Out-of-Earth manufacturing: State of the art and perspective

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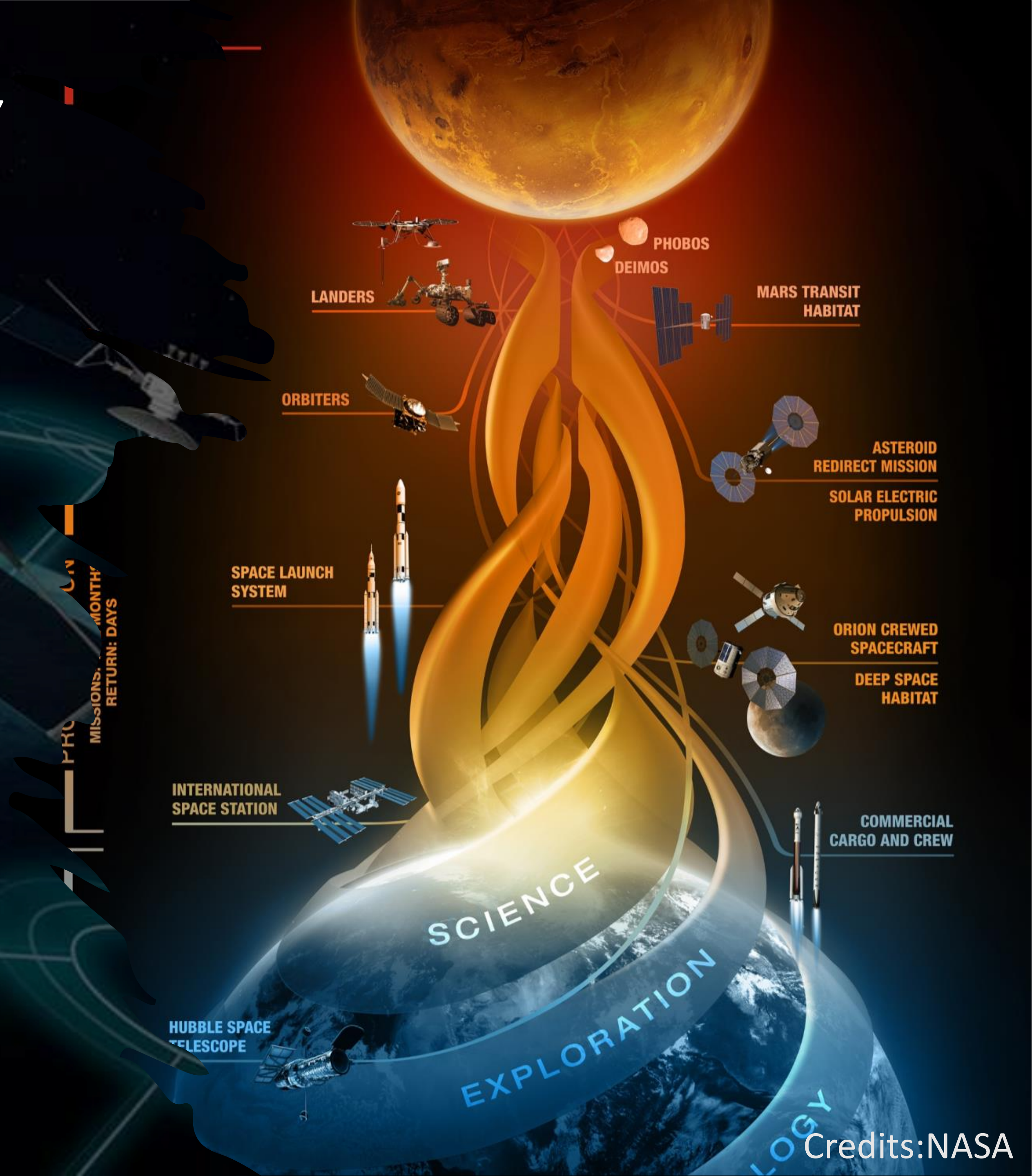
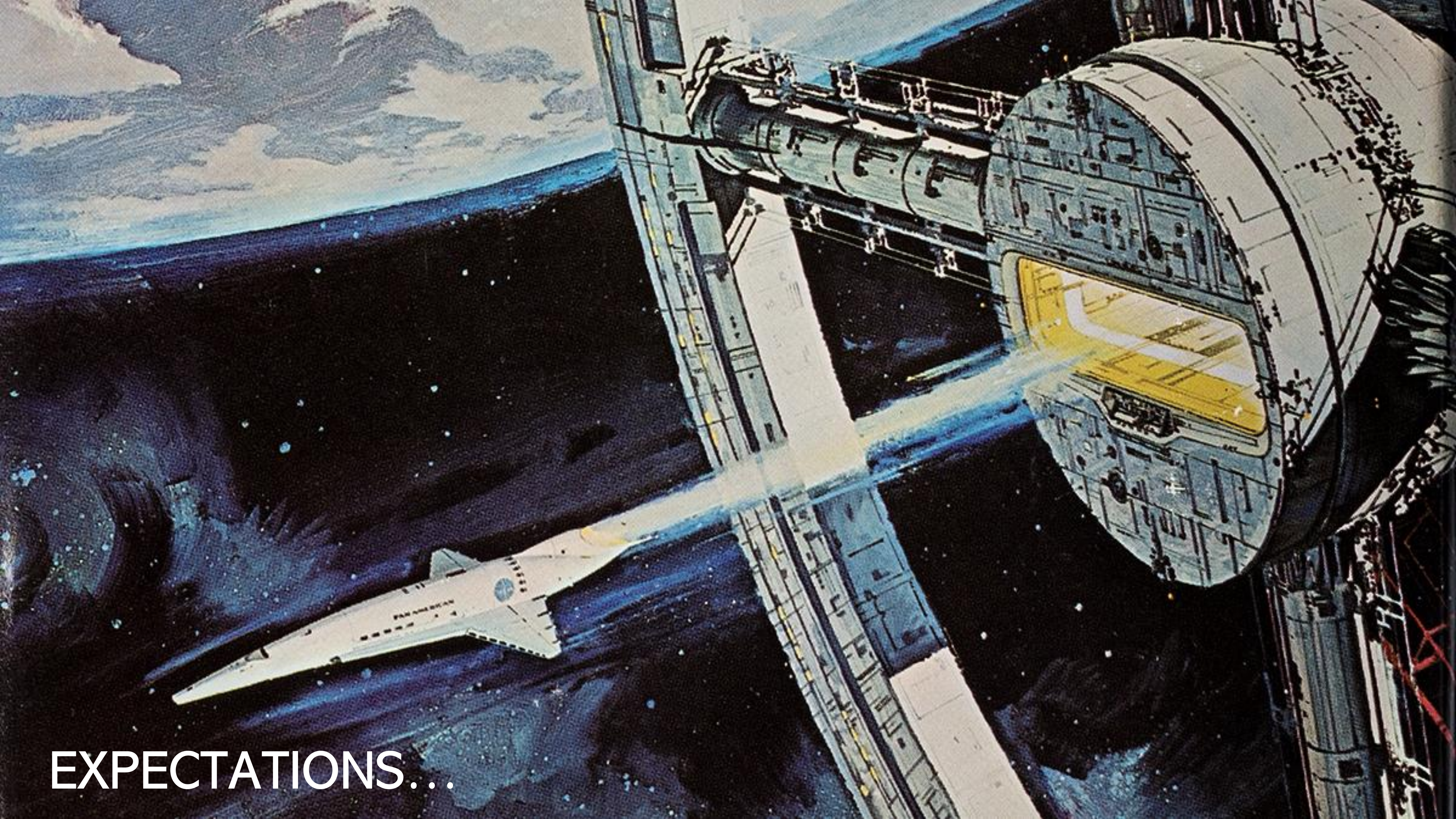
Apollo to Artemis: The next giant leap
June 19th 2024
Scuola Politecnica e delle Scienze di Base – P. le Tecchio

UPCOMING SPACE ACTIVITY CHALLENGES:

- Exploration
- Exploitation
- Sustainability
- Responsibility

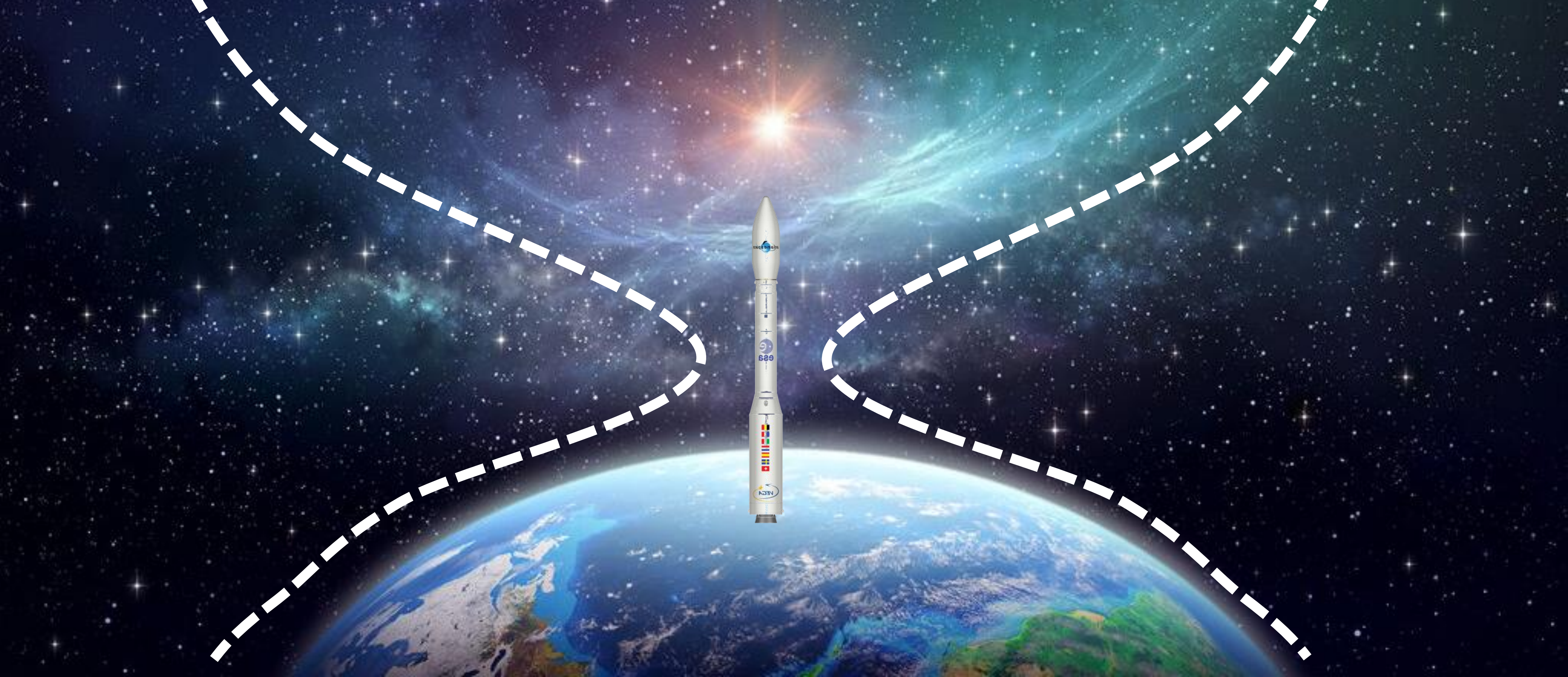


Credits:NASA


EXPECTATIONS…

WHERE WE ARE...

THE ACCESS TO SPACE REPRESENTS A BOTTLENECK FOR THE SPACE EXPLORATION

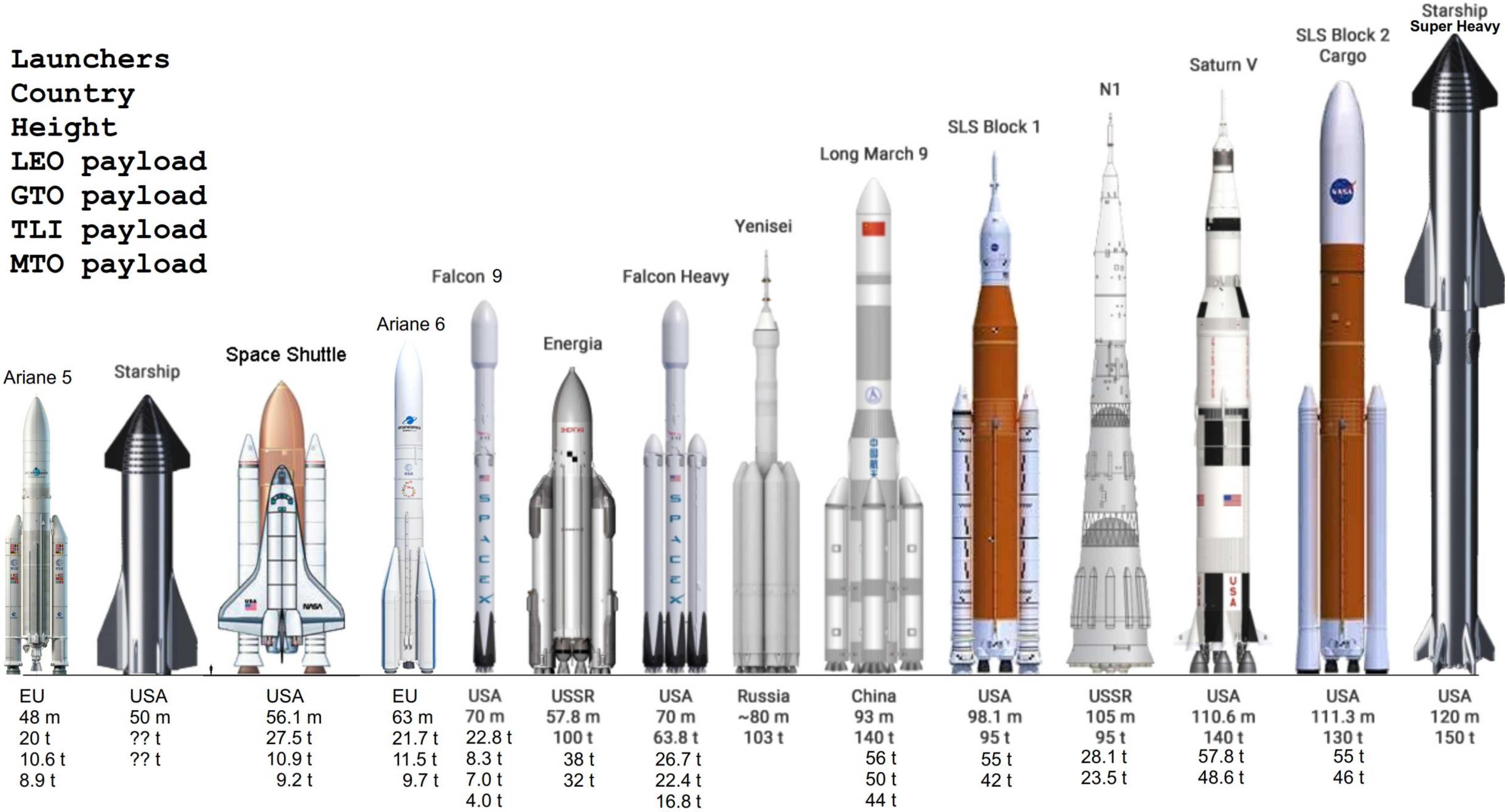


NEW PARADIGMS FOR A NEW SPACE

SPACE ACCESS

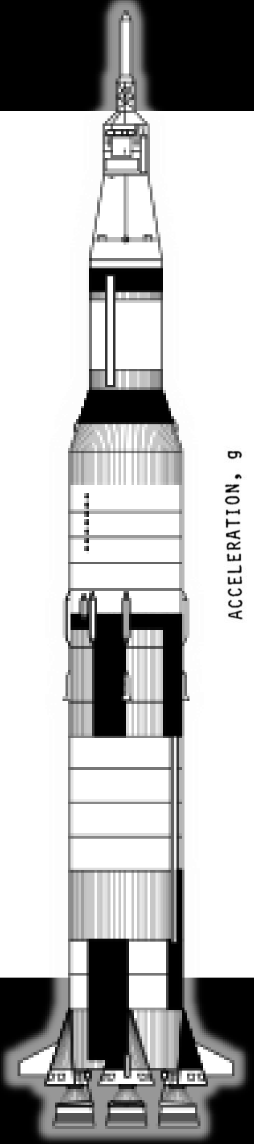
The access to space represents a bottleneck in the actual scenario of the space missions:

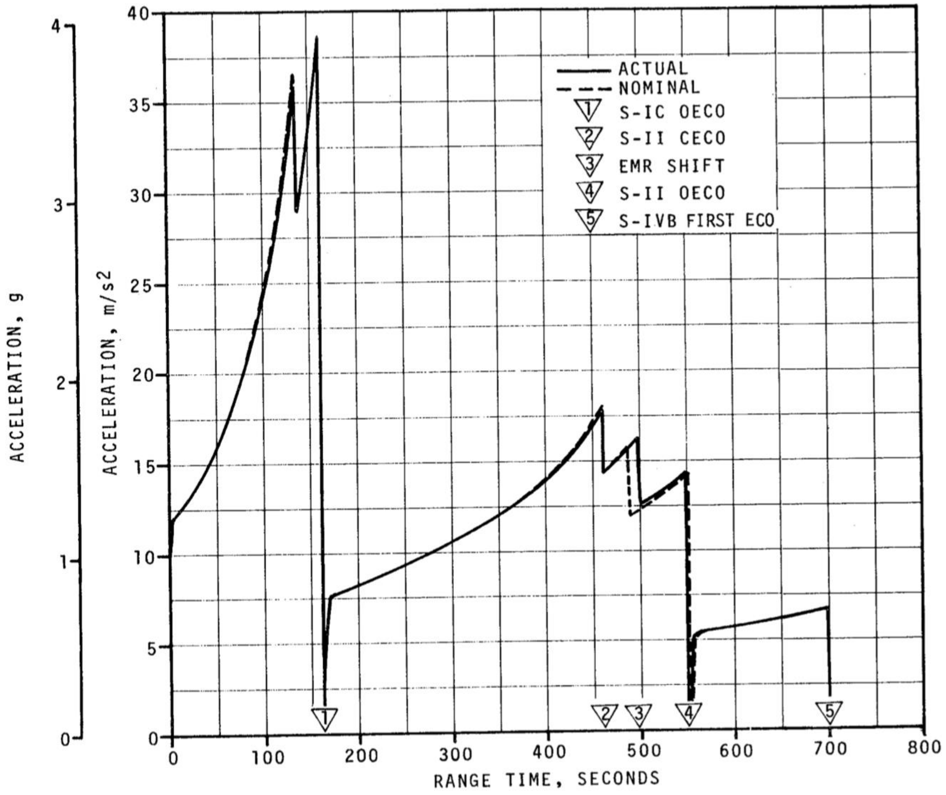
- Volume limited by the launcher fairing
- Mass limits due to the launcher performances
- Design for the launch and not for the mission
- Long time to market



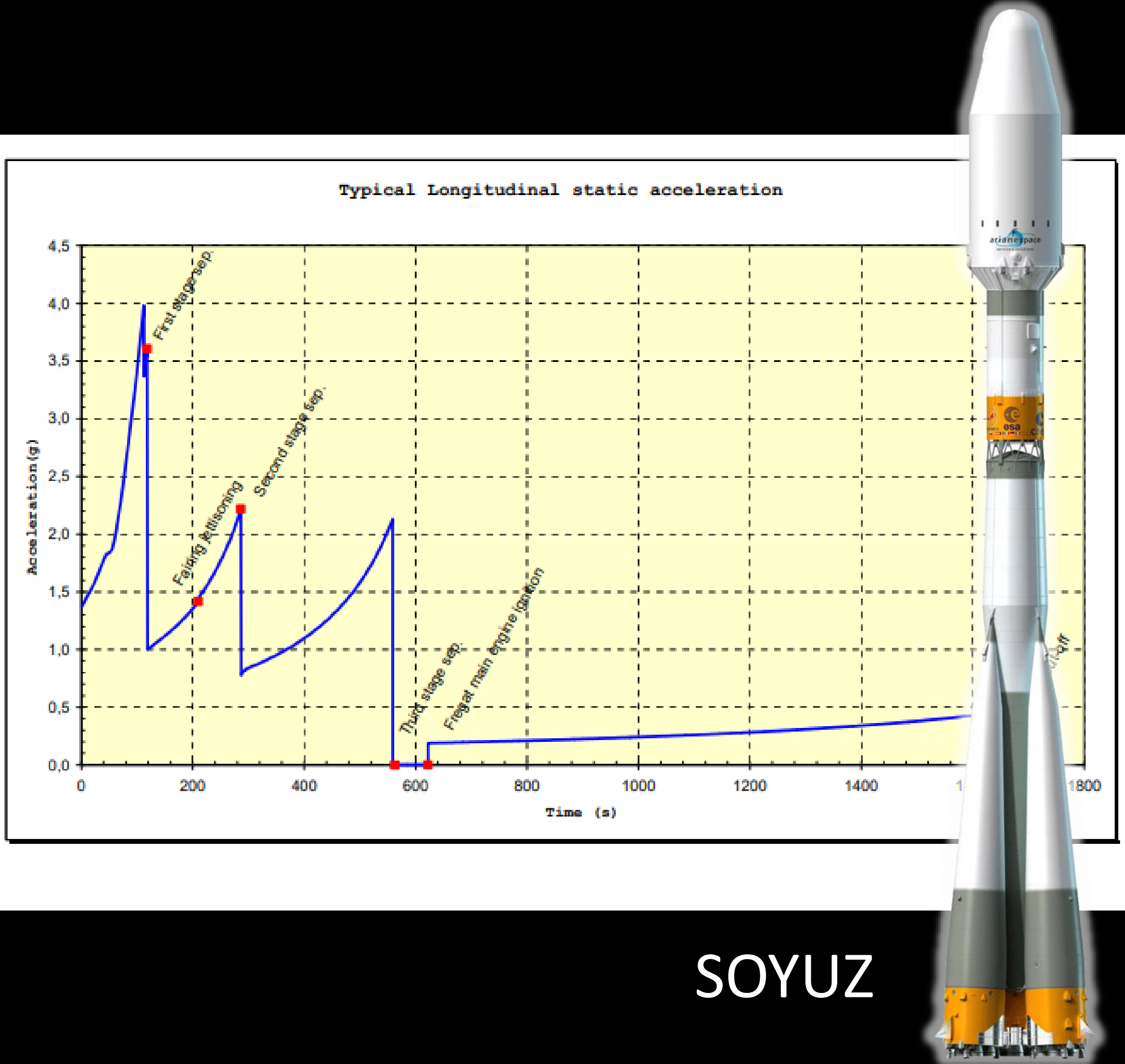
Launchers
Country
Height
LEO payload
GTO payload
TLI payload
MTO payload
Ariane 5
EU
48 m
20 t
10.6 t
8.9 t
Starship
USA
50 m
?? t
?? t
Space Shuttle
USA
56.1 m
27.5 t
10.9 t
9.2 t
Ariane 6
EU
63 m
21.7 t
11.5 t
9.7 t
Falcon 9
USA
70 m
22.8 t
8.3 t
7.0 t
4.0 t
Energia
USSR
57.8 m
100 t
38 t
32 t
Falcon Heavy
USA
70 m
63.8 t
26.7 t
22.4 t
16.8 t
Yenisei
Russia
~80 m
103 t
Long March 9
China
93 m
140 t
56 t
50 t
44 t
SLS Block 1
USA
98.1 m
95 t
55 t
42 t
N1
USSR
105 m
95 t
28.1 t
23.5 t
Saturn V
USA
110.6 m
140 t
57.8 t
48.6 t
SLS Block 2 Cargo
USA
111.3 m
130 t
55 t
46 t
Starship Super Heavy
USA
120 m
150 t

TYPICAL LONGITUDINAL STATIC ACCELERATION



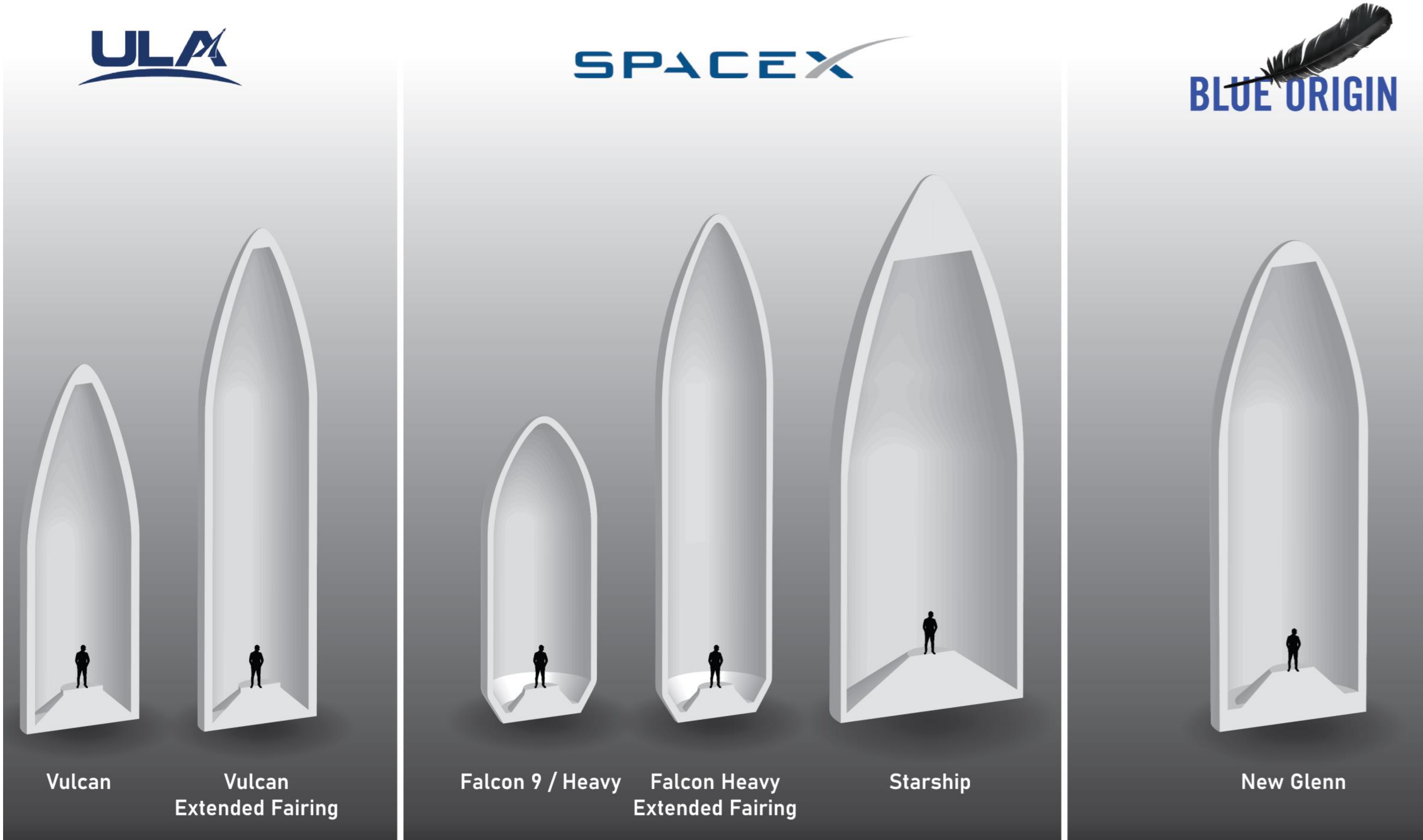


SATURN 5

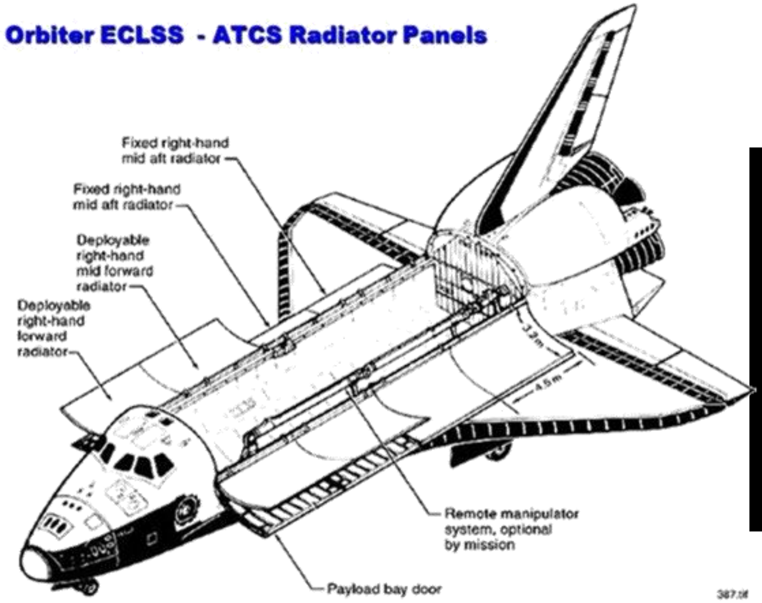


SOYUZ

FAIRING DIMENSIONS

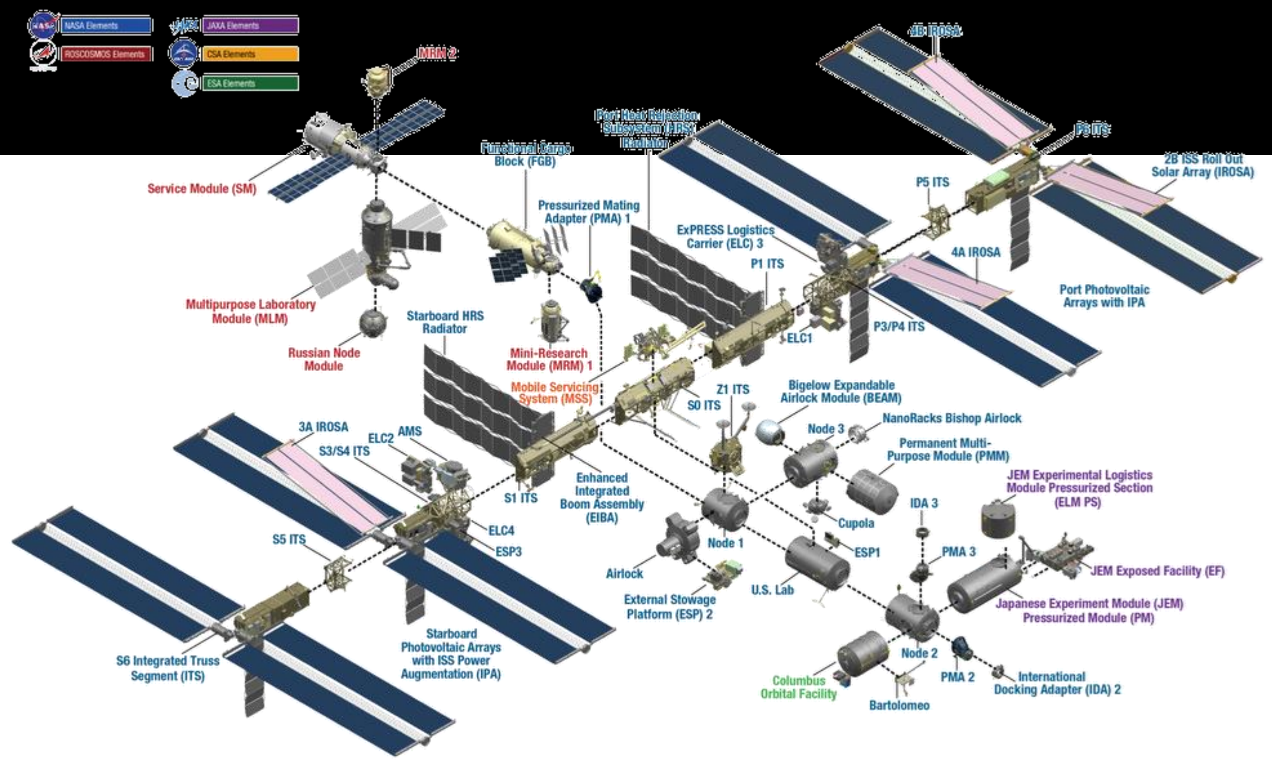


ISS EXPERIENCE



Space Shuttle Cargo Bay

- 20 ton
- 18m long
- 4.5m wide



- Pressurized Module Length: 218 feet along the major axis (67 meters – 4 missions)
- Truss Length: 310 feet (94 meters – 6 missions)
- Solar Array Length: 239 feet across both longitudinally aligned arrays (73 meters)
- Mass: 925,335 pounds (419,725 kilograms - 20 missions)
- Habitable Volume: 13,696 cubic feet (388 cubic meters) not including visiting vehicles
- Pressurized Volume: 35,491 cubic feet (1,005 cubic meters)
- Power Generation: 8 solar arrays provide 75 to 90 kilowatts of power
- Lines of Computer Code: approximately 1.5 million

MORE THAN 40 MISSIONS HAVE BEEN PERFORMED SINCE 1998 TO ASSEMBLY THE ISS

NEW PARADIGMS FOR A NEW SPACE
EARTH DEPENDENCY

Supplies for human exploration missions are at the moment provided from Earth, as redundancy payload or through regular cargo missions.

High launch costs are associated to cargo missions

Not practical for future missions to remote destinations (e.g. Mars)

Credits:ESA

NEW PARADIGMS FOR A NEW SPACE
LOGISTICS – ISS LESSON LEARNED

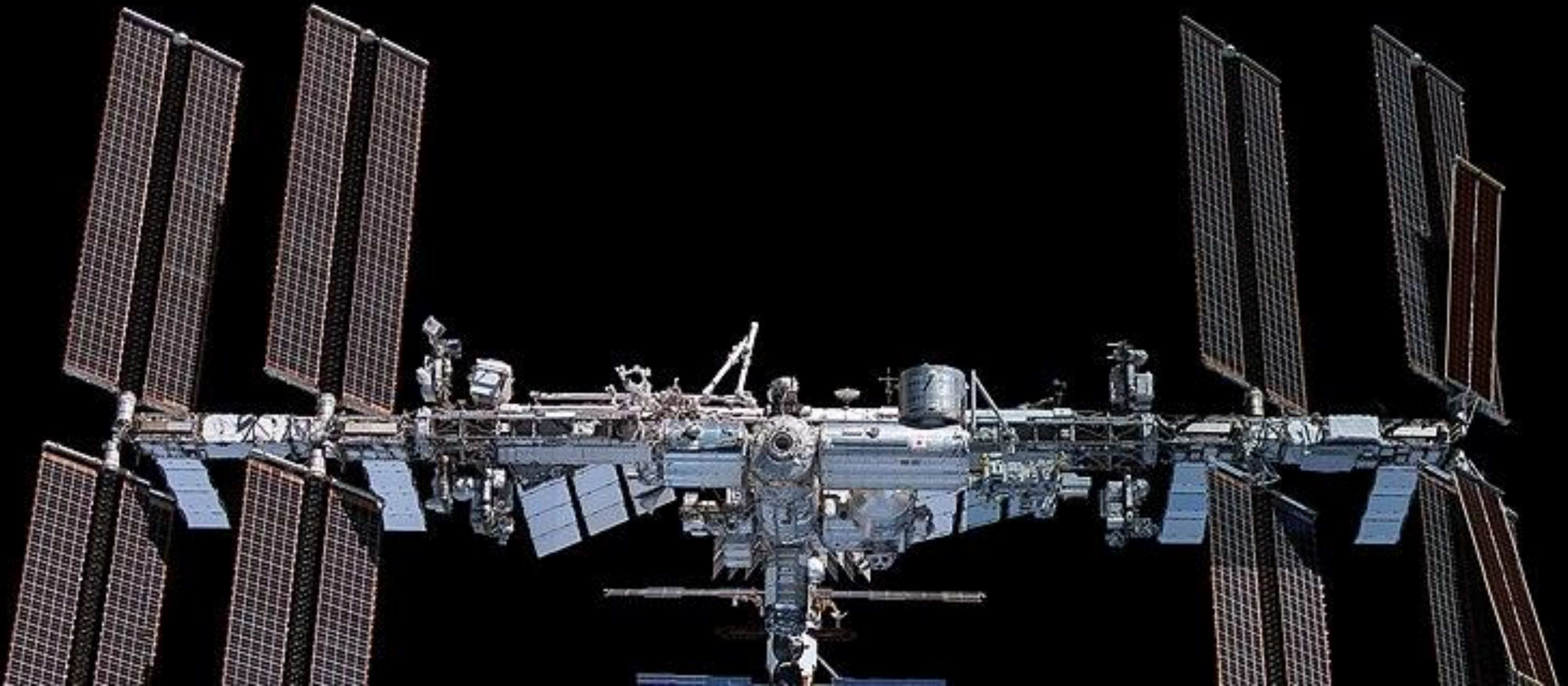
13ton
of spares actually on board of the ISS

95%
of spares will never be used

3ton
Upmass per year

Impossible to know which spares will be needed

Unanticipated system issues always appear, even after years of testing and operations



Credits:NASA

Source:
Bill Cirillo (LaRC) and Andrew Owens (MIT)

OUT OF EARTH MANUFACTURING

Manufacturing in space has clear mission benefits beyond low earth orbit, where cargo resupply opportunities become more limited. These technologies are key enablers for sustainable space exploration.

Additive Manufacturing is the most promising technology to be applied out of our planet.

The development of out of earth manufacturing technologies is at the basis of the space exploration programs but a strong impact is expected also on the earth orbit operations and services as well as on the down-stream activities.

- CREATING REPLACEMENT COMPONENTS IN SPACE
- RECYCLING IN SPACE
- CREATE STRUCTURES DIFFICULT TO PRODUCE ON OR TRANSPORT FROM EARTH
- CREATE SENSORS, SENSOR SYSTEMS, AND SATELLITES
- CREATE ‘IMPOSSIBLE’ MATERIALS

OUT OF EARTH MANUFACTURING IMPACT

1 Spare parts can be made on-demand. ISM capabilities can enable on-orbit servicing and repair of equipment

2 Recycling is a critical point to enable long duration mission; disposed components can be used to feed 3d printers

3 ISM enables structures whose size is limited only by the fabrication volume of the ISM capability

4 ISM enables structures which are optimized for operation in space, not for launch loads

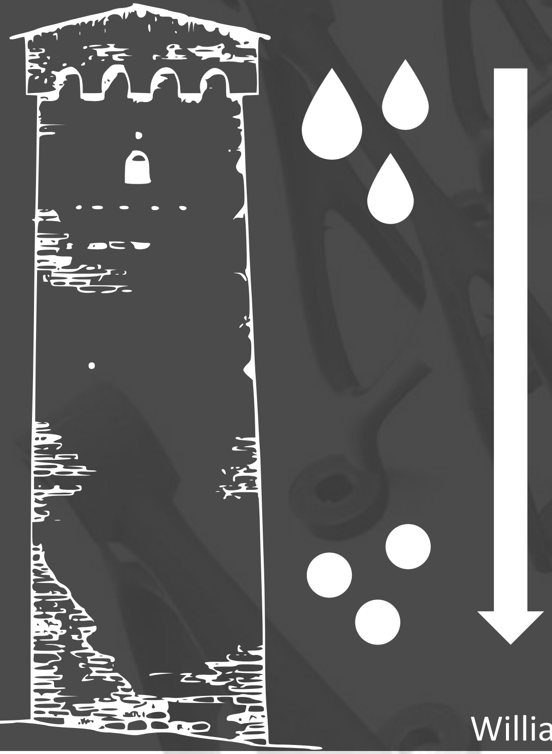
5 In-situ construction of infrastructure; in-situ manufacturing of hardware

Moraguez, Matthew. “Technology Development Targets for In-Space Manufacturing.” Master’s thesis. MIT, 2018

ISM DOWNSTREAM IMPACT

SHOT TOWER

Micrograviity has been used since the 18th century to produce spherical shot:



Droplets of molten lead assume a perfectly spherical shape during the freefall thanks to the surface tension.

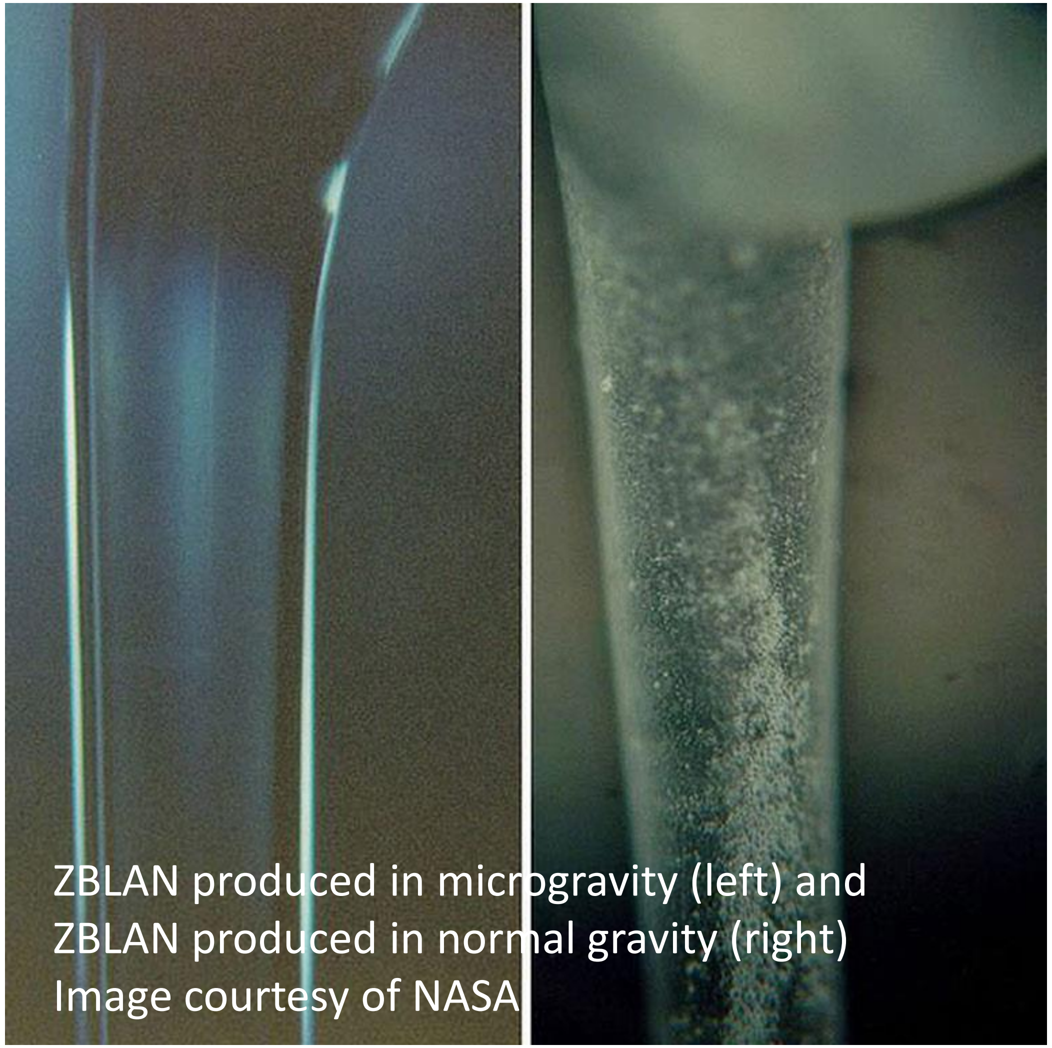
William watts of Bristol, 1753

Microgravity offers a unique environment to produce 'Impossible' materials. Among the others, microgravity offers the following advantages for the manufacturing of innovative materials or the development of research programs:

- Minimize convection;
- Promote uniform particle distribution;
- Do not require container;

ISM offers a plenty of opportunities for innovations and will promote the new Space Economy.

ZBLAN



ZBLAN produced in microgravity (left) and ZBLAN produced in normal gravity (right)
Image courtesy of NASA

These optical fibers are most commonly made of silica (SiO_2) glass. While silica fibers are easily produced using well-established methods, optical losses in the fiber requires the use of expensive repeaters to boost the signal across long transmission distances.

The fluoride glass optical fiber, ZrF_4-BaF_2-LaF_3-AlF_3-NaF, commonly known as ZBLAN, at its theoretical best can have 10 to 100 times lower signal loss than silica fiber. However, when ZBLAN is produced on Earth, convection and other gravity-driven phenomena can cause imperfections because of the nonuniform distribution of the various chemical components within the fiber.

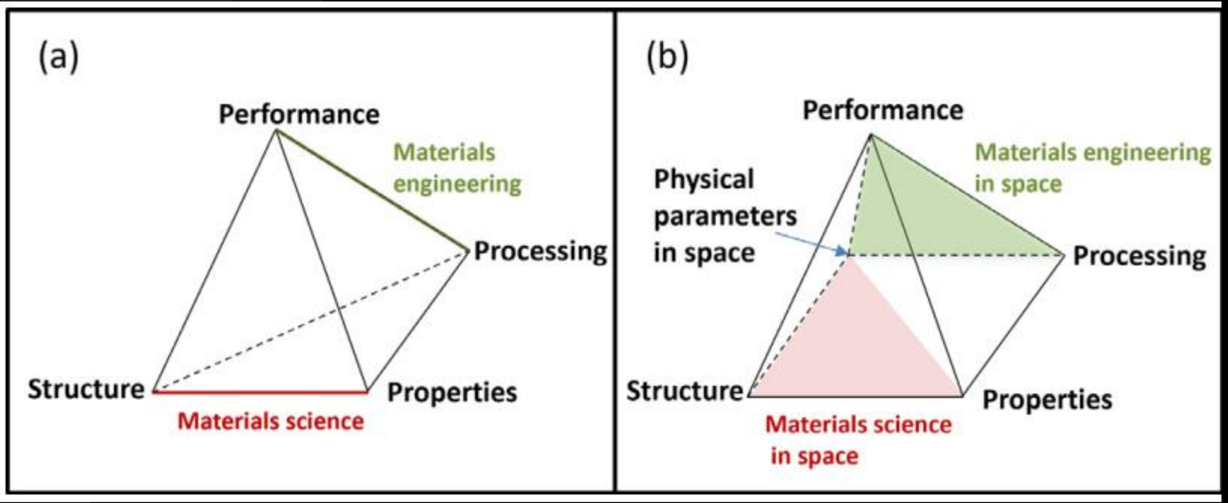
ISM CHALLENGES

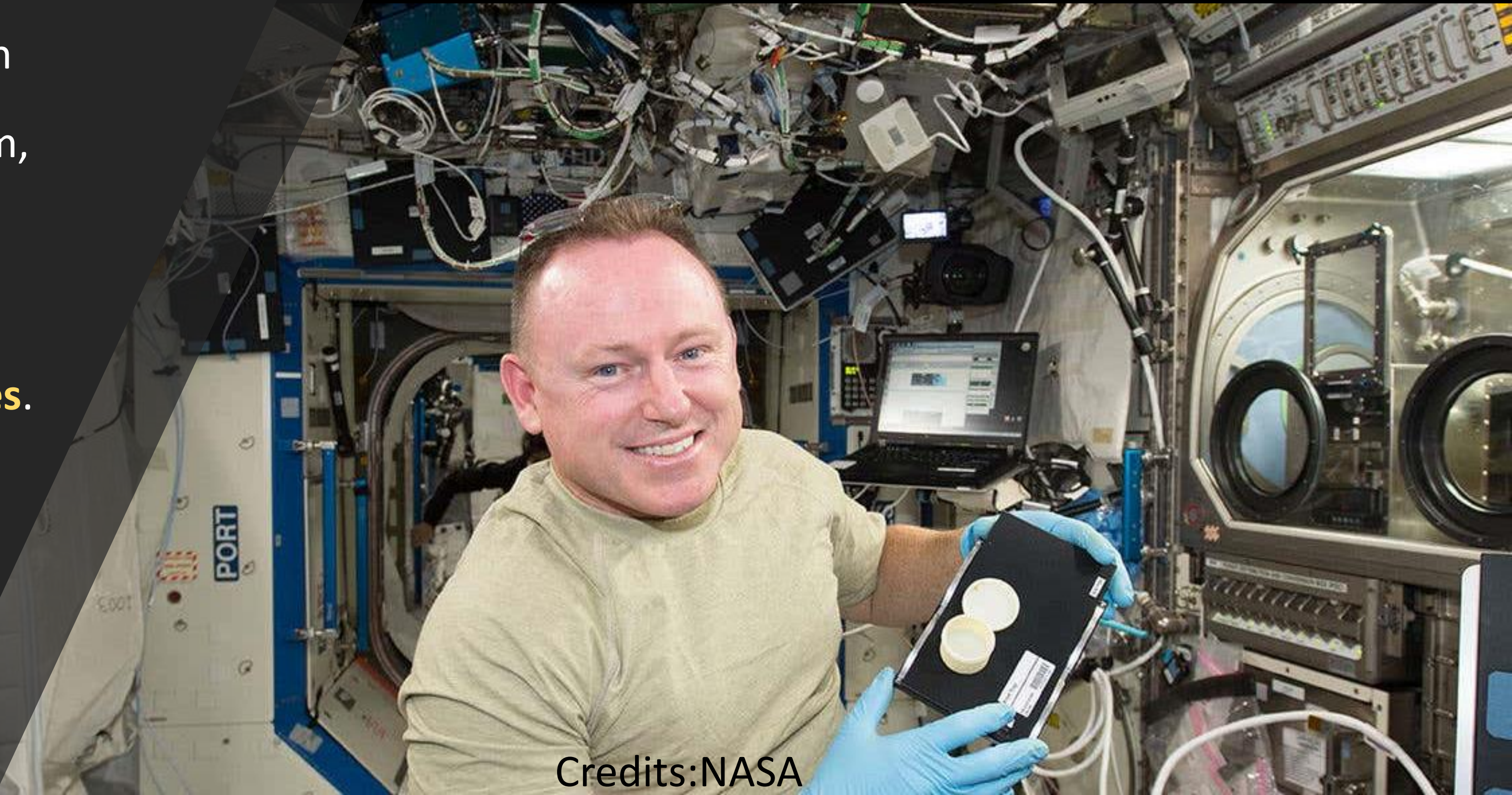
- In AM, the final material properties and manufacturing technologies are more closely related than in most other conventional manufacturing technologies. **In AM, the bulk material is created together with the part**.

- **The physical parameters are very different from those on Earth**. In addition to gravitation (from microgravity to the reduced gravity on the Moon and Mars), the atmosphere/vacuum, temperature, and radiation need to be considered.

- Technologies and processes able to accept feedstocks within a certain **range of properties**.

- The availability of **platforms for experimental work** in space or simulating space environments is generally limited.

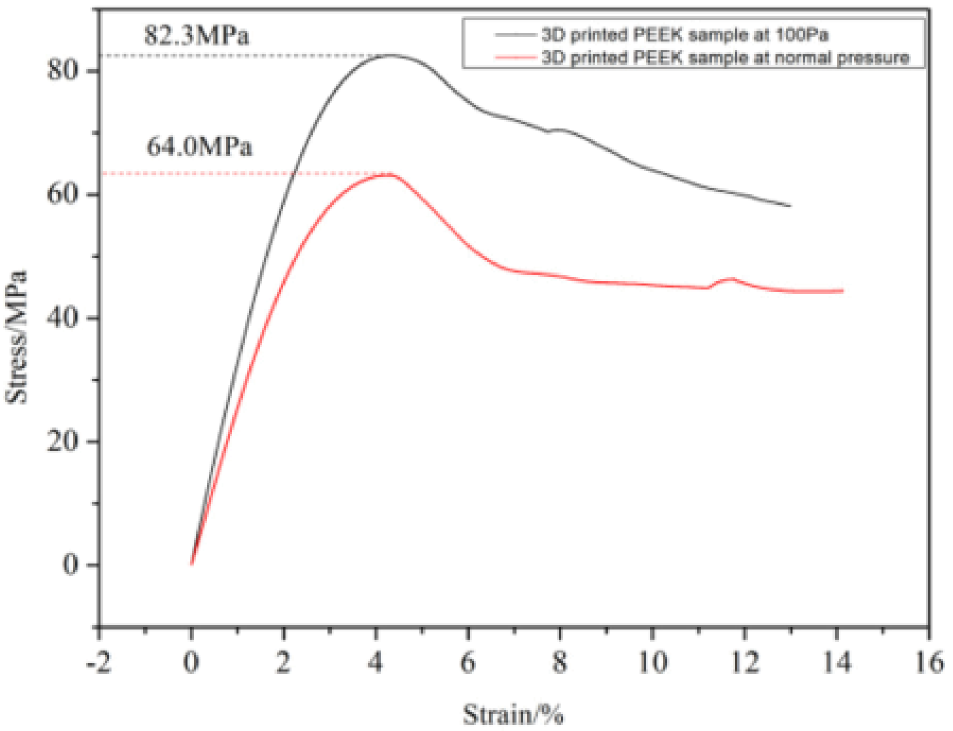




Credits:NASA

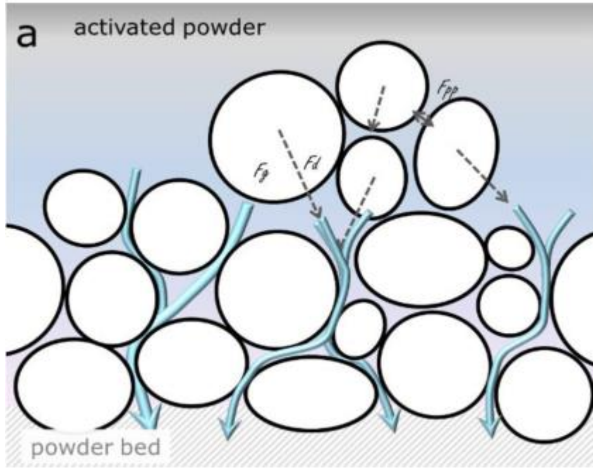
3D PRINTING IN SPACE

HEAT TRANSFER



Because of the low efficiency of the thermal radiation, heat cannot be efficiently dissipated from the extruded materials. As such, they may reach at a higher temperature than the initial crystallization temperature and obtain a high crystallinity and interlayer bonding.

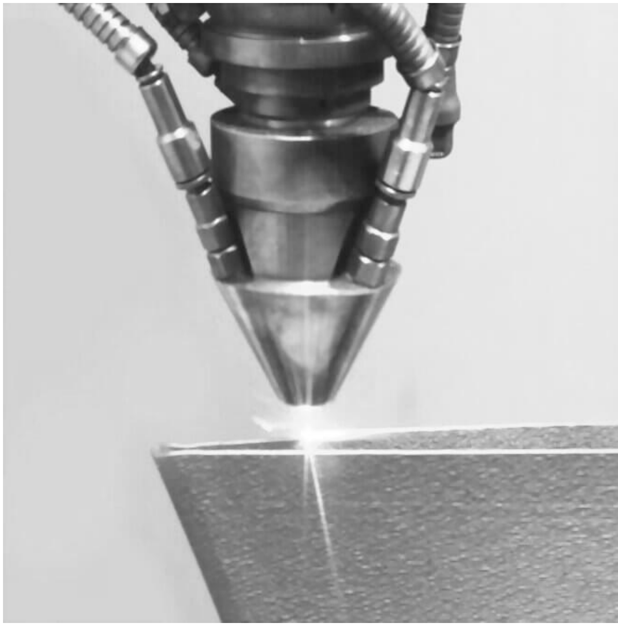
MICRO-GRAVITY



To compensate for the missing or reduced gravitational forces the “gas flow-assisted powder deposition” has been developed.

VACUM

At pressures lower than 10−8 Pa, the reaction of the metal powders with the atmosphere is virtually non-existent. The powder layer deposition process in principle could be performed in open space e.g. by means of a rotating drum and feeder system to simulate gravitation.



ISM - 3D Printing in Zero G

NASA used a 3D printer for two rounds of operations from 2014-2016

The device is similar in size to a desktop 3D printer for plastics which you may have seen in homes, labs, or schools. Using a fused filament fabrication process, the system's nozzle feeds a continuous thread of plastic through a heated extruder

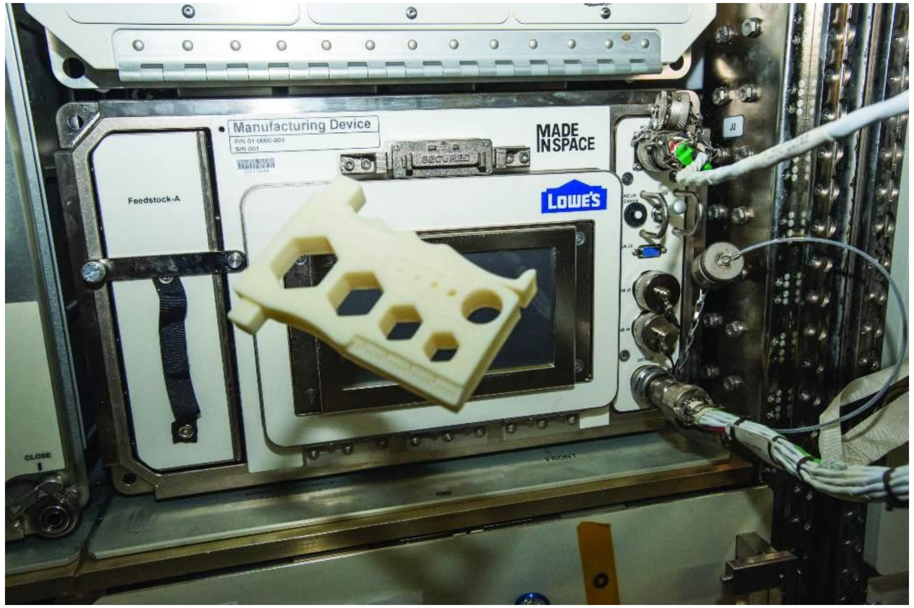
Analysis of specimens returned from orbit in conjunction with material modeling efforts suggested that microgravity did not lead to engineering-significant effects on the polymer parts, paving the way for increased use of this technology in space.

ISM - Additive Manufacturing Facility

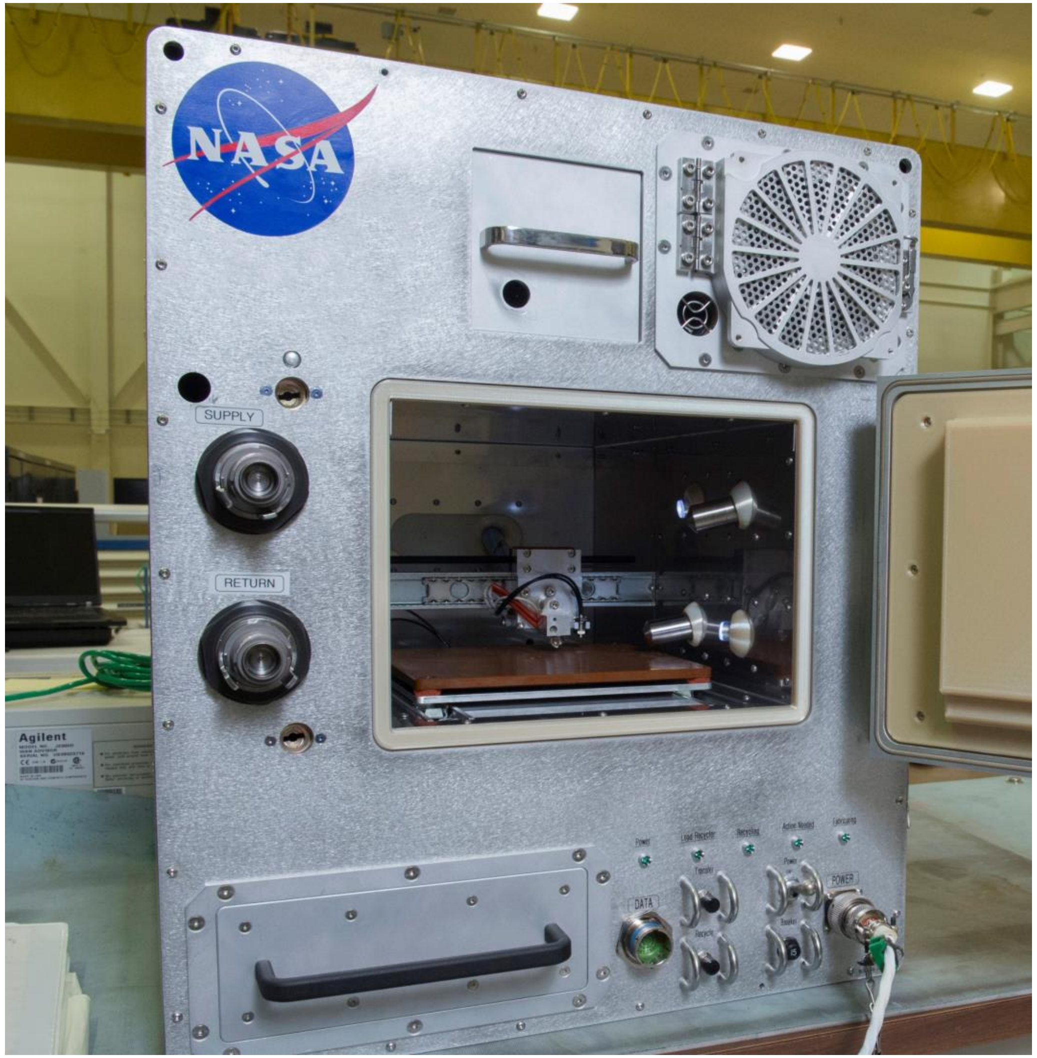
The Additive Manufacturing Facility (AMF) started under a NASA SBIR with MIS. The AMF was installed in an ISS EXPRESS rack in April 2016 and provides commercial 3D printing capability to customers through the ISS National Laboratory and the Center for the Advancement of Science in Space (CASIS), as well as manufacturing of NASA parts through an Indefinite Delivery/Indefinite Quantity contract.

Key technologies of AMF:

1) **Modular**: Using replaceable subassemblies, the AMF was designed so that it could easily be upgraded to add new functionality and manufacturing methods in the future.
2) **Longlasting**: The AMF is designed to last the entire lifetime of the ISS
3) **Multiple Materials**: The AMF printer is designed to work with a wide range of various extrudable materials including flexible polymers and aerospace grade composites.
4) **EXPRESS Rack dimensions**: Designed to operate in an EXPRESS Rack Mid-Deck Locker, once installed the printer will be easily accessible by the crew at all times.



ISM - Recycling in Space



The ReFabricator unit, from the Seattle, WA-based aerospace company Tethers Unlimited, was flown to ISS in 2019. ReFabricator is designed to print parts with ULTEM 9085, which can then be recycled back into feedstock for further printing. A reuse capability enables NASA to “close the manufacturing loop” on long-duration missions so that the feedstock for the printers does not have to be launched.

In Space Manufacturing – outlook

ISM includes work in many development areas that are key to reducing reliance on Earth-based platforms and enabling sustainable, safe exploration. These include:

- **Feedstock recycling**—The feedstock recycler, which will recycle/reclaim 3D printed parts and/or packing materials into feedstock materials which can then be used to manufacture parts using 3D printing facilities on station.

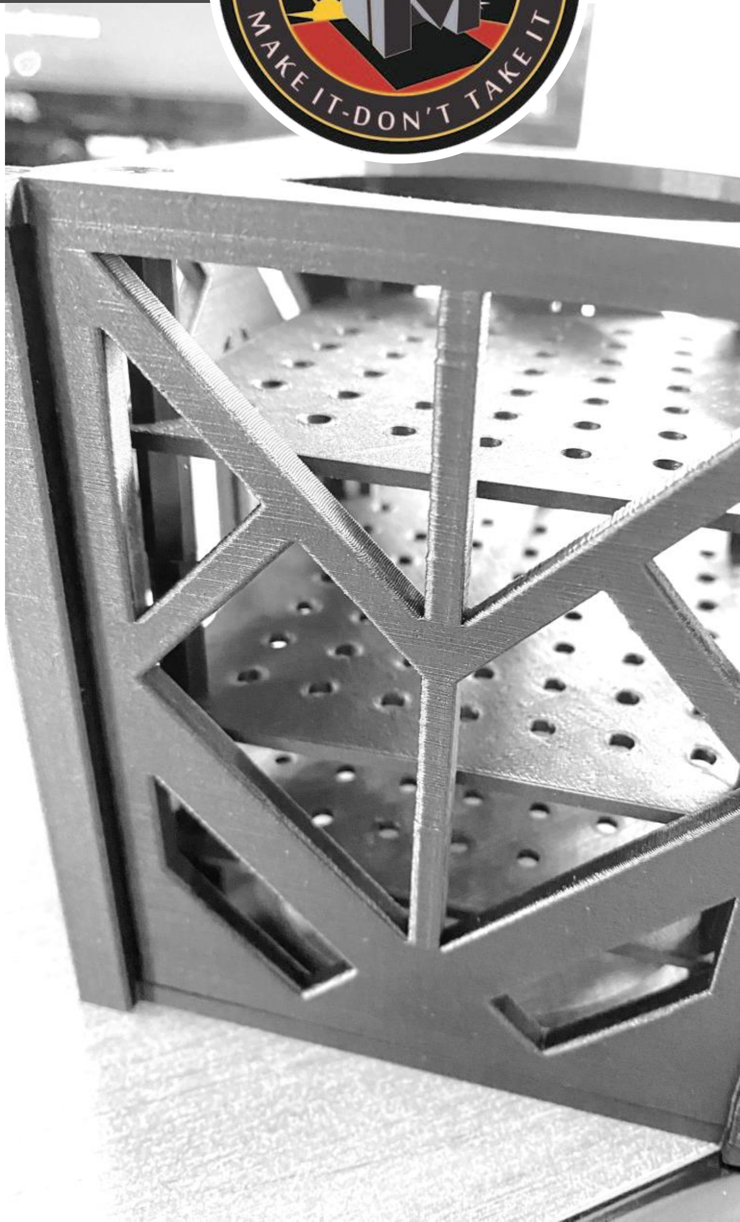
- **Printed electronics**—Leverage ground-based developments to enable ISM of functional electronic components, sensors, and circuits.

- **Printable satellites**—The combination of 3DP coupled with printable electronics enables the on-orbit capability to produce small satellites ‘on demand.’

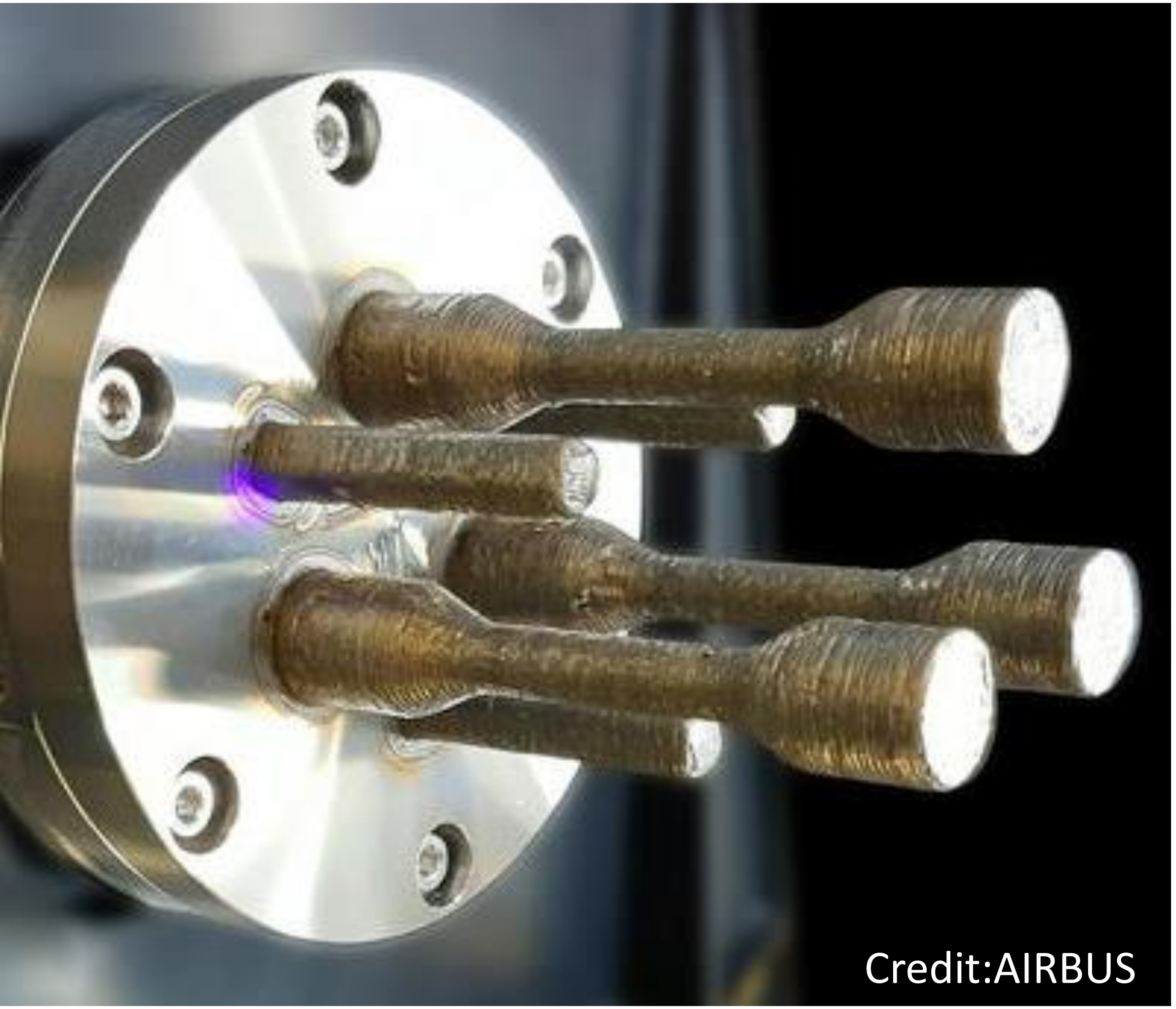
- **Multimaterial 3D printing**—Additively manufacturing metallic parts in space is a desirable capability for large structures, components with high strength requirements, and repairs.

- **External structures and repairs**—Throughout the lifecycle of space structures, astronauts will need to perform repairs on tools, components, and structures in space.

- **Additive construction**—These activities are focused on developing a capability to print structures on planetary bodies or asteroids using available resources.



ISM - Recent advances



The size of the machine has been a challenge. A miniaturisation is needed in order to fit inside the rack in which the printer will be housed on board the ISS' Columbus Laboratory.

Protecting the ISS from the aggressive printing environment caused by the laser and the heat it generates is achallenge. The printer sits in a sealed metal box, which acts like a safe. The melting point of metal alloys compatible with this process can be far over 1,200°C degrees compared to around 200°C degrees for plastic, which implies drastic thermal control.

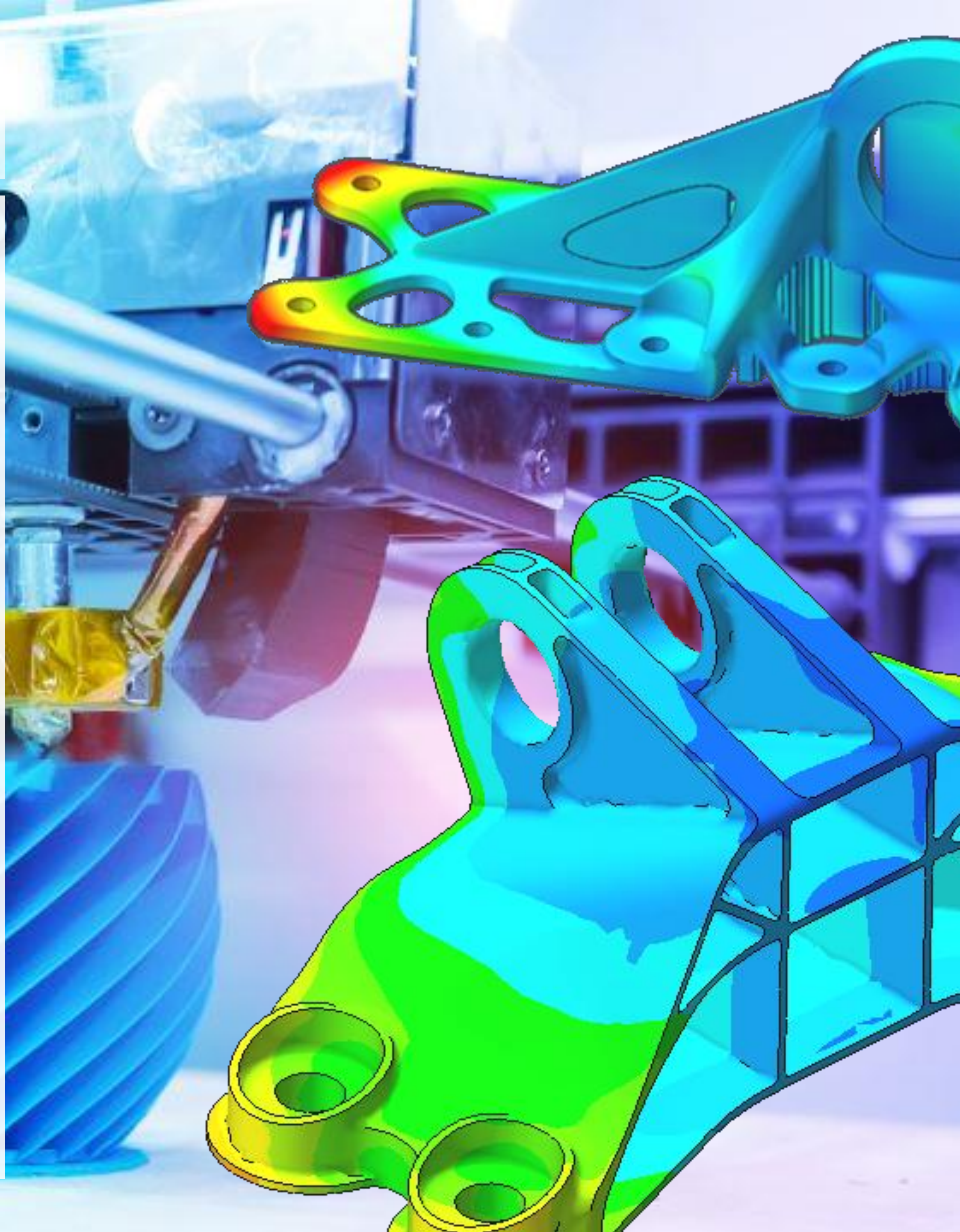
Wire-based printing technology has been used. The wire is independent of gravity unlike the powder-based system, which always has to fall to the ground

VIRTUAL MANUFACTURING

The shortage of experimental platforms for the development of innovative in space manufacturing processes can be filled by use of virtual manufacturing tools.

The simulation of the manufacturing process is expected to:

- **Planning and reducing the time/cost for the experimental campaigns;**
- **Correlate the impact of the process/environment parameters on the final performances of the components;**
- **Implement an effective design for manufacturing approach;**
- **Optimize the manufacturing process;**
- **Identify innovative manufacturing strategies.**



The actual numerical models are not able to deal with the manufacturing process simulations.

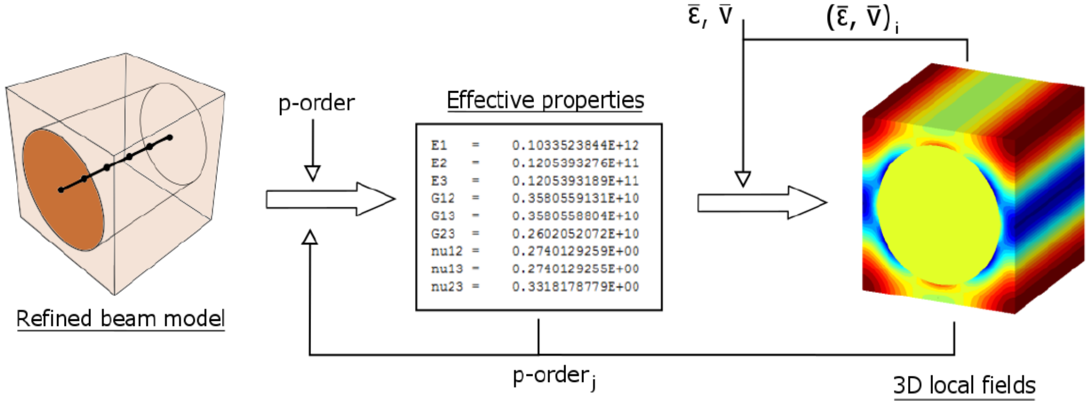
A paradigm shift in simulation tools is required to face the complexities of the problem.

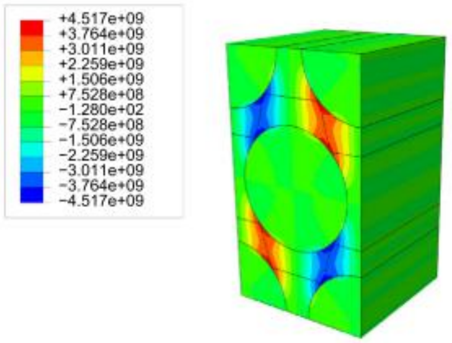
VIRTUAL MANUFACTURING TOOL CHALLENGES

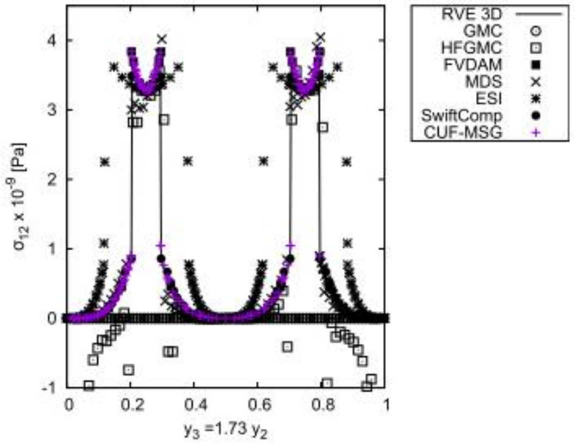
- INTERFACES
- NON-LINEARITIES
- HIGH-ACCURACY
- DATA DRIVEN MODELS
- HIGH-EFFICIENCY
- MULTI-PHYSICS
- MULTI-SCALE

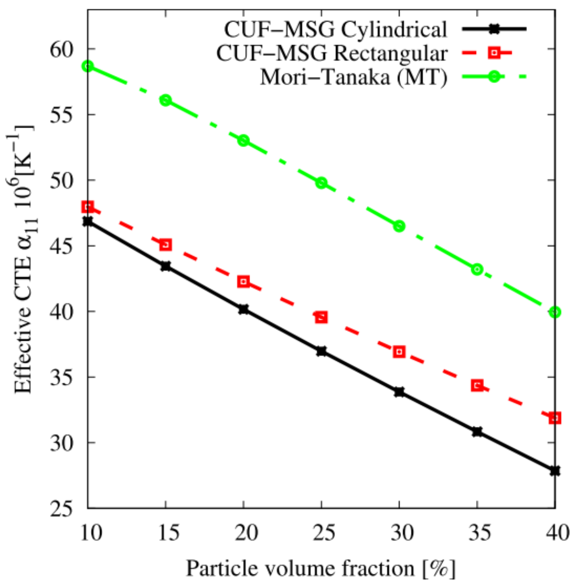
MUL2

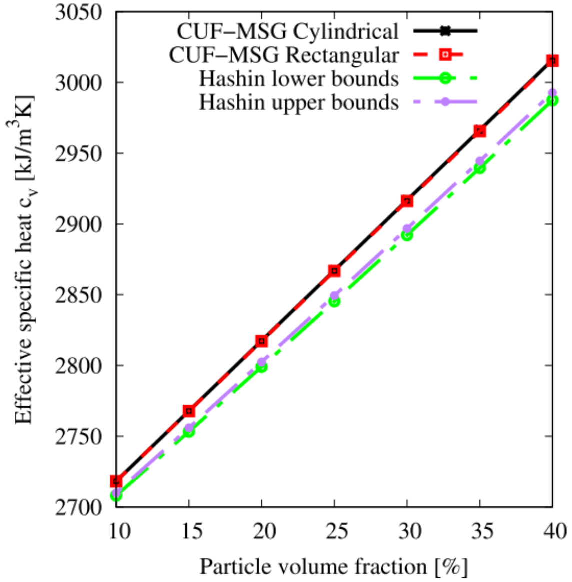
MULTISCALE MODELS

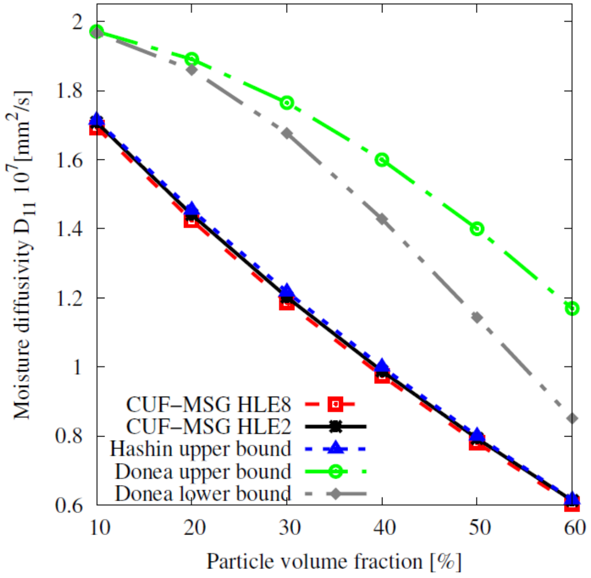








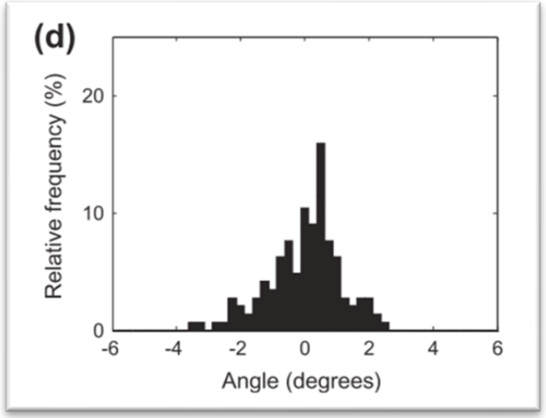


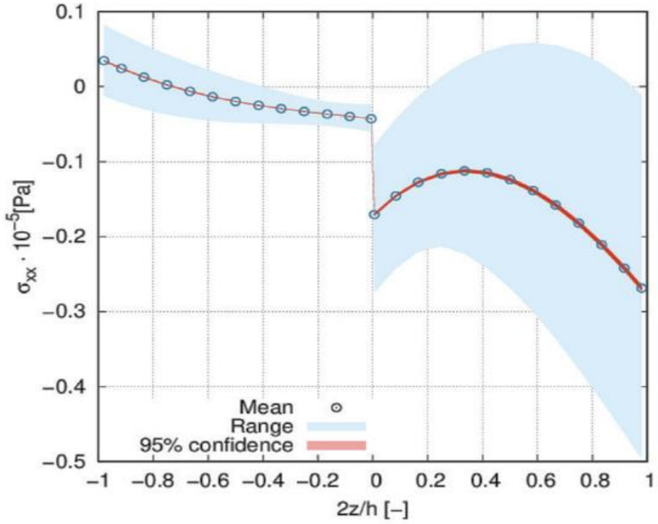


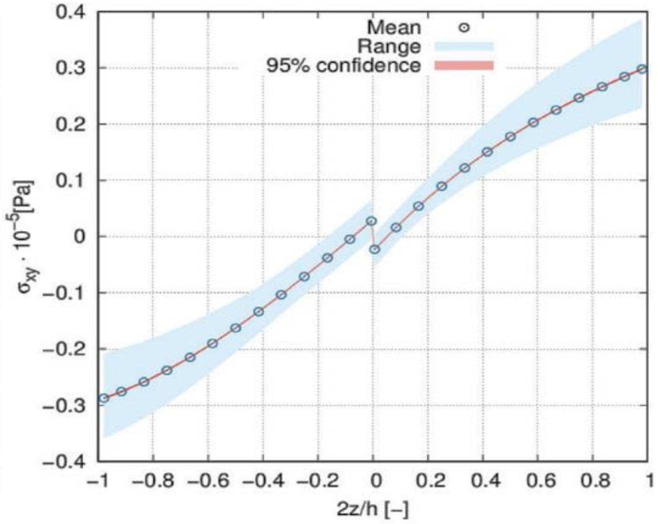
A representative volume element approach can be used to bridge the properties of the material among different scales, including mechanical, thermal and hygroscopic properties.

DEFECTS-TOLERANT STRUCTURES

Process-induced defects can be reduced but not eliminated. The effective strength of the structures strictly depends on local stress fields. A statistical approach may increase the confidence we have in our design.

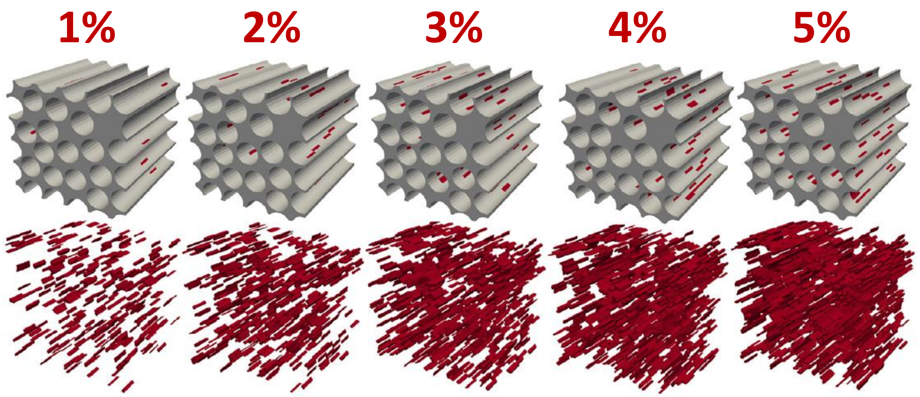




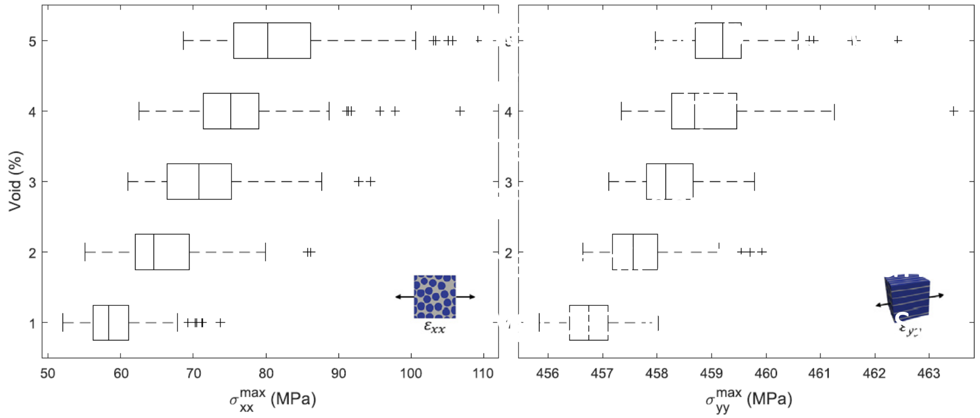


MANUFACTURING UNCERTAINTIES

IMPACT OF VOIDS



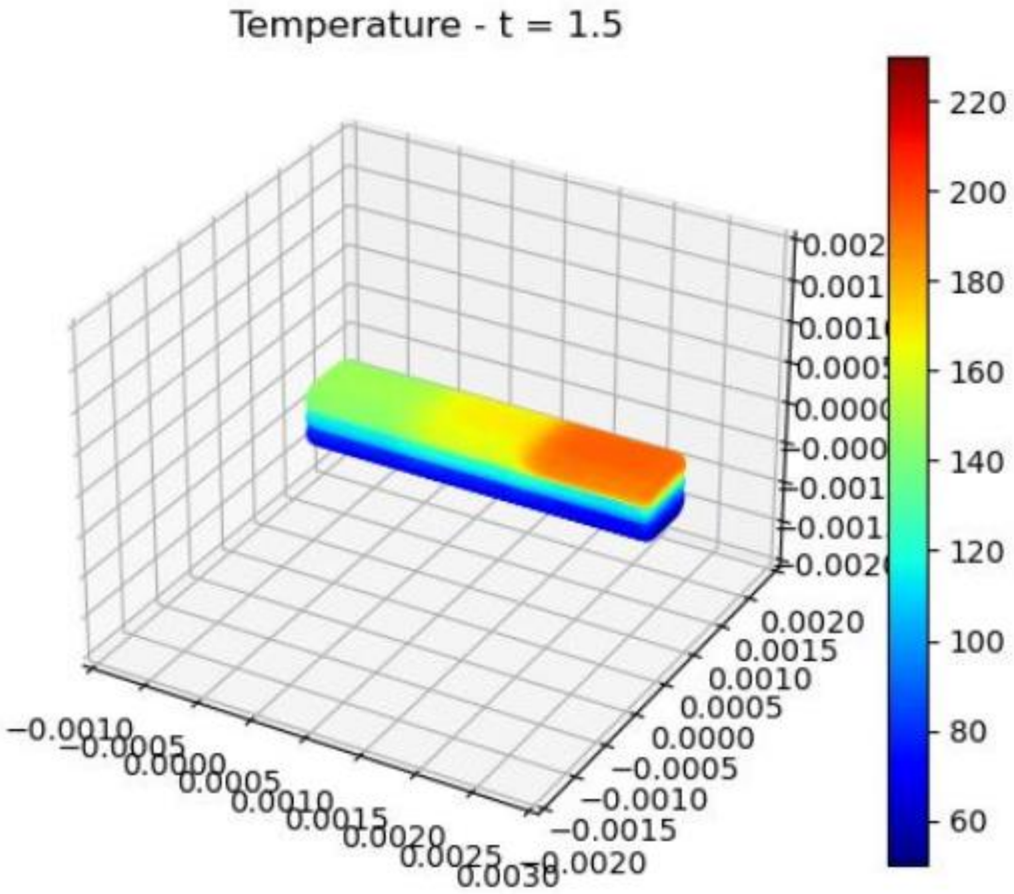
RVE models with increasing void content [1]

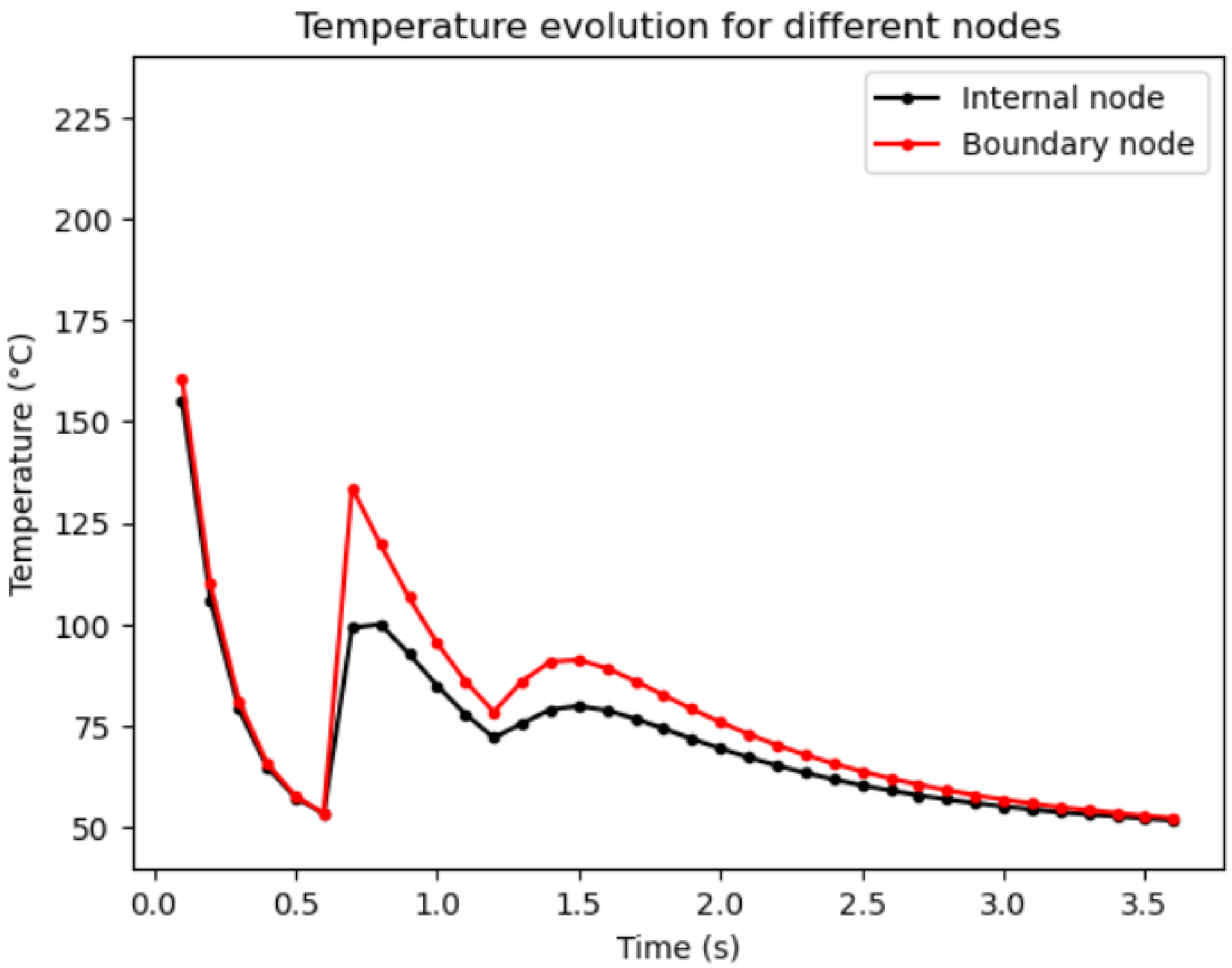


Maximum local stress with increasing void content

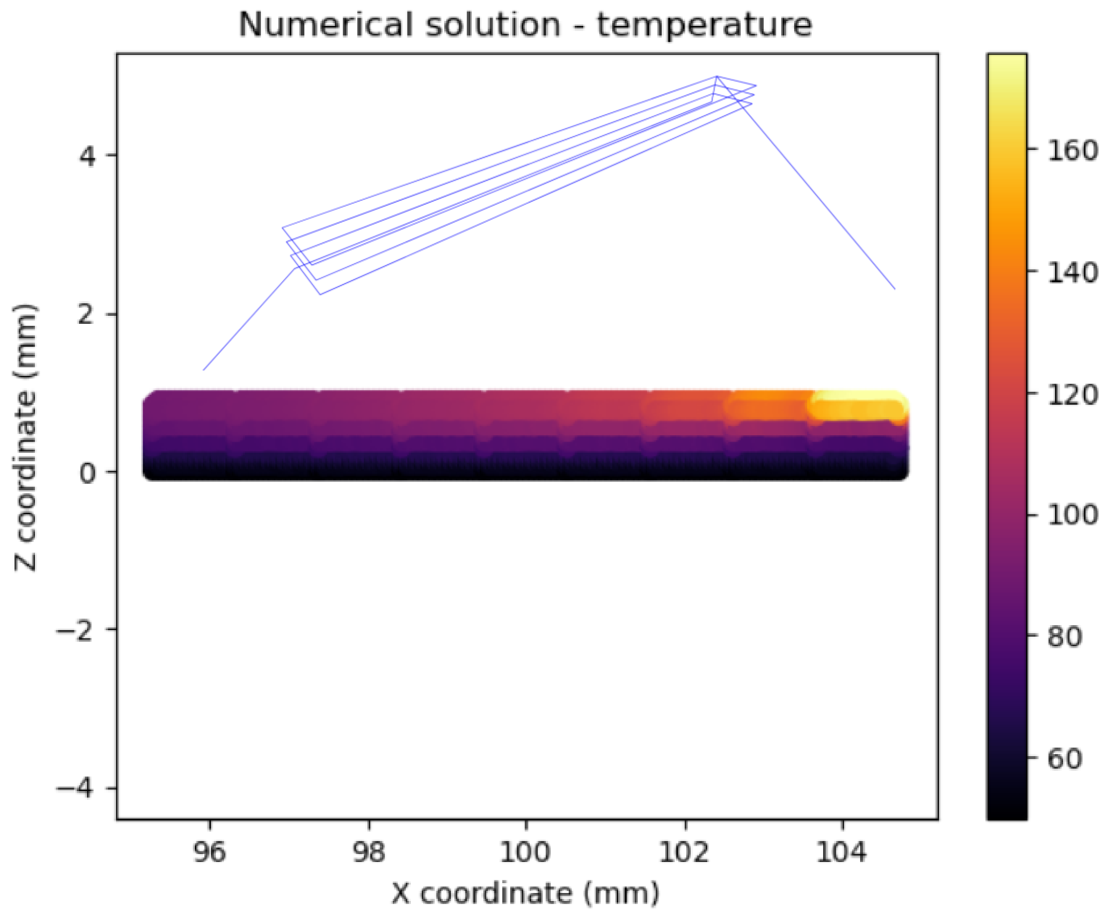
Carrera, E. et al. (2020). Composite Structures, 254, 112833

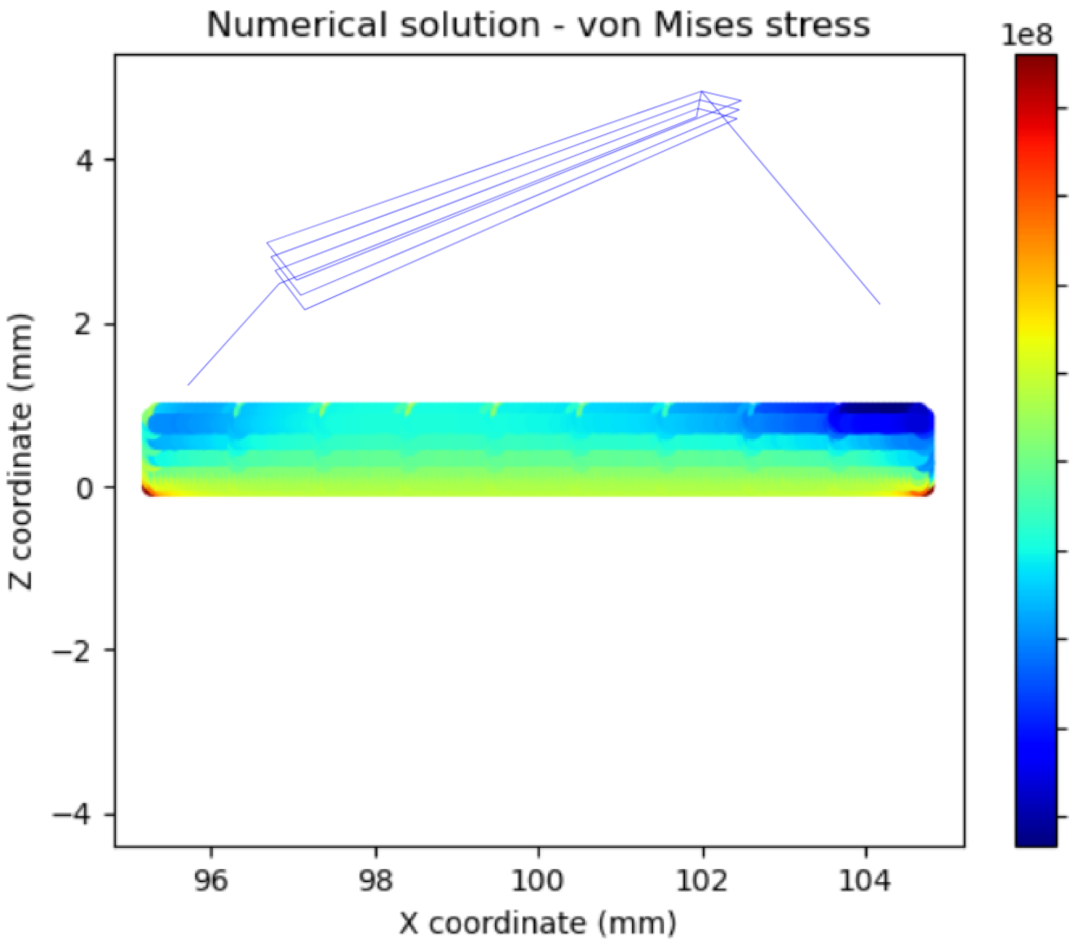
PROCESS SIMULATION



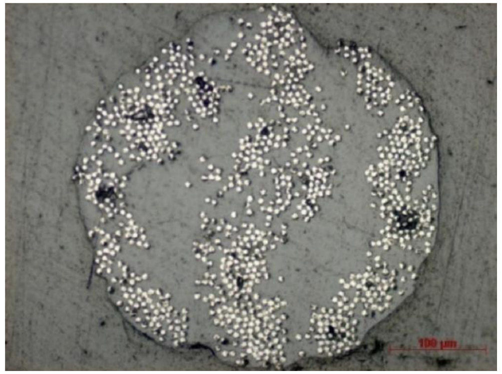


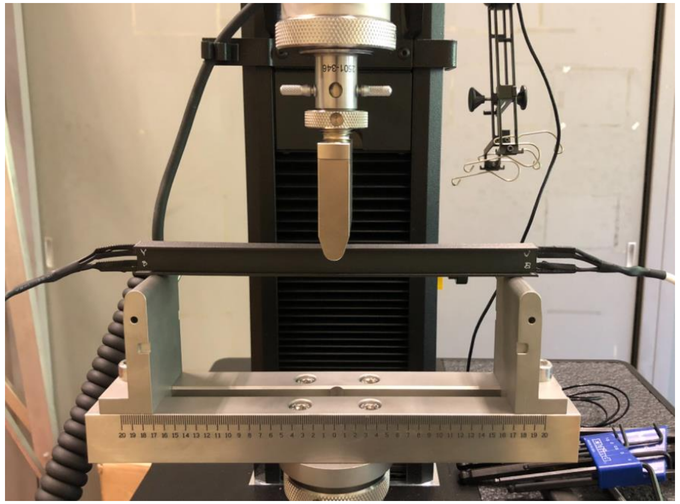
PROCESS SIMULATION

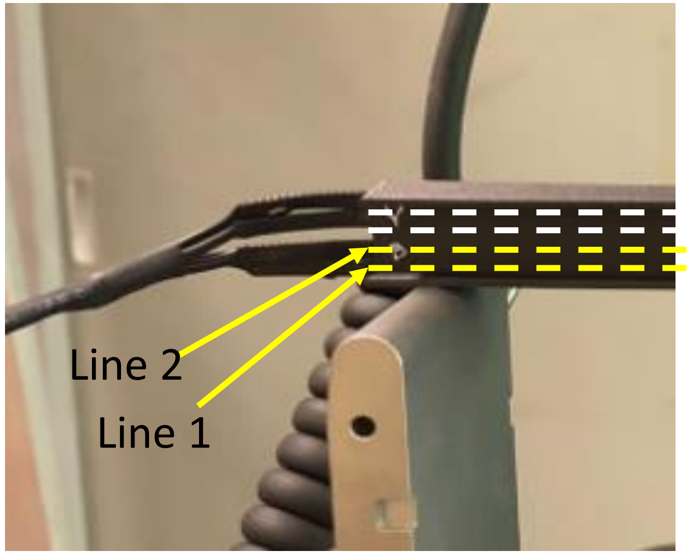


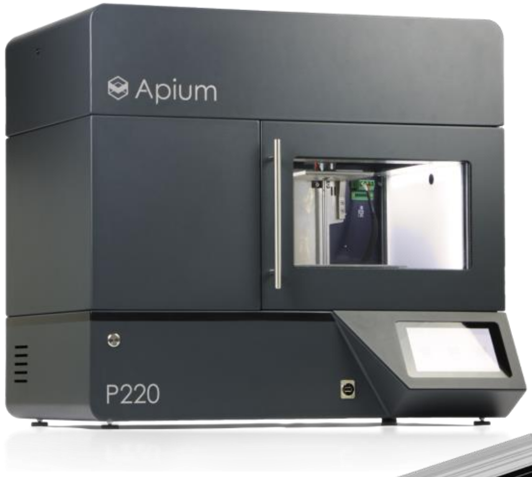


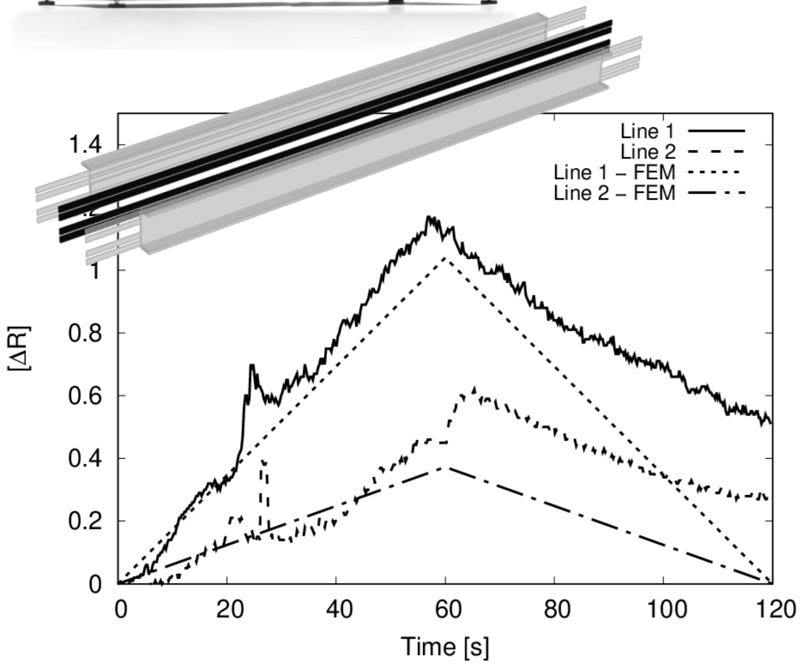
3D PRINTING OF CONTINOUS FIBERS REINFORCED STRUCTURES











The piezo-resistivity of continuous carbon-fiber can be used to develop self-sensing 3D printed functional components.

ISM ONGOING PROJECTs

ESA OMAR

NASA In-space Manufacturing Project 2014

DARPA NOMAD 2021

ESA Out of Earth Manufacturing

2024 AEROSPACE ITALY

34th Congress of the International Council of the Aeronautical Sciences
ICAS Florence CONGRESS
September 9-13 2024 ITALY

AIAA CEAS Council of European Aerospace Societies
AIAA/CEAS Aeroacoustics Conference

MILAN 2024 iac 75th
RESPONSIBLE SPACE FOR SUSTAINABILITY

https://www.aidaa.it/aerospaceitaly2024/

#aerospaceitaly2024