# 自由曲面の製造
# Manufacturing of free-form optics

**Mikio Kurita**
**Kyoto Univ.**

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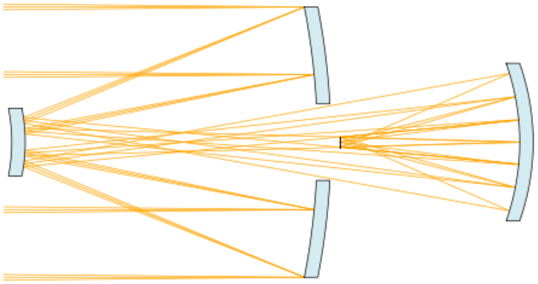
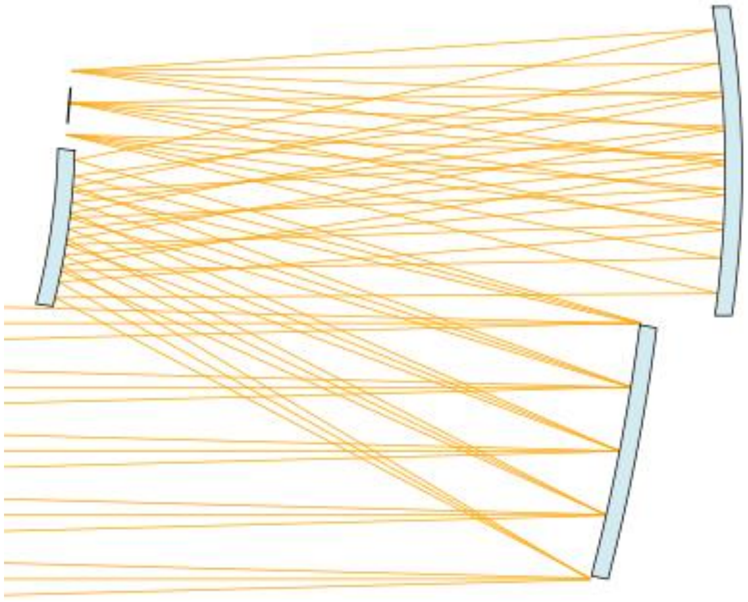
京都大学　セミナーハウス
20221223

# Introduction: Potential of Free-form Optics



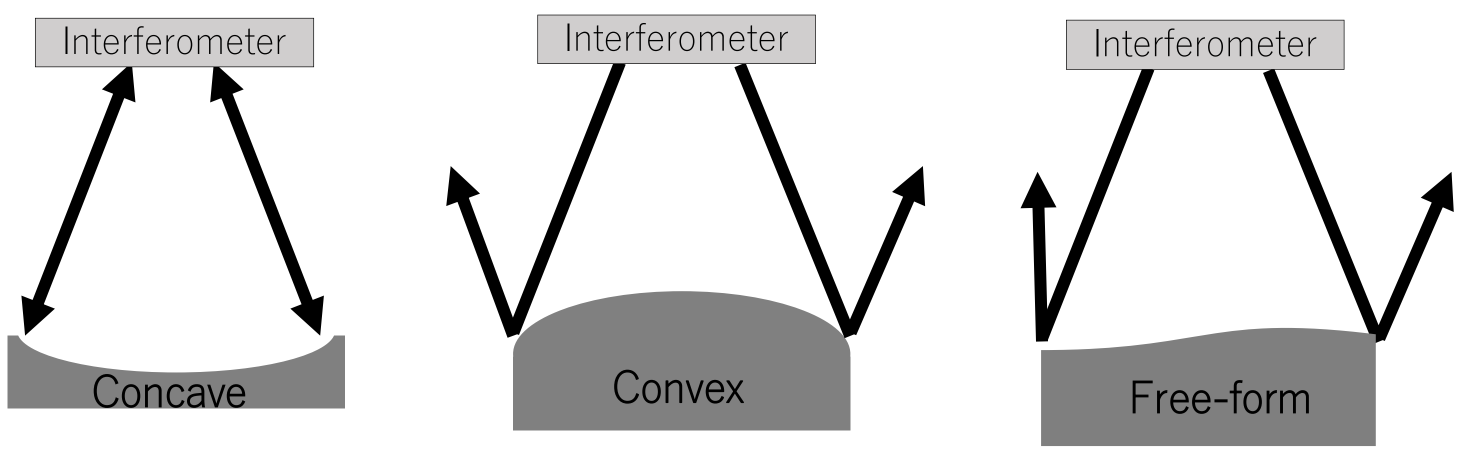
Conventional Optical Design
Korsch FoV ～Φ1 deg



Three Mirror Anastigmat
TMA (designed by us) FoV ～Φ4 deg

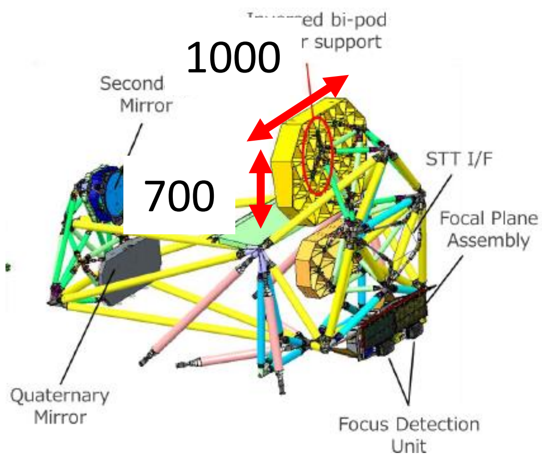
# Introduction
# Limitation of Interferometer

- Interferometer is a powerful tool for a test of optics.
  - requiring an accurate and custom-made reference surface (null optics)
  - requiring a stable and large space equivalent to the radius of curvature (RoC) of the test mirror
  - challenging to test a large flat, and convex surface
    nearly impossible to test free-form optics highly aspheric

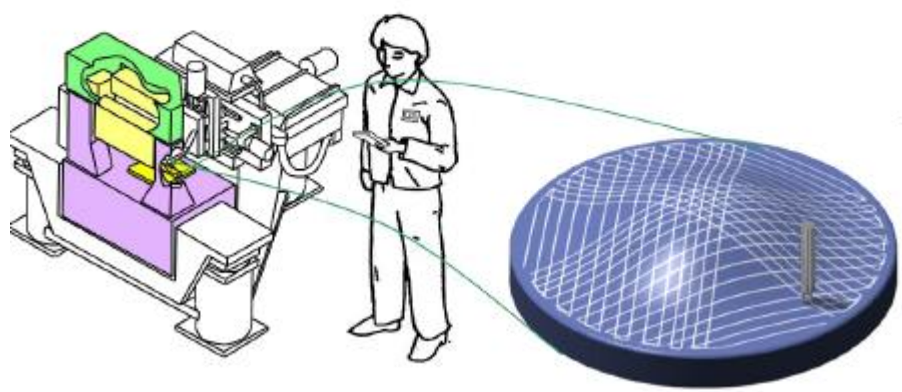


# Introduction
# Limitation of CMM/Mechanical method

- Coordinate measurement machine is a powerful tool for testing free-form optics.
  - limited to size up to 1 m
  - very few tools which can both test and polish

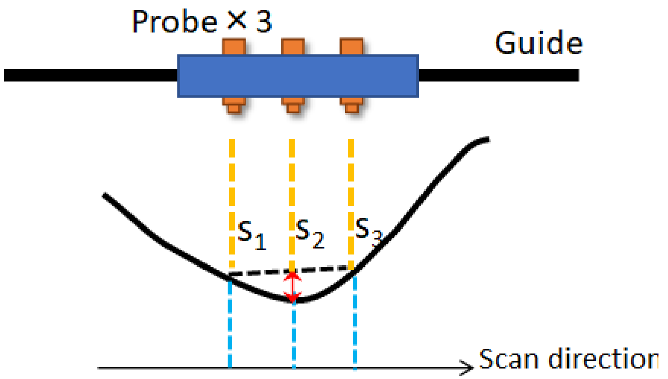



Off-axis four mirror optics
ALOS-3 (JAXA), Watarai+2018



“A–Ruler” developed by Canon Inc
Watarai+2018

# Three Point Method (TPM)




- Three-sensor unit travels with linear guide
- Sag or hump (local curvature) is obtained with $2s_2\text{-}s_1\text{-}s_3$
- Local curvatures are doubly integrated along the scanning path
- The cross-sectional shape of the test surface is obtained

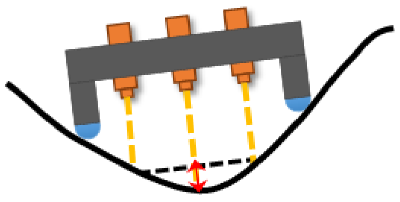
☺

- Measuring local curvature is insensitive to motion error of the unit
- Precise reference (null optics) is not required → Free-form

☹

- Low spatial resolution
- Sensor noise is also magnified with the integration process.
- Inapplicable to surface departing from flat

# Dragging TPM



Dragging TPM

- Dragging TPM drags a probe unit on the test surface.
- Difference of the local curvature from the design value is integrated along the path for obtaining the figure error.

☺

A linear guide is not required.

A large measurement range of sensors is not required.

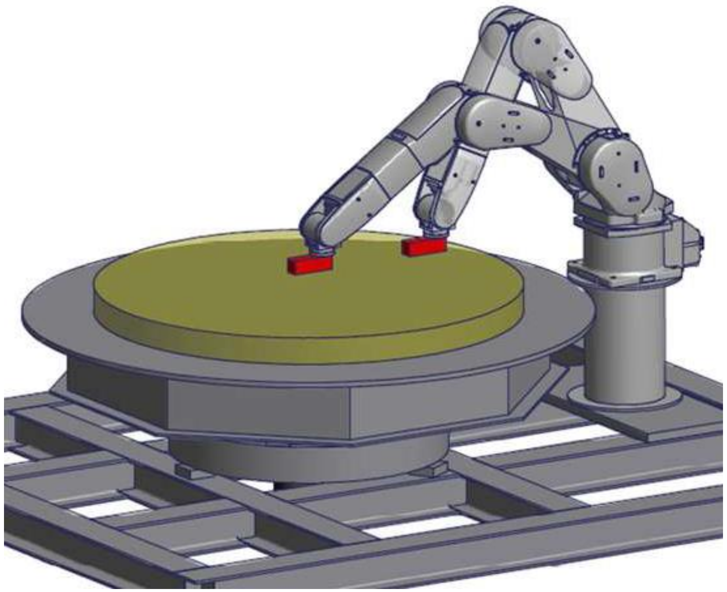
Resistant to temperature changes and vibration

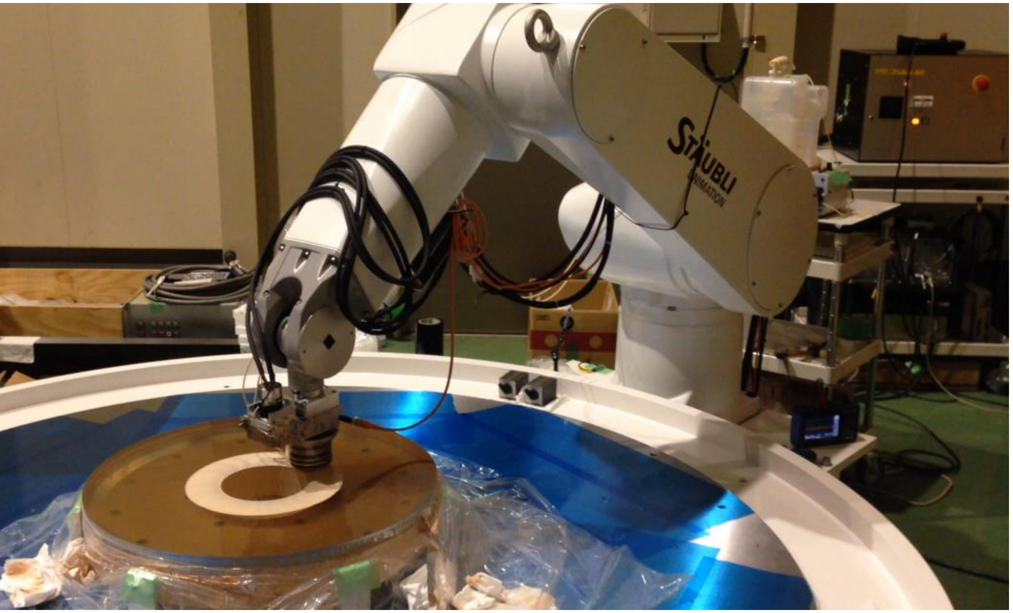
It can be mounted on a polishing machine.

→Measurable range is not limited

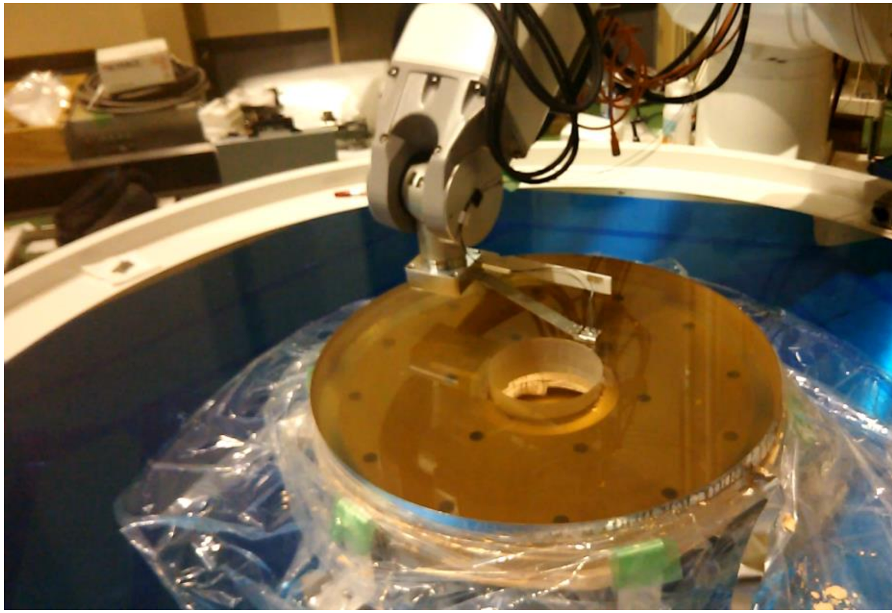
# Robot Arm System

- Polish & Profilometer
- Work Area: ϕ1.8m
- Small space
- Robust
- Cost saving






Polish



Measurement

# Data Stitching Algorithm

- Sensor error is emphasized with the integral procedure.
- The cross-sectional data is inconsistent with each other at the intersection after least squares.
- New algorithm deals with the data as a deformable *linear elastic body* and stitches the data without inconsistency.
- The solver is based on FEM (minimum energy).

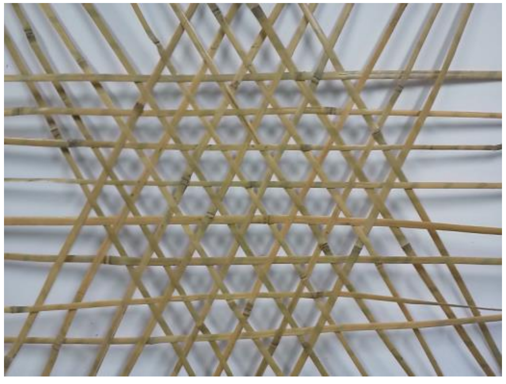
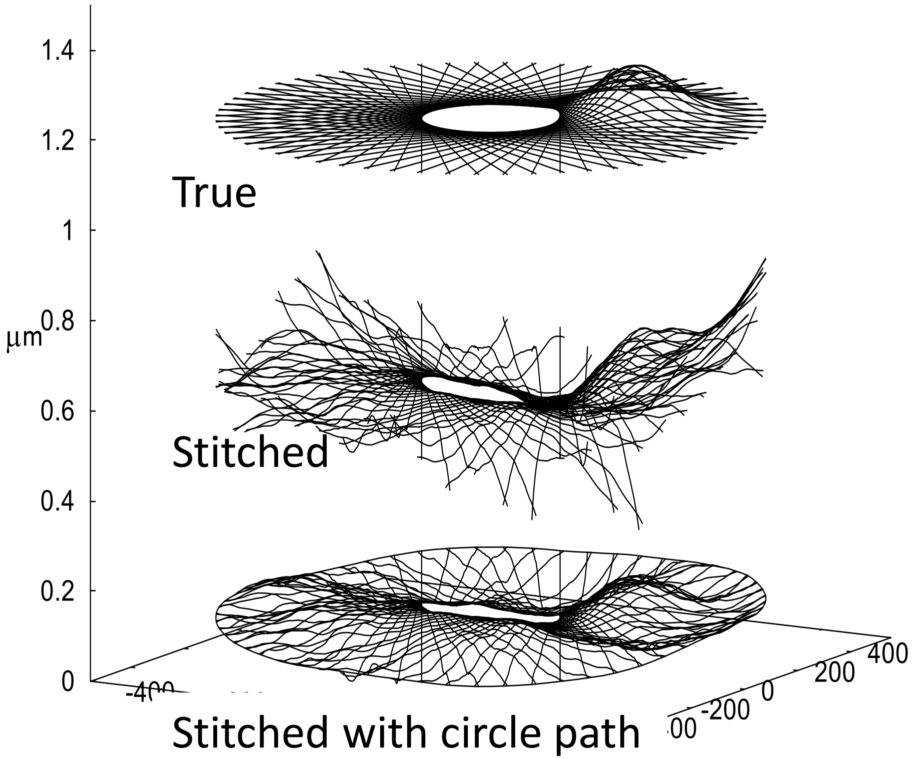
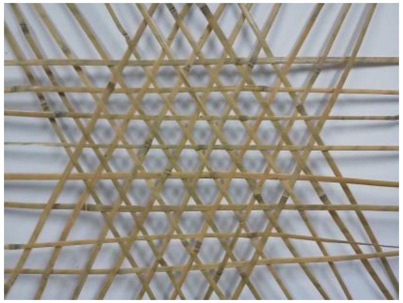


Image of stitching elastic bodies

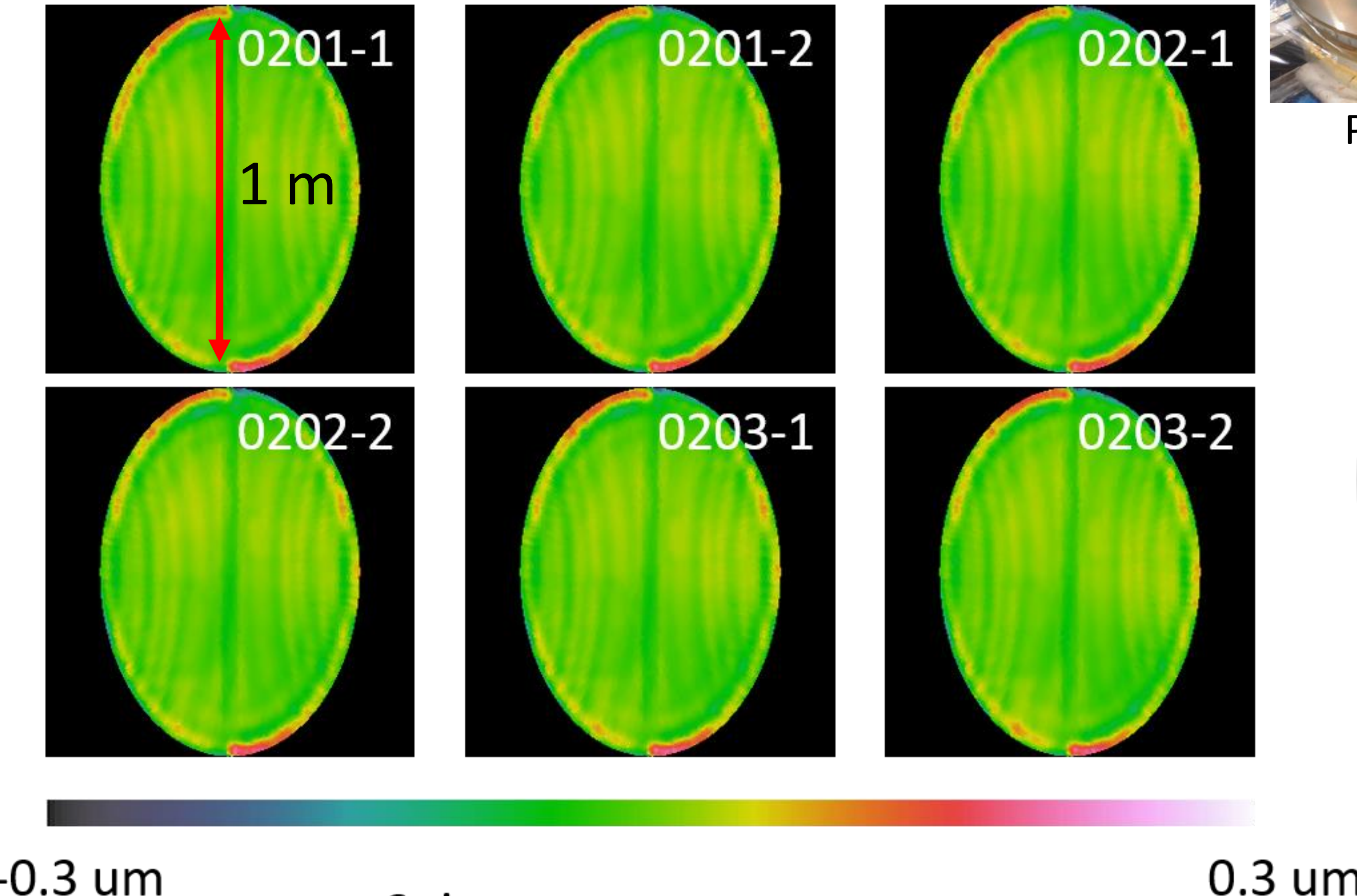
# Simulation



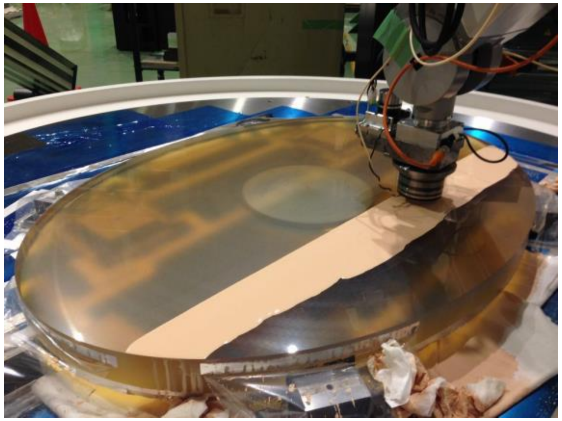
Raw data is made using a three-point method with a sensor noise of 1 nm and 100 steps.
Raw data has inconsistencies at the intersections and has a discontinuous surface.
Stitched surface reduces figure error and has a continuous surface.
The circle path at the edge dramatically improves the figure error.

# Repeatability on flat mirror

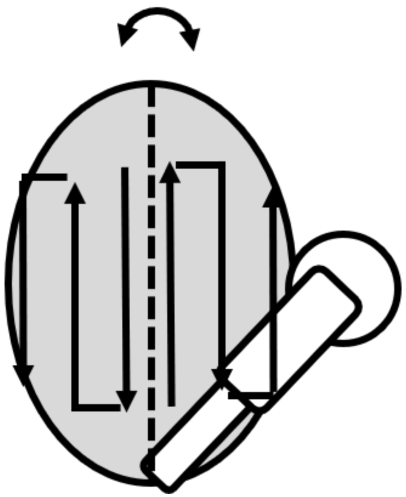



6 times measurements

RMS < 10 nm



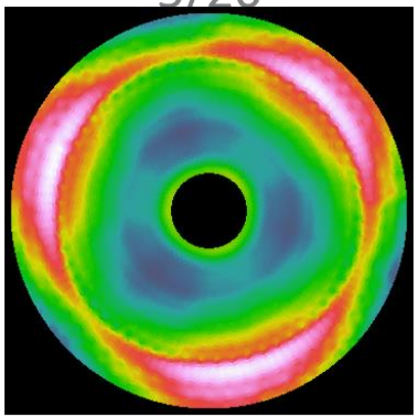
Polishing flat mirror



Motion of robot-arm and table

# Convex Aspheric

5/26

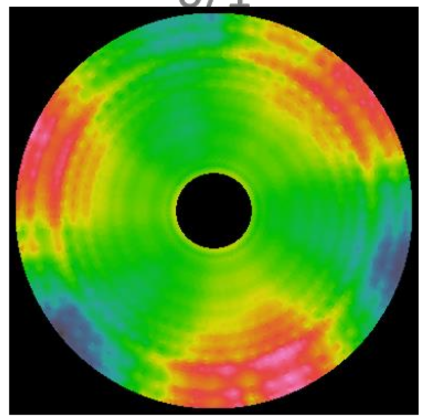


P-V = 2,400 nm

RMS = 550 nm

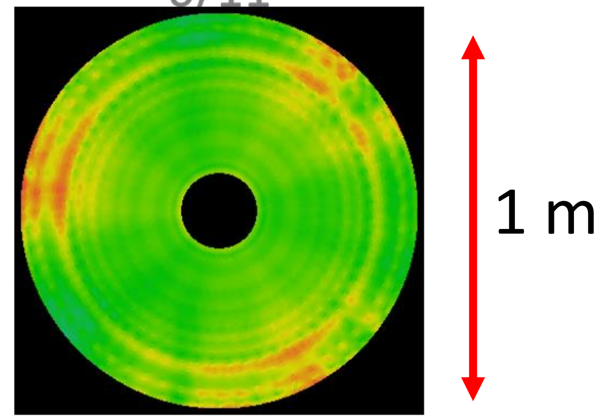
After grinding

6/1



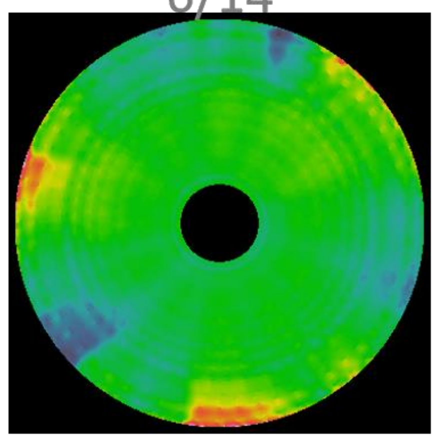
RMS = 350 nm

6/11



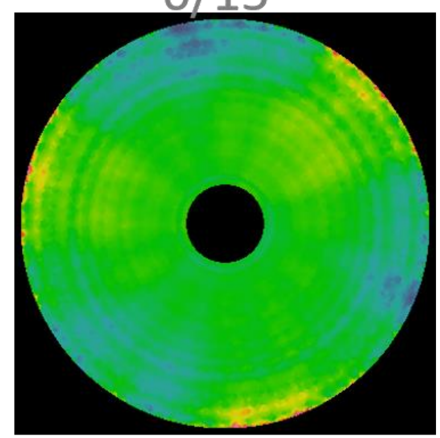

RMS = 150 nm

6/14



RMS = 130 nm

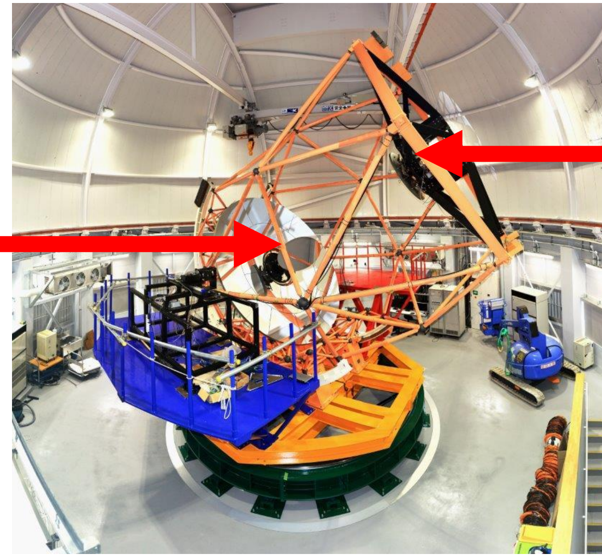
6/15



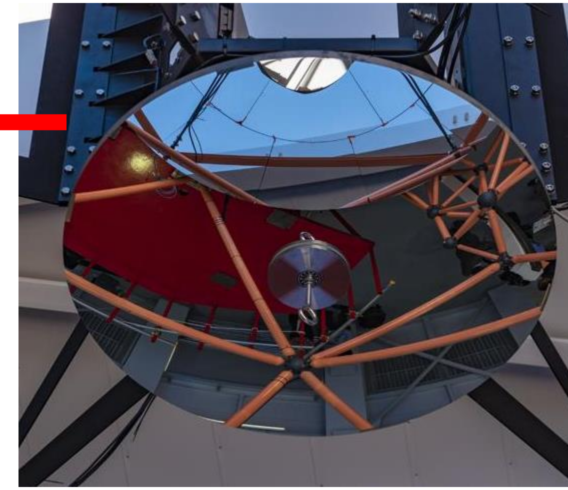
RMS = 35 nm

# Seimei Telescope

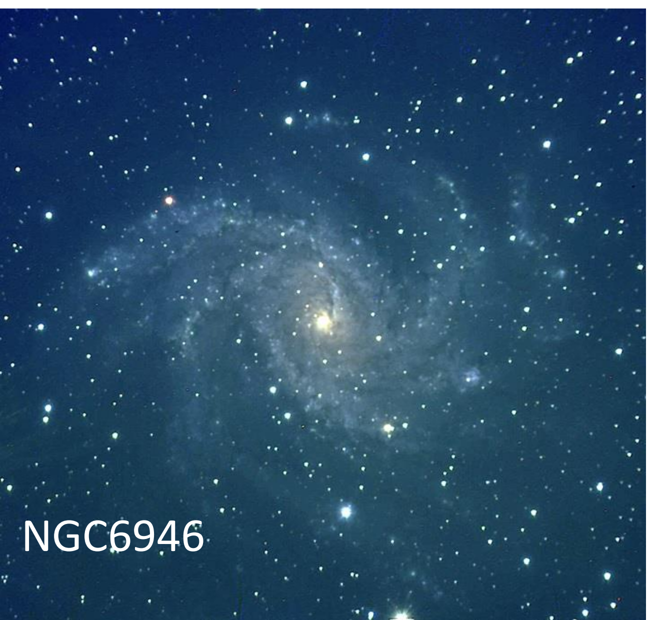
Flat mirror

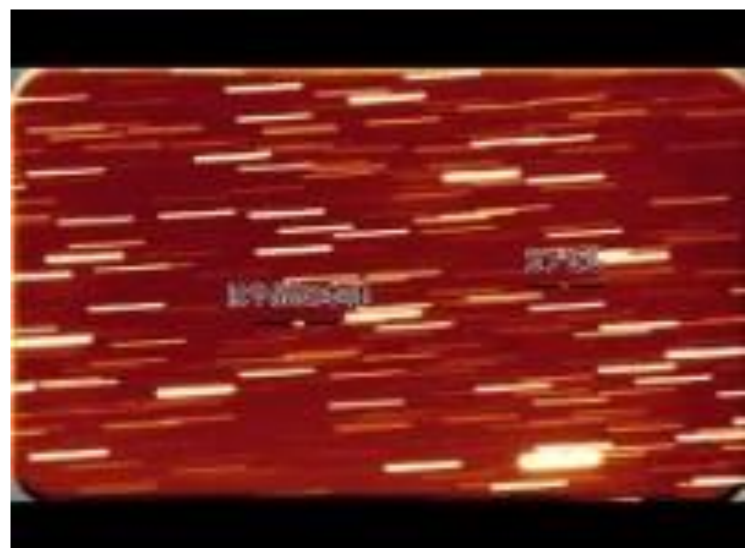


Seimei 3.8 m telescope
The largest telescope in East-Asia

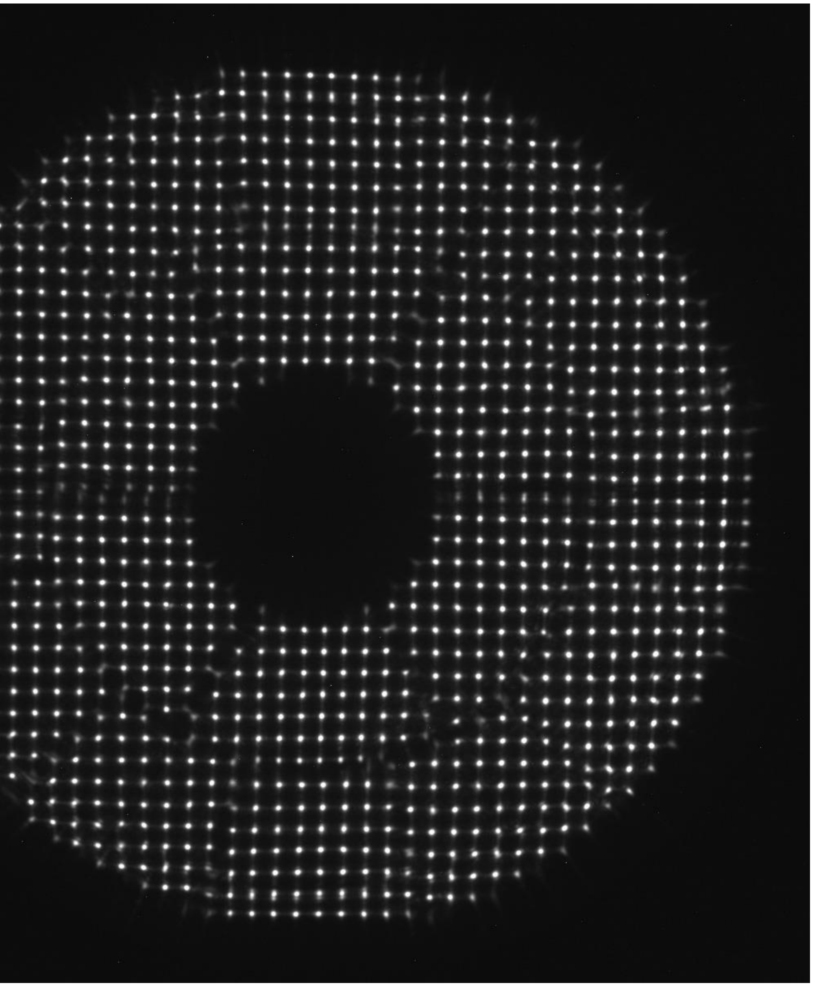


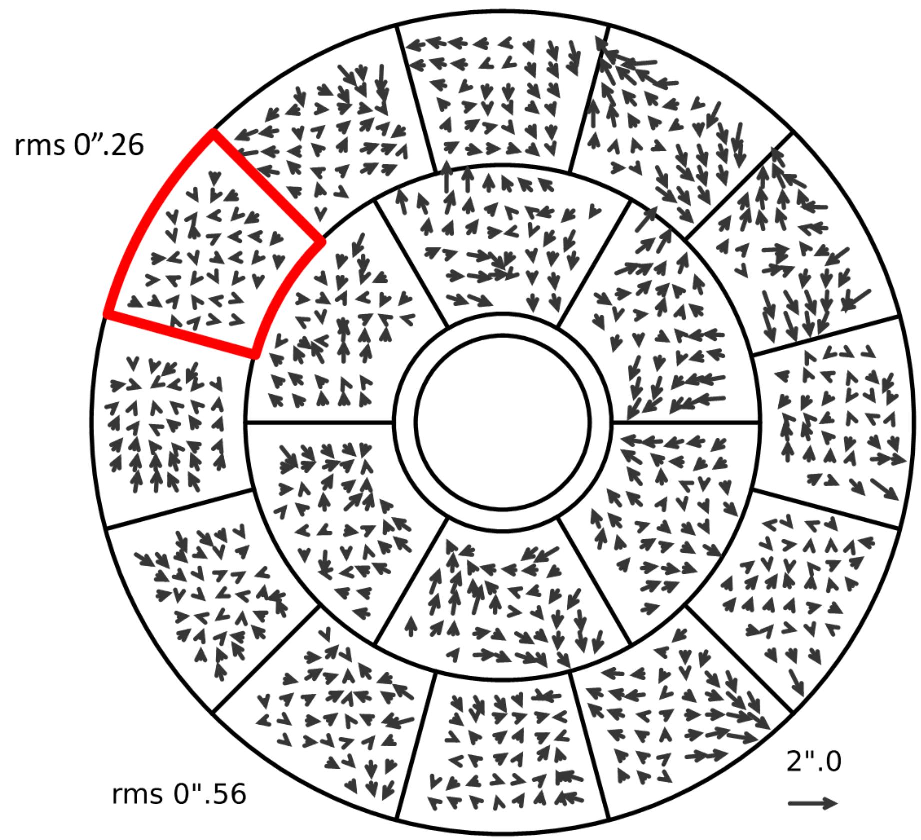
Convex Aspheric



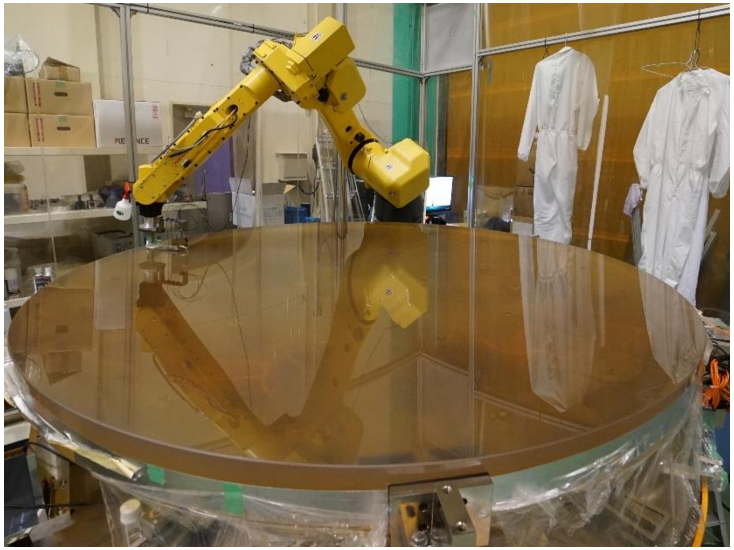
# Hartmann Test



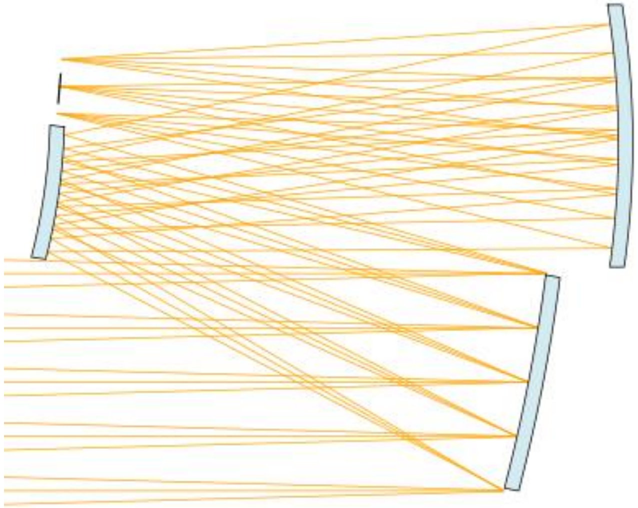


# Current and Future Work

- 2-m off axis parabola
  - Telescope for observing planets in our solar system
- Three mirror anastigmat (TMA) telescope
  - 0.5 m aperture
  - FoV of Φ4 deg
  - Off-axis and good MTF



2-m off axis parabola for PLANETS



# Conclusion

- We developed new manufacturing system for free form and one-meter scale optics.
- The system figured out the M2 and M3 mirrors of Seimei telescope.
- The system finished 1m convex M2 within one month with the figure error of 35 nm RMS.
- We confirmed the optical performance of M2 and M3 with the Shack Hartmann test and obtained the Hartmann constant of 0”.26.