ESA Technology CubeSats: Pushing the Mission Autonomy Envelope

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ESA ESTEC

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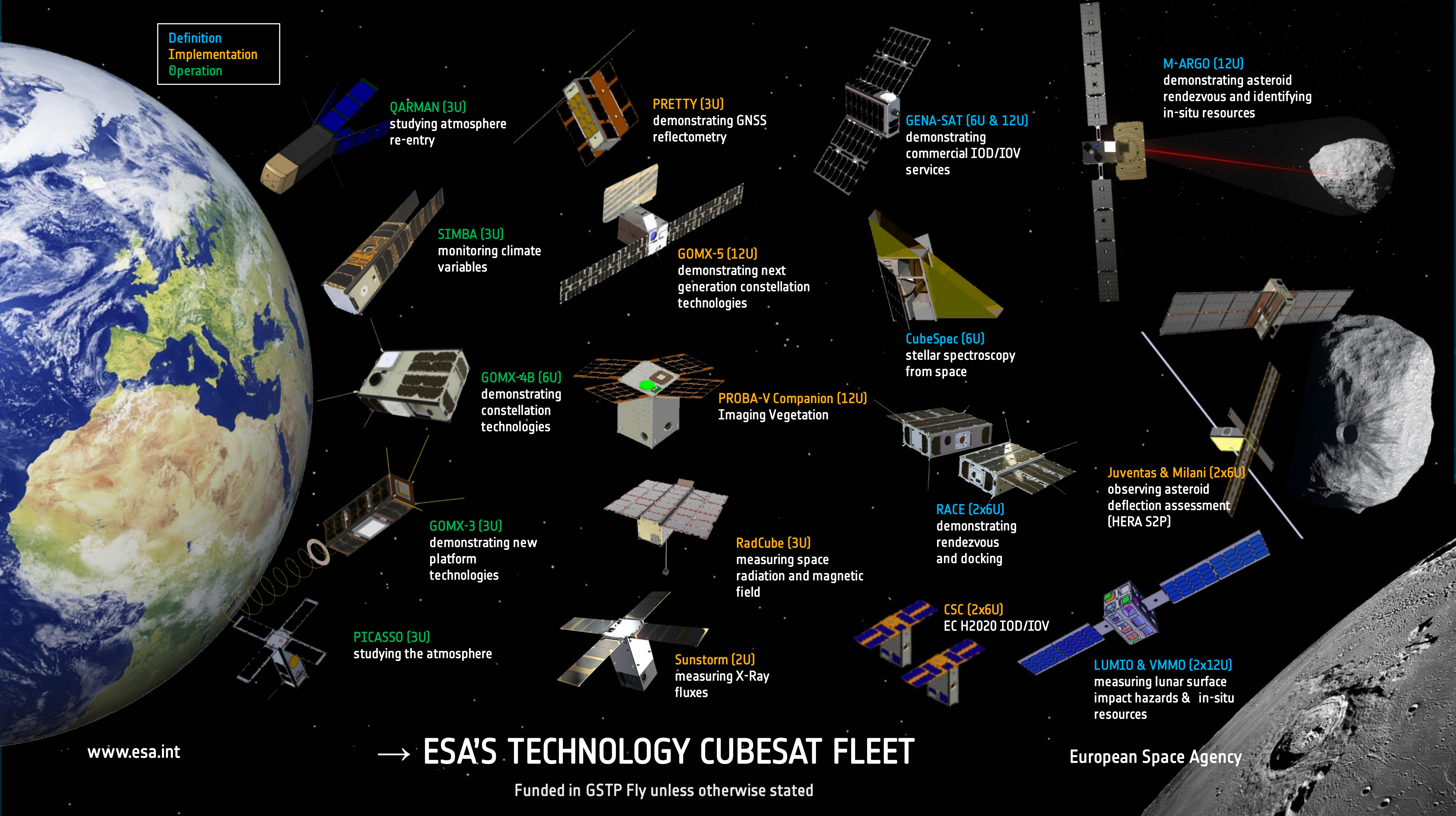
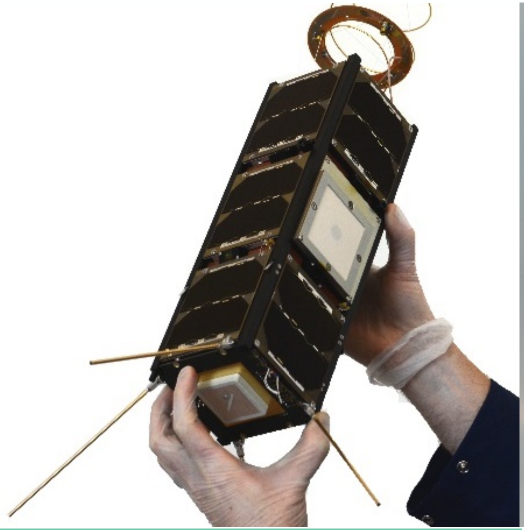
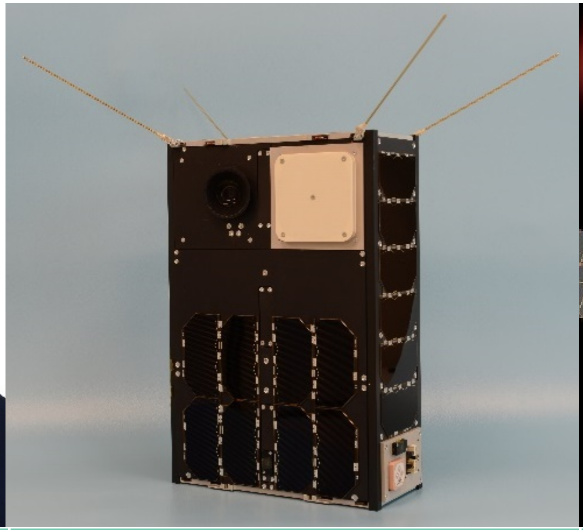


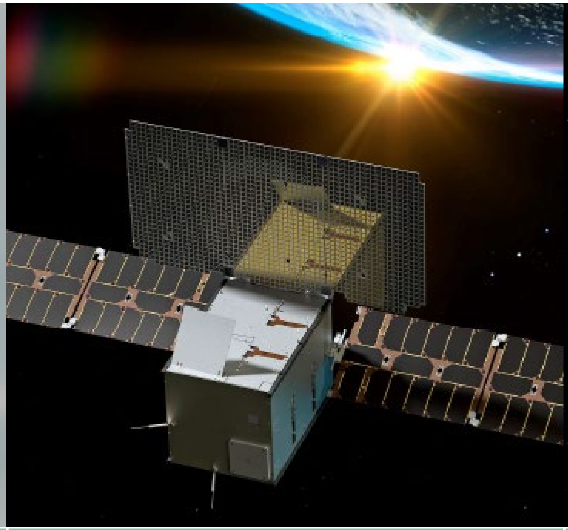
Definition
Implementation
Operation
QARMAN (3U)
studying atmosphere re-entry
PRETTY (3U)
demonstrating GNSS reflectometry
GENA-SAT (6U & 12U)
demonstrating commercial IOD/IOV services
M-ARGO (12U)
demonstrating asteroid rendezvous and identifying in-situ resources
SIMBA (3U)
monitoring climate variables
GOMX-5 (12U)
demonstrating next generation constellation technologies
CubeSpec (6U)
stellar spectroscopy from space
GOMX-4B (6U)
demonstrating constellation technologies
PROBA-V Companion (12U)
Imaging Vegetation
RACE (2x6U)
demonstrating rendezvous and docking
Juventas & Milani (2x6U)
observing asteroid deflection assessment (HERA S2P)
GOMX-3 (3U)
demonstrating new platform technologies
RadCube (3U)
measuring space radiation and magnetic field
CSC (2x6U)
EC H2020 IOD/IOV
PICASSO (3U)
studying the atmosphere
Sunstorm (2U)
measuring X-Ray fluxes
LUMIO & VMMO (2x12U)
measuring lunar surface impact hazards & in-situ resources
www.esa.int
→ ESA'S TECHNOLOGY CUBESAT FLEET
Funded in GSTP Fly unless otherwise stated
European Space Agency

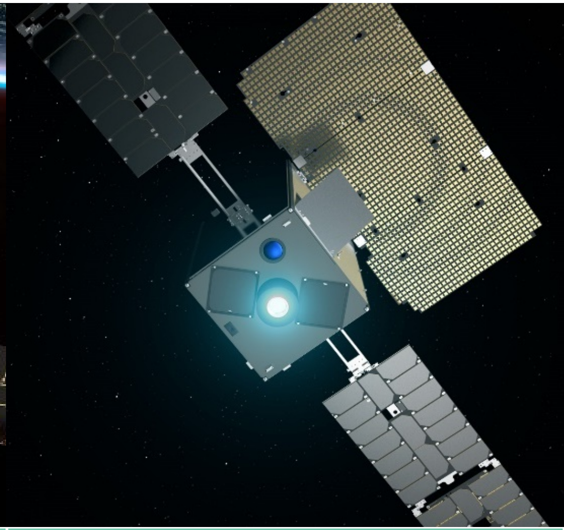
The Evolution of the CubeSat (ESA)

Rapid growth in size & advances in performance for real operational missions









Size	3U	6U	12U	12U XL
Mission	GOMX-3	GOMX-4B	GOMX-5	M-ARGO
Power (max)	6 W	12 W	120 W	150W
Pointing acc.	2 deg (3-axis)	0.5 deg (3-axis)	0.2 deg (3-axis)	0.1 deg (3-axis)
Comms D/L	3000 kbps (X-band)	2000 kbps (S-band)	225000 kbps (X-band)	8 kbps @ 1 AU (X-band)
Delta-V	0 m/s	10 m/s (cold gas)	250 m/s (electric)	3000 m/s (electric)
Launch	2015	2018	2022	2024-25

CubeSat Evolutionary Tree (Europe)

1st wave: educational

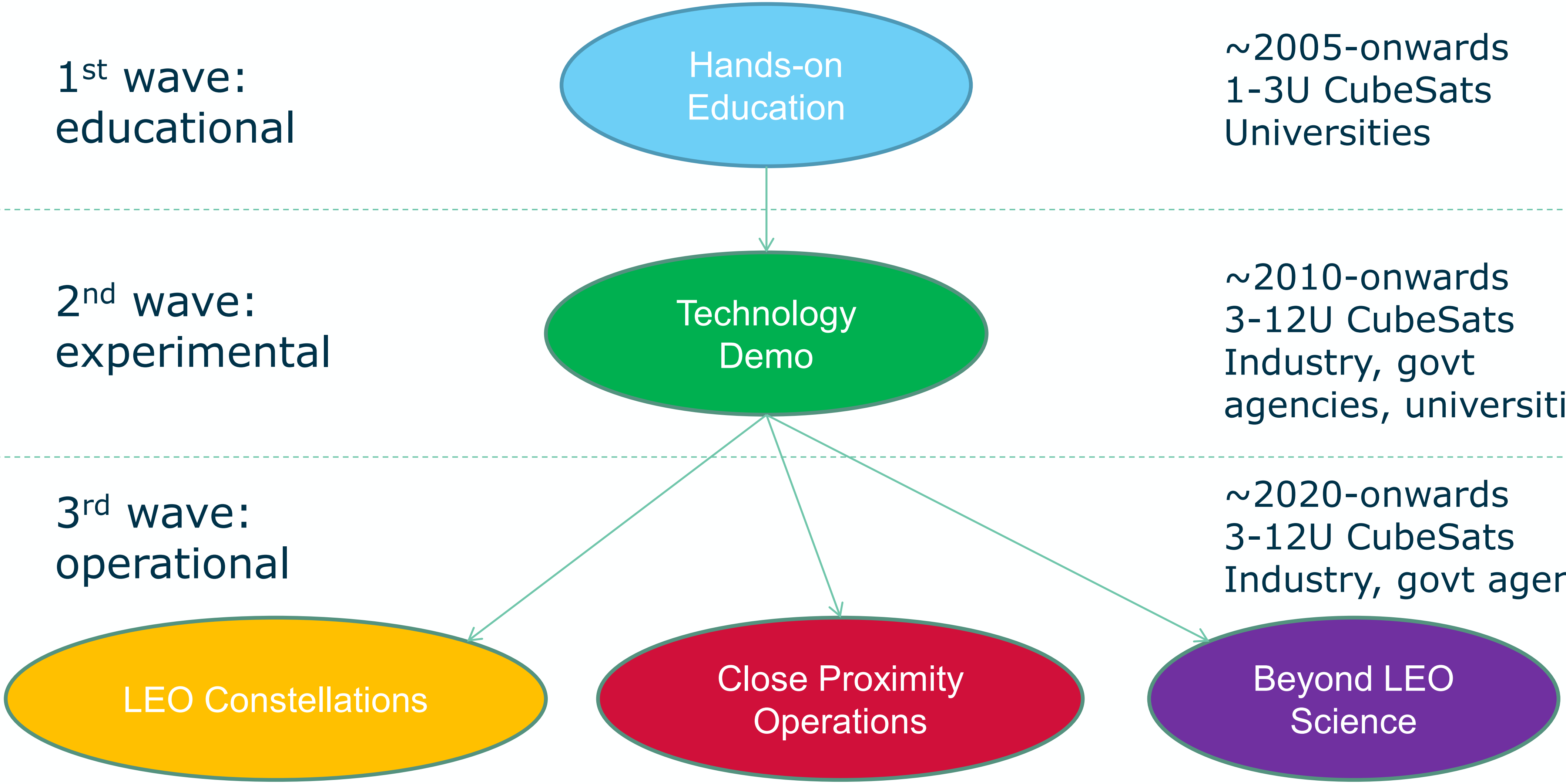
~2005-onwards
1-3U CubeSats
Universities

2nd wave: experimental

~2010-onwards
3-12U CubeSats
Industry, govt agencies, universities

3rd wave: operational

~2020-onwards
3-12U CubeSats
Industry, govt agencies



CubeSat On-Board Autonomy: Rationale

- Significant **decrease in space segment** cost due to miniaturization, usage of COTS, modularity & ease of AIT from mechanical/electrical interface standards…
- Significant **decrease in launch segment** cost due to mass reductions, containerized piggyback launch, standard launcher interfaces & streamlined qualification requirements

BUT

- Ground Segment & **Operations costs DO NOT scale with s/c size & mass**
- For **constellations**, **operational complexity is increasing** dramatically due to **higher no. of s/c** & ground stations, **manoeuvre needs** (station keeping, collision avoidance, de-orbiting)
- For **close proximity operations** (formations, RVD, inspection), a **manual or classical TTQ control** & monitoring approach is **not feasible**
- For **lunar & deep space missions**, eventually in fleets, **large ground station networks needed** (with constraints on availability), **precise navigation** with flight dynamics needed, **mission-critical events** (burns shortly after launch injection, escape manoeuvres, planet/small body approach)

Towards Level 4 Autonomy

"On board autonomy management addresses all aspects of on-board autonomous functions that provide the space segment with the capability to continue mission operations and to survive critical situations without relying on ground segment intervention"

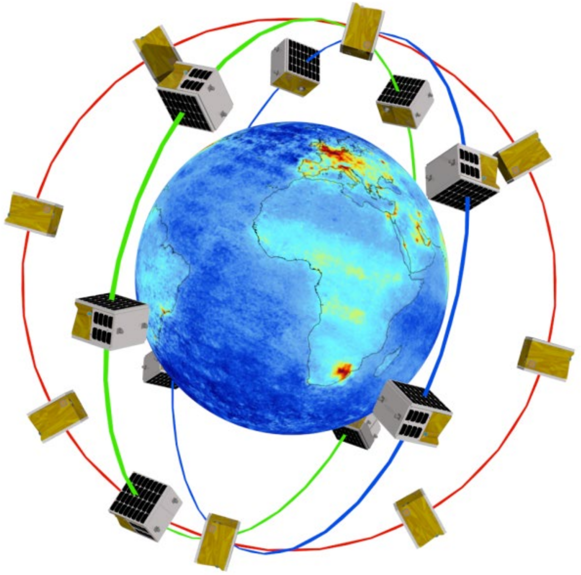
WE ARE HERE

Level	Description	Functions	Naming
E1	Mission execution from ground control; limited onboard capability for safety issues	Real-time control from ground for nominal operations. Execution of time-tagged commands for safety issues	Real-time control with pre-programmed sequences
E2	Execution of pre-planned, ground-defined, mission operations on-board	Capability to store time-based commands in an on-board scheduler	Pre-planned
E3	Execution of adaptive mission operations on-board	Event-based autonomous operations. Execution of on-board operations control procedures	Semi-autonomous, also called "Adaptive"
E4	Execution of goal-oriented mission operations on-board	Goal-oriented mission (re-)planning	Goal-Oriented Operation

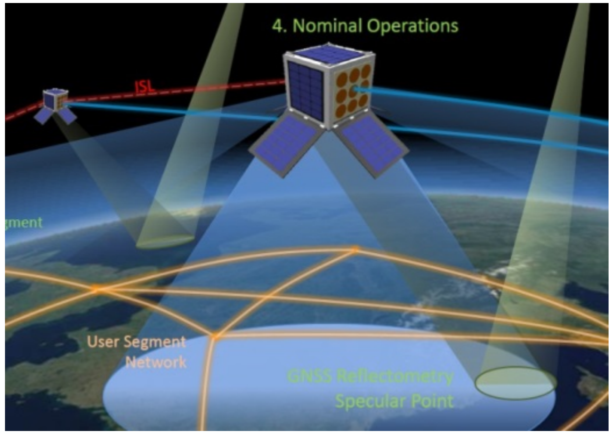
WE NEED TO BE HERE

Table 1-2 Autonomy Levels as defined in the European ECSS Space Segment Operability Standard

Future LEO Constellations



- Earth Observation applications (EO programmes):
  - High-resolution atmospheric monitoring for public health & climate change over the diurnal cycle => compact NO2, CH4 imagers
  - Global tropospheric measurements for weather prediction => GNSS-RO/R receivers, microwave radiometers
  - Change detection of land, flood, fire hazards => hyperspectral imagers & onboard AI
- Other applications (ARTES, S2P programmes):
  - Telecom: IoT/M2M, asset tracking, ship & aircraft tracking, situational awareness
  - Space weather: ionosphere, radiation, magnetosphere
- Autonomy-related trends:
  - Hardware: Inter-Satellite Links, On-board orbit determination (GNSS) & Propulsion (cold gas, chemical, electric)
  - Software: Autonomous Guidance & Control for station acquisition & keeping, collision avoidance, de-orbiting
  - Goal-driven FDIR at constellation system level (self aware, self-repairing)



Next Generation Constellation Technology Demo

- Programme: GSTP Fly
- Project: GOMX-5
- Prime contractor: GomSpace (DK)
- Platform: 12U CubeSat
- IOD Mission:
    - Large orbit transfers using electric propulsion (ThrustMe NPT30-I2-1.5U)
    - High rate X-Band downlink comms (>225 Mbps) using Reflectarray High Gain antenna
    - High accuracy GNSS P2OD Receivers with wide band antenna (<10 cm pos. error 3D rms in real-time OB)
    - Additional 6 IOD Payloads from European industry (incl. autonomy experiment)
- Launch: Q3 2022 to SSO 500 km
- Operations: EP apogee raise >800 km, perigee lower <450 km
- Status: PDR successful (Dec. 2019), Phase C/D ongoing
- Payload Consolidation Review completed, CDR planned in September 2021

On-board Autonomy Demonstration on GOMX-5

MiRAGE:
- Software library runs on S/C OBC enabling autonomous operations
- Combination of: Artificial Intelligence/Deep Learning algorithms, Expert Systems and Intelligent Agents
- Runs on s/c OBC and processes spacecraft data (telemetry, payload) to take decisions autonomously during the mission

IOD Experiments on-board GOMX-5:

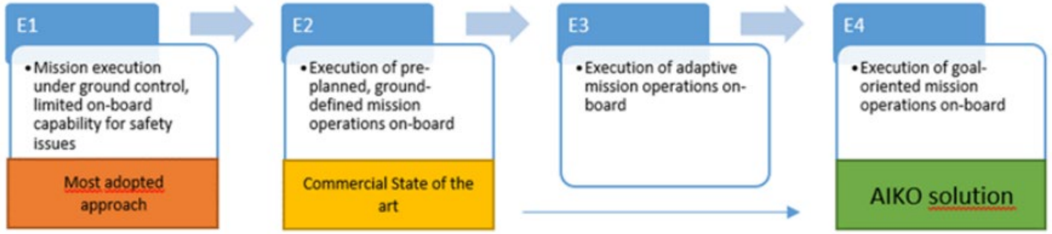
Deep Learning processing of payload data
- Experiment: classification, object detection & segmentation
- Data: access to optical payload imagery (visible, multi-spectral)

AI processing of telemetry data
- Experiment: trend predictions, anomaly detection, insight generation
- Data: access to on-board telemetries of selected equipment

Goal Generation
- Experiment: from detected events, to generation of goals
- Data: access to on-board orbit determination (GNSS receiver)

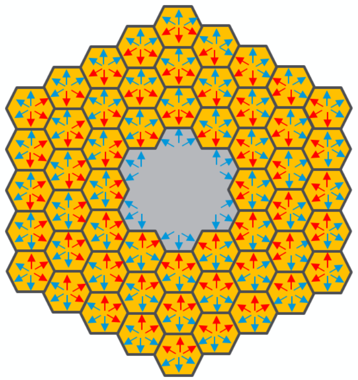
Autonomous Replanning
- Experiment: from a list of goals, to reschedule the mission timeline
- Data: any of the above event detections, or new goal generation

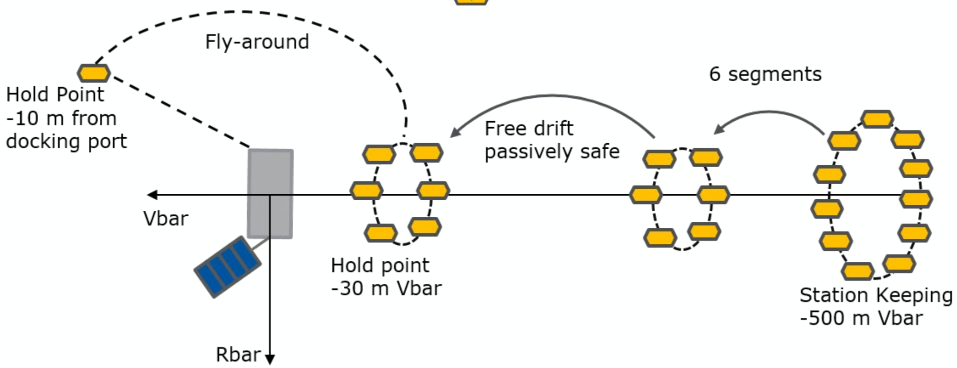
AUTONOMOUS SPACE MISSIONS

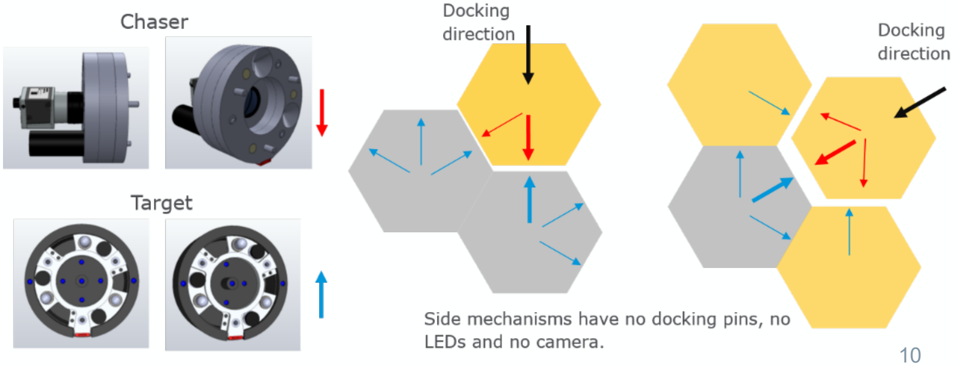


Future Close Proximity Operations Missions

- Applications:
  - On-Orbit Assembly of large structures from smaller building blocks (e.g optical telescopes, RF antennas)
  - On-Orbit Servicing of larger satellites (e.g. avionics replacement/upgrade)
  - Close inspection & repair (e.g. large satellites, space stations, debris objects)
  - Sparse aperture swarm formations (multi-static radar interferometry & 3D optical)
- Autonomy-related trends:
  - Vision Based Navigation @ close range (e.g. LED pattern + filtered visual camera + RT image processing)
  - GNSS receiver @ long range for relative (DCP) & absolute (PPP) navigation
  - 6 Degree of Freedom propulsion module(s) with low Minimum Impulse Bit
  - Robust accurate GNC/FDIR system for phasing & close proximity operations







Rendezvous Autonomous Cubesats Experiment (RACE)

Mission concept:
- two 6U CubeSats
- launched together in a 12U POD
- separate deployment & commissioning
- series of docking and fly around manoeuvres
- testbed for different GNC algorithms

Demo of:
-Visual based navigation
-6 DoF cold gas propulsion
-Robust accurate GNC/FDIR
-Mini docking mechanism

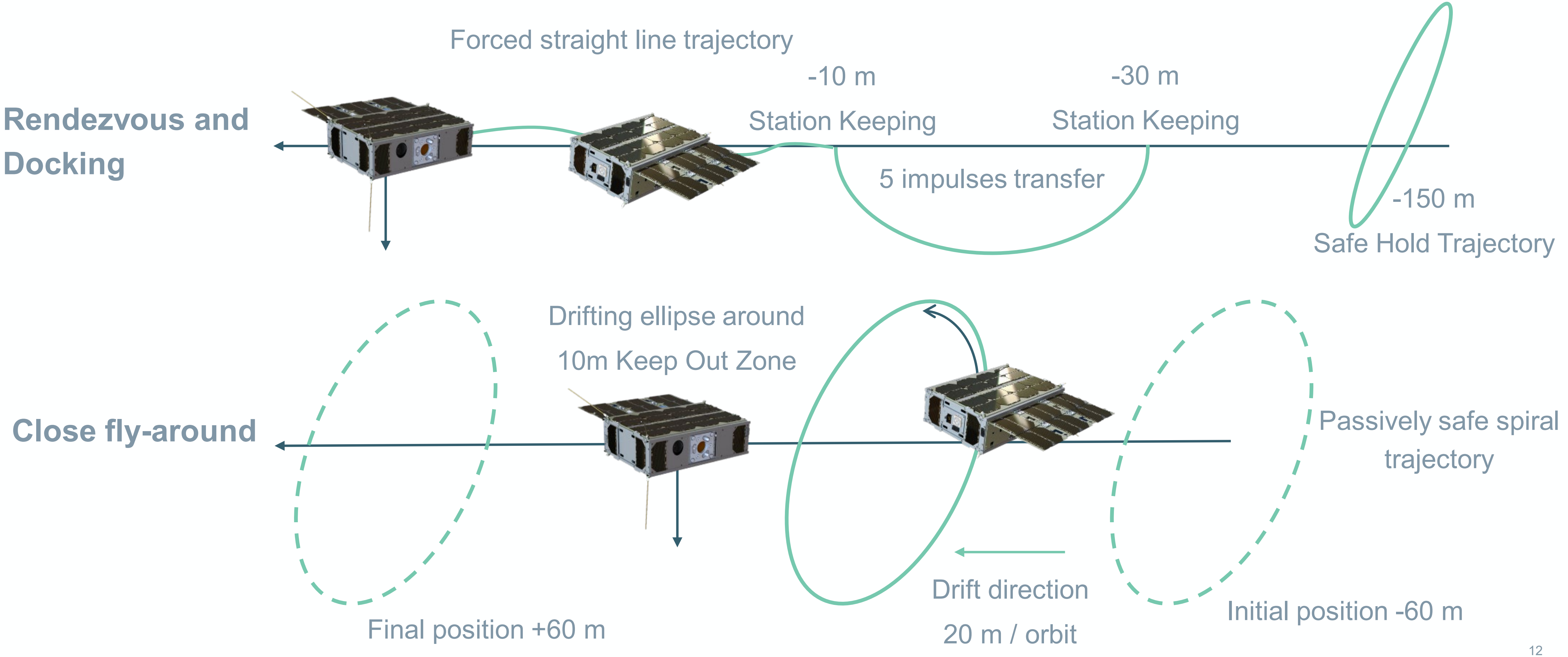
Future applications:
-autonomous on-orbit assembly of large structures using building blocks
-on-orbit servicing/inspection

Phase A/B completed (GSTP Fly) with GomSpace DK, GMV PL & RO, Almatech, Micos CH

Phase C/D/E/F KO in Q1 2022 after change of prime & subject to funding
Launch Q1 2024

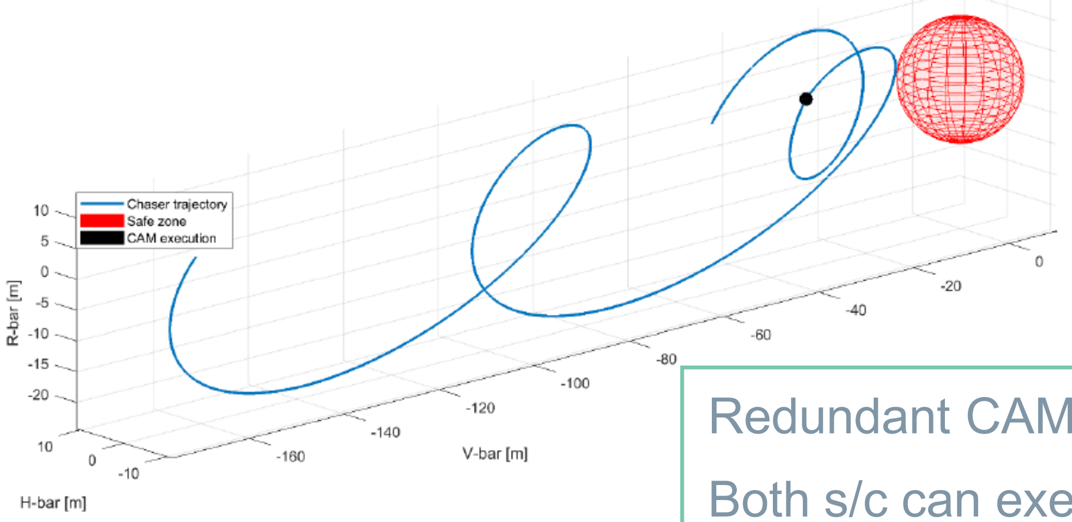
RACE Mission Phases

Orbit: 550 km SSO, LTAN: 9AM (1PM) to 11AM (15PM).



Autonomous GNC/FDIR Demo on RACE

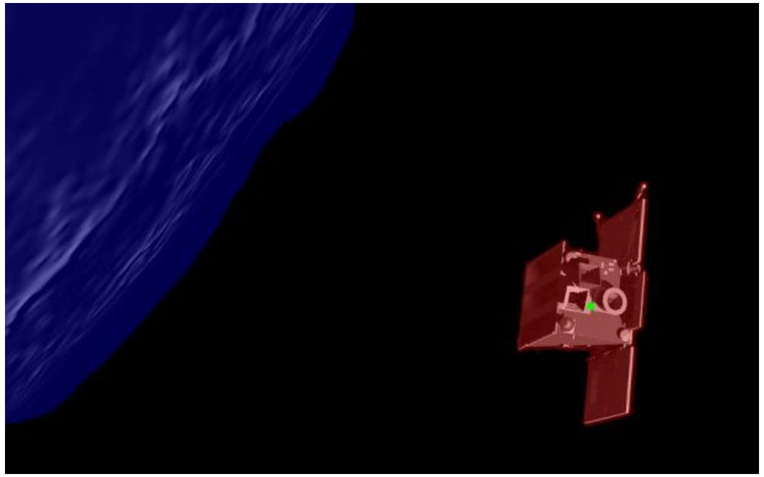
- H-Infinity controller (baseline)
- Cooperative vision navigation using camera and LEDs for RVD
- Uncooperative camera navigation for CFA
- Collision Avoidance Manoeuver (CAM) algorithm triggers if trajectory predicted to enter Keep Out Zone (CFA) or breach approach corridor (RVD)
- Mu-analysis for robust stability and robust performance
- Advanced FDIR: Robust thruster Fault Diagnosis and Accommodation (docking with 1 failed thruster)



Redundant CAM strategy:

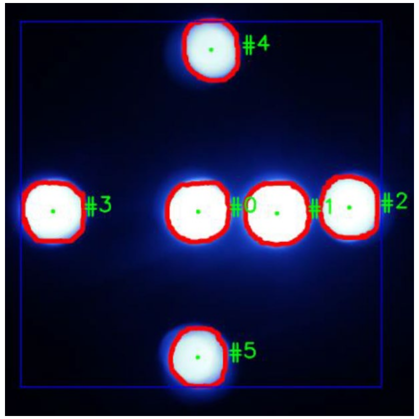
Both s/c can execute CAMs

Uncooperative camera navigation based on Centre of Brightness



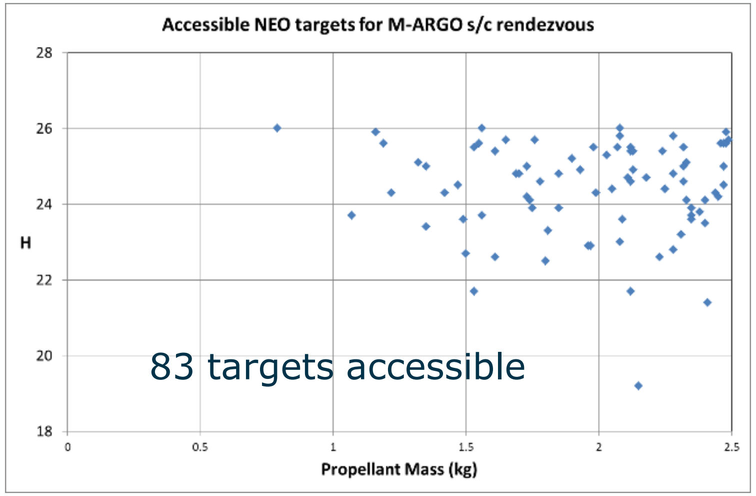
Cooperative vision navigation:

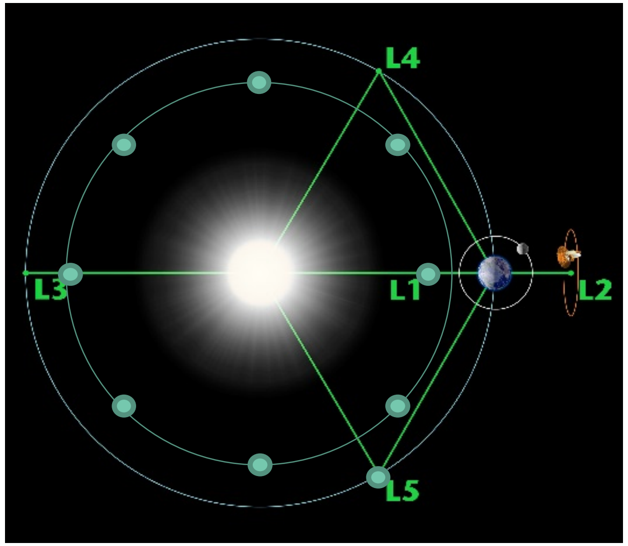
LEDs detection & centroiding



Future Stand-Alone Deep Space Missions

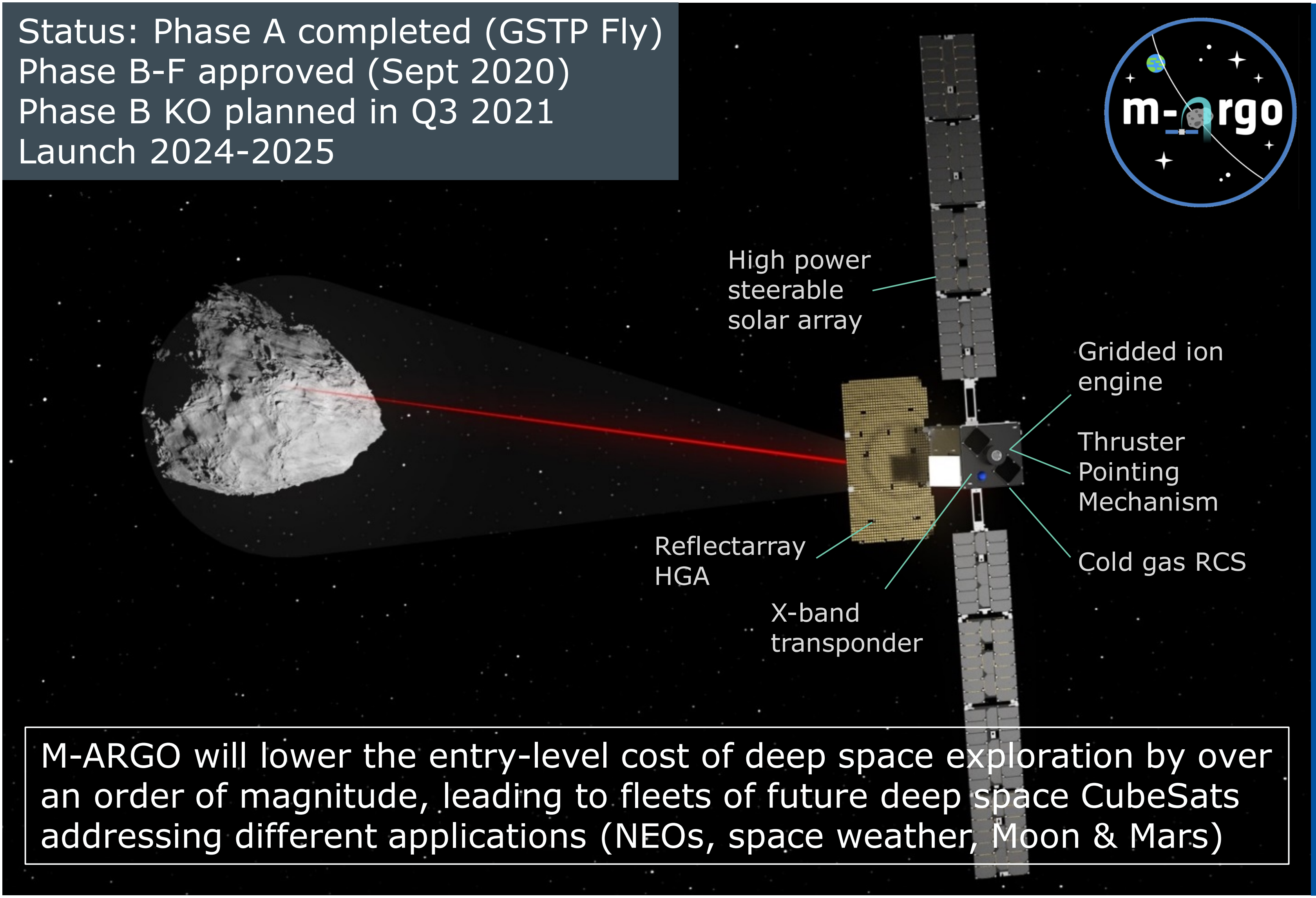
- Applications of distributed nano-spacecraft fleets:
  - wide survey of the Near Earth Asteroid population for:
    - science (diversity of early solar system bodies)
    - planetary defence (know your enemy)
    - in-situ resource exploration (prerequisite for exploitation)
  - simultaneous in-situ monitoring of space weather at multiple locations in the heliosphere (L1, L5, inner Earth orbits) or in reconfigurable swarms
  - constellations in lunar and Mars orbit (comms relay & navigation, simultaneous global coverage remote sensing)
- Autonomy-related trends:
  - On-board visual navigation (supplementing radio navigation where possible)
  - Autonomous Guidance & Control (robust real-time trajectory optimization within constraints)
  - Goal-driven FDIR (from reconfiguration/recovery to mission re-planning)





Miniaturised Asteroid Remote Geophysical Observer

Status: Phase A completed (GSTP Fly)
Phase B-F approved (Sept 2020)
Phase B KO planned in Q3 2021
Launch 2024-2025



M-ARGO will lower the entry-level cost of deep space exploration by over an order of magnitude, leading to fleets of future deep space CubeSats addressing different applications (NEOs, space weather, Moon & Mars)

Objectives:

- Demonstrate critical technologies & operations for stand-alone deep space CubeSats in the relevant environment
- Rendezvous with a Near Earth Object
- NEO physical characterisation for in-situ resource exploration purposes
- Test autonomous GNC techniques

Mission concept:

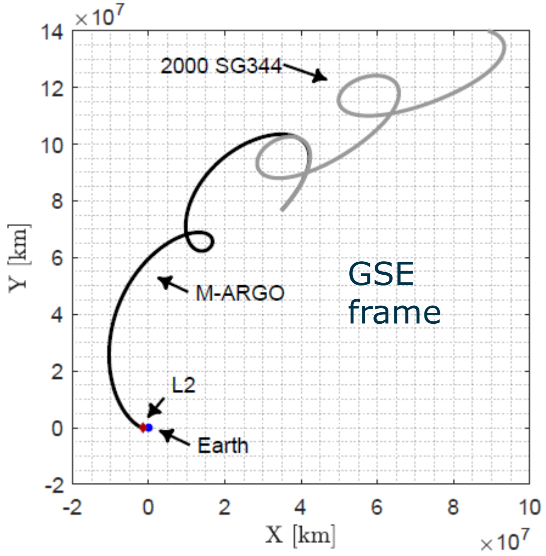
- 12U XL CubeSat
- piggyback launch to Sun-Earth L2 transfer or Earth escape
- 1-3 year low-thrust interplanetary transfer (ΔV 2-3 km/s)
- 6-month close proximity ops at NEO
- 120 different NEO targets accessible

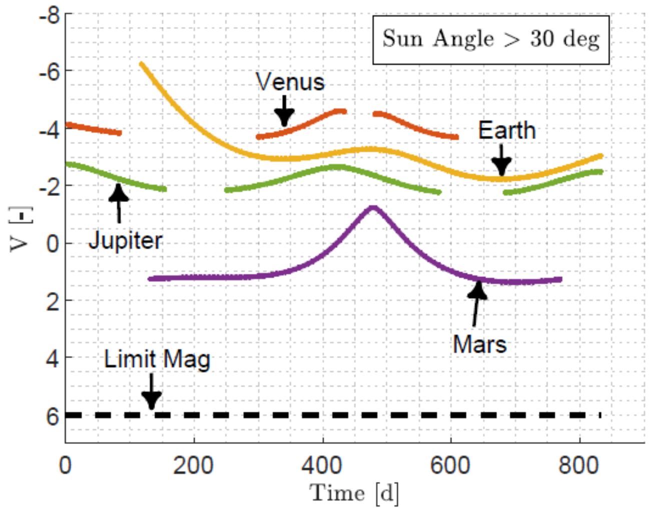
Autonomous GNC demonstration on M-ARGO

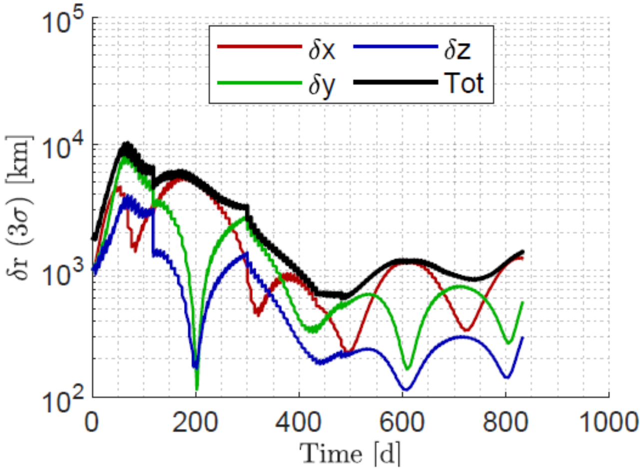
- Developer: Politecnico di Milano
- Experiment consists of:
  - Deep space optical navigation using line-of-sight observations of planets using CubeSat star trackers/navigation camera*
  - Real-time on-board trajectory optimization for update of guidance profile to NEO rendezvous
  - Robust control techniques
- Planned to be executed 3 times over 2-week arc during cruise phase to NEO target

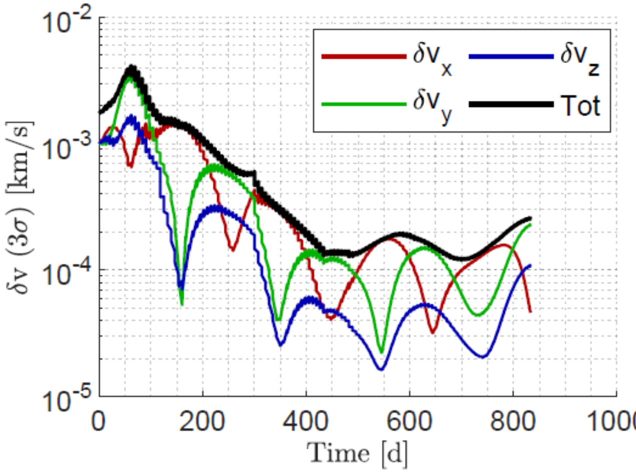
POLITECNICO
MILANO 1863

*V. Franzese PhD research
Co-sponsored by ESA









Summary

- CubeSat systems are becoming more capable for supporting future operational missions involving distributed systems, including LEO constellations, close proximity operation swarms and deep space LEO fleets
- Operations costs do not scale with s/c size & mass, complexity much higher for distributed systems
- On-board autonomy is a must for distributed systems in LEO and beyond
- Hardware enabling greater on-board autonomy is in development (e.g. ISLs, Propulsion, OBCs, GNSS receivers, navigation cameras)
- On-board autonomy research ongoing with advanced GNC/FDIR techniques
- Broad portfolio of ESA IOD CubeSat missions funded in GSTP Fly to rapidly demonstrate higher levels of autonomy (amongst many other technologies) at low-cost
- IOD missions aim to go well beyond the state-of-art, enabling new (distributed) system capabilities and new operational missions in future
- Relevant not only CubeSat-based missions, but also larger ESA missions once de-risked