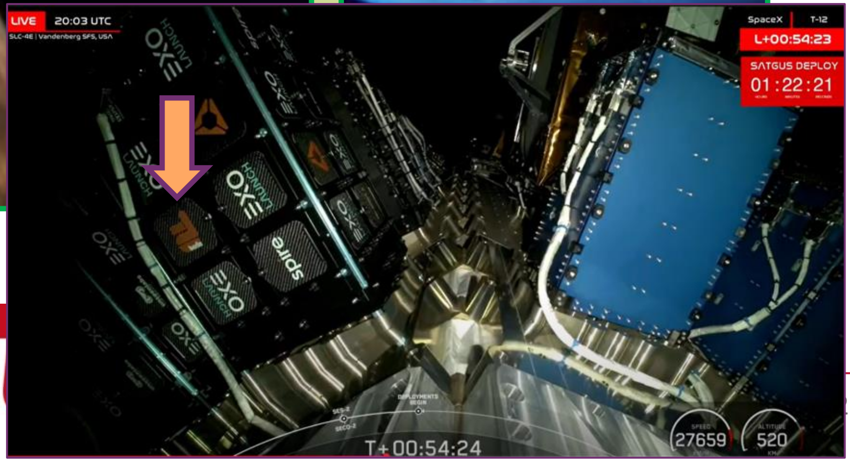
# The Challenges of In-Space Manufacturing and Assembly Using Small Satellites

**Enrico Stoll**
**Chair of Space Technology, TU Berlin**

# Chair of Space Technology

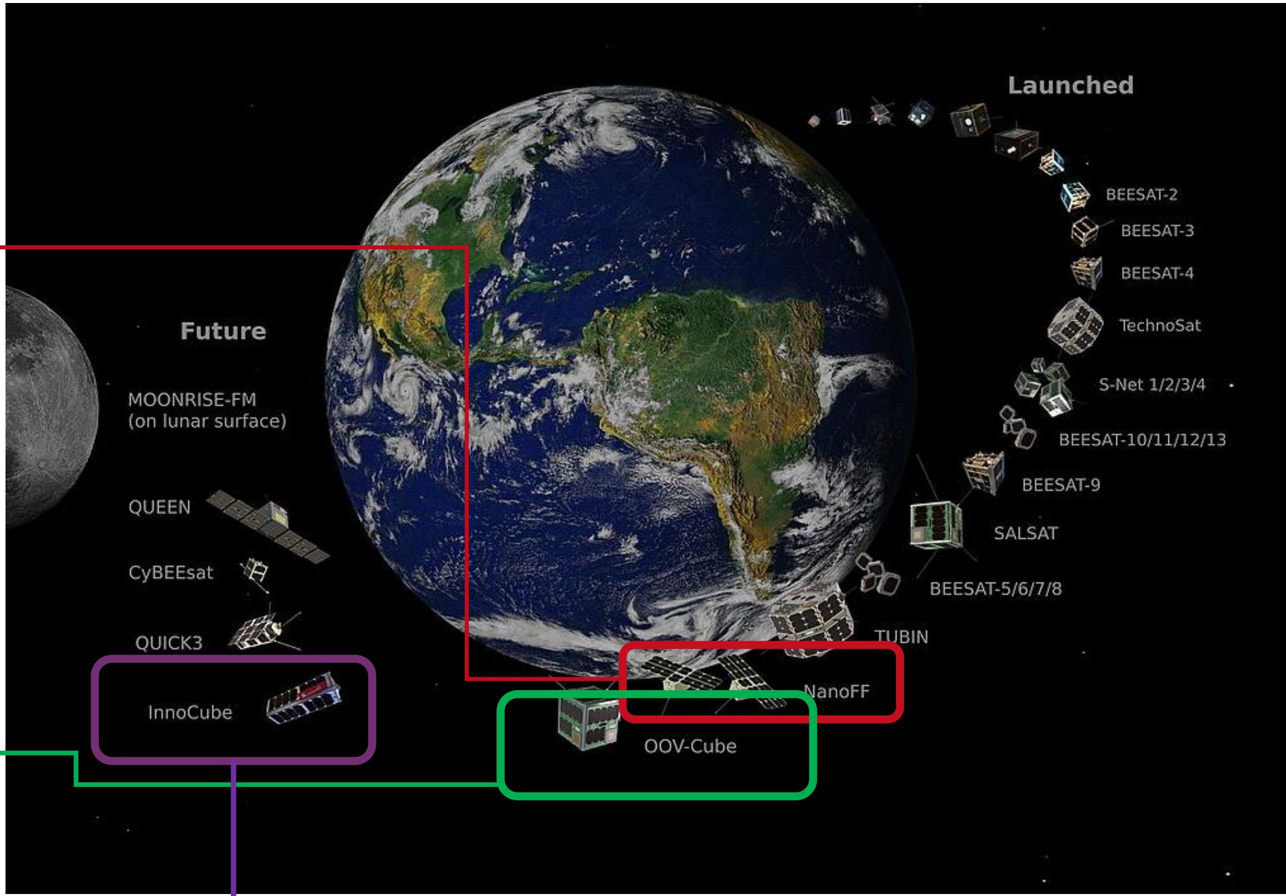
SpaceX
Transporter 9
Dec 2023

Ariane 6
Maiden Flight
July 2024



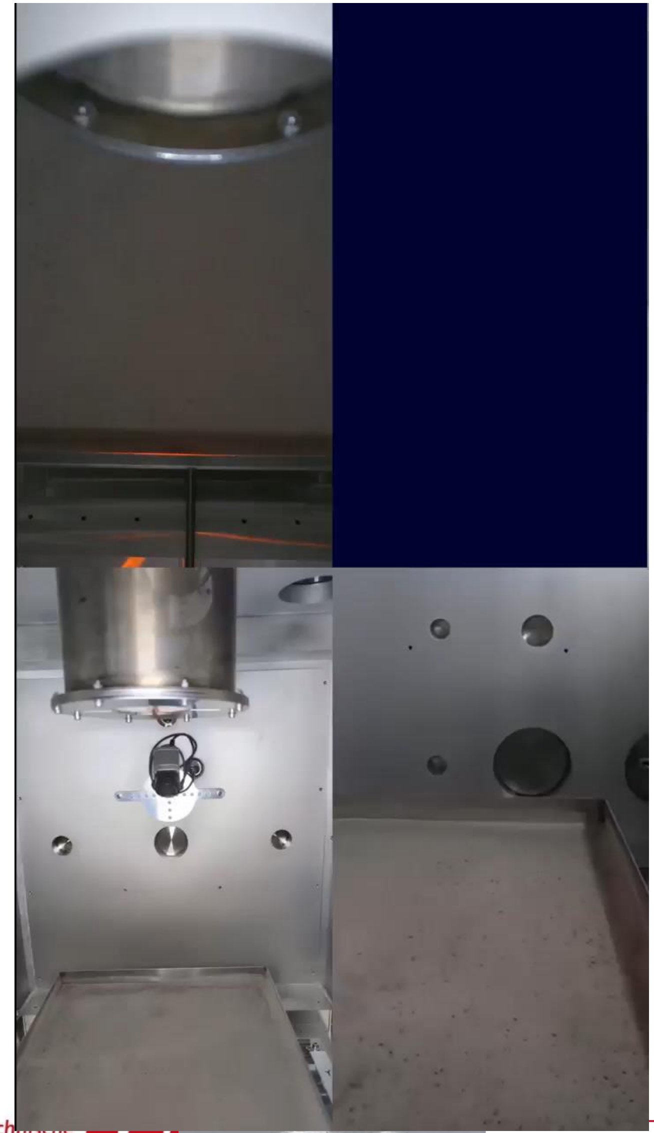

SpaceX
Transporter 12

Jan 2025

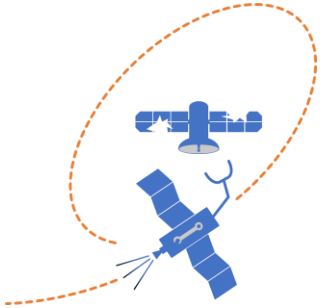



Technische Universität Berlin

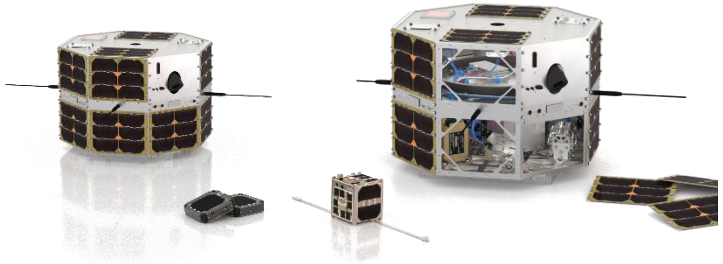
# Chair of Space Technology

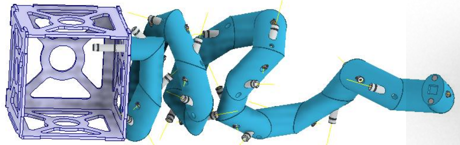


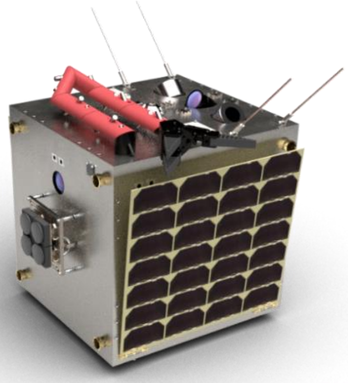
Distributed Space Systems

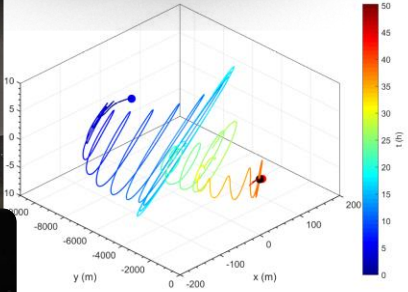


SmallSat Rendezvous & Robotics





# Additive Manufacturing under reduced Gravity

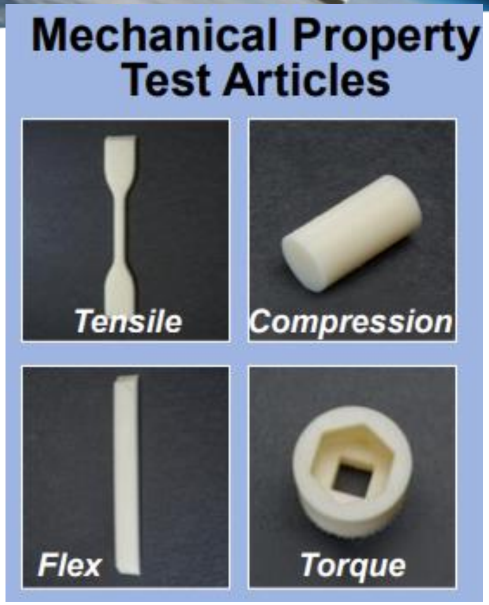
# First 3D Printer in Space (2014)

- **Mission:** NASA & Made In Space Inc.

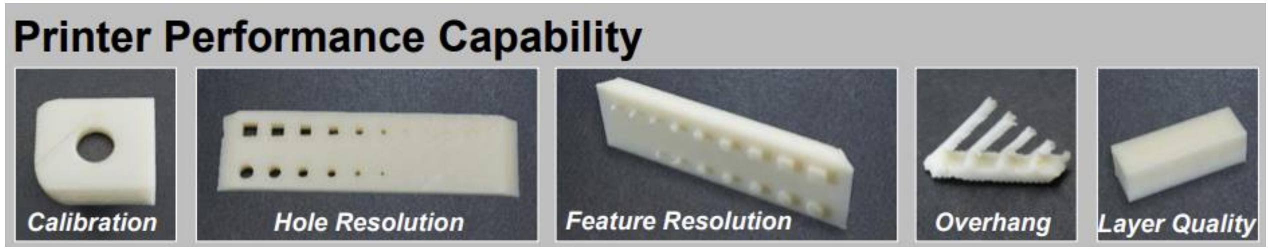
- **Objective:** Test 3D printing technology in microgravity.

- **Details:**
    - the first 3D printer designed for microgravity was sent to the ISS aboard the SpaceX CRS-4 mission
    - utilized Fused Deposition Modeling (FDM) to create objects layer by layer using plastic filament
    - printed 21 objects, including a ratchet wrench, demonstrating the feasibility of in-space manufacturing.

Parts printed aboard the International Space Station with Made In Space's 3D printer [NASA] ▼►







# Refabricator (2019) – Combining 3D Printing with Recycling

- **Mission:** NASA & Tethers Unlimited

- **Objective:** Develop a system that combines 3D printing with plastic recycling to create a sustainable in-space manufacturing process.

- **Details:**
  - The Refabricator is a hybrid 3D printer and recycler that processes plastic waste into 3D printable filament.
  - Installed on the ISS in 2019, it aimed to reduce the need for resupply missions by enabling astronauts to recycle and reuse materials.

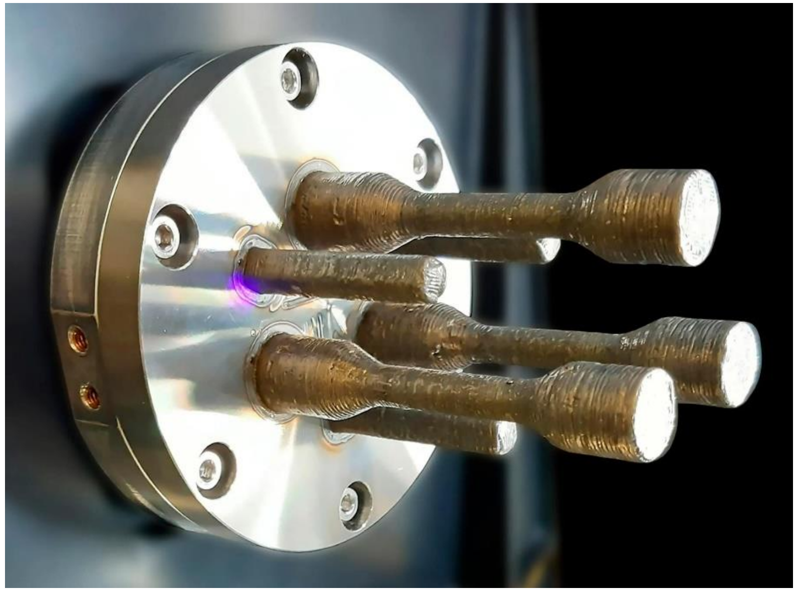
In space manufacturing patch [NASA] ▼

# Metal 3D Printing (2023) on ISS

- **Mission:** European Space Agency (ESA) & Airbus

- **Objective:** Test metal 3D printing capabilities in microgravity environments.

- **Details:**
  - In 2023, ESA and Airbus conducted experiments on metal 3D printing aboard the ISS.
  - The goal was to assess the feasibility of producing metal parts in space, which are essential for robust spacecraft components and repairs.

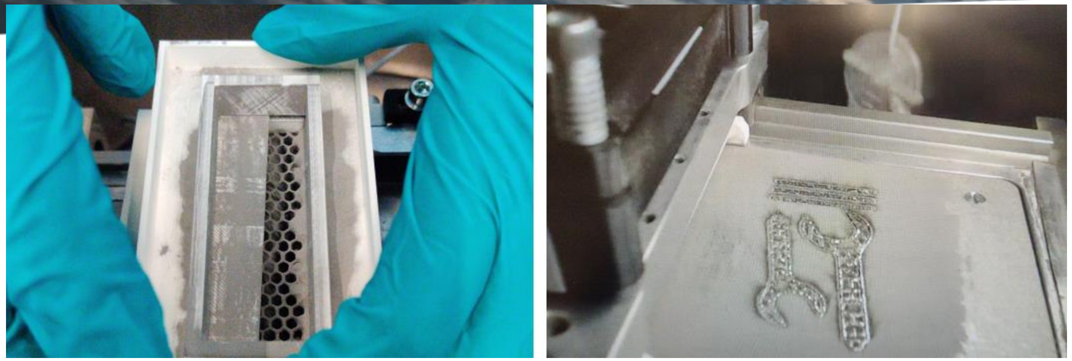


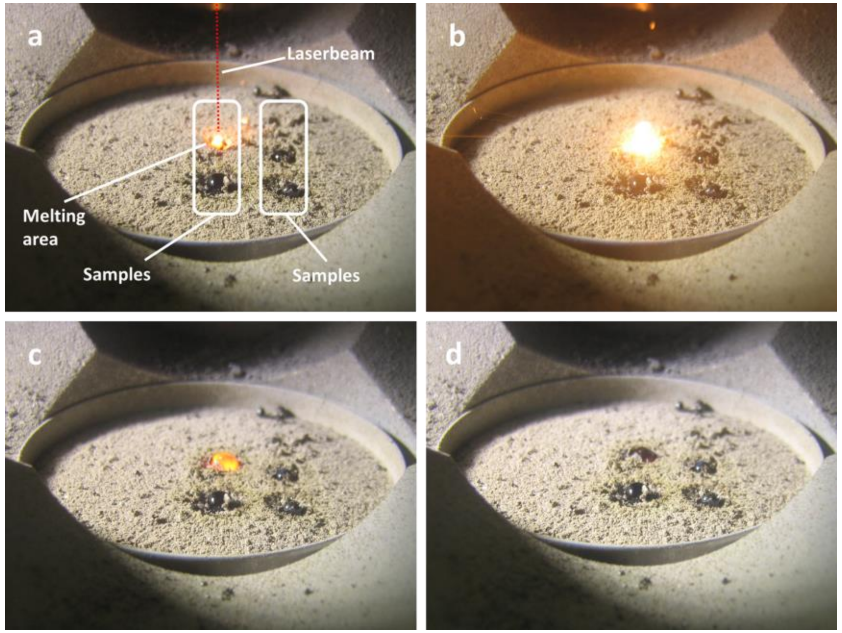
The stainless-steel wire is fed into the printing area, which is heated by a high-power laser at about 1400 °C [ESA] ►


Technische Universität Berlin

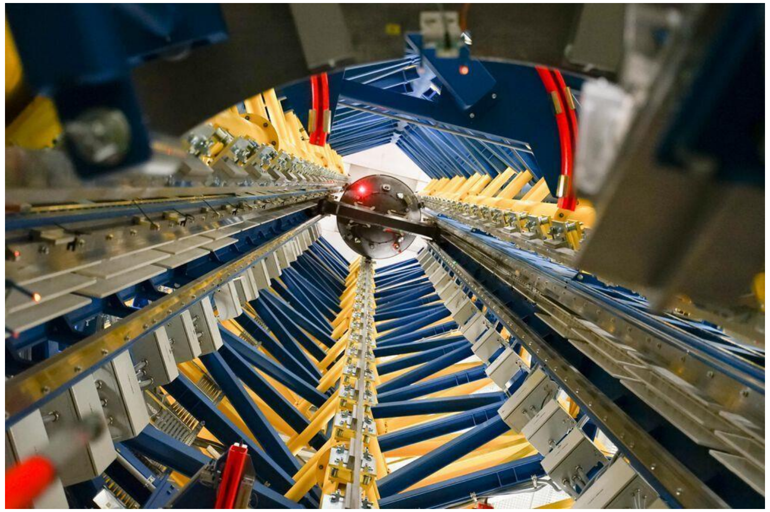
# 3D Printing on parabolic flights / drop towers

recoater design improves layer quality in 3D printing with metallic powder [BAM, Federal Institute for Materials Research and Testing.] ►





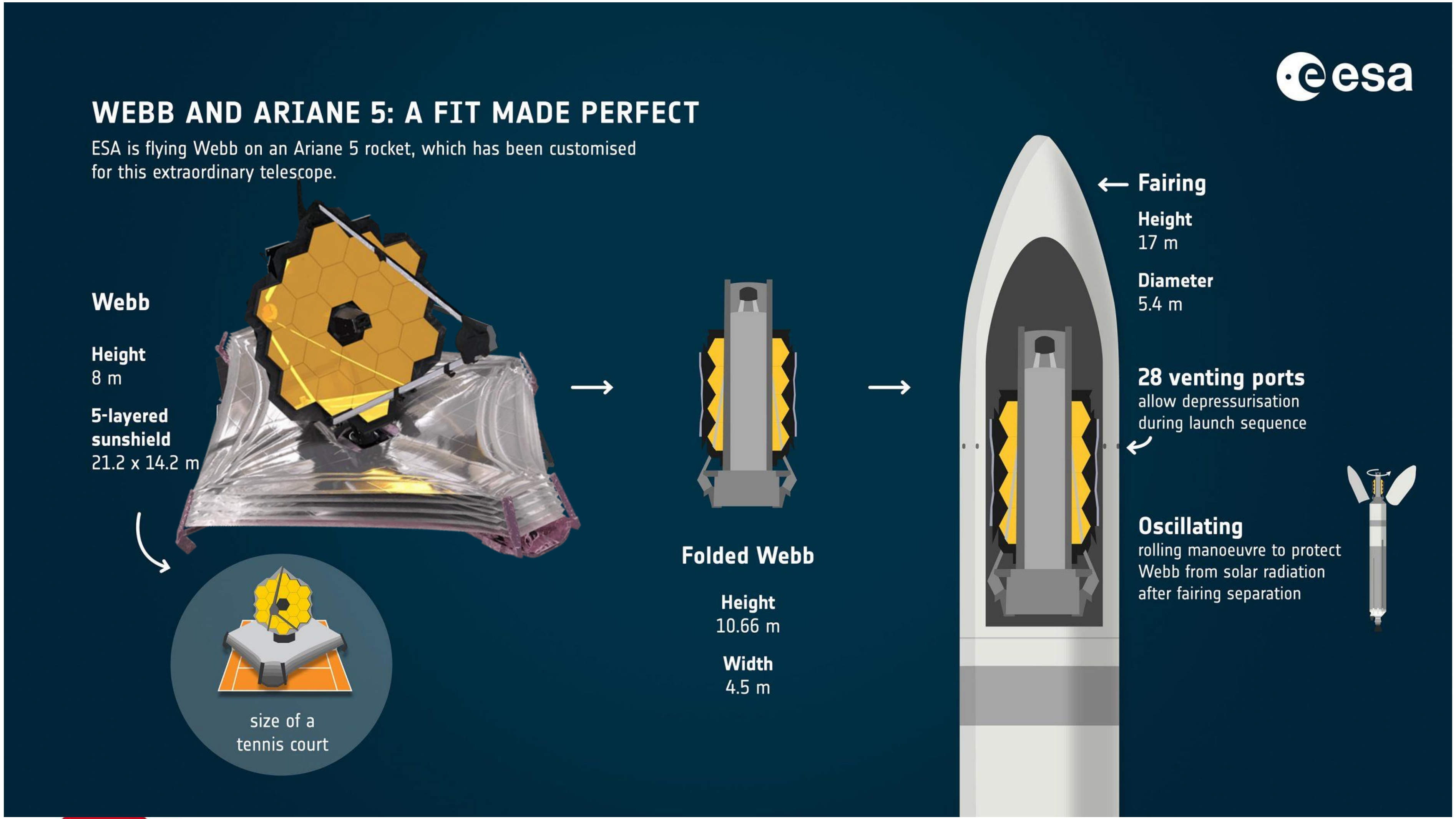

▲ View into the test chamber a) activation of the laser b) formation of the melt c) end of the laser irradiation d) solidified sample



▲ Einstein Elevator for lunar gravity environment [Source: HITec, Leibniz Universität Hannover]

# Space Robotics & In-Space Manufacturing and Assembly

# Space Robotics - Motivation




Webb and Ariane 5 [Source: ESA] ▲

James Webb space telescope stowed in an Ariane V [Source: NASA] ▲

# Robotic applications / services

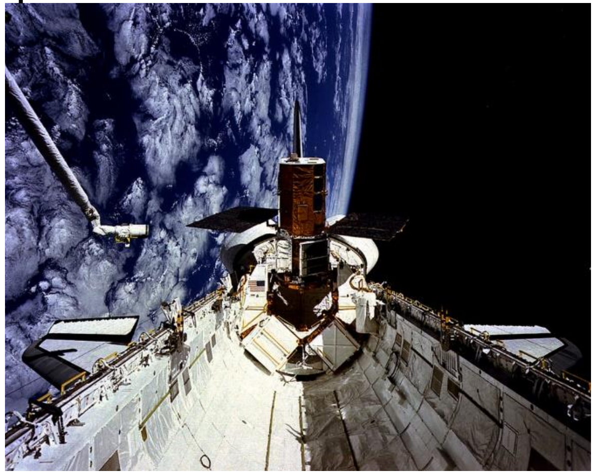
- In-orbit refuelling: provision and transfer of propellant, fuel pressurants, or coolants
- In-orbit repair: replacing parts of a space system in orbit in order to extend or maintain the system in operational conditions.
- Active Debris Removal: a space system is being captured to relocate it to a graveyard orbit or to accelerate its atmospheric re-entry.
- In-orbit inspection: assessing the physical status and conditions of a satellite to detect anomalies or assess the consequences of a failure, attack, or collision.
- In-orbit recharging: provision of electric power to a space system in orbit through power beaming or docking to power the batteries.
- Station-keeping: process of docking with a satellite to keep it in a particular orbit or altitude.
- In-orbit relocation: modifying or maintaining the position, orientation, location, or orbital parameters of the space system.
- Last Mile Delivery: transport of a spacecraft from the separation phase of the launch to the final orbital destination using e.g., an Orbital Transfer Vehicle (OTV).
- In-orbit assembly: in-orbit aggregation and connection of components to constitute a spacecraft or spacecraft subsystem.
- In-orbit manufacturing: activities related to the in-orbit transformation of raw materials into usable spacecraft components.

Definitions of types of on-orbit servicing, assembly, and manufacturing [ESPI] ►

# Road side assistance in space

▲ first US space station Skylab 1973, was damage during start; micrometeoroid shield was torn during launch and solar cells did not deploy. [source: NASA]

Solar Maximum Mission (1980) was retrieved by hand and the attitude control system was repaired in the in the Space Shuttle Bay in 1984.[source: NASA] ▼

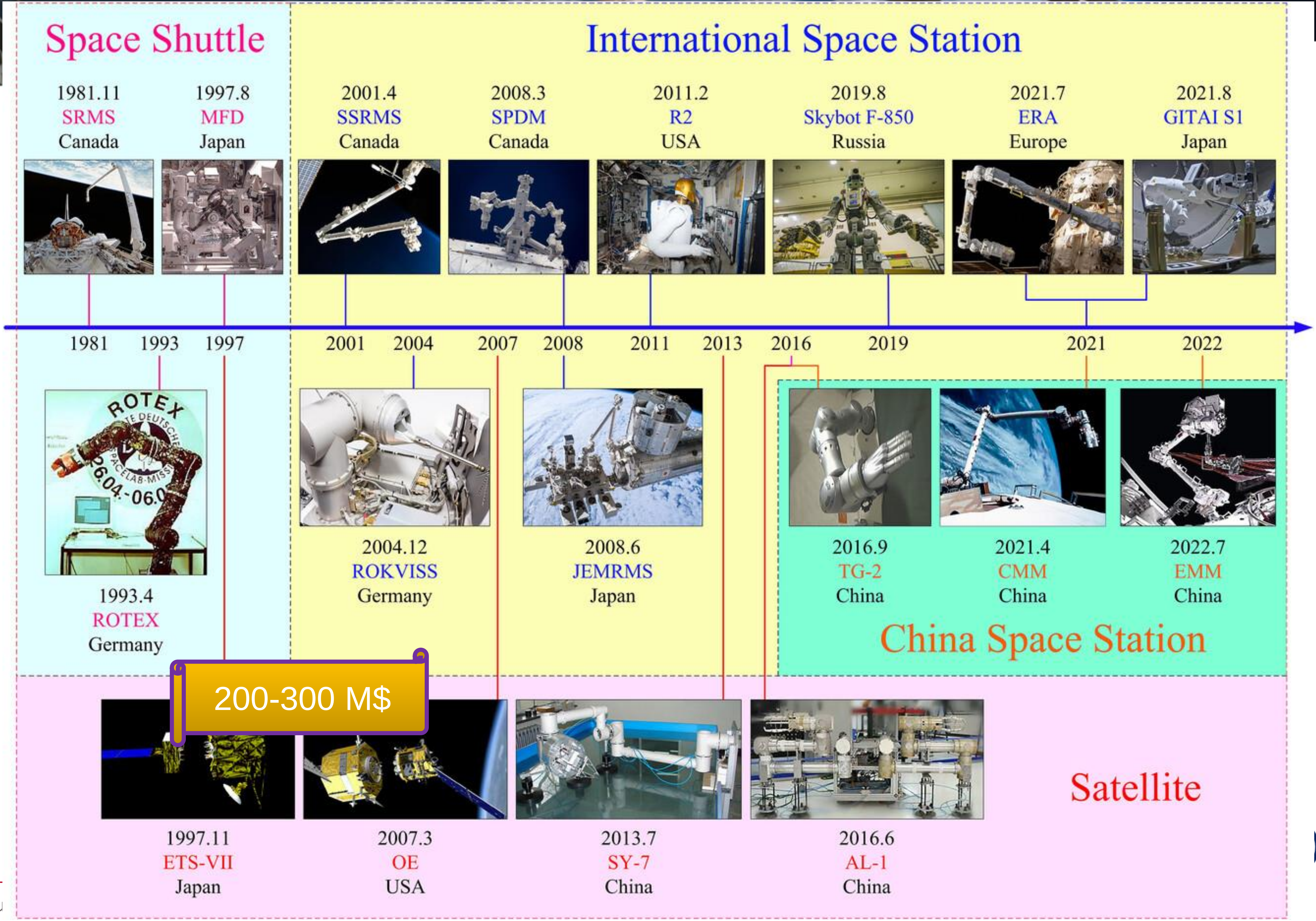


▲ In 1984 the communications satellites Westar 6 and Palapa B2, became stranded in useless elliptical orbits after their perigee kick motors misfired. They were was returned to Earth, refurbishment and eventual relaunched. [source: NASA]

**STS-61 (1993)**
installation of an optical correction system in the main mirror (wrong grinding → fuzzy images), exchange of solar panels [source: NASA]

Technische Universität Berlin

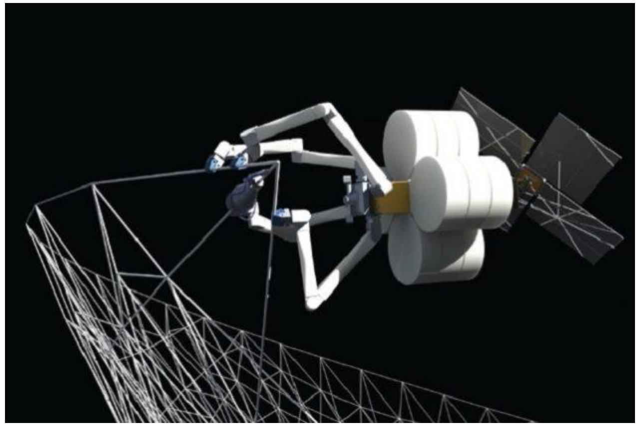
# Overview




200-300 M$

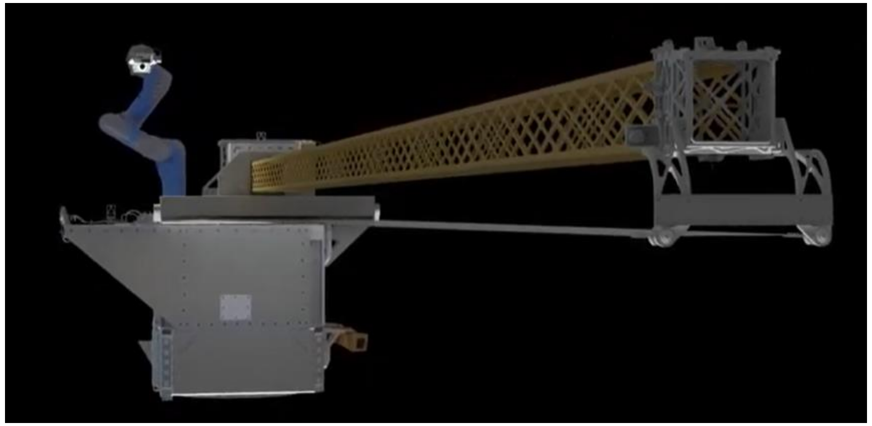
Representative space robotic programs for OOS. [source: Boyu Ma et al, Advances in Space Robots for On-Orbit Servicing: A Comprehensive Review, *Advanced Intelligent Systems* (2023).] ►

# Future missions?



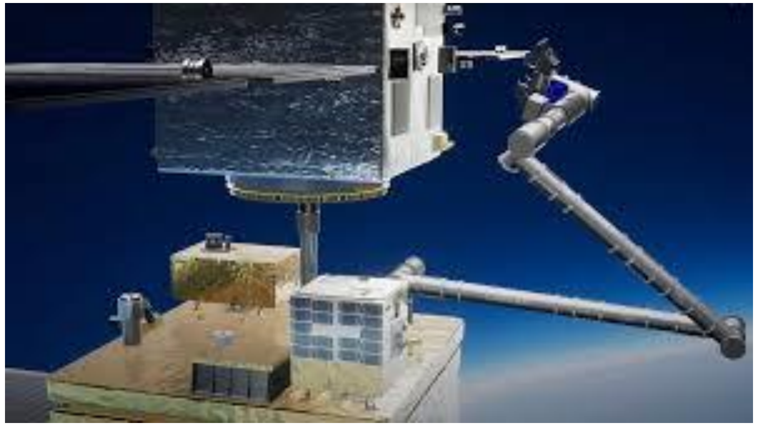
[Source: Spider Fab] ▲

- Spider Fab (Tethers unlimited)
- In-Space Construction of Large Structures
- 3D Printing and Automated Assembly
- demonstrated ground-based prototypes for on-orbit assembly



[Source: NASA / RedWire] ▲

- Archinaut One (NASA / RedWire)
- additive manufacturing of two extending 10 meter beams from each side of the system
- Each beam will enable two solar arrays
- funded in 2019 with 73.7 M$
- cancelled in 2023



[Source: EC / EROSS] ▲

- European Robotic Orbital Support Services (EROSS) funded by the EC (26 M€)
- EROSS IOD: Focused on developing autonomous robotic technologies for on-orbit servicing tasks
- EROSS SC: satellite with various tasks such as robotic maneuvers, extending satellite lifespan, and conducting inspections.

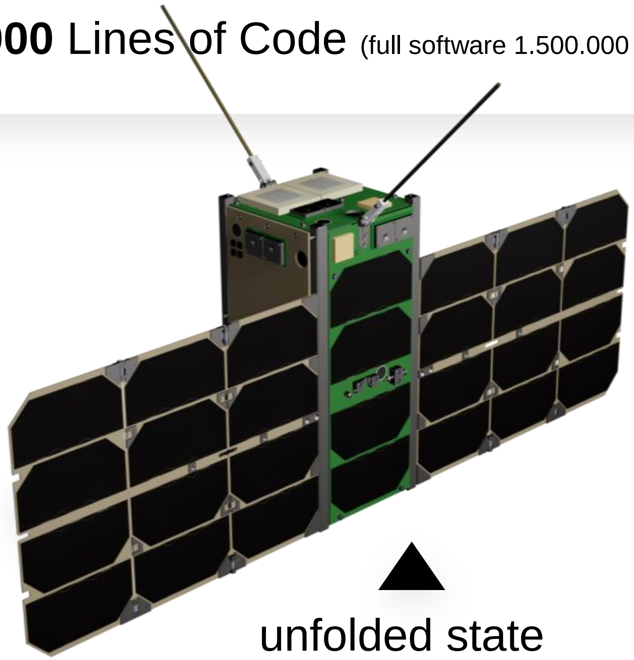
# Stop thinking BIG!

## Let’s use smaller satellites

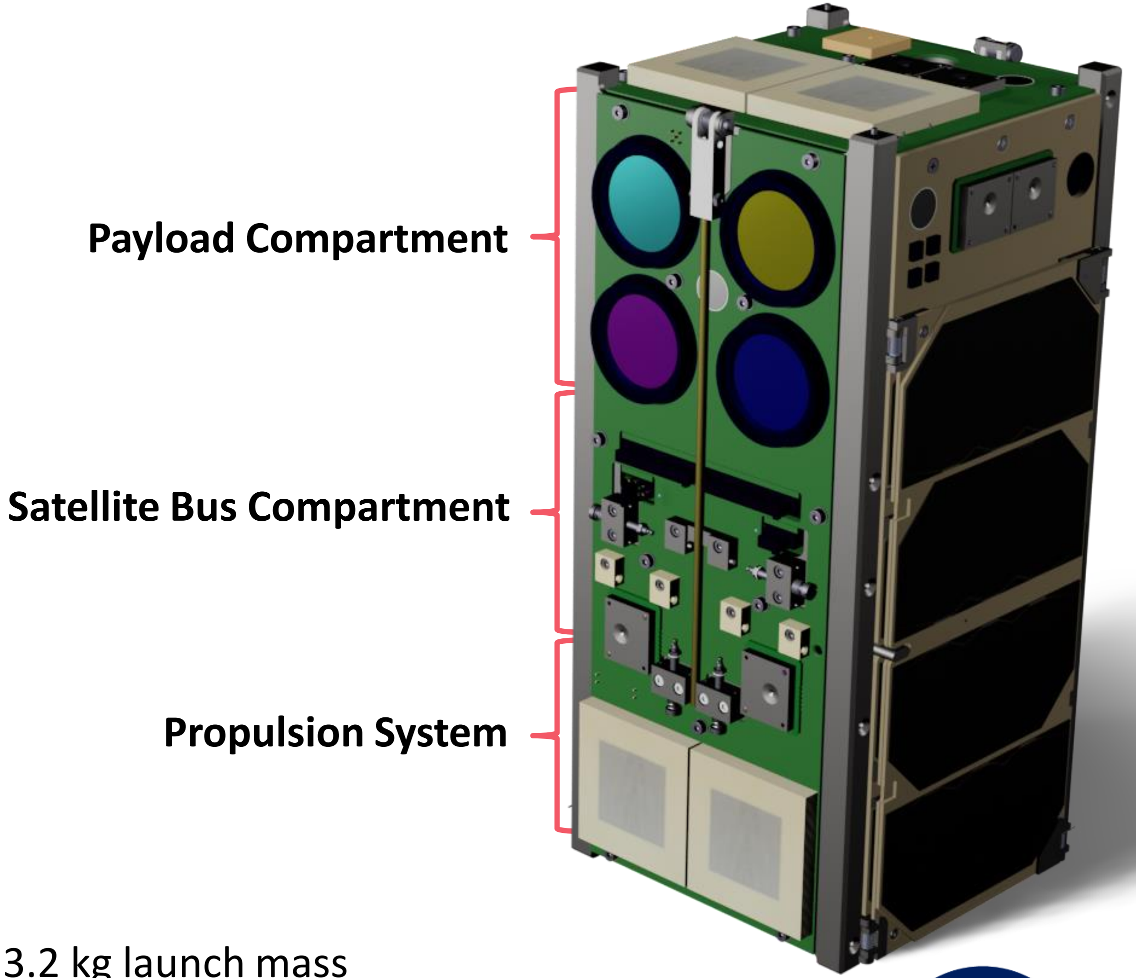
# NanoFF

**Satellites:**

- Two **2U CubeSats** (20x10x10 cm$^3$)
- **Single-failure tolerant** design
- **5.5+ years development**
- **10 subsystems**
- **21 Microcontrollers**
- ~ **133,000** Lines of Code (full software 1.500.000 )



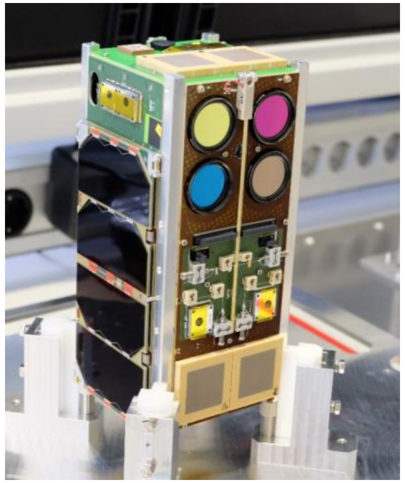
▲ unfolded state



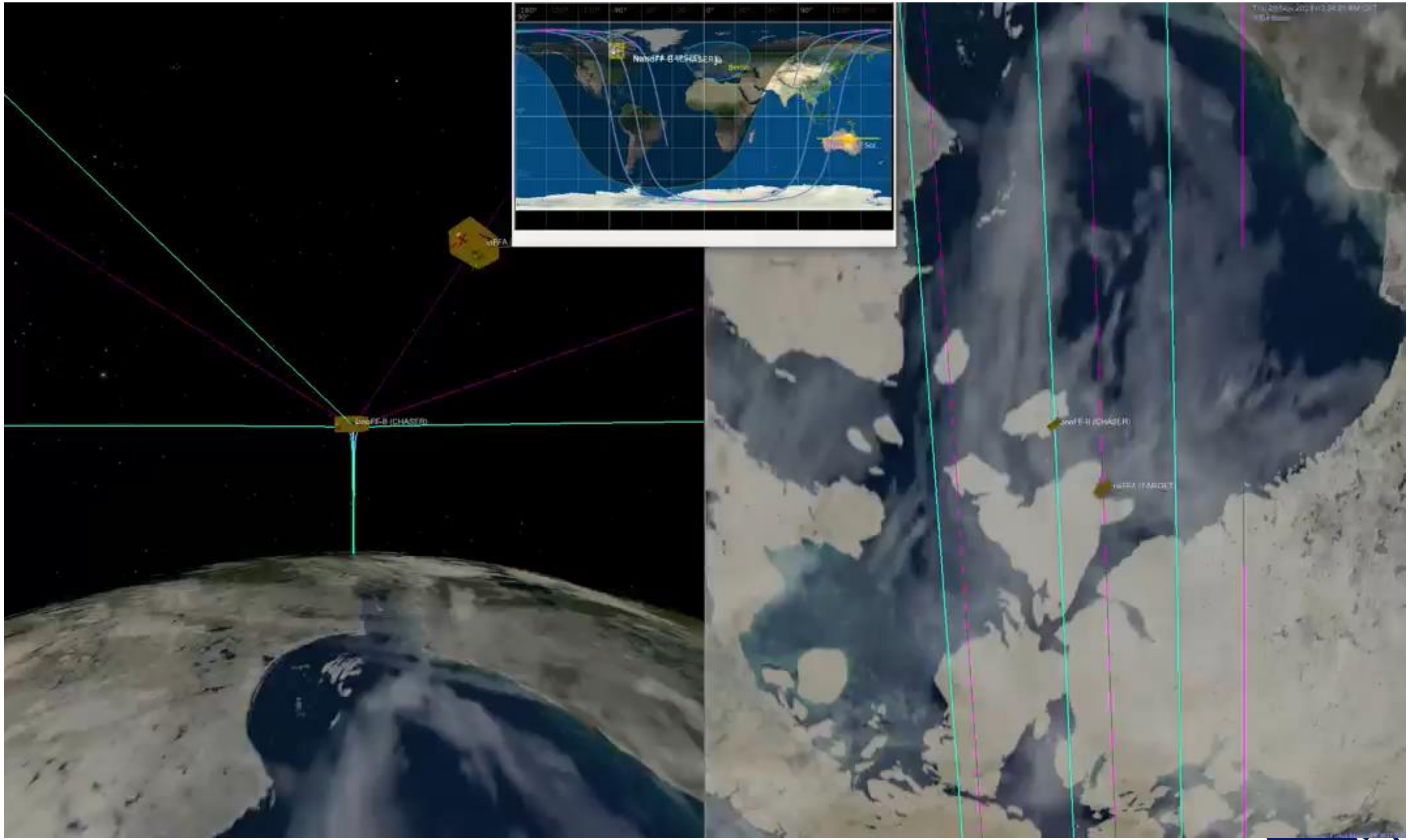

- 2U CubeSat with 3.2 kg launch mass
- Deployable solar panels, 22W of power generation

Technische Universität Berlin

# Formation flight

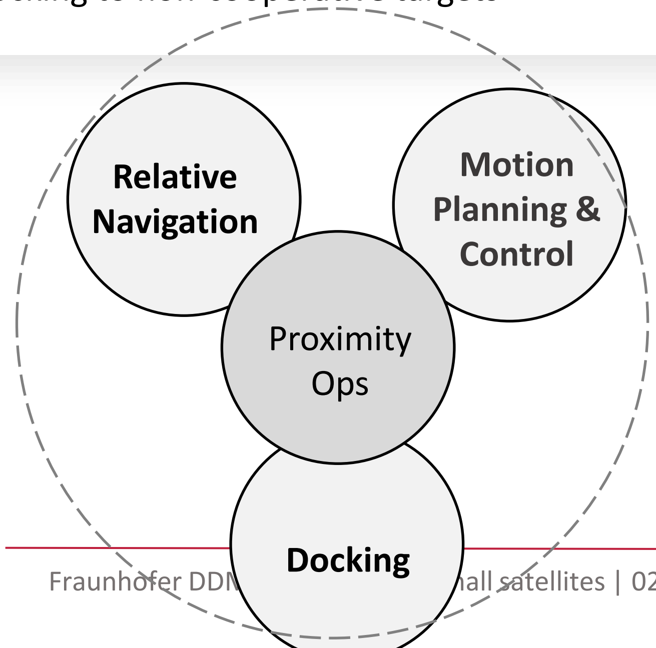


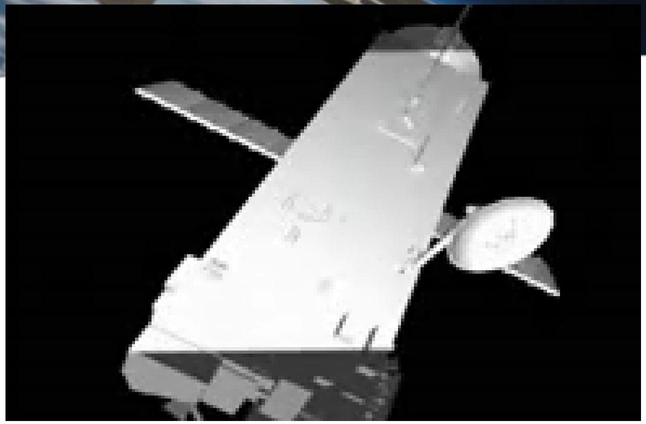
- **Circular Orbit** (SSO)
- Altitude: **~ 560 km**
- LTAN: **22:00**
- Velocity: **7.58 km/s**
- Period: **95.71 min**



# Challenges of small (nano) satellites

- **Limitations of small satellites**
  - Power (depends on solar cell area)
  - communication (depends on antenna size, power, precision pointing)
  - Limited proximity operations sensors (LIDAR, radar, stereo cameras,…)
    - Essential for a wide rang of missions:
    - Active Debris Removal (ADR)
    - In-Space Manufacturing and Assembly
- **General technology gaps**
  - image data base
  - docking to non-cooperative targets



▲ tumbling ENVISAT [Quelle: Spacecraft Robotics and Control Laboratory; Carleton University]

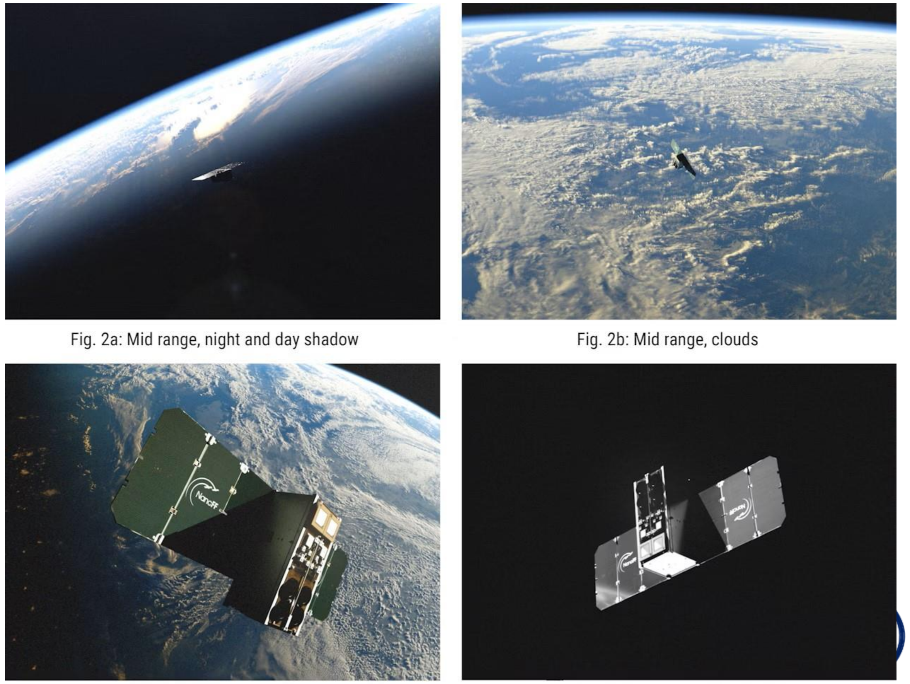


Fig. 2a: Mid range, night and day shadow

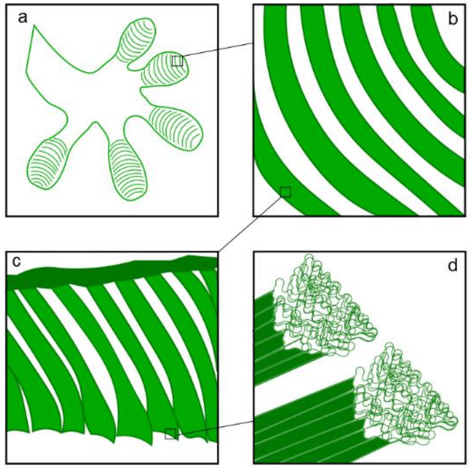
Fig. 2b: Mid range, clouds

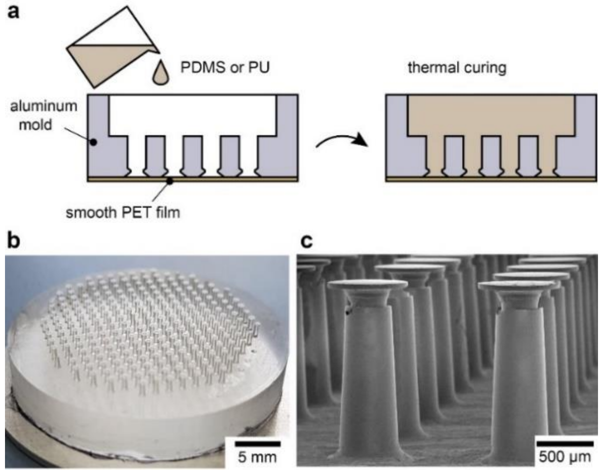
Fig. 2c: Close range, color

Fig. 2d: Close range, black/white

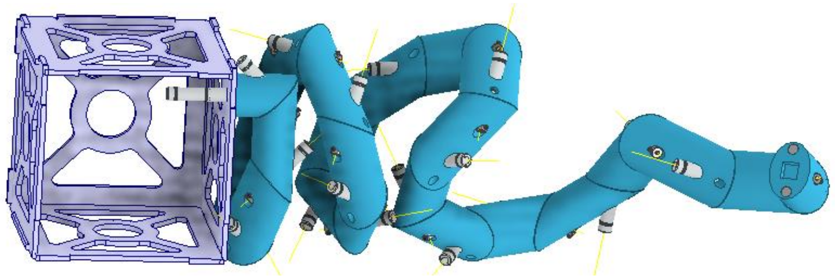
Fig. 2: Synthetic images rendered with NanoFF camera specs, and common noise and artifact effects

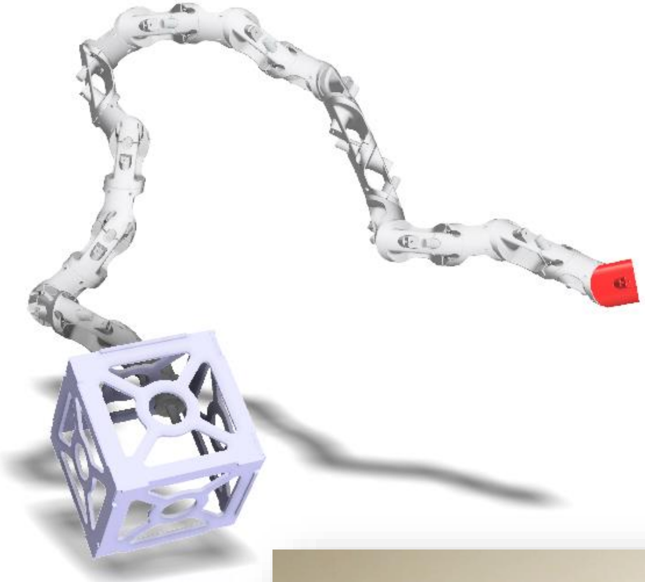
# Gecko material for docking

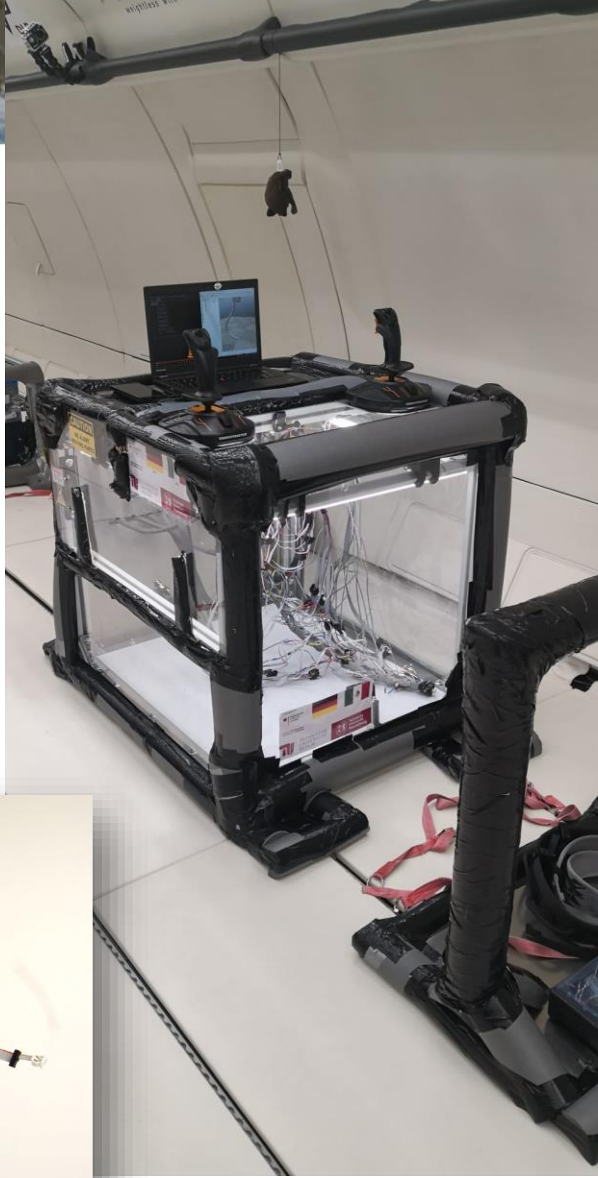


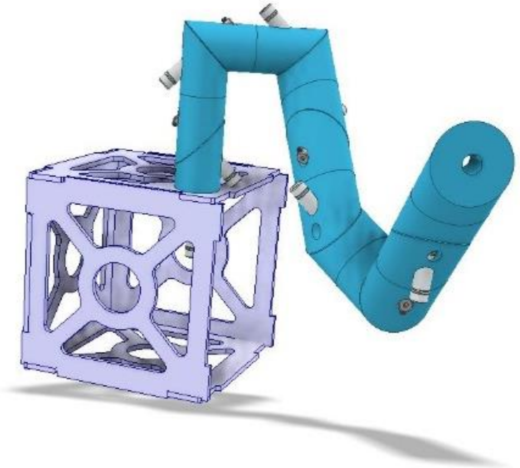



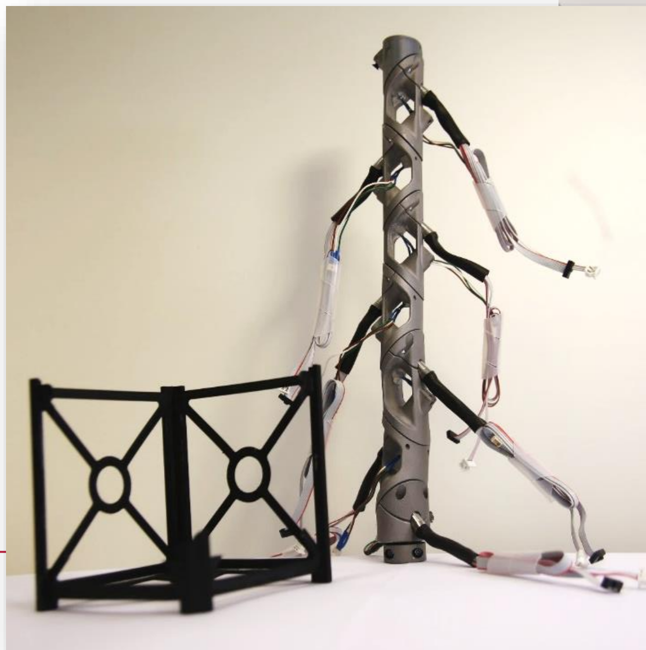

# 1U robotic arm



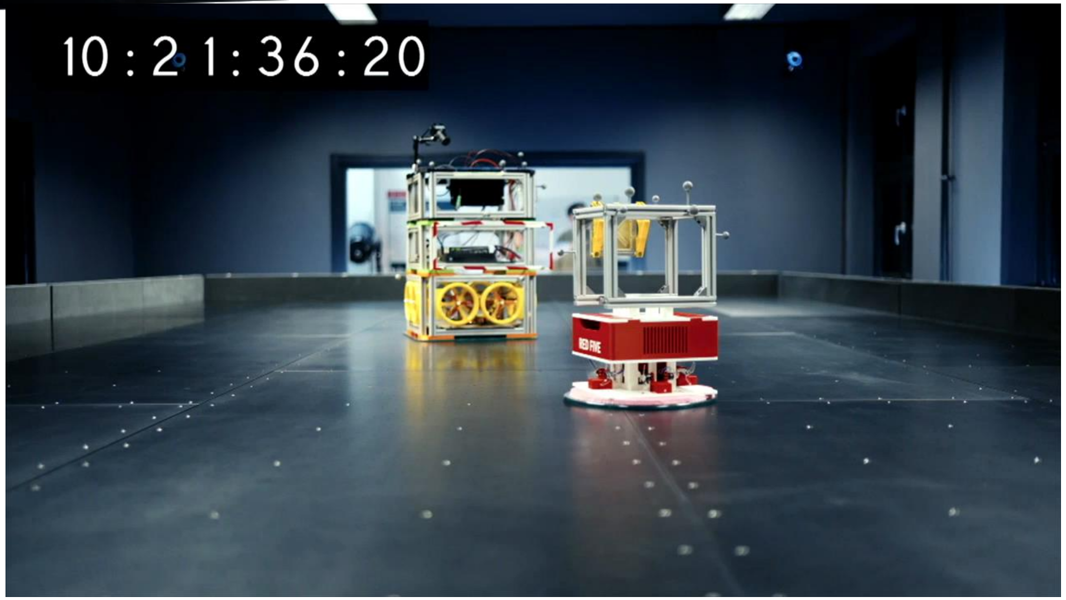




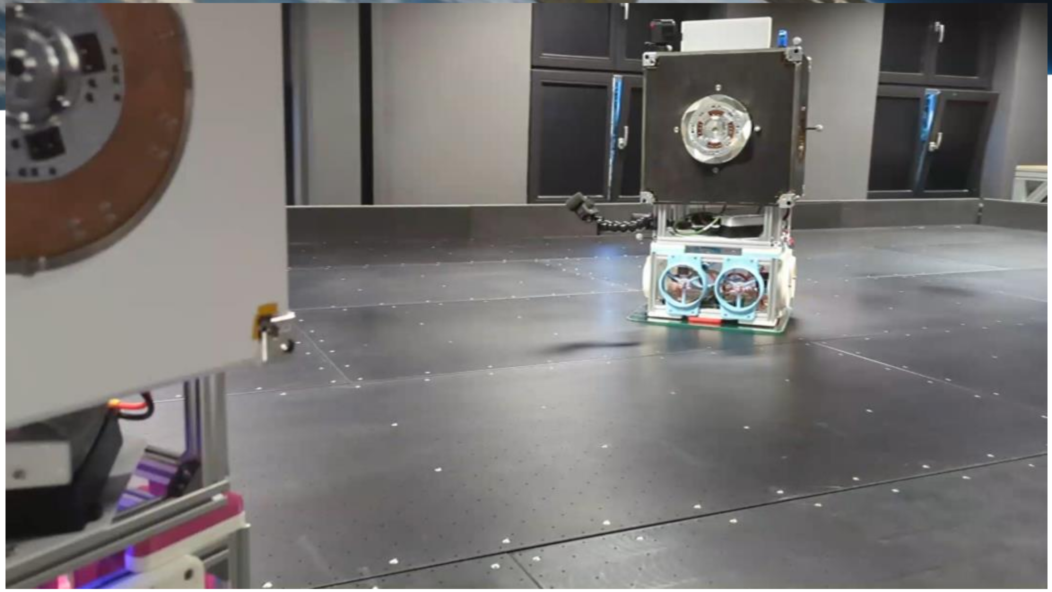




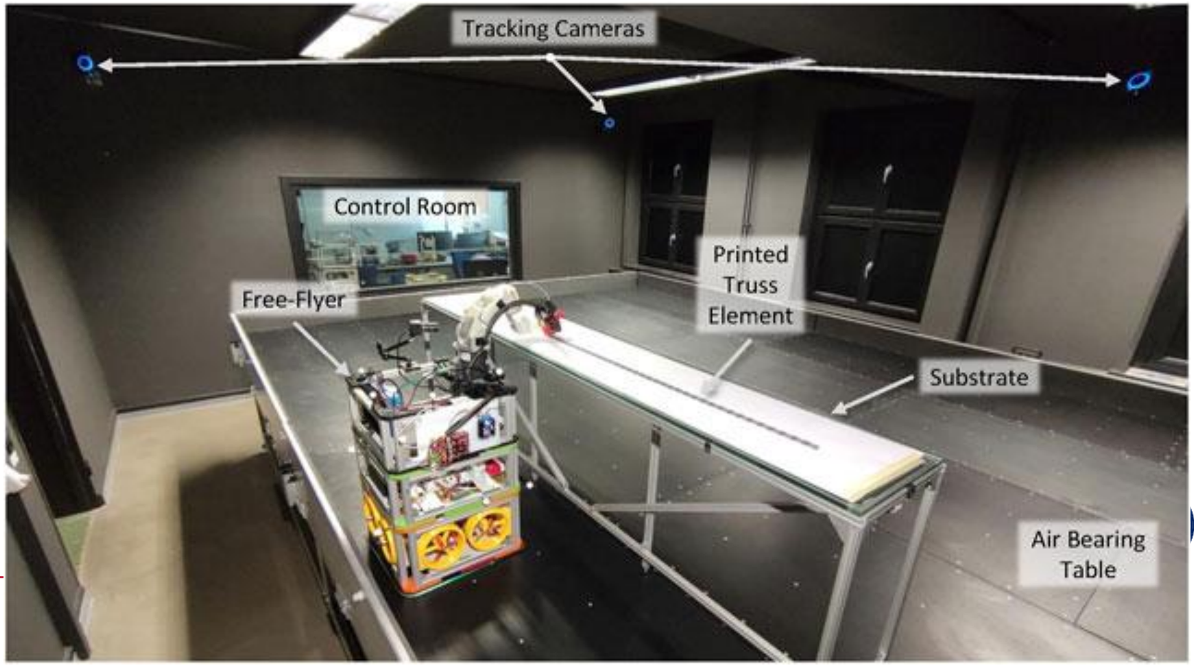
# Ground tests




▲ Final approach to a non-cooperative target (e.g. ADR or OOS) [video credit: ZDF]



▲ Docking with a standardized iSSI interface

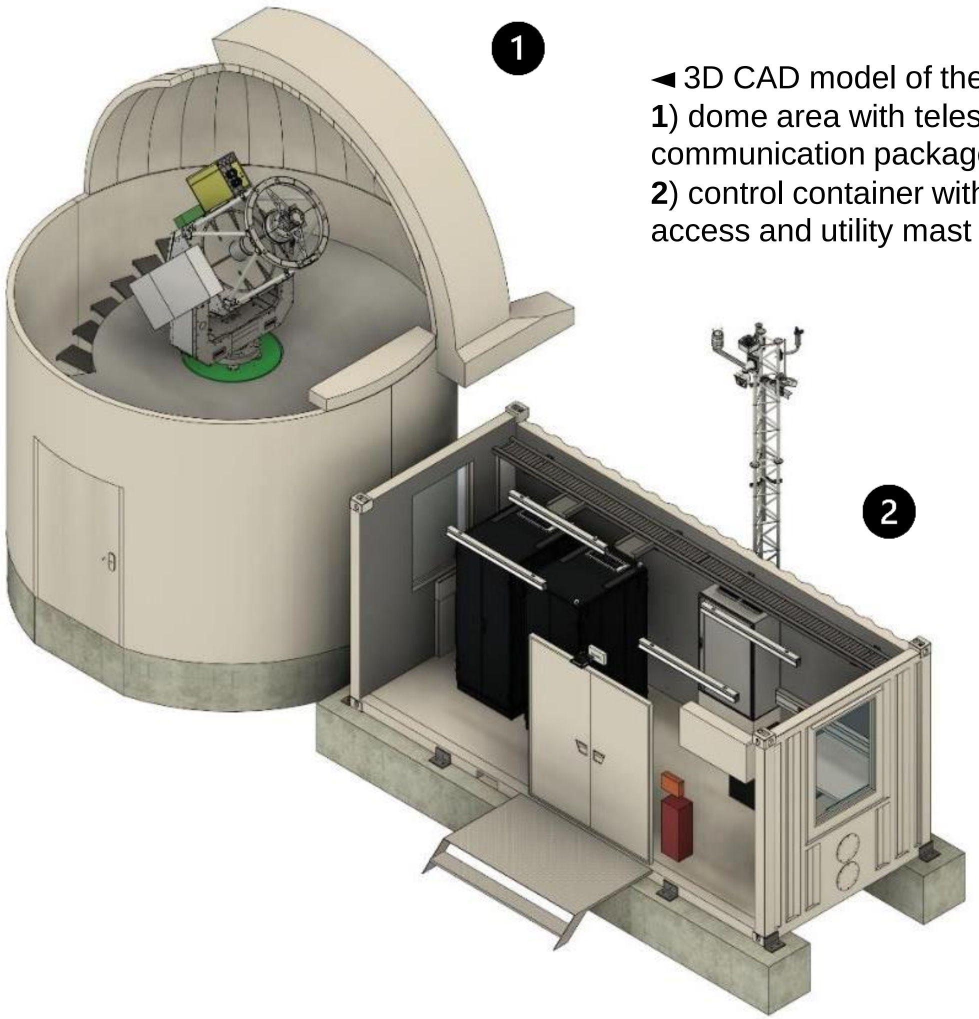



► Freeform 3D Printing setup for In-Space Manufacturing in cooperation with TU Braunschweig [video credit: TUBS/TUB]

# Precise Motion Planning & Control

- **Sensor/actuator suite**
  - Sensor fusion
  - Increased control cycle frequency
- **Advanced Algorithms**
  - Focus on analytic approaches in contrast to optimization-based ones
  - collision safety, efficient delta-v usage
  - repeated rendezvous opportunities, and optimal docking velocity ranges.
- **Operations**
  - Focus on operational constraints: propulsion system uncertainties, sunlight conditions, ground station

**Ground station for Optical Communication, Satellite Laser Ranging, and Quantum Key Distribution**




◄ 3D CAD model of the DiGOS TUBOGS
**1**) dome area with telescope and optical communication packages
**2**) control container with working place, remote access and utility mast

# Summary

- **In-Space Manufacturing and Assembly**
  - wide use spectrum
  - small satellites might be cost efficient
  - have to work under limited resources

► NanoFF Ops

Satellite Autonomy

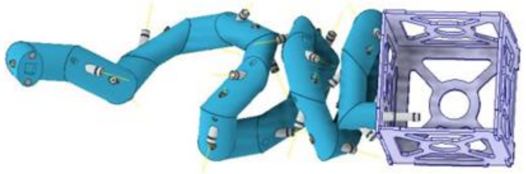
Docking

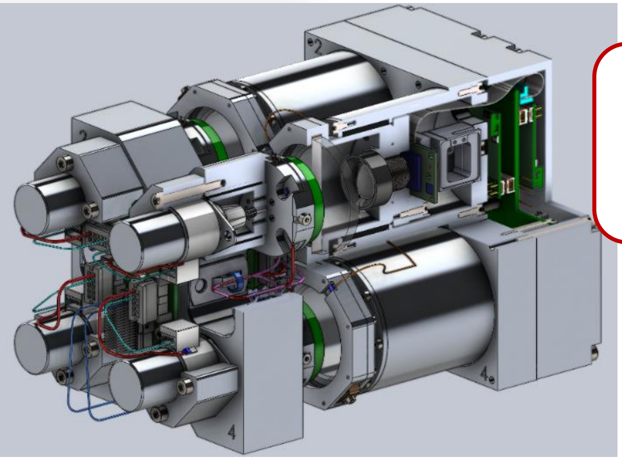
limited resources

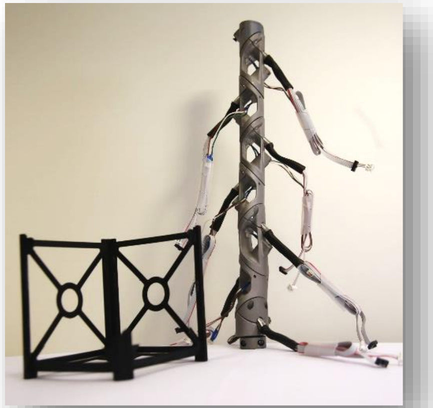
Relative Navigation

Motion Planning and Control

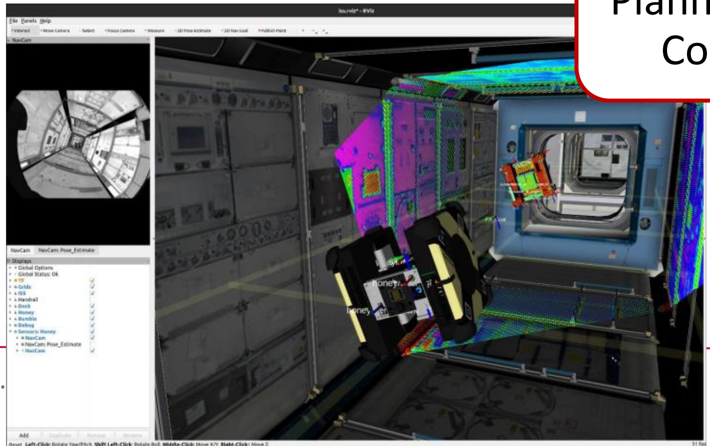
► LIZARD payload on OOV Cube



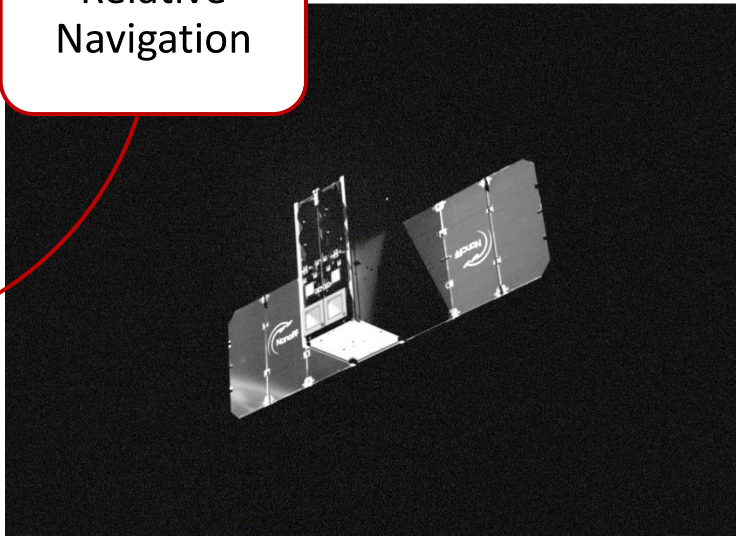




◄ HOMER robotic arm



► Motion planning and control demo on ISS



▲ Synthetic image sandbox

Technische Universität Berlin

RFT

# Thank you!



Technische Universität Berlin

RFT