Ring Astrometric Field Telescope

Deborah Busonero on behalf of the collaboration

INAF-OATo

A future space mission with very high precision astrometry
Paris, 11-13 September 2024

Presentation layout

- Introduction
- Scientific scenario
- Rafter description
- Technological challenges
- Conclusions

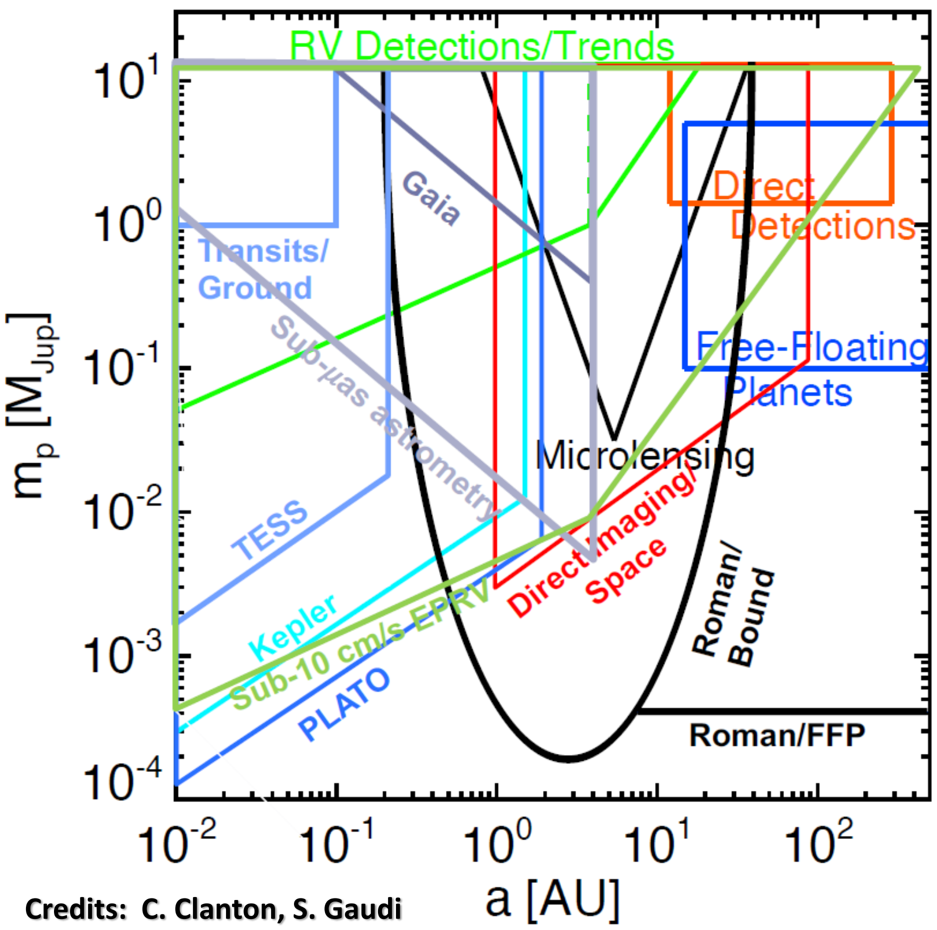
Introduction

- This talk is focused on a dedicated sub-μas astrometry instrument configuration called RAFTER.
- Local-differential astrometry.
- Innovative concept of on-axis TMA which reduces the complications of the classic TMA while maintaining its large corrected field advantage.
- Innovative technique for PSF centering at the 1/5900 pixel level to reach sub-μas astrometry.

Riva, A., et. al., SPIE 2020;

Gai M., et. al., PASP 2022

Main Scientific target



Credits: C. Clanton, S. Gaudi

- Sub-μas astrometry from space is the only technique capable of performing a complete census of Earth-mass planets in the Habitable Zones (HZs) of F-G-K-type stars within 20 pc from the Sun without selection effects. Typical V=8-12 mag

  - ultimate target provider for future space missions such as HWO or LIFE aimed at the spectroscopic detection of bio signatures in the atmospheres of temperate telluric planets

1 Earth mass planet in the HZ(a=1 AU) of a solar-mass star at 10 pc the astrometric signal is ≈0.3 μas

BUT NOT ONLY....

a) shape and dynamics of Dark Matter halos in selected collective systems (dwarf spheroidal galaxies, samples of Milky Way halo stars and hyper-velocity stars);

b) calibration of the cosmic distance ladder on distant pulsating variables (Cepheids, RRLyrae, Miras) well beyond the limits of Gaia (i.e. at the μas level at G $\simeq$15 mag); (changing in time exposition)

c) high-accuracy masses and orbits of X-ray binaries hosting neutron stars and black holes (visible countepart);

d) identification of candidate systems for future gravitational wave observations and measurements of the stochastic background of gravitational waves (in sliding modified configuration Gai this workshop).

Ring astrometric field telescope

- μas astrometry compatible with 1m-class telescopes
- Local astrometry
- Innovative TMA design

Scenario

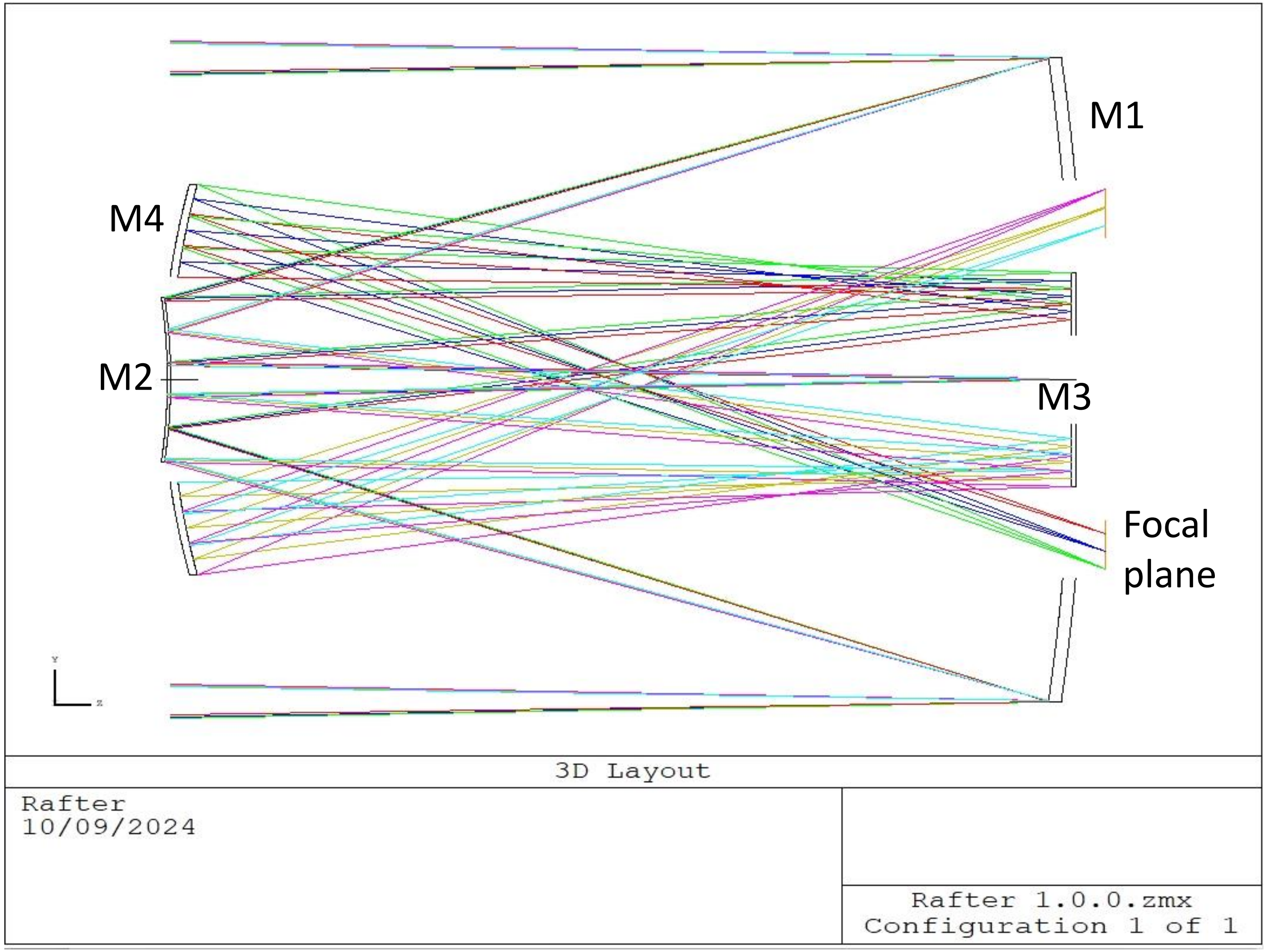
- Large corrected field requires TMA
- Traditional TMA’s require off axis configurations (e.g. JWST, Gaia, …)
- TMA presents lot of issues in alignment procedures and alignment maintenment (metrology issues)-> demanding optomechanics -> low TRL
- IF we accept the central field (around optical axis) obscuration we can design an ON-AXIS TMA -> a lot easier to align (e.g. like traditional telescopes design) -> more relaxed requirements

Idea

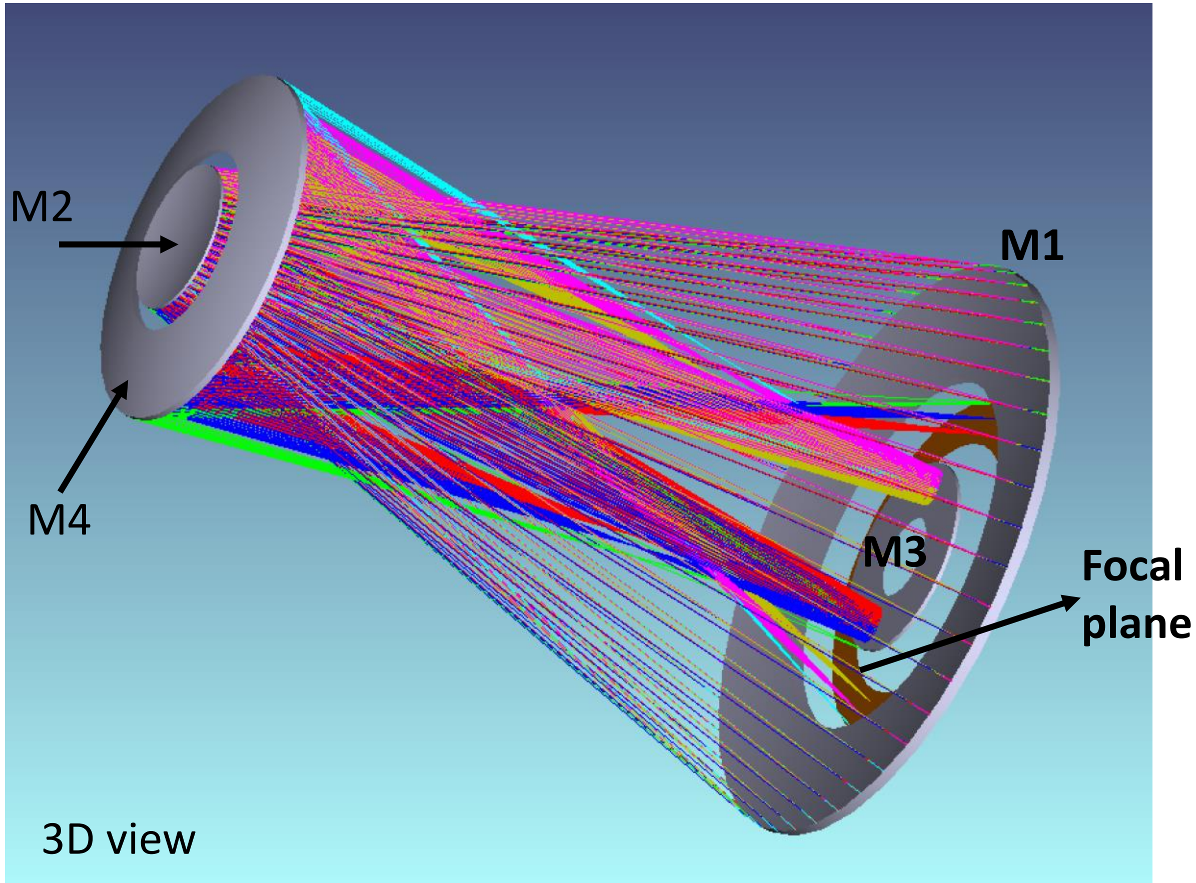
- We propose an on-axis telescope materialized by means of annular mirrors (rings)
- Annular focal plane -> ring of detectors
- Analogies with AGP design [Riva, A., et al, SPIE 2016]

Optical Design: Layout

Design & analysis: Zemax OpticStudio



Optical Design: Layout



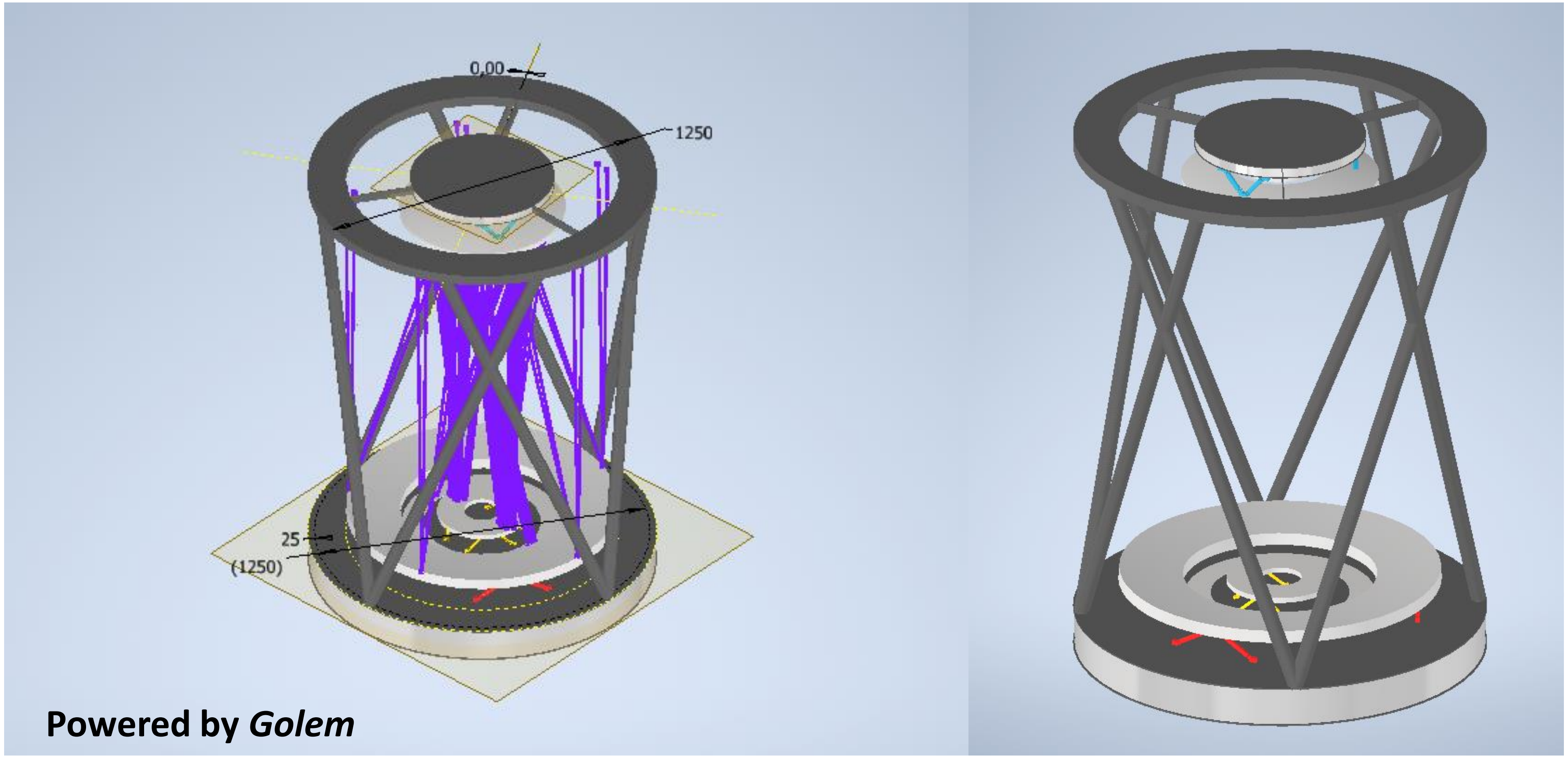
Compact structure → **whole envelope: <2 m**

Simmetry

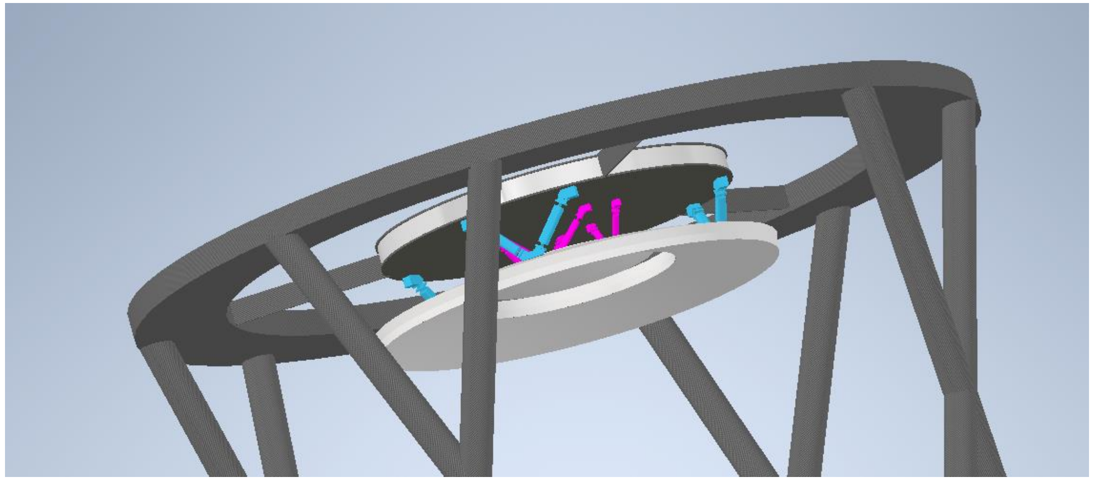
Simplified alignment of M1/M3-M2/M4 zones

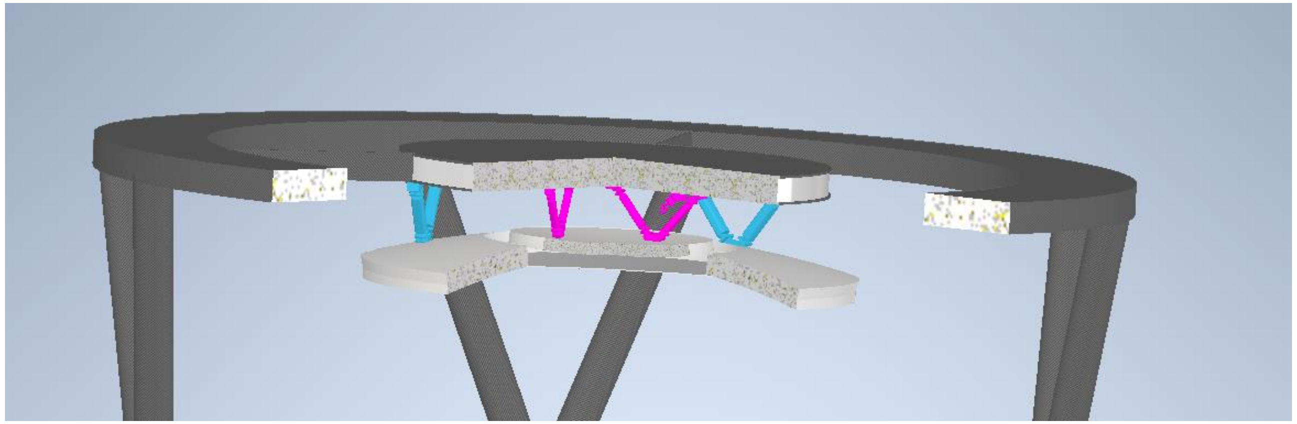
- ✓ The telescope is naturally split into two smaller optomechanical units, facing each other;
- ✓ this arrangement ensures the mutual placement stabiliy of the nearby mirrors, thus relaxing the overall number of degrees of freedom and complexity;
- ✓ each mirror pair is also subject to a common local thermal environment, including its thermo-elastic perturbations

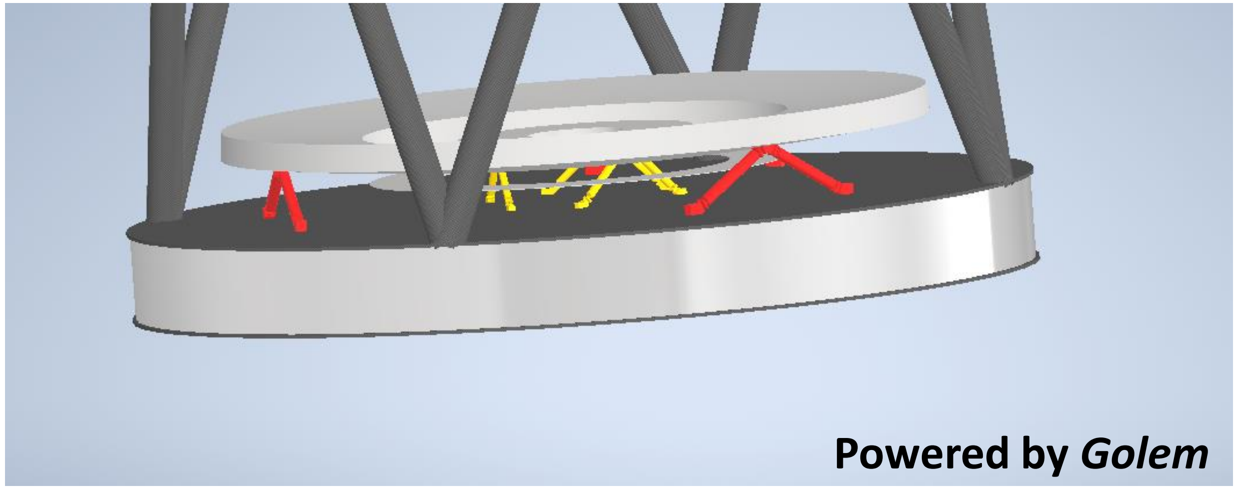
Opto-mechanical concept

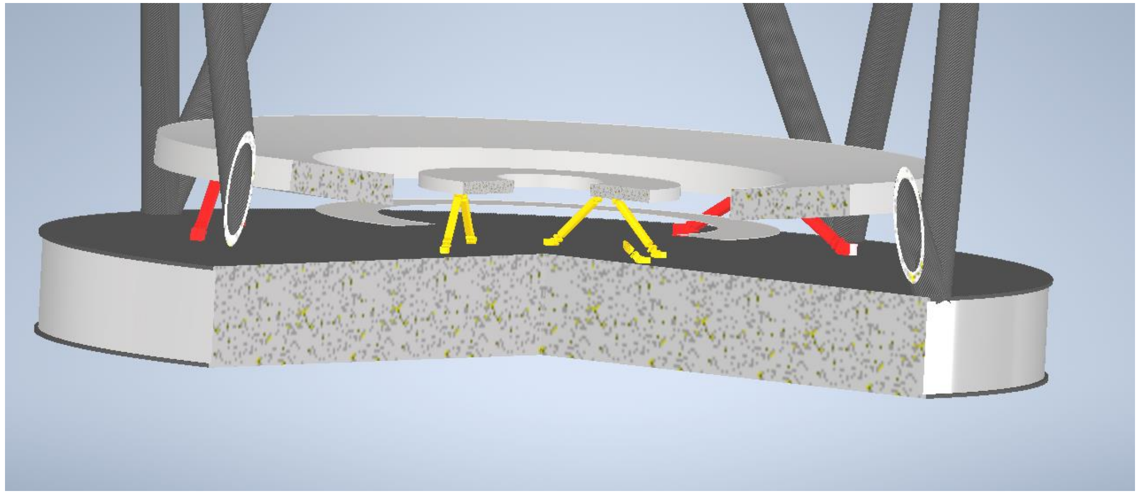


Opto-mechanical concept - details





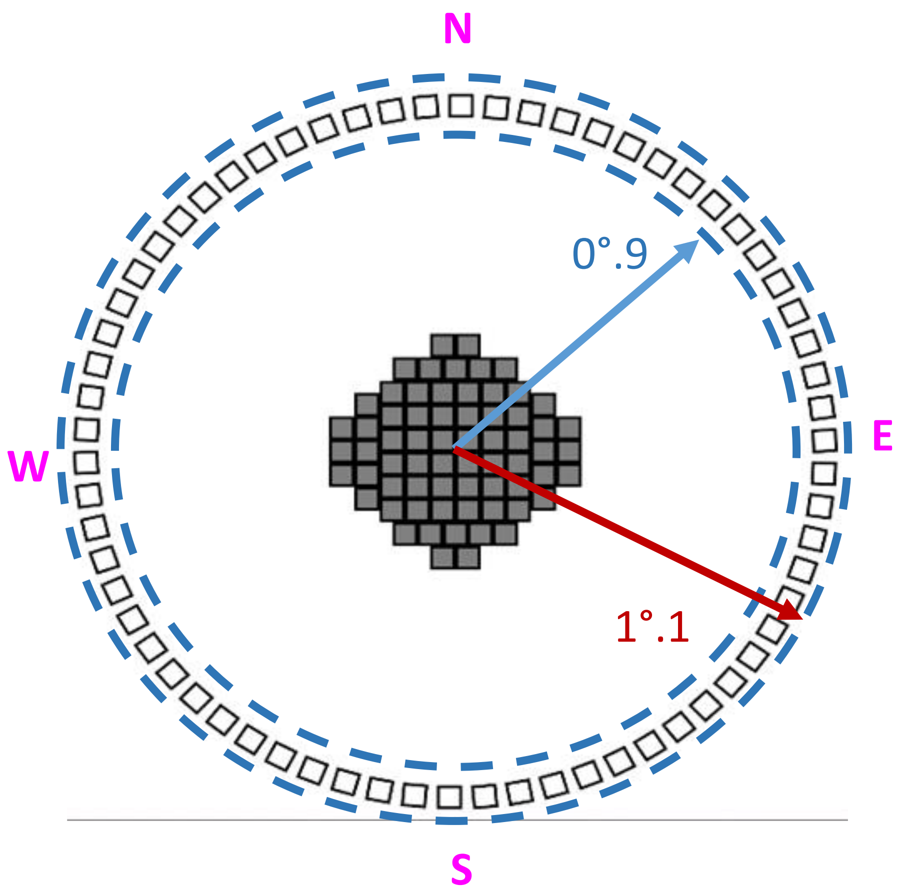




TELESCOPE PARAMETERS

- Diameter: 1 m
- Lenght: 1.4 m
- EFL: 15 m
- f-number: 15
- Diffraction limited

- FOV: 1° +- 10’



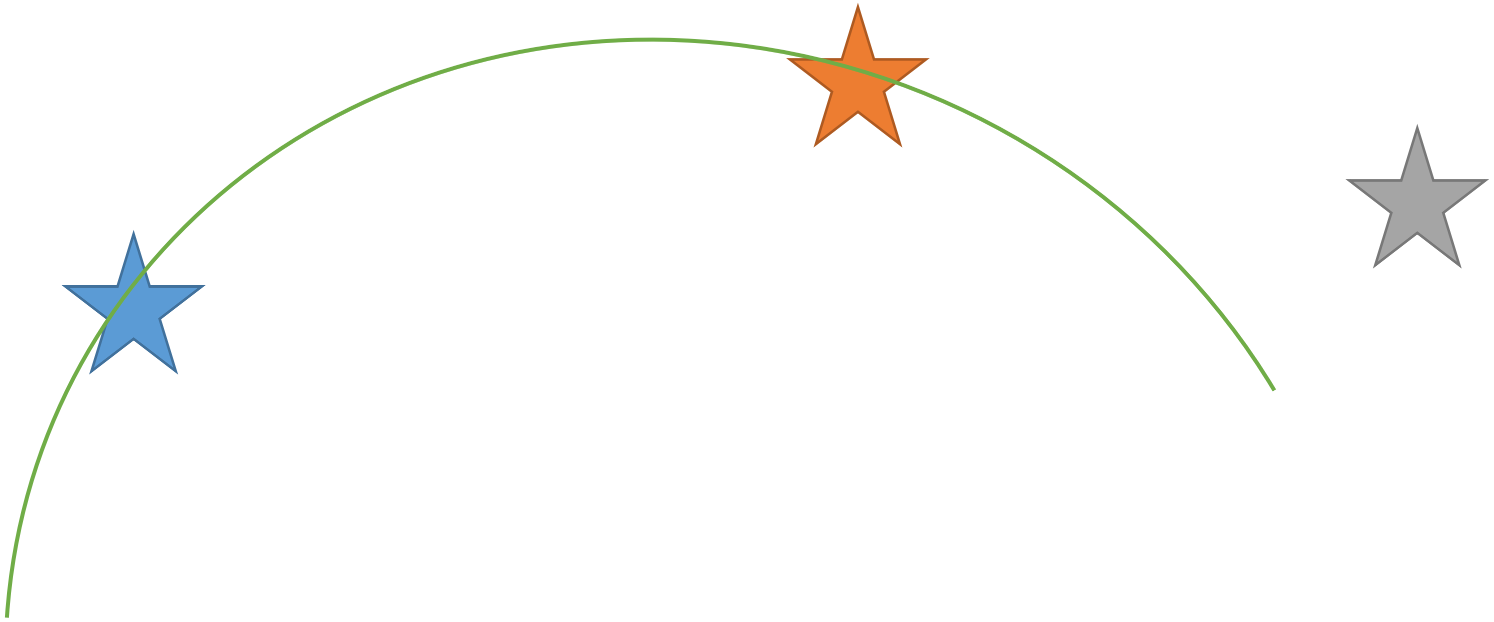
- Platescale 50 mas/pixel

Compatible with 4-5 μm pixel CMOS detectors

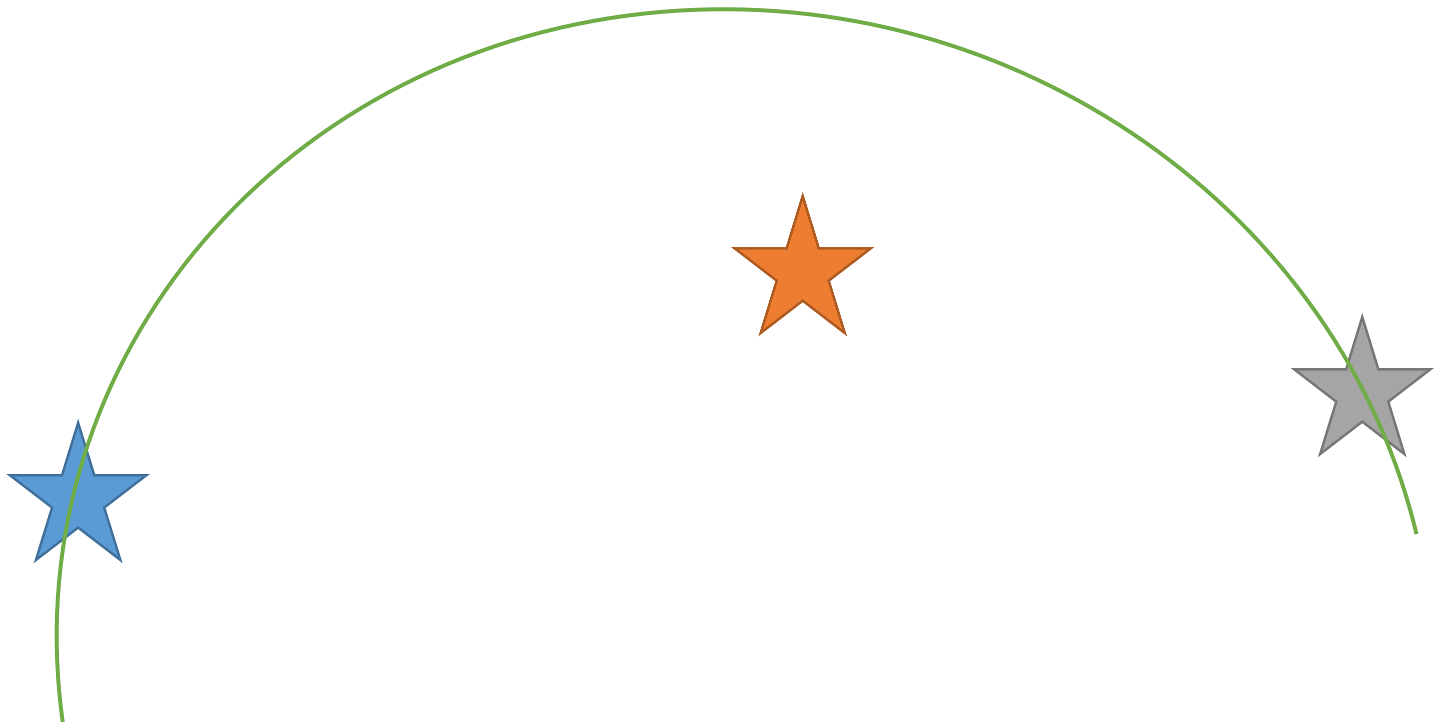
Rings of 66 hypotetical detectors (4k x 4k)

(Same number of device arranged around optical axis for comparison)

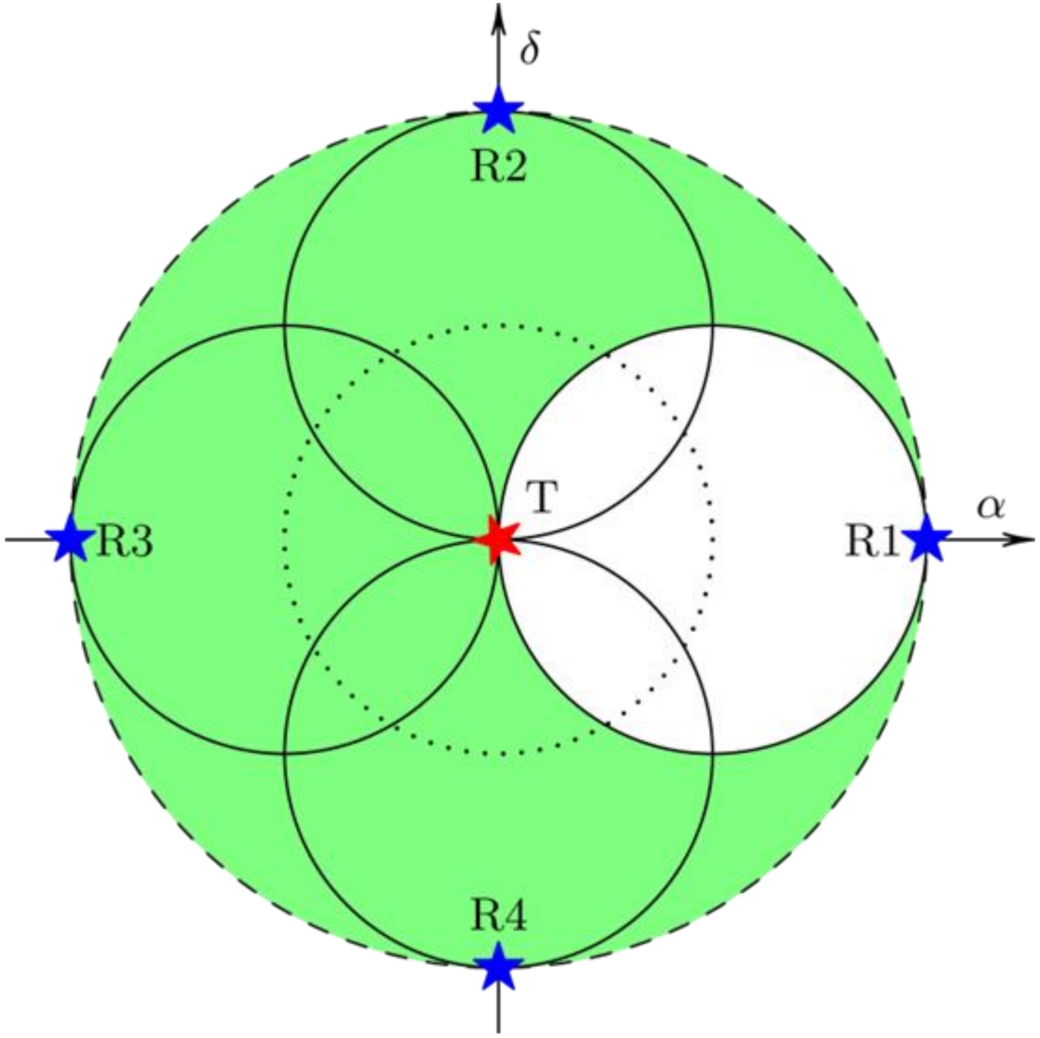
Observation Strategy



Observation Strategy

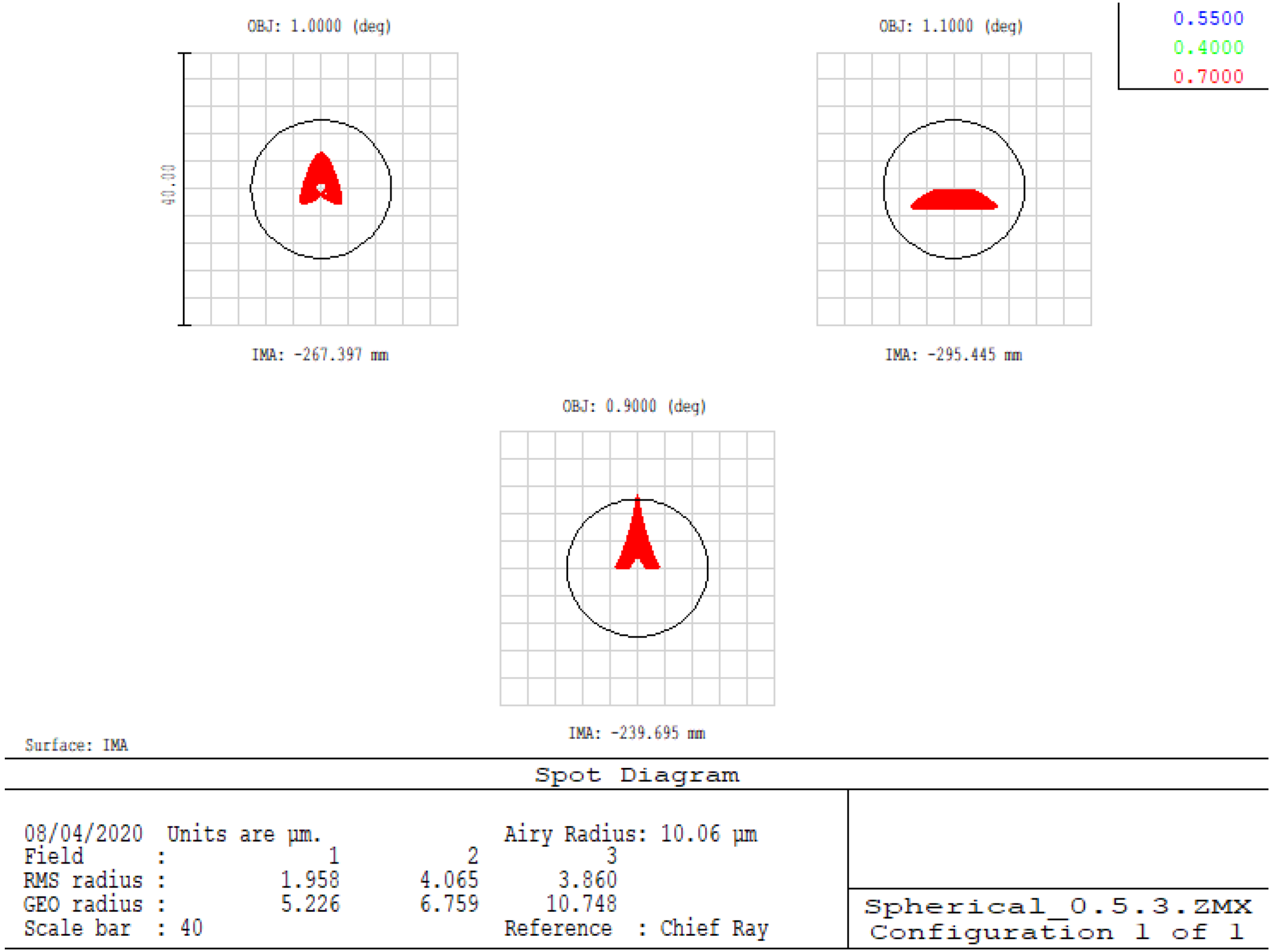


Equivalent field

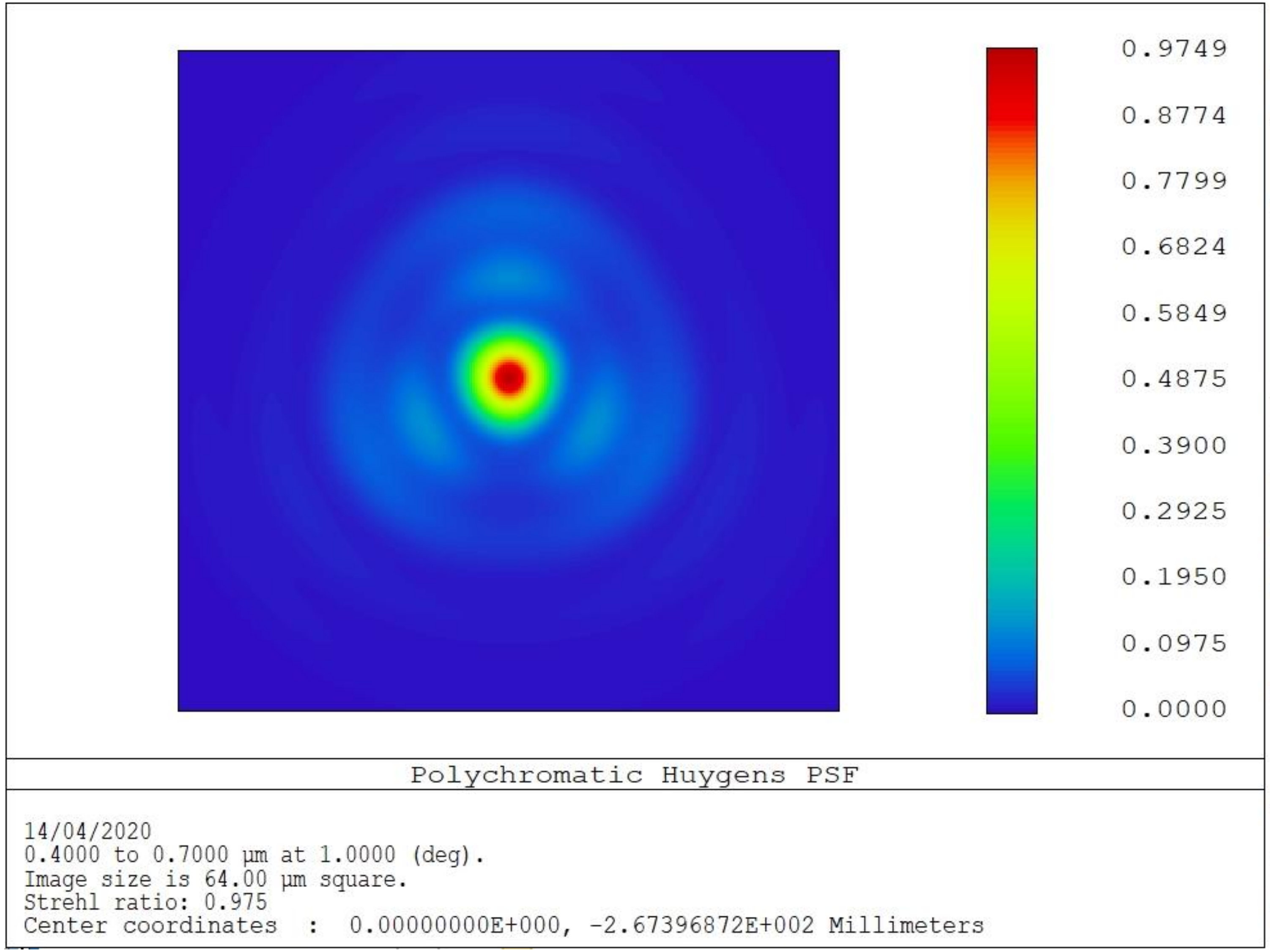


Gai talk, this workshop

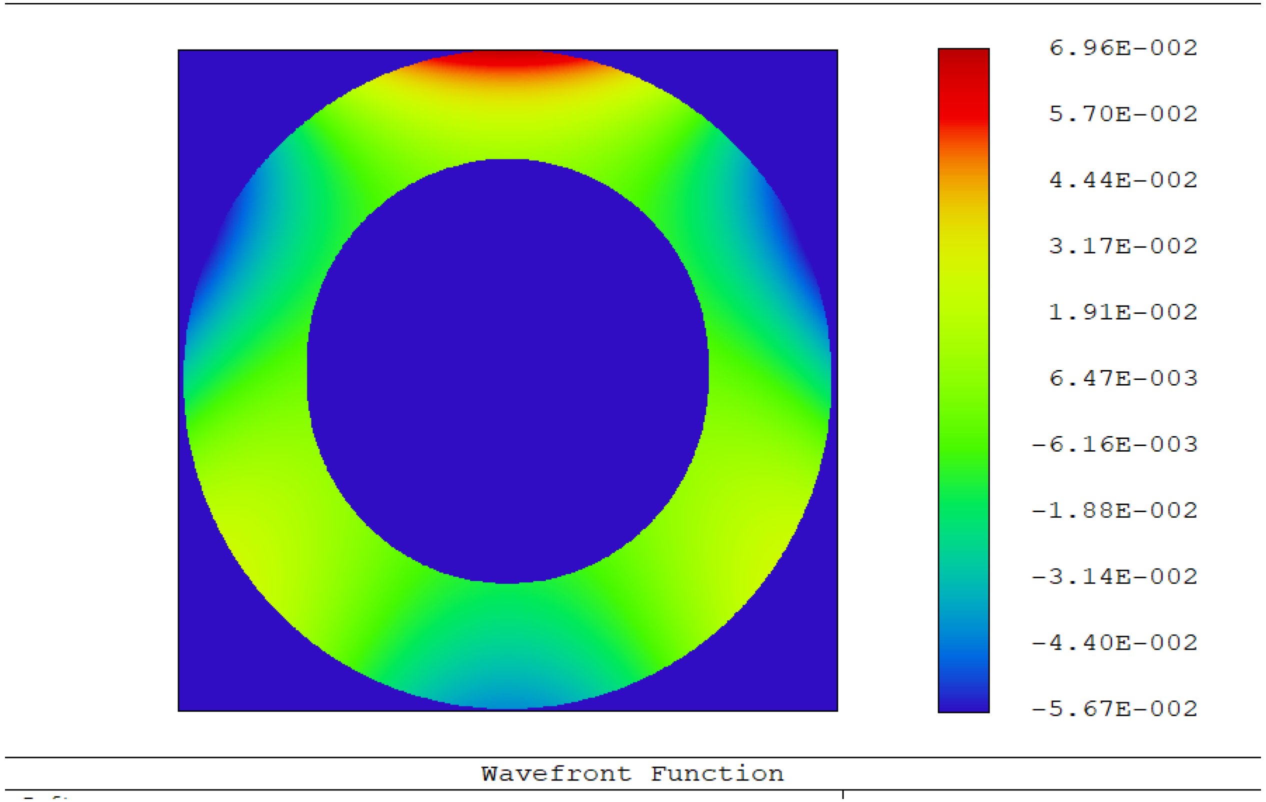
Optical Quality : spot diagram

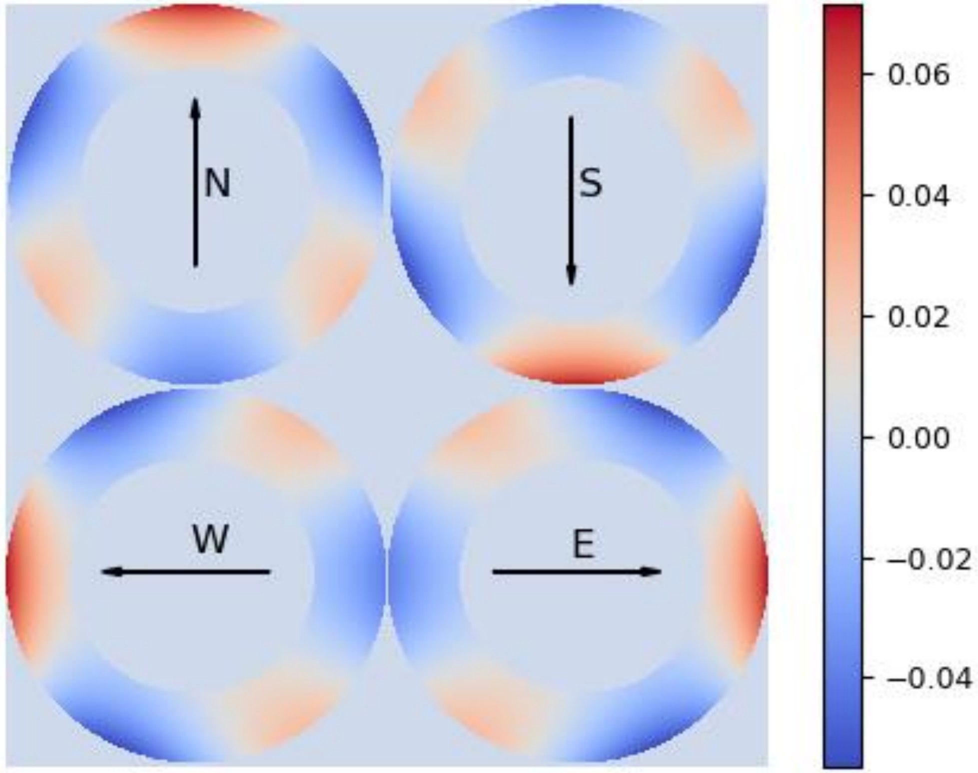


Optical Quality: PSF

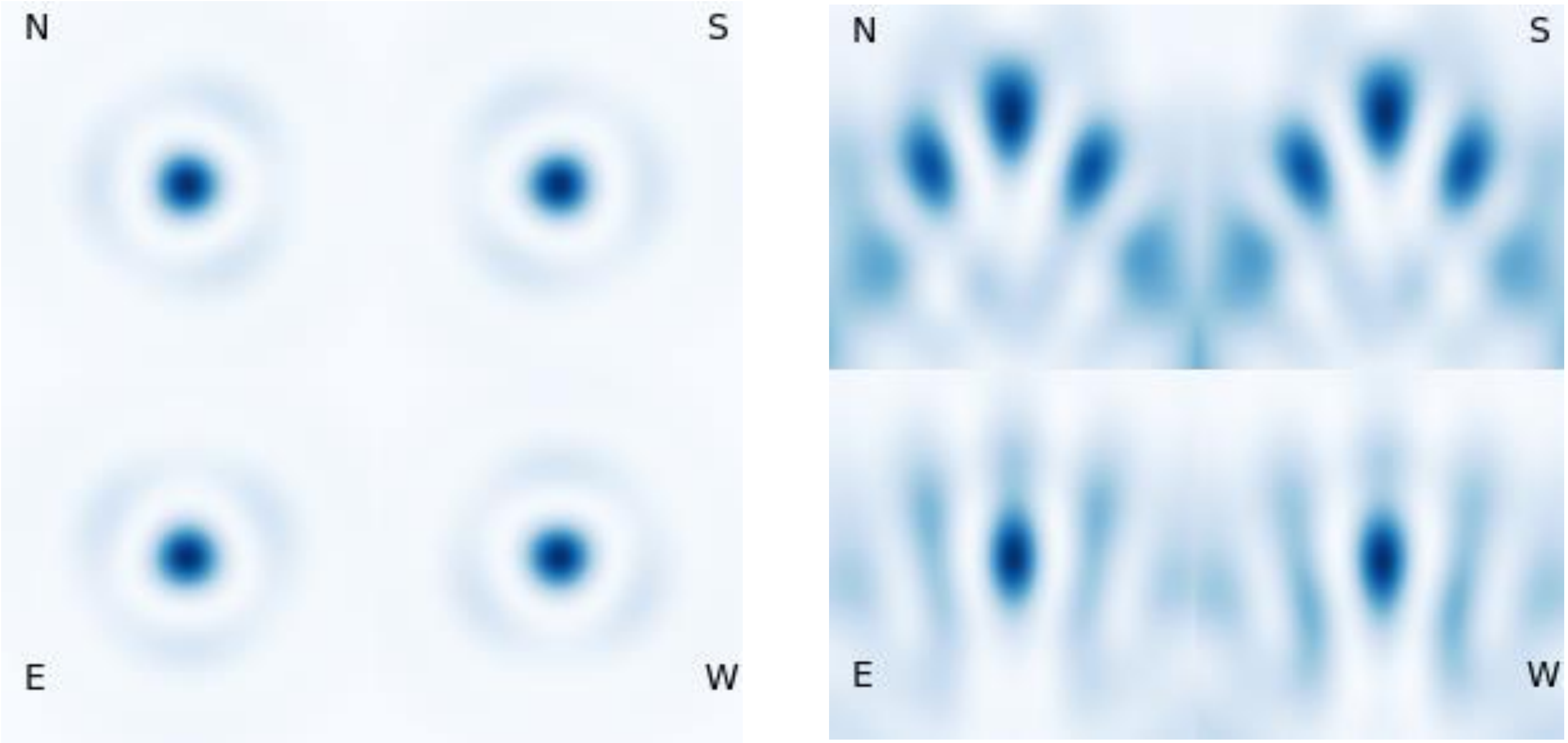


Optical Quality: WaveFront





Optical Quality: perturbations



PSF degradation for medium M1 tilt (1”, left) and large (36”, right)

Main points for TRL improvement

1. Tolerances and sensitivity
2. Mission profile
3. Detectors
4. Thermo-mechanical analysis
5. Straylight and baffles

1. Tolerances

Element	Parameter	Variation	Change
M1	Tilt X and Y	+/- 3'	21.44
M2	Tilt X and Y	+/- 3'	5.48
M1	Movement X and Y	+/- 0.2 μm	2.27
M2	Movement X and Y	+/- 0.2 μm	2.24
FM	Tilt X and Y	+/- 3'	1.97
M1 - M2	Distance	+/- 0.2 μm	1.78
M3	Tilt X and Y	+/- 3'	0.47
M1	Surface irregularity	+ 0.2 Fringes	0.46
M2	Surface irregularity	- 0.2 Fringes	0.22
M1	Radius	- 1 Fringe	0.13
M2	Radius	+ 1 Fringe	0.09
M2 - FM	Distance	+ 0.2 μm	0.04
M3	Movement X and Y	+/- 0.2 μm	0.02

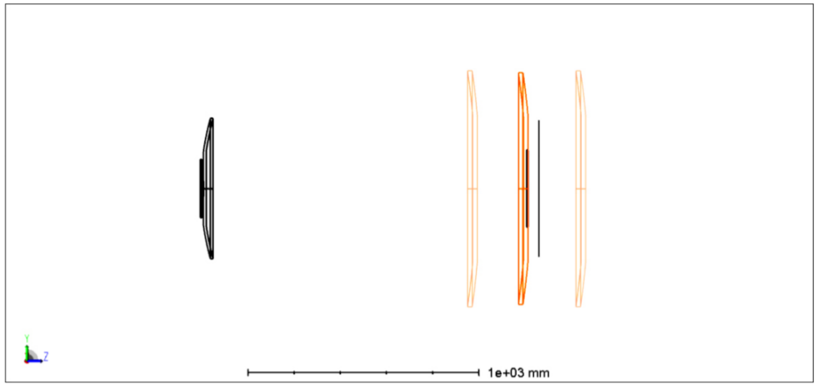
1. Tolerances

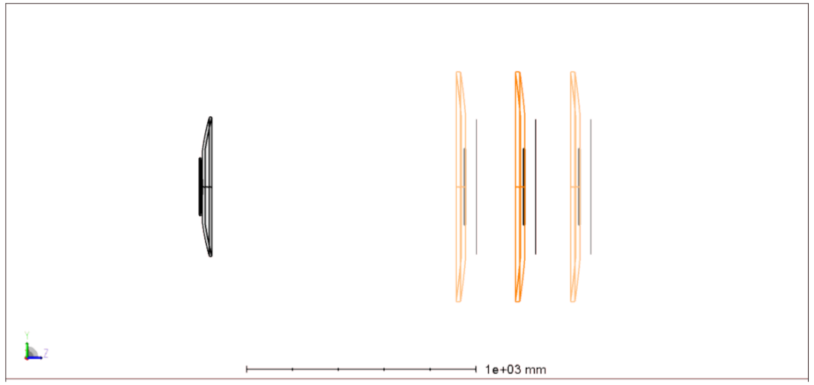
- Dedicated study in collaboration with Politecnico of Torino: Fornasiero, F., et. al., SPIE 2024
- Study of the two zones sensitivity and tolerances

(rigid mounting of nearby components, i.e. the pairs (M1, FM) and (M2, M3) respectively)

- Definition of the experiments to increase TRL

1. Tolerances: two-zones





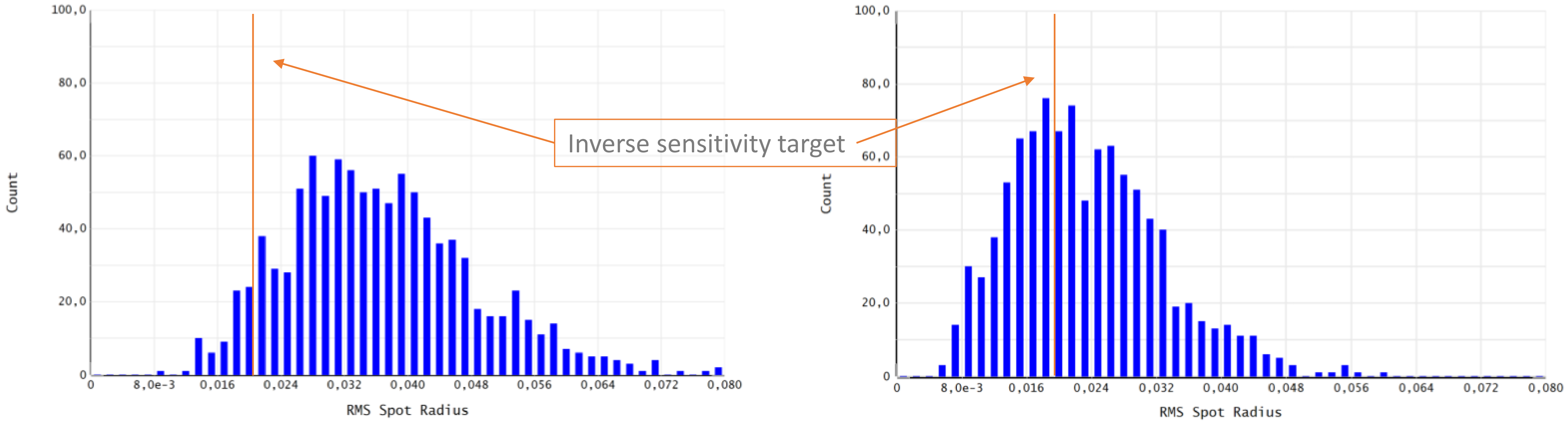
- Mechanical Hypotesis: mounting the mirrors togheter in 2 groups
- How does the optical allowance change?

Degree Of Freedom	Only Primary Mirror Movement	Movement of the two groups
Distance	$\pm 0,011$	$\pm 0,010$
Tilt	$\pm 4,415E-03$	$\pm 0,012$
Decentering	$\pm 0,138$	$\pm 0,137$

The tilting of the elements together seems to be compensating

1. Tolerances: Montecarlo

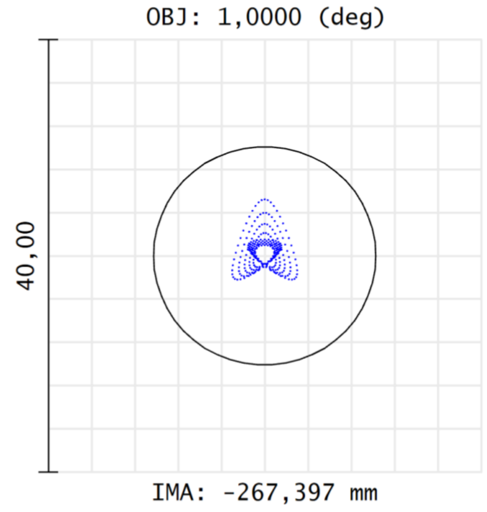
1000 configurations, normal parameter distribution, tolerance from the inverse sensitivity

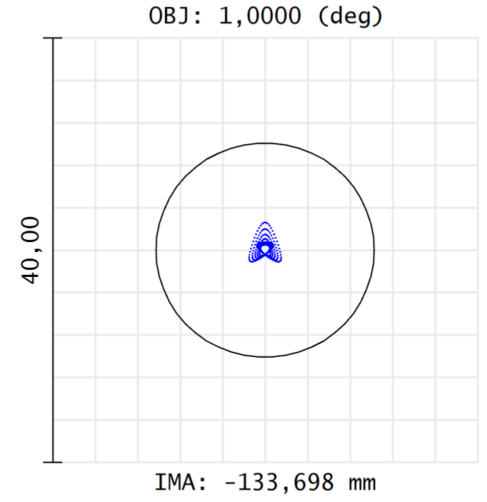


The reduction in degrees of freedoms allow for even bigger difference in real world performance

1. Tolerances: scalability

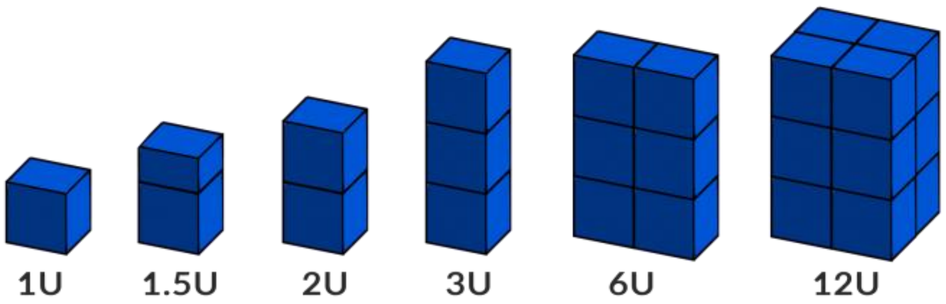
Degree Of Freedom	1.0 scale	0.5 scale	0.25 scale	0.2 scale	0.1 scale
Primary Mirror curvature (1/[mm])	±0, 023	±0, 023	±0, 023	±0, 023	±0, 023
Secondary Mirror curvature (1/[mm])	±0, 034	±0, 035	±0, 036	±0, 035	±0, 035
Folding Mirror curvature (fringes)	±1	±1	±1	±1	±1
Tertiary Mirror curvature (1/[mm])	±0, 200	±0, 200	±0, 200	±0, 200	±0, 200
Primary - Secondary distance	±0, 011	±0, 011	±0, 011	±0, 011	±0, 011
Secondary - Folding distance	±0, 158	±0, 159	±0, 159	±0, 159	±0, 161
Folding - Tertiary distance	±0, 200	±0, 200	±0, 200	±0, 200	±0, 200
Primary Decenter	±0, 138	±0, 139	±0, 141	±0, 139	±0, 142
Primary Tilt	$\pm 4,415E-3$	$\pm 8,879E-03$	±0, 018	±0, 022	±0, 045
Secondary Decenter	±0, 139	±0, 140	±0, 143	±0, 140	±0, 143
Secondary Tilt	±0, 014	±0, 027	±0, 066	±0, 068	±0, 164
Folding Decenter	±0, 200	±0, 200	±0, 200	±0, 200	±0, 200
Folding Tilt	±0, 024	±0, 048	±0, 159	±0, 121	±0, 200
Tertiary Decenter	±0, 200	±0, 200	±0, 200	±0, 200	±0, 200
Tertiary Tilt	±0, 082	±0, 164	±0, 200	±0, 200	±0, 200
Surface Irregularity for all surfaces	±0, 2	±0, 2	±0, 2	±0, 2	±0, 2





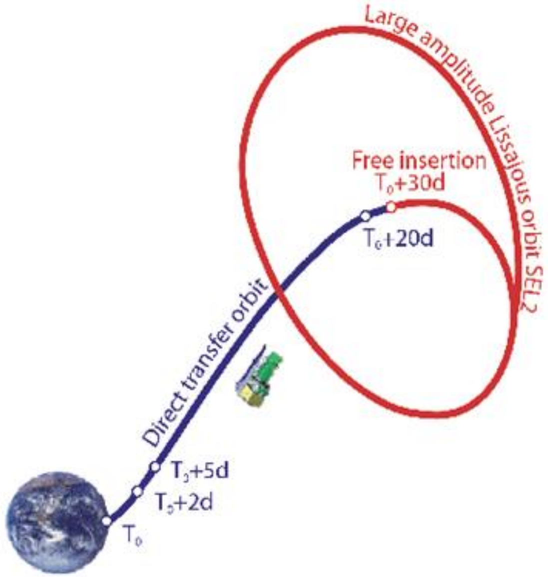
1. Tolerances: miniaturization

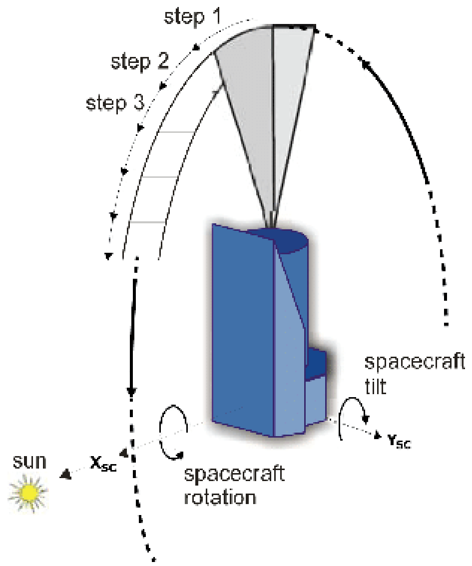
- Objective: test the TRL of the optomechanical aligment
- A 6U – 12U cubesat will be enough to prove the benefits of the optical concept



2. Mission Profile

- Dedicated study in collaboration with Politecnico di Torino: Scandaglia, C., et. al., SPIE 2024
- Halo or Lissajous orbit around Lagrange point L2 of Sun-Earth system
- Observation of target stars for extended periods of time
- Cubesat mission too





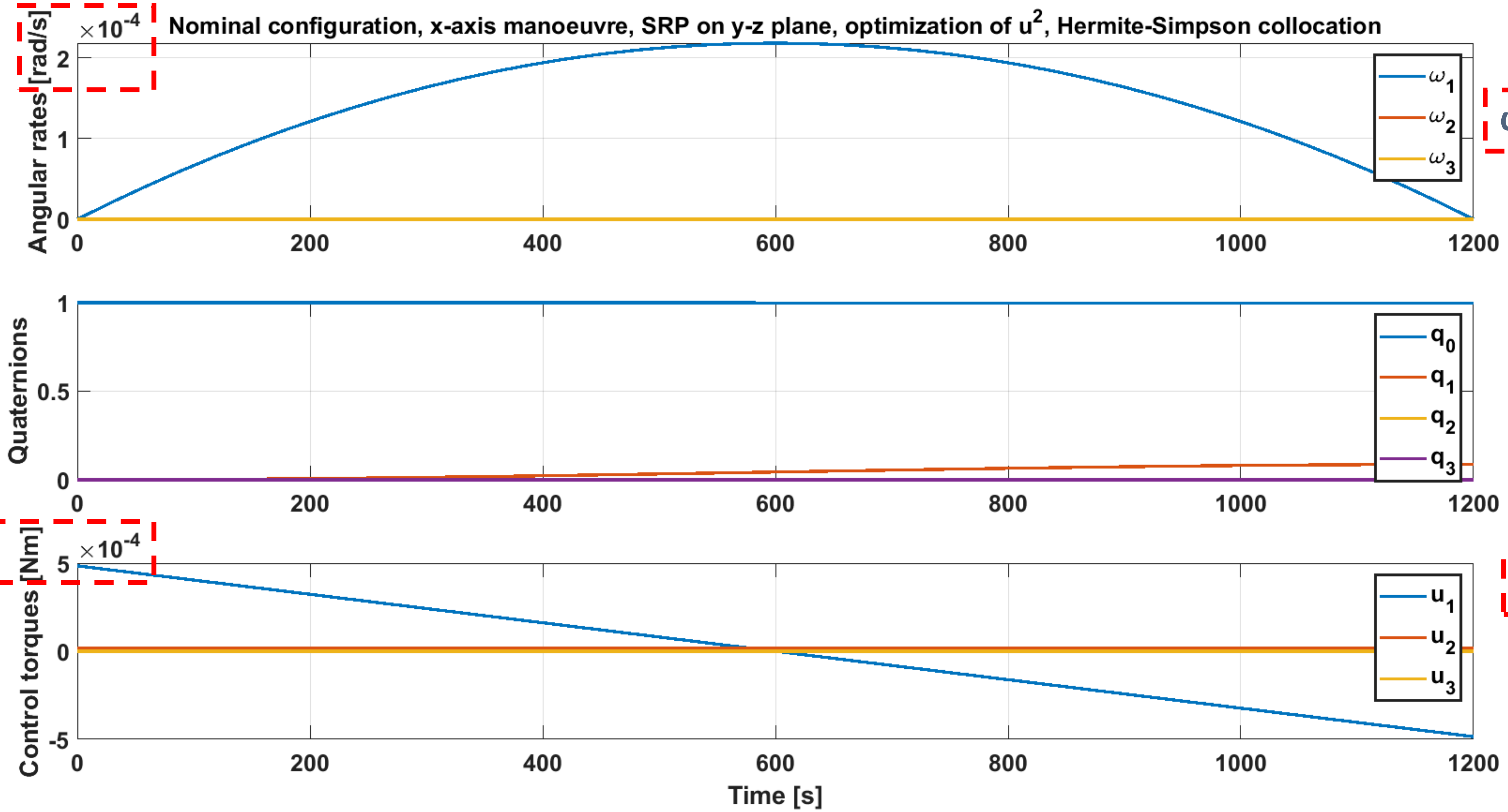
2. Mission Profile

- Mathematical model update to more closely align with a real-world scenario
  - e.g. more accurate representation of solar radiation pressure contribution
- Larger number of parametrization conditions
- Use of indirect optimization methods
- Investigation of unusual behaviours
- Selection and sizing of actuating system
- Pointing stability maintenance over long periods
- We used targets within 20’; 20 min observation; 20 min of movement

2. Mission Profile

No reaction wheels, thrusters enough

γ_T = 1 Nm



ω_{max} = 2.2 · 10^{-4} rad/s

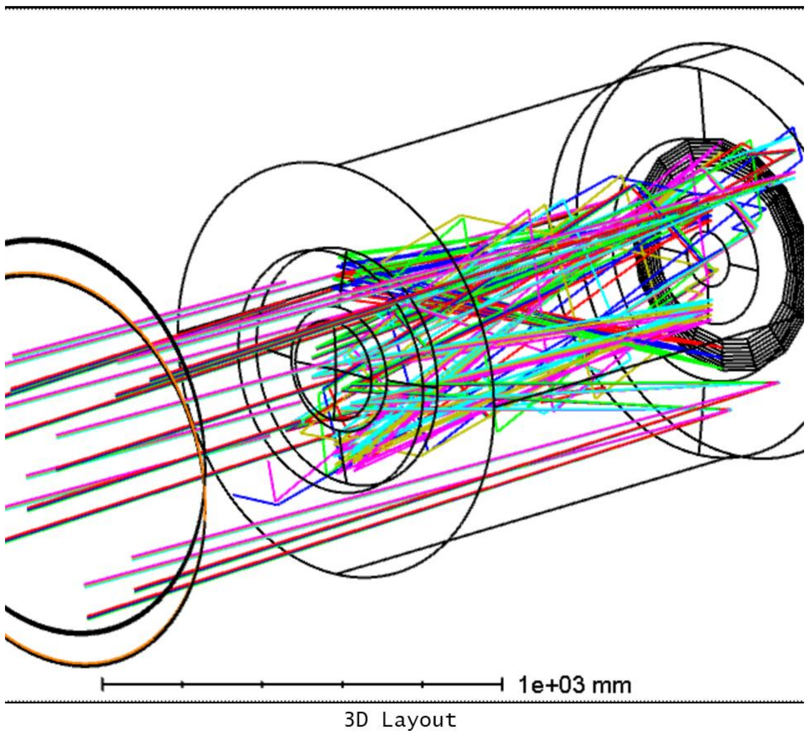
u_{max} = 5 · 10^{-4} Nm

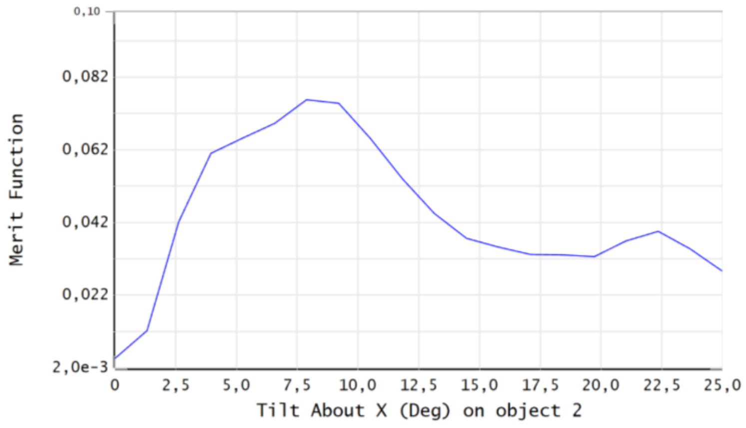
3. Detectors and 4. Thermo-Mechanical analysis

- The proposed detector is only for illustration purposes (i.e. array of 64 4k x 4k)
- A dedicated study has been started in partnership with Arcetri and Bologna INAF Institutes
- STOP (Structural-Thermal-Optical-Performance) analysis
- Laboratory experiments and demostration of the simplified alignment on a scaled (1:8) TMA+FPA System lab prototype.

5. Straylight and baffles

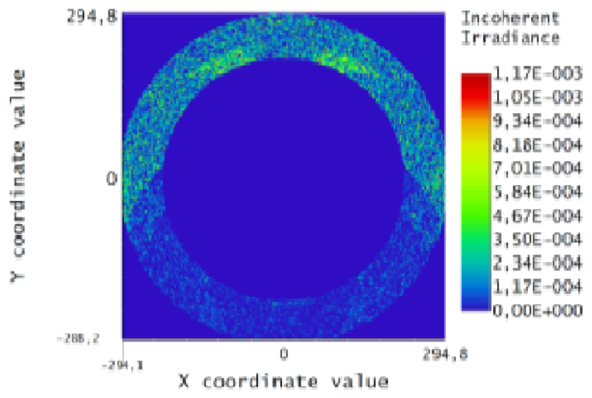
- Dedicated study and collaboration with UniFi expert group





Point Source Transmittance (PST) plot

Irradiance on the focal plane from a 7,5° source (e.g the Moon)



Collaboration

- INAF OATo
- INAF Arcetri
- INAF Bologna
- Laboratory activities at the optics laboratory in Turin, the Space Technologies laboratory in Arcetri and the Cryowaves laboratory in Bologna.
- ……
- We welcome science/technological collaboration

- Politecnico di Torino

Conclusions

- Solid and robust experiment concept
- Good level of study
- Most of the critical issues studied or in progress
- Promising results

Next (parallel) Step

- Evolution of the design for further applications
- Careful focus on following presentation (Gai, M.)