UNIVERSITÀ DEGLI STUDI DI NAPOLI FEDERICO II

INTRODUCTION TO SPACE DEBRIS AND SPACE SURVEILLANCE

Research Activities @ DII

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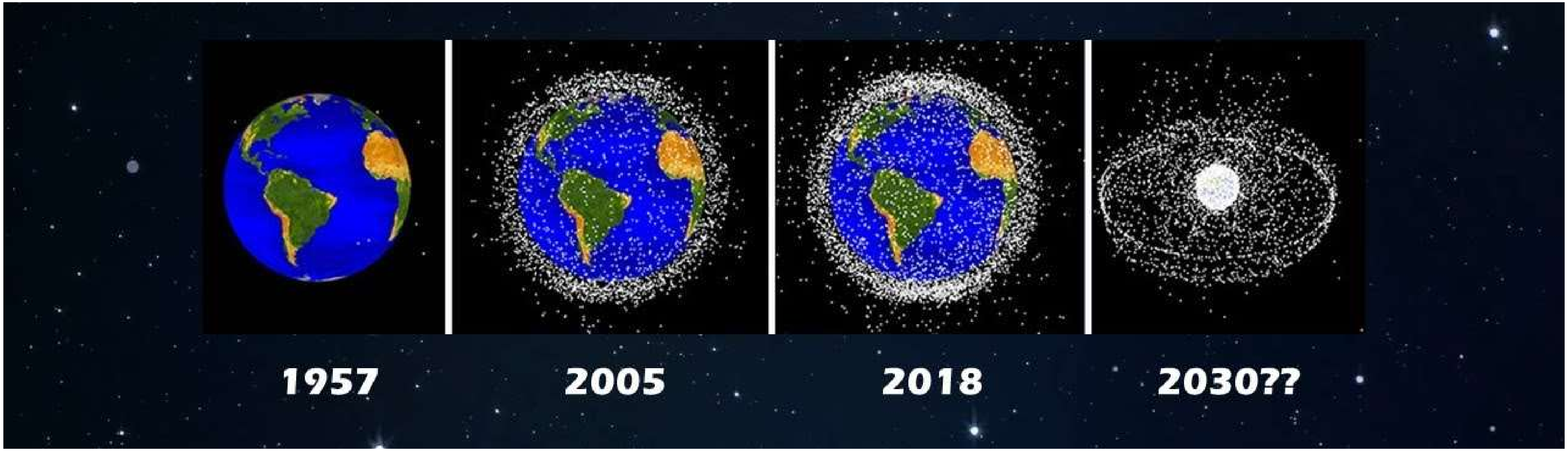
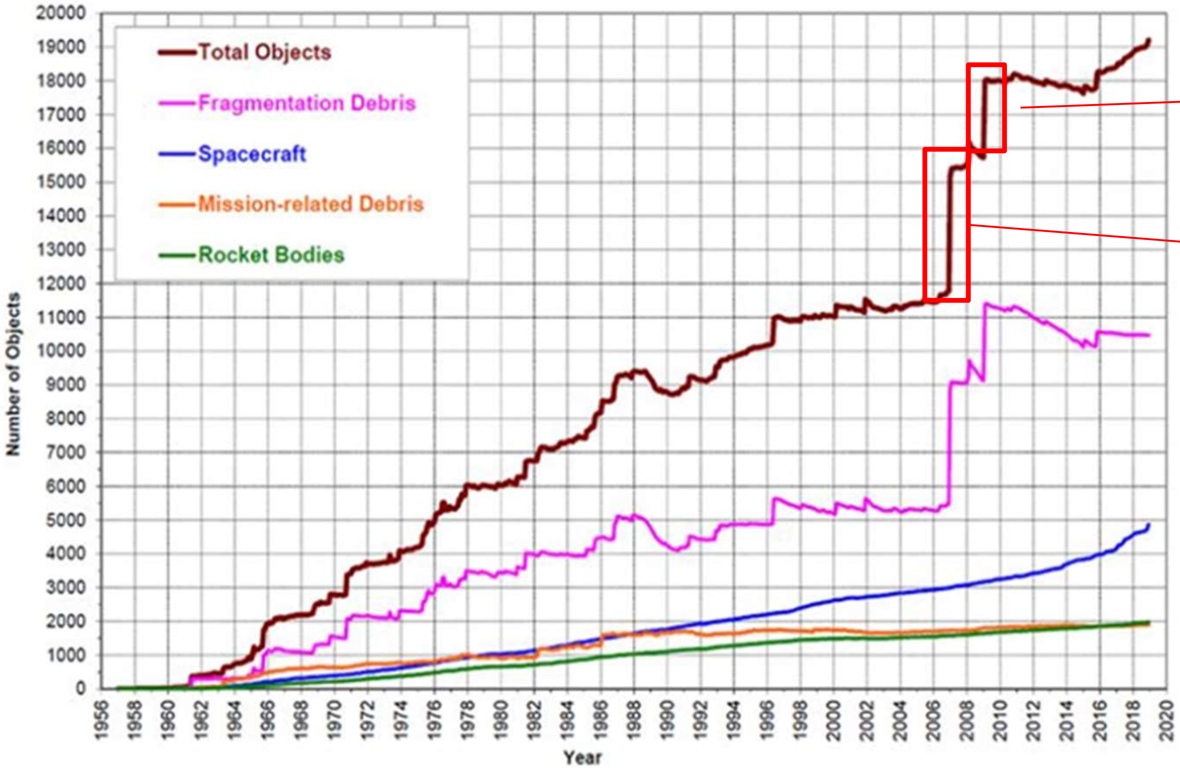
Space debris is defined as all man-made objects, including fragments and elements thereof, in Earth orbit or re-entering the atmosphere, that are not controllable

→ The probability of collisions that could lead to potential damages for operative satellites will consequently increase.



In orbit fragmentation represents the major source of space debris (**Kessler's syndrome**)



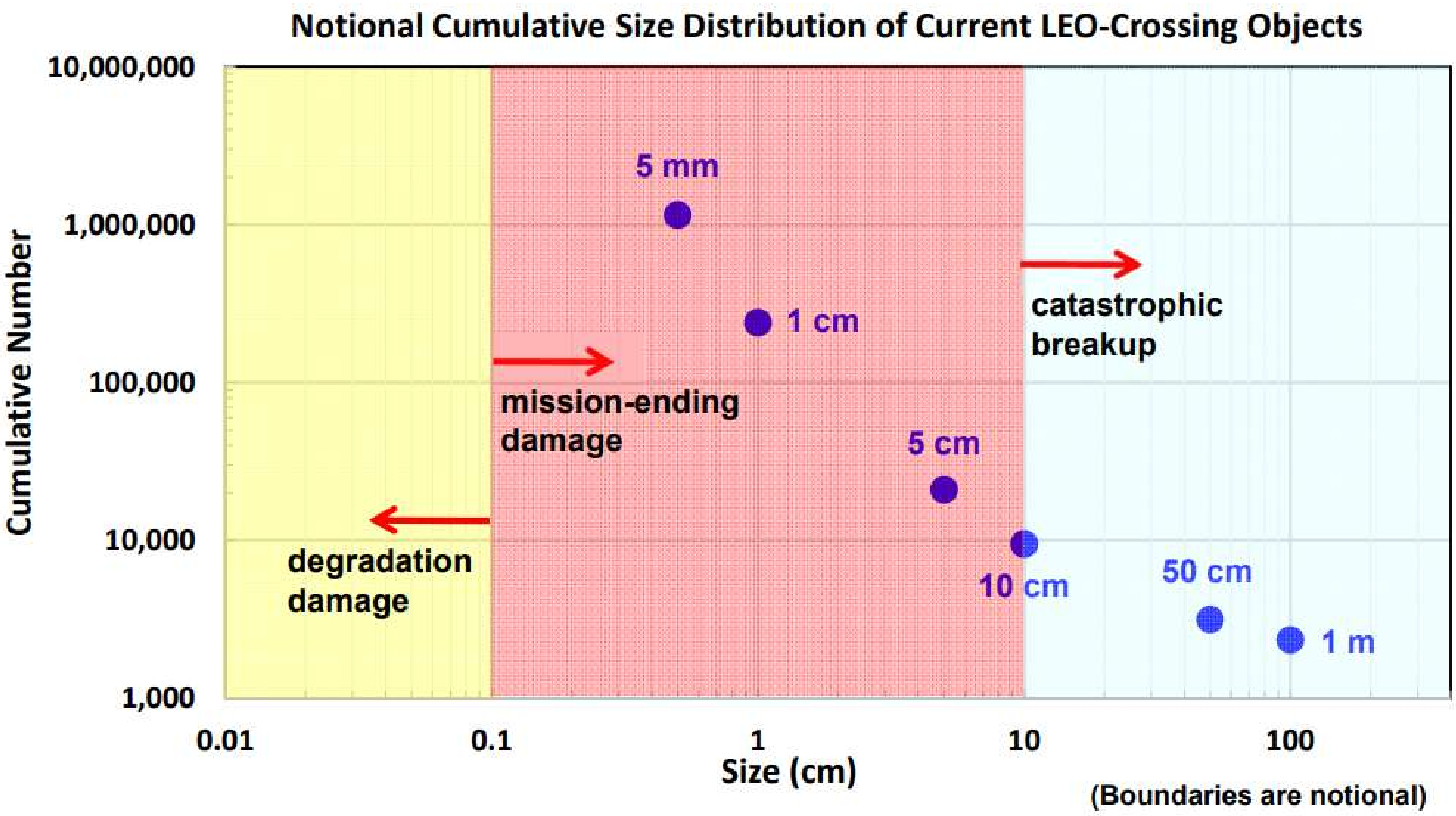
Accidental Collision of Cosmos 2251 and Iridium 33 (2009)

Intentional Destruction of Fengyun-1C (2007)

(Distribution of catalogued resident space objects, 2019)

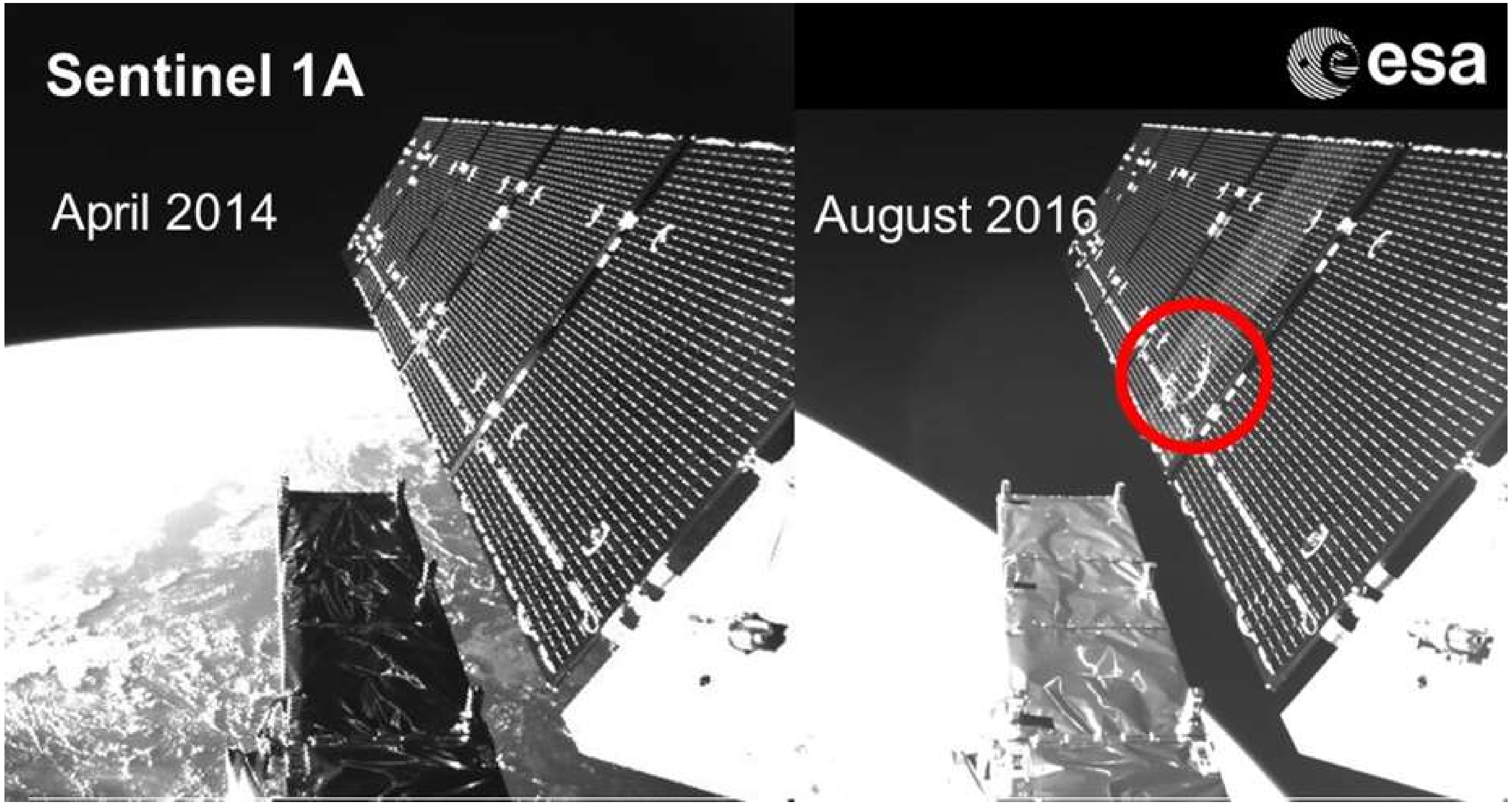
- **Catalogued objects represent only a small fraction of the total number of fragments**, as observation capabilities are mostly limited to sizes > 10 cm, and the orbital debris population follows a power-law size distribution:
  - Estimated number of objects larger than 1 cm: about 500,000
  - Estimated number of objects larger than 1 mm: >100,000,000
  - mission-ending risk is dominated by small debris (1 mm to 1 cm size) impacts
  - **conjunction assessments** and potential **collision avoidance maneuvers against the tracked objects** (which are typically 10 cm and larger) only address a small fraction (<1%) of the orbital debris impact risk
  - **interest in fragmentation modeling** to cope with observation gaps

Space Environment and Fragmentation



(Liou, 2020)

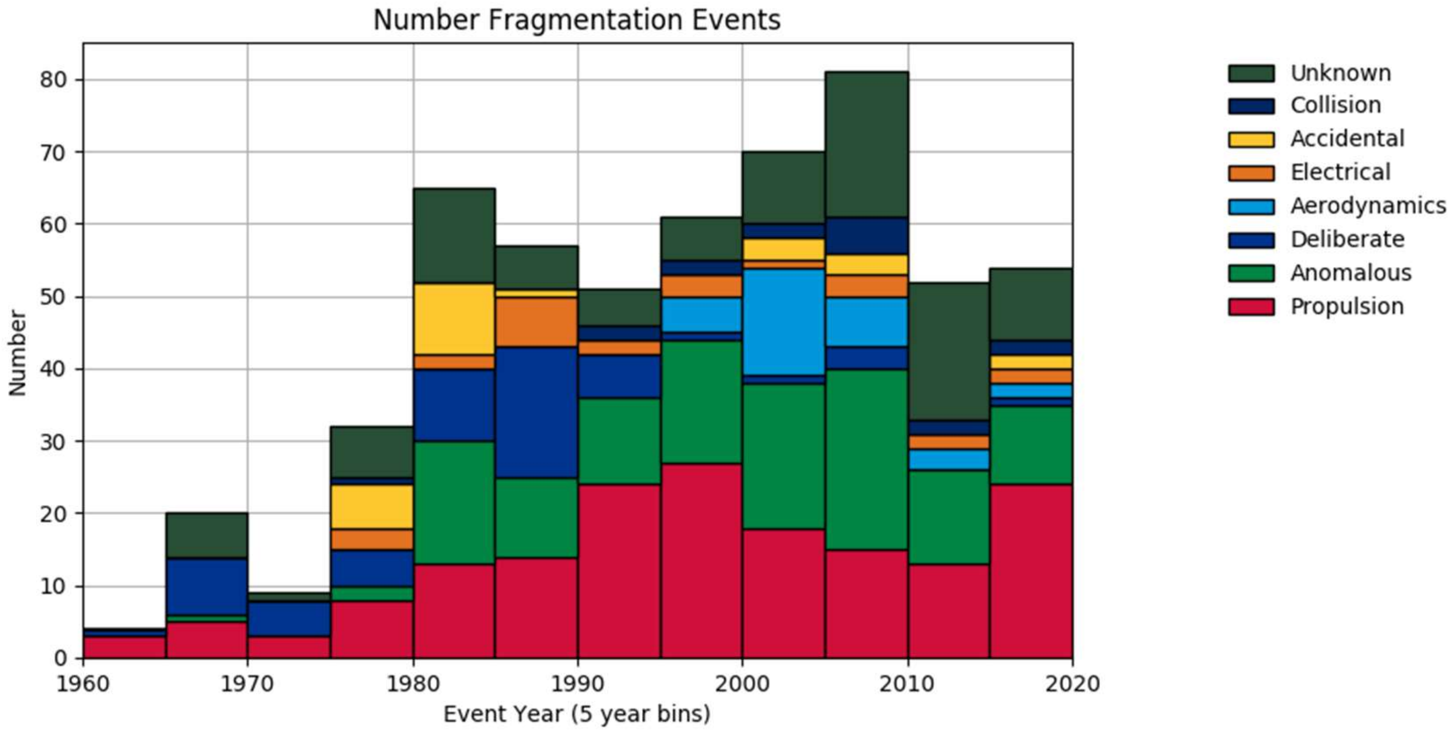
Space Environment and Fragmentation



(Source: ESA)

- A sudden small power reduction was observed in a solar array. Slight changes in the orientation and the orbit of the satellite were also measured at the same time.
- On board cameras, originally carried to monitor the deployment of the solar wings, were switched on
- **A millimeter-size particle created a "crater" of roughly 40 cm of diameter**

Space Environment and Fragmentation



Guidelines for orbital debris mitigation:

- Limit mission-related debris
- Minimize accidental explosions
- Avoid accidental collisions
- **Active debris removal**
- **Follow post-mission disposal** (the **25-year rule**, etc.)

Following the guidelines for space debris mitigation, several **Space Situational Awareness** (SSA) programs arose in the last years.

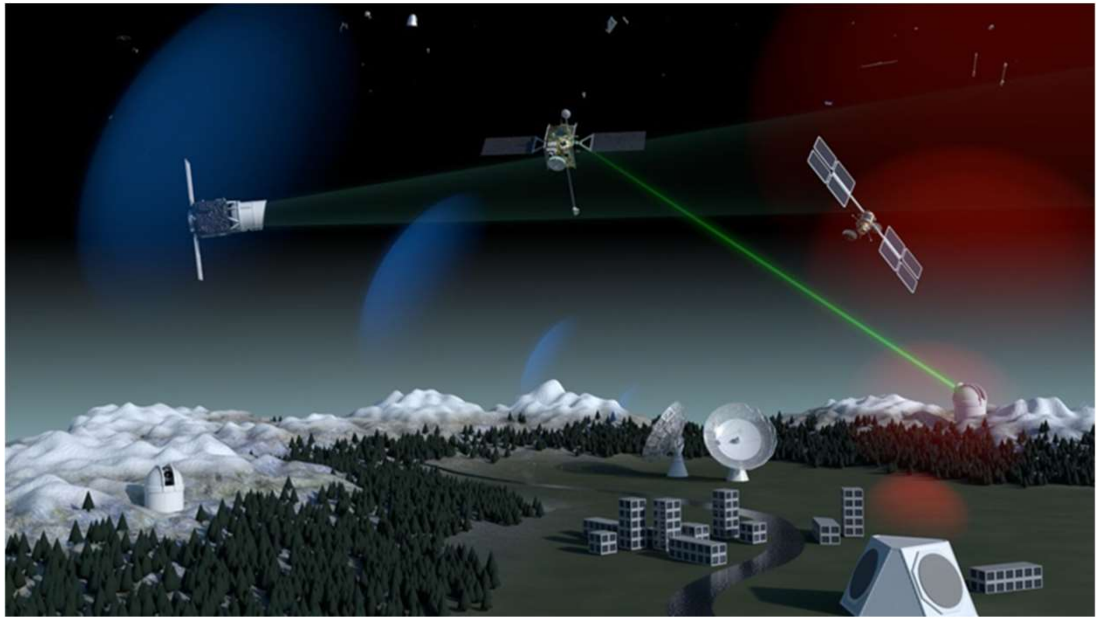
Space Environment and Fragmentation

European Space Agency indicates three important segments in SSA:

- **<u>Space Surveillance and Tracking (SST)</u>**
- Space Weather (SWE)
- Near-Earth Objects (NEO)

SST operations encompass a wide range of activities grouped in three main types of services:

- **<u>Collision Avoidance (CA)</u>**
- **<u>Re-Entry Analysis (RE)</u>**
- **<u>Fragmentation Analysis (FG)</u>**



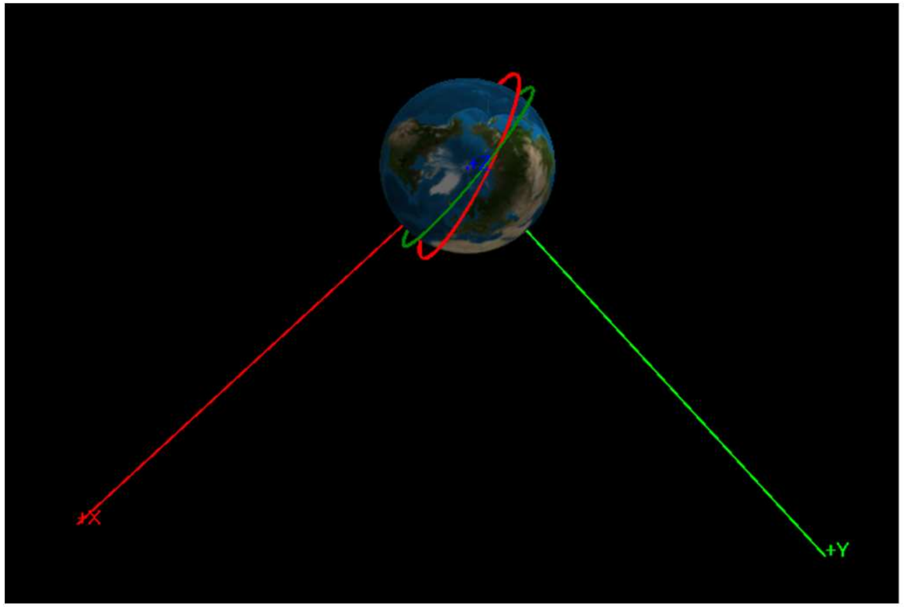
Space Surveillance and Tracking network (Credits: ESA)

In this context, @ DII-UNINA there are several research activities encompassing:

- Fragmentation events modeling and fragments propagation
- Collision risk assessment
- Space object characterization
  - Astrometric and radiometric techniques
  - Machine Learning-based approaches

Research projects are also carried out in cooperation with external partners, such as other Universities, industry and Italian Air Force.

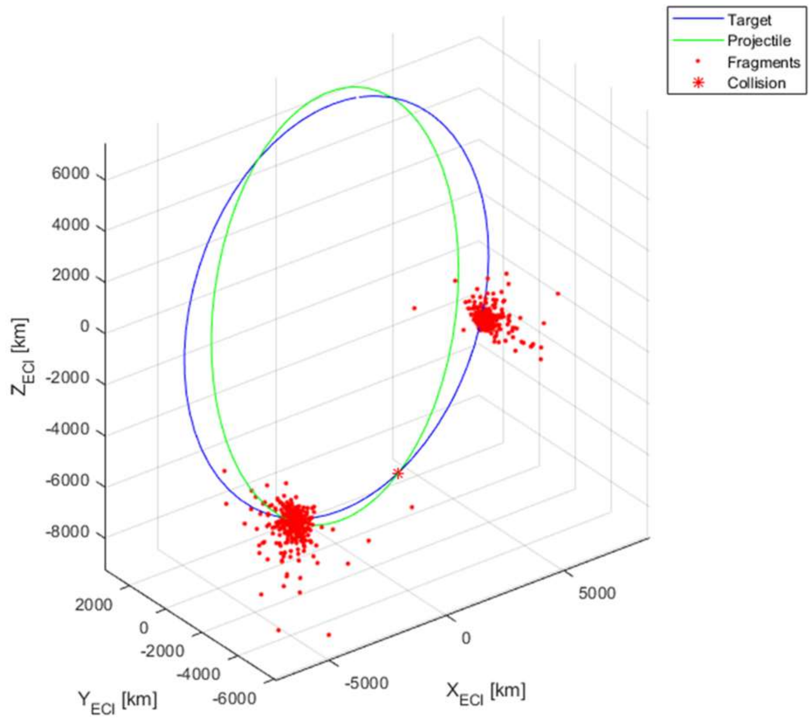
Implementation of NASA Standard Breakup Model for Collisions/Explosions modeling and analysis



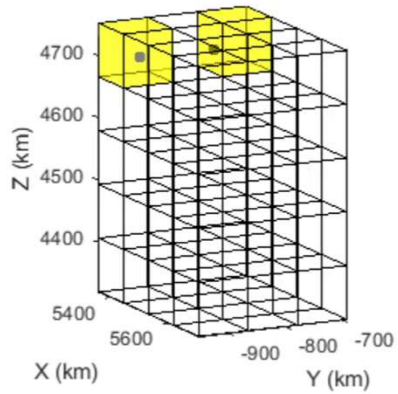
Cosmos 2004

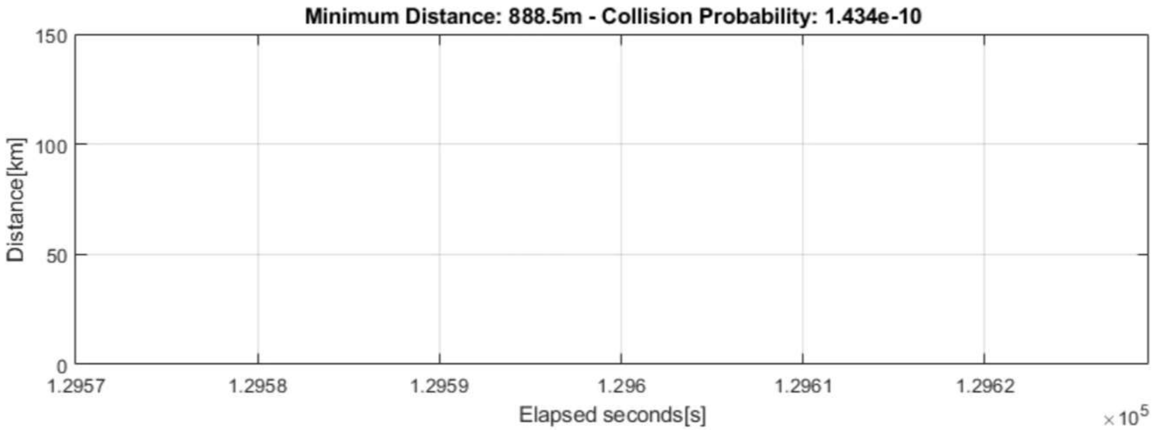
CZ-C4 R/B

Fragments cloud after 15 minutes propagation



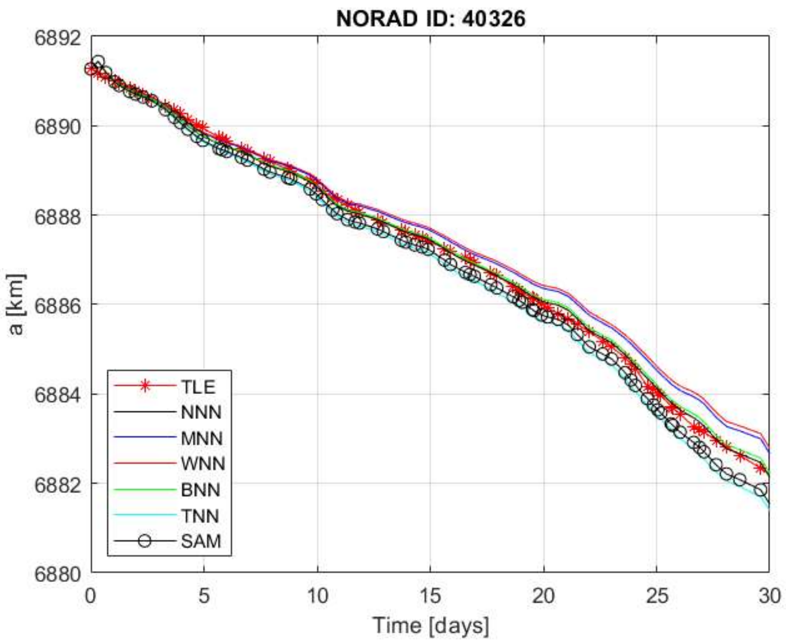
Assessment of the collision risk induced by fragmentation events monitored in the medium term (i.e., few months)



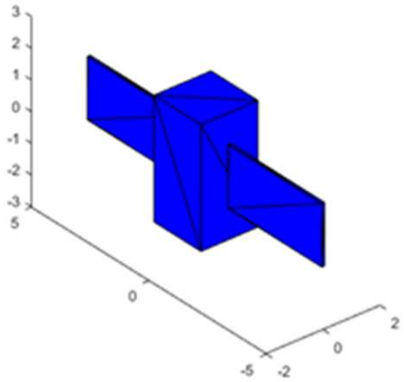


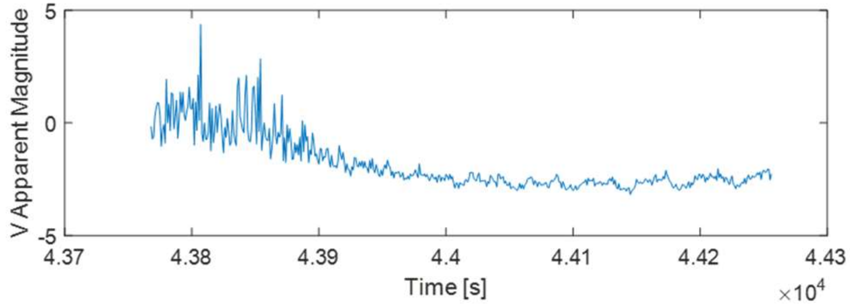
UNINA Activities - Characterization

- Ballistic coefficient estimation using both conventional and Machine Learning-based techniques
- Comparison and potential combination with conventional methods



- Assessment of the satellite operational status by processing sensor data and combining different sources of information
- Focus on light curve-based techniques



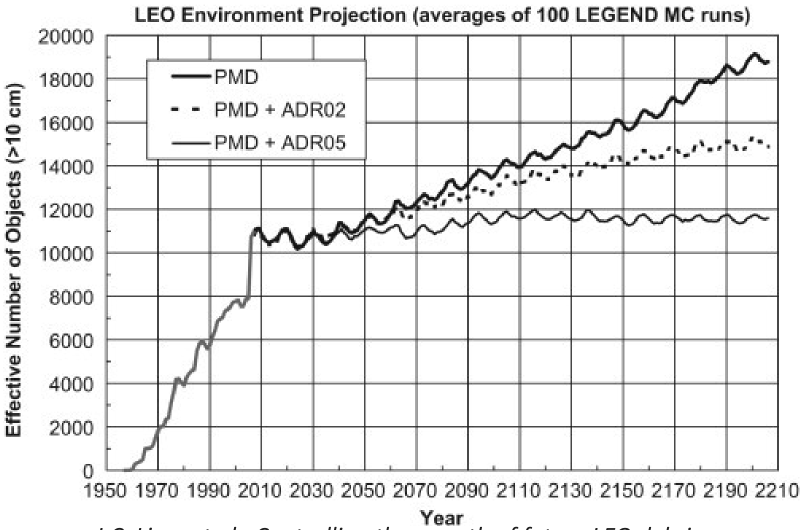


Debris mitigation measures (e.g., post mission disposal) and guidelines (e.g., 25 years rule, 5 years rule) are not enough to control the future growth of the population.

Need of debris remediation measures, e.g., **Active Debris Removal**

ADR requires three phases:

1. Rendezvous,
2. Docking/Berthing (with detumbling if necessary),
3. Deorbiting/altitude lowering (to reduce the remaining orbital lifetime of an object)



J.C. Liou, et al., Controlling the growth of future LEO debris populations with active debris removal, Acta Astronautica, 2010.

Key technical challenges

- Guidance, Navigation and Control technologies
    - Need of autonomy to cope with lack of continuous ground coverage
    - Stringent safety constraints to minimize risk of causing fragmentation events
- Grasping and detumbling mechanism
- Legal aspects → Lack of international legislation

Several international committees push toward solving this issue, e.g., Inter-Agency Space Debris Coordination Committee (IADC)

The importance of IOS

The term **In-Orbit Servicing (IOS)** refers to a large variety of **in-orbit operations involving physical contact or very close proximity motion between two or more space vehicles**.

- **Supply of services** to already existing space assets (e.g., **refueling, repair**)
- **Assembly** of modular parts into functional aggregate structures (e.g., **future Lunar Gateway**)
- **Fabrication** of components in space
- Use of **Spacetugs** for orbit correction, relocation, **debris removal**

IOS is strictly linked to other Space Traffic Management (STM) aspects, e.g., **active debris removal (ADR)**, human in orbit operations, space surveillance.

IOS Impact

The execution of IOS missions has the potential to provide several benefits to customers, e.g.,

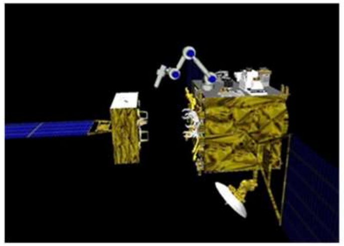
- volumes and launch costs reduction;
- preservation or improvement of satellite performance,
- possibility to ensure a sustainable use of outer space.

Several recent market studies have highlighted that IOS is projected to become a **multi-billion-dollar market** driven by the continuous growth of LEO and GEO commercial activity.

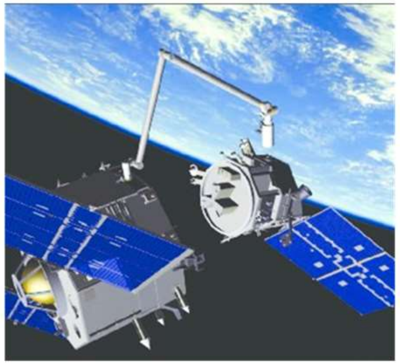
SERVICE NAME
Life extension Station keeping
Refuelling
Deorbiting
Salvage & recycling
Relocation (incl. Deployment)
Robotic manipulation (Orbital replacement units, P/L maintenance and repair, inspection, satellite upgrade)
In-orbit-assembly
In-orbit-manufacturing

IOS technology: state-of-the-art

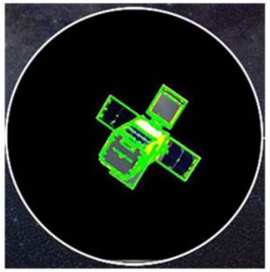
ROTEX (DLR) 1993



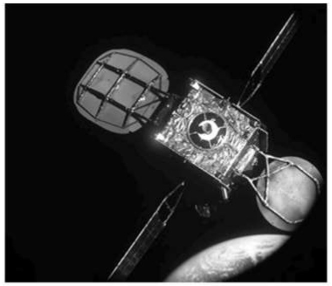
ETS-VII experiment
(JAXA) 1997



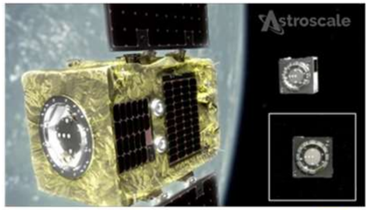
Orbital Express Advanced Technology
(DARPA) 2007



RemoveDebris
(SSTL) 2018



MEV-1 and MEV-2
(Northrop Grumman)
2019, 2020



Elsa-D
(Astroscale) 2021

- **Mission Robotic Vehicle, Northrop Grumman (2024)**
- **Clear Space 1, ESA (2025)**

IOS technology: open challenges

Autonomous Guidance, Navigation and Control (GNC)

- Guidance → design of safe trajectories for monitoring/approaching/capturing, CAM planning.
- Navigation → ensure algorithmic robustness against illumination conditions and fast relative dynamics.
- Control → capability to deal with highly non-linear multi-body dynamics (e.g., attitude control of the stack).

Modularity

- Definition of standard payloads and interconnectors/interfaces (e.g., fluidic, electrical, mechanical).
- Design challenges to avoid introducing additional structural mass which can negatively impact the total life-cycle cost of a spacecraft and its scientific return.

Propulsion systems

- Transfer of propellant and other consumables.
- Identification of most convenient solution depending on mission requirements.

Other aspects

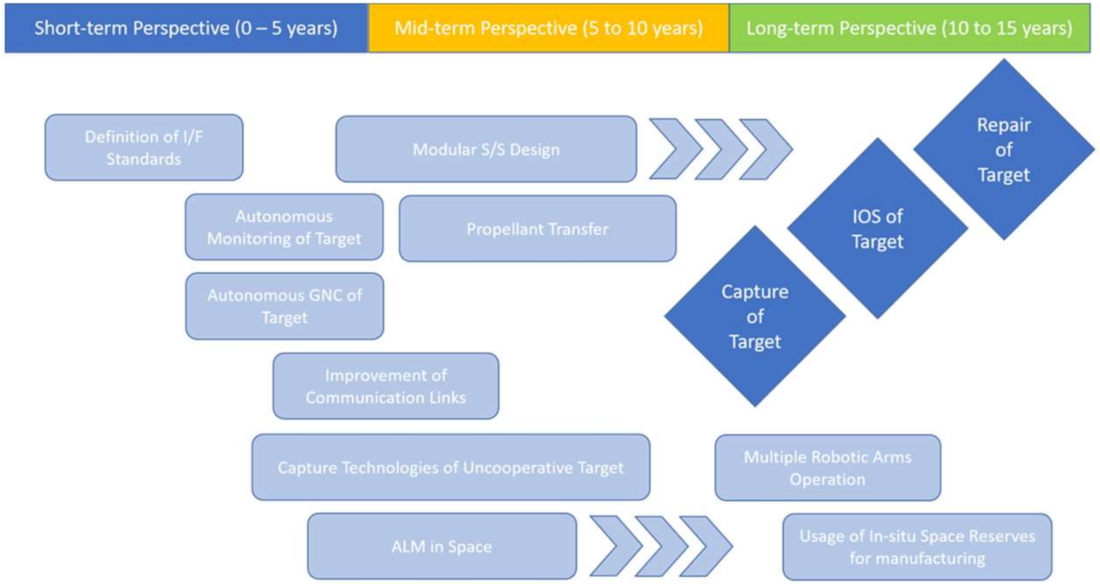
- Improvement in communications infrastructures to support IOS operations in real time.
- Low gravity effect on 3D printing capabilities.

Next steps and recommendations

- Definition of standards and the execution of missions to demonstrate critical technological advancements are expected as a <u>short-term result</u>.

- Technology consolidation, including modular spacecraft design, is expected as a <u>mid-term result</u>.

- The possibility of servicing operations to become routine, the fabrication and assembly of aggregate structures also exploiting products manufactured in orbit is expected as a <u>long-term result</u>.



<u>Technology developments cannot be decoupled from the respective regulatory issues and coordination mechanisms to correctly place IOS into the global STM framework</u>.

GNC for autonomous in orbit operations

Advanced space missions can benefit from an enhanced level of **autonomy**

Need to develop advanced **Guidance, Navigation** and **Control** functionalities

The activities of focus on

- Relative trajectory design, formation control and maintenance (satisfy safety requirements and optimize performance)
- Relative navigation (GNSS and EO-based)
- Guidance & Control for RVD operations

Formation Flying (FF)

On Orbit Servicing (OOS)

Active Debris Removal (ADR)

GNC for autonomous in orbit operations

<u>Recently-funded projects @ DII</u>

- LIDAR-based relative navigation for IOS/ADR **MUR funding**
- Vision-aided navigation assisted by GNSS (VINAG) **ASI funding**
- GNC and Robotic Arm Combined Control (GRACC) **ESA funding**
- Formation flying of CubeSat assemblies for remote sensing (FORCE) **MUR funding**

<u>Recently-funded/ongoing projects</u> (start in 2023)

- The Space Eye mission
- The RODiO mission

Phase A study funded by ASI in the frame of the ALCOR program

- <u>IOS demonstration mission</u> (**<u>PNRR funding</u>**) → support to TAS-I for AOCS design and development
- Autonomous Navigation up to High Earth Orbits (ANHEO) **ASI funding**, Jun. 2023 – Dec. 2024

LIDAR-based RELNAV

Project Title	LIDAR-based relative navigation for IOS/ADR
Funded by	Italian Ministry of University and Research and UNINA-DII

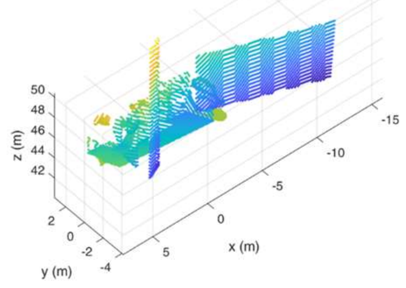
Focus on non-cooperative targets

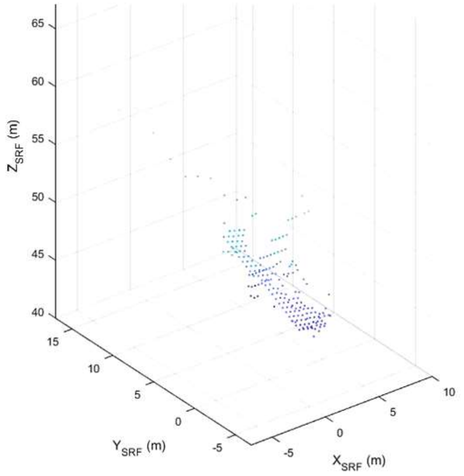
Architecture capabilities

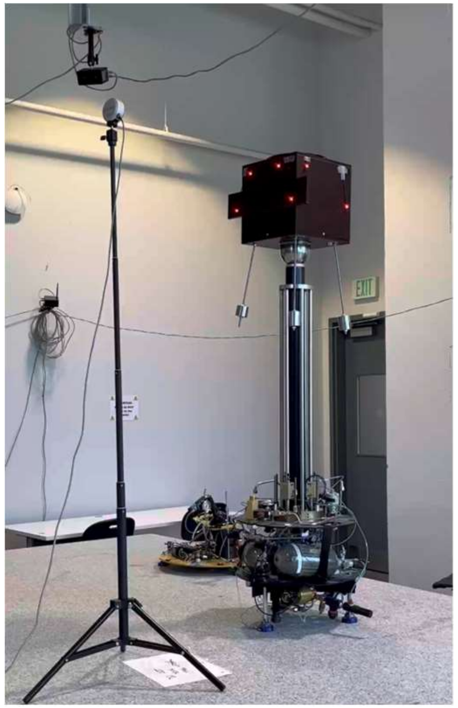
1. Pose determination algorithms
2. Relative state estimation (EKF, UKF)
3. Target Inertia properties estimation

Validation through

- Numerical simulations
- Experimental tests



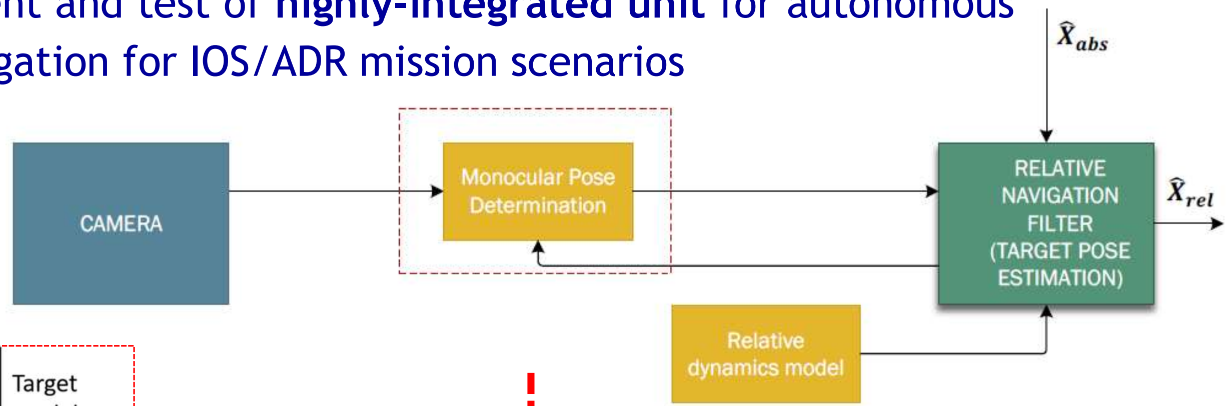


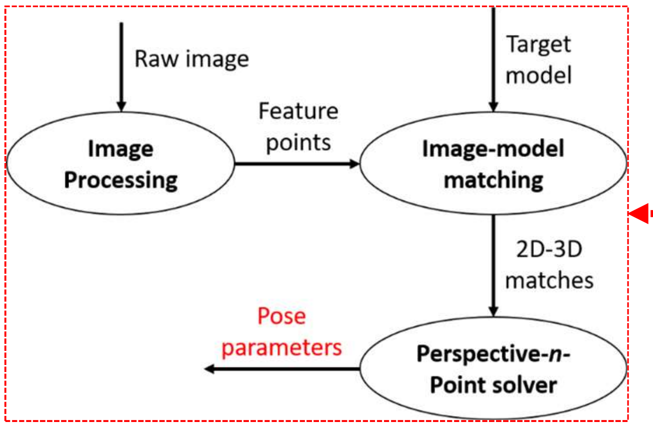


Open collaborations with Embry-Riddle Aeronautical University and Jena Optronik GmbH (Germany)

Project Title	**VISION-AIDED NAVIGATION ASSISTED BY GNSS**
Funded by	Italian Space Agency

Project goal→ Development and test of **highly-integrated unit** for autonomous absolute and relative navigation for IOS/ADR mission scenarios





UniNa role

Model-based algorithms are used for both pose initial acquisition and tracking.

Project Title	Preparation of Enabling Space Technologies and Building Blocks: GNC and Robotic Arm Combined Control
Funded by	European Space Agency

Joint study by three Italian universities

Objectives

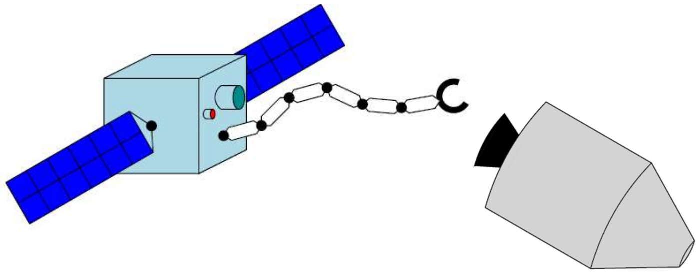
1. Development of innovative algorithmic solutions for

- **Combined control** of the chaser + robotic arm system (POLIMI)
- **Relative navigation** exploiting active/passive Electro-Optical sensors (UNINA)

2. Development of **a relevant simulation environment**, called Functional Engineering Simulator (FES), suitable for the validation of the proposed algorithms and capable of supporting design and analysis of GNC systems for close-proximity operations. (UNIPD)

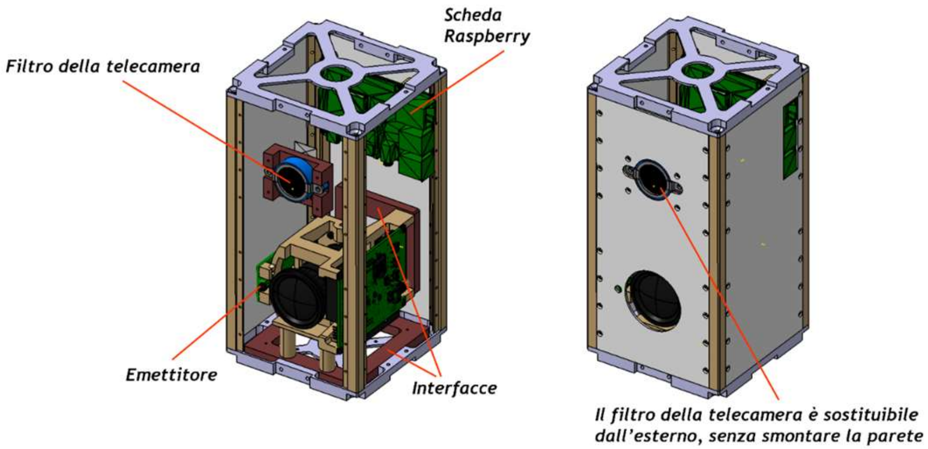
Focus on two phases of future IOS/ADR missions

- Reach and capture
- Stack stabilization after capture



Multisensor RELPOS module for Cubesats

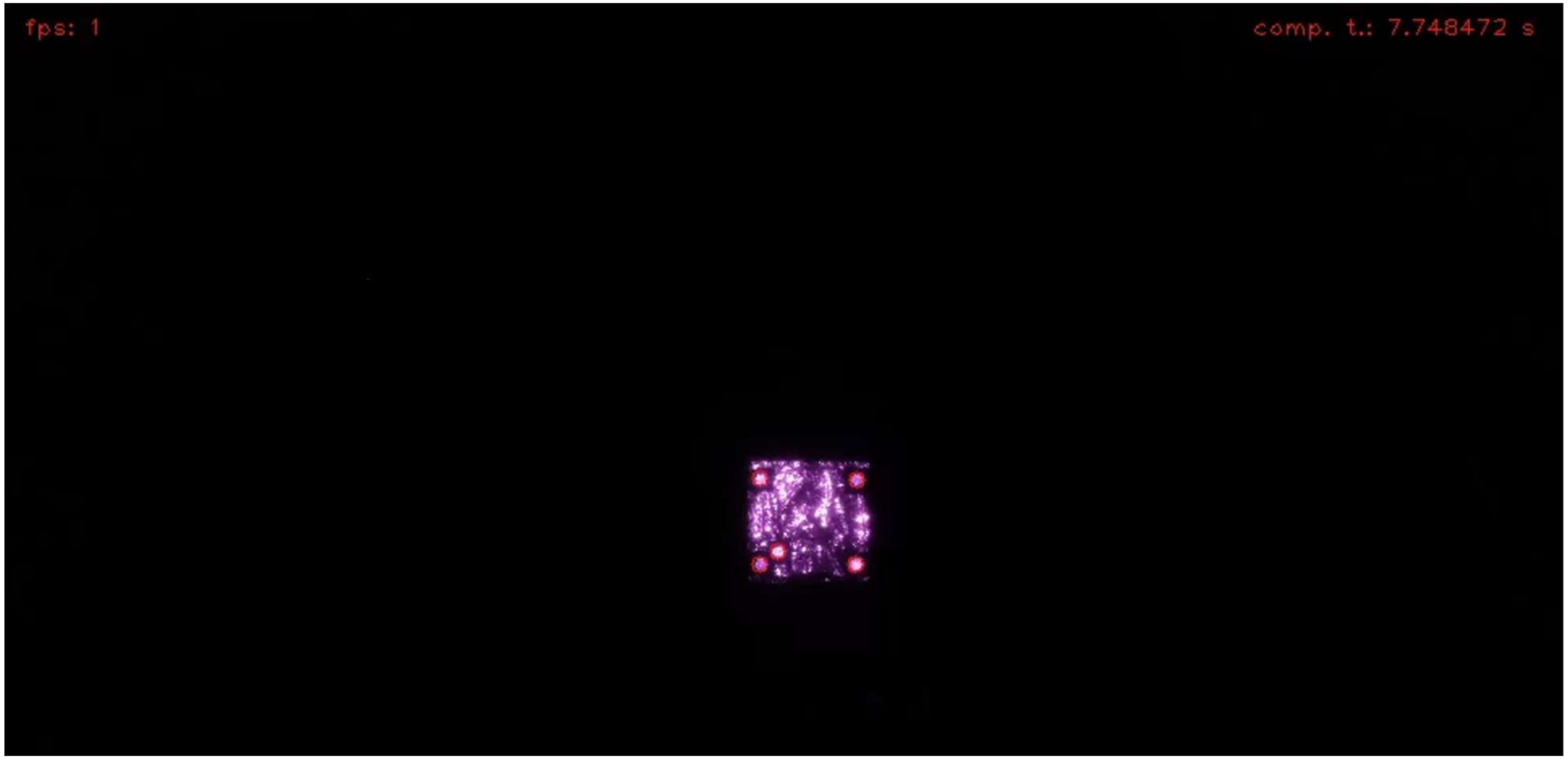
Project Title	**FORmation flying of CubEsat assemblies for remote sensing**
Funded by	**Italian Ministry of University and Research**



Modulo di navigazione relativa multi-sensore per operazioni di prossimità in orbita:

- Sistema di visione monoculare (UNINA-DII)
- Sistema Laser Range Finder (UNINA-DF/Ala Srl)
- Modulo CubeSat-based 2U (Lead Tech Srl)

Results (short range)



Ongoing projects

Project Title	The Space Eye (Speye)
Funded by	Italian Space Agency

Space Eye (SpEye): a two-satellite technology demonstration mission for the in-flight validation of critical technologies and techniques related to advanced ***on-orbit inspection*** and ***formation-flying***, applicable to future operational <u>nano-satellite</u> capabilities and operations.

Goal: demonstrate safe and inexpensive on-orbit inspection and mapping of a target satellite using an agile free flying nanosatellite (a 6U CubeSat) deployed by the same target.

The SpEye mission has been selected by ASI in the framework of the call “Future Missioni CubeSat”, now part of the “Alcor” program.

The UNINA Team is in charge of the relative navigation sub-system. Two operative modes:

- Camera + LRF (EO only mode)
- EO sensors + DGNSS (multisensory mode)

Concluding Remarks

Space Debris Management poses many challenges:

- Need for reliable tools for Fragmentation analysis and fragment orbit prediction
- Need for reliable algorithms and techniques for conjuction analysis and collision risk prediction
- Need for technology advancements and demonstration missions for IOS and ADR