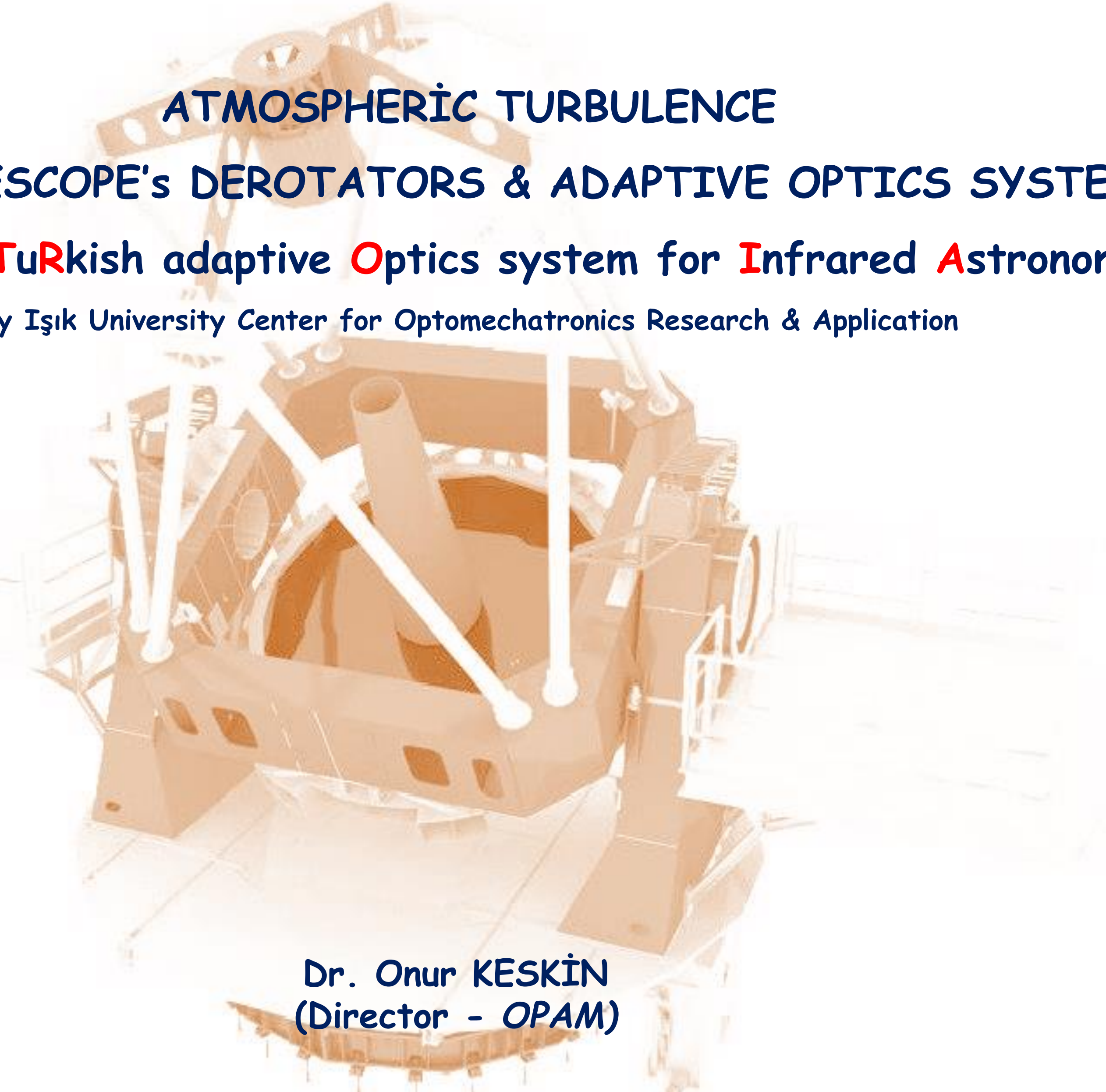

ATMOSPHERİC TURBULENCE

DAG TELESCOPE's DEROTATORS & ADAPTIVE OPTICS SYSTEM

(TROIA – TuRkish adaptive Optics system for Infrared Astronomy)

By Işık University Center for Optomechatronics Research & Application

Dr. Onur KESKİN
(Director - *OPAM*)

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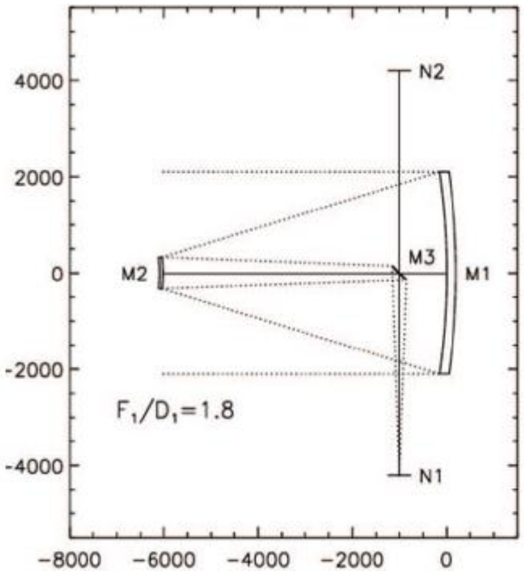
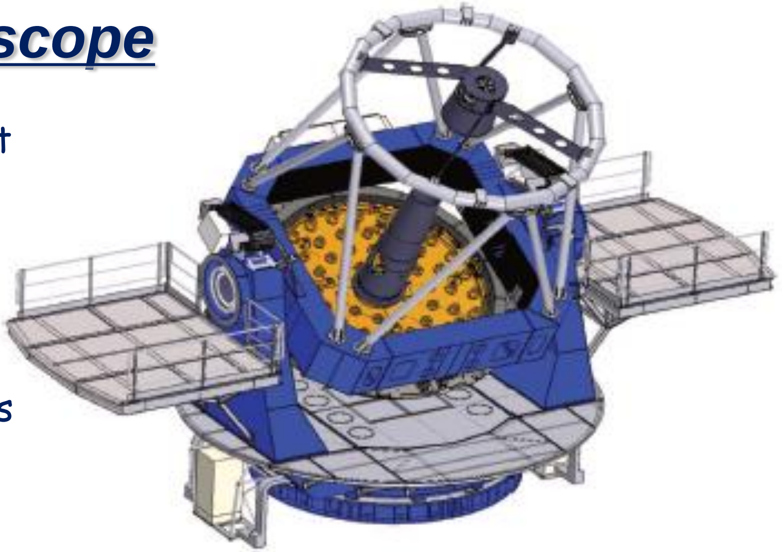


OPAM: DAG Telescope

DAG – Project Management
+
Optomechatronics Design
+
CFI/CFT Preparation
+
Optomechatronics Systems



THE ONLY TELESCOPE ON IT'S CLASS WITH

- RC Configuration
    - Micro Roughness of the 3 Mirrors ≤ 3.2nm
- Active Optics
    - Total WFE Residual Error ≤ 32nm
- 2 Nasmyth Platforms
    - Seeing Limited
        - FoV (30 arcmin; unvignetted 20arcmin)
        - Primary Science Fov 10 arcmin
        - Optical Derotator
    - Diffraction Limited
        - **FoV 7 arcmin**
            - **Optical Derotator(s)**
            - **Adaptive Optics (TROIA)**
                - **Pyramid WFS First Light AO**

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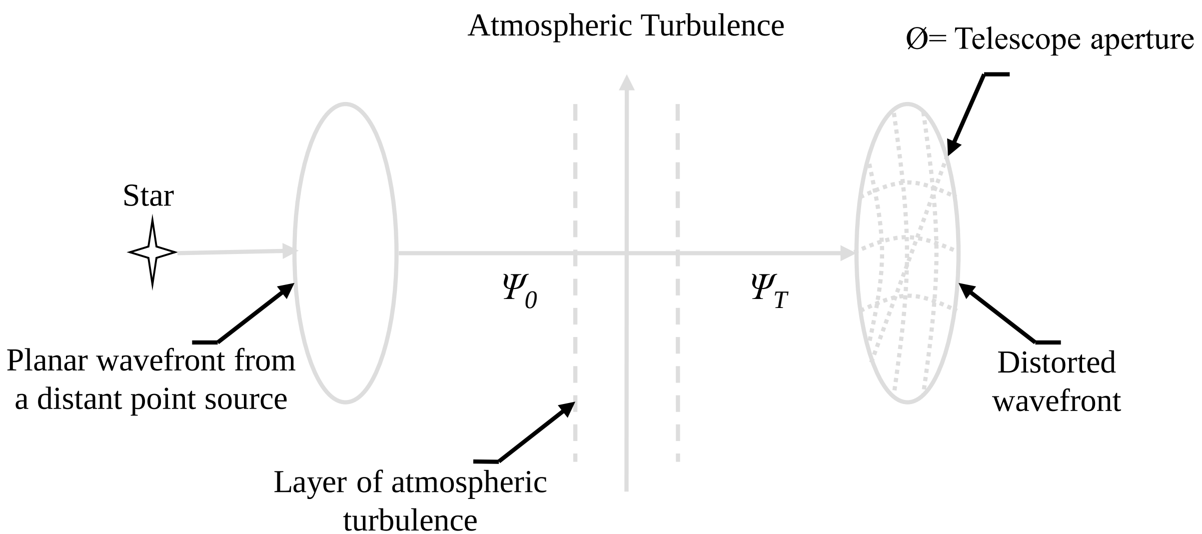
Wavefront Phase Distortions



$$\Psi_0 = A\, e^{i\varphi} \quad \text{and} \quad \Psi_T = A\, e^{i\varphi(r,\rho,\, t)}$$

- ***A* is the wave amplitude, and *φ* is the phase of the field fluctuation.**
- **A surface over which *φ* takes the same value is called the wavefront surface.**

Wavefront Phase Distortions

• In an optical system, it is sometimes useful to present the phase (φ) as a 2D surface over a circular pupil (e.g., telescope pupil).

• The derivation from the flat (planar) wavefront is the wavefront error and is conveniently represented by a series of orthogonal polynomials over the circular pupil (e.g., Zernike Polynomials).

"Tilt"

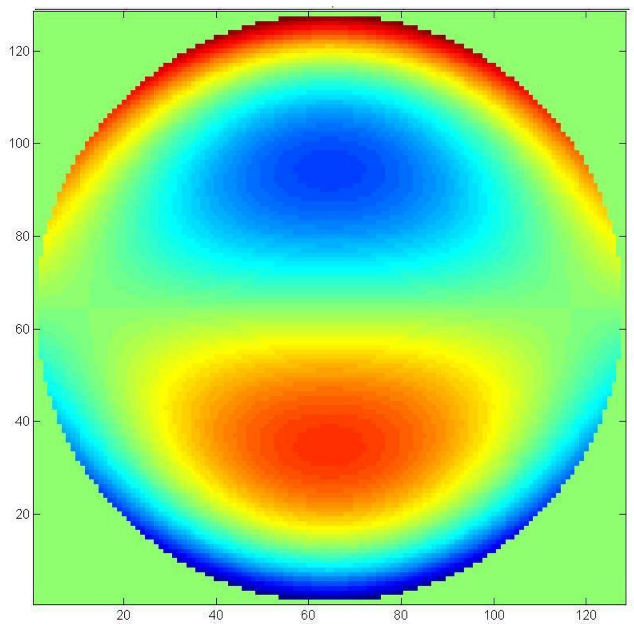
"Tip"

"Piston"

"Defocus"

"Coma"

"Astigmatism"



KARAKAYA site

Seeing survey 2009-2010

(C. Yesilyaprak et al. UAK 2010)

SEEING ANGLE FOR AO MODELING :

Best 0.5’’

Median 1’’

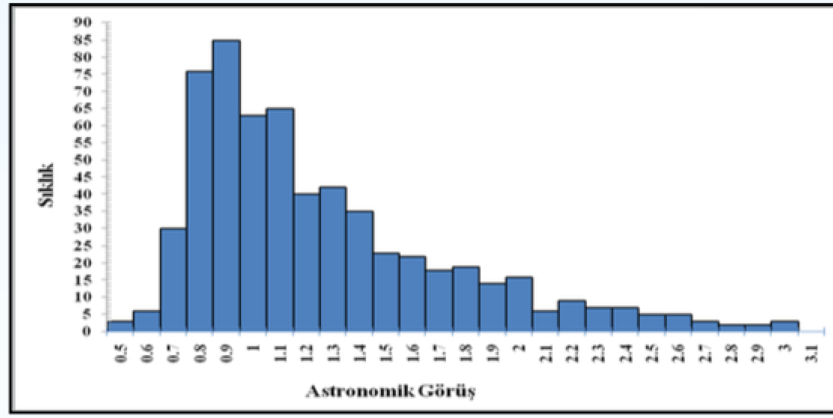
Worse 1.5’’

DM saturation probability

at 1.5’’ < 0.007 %

at 2’’ occurs < 0.3 %

ASTRONOMİK GÖRÜŞ KALİTESİ (DIMM):



Tarih	N	θ_{ort} ('')	θ_{min} ('')	Rüzgar V_{ort} (m/s)	Nem (%)
18.08.2009	36	0.797	0.628	0	35
19.08.2009	72	1.660	0.838	5	81
21.08.2009	34	1.179	0.558	2	49
23.08.2009	55	0.792	0.447	4	2
24.08.2009	65	1.924	1.061	3	11
31.08.2009	32	1.250	0.800	2	61
02.09.2009	67	1.010	0.543	0	53
03.09.2009	62	0.986	0.657	0	27
04.09.2009	69	1.303	0.765	2	25
05.09.2009	81	0.975	0.483	0	33
06.09.2009	33	1.087	0.692	0	26
24.03.2010	43	0.998	0.730	0	93

En düşük görüş: 0.447'' ; Ortanca görüş: 1.060''

Rüzgar ve Nem değerleri, θ_{min} ölçümü anındaki değerlerdir.

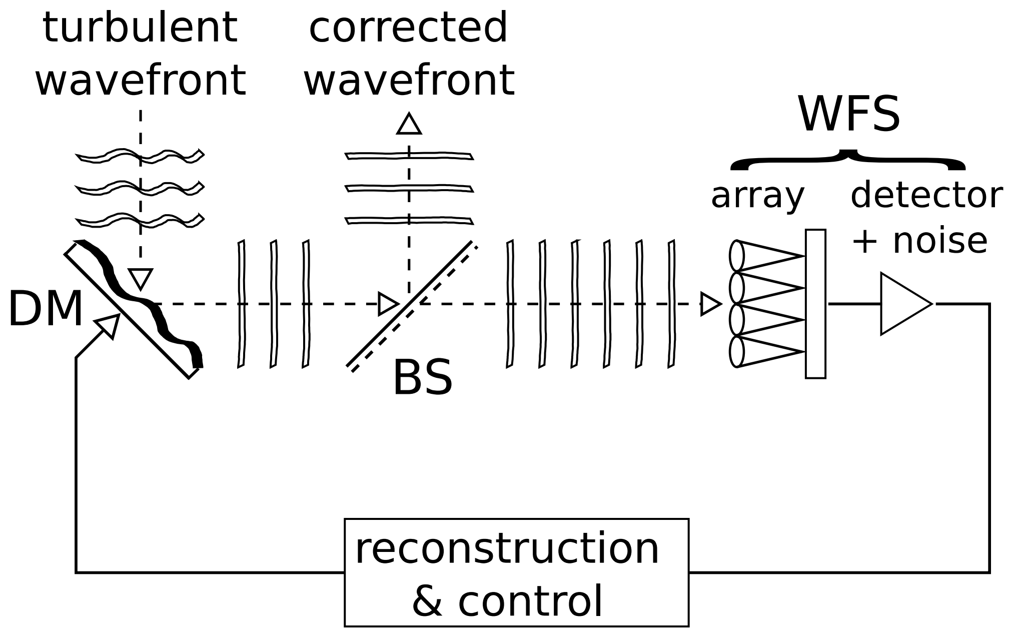
Atmosphere & Telescope

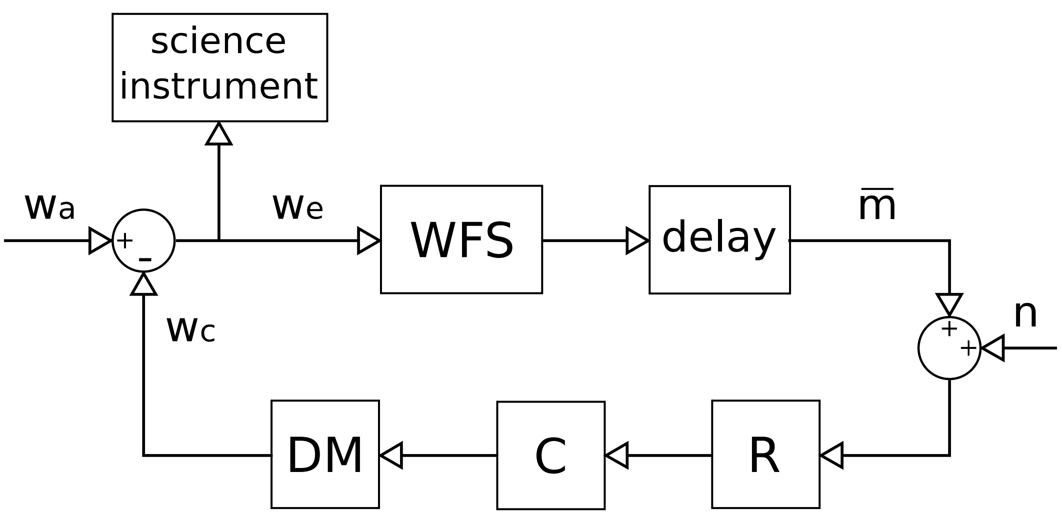
Parameter	Value used in the simulations
Zenith distance	30° (up to 70°)
C_N^2 profile distribution	Paranal observatory conditions
Seeing angle	0.5’’ 1.0’’ 1.5’’ (good median bad)
Outer-scale (L0)	30 m
Wavelength of AO observations	800 nm to 2250 nm (middle @ H band)
Wavelength of AO wavefront sensing	< 800 nm
AO loop time lag	800 µs (ALTAIR case)
WFS type	Shack-Hartmann
WFS CCD read-out noise	Max 2 e^-/px
NGS type	G-type NGS (6000K)
NGS magnitude (V-band)	0 to 16
Number of actuators across the pupil	10 to 18
Telescope optics	D1 = 3.940 m, D2 = 0.975 m, F = 56 m

AO Contractual Design Constraints

- ***Delivering a working AO system is mandatory ☺***
  - *requires a solid, proven design (no tech. risks)*

- ***So we started off with a classical design to satisfy tech specs:***
  - *Single deformable mirror (DM) system: proven tech.*
  - *Natural guide star (NGS) system (limit. V=15)*
  - *Single wavefront sensor (WFS): Shack-Hartmann type*
  - *Field-of-view 7' (diameter)*
  - *Classical control: integrator based*

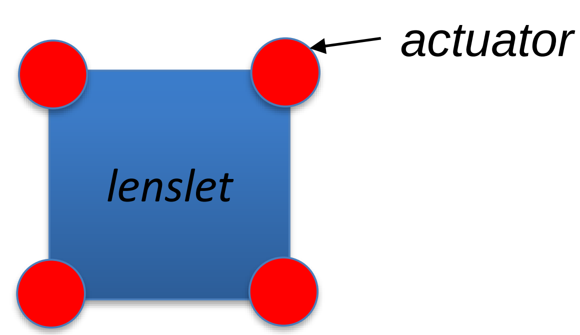




Some definitions

The DM actuator pitch value is given as projected into the primary mirror plane.

The number of lenslets **is the same** as the number of DM actuators.



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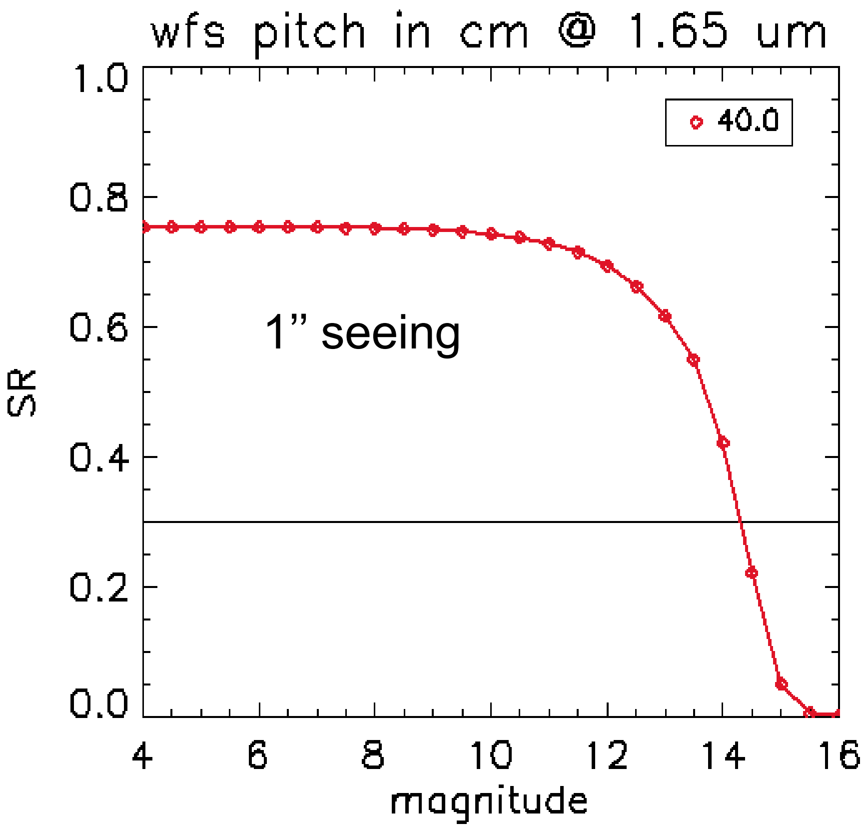
Optimal pitch (basic design)

Telescope active optics (aO) was designed such that telescope residual << than AO residual (telescope is diffraction limited)

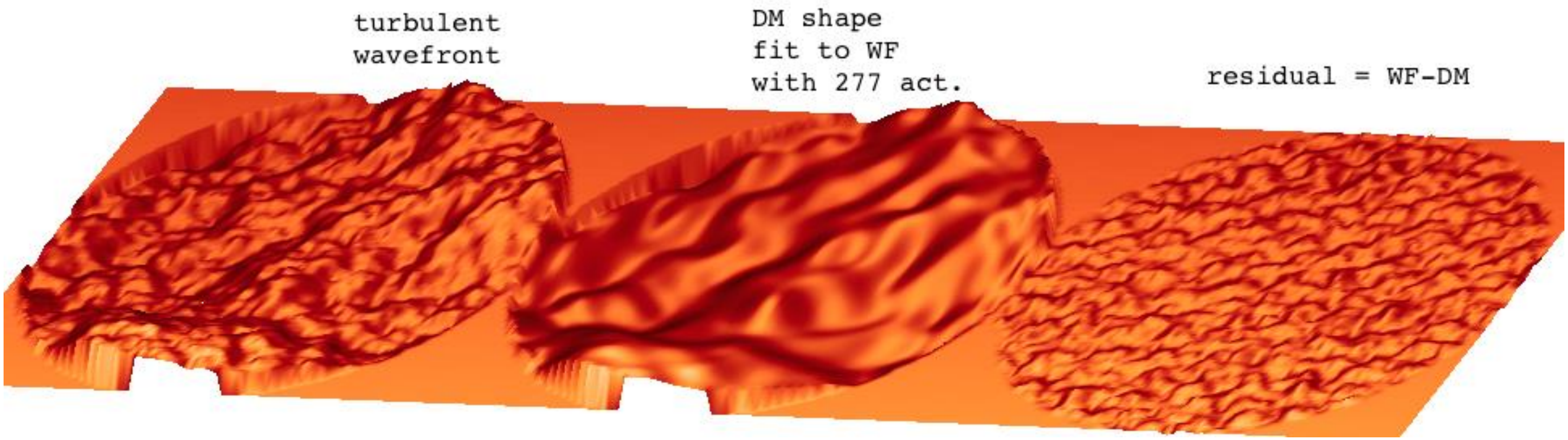
We selected during the telescope design an AO pitch of 40 cm

In H-band, with 40 cm pitch:

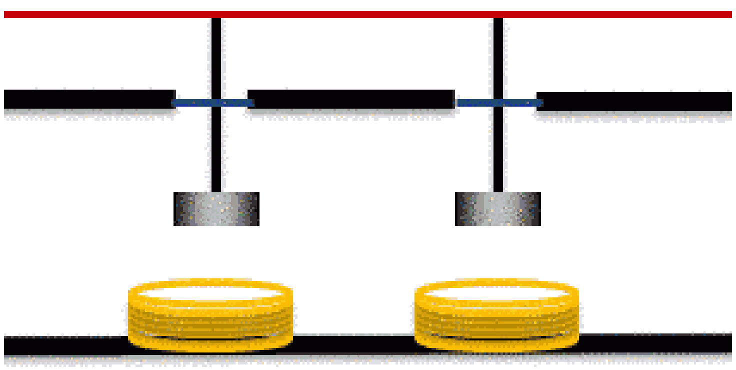
- SR = 0.75 for bright NGS
- SR = 0.30 for V=15



The Flexible AO concept



ALPAO 468 DEFORMABLE MIRROR



DM and TT

mirror stroke

DM amplitude specification

- Turbulent phase amplitude has a Gaussian statistics with variance (rad^2)

$$\sigma_\varphi^2 = 1.0324\,(D/r_0)^{5/3}$$

- If we remove the tip-tilt, the higher orders variance is

$$\sigma_{ho}^2 = 0.134\,(D/r_0)^{5/3}$$

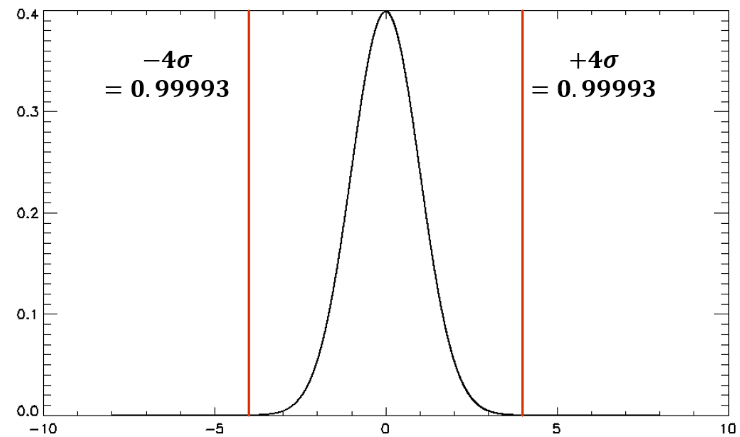
- For 1.5'' seeing, the wavefront error (nm) is

L_0	tip-tilt	higher orders	total	
∞	2266	878	2430	nm
30 m	1127	829	1400	nm

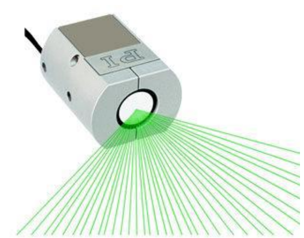
DM & TT mirror stroke specification

- If DM stroke = 4 times 2sigma then saturation less than 0.007 % of the time

L_0	DM stroke
∞	3545 nm
30 m	3351 nm



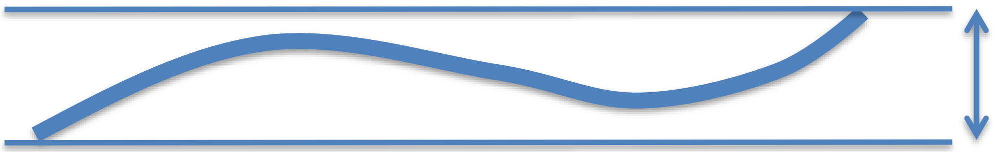
- For the TT mirror $W_t(x, y) = \theta_x\, x + \theta_y\, y$



L_0	TT angle stroke	plus 0.1" instr. jitter	2 cm mir. diameter	5 cm mir. diameter	mir. edge
∞	$\pm$0.467"	$\pm$0.567"	$\pm$113"	$\pm$45"	5.5 μm
30 m	$\pm$0.233"	$\pm$0.333"	$\pm$67"	$\pm$27"	3.2 μm

Single DM+TT mirror required stroke

- With a <u>single DM</u> to compensate both TT + high order



L_0	single DM stroke
∞	14.545 μm
30 m	9.751 μm

Mechanical P2V

Wavefront sensor specifications

WFS specifications

- SH design, lenslet pitch 40 cm
- Lenslet field-of-view
  - Has to be large enough to accommodate residual TT within lenslet + lenslet PSF width

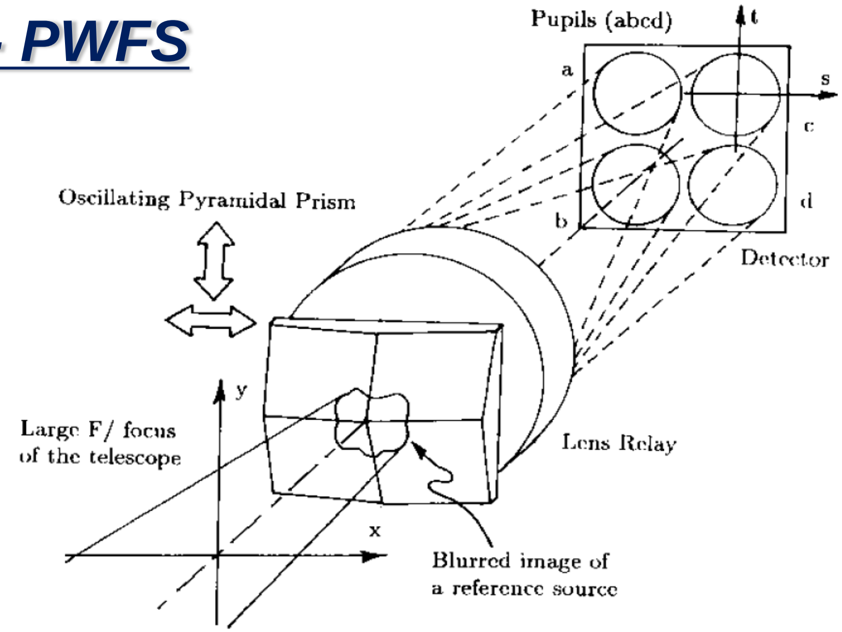
$$\sigma_s^2 = 0.01176 \left(\frac{\lambda}{\Lambda}\right)^2 \left(\frac{\Lambda}{r_0}\right)^{5/3} \quad [\mathrm{rad}^2]$$

  - We chose 4 times 2σ + FWHM : FoV 1.3''

- Pixel size = FWHM of lenslet PSF /2 $\Delta p = 0.155''$

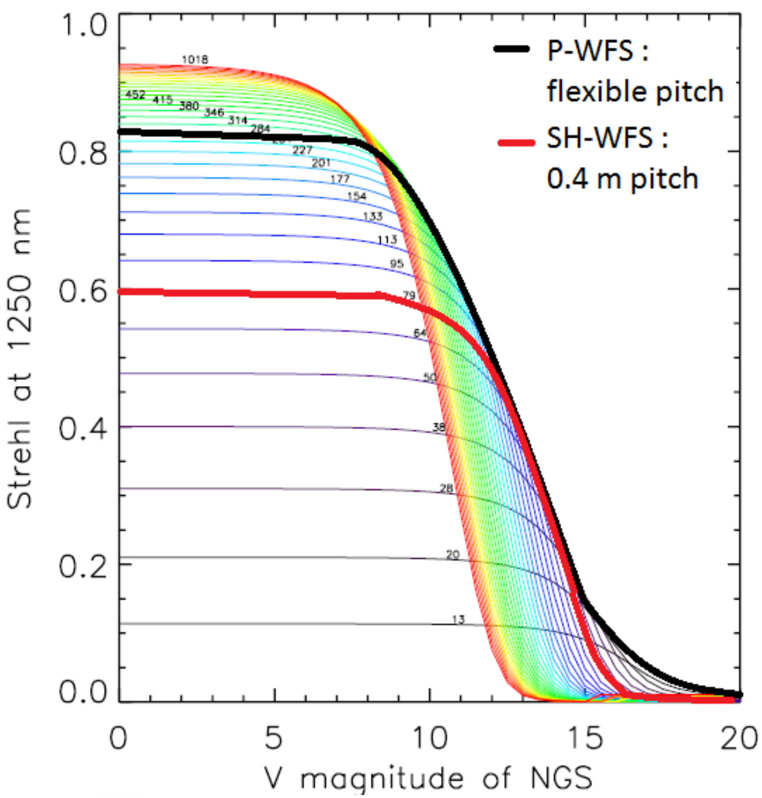
- # of pixels = FoV/dpx = 8.4 px so 10 pixels
- 10 lenslets x 10 pixels + 2 guard pixels = 118 px
  - ➢ 128x128 px detectors (easy to find)
- CCD or CMOS ? "NUVU EMCCD"

Pyramid WFS - PWFS



$$\frac{\partial W}{\partial x} = \delta\theta_x \frac{(S_1 + S_4) - (S_2 + S_3)}{S_1 + S_2 + S_3 + S_4}$$

$$\frac{\partial W}{\partial y} = \delta\theta_y \frac{(S_1 + S_2) - (S_3 + S_4)}{S_1 + S_2 + S_3 + S_4}$$



Advantages over SHWFS

If we have the freedom to chose the pitch, we do not have to compromise between quality of correction and limiting magnitude

- SH system is frozen
- The Pyramid sensor can adapt its spatial sampling

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Loop frequency, time lag, computation power

Loop frequency & time-lag

- Phase time scale is about 1.3 ms (TBC with site data)
- Optimal loop frequency is a function of
  - Pitch size
  - NGS magnitude
  - WFS detector noise
  - Wind velocity
  - Seeing
- Optimization indicates a frequency between 7.8 kHz and 100 Hz
- At 7.8 kHz servo+noise error are very low and we can go much slowly, at 2 kHz
- Time lag for a classical system (ALTAIR) is 0.8 ms

Wavefront error budget

WFE budget for final design

- Each component of AO & telescope generates an unavoidable error
- WFE for each component
  - Some can be computed
  - The others can be estimated
- This WFE budget is the reference for the final design

wavefront error component	RMS [nm]
DM fitting	68
WFS aliasing	39
loop servo-lag[a]	0, 20, 100
WFS noise	0, 20, 100
wavefront reconstruction[b]	20
NCPA & unknown	100
AO total (quad.)	129, 132, 191
telescope post-aO aberration[c]	70
science instrument	100
total (quad.)	177, 180, 227

[a] in bright, moderate and dim NGS conditions, mV=0, 10, 14.

[b] this is a preliminary value, to be confirmed at final design.

[c] telescope and instrument errors are not part of the AO error budget and not the responsibility of the AO project development.

Simulation Tools

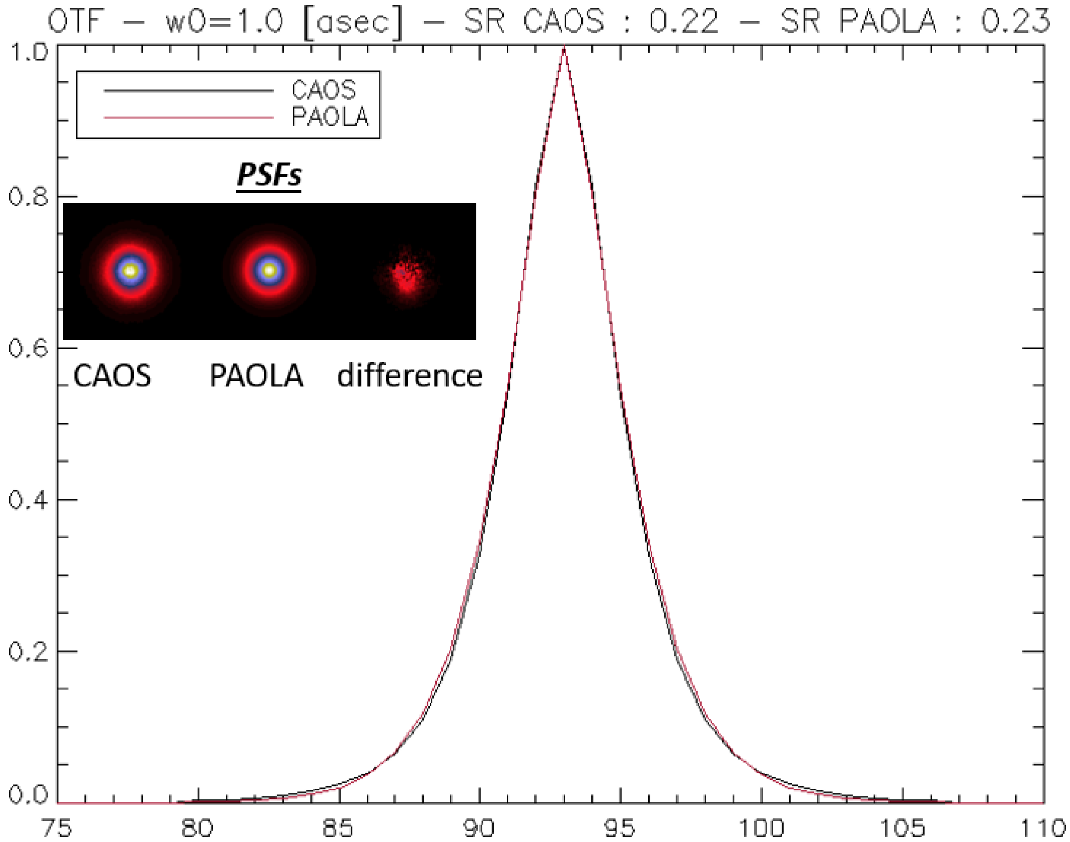
PAOLA

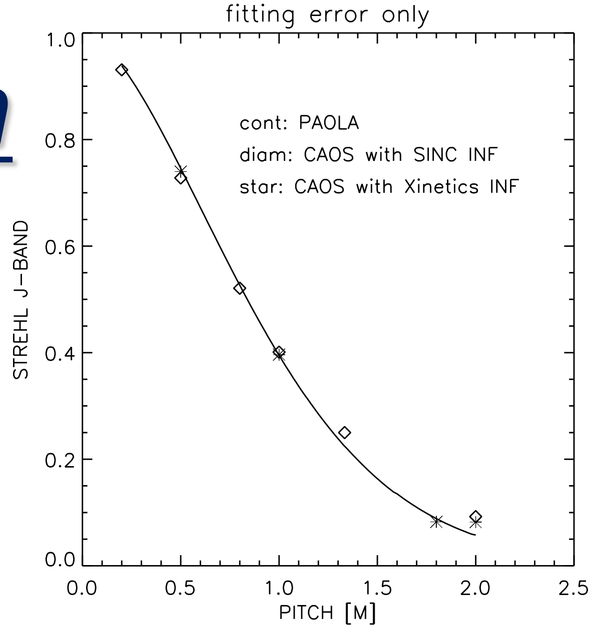
- IDL programing language for AO system modelling
- Simulates the long exposure AO corrected PSF at once
- Allows a fast exploration of the AO parameter space to decide on the preliminary design

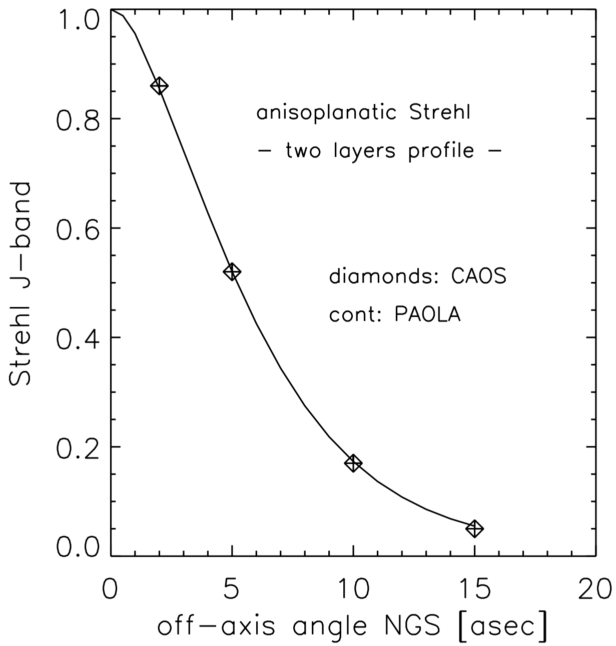
CAOS

- End to end physical simulation of AO system
  - atmospheric propagation of light
  - sensing of the wavefront aberrations
  - Integrator control
  - correction with a deformable mirror
- Simulates an AO system as realistically as possible
- Each AO component of the loop is modelled with a specific module.

PAOLA / CAOS comparison







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AO system and telescope parameters for modeling and design

- **The seeing conditions** at the summit median: 0.87″, mean: 0.9″, minimum: 0.33″ and maximum: 2.34″

The design is contractually finalized with a seeing ≤1.5″. It would be excessive to do a design for a larger seeing angle, the AO system would be over dimensioned, for a seeing that rarely occurs at the site

- **C_N^2 Profile is adopted** using the conditions at Paranal observatory, which are typical of good astronomical sites (where most of the turbulence is close to the ground)
- **Outer scale of optical turbulence:** Median value is set to 30 m, and worst at 60 m, which are typical value everywhere. Stroke amplitude specification is done using the 60 m value.
- **Wavelength of AO science observations:** Is from 800 to 2250 nm
- **Wavelength for AO wavefront sensing**: All NGS light up to 800 nm. A dichroic beamsplitter will separate the science and the WFS light. A neutral density filter will be used for very bright targets
- **WFS type:** Is a Pyramid WFS (first light PWFS AO system)
- **WFS CCD read-out-noise:** EMCCD of 128-by-128 pixel from NUVU, with less than 0.1 e/px
- **NGS type and magnitude:** We consider a G-type NGS (black-body spectrum with effective temperature 6000 K), a range of V magnitudes from 0 to 18 (exceeds the contractual value V=15)
- **Number of pixels across the pupil in the PWFS images:** 33 pixels across the pupil are required. As a gap of 20% of the pupil images diameter is recommended in between the images, it comes that the CCD array must be at least 73 pixels (the detector 128-by-128 from NUVU meets this requirement)
- **Complience with Telescope optics:** Complient
- **Field optical derotator:** inside the central hole of the fork. It allows for a non rotating light beam and a FoV of 7′. The choice to locate the derotator inside the fork is motivated by saving space on the Nasmyth platform for the AO system and instruments, with the consequence of limiting the FoV. But this is actually not a limitation at all, as the AO correction will never (with the current technology) correct a FoV larger than a few arc-minutes
- **Deformable Mirror:** 468 actuator DM to allow EXAO (Extreme AO) in K-Band (bright star conditions) to directly image exoplanets

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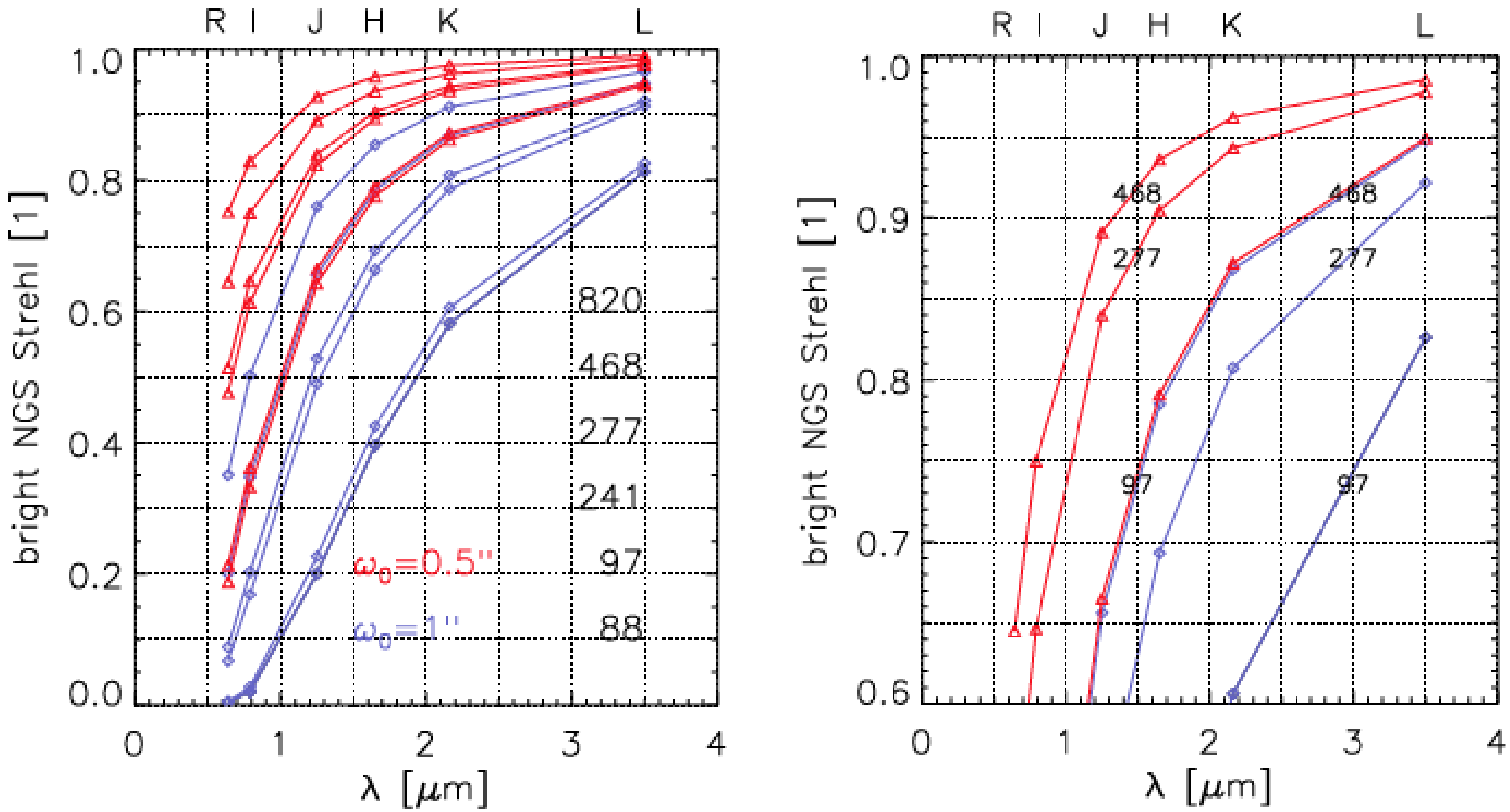
TuRkish adaptive Optics system for Infrared Astronomy

TROIA

Strehl improvement: I-Band:≤ %75; J-Band:≤ % 89; K-Band:≤ % 96; L-Band:≤ % 98



Median 0.5" & Best seeing 1" conditions @ NGS V=0

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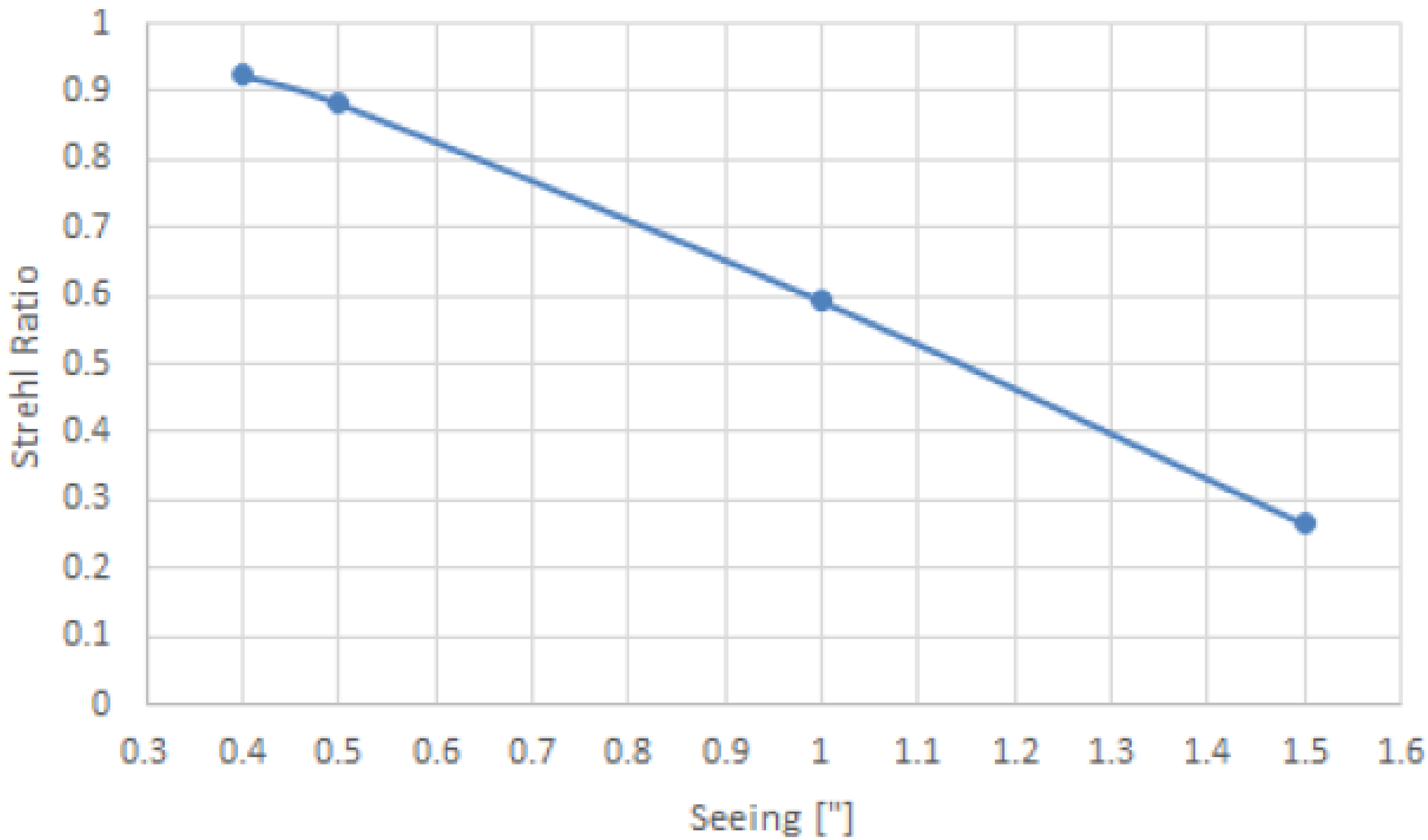
DAG - Adaptive Optics Systems & Working Principle

TuRkish adaptive Optics system for Infrared Astronomy

TROIA



GS Magnitude: 6, Wavelength: 1.65μm

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TuRkish adaptive Optics system for Infrared Astronomy

TROIA

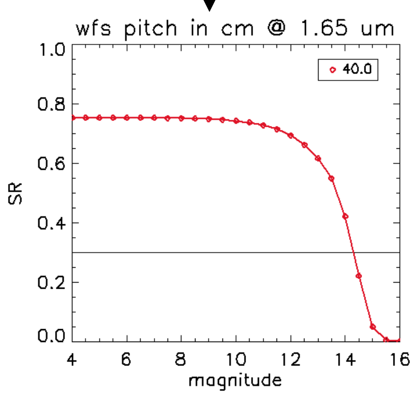
Design of DM pitch : Compromise SR vs limiting magnitude

Contractual

- Flexible AO concept
  - ❖ SCAO
  - ❖ EXAO (K-Band)
  - ❖ GLAO (additional PWFS)
  - ❖ MOAO (additional PWFS + DM Allowing tomographic targeted correction)

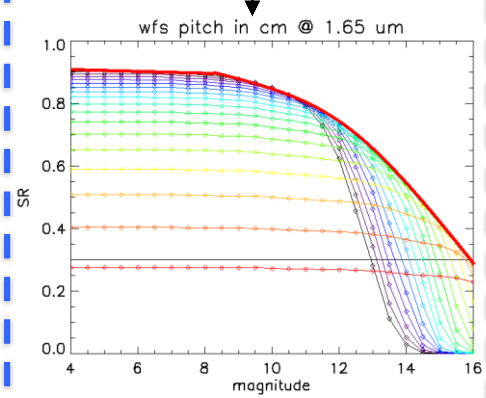
Optimum DM pitch size = Wavefront sensor pitch length

Fixed DM pitch of 0.4 m = Shack-Hartmann Wavefront sensor pitch of 0.4 m



Actual

Flexible DM pitch (binning actuators for larger pitch) = Pyramid Wavefront sensor flexible pitch



- Higher limiting magnitude than SH sensor (up to +2 mV)
- Better performance
- Lower level of spatial aliasing
- Full flexibility of adapting the spatial sampling to the turbulent conditions = free “equivalent lenslet pitch”

GS Magnitude: 6, Wavelength: 1.65μm

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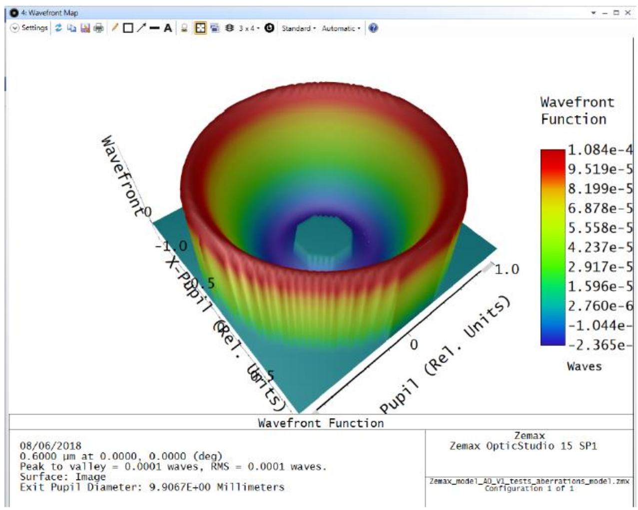
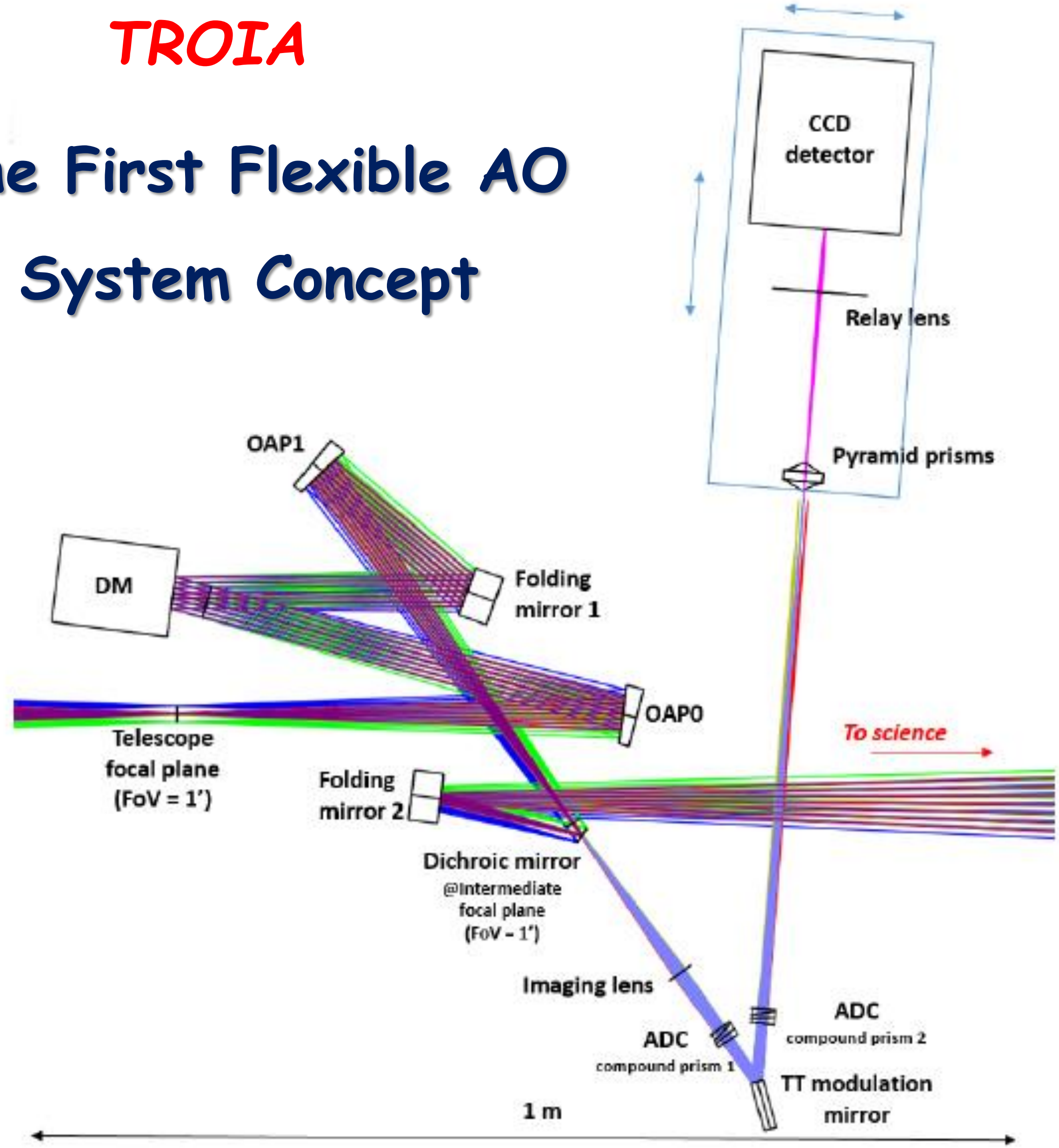
The First Flexible AO System Concept



The AO optical model on Zemax shows that if the alignment and optical surfaces are ideals we should have a total amount of aberration less than 1 nm (largely dominated by spherical aberrations).



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Potential Science Cases by *TROIA*

OUTCOME (FDR accomplished, Production Stage)

The leading AO science cases set are the following :

1. direct imaging of exoplanets (coronagraph),

2. tracking stellar orbits around the black hole in the Galactic Center,

3. investigating the gas content and kinematics of high-redshift galaxies,

4. studying spectroscopic binaries (particularly very-cool low-mass SBs),

5. protostars and young stellar objects,

6. observations of metal poor stars in the Galactic center.

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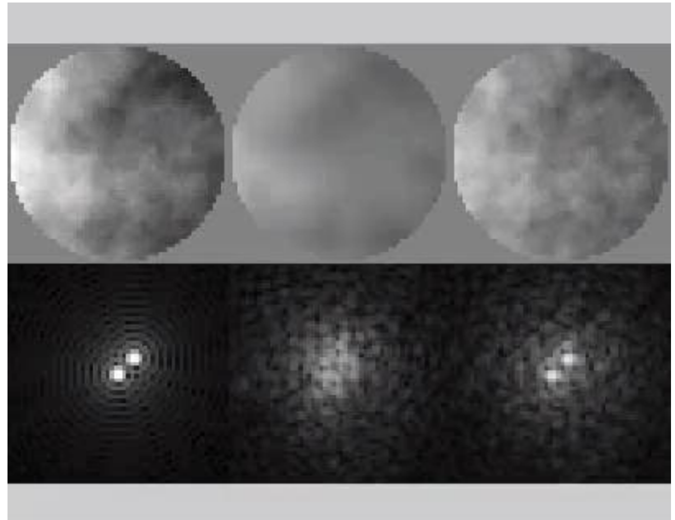
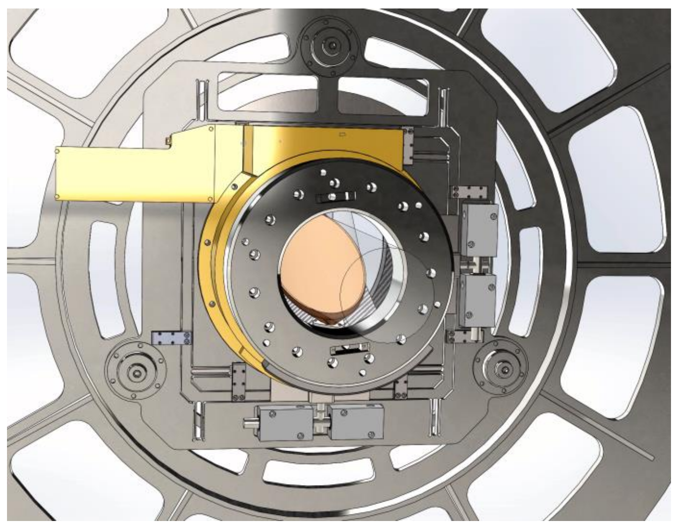
DAG - AOS Project

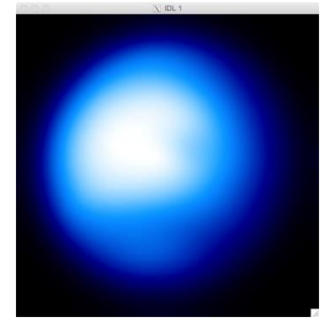
AO SYSTEM



DR SYSTEM(s)

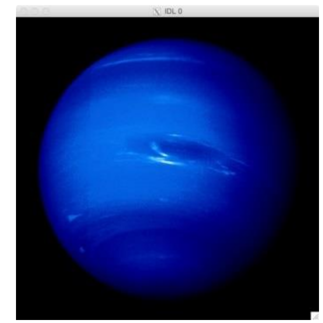


Simulation Result

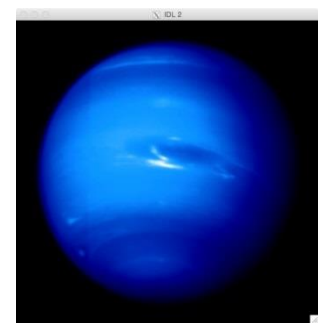


DAG

AO-Off



Voyager



DAG

AO-On

+

DR-On

Neptune

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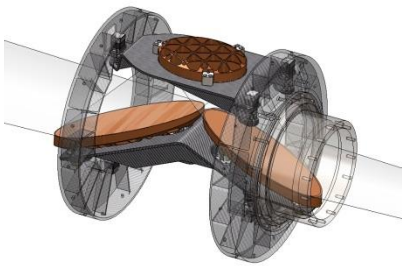
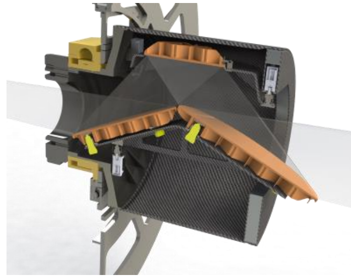
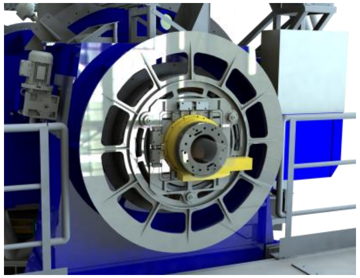
DR-I Contractual Design Constraints

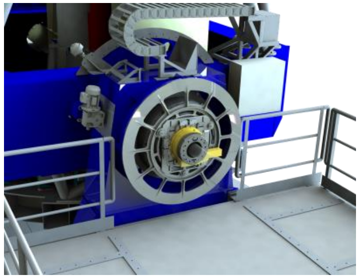
- **Temperature:** Environment operating temperatures must be stated and thermal deformations must be analyzed. Especially for piezo-motors, mirrors and positioning elements that could expand. The temperature range will be from-20° C to 30° C.
- **Vibrations and shocks:** Operational dynamics (from the derotator motor or from the telescope) must not create vibrations that disturb the system.
- **Corrosion and abrasion:** The materials choice must be in agreement with corrosion and wear issues.
- **Geometry and available space:** The derotator field of view is maximized in function of the available space and mechanical considerations. Optically (only according to geometrical considerations), the maximal field of view is about 8.3 arcmin. However due to mechanical constrains (cantilever of the system and internal flexures), the maximal field of view must be reduced to 7 arcmin.
- **Kinematic:** Derotator working accelerations and speeds are really weak. However, the maximal speed and acceleration will be estimated for telescope slewing.
- **Rigidity, stress and deformations:** This is a critical point in the development. Stiffness directly affects the precision of the focal point position.
- **Control system:** The telescope will be controlled with a Beckhoff drive system.
- **Manufacturing processes:** Feasibility of manufacturing processes are taken into account.

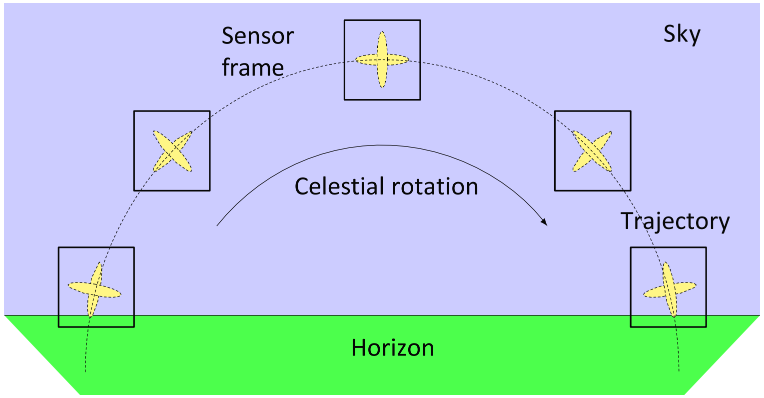
DAG - Derotator System-I

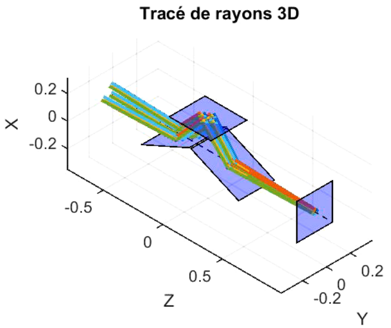


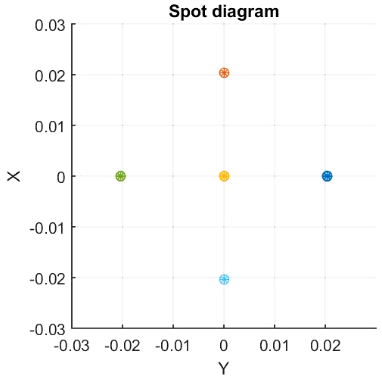












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DAG - Derotator System-I

OUTCOME (FDR accomplished, Production Ongoing)

- FoV: 7 arcmin
- Rotation speed: min 0.02°/s – max 1.1°/s (depending on elevation 0°-85°, & azimuth range 0°-360°)
- Continuous derotation range: ±340°
- Setting: Nasmyth flange (Diffraction Limited Platform)
- Survival temperature: -20° - +35°(contractually)
- Operating temperature: -15° - +15°(contractually)
- Configuration: K-mirror
- Housing: Carbon fiber
- *2 pending international patents

EP18020209.5

EP18020210.3

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DAG - Derotator System-II

Ongoing Design Process (PDR achieved FDR undergoing)

- FoV: 20 arcmin
- Rotation speed: min 0.02°/s – max 1.1°/s (depending on elevation 0°-85°, & azimuth range 0°-360°)
- Continuous derotation range: $\pm 340^{\circ}$
- Setting: Nasmyth Platform (Seeing Limited Platform)
- Survival temperature: -20° - $+35^{\circ}$(contractually)
- Operating temperature: -15° - $+15^{\circ}$(contractually)
- Configuration: K-mirror
- Housing: Carbon fiber

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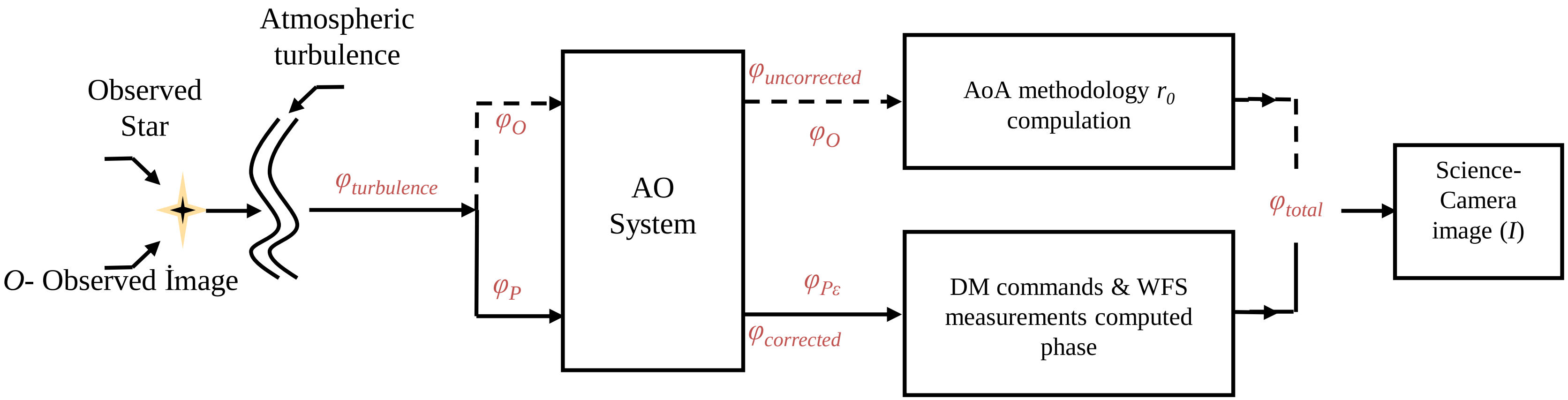
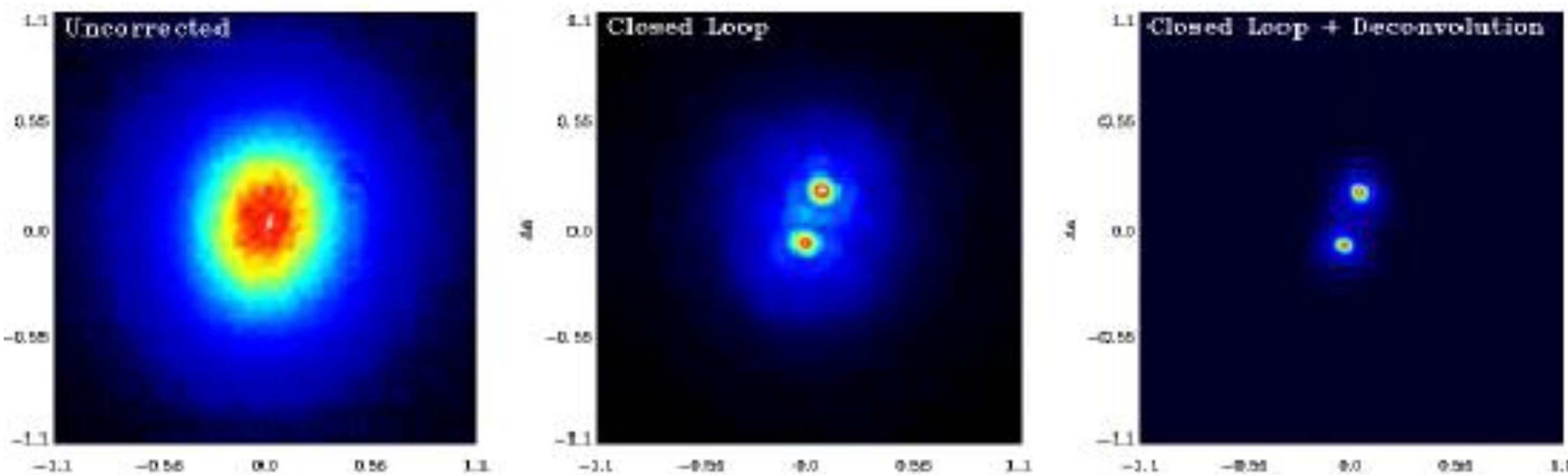
OPAM Prospective Projects: DAG – PSF Reconstruction



$$I = O \otimes PSF$$



a) AO Off   b) AO On   c) PSF reconstruction

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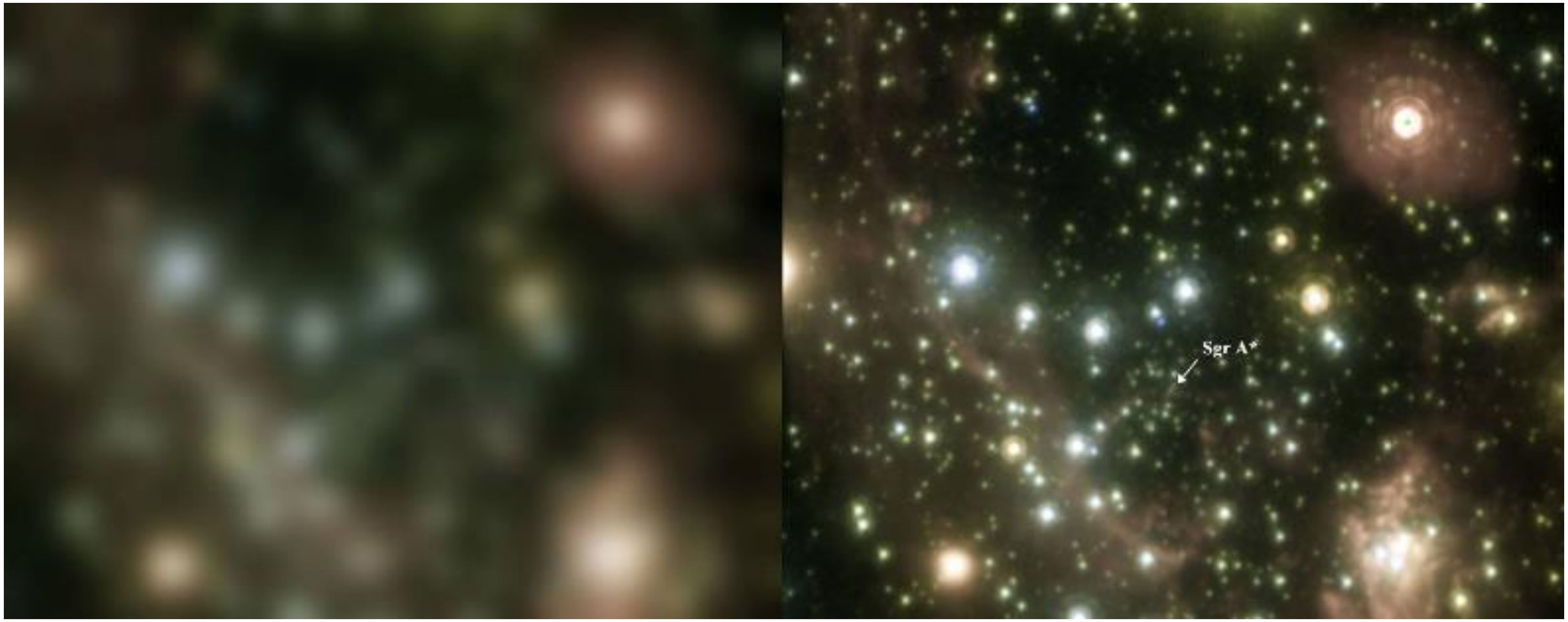
OPAM Abilities

- Telescope Construction Proposal (TMT- 30m Telescope, DAG – ODA Project)
- Telescope Design (DAG – 4m VIS/IR Telescope, TUG 2.5m VIS Telescope)
- CFI/CFT Documentation Preparation (DAG, TUG)
- Project Management (DAG)
- AO system development (TMT - NFIRAOS, DAG – TROIA)
- PSF Reconstruction (TMT, DAG, KECK)
- Derotators (Seeing Limited Platform – DAG; Diffaction Limited Platform – DAG)



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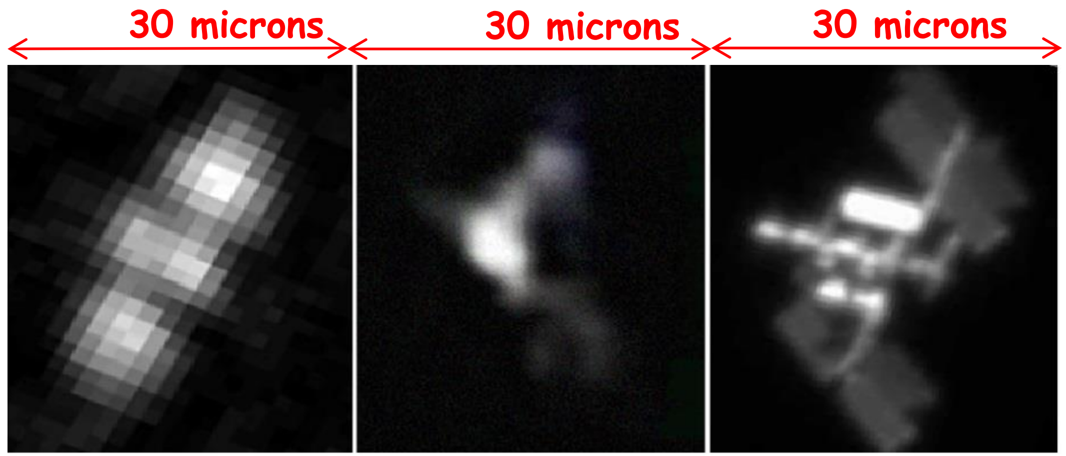
OPAM Abilities

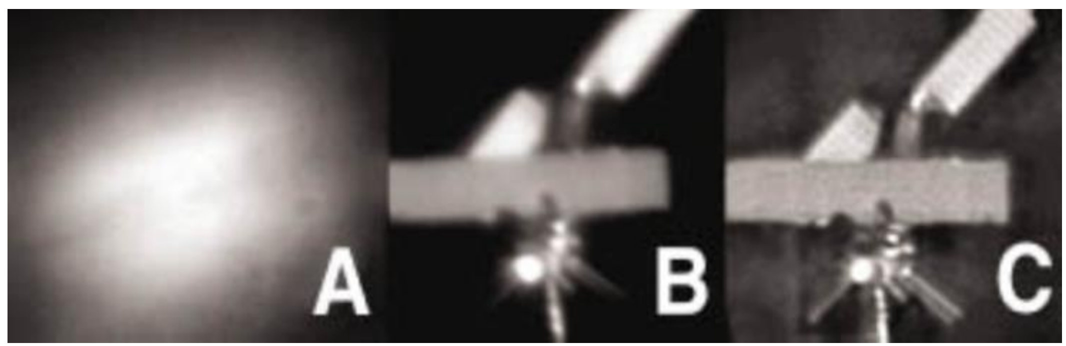
- Space (SST & SSR Applications)

OPAM

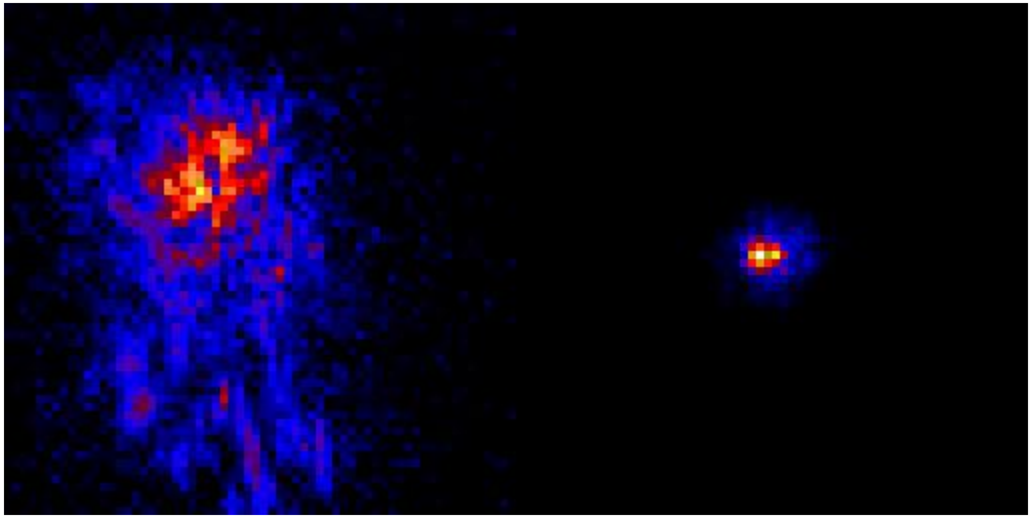
2m Telescope



4m Telescopes



- **Defense and Optical Communication**



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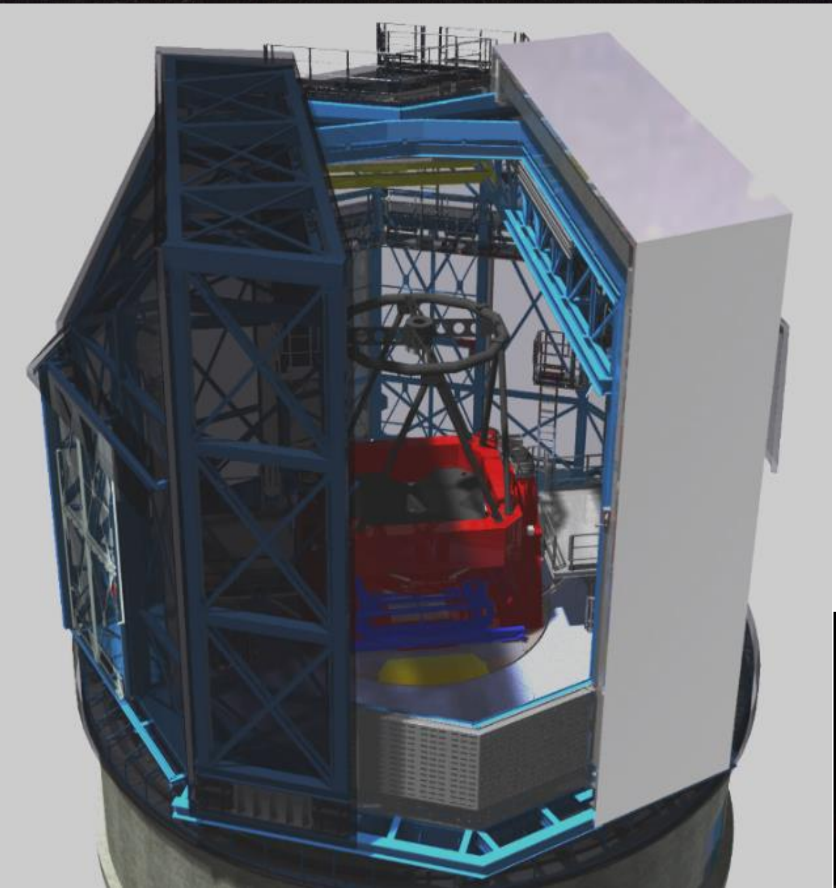
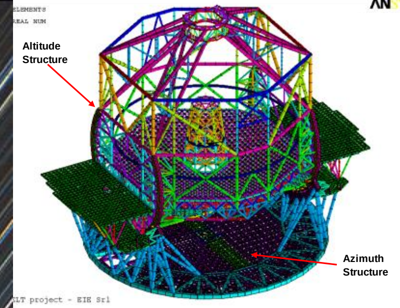
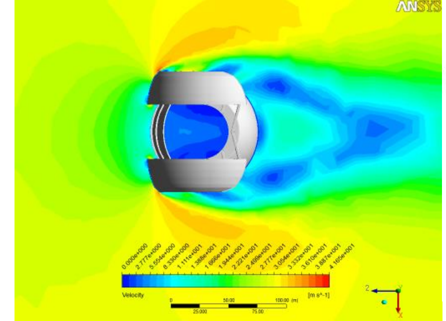


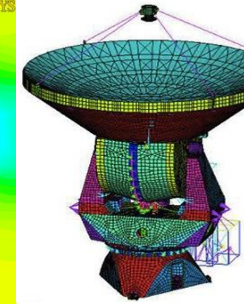
EIE GROUP with OPAM Collaboration FOR SST

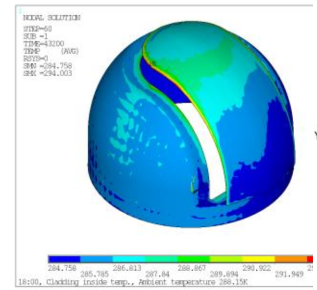
The interest on **SST/SSA** applications is constantly increasing, due to the raise of a large number of commercial satellite operators, the need to protect space assets, the strategic interest related to the possibility to monitor third party space assets.
EIE GROUP experience in the field of telescope design and realization is now at the service of companies and institutions involved in **SST/SSA**. With collaboration of **OPAM** in the field of **Adaptive Optics**, the system can be equipped with state-of-art hardware & software solutions for object identification and tracking.

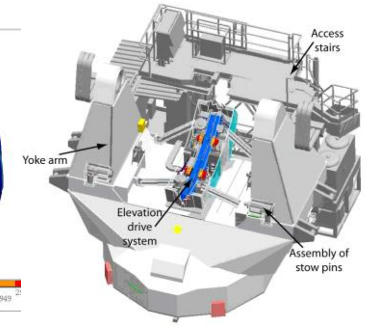
- Design to Cost
- Design/Production on a Custom Basis
- Reliable
- Proven
- Productive
- Tailored
- Sustainable
- Maintainable
- Durable (Long Term Facility)
- Innovation
- Training

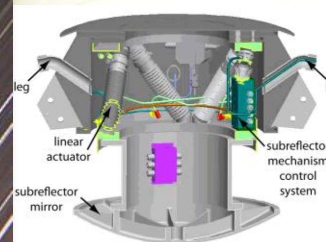


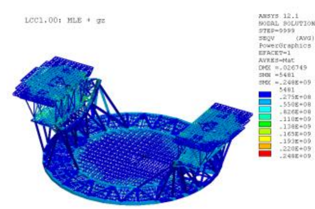


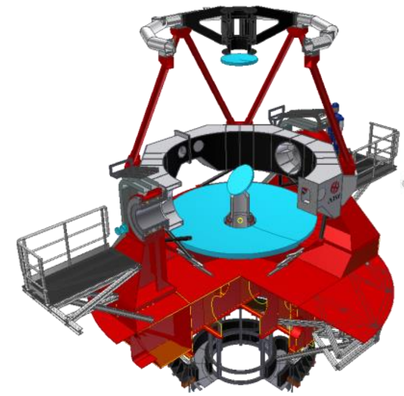










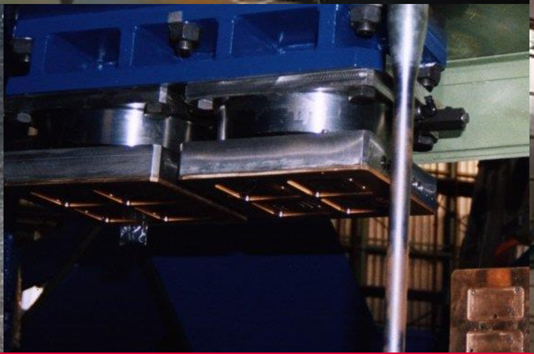


ENGINEERING & DESIGN FOR DEMANDING APPLICATIONS










PRODUCTION & SERVICES

OPAM Collaborations

EIE GROUP

AMOS

heig-vd

ALPAO

MICROGATE

ATASAM

University of Victoria

NRC·CNRC Canada

NATURAM PRIMUM COGNOSCERE RERUM

Australian National University

GEMINI OBSERVATORY

PRESS RELEASE

TMT

THIRTY METER TELESCOPE

W. M. KECK OBSERVATORY

On the summit of Mauna Kea, Island of Hawai'i

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FMV IŞIK ÜNİVERSİTESİ OPTOMEKATRONİK UYGULAMA VE ARAŞTIRMA MERKEZİ İKT. İŞL.

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