High-contrast imaging and spectroscopy by a low-scattering off-set telescope PLANETS and near-infrared Echelle spectrograph ESPRIT

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We are carrying out a 1.8-m aperture off-axis telescope project PLANETS (Polarized Light from Atmospheres of Nearby ExtraTerestrial Systems). The PLANETS telescope is characterized by high-contrast imaging and spectroscopic capability thanks to low-scattering in the optical system by combining off-axis mirror, adaptive-optics (AO), and stable atmospheric conditions of an observatory site at a high-altitude. In particular, the off-axis system brings us no cross-shaped diffraction pattern caused by the secondary mirror support in the optical path, and thus the scattering light of PLANETS is estimated to be more than 10 times better than that of a normal large telescope. PLANETS Foundation (www.planets.life), whose board members are from Japan, USA, Germany, and Brazil, manages this project.

Our major scientific goal is to detect faint emission surrounding planet and satellite in the solar system as well as exoplanets, such as Jovian satellite Europa's plume and Martian ionosphere. These emissions are so faint (10^{-3} to 10^{-6} to the brightness of planetary or satellite disk) close to the main disk (less than a few arcsec) that the measurement of these distributions and time variabilities are difficult. PLANETS is appropriate to observe these targets by taking advantages of high-contrast imaging and spectroscopic capability and monitoring operation optimized for the targets.

The telescope optics has a Gregorian focus with a FOV of 6' (F/13). The main mirror is Clearceram Z-HS with a diameter of 1850 mm and thickness of 100 mm. So far, the glass ceramic blank of main mirror was made by Ohara Inc. in 2010, the rough grinding was carried out by Harris/Excelis in 2012. After that, the main mirror has been stored at the University of Hawaii. Last December, the mirror was shipped to Japan to carry out the final polishing. We glued 36 metal adapters on the backside of mirror to connect the mirror support. The mirror support adopts the whiffletree with warping harness system which is similar to TMT and the Seimei telescope. We made the elemental test of the whiffletree system, and confirmed that the performance for stress input is as expected by the structure model with a finite element method (FEM), and the repeatability (hysteresis) for stress change is in the acceptable range. We are now developing the whiffletree support, and will complete by the end of March 2020. After that, we will carry out the final polishing using a dragging three probe method with a robot-arm system at Logist Lab./Astro-Aerospace within a year. Compared with a traditional CGH-type interferometric metrology, the dragging three probe method and polishing with the robot arm are characterized by the free-form metrology with three-probe. We expect to obtain the accuracy of main mirror better than 20 RMS nm by the final polishing. In addition, we will fabricate the telescope mount and structures using the proto-type mount Seimei telescope now stored at Nagoya University. We will assemble the whole PLANETS telescope, and achieve the first light and technical demonstration, particularly on the high-contrast and low-scattering capability, in Japan within a few years. Further, we already have the construction permit at the summit of Haleakala (CDUP) from the State of Hawaii, and we plan to install PLANETS there as soon as we get the funding for the observatory construction.

P36(C)

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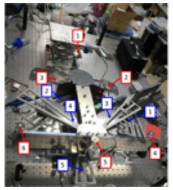
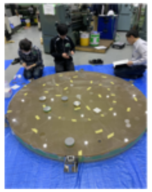
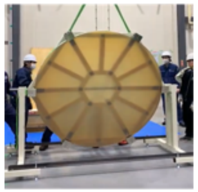
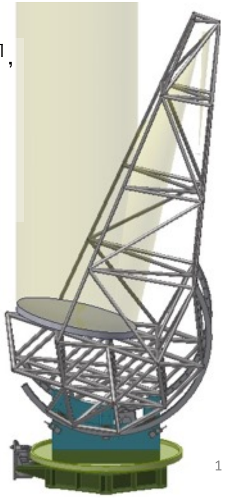
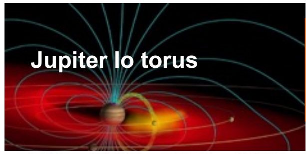
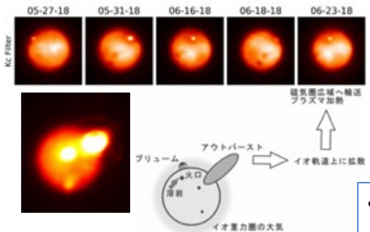





Introduction: Aim and targets



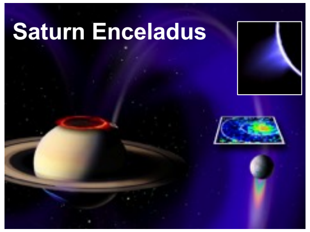
Why is high-contrast observation with high-resolution spectroscopy necessary?

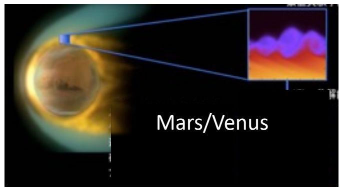


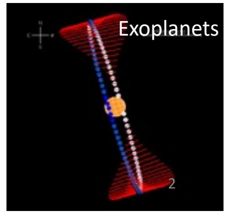
We carried out monitoring of these targets by 60cm telescope at Haleakala. However, high-contrast optics with a larger aperture telescope and high-resolution spectrometer is required to stury these objectives.

- ✓ Emissions of volcanic-origin gases from satellites of Jupiter and Saturn
- ✓ Martian and Venusian exosphere
- ✓ Exoplanetary atmosphere

- Brightness of planetary disk is typically 10^{-5} ～10^{-7} times greater than that of targets.





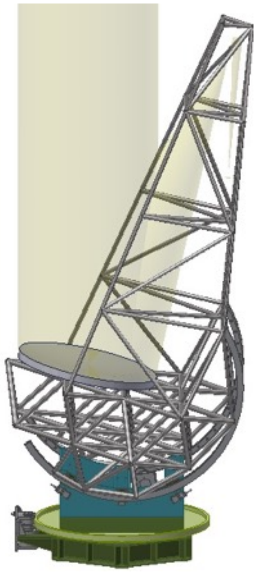


Key technologies of the PLANETS telescope

1.8-m off-axis telescope

- ✓ Low-scattering and high-contrast optical system
- ✓ Coronagraphy
- ✓ Adoptive optics
- ✓ High-resolution spectroscopy in visible to mid-infrared range
- ✓ Fiber imaging/spectroscopy
- ✓ Monitoring capability
- ✓ Flexibility for TOO

PLAENTS makes possible to observe faint emission near the bright main body (which is fainter by 10^{-5} to 10^{-7} than the main body) with sufficient SNR.



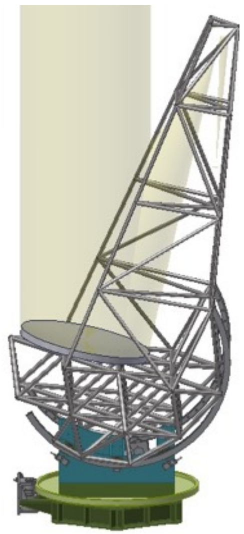
Specification of PLANETS

- Gregorian focus (50-100kg)
  - Fiber bundle (Vis. NIR)
  - Hollow cone fiber (MIR)

  FOV(TBR): 6 arc min (Gregorian)

  1 arc min (def. limted image))
- (Nasmyth or Coude focus)
  - Cryogenic near and mid-infrared Echelle spectrometers
  - Guest instrument

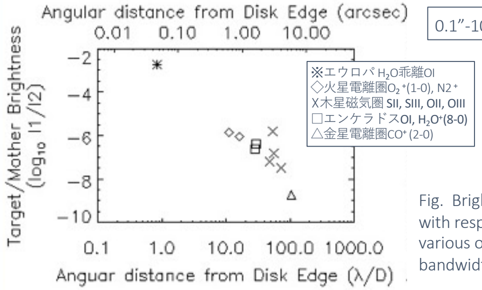
M1: parabola, 1.86m
4.333m fl
M2: ellipse, 12cm
0.26m fl



Dynamic Range of Observing Targets

Tab. 1 Brightness of targets and contamination sources *1 1R=$10^6/4\pi$ ph $cm^{-2}sr^{-1}s^{-1}$, *2 assuming 5-pm bandwidth, R~100,000

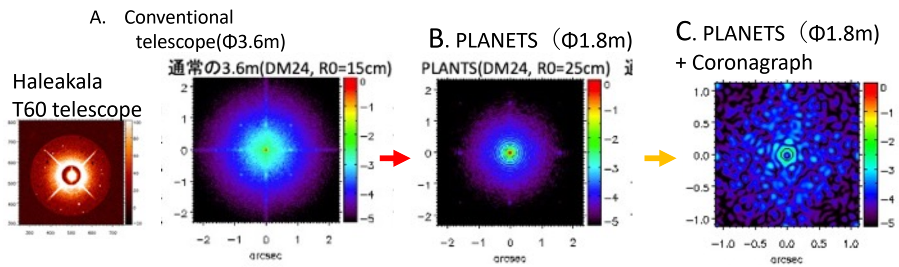
Targets Emissions	λ (nm)	Targets Brightness	Brightness of mother objects*2 (limb darkening k, albedo α)	Angular Diameter of Mother Object (")	Separation from Mother
Europa plume H_2O, dissociative excitation of OI	630	300 R	200 kR	1.0"	0.05"
Martian ionosphere O_2^+ (1-0), N2+	561 391	60 R 20 R	400 kR (k=0.6, α=0.2) 200 kR (k=0.6, α=0.2)	12"	0.7"
Venus ionosphere CO^+ (2-0)	425	20 R	15000 kR (k=1, α=0.70)	30"	5"
Enceladus torus OI / H_2O^+ (8-0)	630 615	10 R 18 R	75 (k=1, α=0.6) 100 kR (α=0.9)	23" (ring)	2"
Jupiter plasma torus $S^+/S^{++}/O^+/O^{++}$	673 631 733 500	500 R 50 R 20 R 10 R	150 kR (k=1, α=0.60)	1.0"	2"



0.1"-10"の範囲で、高ダイナミックレンジ観測を実現する

Fig. Brightness ratio of target emissions to mother objects with respect to angular distance from disk edges for various observing targets. The ratio is derived assuming bandwidth is 5 pm (R ~ 100,000). (pltObjSNR03.pro)

High-contrast performance by the PLANETS telescope



Low-scattering system with an off-axis 1.8m primary

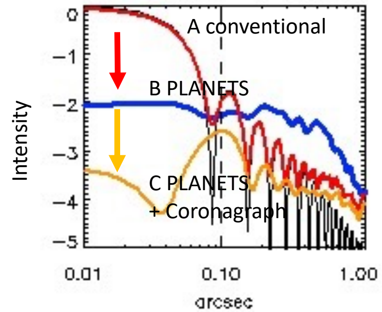
+

Adoptive optics by a deformable secondary mirror to compensate atmospheric turbulence

+

Coronagraphy

High-contrast observation



Distance from main object surface

1.85m primary mirror

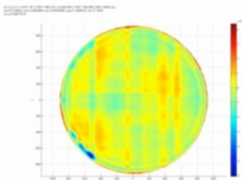
Ohara Clearceram Z-HS

Melting (Dec. 2010)

Φ＝1850mm, t=100mm

Shipping to Los Angels (May 2011)

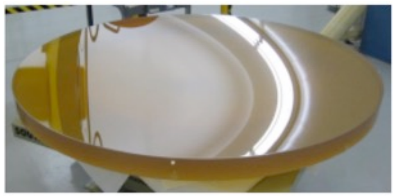
Rough polishing at Harris/EXELIS (July 2012)



10.9μm P-V
1.51μm RMS

Down-sampled data solutions
Average of 10 data collects
Zernike terms 1-11 subtracted,

Arrived in Maui (June 2017)

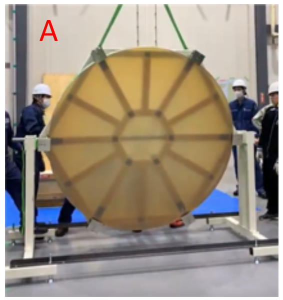


Now at Tohoku Univ., Japan (Jan. 2020)

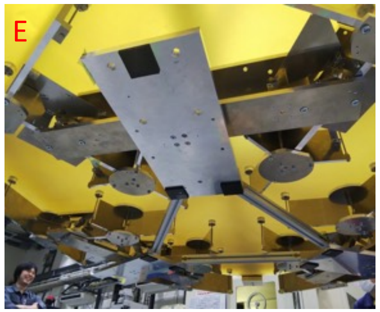
Primary mirror: current status

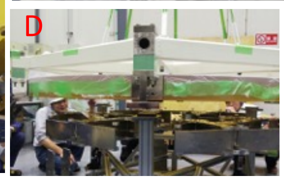
Jan. 2020 Transferred from Hawaii to Tohoku Univ.
Feb. 2020 Metal adopters for the mirror support were glued in the backside(A,B)
Feb. 2020- Now developing the mirror support with whiffle-tree system（C, D, E）

- We adopted the whiffle-tree support system and warping harnesses that is similar to TMT and 3.8m Kyoto Seimei telescope.

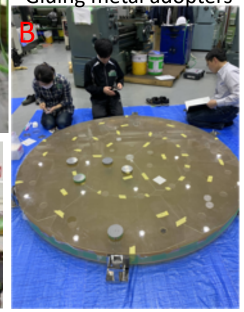


Whiffle-tree mirror support





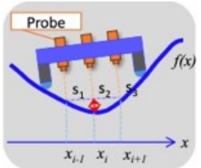
Gluing metal adopters



Final polishing of primary mirror

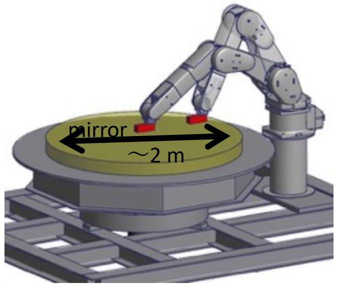
Feb. 2021 -

- Collaboration with Nagoya Univ. Kyoto Univ., and Logist-Laboratory (Astro-Aerospace)
- Polishing by a robot arm
- Metrology by 3-point drag probe



By the only robot-arm, polishing and measuring are executed on large and free form optics (including flat and convex shapes).

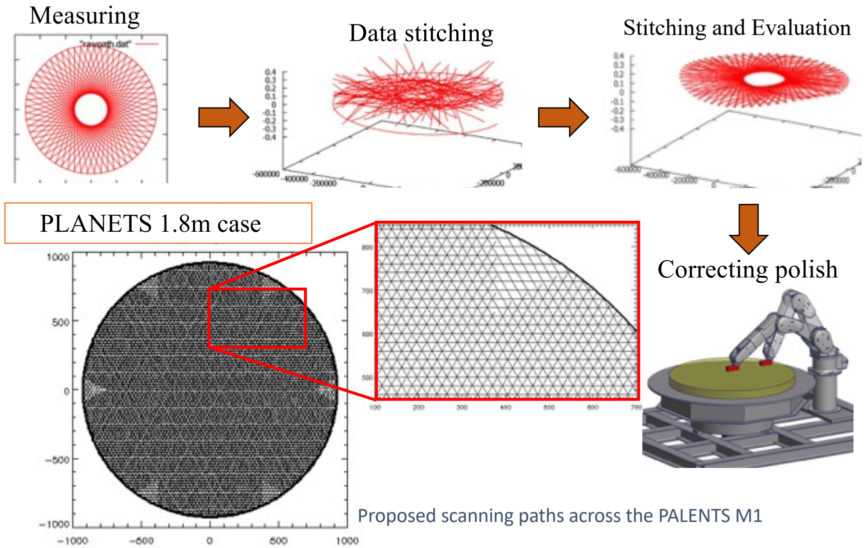
- Dragging 3-point probe method
- Data stitching algorithm
- Flow of data processing
- Sample result



Metrology and polishing by robot arm

Achieved RMS<10nm for the secondary mirror of Seimei(Φ1m)
We require RMS<20nm for PLANETS primary mirror (Φ1.8m)

Feb. 2021 -

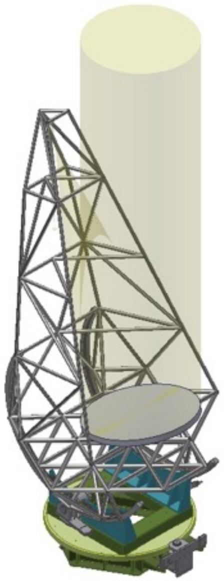


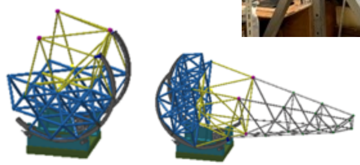
Proposed scanning paths across the PALENTS M1

Telescope mount

March 2020 - ongoing

Reuse of the technical demonstration model of the 3.8m Seimei telescope stored at Nagoya University
Lightweight and robust pedestal
Some parts (R-guides, encoder, servo motor, etc.) and upper truss are newly procured.
Fabrication has been started, and will be completed within a year.





Observation targets suitable for high-contrast capability of PLANETS

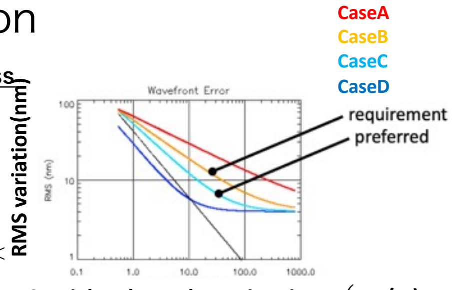
- Volcano on Jupiter's satellite Io and Europa [Collaboration with Hisaki/Juno/JUICE]
- Martian ionosphere/exosphere and escaping gases [Collaboration with MAVEN/MMX/MACO]
- Mercury Na, Ca, K atmosphere [Collaboration with Beppi Colombo/Mio]
- Exoplanetary atmosphere
- Active small bodies like comets and asteroids

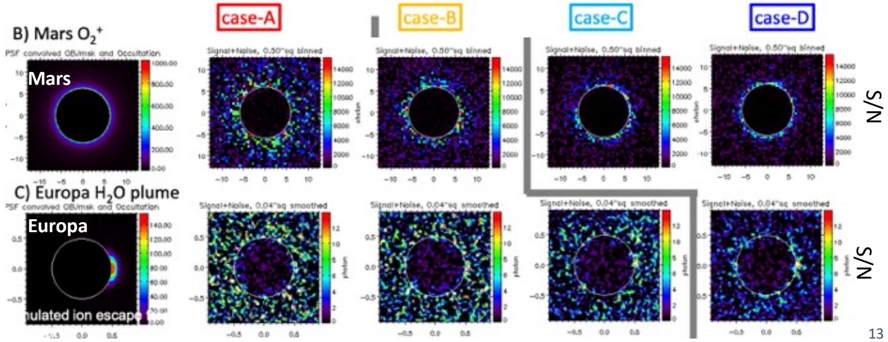
What are the required time and spatial resolutions?

Observation simulation

Four cases in polished mirror roughness

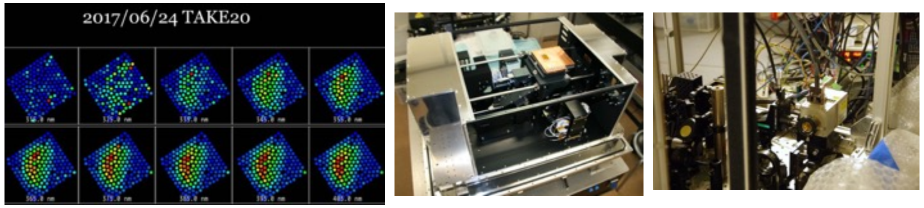
- Black: diffraction limit
- Orange: required （20 nm for 10- cm scale, 6 nm for 1-cm scale),
- Light blue：best case
- Micro-roughness < 4 nm （best case < 2 nm ）





Instruments

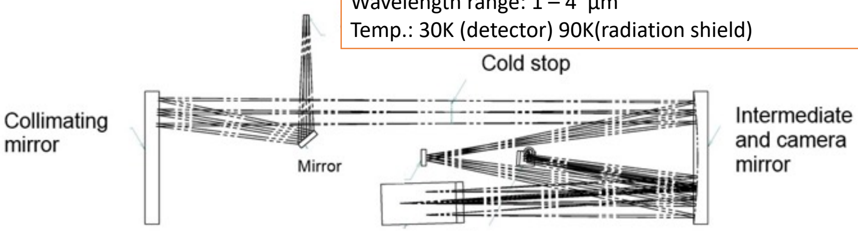
Instrument	Spec.
Fiber : Visible Imager and Spectrograph with Coronagraphy (Vispec)	0.4-0.9µm, FOV~1’ / R~70,000
Fiber : Mid-IR laser heterodyne spectrometer (MILAHI)	7-11µm, R ~ $10^{6\text{-}7}$
Gregorian: DiPOL-2 (Polarization imager) (KIS)	B, V, R polarimetry (DoLP ~ $10^{-5\sim6}$)
Nas: NIR Echelle spectrograph (ESPRIT)	1-4µm, R ~ 20,000
Nas: Mid-IR GIGMICS (Nagoya U.)	7-12µm, R ~ 40,000

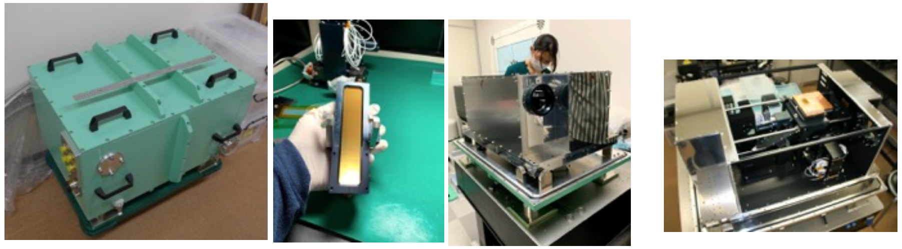


e.g., Near-infrared Ecelle spectrograph(ESPRIT)

on-going

Detector; Raytheon InSb 256x256 array
Imaging and Echelle spectrograph
λ/Δλ; 20,000
Wavelength range: 1 – 4 µm
Temp.: 30K (detector) 90K(radiation shield)



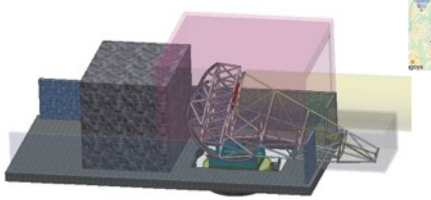


First light in Japan

2021

Fortunately, our Iitate observatory (37.6°N, 2-hour drive from Sendai) is suitable to enclose the telescope structure and carry out the first light detection of stars.

Roll-off roof building in the Iitate observatory



Future plan at Haleakala 2021(TBR) -

- Haleakala High-Altitude Observatory, Maui, Hawaii(3040m, GLAT=20º 42.5’ N, GLON=203º 44.5’ W)
- Got permission (CDUP) for the renovation of Chicago building, University of Hawaii.
- In addition, alternative (and cheaper) renovation of old Ashra house is now under discussion.