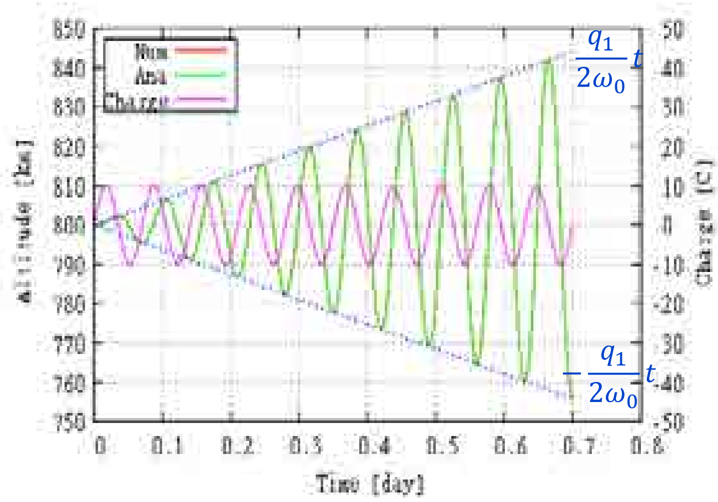
Analytic vs. Numeric

Resonance Oscillation

Initial condition：800 x 800 km, Inclination = 0 deg (Mass = 500+500 kg)
Charge = 1 C （feasible）

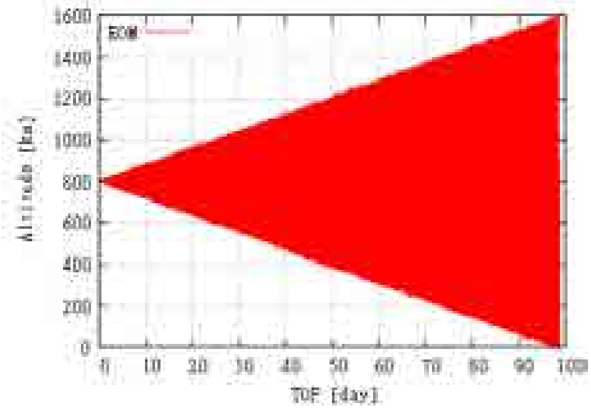


Amplitude increases due to the resonance
when the period of charge control corresponds to the orbital period!

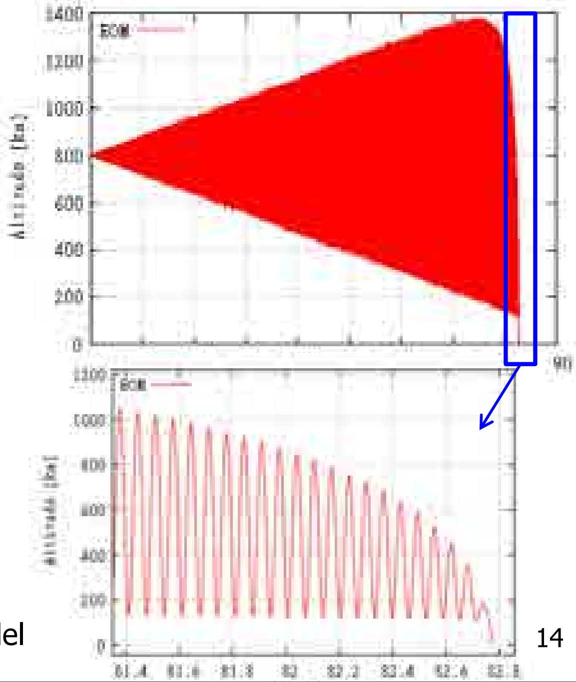
Orbital Charge by Controlled Charged Satellite

Re-entry Time

Without Earth atmosphere



With Earth atmosphere



Charge amount = 1 C
Mass of Debris & CS = 500+500kg
Area = 10 m^2
Coefficient of drag= 2

Atmosphere density = Modified Exponential Model

Comparison between Charged Satellite and Electrodynamic Tethers

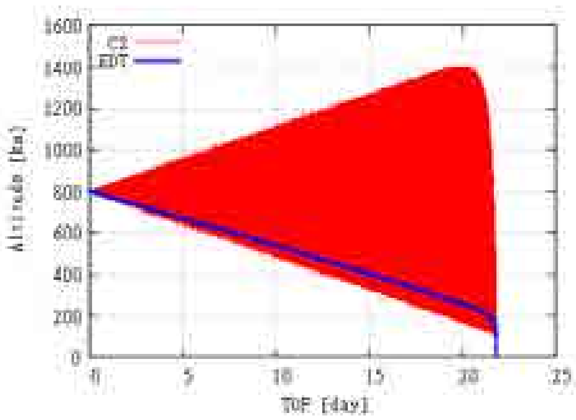
Re-entry Time

Charged Satellite (CS) vs. Electrodynamic Tether (EDT)

Parameters are adjusted so that the re-entry time of CS & EDT becomes equal.
(Altitude=800km, Inclination=0deg, Eccentricity=0)

CS : Charge amount=-3.91C
EDT: Tether length= 10 km, current value= 0.7 A

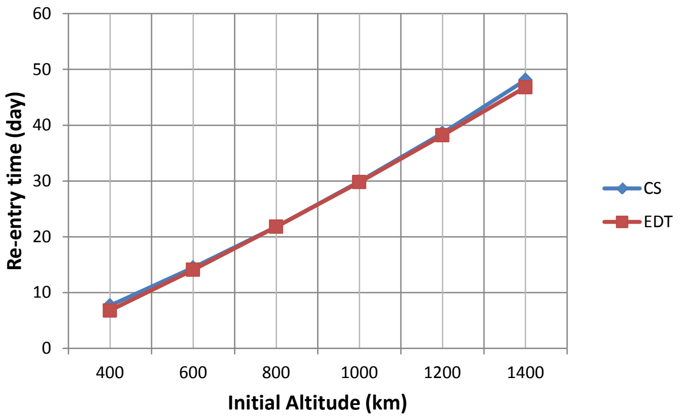
Compare CS with EDT based on this criteria!



Charged Satellite vs. Electrodynamic Tether

Sensitive Analysis of Altitude

<Initial condition>
Inclination = 0 deg, Eccentricity = 0
Charge = -3.91 C, Tether length = 10 km, Current = 0.7 A



Re-entry times of two method are almost same
even the altitude increase !

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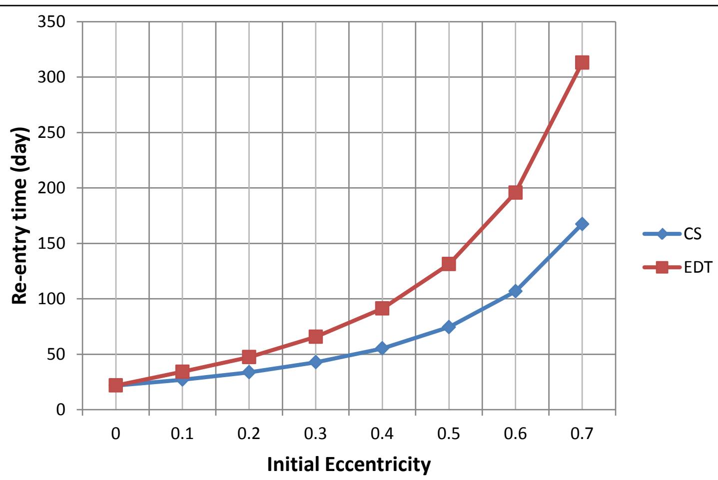
Charged Satellite vs. Electrodynamic Tether

Sensitive Analysis of Eccentricity

<Initial condition>
Altitude = 800 km, Inclination = 0 deg
Charge = -3.91 C, Tether length = 10 km, Current = 0.7 A



Charged satellite is more efficient
with increasing eccentricity !

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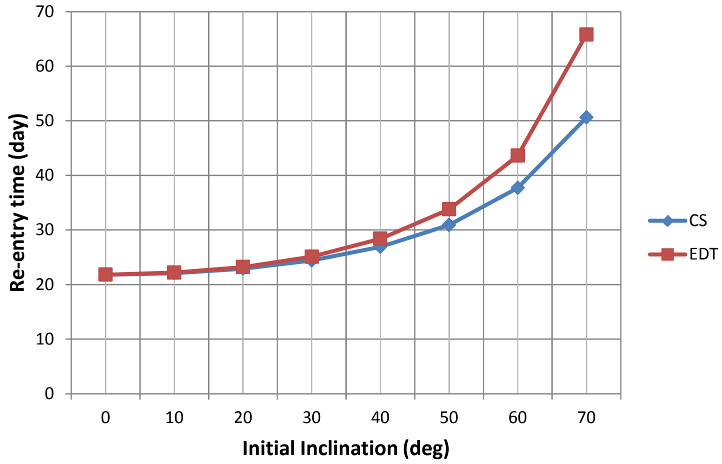
Charged Satellite vs. Electrodynamic Tether

Sensitive Analysis of Inclination

<Initial condition>
Altitude = 800 km, Eccentricity = 0
Charge = -3.91 C, Tether length = 10 km, Current = 0.7 A



Charged satellite is more efficient
with increasing Inclination!

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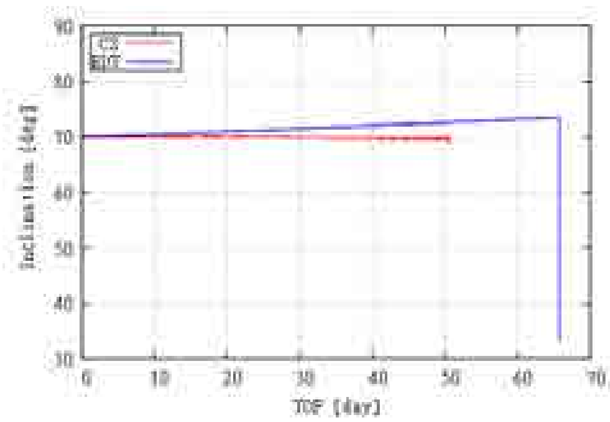
Charged Satellite vs. Electrodynamic Tether

Sensitive Analysis of Inclination

Why CS is more efficient than EDT?



During the orbital change,
the inclination of CS decreases, but that of EDT increases!

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Conclusions

1. Increasing the number of space debris
   → Removal actively by charged satellite!

2. By controlling charge
   → Efficient orbital change by resonance

3. Comparison with Electrodynamic tether
   → Charged satellite is efficient with conditions

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Future Work

1. To derive the approximation solution for the orbit with inclination

2. To analyze the system design of charged satellite

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