Metal 3D Printing on Orbit
A European Achievement and a Building Block towards On-Orbit Manufacturing

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Public Lecture TU Wien
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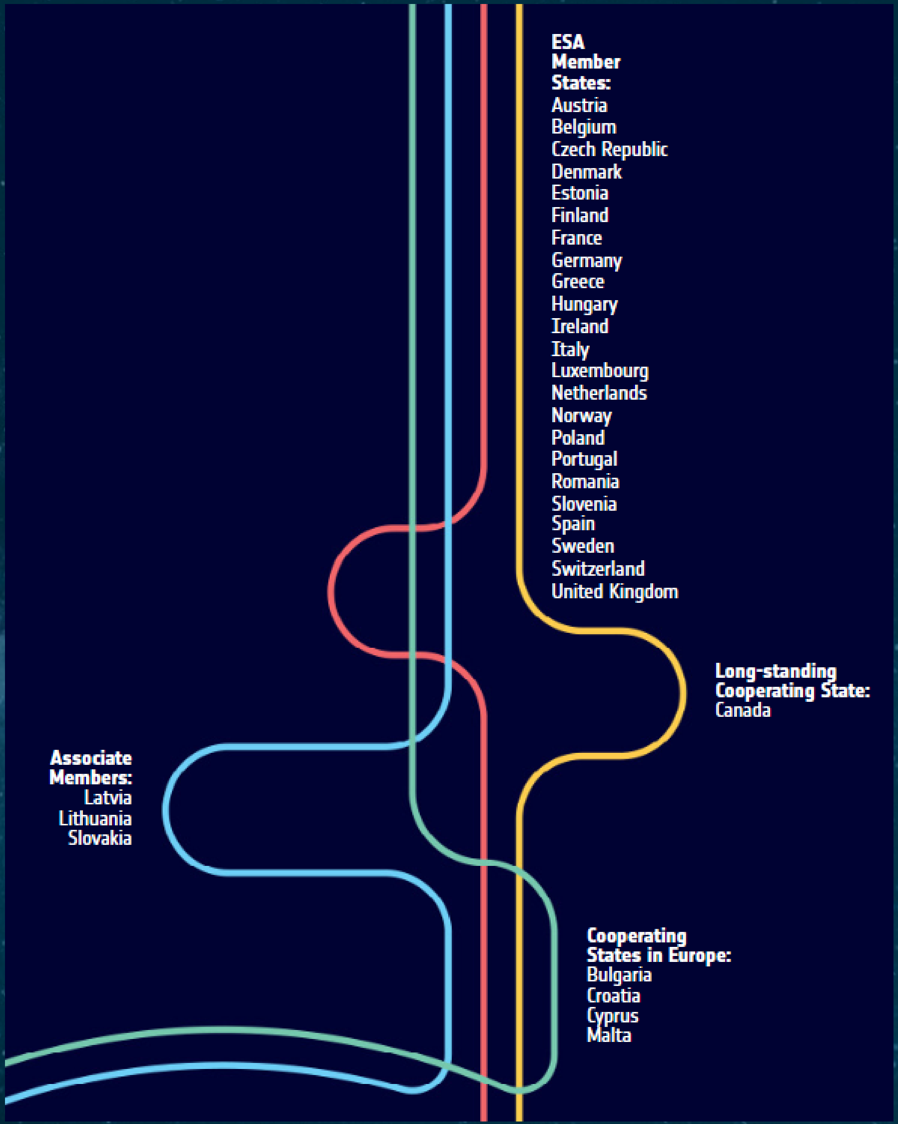
This is ESA

EUROPE’S GATEWAY TO SPACE

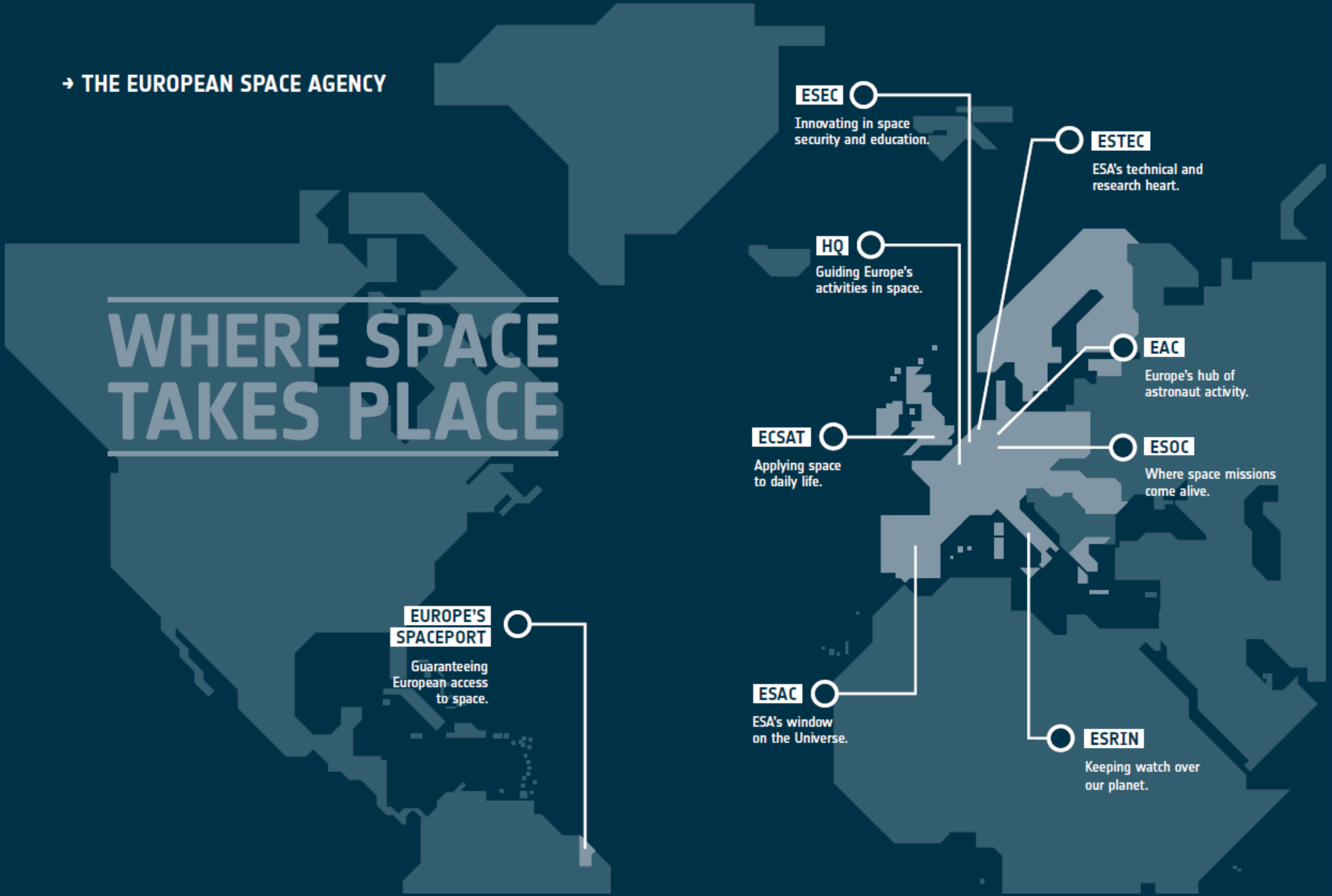
WHAT	23 Member States, 6000 employees
WHY	Exploration and use of space for exclusively peaceful purposes
WHERE	HQ in Paris, 7 sites across Europe and a spaceport in French Guiana
HOW MUCH	€7.79 billion = €15 per European per year

23 Member States, 8 Associated Members and Cooperating States

https://www.esa.int/About_Us/ESA_Publications/This_is_ESA



ESA Establishments



This is ESA

Four pillars. One ESA.

SCIENCE

SPACE TRANSPORTATION

EARTH OBSERVATION

NAVIGATION

COMMERCIALISATION, INDUSTRY & COMPETITIVENESS

HUMAN & ROBOTIC EXPLORATION

OPERATIONS

TECHNOLOGY

CONNECTIVITY & SECURE COMMUNICATIONS

SPACE SAFETY

50 Years of ESA Achievements

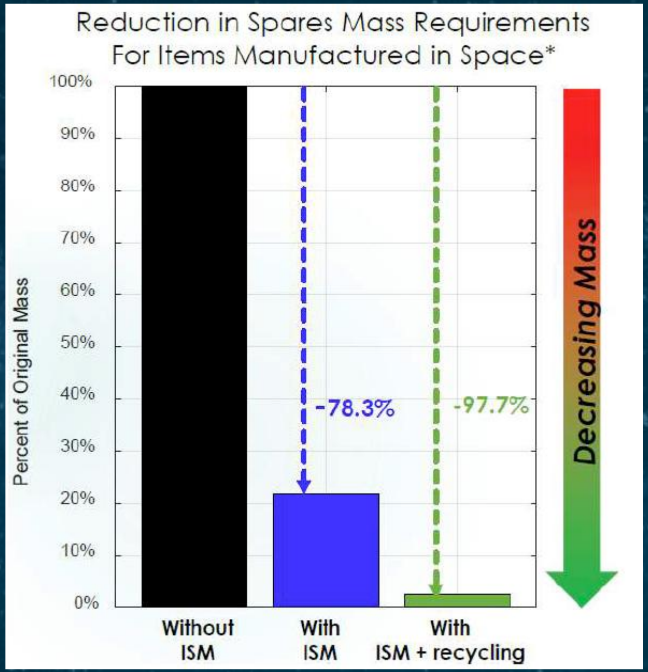
50 Years of ESA Achievements

https://www.esa.int/About_Us/ESA_Publications/ESA_50_Years_booklet

50 Years of ESA Achievements

Background: Manufacturing in Space – Why?

•On-demand manufacturing and recycling of spare parts, tools during long term human exploration missions ⇒ **simplified maintenance logistics** ⇒ savings in resupply missions and materials

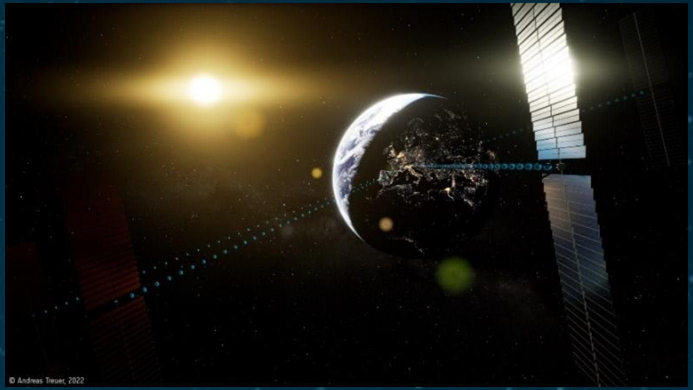


Adapted from A. C. Owens, and O. L. De Weck, AIAA SPACE 2016. 2016. 5394

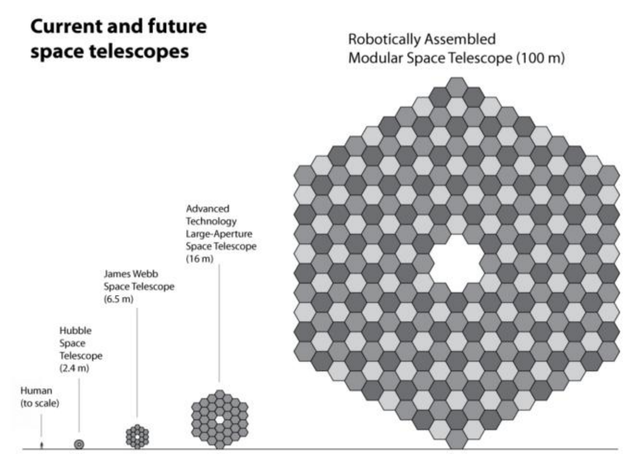
Background: Manufacturing in Space – Why?

- Larger spacecraft structures (no fairing size limitation): e.g.
  - Solar arrays ☞ higher power and **higher payload capacity, higher performance-to-launch-cost**
  - Antennae reflectors ☞ **higher data throughput** for telecoms
  - Large aperture telescope, large Interferometer ☞ **higher science return**
  - Long term: **manufacturing** and **maintenance** of **very large structures** (e.g. space-based solar power)
  - Longer term: **recycling** of end-of-life **spacecraft** structures and **debris**

  ☞ Improving **Space Sustainability**!



Credits: *Andreas Treuer, ESA*



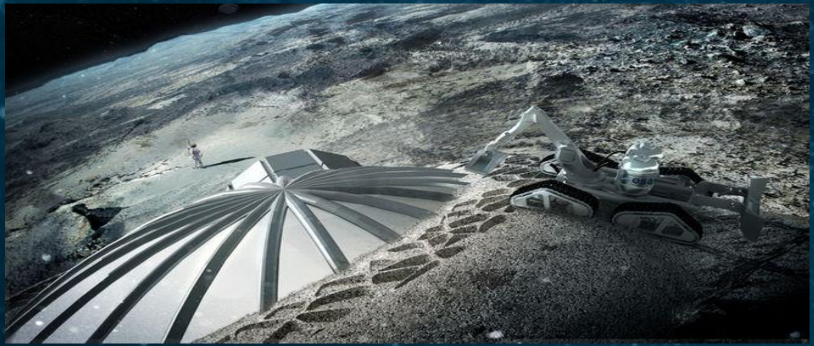
Source: https://www.futuretimeline.net/blog/2016/07/14-2.htm

Credits: NASA/Redwire:

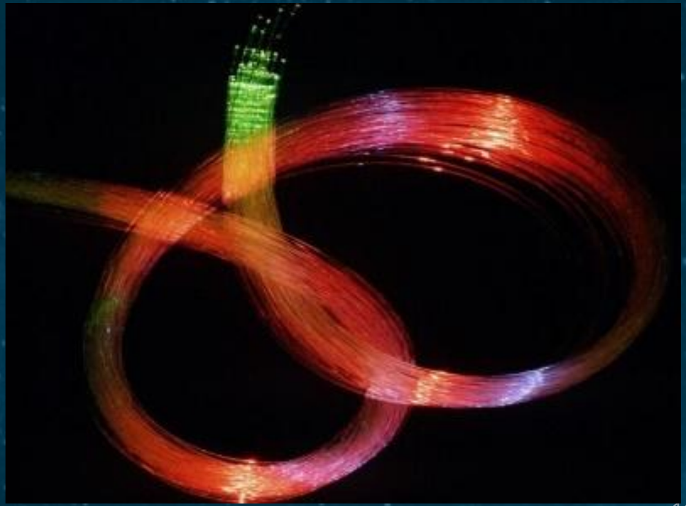
Credit: ESA

Manufacturing in Space: Why?
New Paradigm

- **In-situ construction** of infrastructure, in-situ propellant production and in-situ manufacturing of hardware (e.g. tools) for human exploration to the lunar (and Martian) surface ☞ enabling capabilities for **sustainable** surface exploration, longer term **commercial activities** (e.g. manufacturing-as-a-service)



- **Use of space conditions** for production of materials with enhanced properties (i.e. without defects associated to terrestrial conditions) for **commercialization** on Earth



Challenges and Required Developments

To realise this new paradigm a number of aspects need to be developed, which include:

- **Development of adequate manufacturing processes which can operate in space conditions (microgravity, vacuum, space temperature range, radiation)**
- **Development of in-situ validation methods and procedures for the on-orbit manufactured parts**
- Standardized interfaces
- Definition of on-orbit factory/station
- Design for on-orbit manufacturing
- Large structures AOCS and thermal control

Background: Additive Manufacturing in Space so far Polymers

3DP

- **First print on orbit**
- **ISS**

ABS

FLIGHT
2014

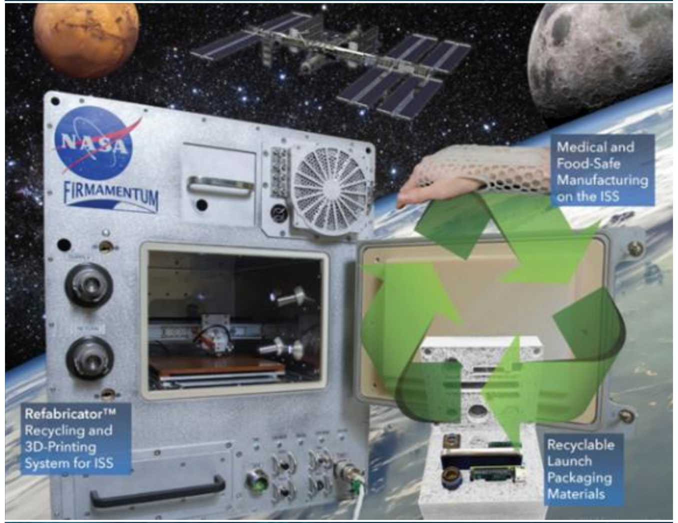
AMF

- **Commercial** Facility
- **ISS**

ABS / PEI-PC / HDPE

FLIGHT
2016

REFABRICATOR



- Integrated 3D **Printer+Recycler**
- **ISS**

PEI/PC (Ultem 9085)

FLIGHT
2018

POP3D

- **FDM Demonstrator**
- **ISS**

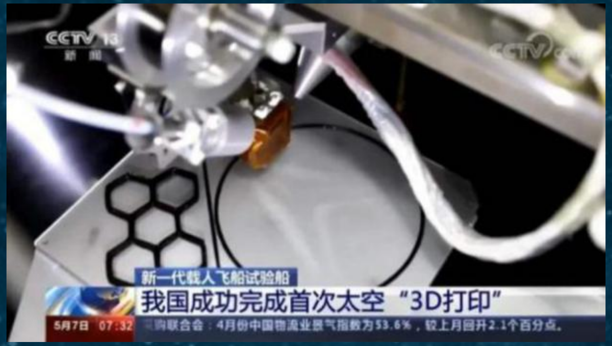
PLA

FLIGHT
2016

Background: Additive Manufacturing in Space so far
CFRP Composites / Metals

esa

中国空间技术研究院
中国航天 China Academy of Space Technology



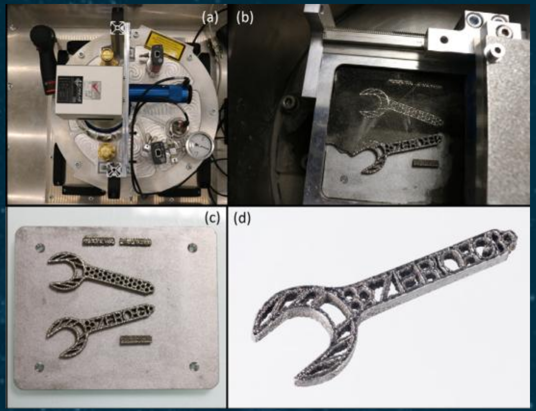
From: Zocca et al., Chinese Journal of Mechanical Engineering: Additive Manufacturing Frontiers 1.1 (2022): 100018.

- **First on-orbit 3D printing of continuous carbon fiber reinforced thermoplastics**
- New generation **Chinese crew spacecraft**

Continuous carbon fiber reinforced polymer

FLIGHT
2020

BAM Bundesanstalt für Materialforschung und -prüfung | TU Clausthal | DLR



From: Zocca et al., Chinese Journal of Mechanical Engineering: Additive Manufacturing Frontiers 1.1 (2022): 100018.

- **First ever demonstration of powder-bed metal additive manufacturing in microgravity**
- **Stainless Steel** in parabolic flight 2018 and **Metallic Glass** in **suborbital sounding rocket** 2021

FLIGHT
2021

☞ **No Metal Additive Manufacturing on Orbit until 2024**

Objectives of the Metal 3D Printer Technology Demonstrator

The objective of this activity is to **develop an AM Machine** that will demonstrate the capabilities of this technology to perform **metal deposition in 3D** under **sustained microgravity** conditions and to **manufacture test specimens**

- ✓ To **understand the limitations** of the metal AM Machine demonstrator in terms of specimen accuracy and quality,
- ✓ To predict the way to improve the demonstrator in order to offer **functional parts** to astronauts and future **in-orbit manufactured systems**,
- ✓ To familiarise with **operations** of an operational Metal 3D Printer in a space habitat, both from the perspective of **crew as well as ground operator**,

Metal 3D Printer Installation: part of Huginn Mission

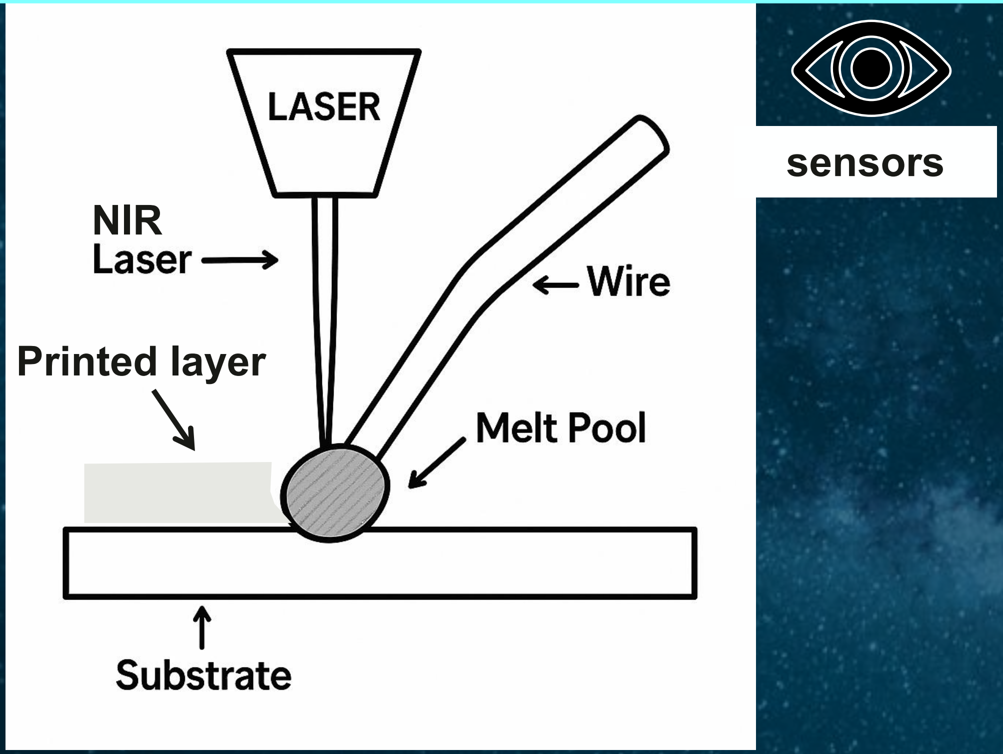
- Launched: 26 August 2023
- Docked to the ISS: 27 August 2023
- Launch site: NASA Kennedy Space Center, Florida, USA
- Spacecraft: SpaceX Crew Dragon Endurance
- Return to Earth: Near Pensacola, Florida, US.
- Undocking from the ISS: 11 March 2024
- Landing: 12 March 2024
- **First non-US pilot on Crew Dragon**
- Performed **>30 European and many international experiments and technology demonstrations**
  - Including **installing Metal 3D Printer technology demonstrator**
- Totalling **199 days in space** during his Huginn mission

The Cooperation behind the Metal 3D Printer Technology Demonstrator

- The Metal 3D Printer TD is developed by **industrial team led by Airbus Defence and Space** under a contract with the European Space Agency, **co-funded** by Airbus Defence and Space.

Metal 3D Printer Technology Demonstrator: the process

Laser Wire Direct Energy Deposition (L-WDED)

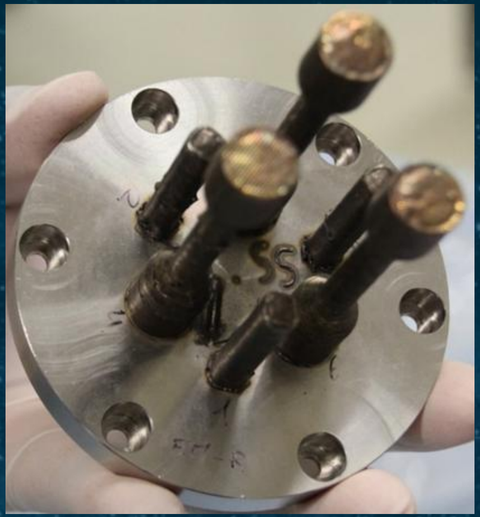


Pressured chamber at 0.88bar N_2

Process parameters

- Laser spot size
- Laser power
- Wire ø & inclination angle
- Wire feed rate
- Travel speed
- Shielding gas

Printing Environment



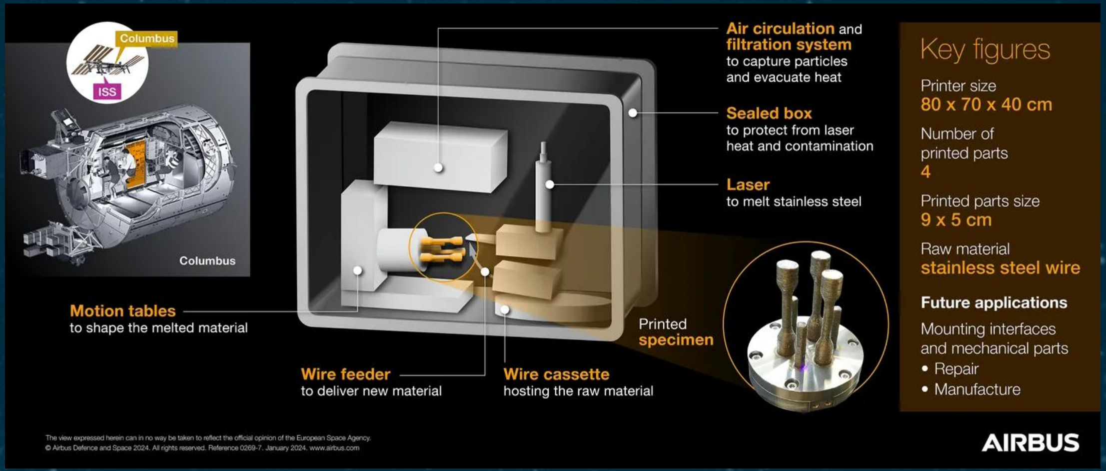
Ground	
Gravity	1g
Thermal behaviour	Predictable due to standard gravity

ISS	
Gravity	Microgravity
Thermal behaviour	Negligible natural convection

0.88 bar N_2

Printing Process Characteristics

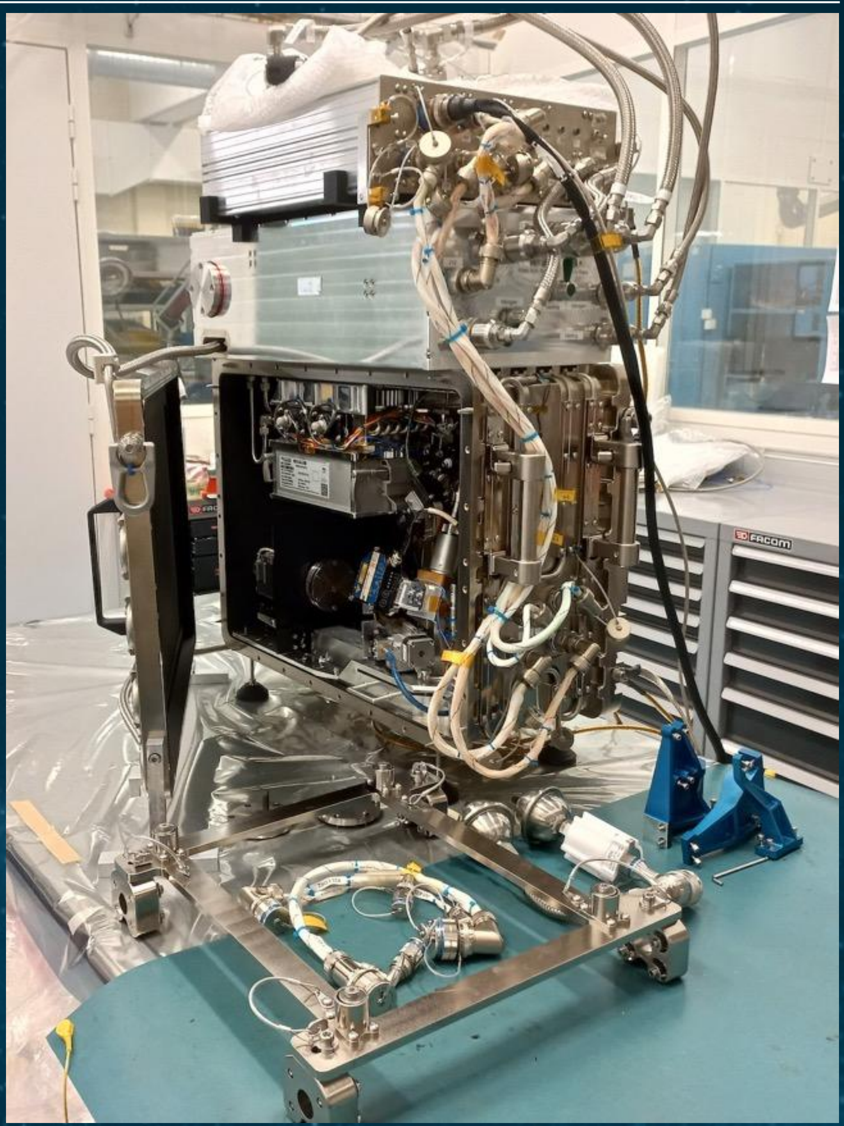
- Printing is based on the **laser wire direct energy deposition** process, creating a melt pool for adding feedstock material
- The specified specimens will be printed with **316L Stainless Steel** on a stainless steel build plate
  - ☞Trade off between feedstock materials, substrate material, shielding gas requirements
- **Wire diameter** is 0.6 mm,
- Laser output power **300 W max**
- **Build volume:** maximum printed part dimensions: ⌀ 5 cm; height 8 cm
- Mass of a printed specimen range from 80 to 200 grams,
- The wire feeder contains 1000 gr of stainless steel
  - ☞ Driven by capacity of the filter which needs to be replaced after 1000 grams of printing



Technology Demonstrator Design

The Metal 3D Printer Technology Demonstrator consists of

- A **Sealed Box**, containing the Additive Manufacturing Machine
  - Conditioning of **Printing Environment**, < 0.5% O_2, 0.88 bar
  - **Protection** of crew and Columbus environment
  - **Laser heat source** and **wire feeder**, fixed
  - **4 D motion table** to align printing with heat spot and wire feed
- A hydraulics assembly, routing cooling, N_2 and venting
- An **Electronics Box**
- **Technology Demonstrator** ⇒ maximises use of **COTS items**
- On the **European Drawer Rack Mark II (EDR2)** in Columbus module
- Provides data communication (incl. high-rate data link), power, cooling, venting, N2 supply



Operations

Operation of the Metal 3D Technology Demonstrator is split between crew and ground console.

Crew will:

- Retrieve the instrument from its bag upon arrival on ISS/Columbus,
- Configure the Metal 3D Printer in preparation of a printing cycle,
- Installation of Metal 3D in EDR2 and connection of jumpers,
- Retrieve the Sealed Box from EDR2 upon conclusion of a printing cycle,
- Retrieval of the printed specimen, and reconfiguration of the Sealed Box, AM machine for a next printing cycle,
- Re-installation,
- Disposal of the Metal 3D (retrieval of complete instrument) upon conclusion of activities.

Operations

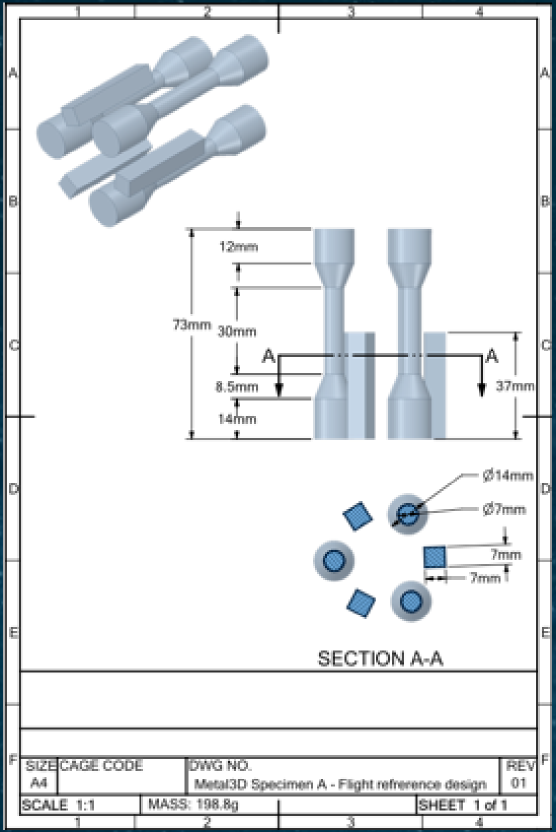
Operation of the Metal 3D Technology Demonstrator is split between crew and ground console.

Ground Console will:

- Perform the switch on and commissioning of the Metal 3D: check of communication ground ↔ Metal 3D, command functionality, interfaces to EDR2 (venting, cooling, N2), AM machine calibration (first printed lines)
- Perform the printing operations of Metal 3D, supported by the Payload Developer
    - Printing time limited to ≈ 4 hours per day due to noise regulations
    - Sensors: profilometric data (deposited layer height, width), camera, temperature, O level, pressure
    - Layer-by-layer consideration of printing parameters based on sensor data

Specimens planned to be printed

1xg Reference Print with Metal 3D TD FM

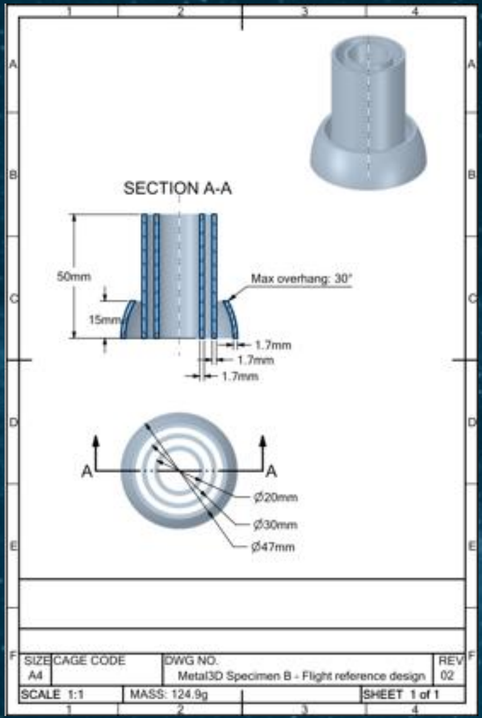


Specimen A
Tensile and Bending Test Specimens

- 3 tensile strength specimens (ISO-6892-1) and 3 bending strength specimens (ISO-3327)
- To assess the structural and mechanical properties of specimens printed on ground and on orbit

Specimens planned to be printed

1xg Reference Print with Metal 3D TD EM

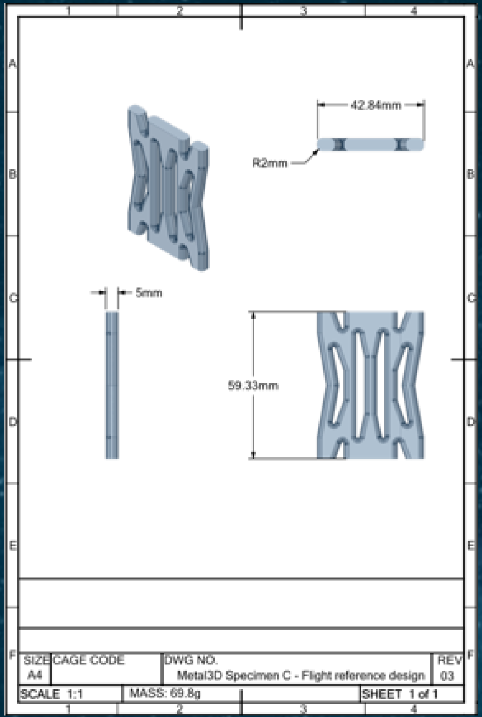


Specimen B
Thin Walls Structure

- Three concentric cylinders with thin walls
- To assess the effect of microgravity on features known to be challenging for wire-based metal 3D printing i.e shape accuracy of thin-wall cylinders with and without overhangs

Specimens planned to be printed

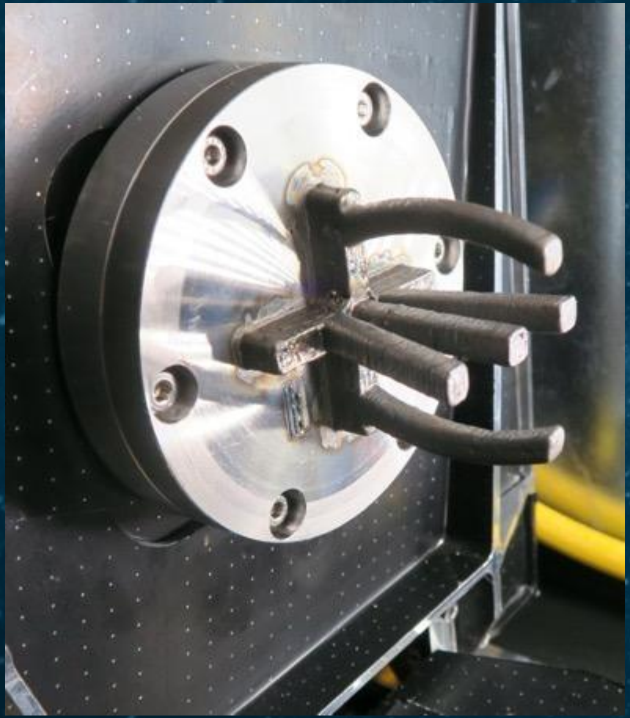
1xg Reference Print with Metal 3D TD EM

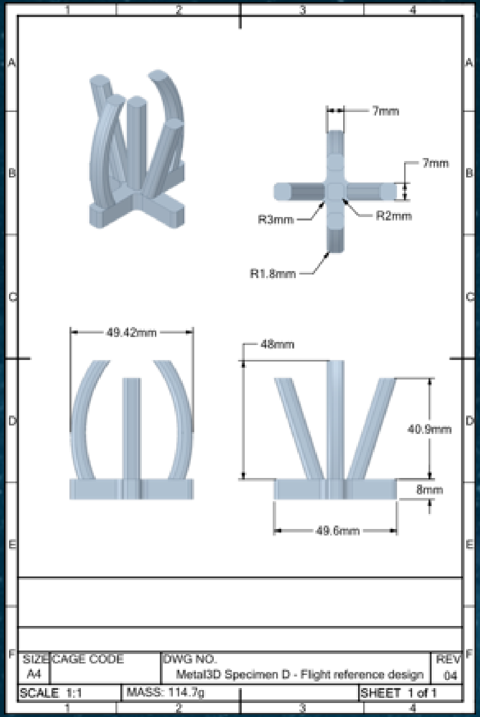


Specimen C
Simplified Compliance Mechanism Tool

- Simplified design for complaint mechanism
- Mimics aspects of a compliant mechanism and captures a number of challenging geometrical elements
- To evaluate future feasibility of in-space manufacturing of dedicated tools and instruments on-demand

Specimens planned to be printed





1xg Reference Print with
Metal 3D TD EM

Specimen D
Spatial Variability
of Thermal Expansion

- Mirror support
- To assess spatial variability of thermal expansion of 3D metal parts printed on ground and under microgravity
- Proposed and to be analysed by the Technical University of Denmark

Planned Specimens and Material Investigations

Specimen A

- Visual Inspection
- X-ray Computer Tomography
- Machining
- Tensile and Bending Testing
- Microscopy
- Hardness

Specimen B

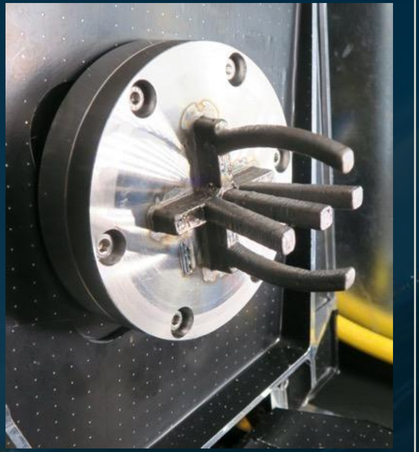
- Visual Inspection
- X-ray Computer Tomography

Specimen C

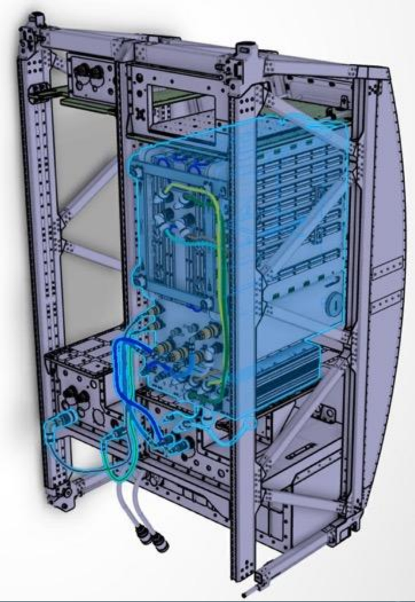
- Visual Inspection
- Laser scanning measurement
- X-ray Computer Tomography
- Microscopy

Specimen D

- Incoming inspection XRF of surface
- X-ray
- Mounting of mirror and beam splitter
- CTE test
- Residual stress analysis
- Metallography

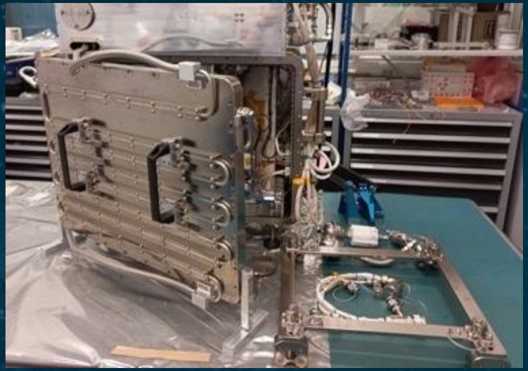


Mission Timeline



Metal 3D design in EDR2
(2019 - 2020)

Metal 3D Engineering Model
(Sept 2020)



MAIT Flight Model
(2023)

Launched on NG-20
ISS Resupply Mission
(30th Jan 2024)

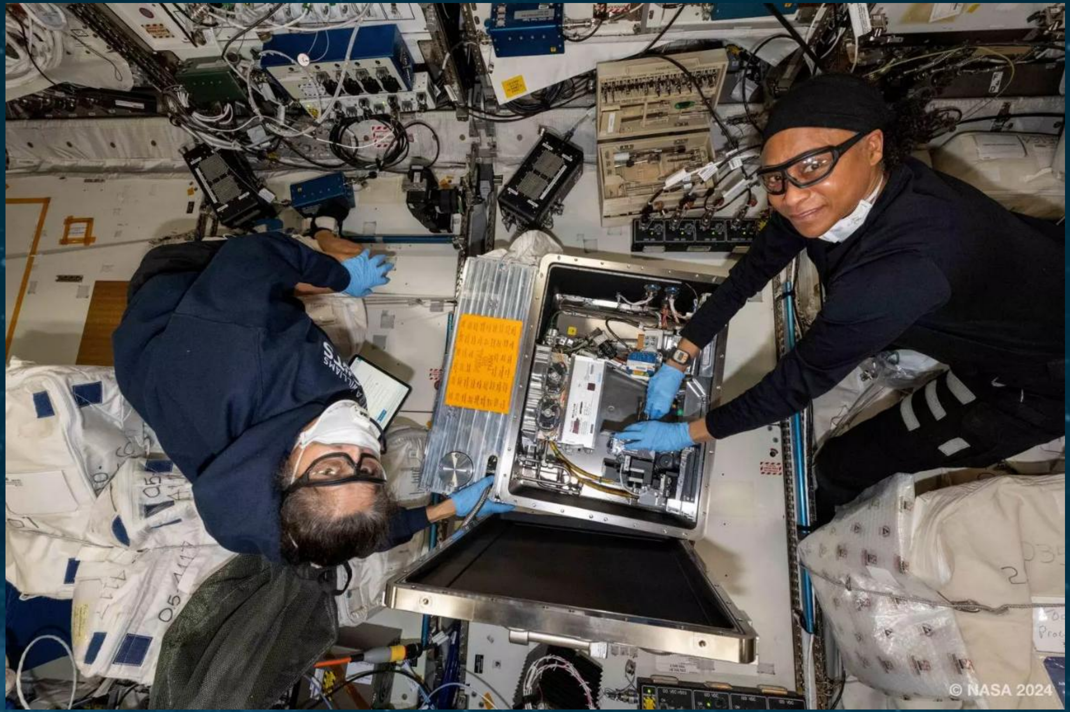
Timeline

Installation in EDR2
(Feb 2024)

Commissioning and First Print
(May 2024)

Timeline

Printing of Specimen A
(May - Aug 2024)
Print complete on 7th Aug 2024 after 25 effective printing days



Removal of Metal 3D from EDR2, printed specimen A retrieval, printer health checks, new build plate installation, printer back in EDR2 for next print
ISS astronauts Jeanette Epps and Sunita Williams
(21st Aug 2024)

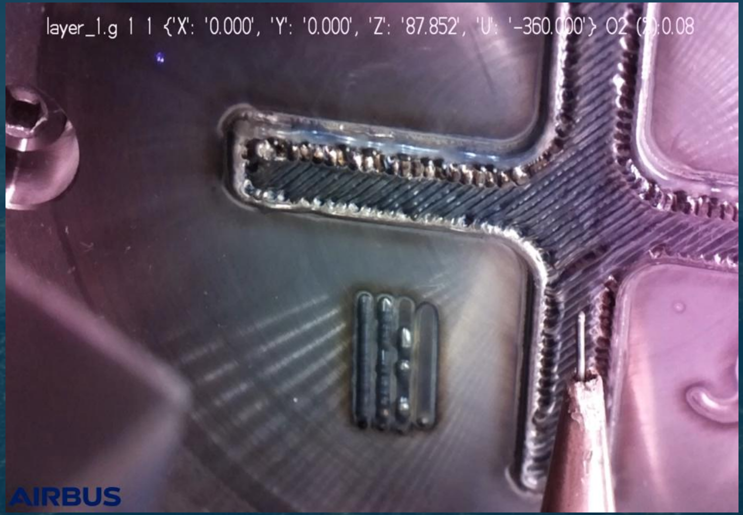
Timeline

7th August 2024
First metallic part fabricated by additive manufacturing on orbit

Other Specimens Status

Completed Succesfully

Specimen B
Thin Walls Structure



Completed Succesfully

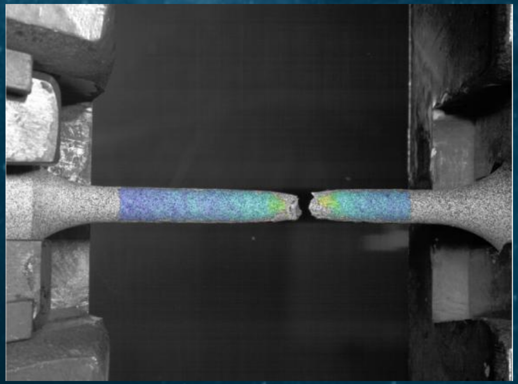
Specimen D
Spatial Variability
of Thermal Expansion

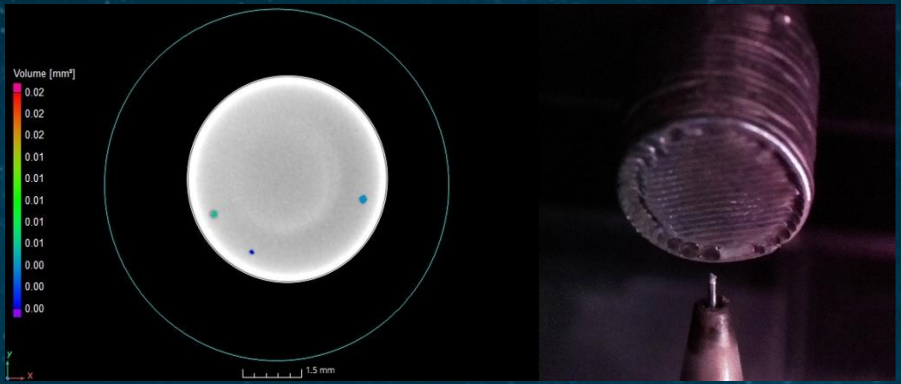
Stopped

Specimen C
Simplified Compliance
Mechanism Tool

Printed Specimens Material Investigation - Ongoing

- Specimen A material investigation ongoing at ESTEC/ECSAT Materials laboratories
- Initial results show:
  - Good correlation between printing history and observed defects
  - Mechanical properties in line with 316 L processed by DED
  - Porosity distribution can be correlated with printing strategy
-

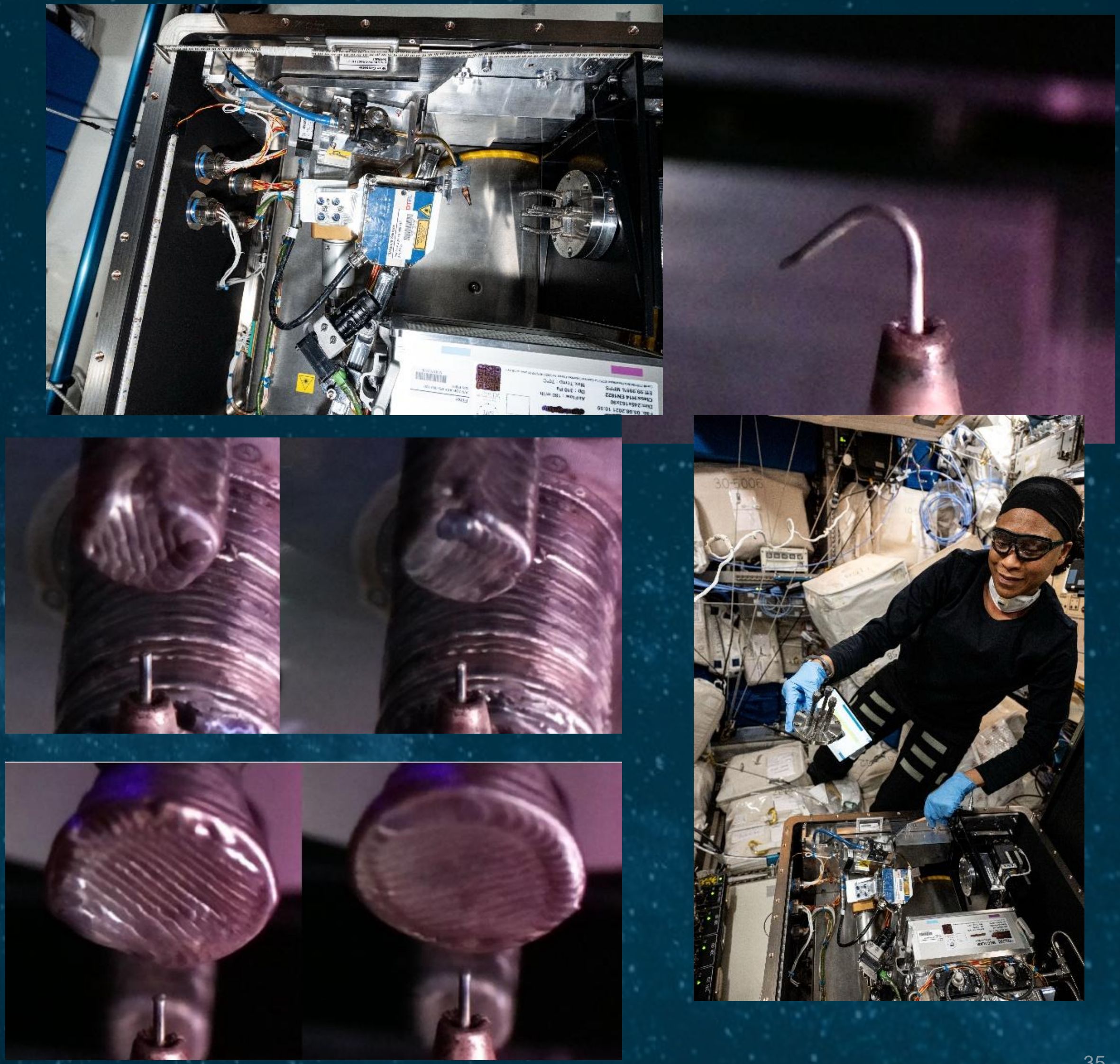




Initial Lessons Learned

Lessons Learned to date

- Ratio of mass/volume of the instrument with respect to the printable volume,
- Extensive crew time required for (re-)installation and specimen retrieval,
- Impact of the Safety Requirements (laser and printing containment, printing gases),
- Finetuning of the printing process is challenging,
- Initial results show that post processing is needed.



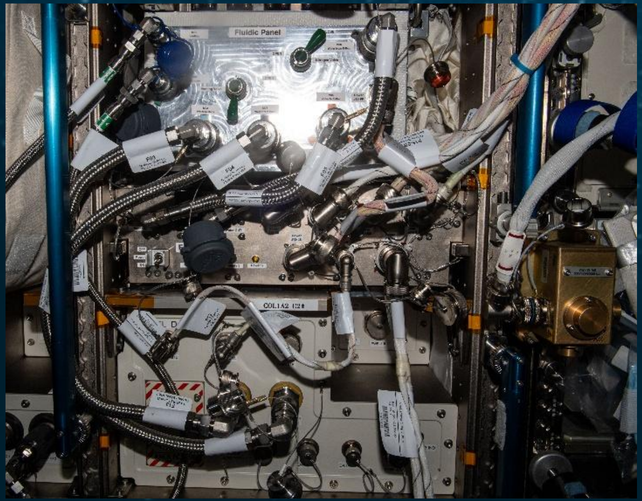
Areas for Improvement

Printing Performance

- Accuracy
- Part Complexity
- Quality (Certification)
- Surface smoothness

Automation

- Process monitoring, control
- Process Modelling, ICME
- Digital Twin, AI



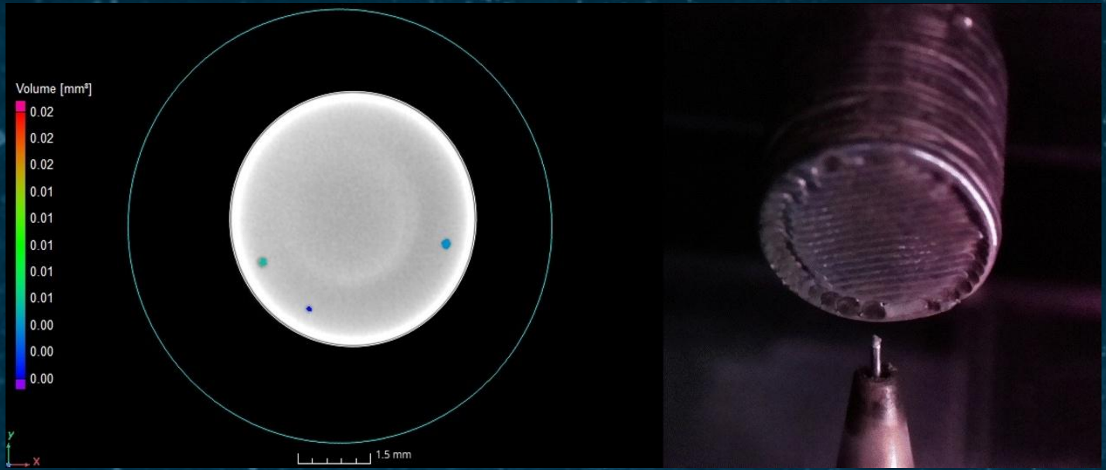
Handling

- Minimising Crew Time
- Complexity
- Exchange
- Circular Approach

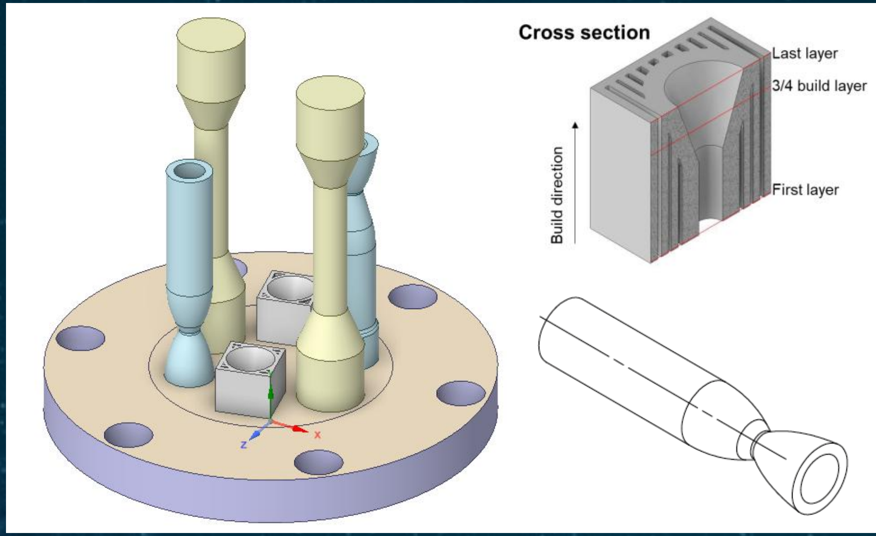
Design

- Miniaturisation
- Limited Resources
- Ratio Printer/Print
- Robustness

Next Steps



Complete Material Investigation of specimens



Printing a 5th Specimen – STARGATE

Publication of Results

- Topical Team on Metal Additive Manufacturing in Space
- Feasibility and Design Study Next Generation Metal 3D Printer

Out of Earth Manufacturing

To realise this new paradigm a number of aspects need to be developed:, which include:

- *Development of **adequate manufacturing processes***
- *Development of in-situ **validation methods** and procedures*

Manufacturing and Assembly Technologies

Out-of-Earth Manufacturing white paper **available here**:

https://esamultimedia.esa.int/docs/technology/White_Paper_OoEM_Final_4_Signed_For_Publication.pdf

Thank you for your attention
Questions?

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