赤外線位置天文観測衛星
JASMINE
Japan Astrometry Satellite Mission for INfrared Exploration

Ryouhei Kano (NAOJ JASMINE Project)

NAOJ Future Planning Symposium 2024

JASMINE overview

Infrared (1.0-1.6μm) **space telescope** (aperture size ～36cm) designed for the following two sciences.

- Launch by Epsilon-S rocket (JAXA) to a sun-synchronized orbit
- Science operation for 3 years in early 2030s

Science Objectives

- **SO1: Astrometry in the Galactic nuclear region**

  Annual parallax precisions: **25μas**～125μas

  Proper motion precisions: 25μas/y～125μas/y

- **SO2: Transit observations to find Earth-like planets in habitable zones around mid-M type stars**

smaller than view angle of the diameter of a hair at the top of Mt. Fuji from Tokyo.

Science Goals

In the mission requirement document,
the science goals for JASMINE mission is stated as:

我々が住む天の川銀河の形成と進化の探究とともに、
生命居住可能領域に存在する地球に似た系外惑星の探究を行う.

In English,

- How did our Milky Way Galaxy form and evolve?
- How frequently Earth-like exoplanets exist in the habitable zone, and what are their environments like?

Answer to the 2nd comment.

Science Objectives

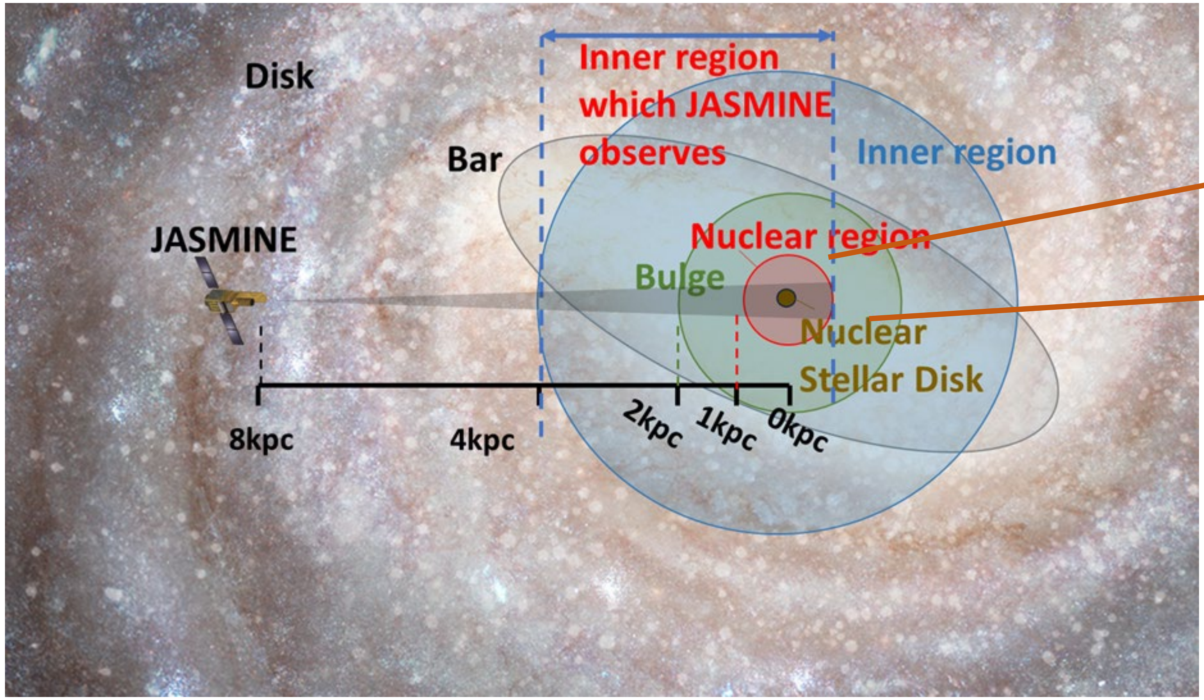
SO1:
Exploration of the structure of the Galactic nuclear region

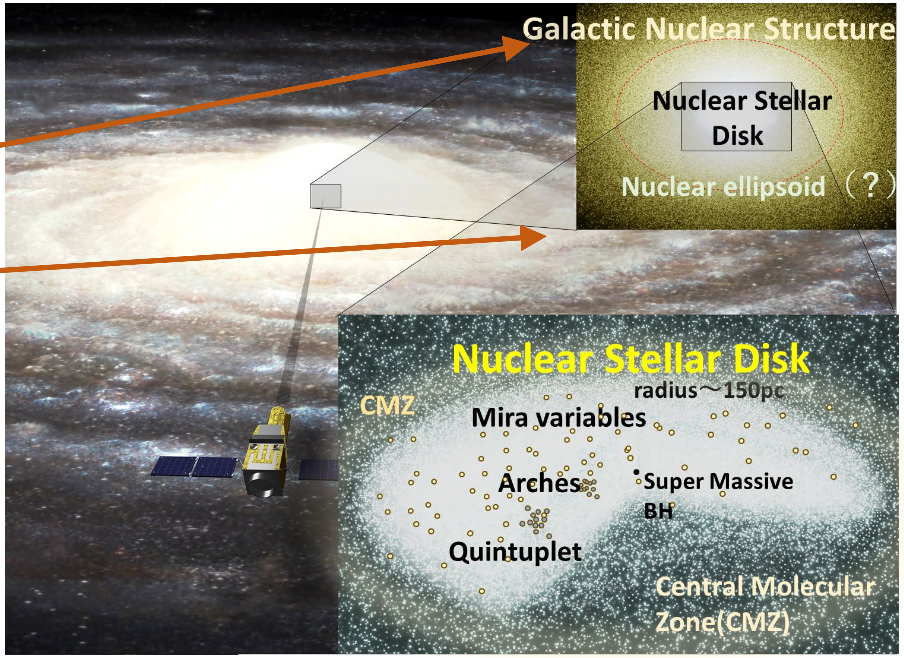
By measuring stellar distances and motions (astrometry),
to explore **the structure of the Galactic nuclear region**,
which plays a key role in the formation/evolution of the Galaxy.

SO2:
Exploration of Earth-like exoplanets

To clarify **the existence of Earth-like exoplanets in habitable zones** that are promising candidates for future life exploration.

S01: Astrometry in the Galactic nuclear region
JASMINE explores beyond-Gaia universe





JASMINE explores

- **Nuclear Region (within ~1kpc from the center)** as well as
- **Galactic Inner Region (within ~4kpc)** along the Galactic plane (bulge, bar, inner disk etc.).

JASMINE will measure ~10^4 (tens of thousand) **stars** in these region (r<4kpc) within an error of 20% in the annual parallax, **while Gaia measures none**.

SO1: Astrometry in the Galactic nuclear region
JASMINE explores beyond-Gaia universe

(1) for Nuclear Stellar Disk (NSD)

- Formation timing using Mira variables
  ➔ to indicate the formation timing of the bar structure in the Galaxy.
- Stellar orbits in NSD
  ➔ to indicate the gravitational potential
- Existence of NSD's non-axisymmetric structure (bar in NSD)?
  ➔ to suggest the gas-feeding to SMBH
- Star-formation history in NSD

(2) for Nuclear Ellipsoid

- Dynamical structure:
  classical bulge or
  "thermally-relaxed state" by BH fall, or
  other structures?
  ➔ to indicate the initial evolution of the Galaxy.

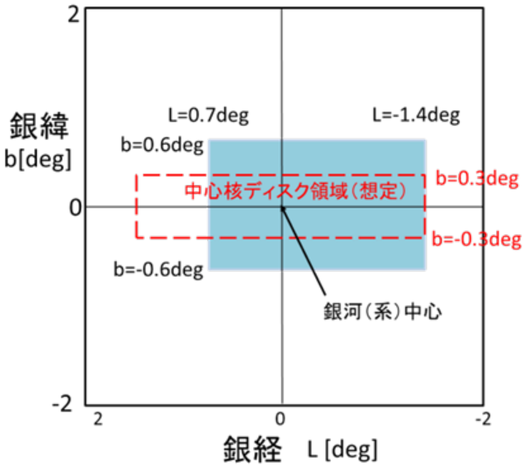
Other dynamical structures:
i.e. bulge, bar, (inner) disk etc.

Other topics

- Dark matter
- X-ray binary
- Magnetic structure
- hidden BN
- hidden clusters

Science Investigations: Output Targets and Mission Requirements

SO1： Structure of the Galactic nuclear region.	**Output Target:** • **Publish the astrometric star catalog** in the direction of the Galactic nuclear region. **Mission Requirements:** • **MR-I**: Astrometric observations in the observation area of **–1.4°< l < +0.7° & –0.6°< b < +0.6°** (blue in the right figure). • **MR-II**: **Parallax measurements with the precision of 40 μas*** for > 2,400 stars in the nuclear region. • **MR-III**: **Proper-motion meas. with the precision of 125 μas/y*** for > 45,000 stars in the nuclear region.
SO2： Earth-like exoplanets	**Output Target:** • Perform photometric observations of mid-M-type stars and **publish their time-series photometric data**. **Mission Requirements:** • **MR-IV**: Time-series photometric observations for **> 17 mid-M-type stars** with detected transit planets, where the observation duration is **> 14 months in total** and **an attenuation of < 0.3%** can be detected.



*:
We aim for **25 μas** and **25 μas/y** as the extra-success.
We also set the threshold requirement at **60 μas**.

“precision” = 1 σ

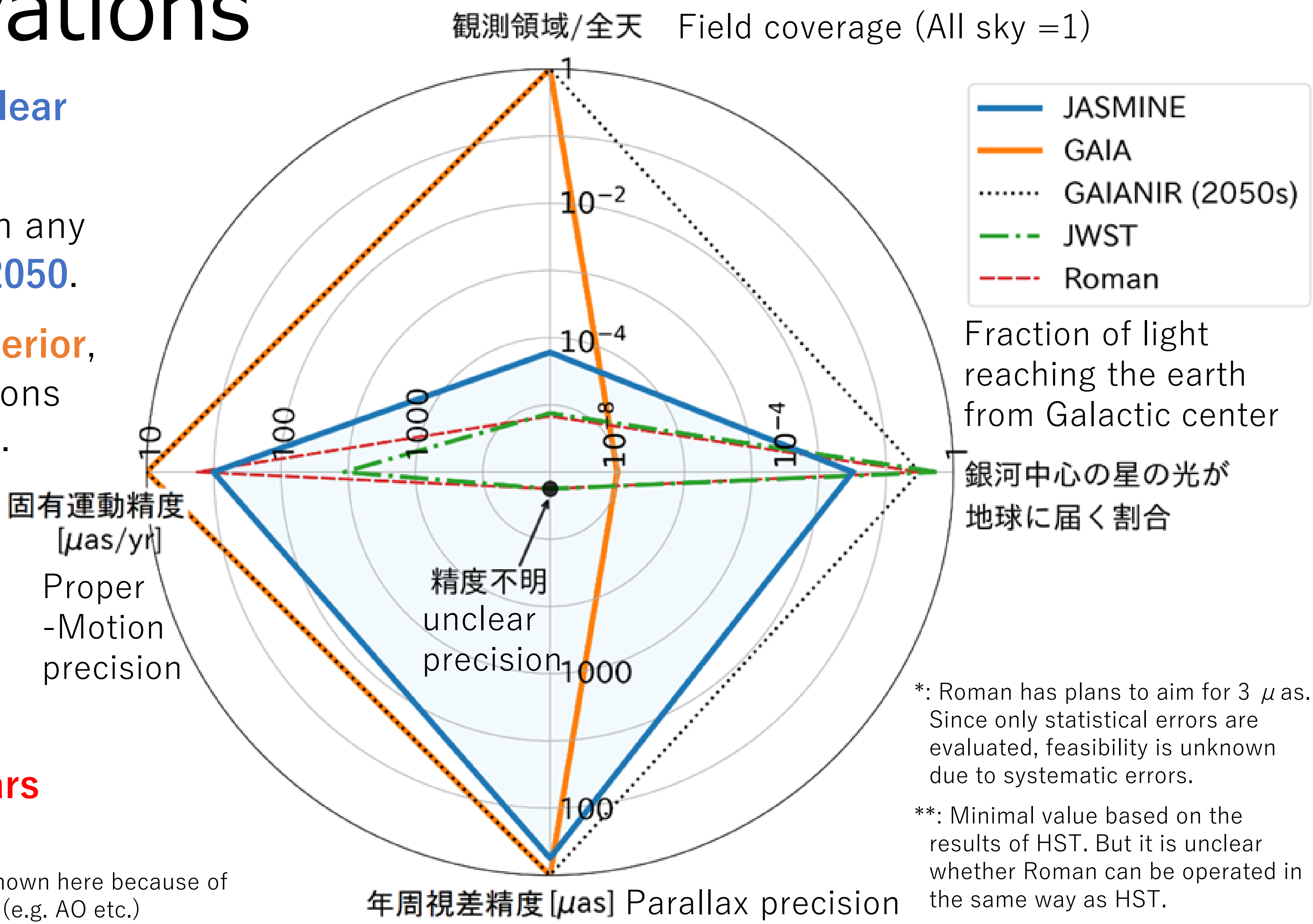
Comparison with other astrometric GC observations

Gaia: **unable to observe the nuclear region** (only in 5 kpc of the Sun).

GaiaNIR: Superior to JASMINE in any topics, **but hard to be realized by 2050**.

JWST: **JASMINE is basically superior**, but slightly inferior for GC observations because of a bit shorter wavelength.

Roman: **JASMINE is superior for parallax* and coverage, and comparable in proper-motion** if extra success**.
It targets faint stars (≳15 mag). Therefore, it is complementary to JASMINE, which targets bright stars (including Mira-type stars).

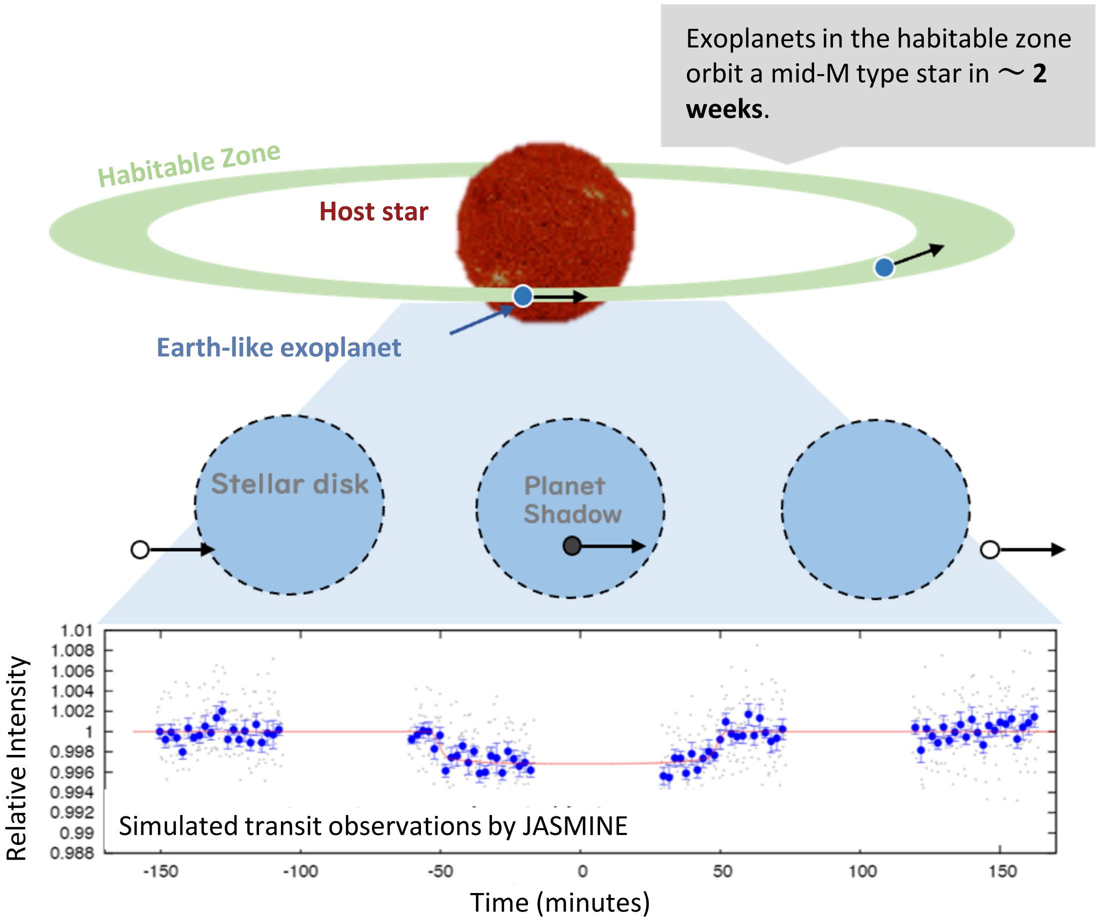


*: Roman has plans to aim for 3 μas. Since only statistical errors are evaluated, feasibility is unknown due to systematic errors.

**: Minimal value based on the results of HST. But it is unclear whether Roman can be operated in the same way as HST.

Ground-based observations are not shown here because of **high precision but very narrow field** (e.g. AO etc.) or, **very wide field but poor precision**

SO2: Transit observations of mid-M type stars: unexplored parameter space for exoplanets



- Required first step to the life exploration is …
  - Discovery of exoplanets with observable atmospheres in habitable zones around various size of stars

- Important to find exoplanets for spectroscopic observations (second step).

1. Exoplanets by "direct imaging"
   Technology is unproven right now.
   → Feasibility study has just begun for NASA's flagship mission after 2040's.

2. Exoplanets by "transit observation"
   Current possible technique.

Therefore, **exploration of transit planets** is critical to the second step in the life exploration.

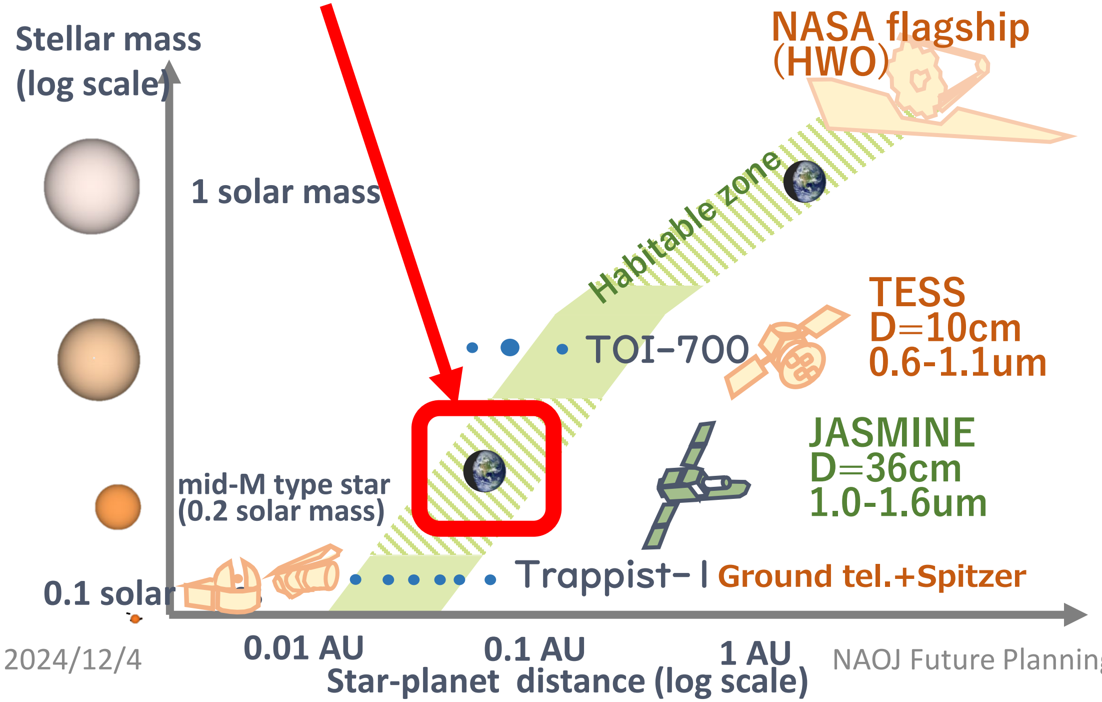
Comparison with some other transit observations for mid M-type stars

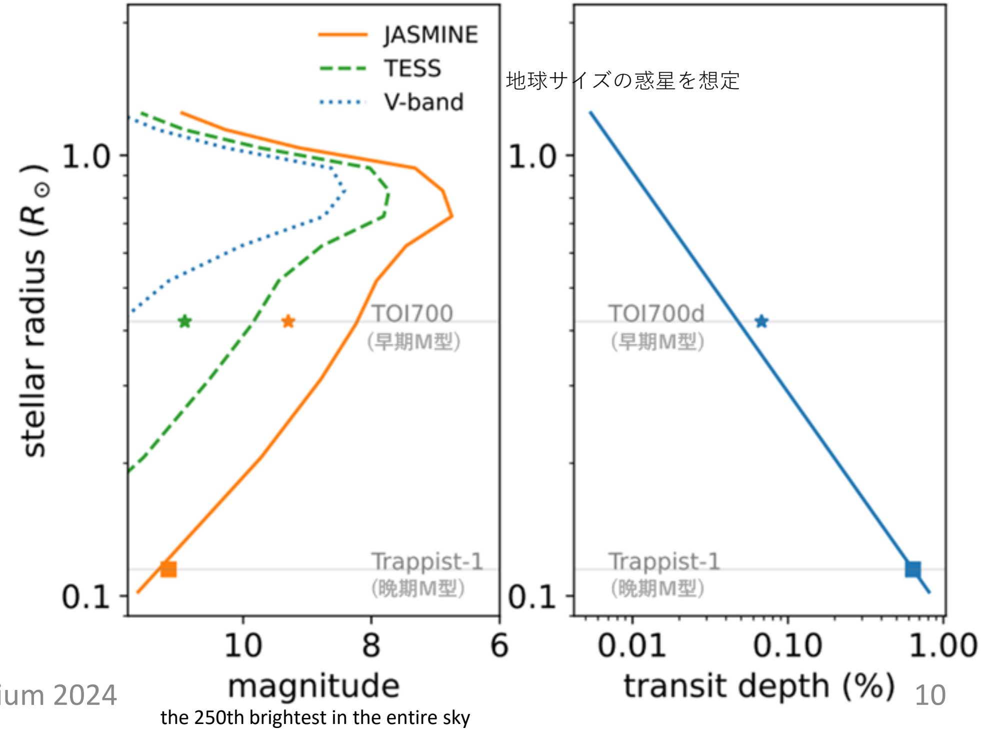
Early M-type stars: The depth of transit signal is small (~0.1%). However, since **stars are relatively bright**, the transit can be easily detected **even with TESS** (a visible 10cm aperture).

Late M-type stars: Stars are faint, but **the depth of transit is large (~1%)**. Therefore, large aperture **ground-based telescopes have advantage**, even if photometric preceision is not so high.

Medium M-type stars: **Rather small depth** of transit (~0.3%) and **rather faint stars** (especially in the visible).
→ A medium aperture telescope with high and **stable** photometric precision is required. Near-infrared is also preferable.

It's JASMINE, which observes transits from space.





Science Investigations: Output Targets and Mission Requirements

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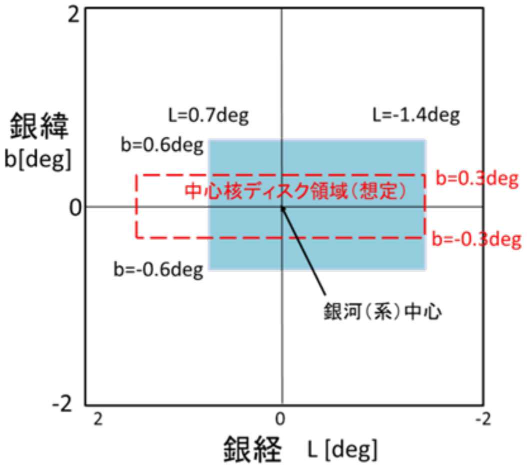

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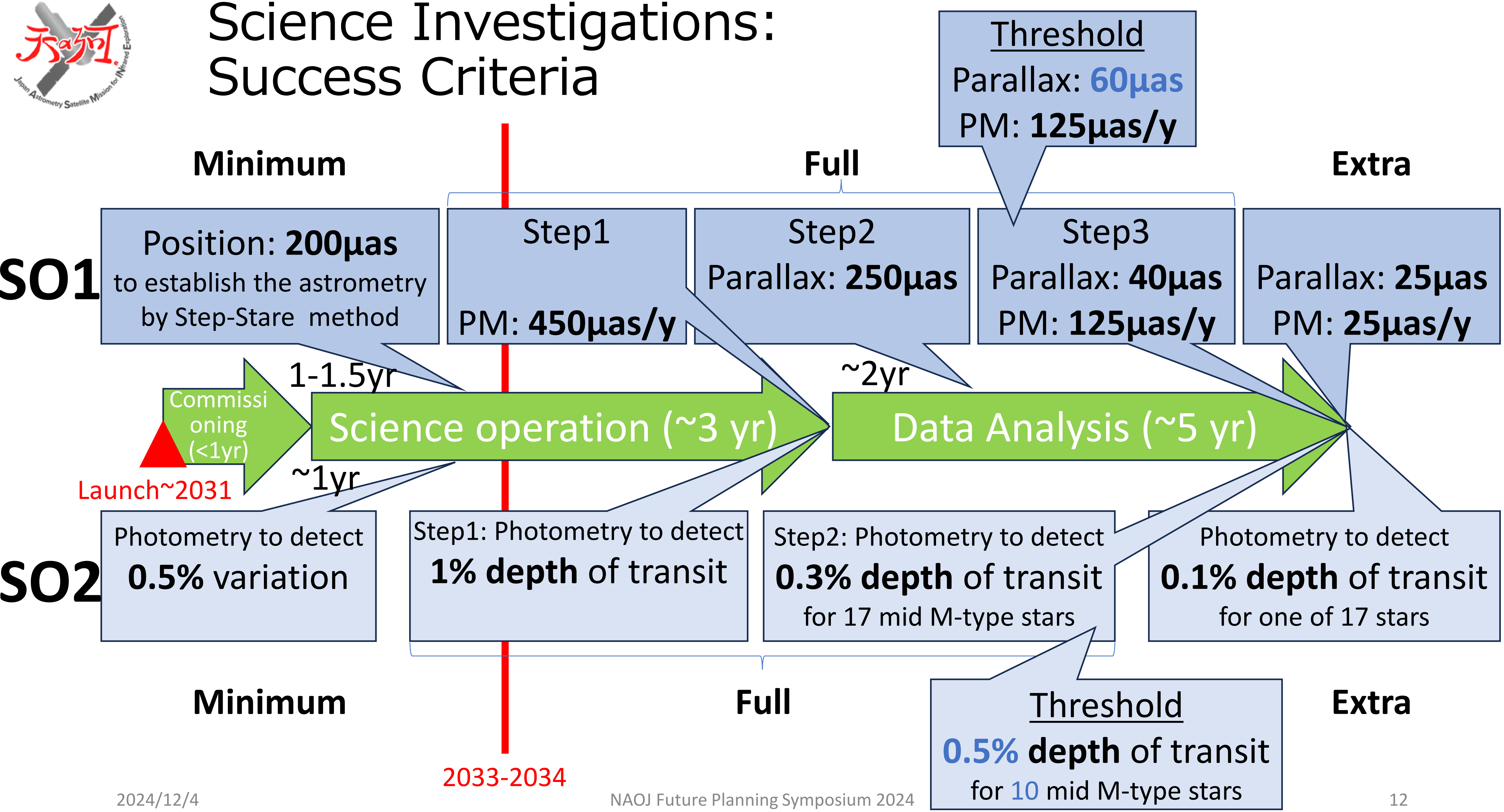
Science Investigations: Success Criteria



Concept of Data Analysis

400 mas/pixel

~4 mas

0.04 mas = 40 µas

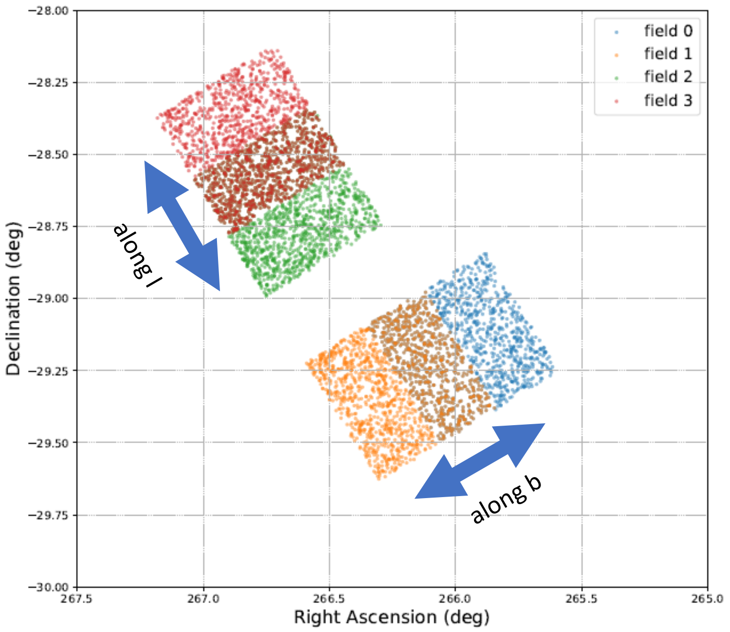
Step0:
take **images with ~10s cadence**, and cut out target stars (~12,000 in an image) to 9x11 pixels for each on board.

Step1:
calculate the intensity center of each star image with the **effective PSF method,** assuming that **PSF is the same for all stars**.

Step2:
remove the image distortion calculated from the comparison of near-by images, which assuming **the image distortions are the same.**

Step3:
calculate astrometric parameters with **reducing the noise at 1/√N** by accumulating huge number (N)oif data.

In a half orbit (~50 min), JASMINE takes images at **4 pointings** to get image **distortions along l or b**.



Required Instrument

To achieve high precisions (e.g. 25μas in parallax),
a good instrument are required
as well as **appropriate data analysis**.

To succeed the data analysis, the following instrument is required :

- **Enough pointing stability** in each exposure
- High and uniform image quality over wide field-of-view ➔ **Korsch optics**
- High stability of imaging properties (esp. image distortion) in time
  ➔ **Thermally stabilized telescope.**

Concept of Data Analysis

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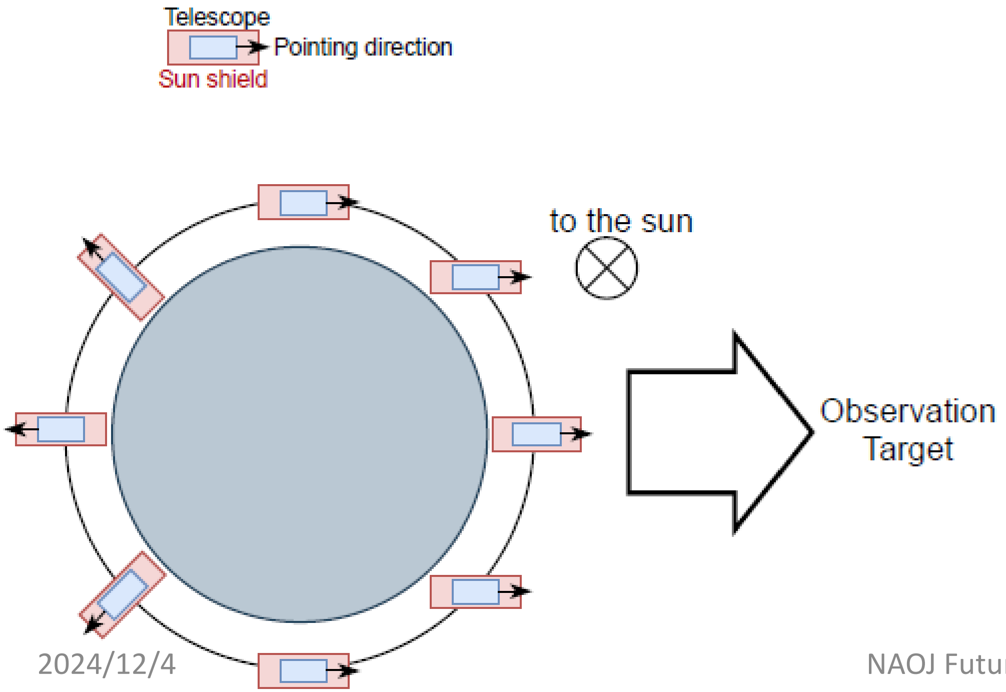
Step3:
calculate astrometric parameters with **reducing the noise at 1/√N** by accumulating huge number (N)oif data.

Observations

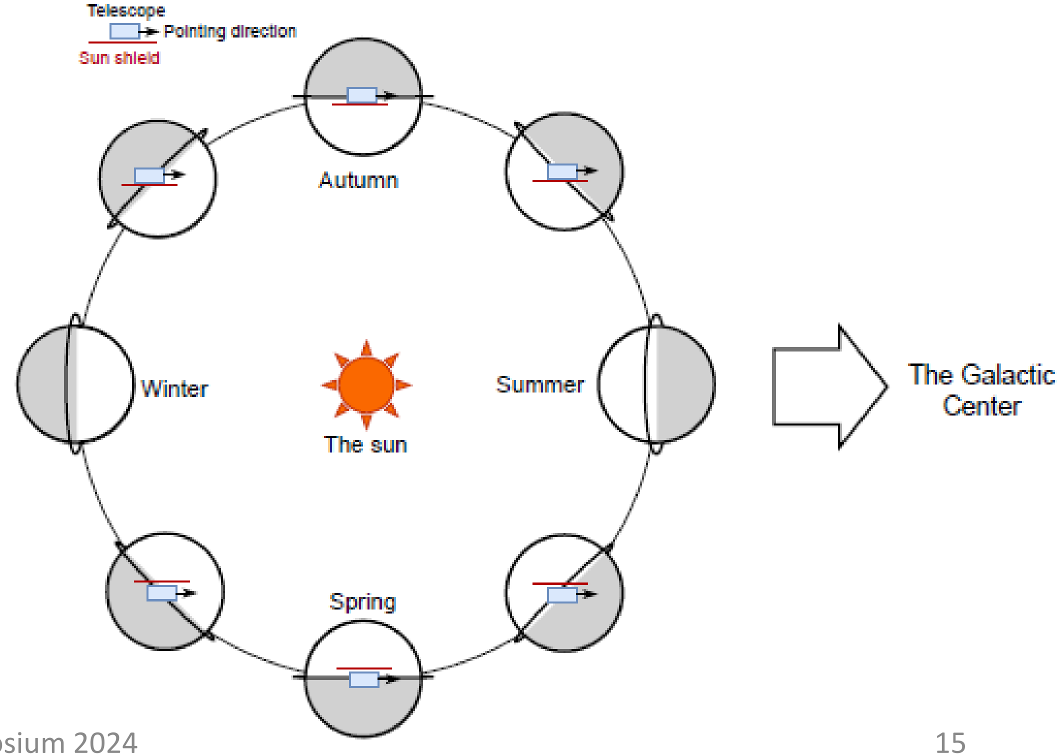
To stabilize the instrument thermally, …

- **Sun-synchronous orbit**
  on the day-night line (dawn-dusk orbit)
- **Sunlight on the side**
- **Observe in half of the orbit**,
  and avoid Earth in the other half.



By taking such orbit and altitude concept, it is hard to observe G.C. in summer and winter. Therefore, …

- **SO1 in spring & autumn**
- **SO2 in summer & winter**

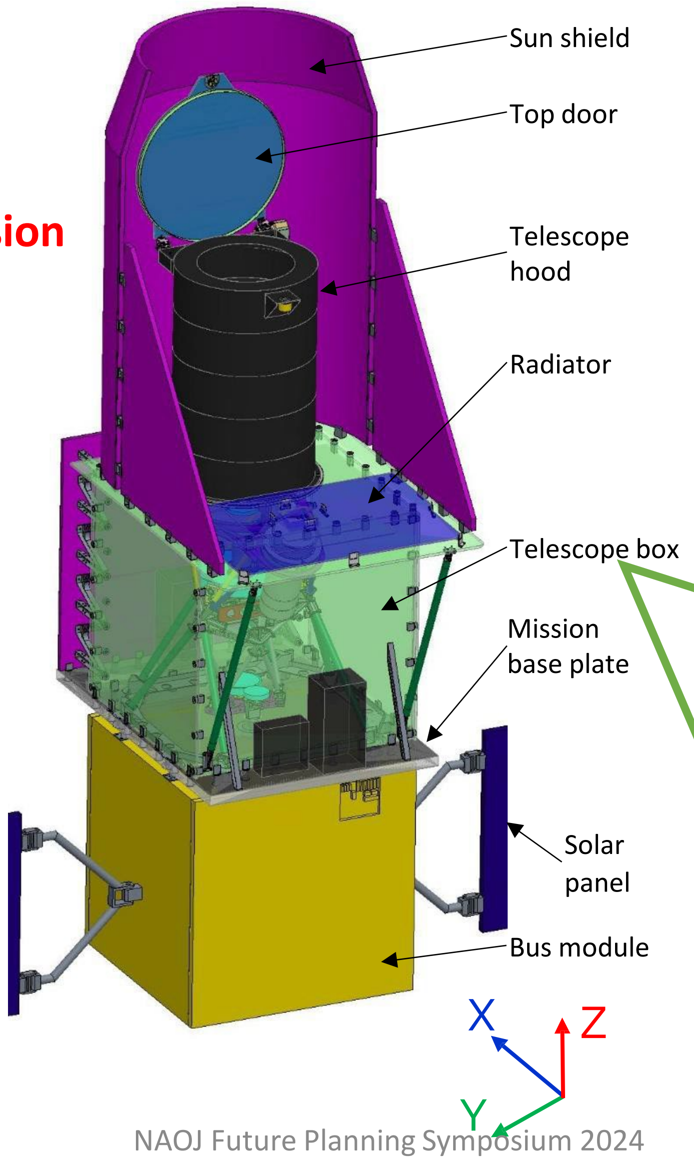


Instrument: Telescope Sub-system

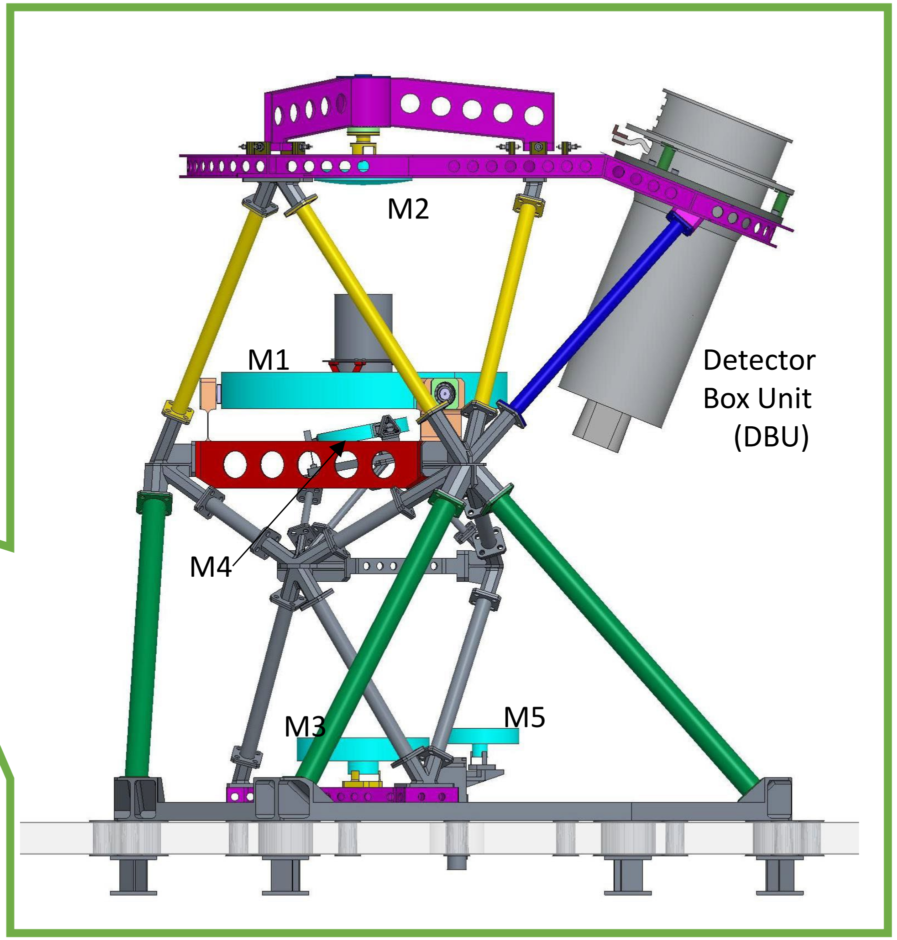
For high-performance and high-stability

- Flat wide-field by **Korsch Optics**
- Small thermal deformation with **CLEARCERAM** mirrors and **zero-expansion Invar (IC-LTX)** structure
- Keeping in **heater-controlled box**

Optics	Korsch Optics
Aperture	36 cmϕ
Focal Length	4.37 m
FoV	0.55° × 0.55°
Requirement	Strehl ratio ≥ 0.9 @λ=1.3 μm



(Isobe et al. 2024, Proc. SPIE)

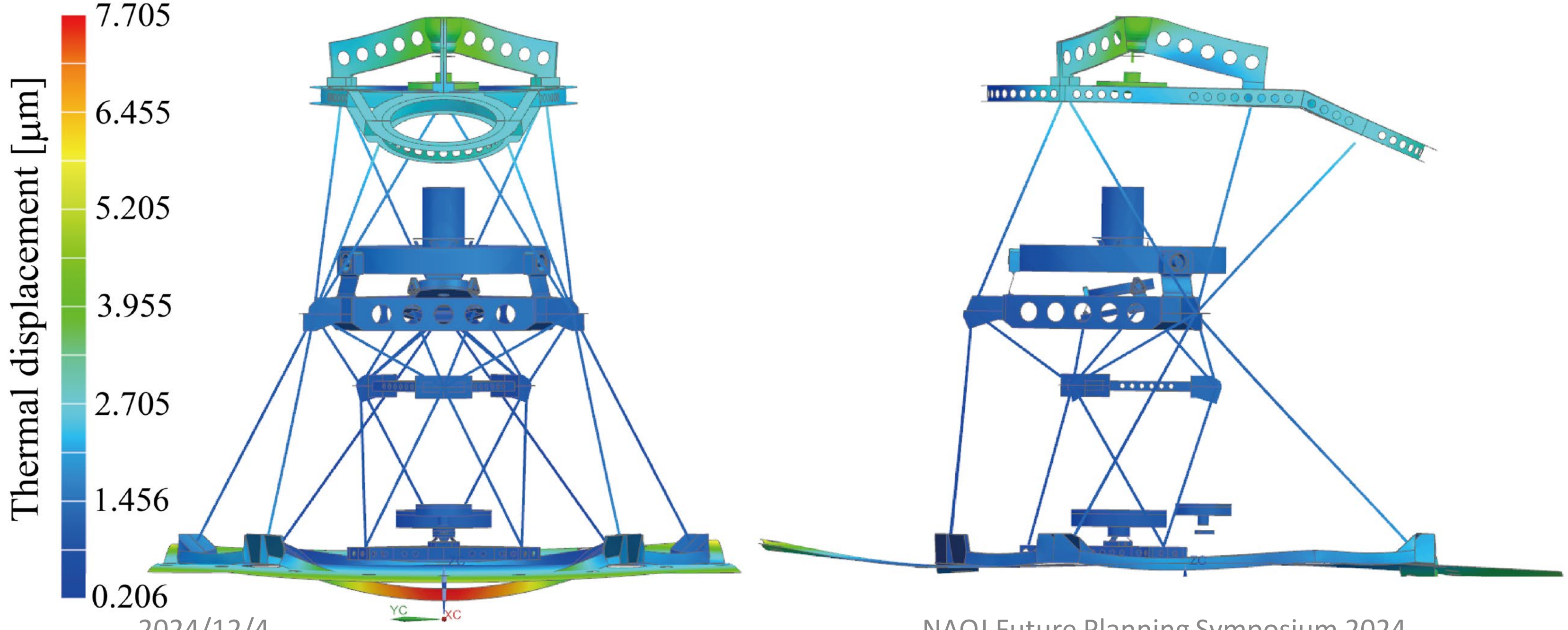


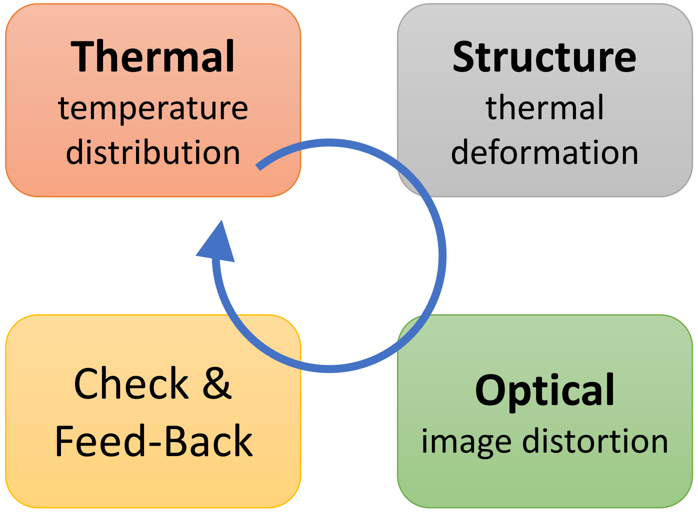
Structure Thermal, and Optical Performance (STOP) analysis

- **To estimate image distortion and its temporal stability**, a coupled analysis among structural, thermal, and optical behavior is required: **“STOP analysis”**.
- We are performing STOP analysis with the Japanese company and **with the support of ATC Optical Design Team** for ...
    - **Thermal deformation from the assembly to on-orbit conditions, and**
    - **Thermal deformation during an orbit**
- Based on this analysis, we will also consider how to confirm high stability before the launch.

(Isobe et al. 2024, Proc. SPIE)

Example: thermal deformation from the assembly at 20℃ to an on-orbit environment (M1 hottest case)



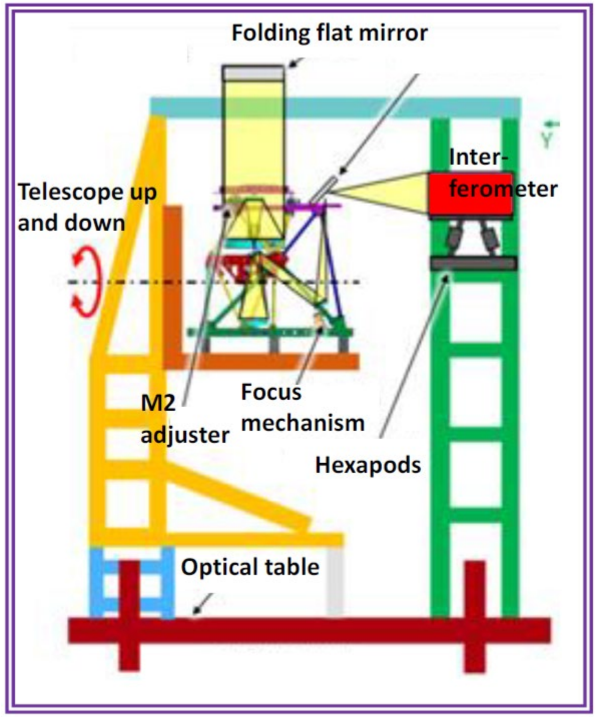


Telescope will be assembled in NAOJ/ATC

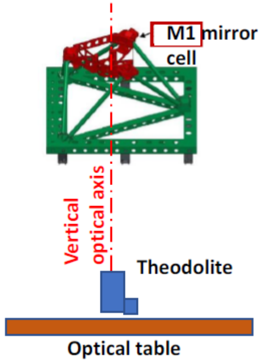
…, based on **the heritage in the assemble of the SOT telescope aboard the Hinode satellite**.

The following plan is **prepared with the ATC Optical Design Team** (Suematsu et al. 2024, Proc. SPIE).

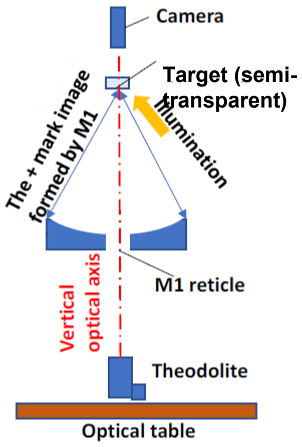
The assemble and measurement are performed on a test tower with a reversible telescope table in a cleanroom.



(1) M1 setting

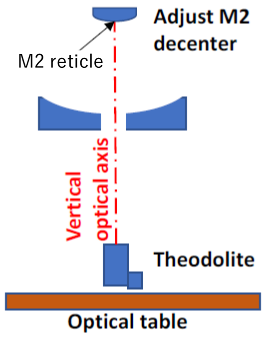


- **Set the optical axis** to the vertical axis by the theodolite.
- Put the structure horizontally

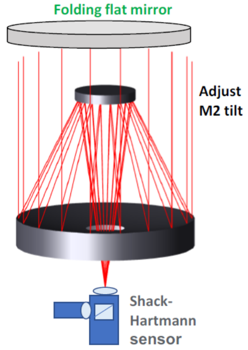


- **Put M1 center and M1 curvature center** on the optical axis by the theodolite.

(2) M2 setting

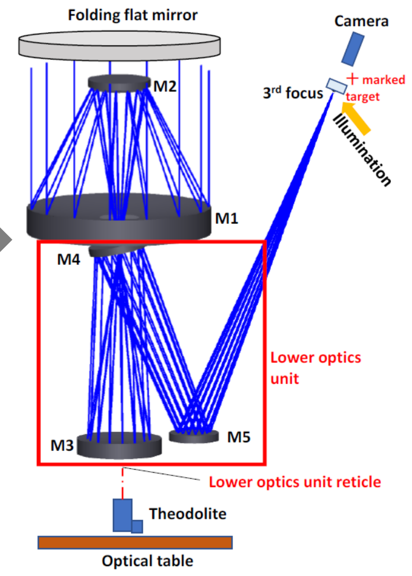


- **Put M2 center** on the optical axis by the theodolite.



- **Adjust M2 tilt** by the SH sensor to minimizing the coma

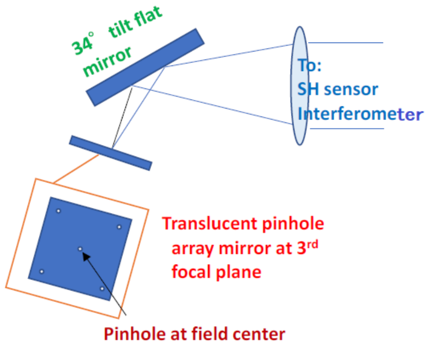
(3) M3, M4, M5 setting



- **Put M3 center** on the optical axis, and **adjust M3 title** by the theodolite.
- **Adjust M4 tilt and M5 tilt** so that the 3rd focus is placed at the designed position.

(4) Fine adjustment & optical performance check

- Set the SH sensor or interferometer by using a **pinhole array mirror** at the 3rd focus.
- **Adjust the tilt of M2, M3, M4, & M5** by the SH sensor, to minimize the coma & astigmatism of the telescope.
- **Measure the wavefront error** of the entire telescope by the interferometer with reversing the telescope for 0G.



Instrument: Detector Sub-system

Detectors	InGaAs hybrid CMOS sensors × 4 1952×1952 pixels/detector 10 µm pitch (～0.5 arcsec)
WL range	1.0～1.6 µm
cadence	12.5 s (TBD)

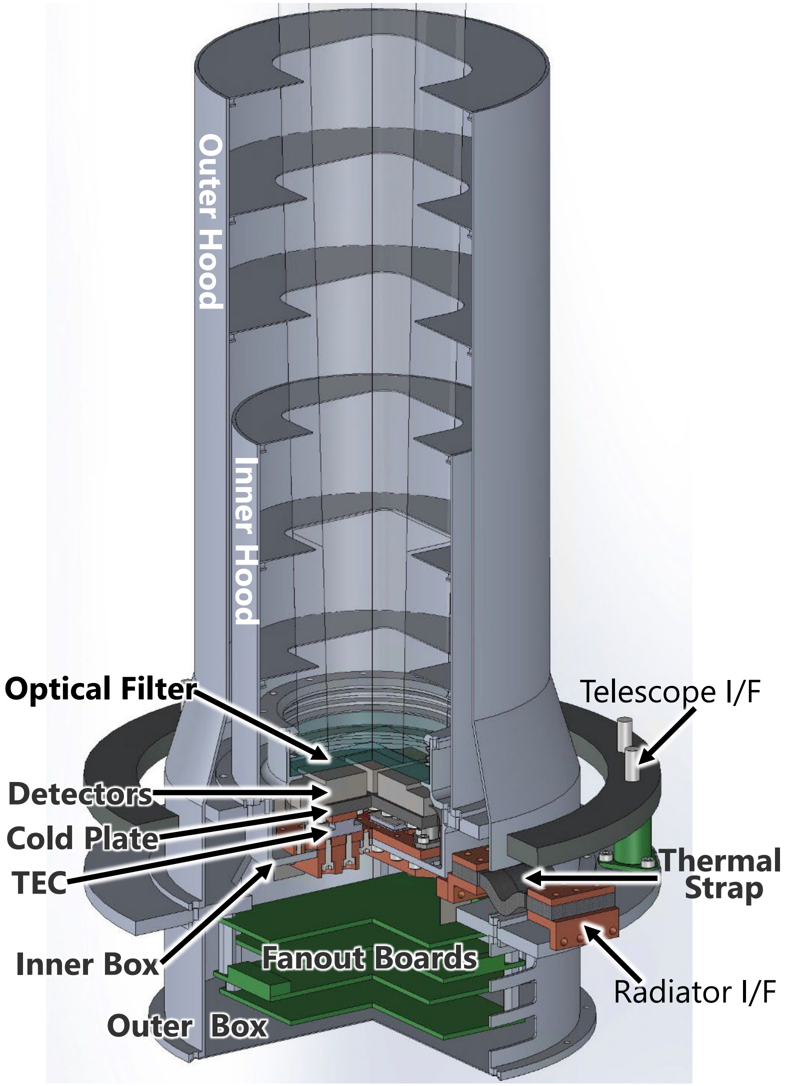
To keep the detectors in cold, the **detector box unit (DBU)** has **double thermal shields (Outer and Inner)**, and **2-step detector cooling system without vibration**:

- **Radiator** cools Inner Hood/Box down to 200K.
- **Peltier devices (TEC)** cools Cold Plate & Detectors down to 173K.

The **ATC Structure Thermal Design Team** is now performing the **conceptual studies of DBU**, and **evaluating performances of key components**:

- Performance of **Peltier devices in cold (200K)** environment.
- Thermal conductance of **thermal strap system**

detector box unit (DBU)



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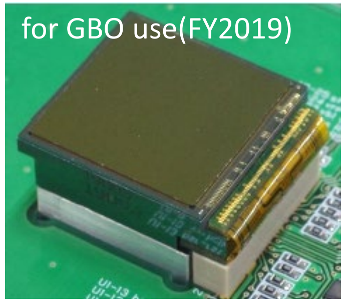
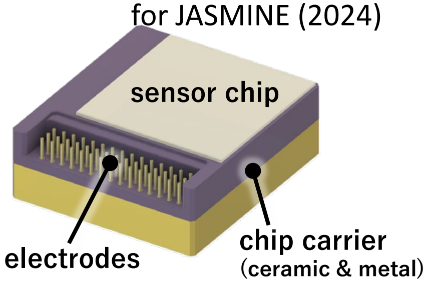
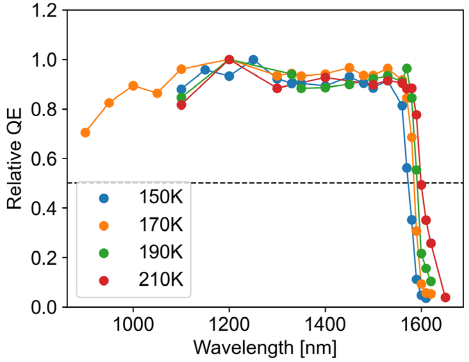
InGaAs Imaging Sensors

- In 2020, NAOJ/ATC with the Japanese company developed InGaAs infrared imaging sensors with 1.3kx1.3k format for ground-based observations (Nakaya et al. 2020).

- We started InGaAs sensors for space use with the support of NAOJ/ATC:
  - **Larger format**：1.3k x 1.3k pixel → **2k x 2k pixel**
  - **InP-base removal** for reducing noise signal of fluorescence by cosmic rays
  - **Radiation harder** on-chip circuit
  - **Sensor package for space use** : 2-side buttable design lead by NAOJ/ATC
  - **On-chip visible-light rejection**
- The evaluation of sensor performances for JASMINE are underway in ISAS/JAXA (Miyakawa et al 2024, Proc. SPIE).
- The vibration test and the radiation test are planed in FY2024.



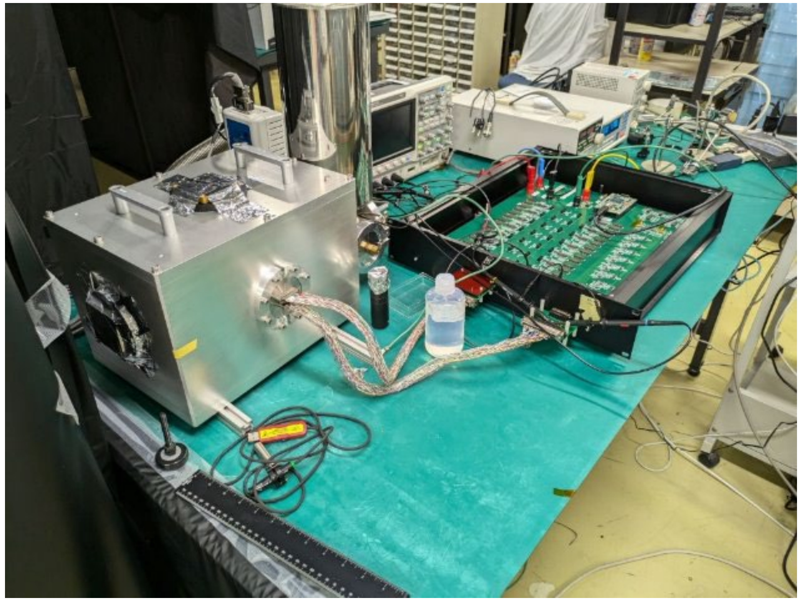




On-board Electronics

Detector controller

- We started the conceptual design with the Japanese company based on the **heritage in the previous IR missions (Akari and SPICA)**.
- It is on-going with the **help and supervision by NAOJ/ATC**.
- The **bread board model (BBM)** has been used to evaluation of 128x128 test device (see right).



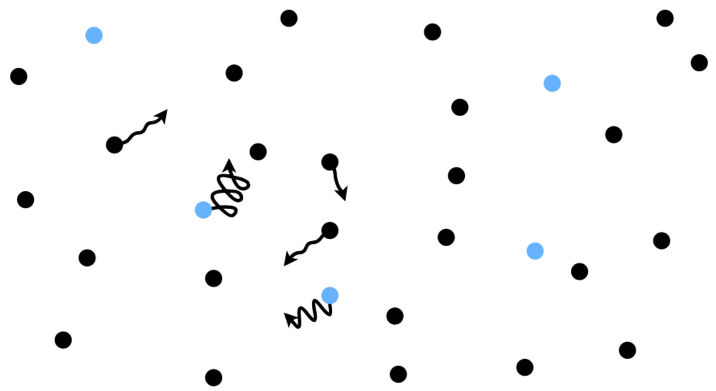
On-board data processing

- **Image cropping around stars** and **loss-less image compression** are necessary on-board, to reduce data volume for the limited telemetry.
- The conceptual study is **supported by NAOJ/ATC** both hardware and software.

Feasibility Study of Data Analysis

Ohsawa et al. (2024, SPIE)

From the 3-year observations, the astrometric information will be calculated.



By using the reduces simulation with the expected instrumental errors etc., we found that the parallax in 40μas and the PM in 125μas are achievable.

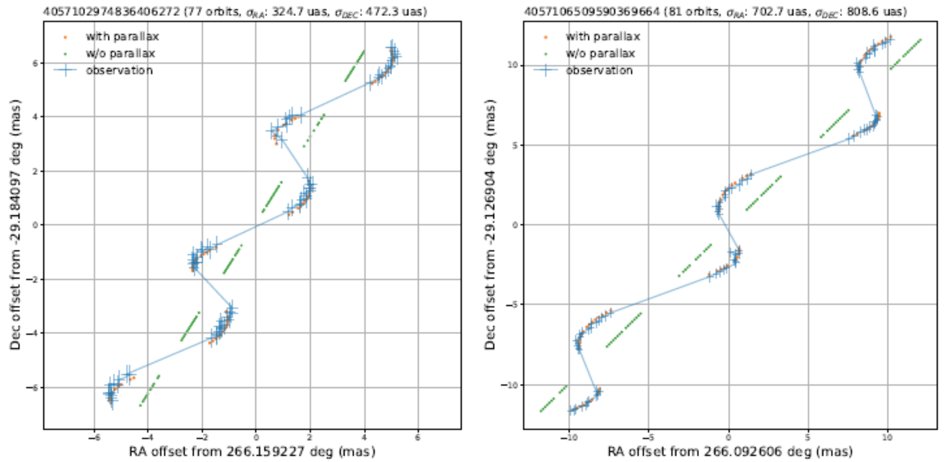


Figure 3.50: 天球面上での参照の解析結果。青が推定された座標で 1σ のエラーバーとともに示している。緑は国際天文基準座標系 ICRS での星の位置で固有運動を示し、オレンジは、固有運動に加えて年周視差を与えた時の星の位置で、これらは真値としてシミュレーションの入力にしたもの。

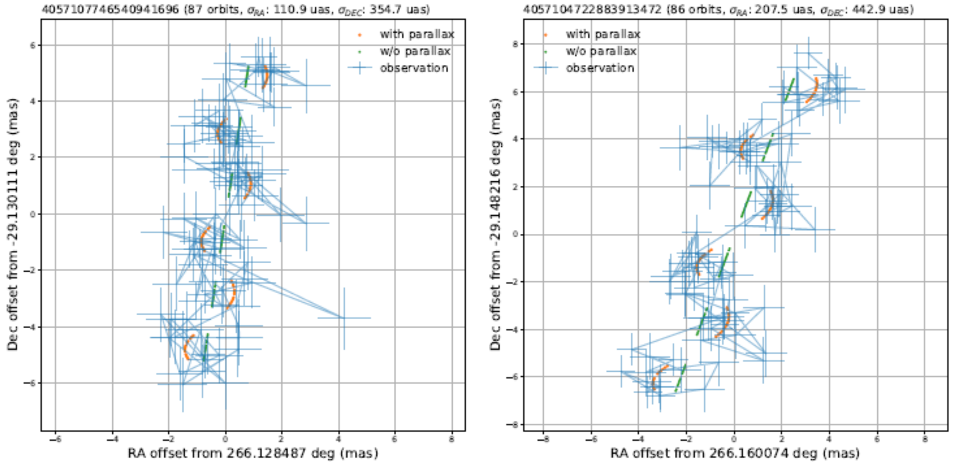
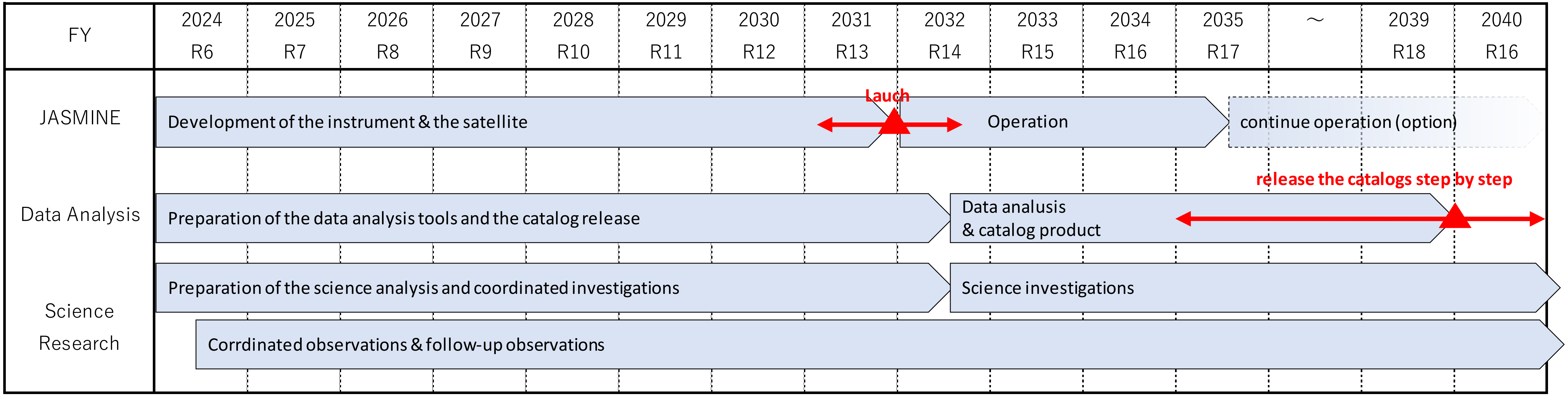


Figure 3.51: 銀河系中心領域内天体の天球面上での解析結果。青が推定された座標で 1σ のエラーバーとともに示している。緑は国際天文基準座標系 ICRS での星の位置で固有運動を示し、オレンジは、固有運動に加えて年周視差を与えた時の星の位置で、これらは真値としてシミュレーションの入力にしたもの。

Schedule outline

JASMINE passed MDR in 2024/7, and is preparing for the review for the pre-project.

The following shows the schedule outline based on the discussion in MDR.



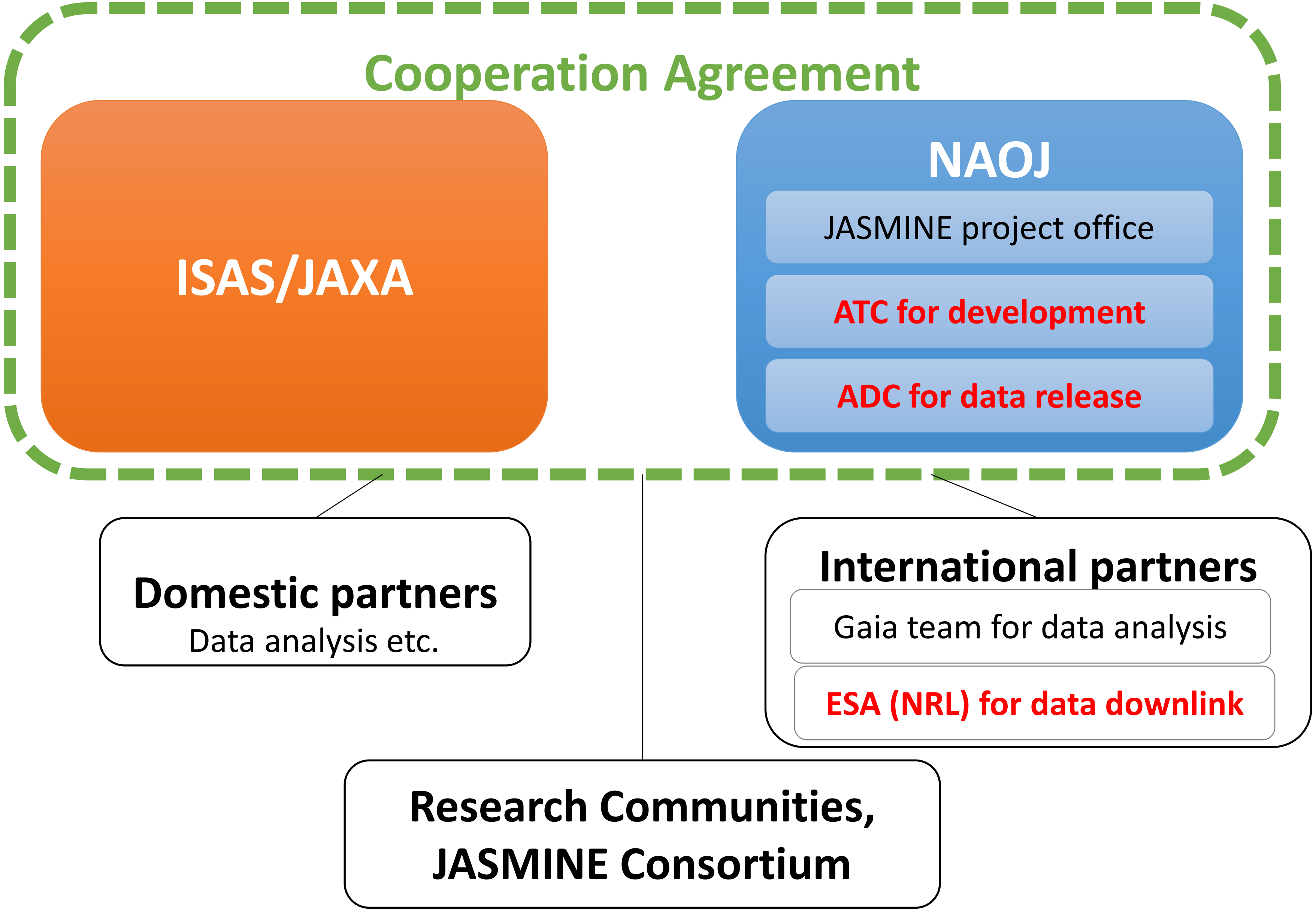
Astrometry

- **Gaia**: JASMINE would like to make the observations not too late after the Gaia's final data release (around 2030).
- **Roman**: It is desirable to be able to observe at the same time **for complementary observations**.
- **PRIME**: Expect to identify **many Mira-type variables near GC prior to JASMINE**.

Exoplanet

- **JWST and Ariel**: JASMINE would like to make the **observations early in the 2030s for follow-up observations**.
- **Roman**: complementary in size and distance from the central star of the exoplanet to be observed.

Project Organization



Draft plan of responsibilities of ISAS and NAOJ

	ISAS	NAOJ
Project promotion	**ISAS promotes the JASMINE project.**	
Study of the instrument	**ISAS, in cooperation with NAOJ, defines** specifications and interfaces for the JASMINE instrument for its development.	NAOJ **studies the development of the detector sub-system** (consisting of the detector box unit, detector electric unit, and on-orbit data processing system), and makes a draft of their specifications. NAOJ supports ISAS in the preparation of specifications/interfaces for the JASMINE instruments.
Development of the instrument	**ISAS, in cooperation with NAOJ, develops** the JASMINE instrument.	NAOJ supports ISAS in the development of the JASMINE instrument, and **provides NAOJ's test facilities/equipment for its development as necessary.** NAOJ supports ISAS in the development of the infrared sensor for JASMINE.
Operation	**ISAS, in cooperation with NAOJ, operates** the JASMINE on-orbit.	NAOJ supports ISAS in the on-orbit operations of JASMINE.
Data analysis & release		**NAOJ conducts JASMINE's data analysis** in cooperation with ISAS. NAOJ will also **creates a data archive** of the results, and **release the archive** for researchers in the world in cooperation with ISAS.

Why NAOJ?

The following activities will be expected in NAOJ:

1. Instrument Development in cooperation with ATC
    - develop the detector sub-system
    - assemble and test the entire instrument will be performed in ATC.
      ATC has the heritage in assembling space telescopes in Hinode, and then get it in SOLAR-C and JASMINE.
2. Data analysis:
    - extract precise astrometric information in cooperation with Gaia
    - release the star catalog in cooperation with ADC.
      As a center of astronomical data, it is meaningful to release the data at ADC.
3. Research promotion in cooperation with related communities.
   We also expect to collaborate with NAOJ/Division of Science.

Cost assessments, budget line and status

- **Essentially**, JASMINE project will be performed by **the budget for the competitive M-class mission in ISAS/JAXA**. However, NAOJ and other partners need to support the human resources.

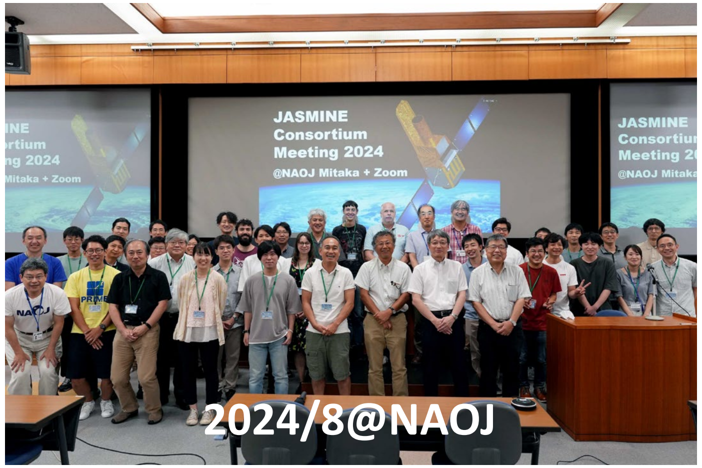
- Therefore, for the NAOJ science roadmap proposal, we estimated the cost in NAOJ for having human resources:
  170 million yen/year,
  corresponding to **18 full-FTE persons in maximum**
  including ATC and ADC supports based on the rough expectations
  and also 5 additional support staff or researchers.

Answer to the 1^{st} comment.

together with the related communities

JASMINE Consortium (since 2019):

to share the information to make the generated data useful for many scientists, and then to achieve the scientific goals.



- Chair: Daisuke Kawata (MSSL, UCL)
- Members: ~60 in Japan (overseas in the future)
- Activities:
  - annual meeting from 2019.
  - white paper publication, Kawata et al. (2024, PASJ)

JASMINE Joint Scientific Research Project @ NAOJ:

to promote preparatory research for scientific research related to the GC region using JASMINE astrometric data, and to encourage young researchers in this field.

- In FY2024, the study of Mira-type variables is adopted

■ White Paper

- Kawata et al. (PASJ, 2024, Vol.76, pp.386-425) https://doi.org/10.1093/pasj/psae020
- 89 authers, including 31 overseas
- Not only astrometry/exoplanet but also other related science topics

Publications of the Astronomical Society of Japan, 2024, **76**(3), 386–425
https://doi.org/10.1093/pasj/psae020
Advance access publication date: 2024 April 10

ASJ OXFORD

JASMINE: Near-infrared astrometry and time-series photometry science

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Received: 2023 July 11; Accepted: 2024 February 27

JASMINE overview (again)

Infrared (1.0-1.6μm) **space telescope** (aperture size ～36cm) designed for the following two sciences.

- Launch by Epsilon-S rocket (JAXA) to a sun-synchronized orbit
- Science operation for 3 years in early 2030s

Science Objectives

- **SO1: Astrometry in the Galactic nuclear region**

  Annual parallax precisions: **25μas**～125μas

  Proper motion precisions: 25μas/y～125μas/y

- **SO2: Transit observations to find Earth-like planets in habitable zones around mid-M type stars**

smaller than view angle of the diameter of a hair at the top of Mt. Fuji from Tokyo.