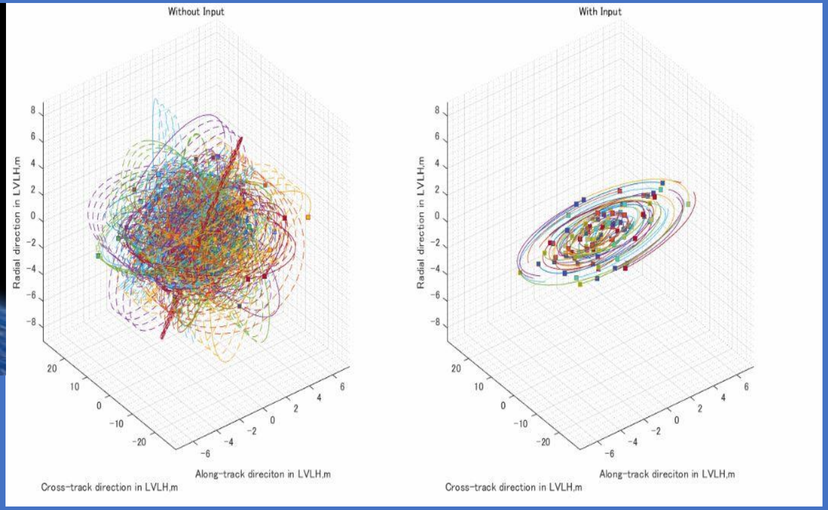
Satellite Specification Research for Distributed Antennas Using Electromagnetic Formation Flight

磁気フォーメーションフライトによる分散アンテナの衛星仕様検討



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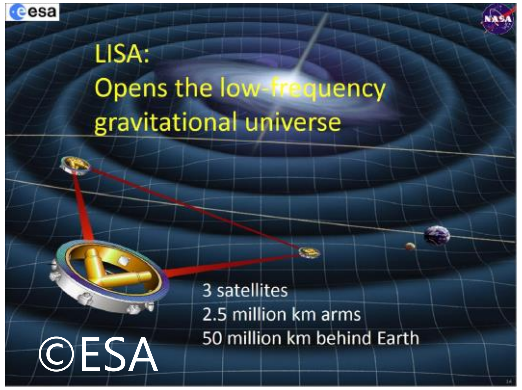
第33回 アストロダイナミクスシンポジウム

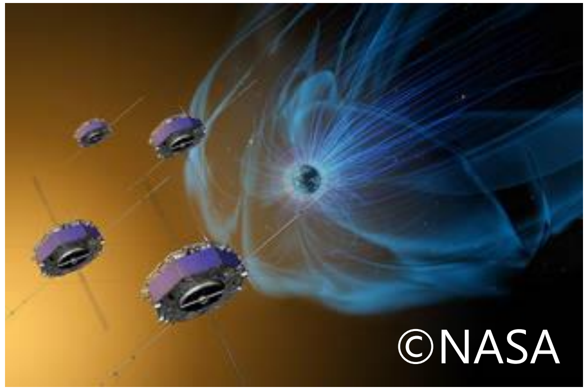
Various Formation Flight Missions

- Formation Flight(FF) enables missions of a scale that cannot be achieved with a monolithic satellite.
- FF is more robust than a monolithic satellite.



LISA

Gravitational wave telescope
Inter-Satellite distance
→2.5 million km



MMS

Multipoint observation
Inter-Satellite distance
→closest : 7 km
furthest : 160km

TanDEM-X

SAR
Inter-Satellite distance
→closest : 200 m
furthest : 500 m

Communication antenna

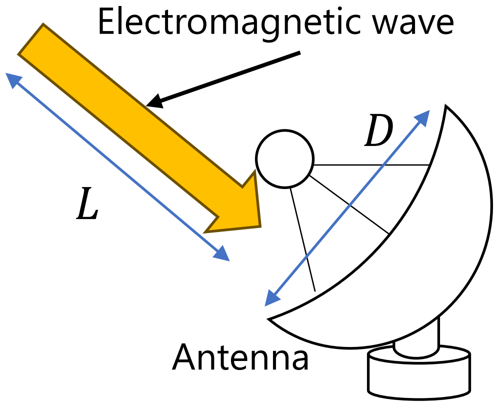
Large distributed antenna
Inter-Satellite distance
→~1m

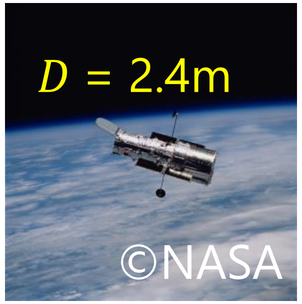
This research focuses a **large distributed antenna**.

Large Antenna by Small Satellites

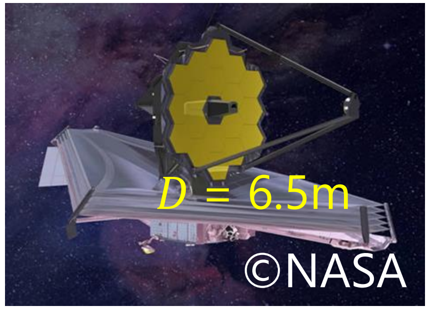
- The resolution of antenna is

$$L/D$$

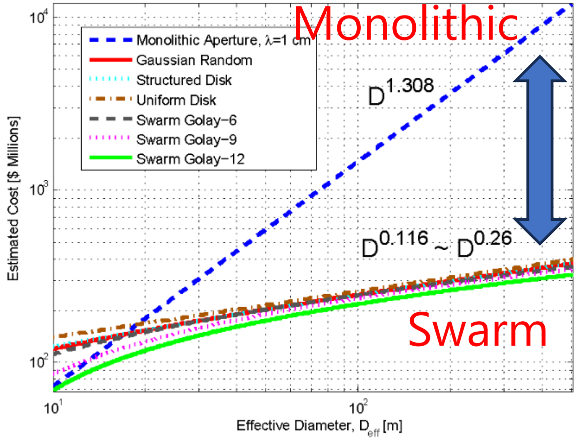




Hubble Space Telescope



James Webb Space Telescope



Comparison of costs between single and swarm satellites (Hadaegh, F., Y., et al., 2016)

Electromagnetic waves	Wavelength
γ-rays	<0.01 nm
X-rays	0.01 – 10 nm
ultra-violet	10 – 300 nm
visible light	0.3 – 0.8 μm
infrared	1 – 1000 μm
radio waves	**0.001 – 30 m**

A large antenna is required.

Distance between satellites is determined by wavelength[1].

$$L/4$$

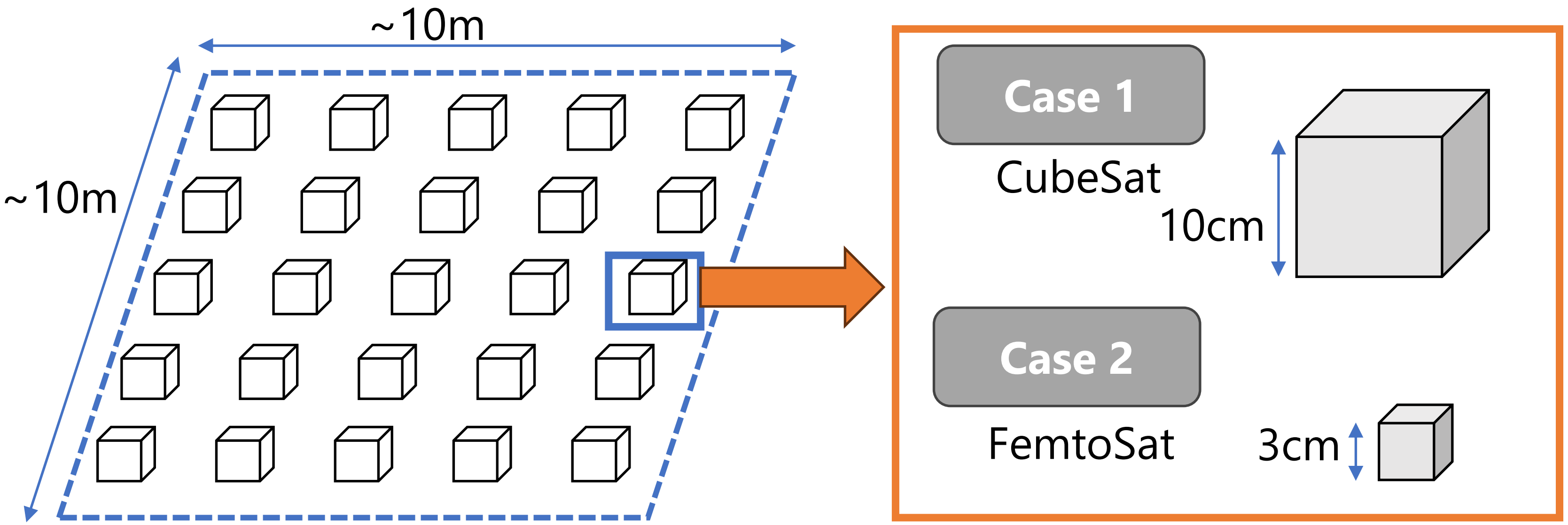
Ex) 1.2GHz → L = 25cm

Distance $\leq$ 6.25 cm

Distributed antennas with low cost and short distance between satellite are required.

[1]野田篤司，"超々小型衛星群のフォーメーションフライト制御と応用" 宇宙科学技術連合講演会，第63回，2019.

The Problem of Large Distributed Antennas Using Thrusters



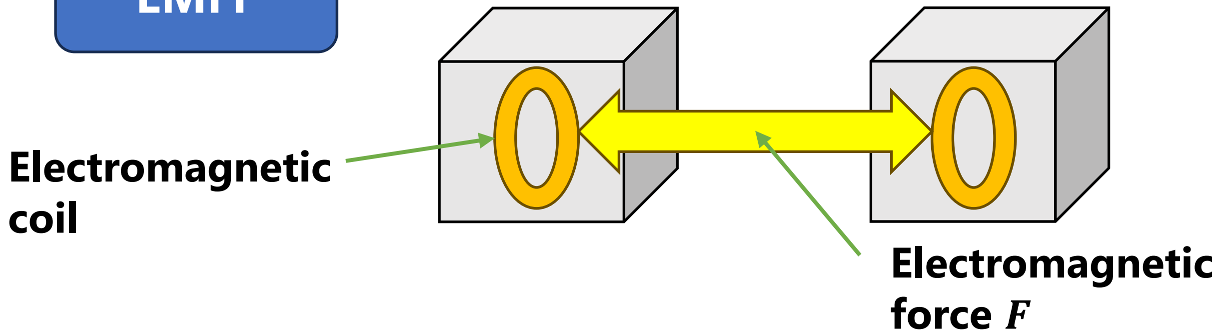
The problem of thrusters

- Plume contamination is generated. → No short-range control
- Continuous force cannot be generated. → No precise control
- Lifetime depends on fuel. → Not suitable for long-term missions
- The structure becomes complex. → Tight cost and size constraints

→ **A method different from conventional formation flying with thrusters is required.**

Electromagnetic Formation Flight (EMFF)

EMFF



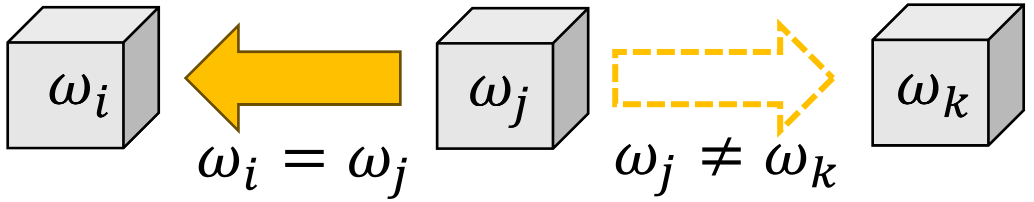
First Demonstration of EMFF in a 6-DOF (Porter, A. K. et al., 2014)

Merit of EMFF

- No plume
- Continuous control
- No fuel
- Simple structure

Alternating Current Control

The amplitude of the alternating current is controlled for satellites with the same frequency.



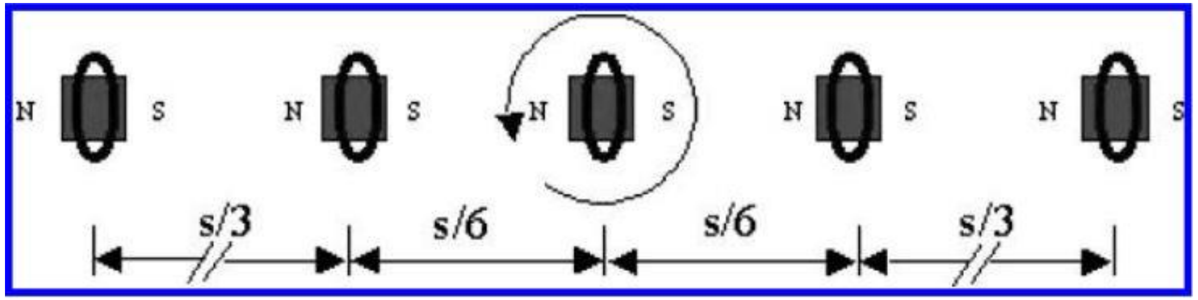
EMFF is suitable for a large distributed antenna.

Optimization of EMFF

- What shape is the formation?
- What are the specifications of the electromagnetic coils?

These are determined by **optimizing the evaluation function J.**

- In a previous study[1]
  - J = rotation rate
  - Superconducting coil is used because of the long distance(s=75m).
  - The max number of satellite is five.



Five-spacecraft EMFF TPF interferometer[1]
(TPF : Terrestrial Planet Finder)

Large distributed antenna

- Normal-conducting coil is sufficient due to the close distance.
- The number of satellite is not defined, but it is expected to be very large.

✓ **Is it possible to maintain the formation with normal-conducting coils?**
✓ **What is the optimal formation for a given size of distributed antenna?**

[1]Edmund M. C. Kong, et al" Electromagnetic Formation Flight for Multisatellite Arrays" Journal of Spacecraft and Rockets, Vol. 41, No. 4, p.659-666, July-August 2004.

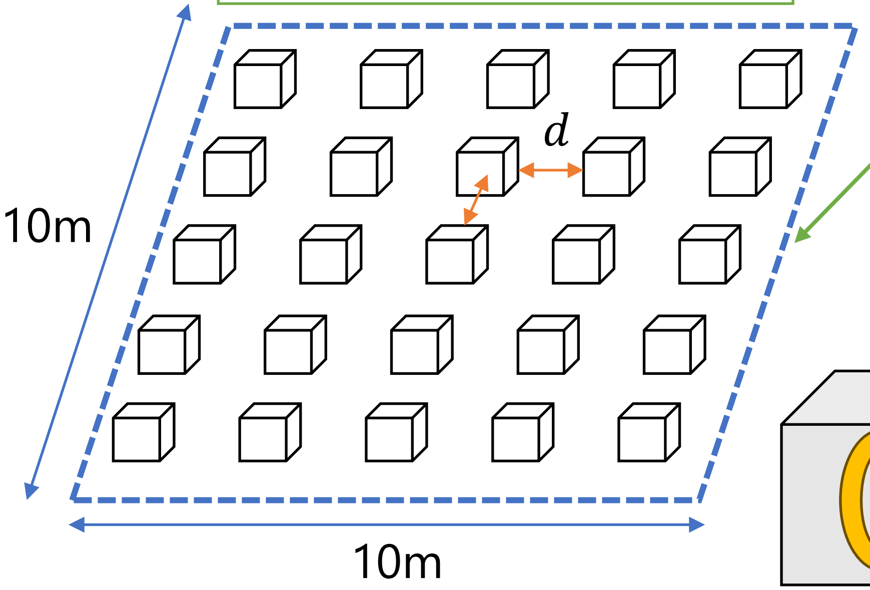
Research Objective

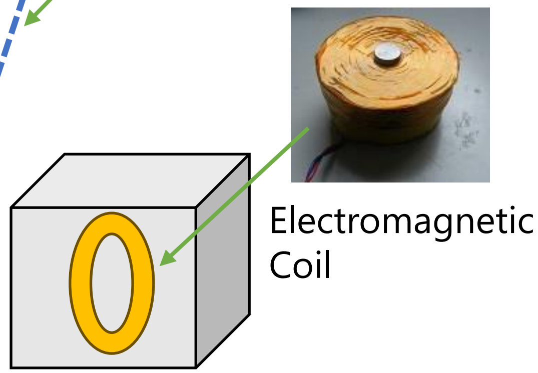
- **Design optimal satellite specifications for distributed antennas.**
- **Provide the general methodology of optimal formation design for a variety of purposes.**

Case Study

Communication antenna orbiting low earth orbit

The number of satellites
$(2n+1)^2$



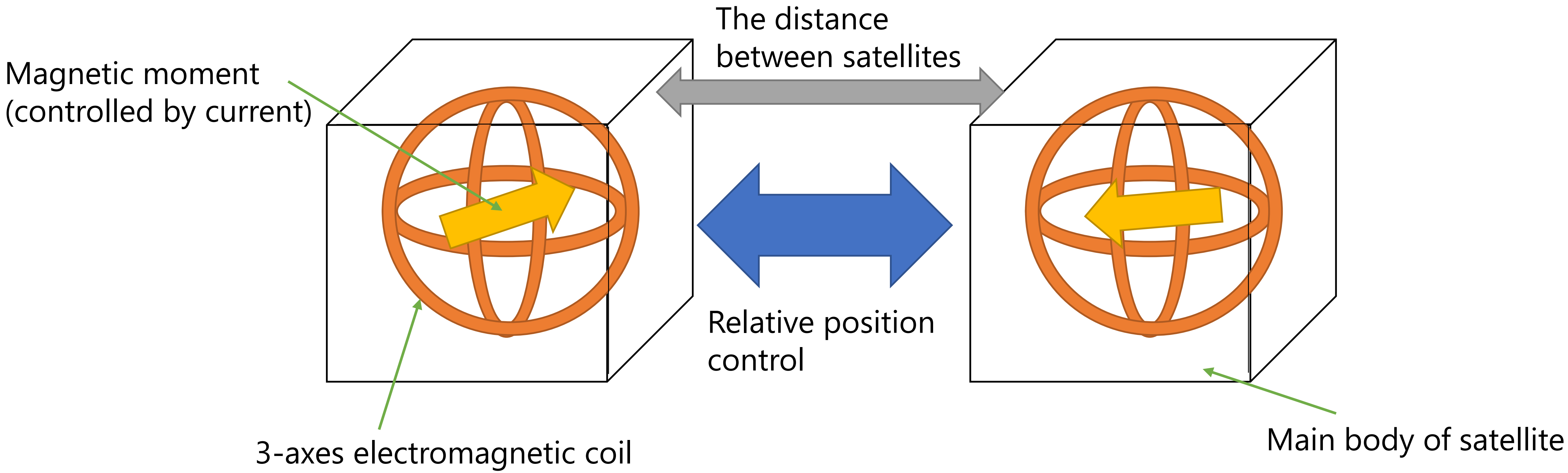


the evaluation function J
$J = n$

The number of satellites is optimized with the formation size determined.

The specifications of the electromagnetic coils and the distance between satellites are investigated to determine if they are feasible.

Satellite Specifications of Electromagnetic Formation Flight



The flow of definition of satellite specifications

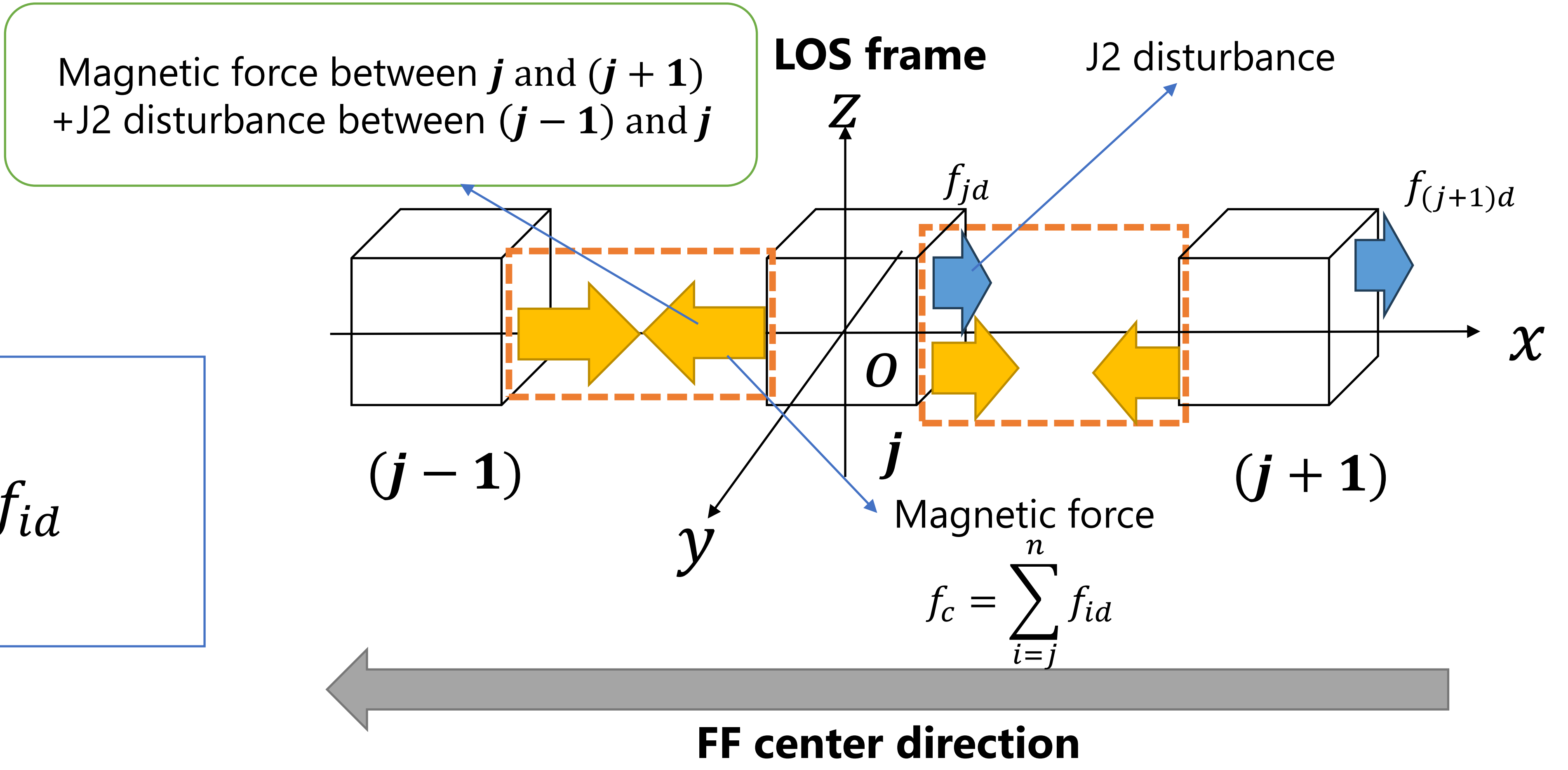
Disturbance force → Magnetic moment → 3-axes electromagnetic coil / The distance between satellites → Satellite size and mass

Constraints 1/3 : J2 Disturbance

- J2 disturbance is caused by the Earth's equatorial bulge
  - It is the largest disturbance in LEO[1].

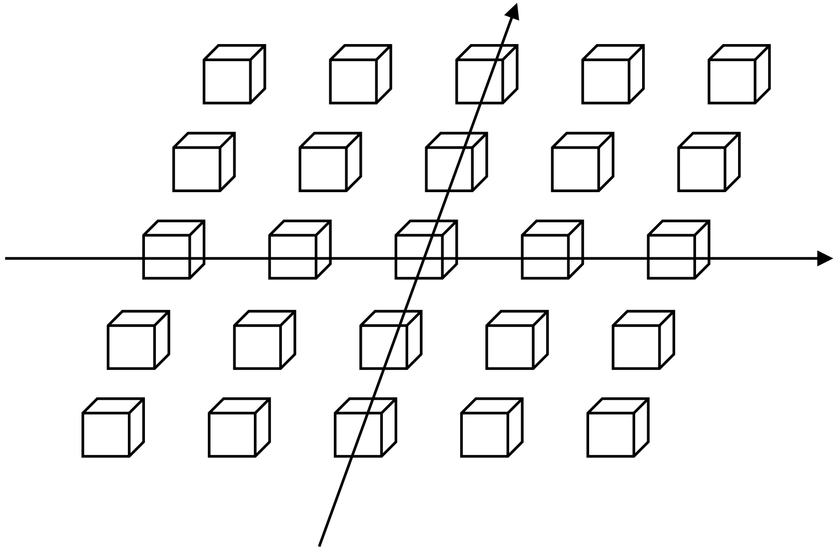
Maximum magnetic force

$$f_{c(0,0)} = \sum_{i=0}^{n} f_{id}$$



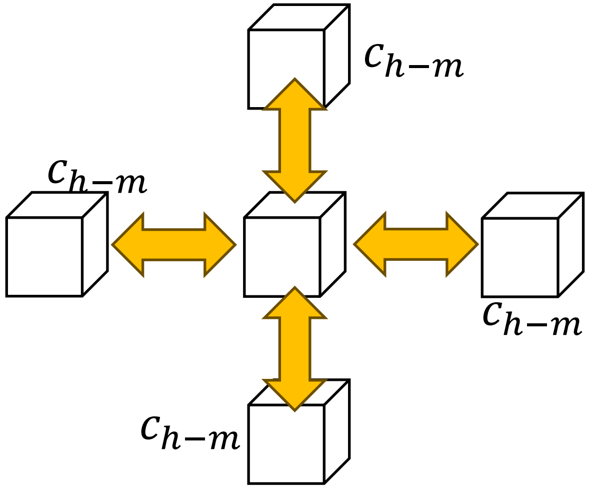
[1]半揚稔雄，"ミッション解析と軌道設計の基礎"，株式会社現代数学社， 2014年11月19日 初版第1刷発行.

Constraints 2/3 : Maximum Current



Formation shape is assumed to be square.

The satellite at the center of the formation cancels disturbances in four directions.



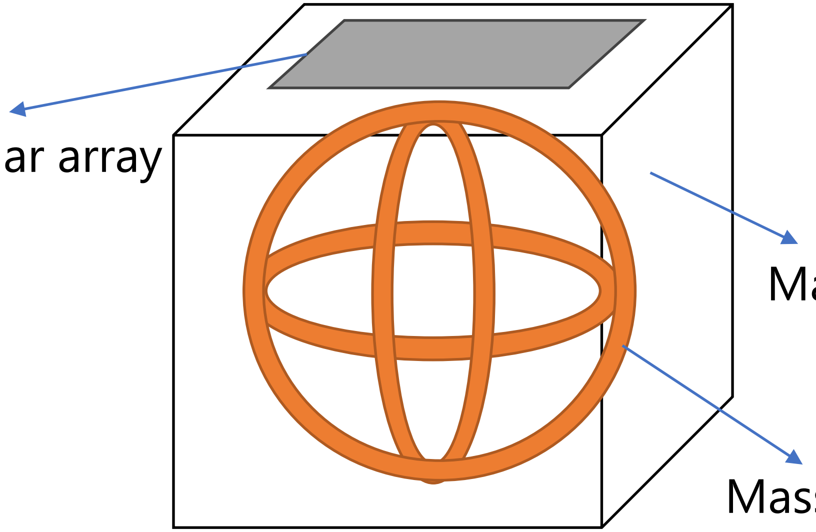
- The current of (0, 0) satellite is required

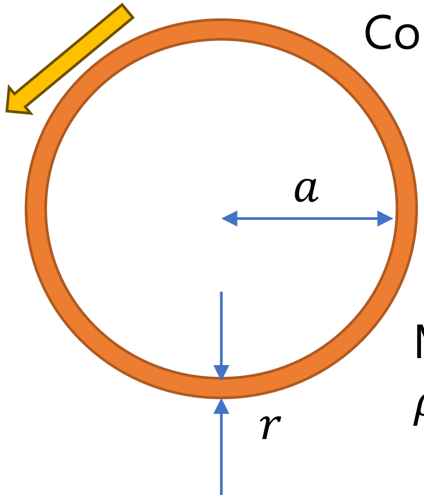
$$c_{h-m(0,0)} = c_{h-m}\sin(\omega_1 t) + c_{h-m}\cos(\omega_1 t) + c_{h-m}\sin(\omega_2 t) + c_{h-m}\cos(\omega_2 t)$$

$$= 2\sqrt{2}c_{h-m}$$

c_{h-m} : Maximum current to suppress disturbance in one direction

Constraints 3/3 : The Mass of One Satellite





$$m_{tot} = m_0 + m_{coil} + m_{sa}$$ [1]

Observation equipment

Max magnetic moment

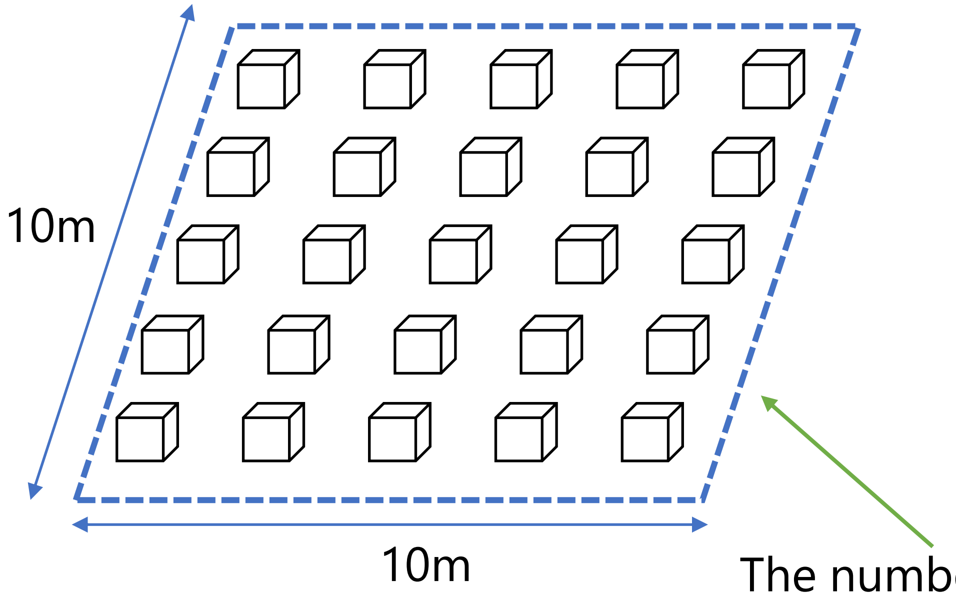
$$\mu = N_t \pi a^2 c_{h-m}$$

Max power consumption

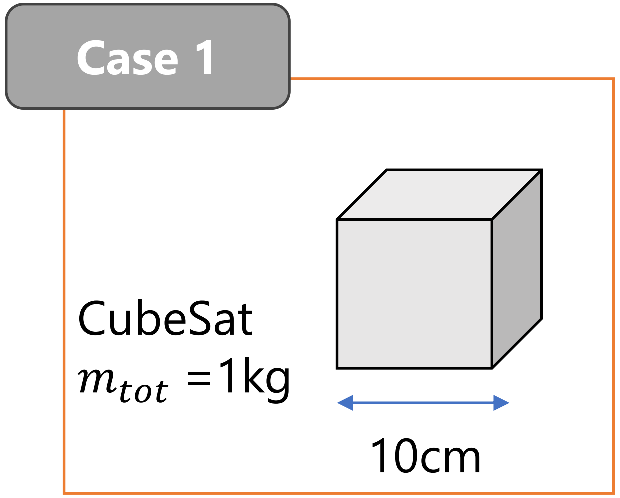
$$P_{h-m} = \frac{2p_{c0}}{r} N_t a^2 c_{h-m}$$

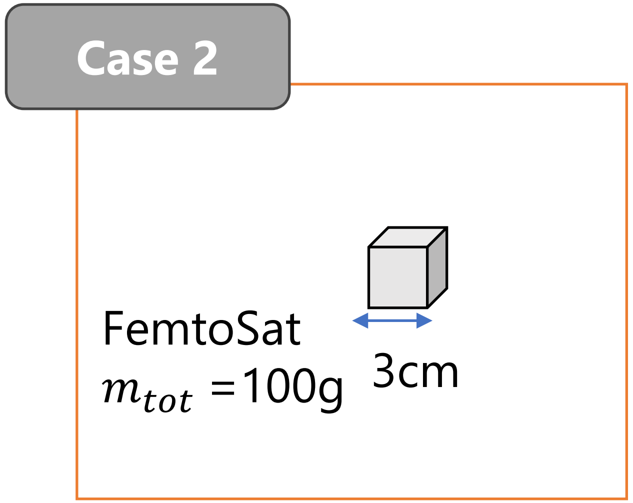
[1]Edmund M. C. Kong, et al" Electromagnetic Formation Flight for Multisatellite Arrays" Journal of Spacecraft and Rockets, Vol. 41, No. 4, p.659-666, July-August 2004.

Analysis Conditions



The number of satellites
$(2n+1)^2$





the evaluation function J

$$J = n$$

- The power system is based on BIRDS[1].
- The power of satellites is only supplied by solar panels. (No battery)
- The payload mass is more than 50% of the total mass of a satellite.

[1] Adolfo Jara, at et al, "On-orbit electrical power system dataset off 1U CubeSat constellation", Data in Brief, Volume 45, 108697, 2022.

Constraint Conditions

- Magnetic Force

$$f_{c(0,0)} = \frac{3\mu_0}{4\pi}\frac{(N_t\pi a^2)^2 c_{h-m}^2}{d^4} = \sum_{i=0}^{n} f_{id}$$

- Maximum Current

$$2\sqrt{2}c_{h-m} \leq \text{Maximum output current of solar panels}$$

- The Mass of Satellite

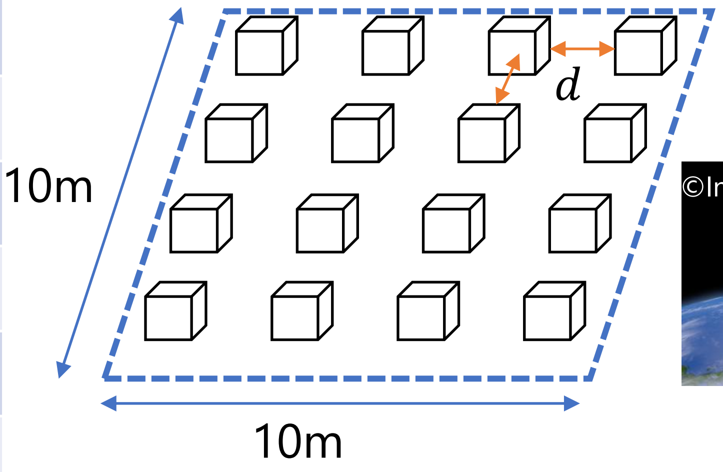
$$m_{tot} = m_0 + m_{coil} + m_{sa}$$

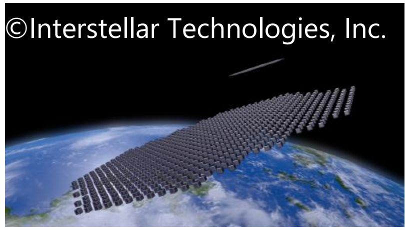
- The Size of Satellite

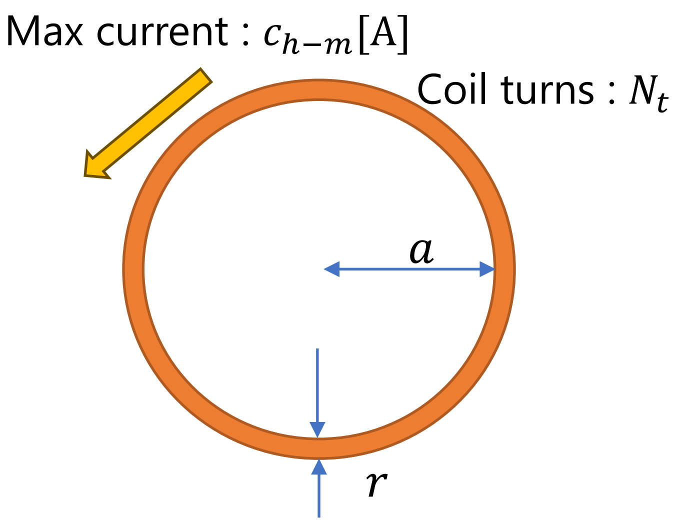
Height of Coil $L \leq$ 0.03 or 0.1 [m]

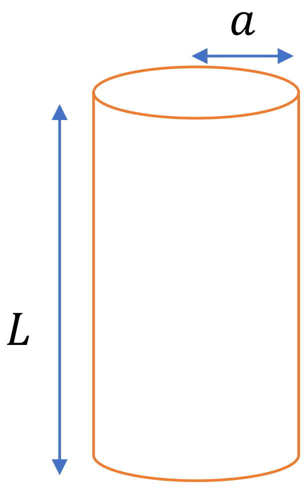
Results of Optimization

	Case1 100g	Case2 1kg
n	77.6	5.41
$(2n+1)^2$	2.44×10^4	140
m_0[kg]	0.0941	0.630
m_{coil}[kg]	0.0029	0.2696
a[m]	0.0150	0.0500
N_t	609	246
r[m]	2.46×10^{-5}	2.03×10^{-4}
μ[Am^2]	0.0052	0.9659
c_{h-m} [A]	0.0120	0.5000
P_{h-m}[W]	0.0730	2.5000
d[m]	**0.0644**	**0.925**
L[m]	0.0300	0.100







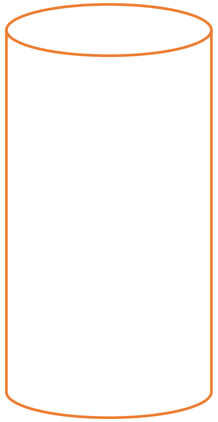


Magnetic moment : $\mu = N_t \pi a^2 c_{h-m}$

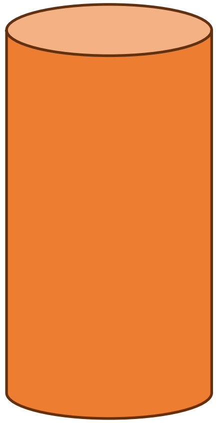
In Case of Core Coil

- Most of the previous studies using EMFF assumed an air core coil.

➡ Whether core coils are more advantageous was examined.



Air core coil



Core coil

N_d is defined by the shape of a core.

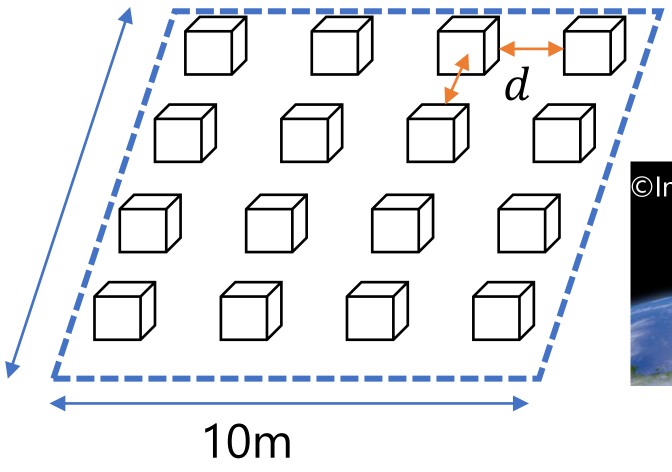
$$\mu = N_t \pi a^2 c_{h-m}$$

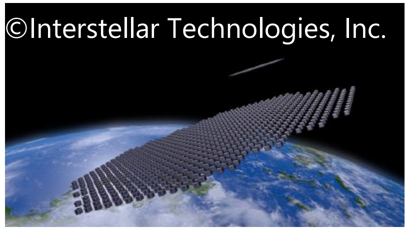
$$\mu = N_t \pi a^2 c_{h-m} \frac{\mu_r + N_d \mu_r}{1 + N_d \mu_r}$$

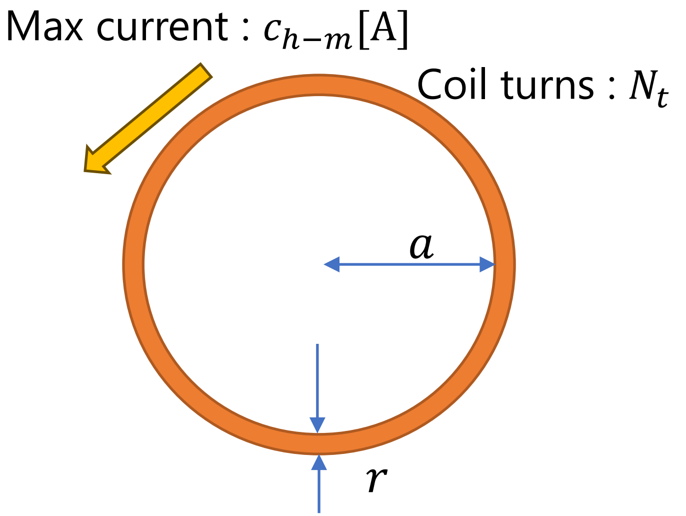
Coil	Merit	Demerit
Air Core Coil	Light	Weak magnetic moment
Core Coil	Strong magnetic moment	Heavy

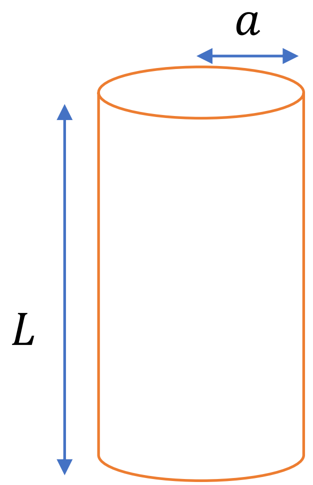
Results of Optimization (Case1 100g Sat)

	Air	Core
n	77.6	58.5
$(2n+1)^2$	2.44×10^4	1.39×10^4
m_0[kg]	0.0941	0.0491
m_{coil}[kg]	0.0029	5.68×10^{-4}
m_{core}[kg]	-	0.0474
a[m]	0.0150	0.0044
N_t	609	919
r[m]	2.46×10^{-5}	1.63×10^{-5}
μ[Am^2]	0.0052	0.0079
c_{h-m} [A]	0.0120	0.0120
P_{h-m}[W]	0.0730	0.0730
d[m]	**0.0644**	**0.0855**
L[m]	0.0300	0.0300





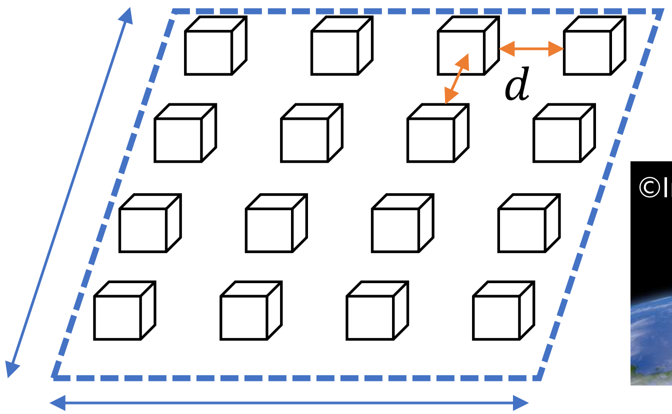


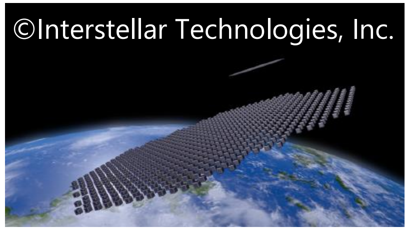


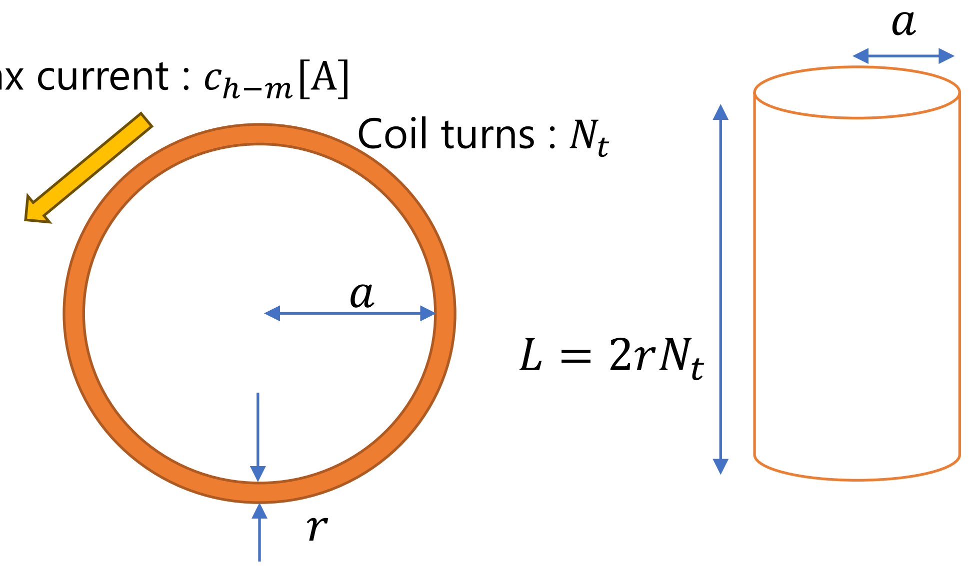
Magnetic moment : $\mu = N_t \pi a^2 c_{h-m}$

Results of Optimization (Case2 1kg Sat)

	Air	Core
n	5.41	7.94
$(2n+1)^2$	140	285
m_0[kg]	0.630	0.490
m_{coil}[kg]	0.2696	0.0456
m_{core}[kg]	-	0.4540
a[m]	0.0500	0.0074
N_t	246	216
r[m]	2.03×10^{-4}	2.31×10^{-4}
μ[Am^2]	**0.9659**	**0.5266**
c_{h-m} [A]	0.5000	0.5000
P_{h-m}[W]	2.5000	0.2502
d[m]	**0.925**	**0.629**
L[m]	0.100	0.100







Magnetic moment : $\mu = N_t \pi a^2 c_{h-m}$

Conclusion and Future Works

Research object

- **Design optimal satellite configuration for distributed antennas.**
- **Provide the general methodology of optimal formation design for a variety of purposes.**

In this presentation

✓ A case study of maintaining the formation of a communication antenna using a normal-conducting coil was performed.
✓ Optimization calculations were performed for the number of satellites.
✓ Comparisons were made between air coils and core coils

Future works

☐ A feasibility study of the parameters obtained by optimization.
☐ Identification of the cause of the small magnetic moment of the core coil.
☐ To simulate under nominal conditions.
☐ To consider a formation that is not a grid.