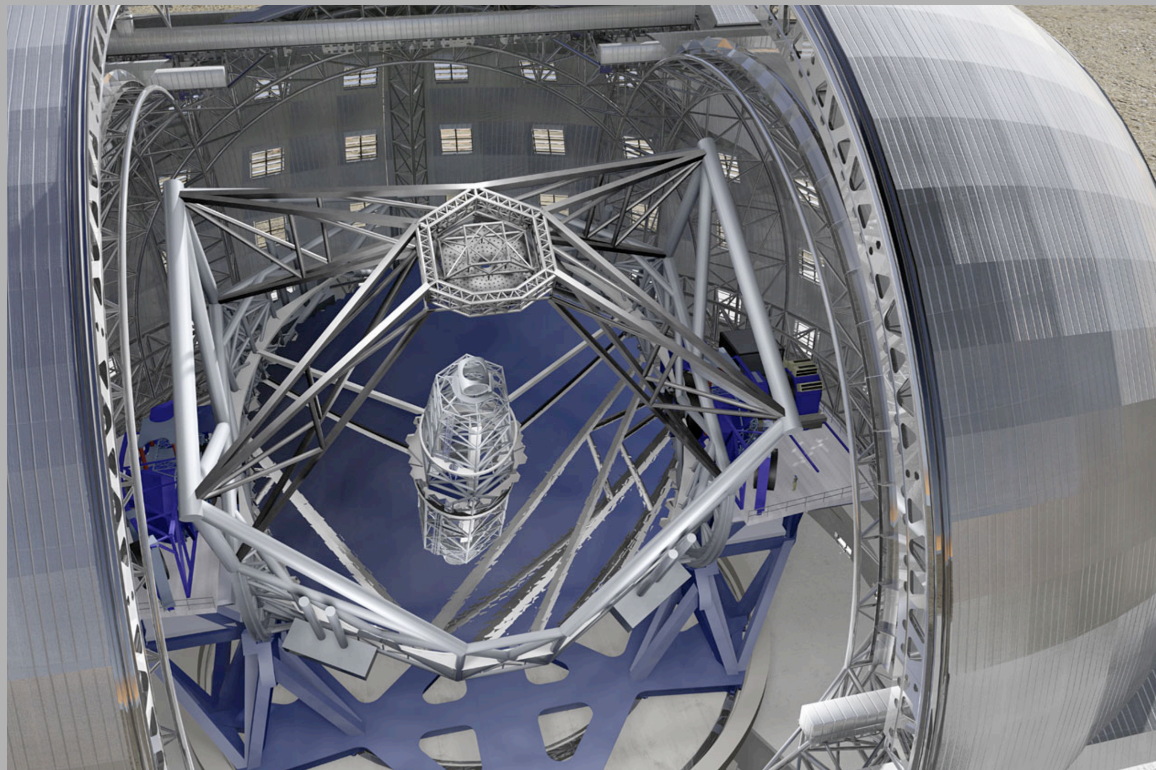
T-REX Unit for the E-ELT mirrors



Giovanni Pareschi

Osservatorio Astronomico di Brera - INAF

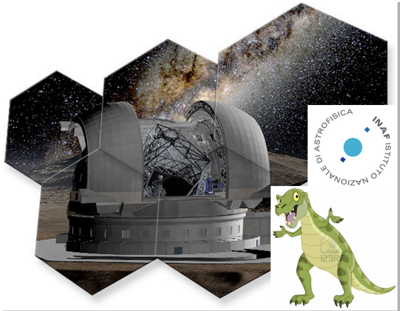
People & Institutes involved

Osservatorio Astronomico di Brera - INAF

Bianco, S. Basso, O. Citterio, M. Civitani, M. Ghigo, G. Pareschi, G. Pariani, M. Riva, G. Sironi, G. Tagliaferri, D. Tresoldi, G. Vecchi, F. Zerbi

Osservatorio Astrofisico di Arcetri - INAF

A. Riccardi, M. Xompero, L. Miglietta, R. Briguglio



WP “core business” & tasks

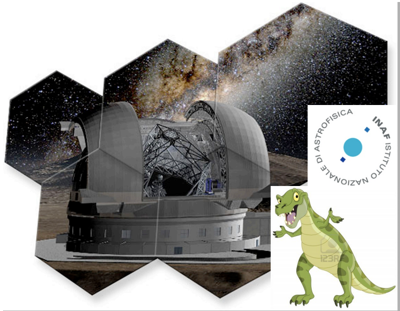
- Design, preparation activities, metrology and calibrations of the EELT mirrors (related to the subprojects in which INAF is involved)

- Support to the industry, by means of prototypes, breadboards and pilot plants, to get the final implementation

M4 ➔ executive design of the adaptive mirror, metrology & calibrations

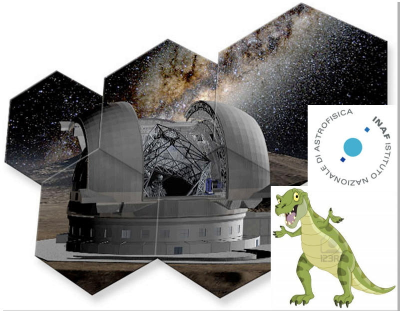
M1 ➔ support to the OpTIC/Zeeko Research+Media Lario effort : ion figuring + innovative metrology

MAORY ➔ pre-production of breadboards and innovative metrology



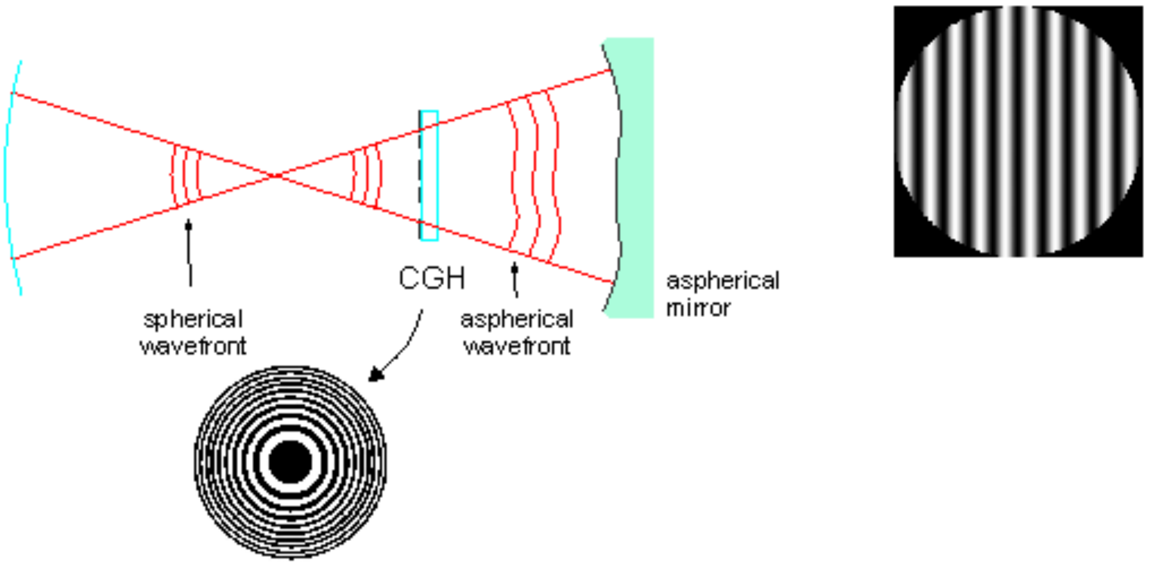
Main R&D activities

- Computer Generated Holograms (CGH) for interferometry of large surface mirrors
- Innovative profilometry of large surface mirrors
- High precision figuring via bonnet polishing and ion figuring
- Development of specific sw for the management and co-phasing of adaptive mirrors



Computer Generated Holograms:
reference surfaces in interferometrical tests

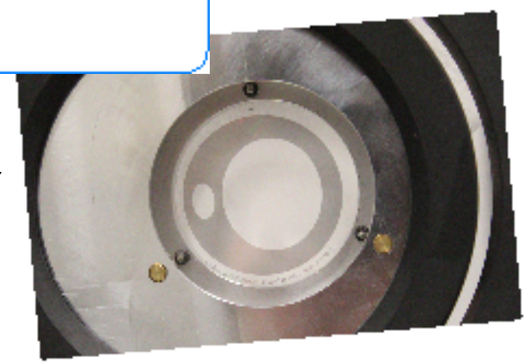
Null Test

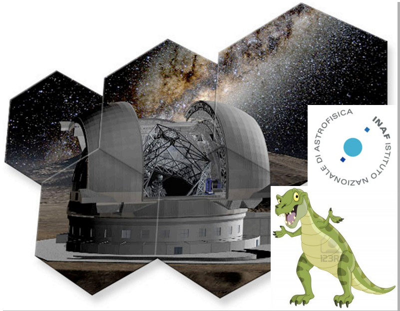


Computer Generated Holograms

CGH: binary representation of the interferogram between the spherical and aspherical wavefront under test. Each line adds $m\lambda$ of OPD and changes the wavefront slope by $\sin(\Theta) = m\lambda/\Lambda$, Λ is the local line spacing.

Binary amplitude and phase patterns





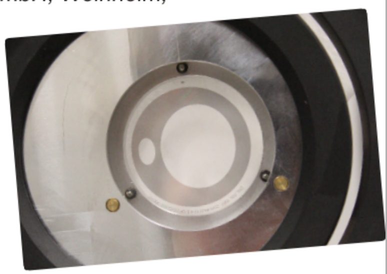
CGH: current capability

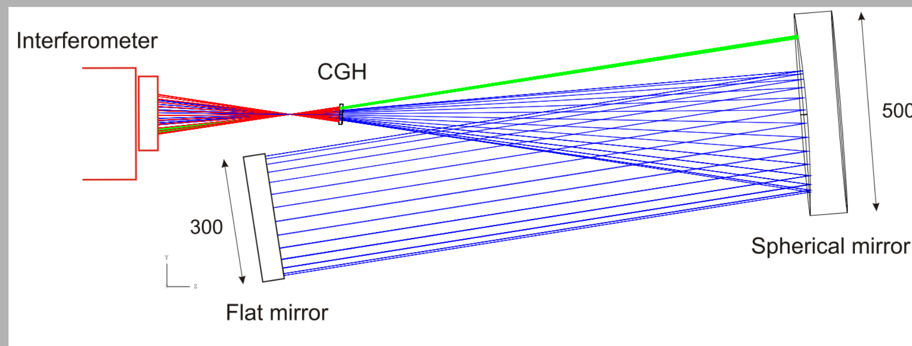
- Full design starting from optical layout: both for testing and alignment patterns
- Assembling of inteferometric set-up based on CGHs
- Performing measurement and data analysis

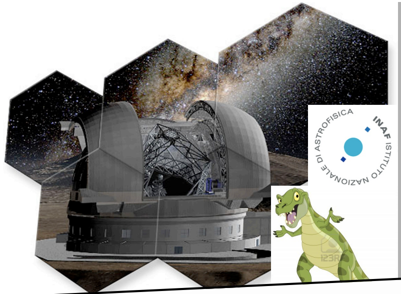
CGH test training facility

- The 500 mm spherical mirror is slightly tilted (4.5 deg, off-axis aberrations minimized)
- The 40 mm CGH introduces WF corrections to collimate the beam with the spherical mirror.
- The 300 mm plane mirror closes the cavity

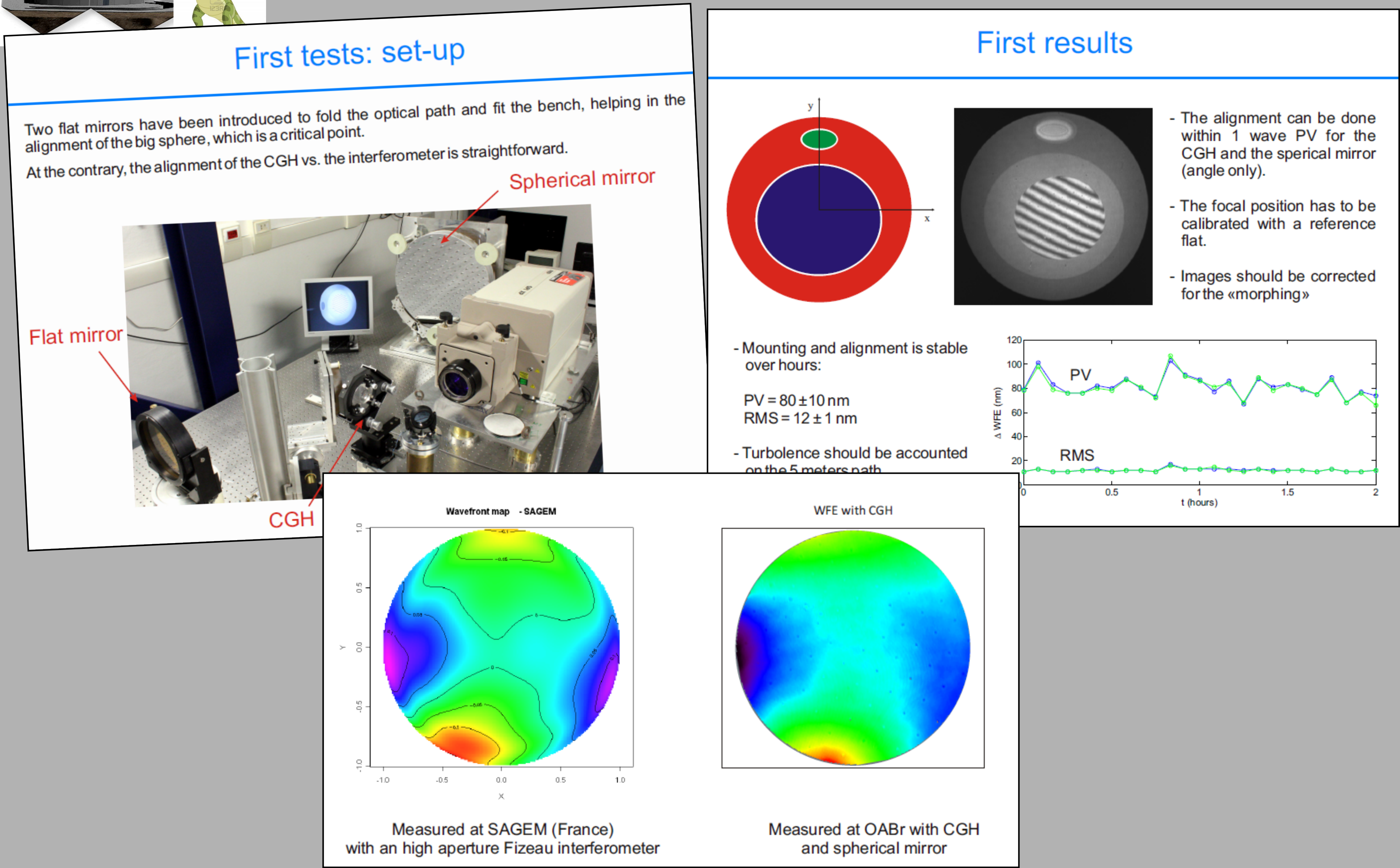
The CGH has been purchased from DIOPTIC GmbH, Weinheim, Germany





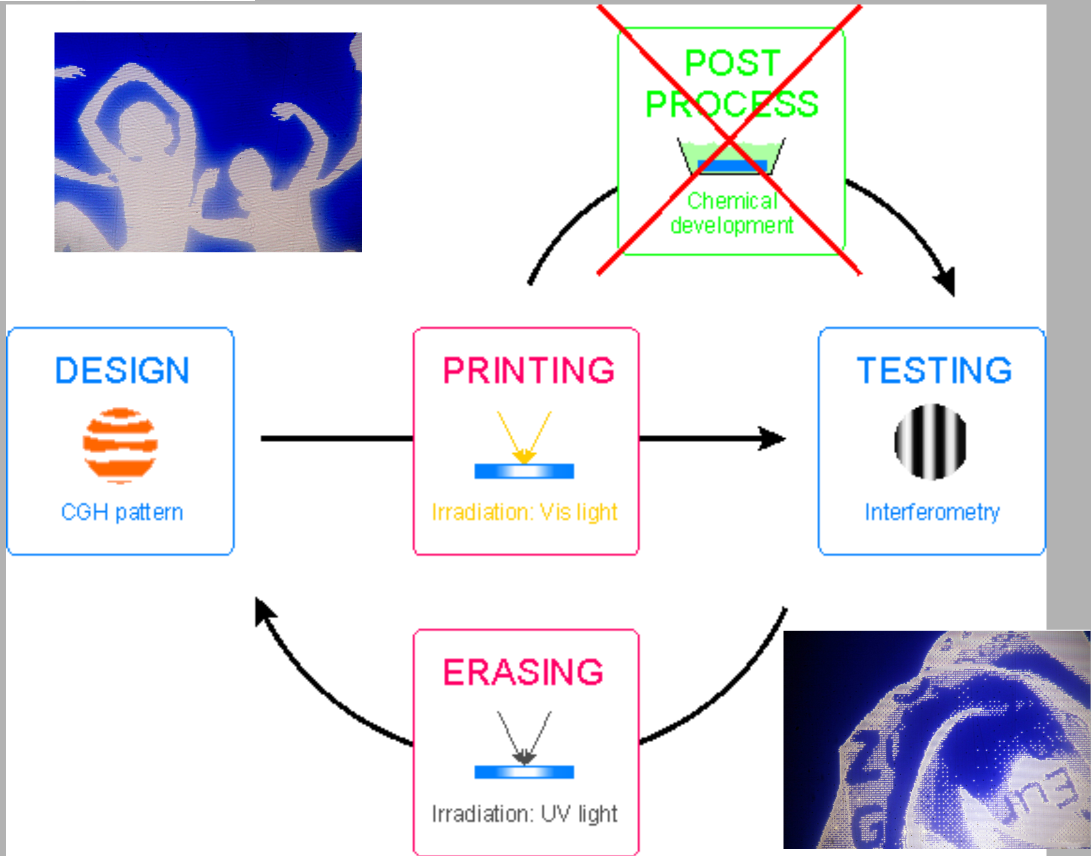


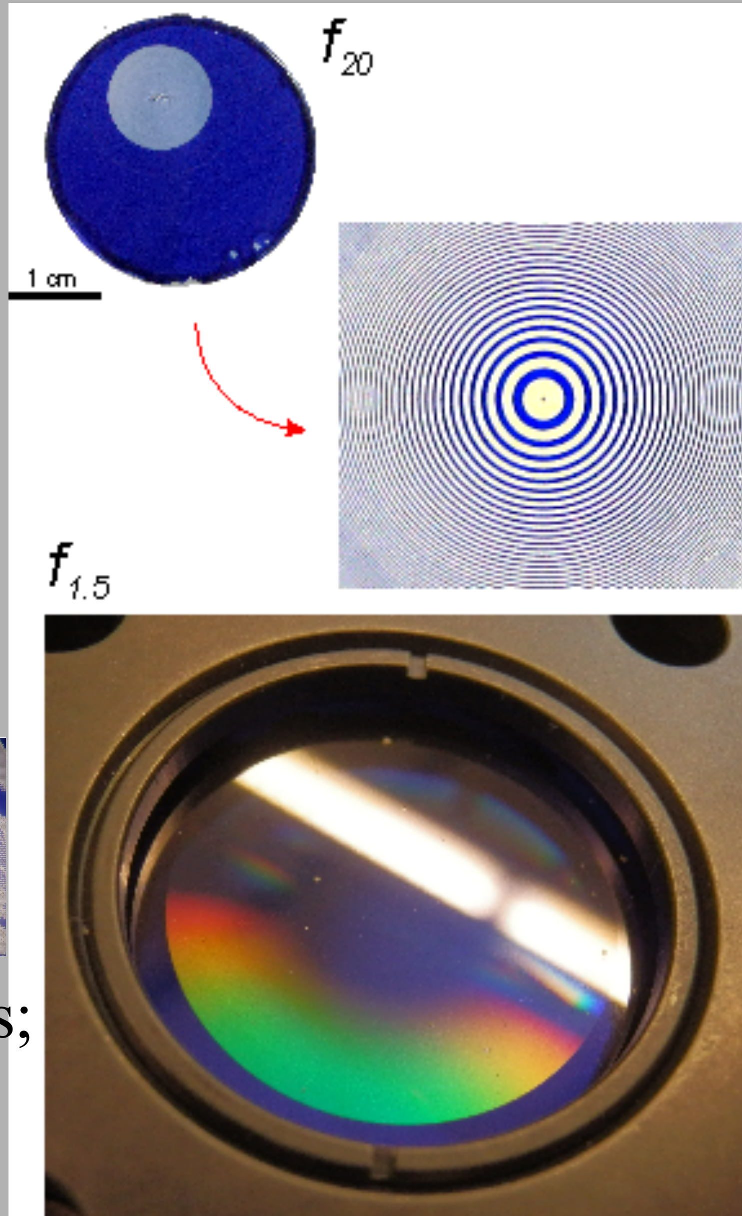
CGH test training facility



G.Pariani, et al *Proc. SPIE*. 8450, 84500Z (2012)

Rewritable Photochromic CGHs

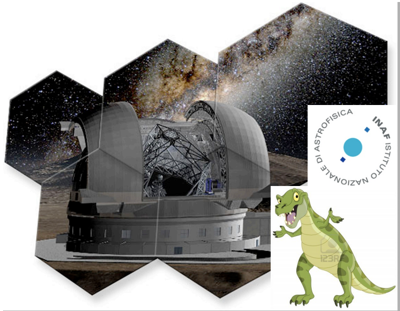




Easy to make: no complex developing process;
Fully rewritable using only light
Adaptable to different optics under test

G. Pariani et al, *Opt. Express, (2011)*

G. Pariani *et al, Proc. SPIE*. 8450, 845010 (2012)

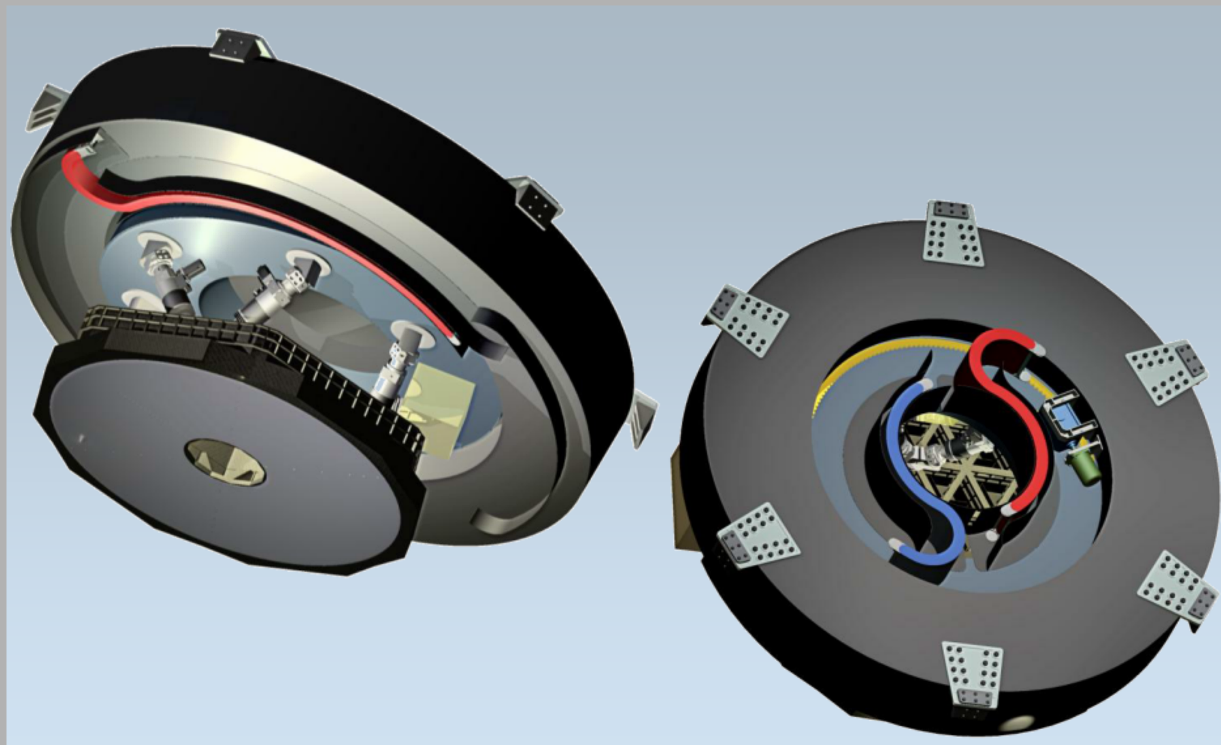


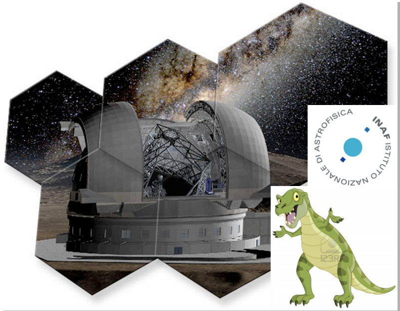
Breakthrough with rewritable CGHs

- Easy to adapt to the testing optics
- Online writing process combined with the interferometer
- Multiplexing
- Ideal for following the machining of a complex optics through the whole production: EELT M1 segments

M4 adaptive sub-unit

- M4 is a flat, 2.4-m diameter, segmented deformable mirror which will be controlled by ~5000 voice-coil actuators

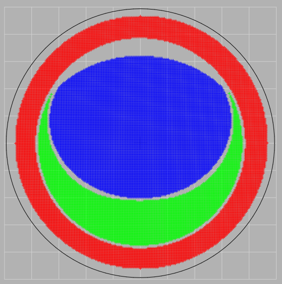




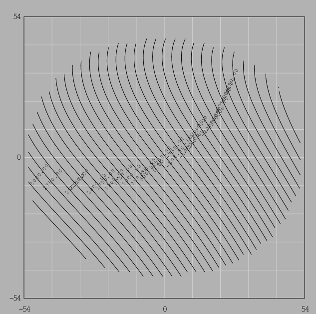
M4 optical test design

Vertical setup with CGH null corrector

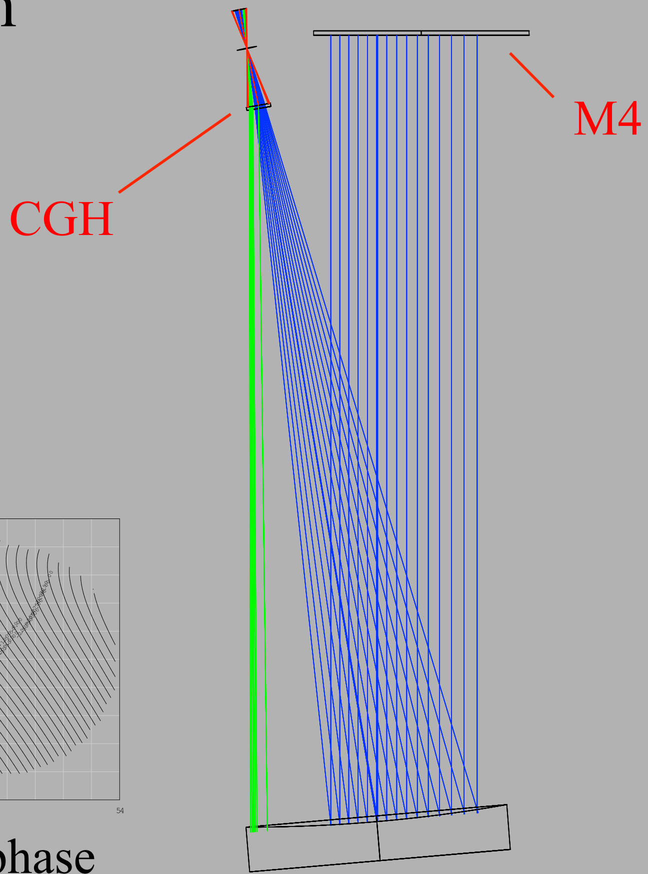
Optical design

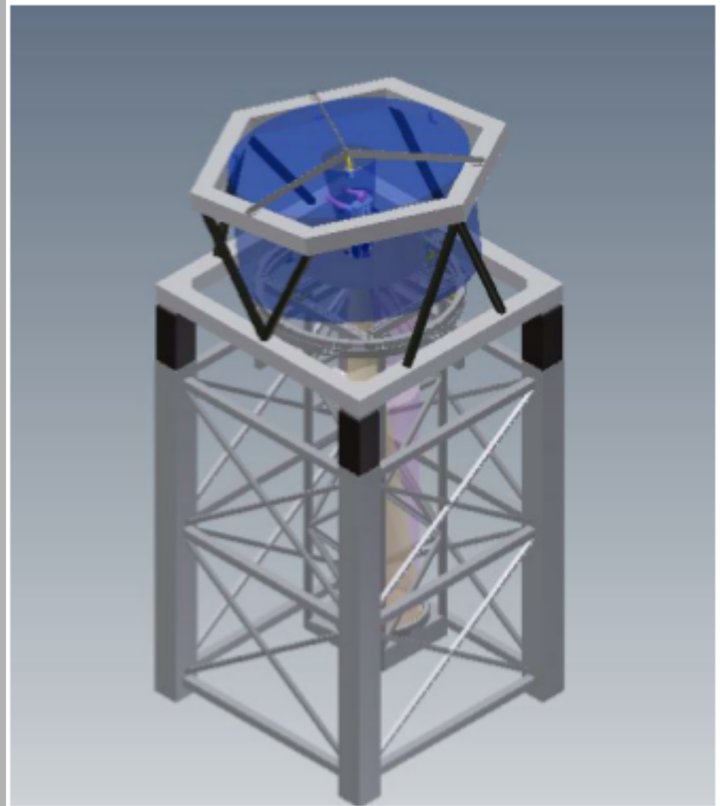


CGH pattern



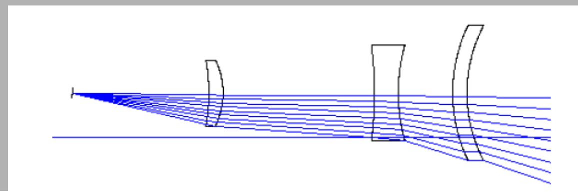
CGH phase

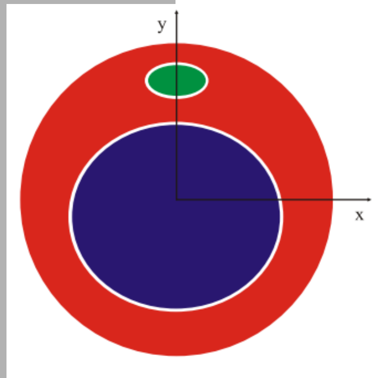


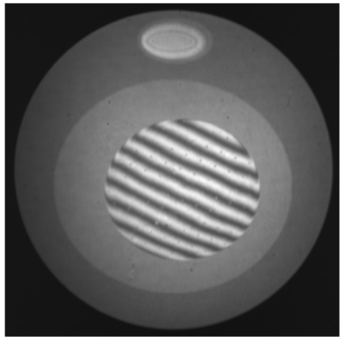


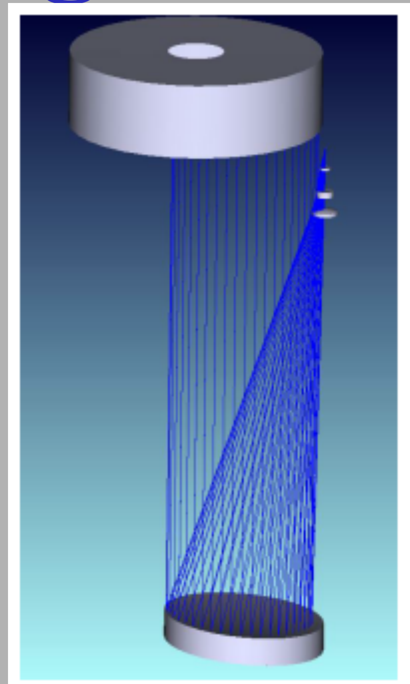
M4 optical test design

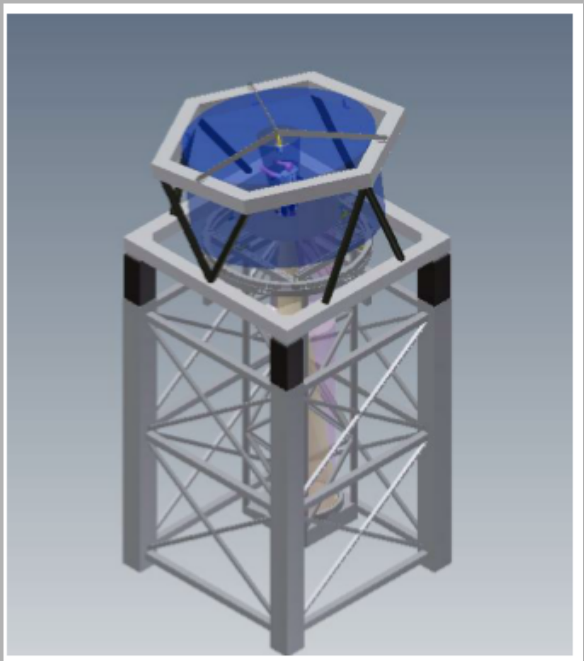
- Baseline Vertical:
  - Null Lens
  - CGH

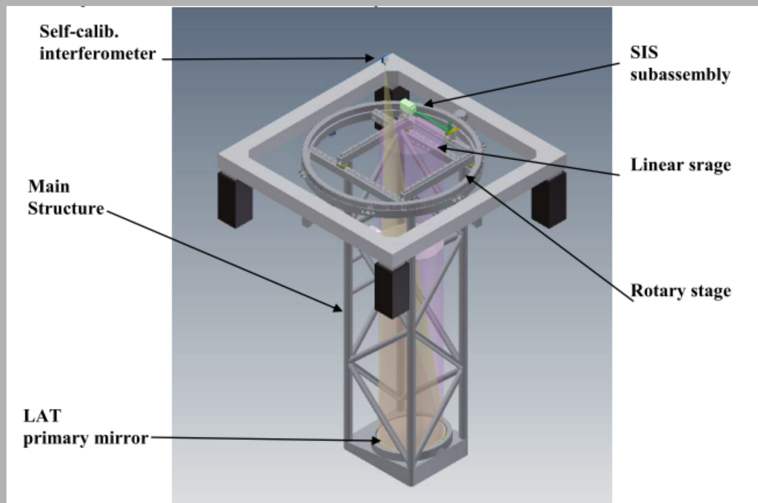


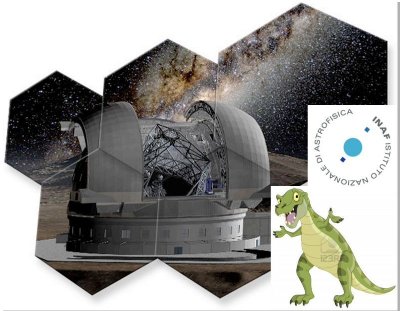












M4 Team Structure

Project Manager	
D.Gallieni	40%

Q.A.	
S.Rizzetto	20%

AO expert	
40%	A.Riccardi (OAA)

System Engineer	
M. Tintori	70%

Support to S.E.	
R.Biasi (MIC)	40%

ADS		
M. Tintori	Engineering	10%
M. Mantegazza	Design	80%
Paolo Lazzarini	Design	50%
Enzo Anaclerio	Prod.& Int. Manager	55%
M. Acerboni	Mechanics	60%
Isaac Facchin	Integration	50%
P. Fumi	Electronics	40%
L. Crimella	Drafting	70%

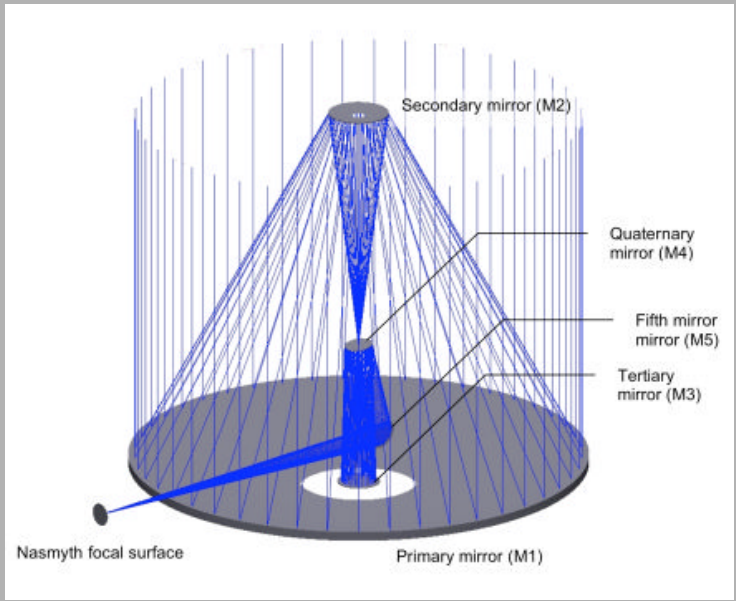
MIC		
M. Andrighettoni	Engineering, logic design	50%
G. Angerer	EL Design	60%
D. Pescoller	SW Design	20%
C. Patauner	Logic & SW design	60%
M. Messner	SW Design	30%
D. Veronese	EL Design	50%
A. Lattisi	Procurement	10%
A. Merler	EL-ME integration	50%
F. Picin	EL integration & test	60%
S. Palmarin	EL integration & test	50%

INAF		
F.M Zerbi	Team leader	20%
Emilio Molinari	Project Scientist	5%
Marco Xompero	AO	50%
Runa Briguglio	AO	50%
Giorgio Toso	Integration Test	10%
Giorgio Pariani	Optics	55%
Marco Riva	System Engineering	15%
Andrea Bianco	Special Optics	20%
Luciano Miglietta	Mechanics	20%
Daniela Tresoldi	Integration - Test	35%

DIA - POLIMI		
P.Mantegazza	Team leader	10%
M.Manetti	Numerical analysis	30%
M.Morandini	Numerical analysis	10%

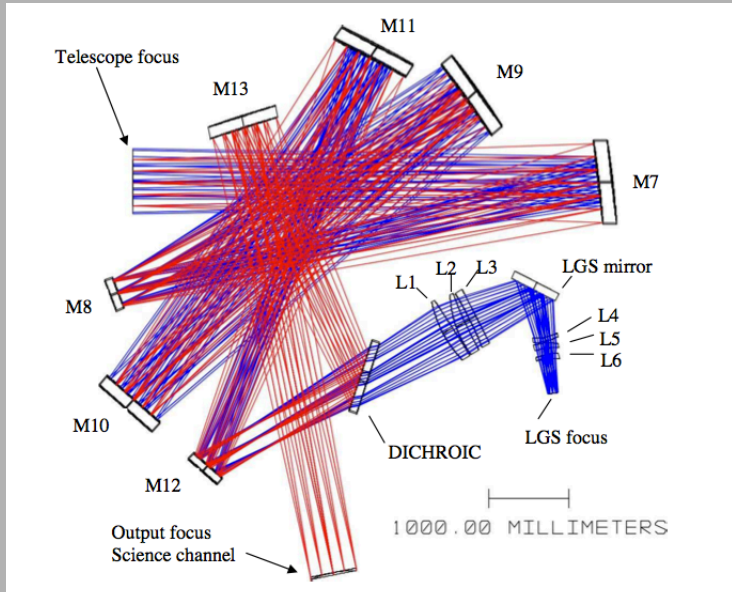
Metrologial needs

E-ELT, M1 segments



MAORY mirrors

DESIGN 2009



DESIGN 2010

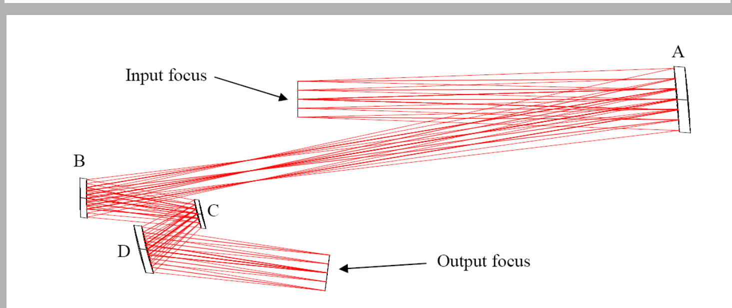
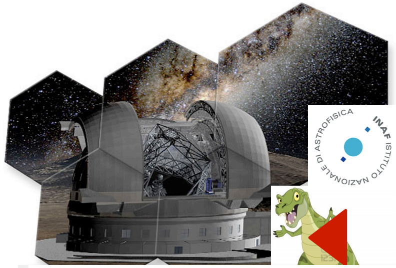
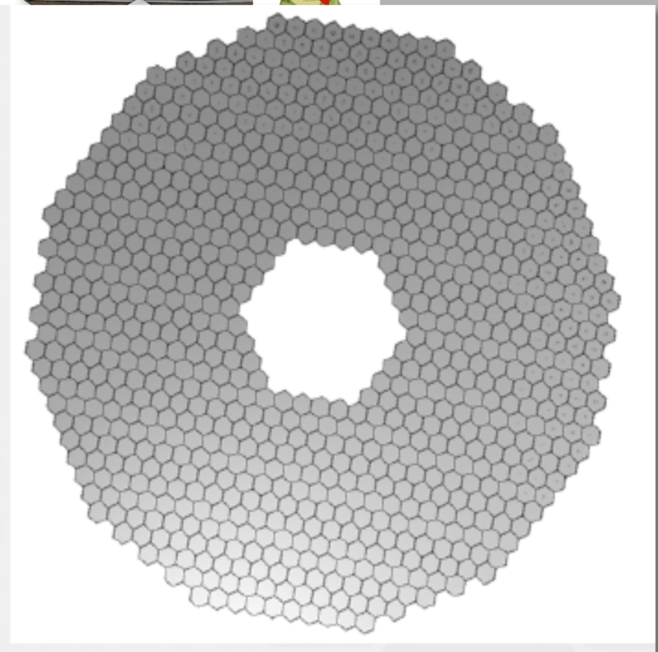


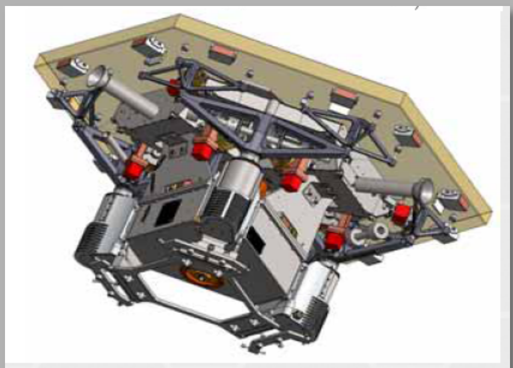
Figure 1. Optical layout of post-focal relay (unfolded version, science channel only).



The M1 segmented mirror

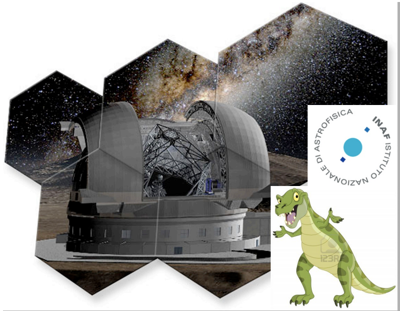


- Elliptical configuration, f-number 0.93 & 39 m diameter
- It will be formed 798 hexagonal segments (in addition 200 other segments, to ensure a proper maintenance turnover)
- 1.45 m maximum size for segments
- Each aspheric segment ➔ 25nm RMS accuracy & e 2nm microroughness

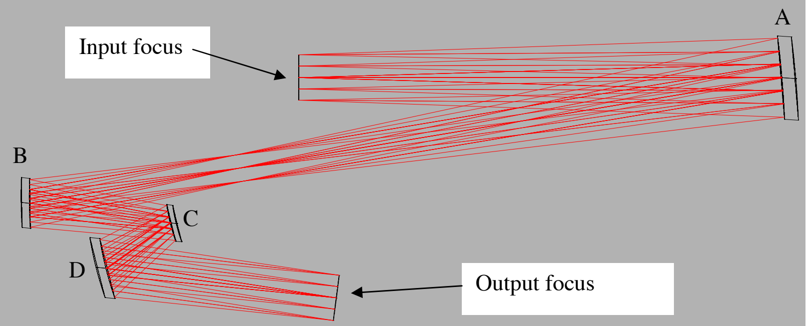


Production time : 4 years

Segment Assembly Delivery Rate (units per month)		
Minimum	Average	Maximum
16	26	36



MAORY mirrors

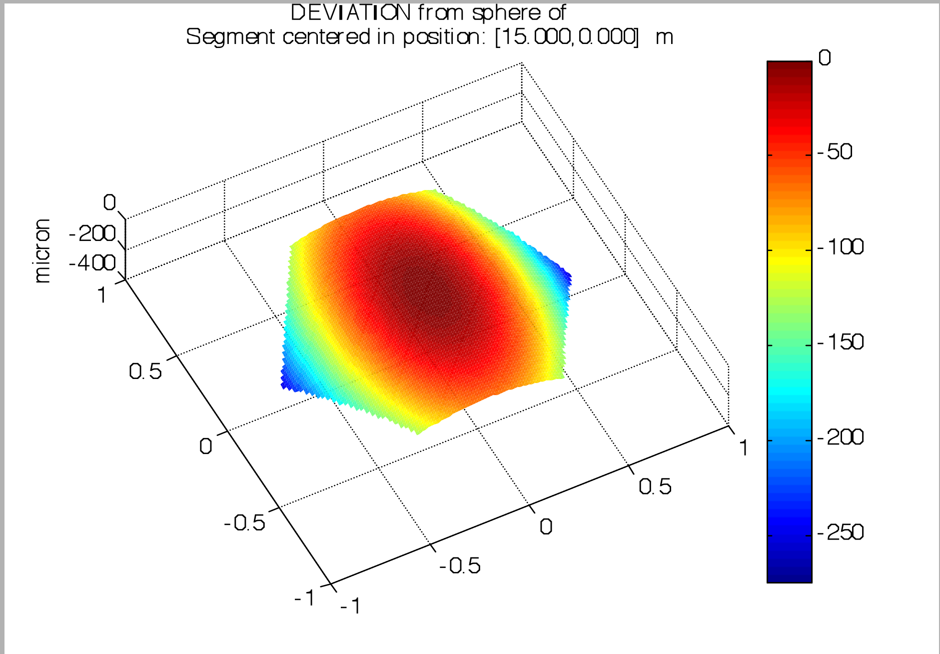


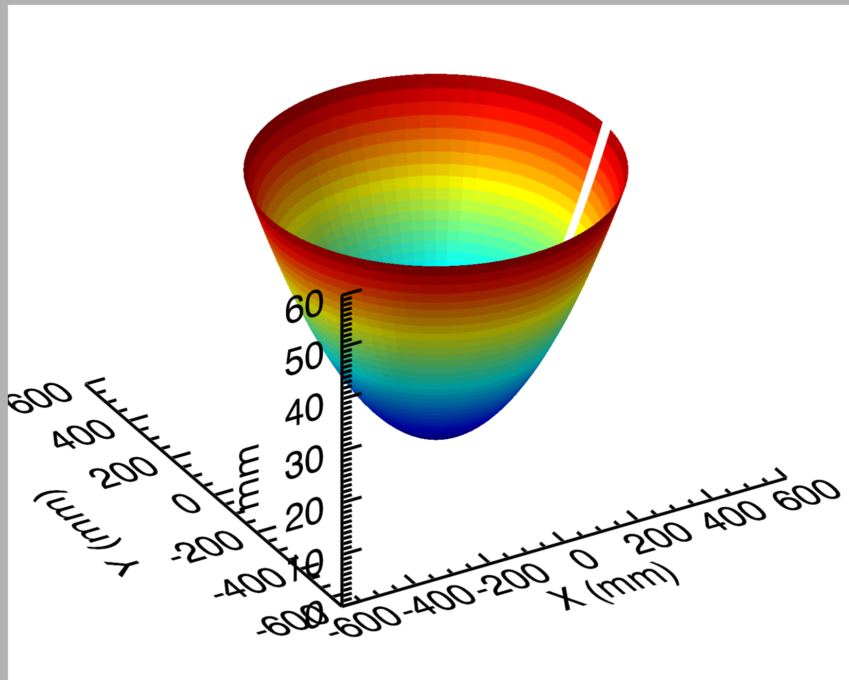
Mirror	Radius [mm]	Conic constant	4nd order asphere	6th order asphere	Off-axis Y [mm]	Size [mm]	Thickness
A	12000.0	-0.575760	N/A	N/A	1602.1	Ø 1050	175
B	6016.0	-1.124322	-3.054E-13	+7.823E-20	519.6	Ø 640	105
C	2005.5	-1.122826	-1.858E-12	+8.805E-19	613.6	Ø 460	75
D	3922.2	-1.175736	-2.395E-13	+2.652E-20	1213.7	Ø 740	125
E	Infinity	N/A	N/A	N/A	N/A	970×690	160

Mirror	Radius [mm]	Conic constant	4th order asphere	6th order asphere	Low-order surface RMS (Z5-Z10)	High-order surface RMS per footprint diameter
A	± 2.3	±0.000476	N/A	N/A	10 nm	10nm, Ø340mm
B	± 1.3	±0.000362	±2E-16	±2E-22	10 nm	10nm, Ø340mm
C	± 0.1	±0.000074	±1E-15	±7E-22	10 nm	10nm, Ø150mm
D	± 0.1	±0.000137	±2E-16	±4E-23	10 nm	10nm, Ø170mm
E	N/A	N/A	N/A	N/A	15 nm	10nm, Ø120mm

Optical quality requirements

MAORY B





Maximum diameter 1.45m (M1 segments)

Maximum surface slope: 6° (MAORY "B")

Rms accuracy: < 10 nm

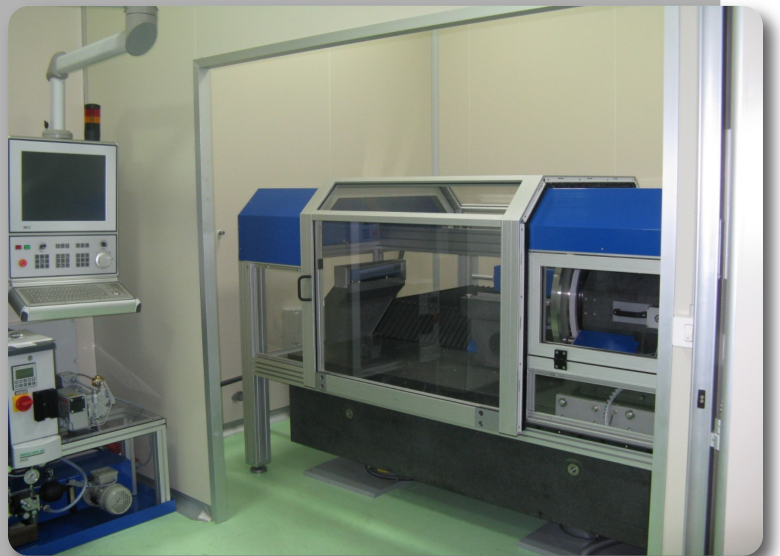
Why a Profilometer

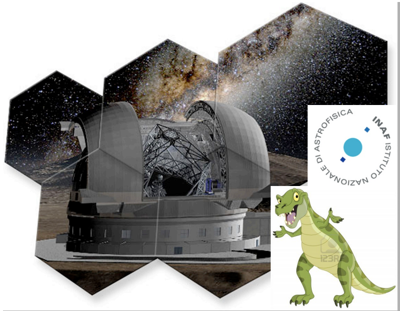
- Profilometry gives a great flexibility!

- It can measure concave, convex and flat profiles without any specific optical components for each shape (as instead required by interferometric measurements !)

- Easy set up for the measurement

- Heritage from swing arm and mpr (eRosita) profilometers





Swing arm profilometer achieved results

@ Steward Observatory, Arizona

Optical Engineering 51(4), 043604 (April 2012)

Swing-arm optical coordinate measuring machine: modal estimation of systematic errors from dual probe shear measurements

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Abstract. The swing-arm optical coordinate measuring machine (SOC), a profilometer with a distance-measuring interferometric probe for *in situ* measurement of the topography of aspheric surfaces,has been used for measuring highly aspheric mirrors with a performance rivaling full aperture interferometric tests. Recently, we implemented a dual probe, self-calibration mode for the SOC. Data from the dual probes can be used to calibrate the swing-arm air bearing errors since both probes see the same bearing errors while measuring different portions of the test surface. Bearing errors are reconstructed from modal estimation of the sheared signal. *© 2012 Society of Photo-Optical Instrumentation Engineers (SPIE).* [DOI: 10.1117/1.OE.51.4.043604]

Subject terms: swing-arm profilometer; profilometry; aspherics; optical testing; stitching; shear test.

Paper 111224P received Sep. 30, 2011; revised manuscript received Feb. 2, 2012; accepted for publication Feb. 10, 2012; published online Apr. 6, 2012.

1 Introduction

The swing-arm optical coordinate measuring machine (SOC) is an important metrology technique for highly aspheric surface testing[1–4] because of its versatility and high accuracy. It is configurable for measuring concave, convex, and plano surfaces; can make *in situ* measurements; and has high precision performance that rivals full aperture interferometric tests.

In our previous work on SOC, we used an independent test method to calibrate SOC systematic errors.[3] Here we show a method for calibrating the SOC with a dual probe lateral shear that makes the SOC self-calibrating. The shear test allows us to reconstruct the test surface without using an external reference. The method we describe is analogous to methods using shear in absolute testing to separate the errors in the test device from errors in the measurand. The shearing method can be applied in either one, as in our case, or two dimensions.[5,6]

Evaluating lateral shearing data has long been discussed in the literature, and several reconstruction methods have been proposed. One of the methods frequently applied is the modal method.[7,8] It models the underlying wavefront or surface signal by a polynomial whose unknown coefficients are determined by least squares. The degree of the polynomials usually has to be chosen in advance. The modal method works particularly well when the signals are smooth. The zonal method, such as Southwell integration,[9] retrieves the wavefront or surface data at discrete measurement points and solves a set of corresponding equations. It can also retrieve the data in a least-squares sense and has the advantage of using regular trapezoidal integration. However, this requires that the lateral shear equals the spacing of the measurement points. For the case where the shear is not small, and does not assume *a prior* knowledge of the wavefront or surface, Elster[10] proposed a particular solution with so-called natural extension and discrete Fourier analysis. By choosing two different shears, the wavefront or surface can be reconstructed exactly at all measurement points.

In this paper, we first review the basic principle and performance of the SOC. Then the design and implementation of a dual probe self-calibration are described. A modal estimate using a Fourier series is chosen to retrieve the swing-arm bearing errors based on our prior knowledge of typical bearing errors for our system.

2 Basic Principle and Performance of the SOC

The basic geometry of the swing-arm profilometer is shown in Fig. 1. A probe is mounted at the end of an arm that swings across the optic under test such that the axis of rotation of the arm goes through the center of curvature of the optic. The arc defined by the probe tip trajectory, for a constant probe reading, lies on a spherical surface defined by this center of curvature. For measuring aspheric surfaces, the probe, which is aligned parallel to the normal to the optical surface at its vertex, reads only the surface departure from spherical. The SOC uses this simple geometry with an optical, non-contact, interferometric probe that measures continuously across the optic. The optic or test part is rotated in azimuth after each profile is measured. The interferometric probe being used is an all-fiber phase-shifting interferometric probe that provides precise, non-contact surface measurements with sub-nanometer sensitivity over a 6-mm range. A spherical wave comes out of the tip of a single mode fiber, reflects from the test surface, and goes back into the fiber. The light reflected from the surface interferes with the light reflected from the fiber tip. Figure 2 shows the basic principle of the fiber distance-measuring interferometric probe. Since a spherical wave from the fiber is incident on the test surface, light from the surface gets back to the probe even when there is an angle of the test surface relative to the probe. This makes the probe insensitive to the angular variation of the test surface up to roughly ±5 deg, giving the probe a large angular

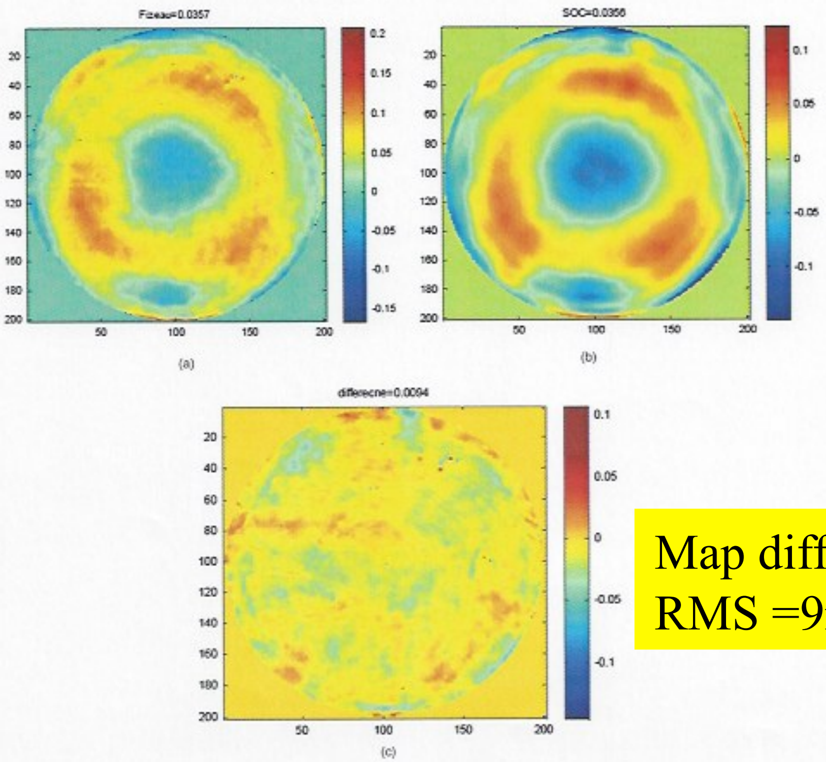


Fig. 4 Comparison of the (a) interferometric Fizeau test data and (b) SOC data, with tilt, power, coma, astigmatism, and trefoil removed. Fizeau test data rms = 0.0357 μm; SOC data rms = 0.0356 μm. (c) The direct subtraction shows only 9 nm rms difference, much of which appears to come from the interferometric test.

Map difference
RMS =9nm

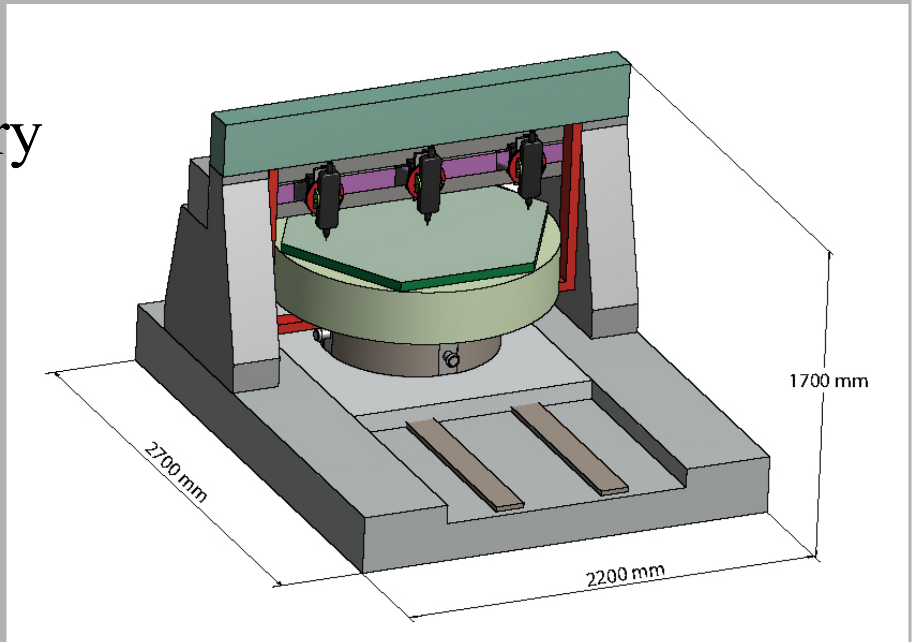
NB: Swing arm profilometers cannot measure the radius of curvature!

Profilometer under-development @OAB : main features

- fast measurement runs!

- accuracy comparable to interferometry

- all measurements referred to a single reference bar



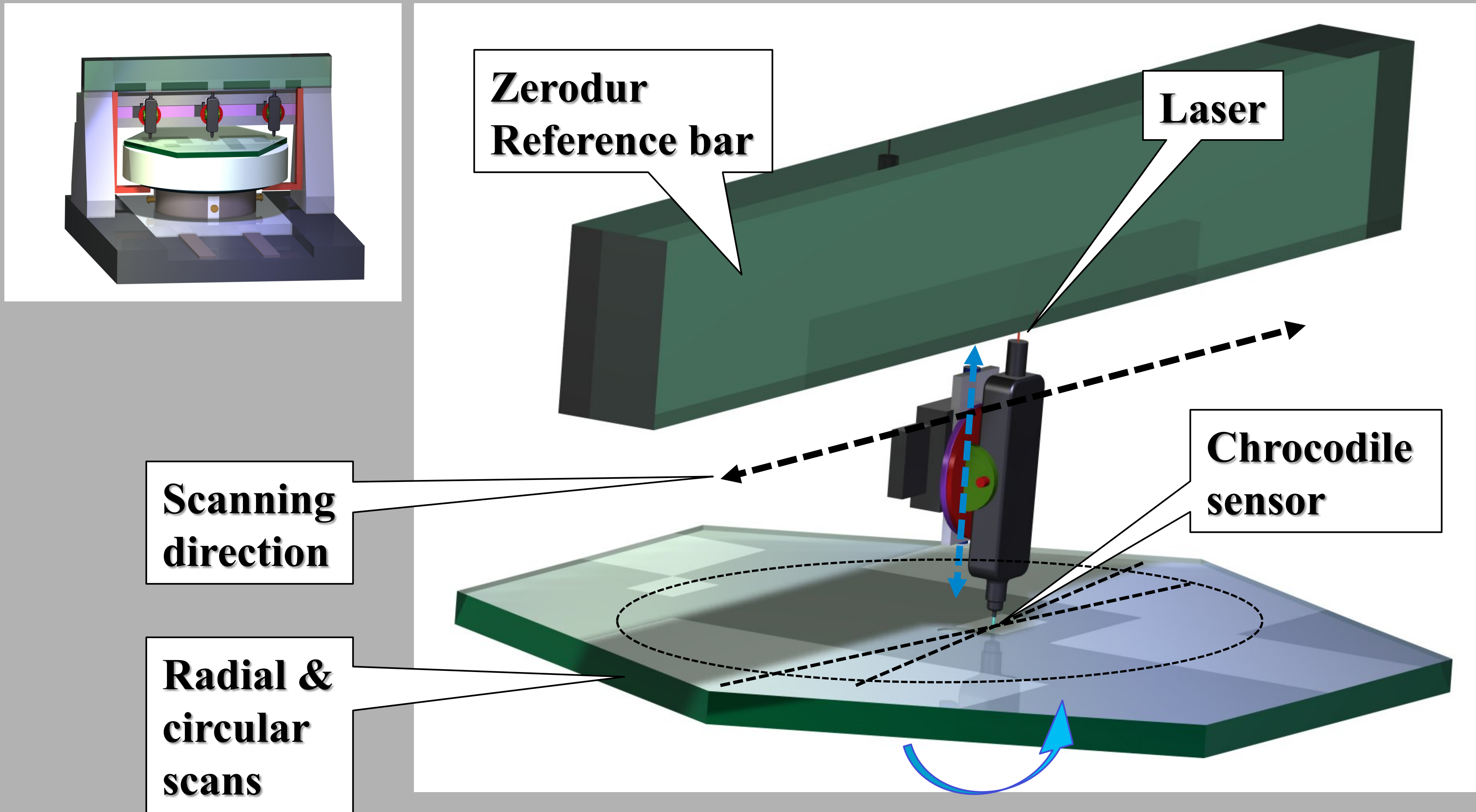
- automatic alignment procedure

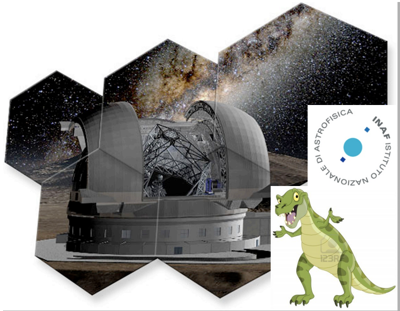
- it measures roc and low frequency errors

- Profile follower **(combination of confocal probe plus laser interfer.)**

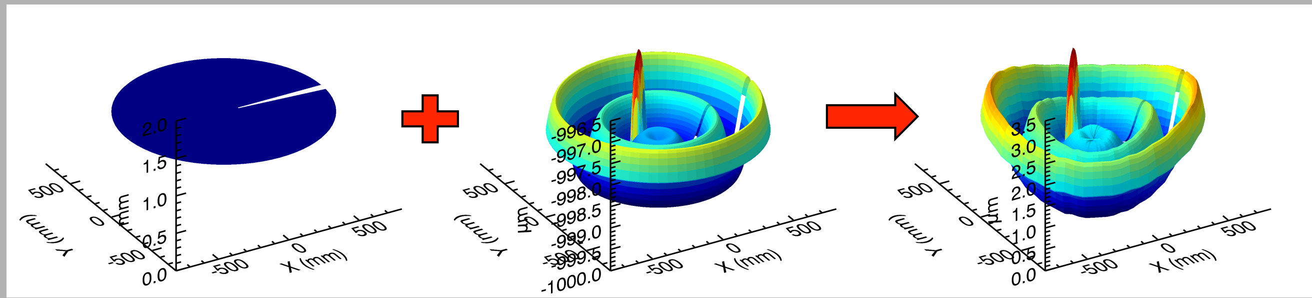
- It can allows laser interferometric measurements on curved surfaces

Working principle

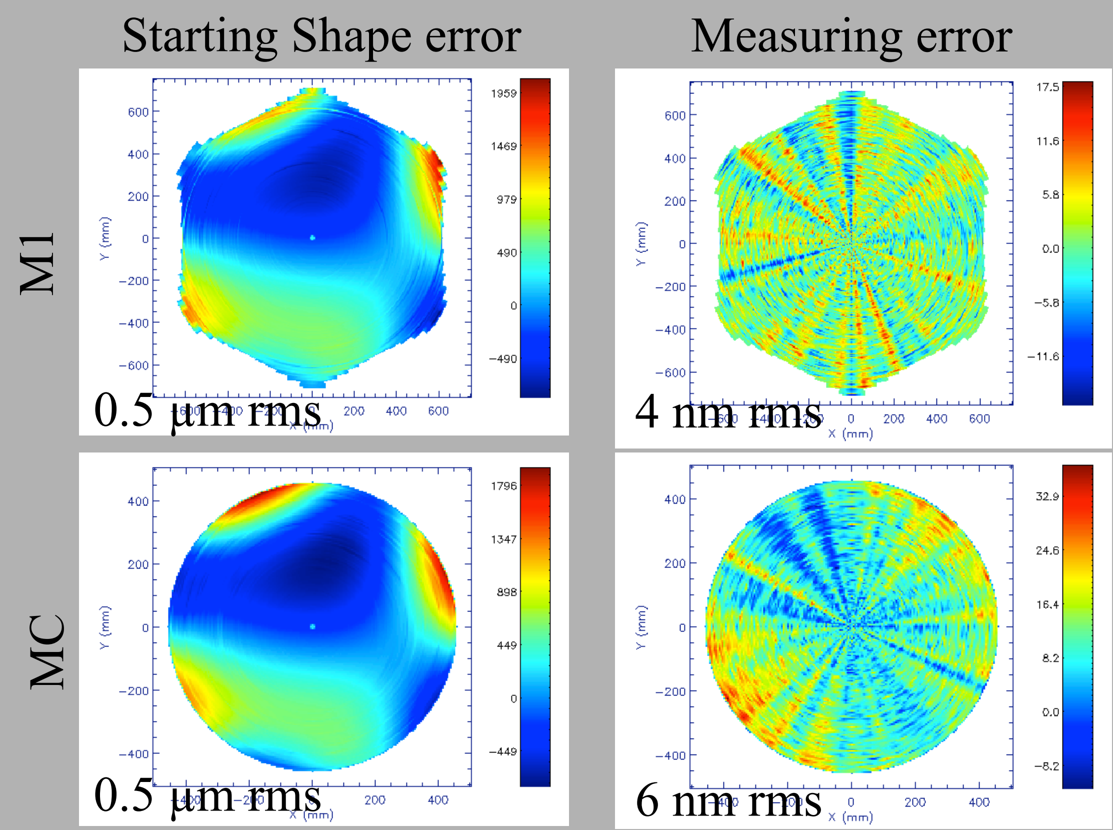




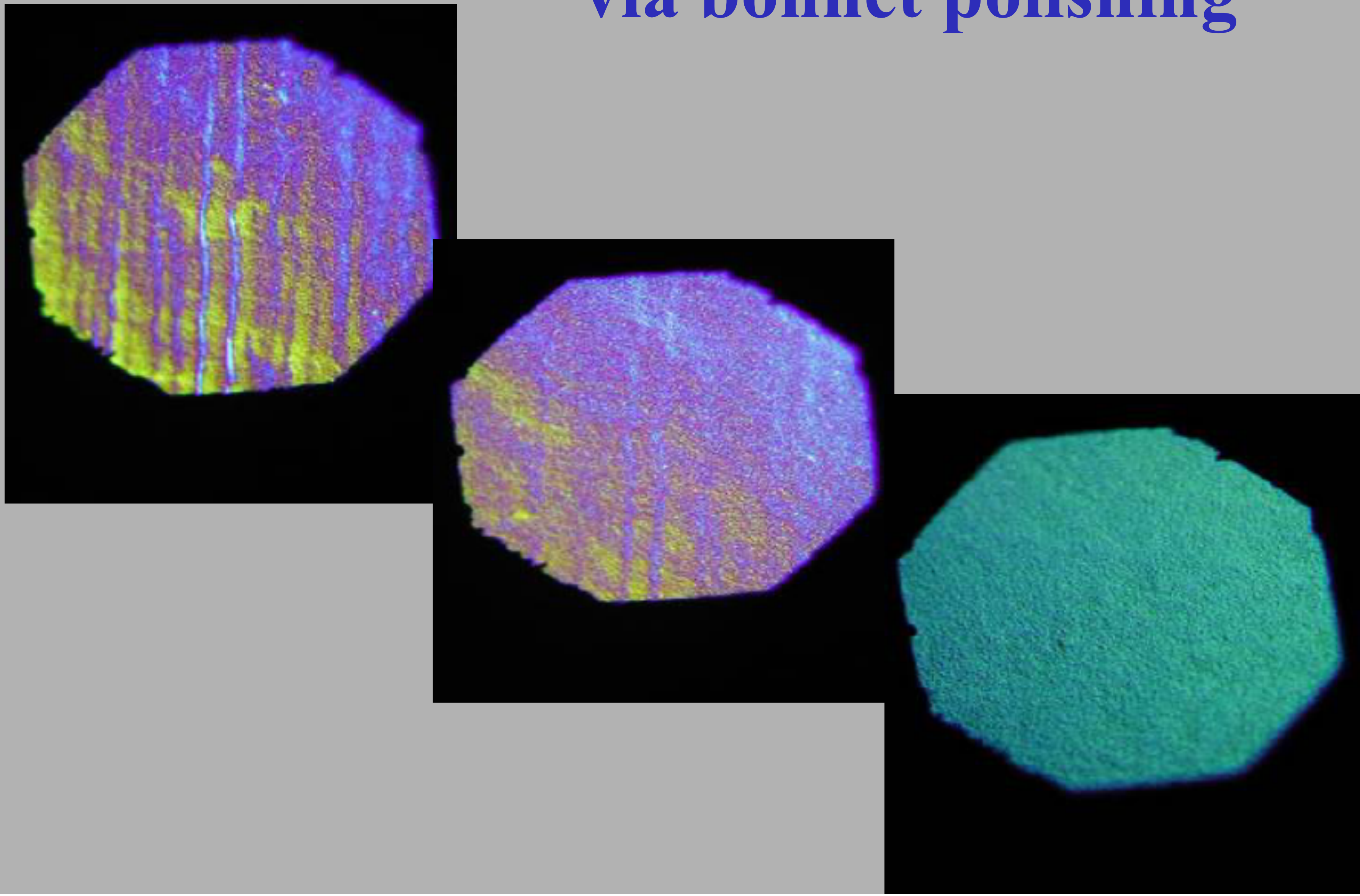
Measuring Simulation

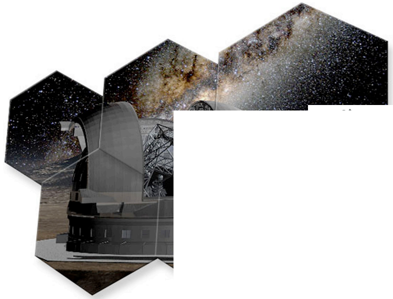


Parameter	Value
Wobble	0.1 ‘’
RunOut	0.15 µm
Piston	20 nm
Straightness	1.2 µm
Positioning Error	0.1 ‘’
Sensors noise	3 nm [rms]
Laser noise	2 nm [rms]



Removal of Mid-Frequencies via bonnet polishing

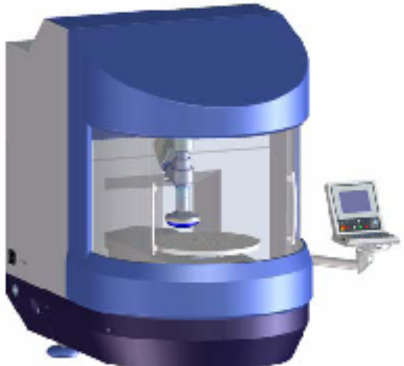




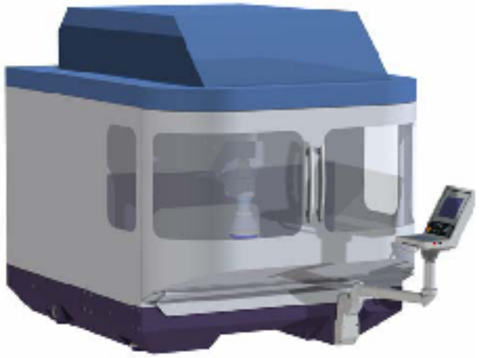
The Zeeko Machine Range for Optics Manufacture

IRP 200

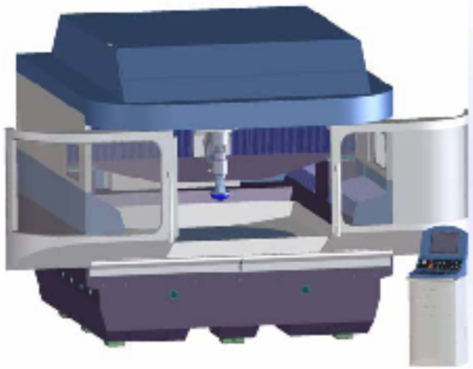
IRP 400



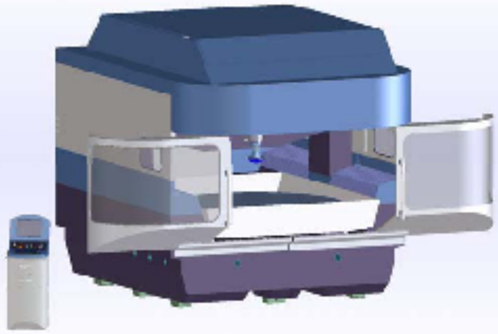
IRP 800



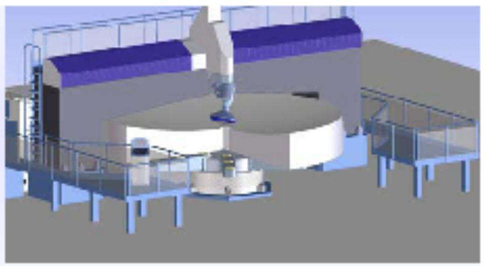
IRP 1000 -1200



IRP 1600

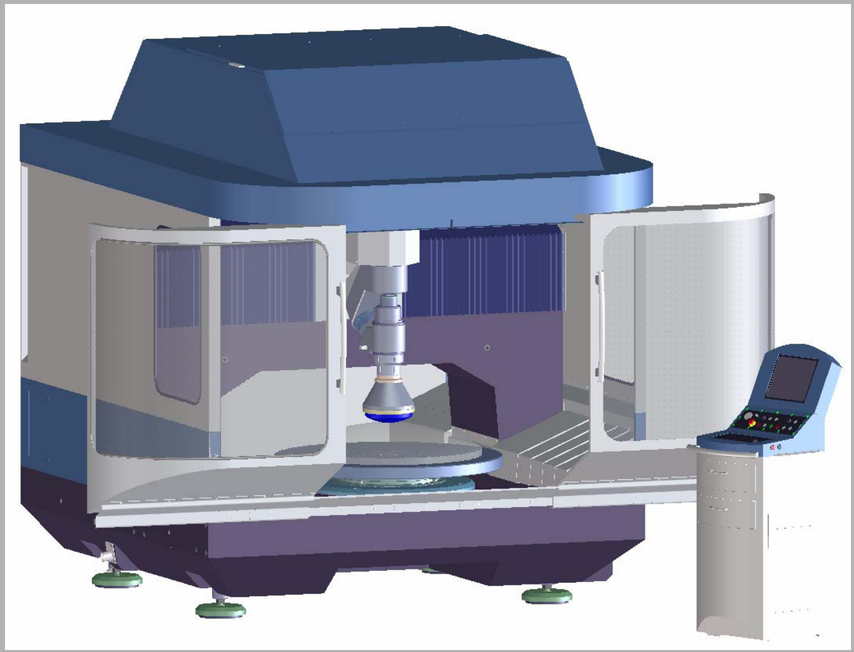


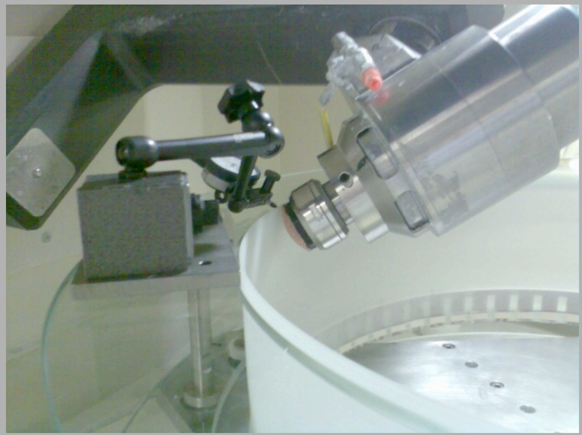
IRP 2400



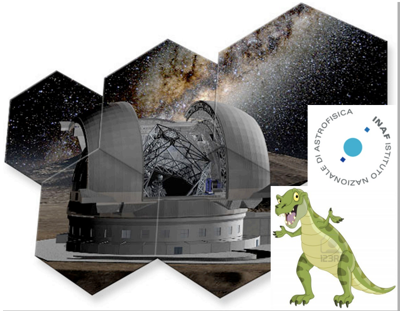
The 3 to 6 Metre Astronomical Range

Zeeko bonnet polishing



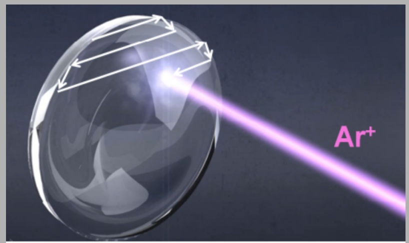


One 1200 Zeeko machine is being implemented at OAB. It will be used to produced breadboards



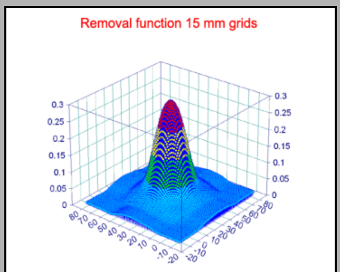
IBF technology

- Deterministic Process
- Pressurless Technique (For Lightweight Optics)

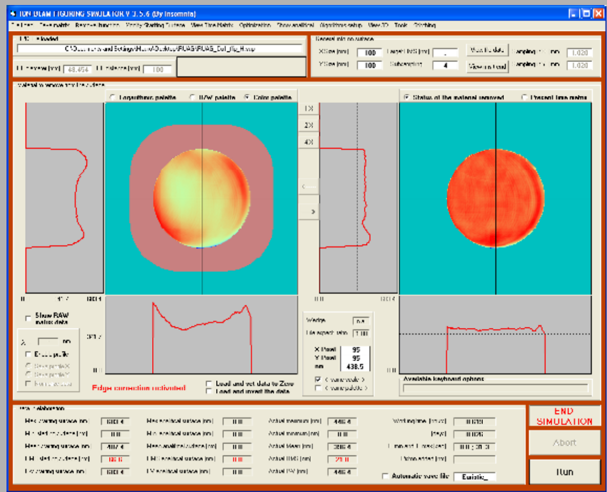


Optic to be corrected

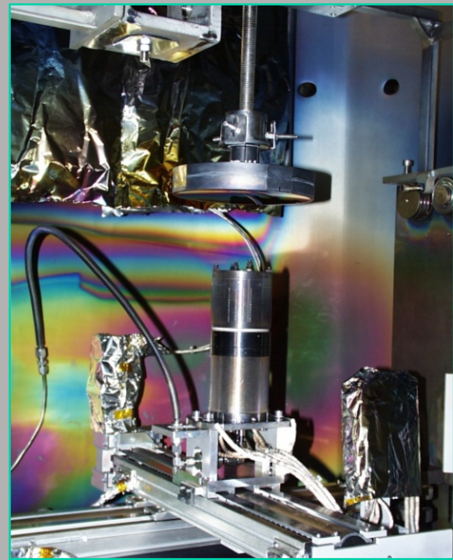
Interferometrical measure



Removal function



Time matrix computation



- Figuring possible on optics already assembled
- Stable removal rate (50/100 nm min.)

Facilities operated @ INAF-OAB

FACILITY 1

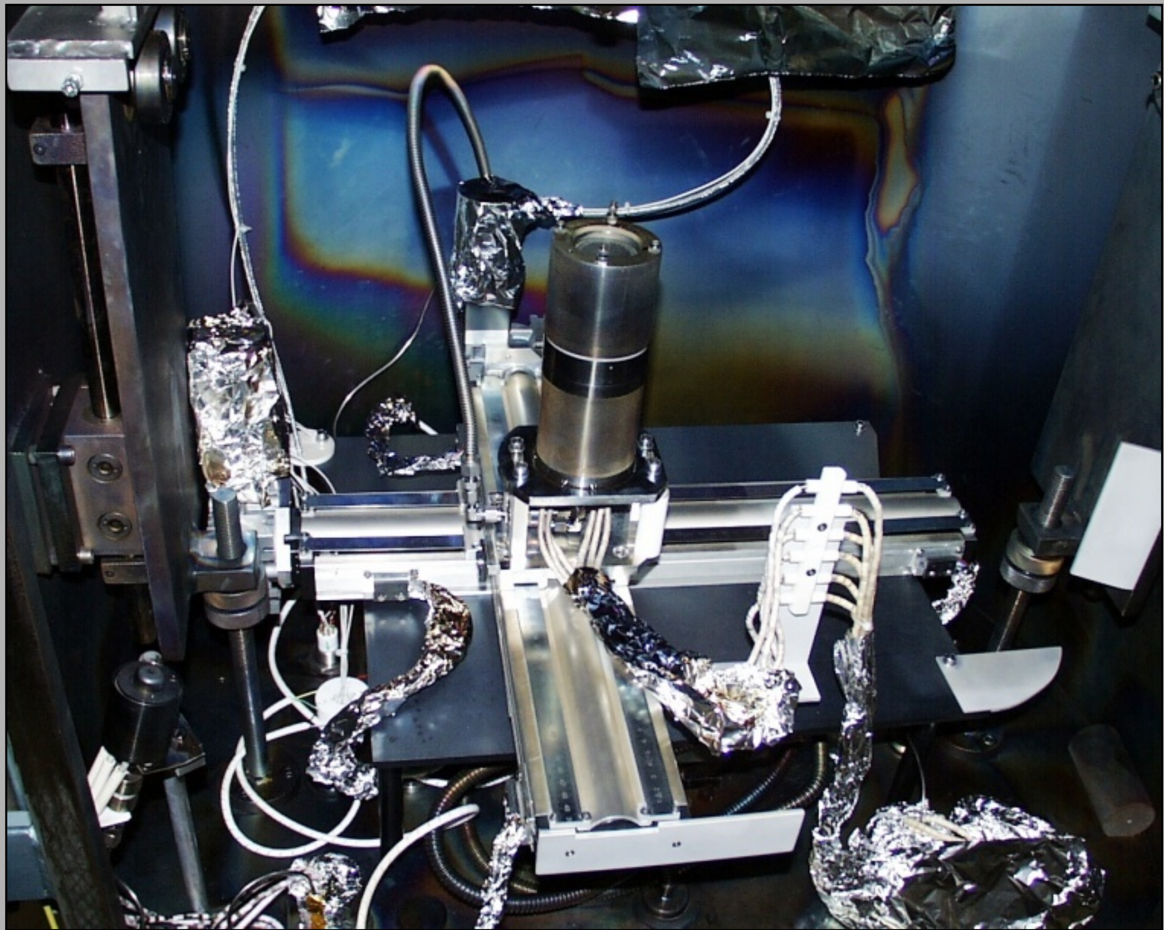
Mirrors up to 350 mm in diameter

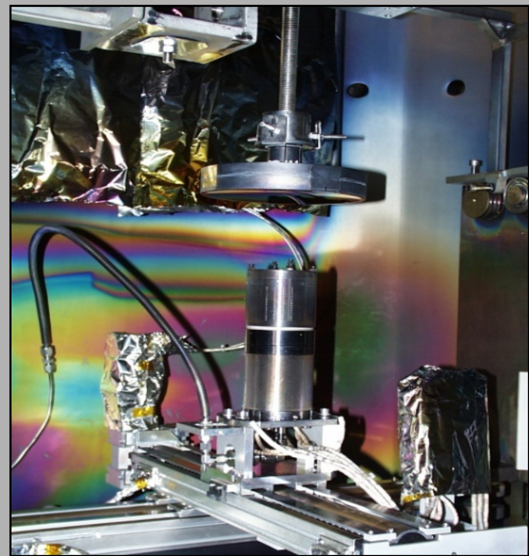
FACILITY 2

Mirrors up to 1500 mm in diameter

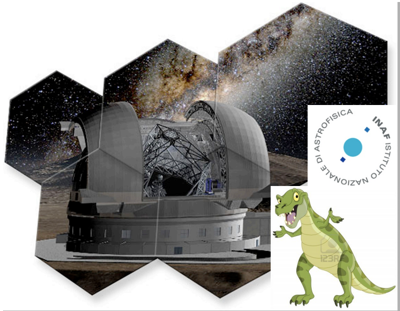
Ion figuring facility

System able to figure optics up to 350 mm in diameter

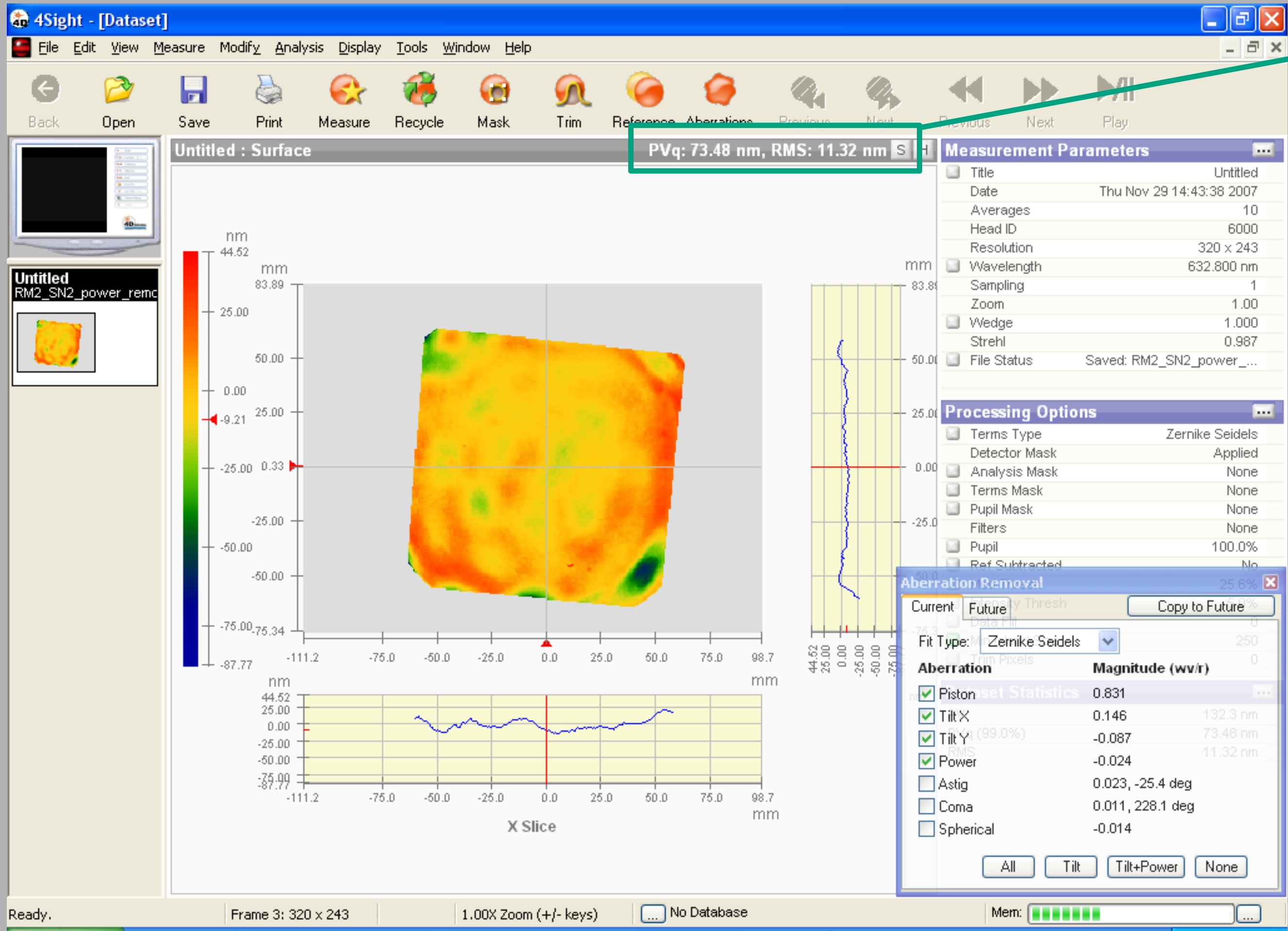




Internal view of the facility



Mirror RM2-sn2 belonging to the optical train of NIRSPEC/JWST



Wavefront error.
The error on the surface is half than this

Initial surface:
PV: 321 nm
Rms: 81.15 nm
λ/7.8 (@632.8 nm)
Microrough. 3 A rms

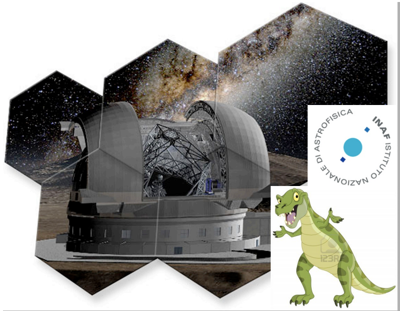
Final surface:
PV: 36.74 nm
Rms: 5.66 nm
Microrough. 4.2 A rms

λ/111.8 (@632.8 nm)

Final surface obtained

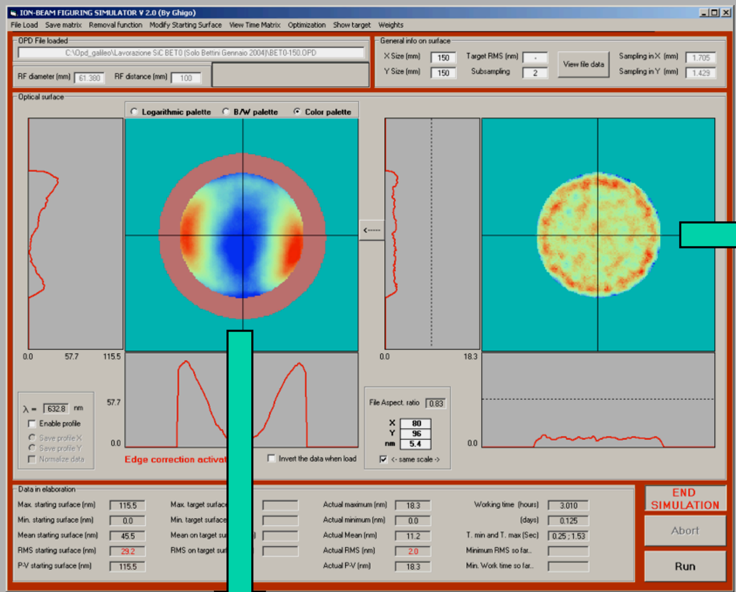
INAF

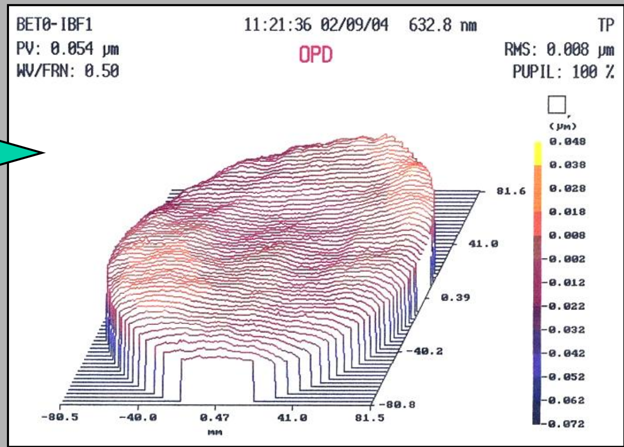
Galileo Avionica



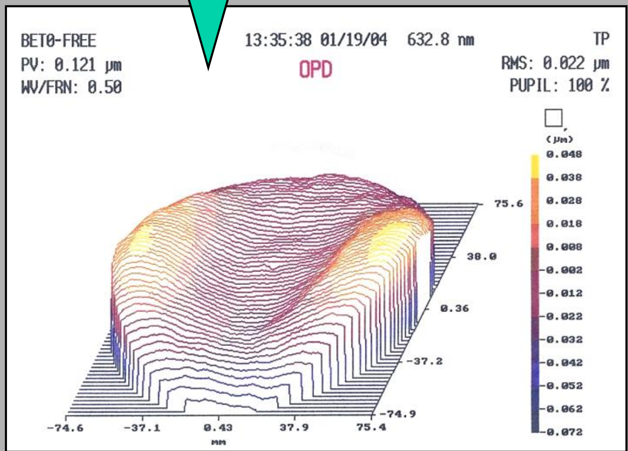
IBF on a spherical mirror for NIRSPEC/JWST

Theoretical computation





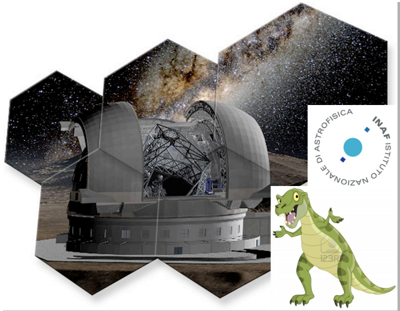
Final surface (residuals)



Initial surface (residuals)

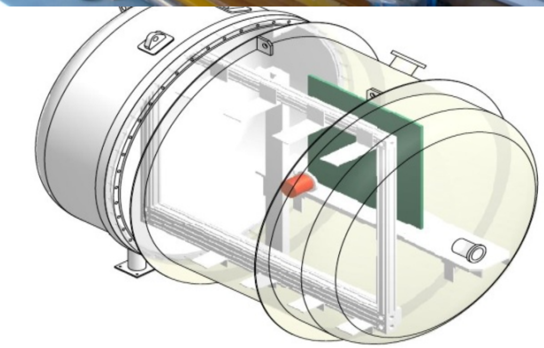
Shape correction of a 150 mm SiC mirror (λ=632.8 nm)

- Starting sup: 22 nm rms (λ/28), 121 nm p-v
- Final sup: 8 nm rms (λ/79), 54 nm p-v
- Working time: 2.0 hours

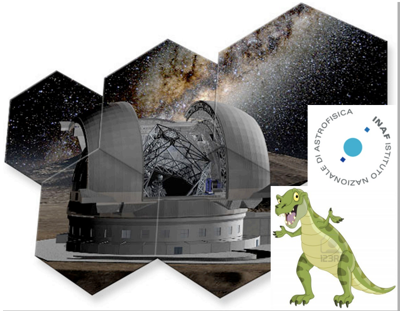


A close view of the new ion figuring plant @OAB

The system is able to figure optics up to 1.5 m in diameter



Two gridset:
- 50 mm for broad beam
- 15 mm focused beam



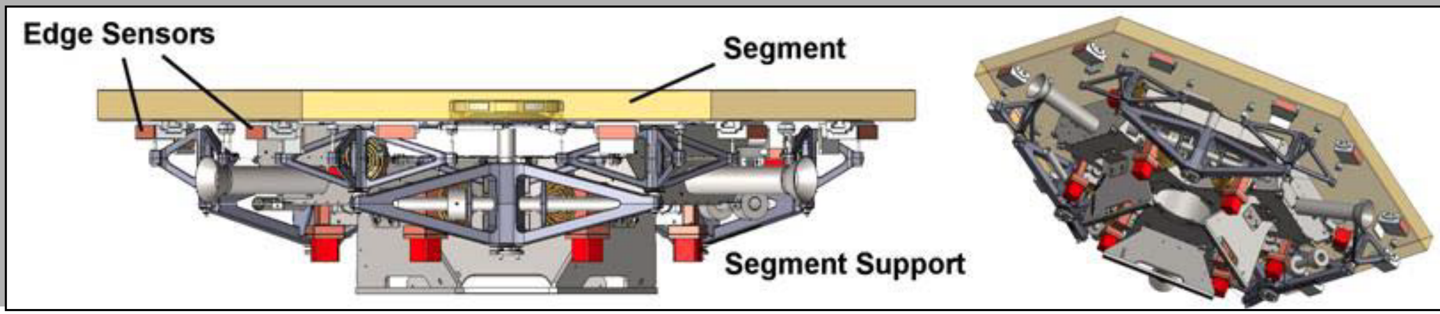
IBF of the ELT/M1 Demonstrative Mirror for M1

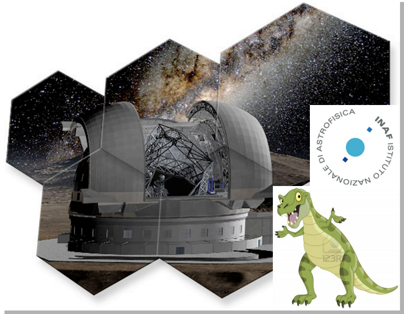
(in collaboration with OPTIK and Media Lario)

1) Figuring of a spherical 1 meter size mirror having RoC of 3 meters with its metrology done in INAF-OAB.

2) Figuring of a spherical 1.4 meter size mirror having RoC of 69 meters and measured with the profilometer developed

3) Figuring of a spherical full size hexagonal 1.4 size mirror with RoC of 69 meters and measured with the profilometer. The mirror will be mounted in the Vacuum chamber on its segment suppor



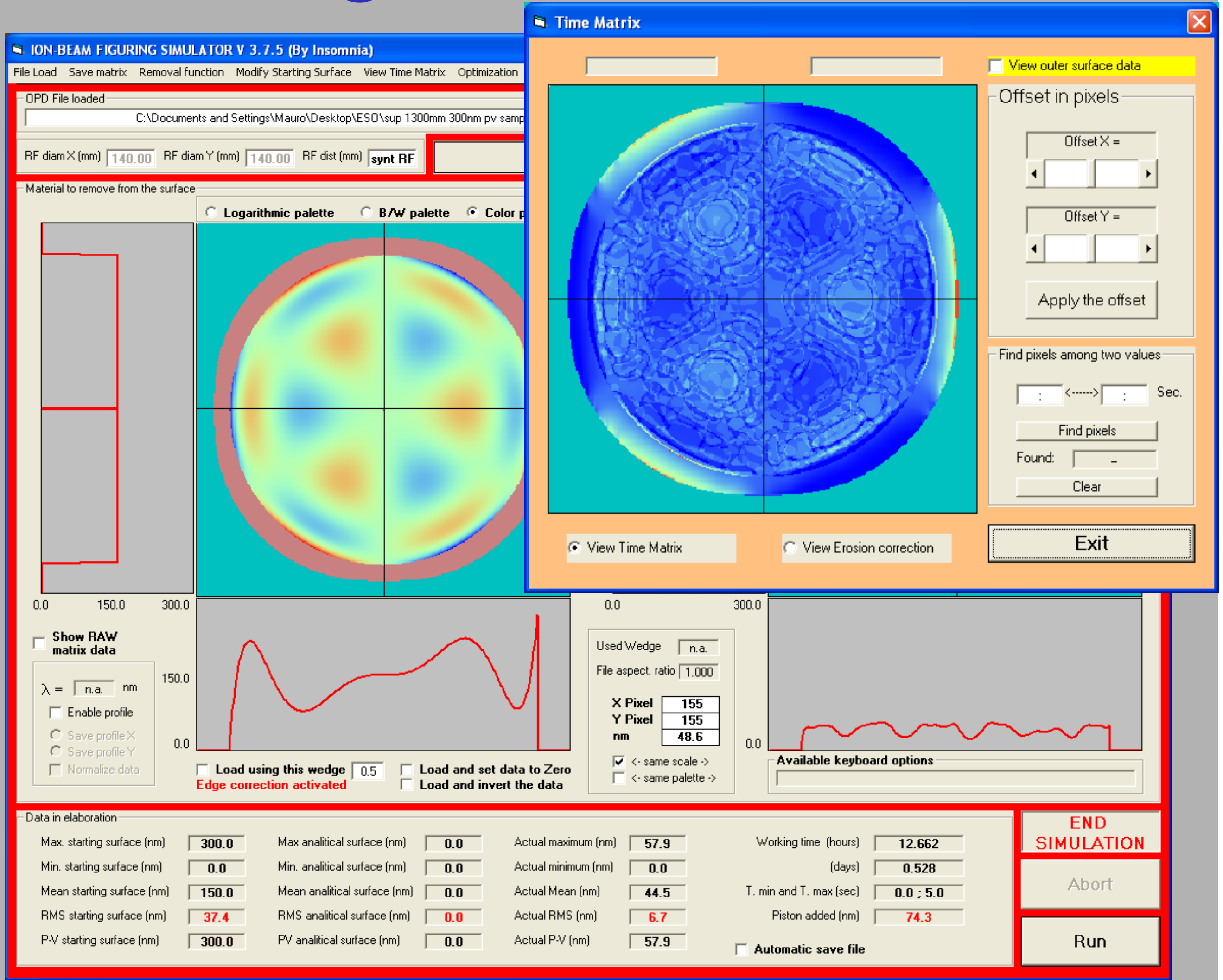


Figuring Simulation of a EELT real segment

Initial error :
Pv: 300 nm
Rms: 37.4 nm

Surface simulated with a 30° order Zernike

Removal rate: 2 nm/ sec on Zerodur



Final error from simulation: Pv: 57.9 nm - rms: 6.7 nm - Working time: 12.66 h