THEME 2: Modern Production Methodologies (WP4 and WP5)

Dr Hermine Schnetler
UKRI – STFC – UK Astronomy Technology Centre
On behalf of WP4 and WP5 consortium
Talk Outline

- Why do we need to modernise our production methodologies
- WP4 – Unlocking the potential of freeform optics for astronomical instrumentation
  - Freeform optics
  - FAME to date
  - FAME+
  - Schedule
  - Summary
- WP5 – Additive Astronomical Integrated-component Manufacturing
  - Objectives
  - Progress to date (WP 5.1 & WP 5.2)
  - Schedule, Milestones and deliverables
  - Impact
Extremely Large Telescope (ELT) Era

- Instruments scale with the aperture
- Instruments for ELT-class telescopes constitute a leap in
  - The number of optical surfaces
  - The size of their optics
  - The overall size and weight of the instrument
- While instruments grow larger and more complex, the tolerances on WFE become more demanding

HARMONI Integral field spectrograph dimensions:
- Height = 4.25 m
- Diameter = 3.5 m

Mid-IR imager and spectrograph:
- Cold optics height = 3 metre and consists of ~ 35 optical surfaces with largest mirror 30 cm diameter, 10 nm RMS surface shape requirement.
Modern production Methodologies

- JRA WP 4 and JRA WP5 are complementary research efforts focussed:
  - Complex optical surfaces,
  - Combining functionality within single components

- to reduce size, weight and cost of astronomical components by using
  - Using innovative manufacturing methods.

- Both are designed to raise the Technology Readiness Levels (TRL) of these techniques in readiness to be used in future instruments.

- The key teams and agencies and industries initially likely to benefit from these advances.

- Teams are also working closely with industry to leverage existing expertise and

- Assist in the transfer knowledge
FAME+
Unlocking the potential of freeform optics for astronomical instrumentation

Team
NOVA: Michiel Rodenhuis (lead),
ATC: Hermine Schnetler, Chris Miller, David Montgomery, Katherine Morris, Wayne Holland
LAM: Emmanuel Hugo
Konkoly: Szigfrid FARKAS, Dávid JÁGER, György MEZŐ
Free-form optics (1)

- Allow optical designs that are compact, have fewer surfaces and offer better performance

Three-mirror anastigmat

Alternative with two mirrors, one freeform
Free-form optics (2)

- Allow optical designs that are compact, have fewer surfaces and offer better performance

However:

- It is very difficult to manufacture Freeform Optics and
- It is also difficult to align components

This is where the Freeform Active Mirror Experiment (FAME) comes in
FAME+: Continuing the FP7 FAME project

- Same consortium
- At the end of the original FAME project:
  - Mirror was assembled
  - Demonstrator setup was built
  - Mirror was not yet tested
- Scope of FAME+
  - Test & characterize the FAME mirror
  - Improve design tools
  - Develop 2nd generation design, cryogenic
  - Develop metrology & control system
  - Demonstrate existing mirror with metrology & control system
FAME: The freeform active mirrors experiment

- Concept: a freeform mirror that can be actively controlled to correct manufacturing & alignment errors
- Consisting of:
  - Face sheet (blue)
  - Active array (red)
  - Actuators (green)
  - Control system
- Inherently stable: ”Set and forget”
FAME mirror characterization

- Needed to predict performance from design, also for 2nd generation mirrors
- Improve finite element design models
- Issues
  - Large effect of deviations of as-built mirror from design
  - Variation between actuators significant due to manufacturing and assembly processes
- Extensive test and measurement campaign was undertaken
- More effort than anticipated
Process Flow Diagram

Oct-18

H2020 Opticon Mid-Term Review
Actuator characterization

- Precise measurement of force vs. translation profile
- Dedicated test setup and automated test procedures developed
- 18 actuators tested
- Each individual actuator behave repeatable
- Variation between actuators significant
As-built FEM model

- Exact position of nodes critical for accurate modelling of mirror behavior
- Small deviations in position, despite custom alignment tool
- FEM model updated based on extensive CMM & laser scanner measurements
Interferometric characterization measurements

- **Sequence:**
  - Mirror shape measured without actuators
  - One actuator mounted, deviations measured
  - All actuators mounted, influence functions measured
  - measured
  - Mirror deformed to predefined shape
FAME 2\textsuperscript{nd} generation design: actuators

- Performance of single actuator repeatable
- Variation between actuators significant
- Actuator consists of many small parts
- Flexures manufactured using wire-EDM, thereafter each flexure need to be formed – it is very difficult even when using a special made jig - to get each flexure identical
- Developing improved actuator using flexure made as single structure
- Actuators should work in a cryogenic environment
FAME 2\textsuperscript{nd} generation design: Face sheet and active layer

- First generation:
  - using hydroforming to manufacture the mirror face sheet introduced stresses and local inhomogeneities
  - gluing nodes onto the back of the face sheet resulted in through print and resulted in an interface that is not well understood and introduced unwanted effects

- FAME+:
  - Developing a design where the face sheet and active layer can be manufactured as a single component

- Excellent case for OPTICON A\textsuperscript{2}IM WP

- Joint design workshop scheduled for November 2018
Metrology

- Not just a single solution but a methodology
- Aim to provide optimal solution based on use case
- Applicable to other active mirrors

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**Measuring wavefront error**
- Separate WFS arm
  - Shack-Hartman
  - Pyramid
  - Optical differencing
- Focal plane WFS
  - Curvature WFS
  - Phase diversity
  - Holographic WFS

**Measuring the mirror shape**
- Measuring the mirror shape optically
- Measuring the mirror shape directly
  - Deflectometry
  - Actuator encoders
  - Separate position sensors
Metrology: Particularities of FAME-type active mirrors

- Initial shape deviations may be large
- Required precise shape control to match the as “as-designed” shape
- Requires high dynamic range and precise accuracy measurement metrology with a slow update rate (minutes – hours)
- Iterative approach allowed
- Emphasis on the mid-spatial frequencies
Example metrology option: Generalised optical differencing

- Principle similar to pyramid WFS, but with tunable, non-linear response

Courtesy: S. Y. Haffert, Leiden Observatory
FAME+ planning

Define mirror nominal geometry
- Material
- Manufacturing technique

Define actuator Array
- Array structure
- Actuator Grid
- Space available

Define desired deformation Modes & amplitudes
- Spatial scale r/D vs amp

Estimate required forces and strokes

Finalise Actuator Requirements Specification

Evaluate component options
- Flexures
- Actuator Driver
- Actuator Mechanism
- Sensors
- Electronics

Component Technical Requirements

Component Design
Manufacture
Test
Prefered design

For each identified option

Component

2017
2018
2019
2020

WP 4.0 characterising the existing FAME mirror
- Writing test plans
- Testing the actuators
- Testing the mirror

WP 4.1 Metrology & Control
- Metrology sys requirements spec
- Metrology sys technology review
- Metrology sys methodology design
- Metrology sys applied design
- Metrology for characterisation, requirements
- Metrology for characterisation, design

WP 4.2 FAME+ design
- Alternative to hydrof. face sheet
- FAME technology envelope study
- FAME+ requirements specification
- FAME+ actuator node layout optimisation
- FAME+ cryogenic design study
- FAME+ systems design
- FAME+ detailed design
- FAME+ modal analyses

WP 4.3 FAME+ integration
- Metrology system parts acquisition
- Metrology system parts manufacture
- FAME & Metrology system integration
- Integrated test campaign

Preferred design
Select

NDV
ATC
LAM
Kaniedy
External

Joint activity led by ATC
Summary

❖ FAME+ developing active free-form mirror technology for next generation of astronomical instruments.
❖ Has potential to reduce complexity and thus size and weight at similar or better performance.
❖ Less components could also have a cost advantage.
❖ Aim to realize a simple and robust system.
❖ Active but stable mirror could allow the correcting of the wavefront error (WFE) of other instrument components.
❖ Could possibly correct drift in performance (due to environment affects) by active control.
❖ Qualified design concept ready by mid-2020.
Additive Astronomy
Integrated-component Manufacturing (A²IM)

Team
ATC: Hermine Schnetler (lead), Chris Miller, David Montgomery, Katherine Morris, Wayne Holland
AIP: Roger Haynes
LAM: Emmanuel Hugo, Melanie Roulet
Konkoly: Szigfrid FARKAS, Dávid JÁGER, György MEZŐ
NOVA:
Exploiting additive manufacturing

Reduction / redistribution

Mass

Stiffer, stronger, lighter, more shapes

Thermal Control

Higher resistance to thermal shock / variation

Cost

Lower life-cycle costs – from design to end of life

Complexity

Reduction of seams, welds and joins

A solution ready for a problem!
AM in astronomy – the motivation

- Not used much so far (instruments tend to be “one-offs”, little time for prototyping, etc...)
- Operation in extreme environments (high vacuum, cryogenic temperatures, space, etc...)
- Component parts need to be reliable and made to last a long time (deep space missions)
- Pressure to have cost savings (design, production and running costs – often no time for R&D – pressure to deliver)
Objectives for A²IM

- Investigate the use of AM components for astronomy instruments (materials, manufacture techniques and post processing)
- Develop 3-D printable test samples and evaluate (surface quality, stiffness, porosity, outgassing, CTE, etc...)
- Down select and prototype an integrated components that can be used in an actual instrument
- Develop a cookbook and toolkit (best practices)
WP 5.1 - Material investigation

- WP5.1.1 Material characterisation (Sheffield University)
- WP5.1.2 Active Control (STFC)
- WP5.1.3 Cooled mirrors (IAC)
- WP5.1.4 Embedded fibres (AIP)
# Programme of work and milestones

<table>
<thead>
<tr>
<th>ID</th>
<th>Task Name</th>
<th>Start</th>
<th>Finish</th>
<th>Duration</th>
<th>2018</th>
<th>2019</th>
<th>2020</th>
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<tbody>
<tr>
<td>1</td>
<td>WP 5.1 Investigating additive materials for cryogenic use</td>
<td>13/02/2018</td>
<td>12/02/2019</td>
<td>52w</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
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<td>2</td>
<td>Select and procure material samples</td>
<td>13/02/2018</td>
<td>12/03/2018</td>
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<td>Investigate integrated component manufacturing techniques</td>
<td>13/02/2018</td>
<td>12/03/2018</td>
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<td>4</td>
<td>Design test samples</td>
<td>13/03/2018</td>
<td>07/05/2018</td>
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<td>Q1</td>
<td>Q2</td>
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<td>5</td>
<td>Prepare test plan</td>
<td>08/05/2018</td>
<td>04/06/2018</td>
<td>4w</td>
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<td>Q3</td>
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<td>6</td>
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<td>02/07/2018</td>
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<td>Q1</td>
<td>Q2</td>
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<td>7</td>
<td>Characterise material samples</td>
<td>03/07/2018</td>
<td>24/09/2018</td>
<td>12w</td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
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<td>8</td>
<td>Prepare Additive Manufacturing Report (D5.1)</td>
<td>25/09/2018</td>
<td>22/10/2018</td>
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<td>19/11/2018</td>
<td>4w</td>
<td>Q1</td>
<td>Q2</td>
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<td>20/11/2018</td>
<td>17/12/2018</td>
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<td>Q1</td>
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<td>Update reports (D5.1 and D5.2)</td>
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<td>14/01/2019</td>
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<td>Q2</td>
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<td>11/02/2019</td>
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<td>12/02/2019</td>
<td>11/01/2021</td>
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<td>Identify two prototypes and develop concept designs</td>
<td>12/02/2019</td>
<td>08/04/2019</td>
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<td>Develop the integrated component requirements</td>
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<td>Q3</td>
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<td>Perform detailed integrated component design</td>
<td>04/06/2019</td>
<td>16/12/2019</td>
<td>28w</td>
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<td>Q2</td>
<td>Q3</td>
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<td>Prepare integrated component design report (D5.3)</td>
<td>17/12/2019</td>
<td>10/02/2020</td>
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<td>Q3</td>
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<td>11/02/2020</td>
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<td>Manufacture component(s)</td>
<td>24/03/2020</td>
<td>15/06/2020</td>
<td>12w</td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
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<td>21</td>
<td>Characterise components in accordance with the test plan</td>
<td>16/06/2020</td>
<td>11/01/2021</td>
<td>30w</td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
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<td>WP 5.3 Additive manufacturing cookbook and toolkit</td>
<td>15/01/2019</td>
<td>16/11/2020</td>
<td>96w</td>
<td>Q1</td>
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<td>Q3</td>
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<td>23</td>
<td>Define material selection guidelines and design rules</td>
<td>15/01/2019</td>
<td>09/03/2020</td>
<td>60w</td>
<td>Q1</td>
<td>Q2</td>
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<td>24</td>
<td>Develop Additive Manufacturing Best Practice Guideline (D5.4)</td>
<td>10/03/2020</td>
<td>16/11/2020</td>
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<td>Q2</td>
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</table>
Work Package Life-cycle

Test samples design and evaluation activity flow diagram

<table>
<thead>
<tr>
<th>Performance Parameters</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
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<tr>
<td>Diameter</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thickness</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Post processing</td>
<td></td>
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</table>

Proven processes → Example parts → Trial manufacture → Performance analysis

- Review of existing components manufactured using AM
- Review test plan and define material key requirements
- Select materials and design test pieces
- Manufacture test pieces
- Confirm test components compliance with the design
- Compare results with application requirements and conventional manufactured components
- Perform performance testing
WP 5.1.1 Material characterisation

- Objectives: To formulate a database of materials and manufacturing methods and use AM to produce test structures relevant to our designs

- Status:
  - Metals tested - SS316, Ti64 and Al
  - Metals still to be tested - Inconel IN718
  - Under test - Al₂O₃, SiC, SiSiC, ZrO₂ and B₄C
  - Polymers to be identified and tested
    - Tusk XC, Proto G,
    - Taurus (ABS like)
    - Extreme (High Impact)
  - SLS polymer technology:
    - Alumide (Blend aluminum powder and Polyamid powder)
    - PA 12
    - PA-GF Glass filled PA
    - TPU 92A – 1 (rubbery like material)
    - PA 2241 FR
Bending tests (Ti and Stainless Steel)
WP 5.1.2 Active control

- Objectives: To identify actuation components that would benefit from AM and test samples

- Status:

![Diagram showing control electronics, actuator, and sensor with LVDT for linear movement sensor and Capacitance concept.](image-url)
### LVDT concept

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>LVDT001</th>
</tr>
</thead>
<tbody>
<tr>
<td>Why?</td>
<td>The ability to print a better, customisable and job specific LVDTs.</td>
</tr>
<tr>
<td>Key feature?</td>
<td>Printing the two materials in one piece</td>
</tr>
<tr>
<td>Material?</td>
<td>Plastics and conductive</td>
</tr>
</tbody>
</table>

- A plastic insulating material
- Any conductive material
Capacitance sensor concept

A flexible plastic insulating material

Any conductive material

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>CapSen001</th>
</tr>
</thead>
<tbody>
<tr>
<td>Why?</td>
<td>The ability to print a better, customisable and job specific capacitance sensors</td>
</tr>
<tr>
<td>Key feature?</td>
<td>Printing the two materials in one piece</td>
</tr>
<tr>
<td>Material?</td>
<td>Plastics: insulator (flexible) + conductive</td>
</tr>
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</table>
Flexure

Ideally thin walls ~ 0.25mm

Direction of force

Flexure point ~ 0.1mm

Sample ID | Flexure001
---|---
Why? | The ability to print a functional flexure in one piece without substantial machining.
Key feature? | Narrow walls, high aspect ratios
Material? | Metal: stainless steel, titanium
Integrated Active array

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>ActMir001</th>
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<tbody>
<tr>
<td>Why?</td>
<td>The ability to print the existing mirror structure in one material</td>
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<tr>
<td>Key feature?</td>
<td>Narrow walls in the actuator design</td>
</tr>
<tr>
<td>Material?</td>
<td>Metal: stainless steel, titanium, aluminium</td>
</tr>
</tbody>
</table>

A Restive Temperature Device (RTD) can be used to control the temperature in closed loop. The RTD is a resistor who’s resistance changes with temperature and can therefore be used as both the “heater” and the “sensor” for the actuator. Platinum, Nickel, and Copper metals are typically used to measure positive temperature coefficients (PTC).

\[ R_T = R_0[1 + \alpha_1 T + \alpha_2 T^2 + \cdots + \alpha_n T^n] \geq R_0[1 + \alpha_1 T] \]

A high thermal expansion material is placed in the centre of a diamond structure. As the material expands and contracts due to temperature it puts a perpendicular force on the attached nodes. Using this technique it is possible to generate high forces from a miniature actuator.
A positive temperature coefficient (PTC) refers to materials that experience an increase in electrical resistance when their temperature is raised. Materials which have useful engineering applications usually show a relatively rapid increase with temperature, i.e. a higher coefficient. The higher the coefficient, the greater an increase in electrical resistance for a given temperature increase.

Metals - All metals produce a positive change in resistance for a positive change in temperature. This, of course, is the main function of an RTD. As we shall soon see, system error is minimized when the nominal value of the RTD resistance is large. This implies a metal wire with a high resistivity. The lower the resistivity of the metal, the more material we will have to use.

The most common RTDs are made of either platinum, nickel, or nickel alloys. The economical nickel derivative wires are used over a limited temperature range. They are quite non-linear and tend to drift with time. For measurement integrity, platinum is the obvious and most common choice.

<table>
<thead>
<tr>
<th>Metal</th>
<th>Resistivity [ohm/cm²f]</th>
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</thead>
<tbody>
<tr>
<td>Gold</td>
<td>13</td>
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<tr>
<td>Silver</td>
<td>8.8</td>
</tr>
<tr>
<td>Copper</td>
<td>9.26</td>
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<tr>
<td>Platinum</td>
<td>59</td>
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<tr>
<td>Tungsten</td>
<td>30</td>
</tr>
<tr>
<td>Nickel</td>
<td>36</td>
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</table>
ABS mirror using a own developed and AM manufactured piezo actuator

A piezo actuator can be printed in the centre of a diamond structure using soft piezoelectric materials which is ideal for *Piezo Actuators and Sensors*.

Ferro-electrically soft piezo ceramic materials can be polarized fairly easily even at relatively low field strengths. This is due to the comparably high domain mobility typical for them. The advantages of soft PZT materials are their large piezoelectric charge coefficient, moderate permittivities and high coupling factors.

<table>
<thead>
<tr>
<th>PIC151</th>
<th>Standard material for actuators of the PICA Stack/Thru and Piezo Tubes series</th>
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</thead>
<tbody>
<tr>
<td>Material</td>
<td>Modified lead zirconate titanate</td>
</tr>
<tr>
<td>Characteristics</td>
<td>High permittivity, large coupling factor, high piezoelectric charge coefficient, relatively high Curie temperature</td>
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<tr>
<td>Suitable for</td>
<td><em>Actuators</em>, low-power ultrasonic transducers, low-frequency sound transducers</td>
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<tr>
<td>Classification in accordance with EN 50324-1</td>
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<td>MIL-Standard DOD-STD-1376A</td>
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</table>
WP5.1.3 Cooled mirrors

- Objectives: To investigate and manufacture structurally-optimised AM mirror samples and cooling topologies

- Status:
  - Extensive literature study has been conducted
  - Ti64 mirror sample have been printed and evaluated
  - Sample pieces to be printed to evaluate the diameter vs thickness relationship
  - It is also necessary to evaluate the various post processing methodologies
Computer aided design of Ti mirror

a) external xy orientation, b) external yz orientation, c) external xyz orientation and d) internal yz cross-sectional view
WP 5.1.4 Embedded fibres

❖ Objectives: To evaluate whether optical fibres can be embedded in a AM mechanical structure

❖ Status:
  ➢ Currently busy with a preliminary experiment
  ➢ Evaluating cutting methodologies
  ➢ Locating features will be added prior to cutting the device
WP5.3 Cookbook

❖ Objectives:

➢ To establish “best practice” design rules for the design of astronomical components that can be additively manufactured

➢ Develop training methods that could lead to established training courses (e.g. presented at conferences etc.)

<table>
<thead>
<tr>
<th>Task#</th>
<th>Task description</th>
<th>2018</th>
<th>2019</th>
<th>2020</th>
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<tbody>
<tr>
<td>1</td>
<td>WP 5.3 Additive manufacturing cookbook and toolkit</td>
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</tr>
<tr>
<td>2</td>
<td>Define/collate material selection guidelines and design rules</td>
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<tr>
<td>3</td>
<td>Development of sample outputs for cookbook and toolkit</td>
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<td>4</td>
<td>Milestone: evaluation of output samples and definition of final output style/structure.</td>
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<tr>
<td>5</td>
<td>Implement output style and structure with collated information</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Develop ‘Additive Manufacturing Best Practice Guideline’ (D5.4)</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>
## Deliverables

<table>
<thead>
<tr>
<th>Del. No.</th>
<th>Deliverable title</th>
<th>Lead Beneficiary</th>
<th>Due Date</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>D5.1</td>
<td>Additive manufacturing material and design report</td>
<td>STFC</td>
<td>Mar 2018 (15 m)</td>
<td>KOM re-planning exercise – new proposed delivery date is Dec 2018</td>
</tr>
<tr>
<td>D5.2</td>
<td>Component prototype design and test report</td>
<td>STFC</td>
<td>Dec 2019 (36 m)</td>
<td>Due to start in Apr 2019</td>
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<tr>
<td>D5.3</td>
<td>Astronomical component prototypes</td>
<td>STFC</td>
<td>Jun 2019 (30 m)</td>
<td>Will start once the prototype designs have been reviewed</td>
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<tr>
<td>D5.4</td>
<td>AM “Best practices guidelines”</td>
<td>NOVA</td>
<td>Dec 2019 (36 m)</td>
<td>Request new delivery date of Jun 2020</td>
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</tbody>
</table>
### Milestones

<table>
<thead>
<tr>
<th>Milestone No.</th>
<th>Milestone Name</th>
<th>Related work package</th>
<th>Due Date (months)</th>
<th>Means of verification</th>
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</thead>
<tbody>
<tr>
<td>M13</td>
<td>Additive Manufacturing Materials Review</td>
<td>WP1</td>
<td>18*</td>
<td>External Review Panel</td>
</tr>
<tr>
<td>M14</td>
<td>Prototype Design Review(s)</td>
<td>WP2</td>
<td>30</td>
<td>Critical Design Review</td>
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<tr>
<td>M15</td>
<td>Prototype Test Report Review</td>
<td>WP2</td>
<td>47</td>
<td>Final review</td>
</tr>
</tbody>
</table>

* This milestone is coupled to deliverable D5.1 and is now planned to take place during the 1st quarter of 2019.
Impact

- AM has the potential to build instruments (and components) that are:
  - Lighter;
  - Smaller;
  - Multi-functional;
  - Self-contained;
  - Easier to assemble;

- Resulting in improved performance and
- Potentially more compact, reliable and cheaper
- Promote and provide the “know how” and test data required for designers to feel comfortable in using AM.