EE-587
Space sustainability, a multidisciplinary approach

Lecture 3 - Space Situational Awareness

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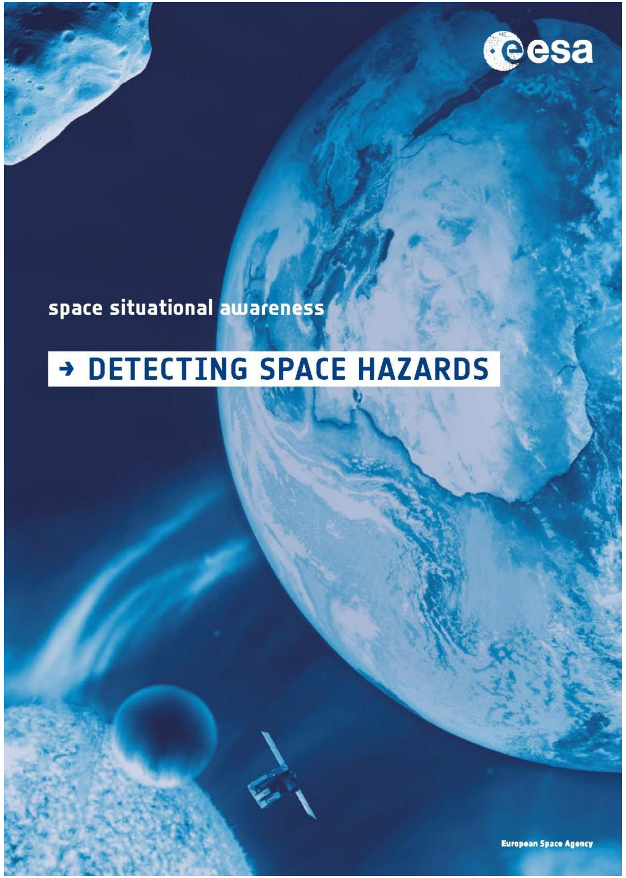
EPFL Space Center

Education

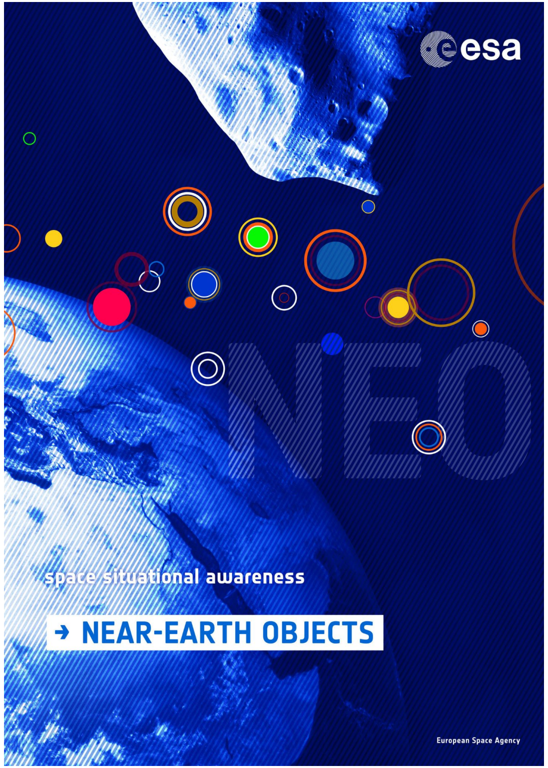
Space Situational Awareness (SSA)

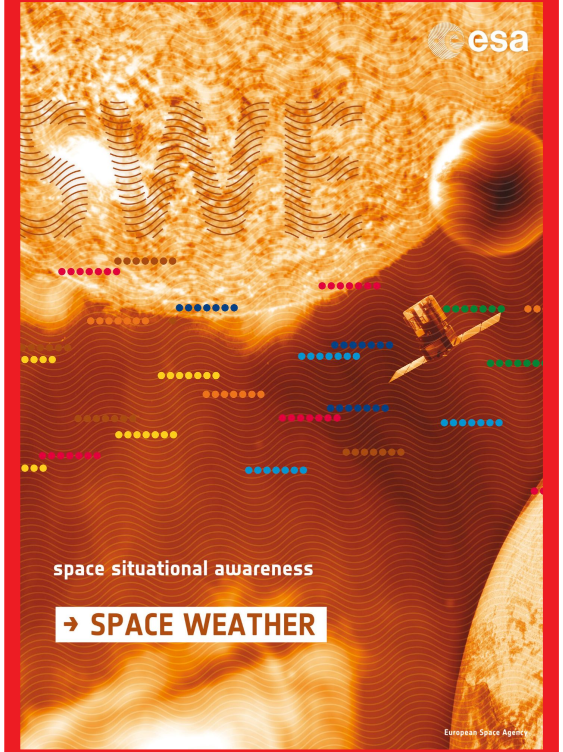
"Space Situational Awareness or 'SSA' means a holistic approach, including comprehensive knowledge and understanding, of the main space hazards, encompassing collision between space objects, fragmentation and re-entry of space objects into the atmosphere, space weather events, and near-Earth objects."

Regulation (EU) 2021/696 of the European Parliament and of the Council of 28 April 2021 establishing the Union Space Programme and the European Union Agency for the Space Programme and repealing Regulations. http://data.europa.eu/eli/reg/2021/696/oj



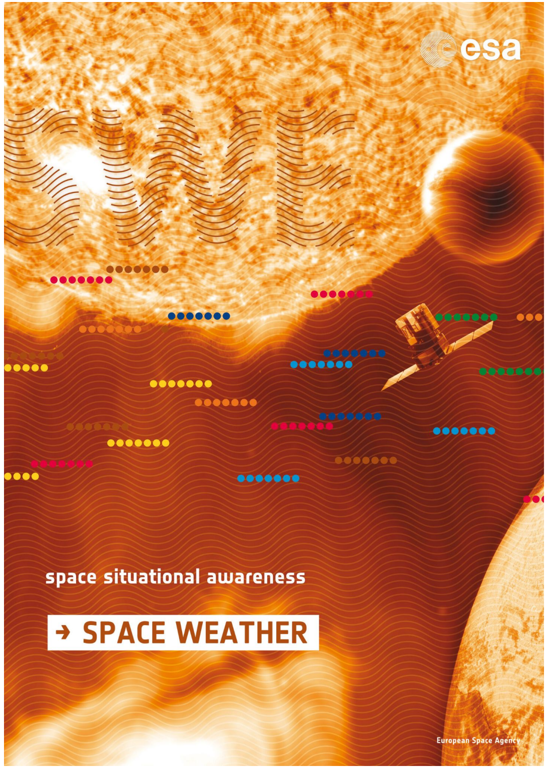
Space Situational Awareness (SSA)





Space Weather

Space Weather is the physical and phenomenological state of natural space environments. The associated discipline aims, through observation, monitoring, analysis and modelling, at understanding and predicting the state of the Sun, the interplanetary and planetary environments, and the solar and non-solar driven perturbations that affect them, and also at forecasting and nowcasting the potential impacts on biological and technological systems.



European Cooperation in the field of Scientific and Technical Research (COST) Action 724,
“**Developing the basis for monitoring, modelling and predicting Space Weather**” , 2009

Space Weather Events

Flare - Emission of electromagnetic radiation in the Sun's atmosphere

Coronal mass ejection (CME) - Ejection of plasma from the Sun's corona into the heliosphere

Solar particle event (SPE) - Particles emitted by the Sun, accelerated during a flare or by a CME

Solar and Heliospheric Observatory (SHOHO)

Space Weather Events

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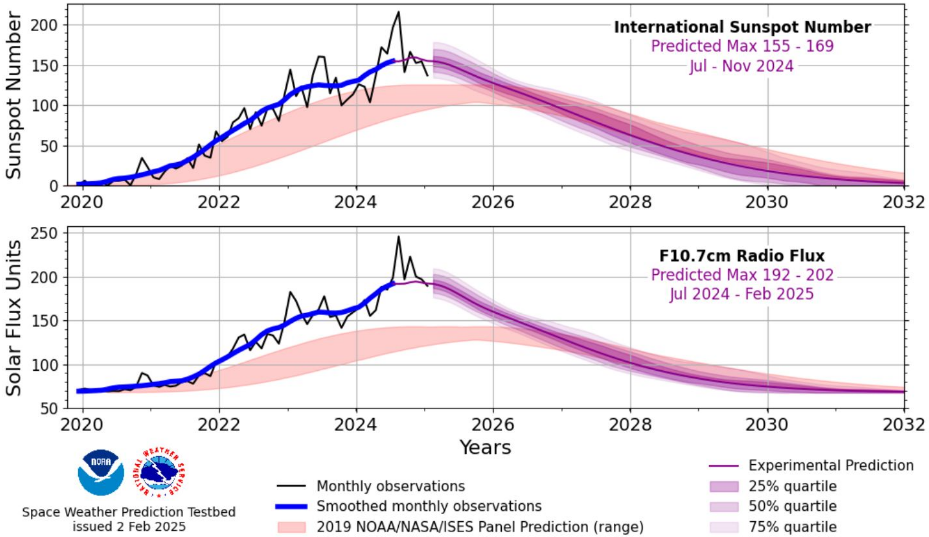


Space Weather Prediction Testbed (SWPT)

Space Weather Consequences

High solar activity causes disruptions to communications, aircraft, spacecraft and power grid

46 of the 70 spacecraft failures reported in 2003 occurred during the October 2003 geomagnetic storm

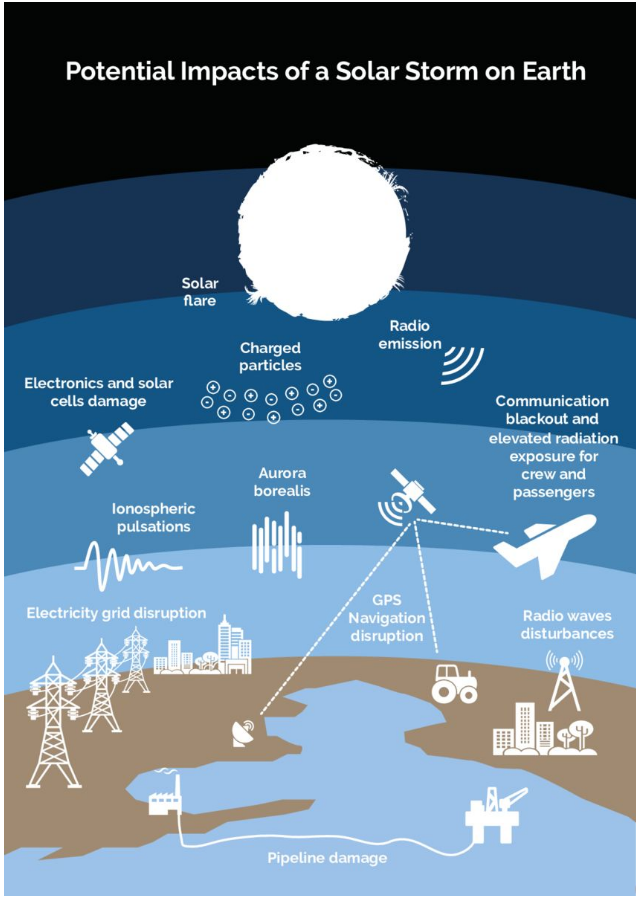
The storm further caused a blackout in Sweden

In February 2022, 38 out of 49 Starlink satellites were lost due to a series of CMEs just after deployment

Table 1
List of Observed CMEs That Contributed to the Geomagnetic Perturbations on 3 and 4 February 2022.

Event no.	Time of CME appearance in LASCO C2 (UT)	CME apex location obtained from GCS (Lat, Lon)[a] (°, °)	3D CME speed from GCS (km s^{-1})	Estimated Earth arrival time from DBEM[b] (UT)	Expected Earth arrival speed (km s^{-1})	Probability of reaching Earth estimated by DBEM
1	2022-01-29 23:36	−6, 329	791	2022-02-01 15:15	573	99% hit
2	2022-01-31 16:10	15, 23	357	2022-02-05 02:44	413	99% hit
3	2022-02-01 07:12	17, 19	458	2022-02-05 04:23	439	98% hit

Y. Baruah et al., "**The Loss of Starlink Satellites in February 2022: How Moderate Geomagnetic Storms Can Adversely Affect Assets in Low-Earth Orbit**," Space Weather, 2024, https://doi.org/10.1029/2023SW003716



M. K. Georgoulis *et al.*, "**The Flare Likelihood and Region Eruption Forecasting (FLARECAST) Project: Flare forecasting in the big data & machine learning era**," 2021, doi: 10.48550/arXiv.2105.05993.

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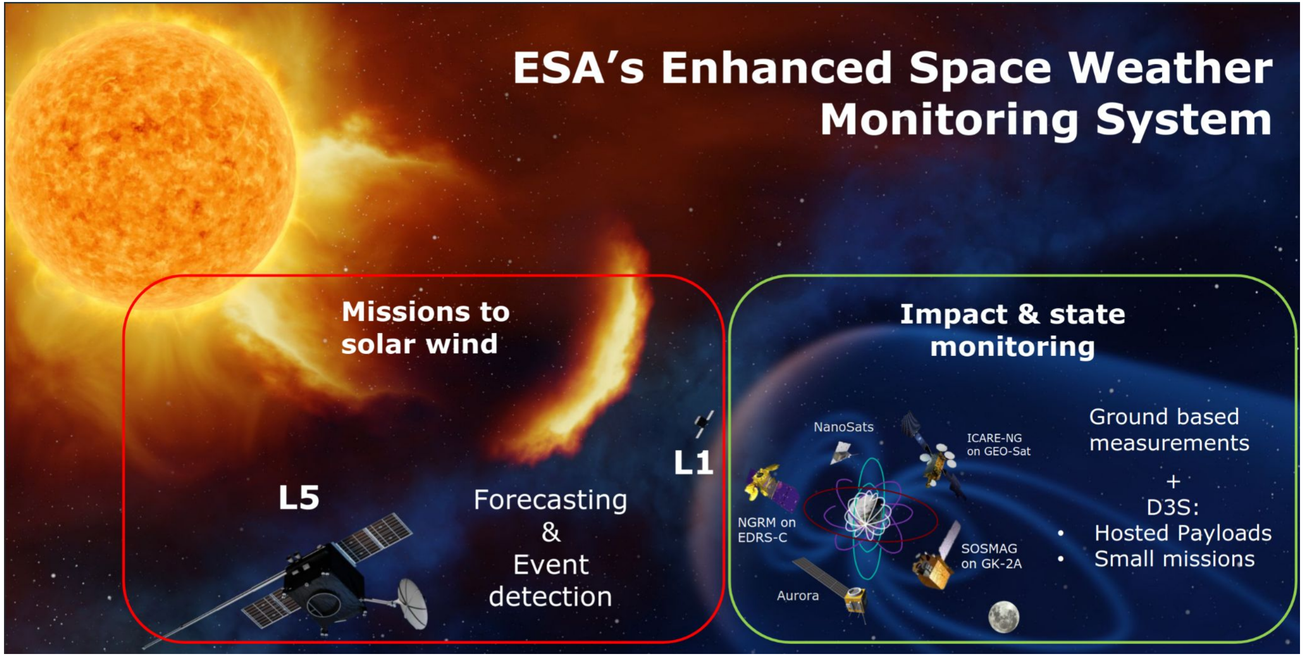
Distributed Space Weather Sensor System

Utilising hosted payload opportunities and dedicated small satellites in LEO, MEO, GEO, HEO and Lunar orbit



M. Heil et al. “**ESA’s Space Weather Monitoring System**”, 17th International Conference on Space Operations, Dubai, 2023, https://star.spaceops.org/2023/user_manudownload.php?doc=652__9bv6w5vl.pdf

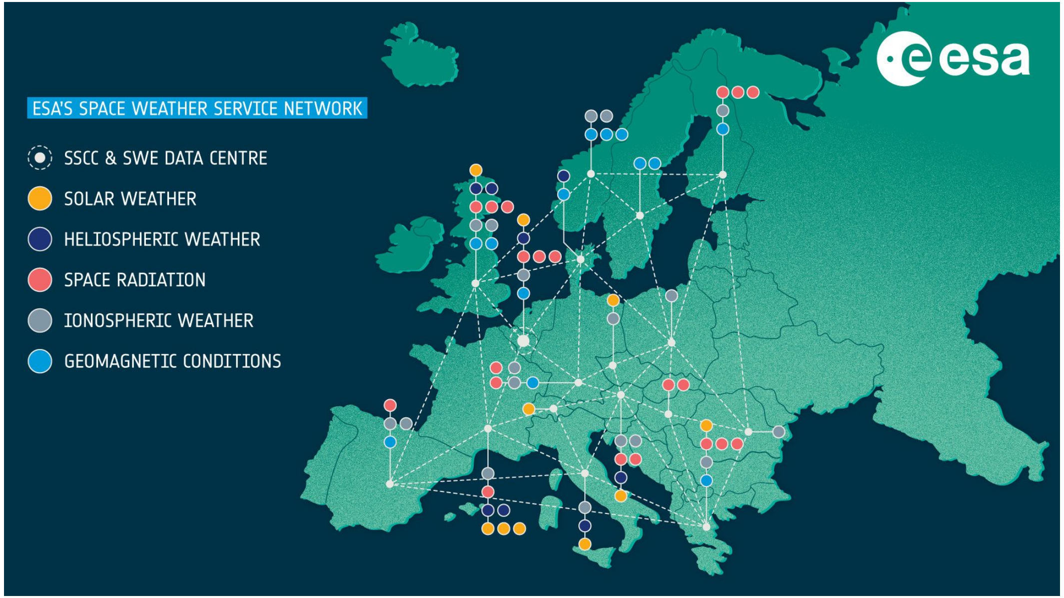
Space Weather Service Network

Provide services, data products and tools to operators

Coupled modelling of the full Sun-Earth chain

Timely and reliable user tailored notifications and alerting

Users from affected sectors, plus national and regional agencies



ESA's Space Weather Service Network

How to protect from Space Weather?

Monitor and analyze solar activity

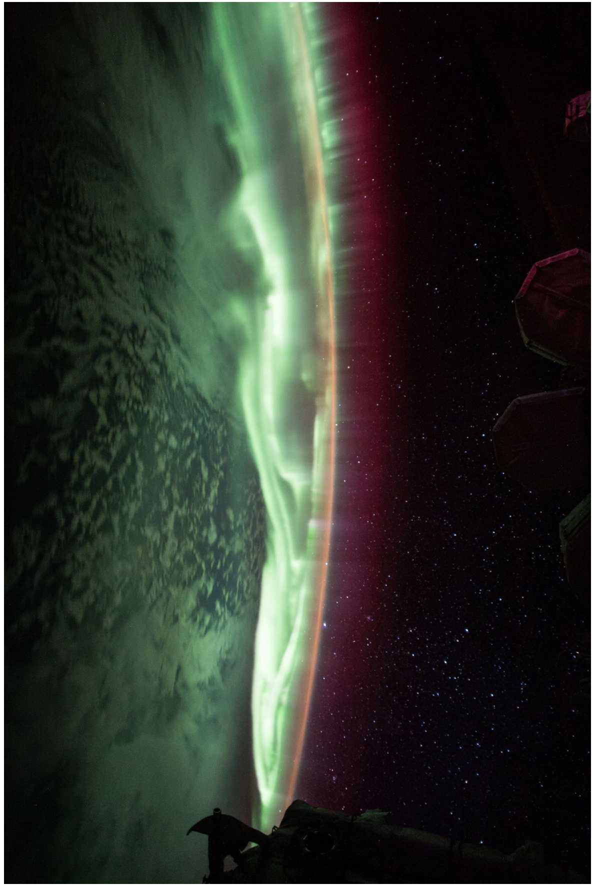
Improve modelling for better predictions and forecasts

Protect ground infrastructure by redundancy and geomagnetic induced current blocking devices

Avoid high-latitude flight routes during high solar activity

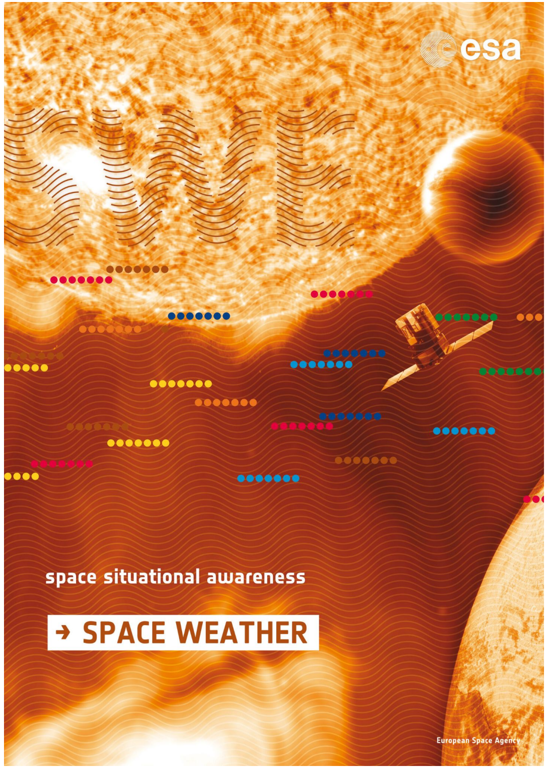
Protect spacecraft through shielding and radiation hardened electronics

Astronauts seek shelter in highly shielded ISS modules or perform emergency evacuation in case of very high radiation events



Auroras captured by the International Space Station on Aug. 6, 2017. Credits: NASA

Near-Earth Objects (NEOs)



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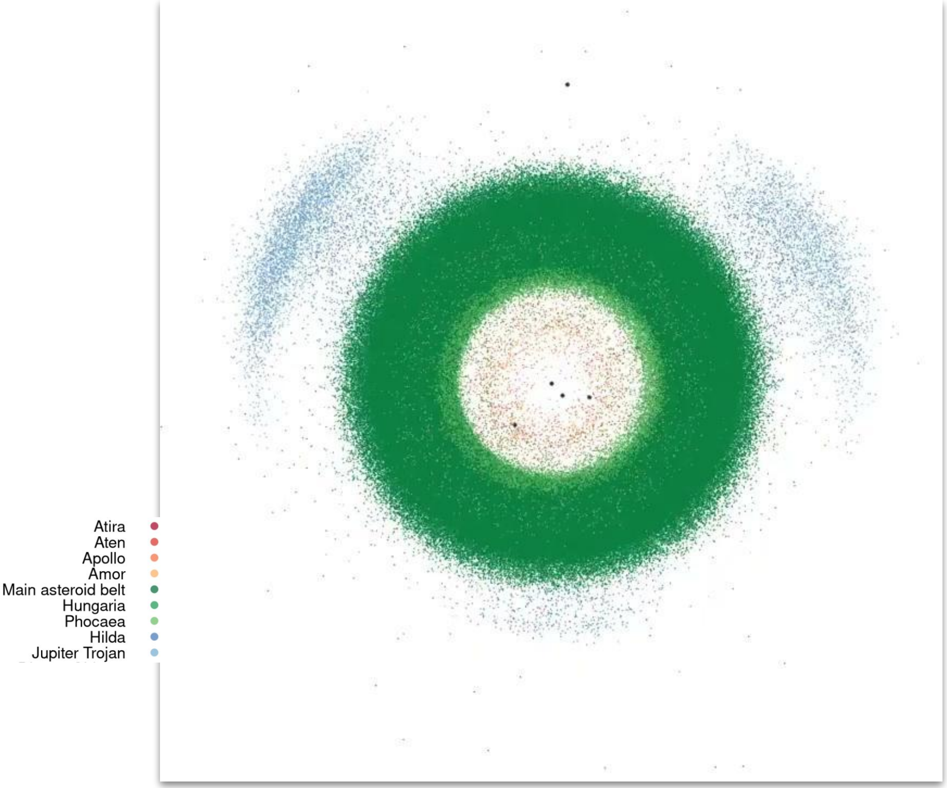


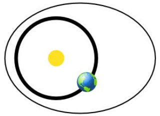
Near Earth Asteroids

q = perihelion distance
Q = aphelion distance
A = semi-major axis

q < 1.3 au

Amors

Earth-approaching NEAs with orbits exterior to Earth's but interior to Mars' (named after asteroid (1221) Amor)



a > 1 au
1.017 au < q < 1.3 au

Apollos

Earth-crossing NEAs with semi-major axes larger than Earth's (named after asteroid (1862) Apollo)

a > 1 au
q < 1.017 au

Atens

Earth-crossing NEAs with semi-major axes smaller than Earth's (named after asteroid (2062) Aten)

a < 1 au
Q > 0.983 au

Atiras

NEAs whose orbits are contained entirely within the orbit of the Earth (named after asteroid (163693) Atira)

a < 1 au
Q < 0.983 au

Potentially Hazardous Asteroids (PHAs)

NEAs whose Minimum Orbit Intersection Distance with the Earth (MOID) <= 0.05 au and whose absolute magnitude H <= 22.0 (D >= ~140 m)

NASA JPL Center for Near Earth Object Studies (CNEOS)

Near-Earth Objects - Consequences

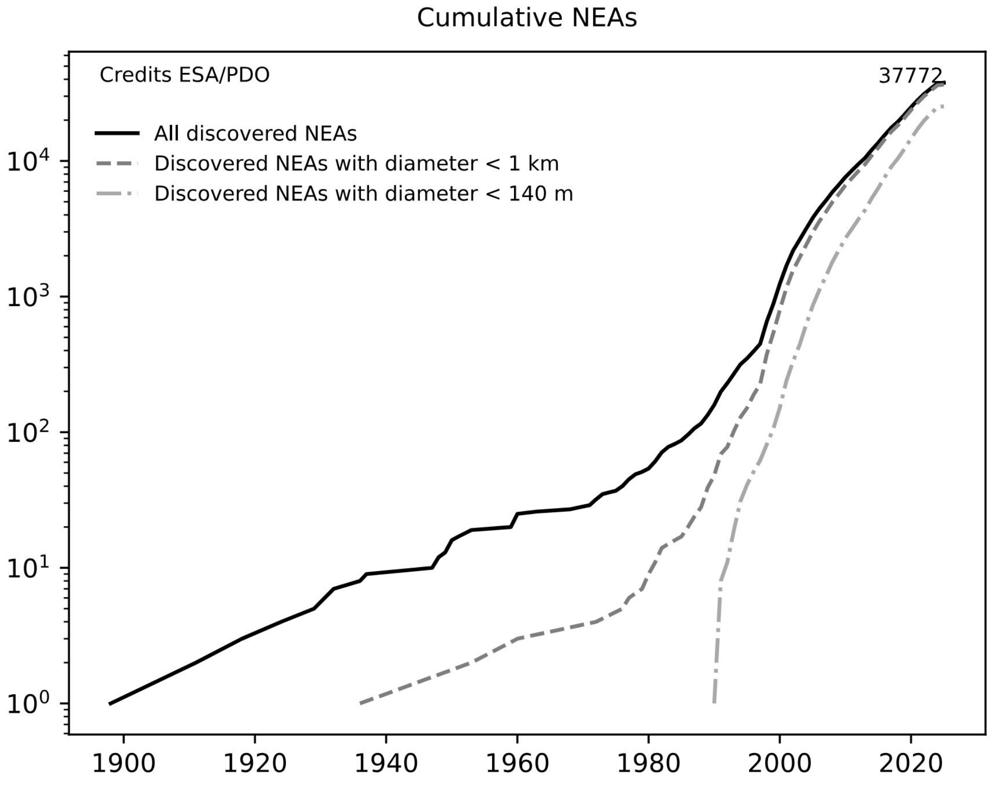
Near-Earth Object Environment

Surveys to search for NEOs started during the 1990s

Today, there are about 38’000 NEOs known

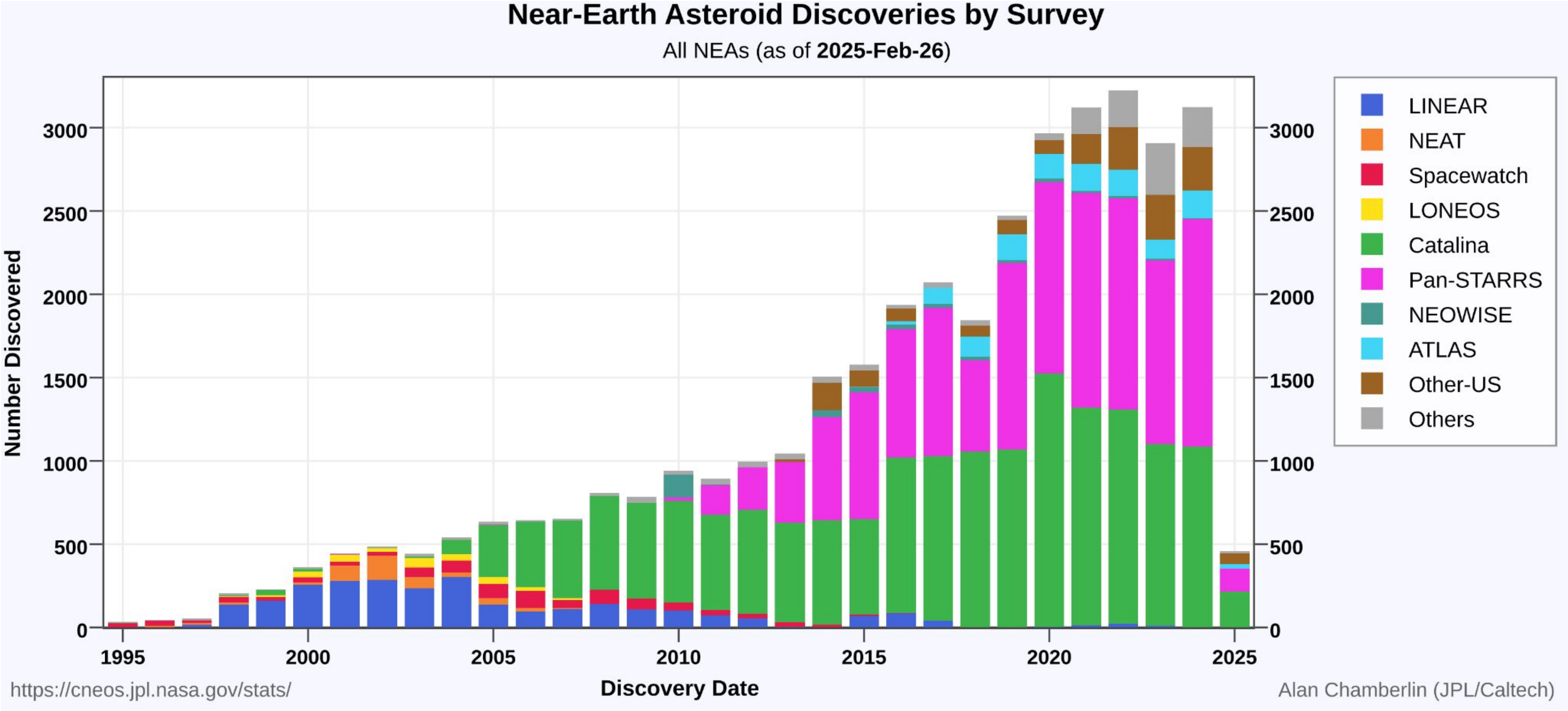
Small (<140 m) diameter objects make up the majority of the population

Only 2’481 NEOs are PHAs



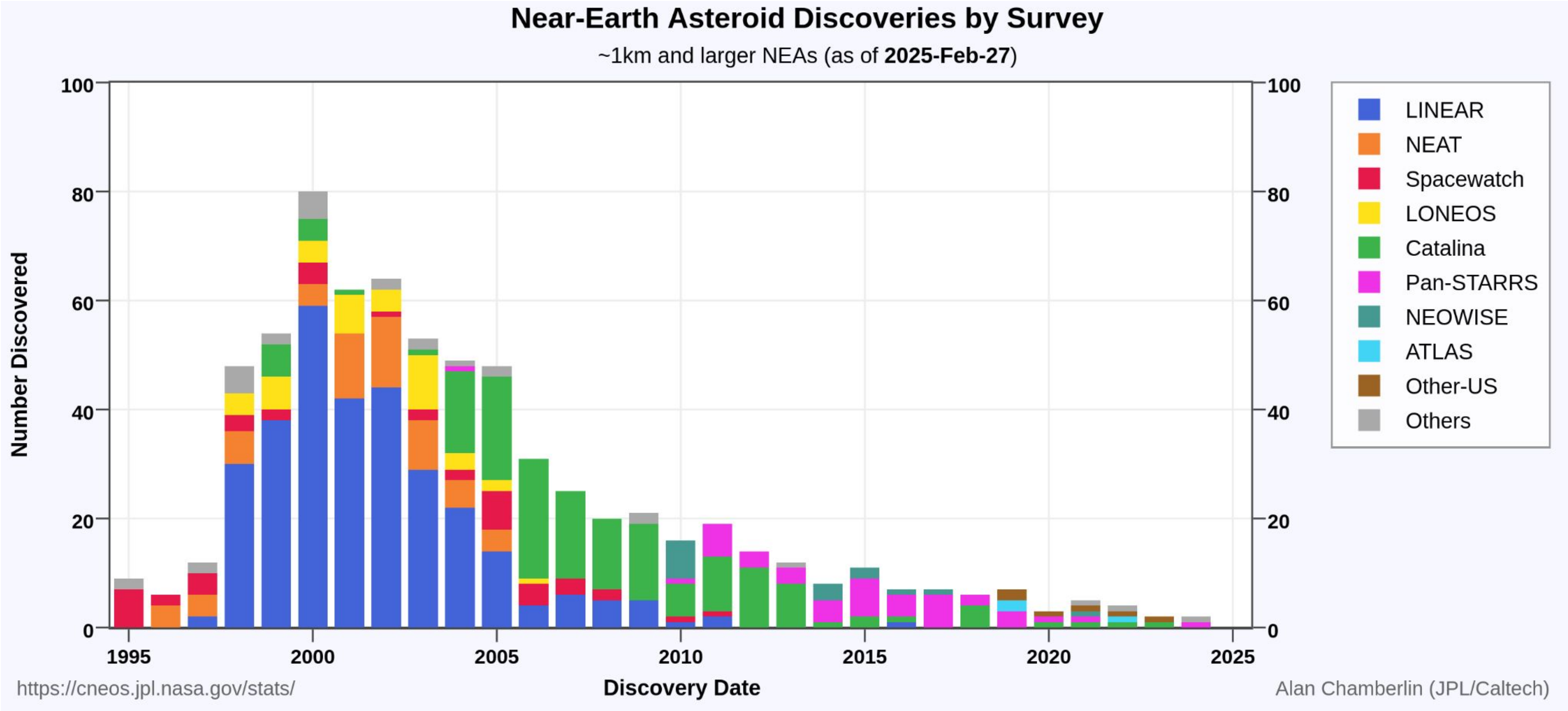
ESA near-earth objects coordination centre (NEOCC)

Near-Earth Object Discoveries



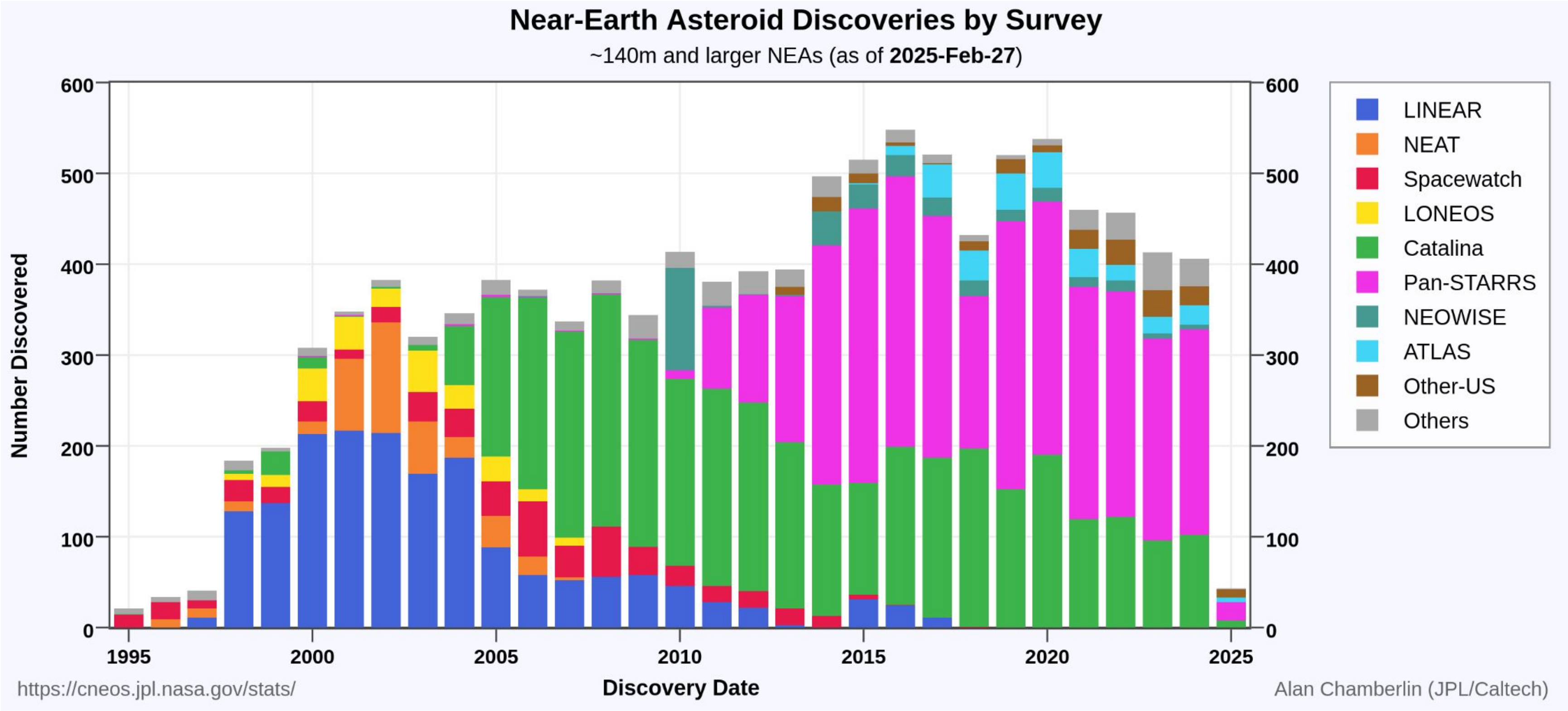
NASA JPL Center for Near Earth Object Studies (CNEOS)

(Large) Near-Earth Object Discoveries



Population of large NEOs is almost entirely discovered.

(Small) Near-Earth Object Discoveries



Population of medium sized NEOs is still not fully discovered.

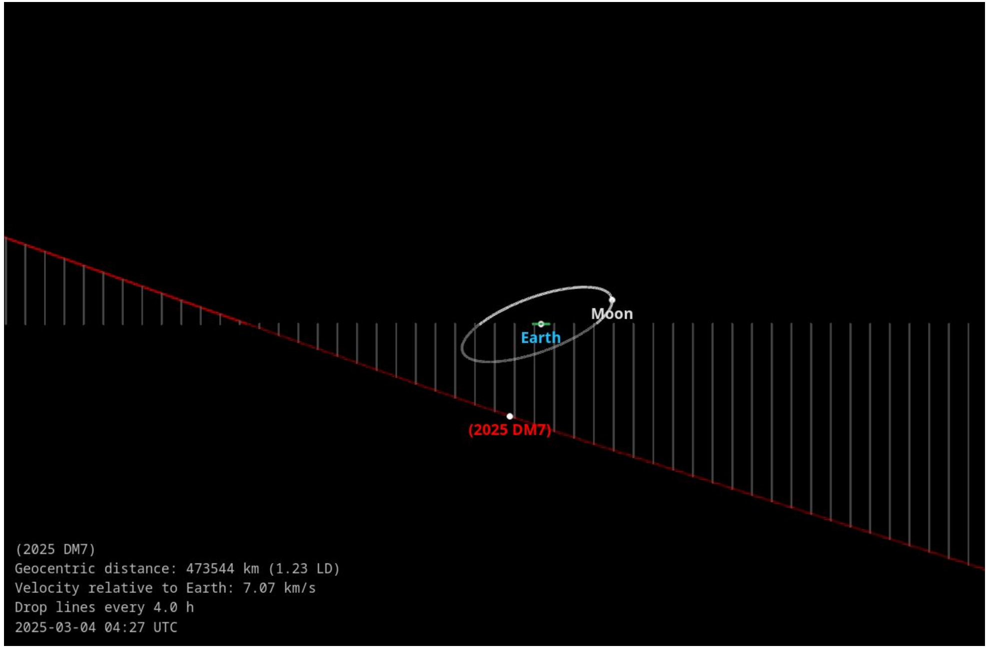
Coordination of the observations

Observations submitted to the Minor Planet Center (MPC)

The MPC publishes all data, performs orbit determination and maintains lists of newly discovered NEOs

Amateur community supports with follow-up observations to constrain the orbits

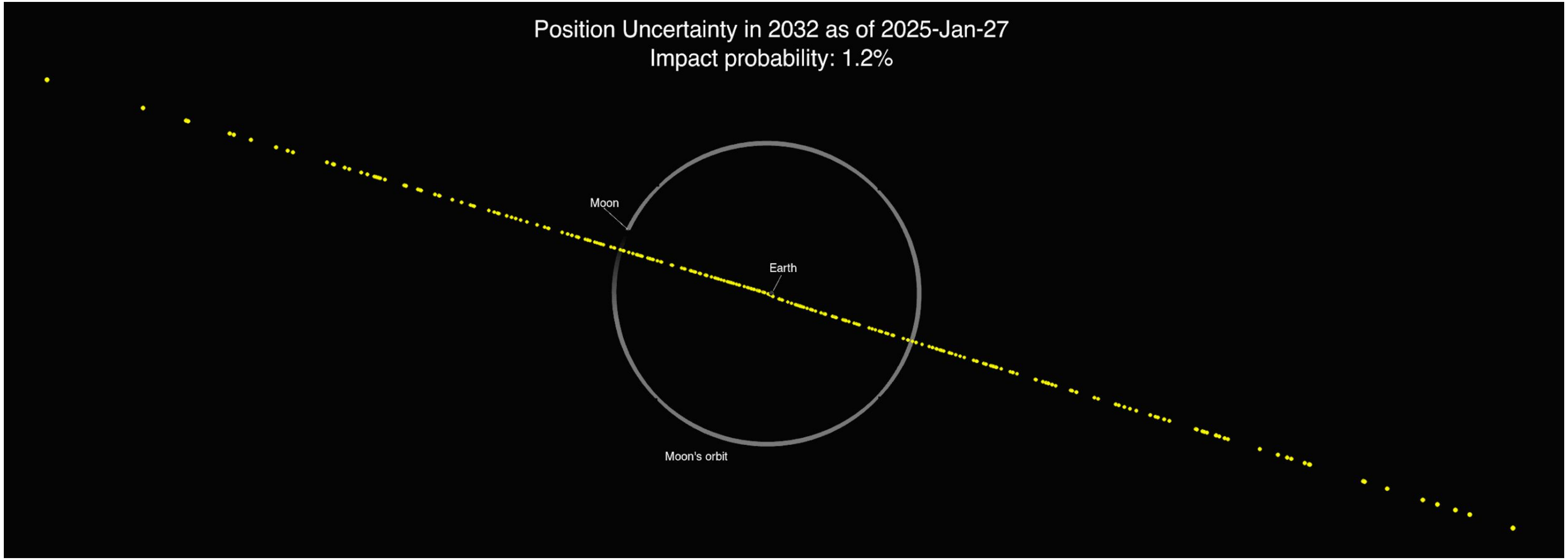
Close approaches happen almost daily



NASA JPL Center for Near Earth Object Studies (CNEOS)

2024 YR4

Latest calculations conclude asteroid 2024 YR4 now poses no significant threat to Earth in 2032 and beyond



NASA Planetary Defense

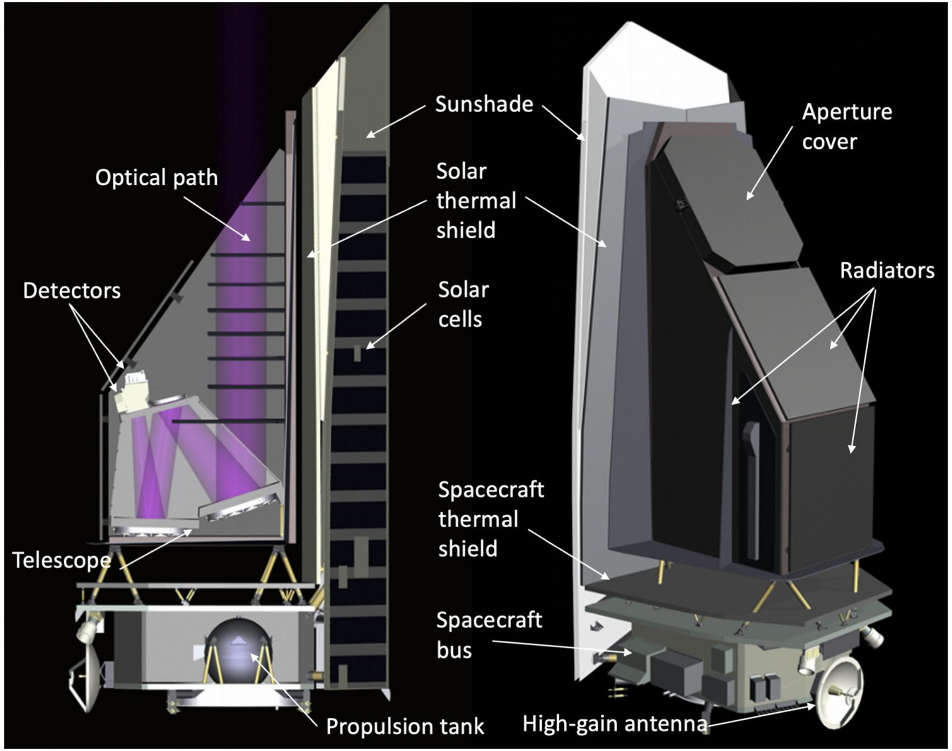
NEO Surveyor - Next Generation Survey

Mission to the Sun-Earth L_1 Lagrangian point (launch in 2027)

Find at least ⅔ of all NEOs larger than 140 m and assess the threat posed by PHAs

Determine orbits, sizes, compositions, rotational states and shapes

Expected to discover 200’000 - 300’000 new NEOs



A. K. Mainzer *et al.*, “**The Near-Earth Object Surveyor Mission**” *The Planetary Science Journal*, 2023, doi: 10.3847/PSJ/ad0468.

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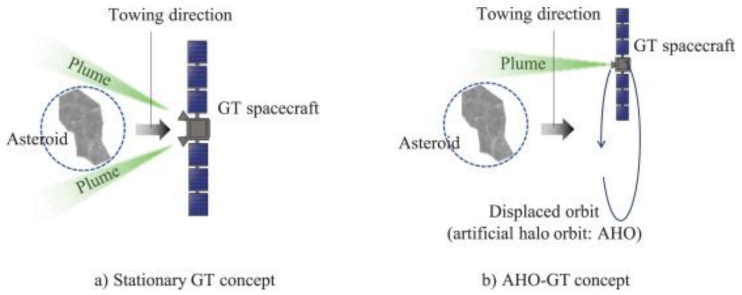
How to protect from Near-Earth Objects?

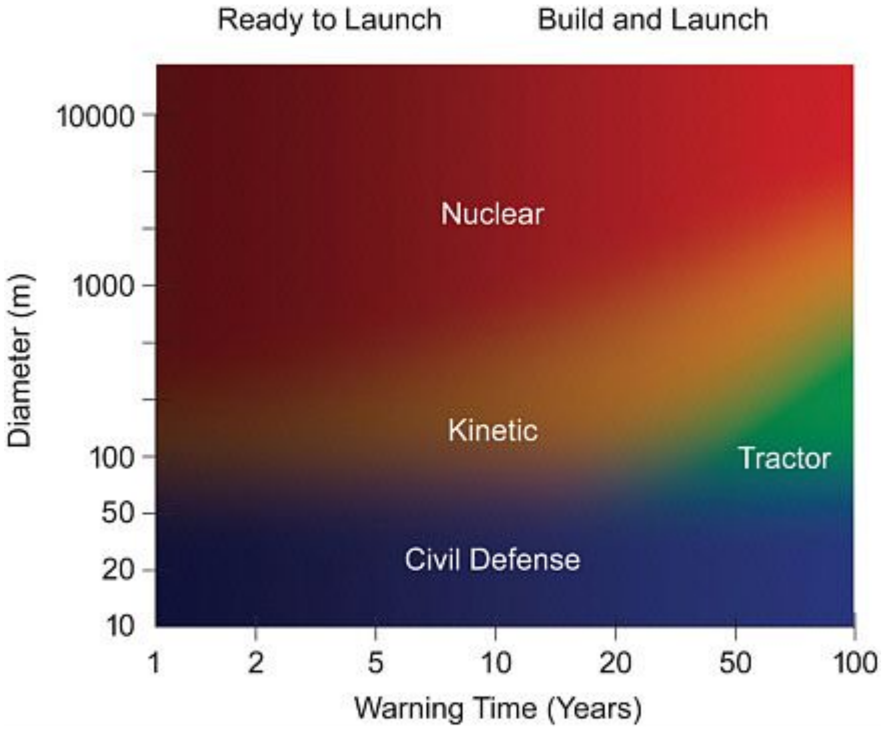
How to protect from NEOs?

Studies to evaluate difference scenarios have been carried out over the last 20 years

First demonstration missions underway



Two types of gravity tractor strategies.
K. Yamaguchi et al. “**Orbital dynamics of gravity tractor spacecraft employing artificial halo orbit**”, Acta Astronautica, 2022, https://doi.org/10.1016/j.actaastro.2022.06.009

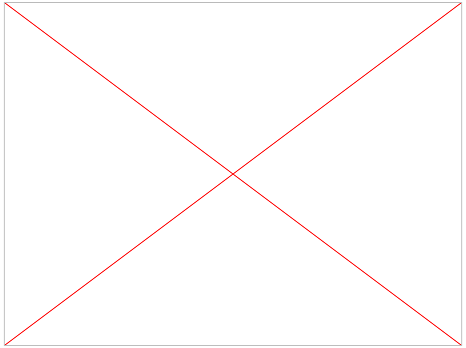


Approximate outline of the regimes of primary applicability of the four types of mitigation.
National Academies of Sciences, Engineering, and Medicine. “**Defending Planet Earth: Near-Earth-Object Surveys and Hazard Mitigation Strategies**”, 2010, https://doi.org/10.17226/12842.

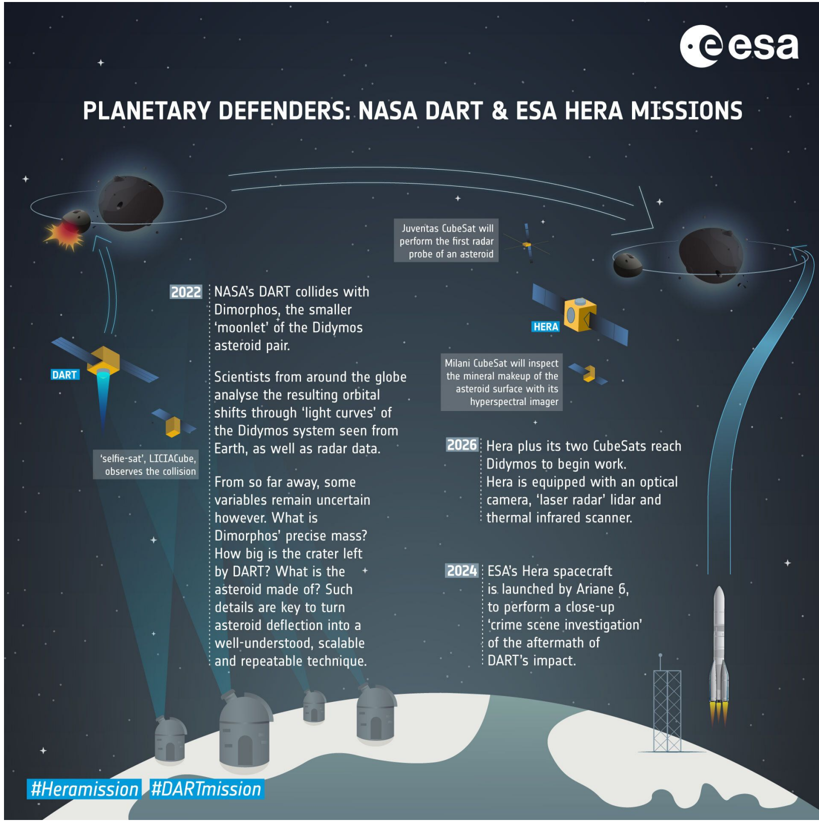
DART and Hera missions

The Double Asteroid Redirection Test (DART) mission impacted Dimorphos, the satellite of binary NEA Didymos, on 2022 September 26

Hera will measure the size and morphology of the crater created as well as the momentum transferred to evaluate the efficiency of the deflection



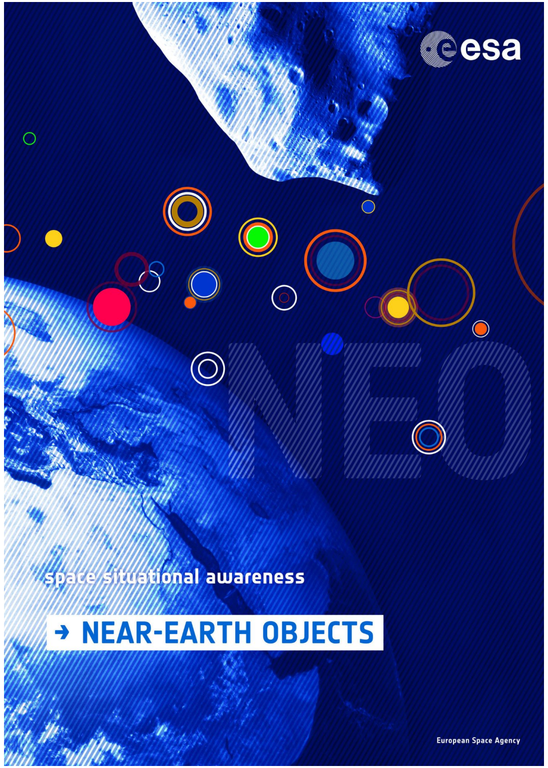
The final five-and-a-half minutes of images leading up to the DART spacecraft's intentional collision with asteroid Dimorphos. Credit: NASA/Johns Hopkins APL

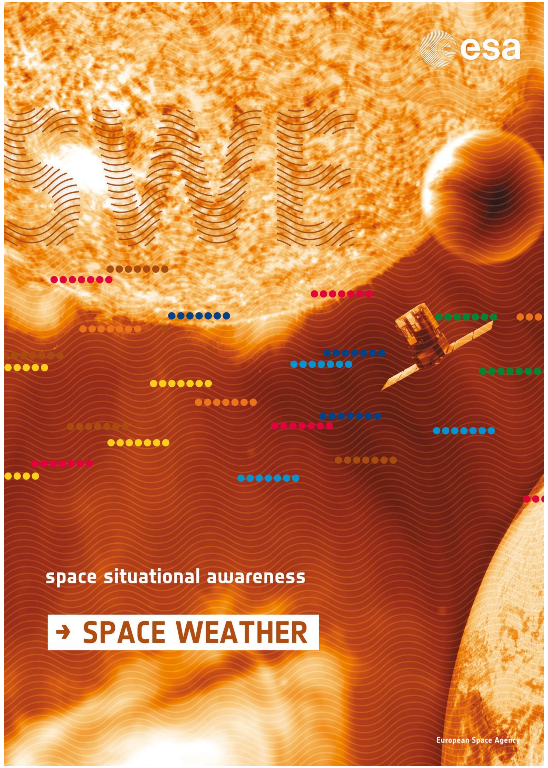


NASA's Double Asteroid Redirect Test, DART and ESA Hera spacecraft to perform a close-up analysis of the diverted asteroid. Credit: ESA

S. P. Naidu et al. "**Orbital and Physical Characterization of Asteroid Dimorphos Following the DART Impact**", The Planetary Science Journal, 2024, https://doi.org/10.3847/PSJ/ad26e7

Space Surveillance and Tracking





The near Earth Space Environment

Rocket launches since the start of the space age in 1957
About 6’840 (excluding failures)

Satellites these rocket launches have placed into Earth orbit
About 20’650

Satellites still in space
About 13’660

More than currently known NEOs!

Satellites still functioning
About 11’000

Space objects tracked by Space Surveillance Networks
About 39’340

Estimated number of break-ups, explosions, collisions
More than 650

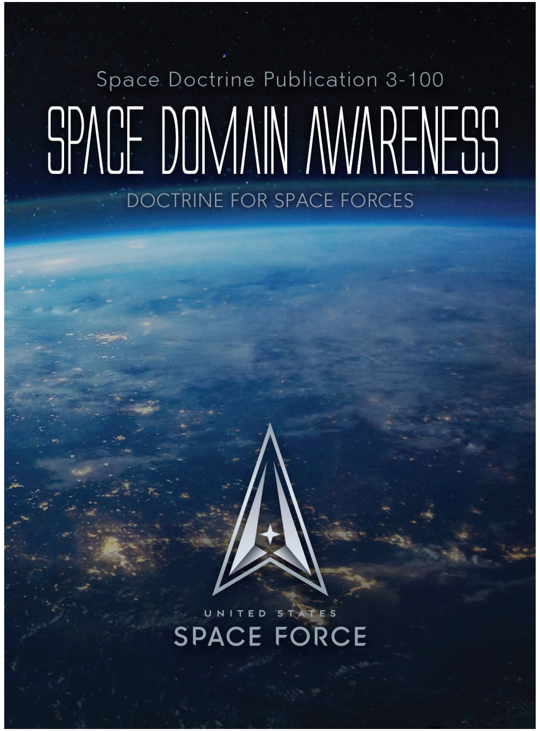
Total mass of all space objects in Earth orbit
More than 13’500 tonnes

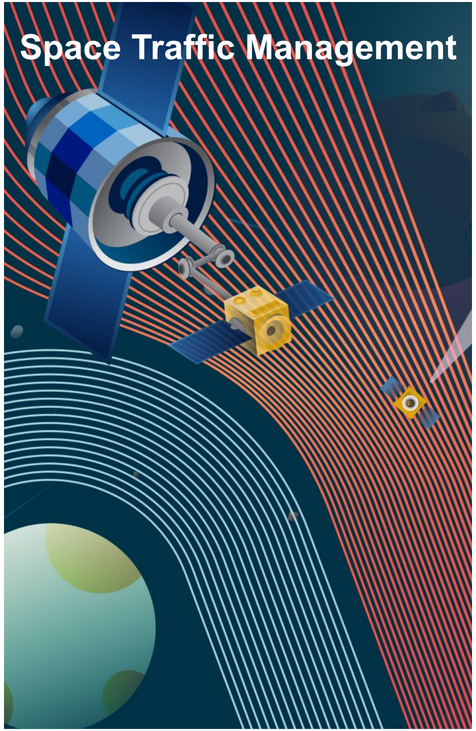
Estimated number of space debris objects
40’500 objects greater than 10 cm
1’100’000 objects from greater than 1 cm to 10 cm
130 million objects from greater than 1 mm to 1 cm

Distribution of space debris in orbit around Earth
Red: satellites (functional or dysfunctional)
Yellow: rocket bodies
Green: mission related objects (covers, caps, adapters, etc.)
Blue: fragments

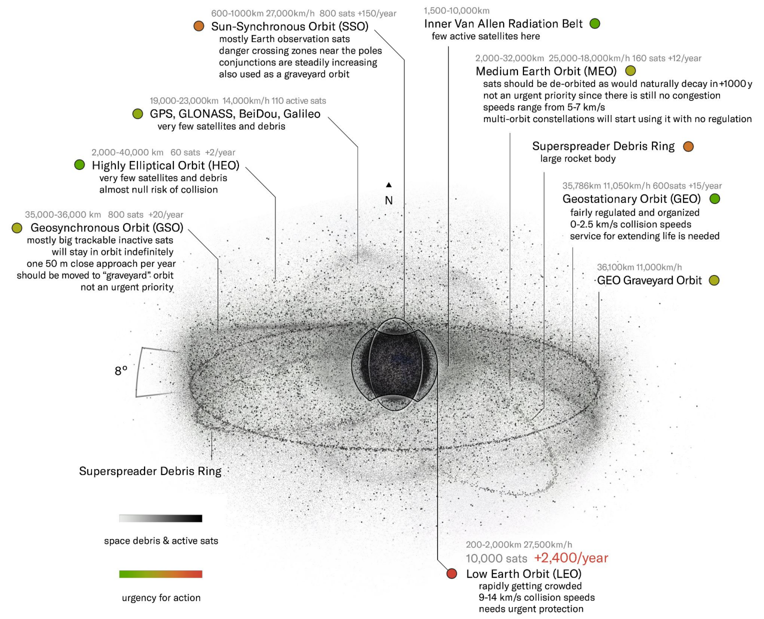
ESA: Space debris by the numbers

Space Surveillance and Tracking (SST)





Space Sustainability



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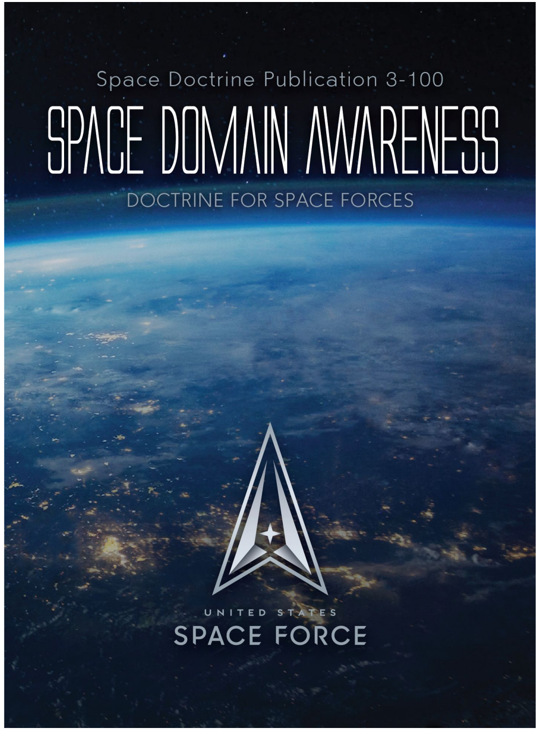
Space Domain Awareness (SDA)

The timely, relevant, and actionable understanding of the operational environment that allows military forces to plan, integrate, execute, and assess space operations.

Space Training and Readiness Command (STARCOM), "**Space Domain Awareness**", Space Doctrine Publication (SDP) 3-100, 2023, https://www.starcom.spaceforce.mil/Portals/2/SDP%203-100%20Space%20Domain%20Awareness%20(November%202023)_pdf_safe.pdf



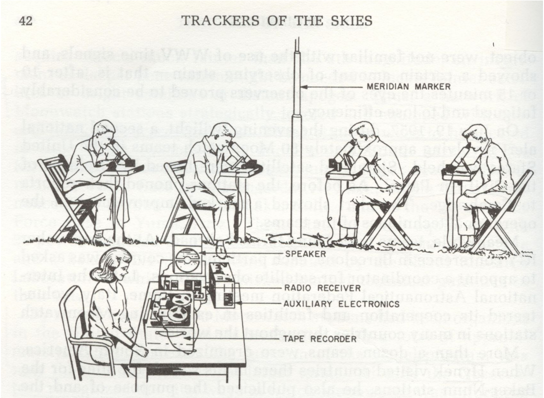


Figure 5. — Typical Moonwatch team in action, 1957.

Operation Moonwatch

Patrick McCray, "**Keep Watching the Skies!: The Story of Operation Moonwatch and the Dawn of the Space Age**", Princeton University Press, 2008, https://www.jstor.org/stable/j.ctv1nj34w4

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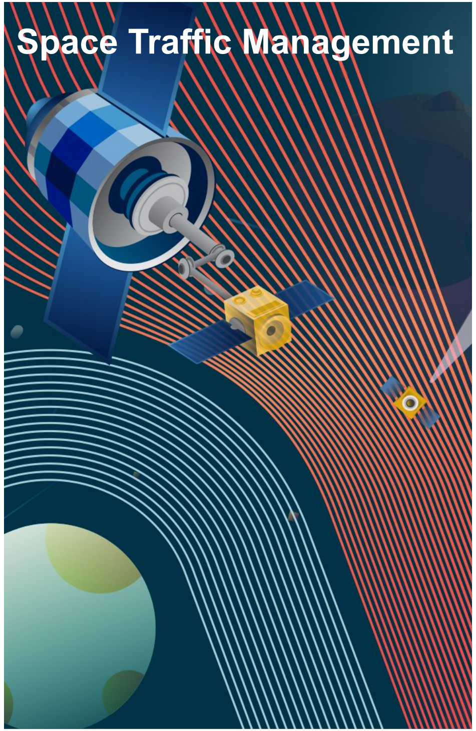
Space Traffic Management (SST)

Space Traffic Management is the assurance value chain that contributes to a safe, secure, and sustainable space operations environment, composed of space traffic coordination and regulation & licensing, and dependent upon a foundation of continuous space situational awareness.

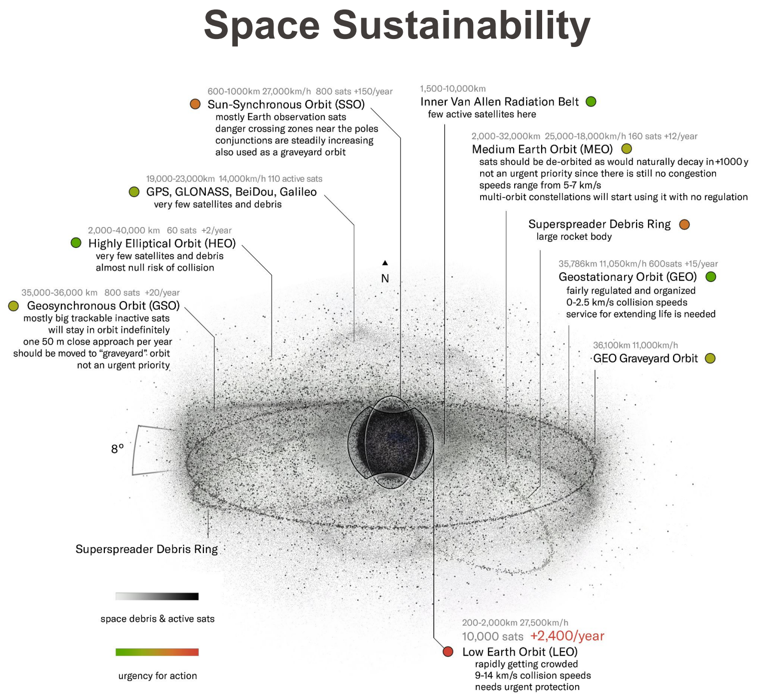
The International Academy of Astronautics (IAA), the International Astronautical Federation (IAF) and the International Institute of Space Law (IISL), "**Cooperative initiative to develop comprehensive approaches and proposals for Space Traffic Management (STM)**", Memorandum of Understanding during the IAC in Bremen, 2018, https://iaaspace.org/wp-content/uploads/iaa/Communication/stm-mou.pdf



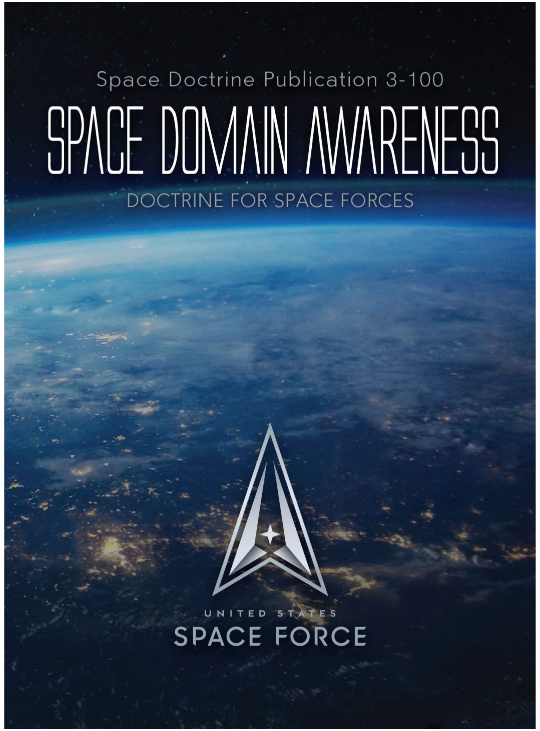
Space Sustainability

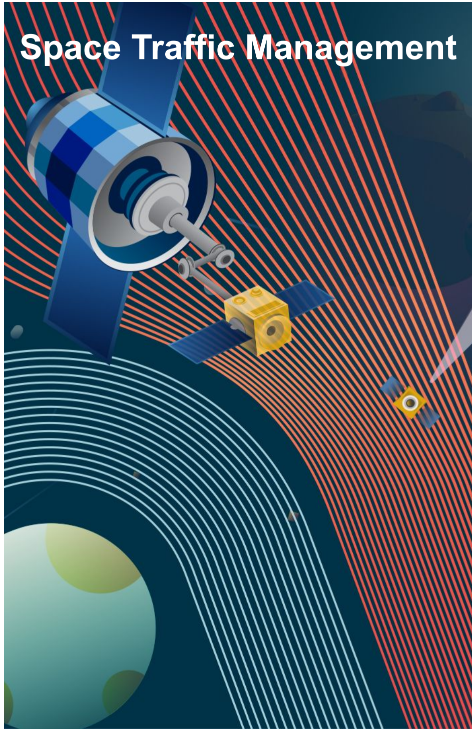
The ability to maintain the conduct of space activities indefinitely into the future in a manner that realizes the objectives of equitable access to the benefits of the exploration and use of outer space for peaceful purposes, in order to meet the needs of the present generations while preserving the outer space environment for future generations.

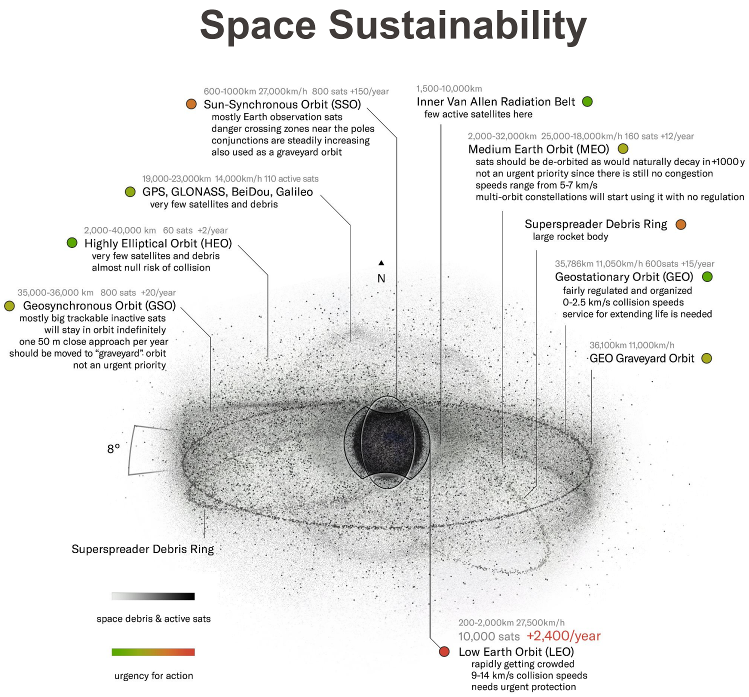
United Nations Office for Outer Space Affairs (UNOOSA), “**Guidelines for the Long-term Sustainability of Outer Space Activities of the Committee on the Peaceful Uses of Outer Space**”, Vienna, 2021, https://www.unoosa.org/documents/pdf/PromotingSpaceSustainability/Publication_Final_English_June2021.pdf



What do they have in common?







Space Surveillance and Tracking (SST)

A Space Surveillance Tracking (SST) system is a network of ground-based and/or space-based sensors capable of surveying and tracking space objects, together with processing capabilities aiming to provide data, information and services on space objects that orbit around the Earth.

EU SST – EU Space Surveillance and Tracking

SST Observation Techniques
Ground-based sensors

Radars to detect and track small debris on **LEO**

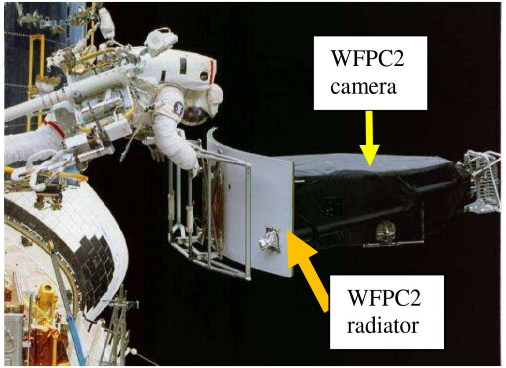
Passive-optical **telescopes** for surveillance of **MEO-GEO** region

Sub-mm debris population characterized by studying **objects returned from orbit**

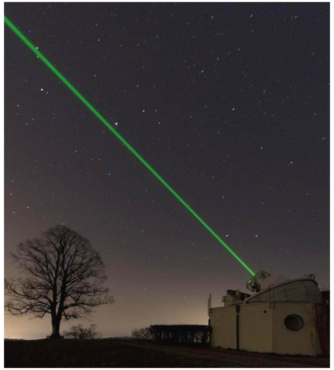
Satellite **Laser Ranging** for **high-precision** localization

LEOLABS Azores Space Radar on Santa Maria Island in the Azores, Portugal. Credit: LEOLABS.

Space Surveillance Telescope in Australia to provide coverage of objects in geosynchronous orbit. Credit: U.S. Air Force



The WFPC2 being installed aboard HST during 1993's Servicing Mission (SM1)
Anz-meador, P. D. et al., "**Sampling and Analysis of Impact Crater Residues Found on the Wide Field Planetary Camera-2 Radiator**", 6th European Conference on Space Debris (2013), https://conference.sdo.esoc.esa.int/proceedings/sdc6/paper/184



Zimmerwald Observatory during SLR observations.
K. Sośnica. "**Determination of Precise Satellite Orbits and Geodetic Parameters using Satellite Laser Ranging**". Astronomical Institute, University of Bern, Switzerland, 2014 ISBN: 8393889804

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SST Observation Techniques
Ground-based sensors

Radars to detect and track small debris on **LEO**

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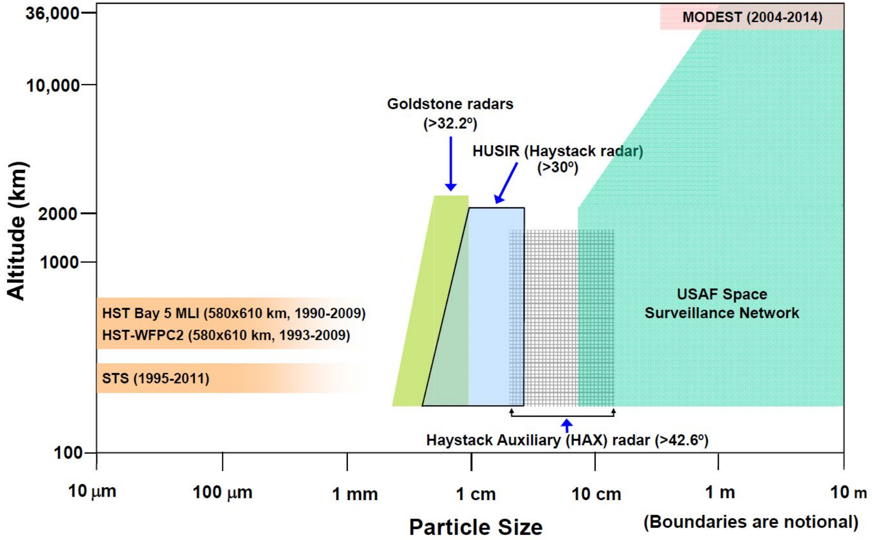
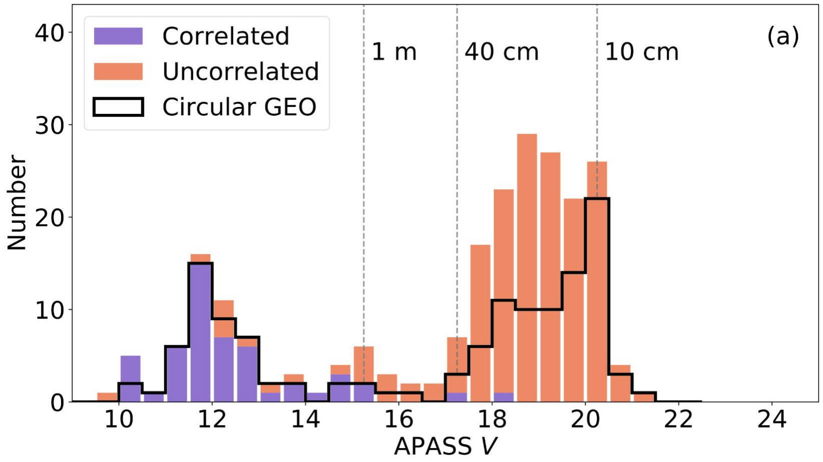


Measurement data used by the NASA Orbital Debris Program Office (ODPO) to describe the orbital debris populations in the near-Earth space environment. Credit: NASA ODPO.



Brightness histogram for the detected objects during DebrisWatch 1
J. A. Blake et al., "**DebrisWatch I: A survey of faint geosynchronous debris**" Advances in Space Research, 2021, https://doi.org/10.1016/j.asr.2020.08.008

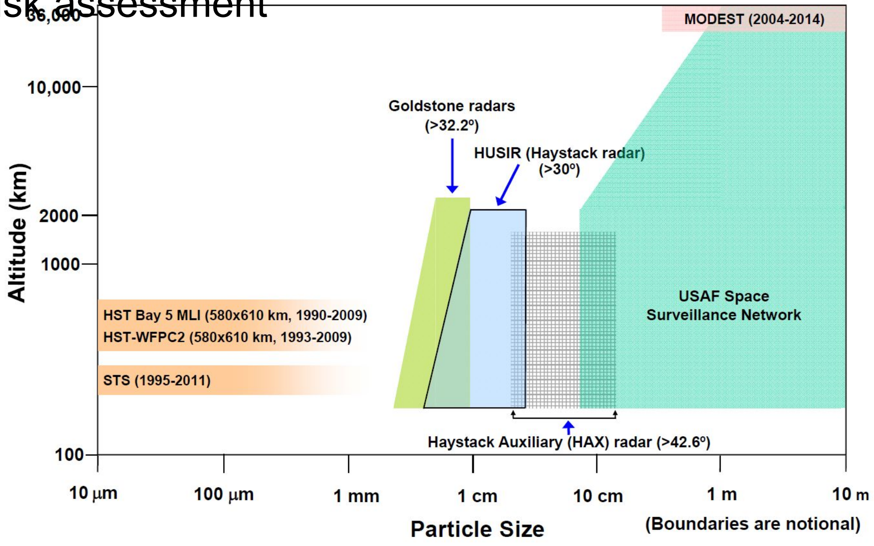
SST Observation Techniques
Knowledge Gaps

Large parts of the small but lethal debris currently not tracked

40,000 objects regularly tracked by Space Surveillance Networks but 1’100’000 objects from greater than 1 cm to 10 cm are expected

Precise orbit propagation requires information on attitude, shape and tumbling states

Risk assessment



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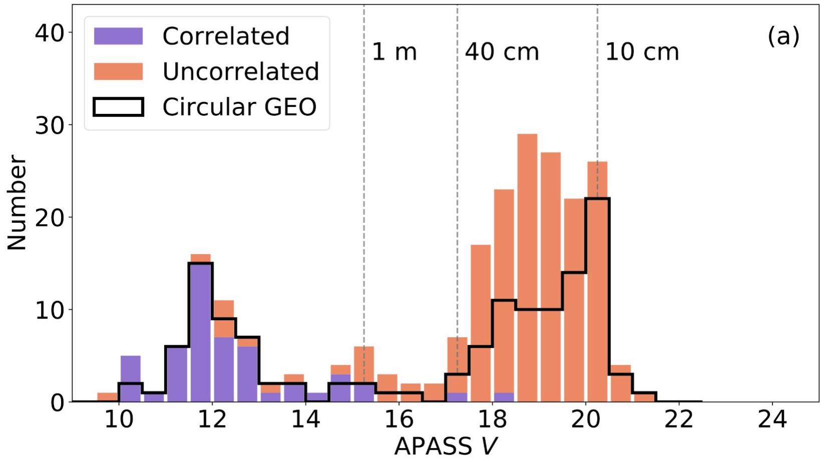

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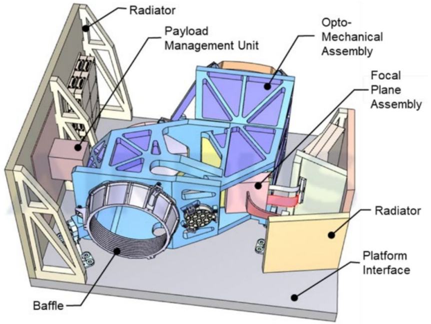
SST Observation Techniques
Upcoming space-based Sensors

ESA VISDOMS: Verification of In-Situ Debris Optical Monitoring from Space (2029)

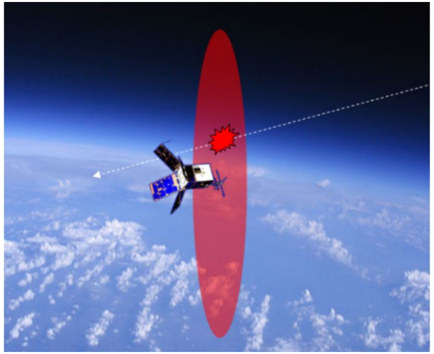
- Statistical monitoring of sub-catalogue sized LEO objects
- Tracking of objects < 1 m in GEO
- 600-900 km Sun-synchronous LEO
- Small satellite platform (250 kg)



Visualization of the VISDOMS Instrument.
S. Kraft et al., "**VISDOMS: Verification of In-Situ Debris Optical Monitoring from Space**," in 22nd IAA Symposium on Space Debris, Milan, Italy: doi: 10.52202/078360-0009.

NASA LARADO: Lightsheet Anomaly Resolution and Debris Observation (2025)

- Detect lethal non-trackable debris
- 500 km circular orbit
- Small satellite (150kg)



Light-sheet concept for local space situational awareness. Credit: U.S. Naval Research Laboratory.

Future Challenges in SSA

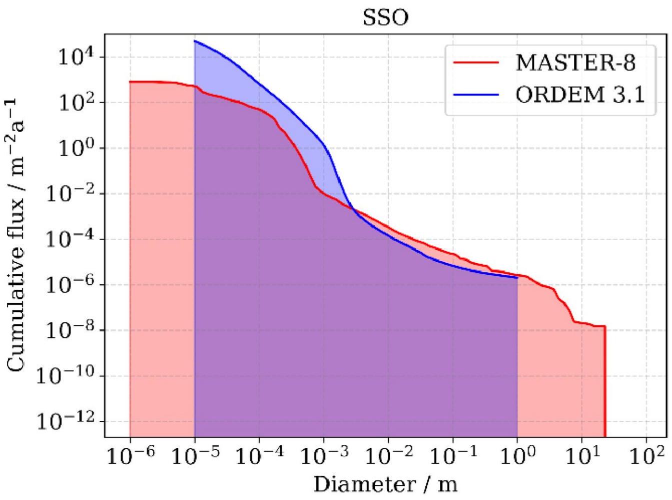
"Space Situational Awareness is essential for safe spacecraft operations in all orbits. Timely, accurate, and shared knowledge of trajectories and activities in Cislunar space, including on the Lunar surface, help to avoid interference and conjunctions as well as encourage responsible behaviors and best practices in space."

NATIONAL CISLUNAR SCIENCE & TECHNOLOGY ACTION PLAN, National Science and Technology Council, 2024, https://bidenwhitehouse.archives.gov/wp-content/uploads/2024/12/Cislunar-Implementation-Plan-Final.pdf

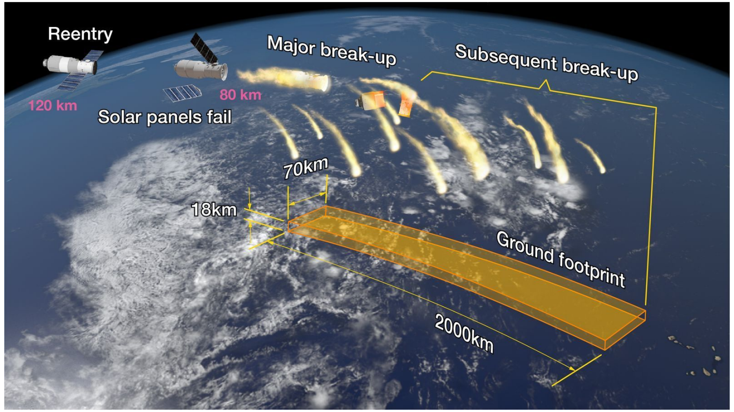
Johns Hopkins Applied Physics Laboratory

Future Challenges in SSA

Developing SST capacities to detect, monitor and characterize the entire population of lethal space debris



Cumulative total flux for a sun-synchronous orbit at 800 km altitude.



Spacecraft reentry (Credit: The Aerospace Corporation)

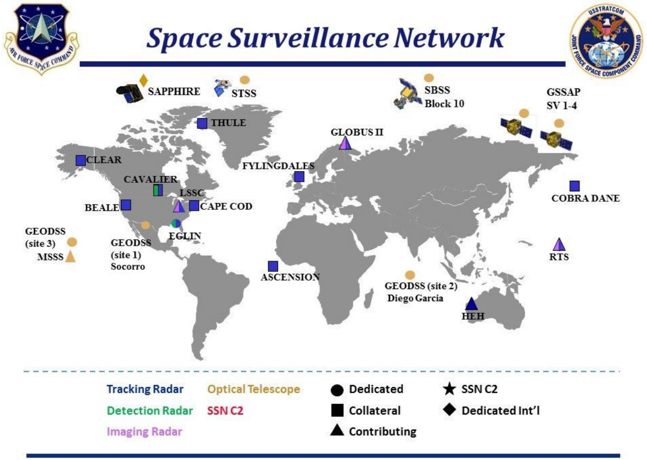
ClearSpace-1 capturing Proba-1 (Credit: ClearSpace)

A. Horstmann et al., "**Flux comparison of MASTER-8 and ORDEM 3.1 modelled space debris population**", 8th European Conference on Space Debris, 2021, https://conference.sdo.esoc.esa.int/proceedings/sdc8/paper/11

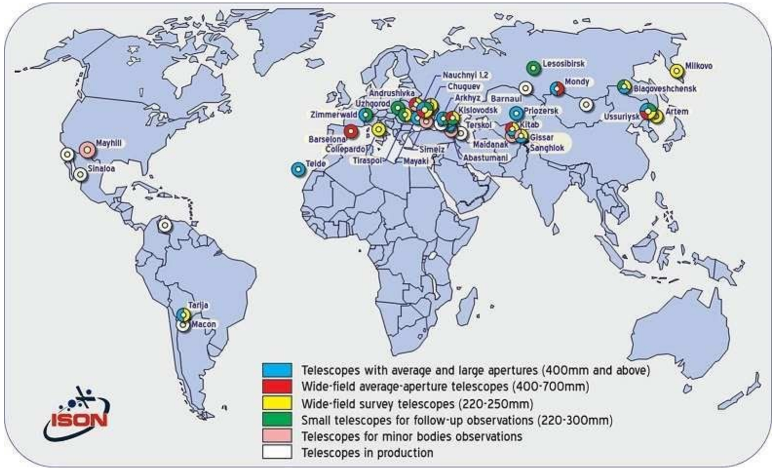
Future Challenges in SSA

Coordinating the space traffic in the increasingly populated LEO regions

Overcoming geopolitical barriers



US Space Surveillance Network



International Scientific Optical Network (ISON)

Future Challenges in SSA

Protecting space activities from space weather

Discovering and monitoring the entire PHA population

Mitigating the increasing interference from satellite mega-constellations in optical and radio astronomy

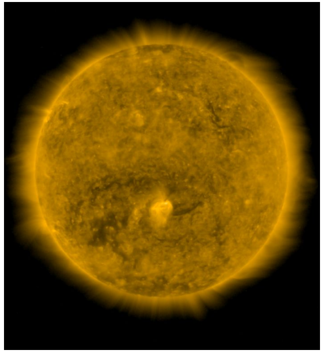
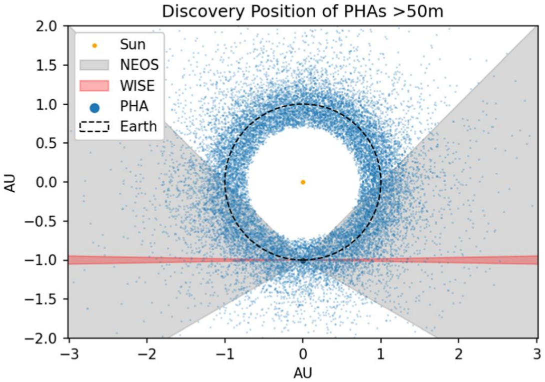
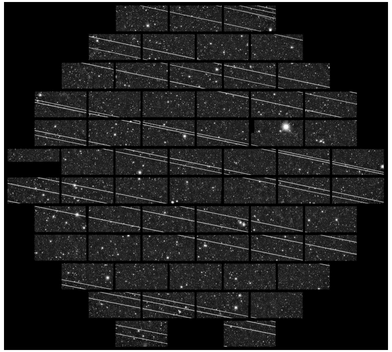


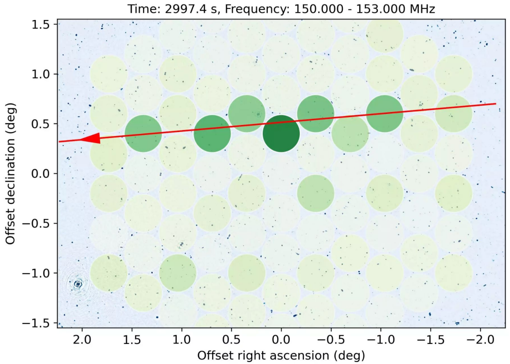
Image of the sun from GOES-16 Solar Ultraviolet Imager (Credit: NOAA's Space Weather Prediction Center)



The NEO Surveyor field of regard (gray cones)
A. K. Mainzer *et al.*, "**The Near-Earth Object Surveyor Mission**" *The Planetary Science Journal*, 2023, doi: 10.3847/PSJ/ad0468.



Starlink train captured by DECam on the Víctor M. Blanco 4-meter Telescope at the Cerro Tololo Inter-American Observatory (Credit:CTIO/NOIRLab/NSF/AURA/DECam DELVE Survey)



Detection of unintended electromagnetic radiation coming from a Starlink satellite with the LOFAR radio telescope
F. Di Vruno et al., "**Unintended electromagnetic radiation from Starlink satellites detected with LOFAR between 110 and 188 MHz**," Astronomy & Astrophysics, Jul. 2023, https://doi.org/10.1051/0004-6361/202346374

Thanks for your Attention!

Any Questions?