The Atmospheric Impacts of Re-entry and Launch (AIRL): High-Priority Actions and Recommendations

Whitepaper: *Outcomes of the AIRL Working Group, urgent short-term research priorities including measurement campaigns to fill knowledge gaps.*

Authors & Editors:

AIRL WG and participants from the [2nd Workshop - Atmospheric Impacts of Spacecraft Launch and Re-entry (23-25 September 2025): Overview · Indico at ESA / ESTEC](#) (See Annex)

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AIRL (Atmospheric Impacts of Spacecraft Launch and Re-entry) is an international scientific working group established in 2023. Its objective is to coordinate the international scientific community, identify key knowledge gaps, and develop evidence based recommendations on the atmospheric impacts of spacecraft launch and re-entry. The group involves experts from universities, research institutes, government agencies, and space organisations worldwide. The whitepaper authors and their affiliations are listed at the end of the document.

Please send any questions, requests, or any communication to: AIRL@esf.org

Executive Summary

Spaceflight activities have expanded at an unprecedented rate over the last decade, leading to satellite launch rates being 10 times higher today than 10 years ago. The growing number of orbiting objects is increasing the risk of accidental collisions, threatening the long-term usability of key orbital regions. To mitigate the orbital risk, current industry standards and institutional regulations now require active and passive end-of-life de-orbiting. They also promote "design-for-demise" approaches, ensuring that satellites ablate (disintegrate) completely upon re-entry to minimise the ground-casualty risk. However, the environmental risks of space activities extend beyond just the orbital environment and Earth's surface. Rocket launches and the ablation of re-entering spacecraft release a variety of gases and particles directly into the middle and upper atmosphere. These emissions include metallic and carbon-rich particles and gases that are chemically and radiatively active. As the frequency of launches and re-entries increases, so do the amounts of these emissions. Yet their distribution, their physicochemical evolution, and radiative properties remain poorly understood with little available data, leaving their broader atmospheric impacts uncertain. Furthermore, tracking where these emissions are ultimately deposited at the Earth's surface is needed to assess potential toxicity and effects on ecosystems. The pace at which the space sector is expanding far outstrips our ability to evaluate its environmental footprint. Addressing the scientific knowledge gaps urgently requires a coordinated programme integrating targeted atmospheric observations, ground-based experiments, and advanced modelling. This will allow us to comprehensively characterise the emissions from space activities and better understand their impacts on, for example, ozone depletion, atmospheric radiative balance and climate forcing. Such work is critical for solid, evidence-based environmental assessments and for developing effective mitigation measures, including alternative propellants and engineering requirements for future missions. Over the past year, the Atmospheric Impacts of Re-entry and Launch (AIRL) working group has developed a detailed research programme and implementation roadmap to close the most pressing and relevant science gaps. We propose this programme as a proportionate, low-cost risk-reduction effort to assess the environmental risks. It builds on existing assets and partnerships, prioritising coordination and transparent data sharing. Key actions include acquiring high-quality experimental and observational data that can be rapidly integrated into plume and ozone-climate models, and fed back into toolchains and regulation and licensing processes. The outcome will provide the scientific, policy-ready, actionable information that enables the sustainable growth of the space sector. The following items are critical, short-term recommendations that require urgent funding commitments.

Recommended near-term research actions (12–24 months, total funding: €6-8M): To accelerate progress, the AIRL Working Group strongly recommend establishing international and operational coordination of research activities, supported by urgent funding decisions on top of current in-kind contributions. Key actions include:

- ⇨ Joint international aircraft campaign: Fly instrumented aircraft in the upper troposphere and lower-most stratosphere to sample background air and transect launch plumes using in-flight harmonised instrumentation and post-flight analyses of collected stratospheric particles.
- ⇨ Targeted stratospheric / mesospheric / thermospheric sampling: Conduct global balloon / aircraft / sounding rocket campaigns to collect aerosols for in-depth laboratory characterisation.
- ⇨ Sampling at and around launch site: Deploy lidar systems combined with in-situ gas/aerosol sampling capabilities, including particulate collection, to characterise launch emissions and track launch plume evolution.
- ⇨ Ground testing: Upgrade ground testing facilities to better determine vaporisation/ablation thresholds as well as chemical reactivity for key space materials, components and emitted particles, under stratospheric and mesospheric conditions.

- ⇨ Model integration: Evaluate and improve plume models and global chemistry–climate models using observations and laboratory measurements in order to assess transport, and physicochemical transformations of spaceflight emissions, and their chemical and radiative impacts.
- ⇨ Sampling on re-entry and reuseable vehicles: Incorporate dedicated sensor and sampling payloads onto re-entry vehicles and reusable launchers to conduct in-situ atmospheric sampling and demonstrate payload recovery capability.
- ⇨ Potential satellite remote sensing: Review existing and future satellite missions to identify which data products could be exploited for atmospheric spaceflight material monitoring.
- ⇨ Ground-based remote sensing of re-entry plumes: Assess the feasibility of ground-based observation of re-entry plumes using e.g. lidar, radar, or emission spectroscopy.

Recommended near-term programmatic actions (12–24 months):
PR1: ESA and Member States

- ⇨ *After the ESA-C Min 25 , 2nd Quarter 2026, ESA and Member States to release the roadmap of the urgent research activities based on AIRL research recommendations with a sanctuarised funding to be implemented within their respective research and development workplans for a rapid execution with regular report on the progress.*

PR2: ESA and Member States:

- ⇨ *Objective to set-up by 2nd Quarter 2026 a specialised operation committee with ESA, based on an agreed "Term of Reference" focused on coordinating and updating regularly the AIRL research activities. Cross-representation between the specialised operation committee and the AIRL research working group will be essential with external observers invited (e.g., ESSC, EC…).*

PR3: Consideration of AIRL objectives in the European Commission Multi Annual Framework workplan:

- ⇨ *Objective is to propose potential activities to be selected in the frame of the next MFF and if selected, preferably developed in coordination with R&D roadmaps already proposed.*

PR4: International research cooperation:

- ⇨ *Objective to co-ordinate co-funding schemes, align research goals and supportive facilities.*

Recommended near-term management actions (12–24 months):
MR1: **Extension of the AIRL Working Group mandate and terms of reference:**

- ⇨ *Objective to update the AIRL group membership and Terms of References early 2026 and, towards the end of 2026, deliver a consolidated scientific assessment and potential additional recommendations that will be revised periodically.*

MR2: Communicate and interact with policymakers and industry:

- ⇨ *Objective to organise meeting(s) between ESA/EC/ESSC and industry associations (Eurospace, SME4Space etc..) and define a way forward for further coordination support communication with policy makers and international bodies, for example to raise awareness within the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) and the United Nations Environment Assembly (UNEA).*

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Background: Awareness on the current scientific findings

Growth in space activities and debris population

Since the beginning of the space age, the number of objects in orbit, their total mass, and their combined cross-sectional area have steadily increased, resulting in rising likelihood of accidental collisions between operational satellites and debris. This ongoing trend raises the risk of a collision cascade, known as the *Kessler Syndrome*, that could ultimately render low Earth orbit (LEO) unusable (Kessler, 1991). [1] [2] To provide a comprehensive analysis of the evolving conditions in the near-Earth space environment and support global debris mitigation efforts, the European Space Agency (ESA) has published the *Space Environment Report* annually since 2017. This publicly available report is regularly updated, and directly supports the awareness-raising guideline established by the United Nations Committee on the Peaceful Uses of Outer Space (UNCOPUOS) in its *Guidelines for the Long-Term Sustainability of Outer Space Activities* (2019). [3] The report aims to provide a transparent overview of global space activities; assess the impact of these activities on the space environment, including risks to space systems; and evaluate the effect of internationally endorsed mitigation measures designed to ensure the long-term sustainability of spaceflight. Looking ahead, future editions must also address the atmospheric consequences of the increasing rates of launches and re-entering satellites. Since 2015, space traffic, particularly in LEO, has changed drastically, fuelled by the miniaturisation of space systems, low cost launch availability and deployment of large constellations, with a growing shift towards commercial operators. While the exponential growth in the number of launched payloads may have paused in 2024 (Fig. 1), the number of launches continued to rise, and both the total mass and area of launched objects remain at record highs. The ongoing expansion of space operations is driving a significant increase in the quantity and cumulative mass of orbital objects (Fig. 2).

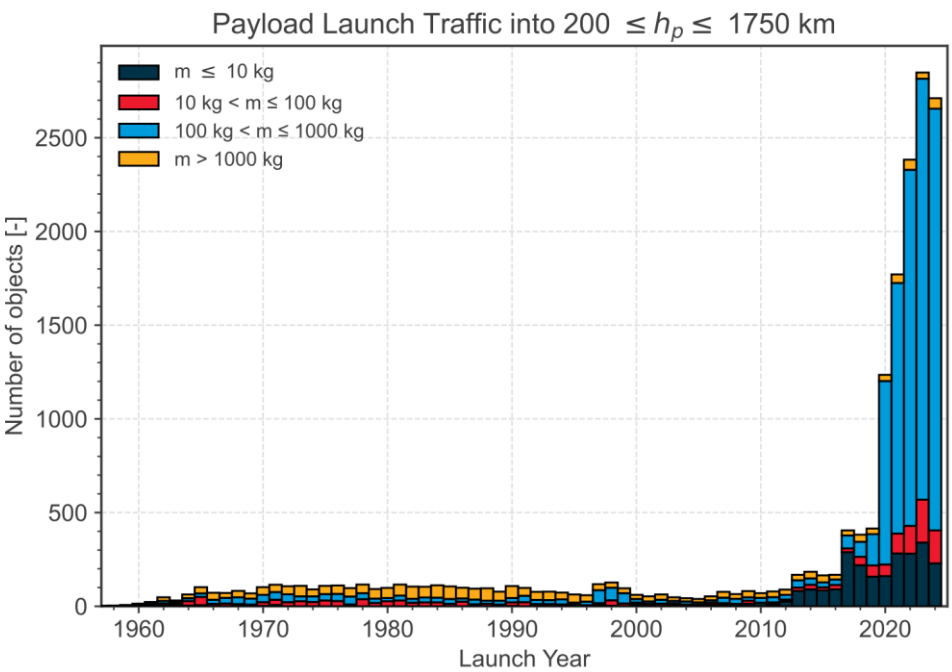
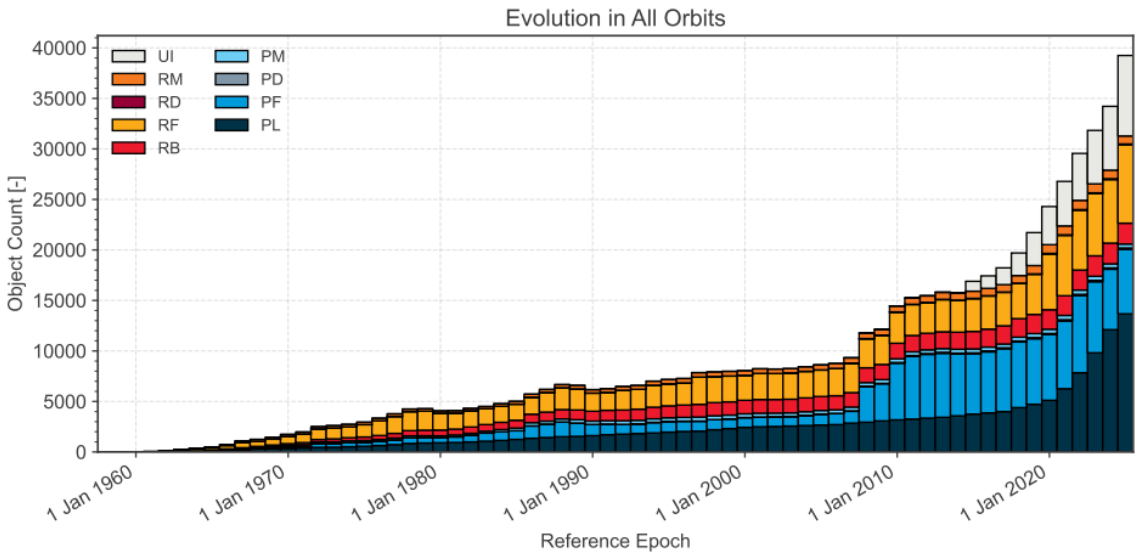
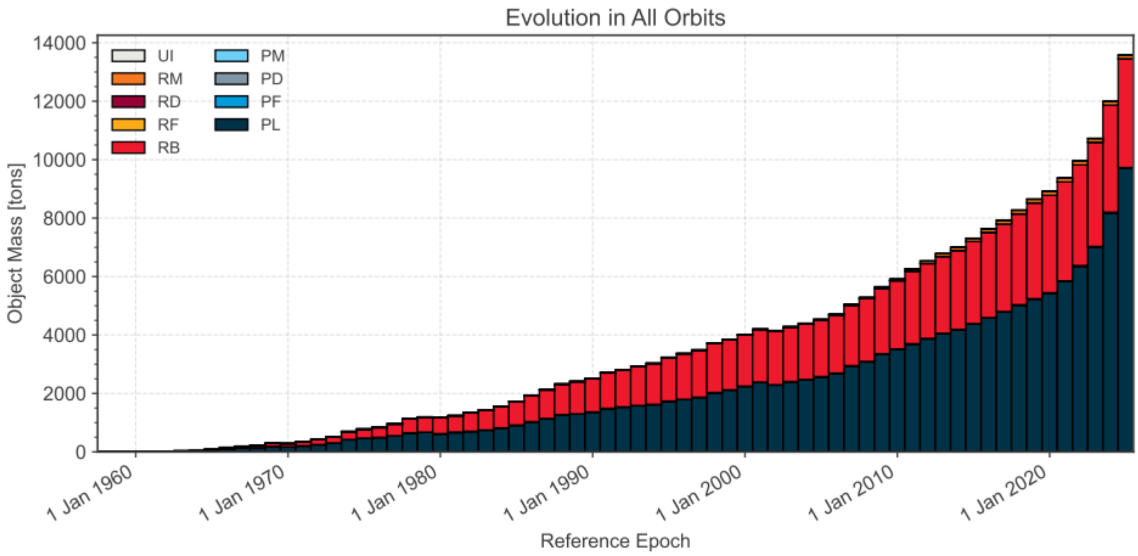


Figure 1: Evolution of the launch traffic per mass category in terms of number of objects in LEO_{IADC} (IADC: Inter-Agency Debris Committee; from ESA Space Debris Office, 2025).



(a) Evolution of number of objects.



(b) Evolution of mass.

Figure 2: a) Evolution of number of objects in geocentric orbit by object class. b) Evolution of the mass of objects in geocentric orbit by object class. PL: Payload; PF: Payload Fragmentation Debris; PD: Payload Debris; PM: Payload Mission Related Object; RB: Rocket Body; RF: Rocket Fragmentation Debris; RD: Rocket Debris; RM: Rocket Mission Related Object; UI: Unidentified (from ESA Space Debris Office, 2025).
https://www.sdo.esoc.esa.int/environment_report/Space_Environment_Report_latest.pdf

Mitigation measures

In response to this trend, the early 2020s saw some significant policy shifts come into force across major spacefaring states across the globe, including, for example, ESA's own adoption of the Zero Debris Approach and the update of its Space Debris Mitigation Standard and associated policy [4] [5]. Among the measures introduced by this revised Standard in 2023 was the reduction in the post-mission lifetime limit from 25 years down to 5 years, also adopted by the Federal Communications Commission (FCC). Specifically, the Space Debris Mitigation Standard requires that the orbit clearance of a spacecraft or launch vehicle orbital element from the LEO protected region shall satisfy two conditions: (1) the orbital lifetime after mission completion must be less than

5 years, and (2) the cumulative probability of collision with space objects larger than 1 cm from end of life until re-entry must remain below 10^{-3} [4]. However, even in the hypothetical case of no further launches into orbit, collisions among existing space debris objects are still expected to cause a continued growth in the space debris population within the LEO region (Fig. 3).

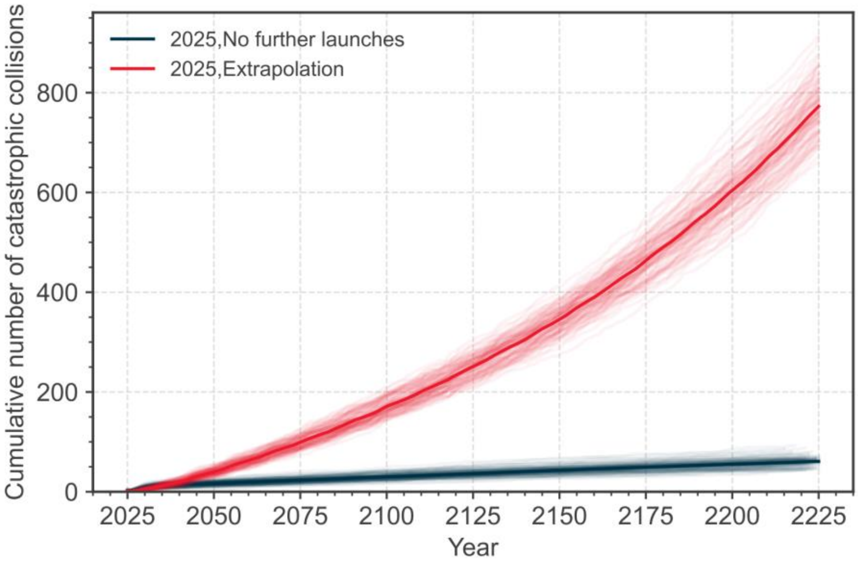


Figure 3: Number of cumulative collisions in LEO_{IADC} in the simulated scenarios of long-term evolution of the environment.

According to ESA's space debris environment model MASTER (Meteoroid and Space Debris Terrestrial Environment Reference), as of the 1st August 2024, the estimated number of space objects in orbit across different size ranges was as follows:

• 54,000 objects greater than 10 cm (including approximately 9300 active payloads),

• 1.2 million objects from 1 cm to 10 cm,

• 140 million objects from 1 mm to 1 cm.

To slow the growth of orbital debris (Fig. 2), space agencies now increasingly prioritise the safe, controlled deorbiting of large, inactive objects, reducing the risk of catastrophic debris-generating collisions in orbit. It is a key element of ESA's Zero Debris Approach which aims to halt the generation of long-lived debris in valuable orbits by 2030, and explore a space circular economy beyond that. Space agencies have also targeted the casualty risk posed by space debris and re-entry fragments reaching the ground. Where feasible, controlled satellites and upper stages are guided during re-entry to demise over remote, unpopulated regions. Another complementary measure is the Design-for-Demise (D4D) strategy, which aims to design satellites that fragment and burn up ("disintegrate") completely during re-entry, thereby reducing the likelihood that surviving components reach the surface. However, D4D does not account for whether gases and tiny fragments released during the burn up of satellites, or which form subsequently through the condensation of metallic vapours, may have detrimental impacts on the atmosphere and ocean. The Zero Debris Technical Booklet (Chapter 6.1.) highlights the need to better understand ablation products and recommends conducting measurements to assess the environmental impact of re-entry.

Environmental concerns

The sector's continued expansion, driven by the establishment of large constellations, means increasing numbers of launches and re-entries, raising questions about their environmental impacts. Rocket launches inject carbon-rich and alumina particles and gases, often propellant combustion byproducts, such as chlorine and nitrogen oxides, throughout the atmosphere while inactive satellites and rocket bodies re-entering the atmosphere fragment and largely burn up (ablate) in the mesosphere and upper stratosphere (between ~40 and ~100 km), releasing metal-rich particles and gases. The potential effects of these particulate and gaseous emissions on stratospheric aerosols, ozone layer, radiative balance, and cloud microphysics are emerging as significant environmental concerns. It is worth pointing out that the upward trend in re-entry emissions is expected to intensify with efforts to shorten the post-mission disposal time limit (for instance from 25 to 5 years), or to design satellites that burn up completely during re-entry. Although the first measure reduces the collision risk in orbit and the second mitigates the casualty risk on the ground, they both ultimately enhance the mass flux of demising hardware and consequently the re-entry emissions into the atmosphere. The issue extends beyond atmospheric effects and include the deposition of heavy elements to the surface, particularly in middle and high latitude regions, where they are expected to accumulate preferentially due to the atmospheric circulation. Metals such as copper and zinc, could have significant environmental and biological impacts, posing risks to ecosystems (flora and fauna) and ultimately human societies and public health.

The presence of particles originating from space activities in the lower stratosphere is now well established. For instance, in 2023, Murphy et al. reported findings from the SABRE aircraft campaign, which sampled the polar lower stratosphere. Already the measurements revealed that ~10% of stratospheric aerosol particles at 19km contained metals derived from the ablation and disintegration of launch vehicles and satellite components during re-entry that occur at much higher altitudes [6] (see Fig. 4). The most prominent signals were associated with aluminium (Al), copper (Cu), lead (Pb) and lithium (Li), reflecting the high Li, Al and Cu content in spacecraft materials and subsystems. More uncommon elements, such as niobium (Nb) and hafnium (Hf), provided unequivocal evidence of ablation from specific rocket body components. The study concluded that the anthropogenic inputs of Li, Al, Pb and Cu to the middle and upper atmosphere from space activities already exceeded the natural inputs, essentially of meteoritic origin. [7] These metallic ablation particles, together with rocket exhaust and other space-related emissions, have the potential to alter the chemistry and radiative balance of the stratosphere, the region that contains the ozone layer. For instance, stratospheric aerosol particles influence Earth's energy balance by scattering and absorbing radiation and some provide surfaces for heterogeneous chemistry that can affect ozone, a key radiatively active gas. Additionally, certain particles may act as nuclei for polar stratospheric clouds, further accelerating ozone loss. With the number of space launches and re-entries expected to continue rising in the coming decades, observable global changes in stratospheric aerosol loading, size distribution, chemical composition, and interaction with existing abundant stratospheric aerosols, notably metal content, are likely. Such changes could in turn perturb the ozone layer and climate. However, fundamental processes controlling the emission, chemical transformations, and microphysical evolution of space activity particles and interactions with other types of stratospheric aerosols remain poorly understood. Consequently, the effects of these emissions on the chemical and optical properties of stratospheric aerosols, and their broader atmospheric impacts, are still largely unknown

Recent studies have attempted to build an integrated understanding of how rocket launches and spacecraft re-entries affect the atmosphere, combining insights on emissions inventories, material-scale chemistry, and atmospheric processes. New global 3-D inventories now map where and when pollutants from launches and re-entries are released, categorised by vehicle type, propellant, altitude, and latitude. These datasets are important inputs to chemistry–climate simulations and policy assessments, [8] while also enabling sensitivity tests, for example, exploring how different fuels or re-entry conditions influence emissions. Current studies indicate that aluminium undergoes fast chemical reaction, producing aluminium oxides and hydroxides. Aluminium vapour may also be oxidized in the presence of atmospheric water vapour and oxygen to form aluminium hydroxides including $Al(OH)_3$. [9] The polymerisation of these species determines the size distribution and reactivity of the aerosols, some of which are known to affect ozone chemistry. [10] [11]. At atmospheric scales, chemistry–climate simulations indicate that rocket exhaust black carbon can alter lower stratospheric temperatures, circulation and ozone. The magnitude of these modelled effects largely depends on fuel type, injection altitude, and the pace of space activity growth, highlighting that propulsion choices appear to largely shape climate and ozone outcome [12]. Other modelling studies explore how particulate matter from re-entries could accumulate in the middle atmosphere and affect ozone and Earth's radiative balance in the coming decades. The impacts were found to depend on particle size distributions, atmospheric dynamics and injection altitudes, emphasising the need to couple realistic particle microphysics to credible launch and re-entry projections in model simulations [13]. In addition to climate and ozone impacts, rocket launches and re-entries can induce upper-atmospheric and near-space effects, including ionospheric disturbances, altered radio propagation, and changes in LEO density. [14] Together, these studies and others point to the need for a coherent research agenda with, as priority, closing key knowledge gaps through greater data transparency, targeted observations, laboratory studies and integrated modelling. This would ultimately enable robust assessments of climate-ozone impacts of space activities and hence provide the scientific basis for designing successful mitigation strategies. This work is essential for the sustainability of the space industry.

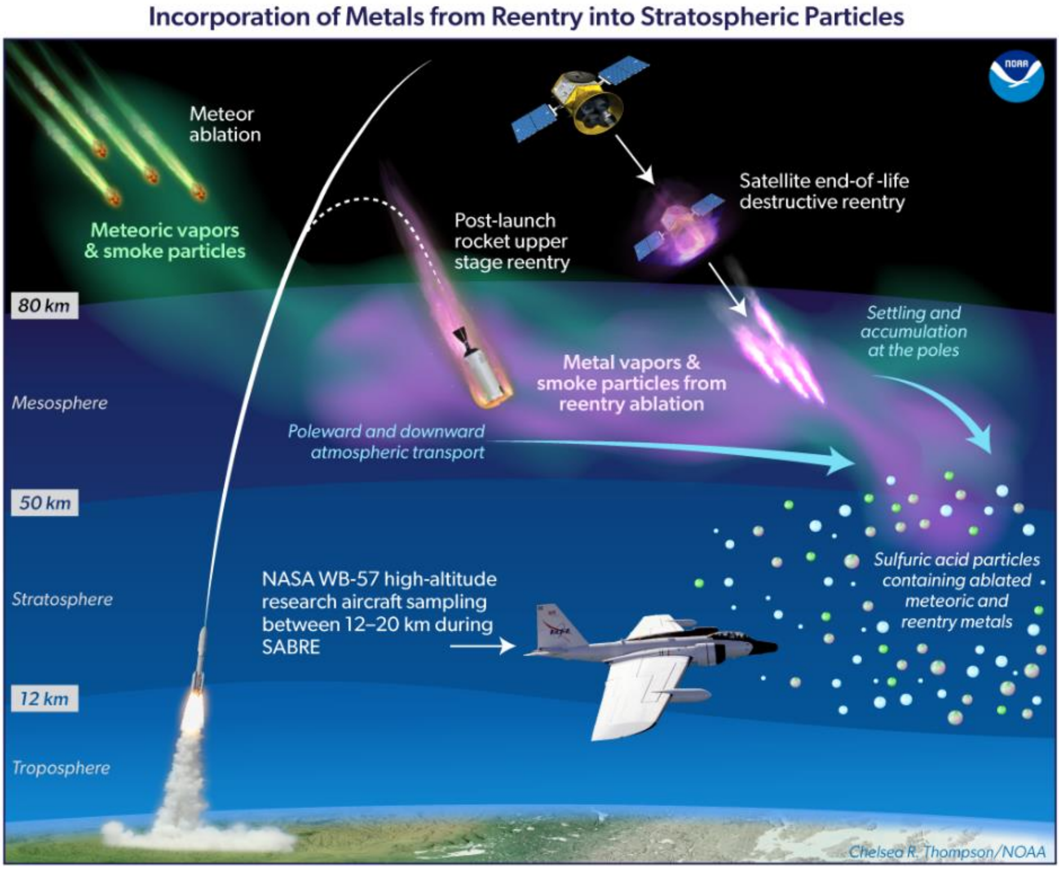


Figure 4: This graphic shows the various layers of Earth's atmosphere and how satellites vaporize as they hit the mesosphere at the end of their lifetimes. This process seeds the middle and upper atmosphere with metal vapours, aerosols, and smoke particles. The mesosphere is also where naturally occurring meteors vaporize. The ozone layer lies within the stratosphere (https://csl.noaa.gov/news/2023/388_1016.html; Graphic: Chelsea Thompson, NOAA). [6]

AIRL Working Group mission and objectives

Reasons for constitution

To address this emerging and urgent issue, the ESA Green Agenda, the European Space Science Committee (ESSC), and leading experts established the Atmospheric Impact of Re-entry and Launches (AIRL) Working Group in November 2023. Its objectives are to assess current knowledge on the sources and atmospheric impacts of pollutants originating from rocket launches and debris re-entries, compile the available evidence, and formulate actionable recommendations. In addition, workshops organised by ESA and ESSC provided valuable scientific input to inform AIRL's future priorities. AIRL is now issuing a first set of urgent actions, to be followed by further recommendations as scientific understanding advances, helping to inform the development of agency programmes, technical standards, and possible regulation.

Participants and Structure of AIRL WG

The AIRL working group was formed to examine the effects of rocket launches and debris re-entries on the atmosphere. Given the global nature of this challenge, the group brings together an international team of experts from key institutions across the space sector. Participants include representatives from major space and research institutions, as well as from regulatory bodies such as the European Commission and United Nations, who will play crucial roles in designing and implementing recommendations and possibly regulations should potential risks be identified. The group is managed by representatives from institutions based in Europe (ESA, ESSC, CNRS, and European Science Foundation (ESF)) but includes members from major spacefaring and research agencies across the globe.

Table 2: Name, acronym, and affiliation of the institutions represented in the AIRL working group.

ESSC	**European Space Sciences Committee**	**Europe**
ESA	**European Space Agency**	**Europe**
CNES	**Centre National d'Études Spatiales**	**FR**
COSPAR	**Committee on Space Research**	**INT**
DLR	**Deutsches Zentrum für Luft- und Raumfahrt**	**DE**
EC	**European Commission**	**Europe**
IAA	**International Academy of Astronautics**	**INT**
UNOOSA	**United Nations Office for Outer Space Affairs**	**INT**
CNRS	**Centre National de la Recherche Scientifique**	**FR**
NCEO	**National Centre for Earth Observation**	**UK**
NASA	**National Space and Aeronautics Administration**	**USA**
NOAA	**National Oceanic and Atmospheric Administration**	**USA**
TU-BS	**Technische Universität Braunschweig**	**DE**
UCL	**University College London**	**UK**
UoL	**University of Leeds**	**UK**
UiT	**The Arctic University of Norway**	**NO**

In addition to the institutions represented in the AIRL WG, private organisations contribute with their own expertise and capabilities to AIRL WG and ESA workshop reflections.

Table 3: Name and country of affiliation of the private organisations contributing to AIRL working group.

B2Space	**ES**
MAIASpace	**FR**
AALTO	**UK**
TESAT	**DE**
Belstead Research	**UK**

Potential Environmental Impacts of Increasing Space Activity

Recent modelling and assessment studies indicate that increasing launch and re-entry activity could have non-negligible impacts on ozone recovery and the upper atmosphere, highlighting the growing importance of rocket emissions in both climate and atmospheric chemistry assessments [15] [16]. When a rocket is launched or an object ablates during atmospheric re-entry, large amounts of gases and particles are emitted into the atmosphere. These high-altitude emissions represent the only anthropogenic emission sources in the middle atmosphere (mesosphere and stratosphere between roughly 15 and 80 km). Since many of the emitted compounds are chemically active, cloud-nucleating, or climate forcers, there is growing concern about their potential environmental impacts, particularly on the stratospheric ozone layer and climate.

Emissions from rocket launches

During a rocket launch, propellant combustion within the engine generates a high-temperature exhaust mixture which is expelled through the nozzle. At the nozzle exit, a jet plume forms with an inner core that remains relatively isolated from the surrounding air, encased by a thin mixing layer where ambient air entrains and reacts with exhaust gases and particles at high temperatures. As the plume moves away from the nozzle, its size increases with the mixing in of air. In the far field, the plume has expanded considerably and cooled to near-ambient temperatures. Its spreading and dispersion are then driven by atmospheric dynamical processes such as wind shear and turbulence. The compounds ultimately released into the atmosphere consist either of primary combustion products or secondary products formed through physicochemical processes occurring within the near-field and far-field exhaust plumes. The composition of rocket emissions varies considerably with the type of propellant used. Multiple propellant formulations are employed in rocket propulsion, each generating distinct emission species. For solid-fuelled rockets (e.g. Ariane), the most environmentally significant emissions are thought to be hydrochloric acid (HCl) and alumina (Al_2O_3) particles. In contrast, hydrocarbon-fuelled rockets (e.g. Falcon 9) emit carbon-based particles, notably black carbon, which are among the most impactful for the atmosphere. In mass, CO_2 and H_2O are the dominant emissions. Nitrogen oxides (NOx), ozone-perturbing radicals, are an unavoidable by-product of all rocket launches and is produced by high-temperature combustion and shock-driven conversion of atmospheric nitrogen, regardless of propellant type.

Emissions from destructive re-entry

During re-entry, space debris (e.g. satellites, upper stages, components) are typically subject to extreme mechanical and thermal stresses. The main demise of space debris occurs once it has fragmented into its separate components. The high entry speed leads to the vehicle components being heated and undergoing physico-chemical changes such as thermal decomposition, oxidation, melting, and vaporisation. As a result, a range of gaseous and particulate compounds are directly released at the surface of demising components. Gases can then experience further physicochemical processing (including phase transitions) within the high temperature shock layer and plume that forms just behind the falling debris. For example, vaporised metals and gases cool and re-condense in the plume wake and surrounding air, where they can also undergo reactions with atmospheric constituents such as O_2, O_3, H_2O and CO_2 to form a range of oxides, hydroxides and carbonates. These molecules are then likely to nucleate as nanometre-scale particles that can then grow by condensation and coagulation. The partitioning between material that fully vaporises versus material that forms coarse pieces, droplets or particles is an important factor determining atmospheric impacts. Typically, most of the re-entering object mass does not survive atmospheric re-entry and ends up being converted and released into the atmosphere in gaseous or particulate forms. Depending on the material composition and structure of re-entry debris, a wide variety of gases and particles are produced, which are subject to chemical transformations during their transit in the middle atmosphere.

Global transport, chemistry, and radiative effects of launch and re-entry emissions

Whatever the nature of particles emitted during a launch or a re-entry, a crucial factor in atmospheric impacts is their size which largely determines their atmospheric residence time. The sub-micron aerosols ($\lesssim$1 µm) are most impactful for ozone chemistry and radiative balance because they typically persist in the middle atmosphere for up to a few years for the smallest particles. They can also mix with other stratospheric aerosols (e.g. sulphate, carbonaceous wild fire, meteoritic), forming more complex aerosol particles whose chemical and optical properties are very uncertain. By contrast, coarse particles (>1 µm) are short-lived because they sediment comparatively quickly out of the middle atmosphere and do not have time to affect the atmosphere significantly. Note that, after deposition at the surface of the ocean/terrestrial environments, there are still open questions about the possible toxicity of space activity particles, notably metallic particles (e.g., Al, Cd, Cr, Pb, Cu and associated oxides and hydroxides).

Gases and small (long-lived) particles emitted in the middle atmosphere by launch and re-entry events can be transported and dispersed on a global scale, driven by the global circulation in the stratosphere, (so-called Brewer–Dobson circulation) and the pole-to-pole meridional circulation in the mesosphere. As a result, even if injected in the tropics, they can end up at high latitudes. During atmospheric transit, depending on their chemical reactivity and optical properties, launch and re-entry particles can affect the chemistry and radiative balance of the middle atmosphere. For example, aluminium oxide/hydroxide particles may provide chemically reactive surfaces, analogous to those associated with polar stratospheric clouds, on which inorganic halogen species can be converted into radicals that catalyse ozone destruction very efficiently. Some of the particles could also act as nuclei in the formation of polar stratospheric clouds, a key driver in polar ozone depletion. As ozone is a key radiative gas in the stratosphere, any change in its distribution indirectly affects the thermal and radiative balance of the stratosphere and the amount of UV radiation reaching the surface. Furthermore, launch and re-entry particles, notably black carbon, directly impact the radiative balance and climate through their ability to scatter and absorb incoming solar radiation.

The added complexity of mixed particles

As launch and re-entry particles sediment into the lower stratosphere, most of them coagulate with sulphuric acid aerosols. As a result, they can become partially covered by sulphuric acid or even entirely immersed in sulfuric acid aerosols. On the one hand, this process may partially 'passivate' or deactivate reactive particle surfaces, thereby limiting some heterogeneous ozone-depleting reactions. On the other hand, sulphate coating and coagulation processes may substantially modify particle microphysical properties, atmospheric residence times, and heterogeneous chemical behaviour. The net effect on ozone chemistry therefore remains uncertain. Overall, large uncertainties remain about the nature and properties of these mixed particles. The morphological shape of the debris particles, the thickness and uniformity of the sulphate coating, and the possible chemical ageing of their surfaces, are poorly constrained. Coating may also favour the adsorption of nitric acid and water, which would alter further particle surface reactivity or possibly even contribute to the formation of polar stratospheric clouds (PSC) at high latitudes. With launch rates rising and upper-stage and satellite re-entries increasing more research is needed about the adsorption of gaseous molecules on launch and re-entry particles and on their interactions with the other stratospheric aerosols. In addition to coagulation with sulphuric acid aerosols, space activity particles may also interact with other non-sulphate aerosol populations present in the lower stratosphere, including biomass burning aerosols. Recent observations demonstrate that wildfire emissions can significantly perturb stratospheric aerosol composition, introducing organic material that alters particle phase state, hygroscopicity, and surface chemistry [17] [18]. Such mixed organic–inorganic particles have been shown to promote heterogeneous chlorine activation and enhanced ozone depletion at moderate temperatures under stratospheric conditions, even outside classical PSC regimes [19]. These findings highlight that space activity particles interacting with organic or combustion-influenced aerosols may follow chemical ageing pathways distinct from particles exposed to sulphate only coating, complicating assumptions about long-term passivation and underscoring the need to consider multi-component aerosol interactions in impact assessments on ozone and climate.

Activities of the AIRL WG:

The AIRL Working Group (WG) has so far held four plenary meetings (November 23, May 24, October 24, February 25), gathering most mandated members and invited experts who presented their latest findings and needs. In addition, specialised workshops with WG members, external experts, and partner organisations were organised to assess the scientific benefits and feasibility of flight campaigns dedicated to atmospheric in-situ measurements. Outcomes of the specialised meetings were reported during AIRL workshops and documented in the meeting minutes.

The data, that would be acquired in dedicated measurement campaigns identified as a key priority by AIRL, are for most of them very complementary: they are shown in the table summarising the scientific gaps versus the research activity needs shared and backed by all AIRL working group members (see Annex).

1) **First Step – Identification of scientific gaps:** The meetings, workshops, and preparatory activities have progressively led to the development, review, and prioritisation of a comprehensive list of scientific knowledge gaps essential for understanding the atmospheric effects of space industry activities.

2) **Second Step - Scientific activities:** the joint WG identified the research activities that would fill the knowledge gaps through selected campaigns of measurements, tests and simulations, for which feasibility assessments have been performed beforehand. This overall research strategy is not new. It is based on a classic 3-pronged approach of observations, modelling, and laboratory experiments and is often used to tackle atmospheric problems. The nature, frequency, spatial extent, and altitude range of the atmospheric measurements that can be performed depend on the platform selected to host the instruments. For example, the main altitude region of space debris ablation, between about 50 and 100 km can only be sampled in-situ from sounding rockets or launch/re-entry vehicles. Balloons are more suited to sample the stratosphere, whereas aircraft can only sample the lowermost stratosphere. Space debris before ablation could also be sampled with LEO platforms. Each platform has its own constraints in terms of instrumentation payload. For some of these activities, a planning process (technical, schedule and funding) is in assessment. All these activities have been clustered under the overarching programme called **"SPHERE"** (Stratospheric Particle and High-Altitude Emissions Research Experiments); they have been categorised by domains of experiments and type of projects as follows:

In-situ atmospheric measurements: Short- to medium-term campaigns (1–2 years) identified as high-priority, affordable, and achievable to deliver crucial missing in-situ data:

- <u>Stratospheric balloons</u>: Using, e.g., CNES, CSA, or B2Space balloon capabilities to sample from 15 km to 35-40 km altitude with particle counters and collectors (first flight in summer 2025; second with a similar payload plus condensation particle counter and gas sensors, spring or summer 2026).

- <u>Aircraft</u>: For example, joint NASA/NOAA/SABRE-ESA mission (tbd 2026), complementing the 2023 SABRE campaign that revealed the presence of significant metals linked to space industry activity in lower stratospheric aerosols

- <u>HAPS</u> (High Altitude Platform): Solar-powered aircraft operating at up to 21 km altitude (during day) equipped with particle instruments for extended missions (several weeks). Plan to fly over the Atlantic Ocean to sample background lower stratospheric aerosols and rocket plumes close to launch sites; a potential mission expected mid 2026

- Sounding rockets: Feasibility under review with DLR facilities to deploy instruments that could be operated during the relatively low velocity apogee phase at high altitudes. In addition, the extension of ESA's FIREWALL activity to sample launch propellent exhaust from, e.g., sounding rocket plumes.
- Re-entry Capsules: Joint assessments with, e.g., KREPE, ATMOS Space Cargo, KLARA, and Space Forge exploring the deployment of sensor arrays and sampling instruments on board of re-entry capsule with possible recovery options.
- European re-usable launcher: Upcoming test flights to include onboard instruments characterising the launcher emissions.
- New type of in-situ instrumentation on LEO platform e.g. time-of-flight mass spectrometer.

Remote sensing: Essentially space missions that might provide relevant data on gases and particles emitted by space activities and on their middle atmospheric impacts.

- Current missions : EarthCARE, CALIPSO, SAGE III onboard ISS, OMPS onboard NPP & NOAA-21, ACE-FTS & MAESTRO on board SCISAT-1, Sentinel-4 onboard MTG-S, Sentinel-5 & IASI-NG on board MetOp-SG.
- Upcoming missions: ALTIUS…
- Planning / under selection: CAIRT, Keystone (EE12), STRIVE (US), AOS HAWC, METAL

Numerical Modelling: Identified needs in terms of model developments and model simulations covering the relevant scales, from small scales (destructive re-entry, re-entry and launch plumes) to global scales. See Annex, Atmospheric Modelling and Impact Assessment page 33.

Ground tests and laboratory studies: Complementary ground tests and laboratory experiments with specific facilities. See Annex, section: Ground testing ablation facilities 27.

Assessment of new observation tools: e.g., new types of remote instrument (not limited to emission/absorption method) and effective in-situ detection (in addition to sampling) to overcome current limitations.

Real-world measurements: Satellite Remote Sensing vs. In-Situ sampling

Remote sensing can typically offer global coverage when performed from space, vertical profiling for limb-viewing instruments, and the ability to map the spatio-temporal evolution of atmospheric constituents. However, its spatial resolution is often too coarse to fully resolve individual plumes, and it provides limited aerosol characterisation, particularly in terms of chemical speciation and size distribution. For instance, it remains challenging to distinguish $Al(OH)_3$ from Al_2O_3 or to identify, let alone quantify, minor aerosol components. Nonetheless, it is worth pointing out that radiative transfer modelling within the CAIRT EE11 project studies has shown that Al_2O_3 exhibits a distinct infrared spectral signature at 12.5 µm, possibly enabling its measurement from limb-sounding observations. The potential for such measurement needs to be explored. In contrast, in-situ sampling using balloons, aircraft, sounding rockets, or capsules enables detailed aerosol characterisation, conducted either online (during flight) or offline (through laboratory analyses of collected aerosol samples), in terms of chemical composition, morphology, and even mixing state. Such insights help to evaluate aerosol chemical reactivity, optical properties, and potentially cloud-nucleating ability. This level of detail is essential for model development and validation. Remote sensing alone cannot provide all these capabilities.

Recommendations

Research Recommendations (RR)

These short-term recommendations, covering the next 12 to 24 months, aim to accelerate scientific understanding and establish a solid foundation for long-term research. Future efforts will build on these initial actions to ensure sustained scientific progress. While these measurements are recommended to advance scientific understanding, most of them have no committed funding.

AIRL's core focus must be on building a robust data foundation through direct field measurements, comprehensive laboratory characterisation, and the enhancement of ground testing facilities. At present, particle microphysics and physicochemical processes in launch and re-entry plumes are insufficiently characterised and understood. As a result, model impact assessments of space activities have to rely heavily on crude and uncertain assumptions. Investing in real-world data collection and testing facilities is a prerequisite for reliable evaluations of environmental impacts. Developing new propellants or new spacecraft demisable materials without comprehensive environmental assessments runs the significant risk that these alternatives may inadvertently cause greater atmospheric damage.

The total estimated cost of the recommended activities is between 6.4 and 8.7 M€.

1

Aircraft sampling of rocket plumes: E.g., the NASA WB-57F can carry flight proven instrumentation such as the SABRE payload for in-situ sampling and/or the SAMI (SCIFLI Airborne Multispectral Imager, NASA Langley Research Center, 2024) remote multispectral imager. More limited measurements can be made from the G-V aircraft.

Purpose: Obtain data on rocket plume chemistry and dynamics as a function of altitude for different propellant types. Such data constrain models of afterburning and NOx and soot emissions.

When: Milestones: Q3 2027 MoU & coordination between ESA, SABRE program, and NASA → Q1 2027 integration & flight planning.

2

Targeted stratospheric sampling: Conduct balloon/aircraft sampling above and within the lower stratospheric sulphate layer for aerosol collection followed by postflight laboratory characterisation (size, detailed composition, morphology, mixing state, chemical and optical properties).

Purpose: Sample above/below the sulphate layer; lab characterisation of size, composition, morphology, reactivity.

When: Q1 2025 payload/sites fixed → Q2–Q3 2025 two launches/transects → Q4 2025 lab analysis → Q1 2026 dataset + report.

3

Rocket sampling – sounding rockets Use sounding rockets to directly sample upper stratospheric and mesospheric aerosols and gases during and after launch/re-entry conditions. Enable collection of particles across the 40–120 km region for laboratory analysis (size, composition, reactivity), complementing aircraft and balloon studies.

Purpose: Provide critical validation data for models of ablation, heterogeneous chemistry, and plume dispersion. Aircraft sampling of sounding rocket plumes of varying the fuel type.

When: Q1 2026 mission definition → Q4 2026 payload integration/tests → Q4 2026 launch campaigns (Esrange/Andøya) → Q1 2027 lab analysis & dataset delivery.

4

Launch-site lidar & spectrometer installations: Deploy permanent/portable lidar to provide continuous vertical profiles of aerosol layers and plume evolution over launch corridors. UV-visible spectrometer at launch site to monitor nitrogen dioxide (NO_2) for estimating NOx emissions.

Purpose: Continuous vertical aerosol profiles over launch corridors to track plume evolution, and provide some constraints on size, particle density, refractive index, and depolarisation.

When: Q3 2026 procurement → Q4 2026 install & acceptance → Q1 2027 monitoring

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5

Ground test synergy: Integrate shock-tube/arc-jet and plasma-wind-tunnel campaigns to determine vaporisation/ablation thresholds and heterogeneous kinetics for key materials. (SMASI (Simulation of Meteor/Spacecraft Ablation at IAA-CSIC) /HEFDiG /PWK4 provides the high-enthalpy flow field), low plasma sources and post-mortem analysis.

Purpose: Determine vaporisation/ablation thresholds and heterogeneous kinetics (γ, α/ε) for key materials under high-enthalpy flow.

When: Q3–Q4 2025 SMASI kinetics → Q2–Q36 2026 PWT/arc-jet runs → Q4 2026 synthesis.

6

Launch-site sampling: Deploy permanent/portable aerosol sampling to provide continuous monitoring of plume evolution during engine tests and launches over launch corridors.

Purpose: Continuous aerosol monitoring over launch corridors (Gerding approach) to track plume evolution. Install sampling probes for launch plume characterisation.

When: Q3 2026 procurement → Q4 2026 install & acceptance → Q1 2027 monitoring

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7

Laboratory characterisation: Controlled laboratory experiments for understanding physical and chemical processes of material/atmospheric interaction.

Purpose: Uptake (including reactive uptake) of inorganic halogen species on surfaces of SAPs, aging/deactivation of SAP surface chemistry, and ice nucleation potential for PSCs.

When: Q2 2026 → Q3 2026–Q1 2027 Lab → Q2 2027 input into models → Q3 2027 policy brief.

8

Laboratory kinetics and model integration: Integrate all measurements into chemistry–climate models (e.g., GEOS-Chem/WACCM, UK-ESM, ICON, IPSL-LMDz-REPROBUS) to quantify transport, chemistry, radiative impacts, and to generate policy-ready assessments.

Purpose: Integrate measurements into global models (e.g.GEOS-Chem, WACCM , TOMCAT/SLIMCAT, UK-ESM, LMDz-REPROBUS, SOCOL); quantify transport, chemistry, radiative impacts; evaluate the impacts of halogen species uptake on space activity (launch and reentry) particles (SAPs), PSC nucleation, surface deactivation

When: Q2 2026 → Q3 2026–Q1 2027 assimilation & sensitivity runs → Q2 2027 intercomparison → Q3 2027 policy brief

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9

High Altitude Platform System – HAPS: To conduct long-duration, high-altitude measurements of aerosols and trace-gas composition in the upper troposphere–lower stratosphere (UTLS). HAPS platforms will allow continuous, spatially resolved observations in regions not routinely sampled, including launch corridors over the Atlantic Ocean, enabling better characterisation of background conditions and transient rocket plume events. This activity will complement balloon, aircraft, and rocket sampling campaigns by providing persistent monitoring capability at ~21 km altitude.

Purpose: Provide sustained, in-situ atmospheric measurements in the UTLS to characterise baseline aerosol and gas composition, detect perturbations associated with launch activities, and generate high-resolution datasets needed to validate atmospheric-chemistry and plume-dispersion models. The HAPS platform enables long-endurance monitoring in poorly sampled regions and strengthens the long-term observational framework supporting AIRL research.

When: Q2 2026 planning → Q3– 2026 development → Q4 2026 flight

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10

Re-entry vehicles and reusable launchers: Integrate dedicated sensor and return payloads onto re-entry vehicles and reusable and expendable launcher stages to conduct in-situ atmospheric sampling and demonstrate payload recovery capability.

Purpose: Advance scientific understanding by collecting in-situ data (T, P, shock layer, particle and gas emissions) during high-enthalpy re-entry 40 to 90km; validate aerothermodynamic and demisability models; demonstrate reliable, low-shock, reusable satellite/cargo return capability / reusable launchers.

When: Q2 2026 planning → Q3 2026–Q1 2027 development → Q1 2028 flight

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11

Feasibility study for space-borne monitoring of orbiting sub-micron debris and middle atmospheric material: Assess space-borne instrumentation potential for in-situ monitoring of micro-debris in LEO and remote sensing of gases and particles from launches and re-entries in the middle stratosphere.

Purpose: Evaluation of space sensors (e.g. TOF-MS) for in-situ characterisation and mapping of both the upflowing population of ablated elements and in-orbit sub micro-debris populations in LEO (before atmospheric re-entry). This in-situ data will help to constrain debris influx above the mesosphere and complement spacecraft material inventories.

Review existing and operational satellite missions to assess what current data products can already be exploited, identify gaps in capabilities and coverage, and determine how new middle atmospheric in-situ measurements would complement and enhance existing space-borne observations.

When: Q2 2026 planning → Q3 2026–Q1 2027 development → Q2 2027

12

Feasibility study for ground-based observation of re-entry plumes: Assess ground-based systems (EISCAT radars, Kühlungsborn lidar, optical/IR spectroscopy) for direct observation of spacecraft re-entries and ablation plumes. Survey current capabilities, define observing strategies, identify needed upgrades, and improve input inventories of re-entering objects (mass, materials, geometry, trajectories).

Purpose: Characterise re-entry plume properties (profiles, particle load, optical signals), constrain ablation/breakup models, provide validation data for atmospheric-impact and debris models, and refine input inventories for observation planning and modelling.

When: Q2 2026 planning → Q3 2026–Q1 2027 → Q2 2027

Programmatic Recommendations (PR)

PR1: ESA and Members States

A strong, coordinated programme is essential to understand the atmospheric impacts of space activities with dedicated research actions. Achieving this goal requires sustained research, close collaboration, and clear integration of scientific findings into policy. Consistent with ESA sustainability's ambitions and environmental responsibility, it could build on the AIRL Working Group's recommendations and establish a harmonised, global "AIRL" roadmap within its R&T and development plans in line with the Zero Debris Technical Booklet (Chapter 6.1). This roadmap could be formally endorsed by ESA Member States and should clearly identify the priority and time-critical activities requiring financial support - whether through ESA programmes, national budgets, or the European Commission funding, depending on the scope and relevance of each activity.

Budget priorities should be initially focused on the short-term, high impact activities. Among them the identified concrete opportunities of atmosphere in-situ measurement campaigns and exploitation of the current spaceborne instruments data stand out.

- ⇨ ***After the ESA-C Min 25 , at 2ndQuarter 2026, ESA and Member States to release the roadmap of the urgent research activities based on AIRL research recommendations with a sanctuarised funding to be implemented within their respective research and development workplans for a rapid execution with regular report on the progress.***

PR2: ESA and Member States:

Member States that already conduct research activities or operate facilities in the identified research domains, are invited to consolidate efforts with ESA through coordinated planning and implementation.

- ⇨ ***Objective to set-up by 2nd quarter 2026 a specialised operation committee with ESA, based on an agreed "Terms of Reference" focused on coordinating and updating regularly the AIRL research activities. Cross-representation between the specialised operation committee and the AIRL research working group will be essential with external observers invited (e.g., ESSC, EC…).***

PR3: Consideration of AIRL objectives in the European Commission Multi Annual Framework workplan:

AIRL is encouraged to provide inputs to the European Commission focusing on the identified R&D priorities areas. This may contribute to the R&D workplan discussions to be carried out in the frame of the next Multiannual Financial Framework (MFF) to be adopted for 2028. In case, such activities are selected, coordination between EC and ESA is recommended to ensure consistency of objectives and overall coherence.

- ⇨ ***Objective is to propose potential activities to be selected in the frame of the next MFF and, if selected, preferably developed in coordination with R&D roadmaps already proposed.***

PR4: International research cooperation:

International collaboration is crucial to achieving a globally coordinated approach to understanding and mitigating the atmospheric impacts of space activities. Building on the joint activities and scientific exchanges already initiated within the AIRL Working Group (e.g., with NASA and NOAA), foster and strengthen international cooperation among space agencies in this domain. Expand partnerships to include additional national agencies and research institutions. Possibly coordinate funding mechanisms and programme planning in the domain across ESA and national agencies, NASA, NOAA, and extending the co-operation with e.g. NCAS, JAXA and ARIA , by aligning calls, timelines, and evaluation criteria, and by promoting jointly funded and complementary work packages. Initiatives such as ARIA's "Scoping Our Planet" and the SLICE doctoral network could serve as models for co-funding collaborative research, enhancing data interoperability, and establishing shared standards for data access and model validation.

⇨ ***Objective to co-ordinate co-funding schemes align research goals and supportive facilities.***

1

Coordinated programme building on AIRL WG recommendations: Prepare long-term research, close collaboration, and clear input into policy. ESA should establish a harmonised, global "AIRL" roadmap within R&T and development plans. Roadmap to be formally endorsed by ESA Member States and should clearly identify the priority and time-critical activities needing funding whether through ESA, national budgets, or the European Union, depending on the nature of each activity.

Purpose: Release roadmap, compendium of activities and workplan endorsed by dedicated supporting funding.
Who: E.g. ESA, ESA Member states; AIRL…
When: Q3 2026 Roadmap → Q4 2026 funding secured

2

Consolidated European research network: Objective to set-up by January 2026 a specialised operation committee with ESA, based on an agreed "Terms of Reference" focused on coordinating and updating regularly the AIRL research activities. Cross-representation between the specialised operation committee and the AIRL research working group will be primordial and external observers will be invited (e.g., ESSC, EC…).

Purpose: Member States owning research activities and facilities in the identified research domains, are invited to join their forces in a consolidated manner with ESA and to coordinate.
Who: E.g. ESA; AIRL; ESA Member States…
When: Q3 2026 Specialised operation committee → Q3 2026 - Q1 2027 Invitation of research groups into network

3

Consideration of AIRL objectives in European Commission Multiannual Financial Framework (MFF): Explore, as appropriate, the possible alignment of relevant elements of the AIRL compendium with the forthcoming EU MFF to be implemented as of 2028, taking into account complementary supports and activities that may fall within the European Commission's perimeter and could be jointly identified with ESA.

Purpose: Share AIRL findings with European Commission.

Who: E.g. European Commission; ESA, AIRL…

When: 2026/2027 introduction of AIRL objectives in new MFF calls

4

International research cooperation: Foster and strengthen international cooperation among space agencies, building on joint activities and scientific exchanges already initiated within the AIRL Working Group (e.g., with NASA and NOAA). Collaboration should be expanded to include additional national agencies and research institutions, ensuring a globally coordinated approach to understanding and mitigating atmospheric impacts of space activities. Coordinate funding mechanisms and programme planning across ESA, NASA, NOAA, NCAS, and ARIA by aligning calls, timelines, and evaluation criteria, and by promoting jointly funded and complementary work packages. Initiatives such as ARIA's "Scoping Our Planet" and the SLICE doctoral network could serve as models for co-funding collaborative research, enhancing data interoperability, and establishing shared standards for data access and model validation.

Purpose: Objective to co-ordinate co-funding schemes align research goals and supportive facilities.

Who: E.g. AIRL; ESA; NASA; NOAA; COSPAR ; CNES; DLR; ASI…

When: Q3 2026 Contact of agencies not currently involved

Management Recommendations (MR)

MR1: Extension of the AIRL Working Group mandate and terms of reference:

Expand the international composition of the AIRL WG to other organisations across the world engaged in the domain.

Mandate the WG to regularly monitor the progress of research activities conducted in Europe and abroad; report on the results, and update the WG workplan accordingly, to be shared with relevant institutions and stakeholders.

Propose a way forward and additional recommendations according to the outcomes of the research activities including possible mitigation strategies.

⇨ ***Objective to update the AIRL group membership and ToR early 2026 and, towards the end of 2026, deliver a consolidated scientific assessment and potential additional recommendations that will be revised periodically.***

MR2: Communicate and interact with policymakers and industry:

Based on the current progress of the AIRL WG recommendations and ESA/EC planning process, support Agency communication and coordination with stakeholders, including industry.

⇨ ***Objective to organise by first quarter 2026 information meeting(s) between ESA/EC/ESSC and industry associations (Eurospace, SME4Space etc.) and define a way forward for further coordination, support communication with policy makers and international bodies, for example to raise awareness within the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) and the United Nations Environment Assembly (UNEA)***

1

Extension of AIRL WG mandate and terms of reference: Extend the composition of the AIRL WG across the world to other organisations engaged in the domain. Mandate the WG to regularly monitor the progress of research activities implemented in Europe and in other nations; report on the results and update the WG workplan accordingly to be shared with relevant institutions and stakeholders. Propose way forward and additional recommendations according to the outcomes of the research activities including possible mitigation strategies, and regulations

Purpose: Objective to update the AIRL group membership and ToR early 2026 and, towards the end of 2026, deliver a consolidated scientific assessment and potential additional recommendations that will be revised periodically.

Who: AIRL

When: Q2 2026 Revision of membership and ToR

2

Communicate and interact with industry: Based on the current progress of the AIRL WG recommendations and ESA/EC planning process, support Agency communication and coordination with stakeholders, including industry.

Purpose: Objective to organise early 2026 a first information meeting between ESA/EC/ESSC and industry associations (Eurospace, SME4Space etc.) and define a way forward for further coordination, then support international coordination. To raise awareness within the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) and the United Nations Environment Assembly (UNEA)

Who: AIRL

When: Q2 2026 Organise first information meeting → Q2 2026 Meeting takes place

Recommendation implementation planning and roadmap

This roadmap presents a preliminary planning framework, visualised through a Gantt chart highlighting key milestones. It reflects the current expectations of the AIRL Working Group regarding the timing, sequencing, and coordination of major research activities.

Designed as a living document, the roadmap is intended to be refined as projects progress, funding opportunities are secured, and international collaborations evolve. It provides a structured overview of how complementary campaigns, laboratory studies, and modelling efforts interlink to close critical knowledge gaps on atmospheric impacts of space activities.

As new partners join and additional datasets become available, this roadmap will be periodically updated to maintain alignment with broader space agency programme planning cycles and to support integration with policy and sustainability objectives, including those of the Zero Debris Charter/Zero debris technical Booklet (Chapter 6.1) and, more generally, ESA's Protect Our Planet and Climate pillar. Where feasible, a range of budget estimates and potential funding sources will be identified, together with clear decision points linked to specific milestones.

Figure 5: Gantt-chart for implementation of recommendations. Cost estimates exclude in-kind-contributions (e.g., platforms).

Conclusion

The rapid growth of global space operations represents an emerging and insufficiently characterised driver of anthropogenic impacts on the middle and upper atmosphere. These impacts arise from emissions produced by rocket launch exhaust and spacecraft re-entry ablation, that interact chemically and physically with the atmosphere, although the detailed mechanisms are still to be identified and quantified.

Although thought to be historically negligible relative to the natural influx (dominated by meteoric origin), recent observations have revealed that spacecraft re-entry now release metals, including aluminium and copper, at rates exceeding natural inputs. Signatures of these anthropogenic inputs have already been detected in stratospheric aerosols, raising concerns about their potential effects on ozone chemistry, radiative balance, and climate. Key uncertainties remain regarding the partitioning between vaporised and condensed material during re-entry; the formation, size distribution and ageing of space activity sub-micron particles; the physiochemistry and optical properties of the various space activity particles; and their transport pathways, residence times and removal on a global scale. The increased traffic and regulations shortening de-orbiting timelines, from approximately 25 years to as little as 5 years, lead to the expected total mass of re-entering material to increase sharply. A quantitative understanding of the processes and impacts is therefore essential to determine whether launch and re-entry remain a marginal source of atmospheric perturbations or become a significant driver of stratospheric and mesospheric changes.

The Atmospheric Impacts of Re-entry and Launch (AIRL) Working Group has emphasised that tackling these knowledge gaps requires an integrated, cross-disciplinary strategy, combining in-situ sampling campaigns, laboratory-based experiments, and advances in plume and chemistry–climate modelling underpinned by open data exchange. In parallel, technological pathways towards mitigation are emerging. Alternative rocket propellants, reusable launch and satellite systems, controlled recovery architectures, and novel material design strategies offer routes to shift away from uncontrolled space activity emissions and towards a circular recovery and reuse economy. For instance, it could turn re-entry from an environmental liability into a demonstrator of sustainable space operations. As satellite traffic continues to expand, the space sector faces an increasingly unquantified risk and a clear choice: either allow atmospheric loading to grow without a robust understanding of its consequences, or embed atmospheric stewardship and sustainability at the core of space governance. The coming five years will be pivotal. Through coordinated action by space agencies, the scientific community, industry, and regulators, the sector can set a global precedent showing that space expansion and environmental protection can progress together.

In summary, immediate priorities to tackle key unknowns include:

- **Atmospheric observations**: Targeted aircraft, balloon, HAPS, sounding rocket, launcher in-situ sampling, satellite and ground-based remote sensing to constrain particle number, composition, size, morphology, and their global distributions and to estimate emission rates of gases and aerosols, altitude distribution and related transport.
- **Laboratory experiments:** Controlled plasma wind tunnel simulations to characterise re-entry ablation processes and the resulting particle production. Atmospheric chamber experiments to investigate the physicochemistry and cloud-nucleating ability of space activity particles, including their optical properties at multiple wavelengths, from the UV to the IR domain, for estimating climate forcing and assessing the feasibility of monitoring space activity particles using remote sensing.
- **Plume and chemistry climate modelling:** modelling of launch and re-entry emissions and plumes, with integration into global models to evaluate microphysical, chemical and radiative impacts.

Progress in each domain will directly inform and reinforce the others, forming the foundation of a robust, evidence based, data driven understanding of the space industries interaction with different layers of Earth's atmosphere.

Annex 1 – Understanding the Atmospheric Effects of Spacecraft Launch and Re-entry

Natural Input vs Anthropogenic Input

Day-to-day influx is dominated by countless tiny particles (smaller than 100 microns), not by the occasional large events, collectively delivering ~15-45 tonnes per day. While large bodies dominate single event energy, they are too rare to meaningfully affect the total mass budget of most species. Because detection is size dependent, a sensor mix is essential: satellite dust detectors for the smallest grains in space, radars and all-sky cameras for mm–metre ablation in the atmosphere, and infrasound/telescopes for the largest objects. Consequently, any realistic assessment of atmospheric inputs, and any comparison with anthropogenic re-entry, must be anchored in the sporadic small-particle background, not occasional large events.
Daniel Kastinen and Johan Kero outline during the 2nd AIRL workshop how the natural meteoroid influx compares with the growing anthropogenic influx from spacecraft re-entries, and argue that the meteor community's instruments and methods can be repurposed to study re-entry plumes. They show observational synergies, meteor trail radars detecting dusty plasma from a Falcon-9 re-entry, all-sky meteor camera networks logging re-entry tracks, and high power radars (EISCAT) long used for meteors and debris calibration, and set a to-do list: better ablation model fitting, clarify radar detectability for small re-entries, and coordinate multi-sensor campaigns to answer the critical questions. Compositional measurements of fragmented satellite material both recent breakup ejecta and remnants from past military tests as well as unburned rocket-fuel residues can be obtained via in-situ mass spectrometry. Although dust and debris smaller than ~10^{-12} kg do not dominate the overall mass influx, they provide valuable compositional information and strong statistics, serving as tracers of larger debris populations. dust fluxes have been measured in situ through sample-return missions, but the relative contributions of natural meteoric dust versus anthropogenic material remain uncertain. Importantly, the compositional signature of this anthropogenic influx differs markedly from that of natural meteoroids: recent in-situ aircraft observations indicate that chemically active elements such as aluminium and lithium are now supplied to the upper atmosphere in greater amounts by spacecraft re-entry than by the natural meteoroid background, while copper and other alloying elements introduce entirely non-meteoritic chemical pathways. This implies that even where anthropogenic dust does not dominate the total overall mass budget, it may already dominate the flux of specific chemically and radiatively important elements.

Table 3: Natural Input from Meteoroids versus Anthropogenic

Attribute	Meteoroids (natural)	Anthropogenic space objects (re-entries)
Typical entry speed	~11–72 km/s (set by heliocentric orbits; upper bound near solar-system escape speed projected at Earth)	~7–8.5 km/s (near circular LEO to highly elliptical; essentially orbital velocity ± de-orbit/ballistic components)
Mass range	10^{-9} – 10^{2} g (dust → small meteoroids)	10^{-1} – 10^{6} g (fragments, components, panels; larger for intact bodies)
Dominant composition	Silicates, organics, metal sulfides, Fe–Ni	Engineering materials: alloys, polymers, composites, batteries/electronics, coatings
Typical trajectory geometry	Often steep/deep; wide radiant distribution (apex/helion/antihelion/toroidal)	Typically shallow, controlled or ballistic re-entry corridors

Share of total influx (mass)	Majority of daily mass (sporadic background dominates)	Small but rising; currently minor vs natural input, but increasing with traffic
Temporal behaviour	"Steady-ish" background with seasonal structure + short shower peaks	Campaign/traffic-driven, tied to launch cadence, disposal policies, mega-constellations
Atmospheric/chemical notes	Ablation yields metal atoms/oxides (Na, Fe, Mg, etc.), seeding metal layers and PMCs	Ablation yields engineered species (Al/Al_2O_3, Cu, Ti, Li, polymers, battery/halogen traces), different reactivity and particle spectra

Although the annual mass from space waste is still about an order of magnitude smaller than the meteoroid influx, the total annual mass influx of space waste to the top of the atmosphere (pre-ablation) was just under ~1 kt/yr from 2015–2020, rose to ~1.6 kt in 2024, and by extrapolating year-to-date entries exceeds ~2.3 kt in 2025. Much higher influxes are expected in high growth scenarios. The increase is driven mainly by mega-constellation satellites and their deploying non-reusable upper stages**,** that accounts for >85% of the anthropogenic mass influx. [20]

Sampling of stratospheric particles

In 1981, the NASA Cosmic Dust Program was created to collect and study cosmic dust particles in the stratosphere between 18-20 km over the United States with campaigns running until the present time. The NASA WB-57 and ER-2 (and until 1986 the U-2) aircraft collect these particles on silicone oil covered plates. Solid particles typically larger than a few microns are manually selected from the plates, washed with hexane and then characterised under optical and Scanning Electron Microscope (SEM). The elemental composition of these micrometric particles is measured by Energy Dispersive X-ray Spectroscopy (EDS). Based on these data, the particles are tentatively classified into 4 groups:

• **Cosmic** (C): originating from asteroids and comets;
• **Terrestrial Contaminant Natural** (TCN): from stratospheric injection of ash from volcanic eruptions and biomass fires, pollens, spores, salts, etc.
• **Terrestrial Contaminant Artificial** (TCA): from re-entry of space objects such as satellites, rocket bodies, and space debris;
• **Aluminium Oxide Spheres** (AOS): from Solid Rocket Motors exhaust. Most likely coming from the Space Shuttle Solid Rocket Boosters, as it was the main source of alumina injected into the stratosphere at this time and that no AOS were reported after this programme ended in 2011.

Taupin et al. (2024) revealed that the population of TCA in these catalogues has increased in the last 10 years. Future work involves quantifying the mass fraction of elements contained in all particles from the NASA Cosmic Dust Catalogs, and to extend this analysis to all Cosmic Dust Catalogs [21]. Furthermore, Taupin et al., estimated that in 2024, the total re-entered dry mass from anthropogenic space activities before ablation in Earth's atmosphere may have represented 20% to 40% of the Earth's cosmic natural input [21] [22].

The high-altitude aircraft (WB57), that can fly up to 19 km took a wide range of *in situ* measurements, using Harvard's instruments including a cascade impactor that collected particles from 180 nm to 3.2 microns, and collected over 400 samples. Using a microscopy technique, STXM to quantify particle composition, Sophie Abou-Rizk highlighted during the 2nd AIRL workshop a wide range of particles even in separate flights a day apart were seen, with varying morphologies and organic contributions. STXM also shows us the organic volume fraction and continues to show large organic contributions to stratospheric aerosols. This is important for surface reactions involving inorganic halogen species.

Fragmentation and Ablation Gaps

Accurately quantifying and characterising the emission profiles of materials injected into the atmosphere during spacecraft launch and re-entry is the essential first step in impact assessment.

The first-order uncertainty that largely governs the atmospheric impact of satellite re-entry is fragmentation and vaporisation. More, specifically, the key questions are: what fraction of the satellite's mass demises during re-entry; what proportion of that demised mass fully vaporises into gas-phase species versus the fraction that survives as small particles, and what are the associated size distributions of those particles?

A critical need exists to better understand spacecraft fragmentation and ablation for typical re-entry trajectories. This specifically involves:

- **Particle Size Distributions and Vaporisation Thresholds:** Improving ground testing facilities, implementing characterisation methods to understand the vaporised material in the wake. This enables models to predict how components break up to sizes where they can be heated significantly to vaporise, the resulting particle size distributions, and vaporisation thresholds under various re-entry conditions (velocity, angle, material composition).

- **Material-Specific Thermochemistry and Surface Interactions:** Existing ablation models must be significantly improved to incorporate material-specific thermochemistry and the complex atmospheric surface interactions that govern phase transitions. This includes understanding the role of particle surface chemistry at all altitudes. Among key issues are the ability of models to capture the heating of re-entering particles in rarefied flows and the catalycity of the surface of the small particles.

- **Gas-Phase vs. Solid-Phase Emissions:** It is crucial to quantify the proportion of material that ablates and vaporises versus what remains as solid particles. Determining the specific vertical profiles over which these phase changes and fragmentation events occur under varying re-entry scenarios (e.g., different velocities, angles, and material compositions) is essential for accurately mapping the initial distribution of pollutants.

Ground Testing Ablation Facilities

Ground testing and controlled laboratory experiments are foundational for understanding the fundamental physical and chemical processes that govern spacecraft material behaviour in the atmosphere. These controlled environments allow for detailed studies that are difficult or impossible to replicate in situ, providing crucial data for model development and validation.

Meteor Ablation Simulators (MASI) and Plasma Wind Tunnels (PWTs)

These specialized facilities are essential for simulating the extreme conditions of atmospheric re-entry and characterizing the resulting emissions.

Improved Ablation Models and Secondary Particle Characterization:

- **Facilities:** Leverage existing facilities such as the Instituto de Astrofísica de Andalucía-SMASI facility, University of Stuttgart - Plasma Wind Tunnel (IRS PWTs), DLR – High-Enthalpy Wind Tunnels, ESTHER -

European Shock-Tube for High Enthalpy Research, PALS – Prague Asterix Laser System, Karlsruhe Institute of Technology - AIDA Simulation Chamber facilities, and Oxford University- Osney Plasma Generator, DROID - University of Southampton, von Kármán Institute for Fluid Dynamics (VKI) – Belgium. Low pressure plasma sources TU Darmstadt.

- **SMASI for Anthropogenic Materials:** The Space Meteor Ablation Simulator (SMASI) is a unique facility that can be modified to carry out ablation experiments with spacecraft debris analogues under realistic atmospheric conditions (e.g., varying pressures, temperatures, gas compositions). This capability is critical for establishing the specific chemical pathways of anthropogenic metals in the lower mesosphere-stratosphere. By pinpointing key molecules that enter stratospheric aerosols, it becomes possible to identify potential changes in their chemical makeup and physical properties. Within SMASI, advanced techniques like mass spectrometry can be employed to directly probe the ablation region. This allows for the detection of polyatomic molecules and radicals that may lack optical spectra, providing a more complete and accurate chemical inventory of ablation products beyond simple elemental analysis. This is crucial because complex molecules, not just individual atoms, can have significant atmospheric impacts.

- **PWTs for Fragmentation and Vaporisation:** PWTs precisely simulate the aerothermodynamic re-entry environment, enabling detailed secondary particle characterization. Further development is needed for understanding the emissions and vaporisation in the wake:
  - Fragment and particle sizing: Assessing the size distributions of ejected aluminium oxide fragments and molten aluminium droplets, and verifying their rapid break-up.
  - Vapour yield and gaseous species: Quantifying vapour production across varied particle sizes and ambient pressures, and identifying major gaseous species produced.
  - Altitude-dependent demise: PWTs' advanced pressure control allows precise altitude simulation to capture the variation of fragmentation and vaporisation effects with atmospheric density, providing essential data for pollutant injection profiles.

- **Gaseous Species and Surface Properties:** Experiments in facilities such as SMASI and plasma wind tunnels (PWTs) help identify the dominant gaseous and particulate products formed under re-entry conditions. These measurements are crucial for understanding how the vaporised fraction interacts with the surrounding atmosphere, including evaporation, recondensation, and the formation of new particles through heterogeneous chemistry and ice nucleation. By characterising how vapours transition into solid or liquid aerosols across different temperature and pressure regimes, we can better predict their eventual fate within the stratosphere and mesosphere. This knowledge underpins models that track how re-entry emissions evolve into long-lived aerosols, influencing radiative balance, cloud formation, and chemical reactivity in the middle and upper atmosphere.

Atmospheric Observations

In terms of necessary measurements, the following table summarizes the required instrumentation to address this fundamental partitioning and the subsequent chemical fate of the products:

Table 4: Required instrumentation for space debris detection in the middle atmosphere

	$Al(OH)_3$ (Aluminium Hydroxide) → Gas	Al_2O_3 (Alumina) → Solid Aerosol	In-Situ Sampling → Validation
Primary Challenge	Weak, broad spectral features that overlap with other gases	Distinguishing from background aerosols (e.g., volcanic ash, meteoric dust) that share similar scattering properties.	Obtaining samples from the mesosphere/stratosphere (high cost, low access).
Remote Sensing Method	UV/Vis/IR Optical Spectroscopy (Limb/Nadir Sounders)	Multi-Wavelength & Polarisation Lidar (Ground/Satellite). Mid-infrared hyperspectral limb-sounding (balloon/satellite)	On-board mass spectrometer to measure eg. Al, AlO, Al_2O_3 to see if which form of Al is transported upward to the satellite altitude.
Required Instrumentation	High-resolution spectrometers optimised for trace gas absorption/emission.	Lidar systems capable of measuring depolarisation ratio (to detect non-spherical particles) and backscatter at multiple wavelengths. Mid-infrared emission limb-sounding spectrometer (to distinguish aerosol particles by use of their spectral signatures, e.g. Al_2O_3).	Not Applicable
In-Situ Instrumentation	Mass Spectrometry on collected samples to identify species and concentrations.	Aerosol Impactors/Collectors followed by Electron Microscopy & Mass Spectrometry for morphology, size, and elemental analysis.	High-altitude aircraft , Balloon/Sounding Rockets, and dedicated plume-capture capsules(both return sample analyses and in-situ mass-spectrometry)

Atmospheric Heterogeneous Chemistry Experiments

Targeted laboratory studies are needed to quantify how space debris particles interact with the stratosphere and mesosphere under realistic conditions. Key questions include how surface reactions are suppressed by sulphate coatings, and the extent to which such particles can nucleate polar stratospheric clouds. These processes strongly influence heterogeneous chemistry and radiative forcing, yet remain poorly constrained. Controlled experiments on particle size, composition, and mixed-material effects are essential to derive uptake rates, deactivation efficiencies, and nucleation thresholds. These parameters will provide the quantitative coefficients required to constrain atmospheric model calculations and accurately predict the long-term impacts of re-entry emissions.

Conducting laboratory experiments is critically important to study the heterogeneous chemistry of acidic gases on relevant particles (e.g., alumina, soot, metallic oxides) under realistic stratospheric and mesospheric conditions. For example, it is well established that halogen reservoir species (i.e. HCl, HBr, $ClONO_2$, $BrONO_2$), along with nitrogen reservoir species such as N_2O_5, undergo heterogeneous reactions on sulphate aerosols and/or polar stratospheric clouds, thereby promoting halogen activation and ozone depletion. Consequently, comprehensive investigations of heterogeneous reaction kinetics, photochemistry, cloud-nucleating ability, and optical properties of Space Activity Particles (SAPs) must be conducted under atmospheric conditions (temperature, pressure, and radiation field), representative of the various regions of the middle atmosphere.

- **Surface reactivity:** Investigating the surface reactivity and uptake coefficients of various atmospheric trace gases (e.g., O_3, NOx, ClOx, BrOx species) on spacecraft-derived aerosols. This includes understanding the role of surface functional groups and crystalline structures in catalytic processes.

- **Uncommon atmospheric chemical species:** Particularly important for newly identified chemical species resulting from spacecraft ablation, as their atmospheric lifetimes, reactive pathways, and potential to form long-lived reservoir species are currently poorly understood. This includes understanding dissociation pathways and radical formation from polyatomic ablation products.

- **Ice nucleating abilities and cloud formation:** A key unknown is the ice nucleating ability and water uptake properties of the SAPs, which can influence the formation of Polar Stratospheric Clouds (PSCs) and Polar Mesospheric Clouds (PMCs). Changes in these clouds may have significant atmospheric implications. For PSC formation in particular, particle morphology (e.g. shape, crystallinity, porosity) and surface chemistry (e.g. active sites, functional groups, hygroscopicity) control how efficiently particles act as nuclei for nitric acid trihydrate or ice clouds. The presence and properties of cloud nuclei determine to a large extent the critical supersaturation for cloud formation and the resulting particle size distributions, with direct consequences for ozone depletion.

- **Optical properties:** Assessing the radiative effects of SAPs requires knowledge of their optical properties across a broad wavelength range, from the UV to the IR. Laboratory studies of collected particles or representative analogues (e.g. using the AIDA chamber) can provide accurate optical constants and support the feasibility of SAPs components detectability by remote sensing.

Effects of Launch Vehicle Emissions

Launch Vehicle Emissions: Altitude-Dependent Impacts

Understanding the atmospheric effects of launch vehicle emissions demands precise characterisation of exhaust products across the entire atmospheric column, as both the emitted species and their subsequent atmospheric fate are highly dependent on injection altitude and local conditions.

Tropospheric Emissions (0~12 km)

In the dense lower troposphere, primary concerns are local and regional air quality.

- Fuel byproducts: Kerosene-LOX (RP-1) & Methane-LOX (CH_4): Produce significant soot (black carbon, BC) and carbon monoxide (CO). BC particle size distribution and morphology are crucial for light absorption, cloud condensation nucleation (CCN) efficiency, and health impacts. CO is a tropospheric ozone precursor.
- LH2-LOX: Primarily forms water vapour (H_2O) and thermal NOx.
- Solid Rocket Motors (SRMs): Emit alumina (Al_2O_3) particles and hydrogen chloride (HCl). HCl rapidly forms hydrochloric acid, contributing to acid rain.
- Water vapour (H_2O) and thermal NOx are produced by all rocket launches, regardless of propellant type.
- Contrail formation: In the upper troposphere, H_2O and other condensables can form persistent contrails that evolve into contrail cirrus, altering the radiative balance by trapping outgoing longwave radiation.
- NOx emissions: Contributes to tropospheric ozone formation and regional air pollution.

Stratospheric Emissions (12~50 km)

Emissions from space activities directly into the stratosphere are rather unique and potentially critical due to the absence of other direct anthropogenic sources and the long atmospheric lifetimes (months to years), resulting in dispersion of emissions over large and global scales. For example, direct injections of gases and of BC and Al_2O_3 particles cause:

- Radiative forcing: BC absorbs solar radiation, leading to stratospheric heating and altered circulation. Al_2O_3 also interacts with radiation and hence can affect atmospheric heating and radiative budget.
- Heterogeneous chemistry: Alumina (Al_2O_3) and soot provide surfaces for heterogeneous reactions. Laboratory studies show that alumina can convert chlorine reservoir species (HCl, $ClONO_2$) into ozone-destroying radicals (Cl, ClO), with a similar conversion of bromine species possibly occurring, especially under cold stratospheric conditions. However, aging or acid-coating may also reduce Al_2O_3 reactivity. Soot (BC) may also promote halogen activation, particularly when partially oxidised or coated with acidic layers.
- Modification of background stratospheric aerosols: Mixing of soot, alumina and other space activity particles into the background stratospheric aerosol population, forming mixed particles and possibly increasing total sulphuric acid surface area available for heterogeneous halogen activation.
- Water vapour increase: Even relatively small H_2O emissions can significantly affect the extremely dry stratosphere. H_2O is a source of ozone-destroying hydrogen radicals, acts as a greenhouse gas, causing stratospheric cooling, and enhances PSC formation, thereby catalysing ozone depletion via heterogeneous halogen activation.
- Chlorine species (from SRMs): HCl directly injected is converted to active chlorine (Cl, ClO) via heterogeneous reactions on aerosols, alumina particles, or PSCs.
- NOx formation: stratospheric NOx destroys ozone in the middle stratosphere but also traps other important ozone-destroying radicals by forming temporary reservoir species (e.g., $ClONO_2$).

Mesospheric Emissions (50~100+ km)

Emissions here affect thermal structure, cloud formation, and ionospheric properties.

- Water vapour: enhances PMC formation, indicating alterations to mesospheric temperature and composition, with radiative and chemical impacts.
- Metallic species and ions: ablation injects metals and oxides that act as nucleation sites for PMCs, and participate in ionospheric chemistry, affecting electron density, ion composition, and electric conductivity/fields, perturbing radio propagation.
- NOx formation: less efficient but still impacts mesospheric chemical balance.
- Mesospheric emissions are transported downward into the stratosphere through the global residual circulation and polar winter descent, allowing re-condensed particles and chemical products to reach lower atmospheric layers.

There are also potential perturbations above the mesosphere:

- Plasma disturbances: High-velocity re-entering objects cause localised ionization and plasma turbulence in the lower thermosphere (above the mesosphere), affecting communication.
- A small fraction of the ions will be transported upward, accessing even the upper part of the ionosphere, contaminating natural origin ions. Their possible effect on the satellite environment (e.g., spacecraft potential, booms, solar panel attachment) are unknown.

Table 5: Summary of the typical propellants used and the primary emission products

Propellant category	Primary emission products
RP-1 / LOX (kerolox)	Black carbon (soot), CO, CO_2, H_2O, thermal NOx, VOCs/PAHs (thermal decomposition),
CH_4 / LOX (methalox)	H_2O (dominant), CO_2/CO , thermal NOx, potentially small BC under fuel-rich/off-design conditions, possible unburned CH_4 ,
LH_2 / LOX (hydrolox)	H_2O (dominant),
Composite solid propellant (AP/HTPB/Al)	Al_2O_3 (alumina) particles, HCl, H_2O, HCl → hydrochloric acid formation, soot/tars
Hypergolic / storable (UDMH / N_2O_4 etc.)	CO, CO_2, thermal and fuel NOx, nitrogen-containing organics / toxic species (hydrazine derivatives), particulate, BC
Hybrid / other (H_2O_2, biofuels, experimental)	Varies: H_2O, CO_2, CO, thermal NOx, possible organics;

Note: *Nitrogen oxides (NO_x) and water vapour are ubiquitous by-products of rocket launches across all propellant types, arising from high-temperature combustion and shock-driven fixation of atmospheric nitrogen, as well as from propellant chemistry itself. As a result, NO_x and H_2O emissions occur irrespective of whether propulsion systems use solid, liquid, or hybrid propellants*

Atmospheric Modelling and Impact Assessment

Once emitted, space activity materials undergo complex chemical and physical transformations and interactions with the environment, during its atmospheric transit driven by the slow circulation and particle sedimentation. Understanding these processes is fundamental to predicting their impact. The aim is to integrate the understanding derived from targeted field data and laboratory results into comprehensive plume and atmospheric models to evaluate the potential global consequences of space activities.

First, small-scale models of launch and re-entry plumes need to be improved with more focus on generated emissions. For example, destructive re-entry models do not yet simulate thoroughly the ablation physics of spacecraft materials and the associated production of gases and particles. Treatments of multiple ablation processes, particle microphysics, and surface interaction processes, integrating updated material datasets from industry to reflect modern spacecraft alloys and composites need to be improved. This would help to derive reliable and standardised source term metrics, including chemical speciation, vaporisation yields, particle size and morphology. Second, the chemical and dynamical evolution of emitted gases and particles in launch/re-entry plumes and in the global atmosphere has to be properly simulated by models. This phase covers their physicochemical transformations and microphysical evolution (e.g. coagulation, condensation/evaporation, sedimentation) during their middle atmospheric transit and global dispersion, which ends with their transport to the troposphere and removal. Global atmospheric models do not need to describe the details of ablation or plume chemistry which can be accounted for in emissions inventories prescribed in atmospheric models.

Establishing this end-to-end understanding is essential for quantifying where and in what form space activity materials are transported, accumulated, and deposited globally. Embedding these results within the Life Cycle Assessment (LCA) framework at the level of the Life Cycle Inventory (LCI) is a first step toward quantifying environmental impacts through Life Cycle Impact Assessment (LCIA). This ensures that environmental impacts of launchers and satellites are fully represented in design and policy decisions, allowing agencies and industry to select propellants, materials, mission architectures, and end-of-life strategies that genuinely minimise environmental impacts. This modelling effort will be underpinned by urgently needed real-world data collection, including ground testing and characterisation, and coordinated middle atmospheric sampling campaigns. Data from ground-based facilities such as SMASI and plasma wind tunnels (PWTs) providing crucial data for the development and validation of re-entry emission datasets derived from ablation modelling. Laboratory studies provide physicochemical rate parameters that are key inputs to atmospheric aerosol-chemistry-climate models. Uncertainties are still too large on chemical kinetics of space activity metals. Finally, continuous measurement and monitoring of metals and submicron aerosols (<1 µm) in the middle atmosphere using in-situ platforms such as balloons, aircraft, and sounding rockets are essential to atmospheric modelling. Comparisons between model simulations and observations help to improve and constrain atmospheric models, and to assess their accuracy. The continuous feedback loop between observation, ground-based experiment, and modelling is critical to improving our understanding and the predictive capability of atmospheric impact assessments.

Integrated ablation processes and resulting emissions

- **Fragmentation Dynamics and First-Order Uncertainties -** Characterise when and how spacecraft fragment during re-entry, including the thermal mechanical coupling that governs breakup altitude, fragment number, and mass distribution. Fragmentation controls all subsequent aerothermal and chemical processes, defining surface area, size distribution, vaporisation and injection altitude, yet remains one of the largest uncertainties in demisability and emissions prediction.

- **Material-Specific Ablation and Pyrolysis Physics -** Establish improved/validated high-temperature ablation and decomposition models for metals and composites. Provides realistic material response and emission characteristics for modern spacecraft components used in destructive re-entry.

- **Shock Layer and Plume Chemistry -** Characterise formation and reaction kinetics of NOx, metal oxides, silicates, and other reactive species in the shock layer and wake. Identify chemical pathways that could result in ozone depletion and radiative forcing from re-entry.

- **High-Fidelity Non-Equilibrium Flow Modelling -** Develop CFD/DSMC-based tools that capture non-equilibrium thermochemistry, surface ablation, and radiation coupling in re-entry and launch regimes. It resolves flow surface interactions and heating behaviour that low-fidelity correlations cannot, improving breakup and demise predictions.

- **Coupled Ablation Radiation Flow Interaction Models -** Integrate ablation species generation into flow solvers to quantify feedback between vaporised materials, gas composition, and radiative heat transfer. It determines how ablation products alter the local aerothermal environment and influence both demise efficiency and emission composition for launch and re-entry events.

- **Multi-Fragment and Debris-Cloud Dynamics -** Simulate interacting fragments and plume coupling in multi-body configurations to capture collective flow-field effects during fragmentation. Reflects real re-entry behaviour where proximity interactions modify heat loads, demise timing, and ablation-product distribution.

- **Plume Evolution and Mixing Processes -** Model the formation and evolution of debris and ablation plumes following breakup, including transport, atmospheric dynamics, wake interactions, particle coagulation, and chemical mixing. The physical and chemical evolution of the plume determines the residence time, dispersion, and atmospheric reactivity of re-entry products, directly influencing their climatic and ozone impacts.

- **Experimental Validation under Flight-Relevant Conditions –** Regarding re-entry, combine plasma-wind-tunnel testing with coordinated in-flight observation missions (e.g., DRACO) to benchmark destructive re-entry models. Regarding rocket launches, carry out sampling of plumes from engine tests and launchers (e.g., MAIASpace). Supplies ground truth across temperature, pressure, and flow regimes, reducing uncertainty in both aerodynamic and chemical predictions.

- **Unified Source-Term Framework (Launch + Re-entry) -** Define a harmonised emissions schematic (species, particle size/morphology, yield vs. heat flux and altitude, uncertainty metadata) covering both launch exhaust and re-entry ablation products. Establishes a consistent foundation for comparing emission datasets and feeding atmospheric models across laboratories, campaigns, and agencies.

Atmospheric processes

- **Injection and Global Transport Mapping -** Advance emission databases with injection altitude, latitude, and timing for launches and re-entries. It enables scaling from individual events to global fluxes and long-term atmospheric loading.

- **Particle Microphysics, including nucleation mechanisms -** Determine size-resolved ageing, hygroscopicity and nucleation of alumina, AlOH, BC, and mixed particles. Uptake coefficients, parameterise deactivation (sulphate coating) and PSC nucleation efficiencies (NAT). Atmospheric models should be refined to explicitly incorporate the impacts of both gases and aerosols from space activities on cloud formation, notably polar stratospheric clouds, and on background sulphate aerosol, in order to accurately quantify consequences for ozone depletion and radiative balance.

- **Criticality of Surface and Optical Properties**: The accurate determination of the surface properties of space-activity particles including surface chemical reactivity (heterogeneous uptake coefficients), emissivity, catalytic activity, optical properties (e.g. refractive index), and surface-dependent cloud-nucleating potential is critical for assessing their atmospheric impacts. Small differences in these properties can lead to large differences in predicted heating, vaporisation, and ablation behaviour, ranging from minimal vaporisation to highly efficient mass loss, underscoring the need for detailed material and surface characterisation. Results from laboratory and ground-based studies must feed directly into atmospheric and re-entry models to enable robust impact assessments of ozone chemistry, cloud formation, and radiative effects.

- **Stratospheric/Mesospheric Nucleation Mechanisms** - While chemistry climate models have the capability to tag and track anthropogenic versus natural particle sources, the limiting factor is the lack of fundamental microphysical data. We need improved understanding of nucleation pathways involving re-entry derived particles (e.g., Al_2O_3, metal oxides, carbonaceous aerosols), their interplay with meteoric smoke, and how these processes seed or modify stratospheric and mesospheric aerosol populations.

- **Integration with Atmospheric Impact and Climate Frameworks -** feed the results of launch and re-entry simulations into whole atmosphere chemistry–climate models. These models can then be used to evaluate the atmospheric fate of re-entry by-products and quantifies their influence on ozone, PSCs, and radiative balance. Anthropogenic metal inputs introduce new chemical pathways that are not currently represented in atmospheric models.

- **Mesospheric/Thermospheric Metal Layer Formation and Perturbation** — The metal layers between ~80–110 km (e.g., Na, Fe, Mg, K) arise from meteoric ablation followed by complex chemistry and dynamical transport. Even small injections of anthropogenic metallic species, particularly reactive ones such as Al, Fe, or Mg from re-entry or launch emissions, may perturb the composition, structure, or temporal variability of these layers. Long-term observations (lidar profiling, repeat sounding-rocket measurements) combined with advanced metal-layer modelling are needed to quantify both downward transport into the stratosphere and the potential upward leakage of metallic species.

- **High-Resolution Upper-Atmosphere Modelling (up to ~150 km)** — Develop and apply high-resolution models spanning the mesosphere and lower thermosphere to better resolve gravity-wave driven transport and mixing, and sedimentation that controls particle lifetimes and vertical redistribution.

- **Ionosphere Atmosphere Coupling** — Extend current chemistry–climate models to include coupling with the ionosphere, enabling interpretation of ion and charged particle measurements in the mesosphere–lower thermosphere. This is important for understanding the ionisation, transport, and chemical evolution of re-entry–derived species and their interaction with natural plasma environments.

- **Develop Lower Complexity and Computationally Efficient Response Models** on the basis of results from complex chemistry-climate models; this is essential for (quickly) assessing uncertainties and a wide range of scenarios; response models need to be developed for several metrics relevant for LCA (from effect on ozone to RF to deposition at surface).

- **Development of Benchmark Datasets and Open Validation Campaigns -** Establish reference test cases and accessible repositories for experimental and numerical results to enable community-wide intercomparison. It promotes transparency, reproducibility, and convergence of modelling approaches across institutions.

- **Model Validation and Observational needs moving forward** - A sustained programme of model validation through continuous atmospheric monitoring is essential to evaluate uncertainties across both launch and re-entry regimes. In particular, the transition to methane-fuelled launch systems (LNG/CH_4) introduces a major new uncertainty: there is currently very limited knowledge of the altitude-dependent emission indices and secondary plume chemistry for large methane rockets, despite their expected dominance in global launch activity by approx. 2040. A dedicated workstream should therefore address the full CH_4-fuelled plume composition, including NOx, HOx, black carbon, PAHs, water vapour, and potential fugitive emissions of unburned methane, supported by targeted measurement and validation campaigns. Observational requirements should be defined explicitly by altitude band.

- **Rapid Experimental Computational Feedback for Sustainable Spacecraft Design -** Develop and link high-fidelity simulation tools with laboratory and ground-test data to enable fast, reliable prediction of material behaviour during re-entry. To create a responsive software framework that allows new materials to be assessed quickly for demisability and environmental impact, so spacecraft can be designed now in alignment with end-of-life policies and low environmental impact re-entry requirements.

Field Data Collection and Flight Campaigns

Flight campaigns, using diverse airborne platforms (e.g. balloons, rockets, aircraft, HAPS), are essential for acquiring real-world, in-flight in-situ measurements and collecting samples across a wide range of altitudes. Laboratory analyses of these samples, especially particulates, provide a level of chemical and physical characterisation that complement in-flight measurements. Together, these in-situ datasets are critical for interpreting and complementing remote sensing observations, validating models, and ultimately determining and understanding the distribution and characteristics of spaceflight emissions.

Sample Collection & In-situ Measurement Actions

- Future collection efforts, particularly from stratospheric air balloons and other platforms, enable detailed, individual particle analysis, especially for metallic or mineral particles, organics. This provides insights into composition, structure, and mixing state using advanced electron microscopy techniques (e.g., TEM, ICP-MS, SEM-EDX, XPS, EELS, STXM-NEXAFS). This dual approach offers complementary and optimised sampling data for atmospheric models.

Field Campaigns

Stratospheric balloons offer unique capabilities over extended periods for in-situ atmospheric measurements throughout the stratosphere, which is largely beyond the reach of aircraft.

- CNES large stratospheric balloons (Ballons Stratosphériques Ouverts - BSO) can carry heavy payloads, up to 1 ton, at altitudes of up to about 40 km, with flight durations ranging from several hours to several days. These large platforms are well suited for deploying comprehensive instrument suites. Measurements should include gases, aerosol microphysical properties (e.g. size distributions from about

10 nm to several microns, chemical composition, shape, mixing state, phase state), and aerosol optical properties (e.g. scattering and extinction at multiple wavelengths, measured in-situ or remotely). These data are required for understanding how spaceflight particles, notably metallic or carbon-based particles, form, evolve and mix with other types of aerosols during their transit in the stratosphere. They also enable to constrain their chemical and radiative properties and, in particular, to test whether they behave radiatively as expected through aerosol radiative closure experiments (consistency between aerosol optical properties directly measured and those calculated from microphysical properties (so-called aerosol radiative closure experiments). This information is crucial for rigorous model evaluation and for improving atmospheric impact assessments.

- Small meteorological or light balloons (e.g. Ballons Légers Dilatables - BLD) can carry lighter payloads (up to 6 kg, or 10 kg to altitudes of up to 30-35 km for several hours. Their low cost and operational simplicity enable frequent launches worldwide, which is essential for rapidly testing instruments, configurations, and chemical analysis protocols. That is the motivation behind on-going development of lightweight aerosol collectors specifically designed for light balloons. Aerosol sampling should be carried out on a variety of collection substrates (e.g. filters, TEM grids), allowing comprehensive morphological and chemical analyses of soluble and insoluble components. These composition measurements can be complemented by in-flight size distribution measurements and, where possible, by in-flight trace gas measurements or the detailed post-flight analysis of collected air samples (e.g., using AirCore systems).

- Super pressure balloons (SPB, or BPS ballon pressurisé stratosphérique) are smaller than ZPB (BSO) but can fly as long as 3 months in the low stratosphere (18-20 km), carrying up to 25 kg payloads. Already particle and aerosol counters have flown and will fly aboard the balloons of the STRATEOLE 2 CNES-CNRS project. Other SPB flights are foreseen in the next 5 years.

- The StratoPart collector, in its standard and lightweight versions, is designed for clean quality controlled aerosol collection on filters and TEM grids, enabling morphological and chemical analysis of soluble and insoluble components. Complementary instruments like particle optical counters (LOAC-v2, POPS) and condensation optical counters (STAC, SMPS) could provide full size distribution data from approximately ten nanometers upwards. AirCore systems offer cryogenically collected air samples for detailed trace gas analysis.

Sounding Rockets

Sounding rockets provide unique access to the mesosphere and lower thermosphere, layers largely inaccessible to balloons and conventional aircraft, and where satellites orbit above.

- Sounding rockets are uniquely suited to measure dust, charged particles, and neutrals in the mesosphere. They can carry payloads sub-orbitally along a parabolic trajectory, making in-situ measurements of every atmospheric layer. The MXD2 launch in July 2025 from Andøya, is an example of a dedicated mission to collect samples of mesospheric dust.

- Advanced techniques allow for the ejection of multiple collection probes from a sounding rocket, enabling multi-point measurements of aerosol particles between altitudes of 17 km and 100 km. Each probe can be equipped with numerous collection samples (e.g., 110 samples of 3 mm diameter), comprising standard TEM carbon grids, glass fibre filter paper, or silicone gel. These samples are exposed over specific height ranges, providing detailed vertical profiles of particle characteristics. This capability, if high impact speed is constrained, is ideal for understanding the composition and evolution of meteoric material, which dominates upper-mesosphere aerosols, and now, anthropogenic material.

- It is also possible to detect upward leaked metallic species (normally ionized). To measure these very minor "leaking" fraction, sounding rocket up to 200 km or even satellite that can dive into < 200 km can be used as the platform of in-situ mass-spectrometry to complete the survey of affecting area (altitude range) by the ablated materials.

High-Altitude Platform Station (HAPS) Vehicles

HAPS vehicles, including solar aircraft and long-endurance balloons, occupy a strategic niche between satellites and conventional aircraft, offering persistent local observation capabilities in the stratosphere.

- HAPS vehicles, such as the AALTO Zephyr solar aircraft, operate in the stratosphere (typically 20 to 24 km altitude), significantly higher than commercial air traffic. They are designed for extended flight durations (up to several months), allowing for continuous monitoring over specific areas. Their ability to operate on renewable energy sources makes them environmentally friendly.

- HAPS vehicles can carry lightweight payloads (e.g., 5 kg for Zephyr, with potential for up to several hundred kilograms for larger HAPS) no power constraints, especially for solar-powered variants. This makes them suitable for deploying environmental sensors, imaging equipment, and communication systems.

- Unlike satellites, HAPS can be quickly positioned over specific areas and can be brought back for repairs or upgrades, ensuring their functionality and adaptability to evolving research needs. This flexibility is critical for targeted atmospheric sampling campaigns, especially near launch sites (e.g., Guyana, Florida) or for sampling far from launch sites to track transport.

Aircraft Campaigns (e.g., DLR HALO)

Dedicated atmospheric research aircraft provide invaluable in-situ measurement capabilities at altitudes typically higher than commercial airliners, bridging the gap between ground-based observations and stratospheric platforms.

- Platforms like the DLR HALO aircraft are essential for deploying advanced instrumentation to measure trace gases, aerosol properties, and cloud microphysics in the upper troposphere and lower stratosphere. They can conduct targeted sampling missions in areas potentially impacted by launch plumes or re-entry corridors, providing crucial data for model validation at relevant altitudes. ESA's Firewall activity and continued support for next steps will be crucial here.

Lidar

Resonance lidar offers a uniquely sensitive and continuous means to monitor metal species in the Mesosphere Lower Thermosphere (MLT), where ablation from re-entering spacecraft injects metal vapours and particulates. Established techniques that probe natural metal layers, principally potassium, sodium, and iron, already retrieve winds and temperatures between ~80 and 120 km. However, systematic observations tailored to anthropogenic inputs are lacking: there is no continuous record of how debris-derived metals spread and evolve on short, seasonal, and interannual timescales. As a result, the chemical and dynamical impacts in the upper atmosphere, and subsequent transport into the stratosphere, remain poorly constrained; current models are necessarily speculative because basic source-term data (speciation, size, reactivity) are missing.

Today's resonance and aerosol lidars are the only platforms capable of routine mesospheric metal and aerosol monitoring, but they are not yet optimised for autonomous, long-duration operation. Conventional systems demand substantial operator time, high optical power, and narrow spectral filtering to detect weak aerosol scattering. Resonance measurements further require precise tuning and stabilisation to specific atomic transitions, many in the ultraviolet, which increases complexity and maintenance. K/Na/Fe are observed systematically at lidar observatories in many parts of the world. However, only recently has a programme to observe the Li layer been started (at Kuhlungsborn, Germany), since this metal is a particularly sensitive marker of space debris ablation. [23] [24] [25] [26]

We need to address those gaps by advancing next-generation, field-deployable resonance lidar specifically configured for debris and launch plume signatures, with robust resonator designs to reduce sensitivity to environmental drift and component ageing. Demonstrated performance for potassium in the near infrared, together with laboratory proof of efficient frequency conversion to the ultraviolet, provides a credible path to accessing additional resonance lines relevant to debris metals, that are autonomous, low maintenance systems capable of continuous operation, and rapid deployment to sites of high relevance for re-entries and launch corridors. Sophisticated middle-atmosphere aerosol lidars can in general measure fine particles and provide some constraints on properties of larger particles such as size, density, and depolarisation. This can be used to learn about the composition of the particles, and their impacts on radiative budget and heterogeneous chemistry. Instruments measuring NO_2 near launch sites can cover an altitude range of up to 8 km, offering detailed information about the plume vertical profile at the early launch stages. MAX-DOAS sample vertically and horizontally, so offer a large sampling footprint covering the launch site and rocket plumes.

Delivering this capability will establish the first sustained observational record of debris-related metal layers in the MLT, enabling the distinction of anthropogenic versus natural sources, constraining microphysical and chemical processes, supplying validated inputs to transport chemistry models, and emission inventories. In doing so, it will close a critical measurement gap and support evidence based stewardship of the upper atmosphere as space activity expands.

Satellite Remote Sensing and Monitoring

During launches and re-entries, emissions can include water vapour, Cl, NO_x, CO, CO_2, soot/black carbon, alumina and other metal oxide particles, along with metallic vapour/aerosols. Satellites contribute by detecting spectral signatures in the UV, visible and infrared that reveal gas and aerosol changes, while polarimetry and lidar help characterise particle properties and vertical layers. Plume formation and rapid mixing in the stratosphere/mesosphere are best captured by high-cadence geostationary sensors, with multi-satellite time series showing how plumes evolve. Naturally, plume-resolving capability of a satellite instrument depends strongly on its spatial resolution, which largely determines the minimum detectable plume width and concentration enhancement Ideally by maintaining background monitoring and assimilating observations into transport–chemistry models, we could constrain persistent high-altitude disruptions and simulate realistically plume dispersion.

Table 6: Current satellite missions, instrumentation and relevance to launch and re-entry emission detection

Satellite / Mission	What it measures / instrument	Relevance to launch/re-entry emissions	Key limitations
Sentinel-5P (TROPOMI)	UV/VIS/NIR/SWIR spectrometer for O_3, NO_2, SO_2, CO, CH_4, HCHO, aerosols, daytime	Detects trace-gas/aerosol anomalies after events; good global context	Limited vertical sensitivity; hard to isolate small plumes from background
TEMPO	Geostationary UV-VIS spectrometer over North America (hourly, daytime)	High cadence for transient signals during/after events in its FOV	North America only; weak vertical resolution; signals may be faint
Sentinel-4 (MTG-S/UVN)	GEO UV/VIS/NIR over Europe/N. Africa, daytime	Regional, frequent observations; anomaly detection over launch/re-entry corridors	Same vertical-resolution challenge; background mixing. Not many launches over the target domain in comparison to TEMPO.
MATS	Mesospheric airglow/aerosol tomography	Observes processes in 50–100 km layer relevant to re-entry effects	Re-entry signals may be weak; separation from natural variability is hard
Other EO platforms (e.g., MetOp-SG, IASI-NG, Copernicus)	Hyperspectral IR sounders, imagers, composition/aerosol products	Provide background fields and constraints for modelling/assimilation	Not optimised for metallic aerosols or brief high-altitude transients

Table 7: Current challenges for space satellite monitoring

Area	Current gap/challenge	Potential remedy / planned missions
Sensitivity & vertical resolution	Troposphere-focused sensors may miss weak, high-altitude or metallic signals	Add lidar/limb capabilities; targeted retrievals for metal species/oxides
Signal vs background	Hard to separate small plumes from natural variability	Event-coincident tasking, GEO cadence, multi-sensor fusion, model assimilation
Coverage/revisit	Limited regional coverage or once-daily overpasses	Mixed LEO+GEO s; coordinated campaigns with tasking
Dedicated instrumentation	No satellite purpose-built for re-entry/rocket by-products	ESA DRACO (~2027) for instrumented re-entry; add metallic-aerosol diagnostics to future chemistry/aerosol missions

Missions/sensors and how to target each atmospheric layer:

Table 8: Current missions sensors and associated coverage.

Mission / Sensor	Modality	Key measurements	Atmospheric layers	How to use for launch/re-entry signals	Notes / limitations
SAGE III-ISS	Solar/lunar occultation (limb)	Stratospheric aerosol extinction; O_3, NO_2, H_2O	Lower–mid stratosphere (~15–35 km)	Detect/background-check any sustained stratospheric aerosol enhancement after clustered launches/re-entries	Sparse sampling; excellent stability/vertical resolution (≈0.5–1 km)
OMPS Limb Profiler (Suomi-NPP/JPSS)	Limb scatter	Stratospheric aerosol & O_3 profiles	Lower–mid stratosphere	Constrain layer altitude/thickness; attribute plumes with trajectories	Coarser than occultation; global coverage
Odin / SMR	Microwave limb sounding	NO, NO_2, H_2O, O_3	Upper troposphere–middle stratosphere (~15–60 km)	Track NO_x and H_2O anomalies linked to launch and re-entry events; provide chemically complementary constraints to OSIRIS for attribution studies	Long multi-decadal record with good vertical resolution; limited temporal sampling

OSIRIS (Odin)	Limb scatter	Aerosol extinction; O_3/NO_2	Lower–mid stratosphere	Build climatology to spot small systematic increases	Long multi-decadal record; aging sensor
Aura / MLS	Microwave limb sounding	HCl, ClO, BrO, HNO_3, H_2O, O_3, T	Lower–middle stratosphere (up to ~60 km)	Diagnose halogen/HOx responses and H_2O anomalies following activity	Coarse horizontal res; vital for chemistry
EarthCARE / ATLID	UV spaceborne lidar	Vertical aerosol/cloud backscatter	Upper troposphere–lower stratosphere (~8–20 km)	Catch thin/lofted layers; place plume top/base	Narrow swath; needs coincidences
TEMPO (GEO, N. America)	UV-VIS spectrometer (hourly)	NO_2, O_3, HCHO, SO_2, aerosols	Troposphere; lower stratosphere (indirect)	Catch transient launch-day anomalies; track down-mixing	Daytime only; regional FOV
GEMS (GEO, E/SE Asia)	UV-VIS (hourly)	NO_2, O_3, SO_2, HCHO, aerosols	Troposphere; lower stratosphere (indirect)	Same as TEMPO	Daytime; retrieval challenges over bright surfaces
Sentinel-4 / UVN (GEO, Europe)	UV-VIS-NIR (hourly)	NO_2, O_3, HCHO, SO_2, aerosols	Troposphere; lower stratosphere (indirect)	Event detection over Europe/N. Africa	Limited vertical sensitivity
Sentinel-5P / TROPOMI (LEO)	UV-VIS-NIR-SWIR	NO_2, SO_2, CO, CH_4, HCHO, aerosol layer height	Troposphere–lower stratosphere (global)	Map downwind anomalies; provide global background for assimilation	Once-daily overpass; mixed vertical sensitivity
PACE (OCI + HARP2 + SPEXone)	Polarimetry + hyperspectral	Aerosol microphysics/absorption	Troposphere; hints into lower stratosphere	Discriminate soot vs metal-oxide-rich plumes to inform microphysics	Type inference is model-dependent
MetOp-SG / 3MI	Multi-angle, multi-pol polarimetry	Aerosol type/height proxies	Troposphere–lower stratosphere	Persistent aerosol characterisation for burden/trend	Retrieval maturity still evolving
MODIS / VIIRS	Multispectral imagers	AOD, plume morphology	Troposphere (global context)	Broad plume detection; DA into transport models	Limited speciation; cloud-sensitive
MATS (Sweden)	Mesospheric airglow / tomography	PMC/airglow structures, waves	Upper stratosphere–mesosphere (~50–100 km)	Context for ablation region; watch wave-aerosol structures	Re-entry signals likely weak; attribution hard

(Planned) MetOp-SG A / IASI-NG, UVNS	IR sounder + UVNS	T/q profiles; SO_2, CO, CH_4, etc.	Troposphere–lower stratosphere	Better 3-D fields for plume DA/chemistry	Not metal-specific
(Planned) ESA DRACO (re-entry demo)	Instrumented object	In-situ breakup/fragment/thermal data	Re-entry corridor (all layers crossed)	Direct evidence on fragmentation & source terms	One-off/demonstrator; not routine monitoring
ACE-FTS (SCISAT, Canada)	Solar occultation (IR FTS, limb)	H_2O, O_3, NO, NO_2, HNO_3, HCl, HF, N_2O_5, $ClONO_2$, CO, CH_4, halocarbons, isotopologues	Upper troposphere–mesosphere (~10–100 km)	Diagnose chemical perturbations (NO_x, halogen reservoirs, H_2O) following launch/re-entry activity; constrain heterogeneous chemistry associated with aerosol perturbations	Sparse sampling; exceptional long-term stability and vertical resolution; potential sensitivity to metal-oxide spectral features (e.g. Al_2O_3) merits targeted investigation

In-situ LEO Space Debris Monitoring

Dr. Veerle Sterken argues during the 2nd AIRL workshop that in-situ composition measurements in LEO can be used as tracers of the elemental composition of larger space debris. Unlike remote sensing methods, in-situ "dust telescopes" (counters, impact-ionisation sensors, TOF-MS, and trajectory sensors) sample particles before they decelerate, re-enter into the atmosphere, and ablate, allowing identification of elemental fingerprints, and helping to validate models of sub-micrometre particle population. Historical detections of debris "swarms" and "clusters" show the environment is dynamic, underscoring the need for continuous monitoring and modern, sunlight tolerant instruments designed for LEO conditions.

Ionosphere

Investigating the impact of emitted species on ionospheric electric conductivity and the electric field, as well as the ionospheric chemistry and resultant effects is also of importance. This includes assessing the effect of charged particles of ablation-origin (e.g. metallic ions) such as the possible impact on spacecrafts and space debris on the ion-neutral interaction [27], or effect of the altered plasma densities on wave propagation and ionospheric electric potential as a part of global atmospheric electric circuit that is directly coupled with thunderstorms and clouds. [28] Although the expected amount of ablated particles leaking upward to >120km is small in average, the cloud of newly ablated atmospheric neutrals and ions might directly be uplifted during space weather phenomena, that accompany strong upward expansion of the atmosphere. If such events allow substantial amount of chemically active ions reaching the LEO satellite orbit of about 300km during severe geomagnetic storms, they might even interact with spacecrafts (like solar panels) and space debris through surface charging and ion surface interaction, interfering with the electrical current system.

The ionosphere represents the transition between the mesosphere, where re-entry ablation injects metals, and the plasma environment of near-Earth space. Metallic atoms produced by ablation of incoming meteorites are accumulated in the upper part of the mesosphere (near ionopause), forming a 10 km thick layer (the "metal layer") at around 80-110 km for metallic, sustained by the mesospheric circulation and chemistry specific for metallic species, at those high altitudes. These metallic atoms can easily be ionised forming metallic ion layer around 90 – 130 km and can further be lifted upward through the ionosphere toward the exobase and even into the magnetosphere. [29] Considering the fact that metallic atoms with much higher mass than atmospheric molecules (28 for N_2 32 for O_2), any anthropogenic metal load from re-entering spacecraft can also be lifted up to the altitudes of the metal layers near the ionopause, and then further propagate far beyond the initial breakup altitude. Past in-situ measurements show that low charge metallic ions (e.g., Fe^+, Mg^+, Ca^+) appear well above the ablation region and occasionally beyond 300 km, implying episodic upward transport; models and lidar observations further suggest storm time lifting and seasonal/polar pathways, but the mechanisms, fluxes, and maximum heights remain poorly constrained. Because remote sensing cannot resolve motion or detailed ion chemistry, the ionosphere is the place where we can directly trace, speciate, and quantify metallic ions and separate natural inputs (meteoroids, lunar sputtering) from anthropogenic contributions linked to space waste ablation. In short, if we want to know whether re-entry metals are contaminating geospace, the ionosphere is where the signal becomes measurable to evaluate the level of anthropogenic contamination.

To close the knowledge gaps, Yamauchi et al. argues during the 2nd AIRL workshop that for modern in-situ ion/neural mass spectrometry with both adequate mass resolution, mass range and sensitivity be deployed in the ionosphere. Practically, that means measuring atoms and ions below ~300 km to characterise "ground-state" species and pollution markers (e.g., Cu^+, Li^+) and abundant tracers above ~300 km (e.g., Fe^+, Mg^+) to follow uplift into the upper ionosphere/exobase. Instrument requirements include $m/\Delta m \gtrsim -50$ (to separate, for example, Cu^+(63) from Fe^+(56) or Li^+(7) from O^{2+}(8) for most outstanding anthropogenic ions from natural ion species of closest mass) detection down to ~0.1–1 cm^{-3}, and preferably some energy discrimination (for this part $m/\Delta m \gtrsim$ 8 is sufficient) to understand how these anthropogenic ions are lifted up to pollute the ionosphere. Orbitally, a polar, drifting LEO with perigee < 300 km (decreasing gradually due to air drag) and apogee up to ~500–1000 km maximises sampling across latitudes and local times, especially over the summer cusp, where models predict access to the exobase. These elements underpin the proposed METAL concept: an upgraded, compact INMS-class payload capable of extracting anthropogenic Cu^+/Li^+ compared to the natural species and even Al^+(27) from N_2^+(28) below 300 km, providing the first systematic survey of how, how much, and how high metallic ions are lifted and whether anthropogenic ions are already present. With such measurements, we can finally quantify ionospheric contamination from ablated space debris, attribute sources (meteoric, lunar, or re-entry), and supply validated constraints to chemistry–transport models and space-weather operations.

Life Cycle Assessment

A significant obstacle to accurate modelling is the lack of comprehensive and transparent material datasets for spacecraft.

- Accurate Material Lists: A key recommendation is that space agencies funding launch and in-orbit activities require industry to provide detailed material composition information for spacecraft and upper stages, with reporting frameworks designed to protect commercial intellectual property. To enable this, a coordinated database with satellite operators and manufacturers is needed to obtain accurate material inventories. This includes the establishment of a materials database capturing composition at the level of elemental and compound stoichiometry, aligned with planned de-orbit trajectories, to ensure that the foundational input data for atmospheric models are complete and reliable. An industry-wide database of materials used and their life-cycle assessment footprint, explicitly including end-of-life atmospheric impacts, is essential for promoting sustainable design choices.

- A rigorous Life Cycle Assessment is essential to compare end-of-life pathways and launch emissions impacts on a like-for-like basis, spanning cradle-to-grave stages (material extraction, manufacture, integration, launch, on orbit operations, end of life, recovery/recycling). LCA should explicitly contrast design-for-demise (DfD), which minimises surviving debris by maximising atmospheric ablation, with design-not-for-demise strategies that enable Re-entry as a Service (RaaS), using radiative heat shields or inflatable aerodynamic decelerators (IADs) for controlled de-orbit and recovery[30]. For DfD, the emphasis is on the atmospheric burden (species speciation, particle size/optics, ocean/land deposition) versus reduced ground risk and simpler operations; for RaaS, the analysis must include added mass/complexity, launch-phase emissions, operations, recovery logistics, inspection/refurbishment, and material recirculation benefits (recycled mass %, avoided virgin production, embodied energy). LCA should also evaluate the baseline uncontrolled burn-up case and post-recovery material recycling scenarios, using harmonised functional units (e.g., per kg payload year) and uncertainty bounds. The outcome is decision grade evidence on climate forcing, ozone/air quality impacts, safety risk, circularity, so programmes can choose options with improved or minimal environmental impacts over various impact categories.

Space Launch Impact on Climate and Environment (SLICE)

SLICE is a Doctoral Network, funded by the European Union under the Horizon Europe Marie Skłodowska-Curie Actions and the Swiss State Secretariat for Education, Research and Innovation (SERI). Duration: 2026 – 2029.

To investigate the Space Launch Impact on Climate and Environment, SLICE will therefore develop a research and training programme that bridges the gaps between aerospace engineering, climate science and calculation of life-cycle environmental impacts. This will not only generate desperately needed novel results, which will enable cutting-edge innovations. It will also satisfy the pressing demand for a new generation of highly skilled and resilient researchers, trained to create and realise these necessary innovations and to develop a natural ecodesign thinking. They will not only be excellent specialists in their respective field, but who also have a thorough understanding for the complexity, multidisciplinary and internationality of launchers and their environmental impacts. They will have the skills to find solutions for current and future challenges and lead the European effort to a sustainable space utilisation. This includes recognising requirements from different stakeholders (e.g. space agencies, industry primes and law-makers) and having the complementary transferable skills to ascend beyond the current PhD standard.

SLICE is also highly needed to support current policy efforts, including the European Green Deal and the SDGs, particularly 9, 12, 13 and 17. SLICE further supports ESA's Agenda 2025 and Green Agenda. The upcoming EU Space Law and national space laws might also be impacted by SLICE and industry is already eagerly awaiting results to support the Corporate Sustainability Due Diligence Directive (CSDDD). Moreover, SLICE will deliver crucial inputs for the Product Environmental Footprint (PEF) regulations at European level ((EU)2021/2279) and thus the development of PEF Category Rules (PEFCR), which are currently under development.

1. **Objectives**

The overarching objective of SLICE is to support the EU's commitment to make Europe the first climate-neutral continent by 2050. Therefore, SLICE will contribute to advance the science of climate change by investigating the impact of space launches on the atmosphere and thus, the climate. This will generate actionable insights, on which SLICE will develop solutions to reduce greenhouse gas emissions and accelerate the delivery of the Green Deal and establish an environmentally sustainable access to space. Detailed analysis of the involved challenges revealed the most pressing issues that are represented by the following specific sub-objectives of SLICE:

2. **A database of emissions** of launchers during the operational phase from lift-off to landing/re-entry, using synergetic and complementary experimental and numerical approaches.
3. **Tools developed to assess the interaction** between the emitted pollutants and the surrounding atmosphere and the resulting climate impact based on various market development trajectories.
4. **Methodologies to implement environmental considerations** in early phases of launcher system design while ensuring compatibility with the full LCA of launchers to consider all development phases.
5. **18 creative, entrepreneurial, innovative & resilient PhDs** via an international, inter-sectoral and multi/inter-disciplinary training, able to generate economic and social benefit in face of current and future challenges.
6. **Concrete actionable recommendations for stakeholders** to minimise the environmental and climate impact, especially targeting launch service providers and the industrial supply chain as well as policy makers.

Overview of the research programme

The main idea behind SLICE is to bridge the current divide between space engineering and climate science to close the gaps that exist in the LCA of space launch systems. The structure of the SLICE research and training programme is arranged around the 3 most pressing research areas of this field: Launch Vehicle Emissions, Atmospheric Interaction & Climate Impact and System Analysis & Design. These areas will be organised into a set of interconnected technical WPs and complemented by an intensive programme of training courses and network-wide training events. Each DC will work within a high-level Individual Research Project (IRP) with strong interactions to other DCs and side-by-side with lead scientists at world-leading institutions. This will be reinforced by secondments to universities, research centres, companies and (inter-)governmental space authorities across disciplines and sectors for the exchange and sharing of ideas and methodologies. The consortium will provide a supportive and enthusiastic environment for the DCs to perfect research skills acquired in training courses by putting them into practice. The quality of the supervision is a key element of the project and emphasis will be put on dedicated arrangements. The network-wide activities will allow the dissemination and transfer of knowledge to other DCs and to the wider scientific and industrial community. It will also reinforce cooperation and create synergies to facilitate future partnerships between the DCs. These networking activities will be key to open up career opportunities across the range of scientific disciplines and sectors.

Annex 2 - Legal Aspects - Researching and Implementing Policy Solutions

As space activity scales, the environmental footprint of launch and re-entry ablation increases, and the regulatory aspects come into question. The core difficulty is alignment: space related impacts are cumulative and transboundary, whereas many existing tools address local, short-term effects. This difference introduces coordination challenges, including common resource strain, unmanaged externalities, and incremental decisions that add up over time. A key point presented by Rachael Craufurd-Smith during the 2nd AIRL workshop was the relevance of international environmental law frameworks particularly the model of framework conventions supported by evolving protocols, as a tool for managing emerging environmental risks. The Vienna Convention for the Protection of the Ozone Layer provides a strong example: with 198 state parties, it commits countries to take "appropriate measures" to protect human health and the environment from activities that modify or risk modifying the ozone layer. It also obliges states to cooperate in scientific research, exchange information, adopt legislative and administrative measures, and work with international bodies to implement agreed procedures and standards. This adaptive, science-driven structure is directly applicable to the space sector, where rapid growth in launches, re-entries, and new technologies is outpacing regulatory understanding. As evidence accumulates on the atmospheric impacts of rocket emissions, re-entry debris, and upper-atmospheric perturbations, a similar framework-convention approach could provide a flexible, globally coordinated mechanism for advancing research, harmonising standards, and developing future protocols as the science matures.

What the current space treaties do and don't do

The Outer Space Treaty, the Liability Convention, and the Registration Convention form a binding, authoritative framework: they codify due regard, state responsibility, registration, and liability for damage. Space is not lawless and free of legal constraints, reporting and general constraints exist, but they largely lack specific environmental standards, enforceable limits, or monitoring obligations. Even non-binding instruments (e.g., 2019 UN Long-Term Sustainability guidelines) take years to agree and stop short of concrete thresholds for emissions or re-entry materials, and contain little on national implementation.

Can other bodies of law help?

States must conduct space activities in accordance with international law. Yet most major environmental treaties (e.g., CLRTAP, Vienna Convention/Montreal Protocol, UNFCCC) have limited direct application to space operations. Their techniques, however, registration, phase-downs, lists of controlled substances, impact assessments, offer models that could be adapted to space-related emissions. The Espoo Convention points to transboundary EIA practice (though it does not yet cover space); the Aarhus Convention underlines public access to environmental information, mitigating any "we didn't know" defence.

The Stockholm Declaration 1972 has been applied to the space environment and focuses on the responsibility of states to ensure that activities within their control do not cause damage to the environment of areas beyond the limits of national jurisdiction such as space. This is echoed in the Rio Declaration on Environment and Development 1992.

Emerging rights

Recent rulings and legal interpretations (e.g., KlimaSeniorinnen v. Switzerland; ICJ Advisory opinion on climate obligations, 2025) recognise a right to a clean, healthy, and sustainable environment and reinforce customary duties that already bind states:

- Prevent significant transboundary harm;
- Exercise due diligence, including conducting environmental impact assessments where risk is plausible; and
- Co-operate in monitoring, sharing data, and mitigating harm. General principles, sustainable development, common but differentiated responsibilities, equity, and the precautionary principle, guide interpretation and fill gaps.

In its 1996 advisory opinion on The Legality of the Threat or Use of Nuclear Weapons, the ICJ recognised the rights of "generations unborn" and the concept of "intergenerational equity".

Where national licensing fits and what's missing

Launch and spaceport licences typically require an Assessment of Environmental Effects (AEE), or other environmental impact assessments, covering factors like human health, air quality, climate, land/soils, and marine impacts. Two gaps stand out:

1. AEEs rarely address upper-atmosphere/ozone chemistry explicitly; and
2. They do not extend to end-of-life re-entry of upper stages or spacecraft ablation profiles. For orbital operator licences, regulators focus on safety and orbital sustainability (ALARP, debris mitigation). They have powers to impose conditions to prevent "adverse changes in the environment of the Earth," but practice centres on the orbital domain, not atmospheric chemistry.

There is a growing focus on end-of-life re-entry plans as a licensing condition, but without precise requirements and little if anything on atmospheric ablation.

Practical questions for regulators and industry

- Information: Who should disclose materials composition, and ablation-relevant data, spacecraft manufacturers, launch/spaceport operators, or orbital operators, and at what stage? Transparency must be balanced with commercial/security constraints through effective licensing.
- Scope creep vs. system view: Atmospheric effects are sector-level, not just operator-level. Individual licence processes and procedures can ask targeted questions (materials substitutions, orientation of descent, extended lifetime, servicing/repair), while sector guidance standardises expectations.
- Forum shopping: Divergent regional rules risk regulatory arbitrage. The proposed EU Space Act and aligned member-state processes are an opportunity to harmonise expectations, to some extent.

A credible path forward (law + practice)

1. Extend AEEs/TQS to include upper-atmosphere impacts of re-entry: require material inventories for ablation-relevant components and a screening of ozone/stratospheric chemistry risks.
2. Standardise disclosures and information sharing at an international level: a sector template for material composition, coatings, propellants, and thermal-protection systems, and operations linked to publicly curated emissions/ablation factors.

3. Data and cooperation: mandate post-flight reporting requirements (re-entry timing, corridor, breakup altitude) and support research collaborations (balloons, aircraft, HAPS, ground lidars) to validate models.
4. Private standards and innovation: incentivise industry standards (ISO and others) for re-entry environmental assessment; support eco-design (materials substitution, design-for-benign-ablation) through grants and procurement criteria.
5. Apply precaution proportionately: where evidence of risk is credible but uncertain, require risk-reduction measures commensurate with potential harm while research fills the gaps.
6. Link to access to insurance and insurance and finance due diligence and consider the implementation of effective insurance models to create effective incentives at commercial level.

The law already supplies duties and principles strong enough to justify action; what's needed now is to connect them to re-entry practice, through smarter licensing, insurance, harmonised disclosures, and cooperative monitoring, and the implementation of effective practical standards, so that a growing space sector aligns with the emerging right to a healthy environment and avoids the pitfalls of cumulative, transboundary harm and environmental harm to areas beyond national jurisdiction such as outer space.

Annex 3 - Re-entry and recovery as a service

At the same time this challenge also presents a clear opportunity. Whilst we wait for the eventual in space circular economy to develop, controlled, low-emission re-entry using non-ablative (radiative) heat shields and inflatable aerodynamic decelerators (IAD) is technically credible for planetary return.

Several commercial platforms are flight testing returnable LEO microgravity modules for high value manufacturing (e.g., semiconductors, pharmaceuticals and other sensitive payloads) with precise, recoverable Earth return. The same architectures can be scaled to return satellites to designated recovery zones. This approach virtually eliminates ablation derived particulates and ocean deposition; the only significant atmospheric pollutant is thermal NOx generated in the shock layer. Trajectory and heat load management can further minimise NOx formation if needed. Doing so would convert end-of-life hardware from debris into recoverable assets, enabling component refurbishment and materials recycling.

With feasibility studies, coordinated standards, monitoring and investment, controlled return could become the default end-of-life pathway, closing material loops while keeping the stratosphere/mesosphere free from anthropogenic material influence.

The EU Critical Raw Materials Act highlights the strategic importance of securing reliable access to materials that underpin Europe's technological sovereignty, including rare earth elements and specialty metals essential for space systems. Considerable effort is invested in sourcing, refining, and safeguarding these materials often through complex global supply chains and reliance on external imports yet current end-of-life policies for spacecraft prioritise rapid atmospheric demise, typically within five years, resulting in the irreversible loss of materials that are explicitly identified as critical to the space industry. While the substitution of non-critical materials can reduce some supply risks, it cannot fully address the growing demand for high-performance components. This tension strengthens the case for complementing demise based mitigation strategies with dedicated recovery and recycling approaches, including controlled de-orbiting to designated recovery zones. Such strategies would allow valuable materials to be reclaimed, reduce dependency on external supply chains, and align space sustainability practices with broader EU objectives on resource efficiency, circular economy principles, and strategic autonomy.

Annex 4 - Useful Resources

- Understanding the Atmospheric Effects of Spacecraft Re-entry (10-January 11, 2024) · Indico at ESA / ESTEC
- 2nd Workshop - Atmospheric Impacts of Spacecraft Launch and Re-entry (23-September 25, 2025): Overview · Indico at ESA / ESTEC
- Grav (ESA): Simulations for re-entry risk estimation. - https://estimate.sdo.esoc.esa.int/
- DISCOS (Database and Information System Characterising Objects in Space): Comprehensive database of space objects. - https://discosweb.esoc.esa.int/
- DRAMA (Debris Risk Assessment and Mitigation Analysis): Tools for assessing and mitigating debris risk. - https://sdup.esoc.esa.int/
- General Catalog of Artificial Space Objects: Additional information on space objects. J. McDowell : https://planet4589.org/space/gcat/
- Object Re-entry Emissions and Rocket Launch Emissions – Atmospheric Composition and Air Quality Group UCL: Relevant research on emissions from space activities: https://maraisresearchgroup.co.uk/rockets.html, https://maraisresearchgroup.co.uk/reentry_emis.html
- A Pathway for Closing the Knowledge Gaps for a Comprehensive Life Cycle Assessment and Ecodesign of Space Transportation Systems - Results of the 3rd Workshop on Life Cycle Assessment of Space Transportation Systems
- WMO/UNEP Scientific Assessment of Ozone Depletion 2022: Downloads
- Space Track, USSPACECOM : https://www.space-track.org/auth/login
- Online Index of Objects Launched into Outer Space, UNOOSA : https://www.unoosa.org/oosa/osoindex/search-ng.jspx
- DEBRISK (CNES tool for assessing and mitigating debris risks) : https://www.connectbycnes.fr/debrisk
- ORSAT (NASA tool for assessing and mitigating debris risks) : https://orbitaldebris.jsc.nasa.gov/reentry/orsat.html
- NASA Cosmic Dust Catalogs (public information on stratospheric solid particles collected by NASA aircraft in 1981-2020) : https://curator.jsc.nasa.gov/dust/catalogs/
- SLICE: Project Website: www.slice-dn.eu
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Zero Debris Technical Booklet

Following the first Atmospheric Workshop Jan 2024 , the AIRL working group and the scientific community helped deliver the Whitepaper and define the activities that are explicitly included in the Zero Debris Technical Booklet (Chapter 6.1) – Understand Environmental Impacts of Re-entry. The Zero Debris Technical Booklet identifies technical solutions which will contribute to a Zero Debris future. This is a valuable companion to the Zero Debris Charter and lays out some of the most important technical developments required to achieve the Charter's ambitious targets.

Zero Debris Technical Booklet:

6. UNDERSTAND AND MITIGATE ADVERSE CONSEQUENCES OF SPACE OBJECTS AND DEBRIS

6.1. UNDERSTAND ENVIRONMENTAL IMPACTS OF RE-ENTRY

Debris of all sizes re-entering the atmosphere and potentially reaching the ground or oceans could have various adverse effects on the environment, which are not yet fully understood or quantified. Solutions to meet this need include:

A. Characterisation of materials used in spacecraft and their behaviour during re-entry for assessing their environmental impact

Key Enablers:

1. Characterisation of ablation products formed when undergoing a destructive re-entry (e.g. understanding the particle-induced erosion and heat flux augmentation on ablators in re-entry)
2. Improved knowledge on size distribution and optical properties of emitted materials and their physical state
3. Understanding the composition of materials in rocket bodies, spacecraft and ancillary items used to deploy payloads
4. Investigation of the proportion of surviving re-entering objects
5. Characterisation of unused propellant chemistry and particle size distribution

B. Characterisation of impacts of re-entry on the atmosphere for grasping the long-term consequences of re-entry events

Key Enablers:

1. Lab and in-situ measurements (e.g. sounding rockets-based flight experiments for atmospheric studies, dedicated sensing technologies) to characterise atmospheric impacts of demise, leading to enhanced re-entry models that include emissions.
2. Improvement in the modelling of physical and chemical processes in the upper atmosphere to assess the long-term impact of the injected material on the atmosphere
3. Studies on the demise chemistry, focusing on ablation heights and altitude dependant emission profiles (e.g. chemistry of emitted materials and compounds in mesosphere and stratosphere)
4. Characterisation of the impacts of re-entered propellant products

C. Characterisation of impacts of re-entry on terrestrial and oceanic environments

Key Enablers:

1. Lab and in-situ measurements to characterise material deposition in oceans and on land
2. Investigation into potential detrimental environmental impacts of surviving spacecraft elements

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Prepared by

*AIRL working group members

Lead authors:

Dr Adam Mitchell* - Space Sustainability Engineer, HE Space for ESA - European Space Agency

Dr Slimane Bekki* - Centre National de la Recherche Scientifique

Serge Flamenbaum* - European Space Sciences Committee

Dr Jean-David Bodénan* - European Science Foundation

Prof John Plane* FRS – Professor of Atmospheric Chemistry, University of Leeds

Prof Eloise Marais* - Professor of Atmospheric Chemistry and Air Quality, University College London

Leonard Schulz* - Institute of Geophysics and Extraterrestrial Physics, Technische Universität Braunschweig

Contributors:

Dr Daniel Murphy* – NOAA Chemical Sciences Laboratory and Purdue University

Prof Daniel Cziczo – Atmospheric Sciences, Purdue University

Dr Connor Barker – Research Fellow in Atmospheric Chemistry/Physical Geography, University College London

Dr Michael Gerding – Research Associate, Leibniz Institute for Atmospheric Physics

Dr Gerd Baumgarten - Leibniz Institute for Atmospheric Physics

Dr Juan Carlos Gomez Martin – Senior Research Scientist, Spanish National Research Council, Institute of Astrophysics of Andalusia

Dr James Beck* – Director Belstead Research

Dr Masatoshi Yamauchi – Senior Scientist, Swedish Institute of Space Physics (IRF)

Dr Daniel Kastinen – Solar Terrestrial and Atmospheric Research, Swedish Institute of Space Physics (IRF)

Dr Johan Kero - Swedish Institute of Space Physics (IRF)

Prof. Dr. Björn-Martin Sinnhuber - Karlsruhe Institute of Technology (KIT), Institute of Meteorology and Climate Research IMK-ASF

Dr Michael Hopfner - Karlsruhe Institute of Technology (KIT), Institute of Meteorology and Climate Research IMK-ASF

Dr Miriam Sinnhuber - Karlsruhe Institute of Technology (KIT), Institute of Meteorology and Climate Research IMK-ASF

Prof Martyn Chipperfield* – UK National Centre for Earth Observation (NCEO) and University of Leeds

Dr Jeremie Lasue* - Astronomer, IRAP-CNRS, Toulouse France, (IRAP - Institute for Research in Astrophysics and Planetology)

Dr Rachael Craufurd-Smith – School of Law, The University of Edinburgh

Dr Michael Hennessy Picard - Lecturer in International Environmental Law - The University of Edinburgh

Dr Veerle Sterken - École Polytechnique Fédérale de Lausanne (EPFL)

Dr Joanna Egan – University of Leeds

Dr Jan Steffen – Research Assistant, Institute of Space Systems, University of Stuttgart

Dennis Michael Jöckel - TESAT Spacecom GmbH & Co. KG and TU Darmstadt - Project Lead for Space Sustainability

Dr Kathrin Schoppmann - Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR)

Dr Andreas Marsing - Institute of Atmospheric Physics, Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR)

Sophie Abou-Rizk – PhD student – Department of Chemistry and Chemical Biology – Harvard University

Dr Karen Rosenlof* - Independent Researcher, Superior, CO USA

Quentin Taupin* - PhD student at CNES/IRAP/LATMOS

Dr Gwenael Bethet* – Researcher, CNRS/LP2CE

Dr Jean-Baptiste Renard – Researcher, CNRS/PL2CE

Dr Hiroshi Yamashita* - Deutsches Zentrum für Luft- und Raumfahrt, Institut für Physik der Atmosphäre

Dr Matthias Nuetzel* - Deutsches Zentrum für Luft- und Raumfahrt, Institut für Physik der Atmosphäre and Meteorologisches Institut München, Ludwig-Maximilians-Universität München

Prof Anja Schmidt - Deutsches Zentrum für Luft- und Raumfahrt, Institut für Physik der Atmosphäre and Meteorologisches Institut München, Ludwig-Maximilians-Universität München

Karin Treyer – Senior Researcher, Paul Scherrer Institute (PSI)

Dr Christian Bach* - Head of Space Transportation, Institute of Aerospace Engineering, Technische Universität Dresden

Dr Timofei Sukhodolov - Physical-Meteorological Observatory Davos / World Radiation Center (PMOD/WRC)

Maylis Gaulin – PhD student – LATMOS, CNRS, UVSQ

José P. Ferreira – Research Fellow – University of Southern California.

Dominik Kuenstler - High Enthalpy Flow Diagnostics Group (HEFDiG), Institute of Space Systems (IRS), University of Stuttgart

Mr Yoshihiro Yokoyama- Institute of Physics and Technology, UiT, The Arctic University of Norway, Tromsø, Norway

Prof Ingrid Mann* - Institute of Physics and Technology, UiT, The Arctic University of Norway, Tromsø, Norway.

Prof Joanne Wheeler* - Alden Legal and the Earth & Space Sustainability Initiative

Dr Alex Barber* - Chelsea and Westminster Hospital and the Earth & Space Sustainability Initiative

Dr Anni Määttänen - Research Director at Centre National de la Recherche Scientifique, LATMOS

Agwilh Collet – Environmental Action Coordinator, CNES

Participants of the 2nd Workshop - Atmospheric Impacts of Spacecraft Launch and Re-entry (23-September 25, 2025): Overview · Indico at ESA / ESTEC