Freeform Active Mirror Element (WP5)  
OPTICON Board  
Granada, Oct 29th 2014

On behalf of the FAME team:
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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
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

- Long Term Stability
- Freeform Optics
- Non Pupil plane correction
- Active Optics
- Primary Observing Path Metrology
- Cryogenic Space Optics
DEFINITIONS

Classic Freeform
No-rotational symmetry
Not defined by conicoids

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

Active Freeform
Combining extreme freeforms and deformable mirrors
→ R&D developments on optical design, opto-mechanics, optical fabrication, control/command

Provided by any good deformable mirror on the market
Manufacturing issues
THIS is a challenge!
BREAKDOWN

Face sheet
Active Array
Actuation Layer

Wave front sensing system
Control and Actuator Drive Electronics
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 $\lambda$
- 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
“MOS” TYPE SYSTEM

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

Deviation from BFS is 0.06mm PV

Sag

Residuals (PV = 0.081270 mm)

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

* Made slower to fit det. pixels

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

FAME M2 mid order terms (5\(\mu m\) RMS)

FAME M2 freeform shape (60\(\mu m\) RMS)

FAME M2 high order terms (0.6\(\mu m\) RMS)

Residuals (PV = 0.303347 mm)

FAME/GRANADA – LARS VENEMA
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

\[
\nabla^2 \nabla^2 z = \frac{q}{D}
\]

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

Rigidity

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

In-situ actuation

Stress-\(\sigma\) vs Strain-\(\varepsilon\)

- Elastic domain
- Plastic domain
- Yield strength
- Elastic limit
- Proportional limit
- Permanent deformation
- Active optical correction
- Fracture

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
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

Pressures:
- deformation: 450 bars
- clamping: 100 bars

$z_{mould}(vertex) = 13.397 \text{ mm}$
$z_{mirror}(vertex) = 11.899 \text{ mm}$
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
$22\varnothing_{\text{total}}$, 140 mm
MANUFACTURING STEP — PLASTICIZED MIRRORS QUALITY

Optical performance: FEA vs. Experiment

- **Mid aspherical mirror**
  - Depart. from BFS: 280 µm ptv
  - 66 µm rms
  - F/0.5 aperture

- **Moderate aspherical mirror**
  - Depart. from BFS: 61 µm ptv
  - 17 µm rms
  - F/4 aperture

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

Roughness

<table>
<thead>
<tr>
<th>Aperture</th>
<th>Roughness (µm rms)</th>
<th>Focus (µm rms)</th>
<th>Astig. (µm rms)</th>
</tr>
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<tbody>
<tr>
<td>F/0.5</td>
<td>70 ± 20</td>
<td>5 ± 2</td>
<td>3 ± 1</td>
</tr>
<tr>
<td>F/4</td>
<td>15 ± 4</td>
<td>2 ± 0.5</td>
<td>1 ± 0.3</td>
</tr>
<tr>
<td>F/10</td>
<td>8 ± 1</td>
<td>0.38 ± 0.2</td>
<td>0.38 ± 0.15</td>
</tr>
</tbody>
</table>

Residuals

- ~ 25 µm rms
- 14 µm rms
- 11 µm 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 ≡ Ø 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. Reshaping stiff structure
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

Actuator count
- 42
- 102
- 126

Generated shape
- 6.1 μm RMS
- 6.2 μm RMS
- 62.5 μm RMS

Residuals
- 15.1 μm RMS
- 8.7 μm RMS
- 4.5 μm RMS
53 $\rightarrow$ 38 actuators, removing those with less impact. The active 38 actuators are highlighted but the others’ stiffness is also taken into account $\rightarrow$ 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

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

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

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<th>Id</th>
<th>Taaknaam</th>
<th>Duur</th>
<th>Begindatum</th>
<th>Einddatum</th>
<th>Vooraf genomen</th>
<th>Jaar</th>
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<td>Design Active Array Concept</td>
<td>66 dagen</td>
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<td>Develop control software</td>
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<td>90 dagen</td>
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<td>Select actuators and Sensor (test setup)</td>
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<td>zon 26 6 16</td>
<td>36</td>
<td>FAME/GRANADA – LARS VENEMA 36</td>
</tr>
</tbody>
</table>
OUTREACH

Papers/presentations/posters @ conferences
Papers in scientific magazines
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
Refereed:

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