FAME

Freeform Active Mirror Element (WP5)

OPTICON Board

Granada, Oct 29th 2014

On behalf of the FAME team:

ATC:	Martin Black, Chris Miller, Hermine Schnetler
Konkoly Observatory:	Evelin Banyai, Attila Jaskó
LAM:	Zalpha Challita, Emmanuel Hugot
NOVA-ASTRON:	Tibor Agócs, Gabby Kroes, Lars Venema (+ Felix Bettonvil, Rik ter Horst)

OUTLINE

Classic freeforms, extreme freeforms, active freeforms,

Definitions, overview and interests

I. FAME optical design study

F/2-4, 7x5.4deg, 2-mirrors design and performance

II. FAME optical fabrication study

Hydroforming thin freeform shapes: FEA and experiments

III. FAME optical active array study

opto-mechanical design, FEA and performance

IV. Metrology and control

depending on tools developed in III – local and global

Towards an integrated system

Programmatics

GOAL

Freeform Active Mirror production development to simplify systems complexity and boost performance of (Astronomical) optical systems

Opticon Phase 2 – a strong focus on realizing FAME

- WP 5.1: System studies, E-ELT instrument optimisation
- WP 5.2: Conception, simulations and preparatory tests of models
- WP 5.3: Manufacturing, assembly, integration and performance characterisation of the Active Freeform Mirror


SEARCH
CeFO
THE CENTER FOR FREEFORM OPTICS
AN INDUSTRY/UNIVERSITY COOPERATIVE RESEARCH CENTER
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THE TEAM
ROADMAP
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NEWS & EVENTS
Liquid Crystal Chiroptical Polarization Rotators
optics.org announces launch of Center for Freeform Optics
Certification, Self-calibration and Uncertainty in Optical Surface Testing
Interdisciplinary Training in Freeform Optics
Enhanced Laser Damage Resistance
Fabrication and Characterization of a Biomimetic Polarization Selective Lens
Adapting Interferometric Technology for Freeform Surfaces
9
days until Fall CeFO IAB meeting
AFFILIATES:
The Air Force Research Laboratory • Ball Aerospace & Technologies Corp. • OptiPro Systems, LLC • PerkinElmer • PolymerPlus LLC • Rochester Precision Optics • SCHOTT North America, Inc. • Zygo Corporation
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INCREASING FOCUS

Active mirrors used in industry

ASML, Power laser systems, Drone applications (→AO-DMs useless)

Active Optics in Space

Recent ESA tender: "(cryogenic) deformable mirror and correction"

Many parties interested: University of Münster – Thales – TNO – LAM – NOVA - …

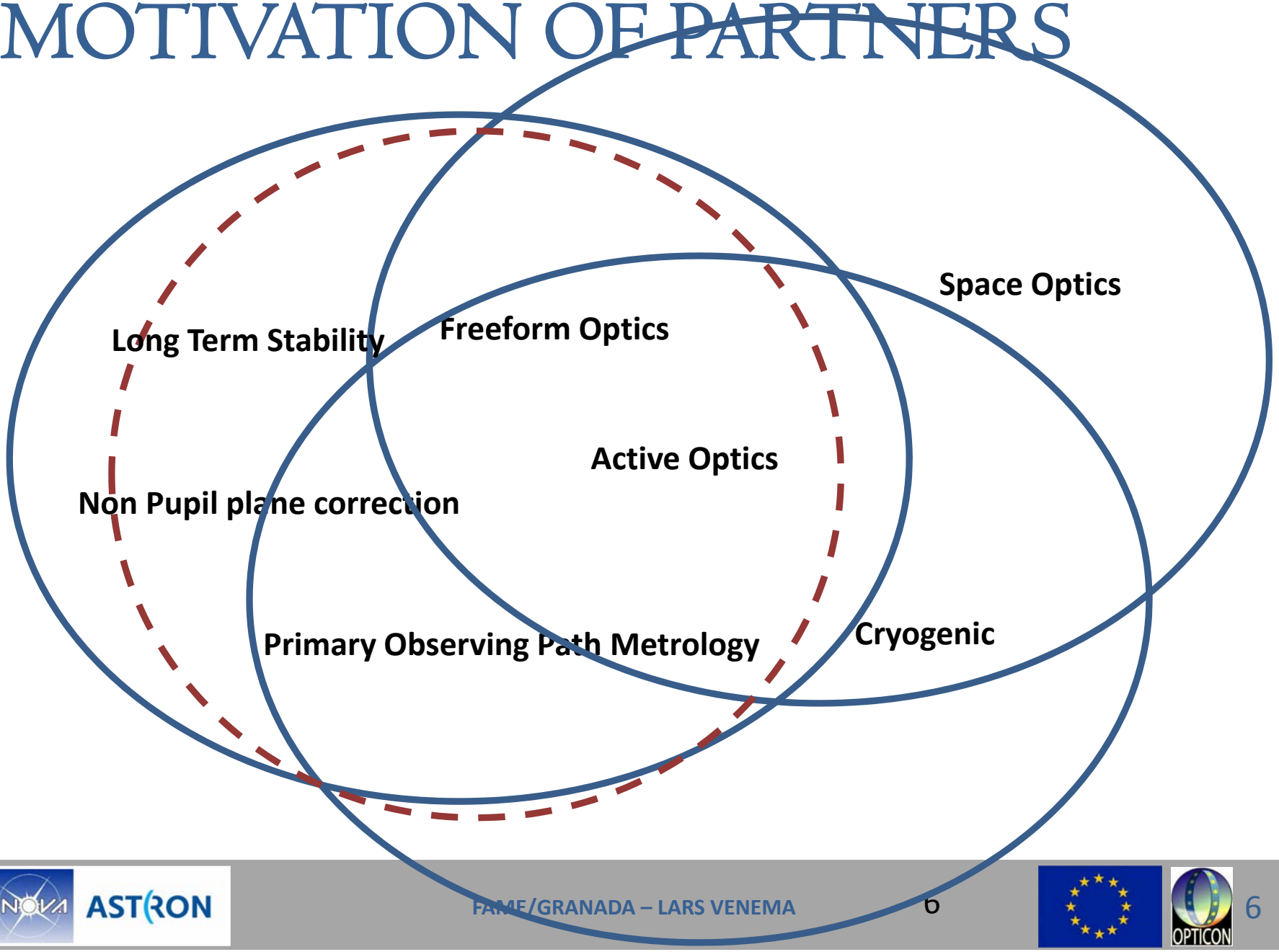
Extreme shapes

Generally specials – Used in molds (mobile phones) - beamers

Problem for general approach

Each application has very different requirements

MOTIVATION OF PARTNERS



DEFINITIONS

Classic Freeform

No-rotational symmetry

Not defined by conicoids

Provided by any good deformable mirror on the market

Extreme Freeform

A freeform with a deviation from the BFS higher than 100µm on small diameters

Manufacturing issues

Active Freeform

Combining extreme freeforms and deformable mirrors

→ *R&D developments on optical design, opto-mechanics, optical fabrication, control/command*

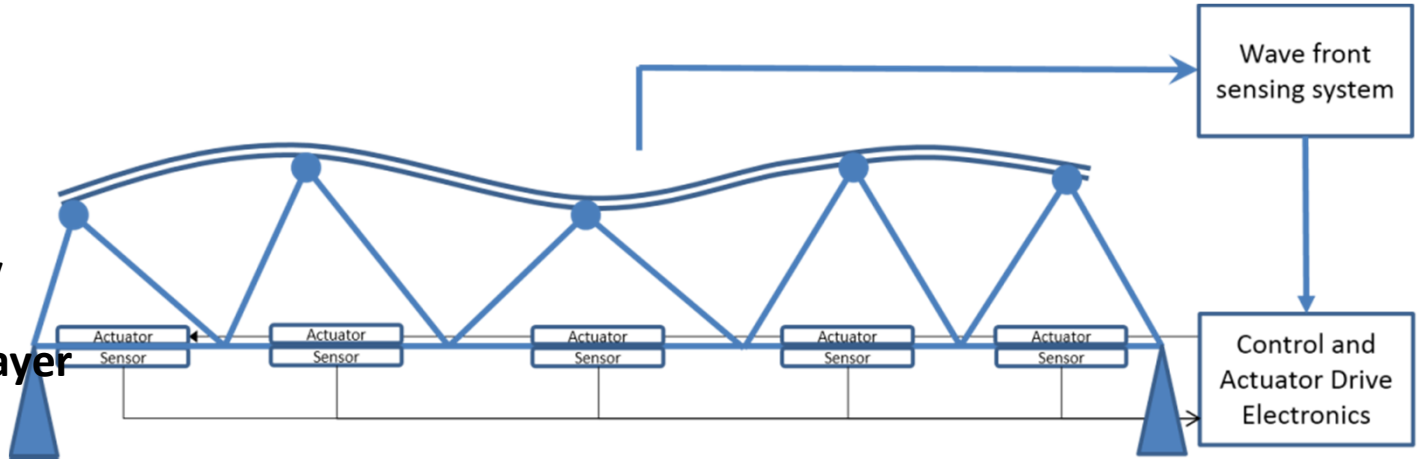
THIS is a challenge!

BREAKDOWN

Face sheet

Active Array

Actuation Layer



OPTICAL DESIGN

(SELECTION)

DEVELOPED TOOLS

PAST

- non-Zernike polynomial extension for ZEMAX
- Optimization method limiting and steering DOF in design
- Developing translation method projecting wfe of pupil plane to location of actual optics

CASES

METIS

mid-IR instrument for the EELT – impact of freeform on design

MOS Spectroscope

A freeform with a deviation from the BFS higher than 100µm on small diameters

Extreme systems (3 freeforms in one system)

Work also done by CeFO very nice but also expensive

F/4 THREE FREEFORMS DESIGN

Based on Fürschbach system (2011)
Uses extreme freeform mirrors (sag BFS: 1.2 – 1.3 mm and 0.4 mm respect.

3-freeform mirrors f500

No central obscuration

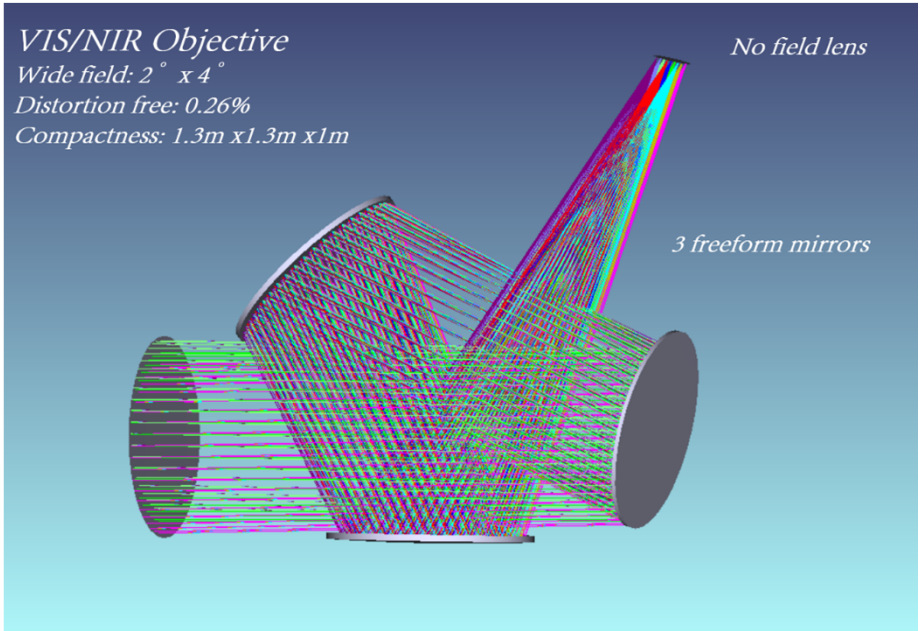
No corrective field lens

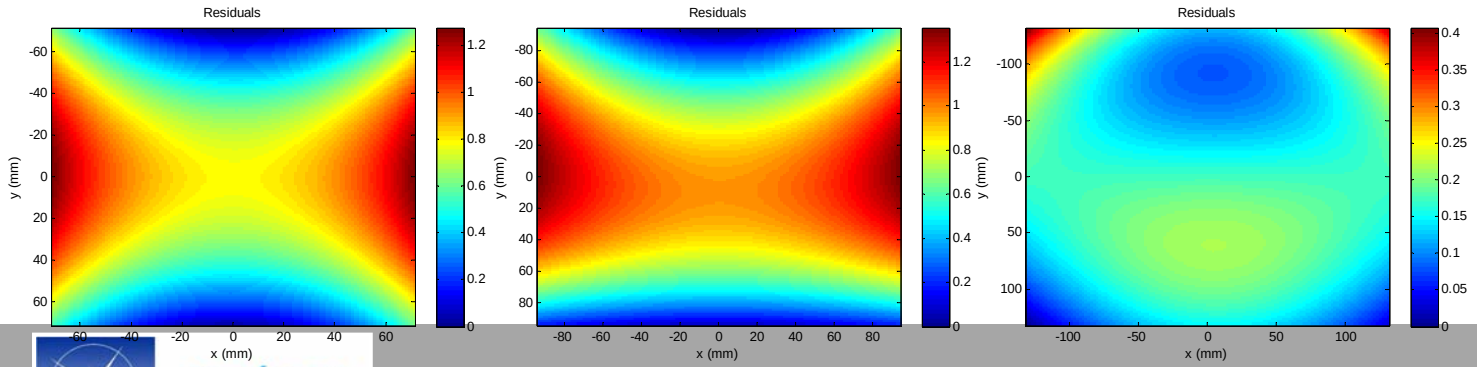
Flat focal plane

Distortion free,

Diffraction limited 0.2µm – 1µm

Field 2x4 deg²



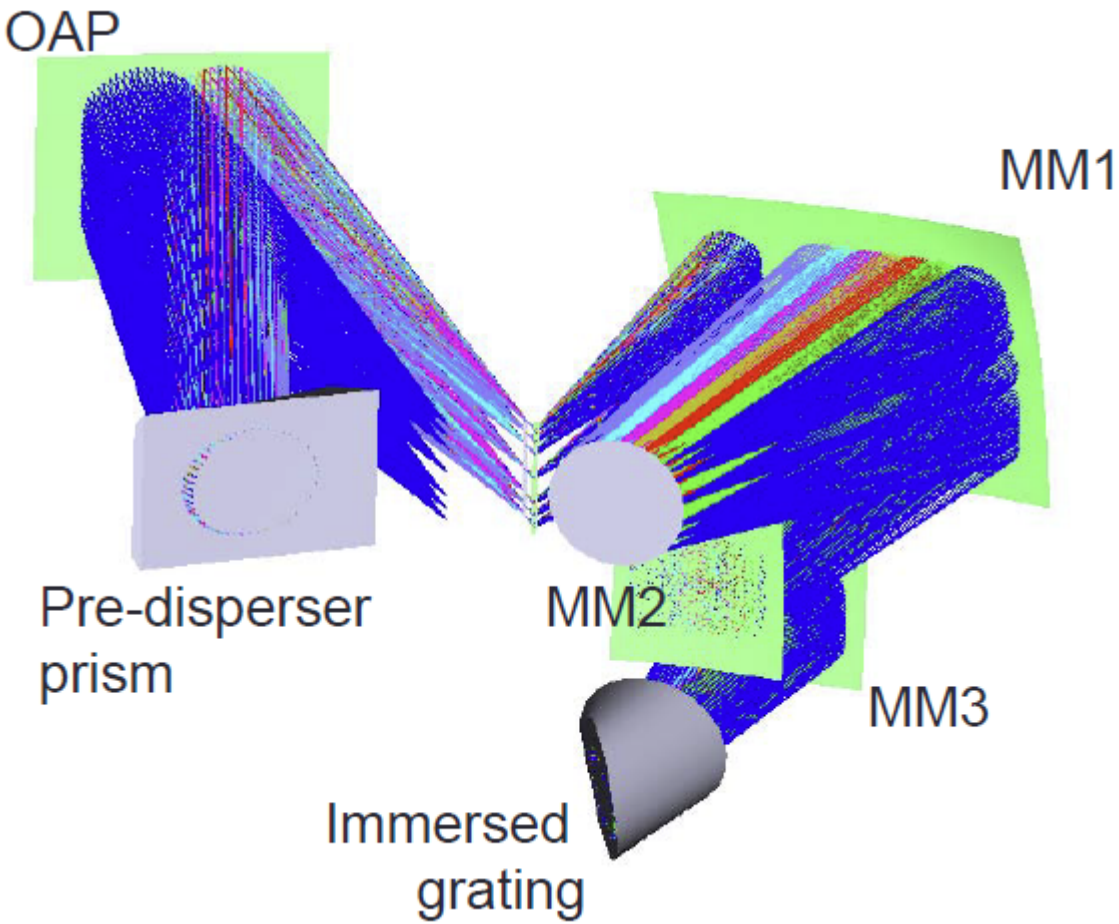


“METIS” SPECTROMETER

- DL at shortest λ
- Except extreme
- corners
- Optics costly

- Alternatives:

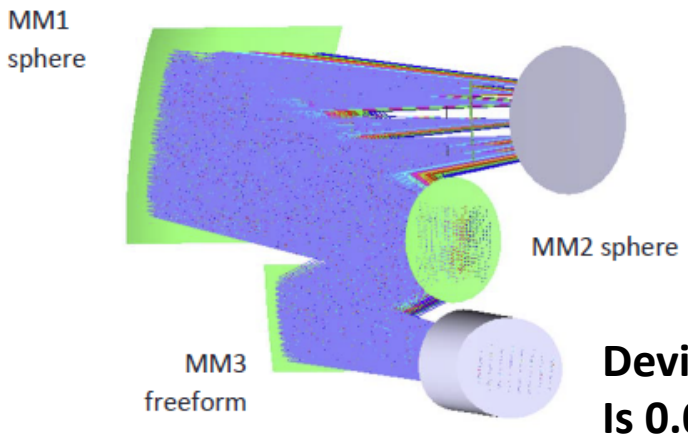
➔Better quality



“METIS” “VERSION 2”

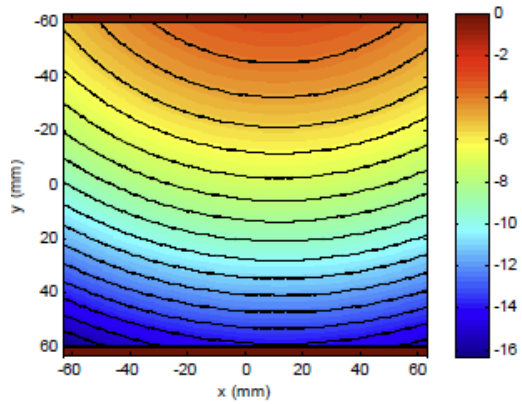
Move all complexity into one component

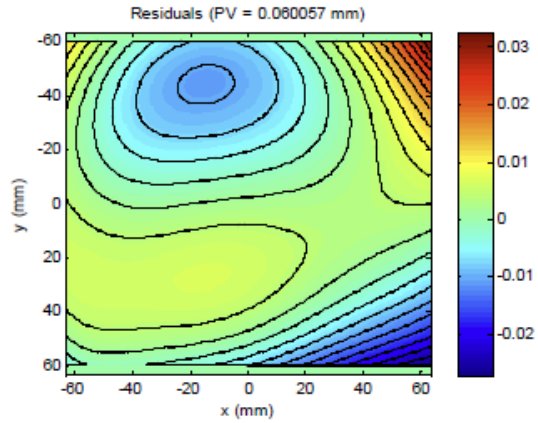
Optical quality “improved”



Deviation from BFS Is 0.06mm PV

Sag

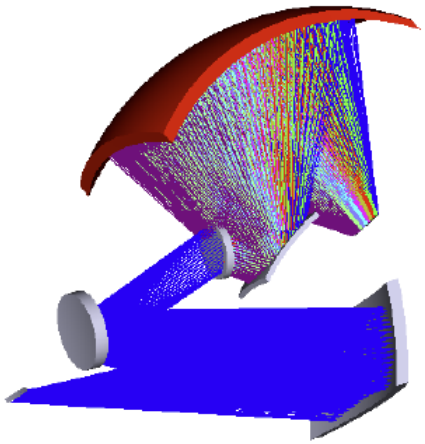




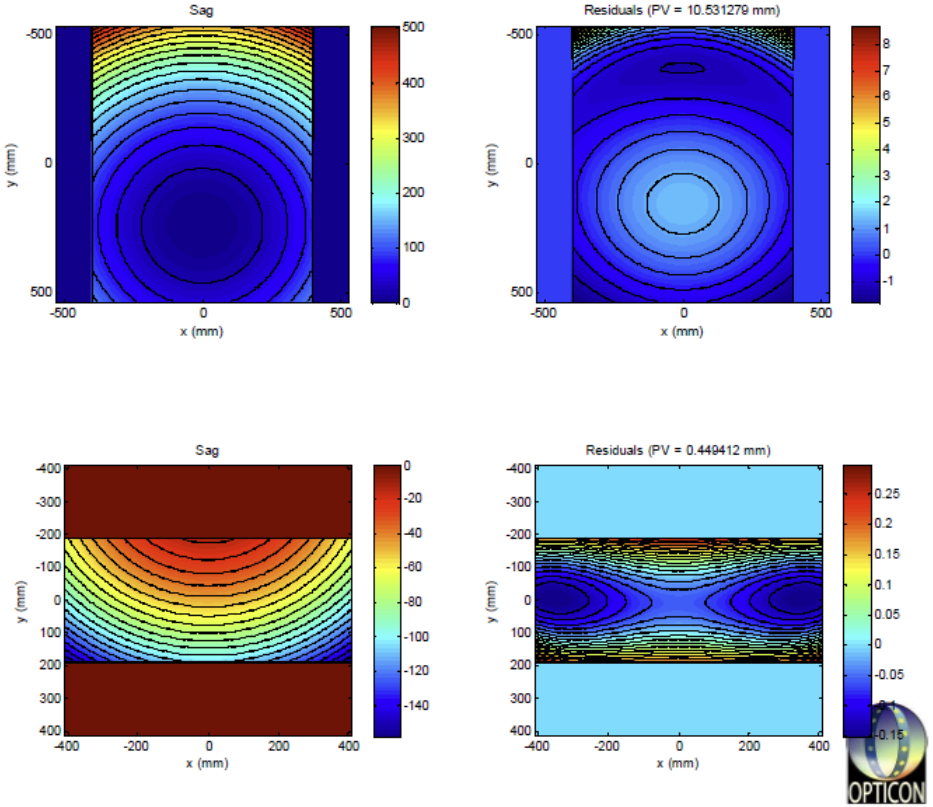
“MOS” TYPE SYSTEM

Two freeforms – complete spectrograph (220mm pupil, 176mm slit, F1.8 camera)

M4 freeform



M1 freeform



F2-4* TWO MIRROR SYSTEM

Compact freeform based optical system (re-imaging systems)

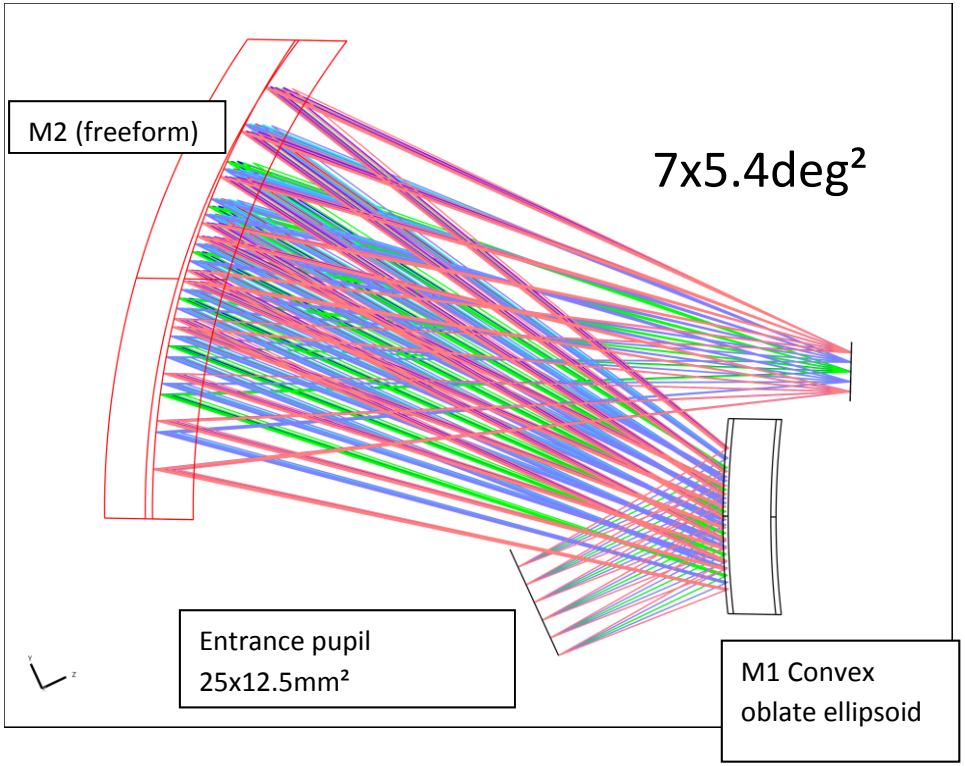
- Very good image quality
- Fast F-ratio

Freeform mirror M2

- Size 100mm diameter
- Deviation from BFS: 0.3mm PV
- Handled in ZEMAX:
  - Optimized set of Zernike

Testing & control

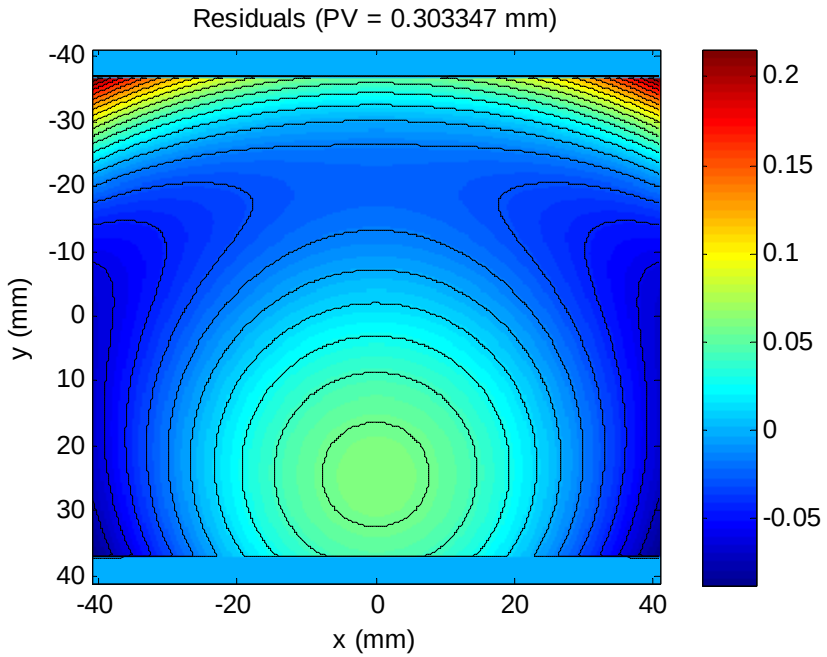
- Using the optical system itself
- Accessible entrance pupil
- for Phase diversity

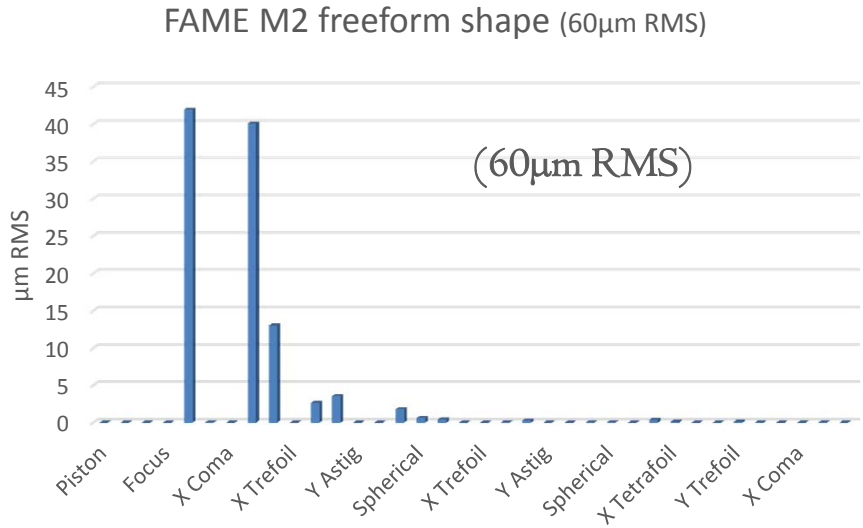


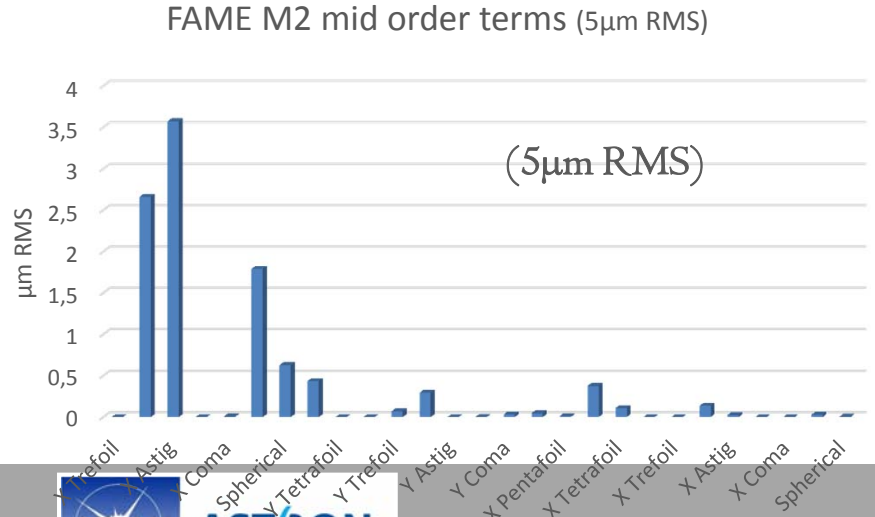
For 1.7µm pix, 3800x2700pix
→ pix size = 6.6x7.2arcsec.

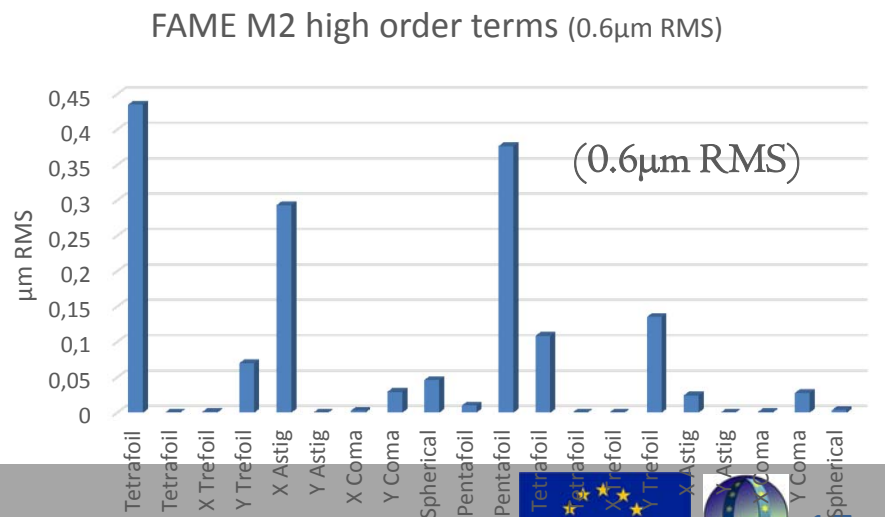
* Made slower to fit det. pixels

ZERNIKE DESCRIPTION









FACE SHEET

Active Optics techniques

Beyond the elastic limit: plasticizing

- **Permanent deformations**
- **Large sags** ⇒ extreme shape
- **Elastic domain recovered** ⇒ active compensation system

Large displacements

$$\frac{\text{displacements}}{\text{thickness}} > \frac{1}{3}$$

Variable curvature mirrors
(VCM/VLTI delay lines)
[Ferrari, 1998]

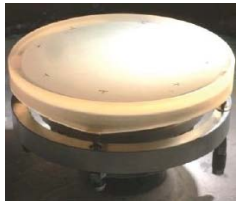
Elasticity theory

Circular plates

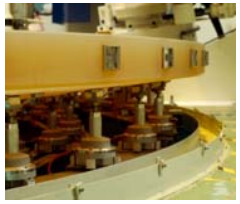
$$\nabla^2\nabla^2 z = \frac{q}{D}$$

Rigidity

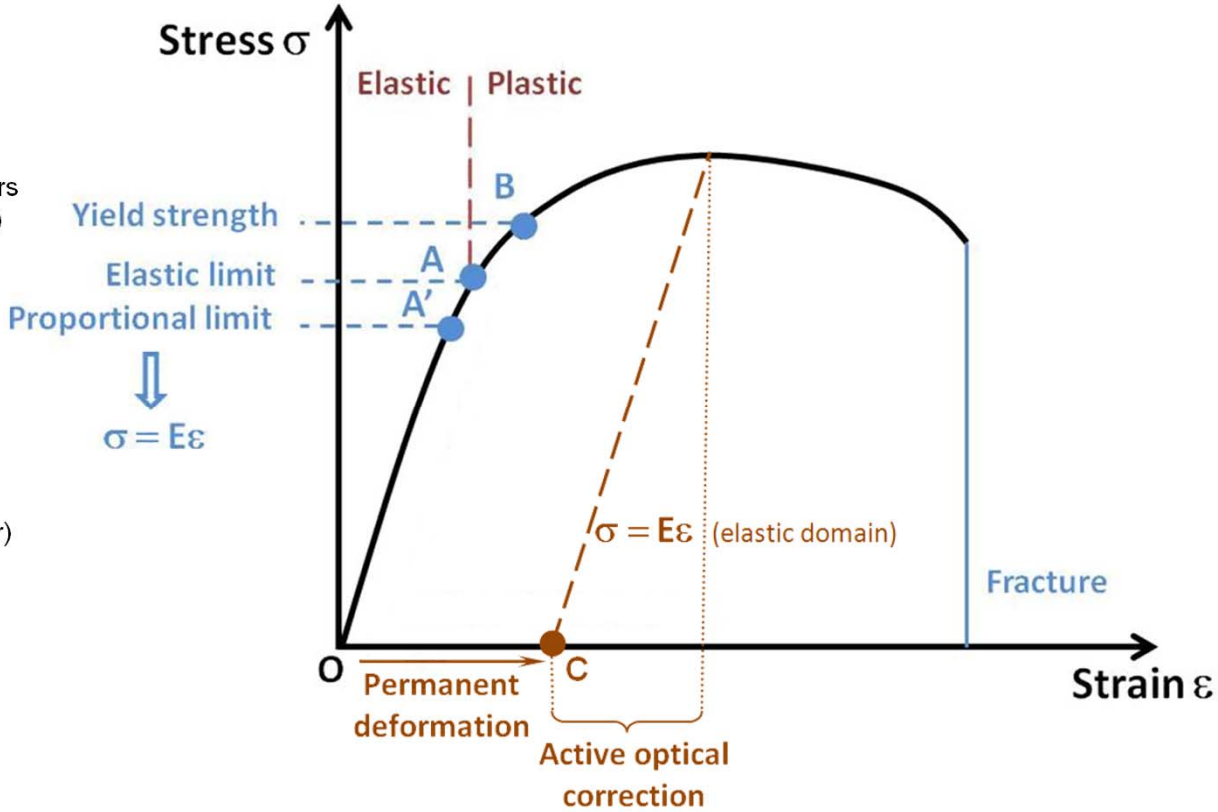
$$D = \frac{Et^3}{12\times(1-\nu^2)}$$



Stress polishing
(Sphere/VLT toric mirror)
[Hugot et al., 2012]



In-situ actuation



High material history dependency ⇒ need of simulations & experimentation

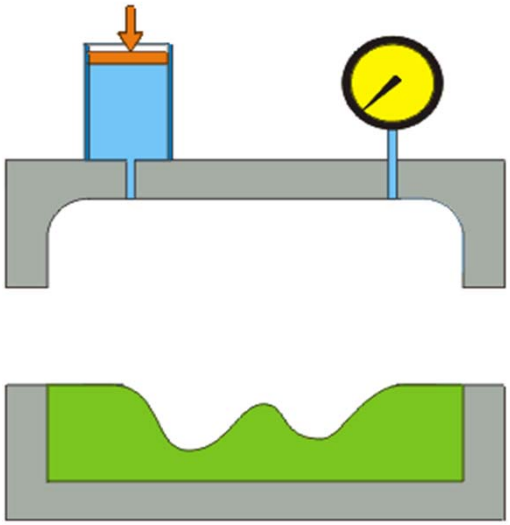
Operating mode

Fast (few minutes) & simple

- Thin substrate
- Specific mould
- High hydraulic pressure

Optical interests

- **No high spatial frequencies residuals**
  - **No tool-marks**
- **Low spatial frequencies actively compensated**
- **Flat or spherical polishing**



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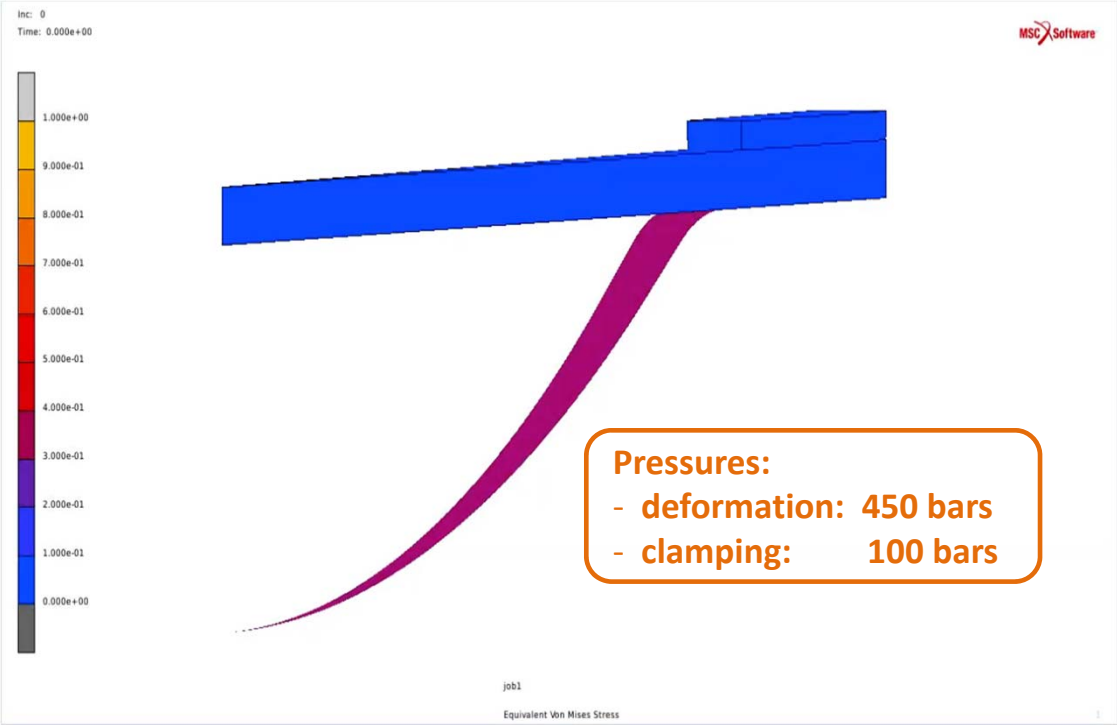


z_{mould}(vertex) = 13.397 mm z_{mirror}(vertex) = 11.899 mm

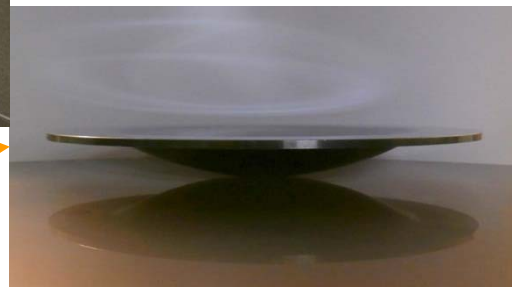
EQUIPMENT

Dedicated hydroforming engine

- 700 bars hydraulic oil pressure
- Clamping system with hydraulic jack
- Adaptable mold shape/material

Internal cavity with blank-holder

Mirror & mold integration



Mirror deformed after processing

AISI420b stainless steel
1 mm & 2 mm thicknesses
22$\varnothing_{total}$ 140 mm

Manufacturing step - Plasticized mirrors quality

Optical performance: FEA vs. Experiment

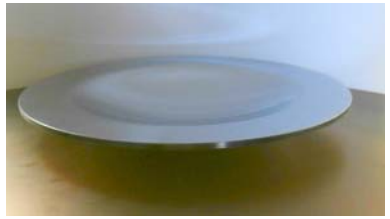
- Full-size tool polishing - Roughness: < 10 nm rms, Focus: < 5 µm rms, Astig. : < 3 µm rms
- Thickness: 1 mm (case 3) & 2 mm (case 1 and 2) – AISI 420b stainless steel
- Optical surface: ∅100 mm

Roughness

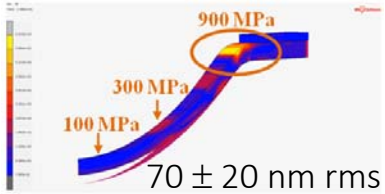
EVM stress repartition

Residuals

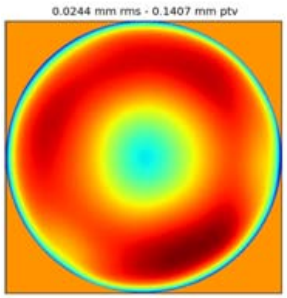
Mid aspherical mirror

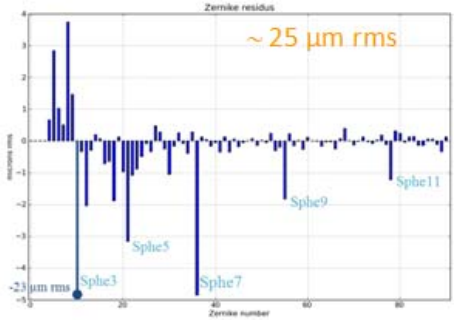


- Depart. from BFS:
  280 µm ptv
  66 µm rms
- F/0.5 aperture

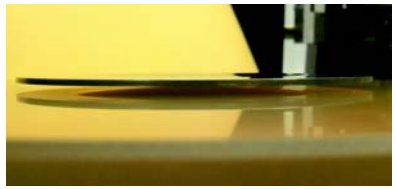


70 ± 20 nm rms

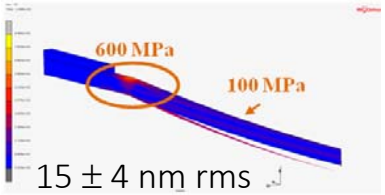




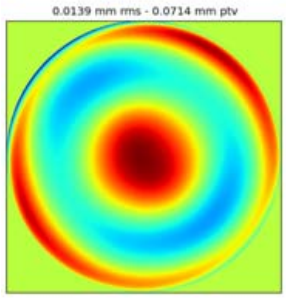
Moderate aspherical mirror

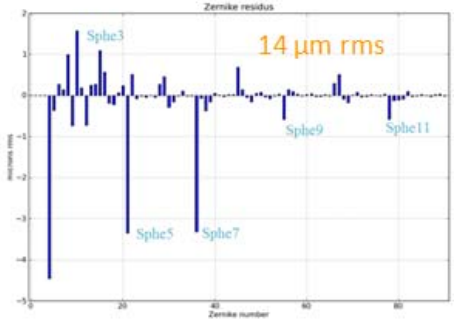


- Depart. from BFS:
  61 µm ptv
  17 µm rms
- F/4 aperture



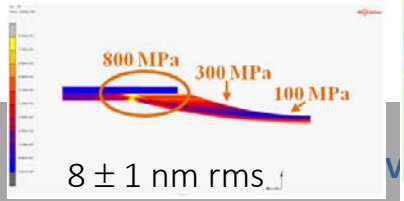
15 ± 4 nm rms



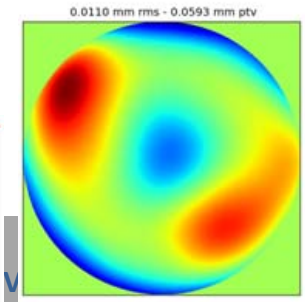


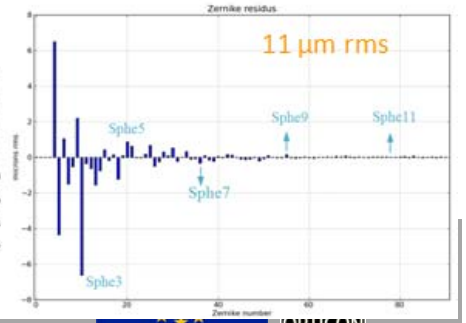
Spherical mirror

- Error from BFS:
  1.8 µm ptv
  0.38 µm rms
- F/10 aperture



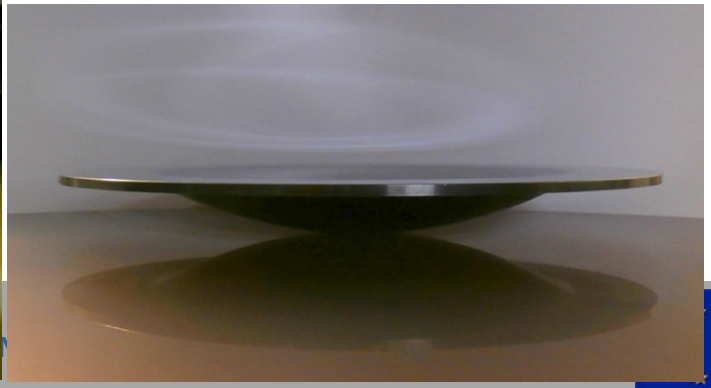
8 ± 1 nm rms





MANUFACTURING STEP - ENJOY ;) !

- Plasticizing operation needs ~ 5 minutes
- Tests realized on thickness 2 mm & 1 mm
- Tests on 1.5 mm are in preparation



GLOBAL RESULTS:

Optical surface ≡ ∅ 100 mm

Form residuals: < 25 µm rms,
then compensated by *in-situ* active system.

High frequencies residuals: ≤ 10 nm rms,
coming from the flat polishing only.

Roughness evolution: < 20 nm rms,
Obtained on moderate plastic deformations.

ACTIVE ARRAY

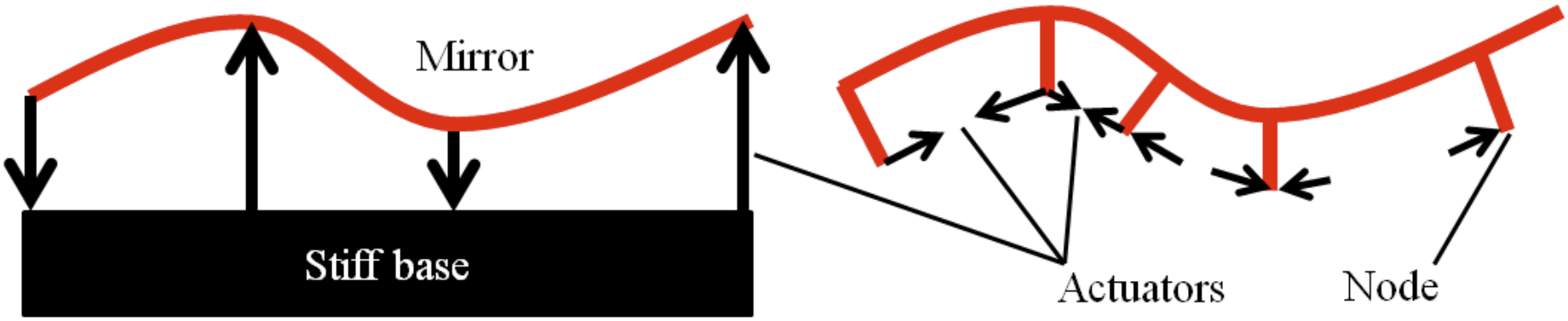
ACTIVE ARRAY

Aim of the active array within FAME

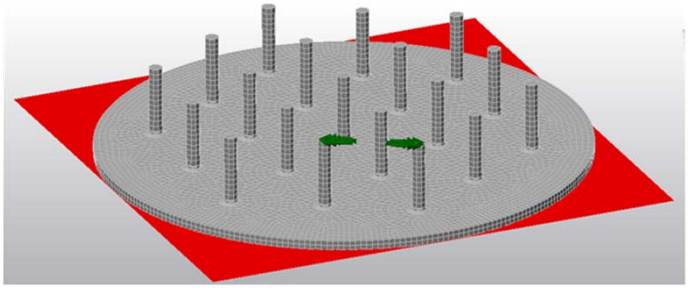
Generate the full freeform shape or compensate for manufacturing errors

Face Sheet Deformation

1. Towards additional stiff structure (Conventional AO mirrors)
2. <u>Reshaping stiff structure</u>

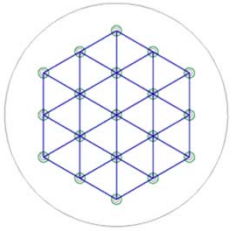


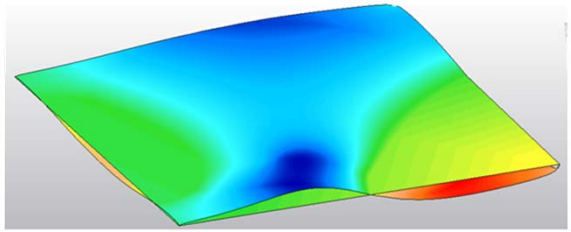
ACTIVE ARRAY ISSUES



Pillars distribution

- Pattern optimization
- Related performance





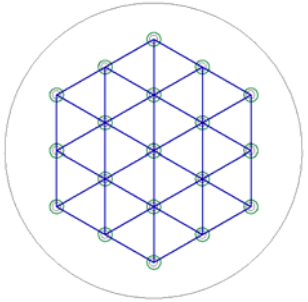
Pillars shape

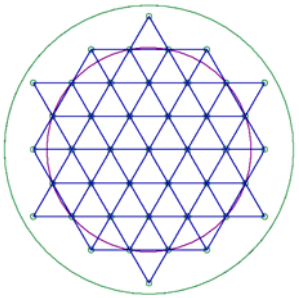
- Reduce print through
- Improve influence function shape and surface generation

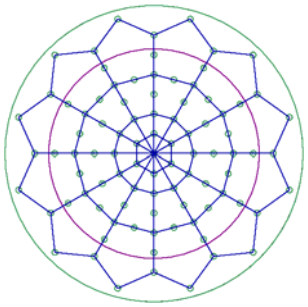
PATTERN OPTIMISATION

3 different shapes

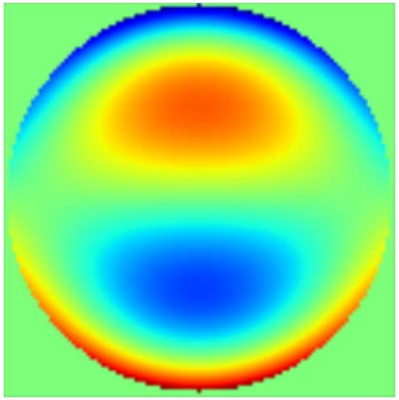
Shearing actuators

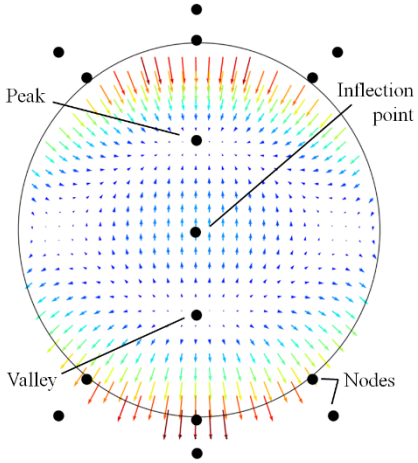


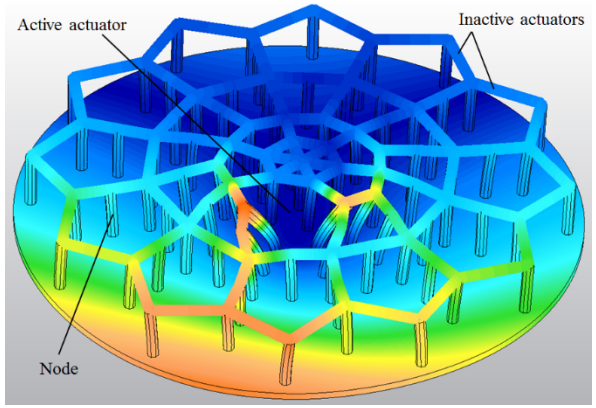




Optimization based on gradient method + FEA



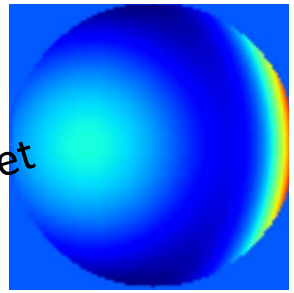


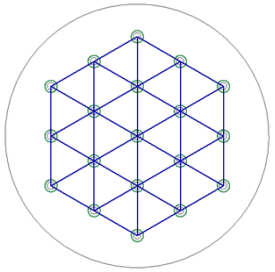
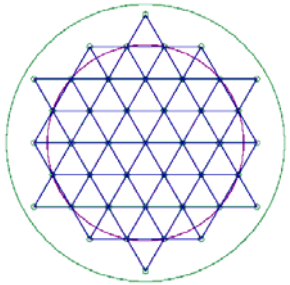
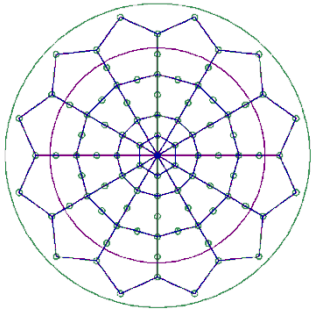
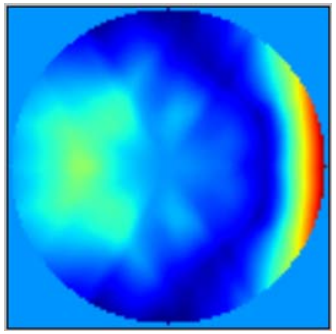
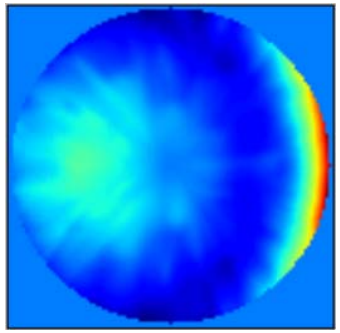
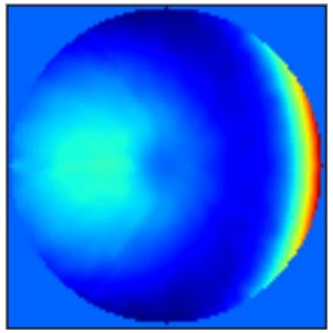
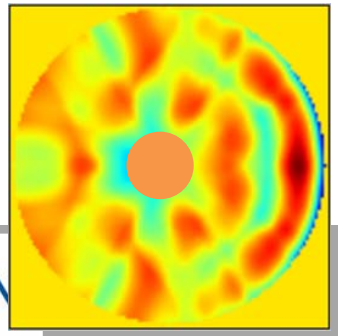
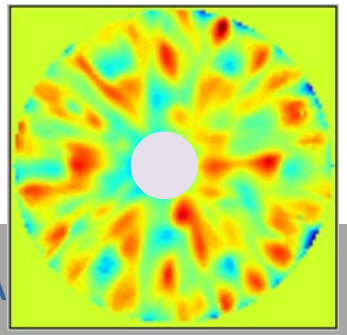
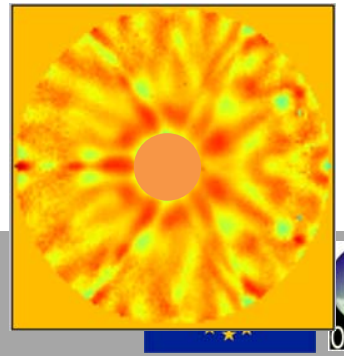


Directly inspired from optimized pattern developed @ CalTech

(M. Laslandes SPIE 9148-151)

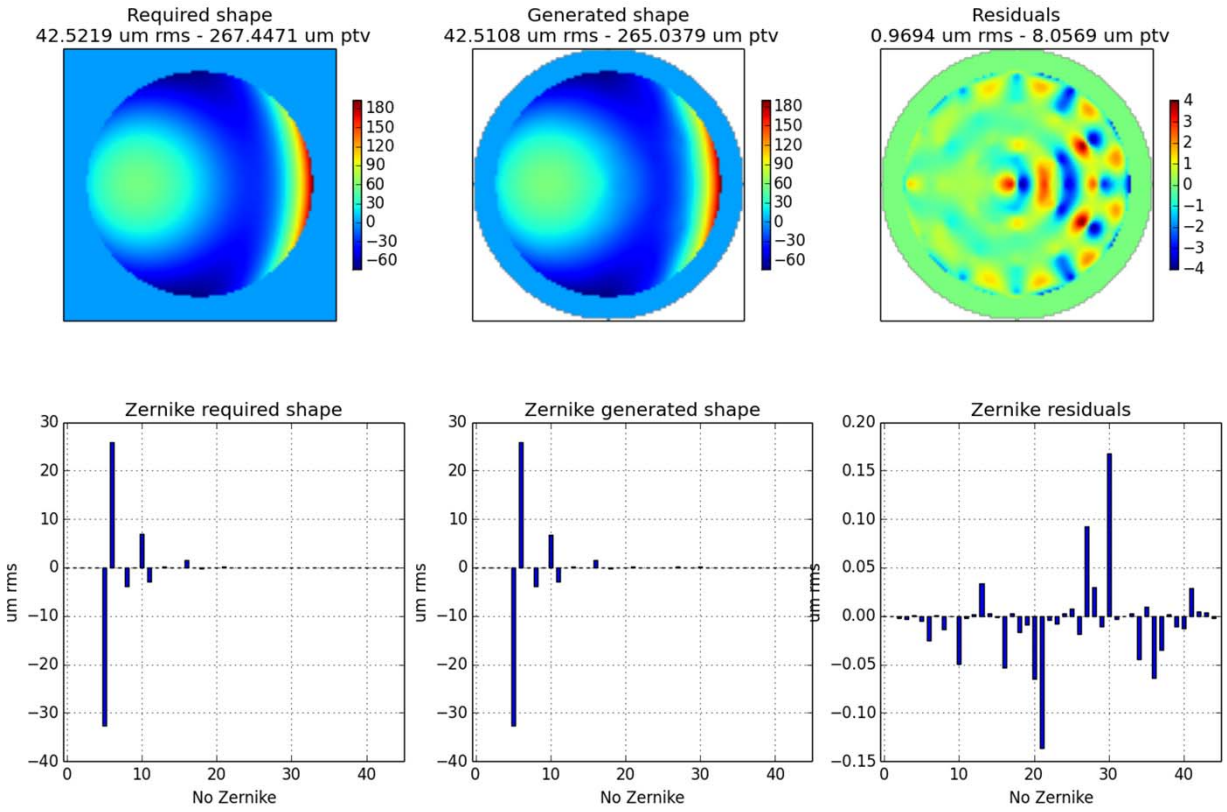
PERFORMANCE OF ARRAYS

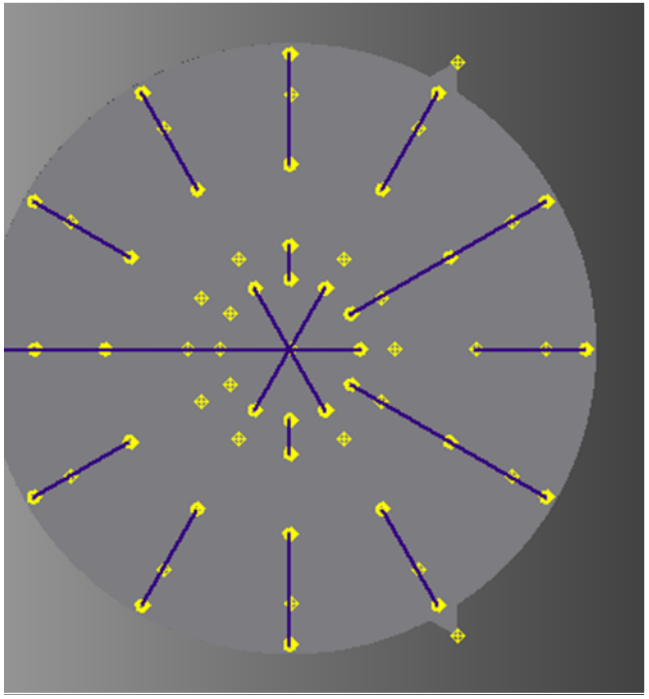


	42	102	126
Actuator count			
lay-out			
Generated shape	 61 µm RMS	 62 µm RMS	 62.5 µm RMS
Residuals	 15.1 µm RMS	 8.7 µm RMS	 4.5 µm RMS

REDUCTION D.O.F.

53 → 38 actuators, removing those with less impact. The active 38 actuators are highlighted but the others' stiffness is also taken into account -> uniform stiffness distribution
Performance similar – needs some further improvement
Removing Zernike Bias will reduce #actuators





ERROR BUDGET ON BUILDING BLOCKS

Optical fabrication

Provide a freeform surface as accurate as possible

Focused on form generation

No high spatial frequencies

Target: WFE <50µm

Active Array

Provide the second stage of freeform generation

Target: WFE < 1µm

Provide a fine tuning of the surface
Compensate for environment variations

Target: WFE <1µm

ACTUATION LAYER

Activities on hold – depends on final scale of system – information available within few months

Actuators/Sensor Inventory prepared

Metrology Ideas present

- Actuator verification (local)
- PSF analysis (for large deviation)
- PD when errors sufficiently small (first tests this year)

Demonstrator

Starts next year – to be completed in 2016

GLOBAL METROLOGY

One flavour of Phase Diversity

Pre-selection ongoing

PD methods	Method types	location of introducing phase retrieval	No. of measurements	phase alteration type	Alteration means	Characteristic of the methods	Accuracy	Application	Robustness
FF+GS	N/A	Pupil amplitude	N/A	N/A	N/A	N/A	10.027nm RMS (15.40 nm rms for FF only)	N/A	Not robust. Relies on small WF aberrations and pupil symmetries
dOTF	Non-iterative	Pupil plane	At least 2 sets	Obscuration in pupil or poking the DM	Wire or actuator	Always converging and easy implementation	<5nm rms	Not in AO systems, possibly JWST segment phasing	Will increase by taking a movie per position = more light without saturation
Transverse translation-diverse	Iterative	Aperture	About 40 for 33.32 mm aperture	Transverse translation of the aperture	Subapertu mask	Overcome NA limitation/undersa	6.7 nm(0.0107 waves) RMS	Measuring fast beams and optical surfaces metrology	Multiple overlap of subapertures
Hybrid diversity algorithm	N/A	N/A	N/A	N/A	N/A	Extended dynamic range and recover high-spatial-frequency	<5nm accuracy	JWST	N/A

TOWARD FAME PROTOTYPE

On going work

Identify actuators solutions

Command Control system

Interface thin mirrors with active array -> manage the integration WFE

Issues to be addressed

Shape of pillars to reduce High spatial frequency residuals

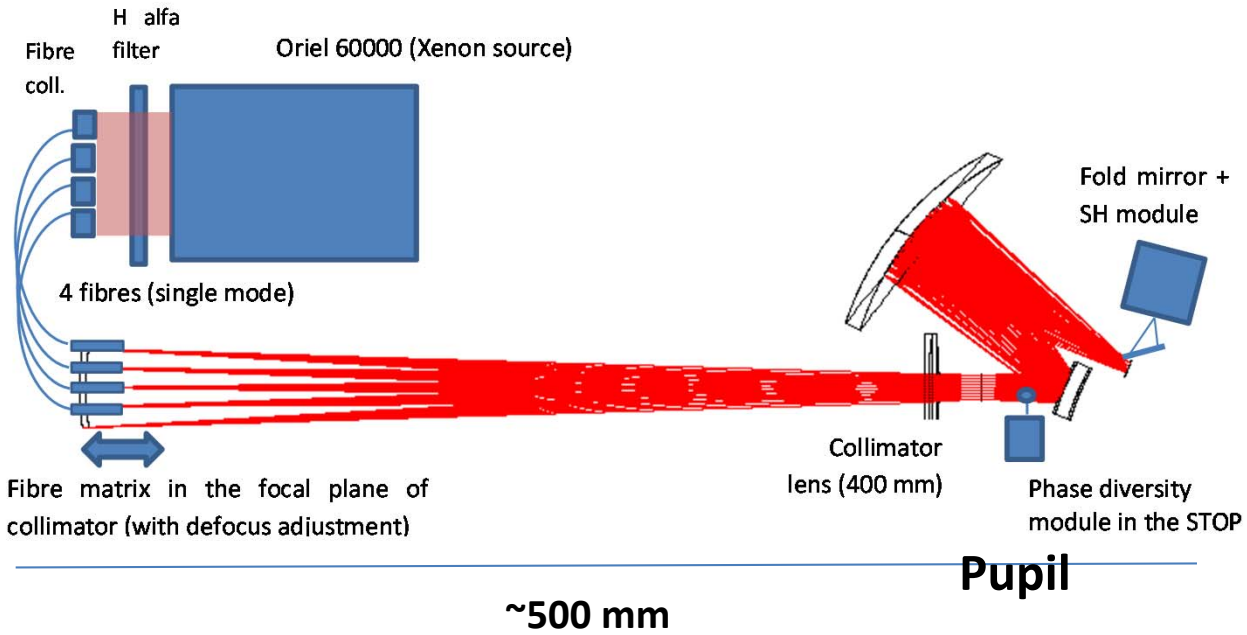
Two stage approach for coarse and fine corrections

Design a characterization test bed

Prototyping

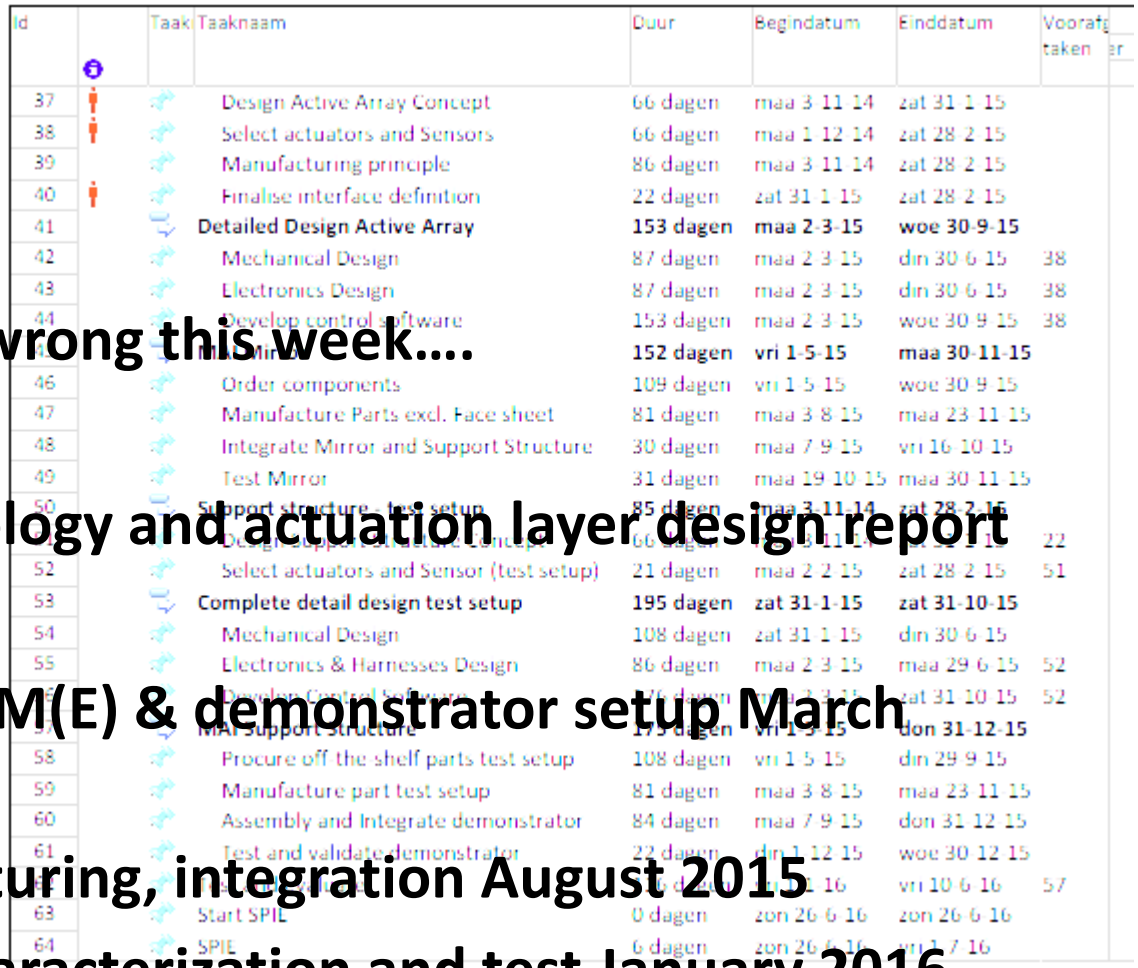
Starts next year – to be completed in 2016

DEMONSTRATOR



Shack Hartmann sensor to validate principle

PLANNING



Id		Taak	Taaknaam	Duur	Begindatum	Einddatum	Voorafgaande taken
37			Design Active Array Concept	66 dagen	maa 3-11-14	zat 31-1-15	
38			Select actuators and Sensors	66 dagen	maa 1-12-14	zat 28-2-15	
39			Manufacturing principle	86 dagen	maa 3-11-14	zat 28-2-15	
40			Finalise interface definition	22 dagen	zat 31-1-15	zat 28-2-15	
41			**Detailed Design Active Array**	**153 dagen**	**maa 2-3-15**	**woe 30-9-15**	
42			Mechanical Design	87 dagen	maa 2-3-15	din 30-6-15	38
43			Electronics Design	87 dagen	maa 2-3-15	din 30-6-15	38
44			Develop control software	153 dagen	maa 2-3-15	woe 30-9-15	38
[illegible]			**[illegible]**	**152 dagen**	**vri 1-5-15**	**maa 30-11-15**	
46			Order components	109 dagen	vri 1-5-15	woe 30-9-15	
47			Manufacture Parts excl. Face sheet	81 dagen	maa 3-8-15	maa 23-11-15	
48			Integrate Mirror and Support Structure	30 dagen	maa 7-9-15	vri 16-10-15	
49			Test Mirror	31 dagen	maa 19-10-15	maa 30-11-15	
50			**Support structure - test setup**	**85 dagen**	**maa 3-11-14**	**zat 28-2-15**	
[illegible]			Design support structure concept	66 dagen	[illegible]	[illegible]	22
52			Select actuators and Sensor (test setup)	21 dagen	maa 2-2-15	zat 28-2-15	51
53			**Complete detail design test setup**	**195 dagen**	**zat 31-1-15**	**zat 31-10-15**	
54			Mechanical Design	108 dagen	zat 31-1-15	din 30-6-15	
55			Electronics & Harnesses Design	86 dagen	maa 2-3-15	maa 29-6-15	52
[illegible]			Develop Control Software	[illegible]	[illegible]	zat 31-10-15	52
[illegible]			**MAI Support Structure**	**175 dagen**	**vri 1-5-15**	**don 31-12-15**	
58			Procure off the shelf parts test setup	108 dagen	vri 1-5-15	din 29-9-15	
59			Manufacture part test setup	81 dagen	maa 3-8-15	maa 23-11-15	
60			Assembly and Integrate demonstrator	84 dagen	maa 7-9-15	don 31-12-15	
61			Test and validate demonstrator	22 dagen	din 1-12-15	woe 30-12-15	
[illegible]			[illegible]	[illegible]	[illegible]	vri 10-6-16	57
63			Start SPIE	0 dagen	zon 26-6-16	zon 26-6-16	
64			SPIE	6 dagen	zon 26-6-16	vri 1-7-16	

GGANT chart went wrong this week….

March 2015 – metrology and actuation layer design report

Start final design FAM(E) & demonstrator setup March 2015

Procuring, manufacturing, integration August 2015

System ready for characterization and test January 2016

Demonstrator @ SPIE June 2016

OUTREACH

Papers/presentations/posters @ conferences

Papers in scientific magazins

Demonstrator at SPIE 2016 (Edinburgh)

Technology Transfer

- **Expertise @ LAM often shared with industry to develop new technologies in industry (PhDs with confunding from Industry)**
- **Expertise @ ATC and NOVA shared with industrial partners**

PAPERS

Refereed:

Challita Z, et al., “Design and development of an active freeform mirror for an astronomy application”, Opt. Eng. 0001;53(3):031311. (2014)

SPIE 2014

E. Hugot et al, “Freeform Active Mirrors Experiment”

Z. Challita et al, “Freeform mirrors and active optics: development of a thin freeform manufacturing process for the FAME project”

T. Agócs et al, “Freeform mirror based optical systems for FAME”

A. Jaskó et al, “Active array design for FAME: Freeform Active Mirror Experiment”

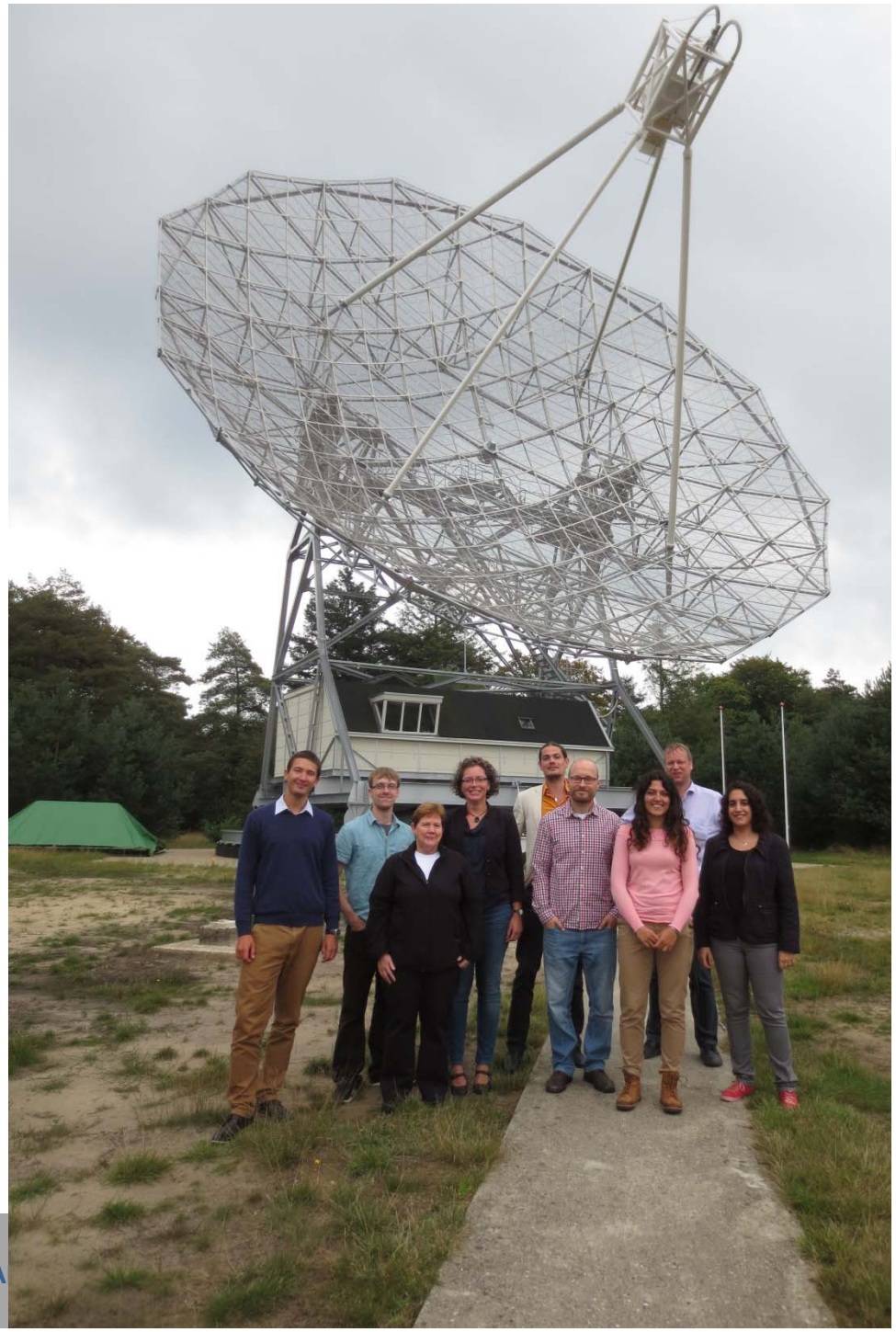
ICSO 2014

T. Agócs, R. Navarro, L. Venema, “Variations on a theme: Novel Immersed Grating Based Spectrometer Designs For Space”

MEETINGS

Kick Off	**26/27-03-2013**
TM1	**02/03-10-2013**
TM2	**11/12-02-2014**
TM3	**02/03-09-2014**

Great team!!!



CONCLUSIONS

Well on track

Very important partial results achieved – tools developed

Budget is very tight, but spending match expectations

HORIZON 2020

Active Optics and Freeform Optics become even more important

Should consider how to shape this in the European context? Cf. American example – concentrate on specific Optical problem

Extend into space and cryogenic development…

Explore Additive manufacturing Capabilities (3D printing of lightweight structures, Mirror substrates, Layered materials)

Active structures