Magnetic Plasma De-orbit (MPD) system using MTQs for nano-satellites

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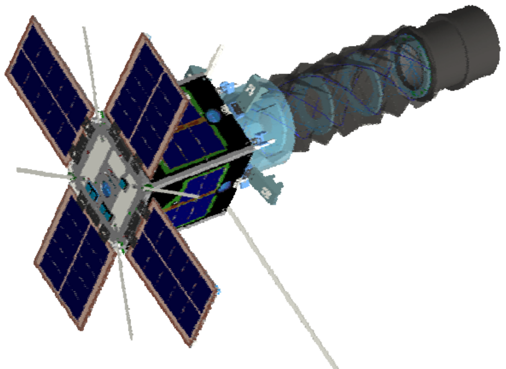
Space applications using nano- and micro-satellites (1kg-100kg)

Features of nano-satellites

- Nano-satellites can be developed and launched with
  - Shorter development time.
  - Smaller costs.

- **Many nano-satellites have been applied to various missions such as**
  - **Remote sensing.**
  - **Astronomical observations.**



More and more nano-satellites will be developed and launched to LEO orbits.

Space debris caused by nano- and micro-satelltíes

- Almost all satellites
  - stay at their orbits after their missions because of small drag forces.
  - cannot install any de-orbit systems because of their strict constraints of mass and cost.

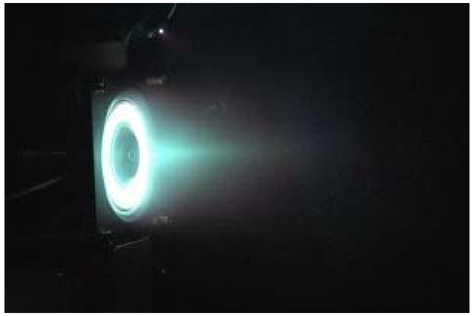
Orbital space debris caused from these satellites are of increasing concern to all satellites.

- Nano-satellites need deorbit systems to prevent generating space debris in their orbits.

Previous methods for the satellite de-orbit

Deorbit using thrusters

- Nano-satellites achieve the deorbit using a propulsion force.
- Nano-satellites need additional propellant for the deorbit.



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Deorbit using an air drag force

- Nano-satellites achieve a large area and make a large air drag force in orbit with extensible structures.
- Nano-satellites need additional structures for the deorbit.

Few nano- satellites have de-orbit systems, because they make nano-satellites larger mass, higher cost, and lower reliability satellites.

Requirements for deorbit systems in nano-satellites

The reasons why nano-satellites cannot utilize the previous deorbit systems

- For the deorbit operation, nano-satellites need **additional** thruster, propellant, and structures.
  - larger mass,
  - higher cost,
  - lower reliability caused by complicated deorbit components.

Requirements for deorbit systems

Satellites

- do not need additional components（or small costs for additional components）.
  - The deorbit components should not decrease the probability of mission success.
- can obtain an effective force for the deorbit to complete the operation relatively small period.

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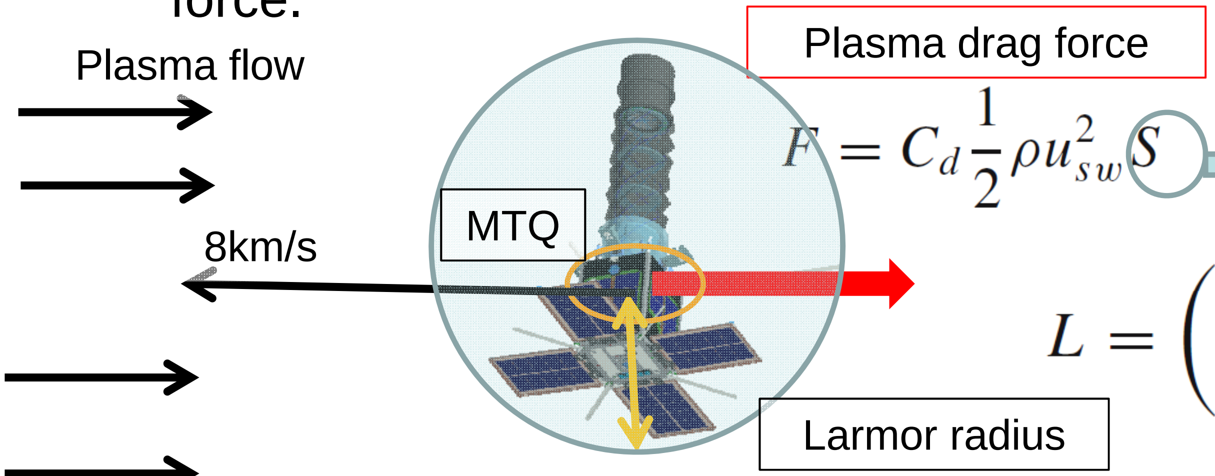
Magnetic Plasma Deorbit (MPD)
Satellite Deorbit using in-orbit Plasma

- Nano-satellite generates a magnetic moment using MTQs which interacts with the space plasma in a LEO orbit and makes a drag force.



$$F = C_d \frac{1}{2} \rho u_{sw}^2 S \Rightarrow \pi L^2$$

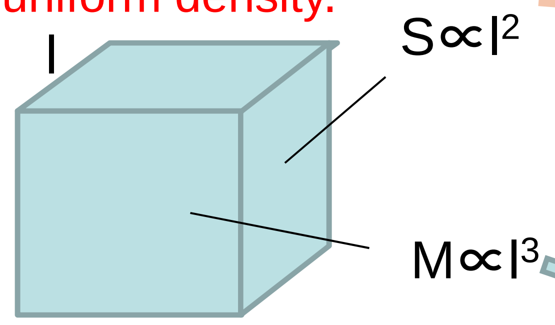
$$L = \left(\frac{M_d^2}{8 \mu_0 \pi^2 n \, m_i \, u_{sw}^2} \right)^{1/6}$$

Ikkoh Funaki · Hidenori Kojima · Hiroshi Yamakawa · Yoshinori Nakayama · Yukio Shimizu, "Laboratory Experiment of Plasma Flow Around Magnetic Sail", Astrophys Space Sci (2007) 307:63–68

- Satellites do not need to install additional components for the de-orbit operation.
  - Almost all nano-satellites generally utilize MTQs for their attitude control system.
- The proposed method can be utilized in many nano-satellites.

Scale dependency of the proposed MPD method

A satellite is assumed to be uniform density.



Relationship between the satellite scale and the drag force.

- $F \propto M_d^{2/3} \propto S^{2/3} \propto l^{4/3}$

The strength of the MTQ is assumed to be proportional to *S*

The satellite can make a stronger force in larger satellites.

Plasma drag force

$$F = C_d \frac{1}{2} \rho u_{sw}^2 S \quad \pi L^2$$

$$L = \left(\frac{M_d^2}{8 \mu_0 \pi^2 n \, m_i \, u_{sw}^2} \right)^{1/6}$$

Relationship between the satellite scale and the acceleration.

- $a \propto F/M \propto l^{4/3}/l^3 \propto l^{-5/3}$

The satellite can make larger acceleration for orbit control in smaller size satellites.

The proposed magnetic plasma deorbit is more effective in smaller satellites

Analysis using a simple model

Assumption ①
The density of the space plasma is assumed to be constant in time. The density is assumed to be as follows:

$$\rho = \rho_r \exp\left(-\frac{a^{0.5} - a_r^{0.5}}{H}\right)$$

ρ: plasma density
a: semi-major axis

Perturbation equation for the semi-major axis:

$$\frac{da}{dt} = \frac{2a^2 v}{\mu}\frac{f}{m}$$

Here the equation is:

$$\frac{da}{dt} = -\frac{2a^2 v}{\mu}\frac{1}{2m}C_d \rho S v^2$$

m: satellite mass
v: satellite velocity
μ: standard gravitational parameter
C_d: drag coefficient

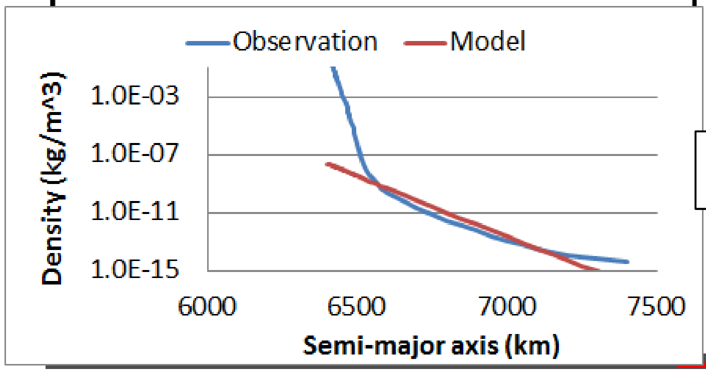
Assumption ②
The orbit is assumed to be a circular orbit

$$v = \sqrt{\frac{\mu}{a}}$$

The perturbation of orbital parameters except for semi-major axis is ignored.

Assumption ③
Plasma drag force

$$F = C_d \frac{1}{2}\rho u_{sw}^2 S$$



Analytical solution

$$a = H^2\left(\ln\left(\frac{-C_d S \mu^{\frac{1}{2}} \rho_r \frac{1}{m} t + C_0}{2}\right) + a_r^{\frac{1}{2}}\right)^2 \qquad C_0 = 2\exp\left(\frac{a_0^{\frac{1}{2}} - a_r^{\frac{1}{2}}}{H}\right)$$

Result of the analysis

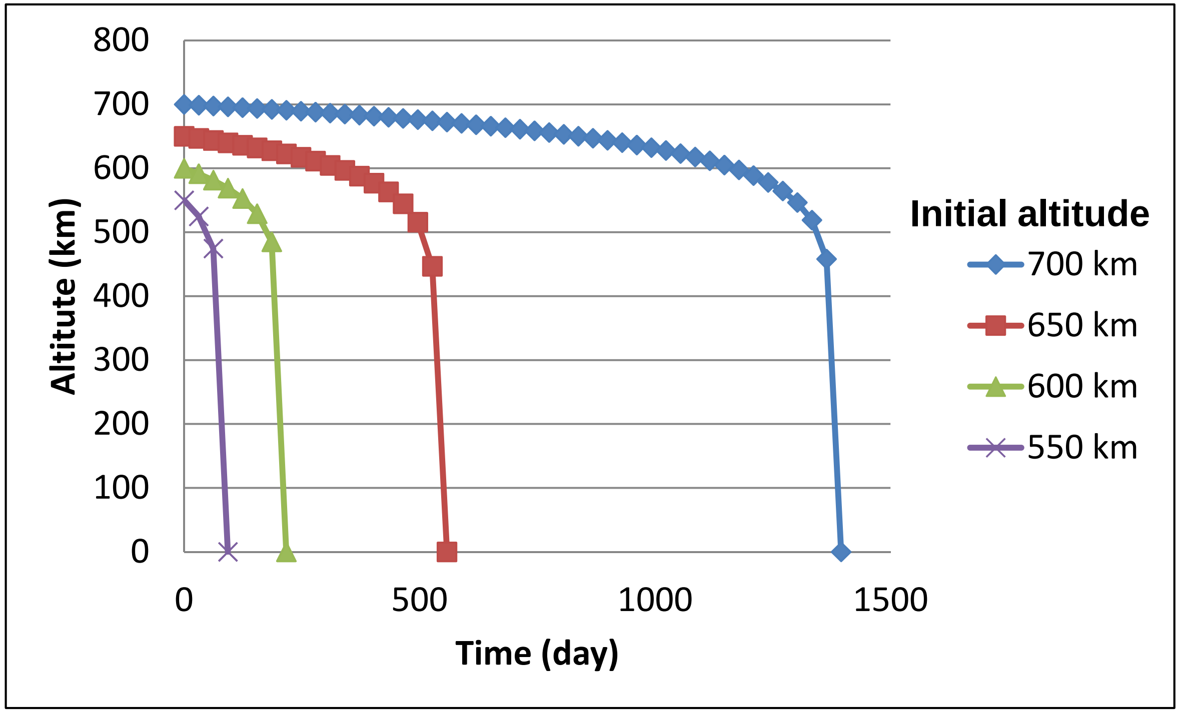


Fig. 1. Analysis results representing descend trajectories using the proposed de-orbit system.

– Satellite mass
  - 10kg
– MTQ
  - 20Am^2
  - 2kg
  - 1w

- A satellite completes de-orbit within 2 years, if the initial altitude is lower than 650 km.

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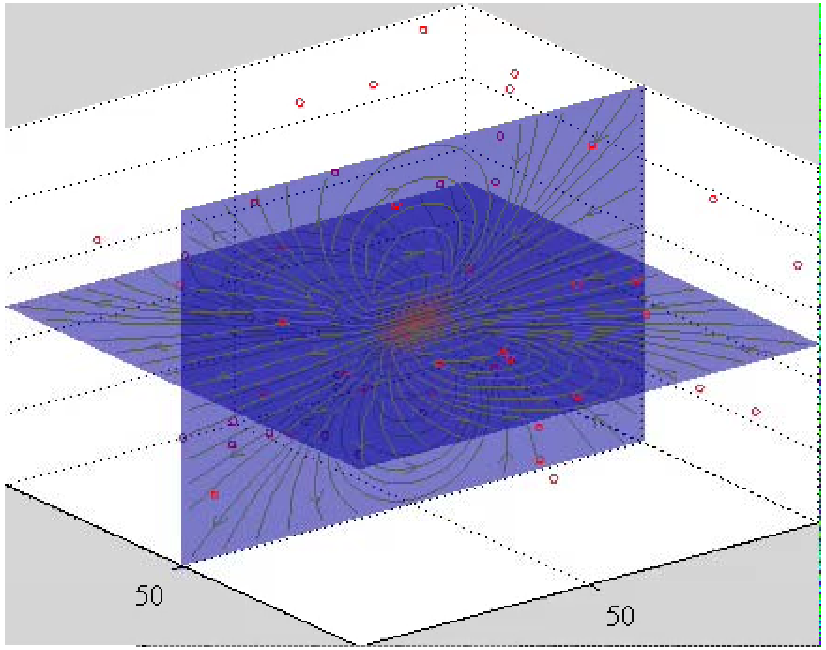
Plasma simulation with Particle In Cell



Motion of ions around magnetic field of MTQs

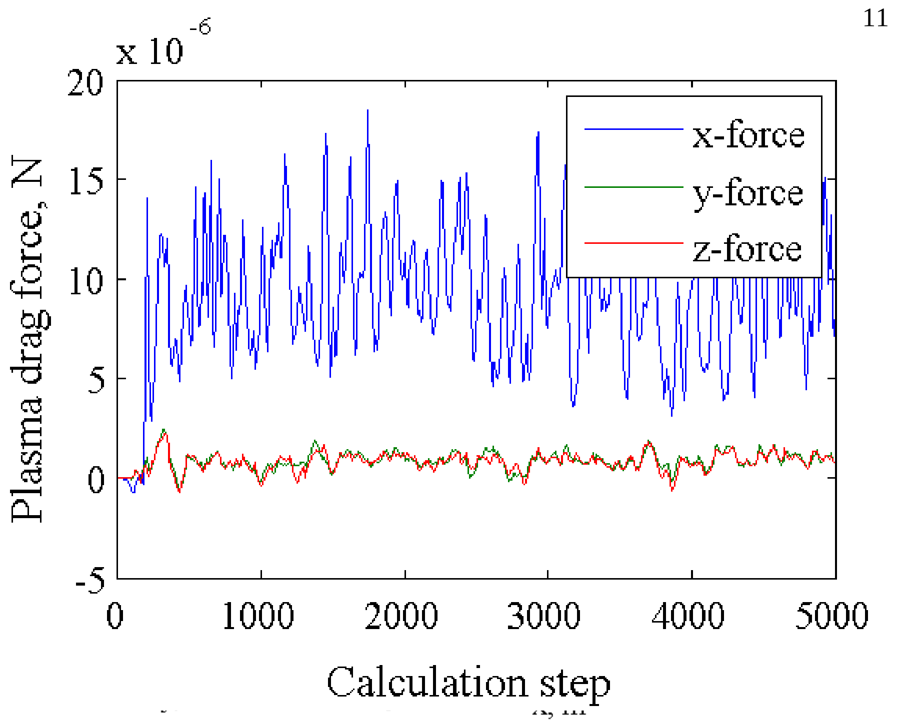
Particle-in-cell (PIC) Method

Rarefied fluid simulation by tracking particles in grid system

Plasma Simulation with PIC

Ions' and Electrons' Motion Calculation	**4th-order Runge-Kutta**
× **Coupling**	
Electrostatic Field Calculation	**2nd-order Poisson's equation solver**

Plasma drag forces calculated by PIC



Plasma drag forces on 3 axes vs. calculation step

Streamlines of ions on ion number density distribution

Plasma drag forces
are calculated by
momentum change of ions

Drag force table is created with parameters of

- **Ion number density**
- **Satellite velocity**
- **Magnetic moment**

Utilized in satellite's orbit simulation

Numerical simulations

- **Include International Standard Atmosphere model.**
- **Include Plasma density and drag force model obtained by the PIC simulations.**

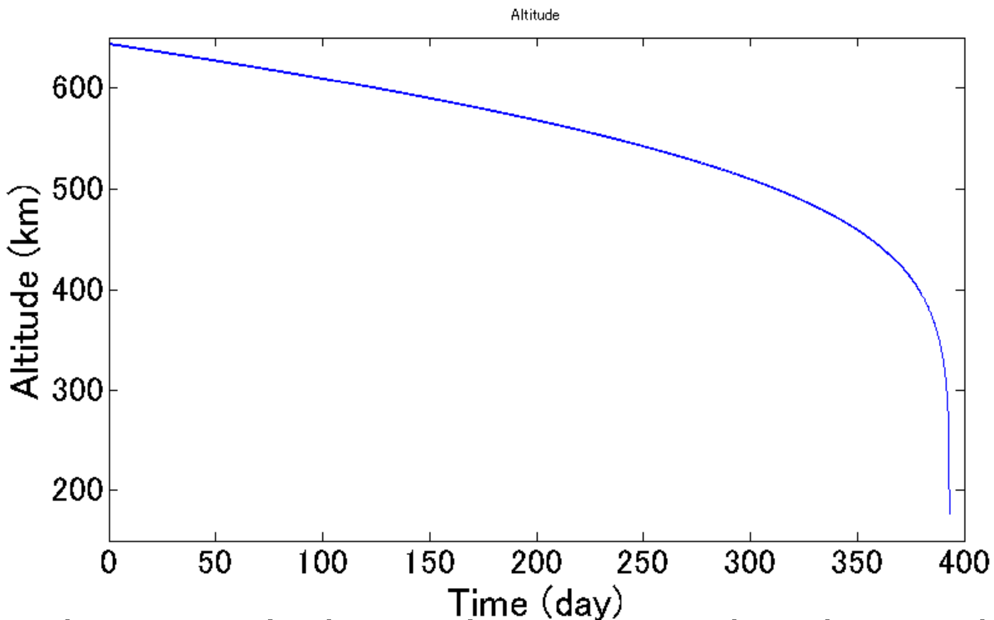


Fig. 2. Analysis results representing descend trajectories using the proposed de-orbit system.

Table 1 Parameters for the numerical simulations

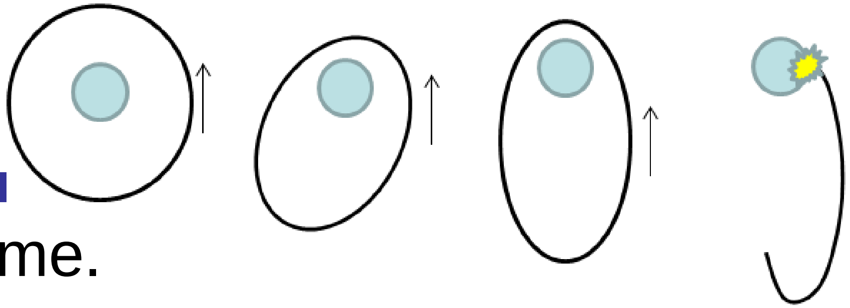
Satellite	Size	200×200 ×200 mm
	Mass	10 kg
MTQ	Magnetic moment	20Am2
	Mass	2kg
	Power consumption	1w

A 10 kg and 650 km altitude nano-satellite completes its de-orbit operation within 2 years with a 20 Am^2 MTQ.

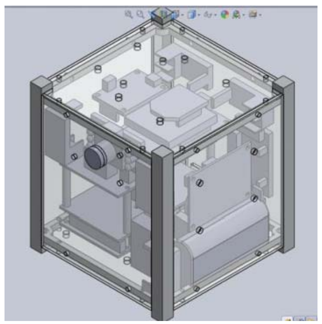
Conclusion

- Almost all nano- satellites do not have any de-orbit systems, because they make nano-satellites larger mass, higher cost, and lower reliability satellites.
- Nano-satellite generates a magnetic moment using MTQs which interacts with space plasma and makes a drag force.
  - Satellites do not need to install any **additional components** for the de-orbit operation.
- A 10 kg and 650 km altitude nano-satellite completes its de-orbit operation within 2 years with a 20 Am^2 MTQ.

Future works



- Shorten the MPD operation time.
  - Improve magnetic field shapes.
  - Improve orbit control methods.
- On-orbit experiments.
  - We have plans for on-orbit experiments using nano-satellites.



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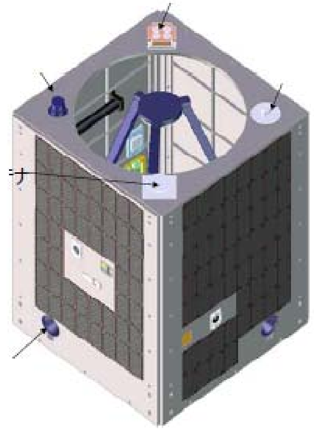

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Appendix

Comparison between proposed MPD and the previous methods

Previous method

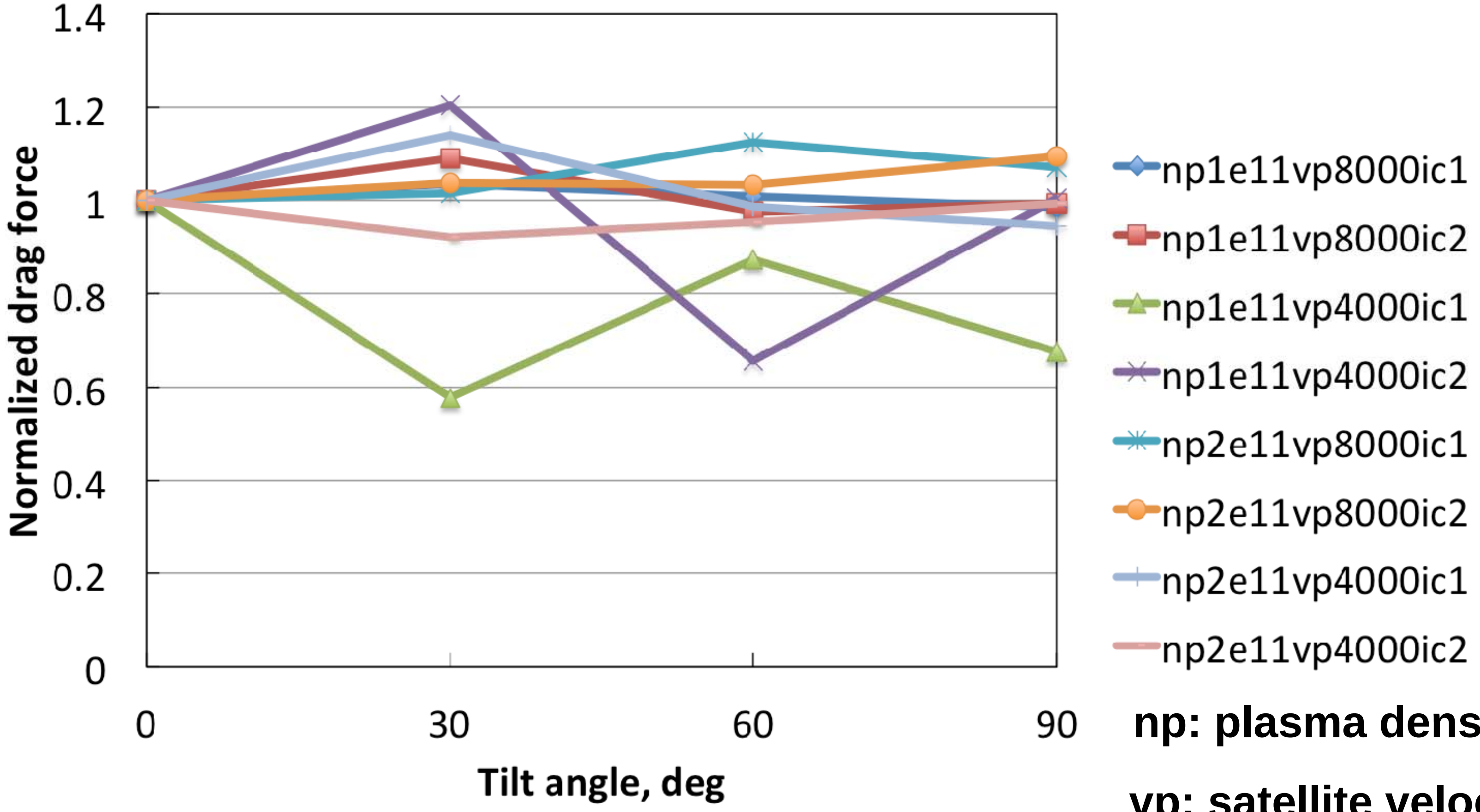
- Deorbit using an air drag force. Nano-Satellites …
  - Need additional extensible structures to achieve a large area in orbit.
  - **Generate only a time constant force which is not useful for orbit control for other purpose such** as formation flight.

⇕

Proposed method

- Deorbit using an plasma drag force. Nano-Satellites …
  - Do not need additional structure
  - Need only MTQs for their deorbit operations.
  - Generate **time-variable force which is useful for orbit control such as formation flight**.

Effect of satellite attitude - Coil tilt angle



np: plasma density

vp: satellite velocity

ic: current in MTQ