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ORIGINAL PAPER

Motivation, structure and goals of the Collaborative Research Centre 1667: Advancing Technologies of very Low-Altitude Satellites—ATLAS

Stefanos Fasoulas[1] · Adam S. Pagan[1] · Constantin Traub[1] · Björn Annighöfer[2] · Stefanie Barz[3] · Andrea Beck[4] · Torbjørn Cunis[5] · Thomas Dekorsy[13] · Stephanie Essig[6] · Walter Fichter[5] · Bernd Flemisch[7] · Georg Herdrich[1] · Thomas Hobiger[8] · Ingmar Kallfass[9] · Johannes Kästner[10] · Sabine Klinkner[1] · Grazia Lamanna[11] · Stefan Loehle[1] · Marcel Pfeiffer[1] · Rico Poser[11] · Johannes Roth[3] · Michael Saliba[6] · Martin Schneider[7] · Nico Sneeuw[12] · Gerd Wagner[13]

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Abstract
The Collaborative Research Centre (CRC) 1667 "Advancing Technologies of Very Low Altitude Satellites—ATLAS" was established in April 2024 with the scientific goal of addressing the fundamental challenges of making satellite operations in Very Low Earth Orbits (VLEO) sustainable. These orbits are beneficial for satellite services that have become indispensable to our modern society. Moreover, access to VLEO offers the opportunity to operate satellites without exposure or contribution to the increasing contamination of traditional orbits with space debris. Seventeen highly interlinked research projects have been selected to investigate and advance accurate numerical and experimental methods for gas–surface interactions, novel concepts utilising the residual atmosphere and minimising the satellite sizes, and mission-related challenges of a selected scenario. In addition, support projects cover topics related to public outreach and academic exchange and assist in achieving the strategic goal of positioning the University of Stuttgart as a key contributor to this internationally very important research area. In summary, the CRC ATLAS aims to constitute a research-oriented profile-building measure at the University of Stuttgart with a strong international reputation.

Keywords Very Low Earth Orbit · Collaborative Research Centre CRC 1667

✉ Stefanos Fasoulas
fasoulas@irs.uni-stuttgart.de

1 Institute of Space Systems, University of Stuttgart, Stuttgart, Germany

2 Institute of Aircraft Systems, University of Stuttgart, Stuttgart, Germany

3 Institute for Functional Matter and Quantum Technologies, University of Stuttgart, Stuttgart, Germany

4 Institute of Aerodynamics and Gas Dynamics, University of Stuttgart, Stuttgart, Germany

5 Institute of Flight Mechanics and Control, University of Stuttgart, Stuttgart, Germany

6 Institute for Photovoltaics, University of Stuttgart, Stuttgart, Germany

7 Institute for Modelling Hydraulic and Environmental Systems, University of Stuttgart, Stuttgart, Germany

8 Institute of Navigation, University of Stuttgart, Stuttgart, Germany

9 Institute of Robust Power Semiconductor Systems, University of Stuttgart, Stuttgart, Germany

10 Institute for Theoretical Chemistry, University of Stuttgart, Stuttgart, Germany

11 Institute of Aerospace Thermodynamics, University of Stuttgart, Stuttgart, Germany

12 Institute of Geodesy (GIS), University of Stuttgart, Stuttgart, Germany

13 Institute of Technical Physics (DLR-TP), German Aerospace Centre DLR, Stuttgart, Germany

1 Introduction

According to the definition of the German Research Foundation (DFG), Collaborative Research Centres (CRC) "are long-term university-based research institutions, established for up to 12 years, in which researchers work together within a multidisciplinary research programme. They allow for tackling innovative, challenging, complex and long-term research undertakings through the coordination and concentration of individuals and resources within the applicant universities. They therefore enable institutional priority area development and structural development" [1].

This basic concept of a CRC has been identified to constitute a uniquely suitable format for closing various knowledge gaps in the basic understanding of the science domains associated with spaceflight in the Very Low Earth Orbit (VLEO) and for a profile-building measure at the University of Stuttgart. Following review and approval of the proposal, the CRC 1667 "Advancing Technologies of Very Low Altitude Satellites—ATLAS" has been established by the DFG in April 2024, for an initial funding period of 4 years. Twenty-three subproject leaders from thirteen institutes of the University of Stuttgart, and the Institute of Technical Physics at the German Aerospace Center are involved.

The CRC ATLAS addresses fundamental challenges of rendering VLEO sustainably accessible. Definitions of VLEO vary, with the distinction from traditional Low Earth Orbit (LEO) often being drawn at perigee altitudes below values of 400 km to 500 km. For the purpose of defining the research goals of the CRC ATLAS, a typical satellite operating in VLEO without dedicated drag mitigation measures is considered to undergo terminal orbital decay within about 6 months. These orbits are beneficial for satellite services that have become indispensable to our modern knowledge, information, and communication society. In addition, access to VLEO offers the opportunity to operate satellites without exposure or contribution to the increasing contamination of traditional orbits with space debris. Attaining sustained and economically viable VLEO flight is, however, challenging due to the unique environmental properties of the lower thermosphere. These properties result most notably in the significant, barely predictable and dynamically changing aerodynamic drag, which leads to a rapid deterioration of any spacecraft's orbit unless mitigated by a combination of active and passive techniques. Thus, the various advantages of VLEO, including its self-cleaning effect due to drag from the residual atmosphere dramatically reducing the dwell times of orbital debris, are to date offset by the disadvantage of an accordingly shortened operational lifetime for satellites that do not employ any dedicated drag mitigation measures. The leading research question of the CRC ATLAS is therefore:

How can the lifetime of a satellite in VLEO be increased by at least one order of magnitude without the necessity of huge amounts of fuel carried or resupplied continuously from Earth?

The CRC ATLAS aims to answer this leading research question with a scientifically coherent and comprehensive research approach that comprises a broad range in the level of detail. It encompasses various engineering disciplines and requires an innovative and long-term research effort, including a significant variety of research competencies and experimental capabilities, to set the foundations for future satellites in VLEO. The research programme is characterised by strong interdependencies and necessitates intensive cooperation between disciplines that builds on the joint insight of processes at and across their interfaces to comprehensively leverage synergies.

The motivation and challenges of VLEO spaceflight are described below. This is followed by overviews of the state of the art as well as the general structure of the CRC ATLAS, the individual research subprojects and how they are interlinked. As the fundamental ideas and themes of the CRC ATLAS are considered to exhibit significant potential for increasing public interest in spaceflight-related and scientific topics as well as for academic exchange, dedicated supporting projects are foreseen, the goals and measures of which are also briefly introduced.

2 Motivation and challenges

The last years have seen record numbers of orbital launches, and a further increase is expected due to the growing demand for satellite constellations incorporating both public and private investments (Fig. 1). Thus, more than 500 annual launches are likely by the end of this decade. The space sector has evidently entered an exponential growth phase, which is further reinforced by an increase in the number of satellites per rocket launch. Forecasts indicate that the number of launched satellites will rise by one order of magnitude until the end of this decade (Fig. 2).

The new records in launch rates and satellite deployments raise the question about the environmental impact of spaceflight activities in general, which can further be subdivided into impacts on the Earth and space environment, respectively. Concerning the Earth environment, recent studies show, for example, a potentially significant impact on the climate and ozone from launch and re-entry emissions [2–6], and the World Meteorological Organisation expressed concerns about the associated long-term impacts [7]. Related to the space environment, concerns arise in particular for the conventional LEO, i.e. at altitudes above 450–500 km, as this region is subject to the very real risk of becoming congested.

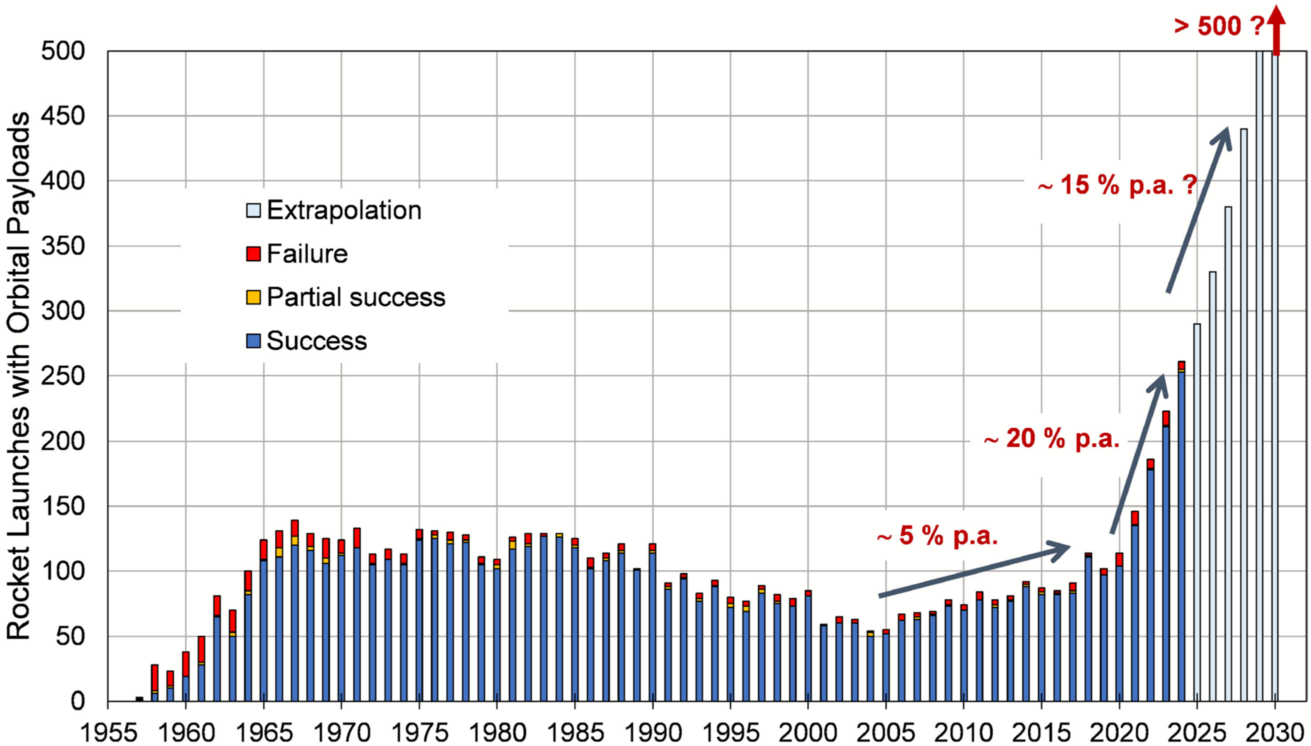


Fig. 1 Worldwide rocket launches with orbital payloads (as of December 31, 2024)

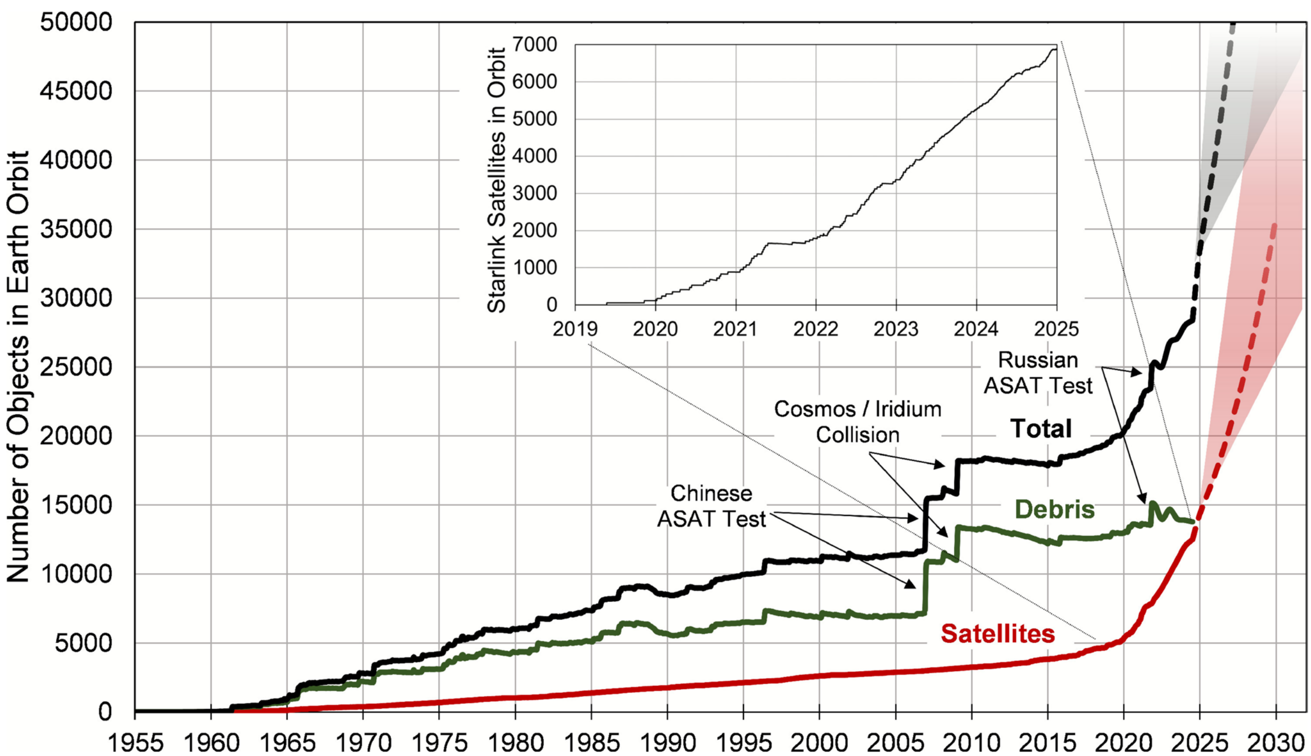


Fig. 2 History and future of Earth-orbiting objects, most in conventional Low Earth Orbit. Historical data extracted from NASA's orbital debris programme office [125] (as of June 9, 2024), Starlink data from J. McDowell [126] (as of December 31, 2024) and future data extrapolated (comparable to prediction by S. Alfano et al. [127])

This is due to the fact that the population of space debris stemming, e.g. from collisions, debris impact, defunct mission hardware, anti-satellite weapon tests and explosions of upper rocket stages increases continuously. In consequence, the LEO is subject to the very real risk of experiencing a collision cascade scenario, which is known as the "Kessler syndrome" [8]. This scenario may close off effective access to LEO for the subsequent decades or even centuries, unless a sufficient number of debris items is removed by yet unavailable technologies or natural orbit decay.

Nowadays, most of the launched satellites are currently positioned in LEO mainly because this allows for an adequate operational lifetime with respect to the investment costs using traditional satellite systems. On the other hand, a lower altitude in VLEO would be beneficial for almost all existing and upcoming near-Earth satellite utilisation cases. Also, the VLEO region offers an attractive alternative in terms of minimising the threat of a collision cascade [9]. The primary benefits of VLEO platforms are in summary:

- A significant increase in measurement accuracy in geophysical science missions, higher resolutions and/or lower payload masses for Earth observation missions.
- Shortened communication response times and reduced transmission power levels.
- A reduction in launch costs due to lower orbits and satellite masses for equivalent tasks, with an indirect additional potential towards minimising the environmental impacts of space activities due to the reduction of required launches and/or burn-up mass during re-entry.
- Sustainable flight within previously only temporarily accessible areas of Earth's thermosphere for atmospheric science missions.
- The possibility of exploiting aerodynamic forces for propellant-less orbit and attitude control of satellites.
- Constituting the single viable alternative towards securing future satellite services, should a collisional cascade lead to an exponentially accelerated increase of space debris in conventional LEO.
- A safe, rapid and passive post-mission disposal, which does not contribute to the growing abundance of space debris.

VLEO flight is, however, challenging due to the barely predictable and dynamically changing aerodynamic drag caused by the residual atmosphere (lower thermosphere). The atmosphere is mostly composed of atomic oxygen in VLEO (depending on model and altitude up to 99%), which is produced by photochemical dissociation reactions and increases in abundance at higher altitudes as illustrated in Fig. 3. Since these reactions mainly depend on the current solar and geomagnetic activity, the variations over a solar cycle with an 11-year period, over the year and even over a day are correspondingly large. A small fraction of the atomic oxygen is ionised, forming the ionosphere and peaking at daytime and within VLEO-relevant regions in general, whilst never exceeding 1% of the total gas density.

The accuracy of predictions of density, temperature, composition, etc. is limited by the inherent inaccuracy of state-of-the-art, semi-empirical atmospheric models, and lies in the range of 10–15% [10–13]. This holds true even if important model parameters such as the solar and geomagnetic activity are known, which themselves are hardly predictable [10, 14]. In addition, the velocity vector of a satellite relative to the atmosphere differs from the inertial satellite velocity vector, which is defined by orbital mechanics, depending on its orbital position (longitude, latitude) and constantly fluctuating atmospheric conditions including thermospheric winds [11]. Finally, as the mean free path of particles in VLEO exceeds typical satellite dimensions, satellites are subject to free molecular flow conditions at relative velocities of 7–8 km/s.

Different research activities have been conducted to investigate potential VLEO utilisation worldwide and at the University of Stuttgart, in most cases concentrating on individual themes. A general overview of related topics is provided in Sect. 4. However, a coordinated research programme is essential to achieve meaningful progress, in particular with regard to coalescing findings from distinct disciplines in engineering sciences. This strongly motivates the CRC 1667 ATLAS, whose overall concept is described in Sect. 5.

3 State of the art

The research topic "VLEO spaceflight" has received increasing attention from the scientific community in recent years. An indicator is the continuously increasing number of scientific publications using the terminology "Very Low Earth Orbit", as depicted in Fig. 4. A closer look reveals the University of Stuttgart to be in one of the leading positions. This is due to some research work conducted in preparation for the CRC ATLAS and also based on the foregoing EU-funded project "Disruptive technologies for very low Earth orbit platforms" (DISCOVERER) under the lead of the University of Manchester. The thereby already established cooperation cluster is clearly visible in Fig. 4. Further intense research activities are noticeable in particular for the TU Delft in Europe, the University of Tokyo in Japan, the University of Colorado Boulder in the USA, the Carleton University in Canada, and the Beihang University in China. All of them are part of research clusters. Based on the available publications, dedicated research foci for these institutions have been as follows:

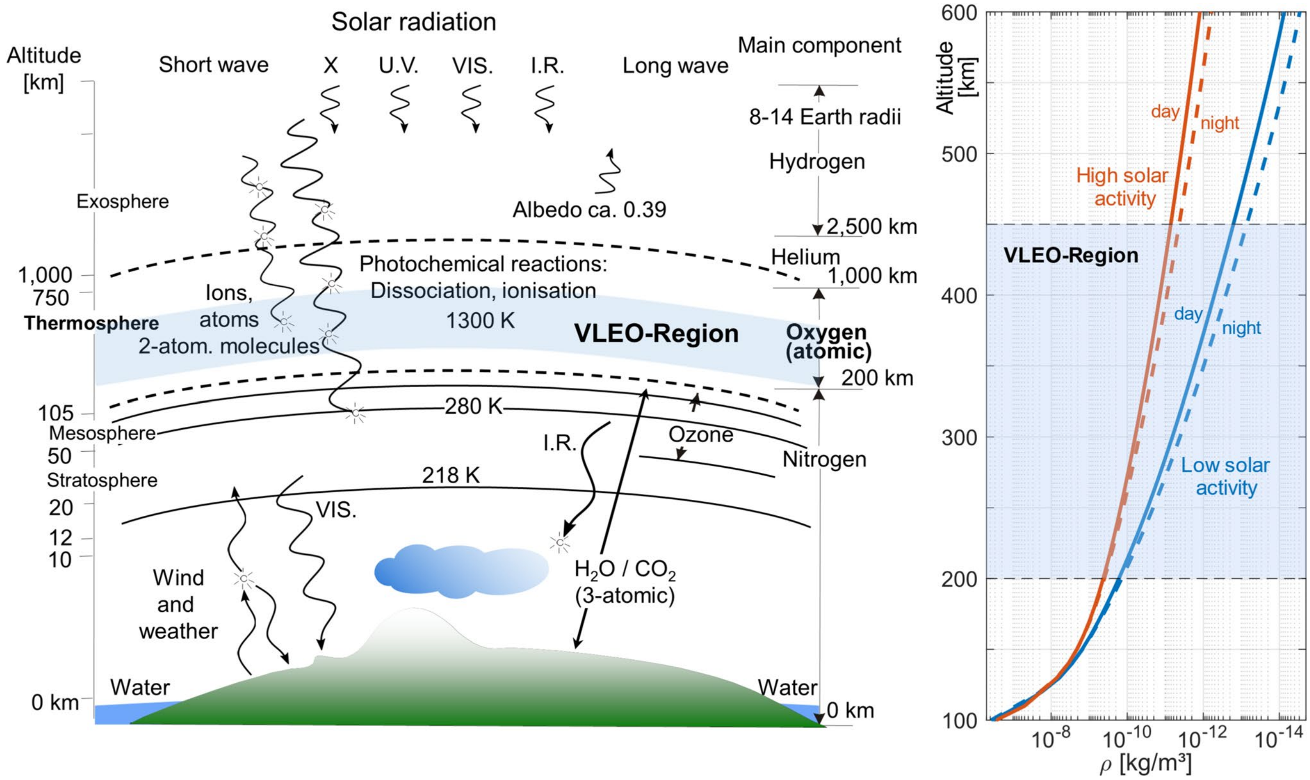


Fig. 3 Regions of Earth's atmosphere (left, adapted from Pisacane [128]) and atmospheric density above Stuttgart (right, atmosphere model NRLMSISE-00 [129])

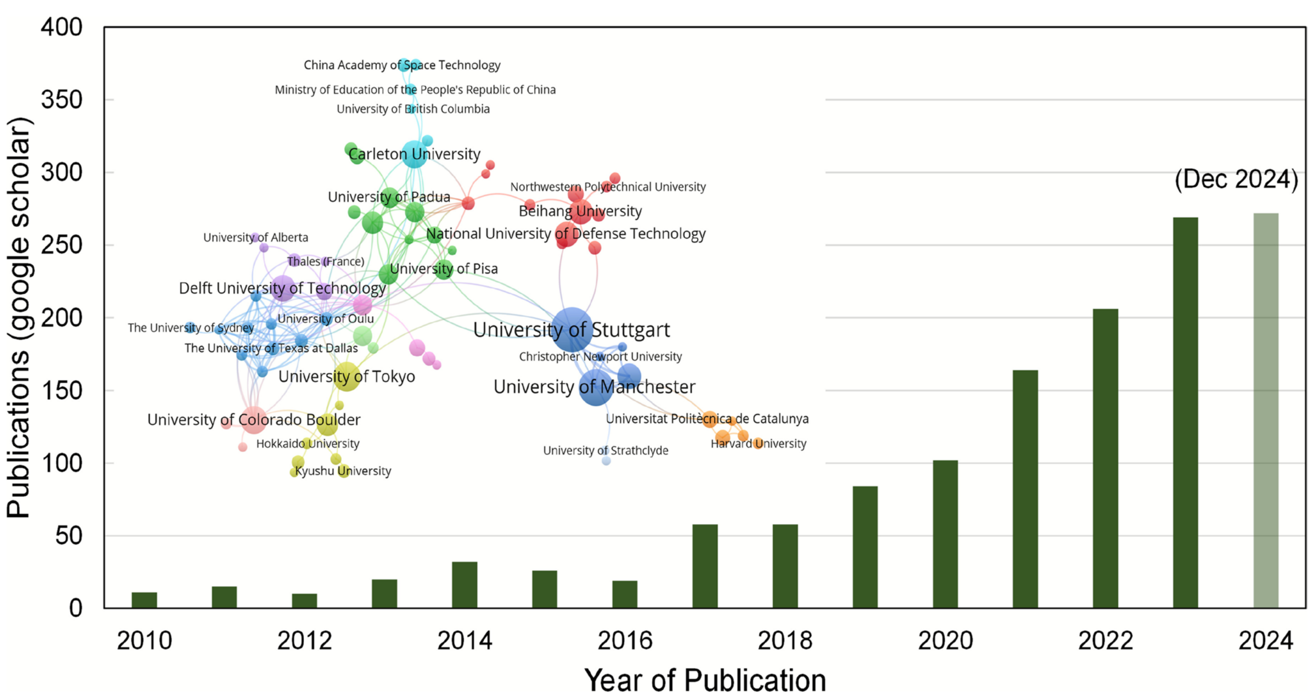


Fig. 4 Publications (based on "google scholar") with the term "Very Low Earth Orbit" in title, abstract or full text (since 2010, as of December 31, 2024) and their origin indicating localisation of research clusters and amount of related activities (database dimensions.ai, as of July 2023) [130, 131]. Important note: The terminology "Very Low Earth Orbit" is actively and more frequently used since about 2015. The illustration should be, therefore, interpreted only as an indicator for the recent developments in the research field

- The University of Manchester concentrated on the application of satellite aerodynamics to attitude control as well as on the characterisation of satellite surface materials, and the lead of DISCOVERER as one of the largest research projects on the topic to date [15–19].
- The University of Tokyo published primarily on topics associated with atmosphere-breathing propulsion technology, specifically small-scale atmosphere-breathing coaxial Pulsed Plasma Thrusters [20–22].
- The University of Colorado Boulder conducted research on low-drag and atomic oxygen-resistant materials as well as on the effect of space weather on satellites and debris in (V)LEO [23–26].
- Carleton University investigated primarily optical wireless satellite networks, also known as free-space optical satellite networks in particular for a deployment in VLEO [27–31].
- The TU Delft has published articles on the design of an attitude determination and control system of a 6U CubeSat for Earth observation as well as contributions to scientific missions in VLEO [32–35].
- Beihang University performed investigations on aerodynamic drag and related reduction strategies for satellites in VLEO, as well as aerodynamic attitude control and intake devices for atmosphere-breathing electric propulsion systems [36–41].

Most of the activities at these institutions concentrate on individual topics as the availability of relevant expertise to cover the required broader research topics on single locations is rare. Nonetheless, it is expected that the worldwide research efforts will further increase for the same or similar motivations as for the CRC ATLAS. Indicators for this are ongoing and emerging major worldwide efforts towards achieving VLEO utilisation. Examples are the announcements of the "Defense Advanced Research Projects Agency" on the programmes "Daedalus" end of 2022 [42] and "Otter" [43]. Other space actors are also active, e.g. ESA [44] or Chinese CASIC [45]. Finally, some companies, including SpaceX with its Starlink constellation, have announced plans to operate satellites between 200 and 400 km [46], however, still relying on existing technologies like ion thrusters fed by on-board stored propellants.

In the following, an overview of the state of the art for individual topics is given, beginning with "space debris mitigation", as it represents a strong motivational argument for the CRC ATLAS. Then an overview of the (limited) knowledge on "VLEO utilisation" is provided, followed by the therewith associated topic of "active drag compensation with atmosphere-breathing electric propulsion". The option of passive drag compensation through dedicated gas–surface interaction properties is subsequently addressed. Outlines for the topics of "space-borne gravity field mapping" and "thermospheric research missions" are then given, as they represent the focal points of future scientific mission scenarios assessed within the CRC ATLAS. Finally, "current trends on relevant satellite subsystems and payloads" are outlined. An interim summary addressing the identified knowledge gaps provides the basis for the subsequent Sects. 5 and 6, which introduce the concept, research questions and goals of the CRC ATLAS.

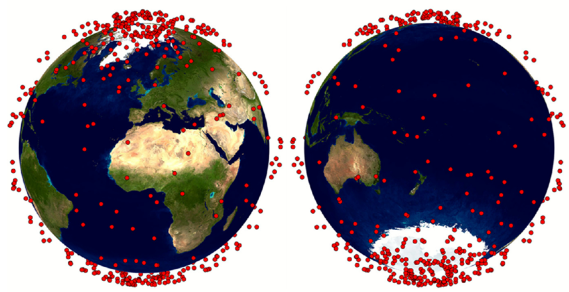
3.1 State of the art on space debris mitigation

Satellites in traditional LEO as well as the International Space Station in VLEO are at constant risk of being impacted by space debris of varying kinetic energies, with only larger items being catalogued and monitored. The first-ever hypervelocity impact occurred between the operational satellite Iridum-33 and the defunct Kosmos-2251 at an altitude of 789 km at a northern polar latitude in February 2009 [47]. This event alone bolstered the population of space debris by about 2,300 trackable items (Fig. 2), indicating how important a swift removal of large, defunct satellites in particular is to operational safety in space. Other, "non-accidental" events, such as the Chinese anti-satellite weapon test (ASAT) in January 2007 and the Russian ASAT in November 2021, further increased the abundance of potentially hazardous space debris (Fig. 2).

Hence, many research efforts worldwide investigate options of actively capturing key debris objects by various means for the purpose of subsequent disposal (e.g. [48–54]). This measure could indeed contribute to reducing the overall risks, especially if larger objects would be removed. However, besides all challenges associated with capturing a non-cooperating target in space, the number of items to be removed would incur considerable expenses. This is additionally aggravated by the lack of a legal basis in an international context today: who is allowed to capture and dispose whose objects, who is responsible and who is going to pay? Because of a variety of particular and partially conflicting interests, it is doubtful whether a worldwide agreement will be attained in the foreseeable future.

Therefore, besides the operational benefits, enabling a sustained operation in VLEO might constitute the only suitable option to continue operating near-Earth spaceflight in the future.

As an example, illustrating the potential danger to operational space hardware, Fig. 5 summarises the proximity warnings triggered for the University of Stuttgart's small satellite "Flying Laptop" since its launch in July 2017 to an altitude of about 596 km. The risk of incurring a Kessler syndrome is greatly exacerbated by the trend towards mega-constellations with thousands of satellites, which are actively being implemented (Fig. 2). This threat is clearly already present today, considering the tremendous increase



Satellite Flying Laptop (Jul 17–Sep 24)	Amount
Total number of events	~750
… of which with known objects (multiple instances possible)	~150
… of which with unknown objects (multiple instances possible)	~110
… closest (predicted) distance	29 m
… largest predicted collision probability	0.708 %

Fig. 5 Metrics and locations at which proximity warnings (pass of tracked debris item within 1 km predicted distance) have been triggered through the Combined Space Operations Center (CSpOC) for the University of Stuttgart's small satellite Flying Laptop since its launch in July 2017 as of September 2024 (initial altitude ≈ 596 km, inclination ≈ 98°)

of calculated maximum collision probabilities in the recent past as illustrated in Fig. 6 [55]. This holds true even if contemporary standards for end-of-life satellite disposal were to be adhered to strictly or even improved upon significantly [56, 57]. One example of new regulations is the announcement of the USA Federal Communications Commission in September 2022 on new rules, specifically requiring satellite operators in LEO to dispose of their satellites within 5 years after completing their missions, which shortens the previously required decades-old 25-year disposal window for deorbiting satellites post-mission [58]. However, it is highly doubtful whether these updated guidelines will suffice in mitigating this risk or whether they will be implemented by all space-faring nations. The need for collision avoidance manoeuvres during operation is nonetheless continuously increasing, e.g. for the ISS [59, 60], and a key question remains unanswered: What happens if a significant number of satellites fail, and control over them, either for collision avoidance or disposal manoeuvres, is no longer possible? With decay times at VLEO-relevant altitudes being intrinsically short, the amount of harmful debris existing therein at any time can be considered sufficiently low, even following the potential fallout of a Kessler syndrome.

It follows that satellites operating in VLEO are intrinsically less susceptible both to falling victim to in-orbit collision events and to themselves significantly contributing to a potentially catastrophic collisional cascade following e.g. in-orbit failure or debris impacts.

3.2 State of the art on VLEO utilisation

Examples on VLEO utilisation range back to the very beginning of spaceflight with necessarily short-lived satellites used primarily for scientific and military reconnaissance purposes. Later, crewed space stations, including the contemporary "International Space Station" (ISS), would be placed in what can now arguably be referred to as VLEO. This, however, results in the requirement of regular orbit-raising manoeuvres conducted in compensation of the orbital decay caused by atmospheric drag. In consequence,

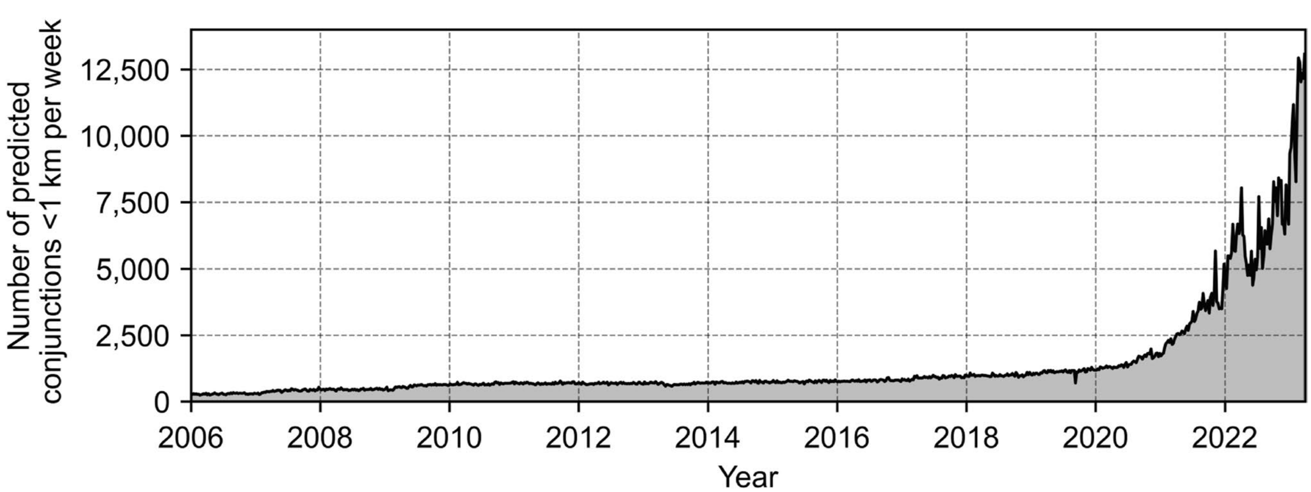


Fig. 6 Predicted conjunctions (< 1 km) per week based on CelesTrak/Socrates Plus computations [55], as of May 2023

they either re-enter within a few months or depend entirely on carefully scheduled re-supply of propellant from Earth for orbit-raising manoeuvres [61].

A rare but prominent example of a spacecraft sustaining a VLEO orbit by its own resources is ESA's "Gravity Field and Steady-State Ocean Circulation Explorer" (GOCE), which maintained a circular orbit at approximately 255 km altitude for 55 months starting in 2009 [62, 63]. The atmospheric drag acting on GOCE was mitigated by a sleek design of the spacecraft itself as well as through highly efficient ion thrusters exerting a constant thrust of 20 mN. GOCE's mass of 1100 kg comprised 40 kg of Xenon as fuel and its lifetime was limited only by the amount of propellant stored on board [64]. GOCE, as one of the best-characterised satellites in terms of its aerodynamic properties, is also an excellent example to illustrate the existing knowledge gaps and uncertainties associated with VLEO spaceflight: on 21st October 2013, ESA stated that GOCE will most likely re-enter in about 2 weeks (early November 2013). The actual re-entry occurred on 11th November 2013, which, from the perspective of the original prediction, corresponds to a relative error of 30% [65, 66].

Another VLEO mission, named "Super Low Altitude Test Satellite" (SLATS), was launched by the Japanese Space Agency JAXA in late 2017 to demonstrate technologies in VLEO between 180 and 250 km altitude, including an ion engine system and the satellite system itself [67]. Some further studies for VLEO systems for remote sensing and technology demonstration purposes have been conducted.

In summary, VLEO missions today are either short-lived or entirely dependent on available on-board fuel or its replenishment from Earth.

3.3 State of the art on active drag compensation by atmosphere-breathing electric propulsion

Following technology research programmes for atmosphere-breathing electric propulsion concepts, interest into the topic of VLEO flight has renewed within the European Space Agency, as demonstrated by an increased output of public invitations to tender for technology development activities on specific topics. This acute rise in interest is certainly in part a result from the continuing struggles with technical as well as international legal issues associated with the intention of establishing a globally coordinated space debris mitigation strategy. Other agencies and institutions worldwide support similar activities. An overview about the current state of the art on atmosphere-breathing electric propulsion is given by Andreussi et al. [68]. In summary and with regards to research on drag mitigation measures in VLEO, a frequent focus lying on atmosphere-breathing electric propulsion and the experimental simulation of atomic oxygen flow conditions, only a few international research activities have so far preceded the CRC ATLAS as indicated in Table 1 [67–74].

One exception in this context is the project DISCOVERER, which was funded through the European Union's Horizon 2020 research and innovation programme. With nine partners in six countries, it constituted one of the largest concentrated research efforts into VLEO satellite concepts so far, covering topics from atmosphere-breathing electric propulsion, low drag and atomic oxygen-resistant materials, aerodynamic attitude and orbit control, and business models for VLEO utilisation with a focus on Earth observation [75]. The University of Stuttgart was involved in the design of an atmosphere-breathing electric propulsion concept based on an inductive plasma thruster, the development of aerodynamic control methods, contributions to the

Table 1 Selected past and present research activities on atmosphere-breathing electric propulsion (ABEP) for VLEO flight

Activity	Focus	Funding agency	Year (initial)
ABIE [69, 132]	Atmosphere-breathing ion thruster, theoretical and experimental activities	JAXA	2003
RAM-EP [71]	Concept study for atmosphere-breathing RIT-10 propulsion system	ESA	2007
ABCHT [72]	Atmosphere-breathing cylindrical Hall-effect thruster, tested with xenon only	The Aerospace Corporation	2009
VIPER [133]	Laboratory tests of small-scale atmosphere-breathing coaxial Pulsed Plasma Thruster (PPT)	University of Tokyo	2015
DISCOVERER [75]	Activity focussing on atmosphere-breathing inductive plasma thruster, investigation of materials with specular reflection properties, aerodynamic attitude and orbit control, and business utilisation scenarios	EU	2017
AETHER [73, 84, 93]	Air-breathing electric thruster; industry-led consortium focussing on increasing technology readiness level	EU	2019
ram-CLEP [91, 92]	Air-breathing cathode-less electric propulsion; follow-up on ABEP system development begun in DISCOVERER, with intent on advancing technical aspects and establishing end-to-end ground test methods	ESA	2021

test facility programme at the University of Manchester, and the support to the development of business case scenarios [76]. Whilst the findings provide a valuable foundation, the CRC ATLAS explores aspects and applications of VLEO satellites beyond the scope of DISCOVERER, specifically geodetic and atmospheric research. Furthermore, topics that were investigated in DISCOVERER are meaningfully expanded upon, and alternative approaches to various challenges posed by the environment of VLEO are explored, informed by the knowledge gained in that activity. The facilities and methods to be developed in the course of the CRC ATLAS are complementary in nature, i.e. non-redundant to those established in the context of DISCOVERER, whose funding period ended in 2022. The DISCOVERER project also sponsored, arranged and performed the "1st International Symposium of Very Low Earth Orbit Missions and Technologies" (28–29 June 2021) as a virtual event due to the corona pandemic. Some of the presented results have been peer-reviewed and were published [77–90]. Other contributions from this symposium are available on the DISCOVERER website [75].

Conceived as a technical follow-up on the ABEP-focussed research activities within DISCOVERER, the ESA-funded project ram-CLEP ("air-breathing Cathode-Less Electric Propulsion") aimed to improve the existing prototype design further, specifically by incorporating a dedicated power processing unit and rescaling the thruster prototype correspondingly [91, 92]. The methods and lessons learnt provide an ideal starting point for further research and design improvements. In addition, first approaches to assess and verify potential platform designs (i.e. VLEO satellites) considering the use of both Earth observation and telecommunication payloads have been developed. These findings are also very fruitful for the activities within the CRC ATLAS.

Another project called AETHER ("Air-breathing Electric Thruster", 2019–2022), which was also funded through the Horizon 2020 programme, focussed primarily on the further development of a concrete concept of an ABEP system on an industrial level. This concept bases on a formerly project performed by the Italian company SITAEL, where a prototype based on a Hall-effect thruster was designed and preliminarily tested successfully in an end-to-end laboratory setup [73, 84, 93]. Nonetheless, the main issue remains in the operation of such a thruster with atmospheric propellant, due to the high concentration of atomic oxygen, a primary source of erosion for critical thruster components, such as grids for radio frequency ion thrusters or discharge channels for Hall-effect thrusters. Moreover, technical restrictions referring to a minimum density at which some of the industrial thrusters can operate lead to limitations of these to lower VLEO altitudes.

In summary, all activities conducted so far indicate that an ABEP system could be feasible, though with many open questions. To give a quantitative example, a GOCE like spacecraft (mass 1,000 kg, cross area 1 m^2) would require a power level of about 2–3 kW to continuously maintain an altitude of about 200 km [83]. These figures, however, base on very rough estimations and assumptions and may vary significantly. Open questions concern, in particular, the intake design, dealing with the high fluctuations in operating conditions, efficiencies, atomic oxygen resilience, and above all experimental verification, to name a few.

3.4 State of the art on gas–surface interaction research

Under VLEO-specific boundary conditions, i.e. a free molecular flow with relative velocities of 7–8 km/s, gas–surface interactions directly lead to a momentum and energy exchange between the incident gas particles and the external surfaces, therefore resulting in forces and torques acting on a spacecraft. Overviews of the state of the art in aerodynamic drag modelling and incorporated gas–surface models for Earth-orbiting satellites are given, for example by Mostaza Prieto et al. [94] and by Livadiotti et al. [95], respectively. In summary, the interactions depend on the physical parameters of the surface (roughness, cleanliness, molecular composition, lattice configuration and temperature) as well as the characteristics of the incident flow (composition, velocity and incident angle).

The associated drag coefficient has usually been assumed to be a constant equal to 2.2, and the lift coefficient has almost always been neglected in the past. Today, it is widely accepted that the coefficients are not constant but dependent on the spacecraft shape as well as the atmospheric temperature and composition at the flight altitude, and that existing models are generally not sufficient for their required prediction accuracy.

The imprecise knowledge of the drag coefficient amplifies the already substantial uncertainty in predicting the atmospheric forces acting on a satellite in VLEO, which results from uncertainties regarding space weather conditions, the inherent inaccuracy of the available semi-empirical density models, inaccurate knowledge of the spacecraft's attitude with respect to the flow, and uncertainties in the modelling of thermospheric wind. Combined, these effects may cause deviations up to one order of magnitude for the predicted force acting on a satellite, as schematically indicated in Fig. 7. Vice versa, atmospheric density models obtained from satellite orbit observations, directly incorporate any error on the drag coefficient as density biases. Any improvement on the knowledge will, therefore, directly impact the accuracy of mission analysis and orbital predictions. Subsequently, for example, a more accurate determination of re-entry paths and debris footprints could be realised. In the context of the CRC ATLAS, a more accurate orbit

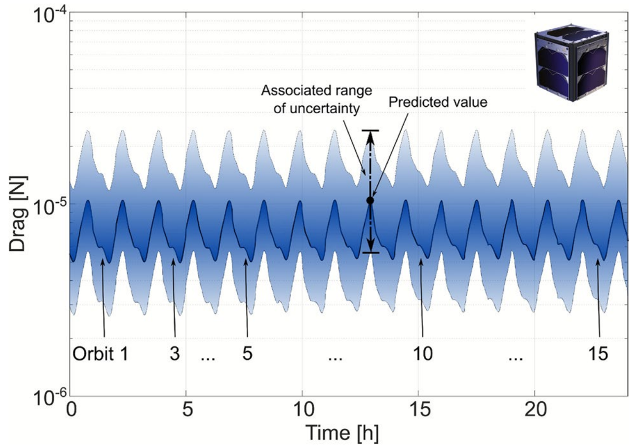


Fig. 7 Estimated drag of a CubeSat (0.10×0.10×0.10 m3) in 350 km altitude illustrating the uncertainties due to density variations and imprecise knowledge of the drag coefficient

determination and tracking of space objects would be possible, allowing, for example, optimum and precise collision avoidance manoeuvres. Also, a comprehensive aerodynamic characterisation of a given spacecraft will allow for the study of new mission concepts in which the aerodynamic forces play an active role, such as passive drag compensation and optimisation, or relative trajectory and attitude control. Passive drag compensation by specifically designed surface materials and spacecraft shapes was already shown to increase the operational lifetime by about 10–30% with realistic (conservative) assumptions on occurring gas–surface interactions and by orders of magnitude with yet unavailable specular reflection properties [96].

3.5 State of the art on space-borne gravity field mapping

Space-borne gravity field mapping is a research field that will considerably benefit from sustained VLEO operations. The fine structure of the gravity field attenuates strongly with height, and hence, gravity sensors should sample the field as close as possible to the attracting masses, i.e. in VLEO. Missions such as CHAMP, GRACE and GRACE-FO were launched into an initial altitude between 450 and 500 km [97–99]. Due to atmospheric drag, their orbits decay(ed) in height naturally into the VLEO regime during their mission lifetime. Only ESA's GOCE mission was actively kept in an orbit around 255 km altitude by continuously counteracting the atmospheric drag. Beyond its scientific success, GOCE was able to demonstrate the scientific potential and value of VLEO platforms, directly motivating the research of technological principles, concepts and an exploration of further application scenarios for a quasi-indefinite VLEO deployment of satellites.

ESA has also supported numerous studies of academic and industrial teams to prepare for a next-generation gravity mission. Such studies have addressed technical aspects, including drag free compensation in VLEO over longer mission durations, or laser ranging options between satellites [100]. Technological advances in the field of cold atom interferometry are monitored closely because future gravity missions would benefit from such novel inertial sensing technologies in various ways: accelerometry, gradiometry and attitude sensing. These possible future payloads have been, for example, partly the focus of the CRC 1464 TerraQ—Relativistic and Quantum-based Geodesy, which has been supported by the DFG since 2021 [101].

Other ESA studies addressed the inherent undersampling of the time-variable gravity field from orbit, and therefore, analysed the design of constellations with multiple satellite pairs on polar and inclined VLEO orbits. However, in an ESA or multi-agency context, the typical mission design involves mid-size or larger satellites and budgets of 200 Mio. € or more. The noted studies are, therefore, complementary to the investigations in the CRC ATLAS, which aim at novel gravity mission concepts pointing at reconfigurable and distributed low-cost architectures.

3.6 State of the art on thermospheric research missions

Research missions in the thermosphere are rare, and thus the knowledge and understanding of the therein occurring phenomena is limited, which leads to the frequently used terminology "ignorosphere" (e.g. [102]). An overview including a gap analysis has been given, for example, by Mlynczak et al. [103]. Space-based observations have been primarily made between 45 and 120 km in altitude (mesosphere and lower thermosphere, MLT). Though quite limited, the understanding of the structure and composition as well as the significance of the MLT has been largely revolutionised as a result of these observations. A key result is the long-term cooling of the MLT because of increasing CO_2 levels [104], which confirms a fundamental prediction of climate change theory [105, 106]. In addition, these data have become vital for the development of next-generation whole-atmosphere prediction models for space weather applications [107, 108].

The long-term cooling of the MLT is further predicted to significantly reduce the atmospheric density at altitudes wherein low-Earth-orbiting satellites operate, and evidence for this effect already exists [109]. The reason is that above 120 km in altitude, long-term changes associated with increasing CO_2 levels are largely driven by physical processes in the "heat sink region" of the MLT between 85 and 125 km in altitude, where radiative cooling by CO_2 dominates [110, 111]. Thermal energy at higher altitudes in the thermosphere is naturally transported downward by heat conduction and is ultimately radiated by CO_2 in the heat sink region. As the amount of CO_2 increases, more energy from the upper thermosphere can, thus, be transported down and radiated from the heat sink, resulting in cooling and decreased density both in the MLT and in the upper thermosphere. This scenario would increase the orbital lifetime of satellites and space debris, which could amplify hazards to all spacecraft in LEO [103].

An example for a planned satellite mission is the "Space Weather Atmospheric Reconfigurable Multiscale Experiment" (SWARM-EX), a CubeSat initiative funded by the US National Science Foundation (NSF). Three identical CubeSats will be launched for the investigation of scientific phenomena in the upper atmosphere (planned launch date in 2025). CU Boulder is leading the project with contributions from Stanford University, Georgia Institute of Technology, Western Michigan University, University of Southern Alabama and Olin College. An atomic oxygen sensor system "FIPEX" from the University of Stuttgart and a Langmuir Probe measuring ion density will be deployed onboard to address the spatial and temporal variability of the equatorial ionisation anomaly and equatorial thermospheric anomaly [112].

Another example is the "Daedalus" mission, which has been proposed to the European Space Agency (ESA) in response to the call for ideas for the Earth Observation programme's "10th Earth Explorer". It was selected in 2018 as one of three candidates for a Phase-0 feasibility study. The mission design aimed to break through the current spacecraft exploration "barrier" of 150 km and to access electrodynamics processes at lower altitudes. In line with ESA's Living Planet Programme, Daedalus constituted an ambitious programme covering a wide range of observations and measurements that are needed to resolve key energy balance issues in one of the most under-sampled regions of the Earth's environment: the "ignorosphere", i.e. lower thermosphere and ionosphere. As it turned out, however, the ambitious mission, based on traditional satellite design, was beyond budget, so Daedalus was not selected for a Phase A study. Nevertheless, there may be a future for Daedalus, albeit in ESA's Science Directorate and no longer in the Earth Observation Directorate [102, 113].

3.7 State of the art and trends on relevant satellite subsystems and payloads

As most visibly by the increasing prevalence of nanosatellites based on the CubeSat standard, a clear trend towards miniaturisation is observed in satellite design, with deployment via launcher ridesharing having become the rule [114]. The considerably reduced development and launch costs have led to an increased abundance of cost-efficient miniature satellites in orbit, which is continuing to exacerbate the challenge of space debris. That very development has further prompted a growing prevalence of single-purpose satellite designs, intentionally built for specific and narrowly bounded scientific or commercial missions, which are in many cases conducted by multiple interlinked spacecraft orbiting in formations or constellations. This design philosophy lies in strong contrast to conventional singular large multi-purpose satellite design approaches. The increased tendency to distribute and coordinate mission- and operations-related tasks between individual platforms necessitates advances in mutual self-organisation capacities and enhanced intra-satellite and ground station communication capabilities, utilising highly efficient means such as laser links.

Fundamentally, any technology potentially contributing to a reduction in a satellite's system mass and increase in efficiency can be considered meaningful for broader spaceflight applications, and numerous eminent advances have been reported in this respect. Examples, which are also investigated within the CRC ATLAS, comprise perovskite solar cells and quantum-based technologies. NASA classifies perovskite solar cells as a notable upcoming technology of considerable value both for and beyond VLEO applications [115]. Following a first successful demonstration of quantum-encoded communication techniques by Shi et al. [116], a notable surge in the global research and commercial interest in quantum technologies is ongoing, owing to their great potentials in a broad range of areas including computation, secure communication, metrology, and many more [117]. It is highly likely that such quantum technologies will become a staple payload for many satellite applications within the next 10 to 15 years; however, the focus of ongoing developments primarily lies on their deployment in conventional LEO orbits. For example, a white paper on satellite-based quantum communication missions has been published by Jennewein et al. [118]. As these conventional orbits become exceedingly populated, greater demands and requirements are placed on the exact determination and prediction of orbital trajectories, which is motivated in no small part by the desire to improve collision avoidance measures.

Finally, as practically every satellite placed in LEO or fragment thereof will eventually re-enter Earth's atmosphere in an uncontrolled manner, partially burning up in the process, various dedicated research activities around the globe investigate "Design for Demise" strategies by which to reduce the risk of any residual debris causing harm to life and property on impact [119–121].

3.8 Conclusion of the state of the art

The CRC ATLAS builds upon the level of knowledge achieved in VLEO spaceflight so far and aims to close the various existing knowledge gaps in the basic understanding thereof by considering the foreseeable trends in satellite technologies and applications. Unleashing the full potential of VLEO utilisation necessitates significant advancements with regard to the interaction and integration of physical models as well as experimental and numerical methods to achieve the levels of required understanding. The need for this advancement results from the current state of the art, which reveals urgent research requirements, in particular in the fields of gas–surface interactions, enabling subsystems and VLEO mission-related challenges.

The mission examples for thermospheric research and space-borne gravity field mapping have been chosen to illustrate the international research interest for long-term in situ investigations and the associated needs for appropriate satellites, and to indicate the potential impact of related research findings. These entirely new mission scenarios are an additional motivation for the CRC ATLAS and completely independent of the mentioned space debris issues. This is also the reason why the focus for respective reference scenarios has been chosen as a guiding element in the CRC ATLAS.

4 Conception of the CRC 1667 ATLAS

4.1 Research goals

Based on the previous discussion, open research questions related to VLEO utilisation comprise the following, mutually influencing challenges:

- Knowledge gaps in modelling and experimental testing of a free molecular, high-speed, and chemically aggressive flow, covering all relevant spatial scales.
- Missing methodological and technological knowledge concerning utilisation of the residual atmosphere.
- Need for technological subsystem concepts that offer design options to minimise mass, volume and especially cross-sectional requirements.
- Lack of concepts to deal with significantly shorter transmission and communication windows.
- Missing solutions for reliable autonomous response to unpredictable events with widely varying time scales, including low latency precise orbit determination.

As a result of these challenges, the research goals of the CRC ATLAS towards rendering VLEO sustainably accessible for long-term satellite operations are:

- *Mastering of rarefied flow aerodynamics and gas–surface interactions with unprecedented accuracy*: The total drag can be reduced through an accordingly optimised spacecraft design, which, however, is strongly dependent on surface properties, overall configuration and specific utilisation scenarios. The basic understanding of gas–surface interactions under VLEO conditions and a related characterisation of surface materials will allow to control and direct them to further reduce the drag coefficient. The impulse and energy exchange between individual gas particles and surfaces depend on microscopic gas–surface interactions. On the other hand, the drag coefficient must be known precisely on a macroscopic level for the entire satellite. The gas–surface interactions are mainly dominated by material and surface properties, e.g. roughness, temperature, incident angle, absorption, desorption and chemical reactions with atomic oxygen [94, 95]. The chemically highly corrosive nature of atomic oxygen is an additional challenge, particularly in conjunction with UV radiation, thermal cycling and micrometeoroid impacts.
- *Solutions for aerodynamic drag mitigation:* Longer mission durations require drag-mitigating systems that operate either entirely without propellant, e.g. by utilising lift and drag for orbit and attitude control purposes [122], or collect residual atmospheric gases to be used as such [123, 124]. Harvesting of the residual atmosphere for later propulsion purposes is challenging due to the rarefied flow conditions. Thus, the idea has not yet developed above pure conceptual status. Passive utilisation of aerodynamic drag or lift has not yet been applied in a detail as required for satellites in VLEO. For potential in situ propellant collectors and subsequently therewith fed electric propulsion systems, directing and compressing rarefied flows as well as igniting and maintaining a plasma flow consisting of chemically aggressive atomic oxygen requires a breakthrough through modelling and experiments.
- *Methods to handle the dynamic and unpredictable nature of the environmental conditions:* Innovative solutions concerning the flexibility and control of all affected spacecraft subsystems, in particular those for drag mitigation, are required. The dynamic nature necessitates research to characterise and map its behaviour in sufficient detail to improve predictions for VLEO operations. A regular and precise determination of the current orbit and attitude is imperative, prompting the development of high-fidelity, real-time localisation techniques.
- *Subsystem solutions enabling VLEO-specific satellite design options:* Minimising cross-sectional area necessitates new concepts, in particular for solar cell arrays, as they represent large parts of a satellite's surface, which in turn is a system driver to aerodynamic orbit and attitude control. The electrical power demand, e.g. for atmosphere-breathing electric propulsion, will also result in waste heat, which calls for new thermal control solutions assisting synergistically in the drag mitigation or attitude control purpose. Minimising mass and volume demands

requires, in particular, solutions for key components of potential payloads.

- *Solutions for the reduced ground coverage of individual satellites, narrow operational fault tolerances, and autonomy:* The performance improvements associated with shorter distances between satellites and ground stations must be developed and exploited to maintain and improve up- and downlink efficiencies. To establish comprehensive ground coverage, constellations must comprise a relatively increased number of individual spacecraft, which poses additional challenges with regard to coordination, task distribution, and control. The relatively large amount of drag acting on spacecraft operating in VLEO implies that even a partial failure of subsystems associated with drag mitigation will result in a comparatively fast deterioration of their nominal orbit. As a countermeasure, a rapid, automated response to potential faults and functional redundancies is needed to minimise the risk of mission failure.

Many other relevant important topics with large knowledge gaps exist, concerning, e.g. methods for end-of-life disposal. Despite their obvious relevance, they do not represent a strictly VLEO-specific research challenge because the same holds true for the traditional LEO regime.

The outlined research goals are highly interdisciplinary, drawing from the fields of fluid mechanics, thermodynamics, plasma dynamics, material science, chemistry, electrical engineering, communication science, automation and control theory, atmospheric physics, geophysics and geodesy, with many individual research topics incorporating more than one of these fields simultaneously. Thus, a CRC constitutes a uniquely suitable format for closing the various knowledge gaps in the basic understanding of the science domains associated with VLEO spaceflight.

4.2 Anticipated project phases

The overall, long-term scientific vision of the CRC ATLAS is to achieve the fundamental understanding, knowledge and methodology to render a sustained operation in VLEO possible without a continuous re-supply from Earth or an onboard storage of large amounts of fuel. The focus in the first funding period (2024–2027) lies in addressing the fundamental research questions associated with VLEO flight, i.e. setting up the overall framework and the core elements for achieving the long-term vision. It is, therefore, dedicated to the establishment of detailed and accurate numerical and experimental methods for the description of the underlying physical phenomena of gas–surface interactions under VLEO conditions, focussed and validated on selected materials. Enabling subsystem concepts utilising the residual atmosphere and minimising satellite sizes are investigated under consideration of boundary conditions imposed by mission-related challenges of a selected reference scenario. The CRC ATLAS aims thereby at three main objectives:

A. To achieve a fundamental understanding and mastery of gas–surface interactions under VLEO boundary conditions, covering relevant scales in time and space.
B. To ascertain solutions for enabling subsystems with breakthrough potential for attaining sustainable VLEO utilisation.
C. To establish a methodology for solving VLEO mission-related challenges, focussed on thermosphere and gravity field research missions.

These three main objectives motivate the Project Areas A, B and C, respectively, which are outlined in the following Sect. 6.

The research activities in a second funding period (2028–2031) will further be oriented towards the stated main objectives. The emphasis will shift towards integrating and refining the tools, methods and facilities for dedicated research on key components at a subsystem level, considering the various interrelations between the subsystems specific to VLEO platforms. These considerations will be assisted by high-fidelity simulations as well as extensive component experiments, which build on the results of the first period. The goal in this second period will be to provide the understanding and to generate the tools that enable a highly accurate quantitative assessment of subsystems requirements and specifications, including their uncertainties in terms of predictability and operational envelope. First technology transfer projects might arise in parallel, which will be based on the expected results of the first funding period.

A third funding period (2032–2035) will finally concentrate on the synthesis of all findings for dedicated overall system concepts surrounding VLEO flight. It will be focussed on the quantification of the synergies and potentials of highly integrated VLEO satellites and requires the multidisciplinary numerical and experimental validation of the component and subsystem interactions using the corresponding methods developed in the first two funding periods. To further accelerate concrete applications of the research findings, technology transfer projects with partners from space agencies or industry are also anticipated within this funding period. Attaining system-level know-how with all core elements in terms of methodology and technology at the end of the third funding period will finally allow for reliable studies and the development of concrete mission scenarios in VLEO. The latter could be subsequently realised as a demonstration mission in an international cooperation context.

Besides the scientific vision, the strategic vision of the CRC ATLAS is to constitute a profile-building measure at the University of Stuttgart by deepening the interaction of research activities in aerospace engineering, geodesy, aeronomy, physics, electrical engineering and information technology. The influence of the CRC ATLAS will further extend directly and indirectly into the education of aerospace engineers in Germany, throughout Europe and the world, supported by academic and public engagement activities conducted within the dedicated Projects INF and Ö, which are described in Sect. 7.

5 Research projects

The CRC 1667 ATLAS is structured into the following three Project Areas to adequately address the research questions and goals:

A. Gas–surface interactions
B. Enabling subsystems
C. Mission-related challenges

Within the 3 Project Areas A, B and C, a total of 17 deeply integrated research projects form the basis for the first funding period.

In addition, three supporting projects are conducted: Project Ö focuses on the aspects of scientific communication, both within the CRC ATLAS and to the scientific public, as well as educational and public outreach activities and events. Most notably, this includes the planning and execution of an annual Satellite Design Workshop (SDW). A dedicated Project INF assists in the dissemination, exchange, publication and reuse of data, software and methods. Finally, general coordination, management and administrative support for the entire CRC are concentrated in Project Z. An overview of the three scientific project areas detailing their coverage of respective fields of research and subgrouping is given in the following subsections. An illustration of the general setup is given in Fig. 8.

5.1 Project Area A: gas–surface interactions

Project Area A focuses on tools and methods required for a fundamental understanding and mastery of gas–surface interactions from both experimental and numerical modelling points of view, further covering different relevant scales in time and space (Fig. 9).

Starting from a microscopic level, i.e. nano- to micrometre scale, ab-initio and molecular dynamics simulations based on density functional theory are further developed, adapted and applied to calculate interactions of atomic oxygen with possible surface materials of satellites (A01). The results will be used as a boundary condition to develop and implement more accurate gas–surface interaction models for the simulation of rarefied flows on a meso- to macroscopic level with the Direct Simulation Monte Carlo (DSMC) method (A02, A03), i.e. centimetre to metre scale. With DSMC, it is possible to simulate even very complex geometries, thus enabling the calculation of macroscopic drag, lift and momentum coefficients of entire satellite configurations for a certain point in time and for a given inflow boundary condition. With the DSMC method, however, it is not realistically possible to conduct thousands of 3D simulations for all possible uncertainties of the atmosphere model, surface modelling, satellite orientation and shape. Thus, a hybrid uncertainty-quantification model combining detailed DSMC data with a simpler panel method is being created in addition. This approach will provide reliable estimates of the satellite force coefficients under uncertain on-orbit and surface model conditions for selected reference satellite geometries (A02). This analysis also allows for the identification of the primary driver of uncertainty in force coefficient prediction. Modelling of gas–surface interactions requires experimental validation, which will be conducted in a new experimental facility for hyperthermal flow conditions, the set-up of which is also assisted by numerical simulations with the DSMC method (A03), as well as by further developments of dedicated diagnostic tools for the measurement of atomic oxygen (A04). The validation of the numerical modelling under at least very similar boundary conditions is essential, since real VLEO flight conditions cannot be fully reproduced in ground test facilities. From a long-term perspective, the methodology could facilitate the determination of time-dependent drag coefficients by explicitly considering surface alterations caused by erosion, UV radiation and micrometeoroid impacts. Capturing these processes is vital for closing the gap between laboratory testing and in-orbit performance.

The coefficients for various inflow boundary conditions and geometries, and their potential variations, are an indispensable part for the investigation of the potential to utilise aerodynamic forces for new attitude control approaches (A05), which require simulation time frames of up to a few seconds or minutes, and sophisticated orbit control methods (A06), for which time frames of up to days or even months are mandatory. Both will incorporate additional active drag counteracting measures, which are investigated in Project Area B. Vice versa, the tools and findings of Project Area A support the investigations conducted in Project Area B, i.e. atmosphere-breathing electric propulsion and the associated intake design (B01, B03). Also, an exchange with the entire Project Area C is required to iterate on the investigated mission-related challenges therein, with the options offered by a specific satellite design.

To focus the investigations conducted in the first funding period, the surface materials to be examined are chosen to be of particular relevance within ATLAS, i.e. especially

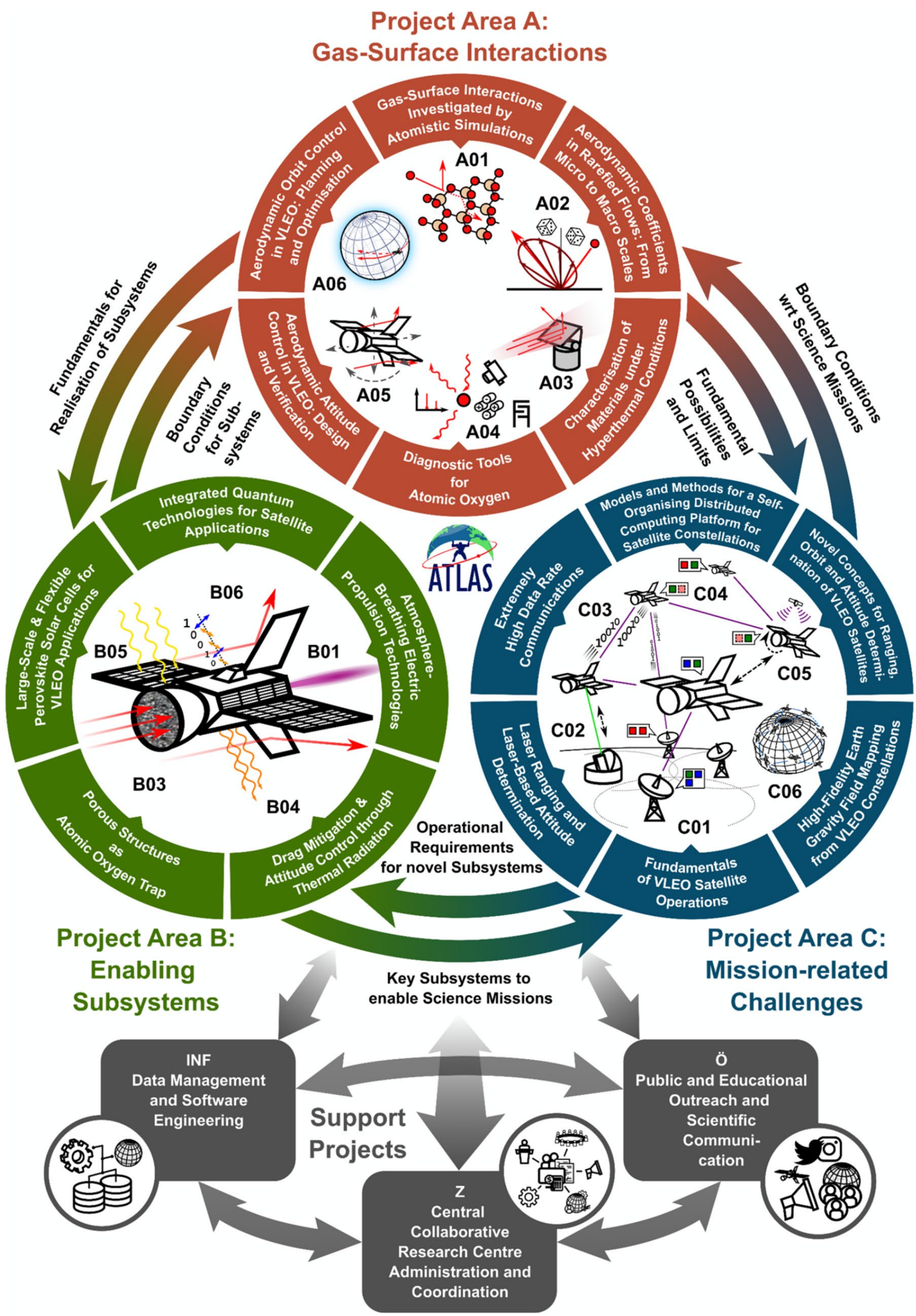


Fig. 8 Overview of the structure of and the interrelations within ATLAS

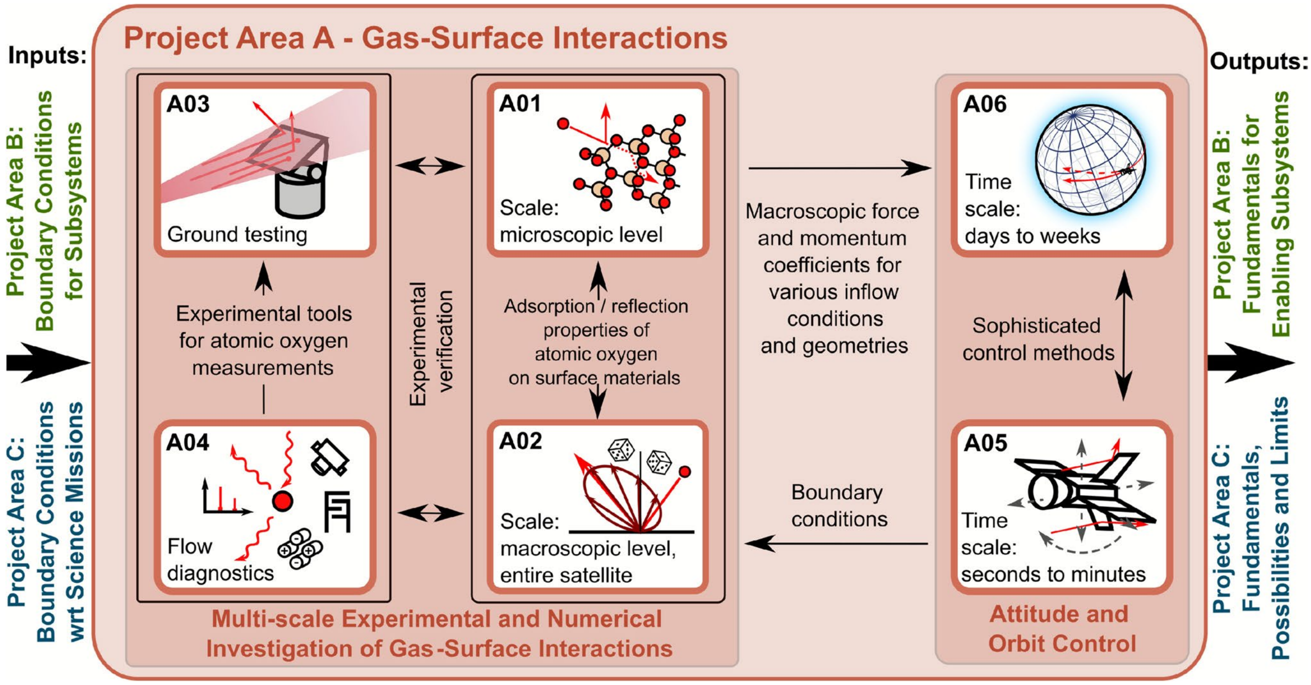


Fig. 9 Overview of Project Area A illustrating project interfaces and sub-clusters

aluminium as a typical structural material, platinum and gold used for the atomic oxygen sensors (A04), and perovskites/silicon dioxide as material/protection for future satellite solar cell arrays (B05).

In subsequent funding periods, Project Area A is planned to expand towards the design of certain beneficial surface properties and configurations, including an assessment of uncertainties in prediction accuracy. Also, the consideration of ionised flow conditions is foreseen, partially including imposed electric surface potentials and active ionisation methods, which would then allow further influencing the aerodynamic coefficients via active plasma flow control by interacting with the ionosphere and magnetic fields.

In summary, Project Area A will deliver the overall methodology, including open-source tools and databases, for the experimental and numerical characterisation of surface materials and functional structures, as well as guidelines for VLEO-capable satellite design configurations.

5.2 Project Area B: enabling technologies

Realising platforms capable of efficient, sustained, controlled and safe VLEO flight requires fundamental technological advances for many spacecraft subsystems. Project Area B focuses, therefore, on solutions with breakthrough potential towards attaining sustainable VLEO utilisation. An overview of the selected projects is given in Fig. 10.

A promising approach for active drag mitigation lies in atmosphere-breathing electric propulsion (ABEP), which directly exploits the residual atmosphere as propellant mass. Based on the development efforts conducted to date, Project B01, therefore, concentrates on the experimental investigation of an entire system with a helicon-mode inductive plasma thruster and a prototype intake. B01 will further define general procedures and provide infrastructure for the experimental investigation of ABEP concepts, linking closely with the planned test facility for atomic oxygen flows and its associated diagnostic tools (A03, A04). Significant improvements concerning intake efficiency are anticipated by the employment of porous structures, which might also be coated with reactive materials to increase the available propellant mass. Project B03 addresses this topic, focussing on the design of adequate porous structures, which raises several research questions on the conceptual and methodological level. Projects B01 and B03 require input from A01 and A02 in terms of detailed gas–surface interactions and themselves provide input to A02, A05 and A06 in terms of spacecraft configurations and thrust levels.

ABEP systems will generate excess heat, which imposes harsher demands on the thermal control system but also provides an additional opportunity for drag mitigation and control of a satellite, as each watt of emitted radiation delivers 3.3 nanonewton of thrust. Project B04 focuses, therefore, on enabling solutions for exploiting both waste heat and solar irradiation through an asymmetric re-emission of the total radiation to support attitude and orbit control strategies, again with close interfaces to Projects A05 and A06. B04 also interacts closely with B05, in which

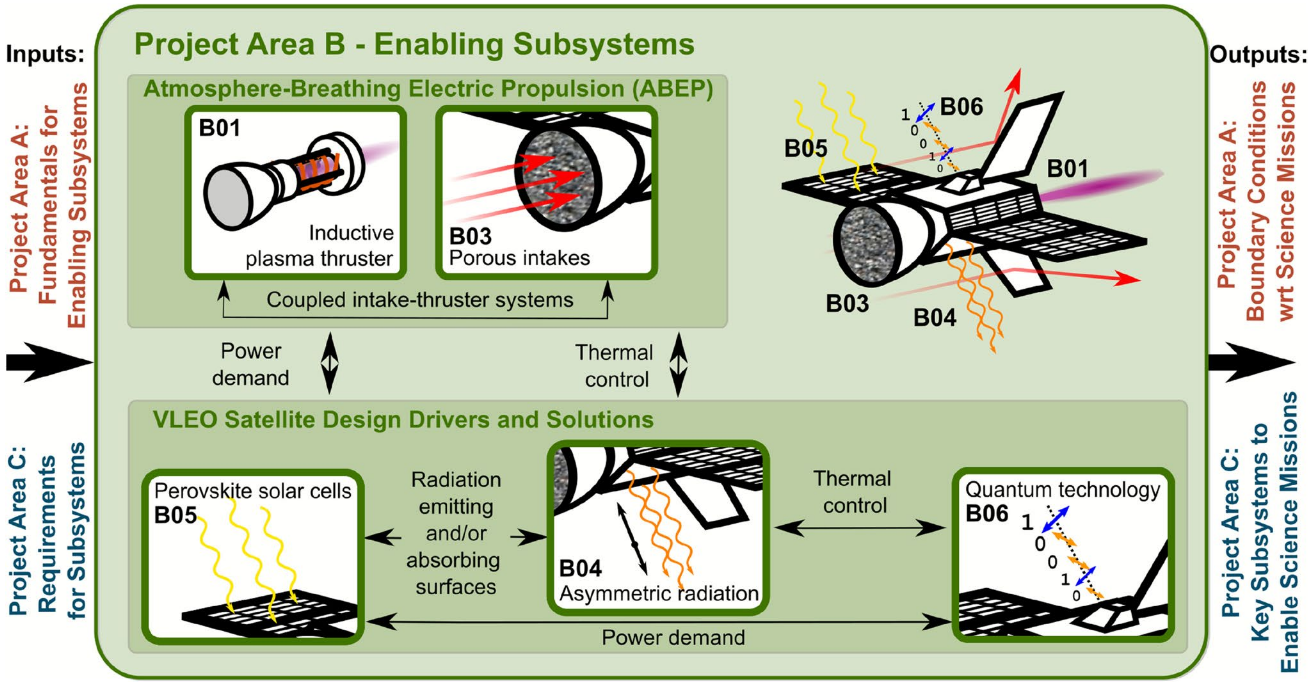


Fig. 10 Overview of Project Area B illustrating project interfaces and sub-clusters

novel, perovskite-based thin-film solar cells are investigated, as they could represent large parts of a heat-emitting and/or solar radiation-absorbing surface. Due to their high efficiency, flexibility and excellent power-to-weight ratio, further permitting direct printing onto a surface from a solution, these thin-film cells are an excellent candidate for VLEO satellites. Accordingly shape-adapted panels could be placed directly on the surface, thus enhancing the aerodynamic properties whilst minimising mass. This significantly increases the design options to be studied and optimised in A02 and A06 and is of significant relevance for all mission-related challenges (Project Area C). On the other hand, however, atomic oxygen resilience must be achieved (e.g. through thin-film aluminium or glass coatings) and an understanding of the relevant gas–surface interactions must be attained (Project Area A). In Project B06, the exploration of the ground-breaking potential of quantum technologies is initiated. The goal is to research key components for the realisation of quantum applications in space, with a special focus on the miniaturisation and shielding requirements associated with VLEO deployment. Project B06 further assumes a technology-oriented perspective by studying miniaturised integrated optics as a key component for a variety of future quantum-based applications. The project will focus on solutions that are satellite-compatible, meaning miniaturisation and optimising payloads will be crucial. The integrated quantum optical components could then be deployed for secure quantum-key-based satellite communication, quantum computing or space-based quantum measurements, which may be assessed in a future funding period, further illustrating the interrelations with Project Area C. The key is to achieve the same functionality that today requires cubic metres (i.e. bulky optics setups) on a scale of cubic millimetres or centimetres.

An important additional connecting element within Project Area B is electrical power demand and management, and the therewith related aspect of thermal control. These have a direct impact on optimisation strategies for satellites in VLEO and vice versa (Project Area C). From the methodical point of view, a close cooperation of Projects A02, A03, B01, and B03 for the application of the open-source particle code "PICLas" is foreseen, which is a parallel high-order three-dimensional PIC-DSMC solver allowing the prediction of rarefied gas and plasma flows under the influence of electromagnetic forces.

In subsequent periods, the investigation of ABEP-related topics could merge into a favoured overall subsystem concept, which will then be explored and optimised thoroughly. Similarly, the investigations on the key elements of power supply, thermal control and integrated optical systems will stepwise evolve towards enabling as precisely as possible the quantitative assessment of subsystems requirements and specifications, and in particular their synergetic potential towards overall system concepts.

In summary, Project Area B will deliver technological approaches directly pursuing sustainable VLEO spacecraft deployment in terms of counteracting drag through passive

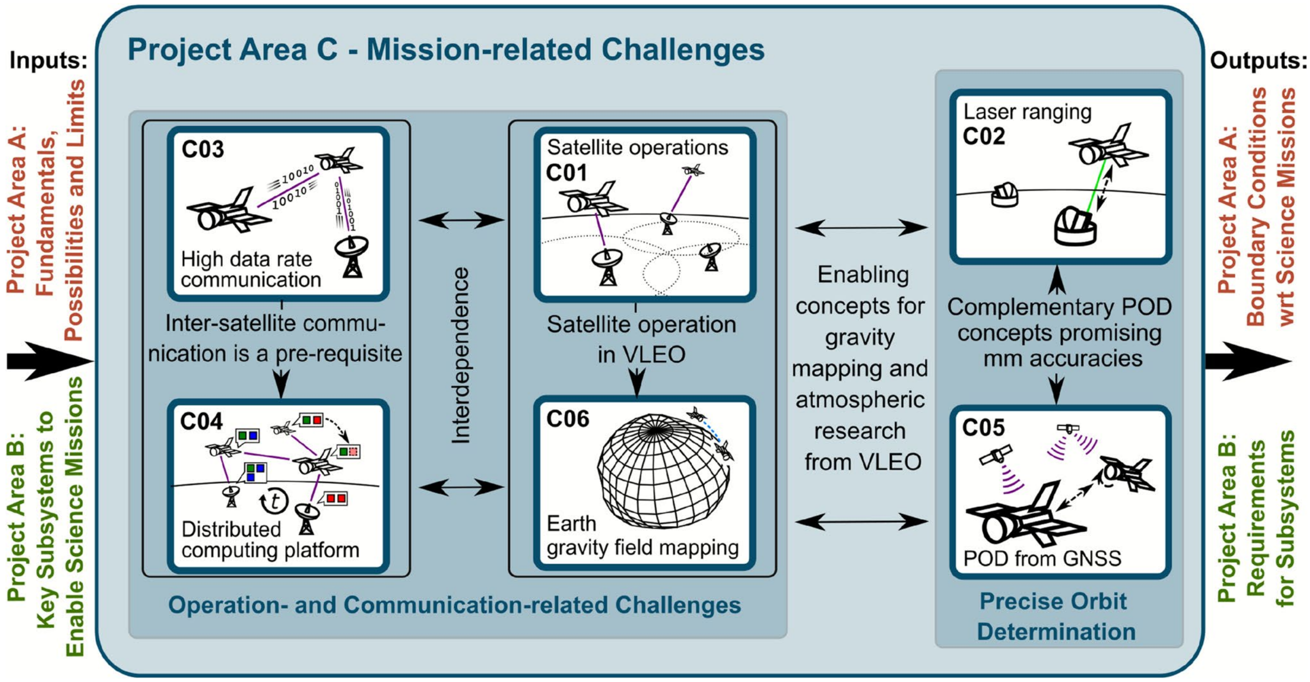


Fig. 11 Overview of Project Area C illustrating project interfaces and sub-clusters

and active measures and simultaneously minimising mass, volume and/or power requirements for the needed subsystems and payloads.

5.3 Project Area C: mission-related challenges

Ultimately, striving towards VLEO flight is justified by the prospect of notably improved or novel application scenarios. Aside from the potential of single satellites or formations, a likely deployment scenario will be that of larger constellations. Whilst bearing the full variety of applications in mind, Project Area C concentrates on the challenges associated with a specific set of utilisation scenarios, namely the investigation of the thermosphere and gravity field, as this exemplarily allows to consider single satellites, formations and even small constellations on a focussed level. An overview of the projects is given in Fig. 11.

VLEO poses a fundamental change compared to traditional LEO for any kind of operations: lower orbits lead to shorter and fewer contact times to ground stations, an increased influence of the atmosphere on attitude and orbit, and subsequently to higher orbit determination, acquisition and tracking efforts. Furthermore, due to the high and unpredictable rates of orbital decay, mission-critical reactions to environmental hazards must occur faster than for conventional satellite missions. Therefore, Project C01 investigates how VLEO spacecraft can be operated, including possible degrees of automation and autonomy for the ground and space segments, such that the mission output is maximised whilst the risk of losing the mission is minimised. To this end, high-precision orbit determination is essential, and the Projects C02 and C05 investigate two new, complementary concepts that promise to achieve accuracies in the range of millimetres, especially if combined, further providing opportunities for attitude determination. Here, C02 investigates ground-based laser systems based on chirp pulse compression of laser radiation in the near-infrared spectral region, whilst C05 assesses the satellite-based synthesis of signals from Global Navigation Satellite Systems (GNSS), i.e. GPS, Galileo, BeiDou, utilising GNSS-like pseudo-random noise code signals on two distinct frequencies.

Considering both the VLEO-specific boundary condition of shorter and fewer contact times to ground stations as well as the communication requirements between satellites, a fast data offload and high data transmission throughput within a brief window of time is essential. The required degree of autonomy further demands deeply integrated, multi-nodal computational capabilities as well as accordingly high data transfer rates. Project C03 advances on this topic by investigating promising, cost- and power-efficient, miniaturised millimetre-wave monolithic integrated circuit technologies for satellite communications in the high millimetre-wave frequency bands (V-, E- and W-band). Extensive inter-satellite communication is a prerequisite for a distributed computing platform, basic concepts of which are investigated in Project C04, which foresees each satellite describing its own architecture, capabilities, computing resources and instruments and sharing this information to create a multi-vehicle distributed computing platform capable of dynamically adapting to changes. An ultra-precise absolute and relative orbit determination of satellites in VLEO, combined with an accurate knowledge of the aerodynamic properties and in situ measurement of the residual atmosphere (with sensors investigated in A04), constitute the ingredients for enabling new gravity mapping mission concepts from VLEO, beyond the classical along-track in-line satellite pair constellation, which is a topic investigated in Project C06. On top of that, ultra-precise absolute and relative orbit and attitude determination, at least during flyovers of ground stations, would allow for an in situ calibration of onboard sensors for atmospheric measurements.

All of the findings in Project Area C have a direct impact on all projects in Project Areas A and B in terms of the definition of requirements and require vice versa input in terms of, e.g. available control authority, power budget, thermal management/control or orbit design.

The goal of the subsequent funding periods, in particular for Project Area C, is to gradually arrive at an overall system view of realistic VLEO-specific satellite applications, though still focussed on atmosphere and gravitational field research missions. Based on the current state of knowledge, it is impossible to judge whether CubeSat-class, medium-sized or large satellites equipped with powerful ABEP systems are best suited for this purpose.

In summary, Project Area C will deliver the boundary conditions and, more importantly, new scenarios for VLEO utilisation focussing on scientific applications. However, its output will be sufficiently broad to illustrate the potential of the overall findings of the CRC ATLAS for future VLEO satellites in general.

6 Academic exchange and public outreach

The fundamental ideas and themes of the CRC ATLAS are considered to exhibit significant potential towards increasing public interest in spaceflight-related and scientific topics in general. Especially as the topic of space debris has found prominent narration and discussion in recent years through various media outlets, even inspiring major blockbuster films, the research programme can be predicted to resonate notably within the general public, as it is also motivated by the desire both to mitigate and to avoid the associated risks. Similar arguments are also valid for the worldwide scientific and academic community. It is, therefore, expected that the CRC ATLAS will result in a very strong interest in academic and educational exchange, especially in an international context. To cover these highly important points adequately, dedicated actions within the supporting Projects Ö, INF, and Z are foreseen for public outreach, research methods and data dissemination, as well as fostering of academic and educational exchanges.

As one of the core actions in Project Ö of the CRC ATLAS, a Satellite Design Workshop (SDW) will be held on an annual basis. The format is motivated by the great success of the “Space Station Design Workshop”, which has been hosted almost annually at the Institute of Space Systems for more than 20 years. In the first funding year, the doctoral researchers within the CRC will be the participants, and in the following years, they will serve as co-organisers/assisting experts of the workshop. For the student participants, half of the planned 30–40 positions will be reserved for applicants from Germany and the other half for worldwide candidates, following an international tender. Over 1 week, the (student) participants will be organised into competitive teams to conduct system and mission design feasibility studies on a representative VLEO satellite project, incorporating the latest results from the individual research activities and utilising accordingly improved and developed analysis tools.

As a measure to focus the activities conducted within the SDW, and to provide a common framework for a regular exchange, synthesis and application of research findings within the CRC ATLAS, a guiding reference mission concept named MEROPE (“Multi satellite Exploratory Research Of Physical Environment in VLEO”) is introduced. Since the potential application areas are extremely broad, the range of scenarios is presently restricted to thermosphere and gravity field research (as also in Project Area C). These areas have already been addressed in past or suggested missions. However, they consistently relied on performance-limited traditional satellite platforms.

The Project INF will ensure that the research data and software originating from the CRC ATLAS follow the FAIR guiding principles (Findable, Accessible, Interoperable and Reusable). By harmonising the handling of data and software, the integration of the results from the individual projects will be standardised and optimised.

The supporting Projects of the CRC ATLAS will conduct further measures to increase the academic exchange and visibility of the topic in the international scientific community. Examples are:

- Organisation of international symposia to foster and enhance cooperation and exchange opportunities. As intended outcomes, the CRC ATLAS will engage with international partners in the preparation of white papers for open research questions.
- Suggestion and organisation of dissemination sessions at national and international conferences.
- Publications on the topic in special issues of peer-reviewed journals.

- Further enhancement of visibility and collaboration with international groups through the establishment of an international scientific advisory group and funding opportunities for postdoctoral researchers/scientists, as well as guest lecturers visiting the CRC ATLAS.
- Collaborations with international partners shall further be advanced via internships of the CRC's doctoral researchers abroad.
- Implementation of public and educational outreach strategies for the CRC ATLAS, including various social network platforms. Planning and organising public exhibitions of activities and findings in appropriate venues.

7 Summary

The Collaborative Research Centre (CRC) 1667 "Advancing Technologies of Very Low Altitude Satellites (ATLAS)" addresses the fundamental scientific and engineering challenges of rendering Very Low Earth Orbit (VLEO, about 200 km to 450 km altitude) accessible. These orbits are particularly beneficial for indispensable satellite services of our modern knowledge, information and communication society. In addition, access to VLEO offers the opportunity to operate satellites without exposure or contribution to the increasing contamination of traditional orbits with space debris.

Attaining sustained and economically viable VLEO flight is challenging due to the unique environmental properties of the lower thermosphere. This is most notably the significant, barely predictable, and dynamically changing drag, which leads to a rapid deterioration of any spacecraft's orbit unless mitigated by a combination of active and passive techniques. Thus, the various advantages of VLEO, including its self-cleaning effect through the residual atmosphere, are to date offset by a prohibitively short operational lifetime. The leading research question of the CRC ATLAS is therefore: how can the lifetime of a satellite in VLEO be increased by at least one order of magnitude without the necessity of large amounts of fuel carried or resupplied continuously from Earth?

To answer this question, an advanced understanding of the interactions between rarefied high-energy flows and functional surfaces, innovations for collecting and utilising the residual atmosphere and novel concepts for designing and operating satellites in these conditions are essential. Within the CRC ATLAS, the basic principles and resulting technological concepts exploiting these findings and ultimately enabling VLEO utilisation will be investigated, established and verified. The scientific potentials of individual satellites, formations and constellations operating in this dynamic environment are explored simultaneously, aligned to a multi-faceted reference mission scenario. The research programme is characterised by strong interdependencies and necessitates an intensive cooperation between various engineering disciplines that builds on the joint insight of processes at and across their interfaces to fully leverage synergies. A strategic goal is to position the University of Stuttgart as an important contributor to this rapidly evolving international research topic. The long-term scientific goal is to provide the spaceflight community with core elements in terms of methodology and technology to facilitate reliable studies and the development of concrete mission scenarios in VLEO.

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Author contribution S.F., A.S.P. and C.T. wrote the main manuscript text and prepared the figures. All authors (i.e. project leaders of the CRC with A.S.P. and C.T. acting as supporting researchers) made substantial contributions to the conception of the CRC 1667 ATLAS.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interests Non-financial interests: S. F. and G.H. are acting as members of the editorial board of the Special Issue "Very Low Earth Orbit Satellites" of the CEAS Space Journal.

References

1. *Collaborative Research Centres.* [Online]. Available: https://www.dfg.de/en/research-funding/funding-opportunities/programmes/coordinated-programmes/collaborative-research-centres (accessed: Dec. 15 2024).

2. Maloney, C.M., Portmann, R.W., Ross, M.N., Rosenlof, K.H.: The climate and ozone impacts of black carbon emissions from global rocket launches. J. Geophys. Res. Atmos. (2022). https://doi.org/10.1029/2021JD036373
3. Ryan, R.G., Marais, E.A., Balhatchet, C.J., Eastham, S.D.: Impact of rocket launch and space debris air pollutant emissions on stratospheric ozone and global climate. Earths Future (2022). https://doi.org/10.1029/2021EF002612
4. Jain, A.K., Hastings, D.E.: Global Climate Effect from Space Debris Reentry: Engineering and Policy Implications. J. Spacecr. Rocket. (2024). https://doi.org/10.2514/1.A36069
5. Ferreira, J.P., Huang, Z., Nomura, K., Wang, J.: Potential ozone depletion from satellite demise during atmospheric reentry in the era of mega-constellations. Geophys. Res. Lett. (2024). https://doi.org/10.1029/2024GL109280
6. Murphy, D.M., et al.: Metals from spacecraft reentry in stratospheric aerosol particles. Proc. Natl. Acad. Sci. U. S. A. **120**(43), e2313374120 (2023). https://doi.org/10.1073/pnas.2313374120
7. World Meteorological Organization (WMO), "Scientific Assessment of Ozone Depletion: 2022: GAW Report No. 278," 2022.
8. Kessler, D.J., Cour-Palais, B.G.: Collision frequency of artificial satellites: the creation of a debris belt. J. Geophys. Res. **83**(A6), 2637 (1978). https://doi.org/10.1029/JA083iA06p02637
9. Crisp, N.H., et al.: The benefits of very low earth orbit for earth observation missions. Prog. Aerosp. Sci. **117**, 100619 (2020). https://doi.org/10.1016/j.paerosci.2020.100619
10. Vallado, D.A., Finkleman, D.: A critical assessment of satellite drag and atmospheric density modeling. Acta Astronaut. **95**, 141–165 (2014). https://doi.org/10.1016/j.actaastro.2013.10.005
11. Doornbos, E.: Thermospheric density and wind determination from satellite dynamics. Springer Berlin Heidelberg, Berlin, Heidelberg (2012)
12. Bruinsma, S., Sutton, E., Solomon, S.C., Fuller-Rowell, T., Fedrizzi, M.: Space weather modeling capabilities assessment: neutral density for orbit determination at low Earth orbit. Space Weather **16**(11), 1806–1816 (2018). https://doi.org/10.1029/2018SW002027
13. Bruinsma, S., Boniface, C., Sutton, E.K., Fedrizzi, M.: Thermosphere modeling capabilities assessment: geomagnetic storms. J. Space Weather Space Clim. **11**, 12 (2021). https://doi.org/10.1051/swsc/2021002
14. Bruinsma, S., et al.: Thermosphere and satellite drag. Adv. Space Res. (2023). https://doi.org/10.1016/j.asr.2023.05.011
15. Holmes, B.E., Oiko, V.T., Roberts, P.C.: A review of satellite-based atomic oxygen sensing methods. Prog. Aerosp. Sci. **137**, 100886 (2023). https://doi.org/10.1016/j.paerosci.2023.100886
16. Rapisarda, C.: Modelling and simulation of atmosphere-breathing electric propulsion intakes via direct simulation Monte Carlo. CEAS Space J. **15**(2), 357–370 (2023). https://doi.org/10.1007/s12567-021-00414-z
17. Macario-Rojas, A., Smith, K.L., Crisp, N.H., Roberts, P.: Atmospheric interaction with nanosatellites from observed orbital decay. Adv. Space Res. **61**(12), 2972–2982 (2018). https://doi.org/10.1016/j.asr.2018.02.022
18. S. Livadiotti, "Application of orbital aerodynamics to satellite attitude control," Dissertation, The University of Manchester, Manchester, UK, 2021.
19. D. Mostaza-Prieto, "Characterisation and application of aerodynamic torques on satellites," Dissertation, The University of Manchester, Manchester, UK, 2017.
20. Schonherr, T., Komurasaki, K., Romano, F., Massuti-Ballester, B., Herdrich, G.: Analysis of atmosphere-breathing electric propulsion. IEEE Trans. Plasma Sci. **43**(1), 287–294 (2015). https://doi.org/10.1109/TPS.2014.2364053
21. Shoda, K., et al.: Anisotropic molecular scattering at microstructured surface for rarefied gas compression inside air breathing ion engine. CEAS Space J. **15**(3), 403–411 (2023). https://doi.org/10.1007/s12567-022-00430-7
22. Y. Ito, M. Nakano, T. Schonherr, S. Cho, K. Komurasaki, and H. Koizumi, "In-space transportation of a solar power satellite using a hall thruster propulsion system," in *2012 International Conference on Renewable Energy Research and Applications (ICRERA)*, Nagasaki, Japan, 2012, pp. 1–6.
23. Minton, T.K., Schwartzentruber, T.E., Xu, C.: On the utility of coated POSS-polyimides for vehicles in very low Earth orbit. ACS Appl. Mater. Interfaces **13**(43), 51673–51684 (2021). https://doi.org/10.1021/acsami.1c14196
24. Wright, J.S., Jones, A., Farmer, B., Rodman, D.L., Minton, T.K.: POSS-enhanced colorless organic/inorganic nanocomposite (CORIN®) for atomic oxygen resistance in low earth orbit. CEAS Space J. **13**(3), 399–413 (2021). https://doi.org/10.1007/s12567-021-00347-7
25. Berger, T.E., et al.: The thermosphere is a drag: the 2022 Starlink incident and the threat of geomagnetic storms to low Earth orbit space operations. Space Weather (2023). https://doi.org/10.1029/2022sw003330
26. Laskar, F.I., et al.: Thermospheric temperature and density variability during 3–4 February 2022 minor geomagnetic storm. Space Weather (2023). https://doi.org/10.1029/2022sw003349
27. H. Yanikomeroglu, "Wireless Access Architecture: The Next 20+ Years," in *The 4th International Conference on Future Networks and Distributed Systems (ICFNDS)*, St.Petersburg Russian Federation, 2020, p. 1.
28. Chaudhry, A.U., Yanikomeroglu, H.: Laser intersatellite links in a Starlink constellation: a classification and analysis. IEEE Veh. Technol. Mag. **16**(2), 48–56 (2021). https://doi.org/10.1109/mvt.2021.3063706
29. Chaudhry, A.U., Yanikomeroglu, H.: Free space optics for next-generation satellite networks. IEEE Consum. Electron. Mag. **10**(6), 21–31 (2021). https://doi.org/10.1109/mce.2020.3029772
30. A. U. Chaudhry and H. Yanikomeroglu, "On Crossover Distance for Optical Wireless Satellite Networks and Optical Fiber Terrestrial Networks," in *2022 IEEE Future Networks World Forum (FNWF)*, Montreal, QC, Canada, 2022, pp. 480–485.
31. Chaudhry, A.U., Yanikomeroglu, H.: Optical Wireless Satellite Networks versus Optical Fiber Terrestrial Networks: The Latency Perspective. In: Nguyen, H., Le, L., Yahampath, P., Mohamed, E.B. (eds.) Signals and Communication Technology, 30th Biennial Symposium on Communications 2021, pp. 225–234. Springer International Publishing, Cham (2022)
32. Kuiper, H., Dolkens, D.: A cutting edge 6U CubeSat ADCS design for Earth observation with sub-meter spatial resolution at 230–380 km altitude. CEAS Space J. **12**(4), 613–621 (2020). https://doi.org/10.1007/s12567-020-00323-7
33. Garcia, R.F., Doornbos, E., Bruinsma, S., Hebert, H.: Atmospheric gravity waves due to the Tohoku-Oki tsunami observed in the thermosphere by GOCE. J. Geophys. Res. Atmos. **119**(8), 4498–4506 (2014). https://doi.org/10.1002/2013jd021120
34. Garcia, R.F., Bruinsma, S., Lognonné, P., Doornbos, E., Cachoux, F.: GOCE: the first seismometer in orbit around the Earth. Geophys. Res. Lett. **40**(5), 1015–1020 (2013). https://doi.org/10.1002/grl.50205
35. Sarris, T.E., et al.: Daedalus MASE (mission assessment through simulation exercise): a toolset for analysis of in situ missions and for processing global circulation model outputs in the lower thermosphere-ionosphere. Front. Astron. Space Sci. (2023). https://doi.org/10.3389/fspas.2022.1048318
36. Jiang, Y., Zhang, J., Tian, P., Liang, T., Li, Z., Wen, D.: Aerodynamic drag analysis and reduction strategy for satellites in very low Earth orbit. Aerosp. Sci. Technol. **132**, 108077 (2023). https://doi.org/10.1016/j.ast.2022.108077

37. Pei, W.: Staring imaging attitude tracking control laws for video satellites based on image information by hyperbolic tangent fuzzy sliding mode control. Comput. Intell. Neurosci. **2022**, 8289934 (2022). https://doi.org/10.1155/2022/8289934
38. Wu, J., Zheng, P., Zhang, Y., Tang, H.: Recent development of intake devices for atmosphere-breathing electric propulsion system. Prog. Aerosp. Sci. **133**, 100848 (2022). https://doi.org/10.1016/j.paerosci.2022.100848
39. Gao, X., Li, Z., Chen, Q., Ding, Di., Peng, A.: Prediction of orbit decay for large-scale spacecraft considering rarefied aerodynamic perturbation effects. Int. J. Aerosp. Eng. **2022**, 1–13 (2022). https://doi.org/10.1155/2022/8984056
40. Liang, T., Nie, K., Li, Q., Zhang, J.: Advanced analytical model for orbital aerodynamic prediction in LEO. Adv. Space Res. **71**(1), 507–524 (2023). https://doi.org/10.1016/j.asr.2022.09.005
41. L. Chen, H. Gui, and S. Xiao, "Aerodynamic Attitude Control of Ultra-low Earth Orbit Satellite," in *International Conference on Guidance, Navigation and Control*, Tianjin, China, 2022, pp. 5898–5908.
42. K. D. Atherton, "DARPA wants to push the boundaries of where satellites can fly," *Popular Science*, 01 Feb., 2023. https://www.popsci.com/technology/darpa-project-daedalus-satellites/ (accessed: Apr. 23 2023).
43. *Otter.* [Online]. Available: https://www.darpa.mil/research/programs/otter (accessed: Dec. 26 2024).
44. *ESA seeks space applications ideas in Very Low Earth Orbit.* [Online]. Available: https://www.esa.int/Enabling_Support/Preparing_for_the_Future/Discovery_and_Preparation/ESA_seeks_space_applications_ideas_in_Very_Low_Earth_Orbit (accessed: Dec. 26 2024).
45. A. Jones, "China's CASIC to begin launching VLEO satellites in December," *SpaceNews*, 24 Jul., 2023. https://spacenews.com/chinas-casic-to-begin-launching-vleo-satellites-in-december/ (accessed: Dec. 26 2024).
46. C. Henry, "SpaceX seeks FCC permission for operating all first-gen Starlink in lower orbit," *SpaceNews*, 21 Apr., 2020. https://spacenews.com/spacex-seeks-fcc-permission-for-operating-all-first-gen-starlink-in-lower-orbit/ (accessed: Apr. 23 2023).
47. Dr. T.S. Kelso, "Analysis of the Iridium 33-Cosmos 2251 Collision," in *19th AIAA/AAS Astrodynamics Specialist Conference*, Pittsburgh, PA, USA, 2009. Accessed: Apr. 23 2023. [Online]. Available: https://celestrak.org/publications/AAS/09-368/AAS-09-368.pdf
48. Bonnal, C., Ruault, J.-M., Desjean, M.-C.: Active debris removal: recent progress and current trends. Acta Astronaut. **85**, 51–60 (2013). https://doi.org/10.1016/j.actaastro.2012.11.009
49. Ledkov, A., Aslanov, V.: Review of contact and contactless active space debris removal approaches. Prog. Aerosp. Sci. **134**, 100858 (2022). https://doi.org/10.1016/j.paerosci.2022.100858
50. Shan, M., Guo, J., Gill, E.: Review and comparison of active space debris capturing and removal methods. Prog. Aerosp. Sci. **80**, 18–32 (2016). https://doi.org/10.1016/j.paerosci.2015.11.001
51. Svotina, V.V., Cherkasova, M.: Space debris removal – review of technologies and techniques. Flexible or virtual connection between space debris and service spacecraft. Acta Astronaut. **204**, 840–853 (2023). https://doi.org/10.1016/j.actaastro.2022.09.027
52. Zhang, W., Li, F., Li, J., Cheng, Q.: Review of on-orbit robotic arm active debris capture removal methods. Aerospace **10**(1), 13 (2023). https://doi.org/10.3390/aerospace10010013
53. Zhao, P., Liu, J., Wu, C.: Survey on research and development of on-orbit active debris removal methods. Sci. China Technol. Sci. **63**(11), 2188–2210 (2020). https://doi.org/10.1007/s11431-020-1661-7
54. Mark, C.P., Kamath, S.: Review of active space debris removal methods. Space Policy **47**, 194–206 (2019). https://doi.org/10.1016/j.spacepol.2018.12.005
55. T. S. Kelso, *CelesTrak: SOCRATES Plus.* [Online]. Available: https://celestrak.org/SOCRATES (accessed: May 31 2023).
56. Le May, S., Gehly, S., Carter, B.A., Flegel, S.: Space debris collision probability analysis for proposed global broadband constellations. Acta Astronaut. **151**, 445–455 (2018). https://doi.org/10.1016/j.actaastro.2018.06.036
57. Bastida Virgili, B., et al.: Risk to space sustainability from large constellations of satellites. Acta Astronaut. **126**, 154–162 (2016). https://doi.org/10.1016/j.actaastro.2016.03.034
58. Federal Communications Commission, *FCC Adopts New '5-Year Rule' for Deorbiting Satellites.* [Online]. Available: https://www.fcc.gov/document/fcc-adopts-new-5-year-rule-deorbiting-satellites (accessed: Apr. 23 2023).
59. E. Howell, "How often does the International Space Station have to dodge space debris?," *Space*, 13 Mar., 2023. https://www.space.com/international-space-station-space-dodge-debris-how-often (accessed: Apr. 23 2023).
60. B. Tingley, "International Space Station fires thrusters to dodge space junk," *Space*, 14 Mar., 2023. https://www.space.com/international-space-station-dodge-space-junk-march-2023 (accessed: Apr. 23 2023).
61. E. Messerschmid and R. Bertrand, *Space Stations: Systems and Utilization,* 1st ed. Berlin, Heidelberg: Springer Berlin / Heidelberg, 1999. [Online]. Available: https://ebookcentral.proquest.com/lib/kxp/detail.action?docID=3098309
62. C. Steiger, J. Piñeiro, and P. P. Emanuelli, "Operating GOCE, the European Space Agency's Low-flying Gravity Mission," in *SpaceOps 2010 Conference: Huntsville, Alabama, USA, 25 - 30 April 2010*, Huntsville, Alabama, 2010.
63. C. Steiger, "Evolution of Flight Operations for ESA's Gravity Mission GOCE," in *SpaceOps 2012 Conference*, Stockholm, Sweden, 06112012.
64. Wallace, N., Jameson, P., Saunders, C., Fehringer, M., Edwards, C., Floberghagen, R.: "The GOCE Ion Propulsion Assembly -Lessons Learnt from the First 22 Months of Flight Operations," IEPC-2011-327, 32nd International Electric Propulsion Conference. Germany, Wiesbaden (2011)
65. C. Steiger, M. Romanazzo, P. P. Emanuelli, R. Floberghagen, and M. Fehringer, "The Deorbiting of ESA's Gravity Mission GOCE - Spacecraft Operations in Extreme Drag Conditions," in *13th International Conference on Space Operations (SpaceOps 2014): Pasadena, California, USA, 5 - 9 May 2014*, Pasadena, CA, 2014.
66. L. Dell'Elce, "Satellite Orbits in the Atmosphere: Uncertainty Quantification, Propagation and Optimal Control," Dissertation, Université de Liège, Liège, Belgium, 2015. [Online]. Available: https://orbi.uliege.be/handle/2268/180705
67. H. Kawasaki, K. Konoue, H. Hoshino, Y. Kaneko, and M. Sasaki, "Interim Report of Super Low Altitude Satellite Operation," in *IGARSS 2018 - 2018 IEEE International Geoscience and Remote Sensing Symposium*, 2018, pp. 4066–4069.
68. Andreussi, T., Ferrato, E., Giannetti, V.: A review of air-breathing electric propulsion: from mission studies to technology verification. J. Electr. Propuls. **1**(1), 1–57 (2022). https://doi.org/10.1007/s44205-022-00024-9. (**(in En;en)**)
69. K. Nishiyama, "Air Breathing Ion Engine Concept," in *54th International Astronautical Congress of the International Astronautical Federation, the International Academy of Astronautics, and the International Institute of Space Law*, Bremen, Germany, 09292003.
70. K. Hohman, Principal Investigator, and Tech Circle, "Atmosphere breathing electric thruster for planetary exploration," 2012.

[Online]. Available: https://www.semanticscholar.org/paper/ATMOSPHERIC-BREATHING-ELECTRIC-THRUSTER-FOR-Hohman-Investigator/35d5bc275c5ba4149d33a07e647a8ec739be2bcc
71. D. Di Cara *et al.,* "RAM Electric Propulsion for Low Earth Orbit Operation: an ESA study," *IEPC-2007–162, The 30th International Electric Propulsion Conference, Florence, Italy*, 2007.
72. K. Diamant, "A 2-Stage Cylindrical Hall Thruster for Air Breathing Electric Propulsion," in *46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit: 25 July 2010 - 28 July 2010, Nashville, TN*, Nashville, TN, 2010.
73. T. Andreussi *et al.,* "Development Status and Way Forward of SITAEL's Air-breathing Electric Propulsion Engine," in *2019 AIAA/IEEE Electric Aircraft Technologies Symposium (EATS)*, Indianapolis, IN, 2019.
74. K. Diamant, "Microwave Cathode for Air Breathing Electric Propulsion," *31st Int. Electric Propulsion Conference*, 2009. [Online]. Available: https://www.semanticscholar.org/paper/Microwave-Cathode-for-Air-Breathing-Electric-Diamant/200911d5694482ddde62fdc286847d5f48d83830
75. *DISCOVERER Project Homepage.* [Online]. Available: https://discoverer.space/ (accessed: Apr. 23 2023).
76. S. Rodriguez-Donaire *et al.,* "Earth Observation Technologies: Low-End-Market Disruptive Innovation," in *Satellites Missions and Technologies for Geosciences*, V. Demyanov and J. Becedas, Eds.: IntechOpen, 2020.
77. Roberts, P.C.E.: "1st symposium of very low Earth orbit missions and technologies," (in En;en). CEAS Space J. **14**(4), 605–608 (2022). https://doi.org/10.1007/s12567-022-00466-9
78. Berthoud, L., et al.: "Are very low Earth orbit (VLEO) satellites a solution for tomorrow's telecommunication needs?," (in En;en). CEAS Space J. **14**(4), 609–623 (2022). https://doi.org/10.1007/s12567-022-00437-0
79. McGrath, C., Lowe, C., Macdonald, M., Hancock, S.: "Investigation of very low Earth orbits (VLEOs) for global spaceborne lidar," (in En;en). CEAS Space J. **14**(4), 625–636 (2022). https://doi.org/10.1007/s12567-022-00427-2
80. Siemes, C., et al.: "CASPA-ADM: a mission concept for observing thermospheric mass density," (in En;en). CEAS Space J. **14**(4), 637–653 (2022). https://doi.org/10.1007/s12567-021-00412-1
81. Crisp, N.H., et al.: "A method for the experimental characterisation of novel drag-reducing materials for very low Earth orbits using the Satellite for Orbital Aerodynamics Research (SOAR) mission," (in En;en). CEAS Space J. **14**(4), 655–674 (2022). https://doi.org/10.1007/s12567-022-00434-3
82. Reddy, S., et al.: "CubeSat measurements of thermospheric plasma: spacecraft charging effects on a plasma analyzer," (in En;en). CEAS Space J. **14**(4), 675–687 (2022). https://doi.org/10.1007/s12567-022-00439-y
83. Vaidya, S., et al.: "Development and analysis of novel mission scenarios based on Atmosphere-Breathing Electric Propulsion (ABEP)," (in En;en). CEAS Space J. **14**(4), 689–706 (2022). https://doi.org/10.1007/s12567-022-00436-1
84. Andreussi, T., et al.: "The AETHER project: development of air-breathing electric propulsion for VLEO missions," (in En;en). CEAS Space J. **14**(4), 717–740 (2022). https://doi.org/10.1007/s12567-022-00442-3
85. Obrusnik, A., et al.: "Simulation-guided engineering of an air-breathing electric propulsion concept," (in En;en). CEAS Space J. **14**(4), 741–747 (2022). https://doi.org/10.1007/s12567-022-00445-0
86. Miya, Y., Nishiyama, K.: "Performance evaluation of a plasma generator and ion optics for air-breathing ion engine," (in En;en). CEAS Space J. **14**(4), 749–755 (2022). https://doi.org/10.1007/s12567-022-00422-7
87. Tagawa, M., et al.: "Laser-detonation hyperthermal beam source applicable to VLEO environmental simulations," (in En;en). CEAS Space J. **14**(4), 757–765 (2022). https://doi.org/10.1007/s12567-021-00399-9
88. Rodriguez-Donaire, S., et al.: "Strategic similarities between earth observation small satellite constellations in very low earth orbit and low-cost carriers by means of strategy canvas," (in En;en). CEAS Space J. **14**(4), 767–784 (2022). https://doi.org/10.1007/s12567-022-00462-z
89. Rodriguez-Donaire, S., et al.: "Business roadmap for the European Union in the NewSpace ecosystem: a case study for access to space," (in En;en). CEAS Space J. **14**(4), 785–804 (2022). https://doi.org/10.1007/s12567-022-00450-3
90. Romano, F., et al.: "Design of an intake and a thruster for an atmosphere-breathing electric propulsion system," (in En;en). CEAS Space J. **14**(4), 707–715 (2022). https://doi.org/10.1007/s12567-022-00452-1
91. Maier, P., et al.: "System Study of a VLEO Satellite Platform applied with the Electrodeless IRS IPT System," in *8th Edition of the Space Propulsion Conference (SPC)*. Estoril, Portugal (2022)
92. G. H. Herdrich *et al.,* "Platform and system design study of a VLEO satellite platform using the IRS RF Helicon-based Plasma Thruster (Keynote)," in *International Astronatical Congress*, Paris, France, 2022. [Online]. Available: https://www.researchgate.net/publication/364070339_Platform_and_system_design_study_of_a_VLEO_satellite_platform_using_the_IRS_RF_Helicon-based_Plasma_Thruster_Keynote
93. https://aether-h2020.eu. [Online]. Available: https://aether-h2020.eu/ (accessed: Apr. 23 2023).
94. Mostaza Prieto, D., Graziano, B.P., Roberts, P.C.: Spacecraft drag modelling. Prog. Aerosp. Sci. **64**, 56–65 (2014). https://doi.org/10.1016/j.paerosci.2013.09.001
95. Livadiotti, S., et al.: A review of gas-surface interaction models for orbital aerodynamics applications. Prog. Aerosp. Sci. **119**, 100675 (2020). https://doi.org/10.1016/j.paerosci.2020.100675
96. Hild, F., Traub, C., Pfeiffer, M., Beyer, J., Fasoulas, S.: Optimisation of satellite geometries in Very Low Earth Orbits for drag minimisation and lifetime extension. Acta Astronaut. **201**, 340–352 (2022). https://doi.org/10.1016/j.actaastro.2022.09.032
97. Deutsches Geoforschungszentrum Potsdam, *CHAMP – CHAllenging Minisatellite Payload.* [Online]. Available: https://www.gfz-potsdam.de/champ/ (accessed: Apr. 23 2023).
98. Deutsches Geoforschungszentrum Potsdam, *Gravity Recovery and Climate Experiment (GRACE) Mission.* [Online]. Available: https://www.gfz-potsdam.de/grace (accessed: Apr. 23 2023).
99. Deutsches Geoforschungszentrum Potsdam, *Gravity Recovery and Climate Experiment-Follow-On (GRACE-FO) Mission.* [Online]. Available: https://www.gfz-potsdam.de/sektion/globales-geomonitoring-und-schwerefeld/projekte/gravity-recovery-and-climate-experiment-follow-on-grace-fo-mission (accessed: Apr. 23 2023).
100. Haagmans, R., Siemes, C., Massotti, L., Carraz, O., Silvestrin, P.: ESA's next-generation gravity mission concepts. Rend. Fis. Acc. Lincei **31**(S1), 15–25 (2020). https://doi.org/10.1007/s12210-020-00875-0. (**(in En;en)**)
101. CRC 1464 Homepage, *CRC 1464: TerraQ – Relativistic and Quantum-based Geodesy.* [Online]. Available: https://www.terraq.uni-hannover.de/en/
102. Sarris, T.E., et al.: Daedalus: a low-flying spacecraft for in situ exploration of the lower thermosphere–ionosphere. Geosci. Instrum. Method. Data Syst. **9**(1), 153–191 (2020). https://doi.org/10.5194/gi-9-153-2020
103. M. G. Mlynczak, J. Yue, J. McCormack, R. S. Liebermann, N. J. Livesey, "An Observational Gap at the Edge of Space," *American Geophysical Union*, 05 Mar., 2021. https://eos.org/opinions/an-observational-gap-at-the-edge-of-space (accessed: Apr. 23 2023).

104. Garcia, R.R., Yue, J., Russell, J.M.: Middle atmosphere temperature trends in the twentieth and twenty-first centuries simulated with the Whole Atmosphere Community Climate Model (WACCM). JGR Space Phys. **124**(10), 7984–7993 (2019). https://doi.org/10.1029/2019JA026909
105. Roble, R.G., Dickinson, R.E.: How will changes in carbon dioxide and methane modify the mean structure of the mesosphere and thermosphere? Geophys. Res. Lett. **16**(12), 1441–1444 (1989). https://doi.org/10.1029/GL016i012p01441
106. Solomon, S.C., Liu, H.-L., Marsh, D.R., McInerney, J.M., Qian, L., Vitt, F.M.: Whole atmosphere climate change: dependence on solar activity. JGR Space Phys. **124**(5), 3799–3809 (2019). https://doi.org/10.1029/2019JA026678
107. McCormack, J., et al.: Comparison of mesospheric winds from a high-altitude meteorological analysis system and meteor radar observations during the boreal winters of 2009–2010 and 2012–2013. J. Atmos. Solar-Terr. Phys. **154**, 132–166 (2017). https://doi.org/10.1016/j.jastp.2016.12.007
108. Pedatella, N.M., Liu, H.-L., Marsh, D.R., Raeder, K., Anderson, J.L.: Error growth in the mesosphere and lower thermosphere based on hindcast experiments in a whole atmosphere model. Space Weather **17**(10), 1442–1460 (2019). https://doi.org/10.1029/2019SW002221
109. Emmert, J.T.: Altitude and solar activity dependence of 1967–2005 thermospheric density trends derived from orbital drag. JGR Space Physics **120**(4), 2940–2950 (2015). https://doi.org/10.1002/2015JA021047
110. Mlynczak, M.G., Solomon, S.: A detailed evaluation of the heating efficiency in the middle atmosphere. J. Geophys. Res. **98**(D6), 10517 (1993). https://doi.org/10.1029/93JD00315
111. Mlynczak, M.G., et al.: Space-based sentinels for measurement of infrared cooling in the thermosphere for space weather nowcasting and forecasting. Space Weather **16**(4), 363–375 (2018). https://doi.org/10.1002/2017SW001757
112. D. J. Fitzpatrick, E. Bauch, R. Agarwal, and S. E. Palo, "Maximizing Mission Utility within Operational Constraints for the SWARM-EX CubeSat Mission," in *AIAA SCITECH 2022 Forum*, San Diego, CA & Virtual, 2022.
113. Palmroth, M., et al.: Lower-thermosphere–ionosphere (LTI) quantities: current status of measuring techniques and models. Ann. Geophys. **39**(1), 189–237 (2021). https://doi.org/10.5194/angeo-39-189-2021
114. B. Yost and S. Weston, *Small Spacecraft Technology: State-of-the-Art.* [Online]. Available: https://www.nasa.gov/sites/default/files/atoms/files/2022_soa_full_0.pdf
115. VanSant, K.T., et al.: Combined stress testing of perovskite solar cells for stable operation in space. ACS Appl. Energy Mater. (2023). https://doi.org/10.1021/acsaem.2c03972
116. Shi, S., Tian, L., Wang, Y., Zheng, Y., Xie, C., Peng, K.: Demonstration of channel multiplexing quantum communication exploiting entangled sideband modes. Phys. Rev. Lett. **125**(7), 70502 (2020). https://doi.org/10.1103/PhysRevLett.125.070502
117. Belenchia, A., et al.: Quantum physics in space. Phys. Rep. **951**, 1–70 (2022). https://doi.org/10.1016/j.physrep.2021.11.004
118. T. Jennewein *et al.,* "QEYSSat 2.0 -- White Paper on Satellite-based Quantum Communication Missions in Canada," Jun. 2023. [Online]. Available: https://arxiv.org/pdf/2306.02481
119. Waswa, P.M., Elliot, M., Hoffman, J.A.: Spacecraft design-for-demise implementation strategy & decision-making methodology for low earth orbit missions. Adv. Space Res. **51**(9), 1627–1637 (2013). https://doi.org/10.1016/j.asr.2012.11.020
120. Pagan, A.S., Herdrich, G.: Key parameters governing the ground risk from reentering pressure vessel debris. J Space Safety Eng **9**(2), 189–200 (2022). https://doi.org/10.1016/j.jsse.2022.04.002
121. Lemmens, S., Funke, Q., Krag, H.: On-ground casualty risk reduction by structural design for demise. Adv. Space Res. **55**(11), 2592–2606 (2015). https://doi.org/10.1016/j.asr.2015.02.017
122. Traub, C., et al.: "On the exploitation of differential aerodynamic lift and drag as a means to control satellite formation flight," (in En;en). CEAS Space J. **12**(1), 15–32 (2020). https://doi.org/10.1007/s12567-019-00254-y
123. Romano, F., et al.: Intake design for an atmosphere-breathing electric propulsion system (ABEP). Acta Astronaut. **187**, 225–235 (2021). https://doi.org/10.1016/j.actaastro.2021.06.033
124. Romano, F., et al.: RF helicon-based inductive plasma thruster (IPT) design for an atmosphere-breathing electric propulsion system (ABEP). Acta Astronaut. **176**, 476–483 (2020). https://doi.org/10.1016/j.actaastro.2020.07.008
125. NASA Orbital Debris Program Office, *Orbital Debris Quarterly News 28–3, July 2024.* [Online]. Available: https://www.orbitaldebris.jsc.nasa.gov/quarterly-news/
126. J. McDowell, *Jonathan's Space Report | GCAT.* [Online]. Available: https://planet4589.org/space/gcat/ (accessed: Apr. 23 2023).
127. S. Alfano, D. L. Oltrogge, and R. Shepperd, "LEO Constellation encounter and collision rate estimation: An update," *2nd IAA Conference on Space Situational Awareness, IAA-ICSSA-20–0021*, 2020.
128. Pisacane, V.L.: The space environment and its effects on space systems. American Institute of Aeronautics and Astronautics Inc, Reston, VA (2016)
129. Picone, J.M., Hedin, A.E., Drob, D.P., Aikin, A.C.: NRLM-SISE-00 empirical model of the atmosphere: Statistical comparisons and scientific issues. J. Geophys. Res. **107**, 15–16 (2002). https://doi.org/10.1029/2002JA009430
130. *Digital Science: Dimensions.* [Online]. Available: https://app.dimensions.ai/
131. Hook, D.W., Porter, S.J., Herzog, C.: Dimensions: building context for search and evaluation. Front. Res. Metr. Anal. (2018). https://doi.org/10.3389/frma.2018.00023
132. Nishiyama, K.: A study of air breathing ion engine. Space Technology Japan, The Japan Society for Aeronautical and Space Sciences **4**, 21–27 (2005). https://doi.org/10.2322/stj.4.21
133. T. Schönherr, J. Cepeda, J. Skalden, D. Ilic, G. Herdrich, and K. Komurasaki, "Coaxial Air-Fed Pulsed Plasma Thruster," *Space Propulsion Conference 2018: SP2018–116*, 2018.