SEIRIOS

Space Experiment of IR Interferometric Observation Satellites

Satoshi Ikari (UT),
and SEIRIOS Project team

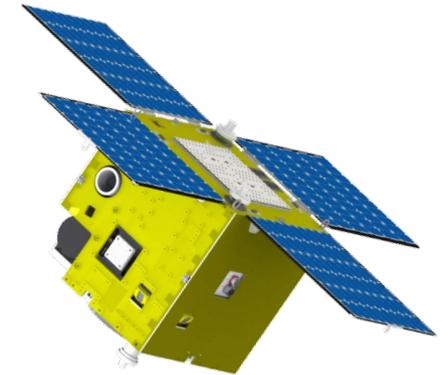**00**

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Self-Introduction

Satoshi Ikari (五十里 哲)

- **2017**
  - Ph.D. (Engineering), Dept. Aero/Astro, UT
- **2017-2023**
  - Assistant Prof., Dept. Aero/Astro, UT
- **2023-2024**
  - Researcher, Meisei Univ.
- **2022-2024**
  - Guest Researcher , German Space Center (DLR)
- **2024-**
  - Assoc. Prof., ISSL, Dept. Aero/Astro, UT

PROCYON

DLR GSOC
German Space Operation Center

Micro/Nano Satellites developed by ISSL, UT

ISSL — Intelligent Space Systems Laboratory
The University of Tokyo

16 Satellites Launched

2 Satellite will be launched soon

22 Years of In-orbit Satellite Operations

XI-IV (2003)
In operation (22 years)
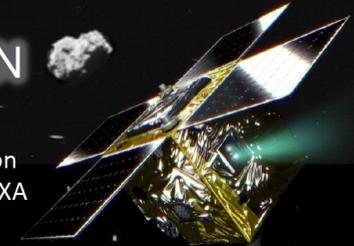
PRISM (2009)
End of operation

HODOYOSHI 1, 3, 4 (2014)
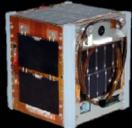1: End of operation   3,4: In operation (11 years)
Collaborator: Axelspace, NESTRA

PROCYON (2014)
End of operation
Collaborator: JAXA

XI-V (2005)
In operation (20 years)

MicroDragon (2019)
In operation
Collaborator: VNSC

G-Satellite (2020)
End of operation
Collaborator: TOCOG, JAXA

EQUULEUS (2022)
End of operation
Collaborator: JAXA

Nano-JASMINE
Launch canceled
Collaborator: NAOJ

TRICOM-1R (2018)
End of operation
Collaborator: JAXA
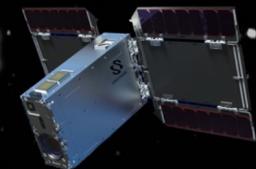
RWASAT-1 (2019)
End of operation
Collaborator: Rwanda

Strix-α (2020)
End of operation
Collaborator: Synspective

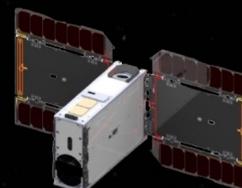SPHERE-1 EYE (2023)
End of operation
Collaborator: SONY

AQT-D(2019)
End of operation
Collaborator: UT-SPL

ONGLAISAT(2024)
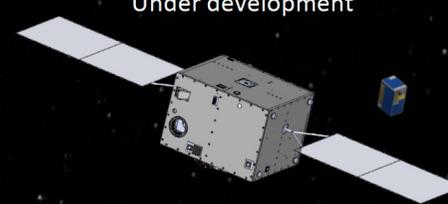End of operation
Collaborator: TASA

GEO-X
Under development

SEIRIOS
Under development

Prof. Nakasuka

Prof. Funase

As of May 2025

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Background

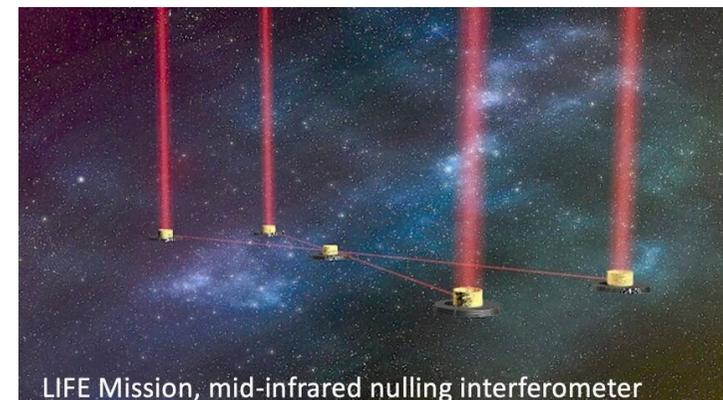# Formation Flying Satellites

- **A mission architecture in which multiple spacecraft measure and/or control their relative positions and attitudes to accomplish objectives that cannot be achieved by a single spacecraft.**
- **Limitation of single spacecraft**
  - Size constraints imposed by the launch vehicle fairing
  - Mission risk in the event of a single-point failure
- **Difference from a Constellation**
  - In a constellation, each satellite operates independently
  - Cooperation occurs at a higher layer (e.g., the data or mission layer), rather than through tight relative motion control
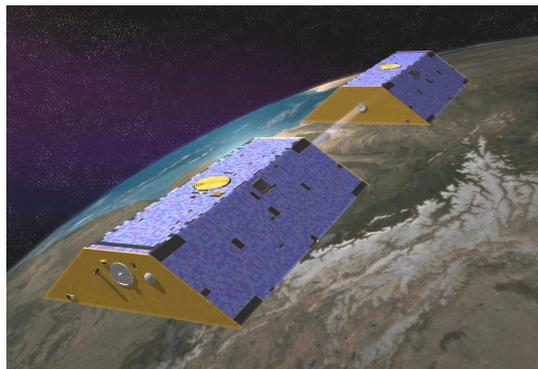
GRACE(2002)

TanDEM-X(2010)

LIFE Mission, mid-infrared nulling interferometer

LIFE (Planned)

6

Increasing demand for high-precision satellite formation flying

Axis labels: Control Accuracy Requirement (m) vs Intersatellite Distance (m)

- Demonstrated
- RVD
- 中精度 FF
- SWARM
- Constellation
- Xray Telescope
- Infrared Interferometer
- Synthetic Aperture Telescope
- Occulter
- Gravitational Wave Antenna

High-precision FF
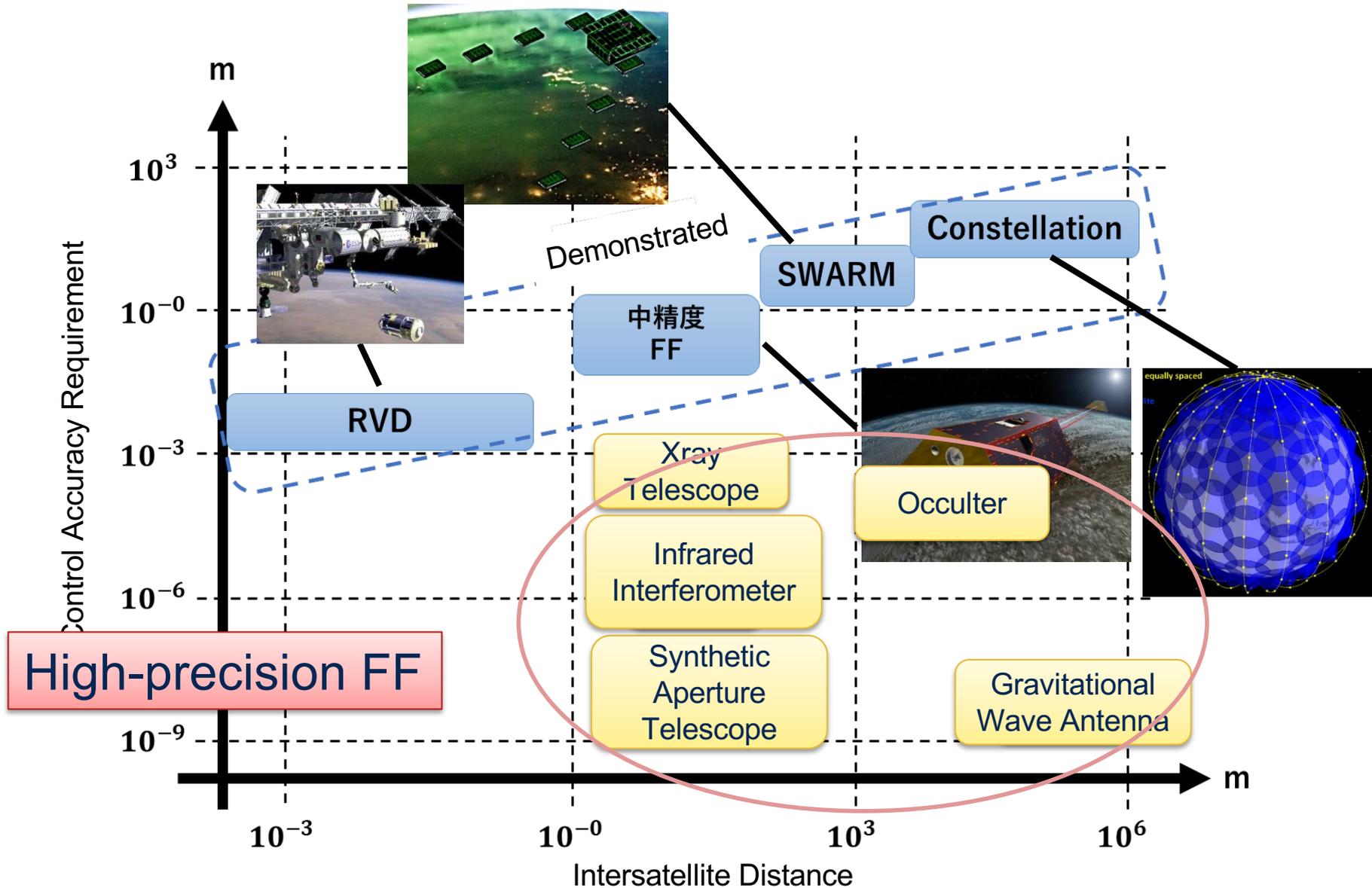
Space Infrared Interferometers with FF

- **High resolution infrared observation requires long-baseline space interferometry**
  - 100m baselines are necessary
  - Ground-based observations are impractical due to atmospheric absorption
- **Several FF infrared space interferometer concepts have been proposed**
  - Unfortunately, these mission plans were stopped.
- **Key challenges:**
  - Cost: Development and launch of multiple large spacecraft
  - Technical risk: Achieving micrometer-level relative position and attitude control accuracy
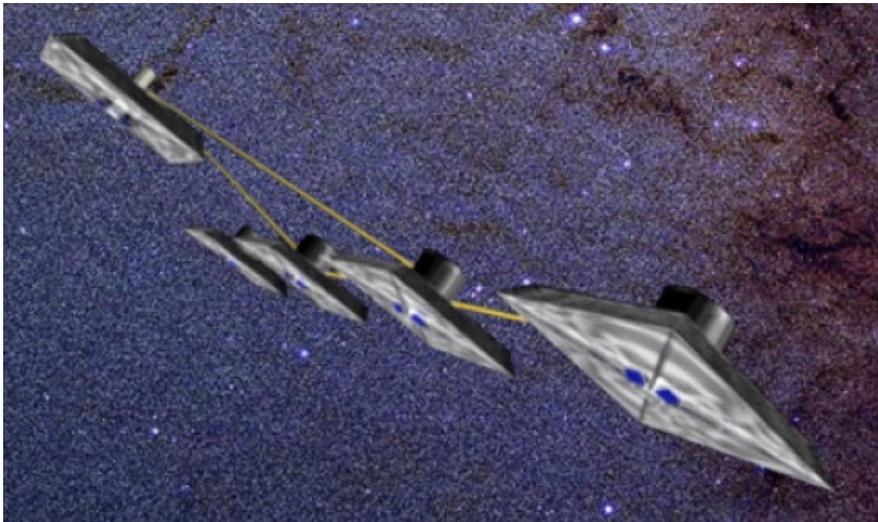
TPF-I

Daniel P Scharf, Fred Y Hadaegh, Zahidul H Rahman, Joel F Shields, and Gurkipal Singh. An Overview of the Formation and Attitude Control System for the Terrestrial Planet Finder Formation Flying Interferometer. No. 818, pp. 1–12, 2017
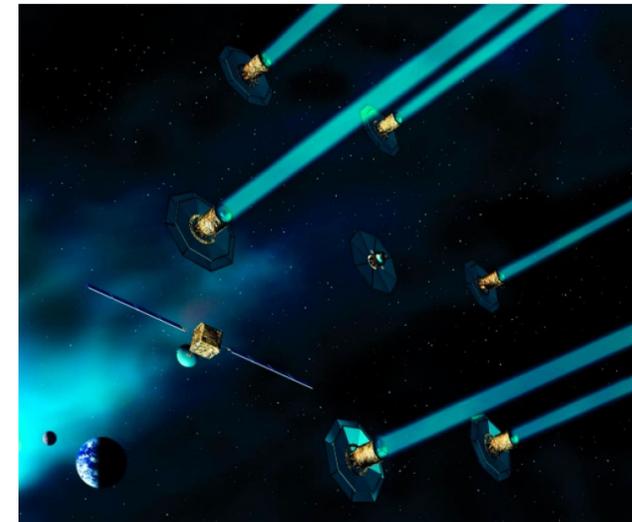
DARWIN

Markus Schlotterer and Stephan Theil. Testbed for On-Orbit Servicing and Formation Flying Dynamics Emulation. AIAA Modeling and Simulation Technologies Conference, No. August 2010, 2010.

Strategy Toward Realizing FF Infrared Space Interferometer

- **Key Challenges of a Formation-Flying Infrared Space Interferometer**
  - Cost: Development and launch of multiple large spacecraft
  - Technical risk: Achieving micrometer-level relative position and attitude control accuracy

- **Strategy Toward Realization**
  - Reduce cost by utilizing microsatellites while enabling ambitious missions
  - Relax the required control accuracy from micrometer-level to millimeter-level by employing a densified pupil spectroscopy interferometer (DPSI)
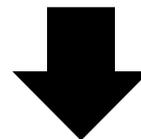
Requirement relaxation
by using
Densified Pupil Spectroscopy
Interferometer

Cost Reduction
by using
Small satellites

SEIRIOS
Space Experiment of IR Interferometric Observation Satellites

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Space Strategy Fund(SSF): High-Precision Satellite FF Technology

宇宙戦略基金

採 択 結 果 （３／３）

技術開発テーマ名	高精度衛星編隊飛行技術
実施機関名（代表機関）	東京大学 大学院
研究代表者名	五十里 哲
技術開発課題の名称	SEIRIOS による超高精度編隊飛行衛星制御技術の獲得

Our Proposal was selected!

Overview of Our Proposal

- World First Space Interferometer

- Infrastructure for Future Mission

- Future Accurate FF Mission

On Orbit Demonstration of SEIRIOS

1: SEIRIOS

10kg

50kg

10 – 100m

10kg

- Accurate FF demonstration with MicroSats
- Infrared Interferometer

2: Test Equipment

100 mm

- Thrust Stand
- GNSS Signal Simulator
- Air Bearing Table
- Numerical Simulator

3: Community

- Symposium for researchers, students, engineers, and business person

02

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SEIRIOS
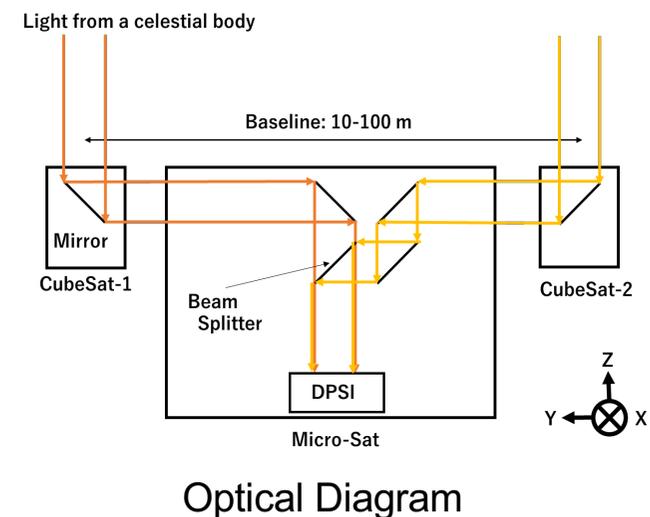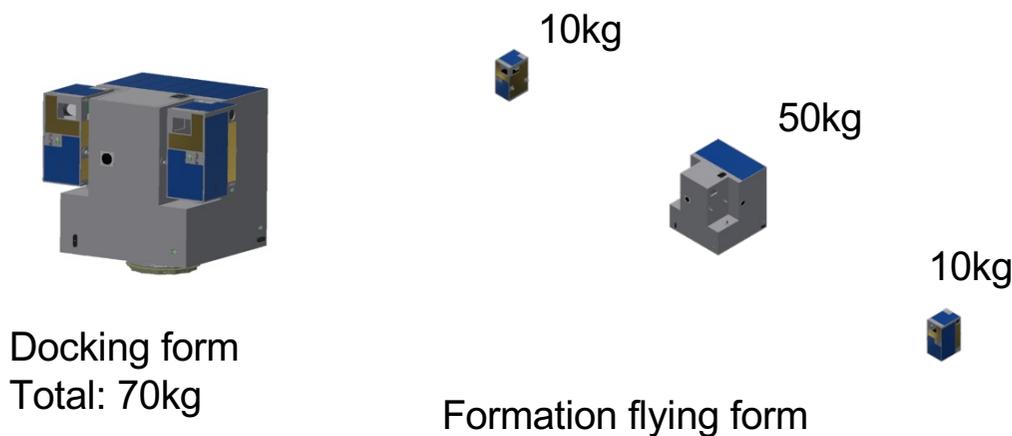
SEIRIOS

- **Space infrared interferometer with densified pupil spectroscopy by three micro/nano-satellites.**
- **Wavelength: 0.7-1um**
- **Aperture diameter : 8.5cm**
- **Two CubeSats reflect the light from a celestial body and the micro-sat combines the two light to observe interferometric fringe with densified pupil spectroscopy interferometer.**

Docking form
Total: 70kg

10kg

50kg

10kg

Formation flying form

Light from a celestial body

Baseline: 10-100 m

Mirror

CubeSat-1

Beam
Splitter

DPSI

Micro-Sat

CubeSat-2

Z

Y ⊗ X

Optical Diagram

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Densified Pupil Spectroscopy Interferometer (DPSI)

- **Two reflected beams are combined at the pupil plane not at the focal plane**
- **The combined beams at pupil plane are sliced**
- **The sliced sub-pupils are densified by concave mirrors**
- **Input the densified sub-pupils to spectrograph to get spectra of the bodies**
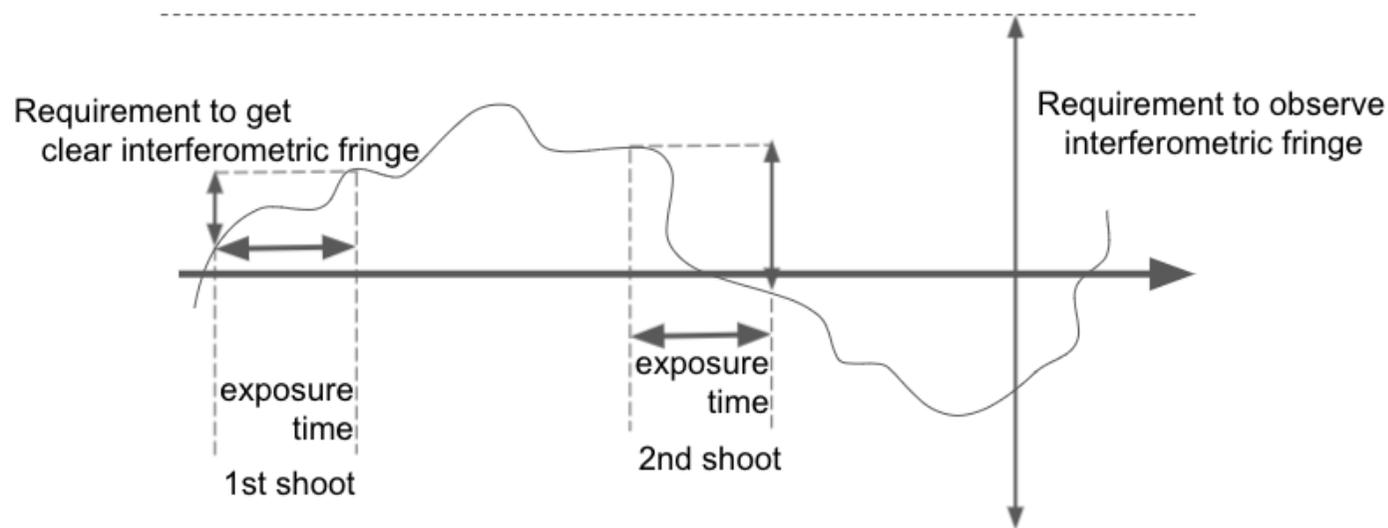- **The DPSI also works as a sensor for relative position and attitude.**
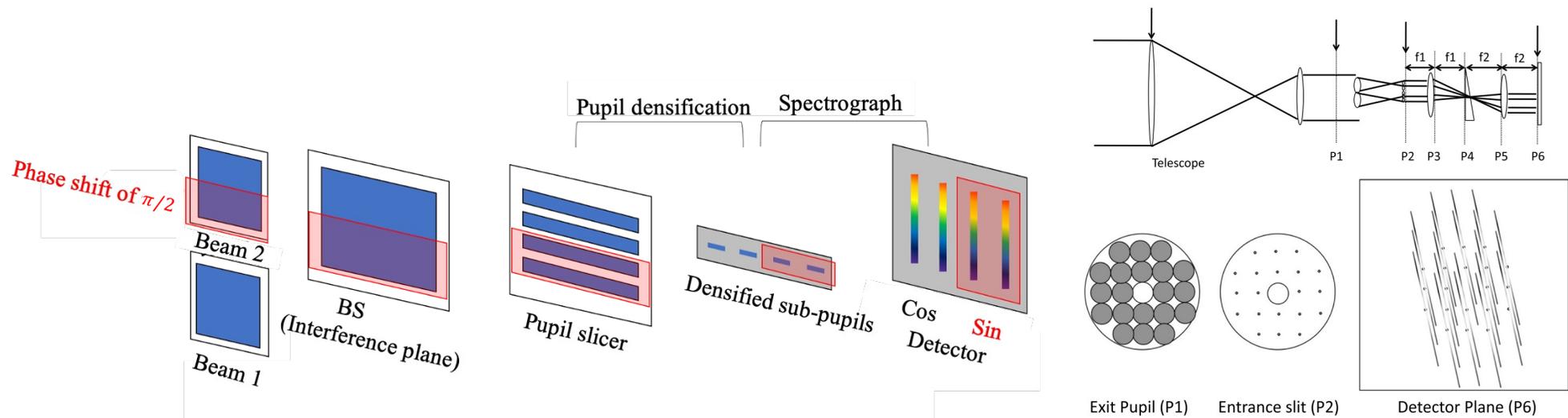
Requirement relaxation by DPSI

- ● **We divide the control accuracy requirement:**
- ● **Requirement to construct interferometric fringe**
  - ○ Long term requirement

  This requirement is dramatically relaxed

- ● **Requirement to get clear interferometric fringe image**
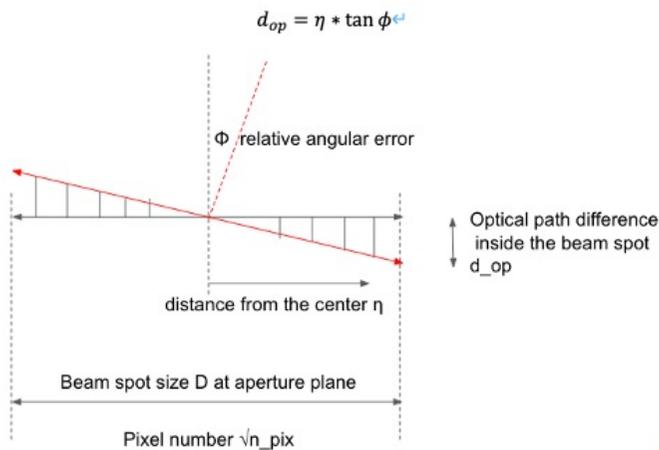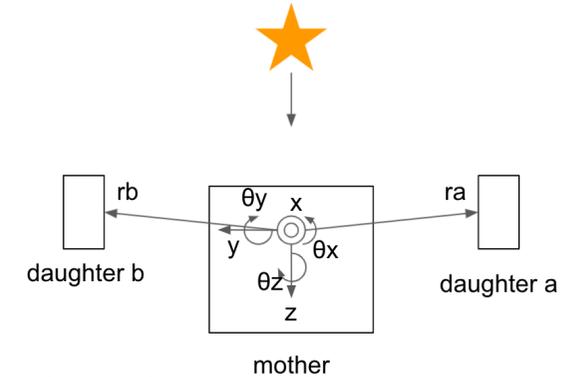 - ○ Short term requirement (during exposure time)

S. Ikari, et al.," SEIRIOS: A Demonstration of Space Infrared Interferometer by Formation Flying of Micro-Satellites", Small Satellite Conference, 2021

Requirement to Construct Interferometric Fringe

- **Relative Position**
  - ○ X: not related with optical path difference(OPD)
  - ○ Y, Z: Directly relate with OPD
    - ■ Coherence length is extended by spectrograph
- **Relative Attitude**
  - ○ θ_x, θ_z: Tow beams should be overlapped
    - ■ It is easer to overlap the beams at pupil plane than focal plane
    - ■ We also have to consider the optical path difference inside the beam at pupil plane, but the requirement is only 100urad order.
  - ○ θ_y: not important

$$d_{op} = \eta * \tan\phi$$

Φ relative angular error

Optical path difference inside the beam spot d_op

distance from the center η

Beam spot size D at aperture plane

Pixel number √n_pix

Axis	Conventional	DPSI	Condition
Δx	1 cm order	1 cm order	Two beams overlapping
Δy	1 μm order	1 mm order	Shorter than coherence length
Δz	1 μm order	1 mm order	
$\Delta\theta_x$	1 μrad order	100μrad order	Two beams overlapping
$\Delta\theta_y$	1 deg	1 deg	-
$\Delta\theta_z$	1 μrad order	100μrad order	Two beams overlapping

S. Ikari, et al.," SEIRIOS: A Demonstration of Space Infrared Interferometer by Formation Flying of Micro-Satellites", Small Satellite Conference, 2021

SEIRIOS Mission Definition

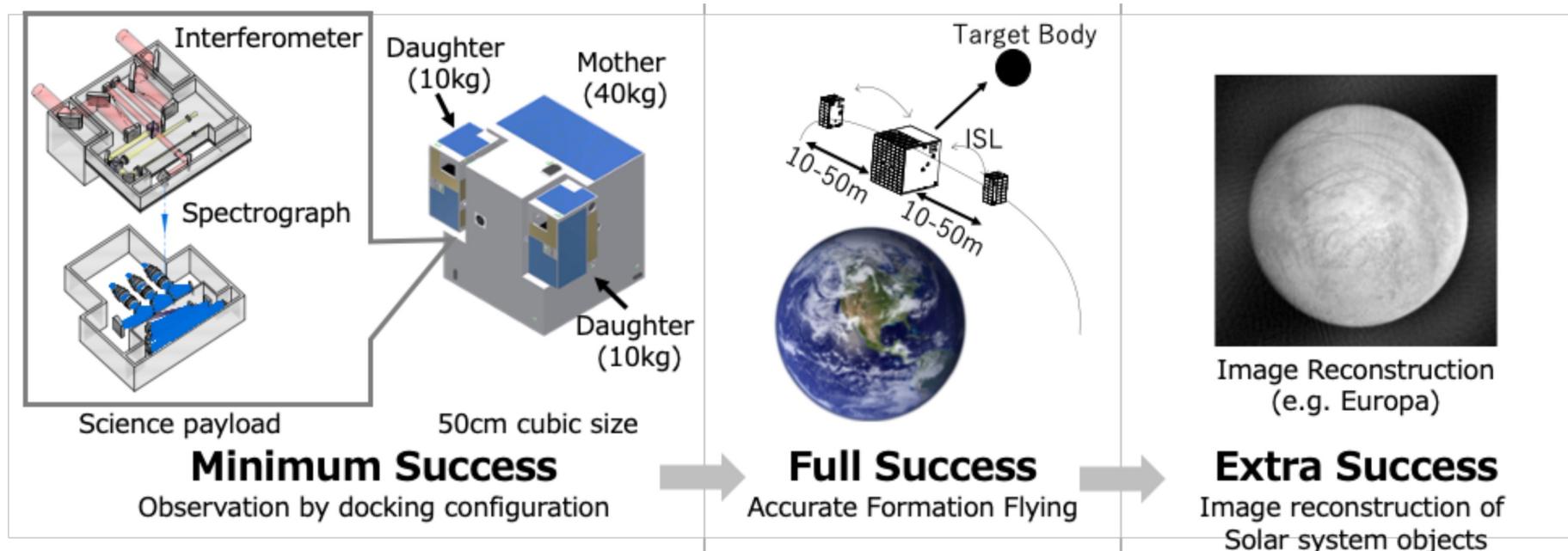● **High-Precision FF Tech. Demo. Project with Micro-Satellites: SEIRIOS**
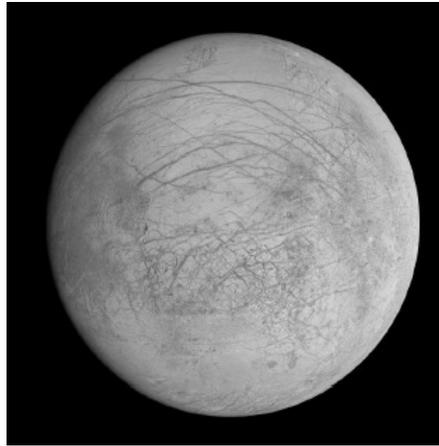 ○ **Targeting an on-orbit demonstration in low Earth orbit (LEO) in 2031**
● **Mission Objective**
  ○ Engineering：Establish sub-millimeter-level precision formation-flying control technology
    ■ Demonstrate real-time, onboard formation flying with three satellites over a wide separation range from meters to sub-millimeters
  ○ Science：Achieve on-orbit measurement of infrared interference fringes with a DPSI
    ■ Ultimately reconstruct images by acquiring multiple interference fringes to fill the u-v plane
    ■ Aim to obtain high-resolution images of natural satellites in the solar system from Earth orbit
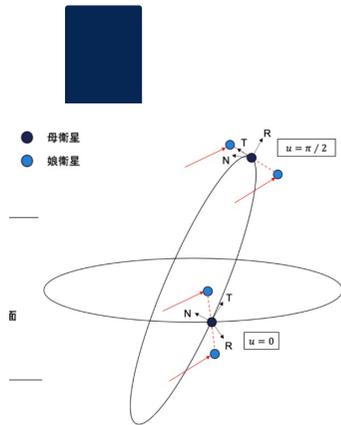
  *Direct imaging of Exoplanet is future work.
 SEIRIOS will be the first step to realize the FF interferometer like LIFE.

Interferometer | Daughter (10kg) | Mother (40kg) | Daughter (10kg)
Spectrograph
Science payload | 50cm cubic size

Minimum Success
Observation by docking configuration

Target Body | 10-50m | ISL | 10-50m

Full Success
Accurate Formation Flying

Image Reconstruction (e.g. Europa)

Extra Success
Image reconstruction of Solar system objects

Observation of SEIRIOS

Target body

100 Fringes

Observed Fringes

Observation with
- Multiple baseline length
- Filling UV plane

Reconstructed image

On-ground Image Analysis
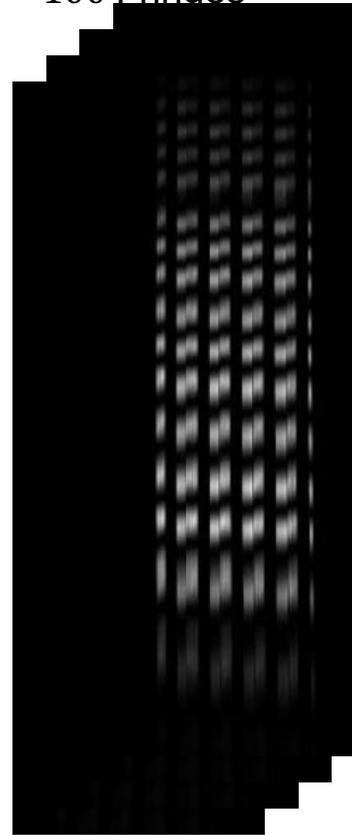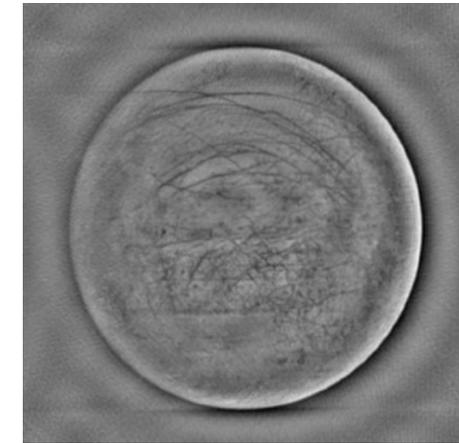
Overview of SEIRIOS Bus System

Launch in docking form

Formation Flying form
(Max baseline: 100m)

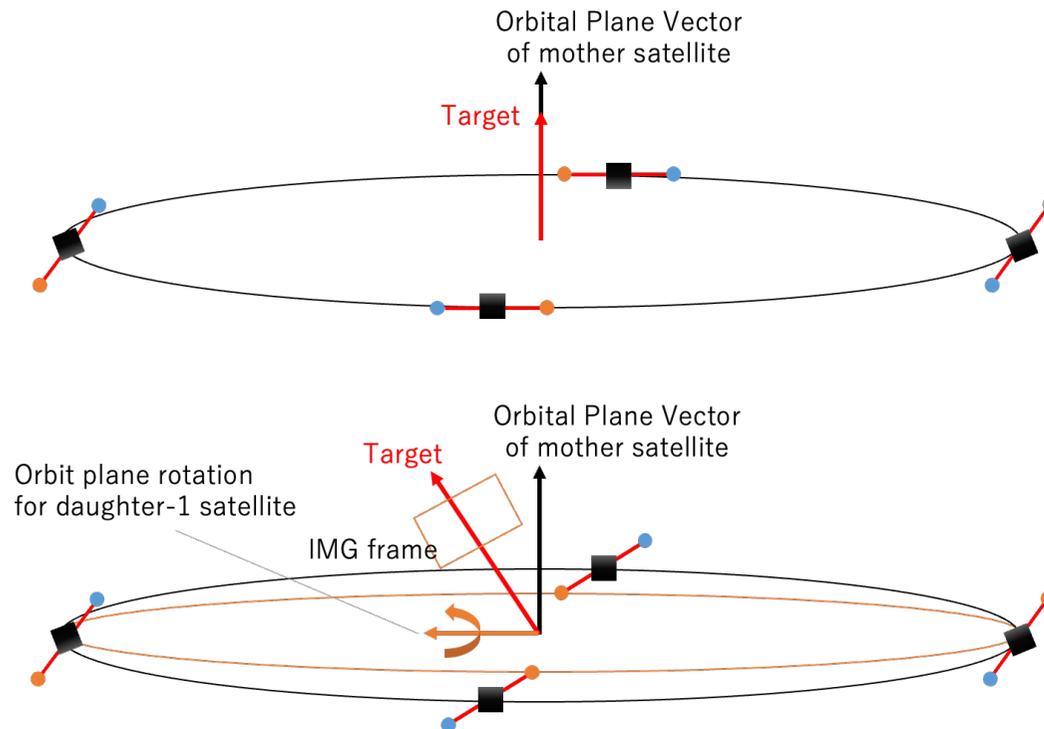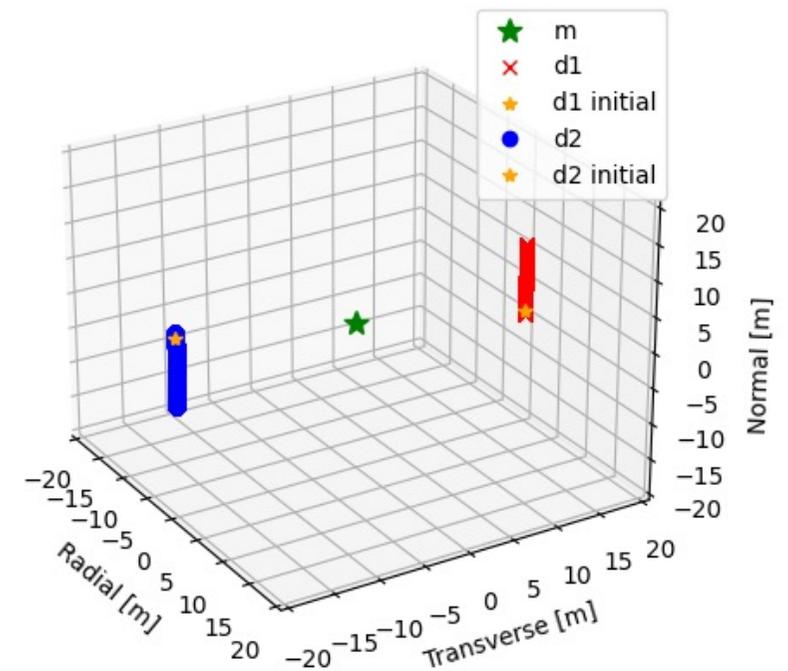| Item	Micro-satellite	CubeSats * 2
Structure	55 kg	10 kg
Thermal	Cooling the CCD to -20 degC	No special design
Power	Max generation: 85W Ave. consumption: 60W	Max generation: 20W Ave. consumption: 15W
Comm.	S-band up: 4 kbps S-band down: 64kbps X-band down: 10Mbps	S-band up: 4 kbps S-band down: 64kbps
Attitude	10 arcsec stability	10 arcsec stability
Formation Flying	CDGPS Inter Sat Link Optical Navigation Laser distant meter Fringe Image FB Thrusters Tip/Tilt, Delay Line	CDGPS Inter Sat Link Thrusters

Hodoyohi-3 and 4 (2014)

EQUULEUS(2022)

Orbit Design

- **Reference orbit (Chief orbit): 600 to 800km, Dawn-Dusk Orbit**
- **Relative Orbit**
  - The deputy satellites primarily operate in an along-track configuration, flying ahead of and behind the chief satellite.
  - To observe directions other than the normal to the orbital plane, the deputy satellites' orbits are inclined

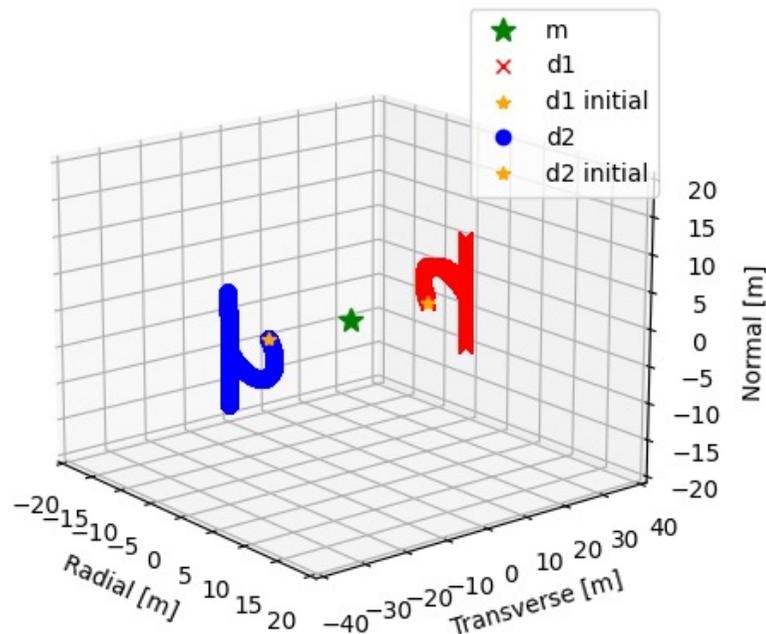Relative motion with inclined orbit (LVLH Frame)

Orbit Maneuver

Baseline length $B = \mathbf{40m}$, Target direction from ref. $\Delta\alpha = \Delta\beta = 0$ deg
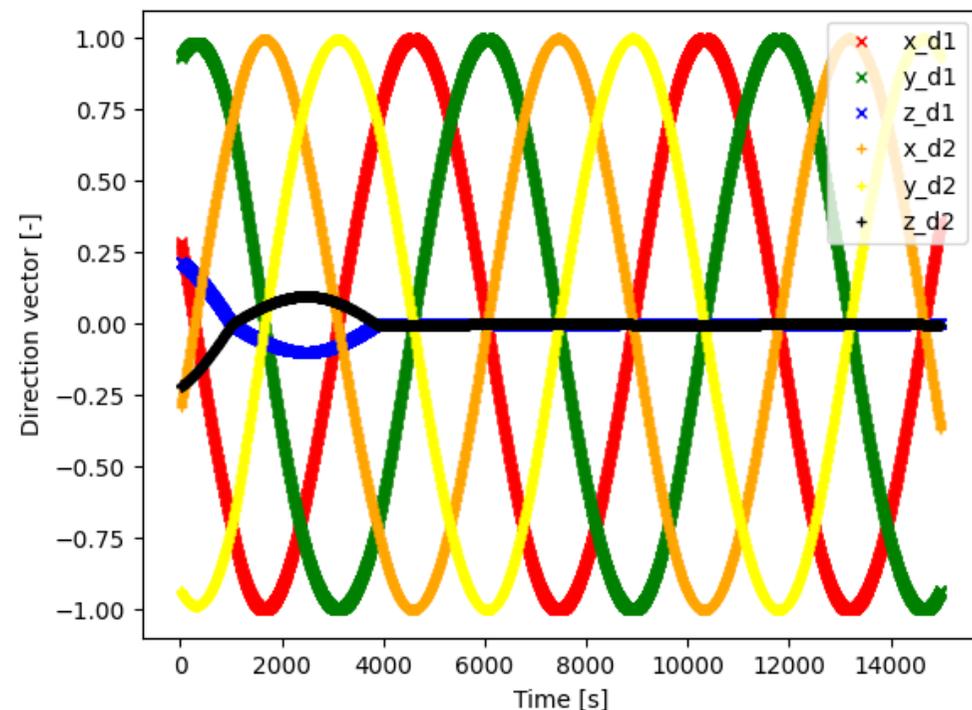
↓

Baseline length $B = \mathbf{60m}$, Target direction from ref. $\Delta\alpha = \Delta\beta = 10$ deg

Impulse	Daughter Satellite A	Daughter Satellite B
First impulse	$[-2.7 \quad 0 \quad 4.12] \times 10^{-3}$ m/s	$[2.7 \quad 0 \quad -4.12] \times 10^{-3}$ m/s
Second impulse	$[-2.7 \quad 0 \quad -4.12] \times 10^{-3}$ m/s	$[2.7 \quad 0 \quad 4.12] \times 10^{-3}$ m/s

Relative Position of Satellites in RTN frame

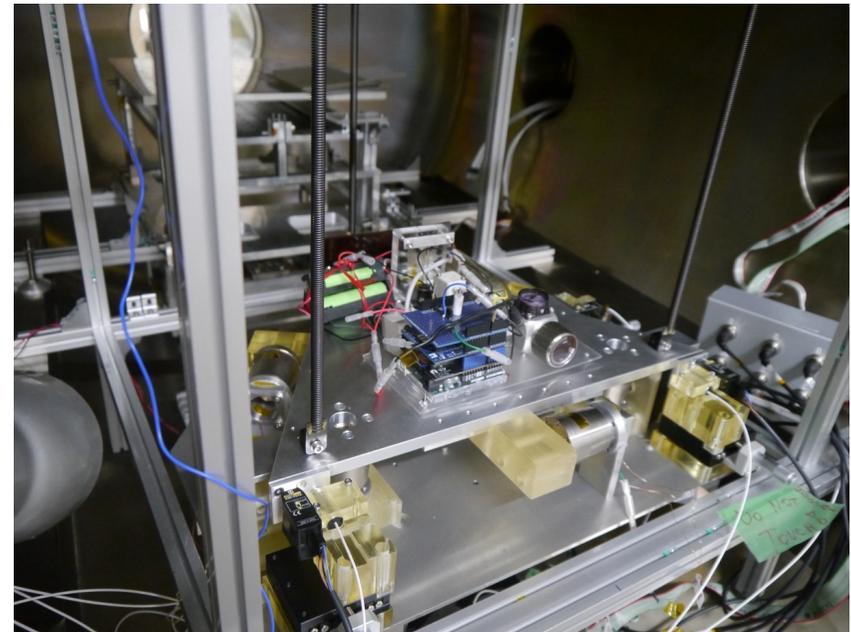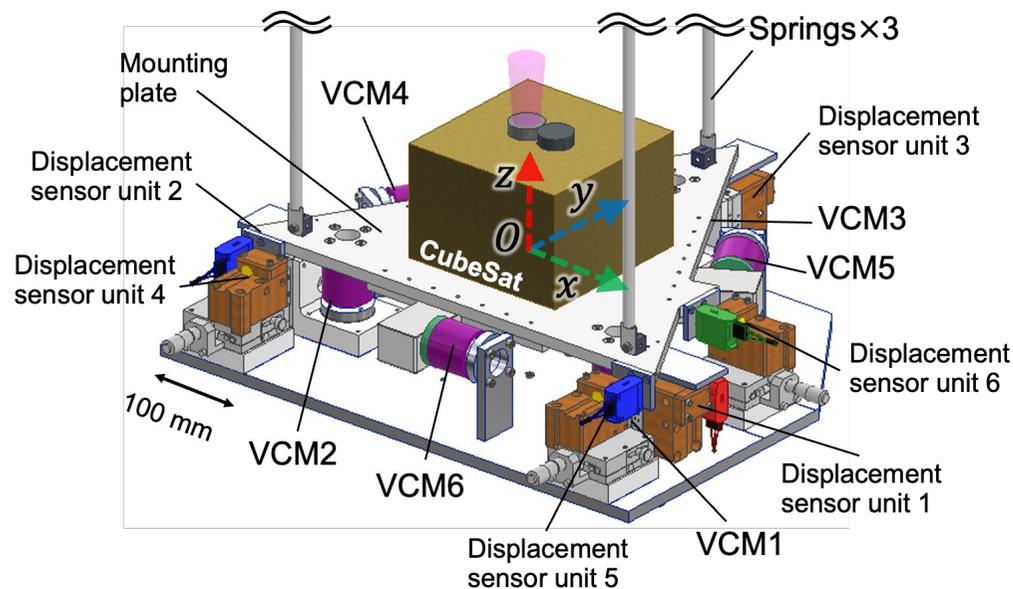Baseline direction in IMG frame

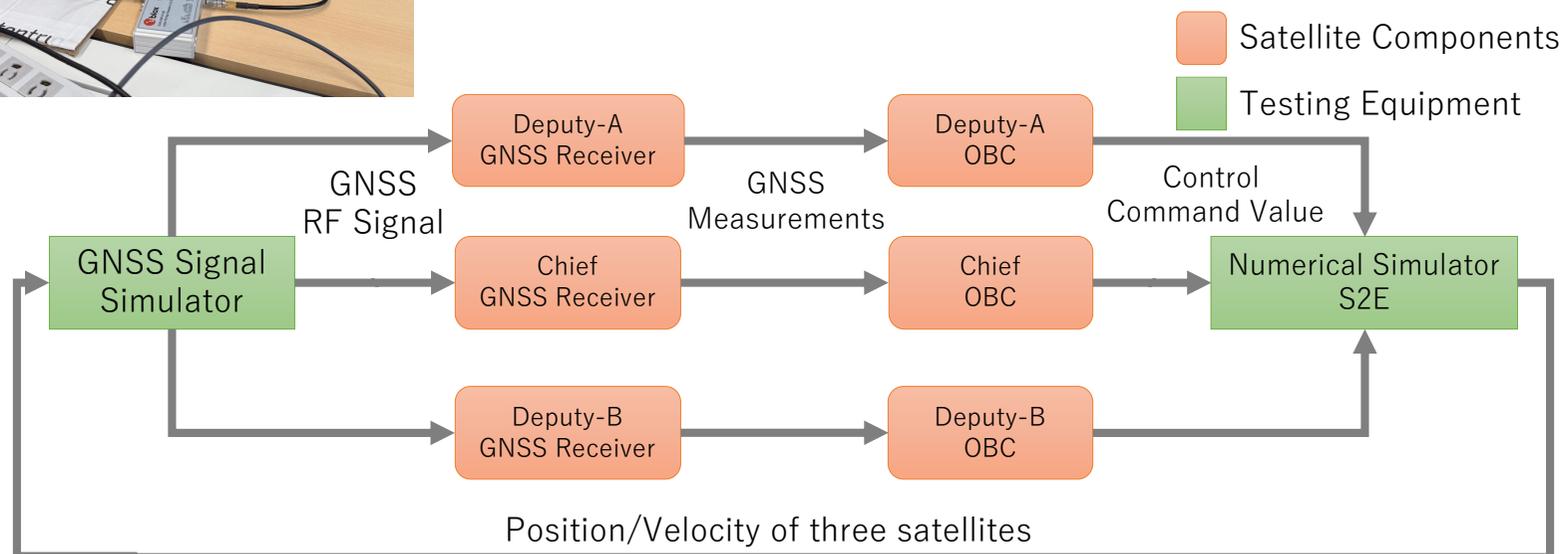**03**

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Ground Experiment Equipment

Development of FF Testing System: 6DoF Thrust Stand

● Micro thrusters are essential for accurate FF mission.

● To measure the detailed feature of thrusters, we will develop 1uN class thrust stand.

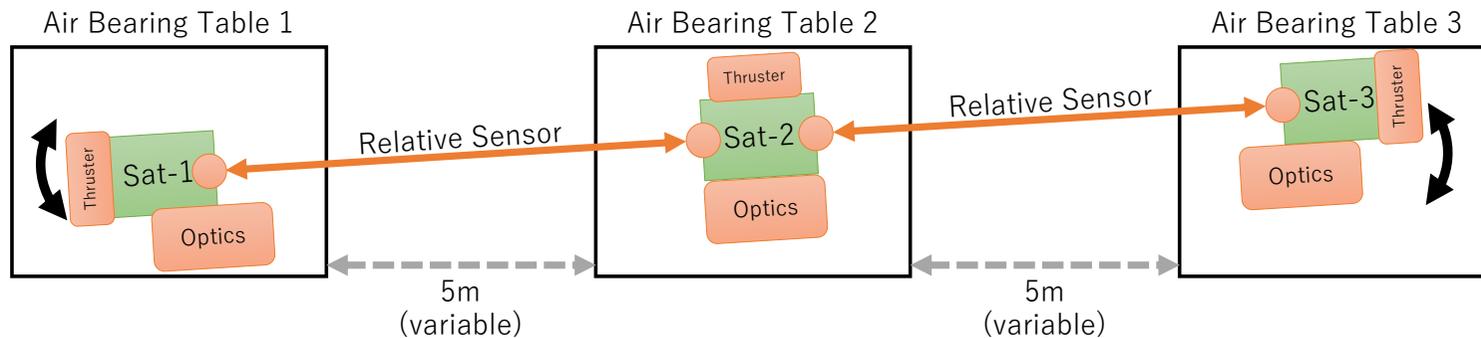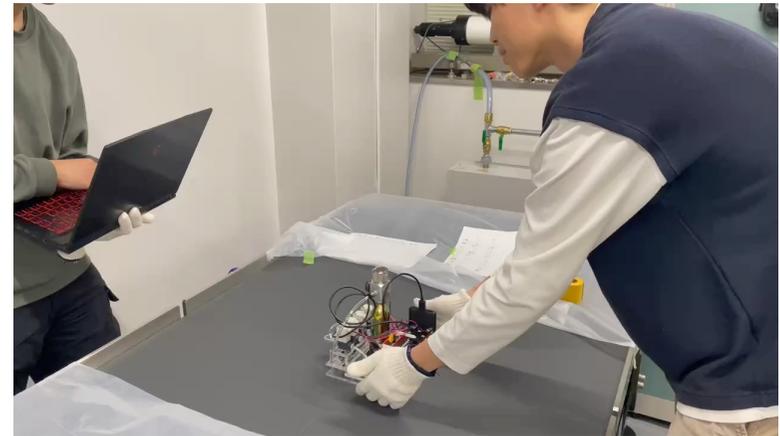● EM and FM of propulsion system will be tested with this stand.

Development of FF Testing System: GNSS Signal Simulator

● Relative Navigation with GNSS-R is essential for accurate FF mission.

● We are developing HILS including GNSS RF signal simulator to evaluate onboard relative navigation and control algorithm.

● The signal simulator and S2E (OSS Astrodynamics simulator) will be integrated.

Satellite Components

Testing Equipment

```
GNSS Signal          Deputy-A          GNSS          Deputy-A          Control          Numerical Simulator
Simulator        →   GNSS Receiver  →  Measurements  OBC          →    Command Value    S2E
          GNSS
          RF Signal

                     Chief         →                 Chief         →                    
                     GNSS Receiver                    OBC

                     Deputy-B      →                  Deputy-B      →
                     GNSS Receiver                    OBC
```

Position/Velocity of three satellites

Development of FF Testing System: Air Bearing Table


- **3 DoF relative motion emulation with frictionless table**
  - Accurate air hockey table with porous ceramic plate
- **Three tables are arranged several meters apart.**
  - Each table supports a satellite mock-up

Air Bearing Table 1   Air Bearing Table 2   Air Bearing Table 3

Relative Sensor

Sat-1   Thruster   Optics

Sat-2   Thruster   Optics

Sat-3   Thruster   Optics
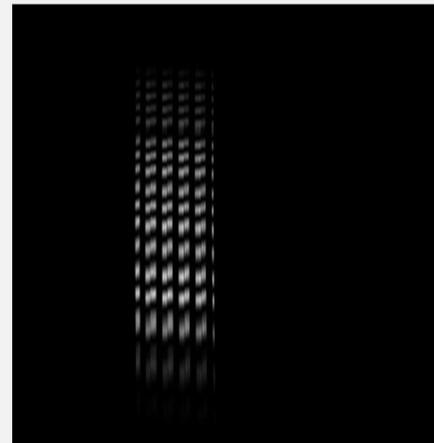
Relative Sensor

5m (variable)

5m (variable)
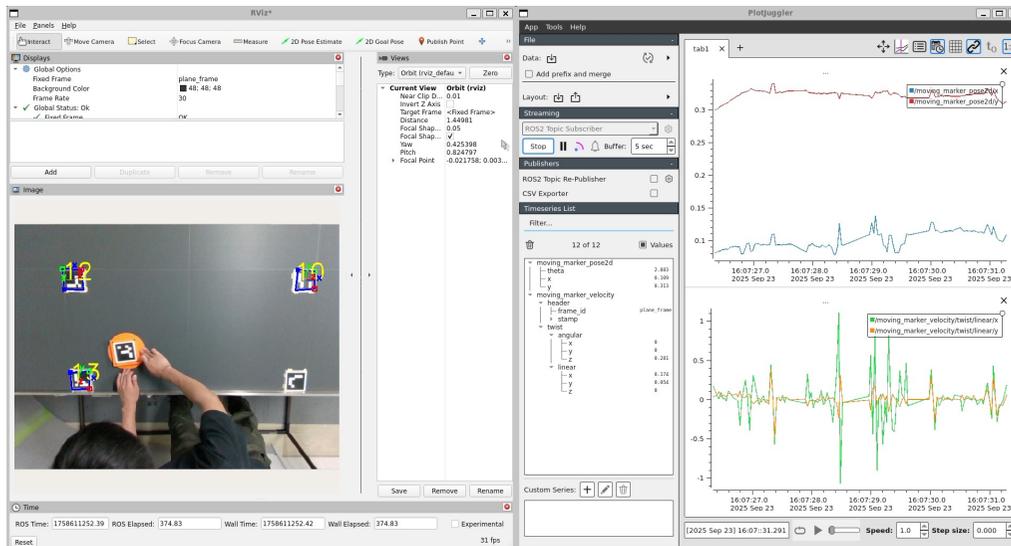
Ground Experiment for DPSI

- **We developed numerical simulator to confirm the control accuracy of spacecraft**
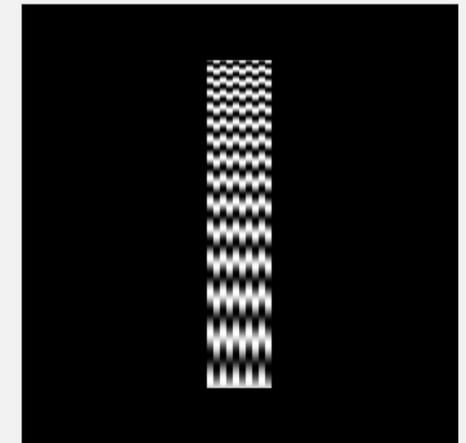- **We also developed ground testbed for delay line control and get interferometric fringe**
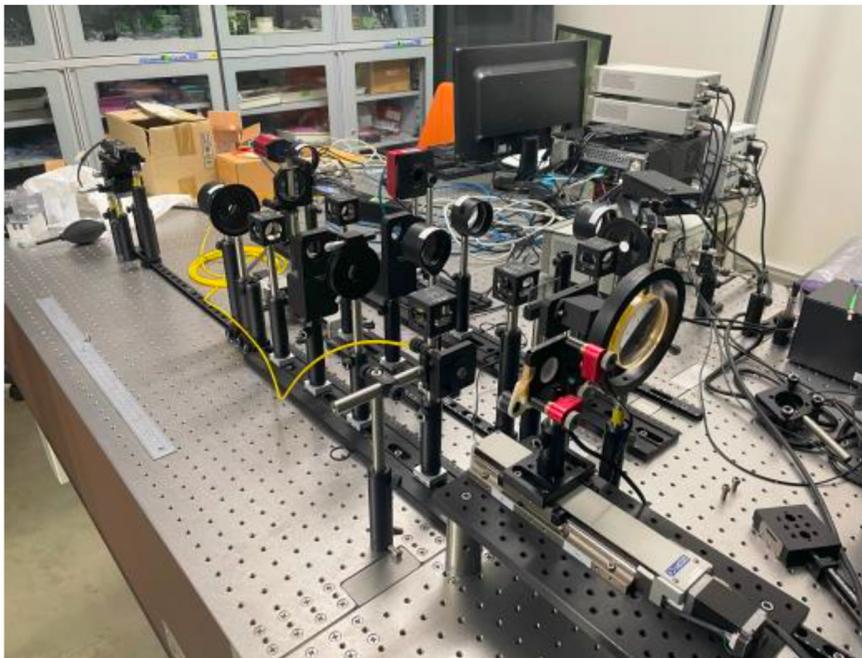
Ground Experiment for DPSI

➤ Ground Test   ➤ Observation simulator

Observed Interferometric Fringe by DPSI

04

Summary

Summary

● **We proposed the SEIRIOS, an accurate FF demonstration project.**
● **It was selected as a R&D theme of the Space Strategy Fund.**
● **We will develop SEIRIOS satellites and testing equipment.**
● **SEIRIOS will be launched in 2030FY.**

| • World First Space Interferometer | • Infrastructure for Future Mission | • Future Accurate FF Mission |

On Orbit Demonstration of SEIRIOS

1: SEIRIOS
10kg
50kg
10 – 100m
10kg
• Accurate FF demonstration with MicroSats
• Infrared Interferometer

2: Test Equipment
CubeSat
100 mm
• Thrust Stand
• GNSS Signal Simulator
• Air Bearing Table
• Numerical Simulator

3: Community
• Symposium for researchers, students, engineers, and business person