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Doctoral Dissertation

Doctoral Program in Management and Production Engineering(38th cycle)

Sustainability in the New Space Economy: a Multidisciplinary Approach

Present and Future Trajectories, and the role of Earth Observation in Aviation

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2025

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Marianna Valente
Turin, 2025

Summary

In recent decades, the space sector has undergone rapid and transformative development, driven by technological innovations, policy reforms, and an increasing number of participants in the field. The advent of the New Space Economy (NSE) era is a crucial milestone in this progression. It is characterised by private enterprise involvement, broader democratisation of space access and innovative business models that diverge significantly from traditional government-driven space initiatives. In this context, sustainability is essential not only for preserving orbital capacity and ensuring the long-term usability of outer space, but also for equitably distributing the benefits of space activities across society and effectively addressing global challenges such as climate change mitigation and disaster resilience.

In this context, the present thesis adopts a multidisciplinary approach to provide a comprehensive overview of sustainability in the space sector. The thesis is organised around two complementary levels of analysis. At the macro level, it investigates the governance and developmental trajectories of space sustainability through a systematic review of 254 scientific articles, complemented by a Delphi study involving 63 international experts. The systematic literature review identifies key thematic clusters, ranging from policy, law, and regulation to debris management, life support systems, resource utilization, and remote sensing. It assesses their alignment with the three pillars of sustainability, environmental, economic, and social, and the United Nations Sustainable Development Goals. The findings highlight a growing yet uneven recognition of sustainability principles across the space sector, emphasizing areas of convergence, such as the imperative of debris mitigation, and divergence, such as the allocation of responsibilities between private and public actors. The Delphi study further refines these insights by incorporating forward-looking perspectives, elucidating the technologies and governance mechanisms most likely to influence sustainable development pathways by 2040. Additionally, this study highlights how geopolitical factors may potentially influence experts' views on the future of space sustainability.

At a micro level, this thesis explores the contribution of space-based technologies, particularly Earth Observation (EO), to aviation sustainability. Using the ESA Aeolus mission as a case study, the assessment evaluates how satellite-derived wind profiles can improve the monitoring of wind gusts. These rapid, disruptive events affect safety and efficiency. The research compares satellite data with airborne campaigns and turbulence models, demonstrating that, despite some temporal and spatial limitations, Aeolus data provide valuable insights into wind variability in both the vertical and horizontal dimensions. Notably, the study finds that EO can supplement traditional methods by detecting spatial patterns of gusts, analyzing seasonal and interannual changes, and enhancing turbulence models through spectral fitting techniques.

Furthermore, the use of EO data for terrestrial applications, as illustrated by the case study, generates benefits that extend beyond the atmosphere. It contributes not only to sustainability on Earth but also in space, by promoting the commercialization of EO data for sustainable purposes, thereby strengthening the economic dimension of space sustainability. From an environmental perspective, integrating multiple EO missions with shared observation goals reduces the need for additional satellite launches, thereby minimizing orbital congestion and helping preserve the long-term health of the space environment.

By integrating governance-oriented inquiry with applied technological analysis, this thesis demonstrates that the sustainability of space requires a comprehensive approach that acknowledges the interdependence among regulatory foresight, economic strategies, and technological innovation. Furthermore, it illustrates how EO, when strategically employed, can support both the long-term resilience of the space environment and the immediate needs of critical terrestrial sectors, such as aviation. The primary contribution of this study lies in its integration of theoretical frameworks with practical applications, thereby establishing a foundation for future research and policy development in the pursuit of a more sustainable New Space Economy.

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First, I want to warmly thank Professor Federico Caviggioli for trusting me and giving me this wonderful opportunity to work on my thesis. I truly appreciate the time and guidance he has generously shared with me over the years. His expertise and support have been incredibly important to both my professional journey and personal development. I also want to sincerely thank Professor Alfonso Pagani for his valuable insights and suggestions, which have truly helped me grow as a researcher. His dedication and professionalism in everything he does are genuinely inspiring. I also want to thank Professor Erasmo Carrera. It has always been a pleasure to hear him speak whenever I visited his office. His insights, mechanical expertise, and passion for research have always captivated me. I want to express my heartfelt gratitude to Giuseppe Palaia for his ongoing and truly invaluable support. His guidance, friendship, and countless helpful suggestions have made this journey incredibly special and meaningful to me. I also thank Professor Giuseppe Scellato for the advice and support he has given me over the years. I sincerely thank Matija Rencelj and the entire ESPI team for warmly hosting me at the European Space Policy Institute in Vienna. Spending four months with them was an enriching experience that let me delve into the exciting world where research meets policy, and I also had the pleasure of making some wonderful new friends and colleagues. I want to thank everyone at MUL2 for fostering a fun and inspiring work environment. You brought laughter, drama, and FEM analyses into my days. I'm truly thankful to all my friends and everyone who has supported and been there for me throughout these years. Your support means the world to me as I continue on this journey. This research was carried out with the support of the Italian Space Agency (ASI), which funded my research scholarship "Responsible Space for Sustainability." Finally, I am deeply grateful for the incredible support of my family and my boyfriend. Their unwavering encouragement meant the world to me, and I truly cherish how they celebrated every small milestone with joy and pride along this journey.

Agli audaci, che la fortuna possa essere sempre a vostro favore

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Introduction

0.1 The New Space Era

The space sector has experienced rapid and transformative growth over the past few decades, driven by technological advancements, policy shifts, and the entry of an increasing number of players into the field. The advent of the New Space Economy (NSE) era represents the pivotal point in this evolution, characterized by the entry of private companies, greater democratization of access to space, and innovative business models that contrast sharply with the traditional government-led space programs of the past [1–3]. This evolution has led to a rapidly growing space economy, projected to exceed $1 trillion by 2040 [4–6].

Historically, the space sector was heavily influenced by geopolitical competition during the Cold War era, resulting in significant milestones such as the Apollo programme and the creation of international frameworks, including the 1966 Outer Space Treaty [7]. These initial developments were primarily overseen by national governments, with space activities driven mainly by strategic and scientific objectives. The shift to the New Space era thus represents not only a technological and economic transformation but also an institutional one, wherein conventional distinctions between the public and private sectors are increasingly becoming indistinct. Startups, medium-sized enterprises (SMEs), and large corporations outside the aerospace industry are now principal actors alongside large companies and space agencies [1, 8].

In order to gain a deeper understanding of this transformation, it is important to draw a relevant distinction. In the space industry, two distinct segments exist: the upstream and downstream segments [9]. The upstream segment involves activities associated with the design, manufacturing, and launching of space infrastructure, which necessitate considerable technological expertise and financial investment. Conversely, the downstream sector is dedicated to converting space-derived data into applications relevant to Earth. This encompasses services such as Earth observation, satellite telecommunications, and navigation. These data are subsequently provided to end-users who employ them across various sectors, including meteorological forecasting, agriculture, and environmental monitoring [10]. Consequently, the commercialization of space is significantly reshaping the sector's dynamics. Firms such as SpaceX, Rocket Lab, and Virgin Galactic, through the development of low-cost and partially reusable launch vehicles, have considerably lowered launch costs, thereby increasing the accessibility of orbit to a broader range of users [11, 12]. Furthermore, the use of Commercial Off-The-Shelf (COTS) components and the development of CubeSats for scientific and telecommunications applications have substantially reduced satellite production costs. This development has made it easier for universities and start-ups to build and use satellites, and has facilitated market entry for companies like Starlink and OneWeb, as well as the development of large constellations, by paralleling the entry of CubeSats [13, 14]. Additionally, the application of satellite data and related technologies is progressively expanding into other sectors for various purposes, such as smart agriculture, surveillance, and mobility. It is principally the rapid growth of the downstream industry that has driven this expansive development [15].

On the one hand, space has become increasingly commercial and accessible; on the other hand, outer space has emerged as a realm of geopolitical competition and strategic importance [16]. Satellites are crucial for communication, navigation, surveillance, and security, making orbital infrastructures indispensable for both civilian and military initiatives. The ability to control orbital allocations, launch capabilities, and mega-constellations is increasingly regarded as a key factor in determining global leadership. Accordingly, space is now acknowledged not merely as a scientific frontier but also as a strategic domain comparable to land, sea, and cyberspace, where issues of sovereignty, security, and influence intersect with commercial and scientific aspirations [17, 18].

Nevertheless, although the expansion of space activities has created unprecedented opportunities for economic development and strategic progress, it has concurrently revealed significant deficiencies, especially within the current legal and regulatory framework. The existing governance structure has not sufficiently evolved to accommodate the sector's exponential growth. Fundamental treaties, such as the Outer Space Treaty (1966) [7], the Liability Convention (1971) [19], and the Registration Convention (1974) [20], were formulated within a geopolitical context dominated by the USA and Russia, before the emergence of commercial space entities. As a result, these treaties establish broad principles but possess limited enforceability. Most agreements remain non-binding and lack effective mechanisms for monitoring compliance or enforcing sanctions. For example, debris mitigation guidelines developed by the Inter-Agency Space Debris Coordination Committee (IADC) [21] or endorsed by the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) [22] rely on voluntary adherence. Furthermore, global organizations such as the United Nations Office for Outer Space Affairs (UNOOSA) play a pivotal role in fostering dialogue, capacity building, and the development of soft-law instruments. However, the absence of binding commitments and the continued reliance on fragmented national approaches have hindered the efficacy of current governance frameworks [23]. Consequently, there is an urgent necessity for the revision of existing frameworks. To ensure that space remains a sustainable and secure environment, it is imperative to strengthen international cooperation, update outdated treaties, and establish more robust institutions [24].

0.2 The Sustainability Challenge in the New Space Era

Sustainability is generally defined as the capacity to satisfy present needs without compromising the ability of future generations to fulfill their own [25]. On Earth, this principle is closely linked to the responsible management of natural resources, the safeguarding of ecosystems, and achieving social and economic development in a manner that sustains planetary health. Conversely, in outer space, sustainability is a more contemporary and continuously developing concept [3]. Historically, space was primarily regarded as a strategic, scientific, and exploratory frontier, with limited focus on the long-term preservation of its environment. Currently, however, the increasing dependence on satellites and space-based services has transformed outer space into a critical domain where sustainability considerations are becoming progressively more urgent [3, 26, 27].

The sustainability challenge in the New Space Era extends well beyond the technical risks of debris accumulation and orbital congestion. Space has evolved into a strategic and contested domain, influenced by escalating geopolitical tensions that shape its future trajectory. The deployment of megaconstellations by private enterprises, often supported by national governments, has heightened concerns regarding spectrum allocation, orbital congestion, and the uneven distribution of benefits [28]. Additionally, the dual-use nature of many space technologies makes it difficult to distinguish between civilian and military applications. This increases the risk of weaponisation and intensifies rivalries among major countries [18]. These developments make space governance more complicated, as national interests often conflict with the idea of space as a global commons.

The current regulatory framework is inadequately equipped to address these emerging realities. They encompass broad principles, such as the prohibition of sovereignty claims and the obligation to prevent harmful contamination, but offer limited guidance regarding emerging issues such as orbital congestion, commercial resource exploitation, or active debris removal [23]. Furthermore, most of the more recent instruments, including the UN Guidelines for the Long-Term Sustainability of Outer Space Activities adopted by COPUOS in 2019, are non-binding. Their efficacy relies on voluntary adherence, resulting in fragmented implementation among states and limited accountability [22]. This regulatory weakness is particularly evident in the domain of debris mitigation. Although technical standards have been established, such as those formulated by the IADC, compliance remains inconsistent. In the absence of binding international commitments, operators may prioritise short-term economic benefits over long-term sustainability, thereby amplifying the risk of cascading collisions and potentially triggering the Kessler Syndrome [1] [29].

Due to the reliance on non-binding treaties and voluntary adherence guidelines, progress in governance remains slow compared to the swift advancements in technological and commercial innovations. The lack of binding regulations and effective oversight mechanisms creates a governance gap at a time when space is becoming increasingly critical for global security, climate monitoring, and economic stability [1, 30]. Enhancing international cooperation is vital, not only to prevent duplication and conflicts but also to ensure equitable access to the benefits derived from space exploration [31].

Addressing these complex challenges requires a systematic approach to space sustainability, which is understood as the capacity to preserve the orbital domain as a safe, accessible, and shared environment for both present and future generations. Ensuring such sustainability must consider three interdependent pillars [32]:

- Economic sustainability: enabling long-term growth in space activities while responsibly managing environmental, social, and cultural impacts.
- Environmental sustainability: safeguarding the space environment from irreversible degradation caused by debris, congestion, or harmful interference.
- Social sustainability: promoting inclusive access, governance, and international cooperation to ensure that space remains a common resource for all.

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[1] Proposed by US NASA consultant Donald J. Kessler in 1978, the Kessler syndrome is a scenario in which space debris in low Earth orbit builds up to such a level that objects often collide, sparking a chain reaction that exponentially increases the volume of debris and the risk of further collisions.

In the following chapters of this thesis, the link between the space economy and space sustainability, as well as its future developments up to 2040, will be analysed in detail.

0.3 Earth Observation as a Strategic Enabler of Sustainability

Earth Observation (EO) utilizes satellites equipped with optical, radar, and thermal sensors to monitor environmental changes worldwide continuously. It supplies data across various spatial and temporal scales, facilitating the analysis of key indicators such as land degradation, biomass loss, greenhouse gas emissions, and urban expansion [33–35]. Beyond its scientific and technological significance, EO also represents a fundamental enabler of sustainability in space-related activities. Linking space infrastructure with terrestrial environmental monitoring is one of the primary channels through which the space sector can actively promote sustainable development.

Primarily, the utilization of EO data contributes to environmental sustainability through monitoring climate conditions, deforestation, biomass indicators, water quality, and various other activities [36–38]. Although still evolving, the application of satellite data, particularly EO, can strengthen the economic and social dimensions of sustainability. For instance, nighttime light observations can be employed to analyze urban economic growth, assess the impacts of conflicts in war zones, or monitor urban heat islands [39, 40].

EO extends its significance beyond terrestrial surveillance; it plays an essential role in aviation and aeronautics, where satellite-derived atmospheric observations support safer operational procedures, optimize flight routes, reduce fuel consumption, and inform adaptive strategies to mitigate climate-induced hazards [41–43]. Nevertheless, there are both technical limitations due to the spatial and temporal resolution of satellites, as well as governance-related challenges. Although satellites generate global information, the ownership, accessibility, and sharing of these datasets remain subject to political, legal, and commercial constraints. Issues related to data sovereignty, privacy, and security influence the manner in which EO outputs are utilized and by whom [44]. Moreover, the dual-use nature of EO, being equally valuable for civilian sustainability initiatives and military intelligence, adds a layer of complexity to its integration within international governance frameworks [18]. In this thesis, Earth observation emerges as a strategic enabler of sustainability; however, its full potential can only be realized by enhancing technical capabilities and strengthening governance.

0.4 Research Objectives and Outline

In this context, the present thesis makes a valuable contribution to the emerging debate on space sustainability by integrating two complementary perspectives: (i) on a macro scale, this thesis examines governance, developments, and future trajectories of sustainability within the space economy through a systematic review of 254 scholarly articles analyzed across various dimensions, combined with a Delphi study involving 63 international experts; (ii) at the micro level, it investigates the potential of space-based technologies, specifically EO, to enhance both sustainability in space and on Earth. A case study focusing on wind gusts, acknowledged as one of the most sudden and disruptive phenomena in aviation, illustrates how satellite data can enhance traditional turbulence models and our understanding of atmospheric hazards, as well as support the commercialization of EO data for sustainable applications.

The thesis is structured into four main chapters, followed by a concluding section:

- **Chapter 1** examines the intersection between the space economy and space sustainability through a systematic literature review of 254 scientific articles. The dataset is analyzed across multiple dimensions: the three pillars of sustainability, the primary locus of the article, either on Earth or in space, and the alignment with the Sustainable Development Goals (SDGs). The review proceeds to identify the most frequently discussed topics, including policy, law and regulation, debris, life support systems and habitat design, remote sensing and data handling, as well as emerging issues such as tourism and ethics. The study ultimately highlights significant gaps and proposes future research directions. Preliminary findings indicate that policy is the most extensively discussed subject within this literature; however, the environmental aspect of sustainability is comparatively less addressed.

- **Chapter 2** delineates the outcomes of a Delphi investigation involving sixty-three specialists from the space sector. Based on insights from Chapter 1, this chapter explores projected trends in space sustainability through 2040 and examines the influence of various stakeholders in shaping these developments. The study, which engaged academic, governmental, and industrial experts, was organized into three iterative rounds; two were carried out consecutively, while the third was conducted one year later to evaluate how expert perspectives evolved in response to geopolitical shifts between 2024 and 2025. The methodology incorporated both open- and closed-ended questions, using a Likert scale, alongside three distinct criteria to measure consensus among the expert panel. Among the principal findings, the need to enhance international cooperation and revise the legal framework to foster and advance sustainability within the sector is evident. Furthermore, in light of recent geopolitical events, there is a divergence of opinions among experts regarding the prospective role of universities in the sustainable development of space technology in the coming years.

- **Chapter 3** provides an overview of Earth Observation applications for sustainability. Following an introduction to the primary EO missions, the chapter analyzes their contributions to the aviation sector, both directly and indirectly. Satellite data, for example, can be employed for route optimisation, enhancement of air traffic management (ATM), monitoring of climate change effects, and improvement of decision-making processes. Among the various contributions of satellite data to this sector, the chapter explores how satellite data can be used to detect turbulence and gusts, phenomena among the most unpredictable and hazardous to aviation safety and significantly influenced by climate change. The chapter also provides an overview of potential payloads that may be utilized, highlights the use of EO data for other sectors, such as aviation, and emphasizes the importance not only for sustainability on Earth but also in space.

- **Chapter 4**, which presents the case study, delves into wind gusts and examines how satellite-based Earth Observation can help monitor and characterize them. The analysis focuses on wind gust power spectral density, using data from the

ESA Aeolus mission and the EUREC4A flight campaign. These two datasets offer different perspectives: Aeolus provides near-global coverage with vertical wind profiles, while the airborne campaign offers localized, high-resolution observations. Together, they enable a multi-scale study of gust dynamics. The results from these EO datasets are then compared with traditional turbulence modeling approaches, such as the von Kármán model. This comparison reveals areas of agreement and disagreement, highlighting the strengths and limitations of both observational and modeling methods.

- **Conclusion** brings together the main findings of the thesis and offers a comprehensive view of their broader impact. It emphasizes that sustainability in the space sector can't be achieved solely through technological innovation or regulations, but rather requires a holistic approach. The results also show the crucial role international collaboration and flexible governance frameworks play in addressing a growing, complex, and geopolitically sensitive space environment. Meanwhile, the in-depth case study on Earth observation highlights the transformative potential of space-based technologies in addressing sustainability issues on Earth, particularly in sectors such as aviation, where the risks associated with atmospheric hazards are worsening due to climate change.

Chapter 1

Mapping the Sustainability in the Space Economy: Trends, Gaps, and Frameworks

This chapter examines the relationship between the Space Economy and sustainability. It presents the results of a systematic literature review (SLR) that analyzes 254 peer-reviewed articles across multiple dimensions. These include the three pillars of sustainability (environmental, social, and economic), the relevance of the Sustainable Development Goals (SDGs), and the spatial focus of sustainability, whether they addressed sustainability in space, on Earth, or both. The review identifies the most discussed topics, significant gaps, and areas where future research and action are most urgently needed. Part of this work was published in [3].

1.1 Methodology

The **systematic literature review** (SLR) is a structured, methodical process used to identify, evaluate, and synthesize existing research on a specific topic, especially across multiple disciplines. This section follows the methodology from recent studies, e.g., [45–47], involving the following key steps (see Fig. 1.1):

1. **Preliminary search and screening**: this phase involves creating an initial search query to find articles and bibliographic data from a selected database. The identified articles are then screened to eliminate false positives and to discover any potentially relevant research areas that might have been missed (false negatives).

2. **Refined search and screening**: based on insights from the initial analysis, the search query is refined, and a wider data collection is performed. Additional screening is conducted to remove false positives.

3. **Article classification**: the selected articles are classified using manual and automated techniques to organise the dataset.

4. **Analysis of the final database**: the screened database is then analyzed to extract valuable insights and synthesize the research findings.

Figure 1.1: Schema of the implementation method.

The scientific publications referenced in this review were obtained from the Scopus database, known for its extensive disciplinary coverage and inclusion of rigorous scientific journals [48]. The selection was limited to peer-reviewed journal articles and reviews written in English[1]. The initial step of the SLR was to identify the boundaries of the topic preliminarily. The main concepts examined are the space economy/sector and sustainability. An article was deemed suitable for inclusion if it mentioned space-related and sustainability-related concepts in the title, abstract, or keywords, either by the authors or as indexed by Scopus. It is presumed that if an article substantially discusses sustainability, this will be evident in at least one of these searchable fields.

To reduce false positives in the search query, articles related to sub-orbital aeronautics and ground operations[2] were omitted, as well as journals focused on regional and urban development where the term "space" is used differently e.g., spatial dimension or geographic location[3]. The following query was used in Scopus in February 2023:

TITLE-ABS-KEY(sustainable OR sustainability OR SDG) AND TITLE-ABS-KEY(space industry OR new space OR space economy OR space science OR space technology OR space technologies OR space sector).

This preliminary query returned 241 articles, which were reviewed to exclude irrelevant ones. The process began by reading the abstracts. Articles were omitted for specific reasons: i) if the term “space” solely referred to the spatial dimension e.g., [49, 50], ii) if they lacked an in-depth analysis or discussion of sustainability issues. Specifically, any article where sustainability was not the main focus or was not meaningfully discussed or evaluated was excluded. For instance, studies that introduce new initiatives or technological applications without adequately addressing their sustainability impact were removed. Such works typically only offer broad references to long-term sustainable outcomes without detailed discussion or qualitative/quantitative measures of sustainability improvements e.g., [51]. This criterion also excluded articles reporting events or initiatives without analytical depth. Examples include [52], which describes a capacity-building effort under the U.N. Programme on Space Applications, and [53], a summary of a conference organized by the European Space Policy Institute.

The analysis of abstracts resulted in a sample of 131 articles. All of these were then thoroughly examined in their full texts to apply the same exclusion criteria and arrive at

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[1] Scopus search syntax: SRCTYPE(j) AND DOCTYPE(ar OR re) AND LANGUAGE(English).

[2] Stopwords: aircraft, airport, airline, aviation.

[3] Excluded journals: Jane S Defence Weekly, Journal Of Urban Economics, Regional Science And Urban Economics, Cities, Marine Policy.

a final sample of 110 articles (46% of the original sample). More importantly, this initial analysis revealed some additional keywords not present in the original search query, which could have led to missing relevant articles (false negatives). The search query was therefore revised as follows:

TITLE-ABS-KEY(sustainable OR sustainability) AND TITLE-ABS-KEY(space industry OR space economy OR space science OR space technology OR space technologies OR space sector OR spaceborne OR spaceflight OR space flight OR outer space OR orbital space OR spacecraft OR space exploration).

The refined search returned a total of 604 articles, of which 363 were additional publications not identified in the initial query. The Fig. 1.2 shows the PRISMA flow diagram [54], which outlines the selection process based on the updated search strategy. Articles were assessed using the same exclusion criteria as before, beginning with abstract screening and, if necessary, followed by a full-text review. The final dataset, comprising articles from both the initial and refined searches, includes 254 publications, about 42% of the total results obtained from Scopus.

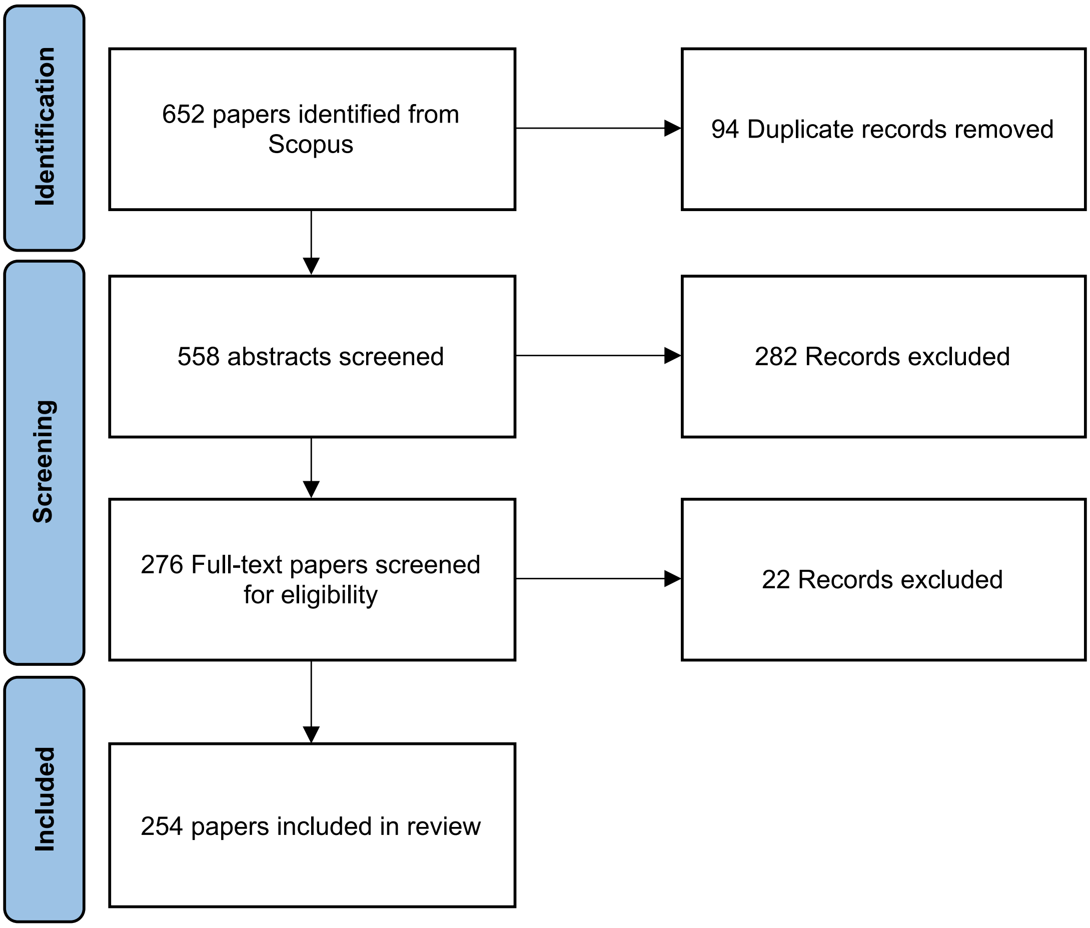

Figure 1.2: PRISMA diagram for SLR.

1.2 Clusters and tagging

The final sampled articles were analyzed across multiple dimensions. The first classification sorts articles into the loci *In space* or *On Earth*. This dimension is based on the distinction between "the sustainability of the space infrastructure" and "the space infrastructure for sustainable development" [55]. It focuses on the concept of sustainability within the space economy, emphasizing the main interest: sustainable activities in outer space and the sustainability impacts on Earth. A full-text review revealed a difference between publications that mainly address missions, operations, and international cooperation beyond Earth's atmosphere, and those that deal with terrestrial aspects of space activities. The latter includes topics like satellite data for Earth observation, the creation and growth of national space agencies or programs, and the terrestrial applications of space technologies. A more detailed analysis was performed on the space *locus*. Using specific keywords, articles are categorized based on whether their main focus is on the Moon, Mars, Orbit (Low Earth Orbit, LEO, or Geostationary Earth Orbit, GEO)[4], or space in general. Note that these categories are not mutually exclusive.

The second classification system assigns each article to one or more sustainability pillars, economic, environmental, and social, and aligns with the growing focus on evaluating the impacts of space activities on sustainability [1, 56, 57]. These three pillars are based on sustainability literature [32]. The studied publications were analyzed through a full-text review, with an emphasis on the primary sustainability themes they addressed.

Each article was also linked to one or more Sustainable Development Goals (SDGs) to enhance the sustainability analysis. The SDGs, 17 interconnected goals adopted by the United Nations General Assembly in 2015 as part of the 2030 Agenda for Sustainable Development [58], seek to address global issues like poverty, inequality, climate change, environmental degradation, peace, and justice. The classification of SDGs was based on Scopus's specific search queries for each goal, as developed by [59]. Articles that matched these queries were marked with the relevant SDG(s). The presence of each article within our dataset was verified by examining whether it appeared among the results of these queries, and the corresponding SDGs were documented. This approach helped reduce the subjectivity often involved in manual classification based only on the researcher's judgment.

The selected articles were categorized based on their main research focus using a two-step process to ensure each article belonged to a unique group. First, an automated classification was performed employing the k-means clustering algorithm through the Carrot2 web platform[5]. This process analyzed the titles, abstracts, and keywords of the articles. The k-means algorithm treats texts as numerical vectors, initially assigning items to a specified number (k) of clusters and then iteratively refining these groupings by minimizing the distances between each article and its cluster centroid. Clusters were finalized once the groupings remained stable (as discussed in [60]). Initial testing suggested that fifteen clusters offered a suitable level of initial detail.

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[4] LEO is relatively close to Earth, usually from about 160 km to 2,000 km above the surface. Satellites in LEO orbit Earth quickly, completing an orbit in roughly 90 minutes to a few hours. GEO is at a much higher altitude, about 35,786 km above the Earth's equator. Satellites in GEO maintain a fixed position relative to Earth's surface, appearing stationary from the ground.

[5] The Carrot2 platform was used (https://search.carrot2.org/, last accessed September 2025).

Manual validation followed, resulting in five refined groups: **Policy, Law and Regulation, Debris, Life Support Systems (LSS) and Habitat, and Remote Sensing and Data Handling**. Some articles covered multiple topics and were assigned to more than one group; however, when this occurred, they were categorized based on their primary focus. Special attention was given to articles concerning debris and related regulatory issues, with a preference for classifying them under the Debris group rather than Law and Regulation (examples include [61, 62]). This choice was made because debris is a central theme in discussions about sustainability. Grouping all the articles dealing with this subject in a single group would improve their analysis and discussion. Finally, seventeen recent articles were included in a residual category labeled **Emerging topics** that might gain importance in upcoming years.

1.3 Sample article overview

The sample of publications mainly consisted of articles (87%), with reviews making up the remaining 13%. Fig. 1.3 shows the publication trend over the years up to February 2023. There was limited publication activity until 2009 (11%), followed by increased activity from 2010 to 2019 (44%), and a significant rise in recent years from 2020 onwards (45%). This trend could be attributed to several factors. For example, the rise of the New Space trend and increasing awareness of sustainability issues, particularly in recent years, may have contributed to this shift. Additionally, global governmental initiatives focused on sustainability, such as the UN's Sustainable Development Agenda 2030 [58], have contributed to this growth.

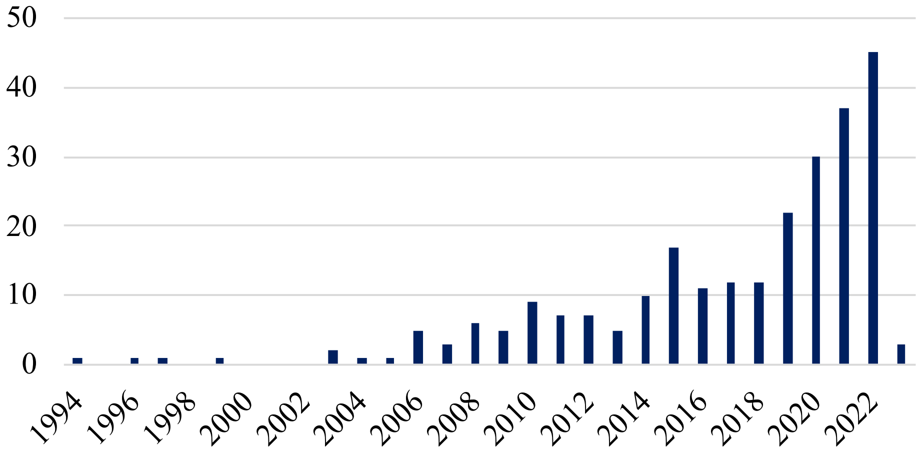

Figure 1.3: Year publication frequency from 1994 to February 2023.

The articles analyzed were published across 101 different journals (Fig. 1.4 shows the journals with more than three articles in our sample). Acta Astronautica (58 articles) and Space Policy (36 articles) comprise 37% of the sample, reflecting the strong focus of these journals on sustainability in the space sector. Additionally, 44% of the papers appeared in journals with fewer than four publications in our sample, suggesting that the topic has gained broad attention across various outlets. This indicates that even journals not explicitly dedicated to space activities are beginning to explore sustainability from different perspectives.

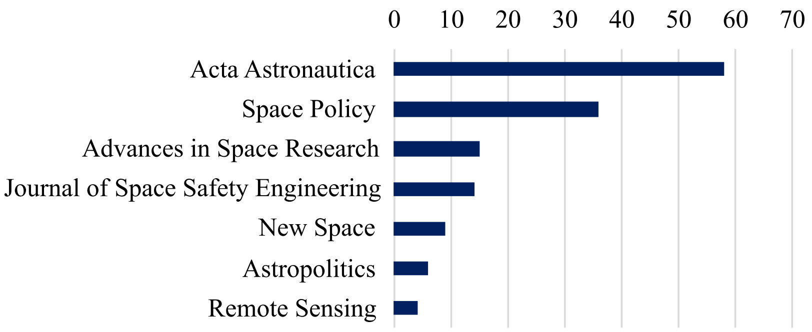

Figure 1.4: Publication frequency across journals.

The articles analyzed were written by 160 researchers, with an average of 3.6 authors per paper. Single-author articles represented 35% of the sample, while those with 2 to 5 authors accounted for 53%. Only 13% involved more than five authors. Fig. 1.5 shows the geographic distribution of the research, indicating the authors' countries of affiliation. The United States (71 articles), France (35), the United Kingdom (24), and Germany (24) were the most frequent contributors. Notably, BRICS countries (Brazil, Russia, India, China, and South Africa) contributed 48 articles to the top 15 countries. Conversely, African and Middle Eastern countries were represented by only 12 articles. The participation of BRICS nations and other emerging economies in space research highlights the growing global interest and collaboration, creating opportunities for new stakeholders to engage in space exploration and technological advancements. Regarding affiliations (Fig. 1.6 shows organizations linked to four or more articles), there are 160 different ones, with NASA and the European Space Agency (ESA) leading in contributions with 18 articles each. Worldwide, government agencies produce the most publications, followed by universities and research centers.

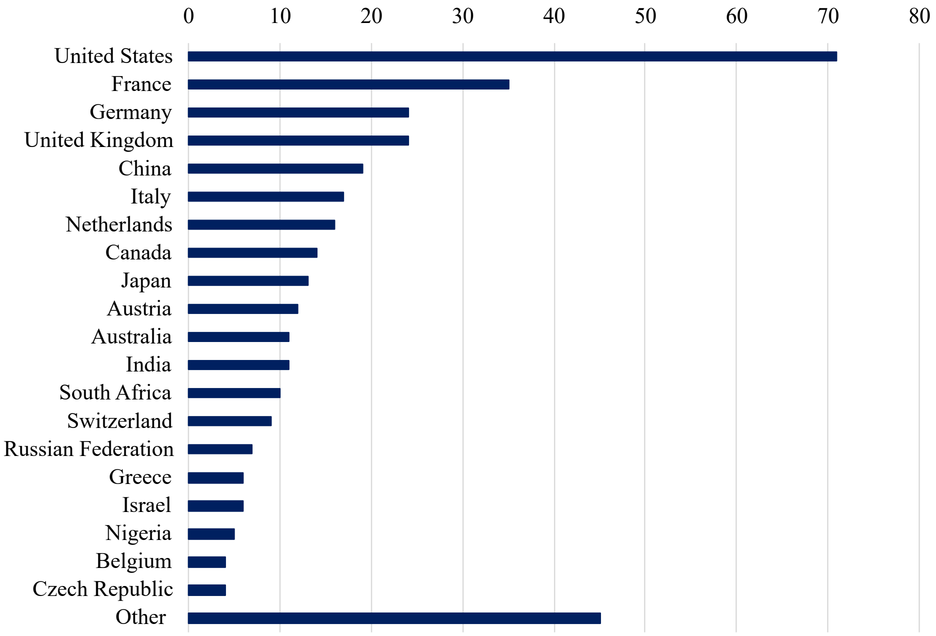

Figure 1.5: Count of documents by affiliation country of the authors.

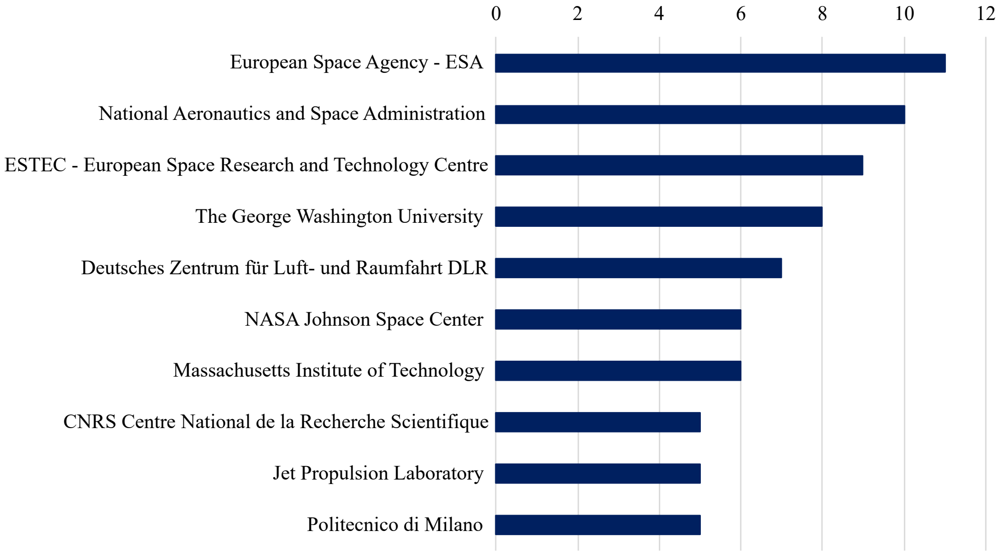

Figure 1.6: Documents by author's affiliation.

1.4 Analysis of the classifications

1.4.1 Locus and sustainability pillars

All articles have been categorized across various analysis dimensions, including the content's locus (whether it focuses on space and/or on Earth), the sustainability focus, the specific research cluster, and the relevant SDGs, as outlined in section 1.2.

Tables 1.1 and 1.2 illustrate the distribution of the identified articles across the spatial dimensions of the locus (either in space or on Earth) and the sustainability pillars. Each table displays the number of articles corresponding to each locus and their distribution according to the sustainability pillars. Additionally, the locus space is further subdivided into sub-loci: Orbit, Moon, Mars, and Other, to provide more detailed information on the distribution of articles within the locus. The final column and row indicate the totals for each locus and pillar, respectively. The number of papers associated with both loci, on Earth and in space, is indicated in brackets. The Appendix A provides detailed information about each article. The majority of the documents (66%) address sustainability in space, while 53% focus on Earth. Additionally, 19% of the sample discuss sustainability in both loci, exploring mainly policies, economic aspects, and legal and regulatory considerations that are relevant to both space and Earth applications e.g., [30, 63, 64]. The space locus analysis is broken down into subcategories: Orbit (20%), Moon (11%), Mars (5%), and outer space in general (33%). We observe that the number of articles increases as the distance from ground activities decreases.

Regarding the sustainability pillars, environmental aspects are the most frequently studied at 58%, followed by economic at 47%, and social at 45%. Most of the sample (61%) focuses on a single pillar e.g., [24, 28, 65]; 28% of the documents explore two pillars simultaneously e.g., [66, 67], while only 11% address all three, mainly through policies promoting comprehensive sustainable development e.g., [68–70].

Table 1.1: Locus/pillar matrix for papers from 1994 to February 2023. The "Total" values in brackets show the number of articles that cover both loci.

Locus / Pillar	**Environmental**	**Economic**	**Social**	**Total**
On Earth	57	75	83	135
In Space	112	73	65	167
Orbit	36	16	11	50
Moon	19	18	12	28
Mars	6	6	7	12
Other	52	36	38	82
Total	**146 (24)**	**119 (29)**	**115 (33)**	**254 (48)**

Table 1.2: Locus/pillar matrix for papers from 1994 to February 2023 in percentage.

Locus / Pillar	**Environmental**	**Economic**	**Social**	**Total**
On Earth	22.4%	29.5%	32.7%	53.2%
In Space	44.1%	28.7%	25.6%	65.8%
Orbit	14.2%	6.3%	4.3%	19.7%
Moon	7.5%	7.1%	4.7%	11.0%
Mars	2.4%	2.4%	2.8%	4.7%
Other	20.5%	14.2%	15.0%	32.3%
Total	**57.5%**	**46.9%**	**45.3%**	**100%**

The comparison between the two main research locations shows that articles focusing on Earth" emphasize the social dimension of sustainability (33%) more than those "in space" (26%). Conversely, environmental aspects are more frequently addressed in the "in space" articles (44%) compared to "on Earth" (22%). The greater focus on social issues "on Earth" is understandable due to two main reasons: i) policy, international cooperation, and regulation are primarily linked to terrestrial organizations e.g., [71, 72]; ii) the sample includes articles discussing the social impacts of space-derived technologies or data on human communities on Earth e.g., [73, 74]. The higher representation of environmental topics in "in space" articles is somewhat unexpected but can be partly attributed to studies on space debris. Interestingly, the environmental dimension of sustainability is least represented "on Earth," mainly involving the use of satellite data for smart agriculture, climate change monitoring, and resource management e.g., [75–77]. This indicates that there is potential for growth in research assessing the environmental impact of space activities on Earth, such as analyzing how data or technologies relate to measurable short- and long-term effects on land, crops, urbanization, and other factors. Alongside the locus and sustainability pillar categories, Fig. 1.7 shows how the research is distributed across the identified research clusters. The most prominent group is Policy, accounting for 27.2%. In the next section, each research cluster will be examined in more detail, considering both the locus and sustainability pillars.

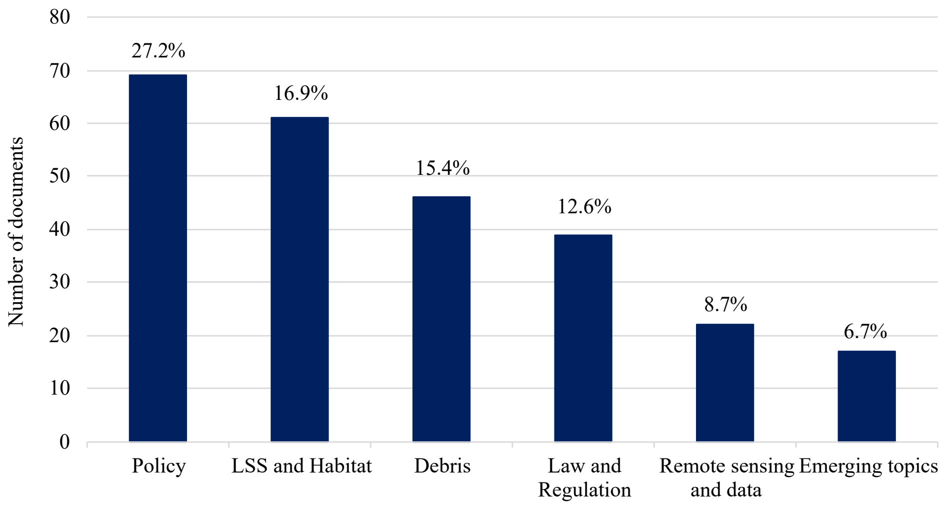

Figure 1.7: Distribution of articles by clusters.

1.4.2 Policy

Policy category is the largest, consisting of 69 articles that focus on similar research topics (see Table 1.3). These articles offer guidance to both national and international authorities on how to facilitate access to space, e.g., [78], for developing or enhancing space programs, e.g., [79, 80], or improving space agencies' operations [81]. The scope of analysis varies from specific space projects [82] to governmental and non-governmental organizations [81, 83], as well as multinational agencies and initiatives involving multiple countries [84], or efforts requiring global coordination e.g., [30, 85]. The selected articles highlight a need for increased international cooperation to enhance the sustainability of space activities. While many space programs involve bilateral or multilateral collaborations, exploring deep space beyond Earth's atmosphere (Moon, Mars, and beyond) demands large-scale, cross-disciplinary international efforts [30]. The authors emphasize the significance of ESA's policy change, which allowed access to some of its allocated time on the International Space Station (ISS) to unfamiliar actors outside traditional parties involved in ISS experiments and activities. This policy facilitates participation from diverse groups, including academic institutions, emerging country agencies, and private companies. Such collaborative approaches accelerate technological innovation and progress, supporting long-term success and sustainable development. Public and private stakeholders can collaborate to create sustainable products and implement strategies that address social and environmental issues [2, 86].

Some articles in this collection explore the features and challenges that space agencies and emerging space programs encounter concerning sustainability, and highlight additional opportunities. For the largest agencies, governance appears to be the main obstacle to future sustainability. Mazzucato and Robinson [8] discuss how NASA's activities have evolved with increased private-sector involvement, raising questions about leadership and control. Sagath et al. examine the challenges faced by ESA, particularly the implementation of shared space policies across all member states [72]. Focusing on smaller agencies, other works analyze African, South American, and Indian space efforts [87–89]. These studies suggest that the sustainability of these emerging countries' space agencies could

Table 1.3: Locus/pillar matrix for the cluster *Policy*. The "Total" values in brackets indicate the number of articles that address both loci.

Research topic: Policy	**Environmental**	**Economic**	**Social**	**Total**
On Earth	15	43	44	60
In Space	11	17	12	25
Orbit	3	2	3	6
Moon	2	4	4	5
Mars	0	2	2	2
Other	6	11	5	14
Total	**20 (4)**	**49 (6)**	**47 (8)**	**69 (11)**

be improved through participation in international initiatives such as the UN's working group on long-term space sustainability [90], developing policies and guidelines to mitigate space debris, and promoting international scientific cooperation via exchange programs to enhance capacity building. Regarding the African context, Froehlich et al. [68] argue that space activities could help reduce digital disparities by improving access to satellite-based services like internet connectivity in remote and underserved areas. Large constellations, which require a certain level of infrastructure, can help close the digital gap, promoting balanced access to information and technology, crucial for economic and social progress. Nonetheless, space policies in emerging nations may also face sustainability challenges. While constructing spaceports, launch sites, and ground stations can bring economic benefits, they also risk causing environmental damage that could harm local communities [86].

Furthermore, the U.N. has officially recognized the importance of small satellites[6] as a means to promote the expansion of broader space programs in developing countries e.g., [30, 78]. These projects have a positive influence on partners with limited expertise in core space technologies. First, emerging nations without an established space sector can access data and services from existing small satellites, such as those for Earth observation, telecommunications, and geolocation, to enhance their local infrastructure. Second, engaging in the technical development of new satellites is vital for achieving greater independence, as nations operate their own spacecraft, thereby enhancing economic and social sustainability. Notably, no detailed reports were found on Chinese space activities, though some studies mention them within the Asia Pacific Space Cooperation Organisation - APSCO [91] or for comparative purposes [85]. Despite China's progress in space technology and exploration over the past 20 years [92], their activities remain insufficiently documented, and further updates are necessary.

By definition, this collection of studies mainly focuses on the On Earth locus, where organizations are established and funded, rather than the space locus. The space locus is discussed in 25 articles that explore policies for sustaining initiatives with a primary focus on outer space. For example, Mankins [93] assessed the feasibility and economic

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[6] Small satellites are lightweight and compact spacecraft. Thanks to miniaturization and technological advances, smaller satellites can be launched more affordably by reducing payload size and costs. Several classes exist based on weight and size, with CubeSats being among the most well-known, measuring 10 cm on each side.

sustainability of building a Moon outpost. At that time, the analysis concluded such a project would not be economically viable. This contrasts with the current “Artemis” program, which aims to establish an orbiting station around the Moon and incorporates technological advancements toward sustainable lunar settlements. The few articles that discuss governance of colonization generally focus not on the Moon but on a generic celestial body. For instance, Schmidt and Bohacek [94] emphasize the importance of integrating science and technology into decision-making due to the harsh space environment. Likewise, adapting to new environments will require different moral and ethical principles and broader changes in human collective behavior.

The articles identified frequently focus on the economic and social aspects of sustainability, while the environmental perspective appears very limited and is almost always considered alongside the other two pillars. For instance, Bohlmann and Koller examine ESA’s activities in the Arctic, one of the most climate-vulnerable areas [95]. Some ESA satellite programs, such as Sentinel, Copernicus, and CryoSat, actively monitor the Arctic environment. Additionally, advancements in satellite technology enhance telecommunication and promote the use of space data. These efforts not only benefit the Arctic but also support all facets of sustainability globally.

1.4.3 Life Support Systems and Habitat

The LSSs and Habitat research cluster focuses primarily on human survival in space. This includes studies emphasizing innovative energy sources, e.g. [96, 97], developing techniques based on in-situ resource utilization (ISRU) for constructing and maintaining habitats, e.g. [86, 98], and advancing closed-loop systems, e.g. [99, 100]. ISRU involves harnessing local natural resources at mission sites instead of transporting supplies from Earth. Closed-loop systems recycle resources and reduce waste, unlike open-loop LSSs, which mainly use materials from Earth and generate waste. While closed-loop systems tend to be more complex and costly due to advanced recycling technology, they are essential for long-term missions or settlements on other planets. As a result, progress in ISRU and closed-loop LSSs is viewed as crucial for achieving sustainable space exploration [101].

Table 1.4: Locus/pillar matrix for the cluster *Life Support System and Habitat*. The "Total" values in brackets indicate the number of articles that address both loci.

Research topic: LSSs and Habitat	**Environmental**	**Economic**	**Social**	**Total**
On Earth	8	9	5	11
In Space	42	29	21	56
Orbit	3	4	2	6
Moon	15	14	6	21
Mars	6	4	5	10
Other	19	8	9	22
Total	**44 (3)**	**32 (2)**	**23 (3)**	**61 (3)**

The technologies studied for enhancing human adaptability when leaving Earth involve both other celestial bodies, e.g. [102, 103], and space stations or spaceships, e.g. [99, 104]. While this group mainly concentrates on the in-space locus (Table 1.4), it also occasionally discusses how LSSs can be used on Earth to improve living conditions, such as water management in hot deserts [105], or to explore alternative energy production methods [97].

Articles focusing on the environmental aspect of sustainability represent the largest group among the three pillars, accounting for 72%. Many discuss the extraction and use of in-situ resources to minimize environmental impact on the host planet, e.g. [106–108]. Others analyze space-specific agricultural techniques, e.g. [101, 109, 110], which help provide fresh food for astronauts and reduce the need for supply launches from Earth. Some studies explore closed-loop systems, showing benefits from waste reduction and recycling, whether human waste [80] or cultivation by-products [99].

52% of the studies in this cluster focus on economic sustainability. Many researchers explore both economic and environmental aspects, emphasizing the benefits and challenges of closed-loop systems, e.g. [100, 111]. Additionally, they balance costs and profits when utilizing in-situ resources in habitat design, e.g. [112, 113]. Although the costs of research and development for closed-loop systems are high, they offer advantages by reducing the resources transported from Earth, e.g. [111, 114]. The "cargo" can then be allocated to other payloads, such as scientific experiments or secondary resources, without increasing fuel consumption. This can lead to smaller launch vehicles and reduced fuel requirements for new missions (see, for example [115]).

The social aspects discussion covers various viewpoints on human health. For instance, Ghidini explores regenerative medicine to improve astronauts' well-being in space [116], while Bijlani et al. examine how radiation and microgravity affect microbial life on the ISS [117]. Some articles also highlight the social benefits of establishing outposts on the Moon, e.g. [108, 118], and Mars (see, for example [119, 120]), as well as using in-situ resources for societal growth [121, 122]. Notably, there is a significant focus on astronauts' mental health and analyzing the social impacts of long missions or hypothetical colonies, e.g. [123, 124].

1.4.4 Debris

The articles within the Debris cluster provide an extensive overview of the issue, which is recognized as a significant challenge to the sustainability of space activities [125]. Owing to the primary focus of these studies, space is the central focus (see Table 1.5): the majority of articles in this group analyze environmental sustainability in space (87%) and specifically target the Orbit sub-locus (71%), where nearly all debris and potential threats are concentrated.

Authors focus on various methods to address debris issues, including tracking and cataloging known objects through improved software and data processing, developing technology to capture, remove, or deorbit debris, and implementing regulations to limit the creation of new debris via responsible practices. Some authors, particularly within the latter subgroup, examine the regulatory framework and knowledge repositories established to mitigate debris. They highlight efforts by UNOOSA over the past decade in creating and managing the U.N. Register of objects launched into outer space, see for example [26, 126]. The consensus emphasizes the importance of a global registry for launched space objects, which can help map debris, prevent collisions, and foster international cooperation, especially in addressing issues of ownership and responsibility, such as those concerning the ISS. Nonetheless, limitations exist, such as the absence of penalties

Table 1.5: Locus/pillar matrix for the cluster *Debris*. The "Total" values in brackets indicate the number of articles that address both loci.

Research topic: Debris	**Environmental**	**Economic**	**Social**	**Total**
On Earth	2	0	3	3
In Space	40	9	4	46
Orbit	27	7	3	33
Moon	0	0	0	0
Mars	0	0	0	0
Other	13	2	1	13
Total	**40 (2)**	**9 (0)**	**4 (3)**	**46 (3)**

for late filings and restrictions that only nations can register objects [127]. Private companies should coordinate with their foreign ministers to notify the U.N. of registrations. Although a standard form is available, not all nations adhere to it. To improve this system, the authors suggest granting the U.N. authority to impose penalties, investigate the accuracy of submissions, and maintain sufficient staffing to manage registration information and serve as a contact point for all countries. Additionally, they recommend that nations be required to send their data to the U.N. in real-time.

Another group of authors focus on guidelines and regulations that address the debris problem, e.g. [128–130]. They highlight the urgent need for governments, institutions, and space agencies to collaborate in developing a regulatory framework that defines rights and responsibilities. Specifically, they emphasize the importance of international agreements to limit the creation of new debris, alongside technical solutions for its removal. There is a general consensus that nations and space agencies should take responsibility and adopt more sustainable practices, establishing guidelines and best practices for space activities to foster responsible behaviour, minimize debris, and promote a safer space environment for everyone [131].

Various authors approach space debris management from different organizational and technological perspectives, especially regarding debris prevention and removal. To prevent debris, improved design and planning during mission phases can better address solutions to limit debris creation and mitigate threats from end-of-life space objects [132]. Implementing post-mission disposal guidelines can effectively reduce satellite impact when applied effectively. Additionally, active space traffic management could organize near-Earth space in the future [133]. Regarding debris removal, some studies focus on technological innovations for active and passive debris elimination. Tracking and removal technologies are crucial, especially in heavily congested regions like LEO, where prevention alone may be insufficient. Removing existing objects is vital to prevent escalation. Currently, most of these technologies are still conceptual or in prototype stages; few studies are available in our sample. For example, Ben-Larbi et al. [134] developed micro-adhesive materials to capture very small debris, which is highly unpredictable but dangerous. This creates a low-cost, low-complexity active removal system. Conversely, Serfontein et al. research passive systems designed to increase debris drag, hastening de-orbiting and ensuring objects burn up upon atmospheric reentry [135]. Recent efforts also aim to extend the operational life of GEO satellites, reducing the number of targets in graveyard orbits, as proposed by Letellier and Lizy-Destrez [136]. These systems are still in early design and analysis stages, with costs, benefits, and potential impacts on performance, durability, and maintenance still under assessment.

This group of articles notably overlooks economic and social sustainability issues, as well as potential impacts on Earth. Such impacts involve a decreased sky observation capacity and the risk of satellite loss from debris impacts, which could threaten essential services such as telecommunications and GPS [137].

1.4.5 Law and Regulation

The Law and Regulation cluster (see Table 1.6) focuses on the sustainability implications and challenges of treaties and frameworks governing space activities. Both areas were discussed, with slightly more articles concentrating on space-related issues. There appears to be potential to enhance current definitions of space law [138], particularly in terms of long-term sustainability. The articles identified indicate this aspect has not been sufficiently addressed to date, e.g. [139]. Additionally, within the space sub-loci, the Orbit and Moon categories are underexplored, especially given the need for coordinated satellite deployment and traffic management, and in light of upcoming ARTEMIS missions to our satellite[7].

Table 1.6: Locus/pillar matrix for the cluster *Law and Regulation*. The "Total" values in brackets indicate the number of articles that address both loci.

Research topic: Law and Regulation	**Environmental**	**Economic**	**Social**	**Total**
On Earth	8	11	18	23
In Space	15	11	19	28
Orbit	3	2	3	4
Moon	2	0	0	2
Mars	0	0	0	0
Other	10	9	14	22
Total	**17 (6)**	**16 (6)**	**26 (11)**	**39 (12)**

Social sustainability is the most studied aspect regarding the "on Earth" locus. Most articles address commercial regulation in various contexts, such as satellite constellations and access to space, e.g., [140, 141]. The authors highlight a recent European initiative to promote digital transformation across member nations and maintain the continent's connectivity amid external challenges. Additionally, there is a rising demand for high-speed broadband services. To boost global competitiveness and reduce Europe's reliance on external suppliers, establishing a European mega-constellation is essential. This could also protect the European telecommunications manufacturing industry. The discussion also covers intellectual property rights [142]. The authors examine the tension between territoriality principles related to IP and the prohibition against exercising territorial

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[7] NASA's Artemis mission consists of four phases: the first two are dedicated to testing the Space Launch System and Orion spacecraft (launch planned for 2025); the third phase in 2026 involves humans landing at the Moon's South Pole; the final phase in 2028 will see astronauts living and working in the Gateway, the first lunar orbiting space station, serving as a platform for scientific research and future missions to Mars and deep space.

sovereignty in outer space, as stated in Article II of the Outer Space Treaty. They conclude that this legal conflict is mainly theoretical, with limited practical impact, since space objects can serve as a link to apply existing national laws to space activities, thereby enabling functional sovereignty under Article VIII of the Outer Space Treaty.

The issue of security is often discussed in relation to cybersecurity [143], highlighting the importance of international law in safeguarding satellite communications from cyberattacks and emphasizing the need to strengthen sanctions against states that do not uphold legal standards. Security is also examined within the context of militarization of space activities, e.g. [144, 145]. The authors emphasize the need to bolster space law to prevent the weaponization of space, which has caused environmental harm, increased debris, and unsettled international stability. They advocate for an international treaty to ban orbital weapons testing, deployment, and use. Conversely, research on Earth's environmental impact remains limited, e.g. [67, 146], though better management of Earth Observation data through shared and fair access could greatly benefit society [140].

1.4.6 Remote Sensing and Data Handling

The Remote Sensing and Data Handling cluster accounts for 9% of the sample. All articles focus on Earth Observation, so the "in space" aspect is not explored, and the primary sustainability pillar is environmental (see Table 1.7). Two main themes emerge: agriculture and land. Several studies investigate how satellite data can enhance agricultural practices. Advancements in smart and precision agriculture aim to improve field efficiency by reducing waste and supporting better decision-making for crop management, e.g. [37, 76, 147]. This research area is especially important for developing countries, e.g. [148–150].

Table 1.7: Locus/pillar matrix for the cluster *Remote Sensing and Data Handling*. The "Total" values in brackets indicate the number of articles that address both loci.

Research topics: Remote sensing and data handling	**Environmental**	**Economic**	**Social**	**Total**
On Earth	20	3	3	22
In Space	0	0	0	0
Orbit	0	0	0	0
Moon	0	0	0	0
Mars	0	0	0	0
Other	0	0	0	0
Total	**20 (0)**	**3 (0)**	**3 (0)**	**22 (0)**

The second major research area focuses on utilizing satellite data to monitor various land types, such as grasslands, wetlands, forests, and deserts, and to analyze global environmental changes, e.g., [34, 77, 151]. It specifically addresses issues related to climate change, e.g. [152, 153] and the sustainable management of natural resources [154]. Both agriculture and land research can benefit from policies that promote data democratization [155]. Expanding access to satellite data for more actors would speed up advances in data processing and enable broader scientific applications. For instance, satellite data, such as nighttime light observations, have recently been used to analyze urban economic growth and evaluate the impacts of conflict in war zones, e.g., [40, 156].

The cluster contains only a few articles focusing specifically on remote sensing for monitoring urban areas, such as those by Maktav and Erbek [39] and Musakwa and Van Niekerk [33][8]. Urban development is closely linked to social sustainability. Therefore, the findings indicate potential for expanding research on remote sensing within urbanization, especially regarding its impact on sustainable social development.

1.4.7 Emerging topics

Seventeen articles (6.7%) do not clearly fit into the other clusters. A subset of studies addresses ethical concerns related to space exploration and sustainability, e.g.[157, 158]. Notably, Beisbart [157] introduces the concept of "transplanetary sustainability" and suggests creating the 18th SDG focused on sustainability in space. This would address the unique challenges of the space environment, including extreme conditions, varying gravity, limited resources on other planets and in outer space, and the significant debris generated by human activities.

The second topic is space tourism, examined from its market and commercial perspectives, e.g. [159–161], as well as its legal and environmental dimensions, e.g. [162, 163]. In 2023, the global space tourism market was valued at 851.4 million U.S. dollars, with a projected compound annual growth rate of 44.8% through 2030 [164]. Despite anticipated economic growth, the literature highlights the need for future legal developments and research on environmental impacts. Padhy and Padhy [162] highlight the current framework's limitations, noting that uncertainty and weak enforcement could hinder sector growth. They advocate for clearer ecological regulations, stronger property rights, internationally coordinated procedures, and regulatory agencies similar to the International Civil Aviation Organization. Frost and Frost [163] focus on the environmental aspects of space tourism, particularly its often-overlooked impact on Earth, which calls for improved regulation under space law.

1.5 Sustainable Development Goals

The articles were further categorized based on the SDGs provided by Scopus. These SDGs encompass a wide range of issues, including economic growth, social inclusion, environmental sustainability, and peacebuilding. Fig. 1.8 illustrates the distribution of articles within the sample. The most frequently referenced SDG is Partnership for the Goals (SDG 17), mainly with a focus on Earth-related topics (70 articles). Other prominent SDGs include SDG 9, Industry, Innovation, and Infrastructure (47 articles), and SDG 12, Responsible Consumption and Production (30 articles). No article specifically addresses Gender Equality (SDG 5). A similar pattern was noted by Cruz Rambaud [9]

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[8] Note that we excluded three journals that focus on urban topics in our selection query; however, a detailed review of their content did not reveal false negatives—meaning we did not exclude articles containing the concepts “sustainability” and “outer space."

[9] They develop a project management tool to support sustainability in the aerospace industry, aiming to describe recent green initiatives in the sector and their contribution to the SDGs.

[165]. They found that in the aerospace industry, the most discussed SDGs were 12, 9, 7, and 13.

Additionally, the Remote Sensing and Data Handling cluster shows that SDGs 2, 15, and 11 are most prevalent. These results are consistent with those of [56], who studied the ESA project's influence on the SDGs and concluded that Earth observation projects mainly affect SDGs 2, 15, and 11.

A group of 60 articles is not connected to any SDG: 50 of them focus on the space locus. This may be because the SDGs were mainly designed for applications on Earth.

The analysis of how SDGs are distributed across different research clusters shows some notable correlations (see Table 1.8). For example, the Debris cluster is closely linked to SDGs 9 and 12, while the LSS and habitat clusters are associated with SDGs 9, 12, and 15. In contrast, the research area of Remote sensing and data handling has a more varied distribution because of its wide range of applications in different contexts, which leads to a broader connection to multiple SDGs. Importantly, clusters that deal with industrial and technical aspects of space activities are most closely related to SDGs 9, 12, and 15.

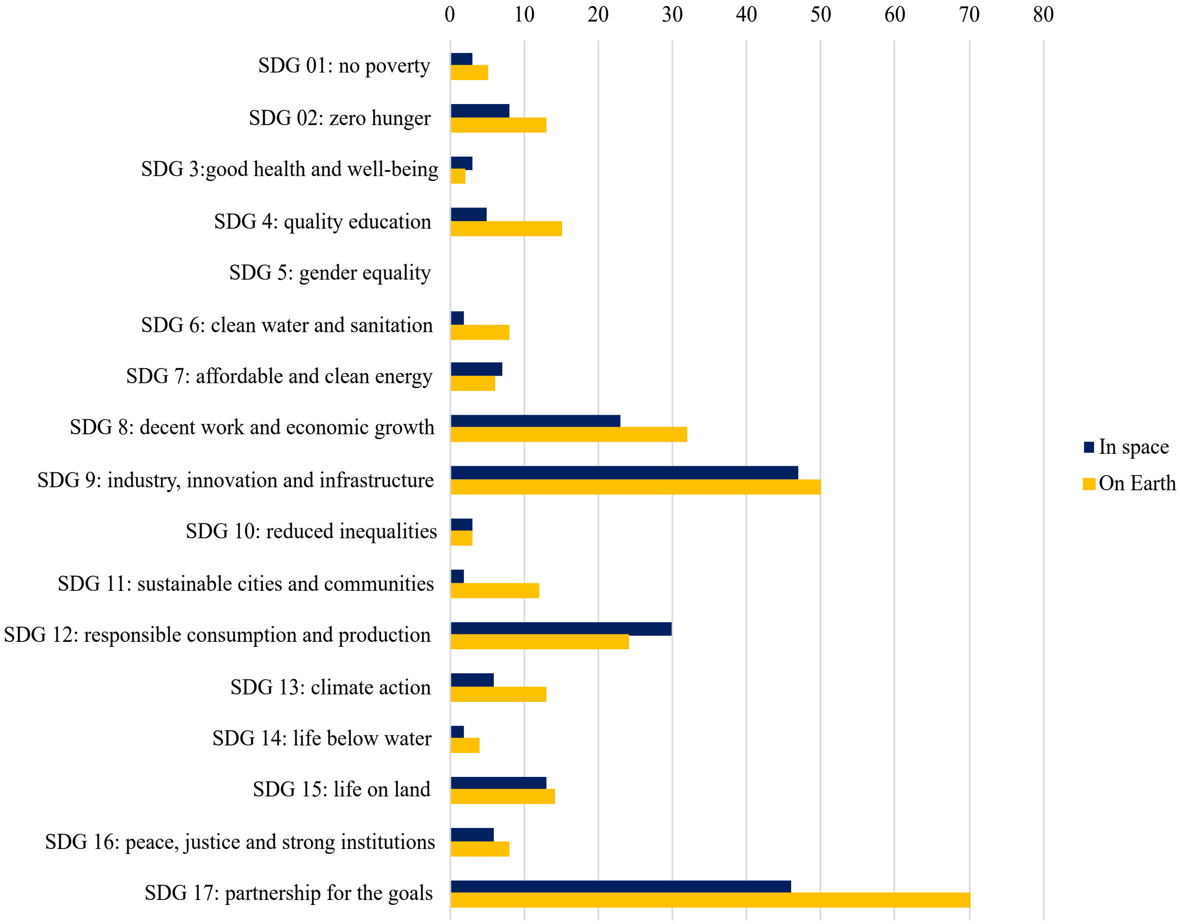

Figure 1.8: Papers distribution by Sustainable Development Goals and loci.

Table 1.8: Percentage Distribution of SDGs across the identified clusters.

	Debris	Law and regulation	LSS and Habitat	Policy	Remote sensing and data handling	Emerging topics
SDG 01			4.3	4.3	2.2	2.2
SDG 02			15.2	10.9	13.0	
SDG 03	4.3					4.3
SDG 04	2.2	2.2	6.5	15.2		8.7
SDG 05						
SDG 06	2.2		6.5	4.3	6.5	
SDG 07	4.3	4.3	10.9	4.3	2.2	
SDG 08	13.0	13.0	10.9	45.7	8.7	8.7
SDG 09	21.7	23.9	43.5	67.4	6.5	10.9
SDG 10			4.3			4.3
SDG 11			6.5	6.5	13.0	
SDG 12	17.4	8.7	23.9	21.7	8.7	13.0
SDG 13	2.2	2.2	2.2	15.2	8.7	2.2
SDG 14			2.2	2.2	4.3	2.2
SDG 15	2.2	2.2	23.9	10.9	13.0	
SDG 16	2.2	6.5	2.2	10.9	2.2	2.2
SDG 17	32.6	47.8	8.7	84.8	23.9	8.7
No SDG	37.0	21.7	41.3	26.1		4.3

1.6 Gaps and future research avenues

The analysis of the existing literature highlights gaps and opportunities for further research. Notably, there are relatively few studies on the impact of space activities on Earth's environmental sustainability. Most of these focus on direct terrestrial connections, such as remote sensing [39], or explore new space technology applications, like the use of LSSs in Earth scenarios [105]. Nonetheless, there is potential to expand research into other areas, particularly by incorporating the perspective of environmental sustainability on Earth. This could include examining international space programs and the organization of national agencies, where increased awareness might catalyze further exploration of this aspect.

Focusing on the "in space" locus of research area, the economic and social aspects of sustainability are less explored than the environmental aspect. Regarding the economic pillar, one promising area for future study is the Debris cluster, as discussed in the following paragraphs. The economic aspect could also be further developed within the LSSs and habitat groups, which appear to have scope for addressing the social challenges associated with living in orbiting stations, spaceships, and colonies on other celestial bodies. Limited resources, confined environments, distance from Earth, and hazardous conditions pose significant risks to astronauts and future inhabitants. These concerns are especially important for scholars and practitioners considering the upcoming Moon missions and planned Mars expeditions.

The analysis of the identified clusters revealed underdeveloped research areas: in some cases, this stems from the inherent definition of the theme (for example, the Earth locus is not addressed in the Debris cluster), while in others, additional studies could enhance understanding of the topic.

The Policy group primarily focuses on terrestrial activities and the policies required to support new space initiatives, promote equitable access to space for developing nations, and foster the growth of space agencies. International collaboration is vital for space exploration. Access to space requires a collective global effort, including the integration of emerging countries into the space sector. Resources should be shared fairly to encourage technological advancement worldwide, along with expanding launch sites and ground facilities, especially at the equator, where launch costs are lower. In this setting, sustainability can serve as a cost-saving approach rather than an additional expense [78], provided measures are taken to prevent environmental damage caused by overexploited natural resources [86].

The involvement of additional partners helps streamline space access management, especially since the countries developing the technology are often different from those providing the launch sites. International collaboration is also crucial due to the scale of projects. Past efforts and upcoming developments, such as new space stations like Axiom Space and the Lunar Gateway, highlight the need for a global ecosystem [30]. These initiatives, led by private entities, involve a worldwide network of diverse partners and suppliers, including agencies, research institutions, and companies. Although the literature recognizes the importance of smooth collaboration, e.g., [72, 84, 89], further analysis that incorporates sustainability is needed. Based on the findings of this work, four main research directions were identified. First, a detailed review of past and current initiatives promoting collaboration is vital to understand what works best, using case studies and qualitative analysis. This research could analyze mechanisms involving emerging countries or propose new ones, such as the UNOOSA working group on long-term sustainability (UNOOSA, 2024), to assess their effectiveness and identify areas for improvement. Second, studies should consider whether new international organizations are necessary or if improving existing ones would be more effective. Third, future research could evaluate the sustainability of government space programs to determine their impact in relation to frameworks like the SDGs. For example, a recent study by Paravano et al. [56] examines ESA's business program portfolio from 2014 to 2022 and its influence on the SDGs. ESA established this activities platform to foster the development, testing, and validation of products, services, and businesses empowered by space technologies. Their research indicates that SDGs 2 and 3, Zero Hunger and Good Health and Well-being, are most affected, along with SDG 11, which focuses on sustainable cities and communication [56]. However, despite substantial investment and recent breakthroughs in space exploration, current studies have not sufficiently addressed the Chinese context despite the significant investment and the recent results obtained in space exploration[10].

Research on the LSS and habitat cluster has only recently begun exploring potential Earth applications for space-developed technologies. Overall, the exploration of the economic impact of developing and deploying LSSs remains limited, both on Earth and in space. Some studies examine the costs and benefits of creating closed-loop systems but lack a detailed analysis of their sustainability. These studies, such as [114] and [111],

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[10] As reported by ESA (https://space-economy.esa.int/article/102/chinas-space-sector-commercialisation-with-chinese-characteristics, accessed June 2024), China's space sector has seen remarkable commercialization over the past decade, with over 100 companies and around ¥40 billion (US$6.5 billion) in funding. China's lunar program began in 2007, with its first rover landing on December 14, 2013. Notable milestones include the first landing on the moon's dark side on March 3, 2019. The Chinese space station Tiangong, launched on April 29, 2021, with its first module, was completed by November 5, 2022.

are somewhat outdated, and recent research is scarce. Future efforts could explore the dual role of LSS as key to space exploration and as a resource on Earth, potentially supporting the achievement of the SDGs. For example, understanding parasite evolution in microgravity might lead to more resilient crops, aiding SDG 2, Zero Hunger (see [109]). Similarly, advancing water management systems could address access to clean water in emerging economies, supporting SDG 6, Clean Water and Sanitation [166]. Although many articles focus on ISRU and LSS, they often overlook sustainability aspects, particularly social sustainability related to Mars exploration and astronaut well-being in spacecraft, stations, or colonies. Incorporating sociological and psychological research could significantly enhance our understanding of these issues.

The Debris cluster emphasizes the importance of international collaboration by advocating for information-sharing systems on orbital debris and the development of more effective, stricter guidelines, especially concerning disposal. Policymakers should consider new research findings to develop comprehensive strategies that balance the growth of the space sector with environmental sustainability. Currently, addressing space debris mainly involves establishing policies that define regulatory frameworks and clarify responsibilities. Improved analyses could help characterize international agreements that exceed non-binding guidelines, promoting enforceable treaties holding nations and private entities accountable for debris management. Legal measures engaging all stakeholders, along with a thorough analysis of debris's economic impact, could further support solutions. Notably, there is a lack of studies on liability for damages caused by debris to other space vehicles. From a technological standpoint, efforts often focus on improving passive or tracking systems rather than developing active debris removal devices. Mitigation strategies remain inconclusive, partly due to their early development stage and the limited data available. However, a comparative analysis, whether qualitative or quantitative, of technological and organizational approaches regarding their effectiveness and sustainability would improve understanding. Future research should also investigate the socioeconomic impacts of space debris on Earth, an area that remains under-investigated. Debris proliferation impairs sky visibility, affecting astronomical observations, and risks damaging satellites, thereby threatening vital services such as telecommunications and GPS [137]. These research directions relate to several SDGs. SDG 9, Industry, Innovation, and Infrastructure, is particularly relevant, considering how space debris growth affects active satellites. Likewise, SDG 17, Partnerships for the Goals, emphasizes the need for international cooperation, regulation, and shared responsibility to address space debris issues.

The Law and Regulation cluster emphasizes the need to enhance space treaties and regulatory frameworks, particularly in terms of sustainability, e.g. [138, 139, 167], with a focus on ensuring Earth's environmental sustainability. The articles collectively emphasize the importance of enhancing international space laws and promoting global cooperation across various domains, including access to space and the regulation of mega-constellations, e.g. [140, 141]. A significant focus is also given to security issues that impact the environment and geopolitical stability [144]. A key challenge is the unclear boundary between airspace and outer space. Airspace is usually considered sovereign territory of nations, whereas outer space is governed by international agreements that prohibit claims of sovereignty. This boundary ambiguity complicates the application of national and international laws to space activities [168, 169]. Therefore, legal frameworks should be updated to address contemporary issues, such as defining territorial boundaries and private property rights. Additionally, more attention should be given to the Moon and Mars to protect environmental sustainability and promote the development of sustainable economic and social colonies.

Within the Remote Sensing and Data Handling cluster, there is potential for future growth by expanding existing research areas, such as agriculture and land use, and exploring new ones, including impact and aviation. Current findings indicate that applying "space-derived" data can further regional and urban analyses, particularly regarding the social dimensions of sustainability, e.g. [33, 39]. Topics for development include enhancing green spaces, precision agriculture, monitoring urban heat islands, tracking migration flows, and assessing urbanization. Additional research could evaluate the positive effects of space data and extend findings on climate change and mitigation in vulnerable areas, e.g. [34, 151, 152], by performing economic assessments of satellite data use. New application areas, such as monitoring changes in wind gusts and turbulence and their impact on aviation, may also emerge as further discussed in Chapter 3. These research avenues can significantly contribute to several SDGs, notably SDG 2 (Zero Hunger) and SDG 6 (Clean Water and Sanitation) through remote sensing in agriculture, and SDG 13 (Climate Action), SDG 15 (Life on Land), and SDG 12 (Responsible Consumption and Production) through climate change monitoring. The UNOOSA report [170] highlights the role of space technology in advancing the entire Agenda 2030.

Regarding the emerging topics cluster, space tourism is an expanding research area; however, studies focusing on sustainability remain in their early stages. As the space industry expands and attracts new players, it is crucial to anticipate future environmental, social, and economic challenges. Doing so will help ensure that these advancements benefit both space and Earth ecosystems.

Chapter 2

The Future of Space Sustainability

This chapter explores the projected development of space sustainability in the forthcoming years. It presents the findings of a Delphi study conducted with a panel of 63 international experts from the space sector. The study examines expected trends in space sustainability through 2040 and the roles of key stakeholders in shaping these trends. Organized into three iterative rounds, the study involved academic, governmental, and industrial experts; two rounds were performed consecutively while the third occurred one year later to assess changes in expert perspectives amid geopolitical shifts between 2024 and 2025. The methodology employed both open and closed-ended questions utilizing a Likert scale, along with three distinct criteria to measure consensus among the expert panel. Among the main findings, the need to strengthen international cooperation and update the legal framework to promote and advance sustainability in the sector is clear. Additionally, given recent geopolitical events, there is a disagreement among experts about the potential role of universities in the future sustainable development of space technology.

2.1 Geopolitics and Defence in Space Exploration

In recent decades, outer space has evolved from being a mainly scientific domain to a strategic arena where geopolitical rivalry, security concerns, and technological ambitions converge. This evolution presents major challenges to the long-term sustainability of space activities [16]. In the current climate of increased international instability, technological independence is now vital for protecting national sovereignty and maintaining space capabilities.

The leading global players, the United States, the European Union, and China, are following parallel, and often competing, paths in this area [171]. The United States maintains a dominant position, supported by a strong public–private ecosystem exemplified by the Artemis program and the growing role of companies like SpaceX. China, on the other hand, is rapidly progressing toward full technological self-sufficiency through developing infrastructures such as the Tian-gong space station and the Chang'e lunar program, both of which have direct implications for national defence. The European Union, although behind in certain aspects, especially in independent access to space, has been working to boost its resilience through initiatives like Galileo, Copernicus, and the upcoming IRIS^2 constellation. These programs aim not only to enhance technological competitiveness but also to lessen dependence on external actors, particularly in key sectors such as navigation, Earth observation, and secure communications [172].

Despite the increasing significance of strategic competition, international collaboration remains essential due to the substantial costs and inherent complexities associated with space exploration [16]. Geopolitical tensions have begun to weaken this cooperative framework. A notable example is the suspension of the ExoMars mission, initially a joint endeavour between the European Space Agency (ESA) and Roscosmos, subsequent to Russia's invasion of Ukraine [173]. Conversely, the NASA-led Artemis program, which involves significant participation from ESA and other agencies, demonstrates how multilateral diplomacy can still be promoted in space activities, particularly through the Artemis Accords. Nevertheless, such frameworks remain vulnerable to evolving national interests and broader political uncertainties. Recent scholarly research highlights that leading space missions frequently extend beyond their scientific objectives, influencing public perception, international relations, and security strategies, thus reinforcing space as a domain of political power and influence [174].

2.2 Methodology

2.2.1 The Delphi method

The Delphi method, adopted in this chapter, is widely acknowledged as one of the most useful techniques for collecting insights and data from field experts and deriving expectations on future trends (see for example, the seminal studies of Dalkey and Helmer [175]; Linstone [176]; and among more recent cases: Di Zio [177]; Jünger et al. [178]; Rowe and Wright [179]; Veugelers et al. [180]). The main objective of the Delphi approach is to achieve the largest consensus among the experts on the subject under examination. The main and most common steps in the application of the Delphi method are the following: 1) the selection of a group of experts; 2) the creation and distribution of an initial questionnaire on the investigated topic; 3) the analysis of the responses; 4) a second questionnaire, allowing panelists to reconsider their views based on the group's aggregated responses. In some cases, steps 2-4 are repeated until a pre-determined number of rounds is reached, or a consensus threshold is achieved.

Experts are typically invited to rate a series of statements on a Likert scale. Data are treated anonymously, and numerical responses are aggregated in mean values and measures of dispersion to facilitate interpretation [180, 181]. Consensus measurement is commonly determined by calculating percent agreement, usually when a threshold of 65-75% of experts is aligned [182], or by analyzing response dispersion [183]. In addition, experts are often requested to provide open-ended responses that contribute to framing a more detailed picture, identifying outliers or minority views, and the reasons for dissent. Analyzing free-text responses presents several methodological challenges, but it can also enhance the interpretation of quantitative data, e.g., [182, 184]. The Delphi method has been employed in numerous studies to evaluate future trends, including recent cases in space exploration and sustainability. These studies have focused on a specific aspect and analyzed the factors that hinder or promote its development. For instance, Aliakbargolkar and Crawley, [185] examine in-orbit transportation infrastructure for human space exploration, outlining key aspects, recommendations, and future requirements. Profitiliotis and Haqq-Misra, [66] focus on Mars exploration and planetary preservation, addressing economic, commercial, and political challenges related to Martian resource utilization and environmental conservation. Spedding et al., [186] investigate issues surrounding lunar outposts and the technological development of in-situ resource utilization (ISRU), nuclear power, and solar energy to promote an established lunar outpost. Finally, Toivonen, [187] explores the sustainability of space tourism, conducting an empirical study on Finnish public perceptions regarding the intersection of space tourism and environmental responsibility. In contrast to the aforementioned studies, which each concentrate on a single theme, this work adopts a more comprehensive approach by examining multiple aspects related to space sustainability and highlighting the role of various stakeholders in fostering sustainable growth within the sector.

2.2.2 Preliminary activities and selection of experts

In early 2024, initial steps were taken to organize the Delphi survey. Relevant topics were identified, experts chosen, and a questionnaire was created and tested to confirm clarity for participants.

Regarding the identification of topics, the work was based on literature concerning space sustainability [56, 86] and on the findings presented in Chapter 1. The topics of interest can be grouped into 8 main clusters, which will represent the corresponding sections of the questionnaire: sustainability in policy and law, debris mitigation technology, access to space technology, remote sensing activities, LSSs and habitat design, spacecraft design, and geopolitics and defence.

Several sources were employed to select the panel of experts. The identification process involved contacting the experts via email, with addresses obtained from i) members of IAF committees, ii) principal investigators featured in projects collected in TechPort, iii) experts were contacted via the professional networking platform LinkedIn, iv) the founders of startup enterprises operating within the space sector, identified and sourced through the Dealroom platform and v) the authors' personal contacts. This resulted in the collection of approximately 950 contacts. A Google Form was created to obtain the willingness of the potential experts to participate in the study. Additionally, experts were contacted passively through the posting of a call for participation on the LinkedIn page of the Italian Association of Aeronautics and Astronautics (AIDAA), which gathers 4000 contacts, including professors, researchers, and experts in the space sector, primarily Italian but also international. Furthermore, the call for participants was posted on the Telegram channels of the Space Generation Advisory Council (SGAC), a community of over 29,000 young space professionals. In the call for participation, all applicants were required to declare that they had at least three years' experience in the field to meet the selection criteria[1]. These activities led to the identification of 63 individuals who expressed their willingness to participate in the study and declared to have at least three years of experience in space-related activities. This preliminary response rate is estimated to be approximately 6%. This group of experts constituted the panel for the rounds of the survey.

2.2.3 Structure of the questionnaire and dissemination

The questionnaire was initially distributed to a limited number of participants to identify ambiguous questions. However, no significant issues were identified, confirming the clarity and relevance of the proposed questions.

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[1] The passive method estimates a pool of 6000 receivers who might overlap with the actively reached contacts.

The questionnaire was administered in three rounds to examine the trajectory of sustainability in space over the coming years and identify the key stakeholders for sustainable development. Two types of questions were included: closed and open-ended. The closed questions were designed using a Likert scale, ranging from 1 to 5. A point of comparison with the existing situation was established by repeating closed questions, focusing on both the present and prospective scenarios for 2040. The year 2040 is significant for space sustainability due to global efforts to address the space debris problem, achieve net-zero emissions in space activities, implement UN sustainability guidelines, and binding international treaties (e.g., [188–190]. The open-ended questions enabled participants to provide further insights and details about their responses, as well as to present their perspectives on the main challenges to sustainable development in each area of investigation. Recurrent themes found in the open-ended responses of the first round were also included as new questions in the second round.

The questionnaire consisted of three main parts, as depicted in Table 2.1. The first, which focused on policy and legal aspects, asks respondents to indicate the extent to which space policies and legal frameworks promote environmental, economic, and social sustainability. In addition, the open-ended question asked participants to identify the main problems in developing space policies and legislation that would better support sustainability. The second part of the questionnaire examines the roles of various stakeholders in the sustainable development of different technologies. Respondents were invited to indicate the importance of each stakeholder (i.e., large and private companies, small and medium-sized enterprises (SMEs), startups, university and public research centers, government organizations, and international institutions) in the sustainable development of space technology or the activity under investigation. Additionally, in the open-ended questions, respondents were asked to identify the key challenges related to the sustainable development of each technology. The final part focused on geopolitical factors, defence and non-defence investment, and their interaction with technological development.

The responses from the first round were collected between April and mid-May 2024. After the initial invitation, two fortnightly reminders were sent to the experts involved (the same approach was applied in all the rounds of survey administration). The second round lasted between mid-June and July 2024 and finally the third round from April to mid-May 2025. Table 2.2 shows the number of experts who participated in the three rounds (with a response rate of 70%, 63% and 55% on the size of the panel, respectively).

After the first round, the results were analyzed to identify consensus in the closed-ended questions. Questions that did not achieve consensus were submitted again in the second round. Further details regarding the consensus criteria can be found in Section 2.2.4. The second objective is to analyze the open-ended questions to identify any significant insights and, subsequently, to consider introducing additional themes for the second round. Indeed, the comments on the sustainable development of space activities highlighted pivotal factors in the following areas: policy and legislation, debris mitigation, life-support systems (LSS) and habitat design, and spacecraft design. These factors were investigated in the second round, using additional closed-ended questions. It is important to note that when divergent opinions were expressed in the open-ended question, both were considered, and the totality of the panel's opinion was investigated. For instance, respondents advocated that implementing international policies could promote more sustainable practices. In contrast, another group preferred the establishment of national policies and a reduction in centralized governance as actions to promote sustainability. In these cases, both opinions were taken into consideration. Finally, the

Table 2.1: Survey structure.* Questions added after the first round, from the analysis of the open-ended questions. ** Questions added in the third round.

Part 1	
Space Policy / Space law and regulations	Q1 Sustainability pillars space law Q2 Sustainability pillars for space policy Q3* Factors that impact sustainability in policies and laws
Part 2	
Debris	Q4 Issues related to debris mitigation Q5 Stakeholders' role in the sustainable development of debris mitigation technology Q6 Issues related to the sustainable development of debris mitigation technology Q7* Factors related to debris mitigation and sustainable development of debris mitigation technology
Access to space technology	Q8 Stakeholders' role in the sustainable development of access to space technology Q9 Issues related to the sustainable development of access to space technology
Spacecraft design	Q10 Stakeholders' role in the sustainable development of spacecraft design Q11 Issues related to the sustainable development of spacecraft design Q12* Factors impacting the sustainable development of spacecraft design
Remote sensing and data handling activities	Q13 Stakeholders' role in the sustainable development of remote sensing activities Q14 Issues related to the sustainable development of remote sensing activities Q15** Which stakeholder do you think will be the main driver of development in the following sub-areas of Remote Sensing in the next 15 years?
LSS and habitat design	Q16 Stakeholders' role in the sustainable development of remote sensing activities Q17 Issues related to the sustainable development of remote sensing activities Q18* Factors impacting the sustainable development of LSSs and habitat design
Part 3	
Geographical leader area	Q19** Considering your previous answers, which geographical area do you expect to lead technological development in each of the following fields?
Private and Public investments	Q20** Looking at the global scenario, will public and private investment in the following technological areas decrease or increase in the next 15 years?
Investments in Defense and Security	Q21** Considering the global scenario, do you expect public and private Defence & Security investments will have an impact on the development of space technology in the next 15 years?

Table 2.2: Survey scheduling.

Round	Survey delivery period	Responses
1	From April to mid-May 2024	44
2	From mid-June to July 2024	40
3	From April to mid-May 2025	39

third round was conducted to investigate whether the experts' views had changed after one year, considering the geopolitical scenario, and to assess the influence of private and public investments, as well as investments in defense and security, on sustainable and technological development in the space sector. Based on the expert feedback and the answer rate, it was concluded that achieving a high response rate for several additional Delphi rounds would be challenging. Given the high stability and consensus observed in the closed-ended questions, as well as the ability to draw relevant conclusions from the open-ended questions, the decision was made to terminate the study after three rounds.

2.2.4 Consesnus Criteria

The definition of consensus in closed-ended questions is based on three measures: the interquartile range (IQR), the degree of polarization in responses, and the mean value. The IQR, defined as the difference between the lower quartile (Q1) and the upper quartile (Q3), is a widely used metric to measure consensus in Delphi studies [181]. According to this criterion, the consensus is reached when the IQR is less than 1. As a secondary criterion, the percentage of responses at each of the two poles is utilized to evaluate the polarization of reactions towards one extreme. Indeed, the 5-point Likert scale ranges from "very negative" to "very positive," and each question is evaluated accordingly. The consensus is reached when the sum of positive and very positive responses, and the sum of negative and very negative responses, exceeds the threshold set at 65%. The mean is used to find consensus when the two criteria give different results. Specifically, consensus is considered reached when the mean is above 3.5 or below 2.5.

2.3 Panel Description

Sixty-three space industry experts participated in this study. The panel comprised professionals from diverse backgrounds, including space technology, environmental science, policymaking, and industry leadership, as indicated by their various affiliations (Fig. 2.1 (left)). More than thirty percent of these experts have over twenty years of experience in the field (Fig. 2.1(right)). This diversity ensured that panelists had a well-rounded understanding of the sustainability challenges and opportunities in the space sector.

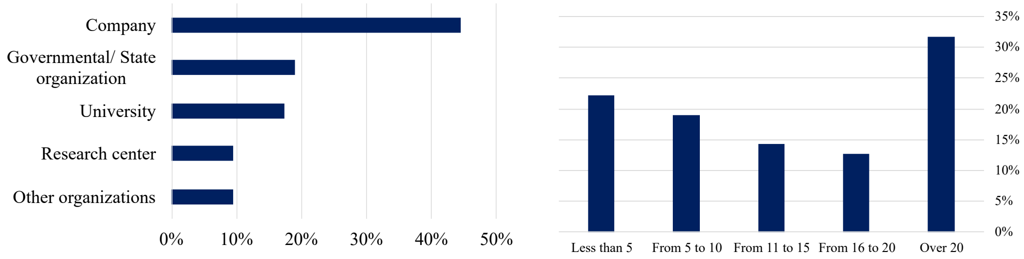

Figure 2.1: Affiliations of experts' panel (left) and years of experience of the experts (right).

Table 2.3 presents the geographical distribution of the experts, with 68% from Europe and 20% from North America. The remaining experts come from different countries across Asia, Oceania, and South America. As shown in Table 2.4, about one-third of the experts are female.

Table 2.3: Geographical distribution of the experts' panel.

Country/State	**% of experts**
Europe	68.3
North America	20.6
South and Centre America	4.8
Asia	3.2
Oceania	3.2

Table 2.4: Gender distribution of the experts' panel.

Gender	**% of experts**
Female	31.7
Male	65.1
Not relevant/prefer not to say	3.2

2.4 Results and discussion

This section highlights the chapter's main findings, focusing on experts' views on the development of space sustainability across each key area studied. It emphasizes the gap between the current state and the expected progress by 2040. Additionally, it outlines the significant challenges to sustainable development identified through open-ended questions in each area. The section also presents results from the third round of investigation for each topic.

The data on the current situation, included here, is used mainly as a benchmark to compare with the anticipated evolution proposed by the experts. These questions were omitted in the second round because most participants reached consensus; however, they are included again in the third round to evaluate experts' opinions one year after the previous phase.

2.4.1 Space Policy and Law

The initial macro area focused on policies, laws, and regulations that support sustainability in space based on the three main pillars: economic, environmental, and social. This section includes three questions:

Q1 Do "Space Laws and Regulations" encourage sustainable practices, considering environmental, social, and economic factors, today? And in 2040?

Q2 How effectively are "space policies" supporting the sustainability of space activities in terms of the environment, economy, and society in the present day? And in 2040?

Q3 Please rate the effectiveness of these initiatives for the sustainable development of "Space Law and Regulations" and "Space Policy" up to 2040.

The results for Q1 and Q2 are summarized in Table 2.5 and Table 2.6. Concerning Law and Regulation, there is agreement on the importance of both environmental and social sustainability. Experts note that current legislation often fails to prioritize sustainability in these areas. In addition, there is a shared view that current policies are inadequate in effectively promoting social sustainability.

Looking ahead to 2040, the second-round survey revealed that 67% of respondents anticipated a significant increase in focus on environmental sustainability (see Appendix B). However, this consensus declined when the same question was asked again during the third round (see Table 2.5). The agreement in the second round reflected ongoing efforts by space agencies to advance international policies and treaties, such as addressing space debris and supporting collaborative initiatives, such as the Artemis Accords for lunar exploration. By the third round, expert opinions became more uncertain. This change highlights growing concerns over unresolved externalities, including orbital debris, atmospheric pollution, and the overuse of Low Earth Orbit (LEO), which require complex regulatory solutions in a fragmented geopolitical landscape. Finally, regarding economic and social sustainability, expert opinions remain inconsistent.

Table 2.5: Results for Q1: Do *Space Laws and Regulations* encourage sustainable practices, considering environmental, social, and economic factors, today? And in 2040? A consensus was reached on the environmental pillar in the second round. However, between the second and third rounds, consensus on environmental sustainability was lost, as indicated by *.

	Law and regulation											
	Today						**By 2040**					
	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus
Environmental sustainability	2.2	1	62.9	28.6	8.6	Yes	3.2	2	28.6	22.9	48.6	No*
Social sustainability	2.2	2	65.7	22.9	11.4	Yes	2.9	2	37.1	31.4	31.4	No
Economic Sustainability	2.4	2	51.4	31.4	17.1	No	3.1	2	34.3	22.9	42.9	No

Table 2.6: Results for Q2: How effectively are s*Space Policies* supporting the sustainability of space activities in terms of the environment, economy, and society in the present day? And in 2040? A consensus was reached on the environmental pillar in the second round. However, between the second and third rounds, consensus on environmental sustainability was lost, as indicated by *.

	Space Policy											
	Today						**By 2040**					
	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus
Environmental sustainability	2.5	1	57.1	22.9	20.0	No	3.3	1	22.9	25.7	51.4	No*
Social sustainability	2.4	1	57.1	34.3	8.6	Yes	2.9	2	28.6	45.7	25.7	No
Economic Sustainability	2.7	1	31.4	57.1	11.4	No	3.4	1	17.1	34.3	48.6	No

The comment section highlighted several obstacles to creating sustainable space policies and laws. The main issues are the lack of international standards and the mismatch between national laws and outdated treaties. Current frameworks, shaped by a few leading nations, overlook the needs of diverse stakeholders, including emerging countries and private companies. A key challenge is the limited incentives for sustainable practices, which hampers innovation, especially for startups and developing nations facing higher costs and technical difficulties. As shown in Table 2.7, experts agree that strengthening legal and regulatory systems at both national and global levels is essential, with a preference for improving existing international organizations rather than creating new ones. Comparing the second and third survey rounds indicates that, although international organizations remain crucial for sustainability, their effectiveness is perceived to have declined, with the average rating dropping from 4.0 to 3.5. There was also disagreement about imposing stricter sanctions. Therefore, experts recommend that future efforts focus on international cooperation and updating legal frameworks to better address challenges in space exploration.

Table 2.7: Results for Q3: Please rate the effectiveness of these initiatives for the sustainable development of *Space Law and Regulations* and *Space Policy* up to 2040.

	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	**Consensus**
Strengthening of National legislative/regulatory bodies	3.7	2	22.9	8.6	68.6	Yes
Strengthening of International legislative/regulatory bodies.	3.5	1	22.9	11.4	65.7	Yes
Creation of New International bodies.	3.0	2	40.0	20.0	40.0	No
Introduction of more severe sanctions.	3.0	2	34.3	28.6	37.1	No

2.4.2 Debris mitigation

The debris mitigation investigation was conducted from two perspectives: policy (Q4) and technology (Q5 and Q6). Moreover, the major challenges and potential mitigation strategies found in the initial survey were discussed with experts during the second round (Q7). This section's questions evaluate experts' opinions on particular issues and mitigation strategies (Q4, Q6, and Q7) as well as the roles of key stakeholders in the NSE (Q5):

Q4 Considering the problem of "space debris", what are the most critical issues in developing effective policies up to 2040?

Q5 Considering the technologies for "debris mitigation", please rate the importance of the following stakeholders in supporting sustainable development.

Q6 Considering "debris mitigation" technologies, what are the most critical issues for sustainable development up to 2040?

Q7 Please rate the impact of the following factors in mitigating "space debris" and supporting sustainable space activities up to 2040.

From a technological standpoint, there is agreement on the crucial role that space agencies and large corporations currently play in debris mitigation, as shown in Table 2.8. However, opinions vary regarding the involvement of other stakeholders. Looking ahead, the panel agrees that large corporations, start-ups, SMEs, and space agencies will be at the forefront of developing sustainable debris-mitigation technologies. Corporations are already creating markets for services such as debris removal, end-of-life disposal, and life-extension technologies. These efforts are crucial because space debris presents a significant global challenge to the space community. On the other hand, experts are split on whether international organizations, universities, and research institutions will participate more actively in the future. Notably, a year ago, the panel believed these stakeholders would play a significant role, but their confidence has since waned. This change reflects growing uncertainty, likely driven by policy trends that favour private sector leadership over academic and research involvement. For international organizations, the reduced consensus is primarily due to rising geopolitical tensions and increasingly nationalist policies, which have hindered international cooperation and reduced the effectiveness of these institutions.

Table 2.8: Results for Q5: Considering the technologies for *debris mitigation*, please rate the importance of the following stakeholders in supporting sustainable development. Between the second and third round, consensus was lost for some stakeholders as indicated by *.

	Debris mitigation technology											
	Today						**By 2040**					
	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus
Large private companies	3.7	2	17.1	17.1	65.7	Yes	4.2	1	8.6	5.7	85.7	Yes
SMEs and startups	3.4	1	17.1	25.7	57.1	No	3.9	2	11.4	14.3	74.3	Yes
Space agencies, national and intergovernmental bodies	4.2	1	8.6	2.9	88.6	Yes	4.1	1	8.6	8.6	82.9	Yes
Universities and public research centers	3.1	1	22.9	42.9	34.3	No	3.5	1	20.0	28.6	51.4	No*
Other international organizations	3.0	2	37.1	25.7	37.1	No	3.5	1	22.9	28.6	48.6	No*

Table 2.9 shows that experts agree that advancing debris mitigation sustainability depends on developing fully reusable systems and investing more in natural deorbiting methods. These measures should be included during the initial mission planning stages. For example, integrating atmospheric drag enhancement systems or implementing more advanced procedures, like autonomous relocation to graveyard orbits, should be considered early. At the same time, there is a strong need to improve debris-tracking technology. However, experts are divided on the best strategies for managing and deploying mapping solutions for space debris monitoring.

Table 2.9: Results for Q7: Please rate the impact of the following factors in mitigating *space debris* and supporting sustainable space activities up to 2040.

	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	**Consensus**
Technological improvements for full-reusability spacecraft.	3.8	1	3.1	31.0	65.5	Yes
More investments in natural deorbiting systems.	3.9	2	6.9	24.1	69.0	Yes
The improvements in debris-tracking technologies.	3.8	2	13.8	17.2	69.0	Yes
Support the creation of a single centralized mapping managed by a public body.	3.5	1	10.3	37.9	51.7	No
Support multiple players (public and private), each with its own mapping approach.	3.2	1	24.1	37.9	37.9	No
Reduce the influence of launcher manufacturers on regulatory bodies dealing with debris to avoid conflicts of interest.	3.5	2	13.8	24.1	62.1	No

2.4.3 Access to Space Technology

"Access to space" in this study refers to the range of activities and technologies that allow humanity to reach and operate in space. This includes carrier technologies, such as launchers and spacecraft, as well as Earth's infrastructure, including spaceports, launch sites, and ground control centers. Space access is a strategic asset for a nation, supporting independence in key sectors like national security, telecommunications, navigation, and weather monitoring. Additionally, it drives innovation, boosts economic growth, and elevates a country's global standing [74]. A growing number of nations are enhancing their infrastructure to facilitate satellite launches into orbit or are depending on other countries for this service. Simultaneously, the importance of sustainability is becoming increasingly prominent. In light of these factors, experts have inquired about Q8 and Q9.

Q8 Considering "Access to Space" technologies, please rate the importance of the following stakeholders in supporting sustainable development.

Q9 Considering "Access to space" technologies, what are the most critical issues for sustainable development up to 2040?

The results for Q8, shown in Table 2.10, indicate that experts see space agencies, large corporations, start-ups, and SMEs as the leading players in promoting sustainable access to space technologies. Looking toward 2040, they do not anticipate significant changes to these roles. However, there is growing awareness of the significance of SMEs and start-ups, as reflected in their rising average score from 3.6 to 4.0. In contrast, opinions about the involvement of universities, research centers, and international organizations remain divided.

Expert responses to Q9 indicate that advancing sustainable space technology depends on overcoming key challenges in the launch industry. The current rocket market is not currently meeting the growing demand, resulting in a significant mismatch between supply and demand. This gap raises payload costs, limiting wider access to space. From a sustainability perspective, increasing investments in green propellants and eco-friendly combustion materials are essential. Improving the reusability of launch systems is also vital, as it helps reduce costs and lessen the environmental footprint of space activities.

Reaching this goal relies on increased investment in research and development. Effective enforcement mechanisms in both the public and private sectors are crucial in promoting these innovations.

Table 2.10: Results for Q8: Considering *Access to Space* technologies, please rate the importance of the following stakeholders in supporting sustainable development.

	Access to space technology											
	Today						**By 2040**					
	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus
Large private companies	4.3	1	5.7	2.9	91.4	Yes	4.3	1	11.4	0.0	88.6	Yes
SMEs and startups	3.6	1	17.1	22.9	60.0	Yes	4.0	1	11.4	5.7	82.9	Yes
Space agencies, national and intergovernmental bodies	4.2	1	5.7	8.6	85.7	Yes	4.2	1	11.4	2.9	85.7	Yes
Universities and public research centers	3.1	2	34.3	28.6	37.1	No	3.1	2	34.3	25.7	40.0	No
Other international organizations	3.0	2	42.9	22.9	34.3	No	3.1	2	40.0	20.0	40.0	No

2.4.4 Spacecraft Design

Another domain of technological research regards sustainable spacecraft design. In the initial phase, questions Q10 and Q11 were posed to investigate the roles of stakeholders and the primary concerns in sustainable development. Subsequently, question Q12 was formulated based on the responses to question Q11.

Q10 Considering technological advancements in "Spacecraft", please rate the importance of the following stakeholders in supporting sustainable development.

Q11 Considering technological advancements in "Spacecraft," what are the most critical issues for sustainable development up to 2040?

Q12 Please rate the impact of the following factors in "Spacecraft" to favour the sustainable development of Space activities up to 2040.

As demonstrated in Table 2.11, the majority of experts concur that large corporations and space agencies currently lead in this domain. Nevertheless, perspectives concerning other stakeholders exhibit variability. Looking toward 2040, experts project that small and medium-sized enterprises, universities, and research centers will also play pivotal roles in the sustainable development of spacecraft design, alongside space agencies and large corporations. Conversely, there is no consensus among the panel regarding the involvement of international organizations; indeed, their viewpoints are entirely contradictory.

Table 2.11: Results for Q10: Considering technological advancements in *Spacecraft*, please rate the importance of the following stakeholders in supporting sustainable development.

	Spacecraft Design											
	Today						**By 2040**					
	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus
Large private companies	4.2	1	5.7	8.6	85.7	Yes	4.4	1	2.9	2.9	94.3	Yes
SMEs and startups	3.5	2	22.9	22.9	54.3	No	4.1	1	5.7	14.3	80.0	Yes
Space agencies, national and intergovernmental bodies	4.3	1	2.9	14.3	82.9	Yes	4.3	1	11.4	0.0	88.6	Yes
Universities and public research centers	3.3	2	28.6	22.9	48.6	No	3.6	1	17.1	20.0	62.9	Yes
Other international organizations	2.5	3	54.3	20.0	25.7	No	2.8	3	45.7	17.1	37.1	No

Analysis of the open-ended responses to Q11 revealed several key factors that could facilitate the sustainable development of spacecraft design. These factors were subsequently evaluated in Q12 to assess the level of consensus among experts, as illustrated in Table 2.12. The panel unanimously agreed on the significance of developing more autonomous and intelligent systems, considering them essential for enhancing mission efficiency, ensuring safer operations, and ultimately reducing costs. Conversely, there was no consensus regarding the other factors. This lack of consensus may reflect broader uncertainties about future priorities, diverse stakeholder perspectives, and the roles these measures could play in supporting sustainable space exploration.

Table 2.12: Results for Q12: Please rate the impact of the following factors in *Spacecraft* to favor the sustainable development of Space activities up to 2040.

	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	**Consensus**
Technological advancements in radiation protection systems	3.7	2	18.5	22.2	59.3	No
The development of more autonomous and intelligent systems	4.3	1	7.4	7.4	85.2	Yes
Development of Space-Based Solar Power technology	3.5	2	22.2	25.9	51.9	No
Development of space weather monitoring	3.3	2	25.9	25.9	48.1	No
Relax the requirements on technological readiness	3.3	2	59.3	29.6	11.1	No

2.4.5 Remote sensing and data handling activities

As previously discussed, the use of satellite data to promote sustainability and enhance our understanding of Earth's phenomena has become a common practice. However, it is not yet fully developed in some aspects. The questions below have been submitted to investigate the role of the stakeholders in this area.

Q13 Considering "Remote sensing and Data handling" activities, please rate the importance of the following stakeholders in supporting sustainable development.

Q14 Considering "Remote sensing and Data handling" activities, what are the most critical issues for sustainable development up to 2040?

Q15 Which stakeholder do you think will be the main driver of development in the following sub-areas of Remote Sensing in the next 15 years?

Table 2.13 demonstrates that experts predominantly concur on the substantial contributions of large corporations, space agencies, SMEs, and startups to the sustainable advancement of remote sensing initiatives. By 2040, these stakeholders are expected to continue in their influential roles, while universities and research centers are anticipated to assume greater importance. Nevertheless, there is no consensus on the future role of international organizations, reflecting uncertainty about their capacity to influence technological and regulatory progress amid the shifting geopolitical landscape.

To conduct a more comprehensive examination of these dynamics, experts responded to Q15, which focused on specific subdivisions within the field of remote sensing, such as Earth observation, telecommunication, and navigation. The objective was to assess stakeholder influence within each area with greater precision. As illustrated in Table 2.14, experts identified space agencies and large companies as the primary drivers of technological progress in both navigation and EO. Conversely, in the telecommunications sector, large companies are anticipated to lead future innovations. This distinction mirrors broader trends within the space industry. Navigation and EO initiatives often involve long-term strategic goals, security considerations, and substantial public funding, with space agencies collaborating closely with industry partners. In contrast, the telecommunications sector has evolved into a highly commercial domain, marked by rapid innovation, market-driven constellation deployments, and active private investment. As a result, large corporations exert dominant influence in this sector, with governmental entities primarily serving as regulators or facilitators rather than direct implementers of technological advancements.

Table 2.13: Results for Q13: Considering *Remote sensing and Data handling* activities, please rate the importance of the following stakeholders in supporting sustainable development.

	Remote sensing and data handling activities											
	Today						**By 2040**					
	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus
Large private companies	4.1	1	2.9	11.4	85.7	Yes	4.3	1	5.7	5.7	88.6	Yes
SMEs and startups	3.9	1	14.3	8.6	77.1	Yes	4.2	1	5.7	5.7	88.6	Yes
Space agencies, national and intergovernmental bodies	4.4	1	2.9	2.9	94.3	Yes	4.4	1	5.7	0.0	94.3	Yes
Universities and public research centers	3.8	2	11.4	25.7	62.9	No	3.8	2	17.1	11.4	71.4	Yes
Other international organizations	3.1	2	40.0	17.1	42.9	No	3.3	3	40.0	8.6	51.4	No

Table 2.14: Results for Q15: Which stakeholder do you think will be the main driver of development in the following sub-areas of *Remote Sensing* in the next 15 years?

	Large private companies	SMEs and startups	Space agencies, national and intergovernmental bodies	Universities and public research centers	Other international organizations	Total
Navigation	37.1	11.4	34.3	5.7	11.4	100.0
Earth Observation	31.4	14.3	40.0	8.6	5.7	100.0
Telecommunication	68.6	11.4	5.7	5.7	8.6	100.0

In Q14, an assessment was conducted concerning the primary challenges associated with the sustainable development of remote sensing activities. A notable finding is the immediate need to enhance data democratization and dissemination, alongside the importance of fostering international collaboration to achieve this goal. Such cooperation is vital to ensure that data accessibility benefits the global space community and promotes equitable growth. From a technological standpoint, congestion in LEO has become a significant concern, underscoring the need for an efficient system to enhance space situational awareness. The increasing number of satellites in LEO complicates orbital management and heightens collision risks, thus making the deployment of advanced tracking and coordination systems essential. An additional challenge is the substantial financial barriers to accessing GEO, which require substantial investments in sophisticated observational instruments for effective operations, particularly compared to LEO satellites. To address these issues, it is crucial to invest in technological advancements that reduce costs associated with GEO access and operations, as well as mitigate congestion in LEO.

2.4.6 Life support systems and in situ resource utilization

The field of technology for life support systems and in situ resource utilization encompasses all technological solutions intended to facilitate human operations in space and on planetary surfaces, as well as those technologies employed to extract resources from celestial bodies for the benefit of astronauts and scientific investigation. An example of such a resource is regolith, which is used to construct radiation shielding and to collect samples for analyzing planetary composition. The present study examined sustainable development in this domain and the role of stakeholders by posing Q16 and Q17 to experts during the initial round and Q18 in the subsequent round.

Q16 Considering technologies for "Life support system and ISRU", please rate the importance of the following stakeholders in supporting sustainable development.

Q17 Considering technologies for "Life support system and ISRU", what are the most critical issues for sustainable development up to 2040?

Q18 Please rate the impact of the following factors in "LSS system and ISRU technologies" on sustainable space development up to 2040.

As shown in Table 2.15, experts agree that space agencies and major corporations currently lead the development of life support systems (LSSs). By 2040, universities, research centers, SMEs, and start-ups are expected to become key contributors as well. This predicted growth likely reflects increasing interest in space tourism and the development of private and commercial space stations. Like the International Space Station (ISS), these stations will require advanced life support systems to maintain the safety and health of humans in space. Experts' opinions about the role of international organizations remain divided. This division likely stems from these organizations' limited involvement in the design and development of LSSs technologies. Their influence primarily concerns setting regulatory standards and guidelines rather than direct innovation or growth.

Table 2.15: Results for Q16: Considering technologies for *Life support system and ISRU*, please rate the importance of the following stakeholders in supporting sustainable development.

	LSSs and habitat design										
	Today						**By 2040**				
	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus
Large private companies	3.6	1	8.6	37.1	54.3	Yes	4.1	1	8.6	5.7	85.7	Yes
SMEs and startups	3.7	2	14.3	28.6	57.1	No	4.1	1	5.7	14.3	80.0	Yes
Space agencies, national and intergovernmental bodies	4.4	1	5.7	0.0	94.3	Yes	4.4	1	5.7	5.7	88.6	Yes
Universities and public research centers	3.7	2	14.3	22.9	62.9	No	3.8	2	14.3	17.1	68.6	Yes
Other international organizations	2.6	3	57.1	8.6	34.3	No	2.9	2	45.7	17.1	37.1	No

Following a comprehensive analysis of the issues discussed in Q17 and re-evaluated in Q18, experts emphasized the critical importance of technological advancements in facilitating the sustainable development of space around LSS and ISRU technologies (see Table 2.16). Among the most influential factors is the enhancement of closed-loop systems, despite the lack of consensus. These systems are designed to recycle waste, such as converting urine into potable water on the ISS, and significantly reduce the need for resupply missions from Earth. Although technically more complex than open-loop systems, closed-loop solutions are considered vital for supporting long-duration missions and deep space exploration. Notably, bio-regenerative closed-loop systems represent a significant advancement, enabling the autonomous regeneration of essential resources, including oxygen, water, and food. However, the absence of agreement among experts does not derive from an underestimation of these systems' potential but rather from differing opinions regarding their readiness, cost-effectiveness, and suitability for various mission scenarios. Some experts regard these systems as indispensable for sustainable, long-term space habitation, while others remain cautious due to current limitations, high costs, and integration challenges. Conversely, there exists widespread consensus regarding the scalability of these technologies. Since existing life support systems tend to be mission-specific, there is a recognized need to develop modular, adaptable solutions that can be used across various spacecraft and platforms, particularly in light of the expansion of commercial stations and planetary habitats.

Experts universally acknowledge the crucial importance of in-orbit servicing, recycling, and manufacturing. These functions are essential for sustainable space infrastructure, as they can extend spacecraft lifespans, reduce reliance on Earth-based launch operations, and enable on-site production of components and materials. In-orbit initiatives are considered strategic in supporting upcoming human missions while simultaneously reducing environmental impacts and operational costs. As these technologies advance, they are set to revolutionize traditional mission architectures, shifting from disposable systems to circular, reusable models. Conversely, international cooperation has yet to reach a consensus, likely due to uncertainties stemming from geopolitical tensions and the fragmented nature of global space governance, which continue to present substantial challenges to effective collaboration and the development of shared, long-term objectives.

Table 2.16: Results for Q18: Please rate the impact of the following factors in *LSSs system and ISRU technologies* on sustainable space development up to 2040.

	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	**Consensus**
Scalability of technologies (larger or new market).	4.1	1	11.1	11.1	77.8	Yes
International collaboration.	3.8	2	14.8	22.2	63.0	No
In-orbit servicing, recycling, and manufacturing in space.	4.0	1	7.4	14.8	77.8	Yes
Development of bio-regenerative life support systems.	4.0	2	11.1	25.9	63.0	No
Developments in new energy generation, e.g., nuclear technology.	4.0	2	7.4	18.5	74.7	Yes
Advancements in closed-loop systems.	4.0	2	7.4	29.6	63.0	No

2.4.7 Geopolitics and Defence

Finally, the influence of geopolitical dynamics on the development of space technologies, along with public and private investments, as well as Defence and Security investments, was examined. Specifically, the following questions were addressed.

Q19 Considering your previous answers, which geographical area do you expect to lead technological development in each of the following fields?

Q20 Looking at the global scenario, will public and private investment in the following technological areas decrease or increase in the next 15 years?

Q21 Considering the global scenario, do you expect public and private Defence & Security investments to have an impact on the development of space technology in the next 15 years?

Table 2.17: Results for Q19: Considering your previous answers, which geographical area do you expect to lead technological development in each of the following fields?

	U.S.	Europe	China	Japan	Other areas	Not sure	Total
Debris	11.4	65.7	2.9	8.6	0.0	11.4	100.0
Access to space	62.9	2.9	28.6	2.9	0.0	2.9	100.0
Navigation (Remote Sensing)	42.9	25.7	20.0	2.9	0.0	8.6	100.0
Earth Observation	28.6	48.6	11.4	2.9	0.0	8.6	100.0
Telecommunication	60.0	5.7	20.0	0.0	2.9	8.6	100.0
LSSs and ISRU	22.9	11.4	51.4	2.9	0.0	11.4	100.0
Spacecraft	51.4	5.7	25.7	2.9	0.0	14.3	100.0

Experts were asked to identify the geographical regions they believe will mainly influence technological progress in the coming years for each analyzed category (see Table 2.17). As shown, Europe is expected to be a key player in debris mitigation technologies and Earth observation initiatives. This is likely due to strong commitments from institutions such as ESA and projects such as ClearSpace-1, as well as the contract signed with Avio to develop a reusable upper stage [12], emphasizing Europe's focus on orbital sustainability and responsible space operations. Europe also has a rich history in Earth observation, especially in collecting and processing environmental and civil data. In contrast, the United States is viewed as the leader in access-to-space technologies, spacecraft development, and telecommunications. This view is supported by the innovations of private companies like SpaceX and Blue Origin, which have transformed access to space with reusable launch systems and large satellite networks, such as Starlink, for global internet. Additionally, the collaboration between U.S. public agencies (NASA, DoD) and private industry ensures ongoing investment, project continuity, and scalability. Meanwhile, China is projected to lead in developing LSS and related technologies for exploration, habitat building, and resource utilization on other celestial bodies. This outlook stems from China's long-term space ambitions, highlighted by successful robotic lunar missions such as Chang'e, the launch of the Tiangong space station, and more ambitious plans for crewed lunar missions and beyond.

Table 2.18: Results for Q20: Looking at the global scenario, will *public and private investment* in the following technological areas decrease or increase in the next 15 years?

	Public and Private Investments					
	mean	IQR	Decrease or Slightly decrease [%]	No variation [%]	Slightly increase or Increase [%]	**Consensus**
Debris	4.0	2	14.3	11.4	74.3	Yes
Access to space	4.6	1	2.9	2.9	94.3	Yes
Navigation (Remote Sensing)	4.1	1	2.9	17.1	80.0	Yes
Earth Observation	4.0	2	5.7	28.6	65.7	Yes
Telecommunication	4.3	1	2.9	11.4	85.7	Yes
LSSs and ISRU	3.8	2	8.6	28.6	62.9	No
Spacecraft	4.0	1	2.9	20.0	77.1	Yes

Table 2.19: Results for Q21: Considering the global scenario, do you expect public and private *Defence & Security investments* to have an impact on the development of space technology in the next 15 years?

	Defence & Security investments					
	mean	IQR	Decrease or Slightly decrease [%]	No variation [%]	Slightly increase or Increase [%]	**Consensus**
Debris	3.5	3	28.6	20.0	51.4	No
Access to space	4.3	1	8.6	11.4	80.0	Yes
Navigation (Remote Sensing)	4.2	1	0.0	20.0	80.0	Yes
Earth Observation	4.3	1	5.7	14.3	80.0	Yes
Telecommunication	4.5	1	0.0	5.7	94.3	Yes
LSSs and ISRU	3.4	1	22.9	31.4	45.7	No
Spacecraft	4.0	1	8.6	11.4	80.0	Yes

Regarding the answers of Q20 reported in Table 2.18, experts agree that over the next 15 years, investments, both public and private, are expected to increase significantly across all studied sectors, except for LSS and ISRU technologies, where consensus is lacking. This uncertainty may partly be due to a bias resulting from the under-representation of Asian experts, particularly those from China, which is considered a leader in these areas, as previous results suggest. Similar trends are seen in defense and security investments, as shown in Table 2.19. A general rise is predicted, except for space debris mitigation, where experts are divided. Overall, there is a strong consensus that increased investment in defense and security will significantly drive the development, innovation, and deployment of space technologies in various fields.

2.5 Closing Remarks

This chapter highlights challenges and opportunities in sustainable space development. Experts predict that by 2040, space laws will better support environmental sustainability, mainly to address environmental issues. However, updating legislation to reflect new technological and political realities, including private sector involvement, is needed to improve sustainability. Moreover, large companies and space agencies are expected to be the leading players in access to space technology, aligning with recent progress by private firms like SpaceX in reusable launch systems. Meanwhile, SMEs and start-ups will make significant contributions to the sustainable development of remote sensing, as the use of Earth observation data expands in sectors such as agriculture and urban planning. Ultimately, the chapter identifies the regions that will lead technological development in the coming years: Europe in the development of debris mitigation technologies and EO, and the US in telecommunications and access to space technology.

Chapter 3

Earth Observation and Sustainability: Applications in Aviation and Aeronautics

This chapter explores the role of Earth Observation (EO) in advancing sustainability, with a specific emphasis on its applications within the fields of aviation and aeronautics. It begins by presenting an overview of the primary mission of EO and the applications of the data collected. The discussion subsequently underscores EO's contribution to the aviation sector, focusing on facilitating route optimization, emissions evaluations, and hazard detection, including volcanic ash, thunderstorms, wind shear, and turbulence. The chapter then focuses on turbulence and gusts, sudden and unpredictable events that affect aviation and are increasing due to climate change. As highlighted in this work, EO technology can contribute to monitoring and predicting these events, although some limitations related to resolution, integration, and operational implementation persist. The chapter concludes by emphasizing EO's dual function as both an operational instrument and a long-term catalyst for resilience, and introduces the case study on wind gusts, which will be thoroughly discussed in Chapter 4.

3.1 Earth Observation: Evolution, Applications and Sustainability Challenges

Remote sensing encompasses a broad range of space-based activities, including satellite navigation, telecommunications, and Earth Observation. Within this spectrum, EO has become increasingly integral to scientific research and the management of natural resources and infrastructure on a global scale. As discussed in the preceding chapter, the sector is distinguished by an increasing specialization of involved actors. While private companies primarily invest in telecommunications, space agencies and universities remain at the forefront of scientific and technological development in EO.

It has experienced a significant evolution over the past six decades. Since the initial images from the Landsat series, launched in 1972, which enabled systematic observation of the Earth's surface [191], a new generation of satellites has emerged, characterized by increasingly refined spatial and temporal resolutions and equipped with multispectral, hyperspectral, and radar sensors. Among these, MODIS (Moderate Resolution Imaging Spectroradiometer) has been instrumental in monitoring vegetation dynamics through advanced indices such as the Enhanced Vegetation Index (EVI) [192]. Equally noteworthy is the European Copernicus programme [193], the largest EO initiative worldwide, offering satellite data that are free and accessible. Its Sentinel satellites provide systematic measurements of land, oceans, and atmosphere, thereby supporting European Union policies and global sustainability efforts. Commercial missions, including WorldView [38] and PlanetScope [194], have further broadened observational capacities by providing high-resolution datasets with frequent revisit times. A pivotal development occurred in 2008, when the Landsat archive was made freely accessible, democratizing access to EO data [195] and fostering the advancement of algorithms for the analysis of spatial data and their applications. Since that time, the utilization of satellite data has expanded beyond the space sector. Indeed, as asserted by [196], the number of scientific publications that employed satellite data had surpassed 45,000 by the year 2020, showcasing an exponential growth trajectory. While Landsat and MODIS dominated the field for decades, the Sentinel missions now represent the fastest-growing programs and are anticipated to become the most influential in the foreseeable future. This is primarily due to the commercialization of spatial data, as well as the wide range of fields in which it is used. Satellite data applications encompass nearly all domains of sustainable development. EO facilitates the monitoring of environmental and climate changes, including deforestation, desertification, ice sheet dynamics, and ocean quality [154, 197]; in agriculture, it supports the transition to precision farming and the efficient use of water resources [37, 147]; in urban settings, it informs resilient planning and the surveillance of urban heat islands [33, 198]; and for disaster management, EO provides near real-time data crucial for detecting floods, wildfires, and volcanic ash, thereby underpinning early warning systems [197, 199]. More recently, EO has also been employed in public health and social sciences, including modeling the spread of vector-borne diseases [200] or assessing the impact of conflicts on urban development [156].

The intersection between EO and sustainability is most prominently observed within the environmental domain, as previously delineated in Chapter 1. Nevertheless, its contribution is progressively extending into economic and social spheres. Andries et al. [201] demonstrated that satellite data can directly or indirectly inform more than one hundred indicators related to the United Nations Sustainable Development Goals (SDGs), particularly those concerning climate, ecosystems, and resilient urban environments. Additionally, Anderson et al. [35] underscored that EO has become an indispensable resource for the 2030 Agenda, providing consistent, comparable, and comprehensive measurements that are challenging to achieve solely through national statistics. Consequently, EO is not merely an observational technology but also a strategic facilitator of sustainability.

Although significant progress has been achieved, Earth Observation data continue to face substantial limitations. Technically, these limitations are primarily due to issues related to resolution and calibration, which necessitate the implementation of sophisticated validation methodologies [202, 203]. The integration of data from various sensors is also inherently complex and may introduce uncertainties. Moreover, the rapid proliferation of satellite constellations has resulted in the emergence of Big Earth Data[1] platforms

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[1] Big Earth Data refers to the extensive, diverse, and rapidly expanding datasets generated by modern EO constellations. The management and analysis of this data demand advanced cloud computing platforms and artificial intelligence techniques to convert raw data into actionable insights for scientific research and policy formulation [204].

such as Google Earth Engine, Amazon Web Services, and Open Data Cube are essential for effective data processing [205]. On a political and institutional level, disparities in access persist significantly. While the United States and Europe are at the forefront of EO data production and usage, numerous countries encounter barriers to access and lack the technical expertise required to leverage these resources fully, despite numerous studies demonstrating how EO can enhance development and resilience in such contexts [74, 88]. As mentioned in Chapter 2, international collaboration is necessary to address these issues.

Both opportunities and challenges characterize the prospects. The expansion of small commercial satellite constellations, such as those operated by Planet Labs, provides near-daily global coverage. Concurrently, advancements in artificial intelligence and machine learning [206, 207] are enabling new ways to analyzing complex and dynamic datasets. Nevertheless, the long-term sustainability of EO depends critically on maintaining the sustainability of space operations itself. The rising number of satellites and constellations in low Earth orbit increases the risks of congestion and space debris, thereby threatening the continuity of observations [208, 209]. EO presents a critical paradox: it is vital for monitoring and fostering sustainability on our planet, yet it depends on the sustainable use of outer space to maintain its operational continuity.

3.2 Earth Observation for Aviation and Aeronautics

As discussed in the previous section, EO has become a strategic enabler for sustainability across multiple domains. Aviation and aeronautics represent a particularly critical case, as they are among the sectors most affected by climate variability and heavily dependent on accurate and timely meteorological information. While the industry has long experience in managing weather-related disruptions [210–212], it is now increasingly exposed to the impacts of climate change [213, 214]. These include new operational norms such as higher average temperatures, stronger and less predictable gusts, sea-level rise threatening coastal airports, and more frequent extreme events [215–218]. Such changes translate into disruptions, infrastructure damage, and heightened safety risks [219, 220]. The IPCC has explicitly identified aviation as a “key vulnerable economic sector” still in the early stages of adaptation planning [221], finding consistent with global airport and airline surveys [42, 222]. In this context, EO emerges as an indispensable resource for understanding evolving risks, informing adaptation, and supporting resilience in a sector central to global mobility.

One of the most direct contributions of EO lies in improving operational efficiency. Satellite-based meteorological products enable airlines to optimize flight routes, minimize fuel consumption, and reduce delays, thereby enhancing punctuality and lowering emissions [223–225]. EO observations also support more efficient air traffic management (ATM) by providing real-time data to predictive models that anticipate adverse conditions and facilitate dynamic rerouting. In practice, the integration of EO into trajectory-based operations (TBO), as promoted by SESAR, exemplifies how satellite information can simultaneously deliver environmental and economic benefits [226].

EO also plays a critical role in environmental monitoring and in assessing the climate impacts of aviation. Beyond CO_2 emissions, the sector’s climate footprint includes nitrogen oxides and contrails, all of which can be detected and quantified through satellite measurements [43, 227]. Missions such as MODIS and Sentinel have been fundamental in tracking aerosols, particulate matter, and water vapor distribution in the atmosphere, thereby enabling improved estimates of aviation's indirect radiative forcing. Furthermore, EO datasets on key parameters such as temperature, wind fields, and humidity are crucial for evaluating how climate change reshapes operating conditions for aviation. Long-term monitoring of jet stream shifts and atmospheric stability patterns, for instance, provides insights into how fuel consumption, flight times, and safety margins may evolve in the coming decades [228, 229].

Table 3.1: Main Earth Observation missions and their contributions to aviation and aeronautics.

Mission	**Sensor type**	**Contribution to aviation**
Landsat (1972–)	Optical multispectral	Long-term environmental datasets for climate trend analysis, including land cover changes near airports and contrail studies.
MODIS Terra & Aqua (1999–)	Multispectral radiometer	Atmospheric and surface observations supporting climate and weather models; inputs for contrail and aerosol monitoring.
Sentinel-1 (2014–2022)	Synthetic Aperture Radar (SAR)	Monitoring surface wind fields, ice and ocean dynamics affecting routes and airport operations.
Sentinel-2 (2015–)	High-resolution multispectral	Land cover analysis and environmental monitoring of airport surroundings, including wildlife habitats and bird migratory corridors.
Sentinel-3 (2016–)	Radiometer and altimeter	Ocean and atmosphere monitoring, sea surface temperature, and flooding risks for coastal airports.
Sentinel-6/Jason-CS (2020–)	Radar altimeter	High-precision measurements of sea level rise with implications for coastal airport resilience.
Aeolus (2018–2023)	Doppler UV lidar	Global wind field observations to improve turbulence forecasting, jet stream monitoring, and route planning.
RainCube (2018)	Ka-band radar	Demonstrated high-resolution detection of convective cells and storm intensity.
TEMPEST-D (2018–2021)	Microwave radiometer	Tracked temporal evolution of storm systems to improve short-term forecasts.
PlanetScope (2013–)	Optical nanosatellite constellation	High-frequency monitoring of critical areas (e.g., airports, flight corridors), useful for environmental and infrastructural assessments.

Safety and risk management represent another domain where EO is indispensable. The eruption of Eyjafjallajökull in 2010, which led to the unprecedented closure of European airspace, underscored the vulnerability of aviation to volcanic ash [230]. Since then, EO missions have become central to the detection and monitoring of such hazards, offering near real-time data that can be assimilated into operational models to ensure safe routing [231]. Satellites also support the detection of thunderstorms, lightning, turbulence, and other extreme weather events that pose immediate threats to flight safety. Sensors such as Sentinel-1 SAR and Aeolus Doppler lidar [232] have shown the capacity to capture fine-scale atmospheric dynamics, and they could contribute to more accurate forecasting and enable timely mitigation strategies for airlines and ATM operators. Table 3.1 summarizes the main EO missions from Landsat to the present day and their direct and indirect contributions to the aviation sector.

Therefore, integrating EO into aviation and aeronautics reinforces the sector's sustainability by reducing emissions, minimizing disruptions, and enhancing resilience against climate-induced risks. Yet, as highlighted by Burbidge et al. [233], significant adaptation gaps remain, particularly in understudied regions and in the assessment of extreme events. EO can help close some of these gaps, providing global, consistent, and long-term data that are otherwise unavailable.

3.2.1 Wind Gusts, Wind Shear, and Turbulence: A Critical Challenge for Aviation

Ensuring the safety and reliability of aircraft operations is a fundamental objective in aeronautics, particularly in light of growing concerns about extreme weather phenomena and advances in flight technology. Aviation safety depends on human factors, such as situational awareness and adherence to established procedures [234], as well as structural integrity, which can be affected by fatigue or unexpected aerodynamic loads [235]. These concerns are intensified by two overarching trends: the global increase in air traffic [236] and the increasing frequency of extreme weather events fuelled by climate change [237, 238]. Concurrently, the shift towards innovative propulsion systems, including hybrid-electric [239, 240] and hydrogen-based [241] architectures, introduces new design constraints and operational conditions. Therefore, to ensure compliance with future airworthiness standards and reduce aviation's environmental impact, it is essential to re-evaluate structural methodologies and maintenance strategies in the context of realistic, dynamically changing atmospheric conditions.

In this context, wind gusts, wind shear, and clear-air turbulence are among the most significant atmospheric hazards to aviation. These phenomena are often sudden, invisible to pilots, and challenging to forecast with conventional meteorological instruments. They consistently threaten flight operations, compromising safety, reducing passenger comfort, and increasing operational costs through delays, rerouting, and heightened fuel consumption [228, 229]. NASA statistics reveal that up to 18% of turbulence-related incidents are associated with convective activity, while nearly 13% originate from clear-air turbulence [242]. The primary sources of turbulence encompass clear-air turbulence linked to jet streams, convectively induced turbulence generated by strong updrafts and thunderstorm outflows, and mountain-wave turbulence resulting from airflow over orography [243, 244].

Climate change is anticipated to amplify specific atmospheric phenomena: the warming of the tropical upper troposphere, in conjunction with the cooling of the lower stratosphere, enhances meridional temperature gradients at cruising altitudes. This intensification consequently strengthens jet streams and increases vertical wind shear [229]. Simulations project that turbulence will occur more frequently and with greater intensity along major flight corridors, such as the North Atlantic, with observable impacts on flight duration, fuel consumption, and emissions [228, 245, 246]. From a design and operational standpoint, these changes have significant implications: stronger gusts and turbulence influence the aerodynamic forces experienced by aircraft, thereby affecting airframe weight, fatigue life, and certification requirements [247, 248]. Operationally, increased headwinds and crosswinds impact take-off and landing performance, occasionally necessitating payload reductions at smaller airports [249]. Increased turbulence directly affects individuals: exposure to whole-body vibrations within the range of 2–20 Hz during turbulent flights can induce fatigue, muscular discomfort, and stress, consequently elevating crew workload and reducing passenger comfort [250–252].

Atmospheric modeling plays a pivotal role in understanding how aircraft interact with such dynamic environments. Early regulatory frameworks simplified gust encounters as step-like disturbances, while subsequent standards introduced parameterized profiles such as the one-minus-cosine "discrete gust" [253, 254]. This analytical model characterizes a vertical velocity disturbance of specified intensity and duration as the aircraft penetrates the gust front and is widely used in certification standards such as FAR/CS-25 and MIL-STD-1797 [254]. It remains fundamental for assessing dynamic structural loads and validating the performance of gust alleviation systems. For stochastic and long-duration phenomena, alternative formulations, such as the Dryden and von Kármán spectral models, depict turbulence as a stochastic field with characteristic energy distributions over spatial scales [254]. These classical models establish a unified theoretical framework linking atmospheric energy to aircraft response, underpinning both active and passive load-alleviation strategies. Adaptive control surfaces, such as flaps, spoilers, and ailerons, integrated with real-time optimization algorithms seek to mitigate transient gust loads and reduce structural mass [255–260]. Nevertheless, gust-induced stresses remain among the primary factors contributing to material fatigue [247, 261], thereby necessitating advanced maintenance protocols and damage-tolerance approaches informed by long-term observational data.

Historically, acquiring representative gust data required extensive, costly flight-testing campaigns with limited spatial coverage. Currently, this paradigm is being transformed by space-based technologies. Earth Observation offers a revolutionary capability for detecting, monitoring, and modeling atmospheric disturbances. Spaceborne lidar and radar instruments, such as those employed in the ESA Aeolus mission, have proven the viability of global wind profiling up to the lower stratosphere [232]. These groundbreaking measurements enhance the accuracy of vertical shear and turbulence precursors within numerical weather prediction models. Complementary missions, such as RainCube and TEMPEST-D, have substantiated the operation of miniature radar and radiometer payloads on CubeSats, illustrating their potential to observe the structure and evolution of convective systems from low Earth orbit [262, 263]. Similarly, EO imagery in infrared water vapor bands has historically been utilized to detect the presence of clear-air turbulence near jet streams and frontal zones, with research indicating moderate to severe turbulence in 80% of instances where water vapor anomalies are observed [264, 265].

Beyond operational forecasting, EO data provide an empirical basis for refining gust and turbulence models. Satellite-derived measurements of wind, temperature, and humidity facilitate the calibration of spectral parameters, including turbulence intensity, integral length scales, and vertical shear gradients, across diverse regions and altitudes. The integration of EO data with in-situ measurements from radiosondes and flight campaigns enables cross-validation of theoretical spectra, ensuring that design standards and load models accurately represent observed atmospheric variability. Consequently, enhanced modeling of gust and turbulence improves safety and efficiency, reducing fuel consumption, structural fatigue, and maintenance costs, whilst aligning aviation practices with global sustainability objectives.

The increasing synergy between EO and aeronautics offers benefits beyond just aviation. By optimizing satellite missions to focus on the most relevant atmospheric data, space environmental sustainability improves through fewer redundant launches, longer mission durations, and higher scientific and economic gains from each satellite. This partnership also boosts economic sustainability by encouraging the use and commercialization of space-based data. This positive cycle links the sustainable development of aviation, making flights safer and more efficient, to the responsible management of the orbital environment. It shows how advances in EO technology can support sustainability on Earth and in Space. Based on these ideas, Chapter 4 delves deeper into this relationship with a case study on vertical wind gusts, using data from the Aeolus satellite and the EUREC4A flight campaign, and comparing findings with the traditional von Kármán turbulence model.

3.2.2 Closing Remarks

This chapter examines the applications of Earth observation in aviation and aeronautics. It highlights the significant opportunities and ongoing challenges of integrating satellite data into these fields. Earth Observation provides global coverage and extensive, consistent historical data, which are essential for monitoring atmospheric variability and addressing long-term climate change. These data offer immediate operational advantages, including enhanced safety, optimized routing, and reduced emissions, as well as strategic benefits for resilience planning and decarbonizing the air transportation sector. Concurrently, notable limitations persist. Satellite observations remain subject to spatial and temporal resolution constraints, limiting their ability to detect localized and transient phenomena. Additionally, EO products often depend on auxiliary meteorological models for interpretation, and their systematic integration into air traffic management systems faces technical, institutional, and regulatory obstacles.

However, in the coming years, a variety of trends are set to influence the future of EO within the aviation sector. Integrating heterogeneous data streams, including EO products, operational meteorology, in-situ observations, and aircraft-based measurements, will be pivotal in improving forecast accuracy and practical utility. Advances in artificial intelligence and machine learning are expected to significantly contribute to assimilating extensive and complex datasets, as well as detecting turbulence predictors in near real-time. Meanwhile, upcoming missions, including ESA's EarthCARE and potential Aeolus follow-ons, are expected to enhance observational capabilities, particularly concerning measuring clouds, aerosols, and vertical wind profiles.

Chapter 4

Case Study: Applying Earth Observation to Aviation and Aeronautics

This chapter explores wind gust dynamics and emphasizes the vital role of satellite-based Earth Observation in their monitoring and analysis. Wind gusts are essential for aviation safety and efficiency, influencing flight stability, turbulence prediction, and fuel consumption. Meanwhile, the development of algorithms for analyzing EO data promotes the commercial use of satellite data to support sustainability. As a result, understanding gust behavior is important not only for aviation but also for advancing sustainability on Earth and in space. The focus is on satellite technologies, particularly data from the ESA Aeolus mission and the EUREC4A flight campaign. These datasets complement each other: Aeolus offers near-global coverage with vertical wind profiles, while EUREC4A provides detailed local measurements. Integrating these sources allows for a multi-scale study of gust dynamics. The results derived from EO data are then compared with traditional turbulence models, such as the von Kármán model, highlighting the similarities and differences between observations and models, and shedding light on their respective strengths and limitations.

4.1 Comparative Dataset Description: Aeolus Satellite and EUREC4A Flight campaign

This section introduces the two databases analyzed in this chapter. The first uses wind gust measurements from the ESA Aeolus satellite [266], while the second relies on data collected during the EUREC4A flight campaign with the SAFIRE ATR 42 research aircraft [267]. These datasets differ notably in terms of spatial and temporal coverage, as well as measurement resolution and methodology. Aeolus provides near-global wind measurements at various altitudes over a four-year operational period (2019-2022). It operates in low Earth orbit (LEO) and, unlike geostationary satellites, does not remain fixed over the same geographic area; instead, it observes different regions along its orbit. Consequently, each observed region is subject to long gaps between consecutive measurements. In contrast, the SAFIRE ATR 42 dataset is geographically limited to a specific area over the tropical Atlantic and temporally confined to the duration of the EUREC4A flight campaign. Despite this, it provides high-resolution measurements at flight altitude, making it especially useful for studying small-scale wind phenomena such as turbulence and gusts.

4.1.1 Aeolus

4.1.1.1 Satellite data

The Aeolus satellite, developed by the European Space Agency (ESA), was an innovative Earth observation mission designed to enhance global atmospheric monitoring. Its main goal was to measure wind profiles worldwide, enhancing our knowledge of weather patterns, atmospheric behavior, and climate processes. Launched on August 22, 2018, Aeolus was the first satellite to directly capture three-dimensional measurements of Earth's wind fields from space. The mission operated until July 28, 2023, when ESA successfully carried out the first controlled de-orbit of an Earth observation satellite, ensuring a safe re-entry into the atmosphere [232]. Although the satellite is no longer active, a five-year post-mission phase is ongoing, focusing on data refinement and reprocessing to support future missions like Aeolus-2 [268, 269]. A visual overview of the satellite and its main parts is shown in Fig. 4.1. Aeolus was designed to address longstanding challenges of sparse and uneven wind data, especially over remote regions such as oceans, deserts, and polar areas. Before Aeolus, global wind observations mainly relied on ground-based weather stations and radiosondes [270, 271], which had limited coverage. In contrast, Aeolus provided near-real-time, global wind data, enabling comprehensive atmospheric profiling that improved weather forecasting, climate models, and understanding of atmospheric dynamics.

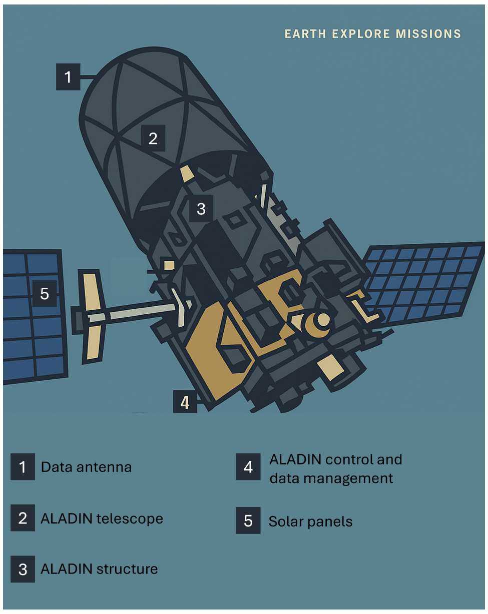

Figure 4.1: Aeolus' main components. Image adapted from [232].

At the core of the Aeolus mission is **ALADIN (Atmospheric Laser Doppler Instrument)**, the first spaceborne Doppler wind lidar (DWL) marking a significant breakthrough in atmospheric remote sensing [272]. ALADIN is designed to accurately measure wind by detecting the movement of air particles at different altitudes through Doppler shift analysis. The instrument emits high-energy ultraviolet (UV) laser pulses at

355 nm into the atmosphere. When these pulses interact with air molecules, aerosols, and cloud droplets, some of the light is backscattered. This backscattered signal is collected by an onboard telescope and analyzed to determine wind speed and direction. The measurement relies on the Doppler frequency shift: as the laser interacts with moving particles, the returned signal's frequency shifts slightly based on the particles' motion. By measuring this shift, ALADIN can derive both Line-of-sight (LOS) speed and Horizontal line-of-sight speed (HLOS), creating wind profiles from the surface up to about 30 km altitude.

ALADIN consists of three major subsystems:

- a high-power UV laser emitter;
- a telescope to collect the backscattered light;
- a highly sensitive receiver with two optical detection channels: the Rayleigh channel and the Mie channel.

Each channel is optimized for specific atmospheric conditions:

- the **Rayleigh channel** analyzes light scattered by small air molecules (primarily nitrogen and oxygen) and is therefore effective in clear-air conditions, particularly at altitudes between 5 and 30 km, where molecular scattering is dominant;
- the **Mie channel**, on the other hand, is designed to capture light scattered by larger particles such as dust, aerosols, and cloud droplets. It performs best in the lower atmosphere (0 to 5 km altitude), where such particulate matter is more prevalent.

ALADIN utilizes a dual Fabry–Pérot interferometer to precisely measure Doppler shifts in backscattered light, capturing signals effectively. Depending on atmospheric conditions, it operates through the Rayleigh channel under clear skies and through the Mie channel in regions with high aerosol concentrations. This dual-channel system enables ALADIN to generate detailed wind profiles across various atmospheric layers, thereby improving the overall accuracy of wind measurements and providing coverage in regions where in-situ or ground-based observations are limited. Nonetheless, this approach presents technical challenges in signal detection and calibration, necessitating advanced data processing algorithms and calibration techniques to maintain measurement reliability [273].

4.1.1.2 Wind gust measurement

Aeolus operated in a near-polar, sun-synchronous orbit at roughly 320 km altitude, enabling nearly global wind observations (see Fig. 4.2 (left)). The onboard DWL was tilted at 35° from vertical, perpendicular to the ground track, creating a lateral offset of about 230 km between the actual ground track and the observed area (Fig. 4.2 (right)). Its measurement principle relied on the Doppler effect: laser radiation backscattered by atmospheric molecules and particles caused a frequency shift in the received signal, enabling the estimation of radial wind velocity along the beam, known as Line-of-Sight (LOS). Since atmospheric models need horizontal wind data, LOS measurements were projected onto the horizontal plane to obtain the Horizontal Line-of-Sight (HLOS), i.e., the horizontal component of wind in the beam's direction, which is commonly used in global forecast models. Aeolus's observations were organized into vertical wind profiles along the satellite's path, rather than single-point measurements. Each profile was recorded approximately every 90 km along the ground track, equating to about 11 seconds of orbital time, making each a spatio-temporal measurement unit. During each interval, the lidar emitted roughly 600 ultraviolet laser pulses at 50 Hz, with each pulse traveling through the atmosphere and being partially backscattered by air molecules (Rayleigh scattering) and aerosols (Mie scattering). These optical signals contained data on radial wind velocity but appeared very noisy and discontinuous. Consequently, individual measurements weren't used alone but were grouped into larger segments. Each pulse corresponded to a minimum sampling length of about 3 km along the observation path, representing the finest horizontal resolution possible. To balance resolution and reliability, hundreds of samples were statistically averaged to produce a single profile every 90 km. This averaging reduced the impact of photon noise and instrument errors, greatly enhancing the signal-to-noise ratio and allowing more accurate detection of small Doppler shifts in the optical return.

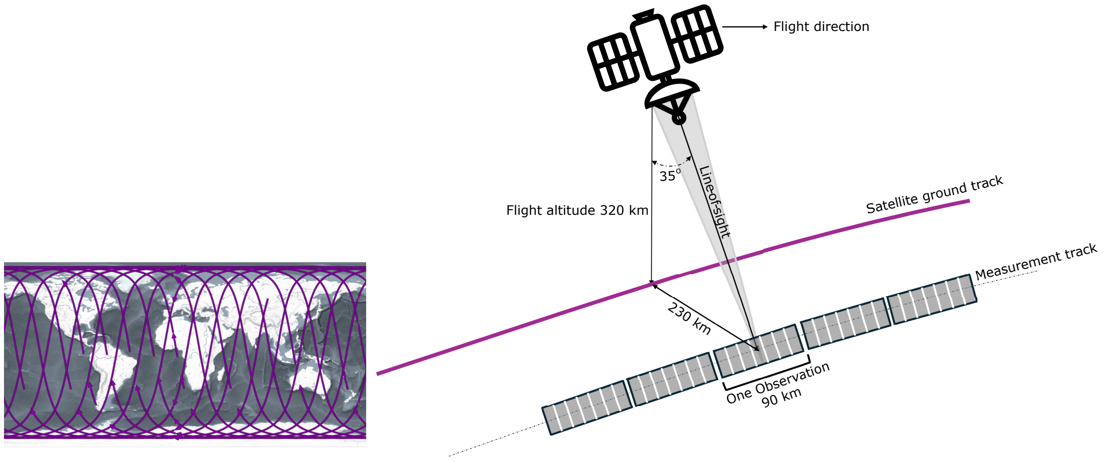

Figure 4.2: Aeolus' ground track in one day (left). Schematic view of Aeolus measurement geometry (right).

To support research and operational uses, ESA offers free access to Aeolus data through the VirES platform [274]. This platform provides pre-processed datasets from both the Rayleigh and Mie channels, enabling users to download observational variables such as LOS wind velocity, HLOS wind velocity, altitude, geolocation, along with quality flags and metadata. Users can specify data for particular regions and timeframes, accessing both global and regional datasets that cover the four-year operational period of the mission. The data are available in NetCDF format, which is compatible with standard analysis tools, including MATLAB and Python, among others. An example of graphical output of LOS velocity is shown in Fig. 4.3, which displays the change in LOS speed in a region of the United States, ranging from 0 to 17 km in altitude. Each observation has a vertical resolution of 1 km and a temporal resolution of 11 seconds, aligned with the satellite's profile acquisition cycle.

4.1.2 Flight Campaign

Elucidating the Role of Clouds–Circulation Coupling in Climate (EUREC4A) was a major European field campaign focused on enhancing our understanding of how clouds,

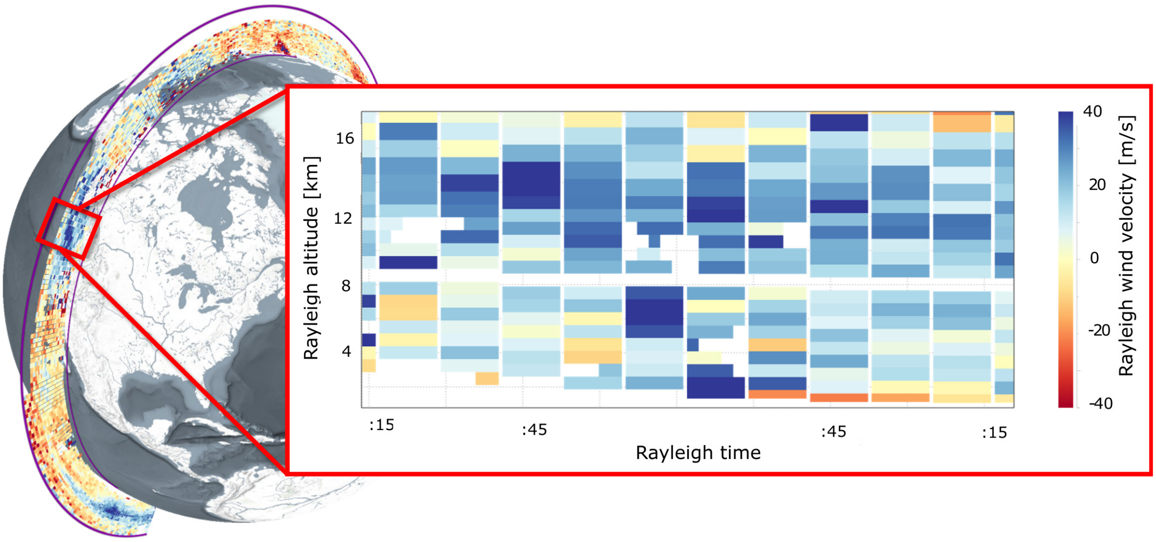

Figure 4.3: Representation of LOS wind gust speed collected by Aeolus at various altitudes along its orbit. Each measurement interval corresponds to a vertical bin of 1 km and spans approximately 11 seconds in time. Image adapted from [275].

atmospheric convection, and large-scale circulation interact, especially in relation to climate change. The campaign took place in the tropical Atlantic east of Barbados from January to February 2020, using a combination of airborne and ground-based instruments. The SAFIRE ATR 42 research aircraft played a crucial role, studying shallow convective clouds near cloud base (600–800 m) and analyzing the turbulent structure of the subcloud layer (300–600 m) [276]. Originally designed as a commercial turboprop, the SAFIRE ATR 42 has been transformed into a cutting-edge flying laboratory. It's equipped with a wide range of scientific instruments, including sensors for temperature, pressure, and humidity, gas analyzers for greenhouse gases such as CO_2 and CH_4, aerosol counters, and advanced LIDAR systems for vertical atmospheric profiling.

Designed with multiple external mounting points on the nose, fuselage, and wings, the aircraft offers flexible and mission-specific deployment of instruments. It has supported numerous international atmospheric research campaigns over the years, making a significant contribution to advancing our understanding of cloud processes and climate model development [276].

During EUREC4A, the SAFIRE ATR 42 operated alongside the German HALO aircraft, which performed high-altitude circular flights ($\sim$ 9 km) to monitor large-scale atmospheric structures. Meanwhile, SAFIRE ATR 42 carried out low-altitude missions focused on high-resolution measurements of turbulence, cloud properties, and near-surface fluxes. Typically, SAFIRE ATR 42 completed two flights daily, totaling 19 flights, each lasting about 4 to 5 hours with a brief refueling stop. All operations occurred at Grantley Adams International Airport (Barbados). The aircraft mainly operated within the western part of the HALO flight circle (200 km diameter), with flight paths covering a core area roughly 120 km × 60 km. This targeted sampling approach supported detailed investigation of cloud dynamics and boundary-layer processes in a tropical marine environment.

The campaign design featured two main flight patterns:

- **R Pattern**: A rectangular trajectory flown near cloud base (typically 700–900 m), comprising at least two loops of approximately 120 km × 15 km. This pattern was intended to measure cloud-base properties and cloud fraction using lidar and radar systems. In some cases, additional legs at higher altitudes were included to investigate stratiform cloud layers near the trade inversion.

- **L Pattern**: Designed for turbulence characterization, this pattern consisted of two straight legs, each about 60 km in length, flown at varying altitudes within the marine atmospheric boundary layer (typically 150–400 m). It was optimized to capture turbulent eddies, vertical mixing, and their relationship to cloud formation.

An example of the SAFIRE ATR 42 flight trajectories are illustrated in Figure 4.4.

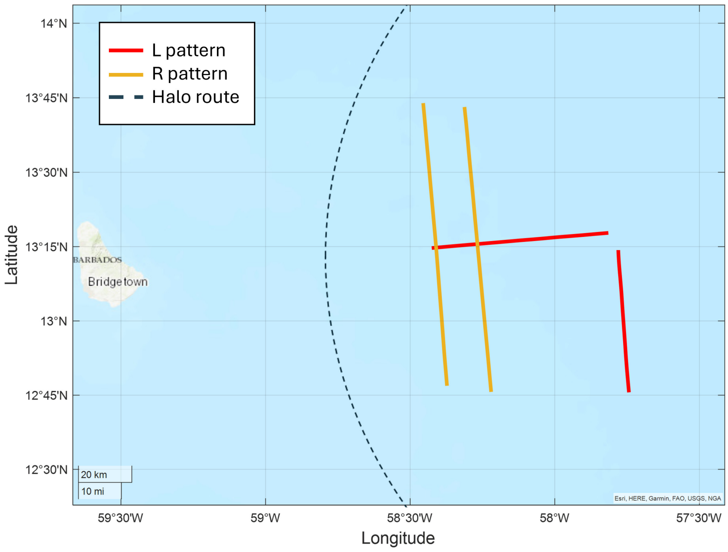

Figure 4.4: The representation of the HALO route, indicated by hatching, while a filled line denotes the ATR 42 route. The yellow lines represent part of the R pattern, and the red lines compose the L pattern.

4.2 Methodology

This section outlines the methodology used to analyze data collected from both satellite and aircraft flight campaigns. The approach follows the general framework shown in Fig. 4.5. Specifically, once the time signal $x(t)$ is extracted, it can take two forms: (i) uniformly sampled without interruptions, or (ii) affected by temporal gaps, where portions of the signal are absent for certain intervals. The first case is typical in flight campaign data, where onboard instruments record a signal throughout the entire mission. The second case can occur with data from LEO satellites, as explained in section 4.1.1; here, the signal is a piecewise function of time, alternating between time intervals with available data and segments without any data. The time intervals where data are present are referred to as *segments*. An example of a continuous signal with and without gaps is shown in Fig. 4.6.

Three distinct methodologies were employed to analyze data retrieved from each designated platform: zero-padding, Welch's method, and length-weighted Power Spectral Density (PSD). The entire process begins with the extraction of the time signal x(t). At

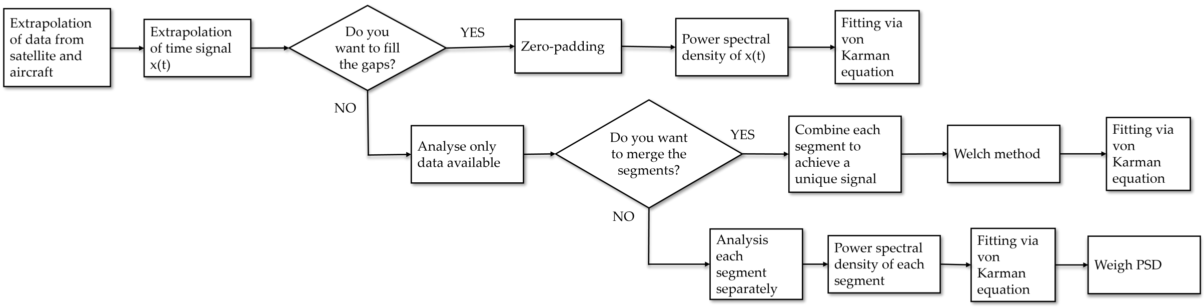

Figure 4.5: Workflow adopted in the proposed methodology.

this stage, the first decision concerns the presence of temporal gaps. If the aim is to fill these gaps, the zero-padding technique is applied, thereby reconstructing a uniformly sampled signal that can be directly used for computing the PSD and its subsequent fitting. If no gap-filling strategy is adopted, two alternative approaches are available. In the first case, the individual signal segments are combined to form a more extended sequence, which is then analyzed using Welch's method to produce a PSD before applying the fitting model. In the second case, each segment is analyzed separately: the PSD of every portion is computed and individually fitted, after which a weighted average of the PSDs is obtained based on segment length. Further elaboration on each methodology is provided in the subsequent sections.

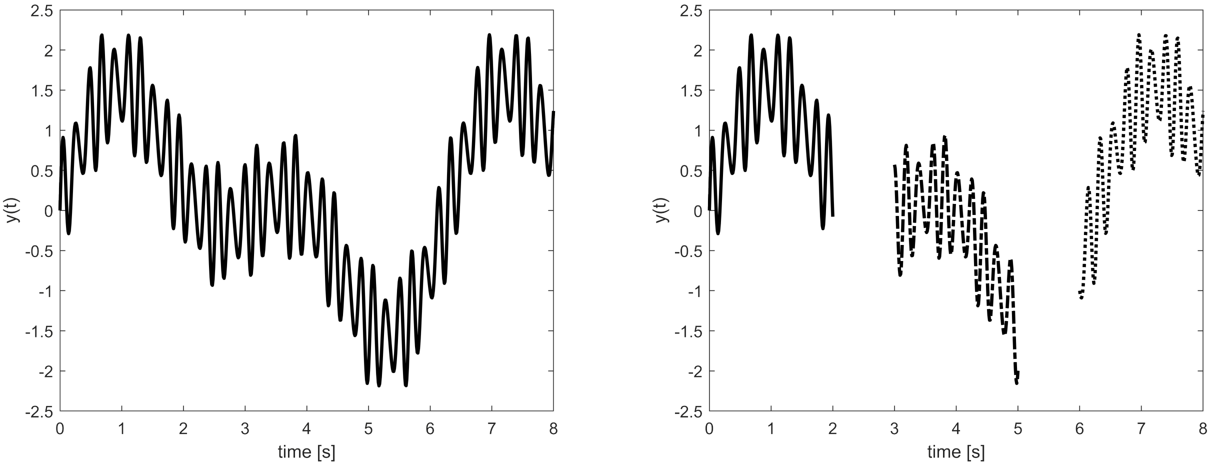

Figure 4.6: Uniformly time sampled signal (left) and piecewise time signal (right).

4.2.1 Spectral Analysis

Power spectral analysis is performed on time-domain signals to investigate their frequency content. Given that the time-domain signals are known (acquired from satellite or flight campaigns), a Discrete Fourier Transform (DFT) is employed to translate the data into the frequency domain. This transformation facilitates access to the spectral components of the signal, from which the PSD can be derived. The DFT is calculated in accordance with Eq. 4.1.

$$X_k = \sum_{n=0}^{N-1} x_n e^{-i2\pi \frac{k}{N} n} \tag{4.1}$$

where x_n represents the $n-th$ component of the signal $x(t)$ in the time domain evaluated at the time nT. T is the signal's sampling interval, and N is the total number of samples, or the length of the signal. The term $e^{-i2\pi\frac{k}{N}n}$ is the complex sinusoid at frequency $f_k = k/N, k \in [0, N-1]$, and X_k represents the corresponding complex value of the signal in the frequency domain. Eq. 4.1 provides information concerning the magnitude and phase spectra of the signal within the frequency domain. Specifically, the amplitude spectrum reveals the strength of different frequency components contained in the signal, thereby enabling the assessment of the relative contributions of each frequency within the time-domain signal. Conversely, the phase spectrum offers valuable insights into the temporal positioning and synchronization of these frequency components, indicating the extent of their phase shifts relative to a reference sinusoid of identical frequency and zero phase. Both the amplitude and phase spectra are integral to comprehensive signal analysis. Notably, the amplitude spectrum delineates the energy distribution across the signal's constituents. This information is effectively encapsulated by the PSD, which measures a signal's power distribution as a function of frequency, highlighting those frequencies with the greatest energy content. The PSD is directly proportional to the square of the Fourier Transform's amplitude and is computed as described in Eq. 4.2

$$PSD(f_k) = \frac{1}{N f_s}|X_k|^2 \tag{4.2}$$

where f_s denotes the sampling frequency. The results of the power spectral analysis are presented in Fig. 4.7.

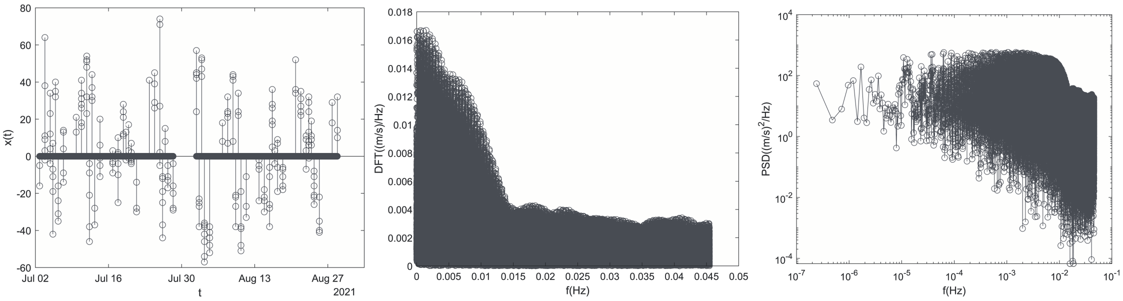

Figure 4.7: Spectral analysis process. Time-domain signal, $x(t)$ (left). The DFT (center). The PSD (right). Image taken from [275].

4.2.2 Zero-padding

The initial approach utilized in this study to address non-uniformly sampled data involves the use of the zero-padding technique to fill in the missing temporal intervals. Fig. 4.8 depicts the implemented process. Upon extraction of the signal, zero-padding is subsequently applied, followed by spectral analysis and ultimately, fitting of the resulting PSD.

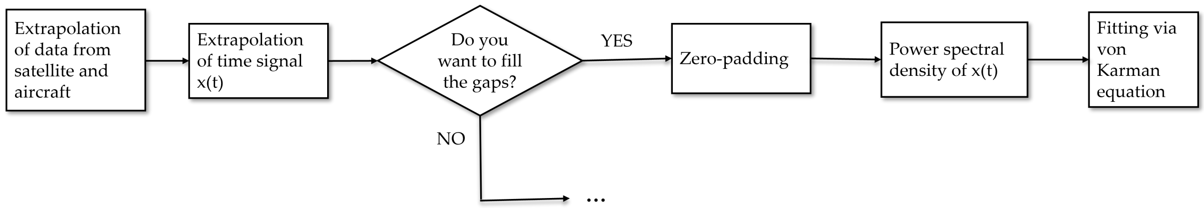

Figure 4.8: Representation of the process for analysing signal data using the zero-padding technique.

The zero-padding technique involves adding zeros to the signal at the intervals where data is missing, ensuring that the resulting signal is uniformly sampled. Once this process is complete, spectral analysis is performed. An example of this application is shown in Fig. 4.9, which demonstrates zero padding applied to a signal retrieved from satellite data.

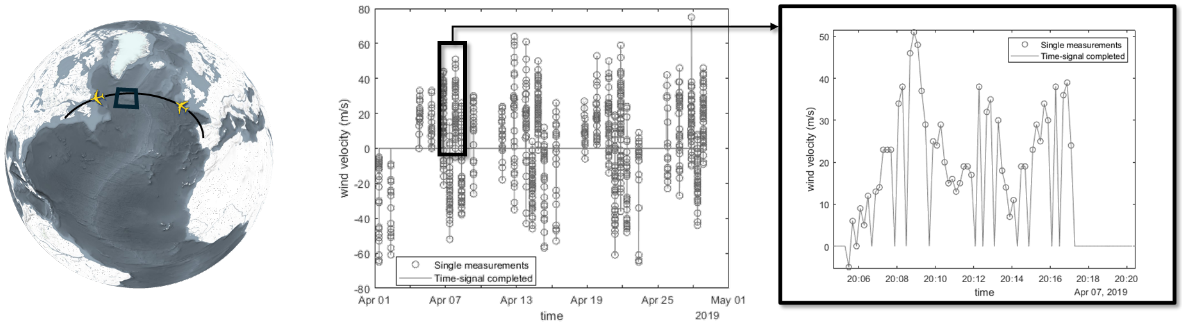

Figure 4.9: Data extracted (right image) from ESA platforms VirES in an area (box of left image) of the transatlantic flight route and zero padding applied on the time signal. Image taken from [275].

4.2.2.1 Fitting model based on the von Kármán equation

To accurately determine a representative curve of the PSD, the data have been fitted using a model based on the von Kármán equation, a renowned mathematical representation for the PSD of vertical and horizontal wind gust [254]. Eq. 4.3 is used for vertical wind gusts

$$PSD_{vk}(f_k) = \frac{\sigma^2 L}{\pi V} \frac{1 + \frac{8}{3}\left(1.339\frac{2\pi L}{V} f\right)^2}{\left[1 + \left(1.339\frac{2\pi L}{V} f\right)^2\right]^{\frac{11}{6}}} \tag{4.3}$$

in which σ represents the root mean square of the vertical wind speed, L denotes the turbulence scale, and V is the air speed. The von Kármán model is calibrated using two key parameters: L and σ. The parameter L determines the frequency at which the slope of Eq. 4.3 increases, providing insight into how gust properties vary spatially, and it is influenced by factors such as altitude. Meanwhile, the parameter σ quantifies turbulence intensity, which depends on the average wind speed and altitude [277]. These parameters are estimated using a non-linear least squares optimization approach to determine the

PSD curve that best fits the data, based on the von Kármán equation. Eq. 4.4 is the parametric equation used in the optimization:

$$PSD_{vk}(f_k) = a\frac{1+\frac{8}{3}\left(bf\right)^2}{\left[1+\left(bf\right)^2\right]^{\frac{11}{6}}} \tag{4.4}$$

with $a = \frac{\sigma^2 L}{\pi V}$ and $b = 1.339\frac{2\pi L}{V}$. This fitting process is illustrated in Figs. 4.7 and 4.10, starting from the time-domain signal and eventually achieving the von Kármán-modeled power spectral density PSD_{vk}. These examples come from satellite data covering an area between 50° and 55° North latitude and 33° and 43° West longitude, with an altitude range from 9.9 to 10.9 km.

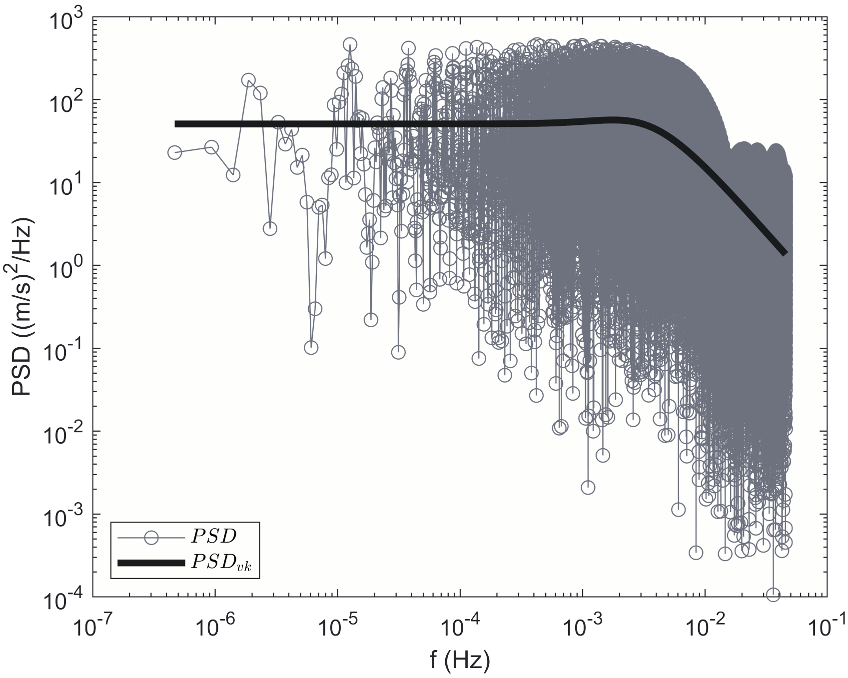

Figure 4.10: PSD and PSD_{vk} of vertical wind velocity signal. Image taken from [275].

4.2.3 Welch's method

The second approach outlined adheres to the methodology depicted in Fig. 4.11. Once the signal has been extracted, any missing data intervals are accordingly removed, and the analysis continues solely on the available data. The individual time intervals are then merged to create a uniformly sampled signal, and Welch's method is then applied. Subsequently, the fitting based on the von Kármán model, as described in section 4.2.2.1, is used.

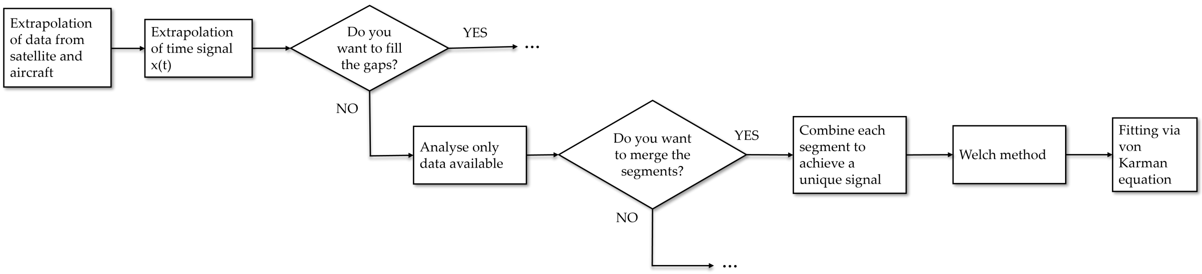

Figure 4.11: Representation of the process for analysing signal data using the Welch's method.

The Welch's method is a common technique for estimating the PSD of a signal [278, 279]. The following steps are involved in Welch's method, specifically when applied to a time-domain signal $x(t)$.

- The signal is divided into M overlapping segments of length L. It is important to note that if the signal alternates time intervals in which the data is missing, as in the case of LEO satellite data, only the available data, i.e., belonging to the segments of the signal, have been considered. The data have been combined to obtain a single discrete signal $x[n]$, as illustrated in Figure 4.12. It is important to note that L is assigned as a function of N_s, the length $x[n]$.
- A window function $w[n]$, is applied to each m-th segment.
- The DFT is then computed for each windowed segment.
- The PSD for each segment is then computed, referred to as the "modified PSD".
- The modified PSDs are then averaged to obtain the PSD estimate of the signal.

Turning to the mathematical formulation, the length of each segment is represented as L, and the interval between successive segments is denoted by D, which is defined as follows:

$$D = (1 - L\alpha) \tag{4.5}$$

where $\alpha \in$ [0,1) represents the overlap ratio. The $m - th$ segment of the signal, with $m = 1, ..., M$ is:

$$x_m[n] = x[n + (m-1)D], \qquad \text{for n} = 0,1..., L-1 \tag{4.6}$$

Subsequently, a window function $w[n]$ is applied to each segment, resulting in the windowed segment $\tilde{x}_m[n]$:

$$\tilde{x}_m[n] = x_m[n]w[n] \tag{4.7}$$

In this work, two different window functions have been employed: the Hamming function (see Eq. 4.8) and the rectangular one (see Eq. 4.9).

$$w[n] = 0.54 - 0.46cos\left(\frac{2\pi n}{L-1}\right), \qquad \text{with } 0 \leq n < L \tag{4.8}$$

$$w[n] = 1, \qquad \text{for } 0 \leq n < L \tag{4.9}$$

At each windowed segment, the DFT is applied, according to Eq. 4.1, thereby obtaining

$$X_m[j] = \sum_{n=0}^{L-1} \tilde{x}_m[n] e^{-i2\pi \frac{j}{L} n} \qquad \text{with j} = 0,1, ...L-1 \tag{4.10}$$

The modified PSD of the *m-th* segment is evaluated according to the following equation

$$PSD_m[j] = \frac{1}{LU} |X_m^2[j]| \tag{4.11}$$

where U is a normalization factor that preserves signal power

$$U = \frac{1}{L} \sum_{n=0}^{L-1} w^2[n] \tag{4.12}$$

Finally, the PSD_w estimate is obtained by averaging the modified PSD_m

$$PSD_w = \frac{1}{M} \sum_{m=0}^{M-1} PSD_m \tag{4.13}$$

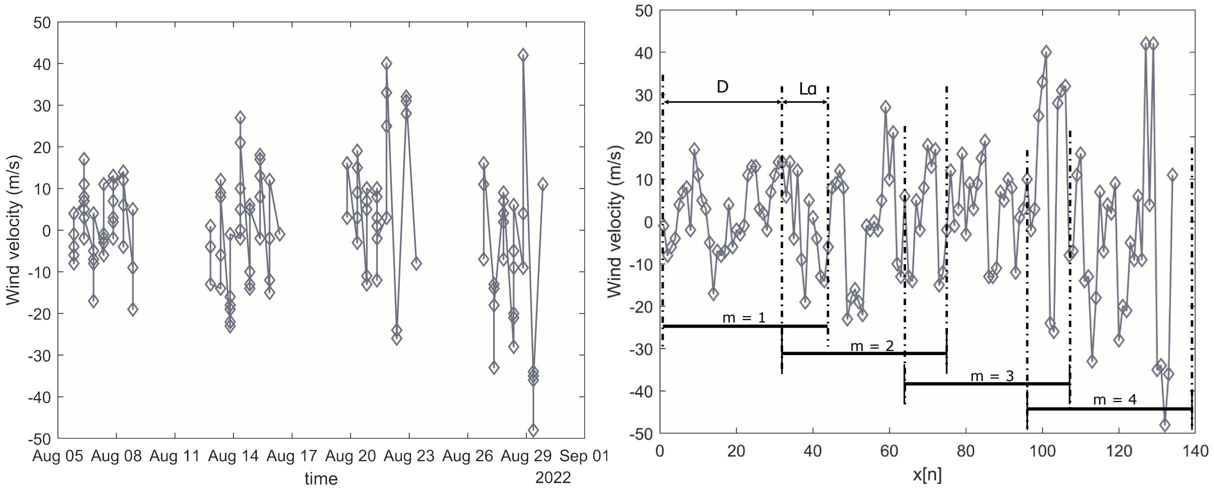

Figure 4.12: The representation of the x(t) signal is shown on the left-hand side of the figure, and the creation of the x[n] signal is shown on the right-hand side.

It is essential to recognize that in this study, the length of each segment used to partition the signal is selected as a parameter, for example, $L = N_s/4$, rather than the number of segments, denoted as M, which is a direct consequence. For instance, as depicted in Fig. 4.13 (left), if $\alpha = 0$, the signal is ideally divided into M segments of length L. However, selecting a non-zero value for α while maintaining a fixed L, the signal partition results in part of the signal being unused, as demonstrated in Fig. 4.13 (center), because it is not feasible to partition the signal into equal segments by imposing specific length and overlap parameters. Similarly, if the overlap parameter increases while L remains fixed, it is possible that the value of M increases, as shown in Fig. 4.13 (right). This occurs because the excess portion of the signal allows to add segment of length L.

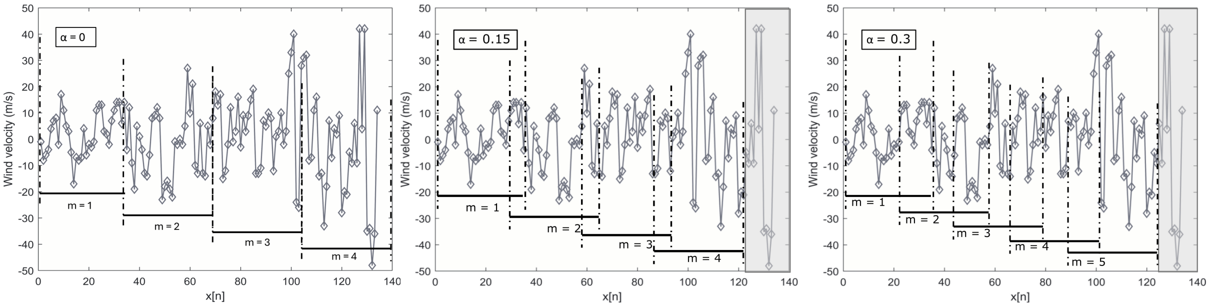

Figure 4.13: Signal to which Welch's method is applied with $L = N_s/4$ and $\alpha = 0$ (left). Same signal with $L = N_s/4$ but $\alpha = 0.15$ (center). Same signal with $L = N_s/4$ and $\alpha = 0.3$ (right). The greyed-out part is the data that is excluded because the overlap and the length of the window do not allow the signal to be split exactly.

4.2.4 Weighed PSD

The last technique proposed, similar to Welch's method presented earlier, focuses on analyzing only usable data. However, unlike Welch's method, it does not reconstruct a single uniformly sampled signal using the available data; instead, it analyzes the available data intervals individually. The process is illustrated in Fig. 4.14.

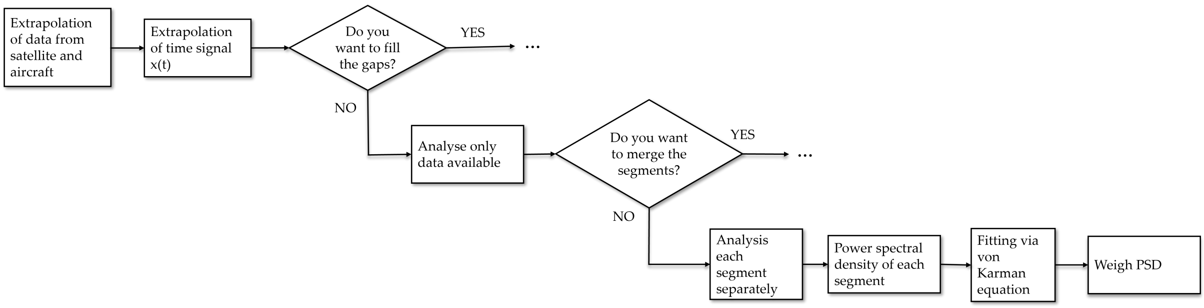

Figure 4.14: Representation of the process for analysing signal data weighting the PSD.

Specifically, for each segment, spectral analysis is conducted, and the fitting process, employing the von Kármán model (detailed in Section 4.2.2.1), is used to produce the PSD, PSD_{vk}. Subsequently, the overall PSD, $\overline{PSD_{vk}}(f_k)$, of the entire signal is then derived as a weighted average based on the length of each segment, as illustrated in Eq. 4.14. Individual segments have different lengths, so once the PSD of each segment is calculated, vectors of different lengths are obtained, which cannot be averaged in MATLAB because it requires vectors of the same length. To overcome this problem, it was decided to average the fits, since the parametric von Kármán model calculates the a and b values that define the curve (Eq. 4.4), which can then be generated with a variable number of points. In this way, the parameters that make up the PSD_{vk} of the individual segments were obtained, the curves were generated using the same number of points, and then the $\overline{PSD_{vk}}(f_k)$ was calculated using a weighted average as described below

$$\overline{PSD_{vk}}(f_k) = \sum_{i=1}^{Z} PSD_{vk_i} W_i \tag{4.14}$$

where PSD_{vf_i} indicates the power spectral density for each $i-th$ segment, and Z is the total number of segments of the time-domain signal. W_i is the weight assigned to each term in the sum, ranging from 0 to 1, depending on the length of the specific signal segment, as shown in the following equation:

$$W_i = \frac{l_i}{\left(\sum_{i=1}^{Z} l_i\right)} \tag{4.15}$$

where l_i indicates the length of the $i-th$ signal segment and the denominator normalizes weights according to the total length of all segments. This weighting scheme ensures that longer segments contribute proportionally more to the signal's power spectral density, thereby maintaining a balance that accurately reflects the data's quality and representativeness.

4.2.5 An alternative fitting method using an agnostic approach

To accurately capture a representative PSD curve, the data were fitted using a model based on the von Kármán formulation discussed in section 4.2.2.1. While the von Kármán model is widely used in the aeronautical industry for sizing aircraft structural components, it is essential to note that recent climate changes have increased the frequency of hazardous phenomena [229]. Consequently, the von Kármán model may no longer effectively describe such complex and evolving phenomena. In this section, an alternative approach is introduced. This new model, called *agnostic* because it does not depend on a specific pre-existing equation, aims to determine the best-fit curve directly from data without relying on a predefined formula. The process begins by identifying a polygonal chain, followed by an optimization procedure to find the best-fit curve. The key steps to determine the polygonal chain are as follows:

1. a set of n points, equally spaced on a logarithmic frequency scale, is defined;
2. for each point is calculated a specific frequency f_n and a corresponding value on the y-axis y_n is assigned;
3. the polygonal chain is defined by the union of $n-1$ segments that connect the n points, with each segment connecting two consecutive points.

The error e_k between the polygonal chain and the PSD is defined according to Eq. 4.2.5, where y_k represents the value of the polygonal chain at the *k-th* frequency f_k. An example of the polygonal chain for $n = 11$ is depicted in Fig. 4.15.

$$e_k = y_k - PSD(f_k) \tag{4.16}$$

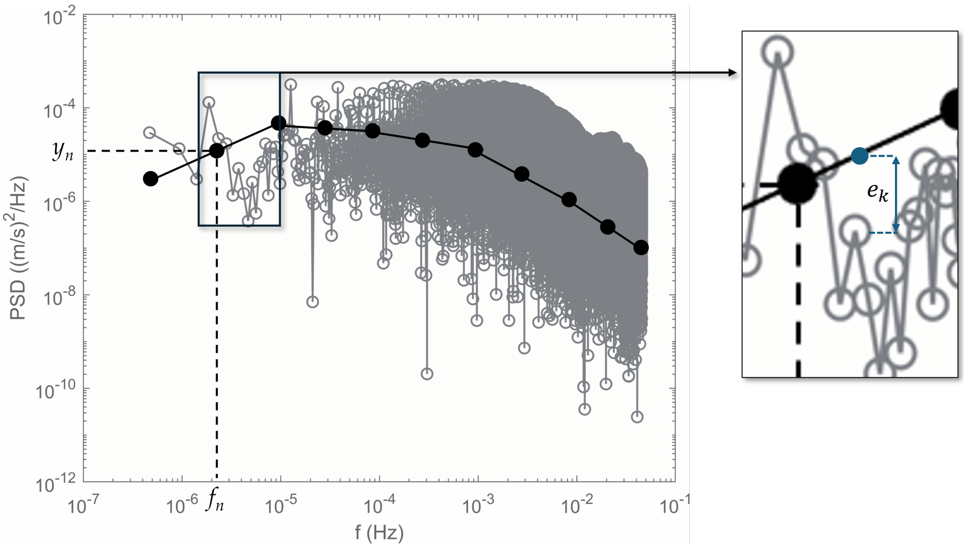

Figure 4.15: An example of polygonal chain with $n = 11$

Once the polygonal chain is defined, an optimization problem is carried out according to Eq. 4.17

$$\begin{cases} \min \dfrac{\sum_{k=0}^{N-1} e_k^2(y_n)}{\sum_{k=0}^{N-1} \left(PSD(f_k) - \dfrac{1}{N} \sum_{j=0}^{N-1} PSD(f_j) \right)} \\ y_{\min} \leq y_n \leq y_{\max} \end{cases} \tag{4.17}$$

The objective function chosen for the optimization problem is the complement of (R^2)[1], as shown in Eq. 4.17. The design variables are the y coordinates y_n of the n points in the polygonal chain, with the upper bound y_{max} and lower bound y_{min} depending on the data used. The optimization utilizes gradient-based algorithms, along with a multi-start approach, to find a solution close to the global minimum. The output of the optimization algorithm is the polynomial chain that best fits the data. The shape of this curve varies with the number of points n, which is discussed in the next section.

4.3 Comparison of fitting models

Applying a fitting model facilitates a more precise representation of the PSD, reduces noise, and allows for the extraction of a representative curve. This curve can subsequently be utilized as a gust model for further analysis and comparison, particularly in relation to the well-established von Kármán turbulence model. Two fitting methodologies were adopted in this study, as delineated in the preceding section: a model-based approach that assumes the von Kármán spectrum and an agnostic approach that maximizes the coefficient R^2. The R^2 value serves as a quantitative metric of the fitting accuracy relative to the sample data, thereby providing a valid criterion for evaluating which model more effectively captures the characteristics of the observed signal.

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[1] In the field of statistics, R^2 is denoted as the coefficient of determination. This coefficient represents the proportion of the variation in the dependent variable that is predictable from the independent variable. It provides a quantitative measure of the extent to which observed outcomes are replicated by the model, based on the proportion of total variation in outcomes explained by the model [280].

The agnostic method involves an iterative convergence process that may lead to higher computational costs, depending on the input data. Fig. 4.16 (left) shows how the R^2 value changes across iterations, and Fig. 4.16 (right) displays the resulting fitting curves at two different stages of the optimization process, using a total of 30 points.

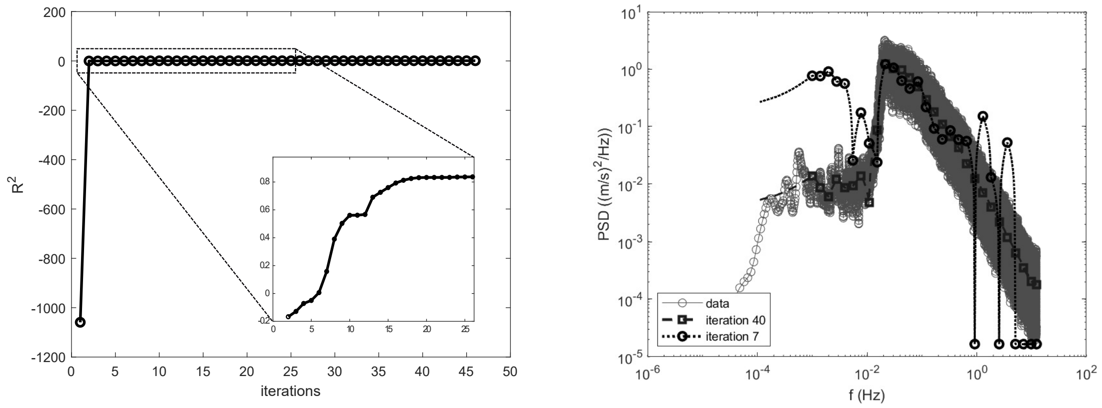


Figure 4.16: The figure on the left shows the R^2 value varying with iterations before reaching the convergence point. The right image depicts two different fits before and after convergence. The curve with points indicates a curve achieved at iteration 7 ($R^2 = 0.64$), while the line with square markers is achieved at convergence, at the 40th iteration ($R^2 = 0.85$). The data used are related to the flight campaign EUREC4A.

Another key factor is the number of points used in the optimization process to define the fitting curve. This number should be determined experimentally. Fig. 4.17 (left) shows how the R^2 values vary with the number of points used in the fitting process. The number of points tested ranges from 6 to 30, with corresponding R^2 values between 0.62 and 0.85. Fig. 4.17 (right) illustrates the different fitting curves with 30 and 10 points. It's clear that using more points leads to a more accurate representation, but the complexity and number of parameters are increasing, thereby raising the computational cost. Therefore, finding a balance between accuracy and computational time is crucial.

Fig. 4.18 presents the fitting results obtained with the von Kármán model (Eq. 4.3) and with the agnostic approach. The von Kármán fit effectively reproduces the spectral behavior at high frequencies but exhibits limitations at low frequencies, resulting in an overall coefficient of determination of $R^2 = 0.7$. The fitting is performed through a least-squares procedure, where the model parameters a and b (defined in Eq. 4.4) are adjusted to minimize the error between the theoretical spectrum and the observed PSD. Conversely, the agnostic approach relies on an optimization algorithm that does not impose a predefined functional form, thereby allowing the spectral shape to be directly inferred from the data. As illustrated in Fig. 4.18, this method provides a more accurate representation across the full frequency range, reflected in an improved $R^2 = 0.85$.

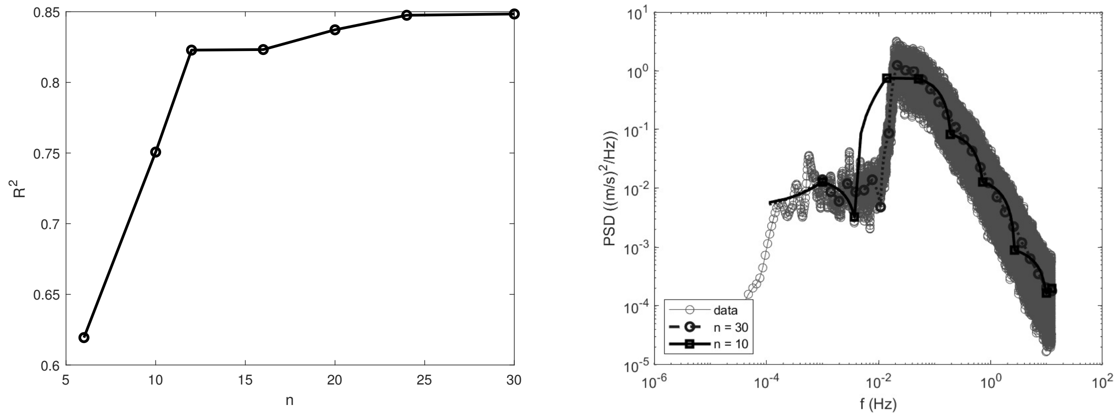


Figure 4.17: The figure on the left shows the R^2 value varying with the number of points. The right image depicts two different fits. The curve with points indicates a curve achieved with 30 points ($R^2 = 0.85$), while the line with square markers is achieved with 10 points ($R^2 = 0.75$). The data used are related to the flight campaign EUREC4A.

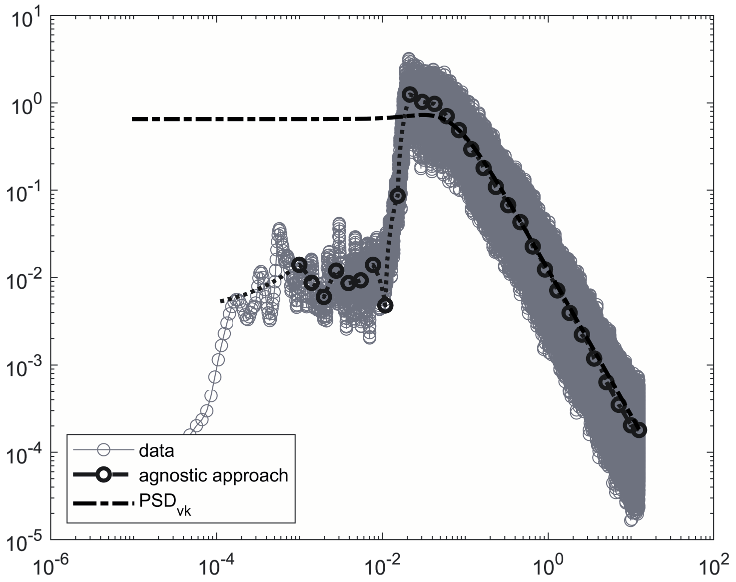


Figure 4.18: The comparison is made between the two fitting models. The agnostic approach is achieved using 30 points, with the data being derived from the flight campaign.

4.4 Exploratory assessment of spectral estimation techniques with discontinuous flight data

This section presents the results obtained by using different methods to derive and manipulate the PSD of the data collected during EUREC4A's flight campaign.

- Firstly, Section 4.4.1 reports the results of applying Welch's method to a discontinuous signal, explicitly highlighting the effect of window type and length, and overlap applied.
- Section 4.4.2, reports the impact of zero-padding on the signals under analysis and the differences between Welch's methods.

- Lastly, the results of weighted averaging of the PSD are shown, and the results obtained with the previous methods are compared in section 4.4.3.

The true underlying spectrum of the wind gust process is unknown, so the objective is not to validate a single method against ground truth, but rather to compare how the estimated PSD changes when classical approaches are used in the presence of data gaps. To this end, the signal shown in Fig. 4.19 was constructed by aggregating flight segments acquired on different days, to reproduce the discontinuities typical of satellite observations. The proposed analyses allow us to observe how different techniques (Welch's method, zero-padding, and weighted averaging) produce PSD estimates with distinct characteristics. The discussion, therefore, focuses on the qualitative differences among the methods and their known limitations, rather than on quantitative validation against the true spectrum.

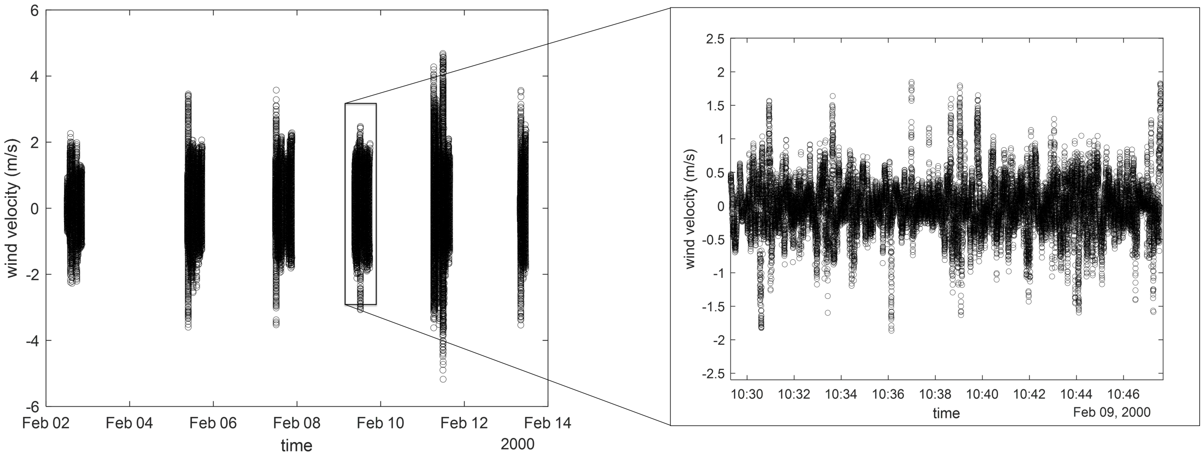


Figure 4.19: Time domain signal of the flight campaign data.

4.4.1 Welch's method - windowing and overlapping influence

The Welch's method depends on critical parameters, including the overlap ratio, the length of the segments, and the type of window function, to compute the PSD. The purpose of this section is to evaluate the influence of these parameters on the PSD assessment.

To examine the impact of windowing on spectral estimates, Hamming and rectangular windows were employed, with the segment length L varied from N_s to $N_s/8$. This approach enabled observation of how different window shapes influence the power spectral density at various segmentation levels. The Fig. 4.20 illustrates the differences induced by the choice of window when $L = N_s/4$ is used with zero overlap ratio.

A noticeable reduction in variance is obtained when Welch's method is applied with either windowing type. The comparison between Hamming and rectangular windows shows that the choice of windowing function has only a minor influence on the estimated PSD. As shown in Fig. 4.20, the Von Kármán fits remain of comparable magnitude in the three cases, while the R^2 value increases when Welch's method is used. This should not be interpreted as a closer agreement with the true wind spectrum, which is unknown, but only as an improved fit with the chosen von Kármán reference model.

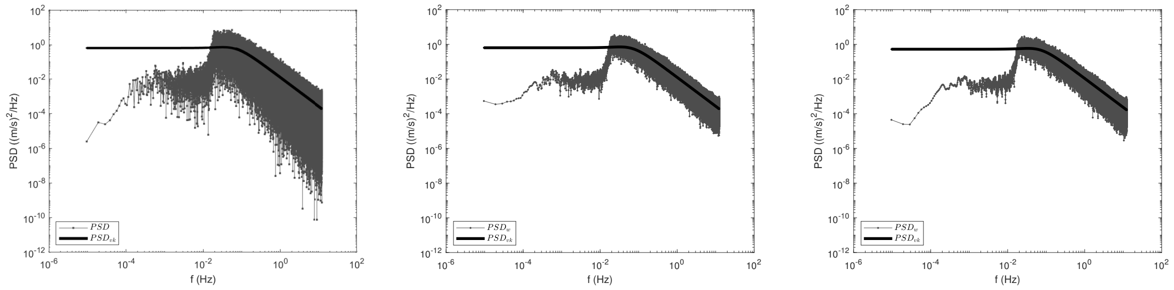


Figure 4.20: Differences between the types of windowing. PSD evaluated with the periodigram approach. $R^2 = 0.41$ (left). PSD_w with rectangular windows, $L = N_s/4$ and zero overlap. $R^2 = 0.65$ (center). PSD_w with Hamming windows, $L = N_s/4$ and zero overlap. $R^2 = 0.66$ (right).

Focusing only on the Hamming window and varying L from N_s to $N_s/8$, it is observed that decreasing the length of segments reduces the noise, as shown in Figs. 4.21 and 4.22, depicting the R^2 varying L. This result is expected, as Welch's method provides a more reliable estimate of the PSD by reducing the variance associated with single-segment Fourier transforms. This is achieved by dividing the signal into multiple segments, applying a window function to each, and averaging the resulting periodograms. Although each segment provides a noisy spectral estimate due to finite data length, averaging smooths out random fluctuations, leading to a PSD that better reflects the signal's spectral content.

It must also be noted that, since the signal is obtained by concatenating independent flight segments, artificial discontinuities are present at the junctions. In the frequency domain, these discontinuities generate broadband contributions across the observable spectrum, contaminating the turbulent content. As a consequence, Welch's method in this context should be interpreted mainly as an illustrative benchmark, since part of the observed energy may derive from stitching artifacts rather than from the actual wind field.

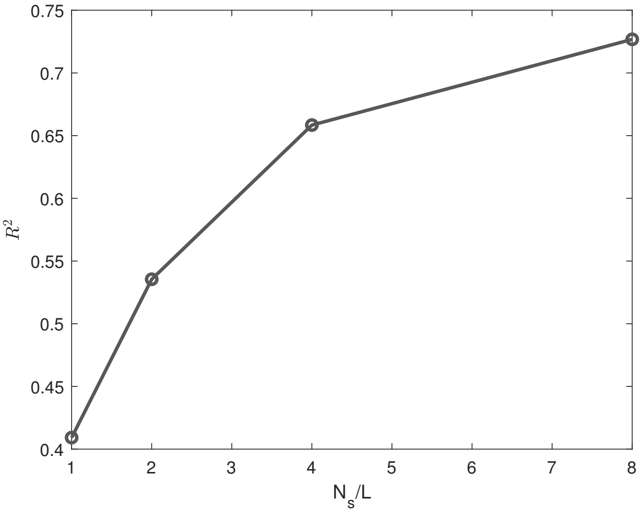
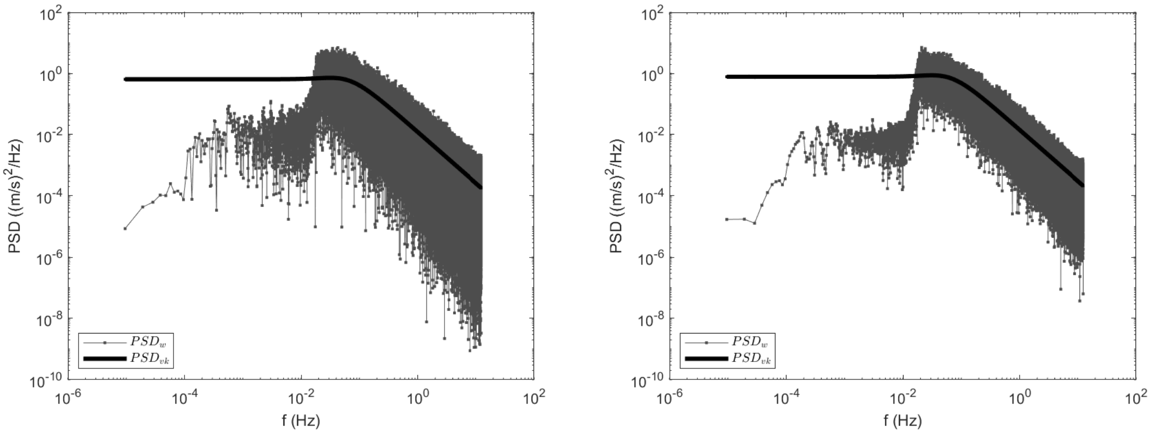
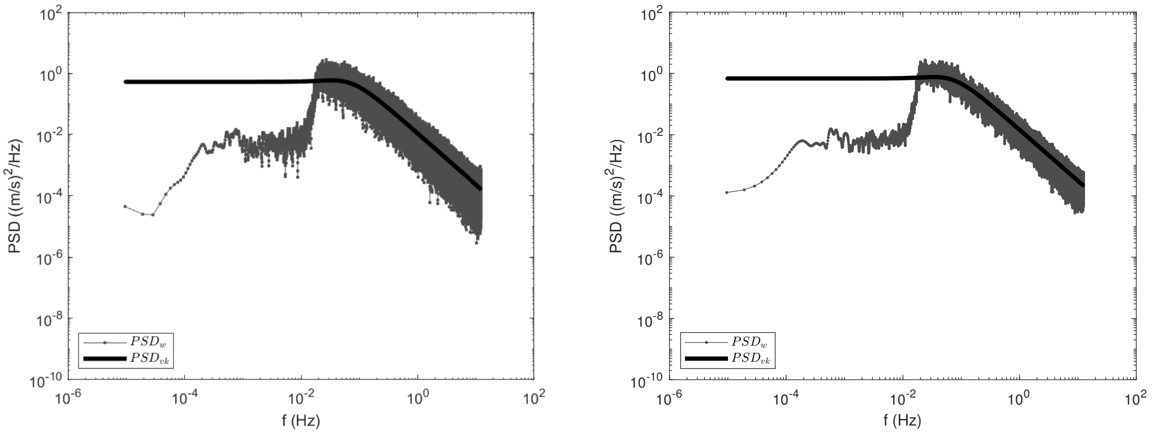


Figure 4.21: R^2 obtained varying the length of the Hamming windodw, L, from N_s to $N_s/8$, with overlap ratio $\alpha = 0$.



(a) One Hamming window. $R^2 = 0.41$ (b) Two Hamming windows. $R^2 = 0.54$



(c) Four Hamming windows. $R^2 = 0.66$ (d) Height Hamming windows. $R^2 = 0.73$

Figure 4.22: Influence of the number of Hamming windows, adopting 0% of overlap.

To assess whether there are any changes in the frequency content, a comparison was conducted between the PSD_{vk} calculated using $L = N_s, N_s/2, N_s/4, N_s/8$, as illustrated in Fig. 4.23. Since the spectra are obtained by fitting a von Kármán model, the overall shape (flat region, knee, and decay) is imposed by the model itself. What changes with L is the estimated spectral level, which shifts slightly in both the low- and high-frequency ranges. These differences are relatively modest, but not strictly monotonic with window length (e.g., the $L = N_s/4$ curve lies below the $L = N_s/8$ case in the zoomed regions). This indicates that, while the fitting procedure constrains the spectral form, the pre-processing with Welch's method still affects the calibration of the PSD amplitude. For applications such as fatigue assessment, where the spectral level directly influences damage predictions, these shifts must be considered to avoid bias in evaluating the contribution of different frequency ranges.

To assess the impact of the overlap ratio, the Hamming window was chosen because its type does not significantly affect the PSD, as explained earlier. The window length L was varied from N_s (i.e., the entire signal length) down to $N_s/8$, while the overlap ratio α was varied from 0 to 0.8. $\alpha = 0$ means that the windows are not overlapped, whereas $\alpha = 0.8$ indicates that the window overlap is 80% of the window length. For each combination of L and α, the corresponding R^2 value was computed. These results are shown in Fig. 4.24, illustrating two main points: i) increasing the length of windows

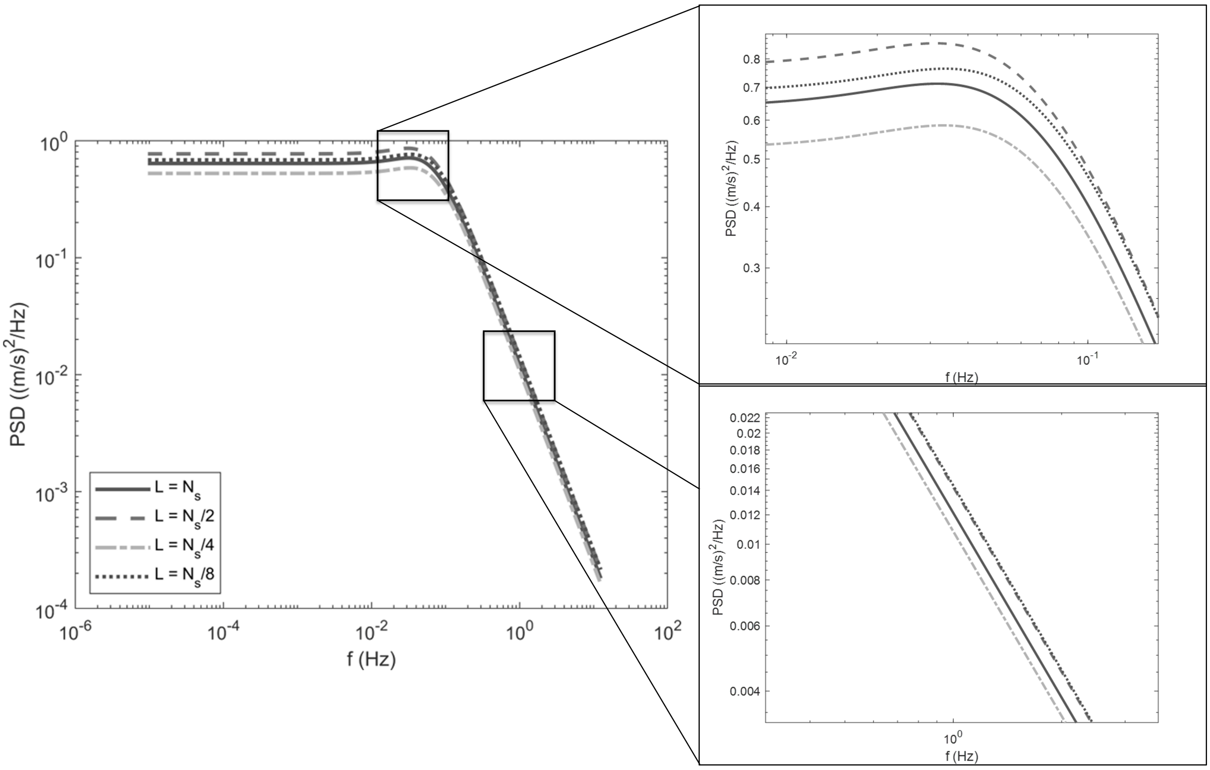


Figure 4.23: Different PSD_{vk} with the length of Hamming windows, L, varying from N_s to $N_s/8$, with overlap $\alpha = 0$.

leads to higher R^2 values, regardless of α, and ii) increasing α has a marginal effect on R^2.

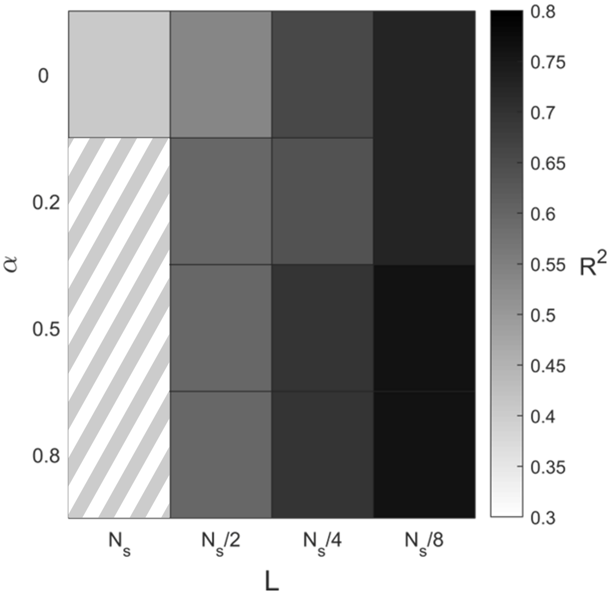
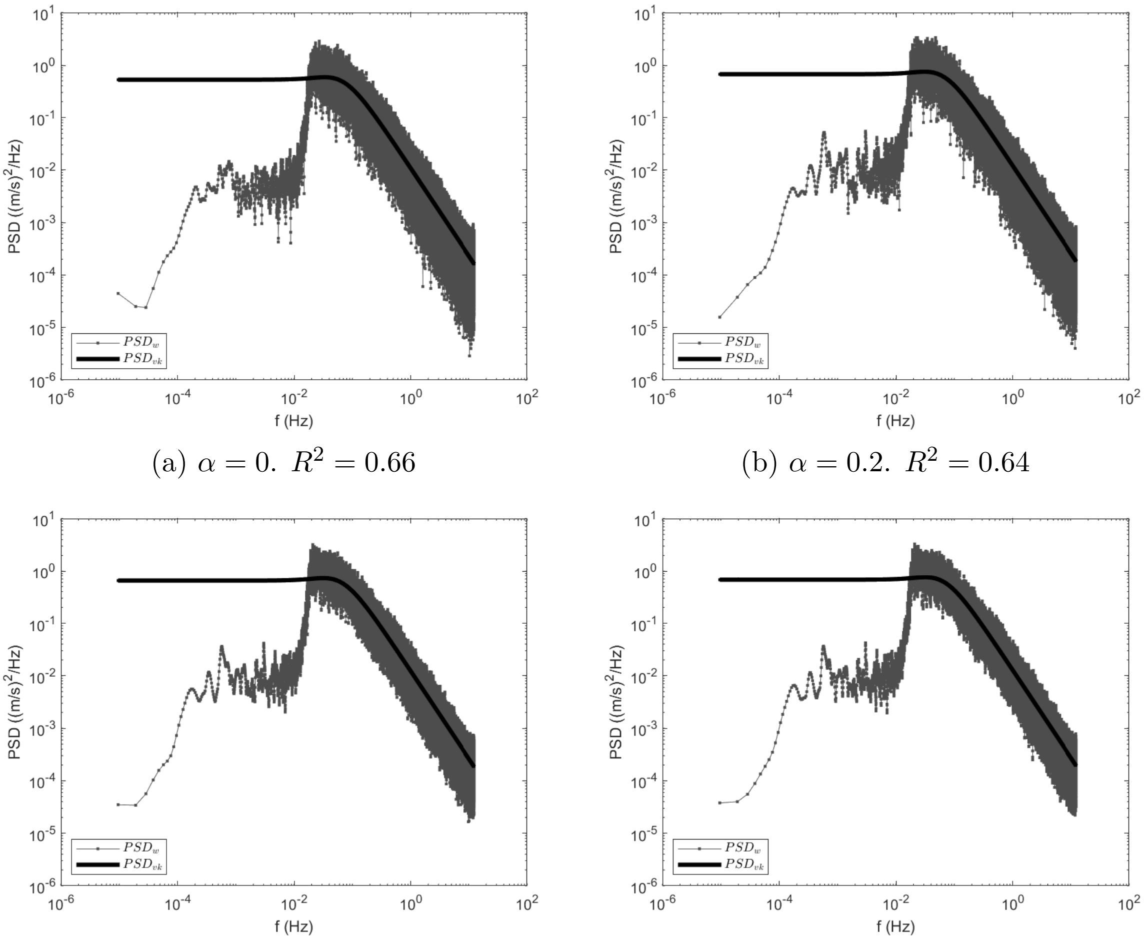


Figure 4.24: R^2 obtained varying α and L, using Hamming windowing. Note that it is not possible to vary the overlap by using only one window.

When the window length L is fixed and the overlap ratio increases, the number of windows M required to span the entire signal also increases. This occurs because greater overlap reduces the step between consecutive windows, leading to more segments that cover the same signal length. Consequently, while L and α are treated as independent parameters, the total number of segments M is inherently dependent on both.

Regarding the power spectral density estimate, increasing the overlap for a fixed window length does not substantially reduce the PSD variance. The primary mechanism by which Welch's method reduces variance is by averaging multiple periodograms from segments. If the segment length remains fixed, increasing overlap only introduces correlation between adjacent windows, yielding little additional statistical benefit in terms of variance reduction. Although a higher overlap may slightly mitigate spectral leakage, the random variability of the spectral estimate remains essentially unchanged. This observation is consistent with the present results, which show that the overlap ratio does not significantly affect R^2. The slight variations in R^2 can be attributed to minor reductions in leakage.

Figs. 4.25 and 4.26 illustrate the case with $L = N_s/4$ and different overlap ratios, supporting this analysis. For a broader examination of the signal's frequency content, a comparison of the PSD_{vk} for each overlap ratio is presented in Fig. 4.27.



(a) $\alpha = 0$. $R^2 = 0.66$

(b) $\alpha = 0.2$. $R^2 = 0.64$

(c) $\alpha = 0.5$. $R^2 = 0.70$

(d) $\alpha = 0.8$. $R^2 = 0.70$

Figure 4.25: Influence of overlap value, adopting $L = N_s/4$ and Hamming windowing.

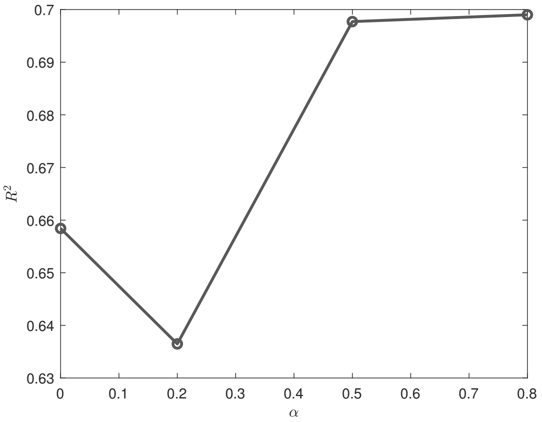


Figure 4.26: R^2 obtained varying α from 0 to 0.8. Hamming windows have been adopted with $L = N_s/4$.

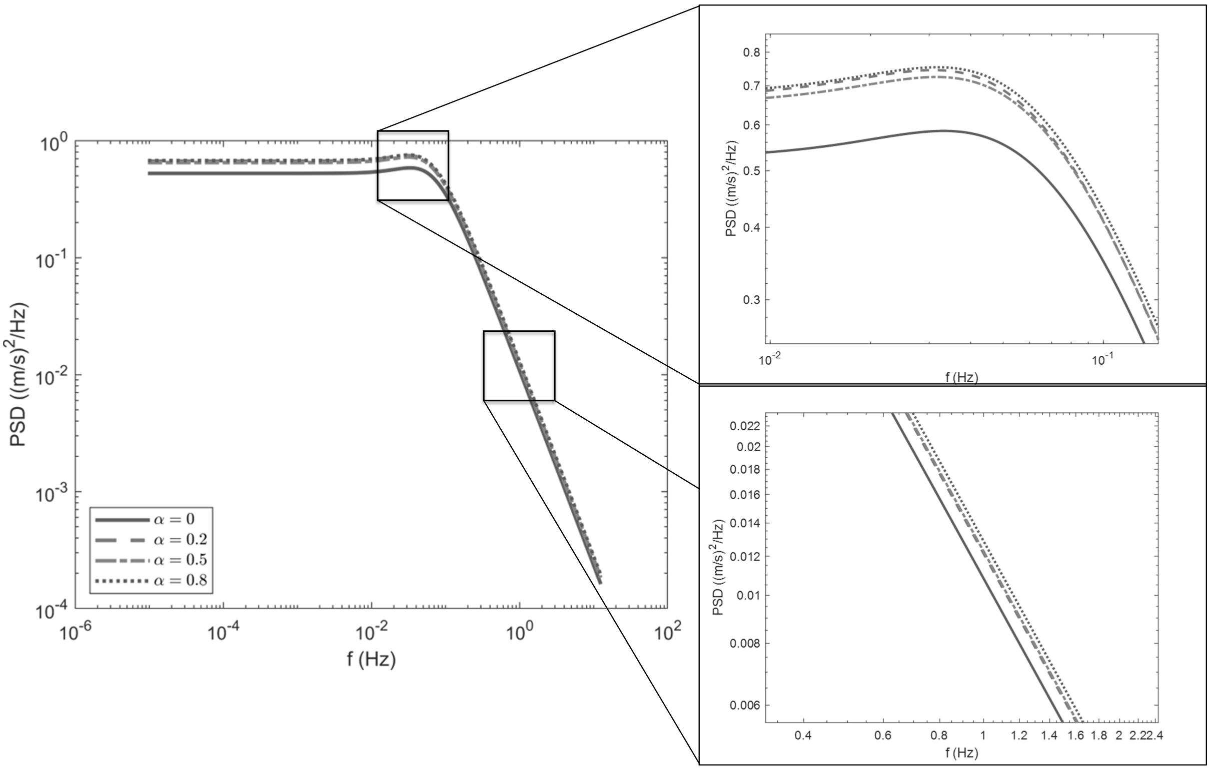


Figure 4.27: Different PSD_{vk} with α, varying from 0 to 0.8. Hamming windows have been adopted with $L = N_s/4$.

4.4.2 Zero-padding

Zero-padding inserts zeros into areas with missing measurements to bridge signal gaps. This process maintains the same sampling interval as the original data and produces the resulting time-domain signal, as shown in Fig. 4.28.

Fig. 4.29 shows the PSD of signals with zero-padding alongside the corresponding PSD_{vk} fit. A comparison between the PSD of the zero-padded signal and the PSD obtained using Welch's method without overlap and with four windows shows that adding

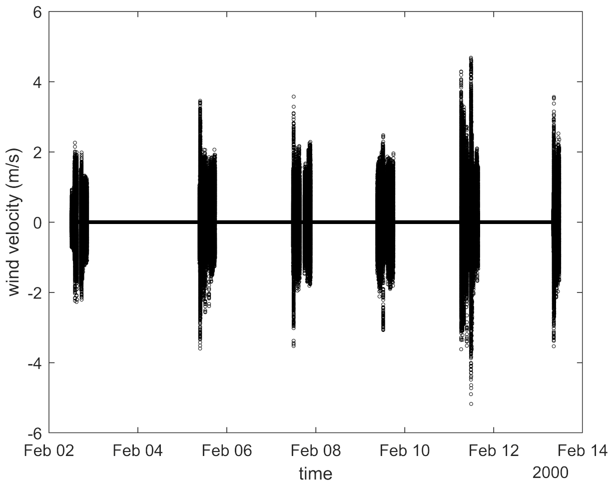
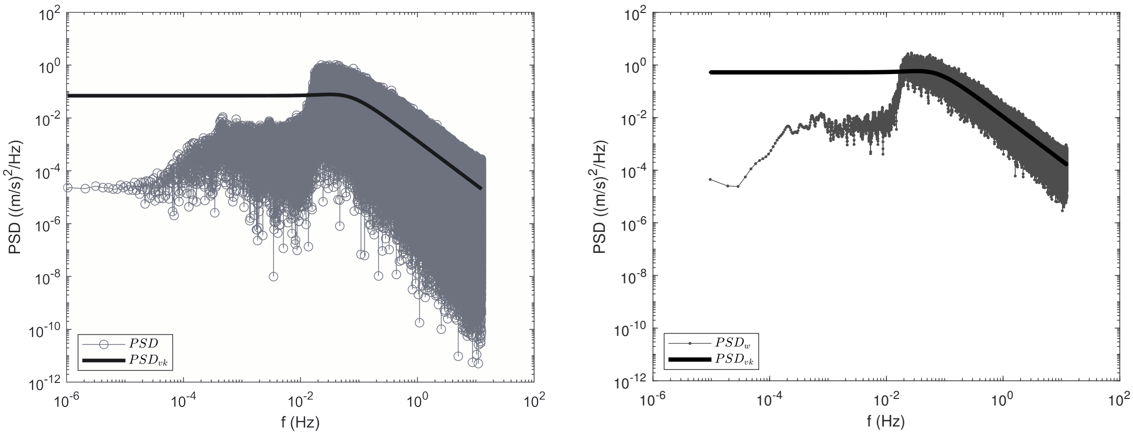


Figure 4.28: Time-domain signal with zero-padding.

zeros slightly reduces the overall spectral magnitude. This reduction is attributable to zero-valued samples, which dilute the signal energy and thereby decrease the spectrum's amplitude. The low R^2 value in the fit can be attributed to the complex, highly variable nature of the signal, indicative of the inherent fluctuations in gust velocity over time.



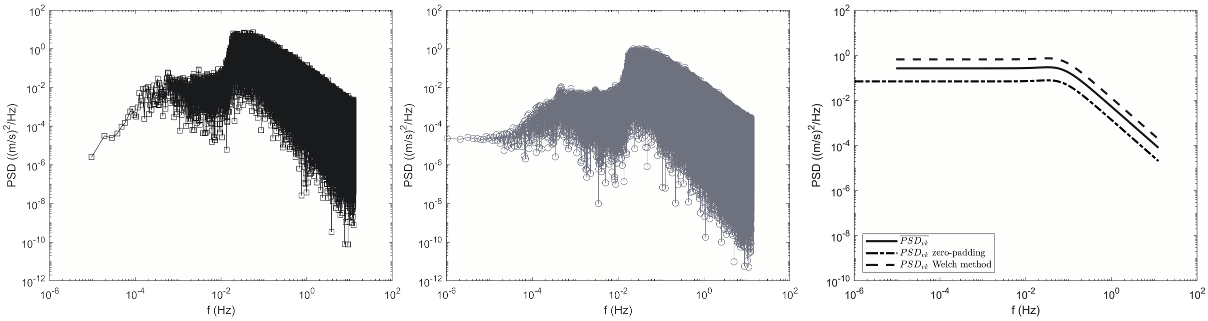
(a) Zero-padding. $R^2 = 0.41$

(b) Welch method. $R^2 = 0.65$

Figure 4.29: Comparison between PSD obtained with zero padded signal and PSD_w obtained with Hamming windows, $L = N_s/4$ and $\alpha = 0$.

4.4.3 Weighted PSD

The final methodology for generating the PSD curve involves implementing the procedure detailed in section 4.4.3. This approach yields a weighted PSD curve, wherein the length of each segment within the time domain determines its influence. Specifically, the longer a segment, the greater its impact. The signal in the time domain is utilized to apply this approach. The resulting $\overline{PSD_{vk}}$ signal is then compared with the one derived using Welch's method (with parameters $L = N_s/8$ and $\alpha = 0.5$), and zero-padding of the signal. In Fig. 4.30, the three approaches provide different PSD levels. The weighted average (solid line), used as a reference and subsequently fit with a von Kármán model, yields an intermediate spectrum that avoids artifacts arising from discontinuities. The zero–padding approach (dash–dot line) underestimates the spectral level, as the insertion of zeros dilutes the signal energy. Conversely, Welch's method applied to concatenated segments (dashed line) produces systematically higher PSD values. This effect is related to the intrinsic characteristics of Welch's averaging procedure (windowing, spectral leakage, and normalization). Therefore, the higher PSD level obtained with Welch's method should be interpreted with caution, as it may not reflect a genuine increase in turbulent energy but rather a methodological bias.



(a) PSD without zero-padding. (b) PSD with zero-padding. (c) PSD fittings comparison

Figure 4.30: Comparison of different methods for obtaining the PSD from a signal with holes. The $\overline{PSD_{vk}}$ is compared with the fit obtained by the Welch method and the fit obtained by zero padding.

Among the three approaches to estimating power spectral density, zero-padding appears to be the least reliable and most conservative. This method artificially inserts zeros when data are absent, thereby reducing the signal's overall amplitude and introducing distortions in its spectral representation. Consequently, since the gust PSD is employed to estimate the fatigue life of structural components, underestimating it may lead to a non-conservative design, potentially compromising structural integrity. In contrast, the weighted-average PSD and Welch's method rely solely on measured data, thus preserving the signal's overall amplitude. The key difference lies in how segment lengths are treated; the weighted-average method gives longer segments greater weight, making it more suitable for varying segment durations. Meanwhile, Welch's method, which divides the data into segments of equal length and averages the periodograms, effectively reduces spectral noise.

4.5 The potentiality of satellite data

This section examines the potential of using satellite data to study wind gusts. As already mentioned in Chapter 3, one of the primary advantages of satellite-based Earth Observation is the ability to collect data from virtually any region of the globe, including remote and oceanic areas that are often inaccessible to ground-based instruments or flight campaigns. This global reach provides an unprecedented opportunity to build long-term, spatially consistent datasets for atmospheric dynamics.

Nevertheless, some intrinsic limitations remain. Geostationary satellites, located at an altitude of approximately 36000 km, offer continuous temporal coverage over the same region, making them particularly well-suited for monitoring rapidly evolving phenomena. However, the large distance from the Earth results in relatively coarse spatial resolution.

In contrast, low Earth orbit satellites operate at altitudes of a few hundred kilometers, enabling them to capture observations with much finer spatial detail. This improvement comes at the expense of temporal coverage. Since LEO platforms follow lower but faster orbits than GEO, a given location is only revisited a limited number of times per day, resulting in gaps in the time series and a reduced capability to track short-lived events. Despite these constraints, missions such as ESA's Aeolus demonstrate the unique potential of EO for atmospheric sciences: equipped with Doppler wind lidar technology, Aeolus can provide wind profiles across different flight altitudes and with nearly global coverage.

In this section, the analysis of satellite data is structured into three main parts:

- section 4.5.1 presents a comprehensive global investigation. Using Aeolus data, severe gust occurrences, classified accordingly [281], were recorded from 2019 to 2022 to identify the most turbulence-prone regions. Variations between years and seasonal trends were analyzed to gain a broader understanding;
- focusing on a highly vulnerable zone prone to severe gusts, the transatlantic route, in section 4.5.2, the previously described methodologies are applied to wind speed data collected by the Aeolus satellite. This data covers part of the transatlantic route (from 50° to 55° North and from 33° to 43° West) during July and August 2021;
- finally, in section 4.5.3, the same dataset is employed to perform comparative analyses that emphasize seasonal and annual variability, as well as the impact of altitude on wind gusts. This method enables an exploratory evaluation of how effectively EO data can be utilized in turbulence research, particularly along one of the busiest air corridors.

4.5.1 Global Scale Analysis

One of the primary advantages of utilizing a satellite in LEO, such as Aeolus, is its capacity to collect data on a global scale. This perspective is essential for identifying broader patterns of turbulence and gust phenomena. Within this section, Aeolus data are employed to conduct a global-scale assessment of severe gust occurrences, following the classification defined by [281]. The analysis focuses on two primary objectives: (i) the identification of geographic hotspots with a higher frequency of severe gusts, and (ii) the examination of seasonal and annual variations to discern potential trends. The comprehensive global coverage provided by Aeolus enables the investigation of regions typically under-monitored, such as the oceans and polar areas, which are nevertheless of significant importance for aviation safety.

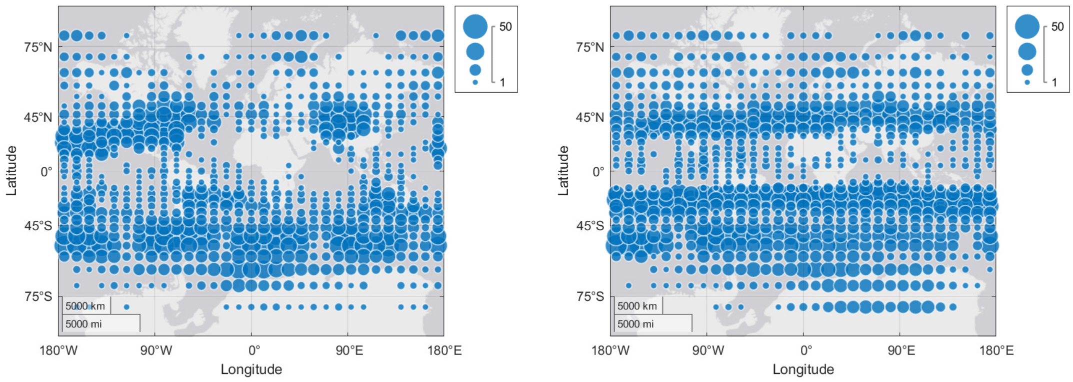
The analysis was carried out through the following steps:

- the globe was subdivided into 961 sub-regions to provide a consistent spatial framework for the study;
- for each three-month observation period, subsequently varied to capture seasonal and annual dynamics, georeferenced Aeolus measurements were assigned to the corresponding sub-region;
- given that the satellite overpasses each area approximately once per day, daily averages of the collected data were computed, and the root mean square, σ, of each signal was derived;

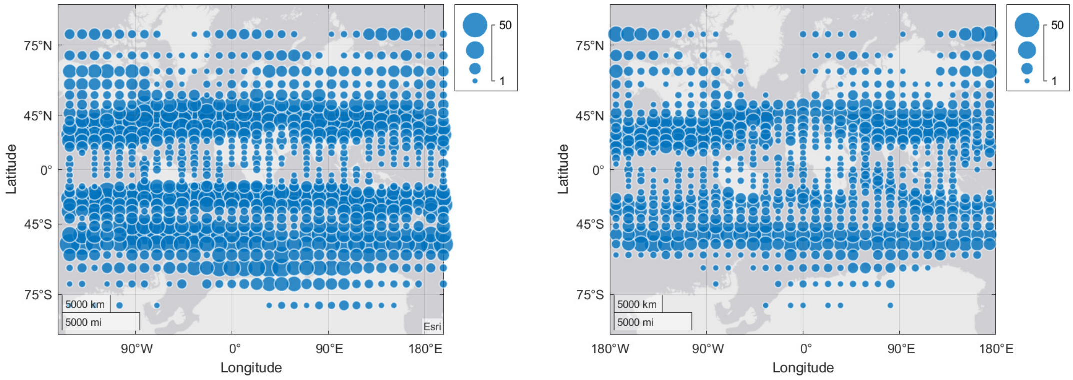
- for each sub-region, the number of days in which σ exceeded the threshold of 20 m/s was recorded, in line with the standard definition of "severe" gusts provided by [281]. This procedure enables the identification of regions most susceptible to hazardous wind conditions.

The results were subsequently visualized using georeferenced maps, as depicted in Fig. 4.31. The dataset encompasses the period from 2019 to 2022, with intervals of three months corresponding to the seasons (e.g., March–May for spring, December–February for winter). For illustrative purposes, only the year 2019 is presented in Fig. 4.31, offering a clear depiction of seasonal variability. In contrast, Fig 4.32 illustrates the variation during the spring months from 2019 to 2022. Nevertheless, the comprehensive maps are provided in Appendix C.

The maps clearly indicate that the most vulnerable areas, marked by larger "bubbles," are primarily located in tropical regions, especially in the Southern Hemisphere. In terms of annual fluctuations, 2020 was notable for having the most widespread and severe gusts, particularly over the North Atlantic and tropical zones. Additionally, the maps highlight the transatlantic route as another significant area affected by gusts. This route, a popular flight corridor, has seen a rise in recorded gusts over recent decades [228].

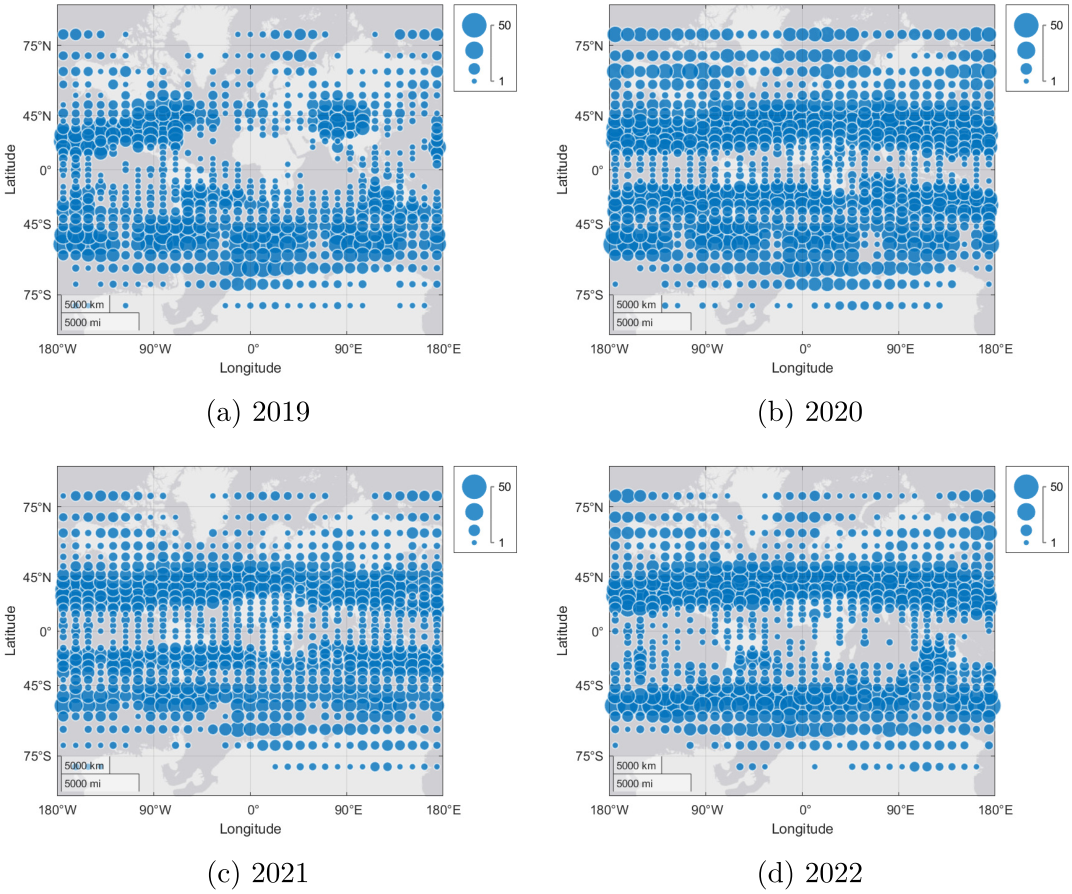


(a) March - April - May (b) June - July - August



(c) September - October - November (d) December - January - February

Figure 4.31: Seasonal variation of wind gust during the 2019.



(a) 2019 (b) 2020

(c) 2021 (d) 2022

Figure 4.32: Annual variation of wind gust during spring from 2019 to 2022.

4.5.2 Application of the fitting model and comparing different methods to obtain a PSD

Focusing specifically on the transatlantic route between approximately 50° to 55° North and 33° to 43° West during July and August 2021, this section compares two fitting models: the von Kármán-based approach and the agnostic method. These are introduced in sections 4.2.2.1 and 4.2.5, but here they are applied to satellite data. Fig. 4.33 shows the results of the agnostic approach and the von Kármán fitting based on data collected in July 2021.

Employing the agnostic approach provides a comprehensive representation of the data, with 16 data points resulting in an R^2 of 0.76. Compared to the agnostic approach, the von Kármán model provides a less accurate data representation; additionally, beyond a narrow frequency range, its PSD tends to be higher than the observed data, thus overestimating the signal's energy. The agnostic approach does not exhibit this overestimation. However, the agnostic approach, which aligns more closely with the data, may also incorporate noise into the fitting process when the data contains significant noise. Applying Welch's method afterward helps reduce this variability, resulting in higher R^2 values.

Concerning the utilization of various techniques to obtain the PSD, Fig. 4.34 illustrates the three methodologies applied to satellite data. It emphasizes that time-domain padding notably reduces the PSD's amplitude compared to the other two methods. The influences of the Welch method (employed with $L = N_s/8$ and $\alpha = 0.5$) and the weighted

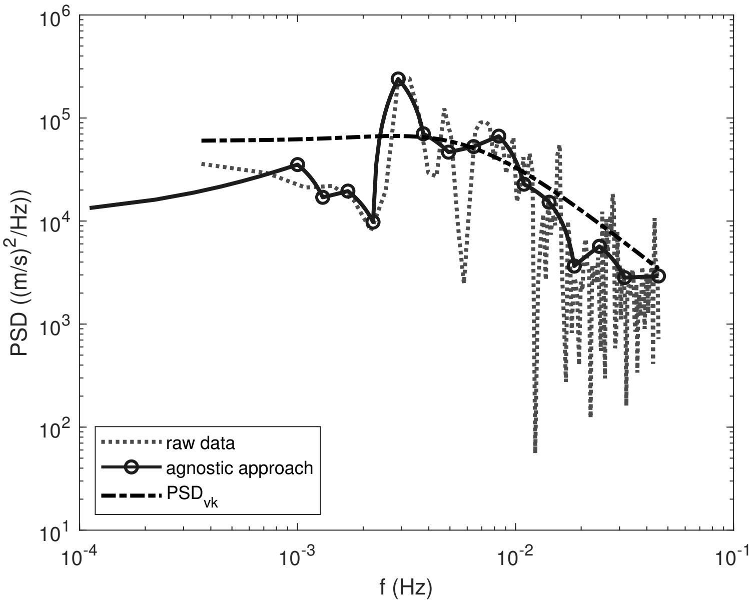


Figure 4.33: Comparison between the von Kármán-based fitting model ($R^2 = 0.36$) and the agnostic approach ($R^2 = 0.76$) used on satellite data from July to August 2021.

average are more noticeable in Fig. 4.34 (right side). A distinct slope at high frequencies and a differing amplitude within the low-frequency range are observable. Additionally, in evaluating the coefficient of determination, R^2, it is noted that the Welch's method attains an R^2 value of 0.33, the weighted PSD achieves an R^2 of 0.011, and zero padding results in an R^2 of 0.28.

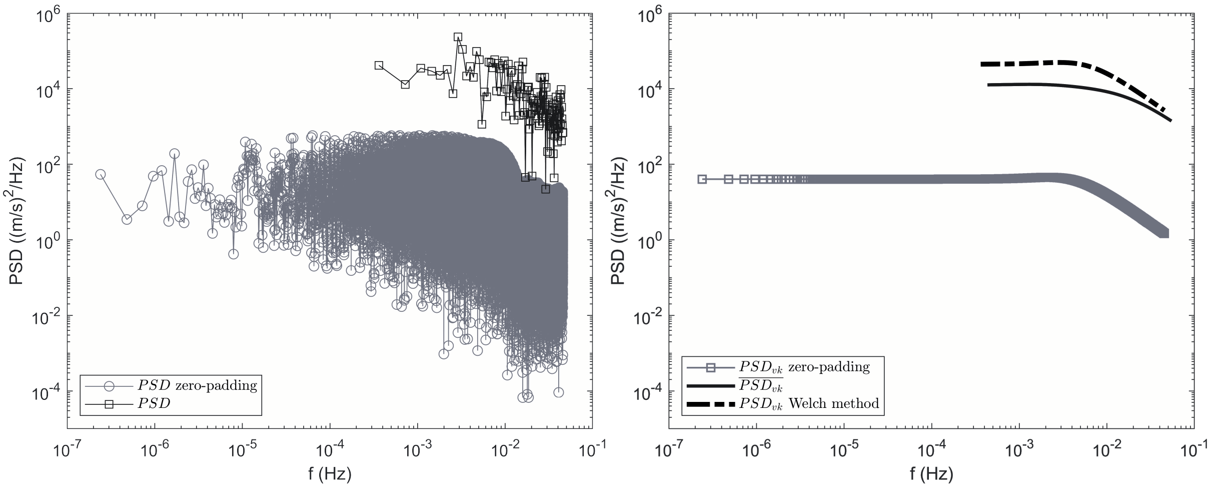


Figure 4.34: Comparison of various methods for extracting the PSD from the satellite signal. The $\overline{PSD_{vk}}$ is compared with the fit from the Welch's method and the fit from zero padding. Additionally, the PSDs with and without zero padding are also shown. The fit is based on the von Kármán model.

Regarding satellite data, Welch's method demonstrates the highest R^2 value among the evaluated techniques. Nonetheless, the satellite's orbital dynamics create significant data gaps, which constrain the attainable R^2 values. It is also noteworthy that Welch's method consistently produces a PSD with higher amplitude, even when applied to satellite data. Additionally, the von Kármán model for fitting the estimated PSD warrants mention. An agnostic approach that better captures the data's spectral characteristics may offer enhanced predictive capabilities relative to the von Kármán formulation. However, due to the higher complexity of the agnostic approach, the subsequent comparative analysis employs the von Kármán-based fitting method instead.

The application of PSD analysis to satellite signals reveals several limitations, predominantly due to the low sampling frequency. This restricts the observable frequency range. Such a constraint is particularly significant in the structural design of aircraft components. For instance, when designing aircraft wings, an accurate fatigue load spectrum should encompass frequencies up to a few hertz, as the primary bending modes of an aircraft wing generally occur within this range. Consequently, the primary limitation does not lie within the spectral estimation techniques themselves but rather in the appropriateness of the dataset for its designated engineering application.

4.5.3 Transatlantic route - Seasonal, Annual and Altitude Influence

The transatlantic corridor connects Europe and North America, hosting a dense flow of commercial flights that are particularly exposed to atmospheric instabilities such as wind gusts and clear-air turbulence. Understanding the variability of these phenomena along this route is therefore of both operational and economic importance, as it directly affects flight safety, scheduling, and fuel efficiency.

Fig. 4.35 illustrates the Aeolus satellite ground track and the area under analysis in red. The study encompasses the latitudinal range between 50° and 55° N and the longitudinal range from 33° to 43° W.

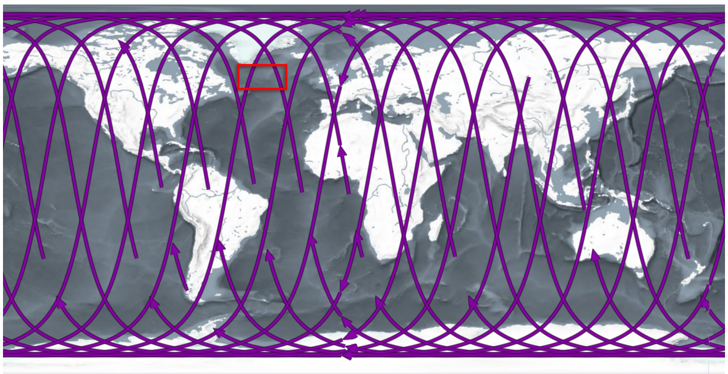


Figure 4.35: Aeolus's ground track with the portion of the transatlantic route analysed highlighted in red.

Because the satellite collects data at a lower sampling rate than the flight campaign, the signal appears less dense and has larger gaps in the time domain. Specifically, the satellite collects data every 11 seconds, and since it is in a low-Earth orbit, there may be several hours between consecutive intervals with actual data. This results in a less dense signal with larger gaps, as shown in Fig. 4.36.

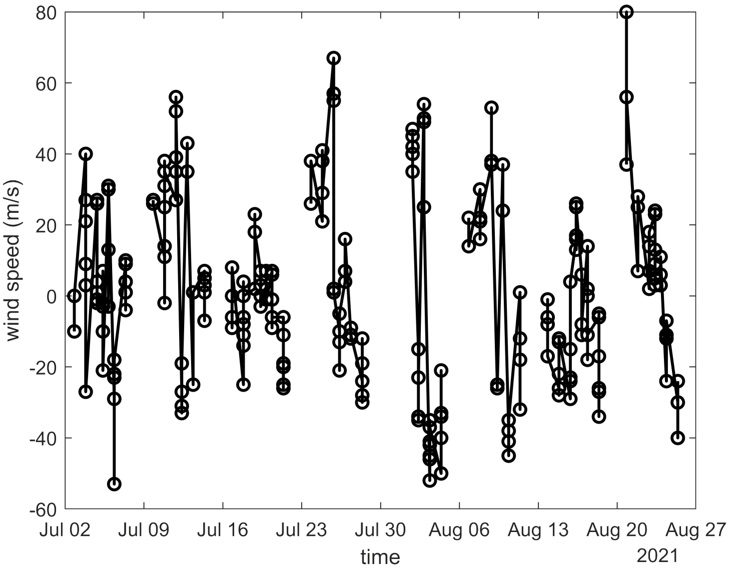


Figure 4.36: Time domain signal of satellite data collected from July to August 2021.

A localized analysis was performed to demonstrate how to evaluate seasonal and annual variability in wind gust occurrence using satellite data in the transatlantic zone. For aviation purposes, such localized insights are particularly pertinent, as turbulence-related risks vary markedly with altitude and across different seasons.

The Aeolus dataset, despite its limited temporal continuity, facilitates the extraction of wind speed distributions at selected pressure levels. This enables a comparative approach: gust intensities are analyzed in relation to both seasonal cycles (winter, spring, summer, autumn) and annual variations over the period 2019–2022. The integration of vertical profiles and temporal segmentation offers a multi-dimensional perspective on gust dynamics.

The raw data were processed employing the Welch's method, which proved to be the most conservative among previously considered analyses, utilizing four windows with Hamming windowing and 50% overlap. The fitting model was based on the von Kármán model, as it is computationally faster and sufficiently representative of transatlantic data, owing to its construction along that route.

The outcomes of the annual variation analysis are displayed in Fig. 4.37.

Examining the figure, it is evident that the variation occurs over time and across different periods. For example, May exhibits the least variation annually, whereas December demonstrates the most significant variation, with the 2022 curve notably lower than the others. A similar comparison is illustrated in Fig. 4.38, which depicts the seasonal patterns observed over the years. Upon examination of the figure, it is evident that spring exhibits the lowest gust intensity among all observed periods. Conversely, the winter months demonstrate the highest intensity. An exception is noted in 2022, wherein July appears to have the highest intensity. For comprehensiveness, Appendix C includes Table C.1, which reports the characteristic parameters σ and L of the von Kármán model, calculated from the parametric model results outlined in Eq. 4.4. The table also lists the R^2 values obtained for each dataset.

An additional analysis was performed at different altitudes. Data collected by Aeolus were examined within the same geographic area and time frame, but at altitudes ranging from 7 km to 12 km. For the sake of brevity, only the data from 2019 and 2022 are displayed in Figs. 4.39 and 4.40, respectively. To ensure a comprehensive understanding,

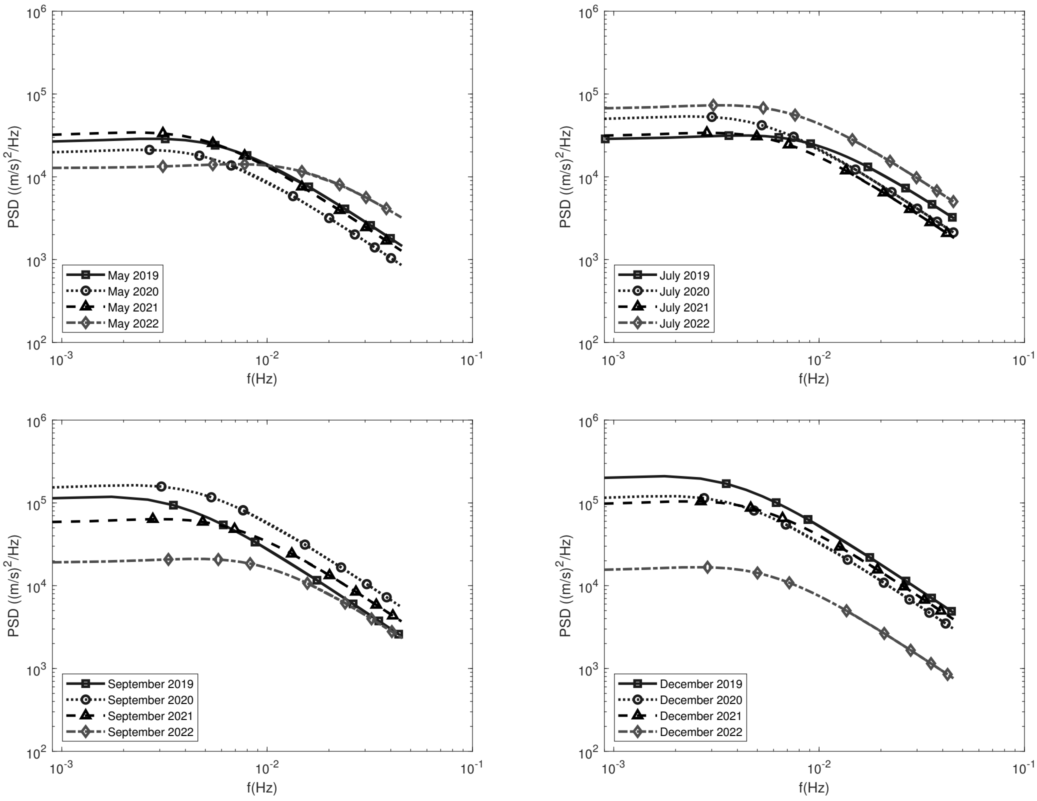


Figure 4.37: Variation of wind gust along years for different months.

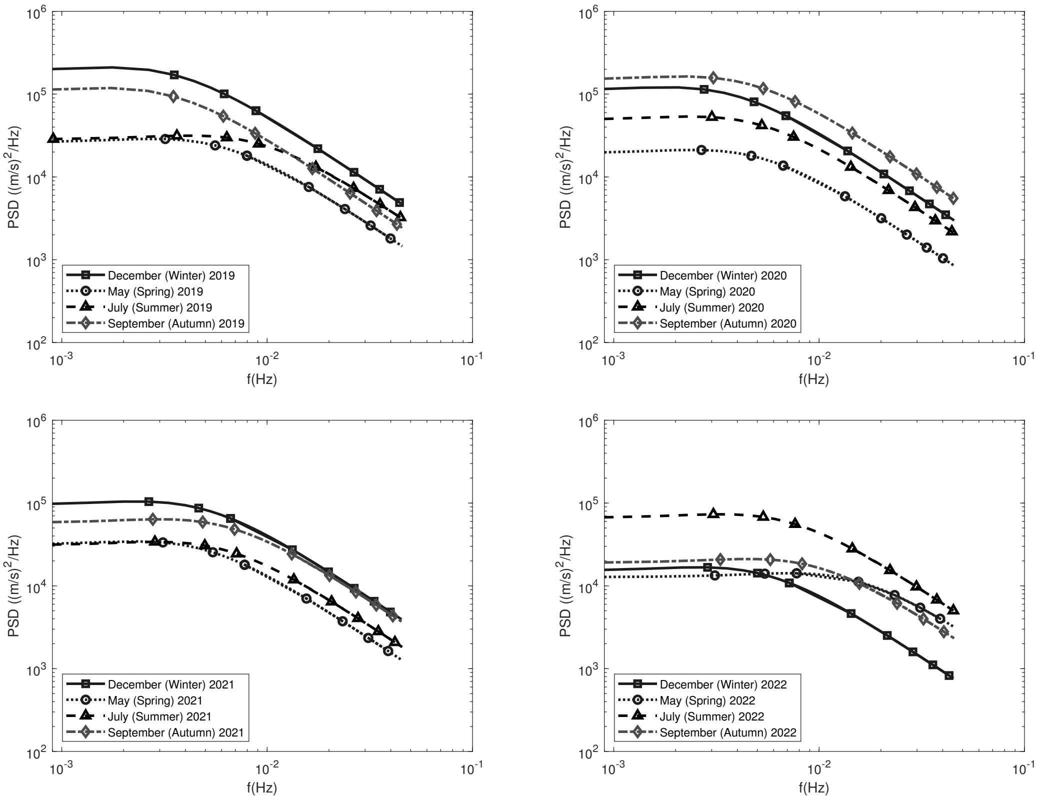
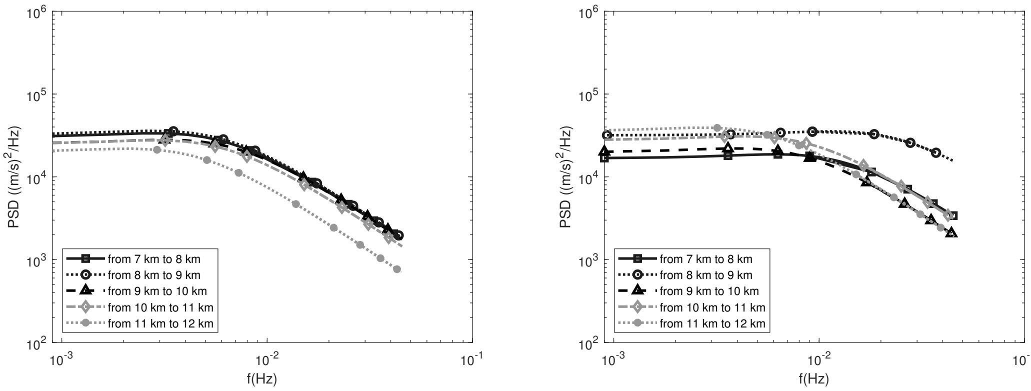


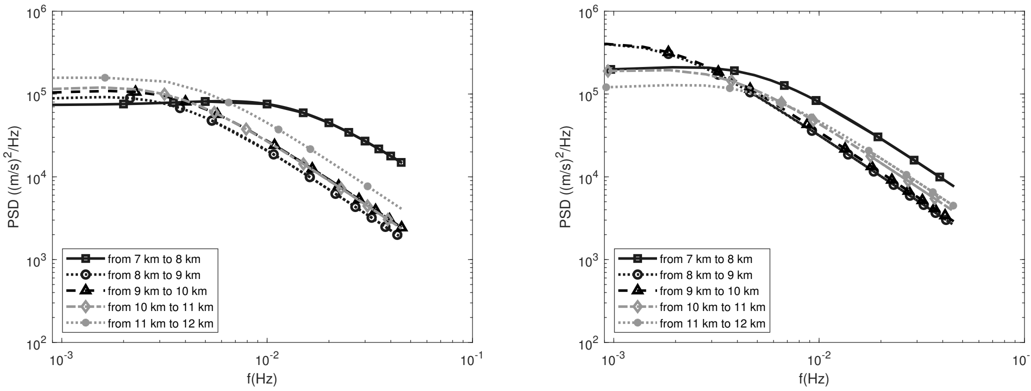
Figure 4.38: Variation of wind gust along season for different years.

Appendix C contains Tables C.2 and C.3, which present the characteristic parameters σ and L of the von Kármán model, along with the associated R^2 values.

The figures indicate no significant differences; the influence of altitude is less prominent compared to the variability observed on a monthly and annual basis. In most instances, the standard cruising altitude, ranging from 10 km to 11 km, is situated centrally between the higher-intensity and lower-intensity curves. This reflects a balancing consideration: lower altitudes produce more vigorous gusts but reduce structural pressure loads. Conversely, higher altitudes lead to less intense gusts but increase structural pressure loads and decrease engine efficiency.



(a) May (b) July

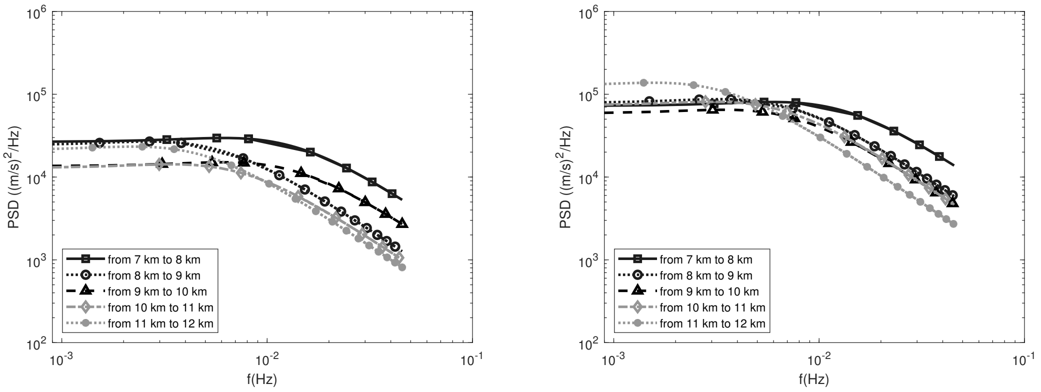


(c) September (d) September

Figure 4.39: Variation of wind gust for different altitudes and along the season during 2019.

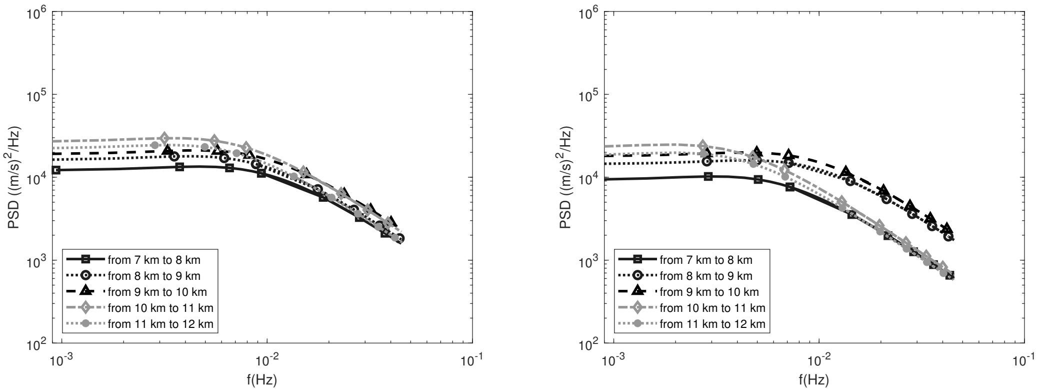
4.6 Closing Remarks

This chapter has demonstrated the contribution of satellite data, especially from the Aeolus mission, to the investigation of wind gusts within the aeronautical sector. The analysis underscored the importance of vertical measurements in characterising the seasonal and spatial variability of gusts, despite certain limitations in temporal resolution and mission duration. The integration of these data with turbulence models and other observational sources offers encouraging prospects for improving the prediction and understanding of phenomena across various scales.



(a) May

(b) July



(c) September

(d) December

Figure 4.40: Variation of wind gust for different altitudes and along the season during 2022.

Conclusion

This thesis contributes to the debate on space sustainability in a twofold manner. Firstly, at the macro level, it investigates the evolution of governance frameworks, technological advancements, and future trajectories of sustainability within the space economy. This analysis combines a systematic review of 254 scholarly contributions, further supplemented by a Delphi study involving 63 international experts. Secondly, at the micro level, the study offers a case example of how EO data can enhance sustainability on Earth and in Space, concentrating on the aviation industry. It examines how space-based technologies can deepen our knowledge of environmental processes. This is demonstrated through a case study of wind gusts, which are among the most sudden and disruptive phenomena in aviation. The study shows how satellite data can refine traditional turbulence models, thereby improving the understanding of atmospheric hazards amid climate change.

The thesis's overall structure reflects its dual focus, with each chapter addressing a different aspect of the problem. The first chapter provides a comprehensive literature review on the current state of space sustainability research. The second chapter expands this analysis through a Delphi study, gathering expert insights on future trajectories and key uncertainties. The third chapter discusses the use of EO applications to support sustainability, particularly within the aviation sector. The final chapter presents an empirical case study that combines satellite and airborne data to evaluate EO's ability to detect and analyse wind gusts, comparing observational data with existing turbulence models.

5.1 Main Findings

The initial part of this thesis, the **systematic literature review**, offered an in-depth overview of the existing research on the relationship between the space economy and sustainability. By examining 254 peer-reviewed articles listed in Scopus, the study categorized the literature based on research *locus* in Space/on Earth, the three pillars of sustainability, environmental, economic and social, and their connection to the Sustainable Development Goals. Using a mixed approach that combined automated clustering with manual analysis, the study identified six main thematic groups: policy, debris, life support systems and habitat design, law and regulation, remote sensing and data handling, and a residual category of emerging topics.

The analysis revealed that, in general, there is a slight prevalence of articles that primarily focus on space as the main locus of research rather than Earth. In terms of sustainability pillars, environmental aspects were the most addressed, followed by economic and social considerations. A further finding was that studies on environmental sustainability were primarily focused on the space locus, whereas articles in the Earth locus predominantly addressed social sustainability. As our planet is constantly facing environmental threats, more research on the environmental issues on Earth is also needed when focusing on the sustainability of the Space Economy: new studies could contribute to investigating the potential benefits that Earth could gain, for example, from an improved collaborative framework for technological development, an extended downstream application of space technologies, or a wider diffusion of space data.

Analyzing the literature reveals differences across research clusters. The Policy group has few studies on the environmental impacts of policy adoption, space agency formation, or programs. Few articles discuss China's space policies, despite rapid development. Practitioners and researchers can learn by comparing strategies and assessing the impacts of policies on sustainability.

Similarly, few studies address the implications of space debris for Earth, especially its economic and social impacts. This is crucial in the NSE because more players, including private companies, have access to space, and there is consensus on the need to improve the legal and regulatory frameworks for space and debris.

Furthermore, there's a gap in research on potential LSSs applied on Earth, especially for waste reduction and improving conditions in challenging or resource-limited areas. Satellite Earth Observation offers a greater scope for studying urban social sustainability, with applications in traffic management and city planning that require long-term impact analysis.

Articles focusing on Earth highlight the need to address legal aspects of sustainability. There is also potential for new studies on lunar and Martian exploration that address economic and social issues. Topics such as risk analysis, economic impacts, and the mental health of astronauts are underexplored, particularly in the context of Mars.

Finally, numerous articles, particularly in the space domain, lack appropriate SDG tags. This indicates that the allocation of SDGs is ineffective for space-related articles. This issue is especially pronounced within the Debris, LSS, and habitat clusters.

This study has some limitations. It relies on the Scopus database, which covers a wide range of scientific fields but excludes certain sources, such as reports and books, particularly in legal studies. The search captures articles that explicitly mention "sustainability," possibly missing others that do not use the term, particularly those that under-represent economic sustainability. Article clustering involved both manual and automated methods to reduce researcher bias. Additionally, the search was limited to English-language articles.

Based on the findings of the systematic literature review, the **Delphi study** provided a forward-looking and expert-driven perspective on the future of space sustainability. By engaging 63 specialists from academia, industry, and government, the study gathered a broad spectrum of informed opinions on anticipated trajectories up to 2040 and the impact of various stakeholders in shaping these developments. The methodology, structured across three rounds, including one conducted a year later to account for evolving geopolitical conditions, ensured not only the robustness of consensus but also the capability to observe how perspectives evolved in response to international events between 2024 and 2025.

The Delphi results identified several prominent themes. A primary focus was the immediate necessity to strengthen international collaboration to mitigate fragmentation and establish a unified framework for sustainable space endeavors. In addition, the need to revise the current legal and regulatory framework was emphasised, with many experts considering it outdated given the rapid pace of technological advancements and increased private-sector involvement. These findings are consistent with the literature review, underscoring the vital role of policy and regulation in driving sustainability within the space economy.

The Delphi process revealed disagreements, particularly about the role of universities and research institutions. Some experts emphasized academia's importance in advancing sustainable technologies and responsible innovation, while others expressed scepticism due to resource constraints and political obstacles. A significant insight was the impact of geopolitical shifts on the sustainability agenda. The changing international landscape, characterized by competition among major space actors and efforts for strategic autonomy, was seen as both a driver of innovation and a source of challenges to global cooperation.

In summary, the Delphi study complemented the systematic review by confirming many of the gaps and challenges identified in the literature, while also providing a more forward-looking, dynamic perspective of the field. The SLR described the current state of knowledge, whereas the Delphi highlighted potential future developments, focusing on opportunities for progress and significant uncertainties that warrant additional research.

The third chapter examined the application of **Earth Observation** in aviation and aeronautics, highlighting both its transformative potential and the challenges of integrating satellite data into these fields. EO offers consistent, long-term coverage of atmospheric changes, providing key advantages for tracking climate change and its effects on aviation. These features deliver immediate operational benefits, including improved flight safety, enhanced routing, and reduced emissions, while also supporting resilience strategies and the broader goal of decarbonizing air travel.

Simultaneously, several critical limitations persist. Satellite observations are constrained by their spatial and temporal resolutions, which hampers the detection of localized or transient atmospheric phenomena. Furthermore, the utility of EO products is often contingent upon their integration with supplementary meteorological models. The systematic incorporation of these products into air traffic management systems also presents technical challenges, alongside institutional and regulatory barriers.

Looking ahead, several trends are likely to influence the role of EO in aviation. Combining diverse data sources, such as EO products, in-situ aircraft data, and traditional weather observations, will be crucial for improving forecast accuracy and operational use. Progress in artificial intelligence and machine learning is expected to play a key role in processing complex datasets, recognizing patterns, and predicting turbulence in near real-time. At the same time, upcoming missions like ESA's EarthCARE and potential successors to Aeolus are expected to significantly enhance observational capabilities, especially for measuring clouds, aerosols, and vertical wind profiles. These developments suggest that EO can make a meaningful contribution to aviation safety and sustainability, provided that regulatory updates and increased institutional collaboration support technological advances.

The fourth chapter analyzed how satellite-based Earth Observation can monitor and assess wind gusts, with particular focus on the ESA Aeolus mission and its comparison to airborne measurements and turbulence models. The multi-scale analyses, encompassing local and global levels, produced several significant insights. For example, the Transatlantic Corridor case study demonstrated the capability of satellite data to monitor wind variability along a critical and strategically important flight route. Although Aeolus's temporal sampling is less frequent than that of in-situ campaigns, its vertical wind profiles provide valuable insights into the seasonal and altitude-dependent behavior of gusts.

Beyond this regional focus, broader assessments emphasized the advantages of EO in complementing traditional observation methods. The global analysis revealed distinct spatial patterns in gust distribution, with tropical regions being especially vulnerable to severe gusts and exhibiting considerable year-to-year variability. These results suggest that satellite missions could play a vital role in enhancing aviation safety and expanding our understanding of atmospheric hazards.

The integration of Aeolus data with turbulence models expanded this perspective. Employing fitting techniques and analyzing PSDs, researchers effectively synchronized satellite observations with theoretical models, thereby proposing a pragmatic method for integrating EO data into operational turbulence forecasting. Nonetheless, the study also identified several challenges, including the sensitivity of Aeolus data to noise, limited temporal resolution, and the relatively brief duration of the mission.

Overall, the case study shows how missions like Aeolus can greatly improve our knowledge of turbulence and wind gusts, which are vital for aviation. Additionally, it emphasizes the importance of EO in sustainable Earth applications and in commercializing data to boost economic sustainability in space.

Employing a multidisciplinary approach, the thesis underscores the interconnectedness of sustainability issues at both macro and micro levels. Naturally, this research is subject to certain limitations. The selected databases and language barriers limited the scope of the literature review, while the Delphi method, despite its comprehensiveness, cannot eliminate subjectivity in expert opinions. The available data and the duration of the mission limited the EO case study. Nonetheless, these limitations present valuable opportunities for future research, including expanding cross-disciplinary datasets, enhancing foresight techniques, utilizing new EO missions, and integrating these with advanced modeling systems.

Ultimately, the findings underscore that achieving sustainability in the space sector necessitates more than just technological advancements or regulatory measures alone. Instead, it calls for a holistic strategy that combines governance, innovation, and cross-sector collaboration. In this light, the thesis not only deepens our comprehension of the current situation but also points towards future directions that shape a sustainable space economy and benefit terrestrial communities.

5.2 Future Activities

In consideration of the findings presented in this thesis, several avenues of future research have been identified. At the macro level, the scope of the literature analysis should be expanded to include non-indexed sources, such as policy papers, agency reports, and industrial standards, to enrich understanding of regulatory and institutional dynamics. Concurrently, comparative cross-country studies, with particular reference to the United States, Europe, China, India, and emerging space-faring nations, have the potential to elucidate discrepancies in approaches to sustainability further. The Delphi method, when complemented by other foresight tools such as scenario building, horizon scanning, and agent-based modelling, has the potential to address the profound uncertainties that characterise the evolving geopolitical landscape of the space sector. At the micro level, progress will depend on broadening EO datasets by integrating multiple missions, including EarthCARE and Aeolus follow-ons, as well as Copernicus and NASA satellites, to overcome temporal limitations and strengthen spatial coverage. The integration of advanced turbulence models and Numerical Weather Prediction systems with artificial intelligence and machine learning algorithms, capable of detecting turbulence predictors in near real-time, has the potential to enhance both scientific and operational outcomes significantly. The construction of long-term climatologies by combining multi-mission datasets would further illuminate interannual variability and the links between gust dynamics and global climate drivers. Finally, concerted efforts are required to bridge the gap between governance frameworks and technological applications, aligning space sustainability policies with the operational use of EO data for terrestrial challenges. The development of novel frameworks that explicitly connect space missions to the Sustainable Development Goals, along with real-time data, has the potential to enhance both scientific and operational outcomes significantly. The identification of institutional and regulatory pathways is an imperative step toward consolidating the impact of space-based technologies. Advancing along these lines has the potential not only to deepen academic understanding of space sustainability but also to translate it into tangible contributions to Earth-based sectors. This, in principle, would reinforce the critical link between the space economy and global sustainability.

Appendix A

Literature Database

In this Appendix, Table A.1 lists the selected publications and their classification.

Table A.1: List of the selected publications and their classification.

Ref.	# pillars	Econ.	Envi.	Soc.	# loci	In space	On Earth	Orbit	Moon	Mars	Other space	Cluster supervised
[282]	1		1		1	1		1	0	0	0	Debris
[133]	1		1		1	1		1	0	0	0	Debris
[26]	2		1	1	1	1		0	0	0	1	Debris
[78]	1			1	2	1	1	1	0	0	0	Debris
[28]	1		1		1	1		0	0	0	1	Debris
[283]	2	1	1		1	1		1	0	0	0	Debris
[208]	1		1		1	1		1	0	0	0	Debris
[131]	1		1		1	1		1	0	0	0	Debris
[284]	1		1		1	1		1	0	0	0	Debris
[285]	1		1		1	1		1	0	0	0	Debris
[130]	1		1		1	1		1	0	0	0	Debris
[87]	1		1		1	1		0	0	0	1	Debris
[126]	1		1		1	1		1	0	0	0	Debris
[286]	1		1		1	1		1	0	0	0	Debris
[287]	2		1	1	2	1	1	1	0	0	0	Debris
[288]	1		1		1	1		1	0	0	0	Debris
[289]	1	1			1	1		1	0	0	0	Debris
[290]	2	1	1		1	1		0	0	0	1	Debris
[291]	1		1		1	1		0	0	0	1	Debris
[132]	1		1		1	1		1	0	0	0	Debris
[128]	1		1		1	1		0	0	0	1	Debris
[292]	1		1		1	1		1	0	0	0	Debris
[293]	1		1		1	1		0	0	0	1	Debris
[135]	1		1		1	1		1	0	0	0	Debris
[129]	2	1	1		1	1		1	0	0	0	Debris
[127]	1		1		1	1		0	0	0	1	Debris
[294]	2		1	1	2	1	1	1	0	0	0	Debris
[295]	1		1		1	1		1	0	0	0	Debris
[296]	1		1		1	1		0	0	0	1	Debris
[297]	1	1			1	1		1	0	0	0	Debris
[134]	1		1		1	1		1	0	0	0	Debris
[298]	1		1		1	1		1	0	0	0	Debris
[22]	1		1		1	1		1	0	0	0	Debris
[299]	1		1		1	1		1	0	0	0	Debris
[300]	2	1	1		1	1		0	0	0	1	Debris

Continues on next page

Ref.	# pillars	Econ.	Envi.	Soc.	# loci	In space	On Earth	Orbit	Moon	Mars	Other space	Cluster supervised
[301]	1		1		1	1		1	0	0	0	Debris
[302]	1		1		1	1		0	0	0	1	Debris
[55]	1	1			1	1		1	0	0	0	Debris
[303]	1	1			1	1		1	0	0	0	Debris
[304]	1	1			1	1		1	0	0	0	Debris
[209]	1		1		1	1		0	0	0	1	Debris
[305]	1		1		1	1		1	0	0	0	Debris
[306]	1		1		1	1		0	0	0	1	Debris
[307]	1		1		1	1		1	0	0	0	Debris
[61]	1		1		1	1		1	0	0	0	Debris
[62]	1		1		1	1		1	0	0	0	Debris
[162]	2	1		1	1	1		0	0	0	1	Emerging topics
[163]	3	1	1	1	2	1	1	0	0	0	1	Emerging topics
[308]	1			1	2	1	1	0	0	0	1	Emerging topics
[309]	1	1			1		1	0	0	0	0	Emerging topics
[155]	1			1	1		1	0	0	0	0	Emerging topics
[161]	2		1	1	2	1	1	0	0	0	1	Emerging topics
[159]	2	1		1	2	1	1	0	0	0	1	Emerging topics
[310]	1			1	1		1	0	0	0	0	Emerging topics
[158]	1			1	1	1		0	0	0	1	Emerging topics
[157]	1			1	2	1	1	0	0	0	1	Emerging topics
[69]	3	1	1	1	1		1	0	0	0	0	Emerging topics
[311]	3	1	1	1	2	1	1	0	0	0	1	Emerging topics
[312]	1	1			2	1	1	0	0	0	1	Emerging topics
[313]	1	1			1		1	0	0	0	0	Emerging topics
[314]	1			1	2	1	1	0	0	0	1	Emerging topics
[187]	2	1	1		2	1	1	0	0	0	1	Emerging topics
[160]	1	1			2	1	1	1	0	0	0	Emerging topics
[315]	1	1			1		1	0	0	0	0	Law and regulation
[316]	2	1		1	1	1		0	0	0	1	Law and regulation

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Ref.	**# pillars**	**Econ.**	**Envi.**	**Soc.**	**# loci**	**In space**	**On Earth**	**Orbit**	**Moon**	**Mars**	**Other space**	**Cluster supervised**
[144]	1			1	1		1	0	0	0	0	Law and regulation
[145]	1			1	1		1	0	0	0	0	Law and regulation
[317]	1			1	2	1	1	0	0	0	1	Law and regulation
[318]	2		1	1	1	1		0	1	0	0	Law and regulation
[140]	2	1		1	1		1	0	0	0	0	Law and regulation
[24]	1		1		1	1		0	0	0	1	Law and regulation
[63]	1		1		2	1	1	0	0	0	1	Law and regulation
[319]	2	1		1	2	1	1	0	0	0	1	Law and regulation
[320]	1			1	1	1		0	0	0	1	Law and regulation
[321]	1	1			1		1	0	0	0	0	Law and regulation
[143]	2	1		1	1	1		1	0	0	0	Law and regulation
[322]	1			1	1		1	0	0	0	0	Law and regulation
[311]	1			1	1	1		0	0	0	1	Law and regulation
[142]	2	1		1	2	1	1	0	0	0	1	Law and regulation
[22]	2	1	1		1	1		0	0	0	1	Law and regulation
[323]	1			1	2	1	1	0	0	0	1	Law and regulation
[324]	1	1			1	1		0	0	0	1	Law and regulation
[325]	1		1		1		1	0	0	0	0	Law and regulation
[326]	1			1	1		1	0	0	0	0	Law and regulation
[327]	1			1	2	1	1	0	0	0	1	Law and regulation
[66]	2	1	1		1		1	0	0	0	0	Law and regulation
[328]	1	1			1	1		0	0	0	1	Law and regulation
[138]	2		1	1	1	1		1	0	0	0	Law and regulation

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Ref.	**# pillars**	**Econ.**	**Envi.**	**Soc.**	**# loci**	**In space**	**On Earth**	**Orbit**	**Moon**	**Mars**	**Other space**	**Cluster supervised**
[65]	1			1	1	1		0	0	0	1	Law and regulation
[146]	3	1	1	1	2	1	1	1	0	0	0	Law and regulation
[23]	1		1		1	1		0	0	0	1	Law and regulation
[329]	2		1	1	2	1	1	0	0	0	1	Law and regulation
[141]	2	1		1	2	1	1	0	0	0	1	Law and regulation
[330]	1		1		1	1		1	0	0	0	Law and regulation
[331]	2	1		1	1		1	0	0	0	0	Law and regulation
[139]	3	1	1	1	2	1	1	0	0	0	1	Law and regulation
[67]	2		1	1	2	1	1	0	0	0	1	Law and regulation
[332]	1		1		1	1		0	0	0	1	Law and regulation
[333]	2		1	1	1	1		0	1	0	0	Law and regulation
[167]	3	1	1	1	2	1	1	0	0	0	1	Law and regulation
[334]	1			1	1		1	0	0	0	0	Law and regulation
[335]	1		1		1	1		0	0	0	1	Law and regulation
[116]	1			1	1	1		0	0	0	1	LSS and habitat
[108]	3	1	1	1	1	1		0	1	0	0	LSS and habitat
[336]	2		1	1	1	1		0	0	0	1	LSS and habitat
[119]	3	1	1	1	2	1	1	0	0	1	0	LSS and habitat
[64]	2	1	1		2	1	1	0	0	0	1	LSS and habitat
[124]	1			1	1	1		0	0	1	0	LSS and habitat
[123]	2	1		1	1	1		0	0	0	1	LSS and habitat
[102]	1		1		1	1		0	0	0	1	LSS and habitat
[107]	1		1		1	1		0	1	0	0	LSS and habitat

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Ref.	**# pillars**	**Econ.**	**Envi.**	**Soc.**	**# loci**	**In space**	**On Earth**	**Orbit**	**Moon**	**Mars**	**Other space**	**Cluster supervised**
[337]	1		1		1	1		0	1	0	0	LSS and habitat
[338]	1	1			1		1	0	0	0	0	LSS and habitat
[339]	2		1	1	1	1		0	0	1	0	LSS and habitat
[120]	1			1	1	1		0	0	1	0	LSS and habitat
[104]	1		1		1	1		0	1	0	0	LSS and habitat
[166]	3	1	1	1	1		1	0	0	0	0	LSS and habitat
[340]	2	1		1	1	1		1	0	0	0	LSS and habitat
[341]	2		1	1	1	1		0	0	0	1	LSS and habitat
[103]	1		1		1	1		0	1	0	0	LSS and habitat
[111]	2	1	1		1	1		0	0	0	1	LSS and habitat
[100]	2	1	1		1	1		0	0	1	0	LSS and habitat
[342]	1		1		1	1		0	0	1	0	LSS and habitat
[105]	1		1		1		1	0	0	0	0	LSS and habitat
[114]	3	1	1	1	1	1		0	0	0	1	LSS and habitat
[80]	1		1		1	1		0	0	0	1	LSS and habitat
[343]	1	1			1	1		0	0	0	1	LSS and habitat
[109]	1		1		1	1		0	0	0	1	LSS and habitat
[117]	1		1		1	1		0	0	0	1	LSS and habitat
[99]	2		1	1	1	1		0	0	0	1	LSS and habitat
[101]	1		1		1	1		0	0	0	1	LSS and habitat
[110]	1		1		1	1		0	0	0	1	LSS and habitat
[344]	2		1	1	2	1	1	0	0	0	1	LSS and habitat
[345]	2		1	1	1	1		1	0	0	0	LSS and habitat

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Ref.	# pillars	Econ.	Envi.	Soc.	# loci	In space	On Earth	Orbit	Moon	Mars	Other space	Cluster supervised
[346]	1	1			1	1		0	1	0	0	LSS and habitat
[347]	2	1	1		1	1		1	0	0	0	LSS and habitat
[348]	2	1	1		2	1	1	0	0	0	1	LSS and habitat
[349]	1	1			1	1		1	0	0	0	LSS and habitat
[96]	1	1			1		1	0	0	0	0	LSS and habitat
[350]	1			1	1	1		0	1	1	0	LSS and habitat
[351]	1			1	1		1	0	0	0	0	LSS and habitat
[97]	3	1	1	1	2	1	1	0	1	0	0	LSS and habitat
[352]	1	1			1	1		0	1	0	0	LSS and habitat
[353]	1		1		1	1		0	0	0	1	LSS and habitat
[354]	2		1	1	1	1		0	0	0	1	LSS and habitat
[355]	1	1			2	1	1	0	1	0	0	LSS and habitat
[356]	1		1		1	1		0	1	0	0	LSS and habitat
[357]	1		1		1	1		0	1	1	0	LSS and habitat
[358]	2	1	1		1	1		0	0	1	0	LSS and habitat
[359]	1	1			1	1		1	0	0	0	LSS and habitat
[360]	2	1	1		1	1		0	1	0	0	LSS and habitat
[119]	3	1	1	1	1	1		0	1	0	0	LSS and habitat
[122]	3	1	1	1	1	1		0	1	0	0	LSS and habitat
[121]	3	1	1	1	1	1		0	1	0	0	LSS and habitat
[98]	2	1	1		1	1		0	1	0	0	LSS and habitat
[113]	1	1			1	1		0	1	0	0	LSS and habitat
[361]	2	1	1		2	1	1	0	0	0	1	LSS and habitat

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Ref.	**# pillars**	**Econ.**	**Envi.**	**Soc.**	**# loci**	**In space**	**On Earth**	**Orbit**	**Moon**	**Mars**	**Other space**	**Cluster supervised**
[118]	3	1	1	1	1	1		0	0	0	1	LSS and habitat
[362]	2	1	1		1	1		0	1	0	0	LSS and habitat
[112]	2	1	1		1	1		0	1	0	0	LSS and habitat
[106]	1		1		1	1		0	0	0	1	LSS and habitat
[363]	1	1			1	1		0	1	1	0	LSS and habitat
[364]	1		1		1	1		1	0	0	0	LSS and habitat
[365]	2	1		1	1		1	0	0	0	0	Policy
[366]	1	1			1		1	0	0	0	0	Policy
[367]	2	1	1		2	1	1	0	1	0	0	Policy
[368]	1	1			1		1	0	0	0	0	Policy
[16]	3	1	1	1	1		1	0	0	0	0	Policy
[369]	2	1		1	2	1	1	0	0	0	1	Policy
[370]	1	1			1		1	0	0	0	0	Policy
[371]	1	1			1		1	0	0	0	0	Policy
[372]	1	1			1		1	0	0	0	0	Policy
[373]	3	1	1	1	1		1	0	0	0	0	Policy
[374]	1	1			2	1	1	0	0	0	1	Policy
[375]	2	1	1		1	1		0	0	0	1	Policy
[376]	2		1	1	1		1	0	0	0	0	Policy
[87]	1			1	1		1	0	0	0	0	Policy
[74]	1			1	2	1	1	1	0	0	0	Policy
[377]	1			1	1		1	0	0	0	0	Policy
[378]	2	1		1	1		1	0	0	0	0	Policy
[379]	2	1		1	1		1	0	0	0	0	Policy
[73]	1			1	1		1	0	0	0	0	Policy
[68]	3	1	1	1	1		1	0	0	0	0	Policy
[380]	1			1	1		1	0	0	0	0	Policy
[381]	3	1	1	1	1		1	0	0	0	0	Policy
[382]	1			1	2	1	1	1	0	0	0	Policy
[83]	2	1		1	1		1	0	0	0	0	Policy
[383]	1			1	1		1	0	0	0	0	Policy
[384]	2	1	1		2	1	1	0	0	0	1	Policy
[72]	2	1		1	1		1	0	0	0	0	Policy
[385]	1	1			1		1	0	0	0	0	Policy
[386]	3	1	1	1	1		1	0	0	0	0	Policy
[387]	2	1		1	1		1	0	0	0	0	Policy
[388]	2	1		1	1		1	0	0	0	0	Policy
[30]	1			1	2	1	1	0	1	0	0	Policy
[389]	1			1	1		1	0	0	0	0	Policy
[85]	3	1	1	1	1		1	0	0	0	0	Policy
[390]	1			1	1		1	0	0	0	0	Policy
[391]	2	1		1	1		1	0	0	0	0	Policy
[84]	1	1			1		1	0	0	0	0	Policy
[94]	1			1	1	1		0	0	0	1	Policy
[79]	2	1		1	1		1	0	0	0	0	Policy
[89]	1			1	1		1	0	0	0	0	Policy
[392]	1			1	1		1	0	0	0	0	Policy

Continues on next page

Ref.	**# pillars**	**Econ.**	**Envi.**	**Soc.**	**# loci**	**In space**	**On Earth**	**Orbit**	**Moon**	**Mars**	**Other space**	**Cluster supervised**
[393]	2	1		1	1		1	0	0	0	0	Policy
[70]	3	1	1	1	1	1		0	0	0	1	Policy
[394]	2	1		1	2	1	1	0	1	1	0	Policy
[395]	2	1		1	1		1	0	0	0	0	Policy
[396]	1			1	1		1	0	0	0	0	Policy
[88]	1			1	2	1	1	0	0	0	1	Policy
[81]	1	1			1		1	0	0	0	0	Policy
[384]	2	1		1	1		1	0	0	0	0	Policy
[397]	1	1			2	1	1	0	0	0	1	Policy
[71]	2	1		1	1		1	0	0	0	0	Policy
[398]	2	1		1	2	1	1	0	1	1	0	Policy
[8]	1	1			1	1		1	0	0	0	Policy
[399]	1		1		2	1	1	1	0	0	0	Policy
[400]	2	1		1	1		1	0	0	0	0	Policy
[93]	3	1	1	1	1	1		0	1	0	0	Policy
[209]	1		1		1	1		0	0	0	1	Policy
[82]	3	1	1	1	2	1	1	0	0	0	1	Policy
[401]	2	1	1		1		1	0	0	0	0	Policy
[402]	1	1			1	1		0	0	0	1	Policy
[403]	1		1		1	1		1	0	0	0	Policy
[404]	2	1		1	1		1	0	0	0	0	Policy
[27]	3	1	1	1	2	1	1	1	0	0	0	Policy
[91]	1			1	1		1	0	0	0	0	Policy
[95]	3	1	1	1	1		1	0	0	0	0	Policy
[400]	2	1		1	1		1	0	0	0	0	Policy
[405]	2	1	1		2	1	1	0	0	0	1	Policy
[406]	1	1			2	1	1	0	0	0	1	Policy
[407]	1	1			1	1		0	0	0	1	Policy
[408]	1	1			1		1	0	0	0	0	Remote sensing
[147]	1		1		1		1	0	0	0	0	Remote sensing
[76]	1		1		1		1	0	0	0	0	Remote sensing
[152]	1		1		1		1	0	0	0	0	Remote sensing
[150]	1		1		1		1	0	0	0	0	Remote sensing
[37]	1		1		1		1	0	0	0	0	Remote sensing
[409]	1		1		1		1	0	0	0	0	Remote sensing
[153]	1		1		1		1	0	0	0	0	Remote sensing
[77]	1		1		1		1	0	0	0	0	Remote sensing
[154]	1		1		1		1	0	0	0	0	Remote sensing
[410]	1		1		1		1	0	0	0	0	Remote sensing

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Ref.	# pillars	Econ.	Envi.	Soc.	# loci	In space	On Earth	Orbit	Moon	Mars	Other space	Cluster supervised
[411]	1		1		1		1	0	0	0	0	Remote sensing
[148]	1		1		1		1	0	0	0	0	Remote sensing
[151]	1		1		1		1	0	0	0	0	Remote sensing
[412]	1		1		1		1	0	0	0	0	Remote sensing
[311]	1		1		1		1	0	0	0	0	Remote sensing
[75]	3	1	1	1	1		1	0	0	0	0	Remote sensing
[34]	1		1		1		1	0	0	0	0	Remote sensing
[39]	1			1	1		1	0	0	0	0	Remote sensing
[33]	1		1		1		1	0	0	0	0	Remote sensing
[413]	2	1	1		1		1	0	0	0	0	Remote sensing
[149]	2		1	1	1		1	0	0	0	0	Remote sensing

Appendix B

Delphi Study Results

This Appendix presents the results of the second round of the Delphi study. It offers a comprehensive review of the entire study's progression and explains the loss of consensus between the second and third rounds, attributed to geopolitical effects.

Table B.1: Results for Q1: Do *Space Laws and Regulations* encourage sustainable practices, considering environmental, social, and economic factors, today? And in 2040?

	Law and regulation											
	Today						**By 2040**					
	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus
Environmental sustainability	2.6	2	50.0	33.3	16.7	No	3.6	1	18.5	14.8	66.7	Yes
Social sustainability	2.5	2	50.0	33.3	16.7	No	2.6	1	51.9	29.6	18.5	No
Economic Sustainability	2.5	2	50.0	38.9	11.1	No	2.6	2	51.9	22.2	25.9	No

Table B.2: Results for Q2: How effectively are *Space Policies* supporting the sustainability of space activities in terms of the environment, economy, and society in the present day? And in 2040?

	Space Policy											
	Today						**By 2040**					
	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus
Environmental sustainability	2.8	2	37.1	37.1	25.7	No	3.2	1	15.4	11.5	73.1	Yes
Social sustainability	2.5	1	45.7	45.7	8.6	No	2.9	2	61.5	3.8	34.6	No
Economic Sustainability	2.7	1	37.1	40.0	22.9	No	3.1	2	34.6	15.4	50.0	No

Table B.3: Results for Q3: Please rate the effectiveness of these initiatives for the sustainable development of *Space Law and Regulations* and *Space Policy* up to 2040.

	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	**Consensus**
Strengthening of National legislative/regulatory bodies	3.7	2	13.8	31.0	55.2	No
Strengthening of International legislative/regulatory bodies.	4.0	1	13.8	10.3	75.9	Yes
Creation of New International bodies.	3.0	2	31.0	27.6	41.4	No
Introduction of more severe sanctions.	2.9	1	44.8	27.6	27.6	No

Table B.4: Results for Q5: Considering the technologies for *debris mitigation*, please rate the importance of the following stakeholders in supporting sustainable development.

	Debris mitigation technology											
	Today						**By 2040**					
	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus
Large private companies	3.5	1	15.2	27.3	57.6	No	4.3	1	6.1	12.1	81.8	Yes
SMEs and startups	3.3	1	18.2	30.3	51.5	No	4.1	1	13.3	6.7	80.0	Yes
Space agencies, national and intergovernmental bodies	4.3	1	9.1	9.1	81.8	Yes	4.6	1	3.0	3.0	93.9	Yes
Universities and public research centers	3.2	2	27.3	36.4	36.4	No	4.0	1	13.3	10.0	76.7	Yes
Other international organizations	3.5	2	18.2	36.4	45.5	No	3.9	2	12.1	15.2	72.7	Yes

Table B.5: Results for Q8: Considering *Access to Space* technologies, please rate the importance of the following stakeholders in supporting sustainable development.

	Access to space technology											
	Today						**By 2040**					
	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus
Large private companies	3.9	2	12.1	15.2	72.7	Yes	4.5	1	3.0	6.1	90.9	Yes
SMEs and startups	3.2	2	30.3	30.3	39.4	No	4.0	2	10.7	14.3	75.0	Yes
Space agencies, national and intergovernmental bodies	4.0	2	6.1	21.2	72.7	Yes	4.2	1	3.0	21.2	75.8	Yes
Universities and public research centers	2.9	2	42.4	24.2	33.3	No	3.6	3	25.0	17.9	57.1	No
Other international organizations	2.7	1	45.5	30.3	24.2	No	3.4	3	32.1	14.3	53.6	No

Table B.6: Results for Q10: Considering technological advancements in *Spacecraft*, please rate the importance of the following stakeholders in supporting sustainable development.

	Spacecraft Design											
	Today						**By 2040**					
	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus
Large private companies	4.2	1	6.9	13.8	79.3	Yes	4.5	1	6.9	3.4	89.7	Yes
SMEs and startups	3.7	2	17.2	24.1	58.6	No	4.1	1	6.9	10.3	82.8	Yes
Space agencies, national and intergovernmental bodies	3.9	2	6.9	34.5	58.6	No	4.4	1	11.1	3.7	85.2	Yes
Universities and public research centers	3.4	1	20.7	31.0	48.3	No	4.0	2	14.8	14.8	70.4	Yes
Other international organizations	2.3	2	55.2	27.6	17.2	No	2.5	2	59.3	11.1	29.6	No

Table B.7: Results for Q13: Considering *Remote sensing and Data handling* activities, please rate the importance of the following stakeholders in supporting sustainable development.

	Remote sensing and data handling activities											
	Today						**By 2040**					
	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus
Large private companies	3.6	1	13.8	31.0	55.2	Yes	4.1	1	3.4	17.2	79.3	Yes
SMEs and startups	3.7	1	10.3	27.6	62.1	Yes	4.1	1	3.4	17.2	79.3	Yes
Space agencies, national and intergovernmental bodies	4.1	2	6.9	20.7	72.4	Yes	4.1	2	3.4	24.1	72.4	Yes
Universities and public research centers	3.4	1	13.8	41.4	44.8	No	3.7	1	13.8	17.2	69.0	Yes
Other international organizations	2.8	2	41.4	31.0	27.6	No	3.5	3	33.3	14.8	51.9	No

Table B.8: Results for Q16: Considering technologies for *Life support system and ISRU*, please rate the importance of the following stakeholders in supporting sustainable development.

	LSSs and habitat design											
	Today						**By 2040**					
	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus
Large private companies	3.3	1	23.3	30.0	46.7	No	4.2	1	6.7	13.3	80.0	Yes
SMEs and startups	3.3	2	33.3	20.0	46.7	No	4.2	2	7.4	18.5	74.1	Yes
Space agencies, national and intergovernmental bodies	4.0	2	10.0	16.7	73.3	Yes	4.0	2	6.7	20.0	73.3	Yes
Universities and public research centers	3.7	3	26.7	6.7	66.7	Yes	3.8	2	16.7	13.3	70.0	Yes
Other international organizations	2.6	3	50.0	23.3	26.7	No	3.2	2	33.3	22.2	44.4	No

Appendix C

Comprehensive overview of satellite data

C.1 von Kármán model parameters

This section presents the parameters derived from the fitting model based on the parametrized von Kármán model. The values of the coefficient of determination, R^2, are likewise provided.

Table C.1: Data on the von Kármán model parameters described. The aircraft speed V is equal to 236 m/s.

Month	**Year**	R^2	$L[m]$	$\sigma[m/s]$
May	2019	0.904	6139	22.2
	2020	0.911	7082	17.7
	2021	0.933	7464	23.0
	2022	0.633	5005	17.3
July	2019	0.864	4042	28.6
	2020	0.844	7175	28.0
	2021	0.891	5920	24.5
	2022	0.827	5132	38.7
September	2019	0.888	10605	34.3
	2020	0.812	7914	46.5
	2021	0.875	5675	34.3
	2022	0.658	3789	24.2
December	2019	0.931	10098	46.7
	2020	0.920	9490	36.6
	2021	0.801	7398	38.5
	2022	0.943	6596	16.3

Table C.2: Data on the von Kármán model parameters described. The aircraft's speed, V, is equal to 236 m/s. Data achieved by varying the altitude and related to 2019.

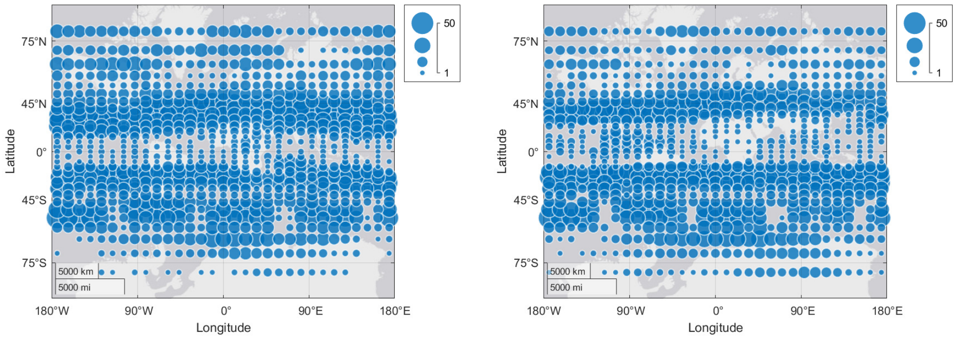
Month	**Altitude**	R^2	$L[m]$	$\sigma[m/s]$
May	from 7 km to 8 km	0.627	6011	24.2
	from 8 km to 9 km	0.874	6095	24.9
	from 9 km to 10 km	0.947	5348	23.4
	from 10 km to 11 km	0.904	6139	22.2
	from 11 km to 12 km	0.949	8138	16.8
July	from 7 km to 8 km	0.293	2781	26.5
	from 8 km to 9 km	0.339	1488	49.9
	from 9 km to 10 km	0.837	4319	23.1
	from 10 km to 11 km	0.864	4042	28.6
	from 11 km to 12 km	0.862	6295	25.6
September	from 7 km to 8 km	0.280	2781	55.6
	from 8 km to 9 km	0.834	10815	29.8
	from 9 km to 10 km	0.771	10116	33.5
	from 10 km to 11 km	0.888	10605	34.3
	from 11 km to 12 km	0.947	9254	42.3
December	from 7 km to 8 km	0.619	7532	54.2
	from 8 km to 9 km	0.834	21232	44.5
	from 9 km to 10 km	0.936	20015	45.9
	from 10 km to 11 km	0.931	10098	46.7
	from 11 km to 12 km	0.939	7770	41.7

Table C.3: Data on the von Kármán model parameters described. The aircraft's speed, V, is equal to 236 m/s. Data achieved by varying the altitude and related to 2022.

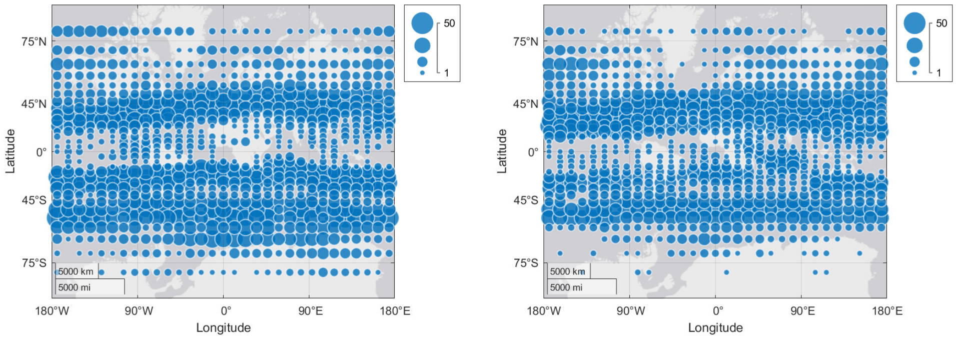
Month	**Altitude**	R^2	$L[m]$	$\sigma[m/s]$
May	from 7 km to 8 km	0.247	2781	33.4
	from 8 km to 9 km	0.620	6393	21.0
	from 9 km to 10 km	0.410	2781	23.8
	from 10 km to 11 km	0.633	5005	17.3
	from 11 km to 12 km	0.706	7702	17.8
July	from 7 km to 8 km	0.666	2867	54.3
	from 8 km to 9 km	0.902	5152	42.1
	from 9 km to 10 km	0.823	4941	37.2
	from 10 km to 11 km	0.827	5132	38.7
	from 11 km to 12 km	0.843	10948	36.4
September	from 7 km to 8 km	0.696	3669	19.6
	from 8 km to 9 km	0.680	4091	21.4
	from 9 km to 10 km	0.656	3786	24.2
	from 10 km to 11 km	0.658	3789	24.2
	from 11 km to 12 km	0.906	5160	22.3
December	from 7 km to 8 km	0.778	5560	13.9
	from 8 km to 9 km	0.788	3812	20.9
	from 9 km to 10 km	0.756	3915	23.1
	from 10 km to 11 km	0.943	6596	16.3
	from 11 km to 12 km	0.941	8615	15.5

C.2 Comprehensive global analysis maps

In this appendix, the comprehensive maps related to the global analysis presented in Chapter 4 are provided.

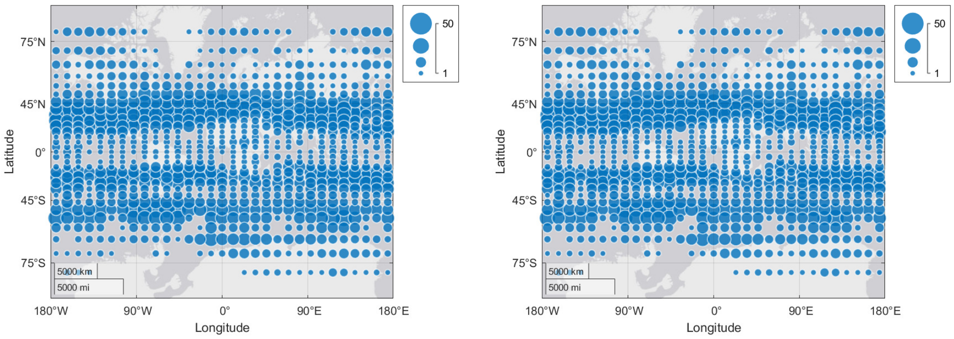


(a) March - April - May (b) June - July - August

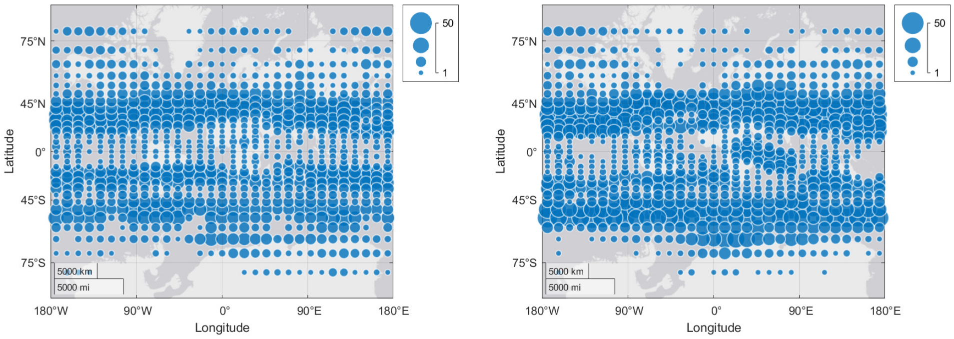


(c) September - October - November (d) December - January - February

Figure C.1: Seasonal variation of wind gust during the 2020.

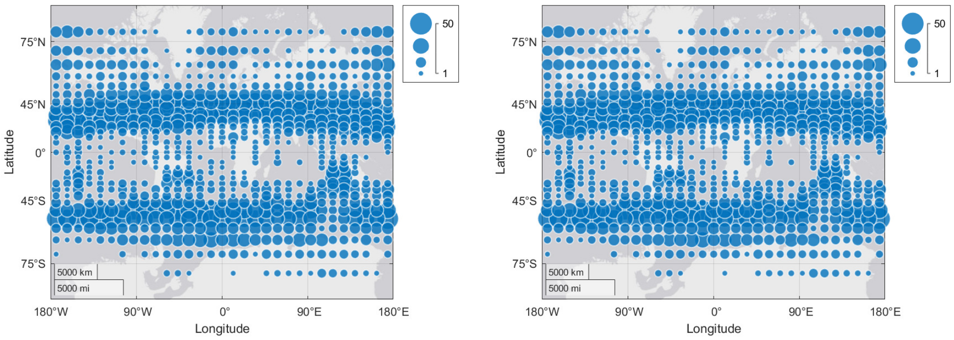


(a) March - April - May (b) June - July - August

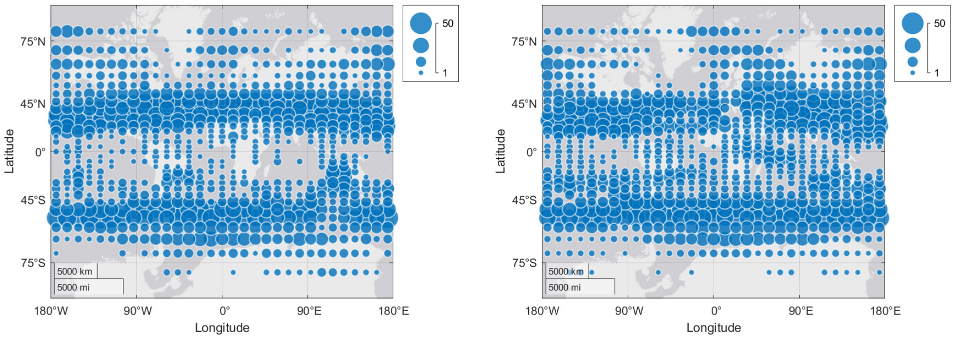


(c) September - October - November (d) December - January - February

Figure C.2: Seasonal variation of wind gust during the 2021.

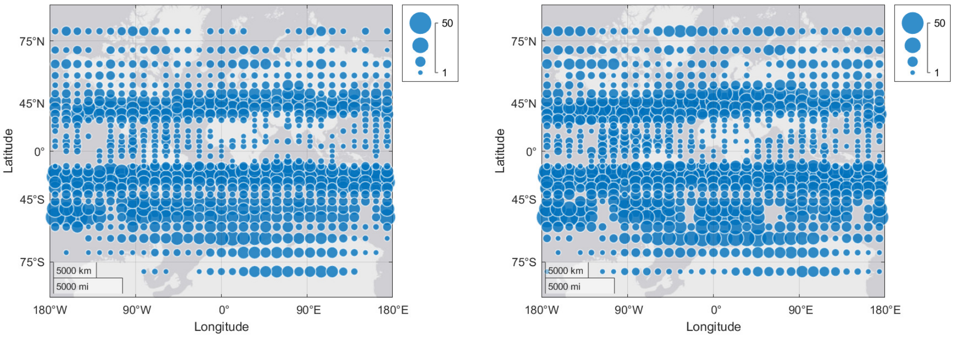


(a) March - April - May (b) June - July - August

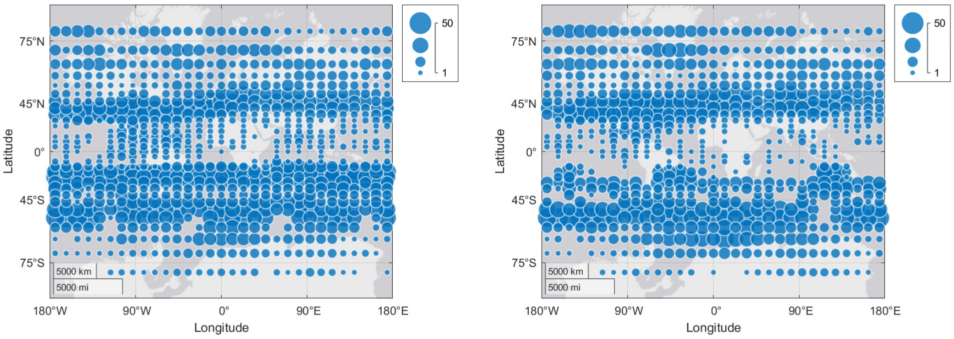


(c) September - October - November (d) December - January - February

Figure C.3: Seasonal variation of wind gust during the 2022.

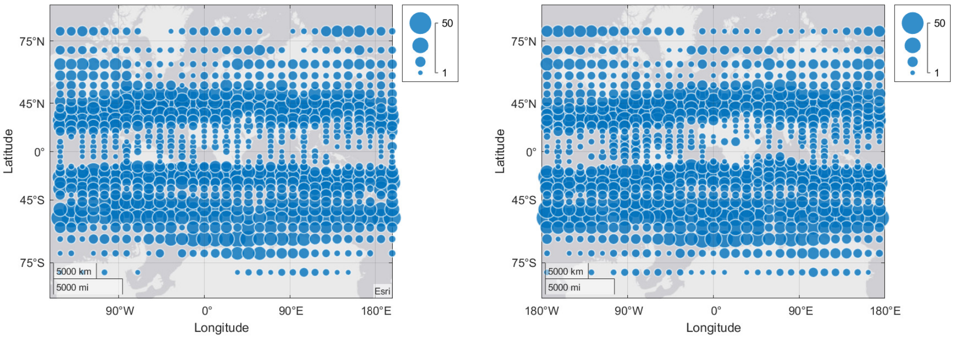


(a) 2019 (b) 2020

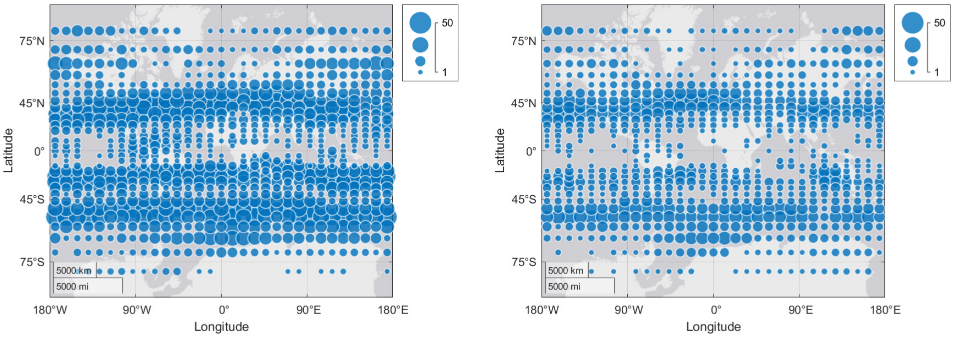


(c) 2021 (d) 2022

Figure C.4: Seasonal variation of wind gust during summer from 2019 to 2022.

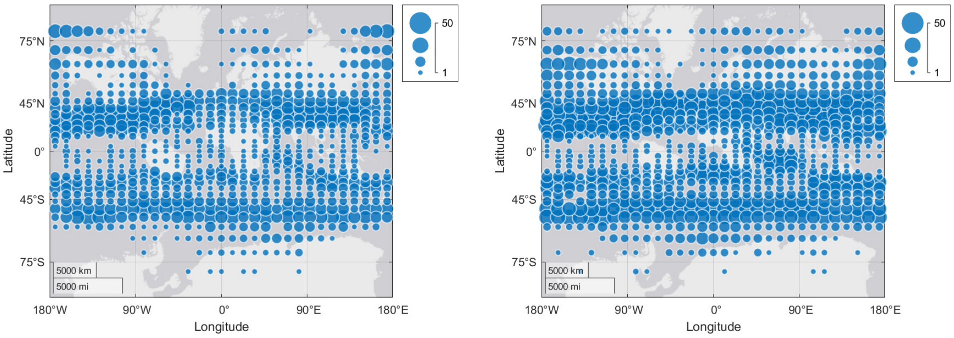


(a) 2019 (b) 2020

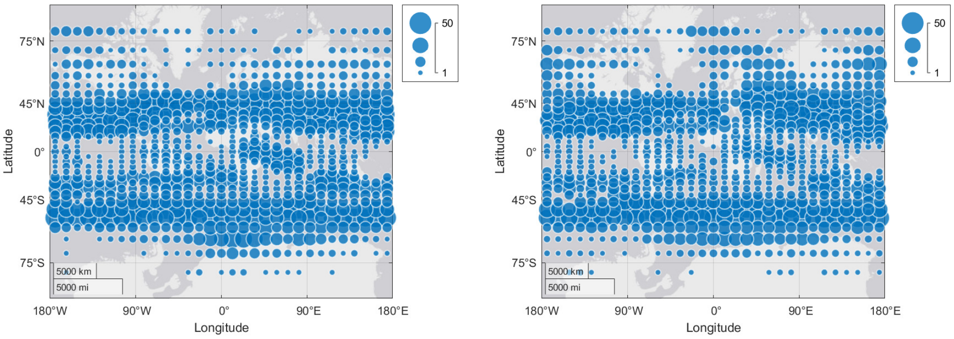


(c) 2021 (d) 2022

Figure C.5: Seasonal variation of wind gust during Autumn from 2019 to 2022.



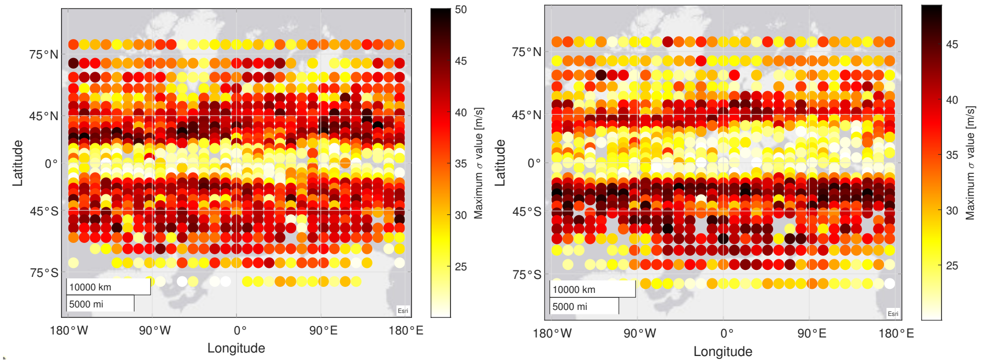
(a) 2019 (b) 2020



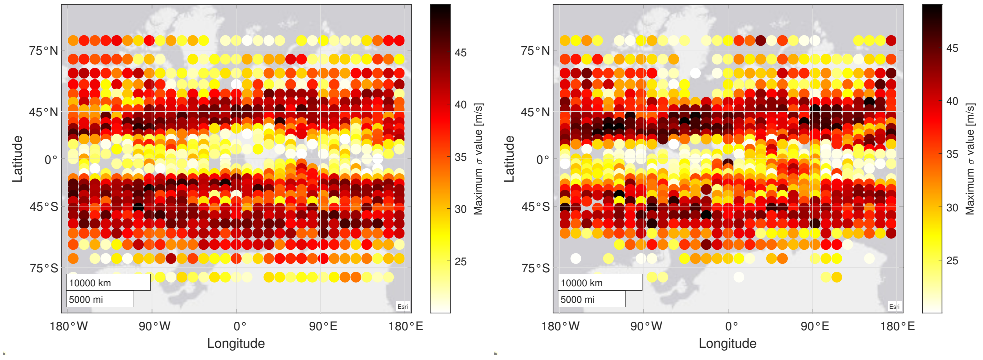
(c) 2021 (d) 2022

Figure C.6: Seasonal variation of wind gust during winter from 2019 to 2022.

The following figures represent the maximum gust values recorded, providing a complete overview of the most turbulence-prone zones.

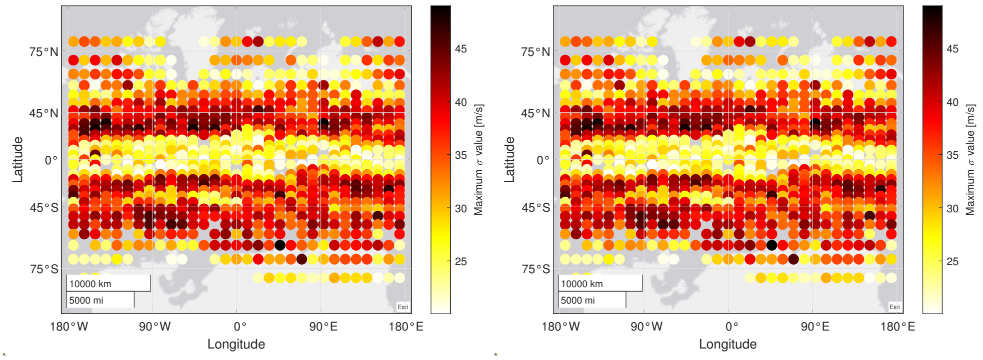


(a) March - April - May (b) June - July - August

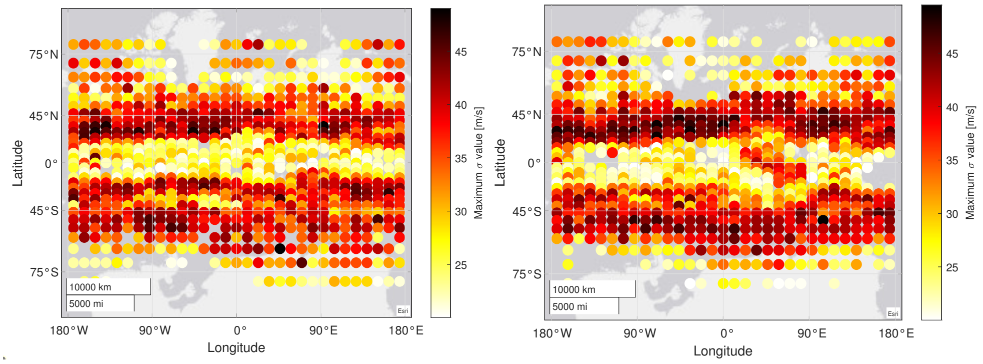


(c) September - October - November (d) December - January - February

Figure C.7: Seasonal variation of wind gust maximum velocity during the 2020.

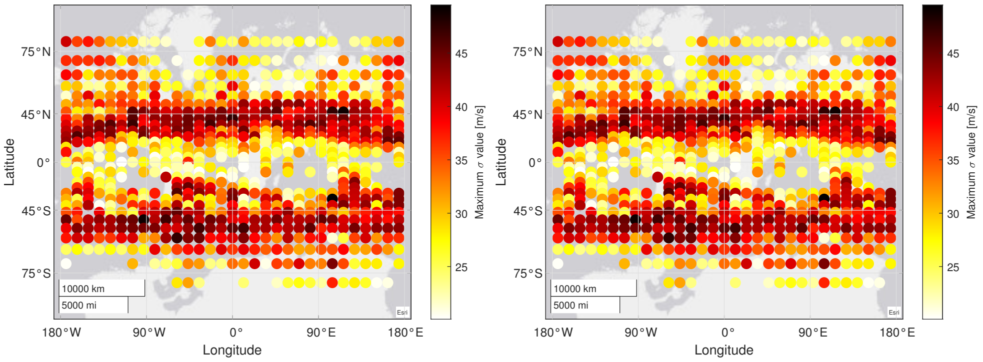


(a) March - April - May (b) June - July - August

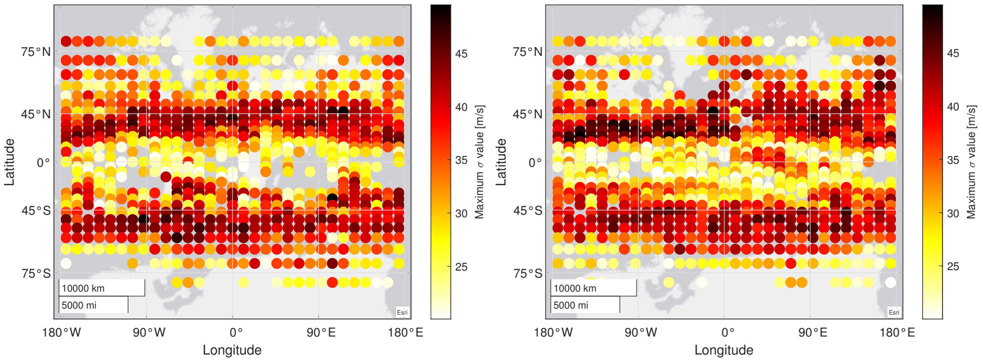


(c) September - October - November (d) December - January - February

Figure C.8: Seasonal variation of wind gust maximum velocity during the 2021.

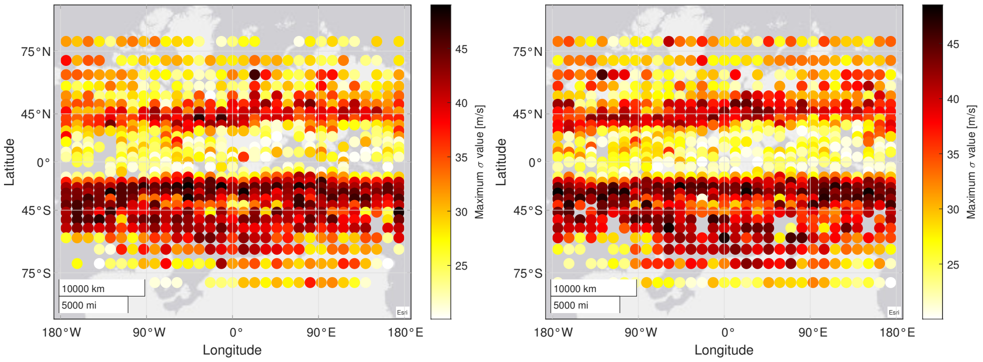


(a) March - April - May (b) June - July - August

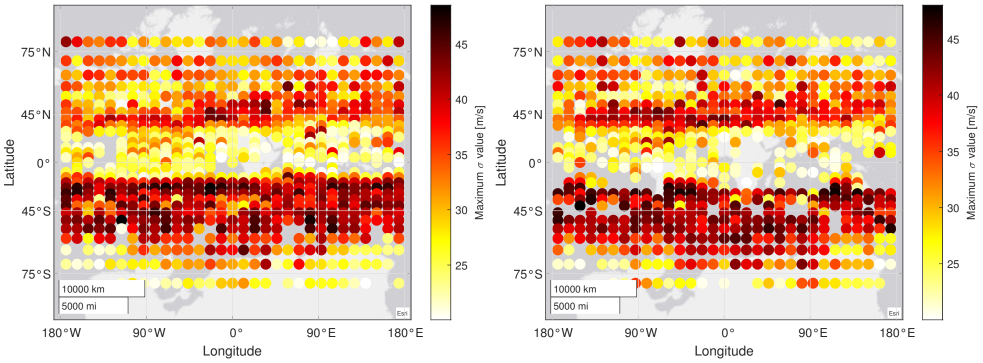


(c) September - October - November (d) December - January - February

Figure C.9: Seasonal variation of wind gust maximum velocity during the 2022.

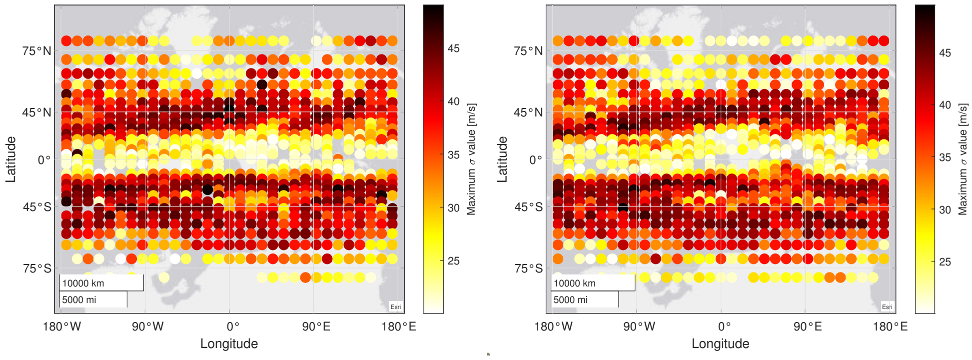


(a) 2019 (b) 2020

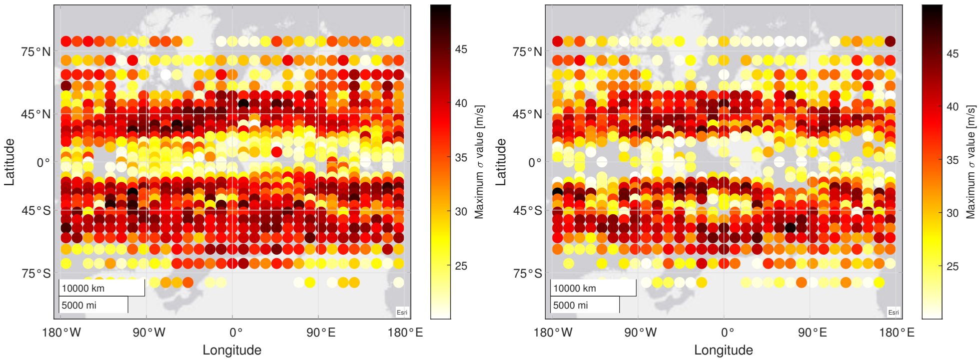


(c) 2021 (d) 2022

Figure C.10: Seasonal variation of wind gust maximum velocity during summer from 2019 to 2022.

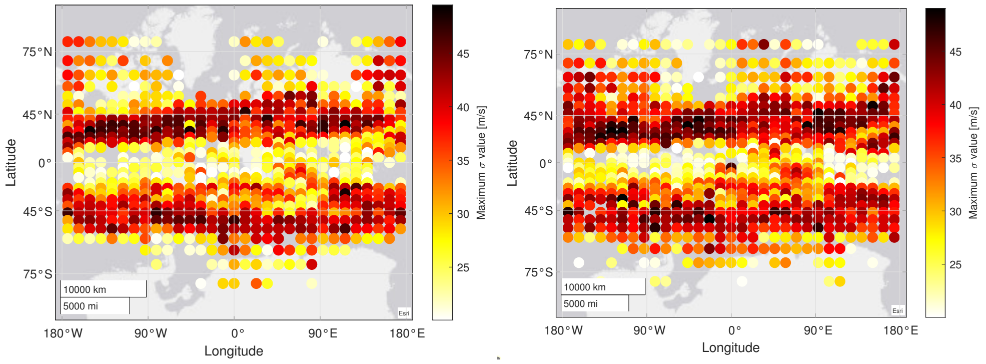


(a) 2019 (b) 2020

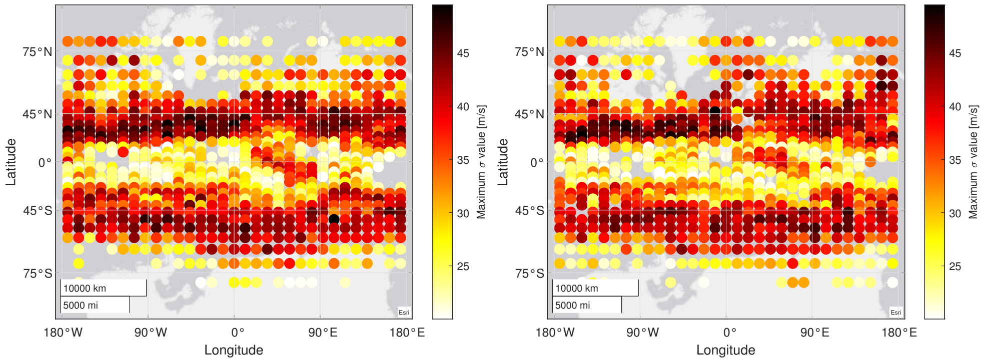


(c) 2021 (d) 2022

Figure C.11: Seasonal variation of wind gust maximum velocity during Autumn from 2019 to 2022.



(a) 2019 (b) 2020



(c) 2021 (d) 2022

Figure C.12: Seasonal variation of wind gust maximum velocity during winter from 2019 to 2022.

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