Space Debris - How can laser technology contribute to a sustainable solution for the further exploitation of space as a resource?

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(*): Head Space Debris Office, ESA Space Safety Programme Office, ESOC, Darmstadt

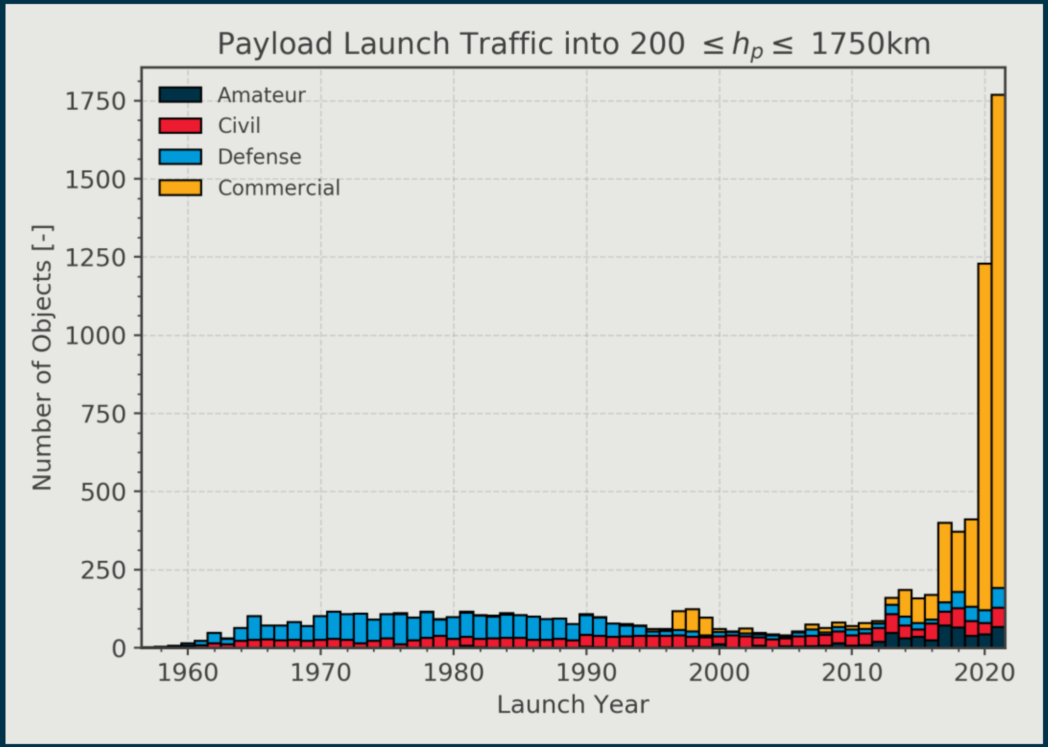
10/11/2022

Outline

- Space debris – what do we (need to) know?
- Need for timely and accurate data
- ESA's Space Safety Programme - addressing technology needs
- Laser ranging to space debris: opportunities and challenges

Key trends for the orbital environment - 1

Drastic **increase of launch rate** and thus increase of close approaches between active spacecraft

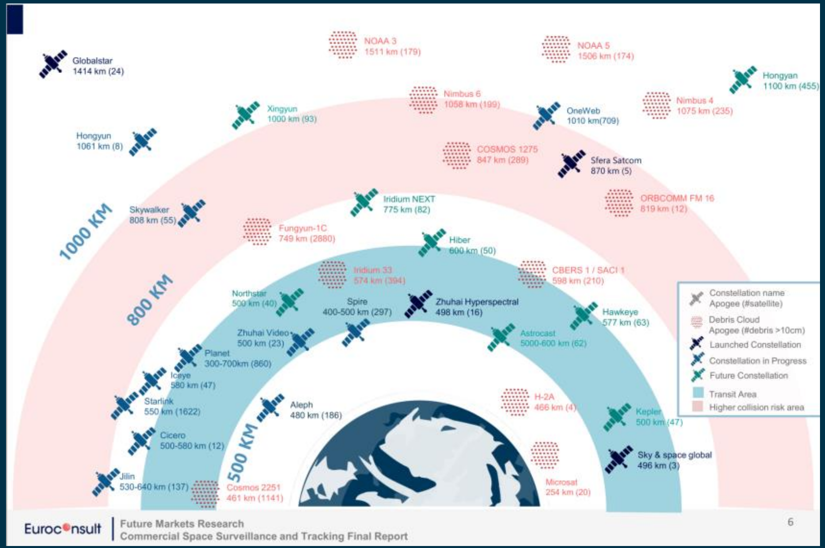


ESA Space Debris User Portal, **Space Environment Statistics**,
https://sdup.esoc.esa.int/discosweb/statistics

2010s vs. 2020s:

- Overall increase 370%
- 460% for LEO/SSO

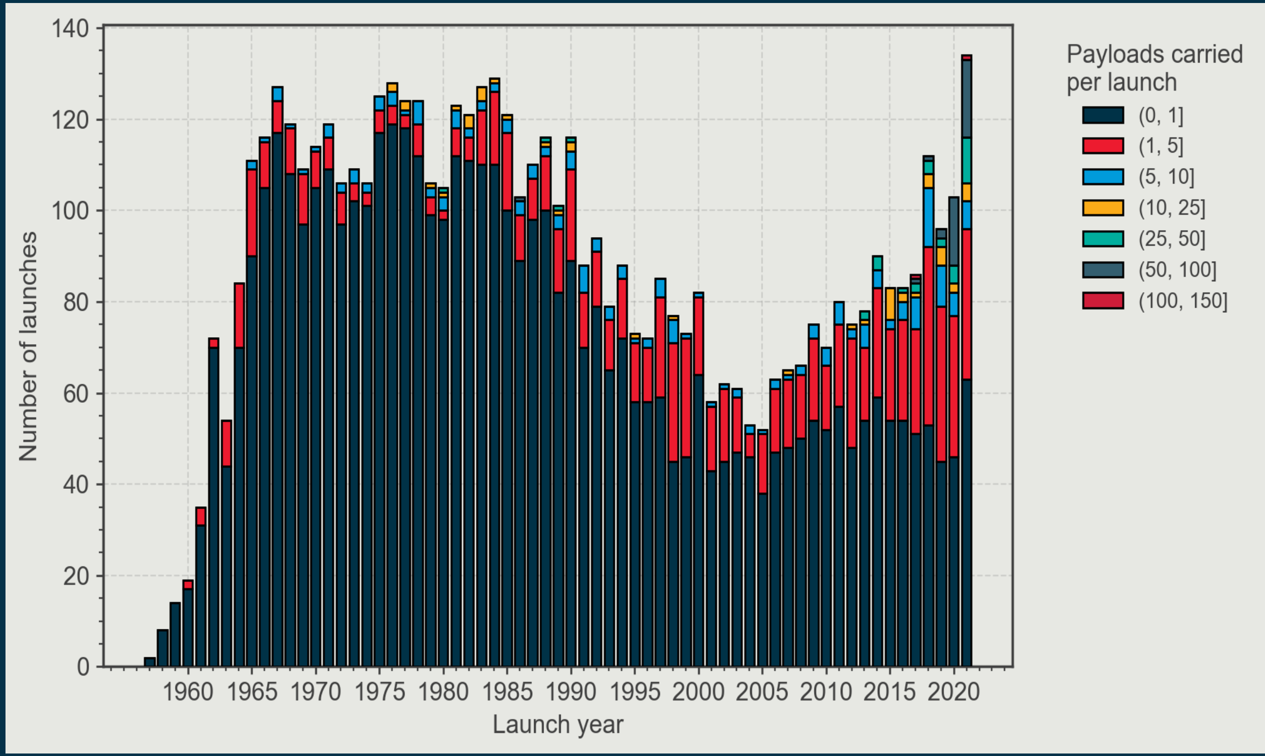
Euroconsult, **Satellites to be built and launched by 2029**, 2020



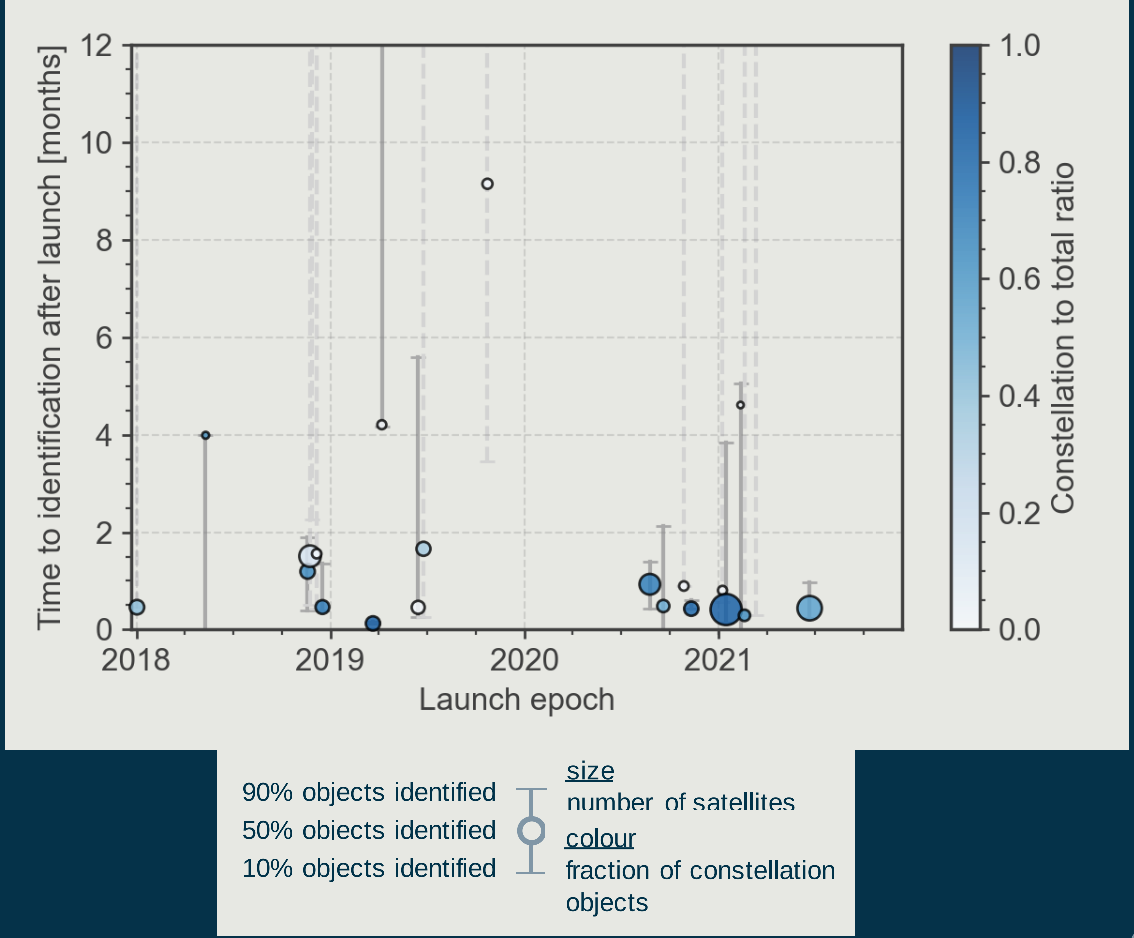
Euroconsult for UKSA, **Commercial Space Surveillance and Tracking**, 2020
https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/917912/Euroconsult_-_Commercial_SST_Market_-_for_publication.pdf

Key trends for the orbital environment - 2

Launches with multiple payloads now represent the majority of all launches



Payload identification for rideshare launches still a significant issue



Space Debris

„Space debris are all human-made objects including fragments and elements thereof, in Earth orbit or re-entering the atmosphere, that are non-functional“

Space Debris: Sources and Sinks

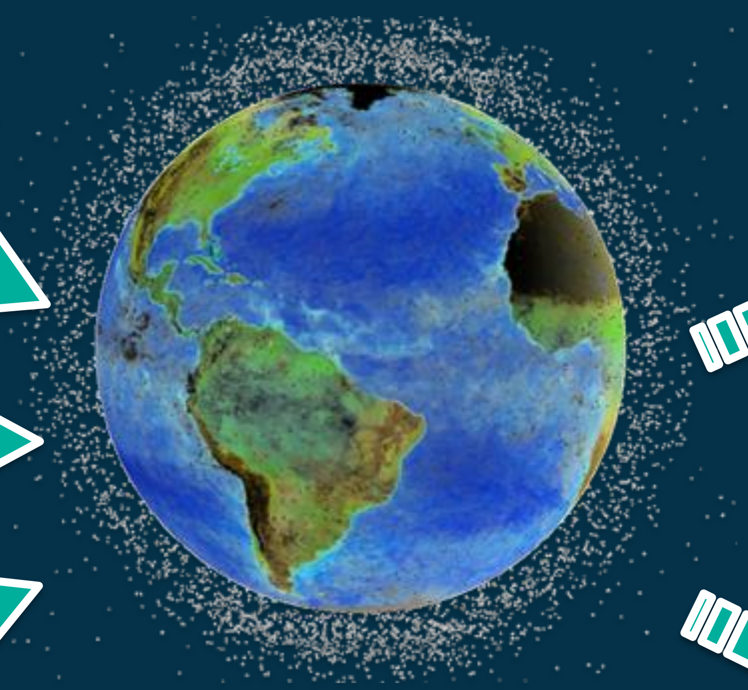
esa

+ Sources +

Launches
- Upper stages
- Payloads
- Mission-related objects

Fragmentations
- Explosions
- Collisions

Other sources
- SRMs
- NaK droplets
- Degrading surfaces

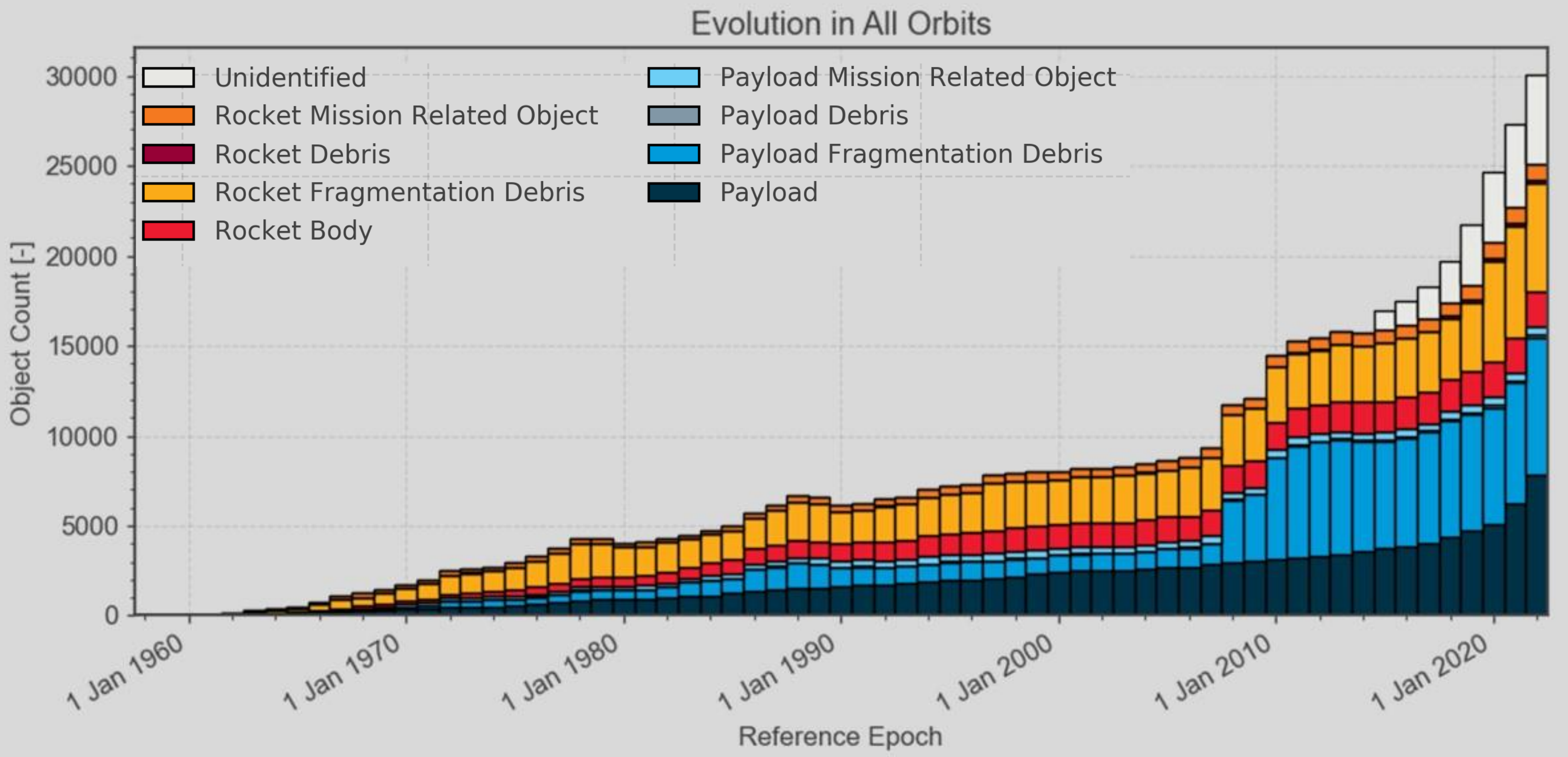


- Sinks -

Natural decay
- Atmospheric drag
- Luni-solar perturbations
- Solar radiation pressure

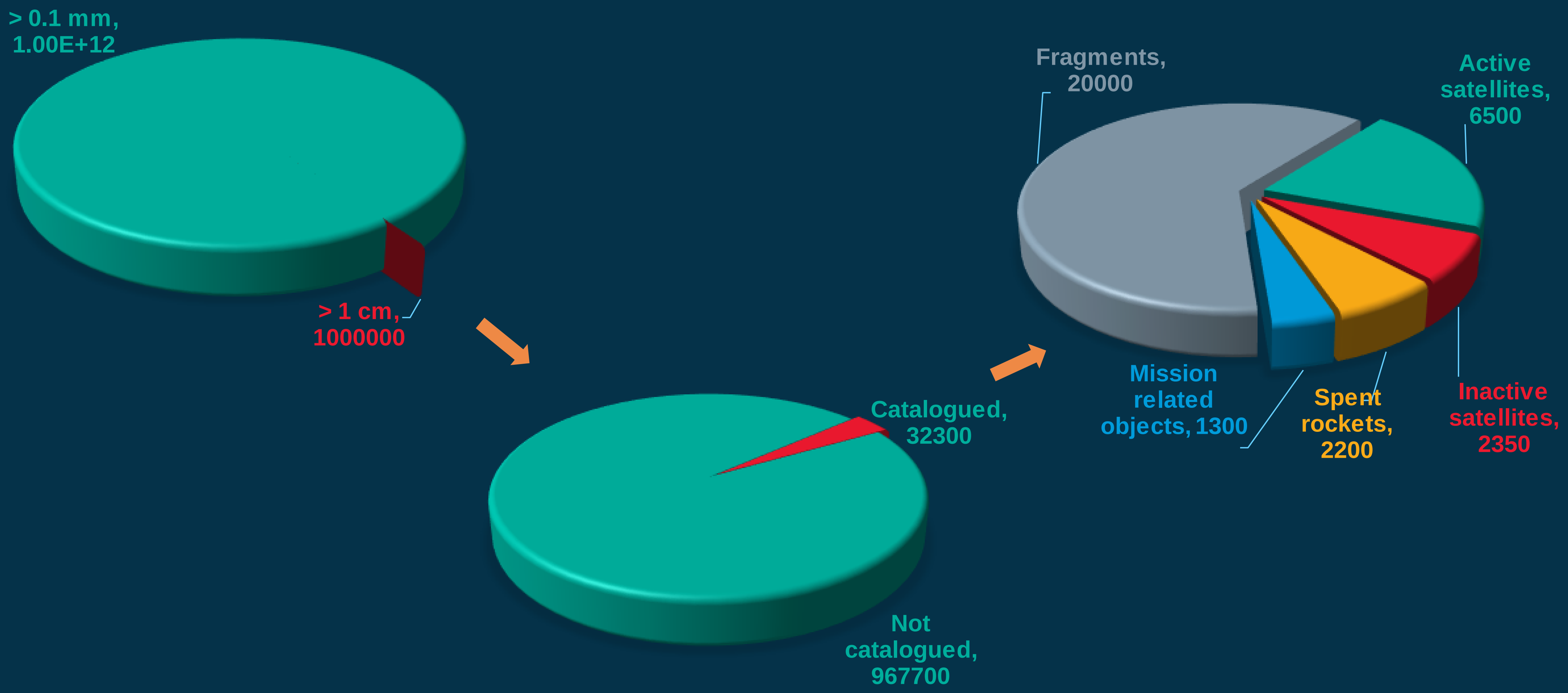
Active manoeuvering
- De-orbit
- Return (Shuttle)

Evolution of tracked object by number



ESA Environment Report
https://www.sdo.esoc.esa.int/environment_report/Space_Environment_Report_latest.pdf

Space Debris - sizes and classes



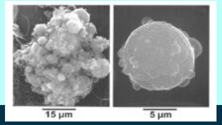
Numbers & Effects

Space debris mitigation measures

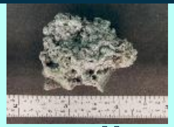
Collision fragments
- » Collision Avoidance
- » Disposal

Surface Degradation Products
- » Limit exposure time to space

Solid Rocket Motor / Pyro Burn Products



- » Stop usage
- » Al-free propellant



Meteoroids

- » unpreventable

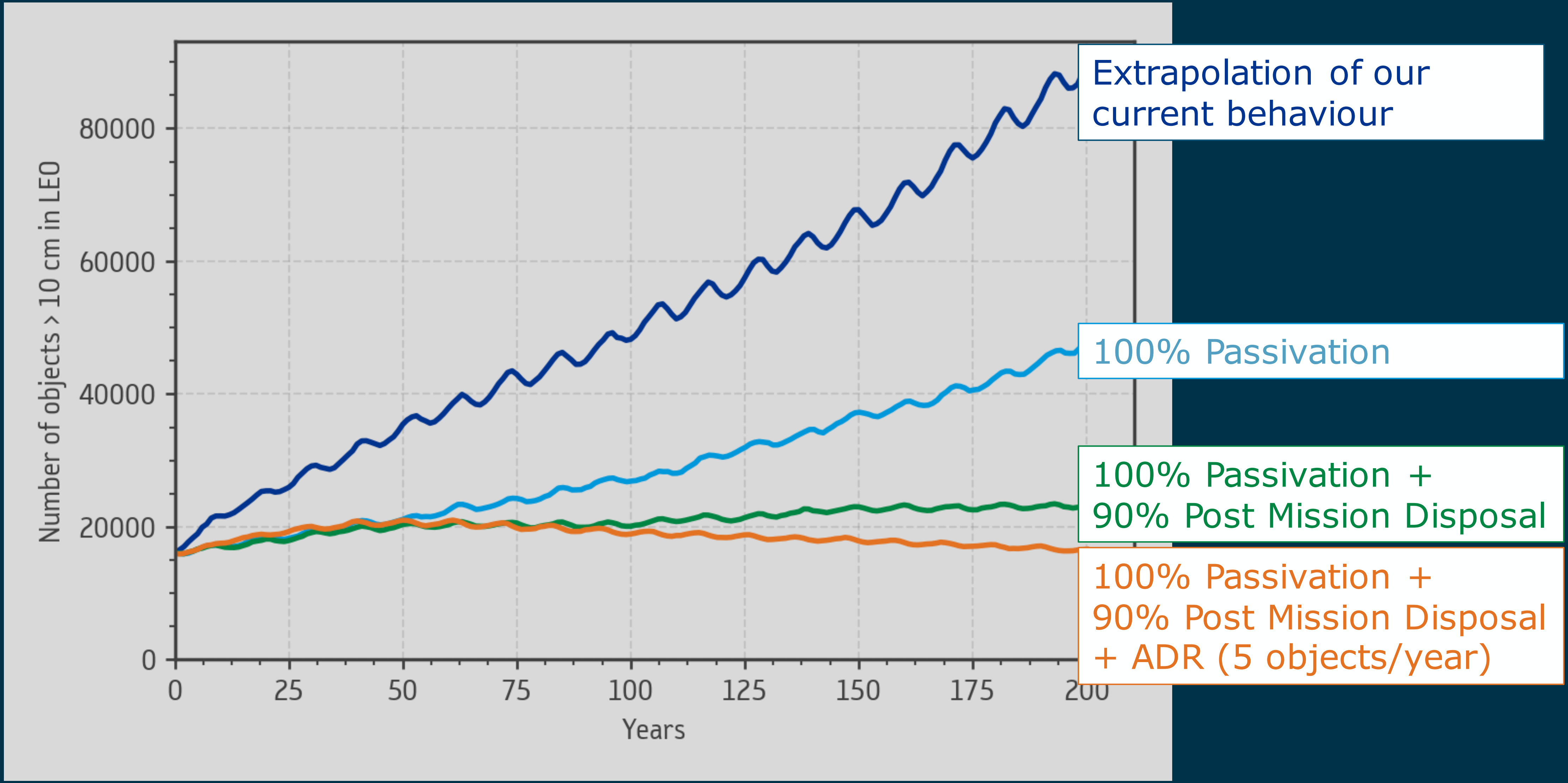
Explosion fragments
- » Passivation

Tracked objects

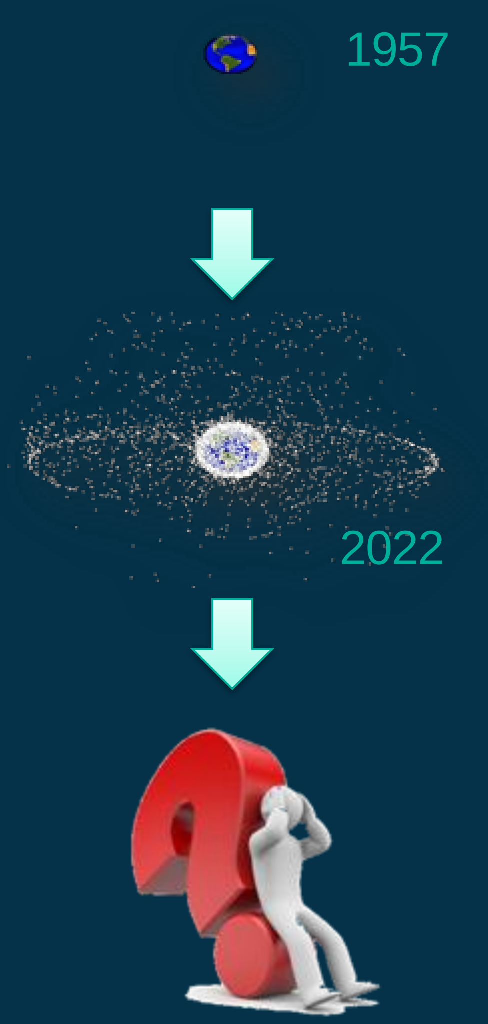
1µm | 10µm | 100µm | 1mm | 1cm | 10cm | 1m | 10m

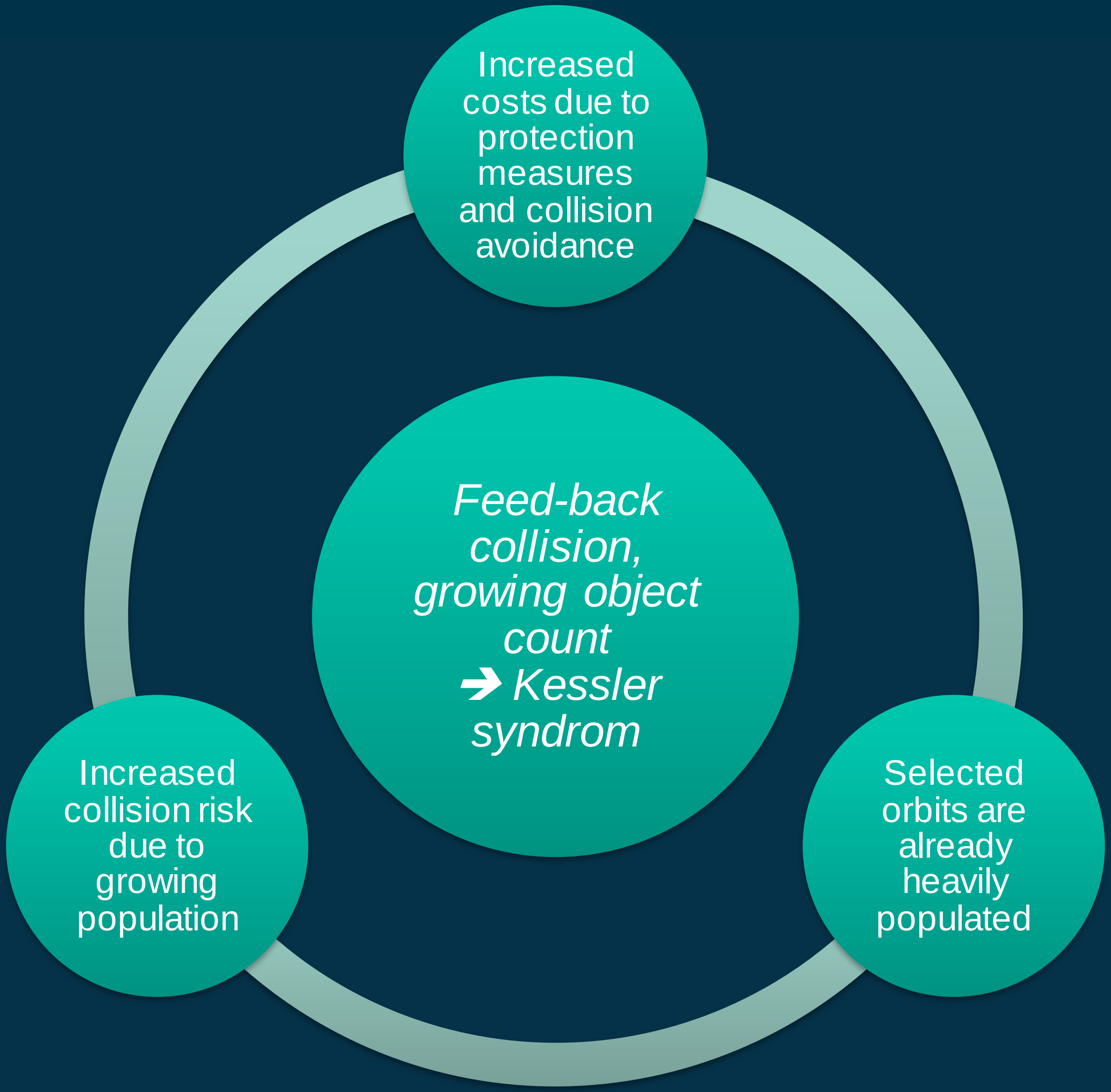
Log(Diameter)

Effectiveness of mitigation measures

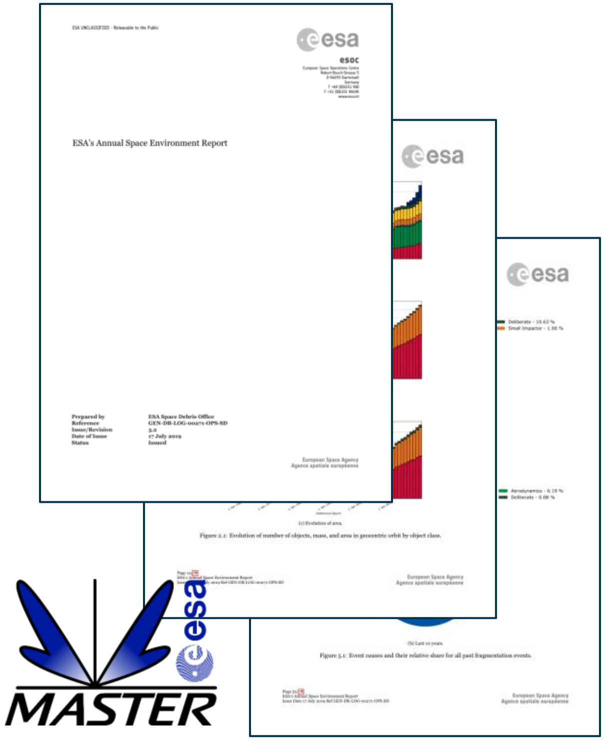


Long-term consequences

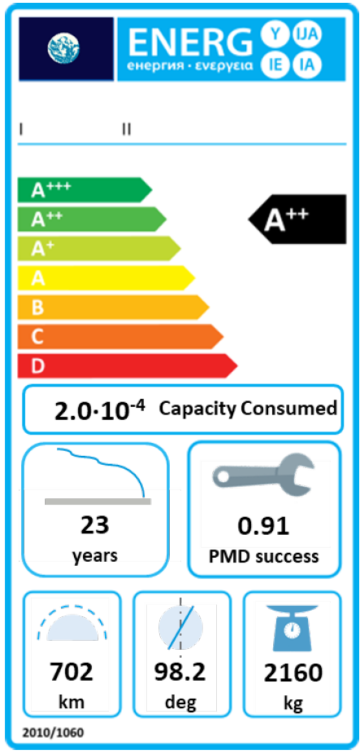




Space sustainability



Monitoring of activities and levels of **compliance** with mitigation measures



Implementation of **risk metrics** to capture the **consequences** on the **environment** and on other **operators,** assess the **environment capacity,** prepare **threshold-based** approach to debris mitigation

Integration within a **rating** to create **awareness** among operators and promote and incentivise **positive behaviours**

"In ESA we are implementing a policy that by 2030, we have a 'net zero pollution' strategy for objects in space, by consistently and reliably removing them from valuable orbits around Earth immediately after they cease operations. We need to lead by example here."

ESA Director General, Josef Aschbacher

Zero Debris Approach

Invent ESA contribution to debris population

Net zero pollution strategy

Leave no trace

Debris neutrality

Zero Debris

This approach is inline with the Net Zero Space charter, which was launched Nov. 12 during the Paris Peace Forum in France

By 2030

Design and operate for **probability of successful disposal well above 90%**

Removal services for remaining in-orbit failures

Current focus

By 2050

Circular economy in space: reuse or recycle 50% of the launched mass.

Zero Debris Approach at ESA

Zero Debris Approach requires **transversal action** - the 4 pillars:

1. Evolution of ESA Policy

Introduce a requirement for removal in case a spacecraft fails

2. Upgrade platforms

System level development and integration of innovative technology

3. Removal services

Demonstrate reliable services, establish standard interfaces

4. Improving operations

Expanding monitoring and operational capabilities

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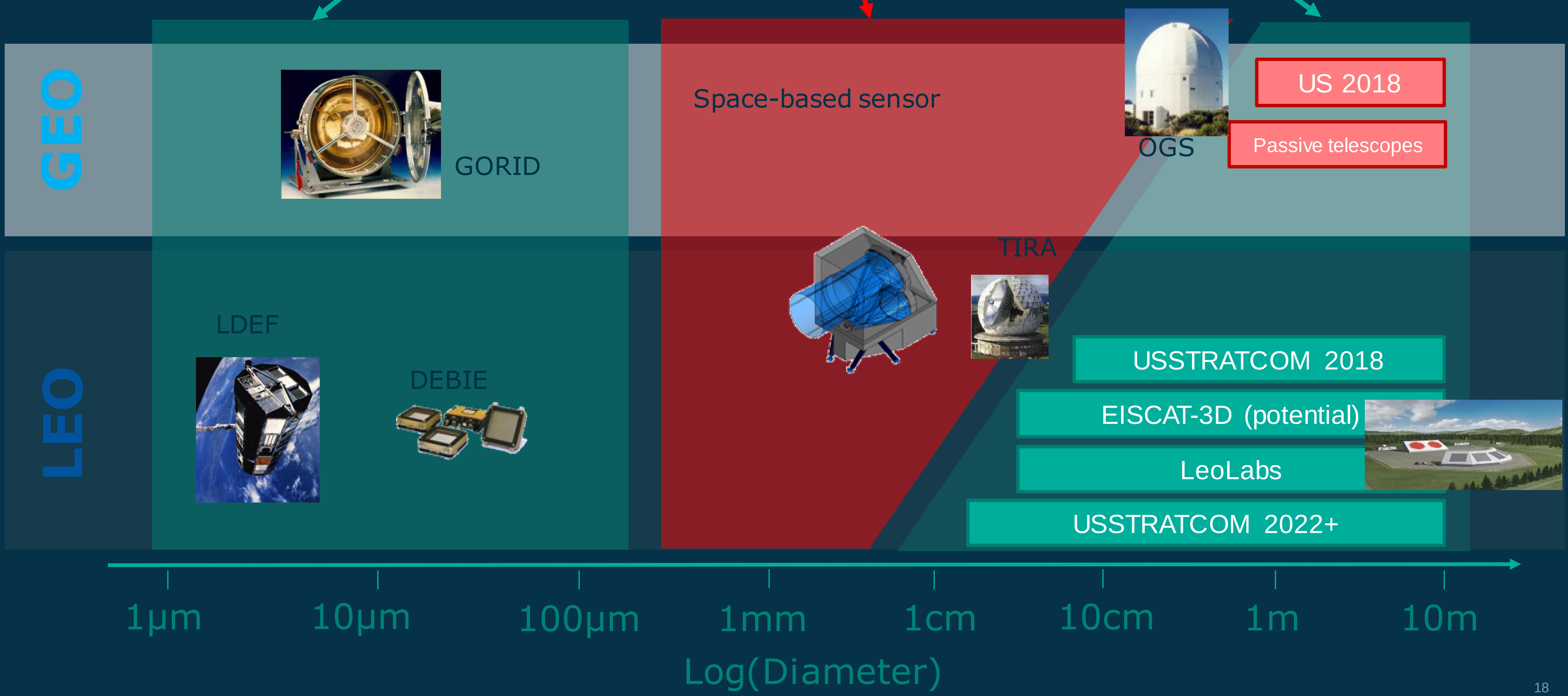
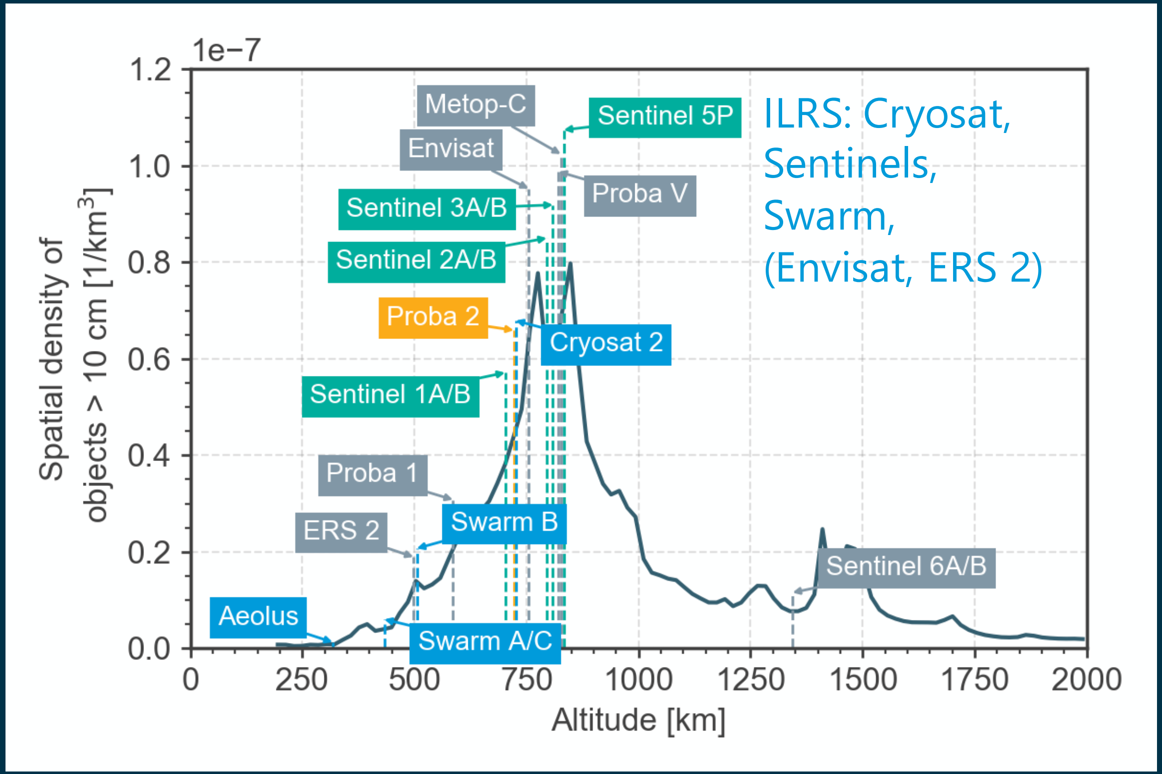
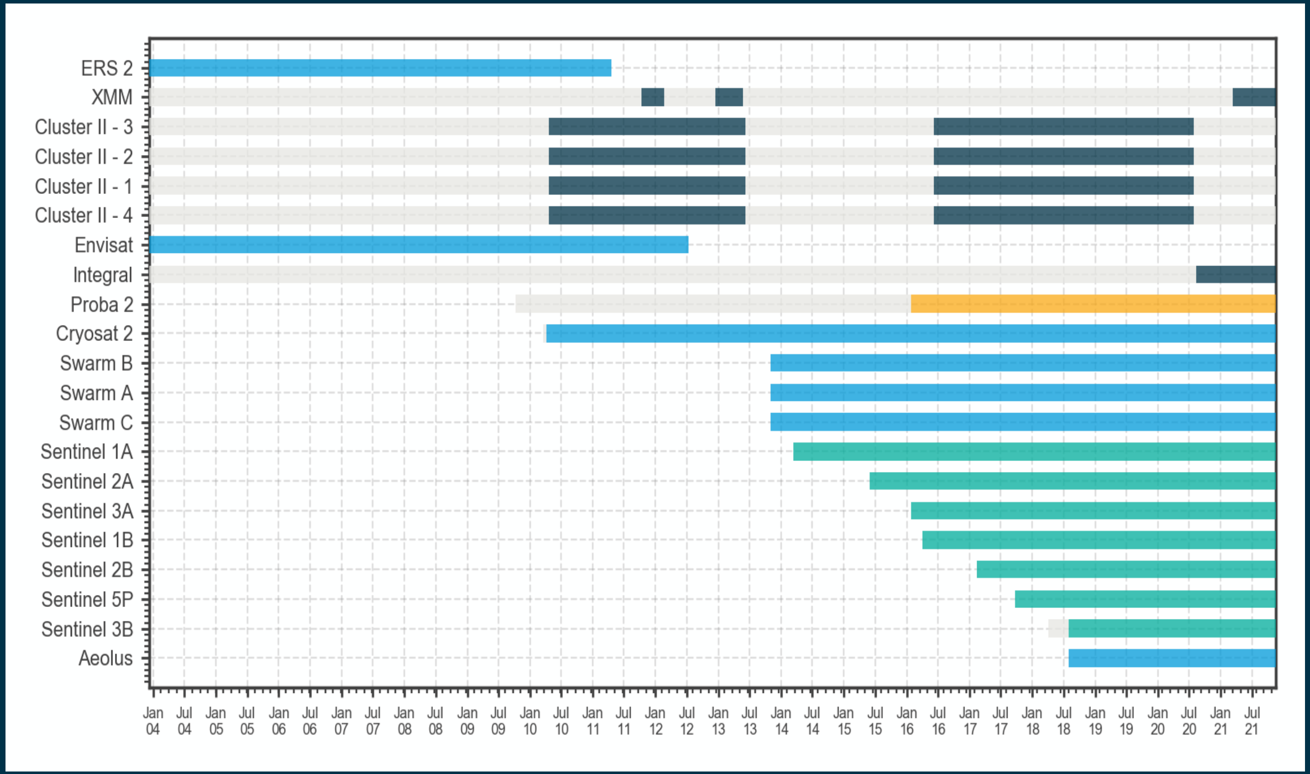
- Laser ranging to space debris: opportunities and challenges

Monitoring Debris



ESA Missions and Collision Avoidance

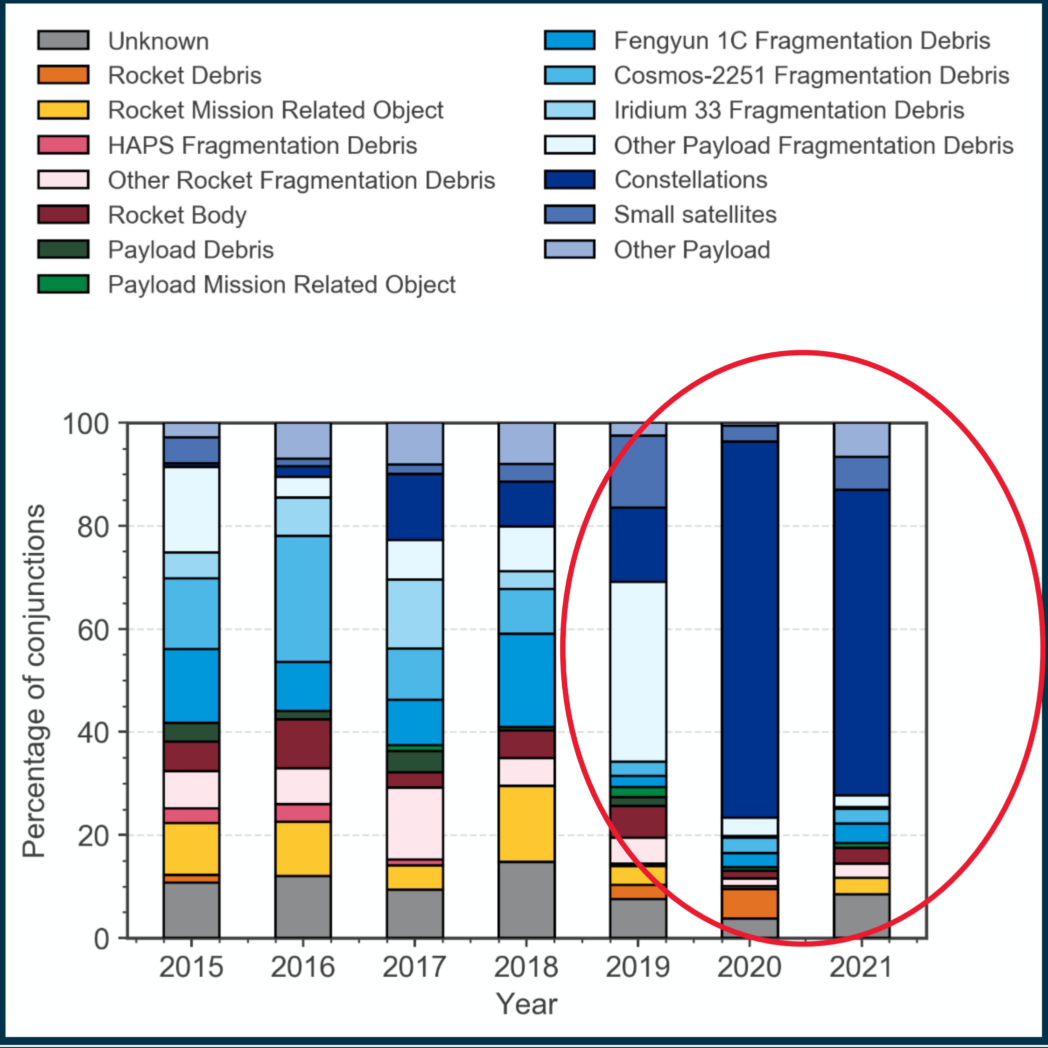




Conjunction statistics

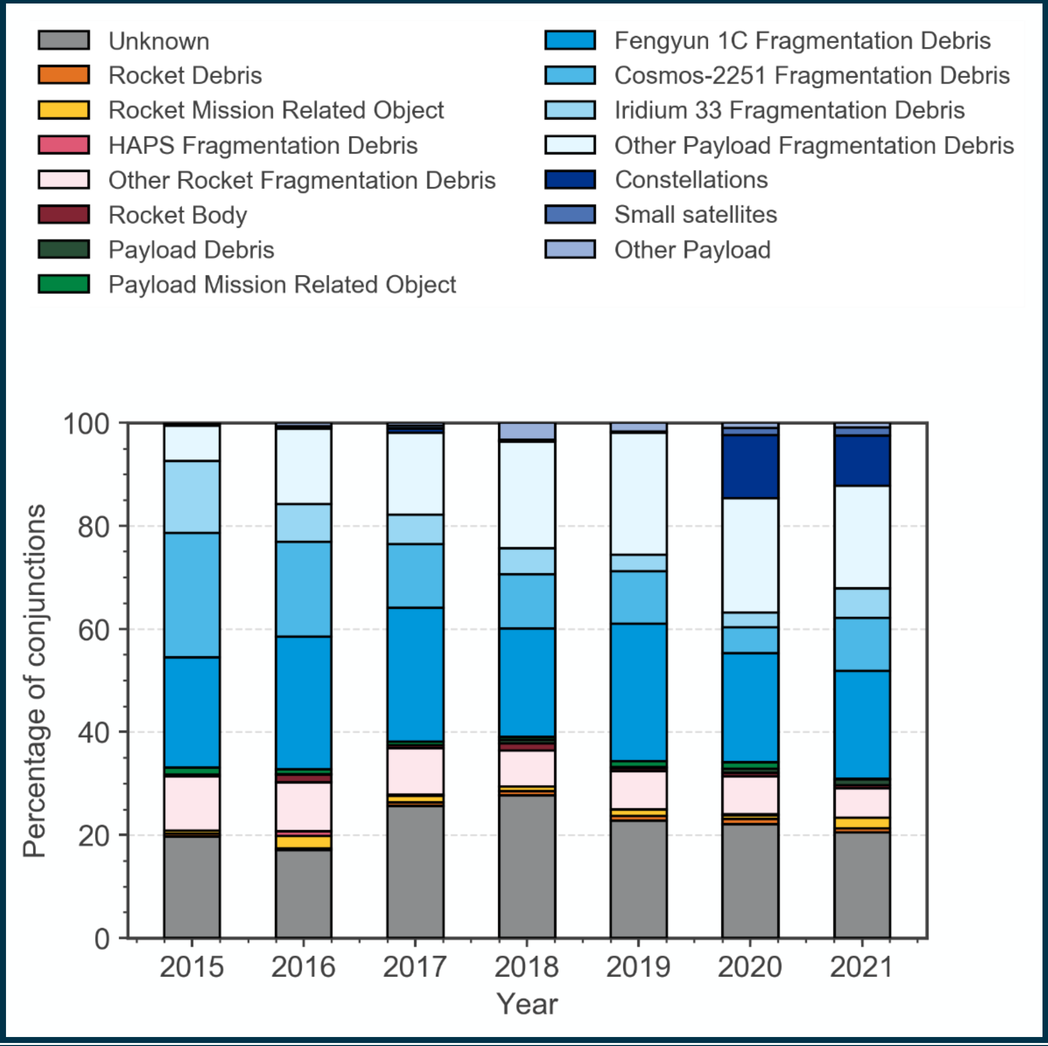
ESA and Copernicus missions in lower LEO

(Aeolus and Swarm)



ESA and Copernicus missions in higher LEO

(Cryosat-2 and Sentinels)



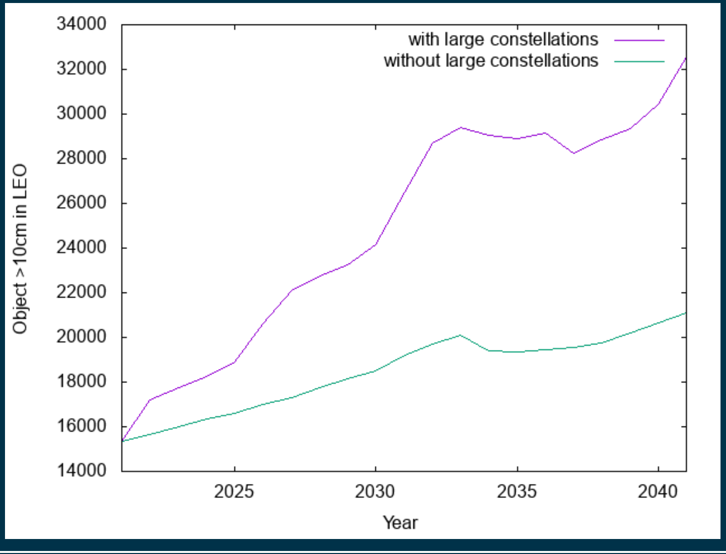
Future trends for collision avoidance

- Larger catalogue(s) (covering smaller object sizes)
  - More known high risk conjunction events and more avoidance actions (unless criteria or uncertainties change)

  ➔ **Factor 3 to 10 more objects in catalogue (tbc)**
- Further increase of launch traffic
  - More conjunctions between active spacecraft
  - Coordination needs

  ➔ + ~50% overall, order of mag in specific altitudes due constellations
- Multiple catalogues and data services
  - (Enlarged) US catalogue, other institutional and commercial services, not accessible to all operators(?)
  - Data fusion needs – opportunity for "on demand SLR"

➢ **Need for increased automation and enhanced decision criteria**
  - Even now CAM preparation represents >50% of "extra effort" in operations



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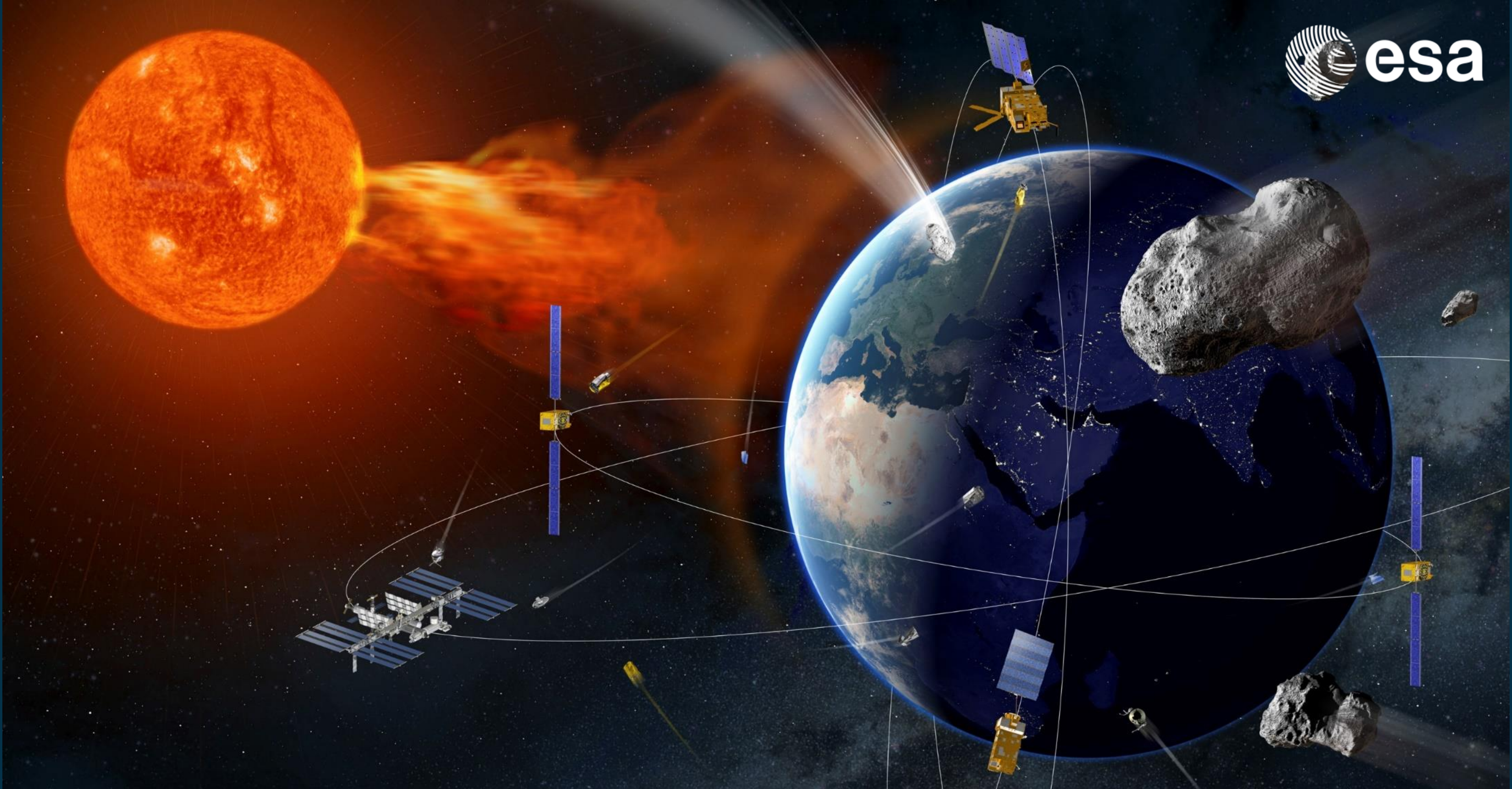


European Space Agency

STRATEGIC OBJECTIVES

Space Safety Goals

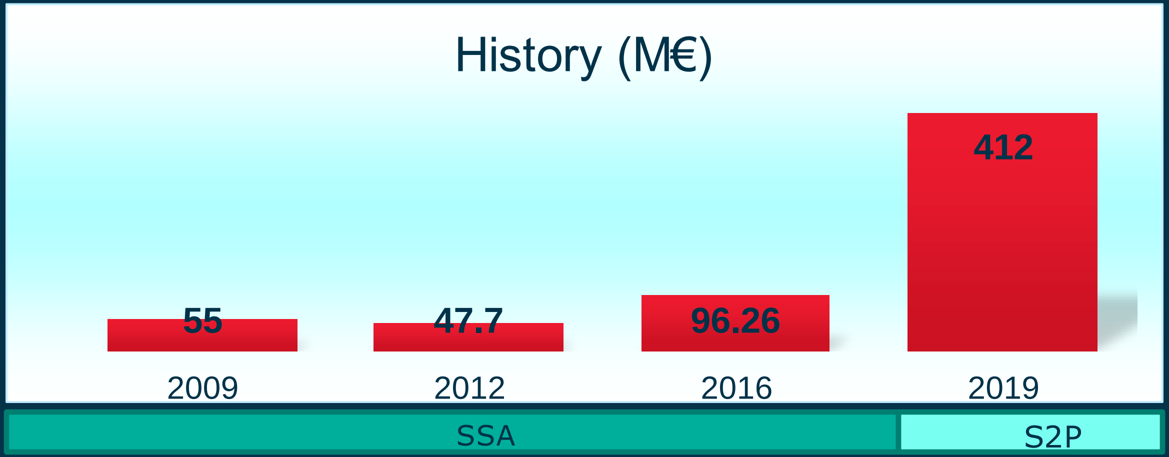
- Space Weather early warning system tailored to European user needs
- Early warnings for asteroids >40 m about three weeks in advance,
- Capability to deflect asteroids smaller than 0.5 km (2 years before)
- Established European players for a growing market of space-traffic technologies and products
- Prepare European industry for a zero-debris policy and a circular economy in space

ESA Space Safety Programme

(based on previous SSA Programme)

Objective:

- Protection of space and ground assets against adverse effects from space
- Three main areas or segments:
  - Space Weather
  - Planetary Defense (NEO)
  - Space Debris



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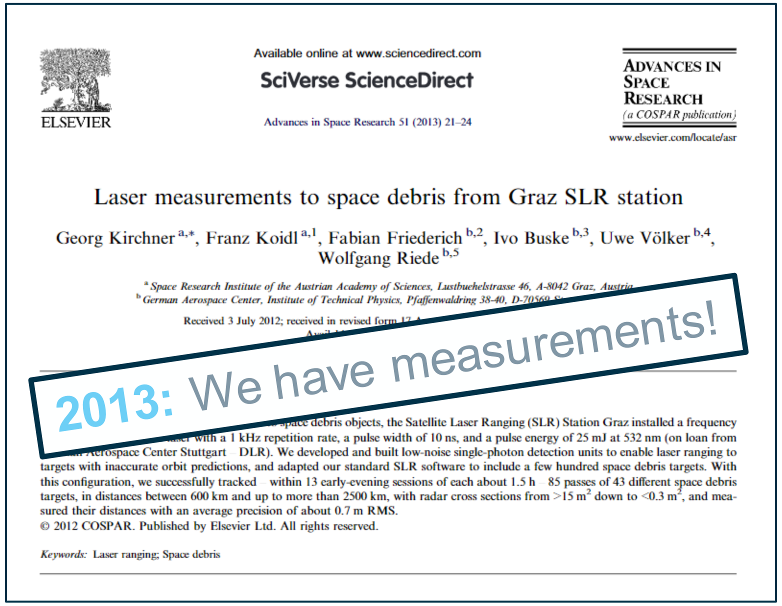
Satellite Laser Ranging to Space Debris

An emerging technology



Available online at www.sciencedirect.com

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Advances in Space Research 51 (2013) 21–24

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Advances in Space Research (a COSPAR publication)

www.elsevier.com/locate/asr

Laser measurements to space debris from Graz SLR station

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[a] Space Research Institute of the Austrian Academy of Sciences, Lustbuehelstrasse 46, A-8042 Graz, Austria

[b] German Aerospace Center, Institute of Technical Physics, Pfaffenwaldring 38-40, D-70569 ...

Received 3 July 2012; received in revised form ...

... space debris objects, the Satellite Laser Ranging (SLR) Station Graz installed a frequency ... laser with a 1 kHz repetition rate, a pulse width of 10 ns, and a pulse energy of 25 mJ at 532 nm (on loan from ... Aerospace Center Stuttgart DLR). We developed and built low-noise single-photon detection units to enable laser ranging to targets with inaccurate orbit predictions, and adapted our standard SLR software to include a few hundred space debris targets. With this configuration, we successfully tracked within 13 early-evening sessions of each about 1.5 h 85 passes of 43 different space debris targets, in distances between 600 km and up to more than 2500 km, with radar cross sections from >15 m² down to <0.3 m², and measured their distances with an average precision of about 0.7 m RMS.

Keywords: Laser ranging; Space debris

2013: We have measurements!

CASE STUDY

ACCURATE ORBIT DETERMINATION OF SPACE DEBRIS WITH LASER TRACKING

With the participation of Germany and Austria

A GSTP activity has shown that recent advances in the technology mean lasers can now be used, with an up to 60% success rate, to track non-cooperative larger space debris objects.

Since the first space mission in 1957 satellites have had a great impact on our daily life. Modern navigation, communication and Earth observation are just examples of the wide range of possible space-based applications. But beside satellites, a lot of inactive objects populate near-Earth orbits too ... debris. The current estimate for LEO ... objects over about 10 cm in ... using radar faciliti...

... the sun or by using radar ... send out a radar beam for the object to reflect ... and determine location." Both techniques have limitations for space debris objects, for the optical method you need sun, and for the radar technique needs a rather high ...

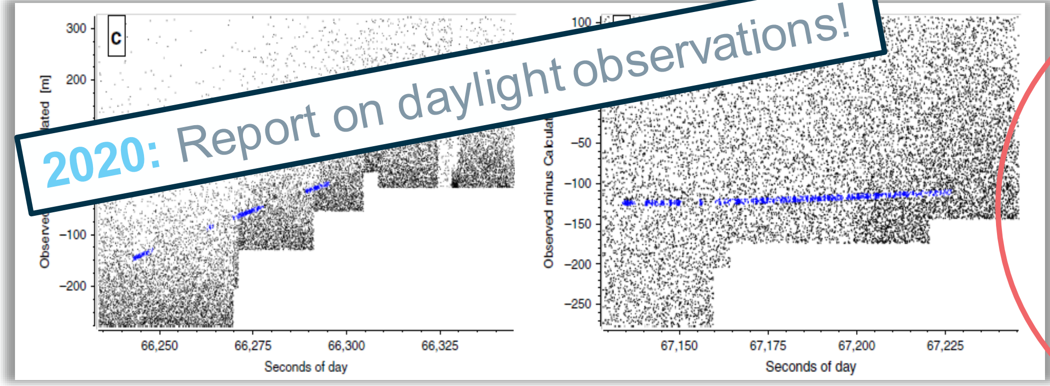
supplemented with a suitable ... space debris.

... developed to estimate the ...

... activity showed that by illuminating the object with a laser beam and using receivers at three sites then they had up to a 60 per cent success rate in tracking the object's orbit accurately. Despite a complex set up and a baseline of several 100s of km, the ground stations could pinpoint non-cooperative objects to one order of magnitude more precisely than when compared with the radar method.

A technology improvement that's vital if. In the future, we are to ...

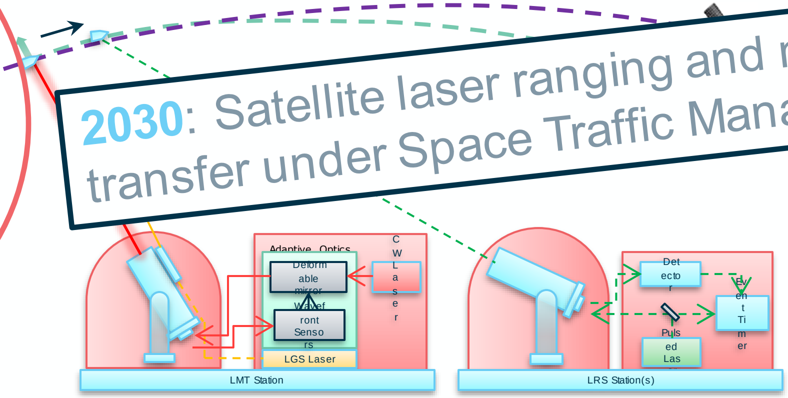
ESA's Annual GSTP report 2018: Very prominent feature on first study on multistatic tracking



2020: Report on daylight observations!

Steindorfer, M.A., Kirchner, G., Koidl, F., Wang, P., Jilete, B., Flohrer, T. Daylight space debris laser ranging. Nature Communications. 11, 3735 (2020). https://doi.org/10.1038/s41467-020-17332-z

Today: requests from operators to provide laser ranging as support to missions and space logistics



2030: Satellite laser ranging and momentum transfer under Space Traffic Management?

ESA Laser Ranging Station as test-bed

First, a space debris laser station is still a laser station!

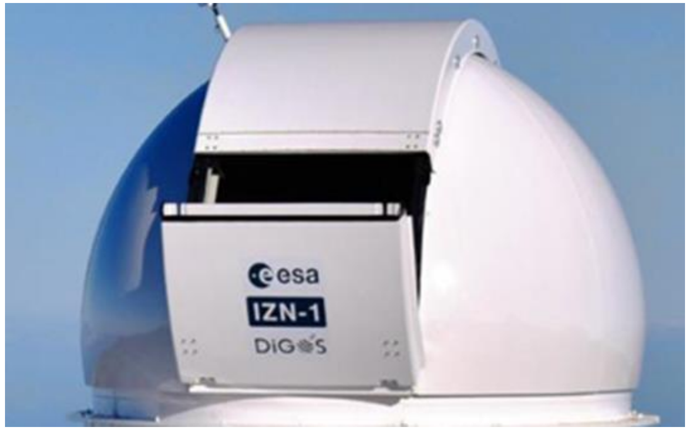
→ Talks by Andrea di Mira and Sven Bauer on ILRS contributions of IZN-1 as new engineering station

Main station subsystems of IZN-1

Telescope
- ASA AZ800
- Ritchey-Chretien 80 cm f/6.8
- Pointing accuracy <5 arcsec

Detector package
- C-SPAD (532 nm)
  PESO Consulting
- IR-SPAD (1064 nm)
  Princeton Lightwave

Dome
- Baader Planetarium 4.2 m
- Lower flap and rolling shutter



Laser package
- Passat Compiler 532/1064 nm
- Nd:YAG PRF 400 Hz

DiGOS

λ	Pulse width	Pulse Energy	Divergence (full-angle)
532 nm	7 ps	400 µJ	28-32 µrad
1064 nm	8.5 ps	500 µJ	56-60 µrad

IZN-1 Future Upgrades

Technology test-bed for ESA member states

Laser Ranging to Space Debris

Technological requirements and possible implementation:

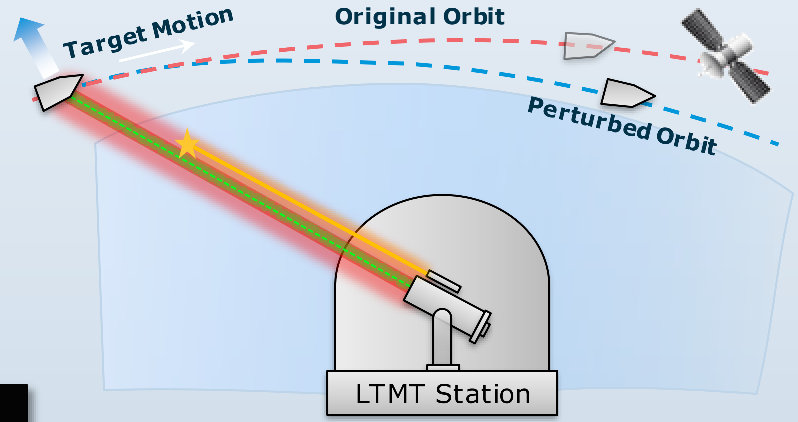
- Average Power 20 - 100 W
- Pulse width ~1 ns
- Laser source: Nd:YAG, Ti:Sap, other
- Range measurement accuracy ~10s of cm

Optimization for daylight tracking & network of space debris tracking stations

➔ on-demand support of collision avoidance services

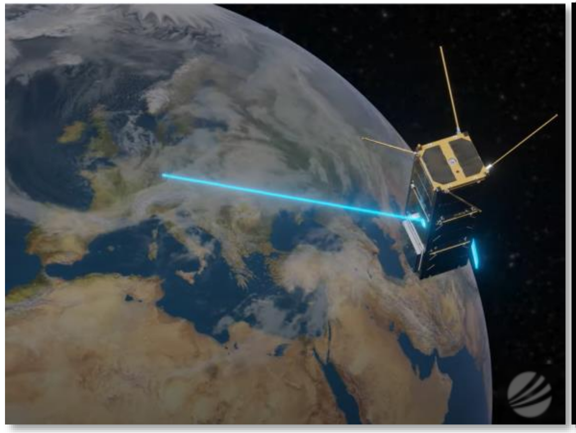
Towards Laser Momentum Transfer

Testbed for debris tracking and support to definition of LMT station requirements on laser tracking.



ESA will address also additional technological challenges will high-power laser generation and transmission:

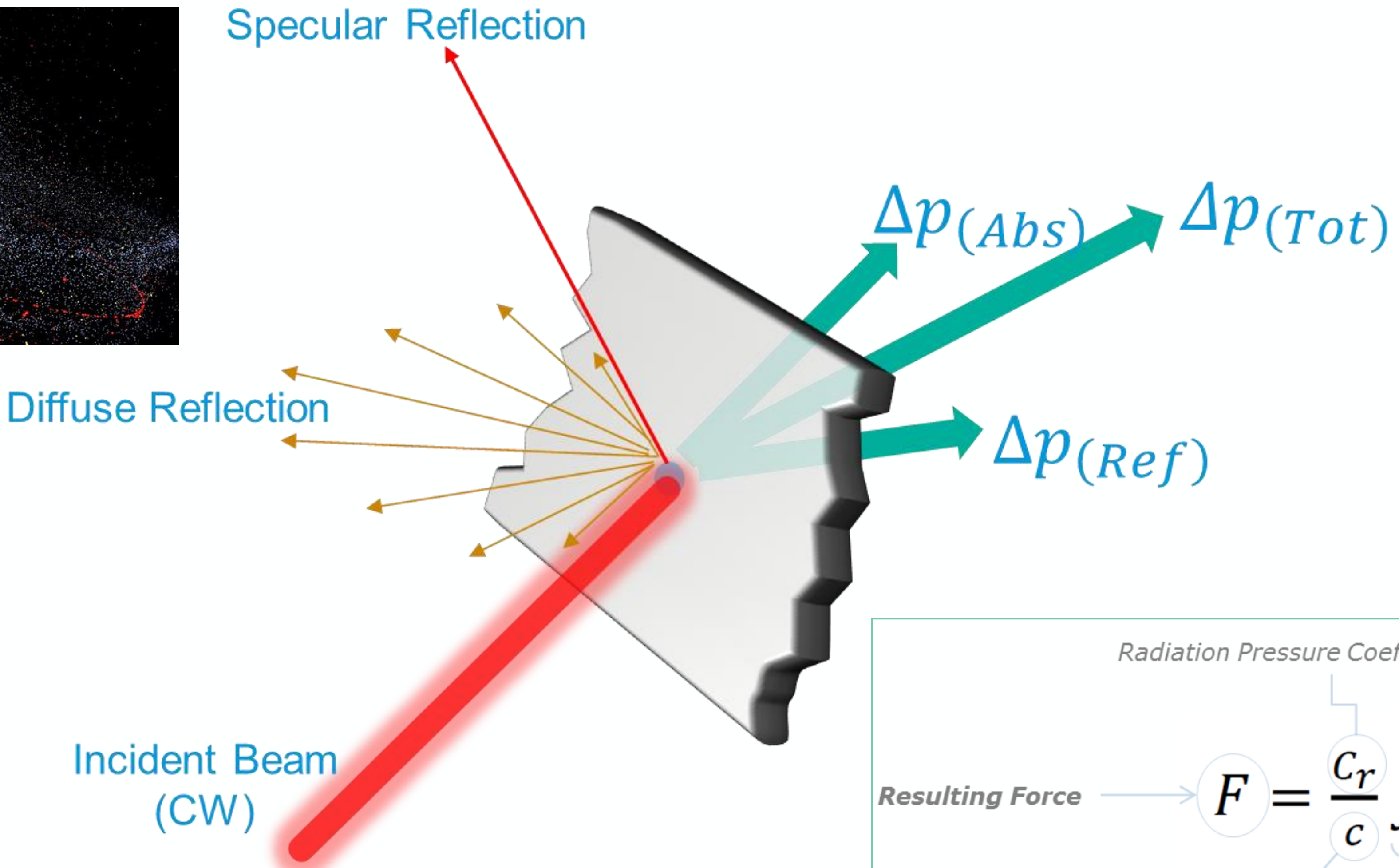
- CW 40kW, Yb-doped fiber 1070 nm
- High-Power Adaptive Optics



On top: LEO-DTE Optical communications

- Implementation of uplink data transmission and beacon at 1536 and 1590 nm (CCSDS O3K and SDA v3 standards)
- 1550 nm downlink reception capability
- Fiber Laser Technology, Average power > 15W

Laser Momentum Transfer (LMT) through Photon Pressure



Radiation Pressure Coefficient [0-2]

Resulting Force →

$$F = \frac{C_r}{c} \int I(x,y)\,dA$$

Speed of light

Integration of laser intensity over illuminated cross-section

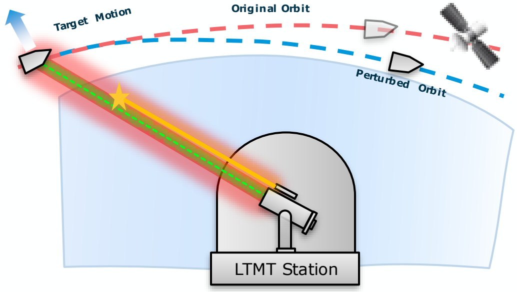
Laser Momentum Transfer: Phase 0 studies

LARAMOTIONS

LAser RAnging and MOmentum Transfer systems evolutION Study

Ground-based technology

- **Laser tracking** and space debris laser catalogue maintenance
  - 5 station tracking network for reduction of false collision alerts (by 90%)
  - 9 station network enough for (temporary, 800 object only) catalogue
- **Momentum transfer** and collision avoidance manoeuvre
  - LTMT network solution: 1 LTMT + 23 LT stations (min.), 10 LTMT stations (optimized)



E. Cordelli, et al., Ground-based laser momentum transfer concept for debris collision avoidance, Journal of Space Safety Engineering, 2022.
S. Scharring, et al., LARAMOTIONS: a conceptual study on laser networks for near-term collision avoidance for space debris in the low Earth orbit, Appl. Opt. 60, 2021.

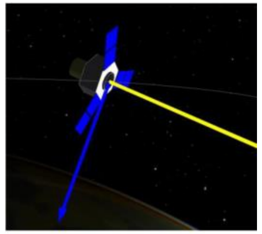
OLaMoT

In-Orbit Laser Momentum Transfer

Space-based technology

A total of 2 satellites @650km plus 2 satellites @950km needed to have access to 80% of debris population targetable within 2 days with space-based momentum transfer

Peltoniemi, Jouni I., et al. "Steering reflective space debris using polarised lasers." Advances in Space Research, 2021.

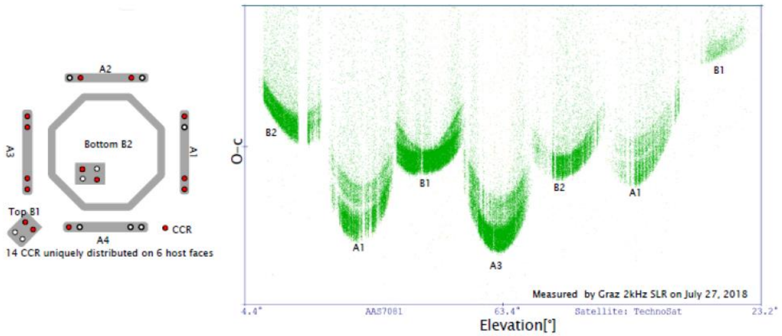


Opportunities for technology development (1)

Further exploitation of synergies between SLR and Space Debris

Re-use of laser technology components for light curve acquisition and **attitude characterization**

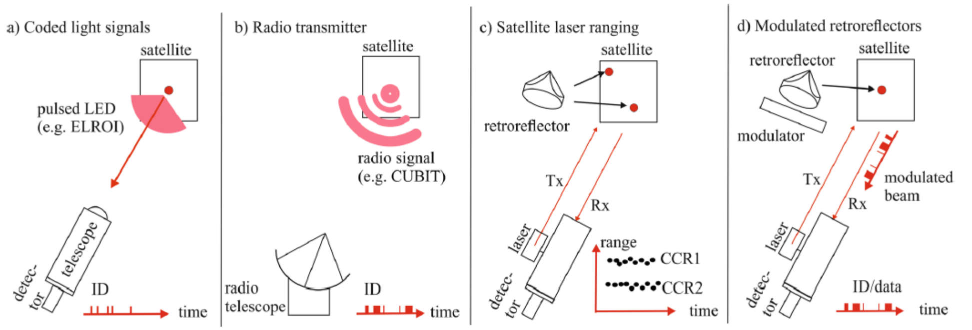
- Using photon counters and high-rate SLR
  → talks by Akiyama et al.; Wang et al.; Schildknecht et al.; …
- Data fusion of different technologies (ESA Study “Tumbling Motion”, iOTA tool): fusing ambiguous data helps in disambiguation



Wang P., Almer H., Kirchner G., Koidl K., Steindorfer M., Barschke M., Werner P., Starke M.: kHz SLR Application on the Attitude Analysis of TechnoSat. Presented at the 21st International Workshop on Laser Ranging, Canberra. (2018)

Space Traffic Management (STM) for space sustainability needs **object identification**

- Using SLR via retroreflectors or other derived technologies
- New: Polarized light-switching retroreflectors
- Needs more (“simple”) stations to support regulators and space logistics providers *(5 stations for ~150 objects/week)*



Bartels, N., Allenspacher, P., Hampf, D. et al. Space object identification via polarimetric satellite laser ranging. Commun Eng 1, 5 (2022). https://doi.org/10.1038/s44172-022-00003-w

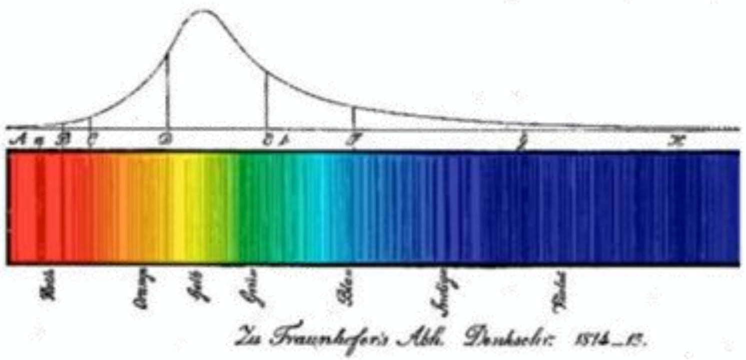
Space Debris (and optical communication needs) push further technology development at lower TRLf or SLR (re-)use

- Daytime passive optical tracking helps for challenging ILRS targets
- Laser safety applications (daytime tracking cameras)
- …

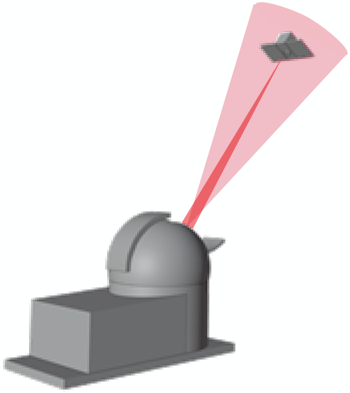
Opportunities for technology development (2)

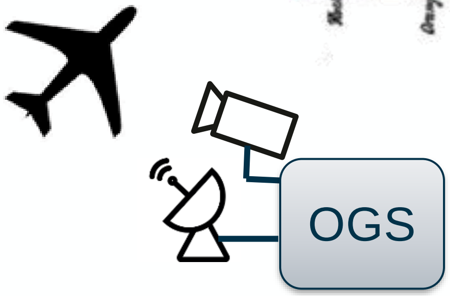
Further exploitation of synergies between SLR and Space Debris

- 2023: **Daylight space debris laser ranging via emission on Fraunhofer lines**
  - High signal-to-noise ratio during daytime for 24/7 operations
  - Proof-of-concept for SLR, space debris and optical comms



- 2023: **Aircraft Detection System for Optical Ground Stations**
  - Multiple detection systems
  - Increased level of in-sky laser safety





- 2023: **Optical Ground Beacon Laser System**
  - CCSDS O3K and SDA v3 compatibility

- **Under preparation**
  - Eye-safe Laser Ranging at 1550 nm
  - Laser Time Transfer
  - Tip/tilt pre-compensation for Laser Tracking and Momentum Transfer
  - Daytime and multispectral space debris observation capabilities
  - Robust satellite link acquisition concept

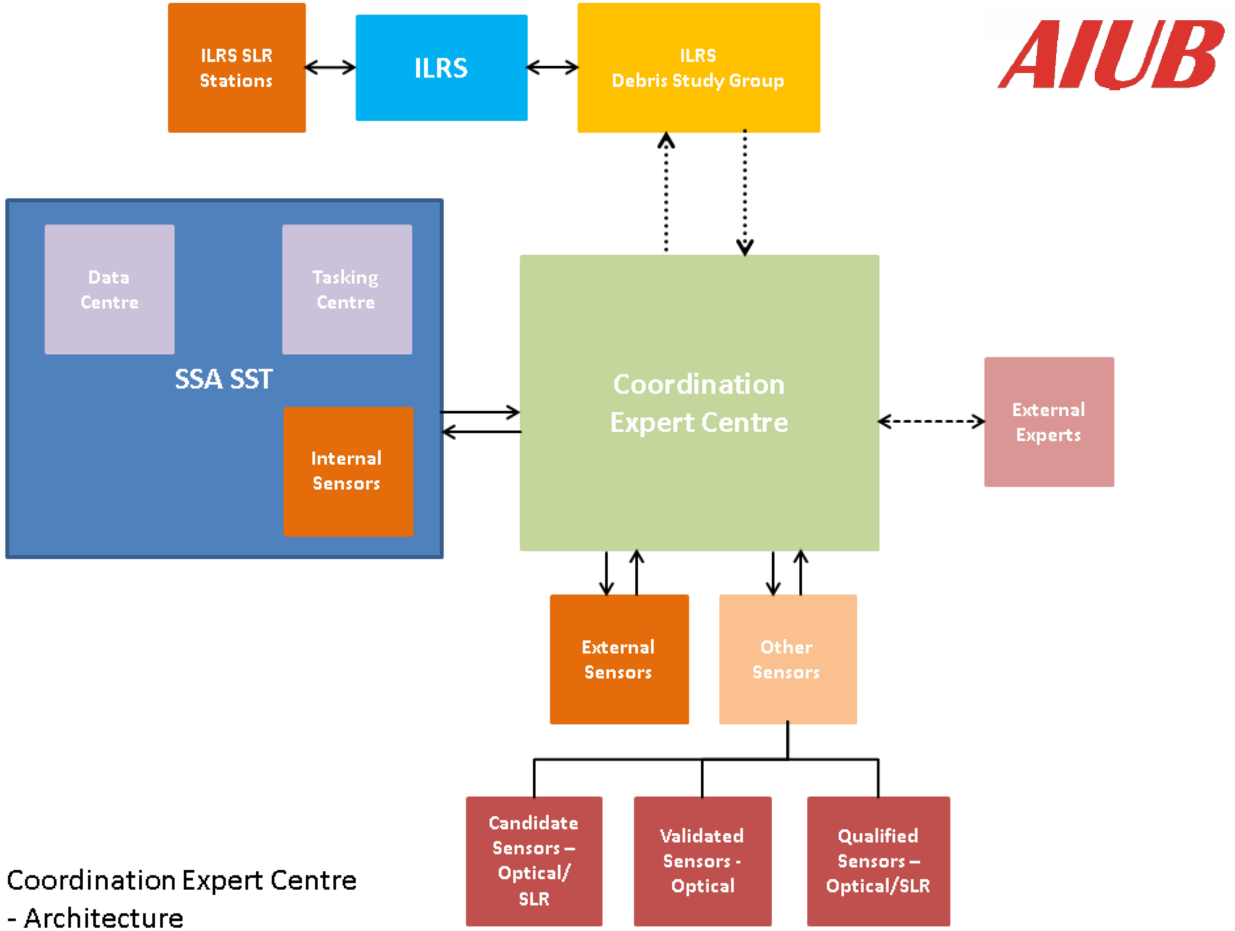
Expert Centre Overview

Space Debris laser ranging is not possible in isolation ➔ Space Surveillance Systems working **with such "External Sensors"** means:

1. **Overhead for coordinating external sensors**
   (proprietary formats and interfaces, sensors capabilities and availability)
2. **Need for proxy between data processing/tasking backend systems and the sensors**
   (as interface, for support services and research, for technology development)

Future tasks: Coordination of attitude/attitude motion estimation

→ Talk by Schildknecht et al.



Coordination Expert Centre - Architecture

Plans for Laser Technology – 4MEUR request tracking & LMT

under Space Safety Period 2 COSMIC for 2023-25

Further advance of laser networking technologies

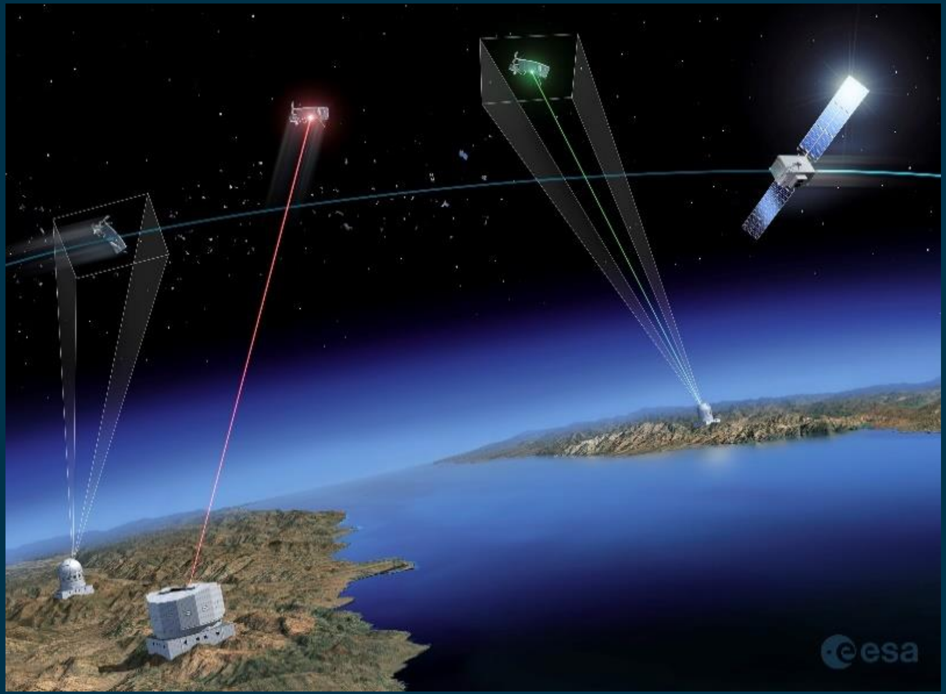
- IZN-1 as test-bed and reference station for experiment support
- Mature laser tracking technology towards a commercial ad-hoc service

Demonstration of the momentum transfer through ground-based lasers

- Phase A/B1 of engineering station
- De-risk components for a future full system of 10 LMT stations

Reducing position uncertainties by advanced precise laser tracking of debris with existing space debris lasers

Enabling **technology transfer** from ESA's laser ranging testbed to national systems



Status:
Test-bed IZN-01 accepted

Upgrading for debris ranging and networking demonstration started
→ GMV
→ Digos

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Summary

Space-based applications are a core, vital, and indispensable element of our modern societies

Space debris is

- A problem caused by human space activities and growing threat to current and future space utilisation
- A significant cost and safety issue in today‘s spacecraft operations
- Detected and catalogued through radar, optical, and in-situ sensors; Laser ranging is emerging**, with strong commercialisation opportunities**, for ad hoc improvements to collision avoidance, for attitude estimation, and for object identification
- Subject to internationally coordinated mitigation measures addressing the pressing need for global Space Traffic Management (STM)

The very near future starts today

- Revolution in space traffic in LEO – managing it calls for **technologies** supporting the needed regulation
- ESA through Space Safety Program advances laser tracking of space debris and studies the feasibility of Laser Momentum Transfer

There are many opportunities – but it is also „Time to act“!