KiboCUBE Academy

Lecture 27

Introduction to Small Satellite Constellation

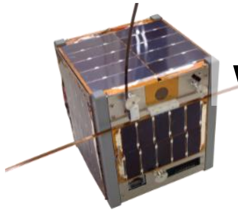
The University of Tokyo

Department of Aeronautics and Astronautics

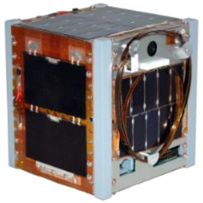
Associate Professor Ryu Funase, Ph.D.

This lecture is NOT specifically about KiboCUBE and covers GENERAL engineering topics of space development and utilization for CubeSats.
The specific information and requirements for applying to KiboCUBE can be found at:
https://www.unoosa.org/oosa/en/ourwork/psa/hsti/kibocube.html

Lecturer Introduction



XI-IV (2003): 1kg
World's first CubeSat



XI-V (2005): 1kg
Tech Demo.

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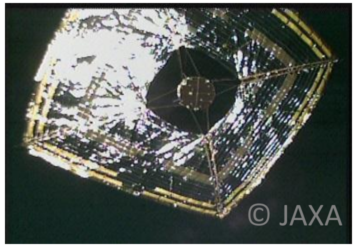
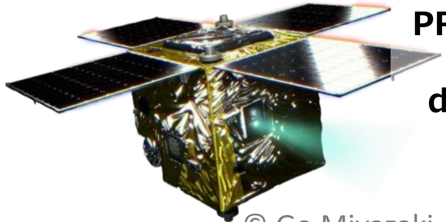


IKAROS (2007-2010): 315kg
World's first interplanetary solar sail



© Go Miyazaki

PROCYON(2014): 65kg
World's first deep space micro-sat

EQUULEUS(2022): 11kg
Trajectory control tech demo within Earth-Moon region

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Ryu Funase, Ph.D.

Position:

2012 – present	Associate Professor Department of Aeronautics and Astronautics, The University of Tokyo
2019 – present	Professor Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency (Cross appointment with The University of Tokyo)

Research Topics:

Spacecraft system design, and guidance, navigation and control of spacecraft

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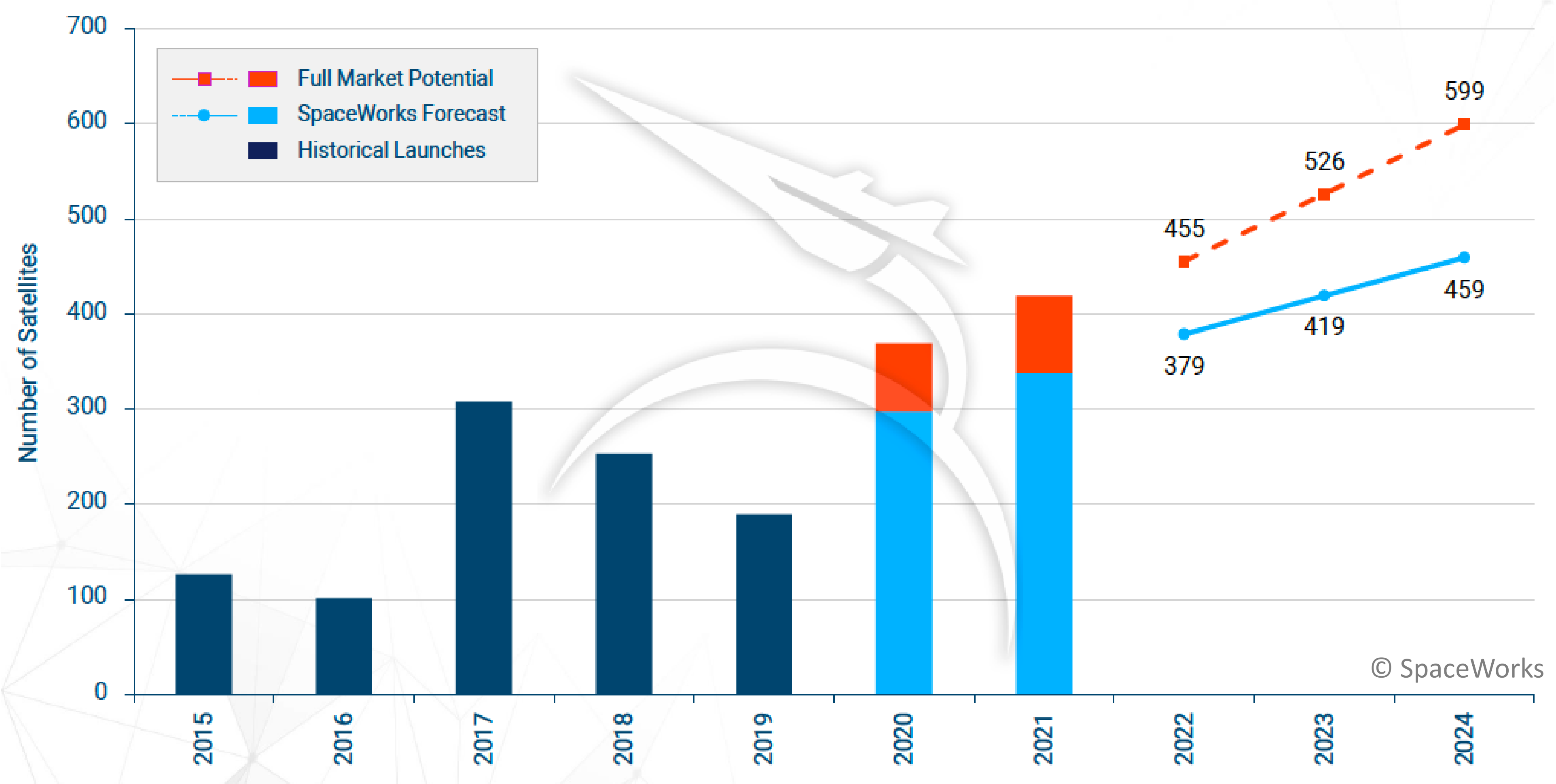
1. Introduction

1.1 Evolution of small satellite technology



1. Introduction

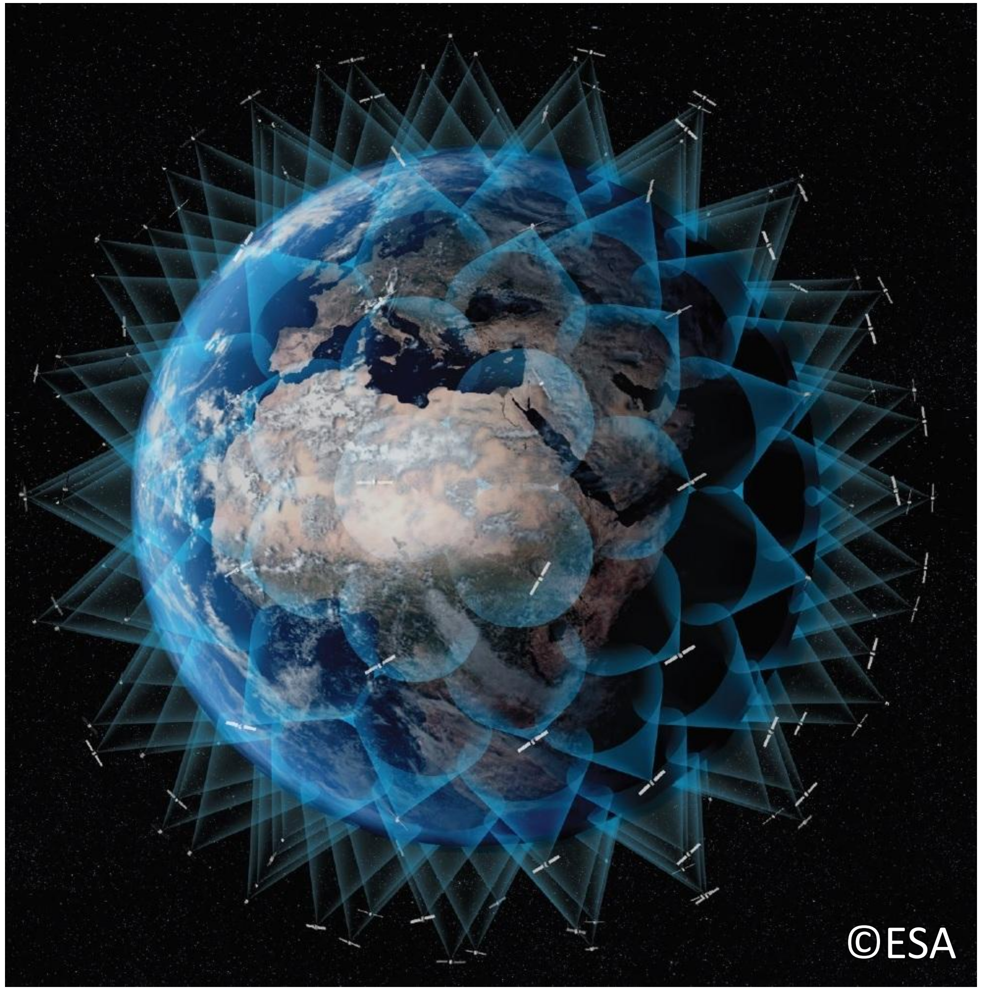
1.2 Concept of small satellite constellation

What are satellite constellations?

According to the IAU (International Astronomical Union) [1],

- *Over the past decades, considerable effort has gone into designing, building, and deploying satellites for many important purposes. Recently, **networks, known as satellite constellations** have been deployed. Constellation deployments are being planned in **ever greater numbers in mainly low-Earth orbits** for a variety of reasons, including providing communication services to underserved or remote areas.*
- *A satellite constellation is **a number of similar satellites**, of a similar type and function, designed to be **in similar, complementary, orbits** for **a shared purpose**, under shared control.*

Utilization of small satellites is key to the realization of the constellation in terms of development cost, development time, and launch cost.



[1] Satellite Constellations, https://www.iau.org/public/themes/satellite-constellations/, accessed on 2025/03/16

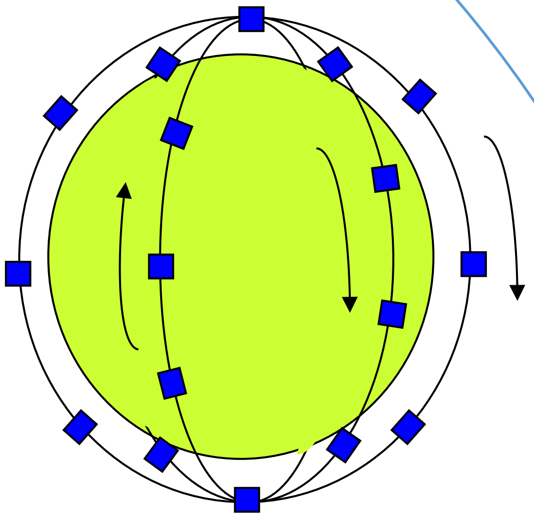
1. Introduction to Satellite Constellations

1.2 Concept of small satellite constellation

LEO (500-800km alt.)

Almost all remote sensing satellites

- High spatial resolution 0.3m – 30m
- Time resolution is several - 40 days
- Several hundreds satellites required for less than 1 hour time resolution → may become feasible in terms of cost and development time due to the small size of the satellite
- Robust against failure due to the large number of the satellite



Constellation of many LEO satellites

GEO (36000km alt.)

A few satellites

- Low spatial resolution (60m – 2 km)
- Continuous monitoring possible
- High time resolution achieved by quick scanning (even 10 min.)

2. Application of small satellite constellations

2. Application of small satellite constellations

2.1 Area of applications and benefits of satellite constellations

Area of Applications

- Constellations are used for **navigation**, satellite-based **communications**, or **Earth Observation**. More recently, companies are planning large scale constellations to provide global satellite internet, or **Internet of Things** to connect machines and systems together directly.

Benefits of satellite constellation

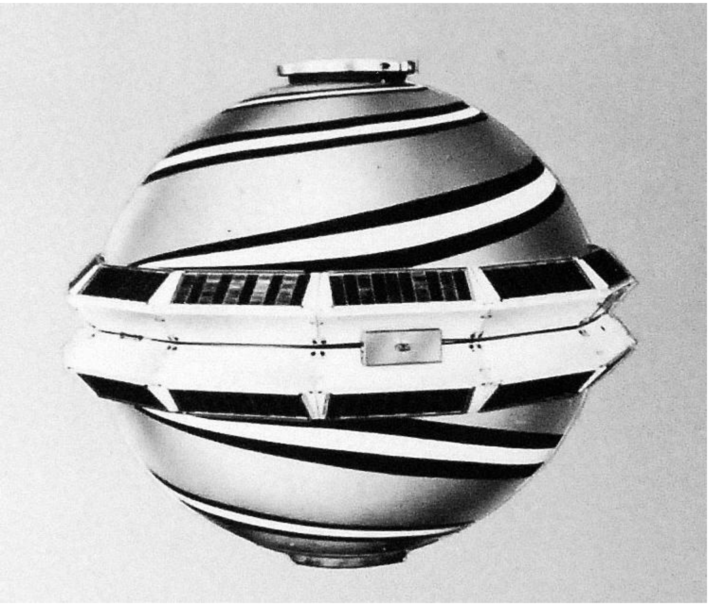
- A constellation with thousands of individual units at low altitude **reduces the signal latency** (i.e. the time taken to signals to move from a ground station providing internet to the satellite and then on to a user), while maintaining **high levels of coverage** especially in remote areas without developed ground infrastructure.

Ref: Satellite Constellations, https://www.iau.org/public/themes/satellite-constellations/, accessed on 2025/03/16

2.2 Early history of satellite constellations

Transit system, also known as **NAVSAT** (Navy Navigation Satellite System)

- Mission: The first satellite navigation system
- Number of satellites: 5 (+5 for backup)
- Orbit: 5 polar orbits with 1,100 km altitude and 106 minutes of orbital period
- Operation: U.S. Navy



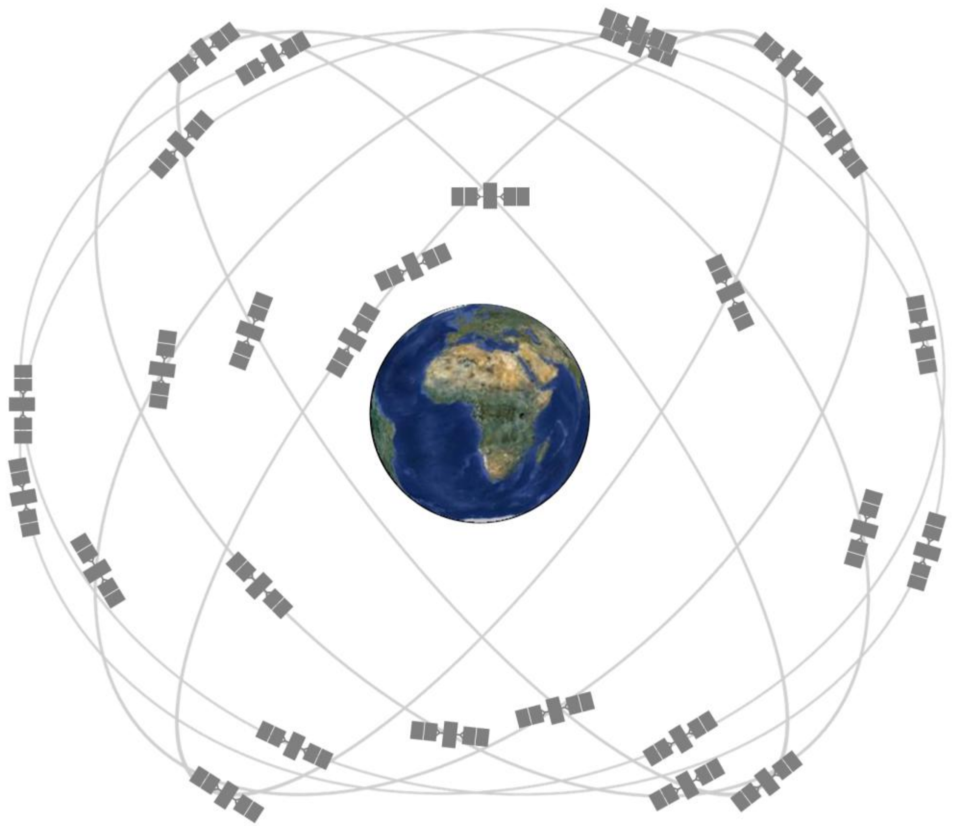
Transit 1B satellite
(Credit: National Museum of the U.S. Navy)

2. Application of small satellite constellations

2.2 Early history of satellite constellations

NAVSTAR/GPS

- Mission: satellite navigation system
- Number of satellites: 4 satellites/orbit plane × 6 orbit planes = 24 (minimum configuration)
- Orbit: MEO (Medium Earth Orbit) with an altitude of 20,000 km and inclination of 55 deg
- Operation: U.S. Government



Constellation configuration of GPS satellites
(Credit : United States Government)

2.2 Early history of satellite constellations

In the early history of satellite constellations, Iridium, a constellation for communications, is another notable example.

The Iridium system was designed to meet the growing need for global communications coverage, including communications needs in areas with insufficient terrestrial communications infrastructure.

Iridium (1998-)

- Mission: telecommunication
- Number of satellites: 66 +
- Orbit: 6 polar orbits (i = 86.4deg) with 780 km altitude, 11 satellites in each orbital plane

2. Application of small satellite constellations

2.3 Utilization in telecommunication applications

Starlink

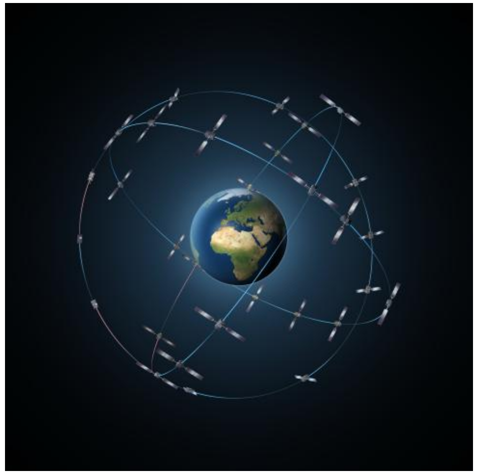
- ~7000 satellites in orbit (as of Jan. 2025) to cover almost all areas of the world
- LEO (~550km altitude, middle to high inclination)
- Multiple “shells” or groups with different altitude, inclination
- Starlink v0.9, v1.0 (260kg), v1.5 (~300kg with optical laser intersatellite comm.)
- Starlink v2-Mini (>500kg, more powerful phased array antenna), v2-Mini-D2C (with Direct to Cell capabilities)
- Huge number of satellites to cover…
- Laser communication capability to enable high-speed communication between satellites
- Highly-efficient hall thruster for orbit maintenance, debris collision avoidance maneuver, etc
- Direct to cell functionality is being implemented

Stacked launch configuration of second-generation Starlink satellites (v2-Mini). (Credit: SpaceX)

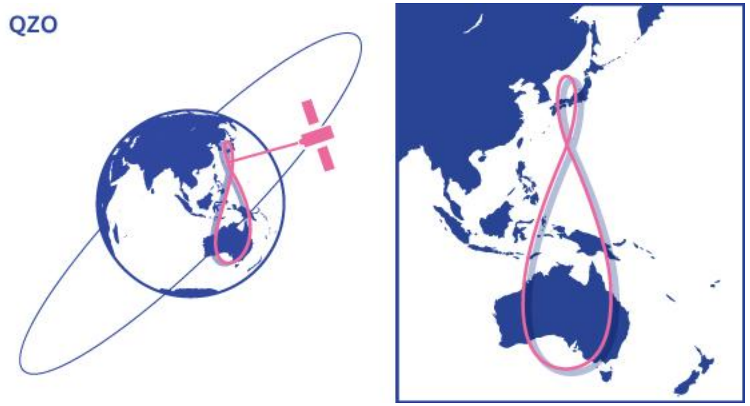
2.4 Utilization in navigation applications

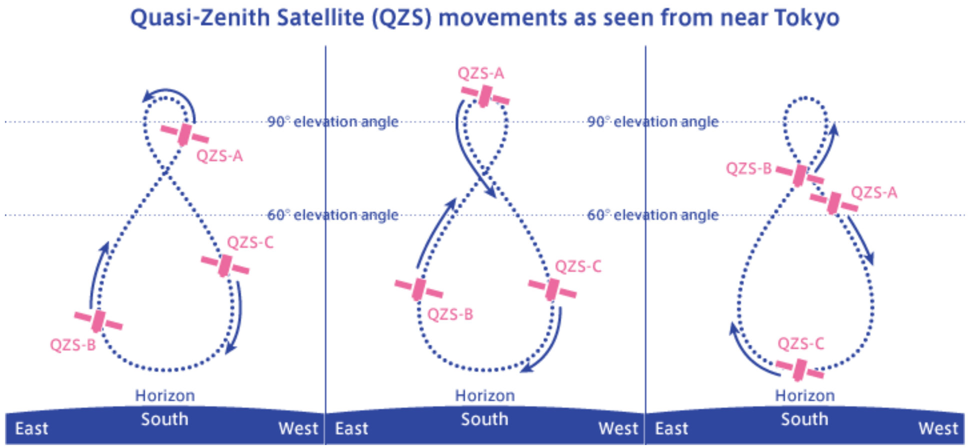
Various GNSS (Global Navigation Satellite System)

- **GPS** (United States)
- **GLONASS** (Russia)
- **Galileo** (Europe)
- **BeiDou** (China)
- **NavIC** (India)
- **QZSS** (Japan)



Galileo constellation (Credit: ESA)





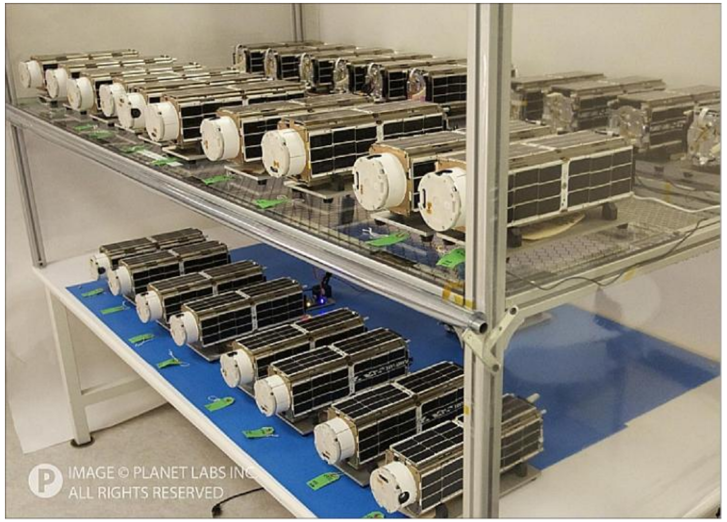
QZSS orbit (from qzss.go.jp)

2. Application of small satellite constellations

2.5 Utilization in earth observation

Earth observation constellation by Planet

- **PlanetScope**
  - ~200 satellites (3U CubeSat)
  - ~4m GSD (Ground Sampling Distance)
  - 8 band imagery
- **SkySat** (2013~)
  - ~20 satellites (~100kg satellite)
  - SkySat-1-15: Sun-synchronous
    SkySat-16-21: inclined, non sun-synchronous
  - 0.5m GSD
  - RGB, Pan and NIR bands



(Credit: Planet Labs)

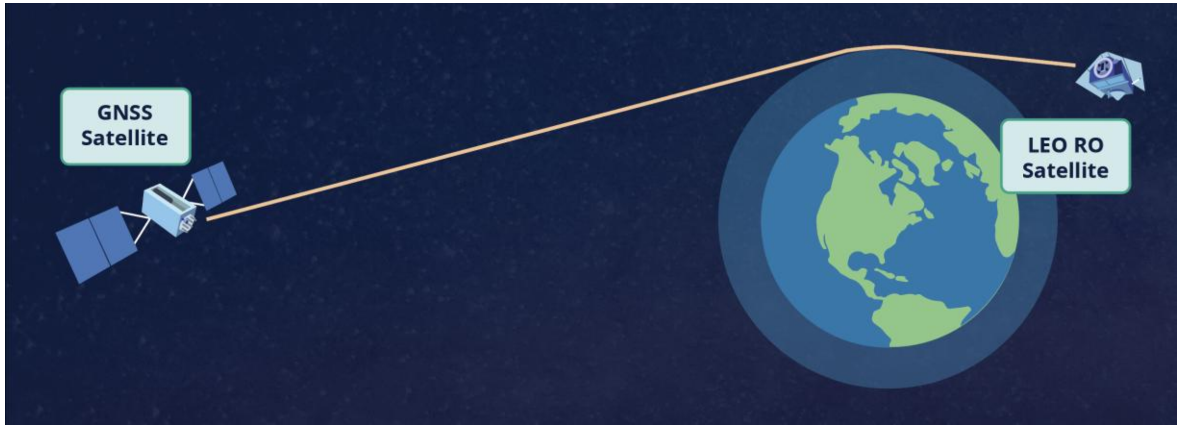
2. Application of small satellite constellations

2.6 Utilization in other fields

Constellation by Spire Global

- Satellite: 4.6kg, 10x10x30cm (3U), >90 satellites operational (as of 2020)
- Orbit: Equatorial, SSO, low, mid and high inclination orbit
- Mission
  - GNSS-RO (Radio Occultation)
  - GNSS-R (Reflectometry)
  - AIS (Automatic Identification System)
  - ADS-B (Automatic Dependent Surveillance-Broadcast)
  - Earth environment measurement

Spire's nano-satellite (Credit: ESA)

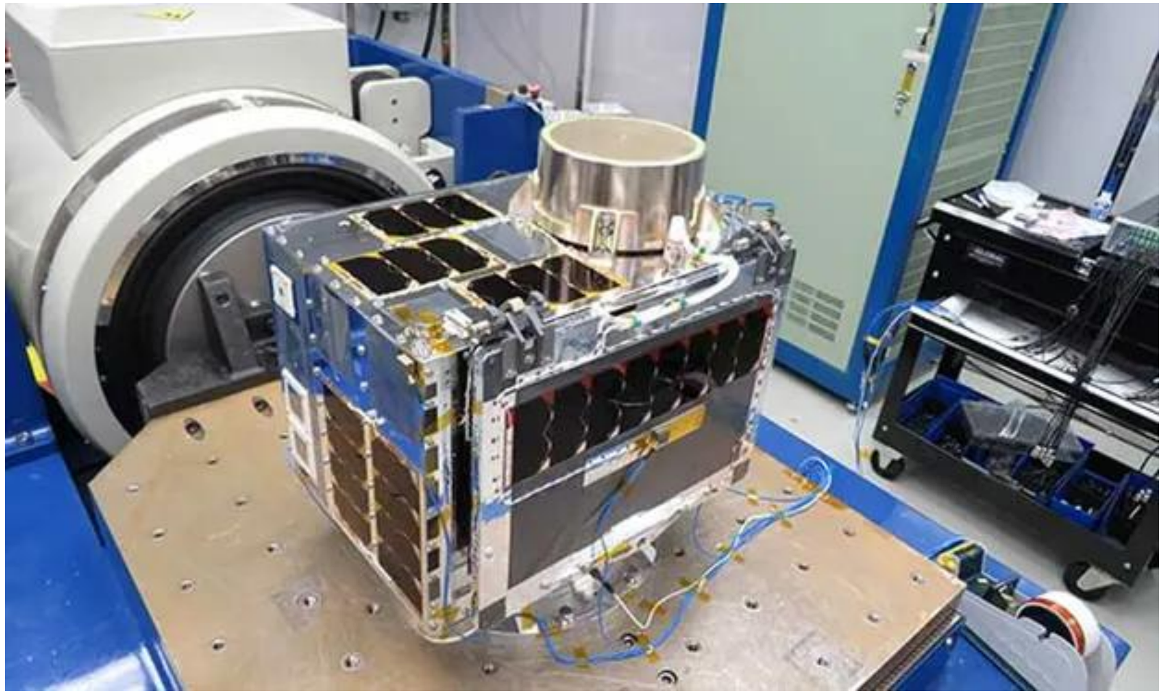


Concept of the radio occultation technique. (Credit: NASA)

2.6 Utilization in other fields

<u>HawkEye 360</u>

- Mission: RF (Radio Frequency) signal detection and analysis
- Potential to help detect smuggling and illegal fishing, etc.
- Instrument: SDR (Software Defined Radio)
- Satellite: 20 x 20 x 40 cm
- ~30 satellites in operation
- Orbit: Mostly in polar orbit, 3 satellites in a orbit



HawkEye 360 (Credit: UTIAS/SFL)

3. Relevant theories on constellation design and utilization

3. Relevant theories on constellation design and utilization

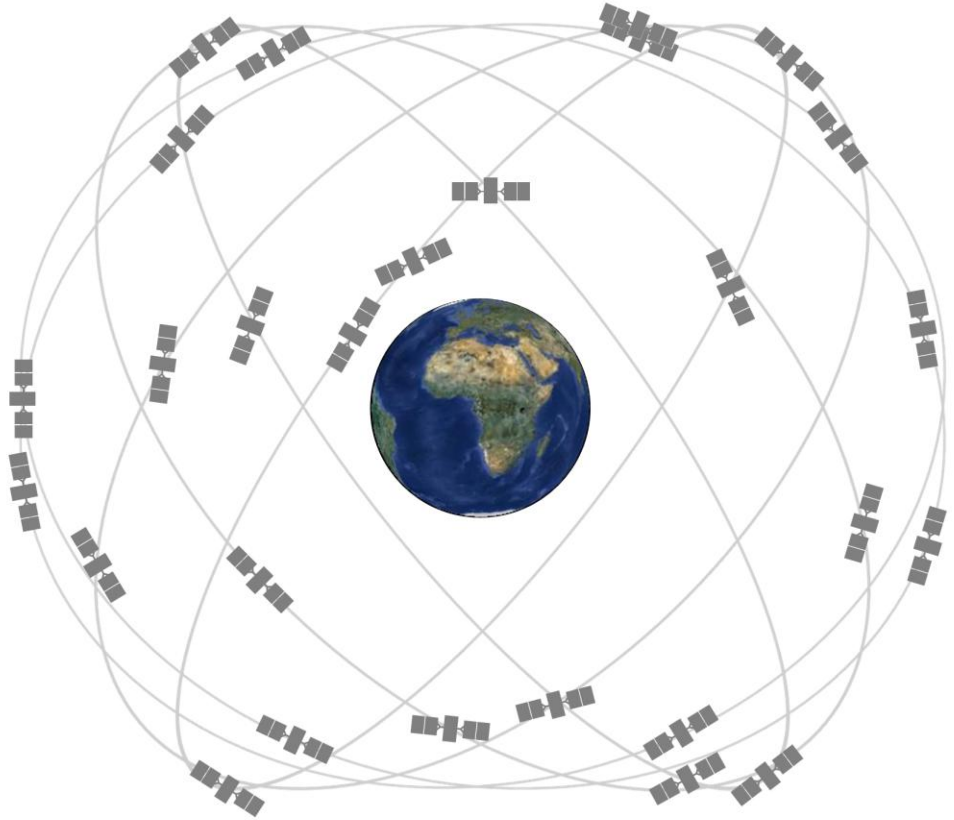
3.1 Constellation orbit design

Walker Constellation

- represents a pattern of satellite constellation orbit which consists of multiple circular orbital planes with a common altitude and inclination uniformly distributed around the equatorial plane
- Is easy to maintain because each satellite has the same altitude and inclination and is subject to the same perturbation

Parameters

- Inclination i
- Total number of satellites T
- Number of orbital planes P
- Phasing parameter F, relative spacing between satellites in adjacent planes. The change in true anomaly (in degrees) for equivalent satellites in neighboring planes is equal to F × 360 / T



Example of walker constellation
(Credit : United States Government)

Ref: Walker, J. G., Satellite Constellations, Journal of British Interplanetary Society, Vol.37, pp.559-571, 1984

3. Relevant theories on constellation design and utilization

3.2 Orbital perturbation

Sources of orbital perturbation

- non-ideal gravitational field of the Earth (e.g., Earth's oblateness)
- Lunar and solar gravity
- Atmospheric drag
- Solar radiation pressure

Gauss planetary equation

$$\frac{da}{dt} = \frac{2e\sin\nu}{n\sqrt{1-e^2}}R + \frac{2a\sqrt{1-e^2}}{nr}S$$

$$\frac{de}{dt} = \frac{\sqrt{1-e^2}\sin\nu}{na}R + \frac{\sqrt{1-e^2}}{na^2e}\left\{\frac{a^2\left(1-e^2\right)}{r} - r\right\}S$$

$$\frac{dM}{dt} = n + \left\{\frac{\left(1-e^2\right)\cos\nu}{nae} - \frac{2r}{na^2}\right\}R - \frac{\left(1-e^2\right)\sin\nu}{nae}\left\{1 + \frac{r}{a\left(1-e^2\right)}\right\}S$$

$$\frac{d\Omega}{dt} = \frac{r\sin u}{na^2\sqrt{1-e^2}\sin i}W$$

$$\frac{d\omega}{dt} = -\frac{\sqrt{1-e^2}\cos\nu}{nae}R + \frac{\sqrt{1-e^2}\sin\nu}{nae}\left\{1 + \frac{r}{a\left(1-e^2\right)}\right\}S - \frac{r\sin u\cot i}{na^2\sqrt{1-e^2}}W$$

$$\frac{di}{dt} = \frac{r\cos u}{na^2\sqrt{1-e^2}}W$$

3. Relevant theories on constellation design and utilization

3.2 Orbital perturbation

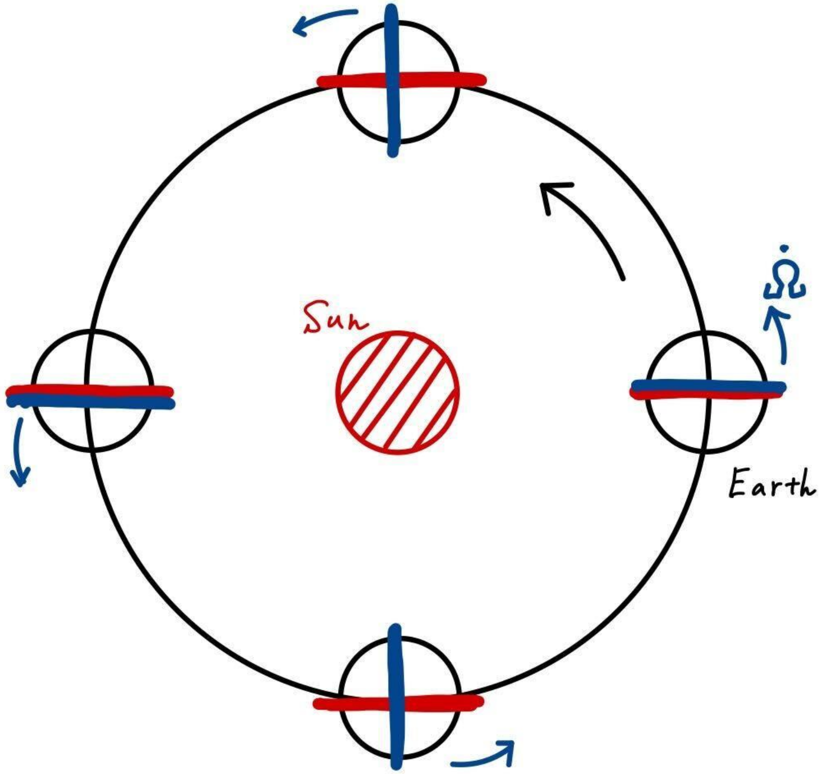
- Example of orbital perturbation: orbital perturbation due to Earth's oblateness ("J2 perturbation")
- Secular perturbation on Ω

$$\frac{\Delta\Omega}{\Delta t} = -\frac{3J_2 r_e^2 n}{2a^2(1-e^2)^2}\cos i$$

  - $J2 = 1.082627 \times 10^{-3}$
  - r_e: Earth's equatorial radius
- Secular perturbation on ω

$$\frac{\Delta\omega}{\Delta t} = \frac{3J_2 r_e^2 n}{2a^2(1-e^2)^2}\left(2-\frac{5}{2}\sin^2 i\right)$$

  - becomes zero when i = 63.4 deg, where the position of the perigee maintains



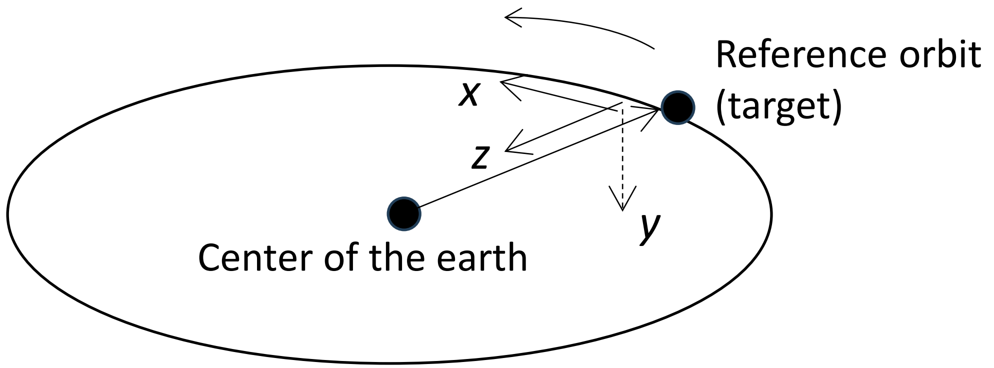
SSO (Sun-Synchronous Orbit), whose orbital plane rotates in synchronization with the orbital angular velocity of the earth by utilizing the perturbation on Ω. (Credit: University of Tokyo)

3. Relevant theories on constellation design and utilization

3.3 Constellation orbit maintenance

- Even if the Walker constellation helps keep the satellites aligned, each satellite's orbit must be corrected occasionally to maintain a perfect constellation.
- When operating a large number of satellites, it may be necessary to temporarily shift the orbits to avoid collisions with other satellites around the Earth.
- For such small orbit corrections, the dynamics expression shown in the Hill equation below is used. The position and velocity of a satellite flying in the vicinity of the reference satellite orbit, which is assumed to be a circular orbit, is expressed in the rotational coordinate frame shown in the right figure.

$$\begin{bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \end{bmatrix} = \begin{bmatrix} 2n\dot{z} + F_x \\ -n^2 y + F_y \\ 3n^2 z - 2n\dot{x} + F_z \end{bmatrix}$$



3. Relevant theories on constellation design and utilization

3.3 Constellation orbit maintenance

- Hill equation has the following linear analytical solution:

$$\begin{bmatrix}\delta \boldsymbol{r}(t)\\ \delta \boldsymbol{v}(t)\end{bmatrix} = \Phi(t)\begin{bmatrix}\delta \boldsymbol{r}(0)\\ \delta \boldsymbol{v}(0)\end{bmatrix}$$

, here

$$\Phi(t) = \begin{bmatrix} 1 & 0 & -6(\sin nt - nt) & \frac{4\sin nt - 3nt}{n} & 0 & \frac{2(1-\cos nt)}{n} \\ 0 & \cos nt & 0 & 0 & \frac{\sin nt}{n} & 0 \\ 0 & 0 & 4 - 3\cos nt & -\frac{2(1-\cos nt)}{n} & 0 & \frac{\sin nt}{n} \\ 0 & 0 & 6n(1-\cos nt) & 4\cos nt - 3 & 0 & 2\sin nt \\ 0 & -n\sin nt & 0 & 0 & \cos nt & 0 \\ 0 & 0 & 3n\sin nt & -2\sin nt & 0 & \cos nt \end{bmatrix}$$

- Given a target orbit to be reached, the ΔV to be generated at departure and the ΔV required at arrival at the target orbit can be calculated from the current relative position and velocity of the satellite and the time of flight to the target orbit You can minimize ΔV by exploring the departure/arrival times and time of flight.

(1) This term should be zero

given

$$\begin{bmatrix}\delta \boldsymbol{r}(t)\\ \delta \boldsymbol{v}(t)\end{bmatrix} = \begin{bmatrix}\Phi_{11}(t) & \Phi_{12}(t)\\ \Phi_{21}(t) & \Phi_{22}(t)\end{bmatrix}\begin{bmatrix}\delta \boldsymbol{r}(0)\\ \delta \boldsymbol{v}(0)\end{bmatrix}$$

$$\delta \boldsymbol{v}(0) = -\Phi_{12}(t)^{-1}\Phi_{11}(t)\delta \boldsymbol{r}_0 \quad (1)$$

$$\delta \boldsymbol{v}(t) = \dots \quad (2)$$

departure velocity can be derived by (1)

(2) Then, velocity at arrival can be derived

4. Challenges for small satellite constellations

4. Challenges for small satellite constellations

4.1 Challenges in satellite design and manufacturing

Cost reduction

- design standardization and mass production

Reliability

- Although a constellation is composed of many satellites, so that the failure of a few satellites will not cause catastrophic damage to the entire constellation, reliability is still important in order not to increase the cost of manufacturing and launching satellites.

Communication capacity

- High-capacity data communication is required to perform wide-area observations at high frequency (in the case of remote sensing services) or to support the communication of many users (in the case of communication services).
- High-speed communications are required not only between the satellite and the ground, but also for inter-satellite communications to relay data via other satellites in some cases.
- For example, optical communication technology are required to achieve low latency and high-capacity data communication.

4. Challenges for small satellite constellations

4.2 Challenges in satellite launch, deployment and operation

Launch cost reduction

- **Challenge** High cost of launching a large number of satellites
- **Solution** Utilization of commercial launch vehicles (e.g., SpaceX‘s Falcon 9) and reduction of launch costs per satellite by increasing the number of simultaneous launchers through optimization of satellite shape and configuration on the launch vehicle

Precise orbit insertion

- **Challenge** There is a limit to the accuracy of orbit injection by a launch vehicle. Also, it is difficult to expect the service to evenly distribute satellites in one orbital plane for the Walker constellation.
- **Solution** Use an OTV service that will put each customer‘s satellite into the desired orbit (e.g., D-orbit’s ION Satellite Carrier) or put a sufficiently capable propulsion system on the satellite (see section 3.3 for trajectory correction)

Stacked launch configuration of second-generation Starlink satellites (v2-Mini). (Credit: SpaceX)

4. Challenges for small satellite constellations

4.2 Challenges in satellite launch, deployment and operation

Automation of operation

- **Challenge** Many satellites need to be operated simultaneously, which requires a lot of manpower and is subject to human operation errors.
- **Solution** Automation of the following tasks is necessary to save human effort and improve the reliability of satellite constellation operations.
  - monitoring of satellite status from telemetry
  - planning of operations based on satellite status and observation requests
  - automatic execution of commands
  - as more highly automated functions, orbital maneuver operations to avoid collisions with other satellites/debris and to adjust satellite placement in constellation

Another challenge in satellite design due to changes in launch costs

- Variations in launch costs will have a significant impact on the optimal solution for what size and specifications of satellites should form the constellation.
- As launch costs fall, it becomes more optimal to launch larger, more powerful satellites.

Ref: Vishnuu Mallik, et al., “An Automated Approach to Maneuver Campaign Management for SkySats”, SSC22-VI-03, Small Satellite Conference, Utah, USA, 2022

4. Challenges for small satellite constellations

4.3 Regulatory and policy issues

Space debris mitigation

- Post-mission disposal
- Collision avoidance, propulsion system

Radio-frequency utilization

- Radio frequency interference, competition for radio frequency spectrum allocation
- Electromagnetic leakage
- Use of laser (optical) communication technology

4. Challenges for small satellite constellations

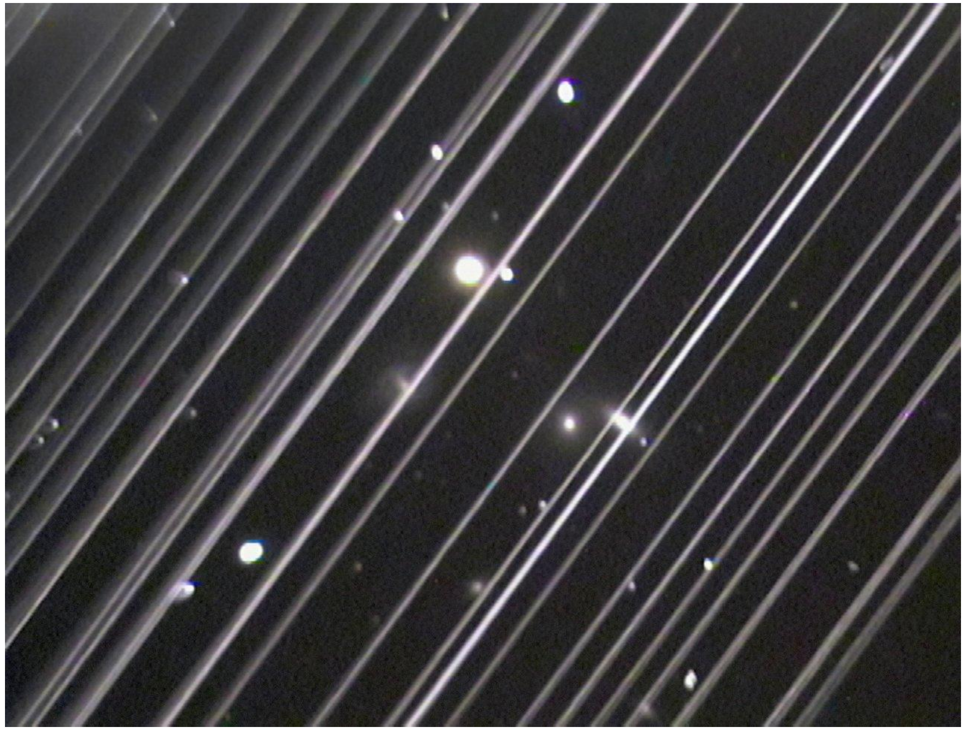
4.3 Regulatory and policy issues

<u>Artificial sky glow</u>

- The light pollution from satellites can obscure faint celestial objects, making it difficult for astronomers to conduct observations. This is especially concerning for the detection of near-Earth objects (NEOs) and other faint astrophysical signals.
- Companies are working on reducing the reflectivity of their satellites. For example, SpaceX has experimented with dark coatings and sunshades to minimize the brightness of their Starlink satellites.

<u>Atmospheric impact of satellite demise upon reentry</u>

- When satellites re-enter the atmosphere, they undergo extreme mechanical and thermal stresses, leading to the release of various gases and particles. These include metal oxide particles, chlorine, and nitrogen oxides, which can affect atmospheric chemistry. Also, substances like chlorine and nitrogen oxides released during reentry can contribute to ozone layer depletion. This is a significant concern as it impacts the Earth's protective ozone shield.



Example of light pollution.
(Credit: Victoria Girgis/Lowell Observatory)

5. Future of small satellite constellations

5. Future of small satellite constellations

5.1 Possibility of technological advancement

Technological advancement

- Miniaturization and cost reduction
- Advanced communication technologies
- Artificial intelligence

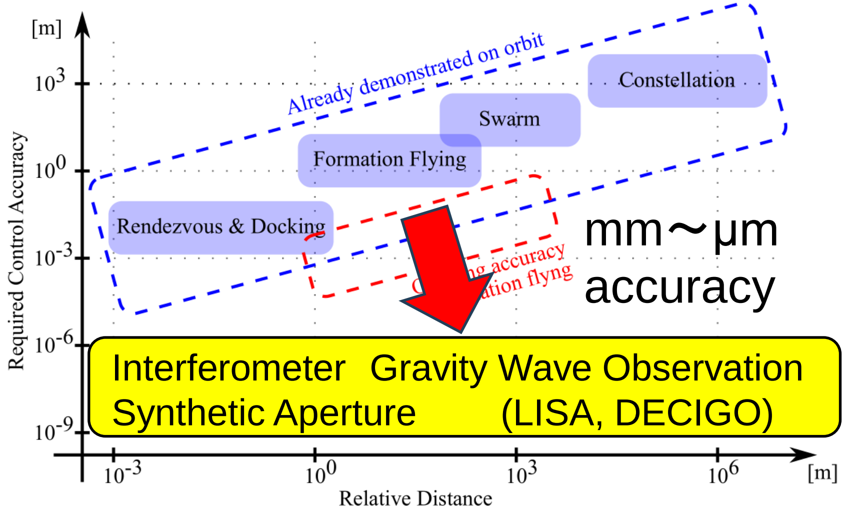
Future of small satellite constellation

- Global internet connection
  - Widespread use of low earth orbit satellite-based Internet services will enable high-speed Internet access in remote areas and developing countries
- Disaster monitoring
  - A constellation of small satellites will be used to quickly assess the situation and monitor the environment in the event of a disaster. This will greatly improve the efficiency of disaster response

5.2 Formation Flight

Formation Flight (FF)

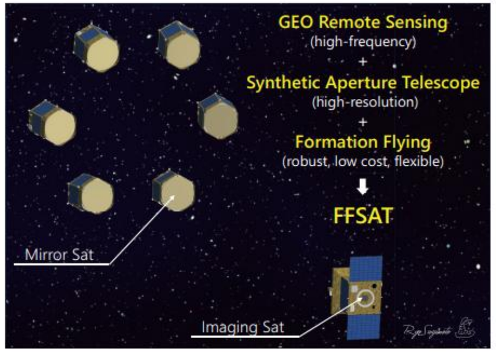
- Both satellite constellations and formation flying involve multiple satellites working together, but they have distinct differences in their configurations and purposes: Formation flying involves multiple satellites maintaining a specific relative position and orientation to each other as they orbit. They work together closely as a coordinated unit.
- May realize high-level astronomical / Earth observation missions that would not be possible with a single spacecraft.
- Requires coordinated control of multiple spacecraft flying near each other.



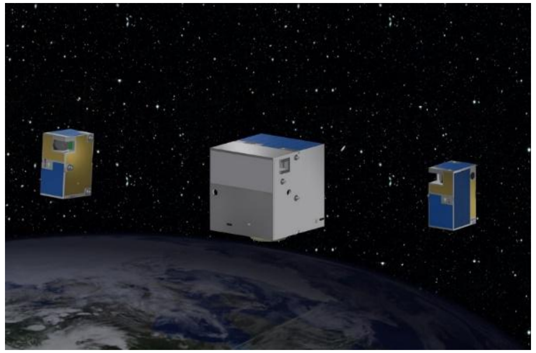
Earth Observation

Astronomy

Synthetic Aperture Telescope "FFSAT"



Infrared Interferometer "SEIRIOS"



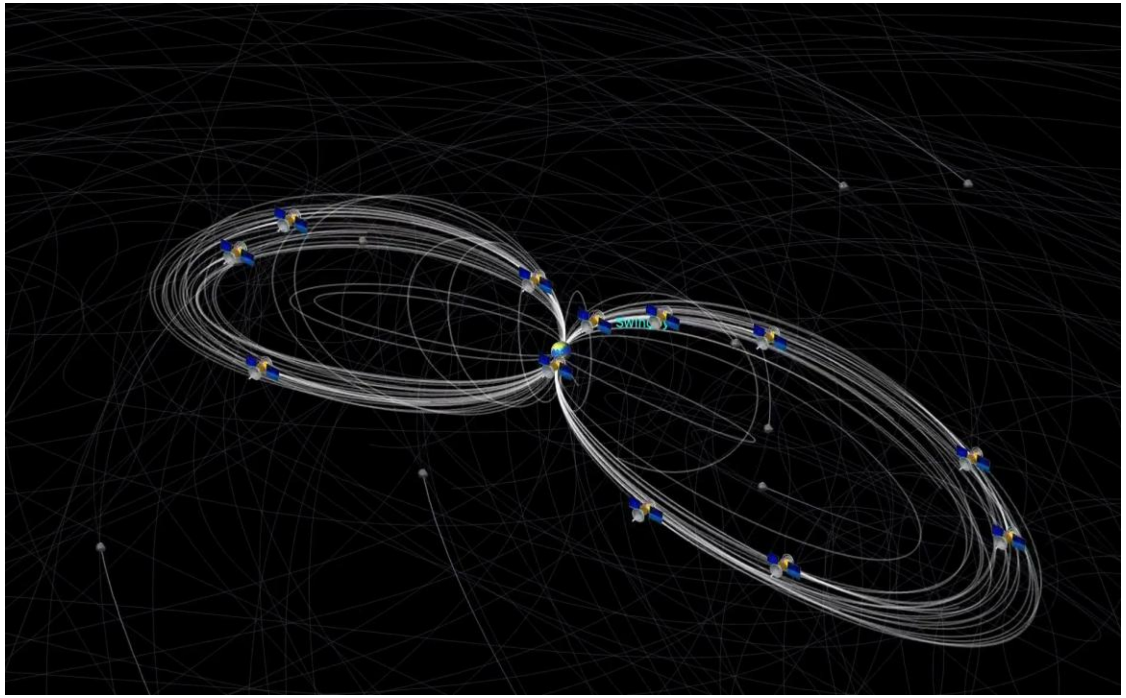
Credit: Intelligent Space Systems Laboratory, University of Tokyo

5. Future of small satellite constellations

5.3 Constellation mission beyond the Earth

Interplanetary satellite constellation

- Some ideas have been developed to expand the satellite constellation concept to interplanetary orbit: multiple spacecraft are placed in cycler orbits that repeat Earth swing-by on a yearly cycle, and Earth swing-by is used to change orbits in order to fly to unexpected exploration targets (such as asteroids) on an ad hoc basis.



(Credit: Naoya Ozaki, Shoya Dozono)

Ref: Naoya Ozaki, Kanta Yanagida, et al. Asteroid Flyby Cycler Trajectory Design Using Deep Neural Networks. Journal of Guidance, Control, and Dynamics, Vol. 45, No. 8, pp. 1496–1511, 2022

6. Conclusion

6. Conclusion

In this lecture, the following things were discussed:

1. With the advancement of small satellites, satellite constellations that cover the entire Earth by placing many satellites in complementary orbits have been planned and realized.

2. The typical applications of constellations are navigation, communications, and earth observation, but other applications are also emerging (e.g., weather monitoring and ground activity monitoring using radio frequency observations).

3. The background theory behind the orbit arrangement design and orbit maintenance methods, which are important in constellation design and operation, was introduced.

4. In addition to technical issues, legal and regulatory issues have been identified for the realization and evolution of small satellite constellations. By solving these issues, more advanced and practical constellations are expected to be realized in the future.

Thank you very much.

[Disclaimer]
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