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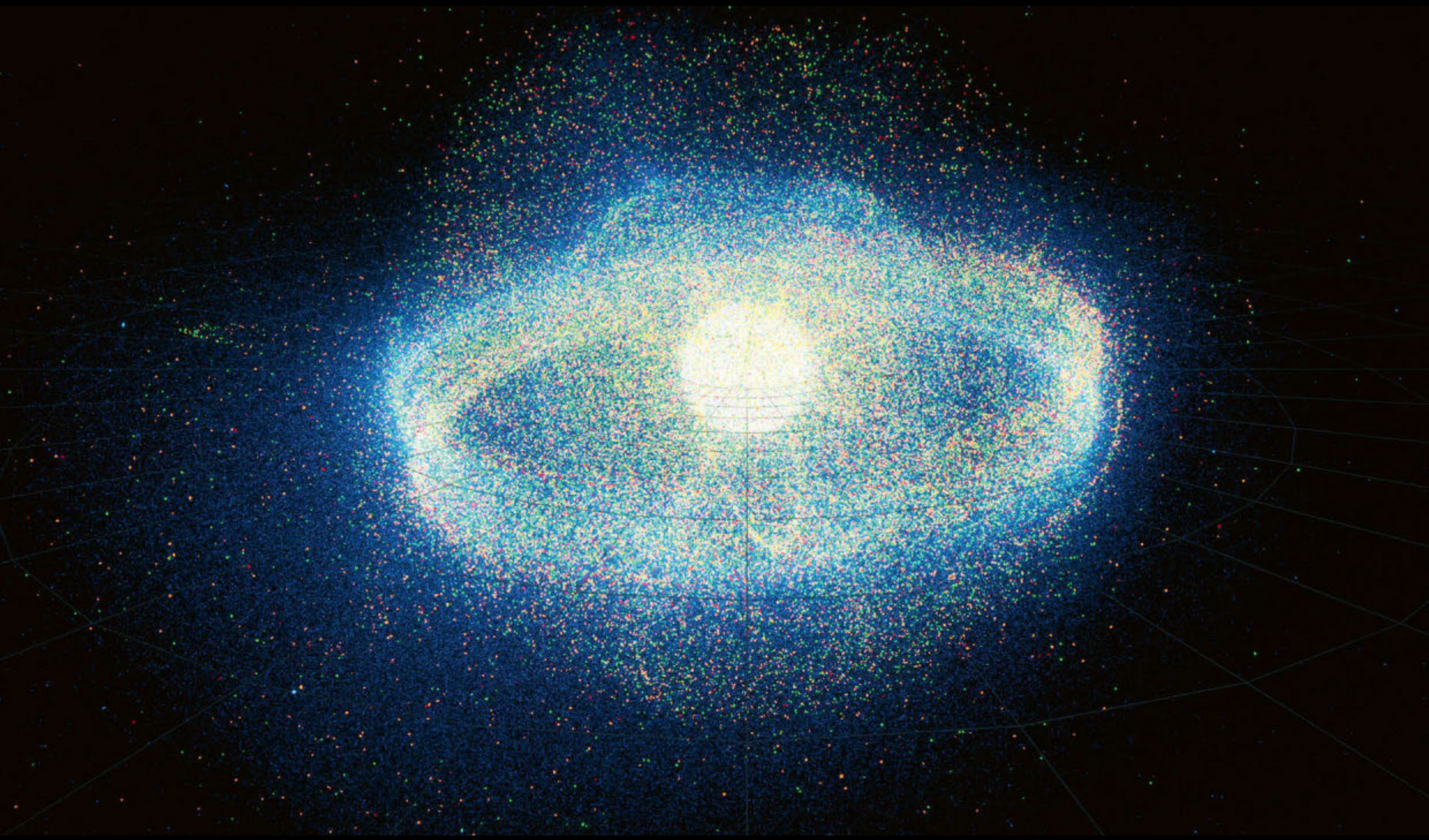
Space Debris



Providing the Scientific Foundation for Sustainable Use of Outer Space

Editorial

Shortly after the beginning of the space age, defined by the launch of the first artificial Earth-orbiting satellites, space flight pioneer Willy Ley predicted already in 1960 that "in time, a number of such accidentally too-lucky shots will accumulate in space and will have to be removed when the era of manned space flight arrives." In 1978, NASA scientist Donald J. Kessler proposed a scenario in which the density of objects in low Earth orbit (LEO) due to space pollution is high enough that collisions between objects could cause a cascade in which each collision generates space debris that increases the likelihood of further collisions. This effect is called Kessler syndrome. Kessler wrote in his famous 1978 paper: "Since the beginning of the space age, thousands of satellites have been placed in earth orbit by various nations. These satellites may be grouped into three categories: payloads, rocket motors, and debris associated with the launch or breakup of a particular payload or rocket; most satellites fall into the last category. Because many of these satellites are in orbits which cross one another, there is a finite probability of collisions between them. Satellite collisions will produce a number of fragments, some of which may be capable of fragmenting another satellite upon collision, creating even more fragments. The result would be an exponential increase in the number of objects with time, creating a belt of debris around the earth."

On 10 February 2009, two communications satellites – the active commercial Iridium 33 and the derelict Russian military Kosmos 2251 – accidentally collided at a speed of 11.7 km/s and an altitude of 789 km above the Taymyr Peninsula in Siberia. Whereas previous incidents had involved a satellite and a piece of space debris, this was the first time a hypervelocity collision occurred between two satellites producing thousands of debris. It was a wake-up event, although the problem was recognized in the scientific community already in the 1980s, when the first observatories began to systematically search for and catalogue space debris using new detectors like Charge-Coupled Devices (CCD) and dedicated image-processing techniques. The Swiss Optical Ground Station and Geodynamics Observatory Zimmerwald took a pioneering role in observing space debris. Today, it is (with respect to the number of telescopes used only for space debris research) the largest observatory worldwide. Its director and space debris pioneer, Prof. Dr. Thomas Schildknecht from the Astronomical Institute of the University of Bern, presented a talk on Space Debris at Pro ISSI on 11 May 2022 providing the scientific foundation for sustainable use of outer space. This issue of *Spatium* is based on that talk.

Andreas Verdun
Zimmerwald, May 2023

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Association Pro ISSI
Hallerstrasse 6, CH-3012 Bern
Phone +41 (0)31 684 48 96
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for the whole *Spatium* series

President
Prof. Dr. Christoph Mordasini
University of Bern

Editor
PD Dr. Andreas Verdun
CH-3086 Zimmerwald

Printing
Stämpfli Communications
CH-3001 Bern

Cover
Snapshot of the current population of about 1 000 000 space debris objects larger than 1 cm as modelled by the ESA statistical model MASTER. (Credit: ESA)

Space Debris
Providing the Scientific Foundation for Sustainable Use of Outer Space

Prof. Dr. Thomas Schildknecht, Astronomical Institute, University of Bern, Switzerland

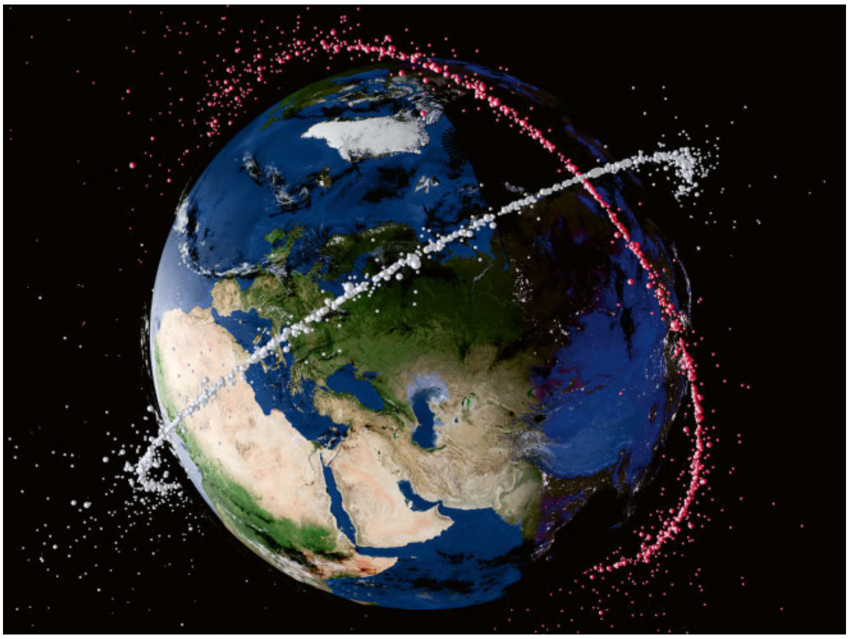
Many of the latest discoveries and findings in astronomy, astrophysics, cosmology, and Earth sciences in general, to name only a few, are based on observations from space. Our modern societies critically depend on services provided by artificial Earth satellites in areas like telecommunication, navigation, logistics, and many more. Space operations have inevitably produced some debris, also called "space debris" or "orbital debris", by abandoning upper stage, spacecraft and mission-related objects in near-Earth space. The proliferation of space debris and the augmented probability of collisions and interference increasingly raise serious concerns about the long-term sustainability of space activities. In order to allow for safe operations in near-Earth space, and to ensure sustainable use of this unique resource, numerous measures are urgently needed. These include inter alia the prevention of collision, the obligation to remove all objects after the end of their mission from the environment, active removal of existing debris, and international efforts to coordinate the traffic and manage the debris environment (cf. Bonnal/McKnight 2017).

1. Space Debris

In the afternoon of 10 February 2009, the active telecommunications satellite Iridium 33 collided with Kosmos 2251, a disused communications satellite, above Siberia at an altitude of nearly 800 km. The satellites collided at a speed of 11.7 km/s, producing a cloud of more than 2000 pieces of debris with sizes of 10 cm and larger **(Figure 1)**. Within a few months, the debris cloud had spread out over a large region in space, creating a risk of further collisions with active satellites. Even today fragments of this event continue to be a major risk for active spacecraft.

The event was a wake-up call for all satellite operators and policy makers. It added a new dimension to an issue that has occupied experts and space agencies for nearly 50 years: the problem of space debris, defunct man-made objects in space. Space debris includes objects of very different types and sizes. The largest debris objects consist of spent rocket upper stages and abandoned satellites. In terms of numbers, however, by far most of the particles with diameters larger than a few centimetres are fragments generated by in-orbit break-ups and collisions. Up to now, more than 600 in-orbit fragmentation events have been recorded, involving spent rocket upper stages, auxiliary motors, and satellites. Apart from collisions,

Figure 1: On 10 February 2009, the active communications satellite Iridium 33 accidentally collided with the decommissioned Kosmos 2251 spacecraft at a velocity of a 11.7 km/s. The event took place at about 800 km altitude over Siberia and created more than 2000 fragments, which spread in the course of the subsequent months over a large region in space. (Credit: IRAS TU Braunschweig)



break-ups may be triggered by several mechanisms: the failure of an internal component containing stored energy (e.g. batteries), the ignition of residual propellant, the explosion of pressurized vessels, and so on.

Collisions between space debris and functional spacecraft as well as mutual collisions among space debris produce additional collisional fragments. This is particularly the case for catastrophic collisions, where the colliding objects are completely disrupted. These new fragments may again collide with each other, and can eventually lead to the exponential growth of the entire population, the so-called Kessler syndrome, named after Donald J. Kessler, who predicted this scenario in 1978 (cf. Kessler/Cour-Palais 1978).

Figure 2: Results from a hypervelocity impact test. A 1 cm aluminium sphere was impacting a massive aluminium target with a velocity of 6.5 km/s (23 400 km/h). (Credit: AIUB)

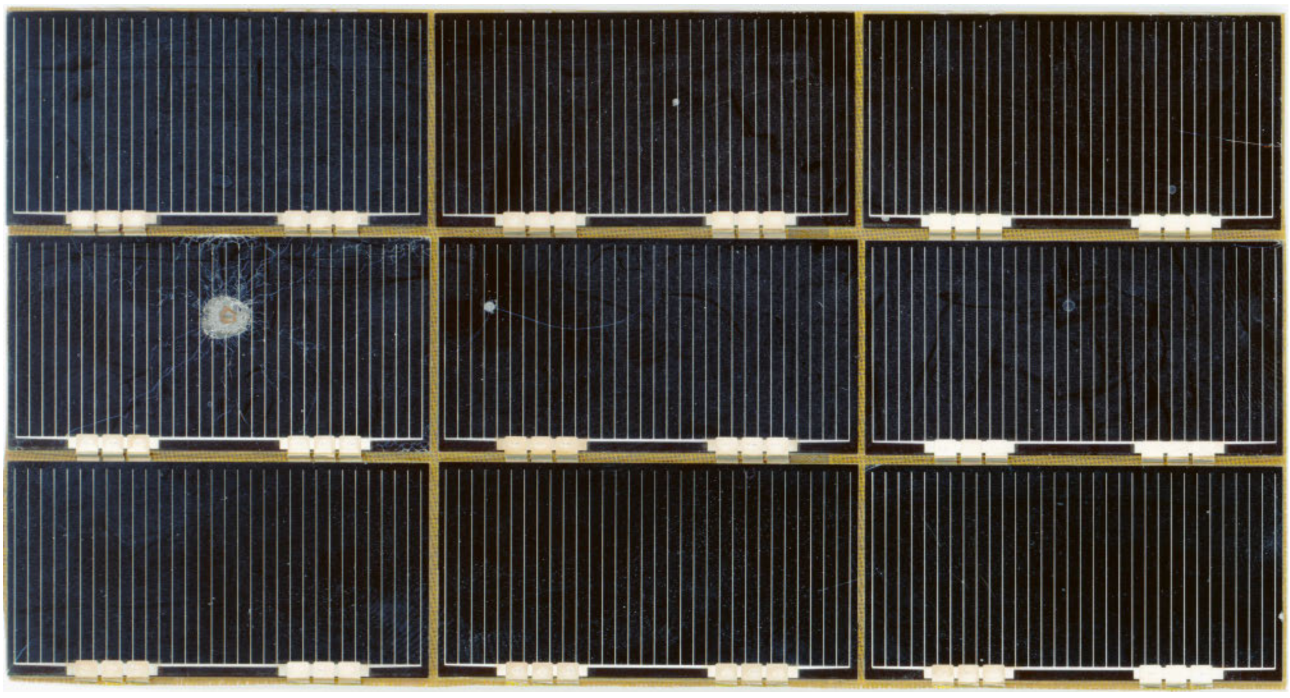


Figure 3: Section of a retrieved Hubble Space Telescope solar array with impact features of several millimetres in diameter generated by millimetre-size particles. (Credit: AIUB)

Old or abandoned artificial objects in space may also produce small-size space debris through aging processes. Outer surfaces of space objects, e.g., paint layers or Multi-layer thermal insulation blankets (MLI), gradually deteriorate due to hard UV radiation and oxidization by residual air molecules and atoms in low orbits. As a consequence of these aging processes, the paint layers may "peel off" and generate myriads of small paint flakes with sizes in the millimetre and sub-millimetre range, or satellites may shed decimetre-size fragments of insulation foils.

Even small space debris objects pose a risk to active spacecraft due to their high relative velocity with respect to other objects in orbit. In low Earth orbit (LEO), objects move with velocities of 7 to 8 km/s (about 27 000 km/h) with respect to an Earth-fixed reference frame. Consequently, the energy released due to an impact is enormous. For a small debris piece of 1 cm in diameter, this energy is comparable to the energy of an exploding hand grenade **(Figure 2)**. As a consequence, a collision with even a tiny piece of debris of a few millimetres or smaller in size may be lethal for spacecraft. A so-called catastrophic collision with an object of 10 cm in LEO would even disrupt the target object completely producing a multitude of new debris objects. Impacts caused by tiny space debris can be directly found and analyzed on the surfaces of space objects which have been retrieved from space **(Figure 3)**.

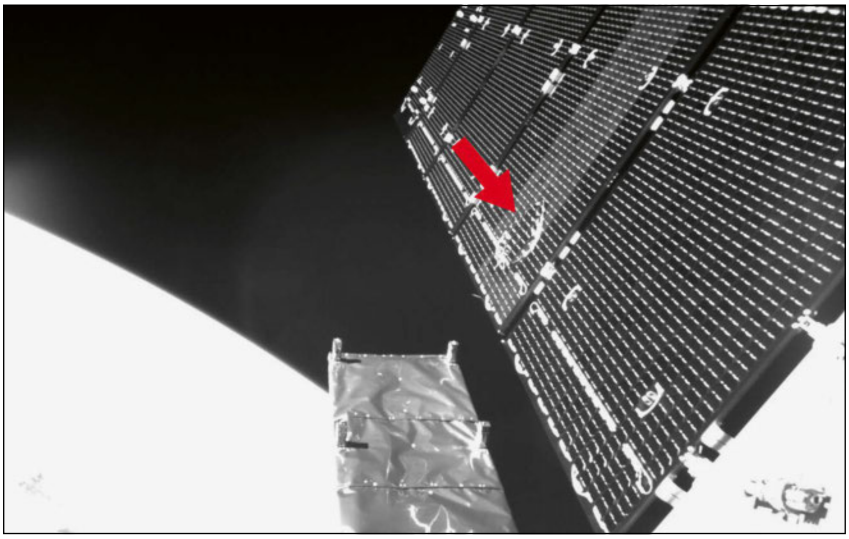


Figure 4: On 23 August 2016, Sentinel-1A was hit by a millimetre-size debris object. The picture from the on-board camera shows a damage area of 40 cm in diameter on the front side of the solar array. (Credit: ESA)

The example in **Figure 4** shows that the collision risk with millimetre-size debris is real: On 23 August 2016, sudden small power reduction and a slight orientation change was observed for Sentinel-1A, orbiting at 700 km altitude. Preliminary investigations suspected a collision with a small debris object, which was confirmed later on by images taken with the onboard camera.

Statistical models based on observations predict a total population of about 1 000 000 space debris objects larger than 1 cm **(Figure 5)** within a sphere of about 10 Earth radii (so-called space debris environment). Among them only about 35 000 objects with sizes above 10 cm are "known" and their orbits tracked on a regular basis. Different stakeholders have diverse reasons why they care about space debris. Spacecraft owners and operators are mainly concerned about the safety of their assets and thus focus on preventing collisions by executing avoidance manoeuvres if required. Spacecraft and mission designers are interested in statistical risk analysis to increase spacecraft resilience through appropriate design and to use optimal mission orbits to minimize potential impact events. Finally, governments, space agencies, and scientists care about critical infrastructure in space and the long-term sustainable use of near-Earth space. Modern civil societies depend increasingly on "services from space". We all take the space-based navigation services we use in our smartphones and car navigation systems for granted. But there is more: our power grid and communication systems as well as weather forecasts would break down without signals and observations from space (cf. *Spatium* 10, *Spatium* 31). More than half of the essential climate variables are measured from space, to provide another example (cf. *Spatium* 46, *Spatium* 49).

2. Space Debris Research

In order to enable modelling of the evolution of the space debris population, and eventually to devise efficient measures to limit the growth of the number of debris objects, we need to better understand the current space debris environment. Space debris research aims at a comprehensive overview of the current state and nature of the population, as well as the physical mechanisms governing the evolution (cf. Schildknecht 2015). We pose a series of questions:

- Concerning the population:
  - how many space debris objects are there?
  - what is the size and density distribution of these objects?
  - in which regions (altitudes) do these objects orbit the Earth?
  - what is the nature of the objects (type of objects, material, etc.)?
  - what are the sources and sinks?
- Concerning the physical mechanisms:
  - how are space debris, in particular fragments, generated (break-up events, collisions, aging effects leading to disintegration of spacecraft surface materials such as solar cells and insulation blankets)?
  - what is the long-term evolution of the orbits of space debris?
  - what is the long-term evolution of the size and density distribution due to fragmentation processes?

Scientists at the Astronomical Institute of the University of Bern (AIUB) are addressing these questions by observing known (catalogued) space debris to improve their orbital elements, by searching for unknown (uncatalogued) debris and eventually determining their orbits, and by characterizing the physical properties of (cata-

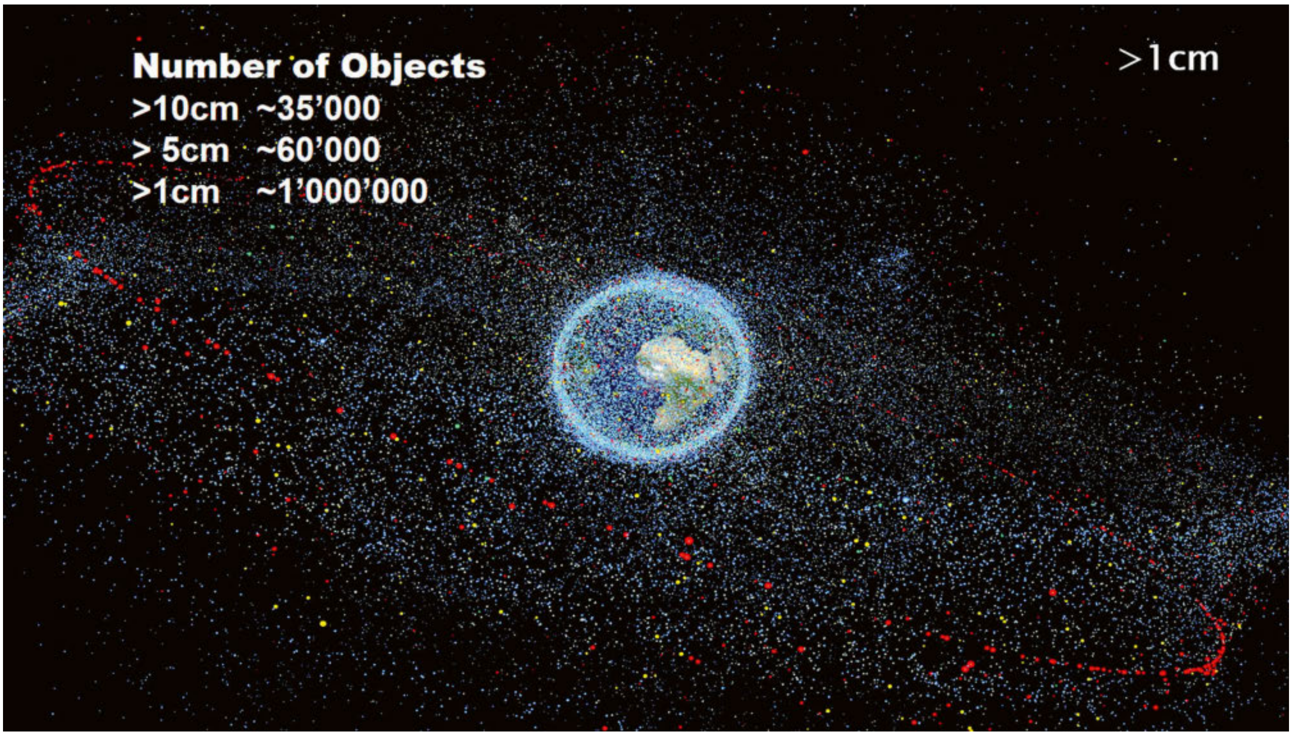


Figure 5: Snapshot of the current population of space debris larger than 1 cm. Statistical models based on observations predict a population of about 1 000 000 space debris objects larger than 1 cm. Among them only about 35 000 objects with sizes above 10 cm are "known" and their orbits tracked on a regular basis. (Credit: IRAS TU Braunschweig)

Figure 6: Swiss Optical Ground Station and Geodynamics Observatory Zimmerwald (SwissOGS). (Credit: AIUB, Manu Friederich)

Figure 7: 0.8 m Zimmerwald Multiple Applications Instrument ZimMAIN. Main applications are surveys for faint debris, and photometric and spectroscopic characterization of debris. (Credit: AIUB, Manu Friederich)

logued and uncatalogued) debris objects. Observations of space debris objects are mostly performed at AIUB's own observatory, the Swiss Optical Ground Station and Geodynamics Observatory Zimmerwald **(Figure 6)**. The observatory consists of 6 optical telescopes hosted in 5 domes, with apertures ranging from 20 cm to 1 m.

The 0.8 m Zimmerwald Multiple Applications Instrument ZimMAIN **(Figure 7)** is primarily used to search for small-size debris objects in high-altitude orbits, in particular in the geostationary ring (GEO). Surveys performed by AIUB with the ESA 1 m telescope in Tenerife complemented with observations from ZimMAIN have revealed a hitherto unknown population of small-size debris in GEO with objects as small as 15 cm in diameter **(Figure 8)**. Blue bars in **Figure 8** indicate objects which could be identified in public orbit catalogues ("correlated") and red bars show objects which were not known before ("uncorrelated"). The blue line indicates the sensitivity limit of the sensors. The cut-off in the number of objects fainter than about magnitude 19 is entirely due to the sensitivity limit of the observation system. The real population is most likely even further

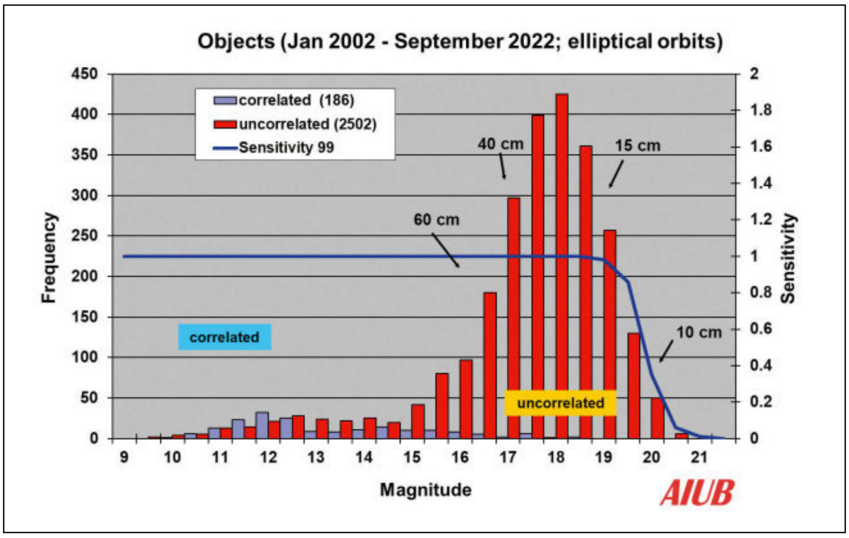


Figure 8: Small-size debris objects discovered by AIUB in the geostationary orbit region (GEO). Blue bars indicate objects which could be identified in public orbit catalogues ("correlated") and red bars show objects which were not known before ("uncorrelated"). The blue line indicates the sensitivity limit of the sensors. (Credit: AIUB)

Figure 9: 1 m Zimmerwald Laser Ranging and Astrometry Telescope ZIMLAT. (Credit: AIUB)

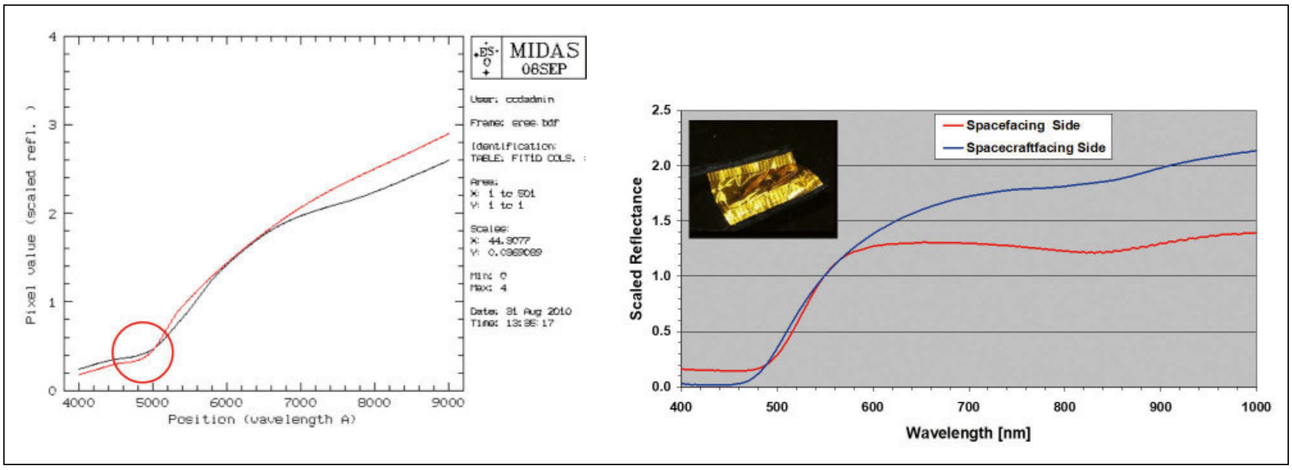


Figure 10: Left: spectra from high AMR debris object. Right: spectra from multi-layer insulation foil taken in the laboratory. (Credit: AIUB)

increasing for smaller sizes. Some of these objects, presumably fragments, were found in "unusual", eccentric, high-altitude orbits. The orbits were unusual in the sense that no potential parent objects like spent upper stages or spacecraft were known in this orbital region. The investigation of the nature and origin of these objects became a central topic in international space debris research and turned out to be a real detective story. Follow-up observations with the 1 m Zimmerwald Laser Ranging and Astrometry Telescope ZIMLAT **(Figure 9)** revealed that the evolution of the orbits was exceptional, and could only be explained if the objects were very lightweight with rather large surface areas or, in other words, had extremely high area-to-mass ratios (AMR) (cf. Schildknecht et al. 2008). For some of the objects with extremely high AMR values the only reasonable hypothesis was to assume they were pieces of multi-layer insulation foils. In order to determine the material type, spectra of some high AMR objects were acquired and compared with spectra of spacecraft outer surface materials (solar cells, MLI, etc.) taken in the laboratory. **Figure 10** shows spectra from a high AMR object (left) and laboratory spectra from MLI. The prominent "knee" at 500 nm is unique and has not been seen in any other material measured in the laboratory, hence a strong evidence supporting the MLI hypothesis (cf. Vananti et al. 2017).

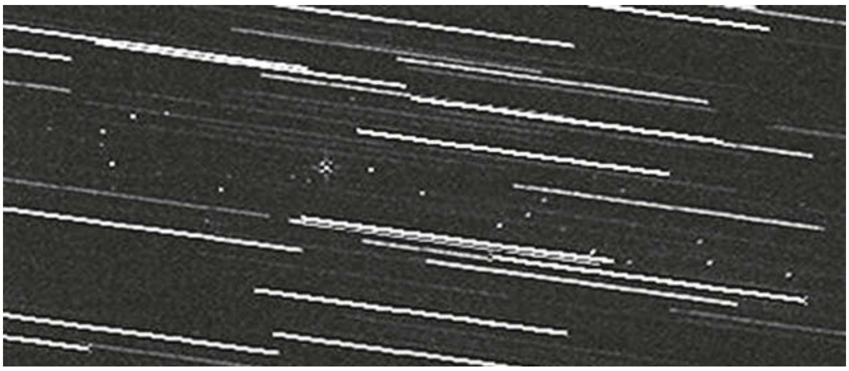


Figure 11: Fragments from the break-up of a rocket upper stage (point-like objects) observed on 27 March 2019 with ZimTWIN. (Credit: AIUB)

Break-up events are still the major source of fragments. Characterizing such events is thus key in understanding this important source. **Figure 11** shows an observation of a fragment cloud from the break-up of a rocket upper stage three days after the event (cf. Schildknecht et al. 2019). The AIUB was informed by Russian colleagues about this event and a joint observation campaign was initiated to catalogue the fragments. More than 7 months later, there were no objects from this and two additional break-up events in the public orbit catalogue while AIUB catalogued the three fragment clouds **(Figure 12)**.

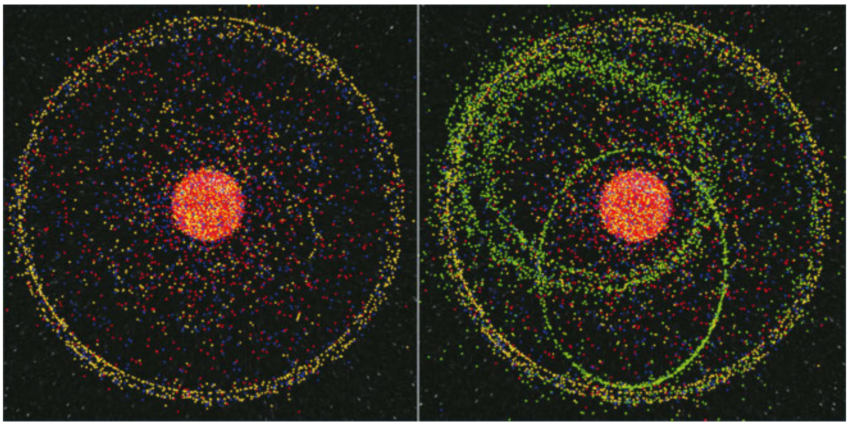


Figure 12: Break-up fragments, 3 December 2019. Left: Public catalogue (credit: Space-track.org). Right: Fragment catalogue (green) superimposed on public catalogue (credit: AIUB).

The Zimmerwald Twin Widefield Instrument (ZimTWIN) counsists of two identical telescopes mounted together and pointing always in the same direction, thus allowing simultaneous observations with different filters **(Figure 13)**. ZimTWIN is also used to characterize the tumbling motion of large debris objects which are potential targets for future removal missions (see next section). **Figure 14** shows the temporal variation of the magnitude (so-called light curve) of a rocket upper stage in two colours (top) and the difference of the two colours, the so-called colour index (bottom). Such observations allow determining the rotation rate and, with the help of the colours, disentangling ambiguities which are due to geometrical symmetries.

Figure 13: Double 0.4 m Zimmerwald Twin Widefield Instrument ZimTWIN. (Credit: AIUB, Manu Friederich)

Global cooperation among scientific organizations, but also collaboration with space agencies and international organizations is key in addressing the challenges posed by the proliferation of space debris. **Figure 15** shows some of the organizations AIUB is collaborating with. Observatories distributed all over the world and joined together to form a network are mandatory, e.g. for following-up observations or continuous time series. AIUB, in close collaboration with the German Aerospace Centre (DLR), builds up and operates a worldwide network of fully robotic telescopes, also known as SMARTnet. Telescopes of this network are located in Australia, South Africa, South America, and Europe. All of them were assembled, equipped with software, and tested at the Zimmerwald Observatory as “Zimmerwald Network Telescopes” (ZimNET).

With the Zimmerwald Small Aperture Robotic Telescope (ZimSMART), a fully automatic small telescope with an aperture of 0.2 m, the sky is systematically searched for artificial objects every night. The aim is to set up and maintain an orbital catalogue of active satellites and space debris objects at an altitude of 36 000 km, the so-called geostationary ring.

Orbits of objects in low Earth orbits are mostly determined using radar measurements. Laser ranging is a promising technique to improve the accuracy of orbits of space debris objects in these orbits by about one order of magnitude compared to traditional radar techniques. On 24 June 2020, AIUB acquired the first ever daylight observations of a space debris object using the geodetic Satellite Laser Ranging (SLR) system of ZIMLAT (cf. Rodriguez et al. 2022). Space debris objects are not carrying retroreflectors, which prevents the use of conventional SLR systems for tracking of debris objects with cross-sections smaller than a few 10 square metres. A new high-power laser system was thus procured and the installation started in 2022. The system will allow tracking of debris objects with diameters as small as 1 m.

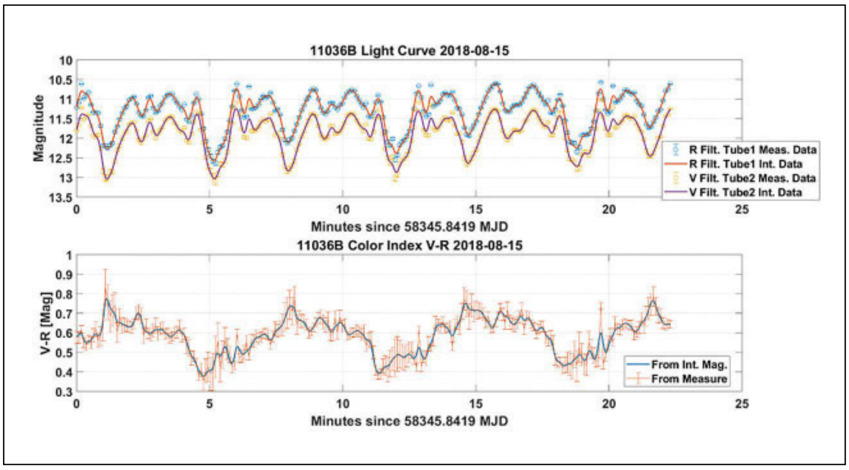
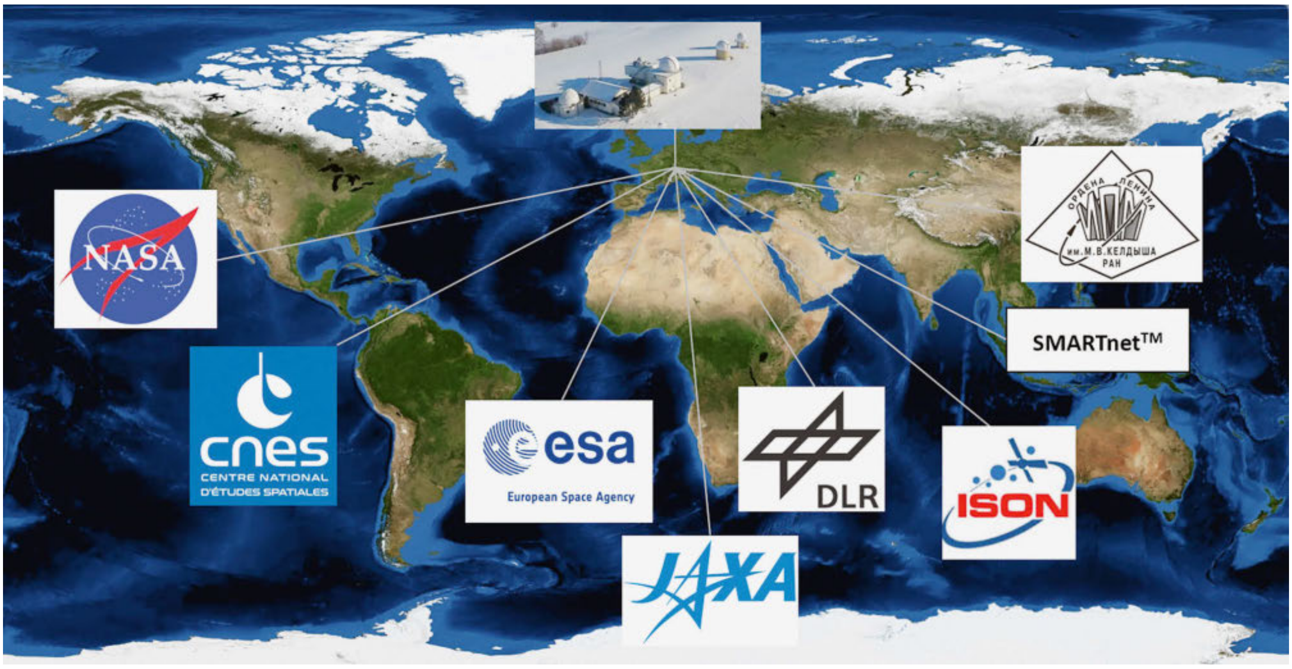


Figure 14: Temporal variation of the magnitude (light curve) of a rocket upper stage in two colours (top). Difference of the two colours (colour index) (bottom). The light curves were take simultaneously with the two telescopes of ZimTWIN. (Credit: AIUB)

Figure 15: Global cooperation with space agencies, research institutions, international organizations, and even the UN is key in addressing the challenges posed by the proliferation of space debris. (Credit: AIUB)



3. Future Evolution and Countermeasures

The proliferation of space debris and the increased probability of collisions and interference raise concerns about the long-term sustainability of space activities, particularly in the low Earth orbit and in the geostationary orbit environments. During recent years, the number of satellites launched to space increased by orders of magnitude in particular due to cost reductions enabled by miniaturization and rideshare launch opportunities, as well as due to the deployment of so-called mega-constellations by private actors. **Figure 16** shows the exponential increase of the number of catalogued objects over the past decade. The reason for this increase is partially due to individual fragmentation events, but in particular also due to the increased launch traffic **(Figure 17)**. Note the substantial increase of commercial objects launched over the past decade.

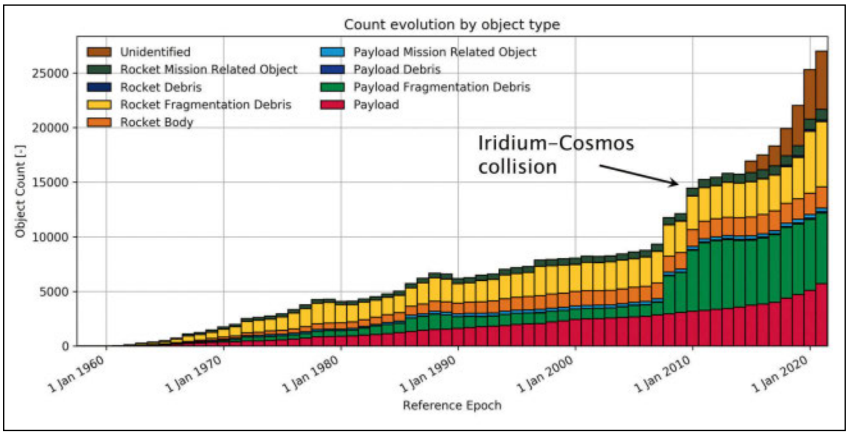


Figure 16: Evolution of catalogued objects. (Credit: ESA)

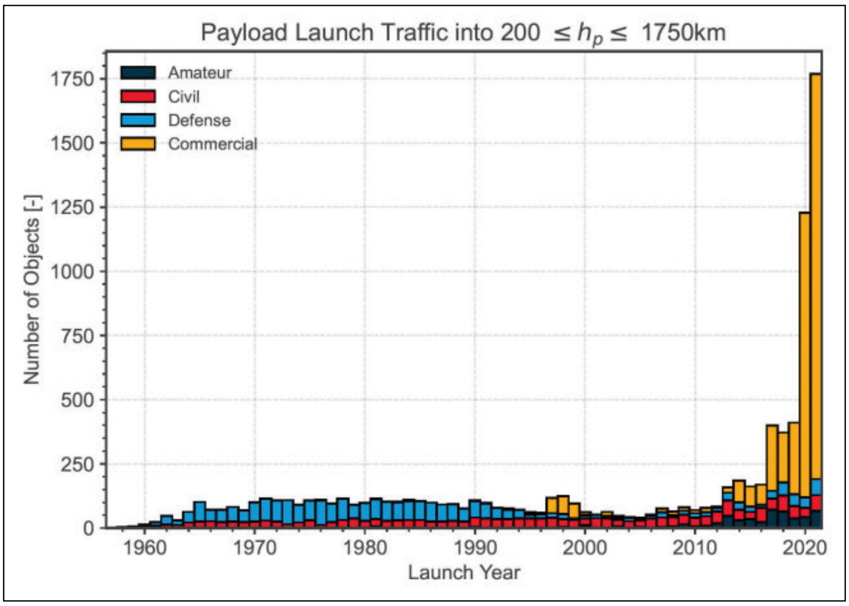


Figure 17: Evolution of launch traffic. Note the increase of commercial objects launched over the past decade. (Credit: ESA)

In order to allow for safe operations in near-Earth space, and to ensure sustainable use of this unique resource, numerous measures are urgently needed. These include inter alia the prevention of collision, the obligation to remove all objects after the end of their mission from the environment, also called post-mission disposal (PMD), active removal of existing debris, and international efforts to coordinate the traffic and manage the debris environment. Results from an evolution model predicting the number of catastrophic collisions over the next 200 years for different post-mission disposal scenarios are shown in **Figure 18**. Further technical measures include the prevention of fragmentations by passivating objects at the end of life (venting of fuel, shortening of batteries, etc.), the active removal of massive debris objects from space (so-called active debris removal, ADR), and the prevention of collision between non-manoeuvrable debris with "just in time collision avoidance" (JCA) techniques like nudging

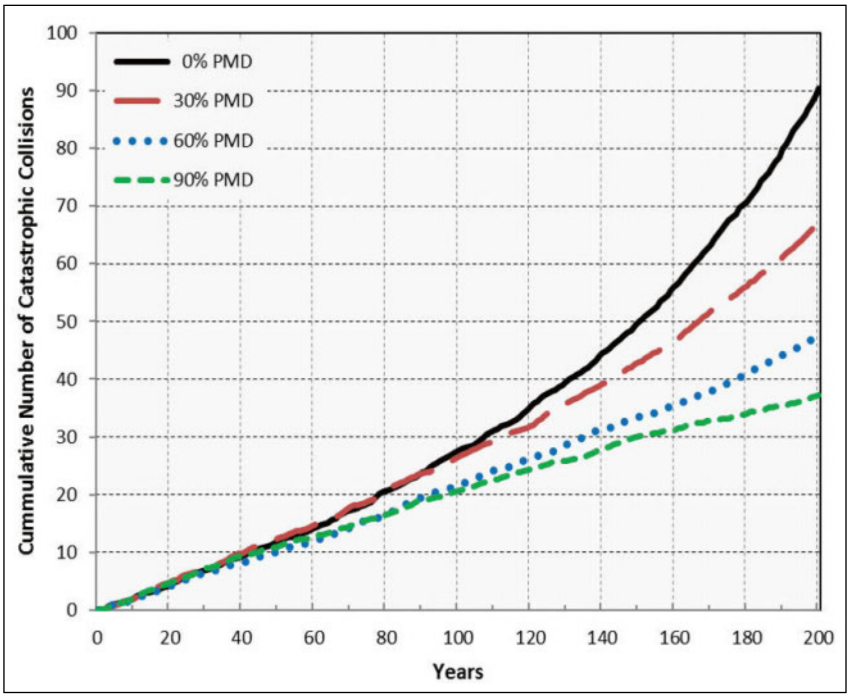


Figure 18: Result from an evolution model predicting the number of catastrophic collisions over the next 200 years for different post-mission disposal (PMD) scenarios. (Credit: ESA)

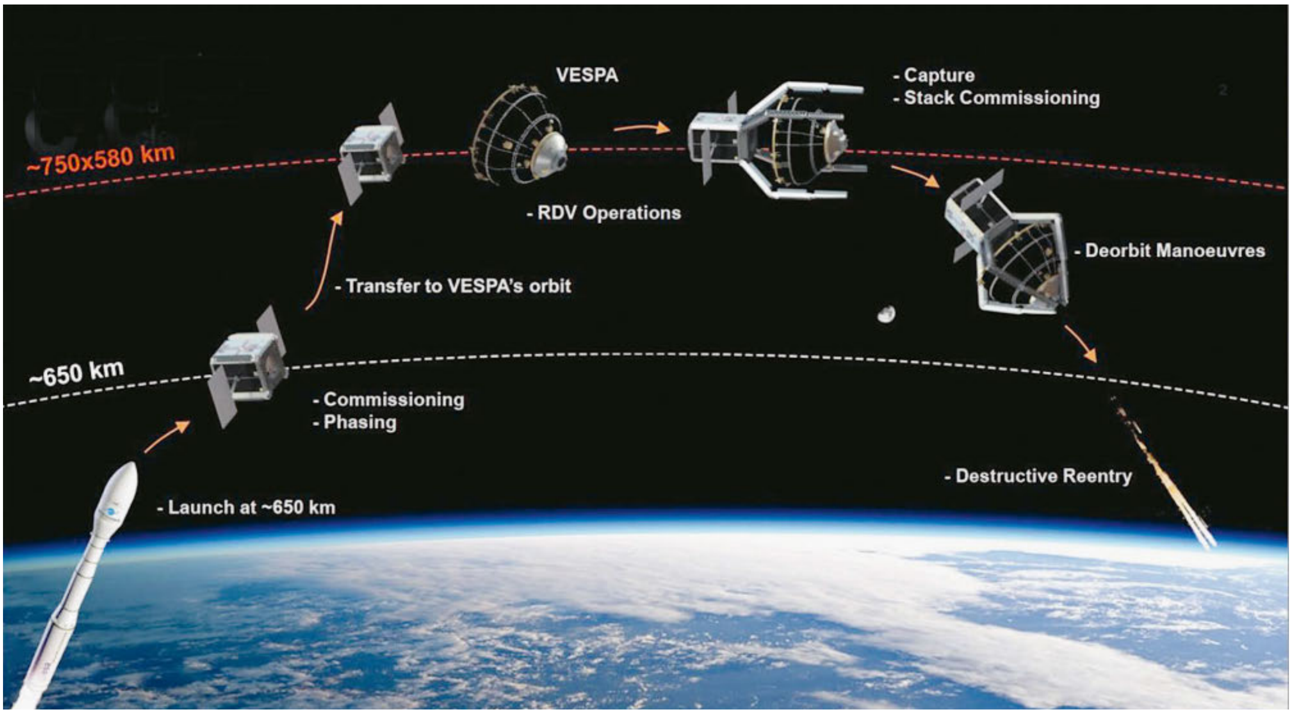


Figure 19: Clearspace-1 active debris removal mission. (Credit: Clearspace)

with ground-based lasers. The Swiss company Clearspace is leading an industry consortium which will conduct Clearspace-1, an ADR mission planned for 2026 as a service for the European Space Agency (ESA). It will be the first mission to remove a piece of space debris from orbit **(Figure 19)**.

4. Space Traffic Coordination and Space Environment Management

Ensuring safe and sustainable use of near-Earth space requires international efforts in three domains **(Figure 20)**:

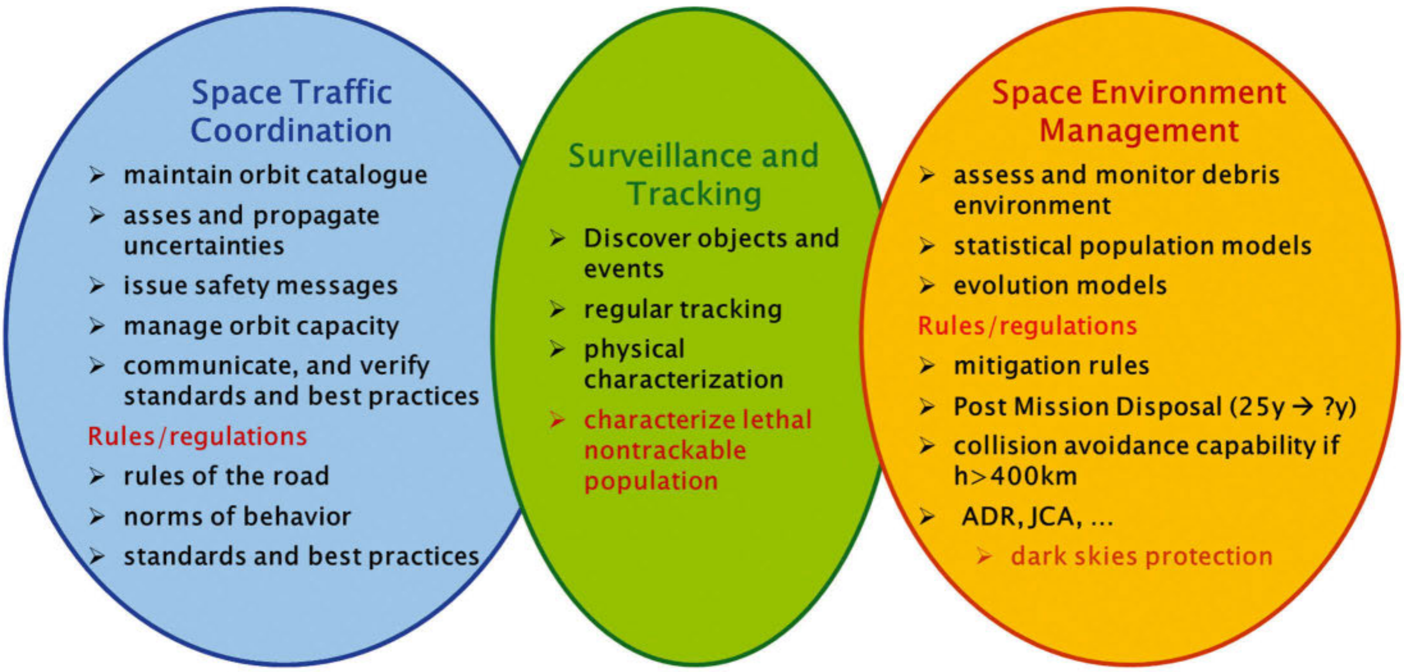
a) A deep understanding and continuous monitoring of the current population of artificial objects in space (active and debris objects) through measurements, also called Space Surveillance and Tracking (SST).

b) Management of the space environment through rules and regulations, based on SST and statistical observation data and evolution models.

c) Coordination of the traffic of active satellites based on SST data, through rules and regulations, with the primary aim of preventing collisions.

The challenges posed by orbital debris and the increased traffic are inherently challenges concerning the entire international community of states. As a consequence, major spacefaring nations started discussion on the technical aspects of space debris in the Inter-Agency Space Debris Coordination Committee (IADC), which was established in 1993. One result of this work was the release of the IADC Space Debris Mitigation Guidelines in 2005, which formed the basis for the 2007 UN Space Debris Mitigation Guidelines. From 2010 to 2018 a working group of the UN Committee for Peaceful Use of Outer Space (COPUOS) elaborated 21 Guidelines for the Long-Term Sustainability of Outer Space Activities, which were finally endorsed in 2018 by the UN General Assembly **(Figure 21)**. Although not legally binding, over the years these international guidelines have clearly had an impact on the behaviour of space actors with respect to space debris.

Figure 20: Space Traffic Coordination (STC), Space Situational Awareness (SSA), Space Environment Management (SEM). (Credit: AIUB)



5. Summary and Outlook

Space debris research at the Astronomical Institute of the University of Bern (AIUB) based on observations from the Swiss Optical Ground Station and Geodynamics Observatory Zimmerwald and the ESA telescope in Tenerife provided substantial contributions to a better understanding of the current space debris population including its sources and long-term evolution. Scientific highlights include the detection of decimetre-size debris in geostationary orbits and the discovery of an unexpected population of debris objects with extremely high area-to-mass ratios. Most of these results required international cooperation among scientific institutions, collaboration with space agencies and international institutions. It is evident that we need a collaborative, international and holistic approach to address the challenges posed by space debris. Space debris research provides the scientific and empirical bases for creating environment and evolution models and for devising efficient debris mitigation and remediation measures – it provides the scientific foundation for sustainable use of near-Earth space.

Figure 21: UN Guidelines for the Long-Term Sustainability of Outer Space Activities 2018. (Credit: AIUB)

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The Author

Prof. Dr. Thomas Schildknecht received his PhD in Astronomy at the University of Bern in 1994 on *Optical astrometry of fast moving objects with CCD detectors*. After his habilitation entitled *The search for space debris in high altitude orbits*, he became associate Professor of the University of Bern in 2009. Since 1989 until present, he is the head of the Optical Astronomy and Space Sustainability Group of the Astronomical Institute of the University of Bern (AIUB). In 2009, he became Vice-Director of the Institute and Director of the Swiss Optical Ground Station and Geodynamics Observatory Zimmerwald, positions he holds until now. His main focus since 1992 is the research in space debris. He became a leading expert on space debris and sustainable use of near-Earth space. Under his leadership, his research group has acquired world-class expertise in the observation and characterization of space debris over more than 25 years. He has served and continues to serve on numerous technical and policy committees at both the national and global level.

In 2014, Thomas Schildknecht was appointed Chair of the European Space Agency's Space Safety Advisory Group, which advises the ESA Director responsible for the Space Safety Programme. He is also a long-standing member of the ESA delegation to the Inter-Agency Space Debris Coordination Committee (IADC), where he chaired the Working Group on Measurements. In this capacity, for example, he participated in the multilateral negotiations of the IADC Space Debris Mitigation Guidelines, which served as the basis for the Space Debris Mitigation Guidelines adopted by the UN in 2007. Since 2010, Thomas Schildknecht has been a member of the Swiss delegation to COPUOS, where he contributed significantly to the work of the working group on "Long-term sustainability of outer space activities" and to the successful adoption of the 21 Guidelines in 2019.

Prof. Dr. Thomas Schildknecht is a full member of the International Academy of Astronautics (IAA), outgoing member of the Space Surveillance Committee of the American Astronautical Society (AAS) and served in the board of several international associations. At the national level, he is President of the Swiss National Committee of the International Astronomical Union (IAU), a member of several national associations and committees, including the Commission for Space Research and the Commission for Astronomy of the Swiss Academy of Sciences. He was also elected in 2019 as a member of the Federal Commission for Space Affairs, which advises the Federal Council.