Telescopes with resilient astrometric response

Mario Gai - INAF-OATo

Presentation layout:

➔ General design considerations

➔ Optical configuration galore

Perspective:

- Single line of sight telescopes optimised for local / relative astrometry
- Converted to global / large angle astrometry with e.g. beam combiner

Science applications

- ➔ **Exoplanets**
- ➔ **Astrophysics**
- ➔ **Gravitation / Gravitational Waves**

Rationale of proposed symmetric configurations:

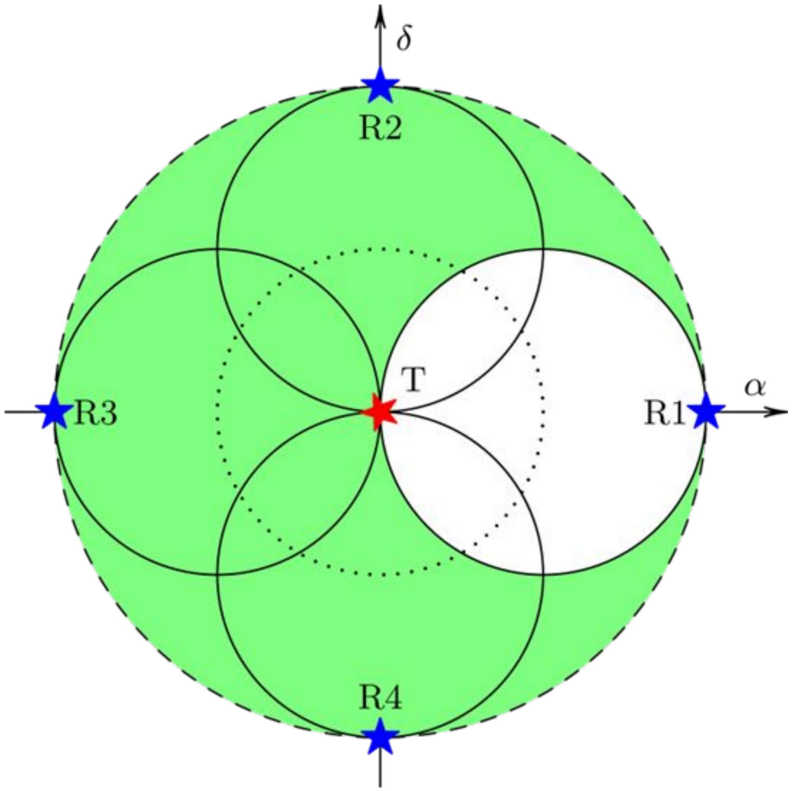
- ★ Allow larger telescopes in given size payload
- ★ Symmetric structure is expected to be more stable
- ★ Symmetric optical response eases calibration
- ★ Compatible with monitoring/metrology systems

Astronomical aside: Cherry-picking reference stars…

Simultaneous observation of all sources over the ring

Sky region accessible: whole circle with radius equal to the ring diameter around selected target, by proper pointing (offset + roll)

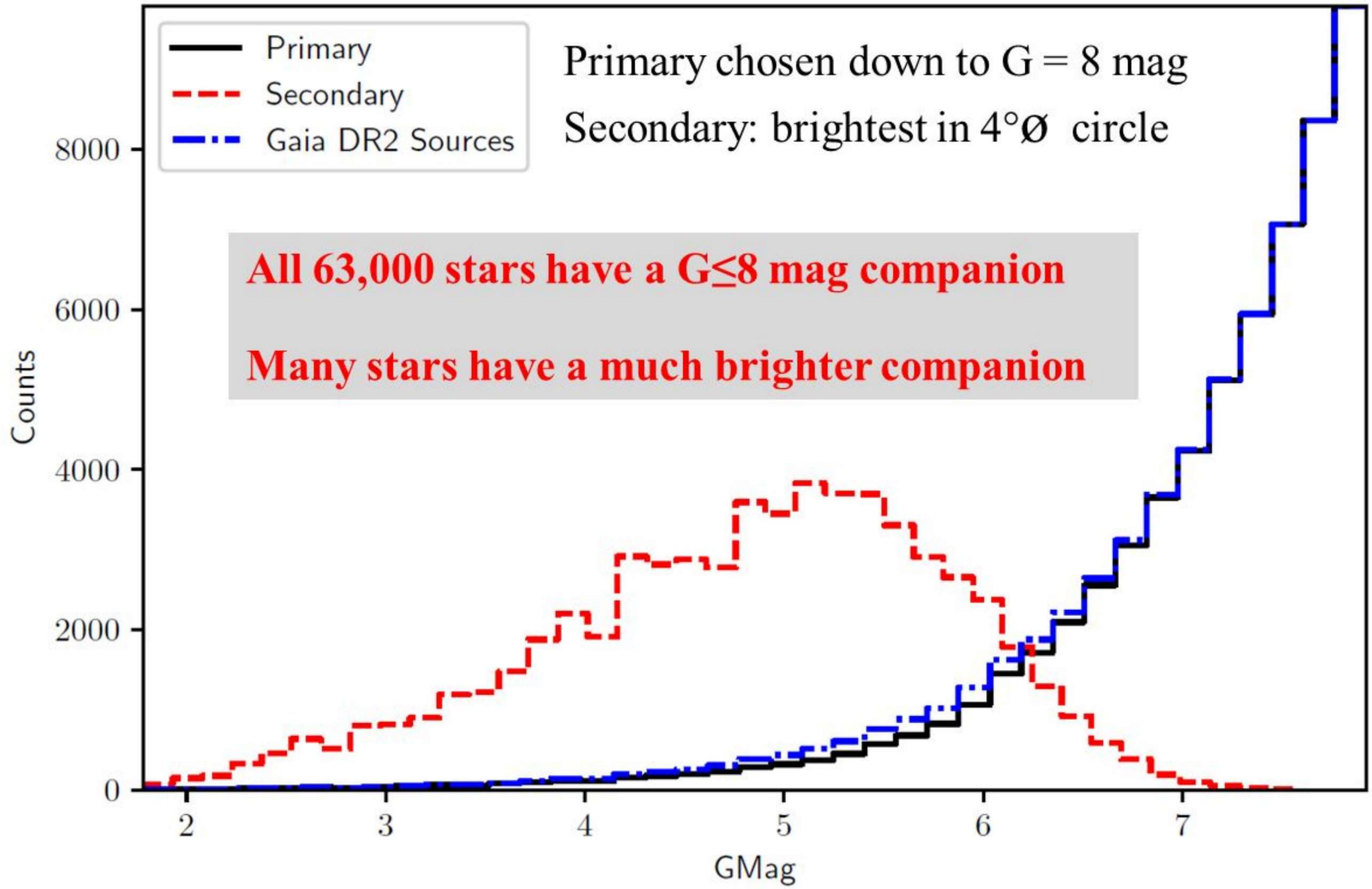
Natural variable separation, switching from rectangular (x, y) to “annular” radial and azimuthal coordinates



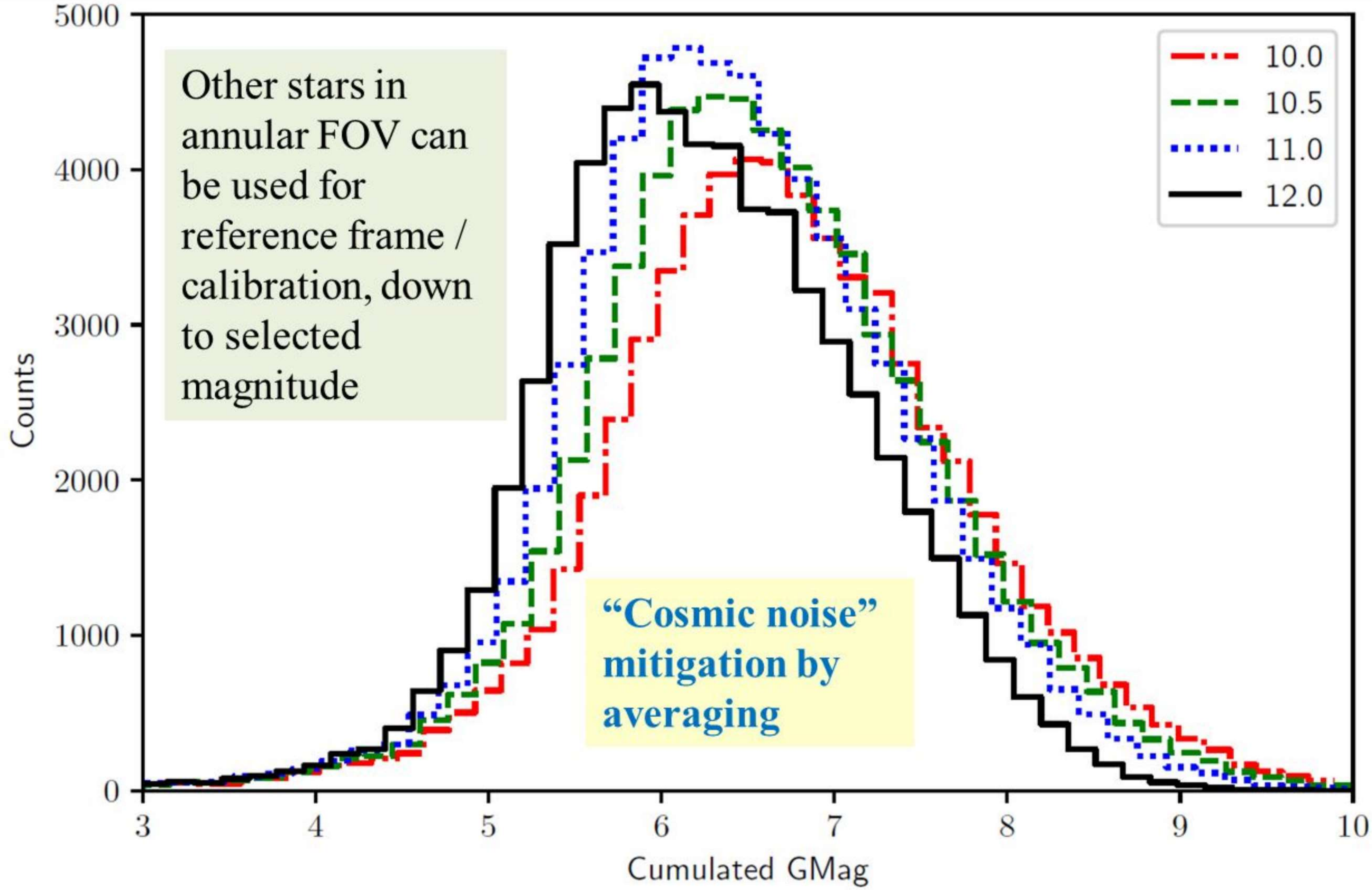
Ring FOV reaches much larger angular separation than compact FOV, using the same number of detectors

Instantaneous FOV:	0.25 square deg
Accessible FOV around target:	~12 sq. deg.

Starcounts from Gaia DR3 - I



Starcounts from Gaia DR3 - II



Separation uncertainty dominated by fainter source

$$\sigma^2(x_1 - x_2) = \sigma_1^2 + \sigma_2^2 \cong \frac{1}{SNR(1)} + \frac{1}{SNR(2)}$$

Secondary brighter than primary by 2 mag ⟹

- **6× faster measurement**
- **6× larger target sample**

Asset of annular field configuration!

Main characteristics of proposed configurations

★ Circular symmetry enforced in the design

★ Good imaging AND astrometric performance

★ Large field of view, e.g. FOV = 0.1 to 0.5 square deg

★ Aperture diameter D = 1 m to 2 m

★ Focal length F = 15 m to 30 m

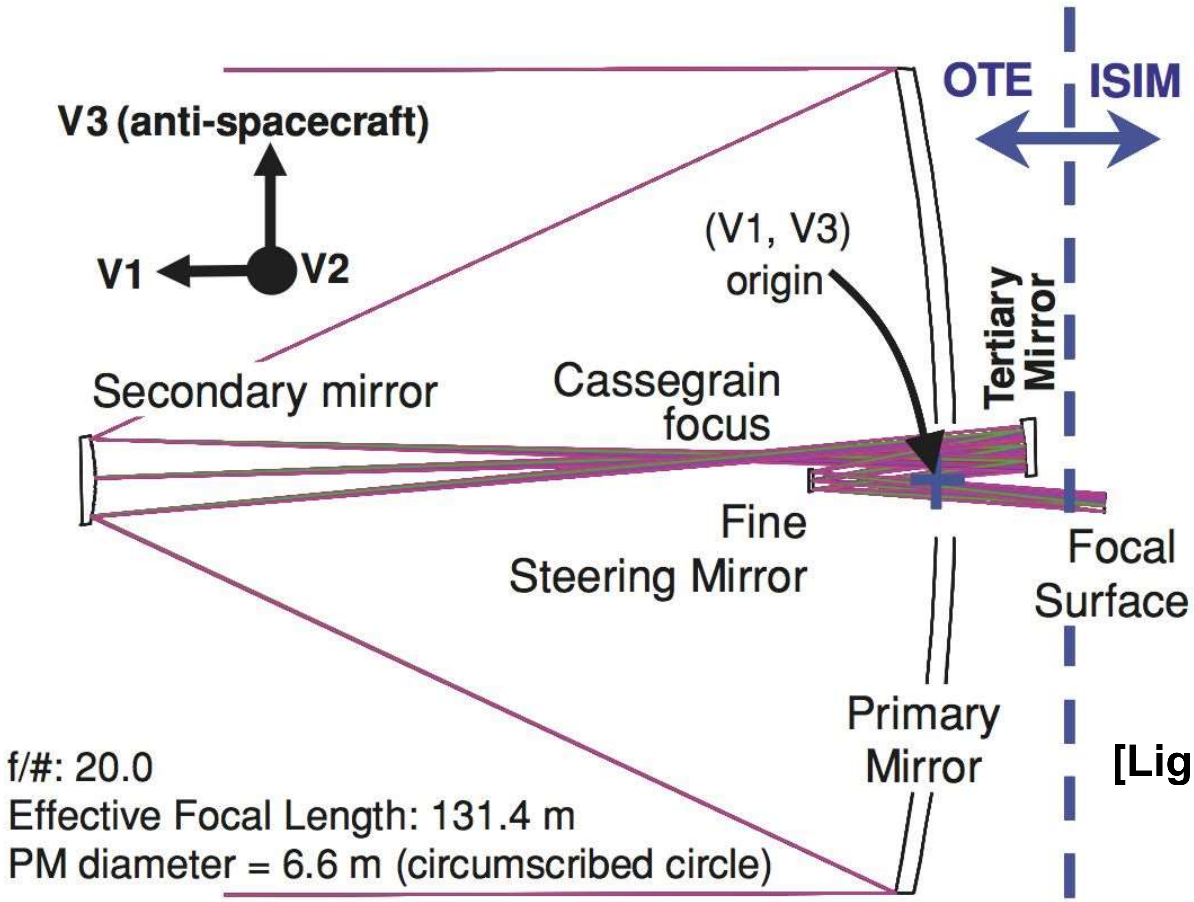
★ Annular or central field

Three-Mirror Anastigmat (TMA) as common design choice

Pro: large corrected field

Con: challenging alignment

Often asymmetric design: off-axis and/or decentered

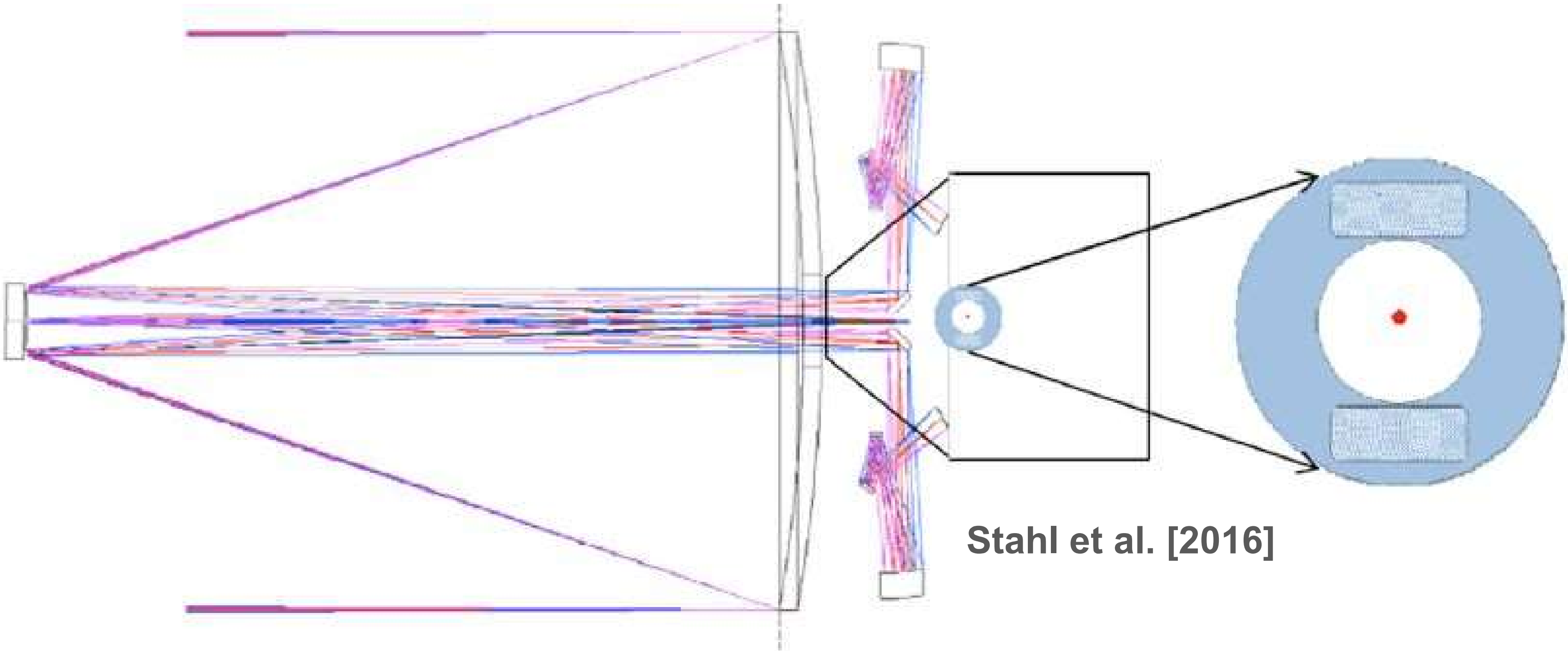


Example: JWST

[Lightsey et al., 2012]

On-axis TMA NASA version: 8 m ATLAST telescope

- Symmetric off-axis fields around on-axis field
- Different focal length for central (Cassegrain) and external (Korsch) fields
- Separate optical trains for side fields



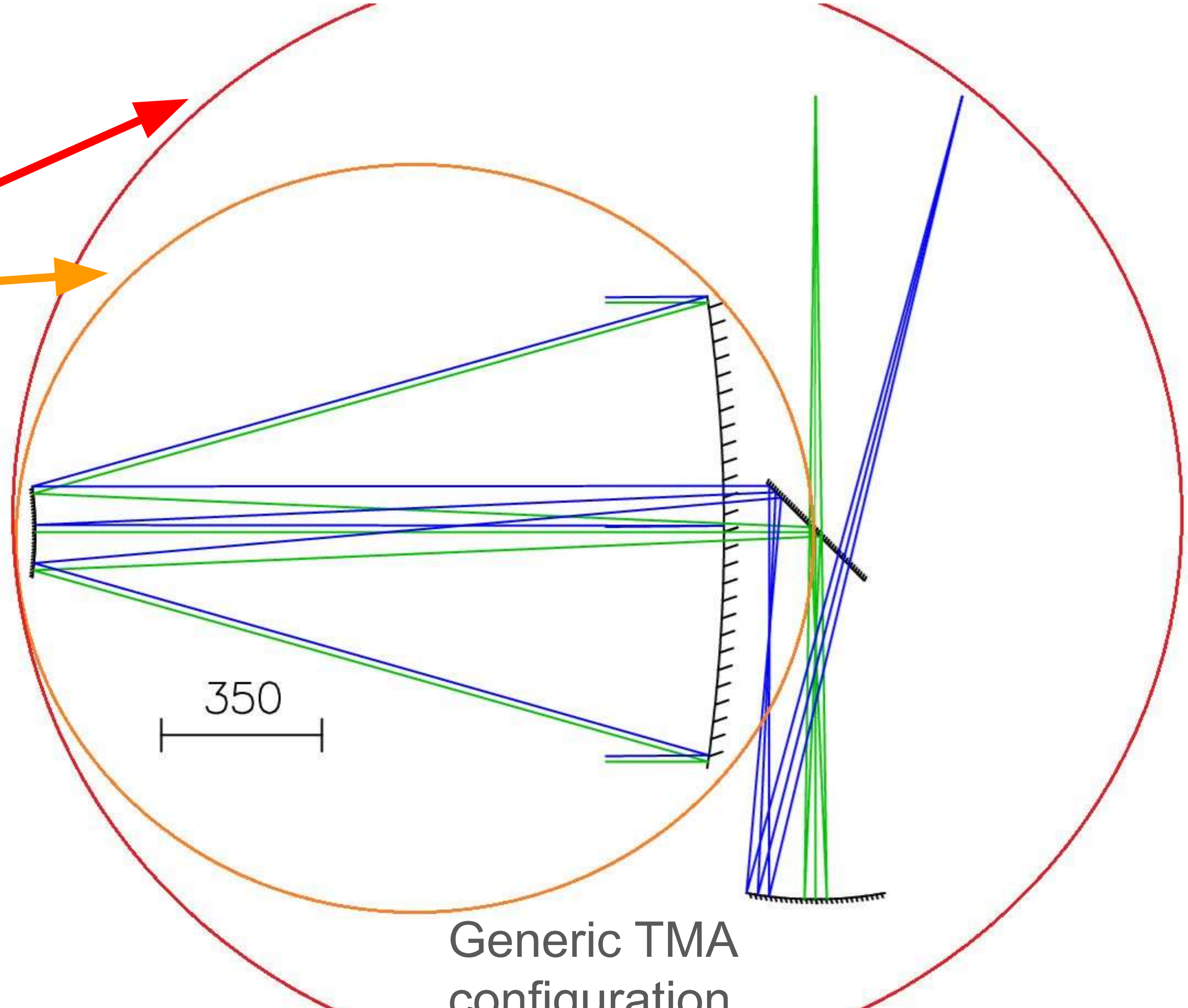
Stahl et al. [2016]

Fig. 9 Optical layout of ATLAST-8 OTA showing 2 off-axis WFOV TMA foci and on-axis narrow FOV Cassegrain focus (at red dot).

TMA implications: volume / structure

Our goal is to squeeze a larger telescope into a smaller volume

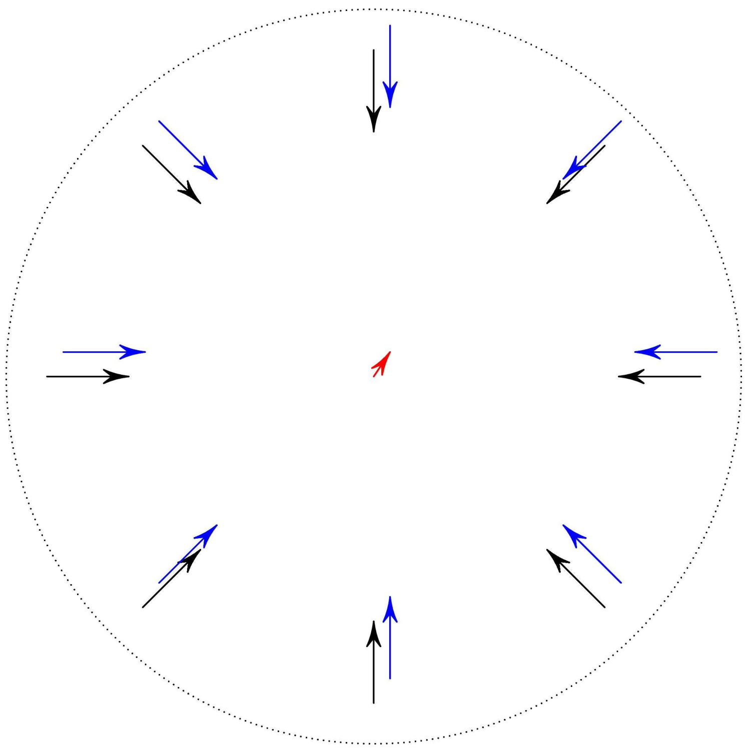
- Larger telescope may fit into given payload envelope
- More compact structure may be more stable

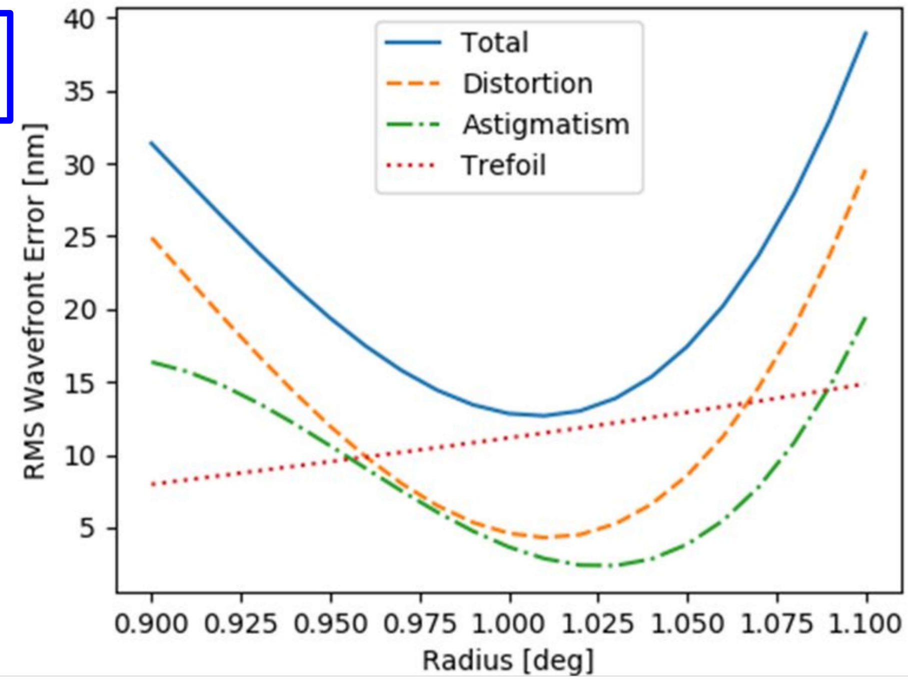


Generic TMA configuration

Aberrations usually depend on powers of field radius

Goal: symmetry



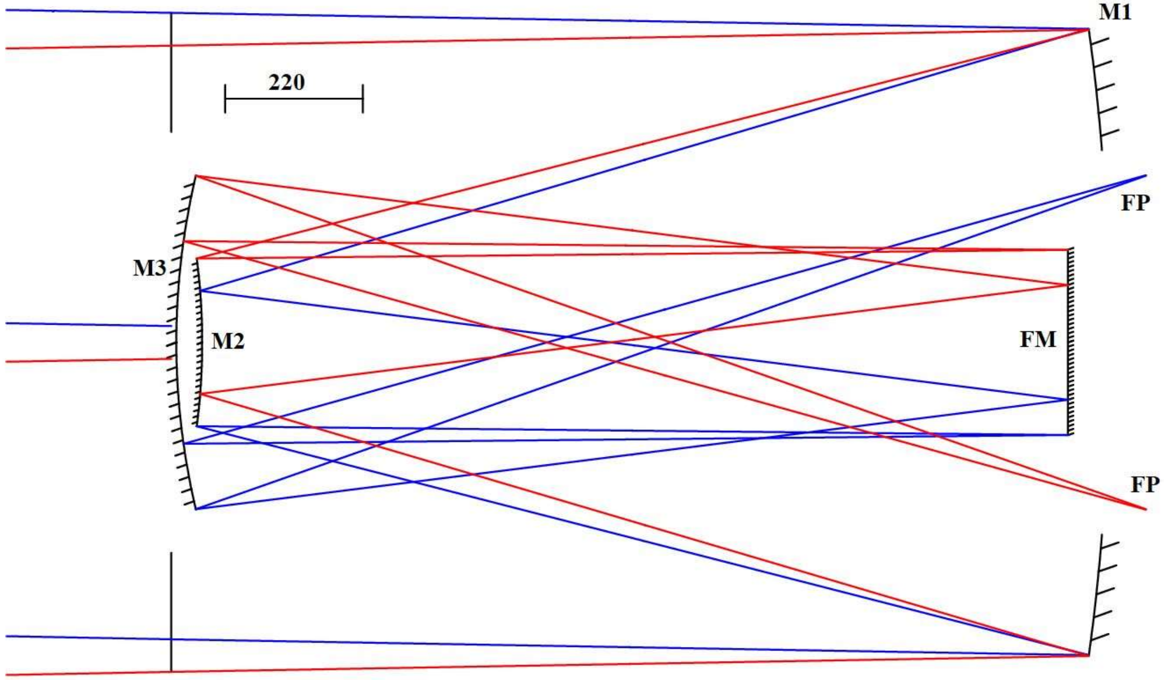


RAFTER [Riva et al., 2020]

Aberration balancing at selected ~1˚ radius

Small perturbations result in a displacement of optical axis (tilt) + higher order terms affecting PSF shape & astrometric response

Reference: RAFTER telescope, D = 1 m, EFL = 15 m

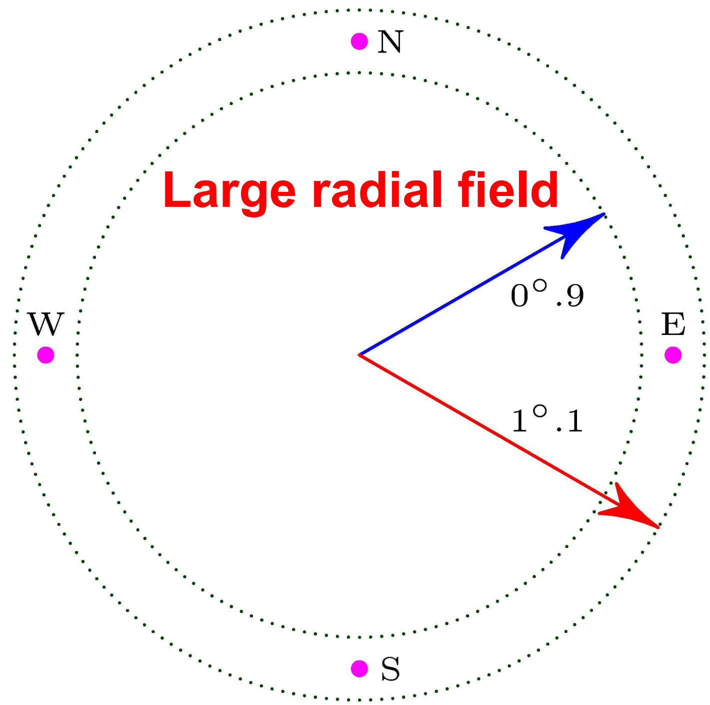


RAFTER, Riva et al. [2020]

Busonero, this workshop

Compatible with 4-5 μm pixel CMOS detectors

Envelope: <2 m



PSF symmetric (zero skewness) vs. any radial axis (i.e. along ring)

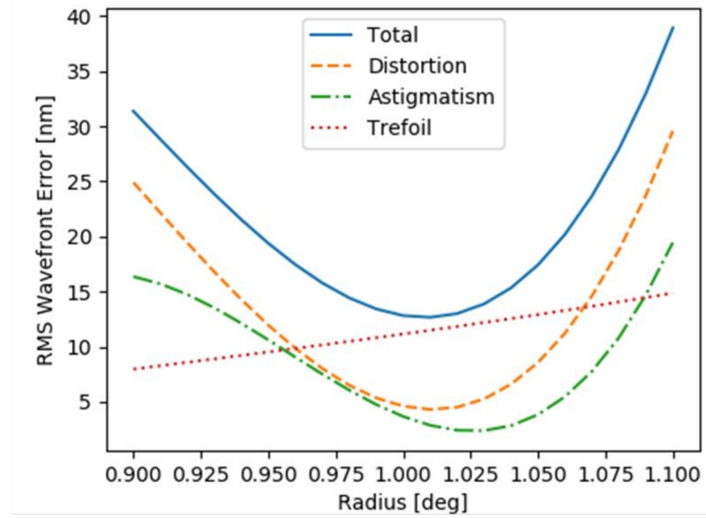
Design & analysis:
Zemax OpticStudio

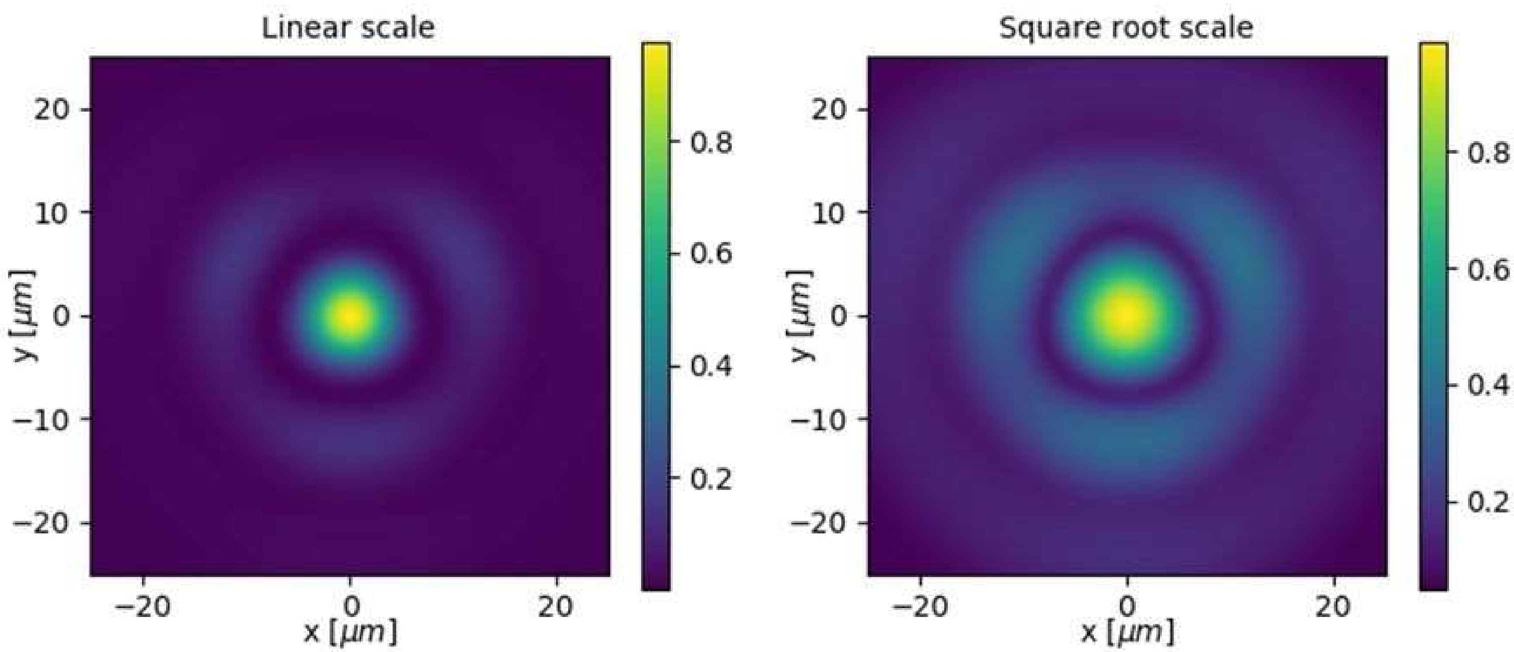
Imaging quality as a function of the field radius

Diffraction limited imaging over whole annulus $0°.9 \leq \varrho \leq 1°.1$

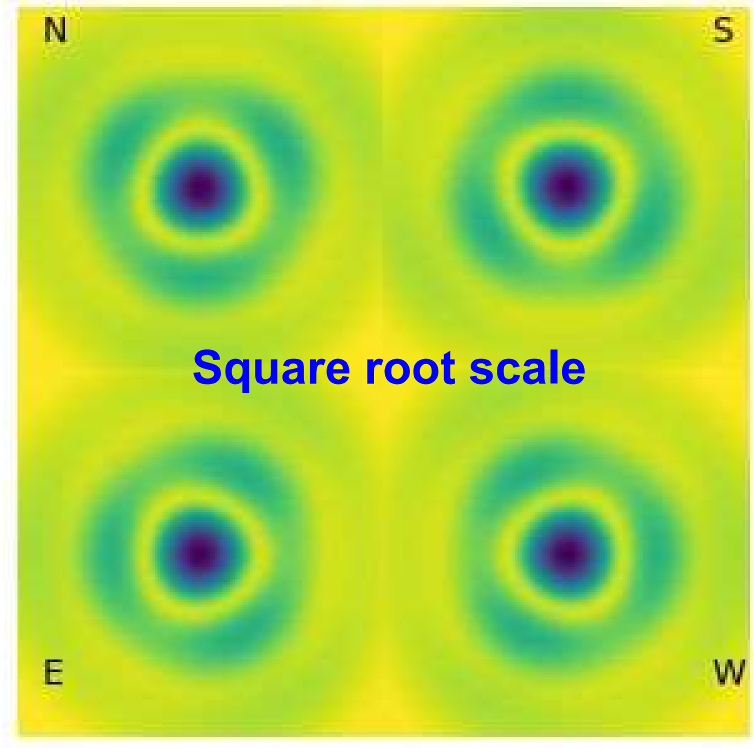
RMS WFE ≤ 39 nm @ l=550 nm, i.e. <λ/14 (0.071 waves)

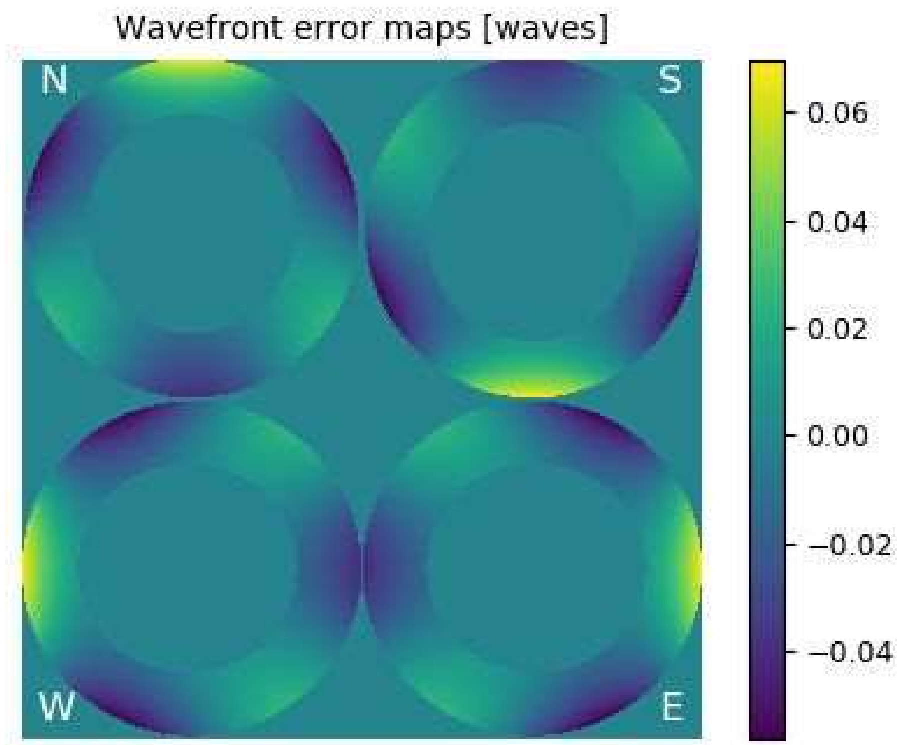
Corrected field >1.256 square degrees





PSF symmetry preserved by rotation around field centre

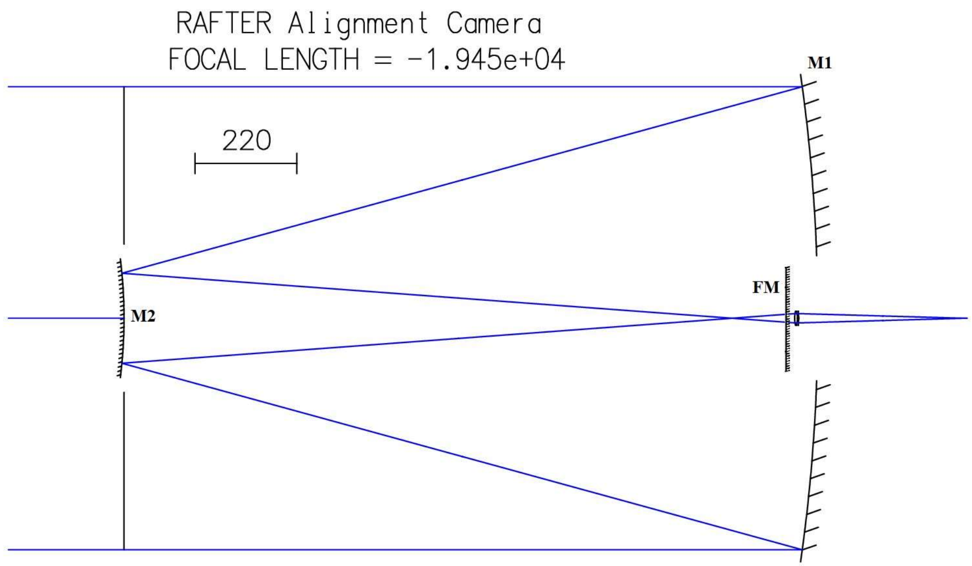




Simple PSF model with small variation in radial direction only

Dominant visual effect: trefoil (radial)

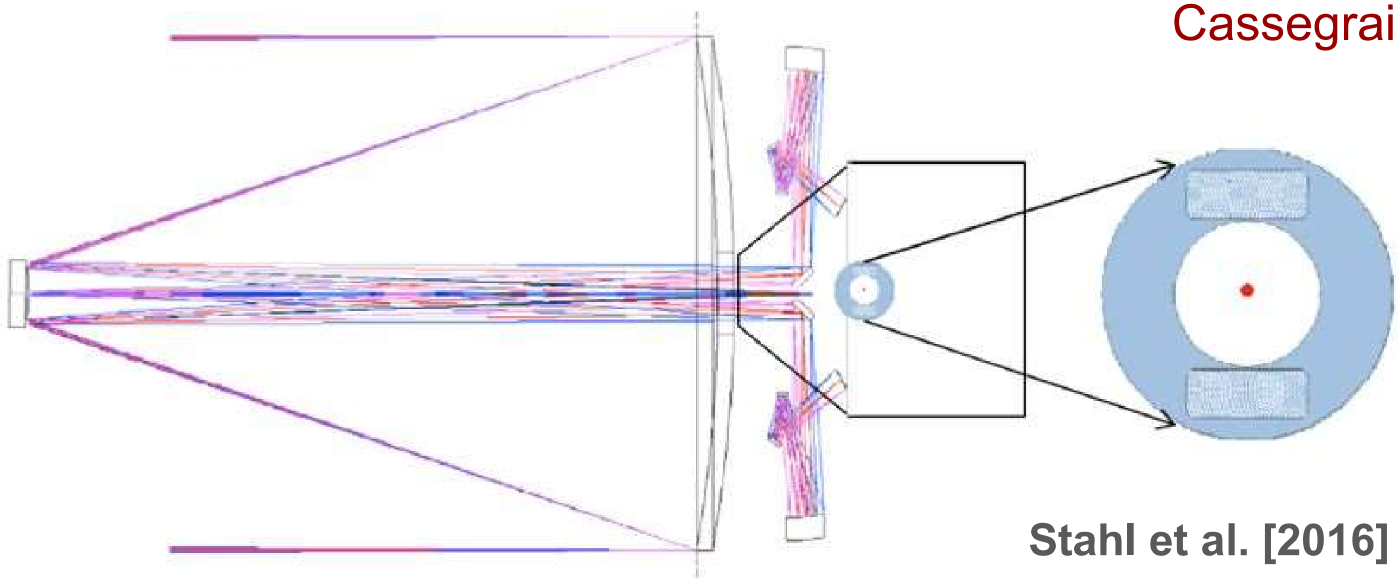
Simplified alignment of M1-M2 section: two-mirror telescope



(M2, M3) and (M1, FM) are assumed to be internally rigid sub-assemblies:

alignment of M2 to M1 implicitly aligns the whole telescope

Simple on-axis alignment and monitoring camera on Cassegrain focus



NASA version: 8 m ATLAST telescope

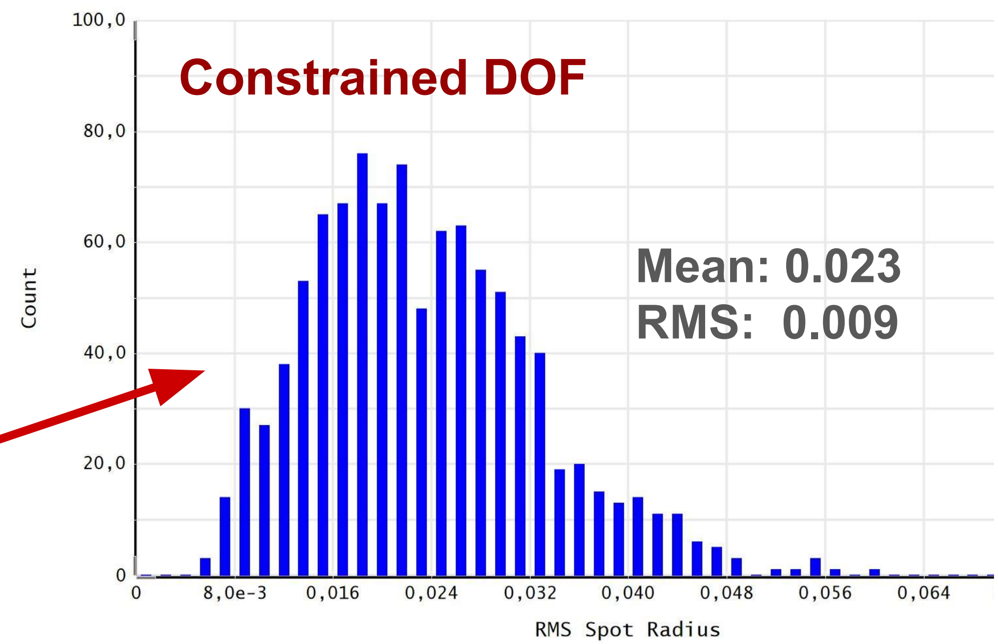
Stahl et al. [2016]

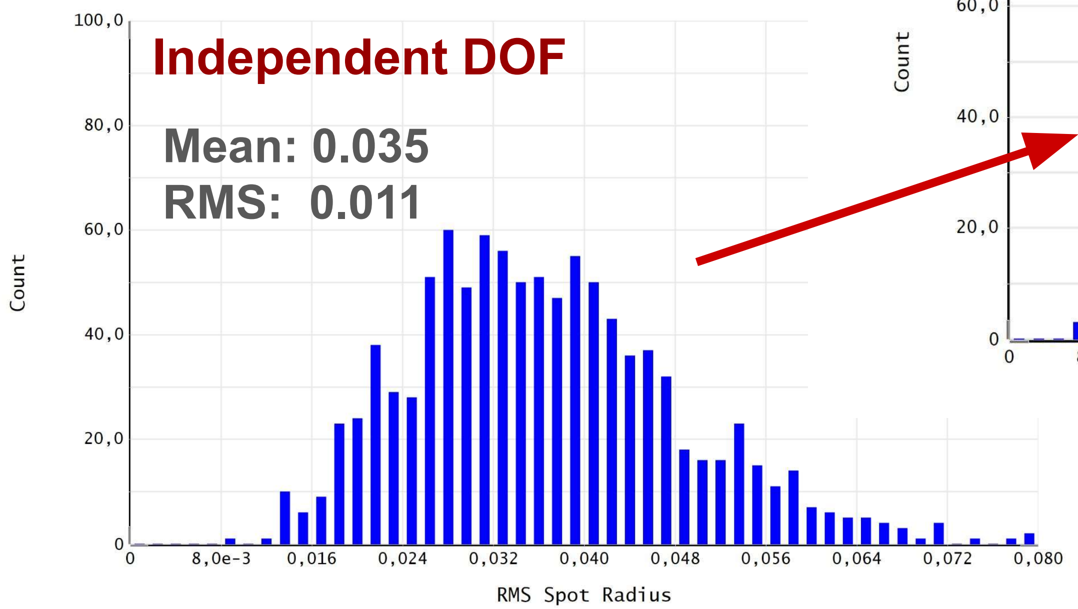
Fig. 9 Optical layout of ATLAST-8 OTA showing 2 off-axis WFOV TMA foci and on-axis narrow FOV Cassegrain focus (at red dot).

Mechanical perturbations: Montecarlo inverse sensitivity

(M2, M3) and (M1, FM) are assumed to be internally rigid sub-assemblies:

reduced number of degrees of freedom result in smaller overall degradation





[Fornasiero et al., 2024]

Histogram	
Rafter 19/12/2023 Using system tolerance data. Operand: RMS Spot Radius Field 0 Config 0 Underflow count: 0 Overflow count: 3	Zemax Ansys Zemax OpticStudio 2022 R2.02 Rafter 1.0.0._full.zmx Configuration 1 of 1

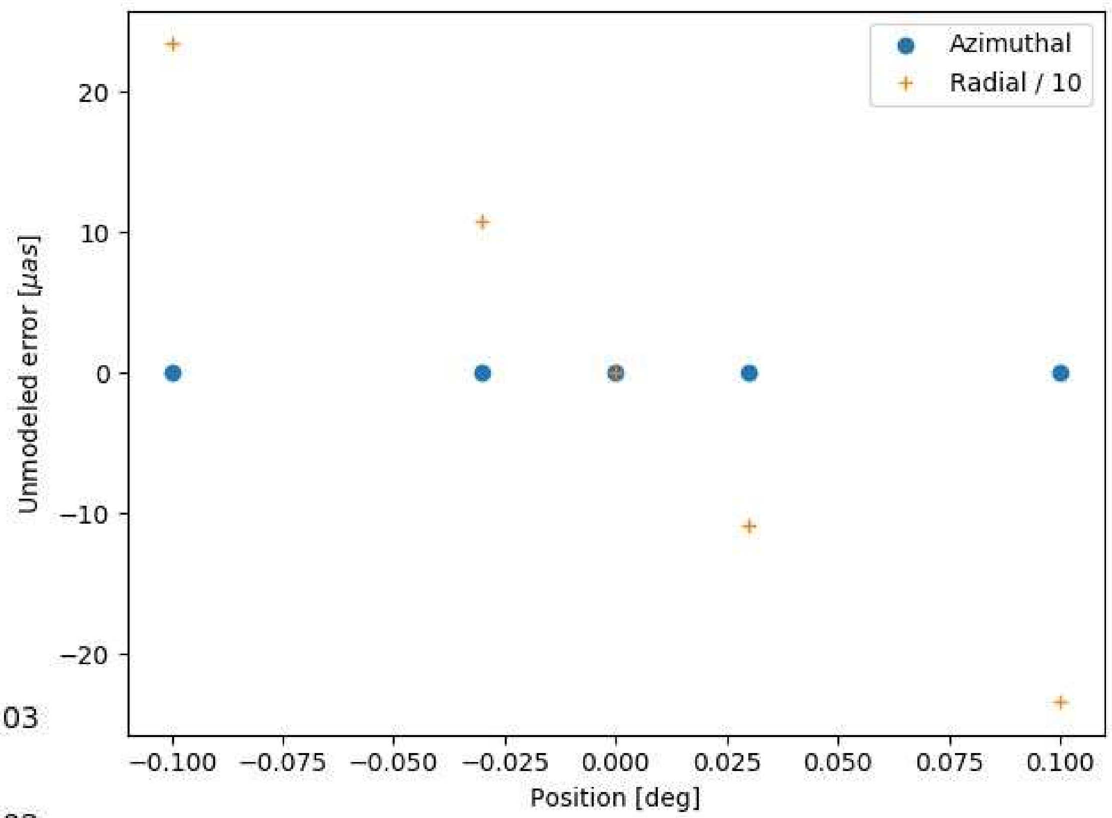
Location error induced by PSF variation

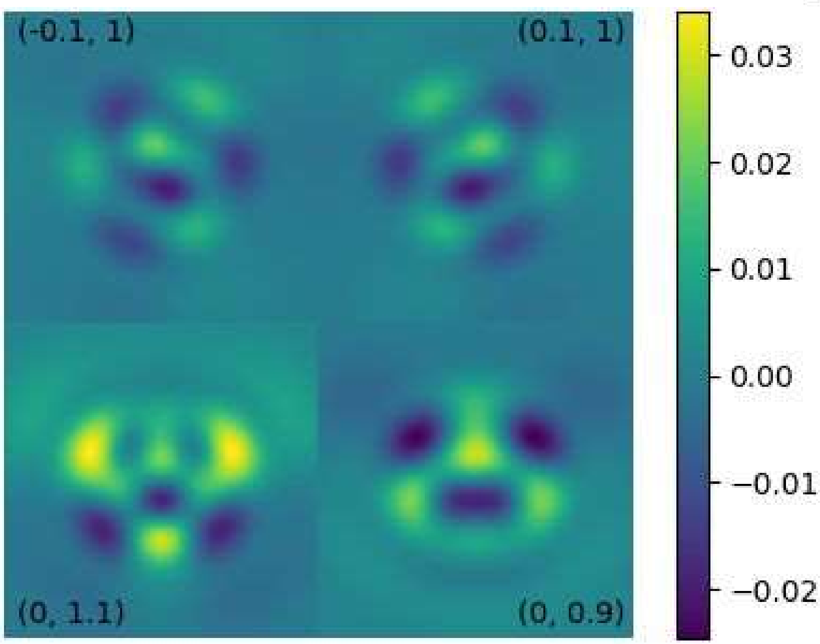
Nominal configuration

Reference: central PSF

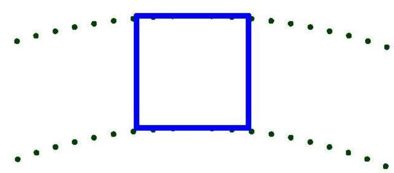
Radial error removed by calibration

Negligible in azimuthal direction (along ring)





Rationale: small (radial) PSF variation over ($0^{\circ}.2 \times 0^{\circ}.2$) section of the focal plane

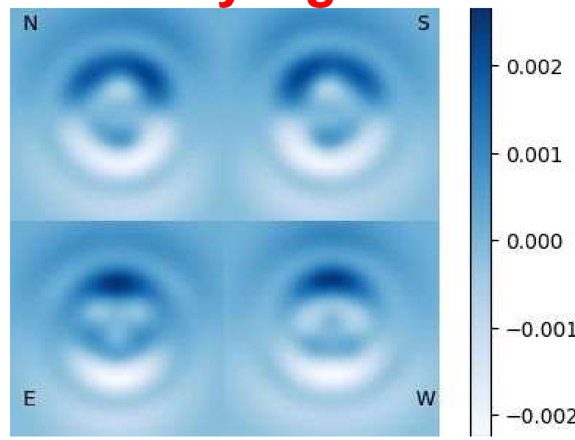


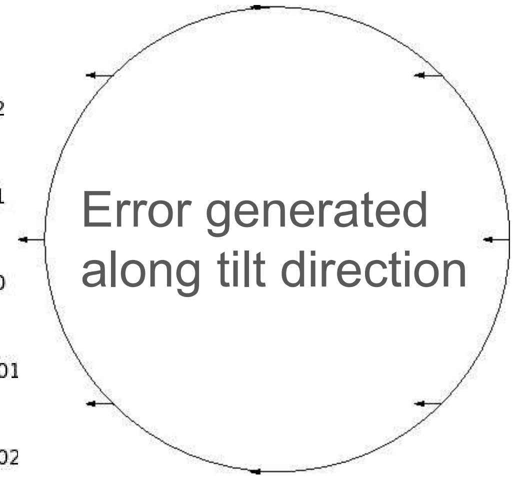
Location error induced by e.g. M1 tilt

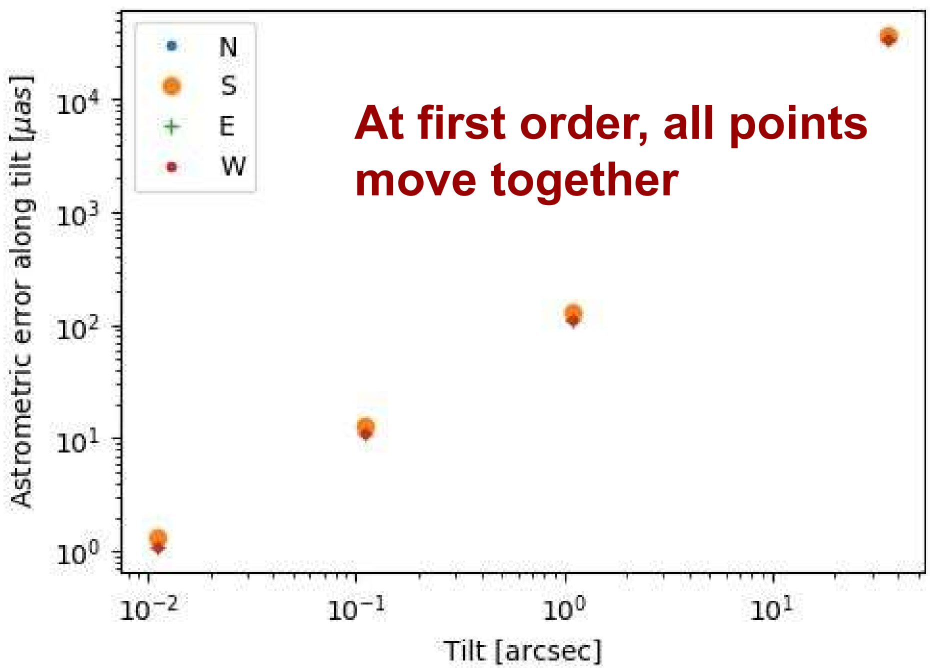
Uniform over the ring

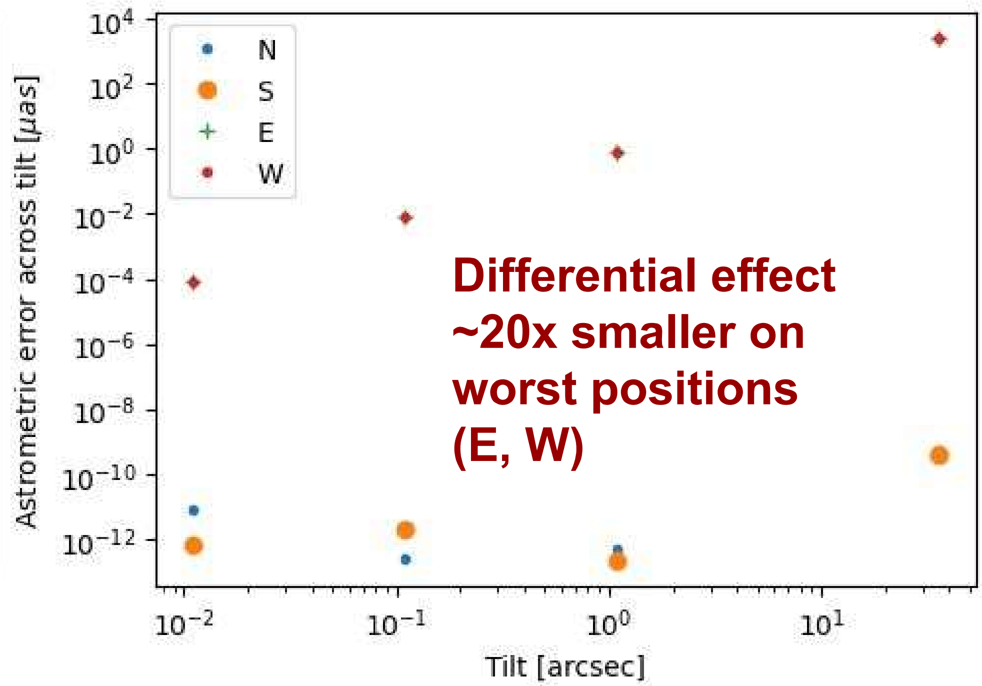
Common mode reduced by a factor ~5,000

Can be calibrated and removed







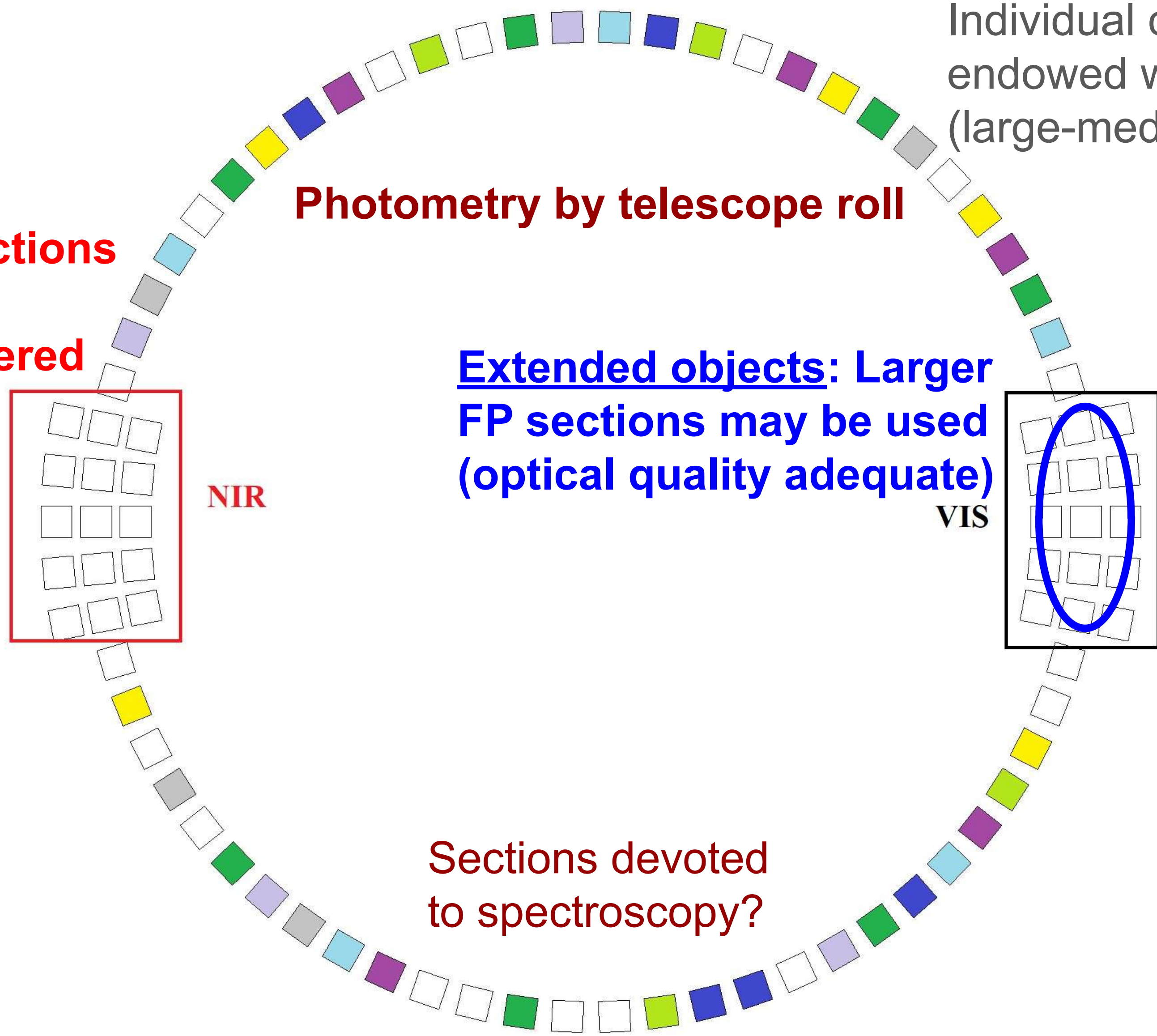


Annular focal plane optimization options

Individual chips may be endowed with color filters (large-medium band)

Photometry by telescope roll

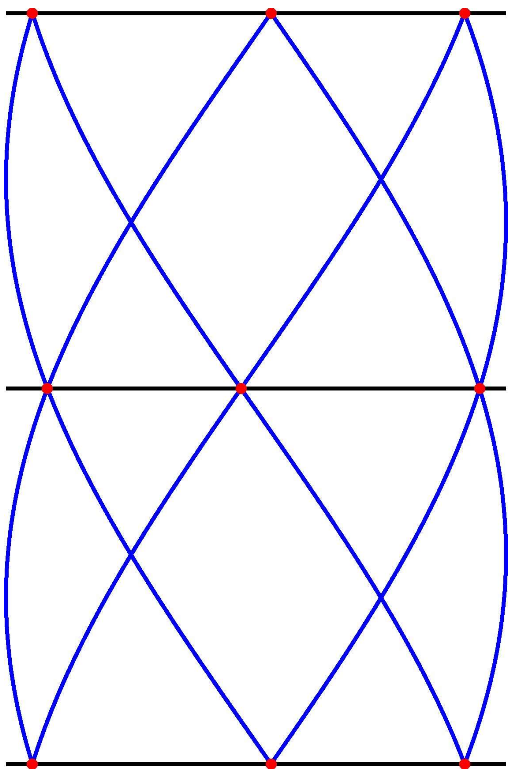
NIR sections may be considered



<u>Extended objects</u>: Larger FP sections may be used (optical quality adequate)

Sections devoted to spectroscopy?

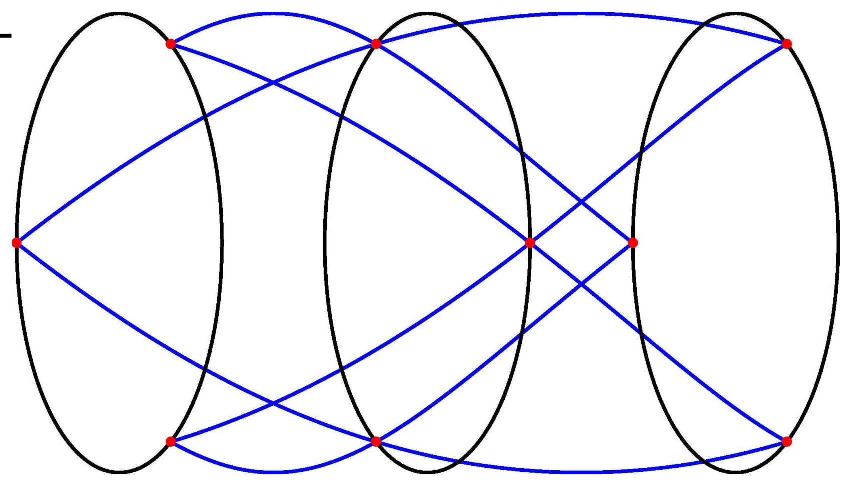
A possible support structure: circular truss



Internal beam path free

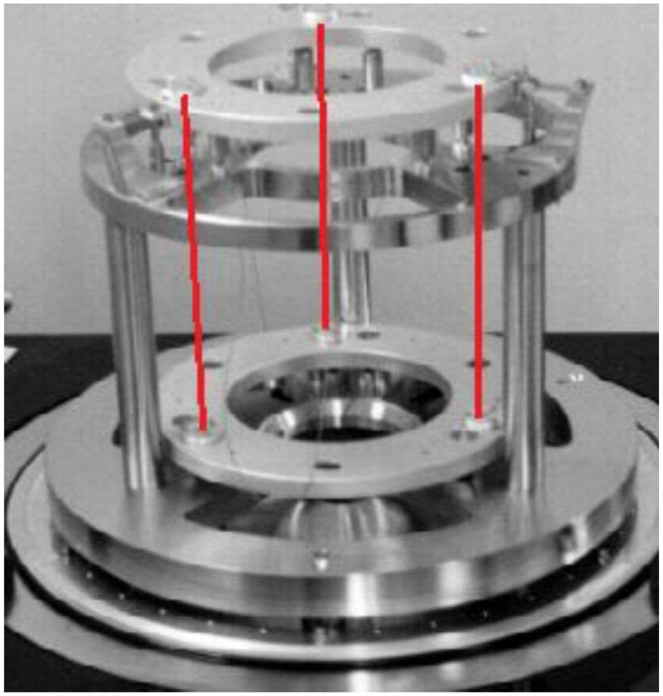
External baffling simple

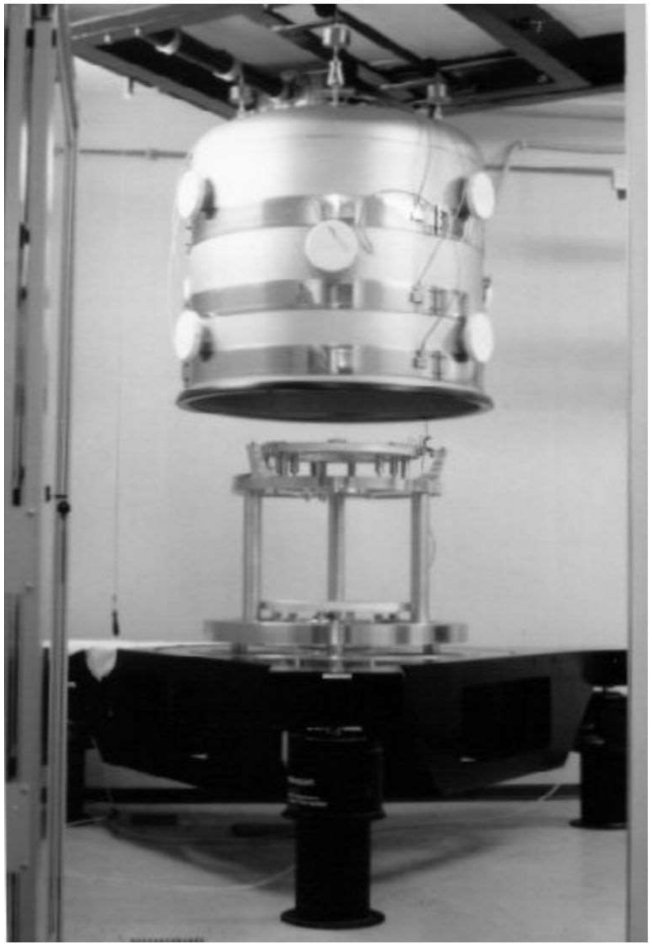
Compatible with hexapod (Stewart platform) 6 DOF actuator



1999 Active Control & Metrology experiment for Gaia

COSI Testbed: stabilized Nd:Yag laser, 3 Fabry-Pérot cavities between two plates, faced at 0.5 m, in vacuo





Bisi et al. [1999]

Test purpose: detect and stabilize distance variations between reference markers on the plates

Test results: distance stabilization < 3 pm over 10 min periods

Ranging over optical designs…

Aperture diameter: D = 1 m to 2 m

Effective focal length: EFL = 15 m to 30 m

D=1 m, EFL=15 m ⇒ 4 μm CMOS pixels

D=1 m, EFL=30 m ⇒ 10 μm CCD pixels

D=2 m, EFL=30 m ⇒ 4 μm CMOS pixels

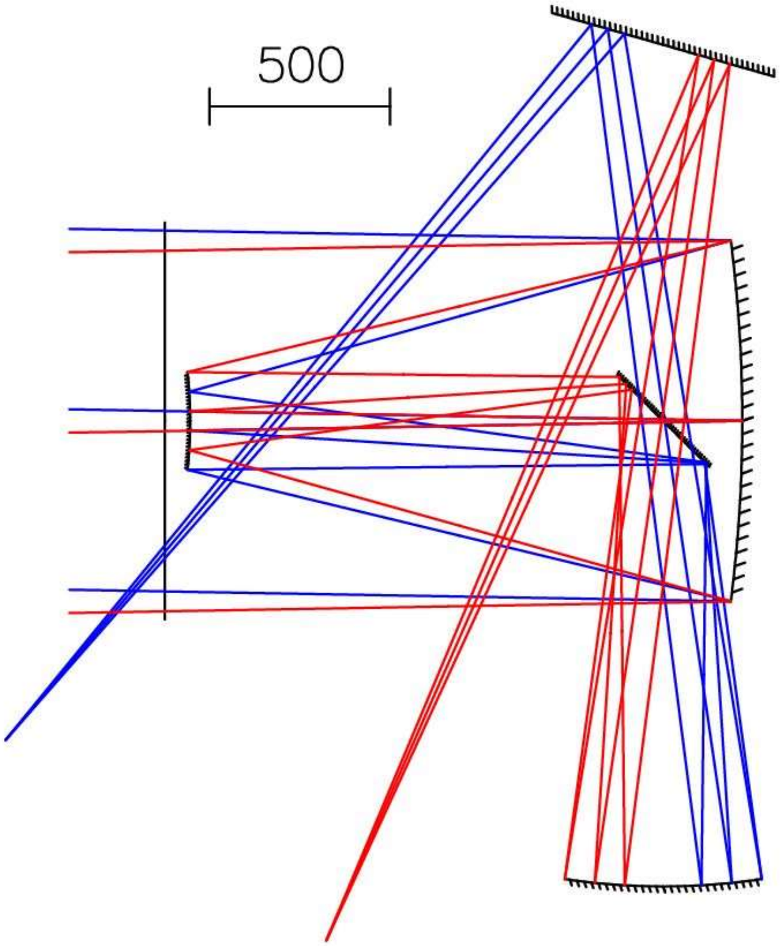
Designs mostly based on conic surfaces

Curved focal planes

Significant central obscuration

Design & analysis: OSLO EDU
(limited performance)

Longer focal length design (1): D = 1 m, F = 30 m

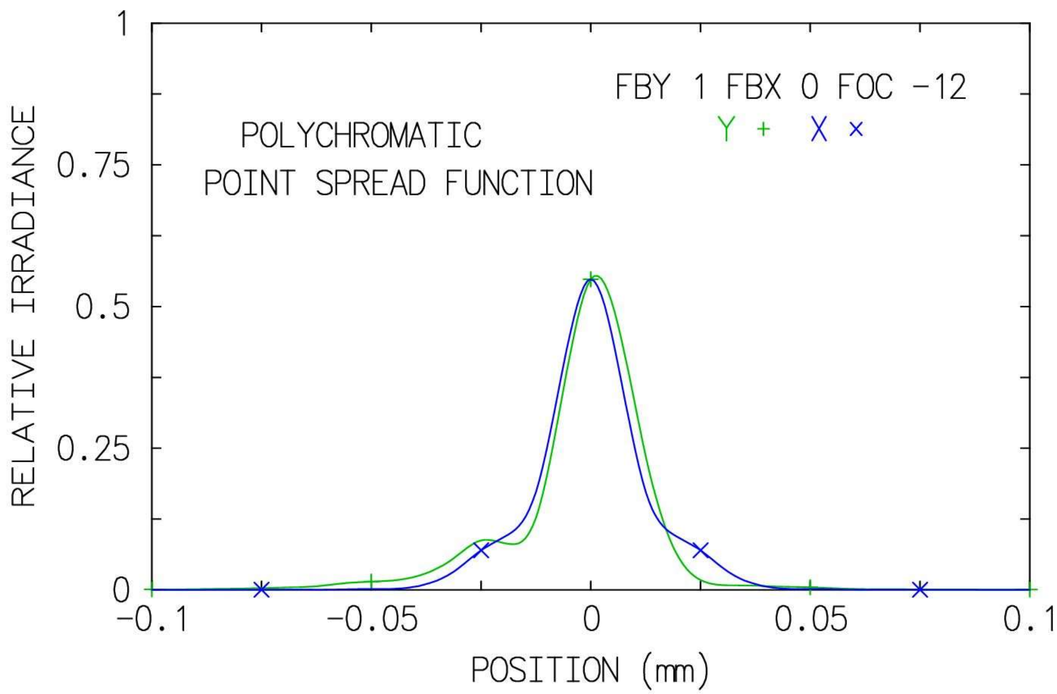


Lost full on-axis layout

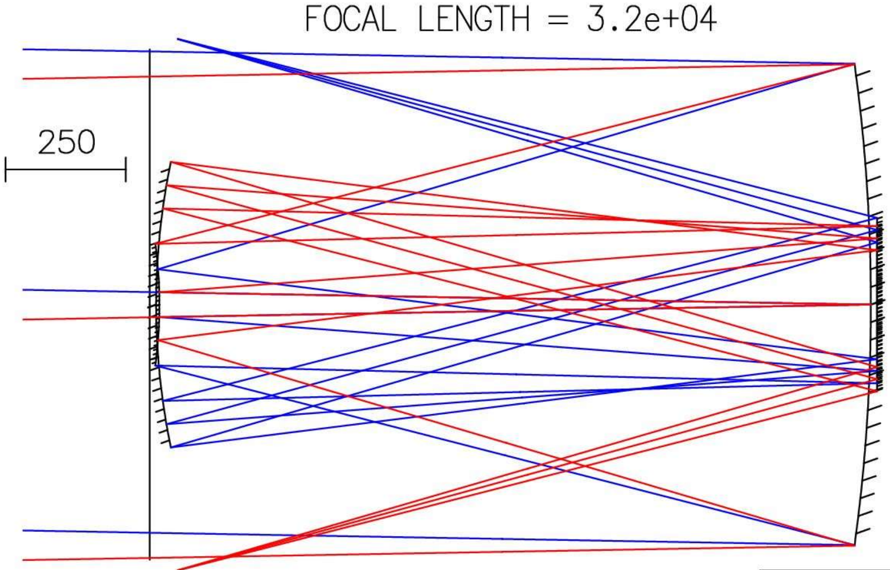
Compatible with 10 μm pixel CCDs

Conic surfaces

Envelope: ~3.2 m



Longer focal length design (2): D = 1 m, F = 32 m

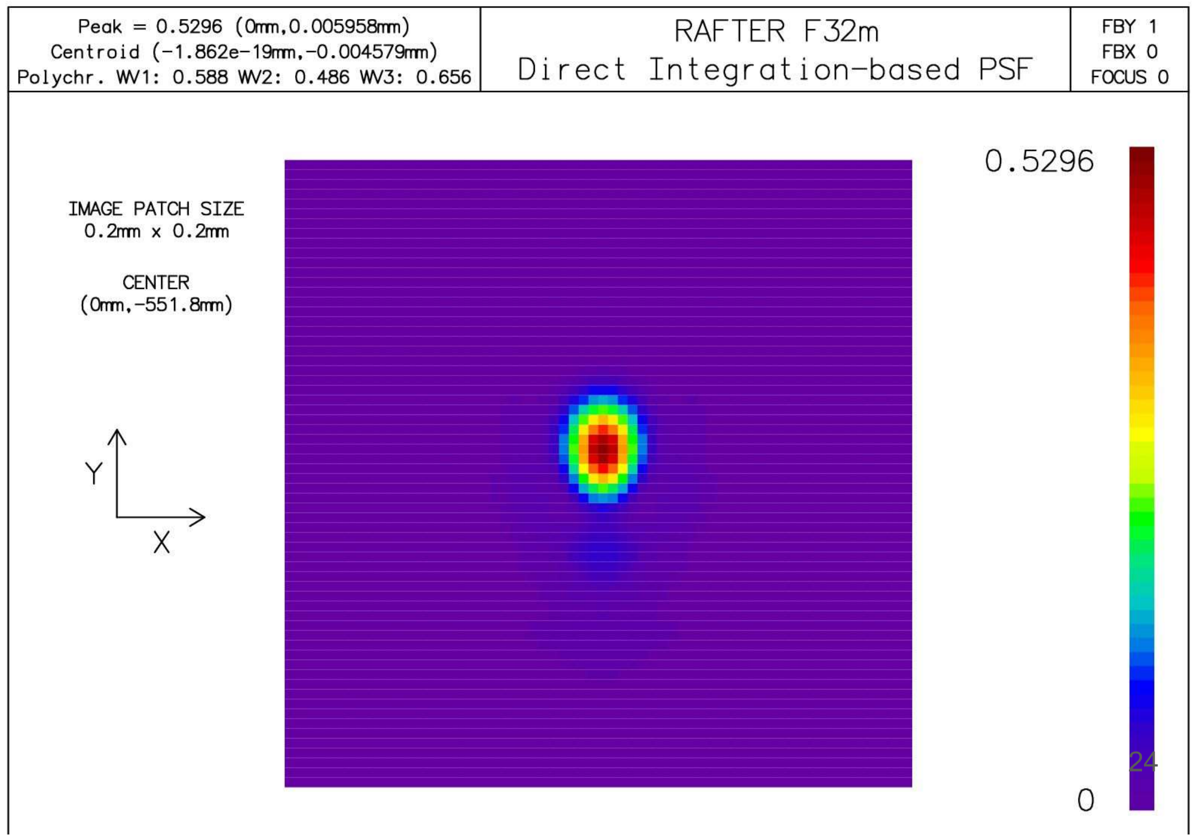


Preserved full on-axis layout

Required IV order aspheric term

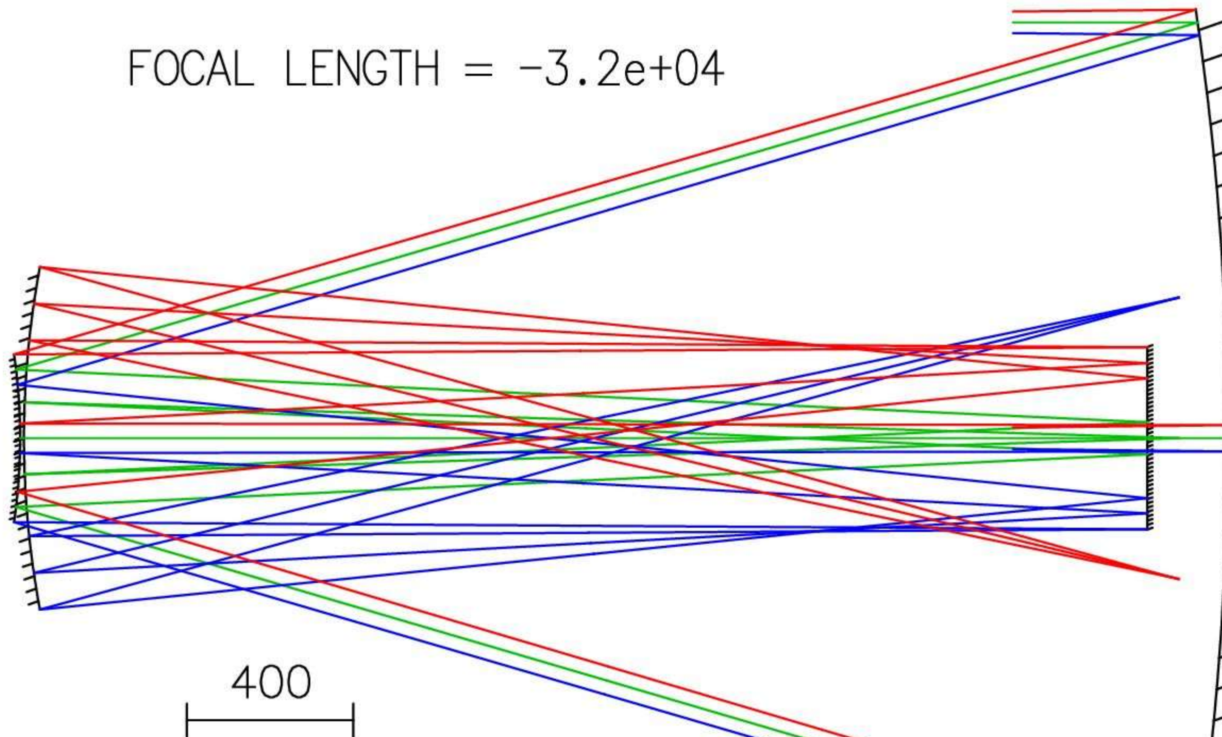
Compatible with 10 μm pixel CCDs

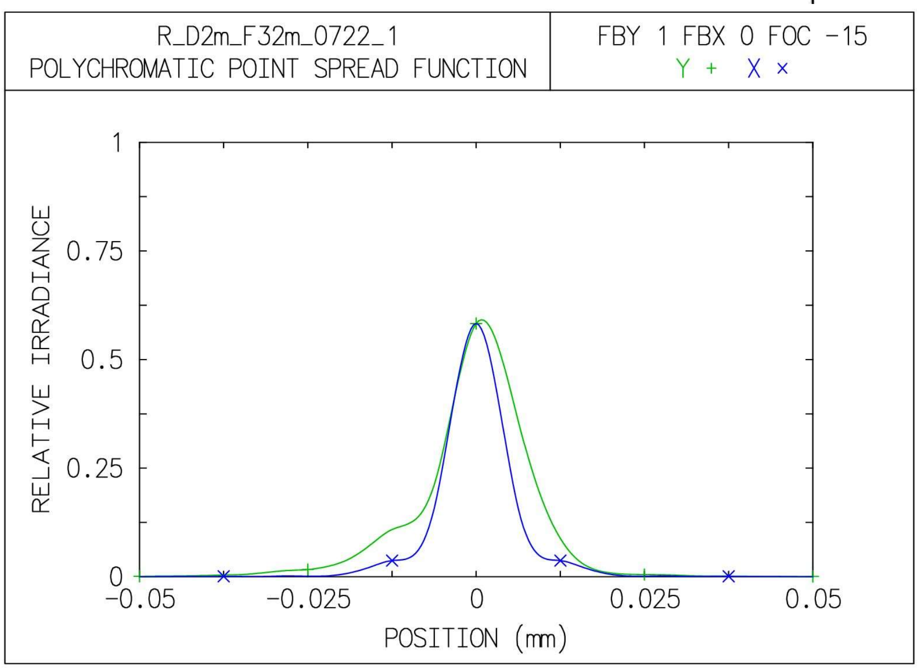
Envelope: <3 m



Larger aperture design:
D = 2 m, F = 32 m

- ❑ Retained full on-axis layout
- ❑ Compatible with 4 μm pixel CMOS
- ❑ Conic surfaces

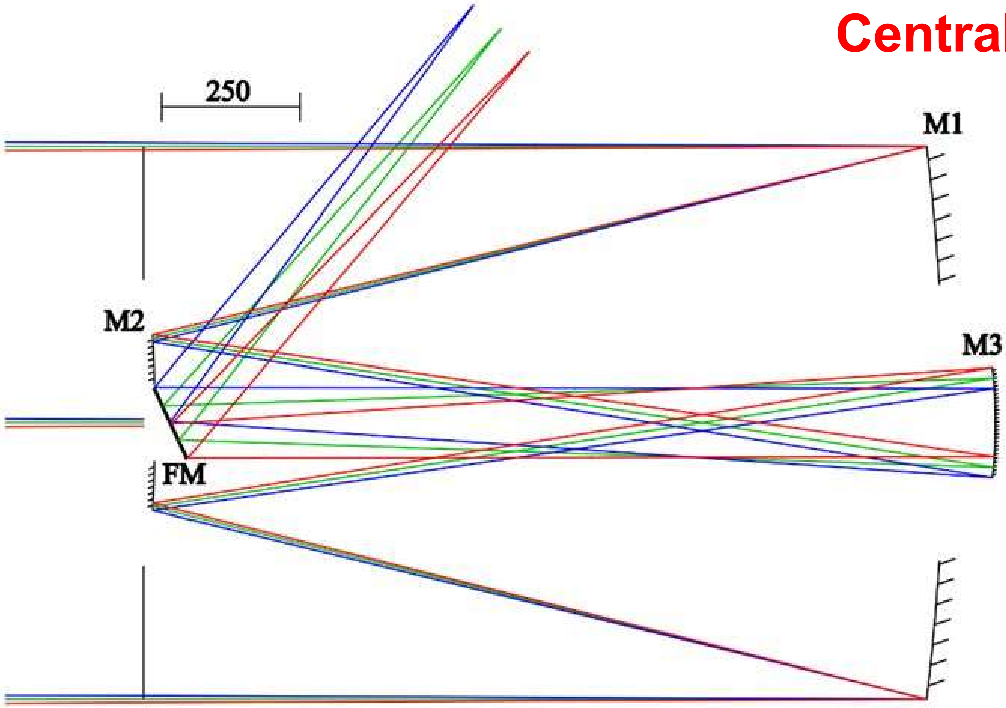




Field radius: 0˚.5

Envelope: ~3.6 m

Central Field TMA: D = 1 m, F = 15 m



Fully centred optics

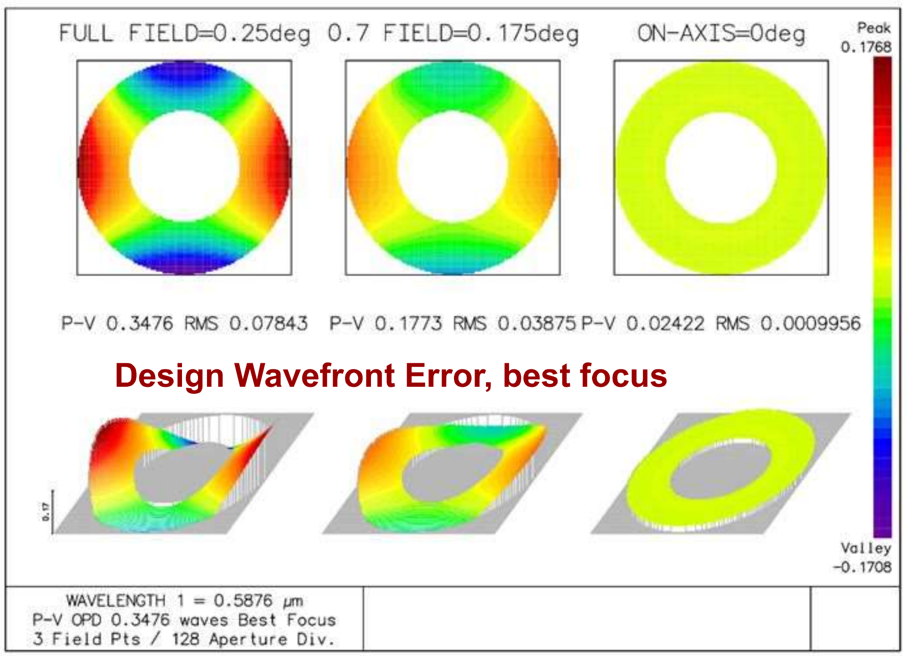
No longer fully on-axis (folding)

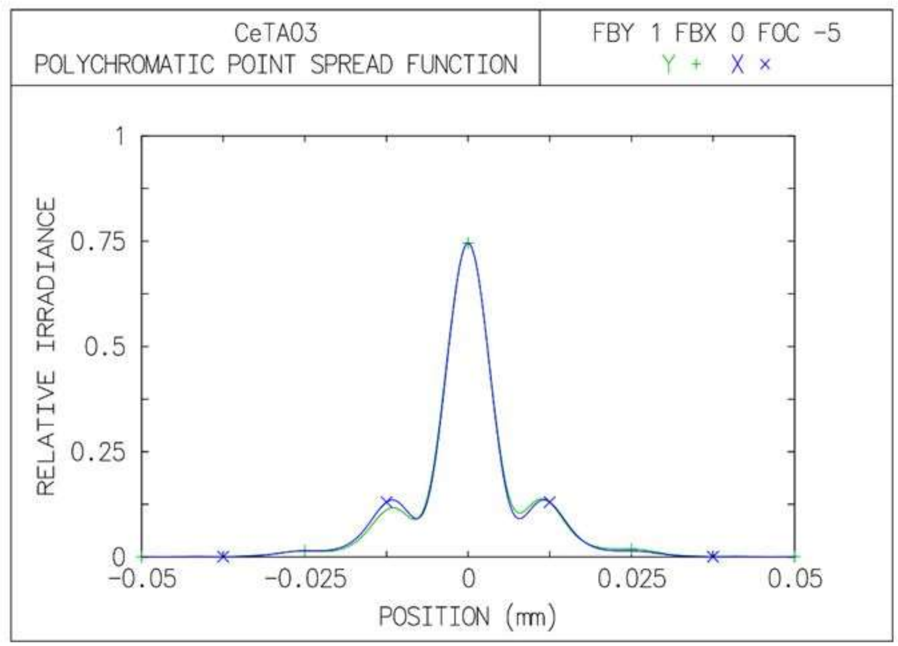
Highly symmetric PSF

Large on-axis field (ρ = 15 arcmin)

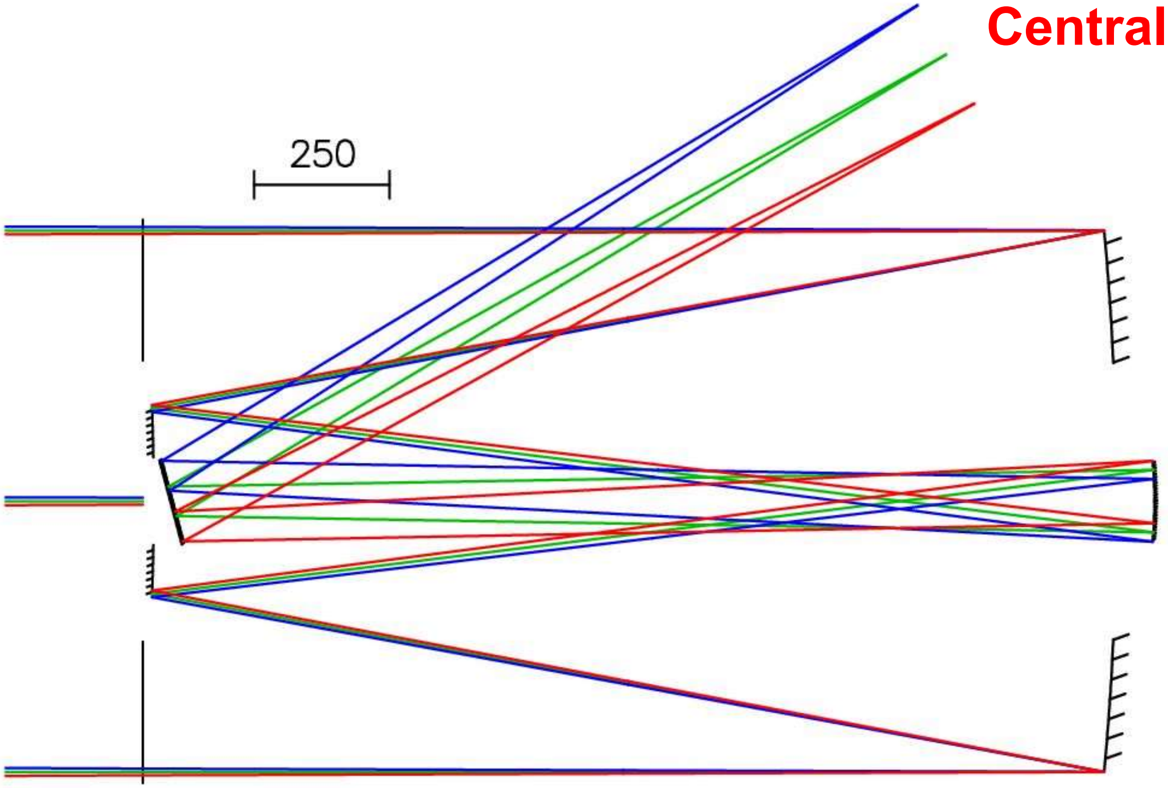
➔ 840 Mpixel CMOS focal plane
➔ ~0.2 square degrees

Envelope: <2 m



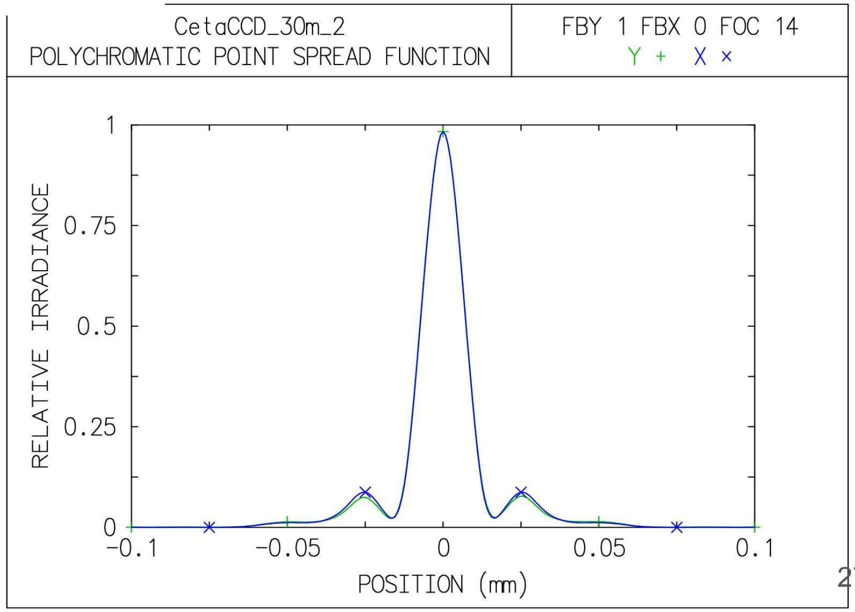


Central Field TMA: D = 1 m, F = 30 m

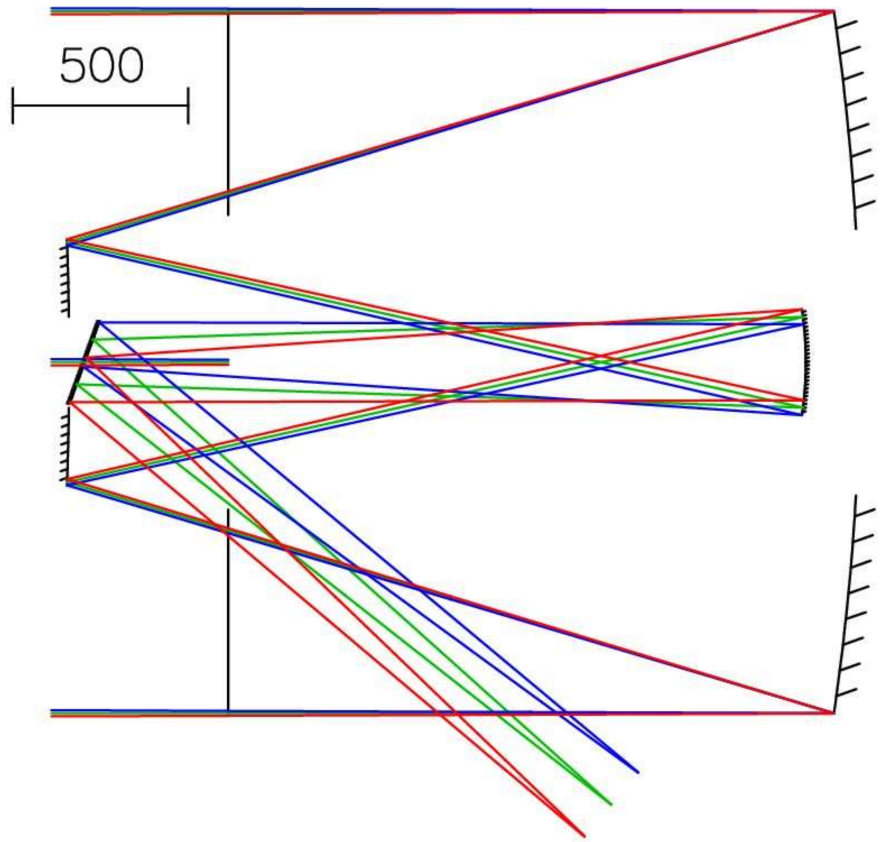


Compatible with 10 μm pixel CCDs

Envelope: ~2 m

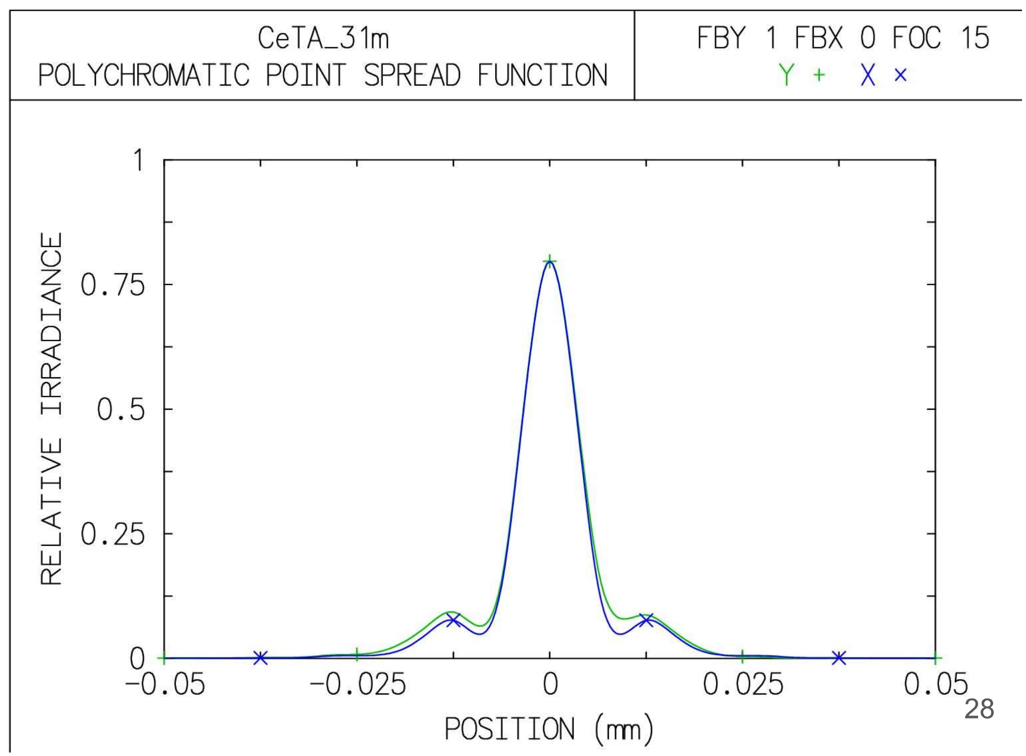


Central Field TMA: D = 2 m, F = 31 m



Compatible with 4 μm pixel CMOS detectors

Envelope: ~3.2 m



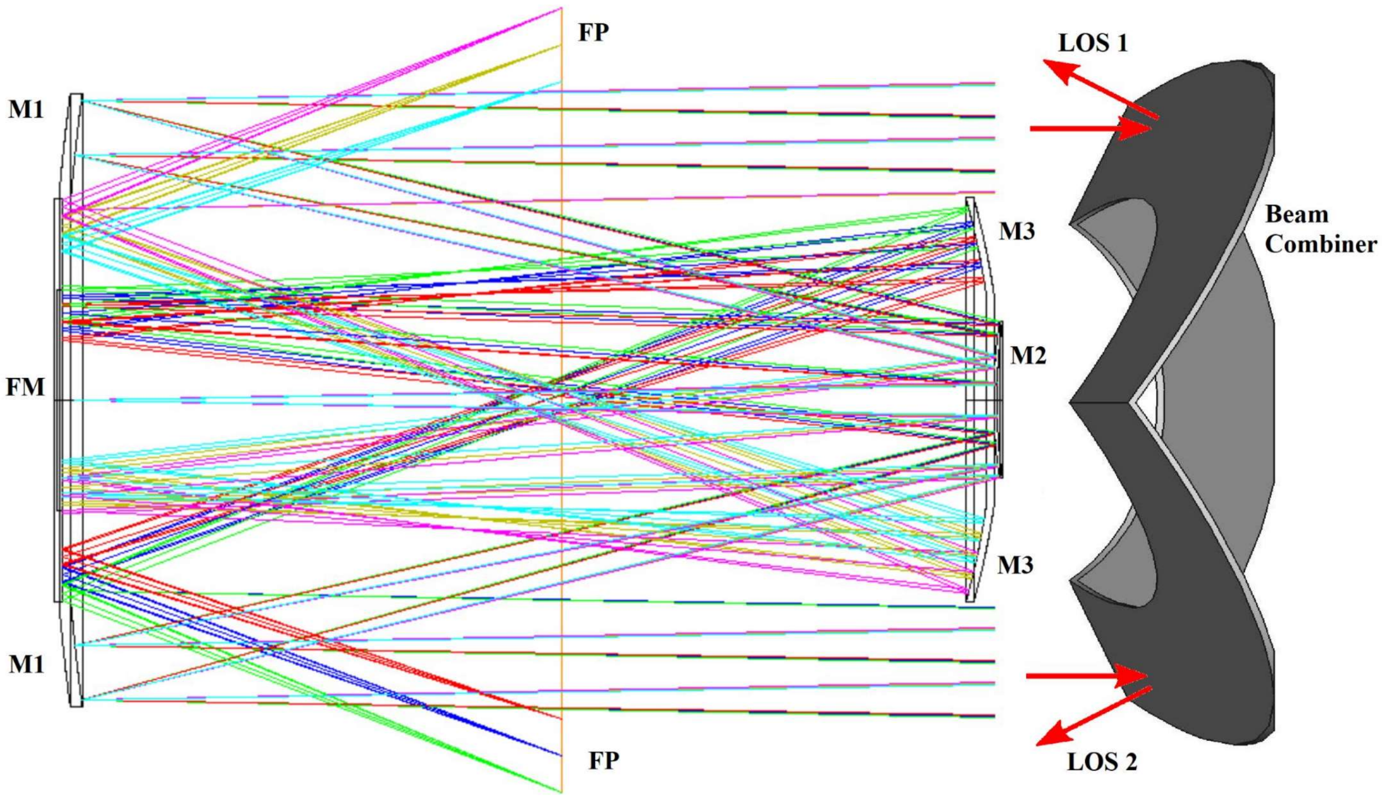
Application: Multiple Line Of Sight Telescope for GW Antenna

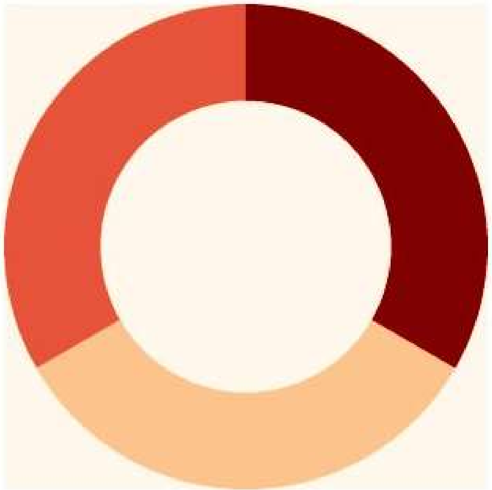
Crosta & Lattanzi, this workshop

Central or annular TMA endowed with pyramid Beam Combiner

Superposed images on common focal plane, easily identified

Challenge: high sensitivity, high stability





Summary

Reference science cases:

➔ Exoplanets
➔ Astrophysics
➔ Gravitational Waves

Main telescope specifications:

➔ Field of view = $0^{\circ}.2$ to $0^{\circ}.5$
➔ Aperture diameter D = 1 m to 2 m
➔ Focal length F = 15 m to 30 m

Rationale of proposed symmetric configurations:

★ Allow larger telescopes in given size payload

★ Symmetric structure is expected to be more stable

★ Symmetric optical response eases calibration

★ Compatible with monitoring/metrology systems