*aerospace*

MDPI

*Review*

# Radar Technologies for Space Debris Detection: A Bibliometric Review

**Antonio del Bosque [1,*], Diego Vergara [1,*], Mateo Burgos-García [2], Félix Pérez-Martínez [2], Jaime Calvo-Gallego [3] and Pablo Fernández-Arias [1]**

[1] Technology, Instruction and Design in Ençgineering and Education Research Group (TiDEE.rg), Facultad de Ciencias y Artes, Universidad Católica de Ávila (UCAV), Calle Canteros s/n, 05005 Ávila, Spain; pablo.fernandezarias@ucavila.es

[2] Microwave and Radar Group, Information Processing and Telecommunications Center, Escuela Técnica Superior de Ingenieros de Telecomunicación, Universidad Politécnica de Madrid, Avenida Complutense 30, 28040 Madrid, Spain; mateo.burgos@upm.es (M.B.-G.); felix.perez.martinez@upm.es (F.P.-M.)

[3] Departamento de Informática y Automática, Campus Viriato, Universidad de Salamanca, Avenida Requejo 33, 49022 Zamora, Spain; jaime.calvo@usal.es

* Correspondence: antonio.bosque@ucavila.es (A.d.B.); diego.vergara@ucavila.es (D.V.)

## Abstract

The proliferation of artificial objects in Earth's orbit has transformed space debris into one of the most critical challenges to space sustainability. Radar technologies play a pivotal role in the detection, tracking, and characterization of these non-functional objects, providing the backbone for global Space Situational Awareness (SSA) and collision avoidance systems. This study presents a comprehensive bibliometric analysis of radar-based space debris detection research published between 2005 and 2025. Using data retrieved from the Scopus and Web of Science databases, a curated dataset of 557 peer-reviewed journal articles was examined. The analysis explores publication trends, institutions, countries, and journals, as well as co-citation and keyword co-occurrence networks to map the intellectual and thematic structure of the field. Results reveal a sustained annual growth rate of 3.76%, with China and the United States leading global research output. Core motor themes—such as space-based radar, synthetic aperture radar, and remote sensing—define the technological foundation of the domain, while emerging clusters reflect growing interest in artificial intelligence and active debris removal. The study highlights a high degree of collaboration among researchers but significant geographic concentration of capabilities. By unveiling the evolution, collaboration patterns, and conceptual frontiers of radar-based space debris research, this work provides a quantitative foundation to guide future investigations and policy strategies aimed at ensuring long-term orbital sustainability.

**Keywords:** space debris radar; space debris detection; radar technology

Check for updates

Academic Editor: Yan (Rockee) Zhang

Received: 3 August 2026
Revised: 26 August 2026
Accepted: 27 August 2026
Published: 28 August 2026

**Copyright:** © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

## 1. Introduction

Since the launch of Sputnik 1 in 1957, the near-Earth space environment has been progressively populated not only with active satellites crucial for communication, navigation, and Earth observation, but also with a rapidly growing amount of non-functional man-made objects known as space debris [1]. This orbital debris, defined by international bodies like the Inter-Agency Space Debris Coordination Committee (IADC) as all non-functional, man-made objects in Earth orbit [2], ranges from defunct satellites and spent rocket upper

stages to small fragments from explosions, collisions, and other anomalies. The proliferation of these objects, particularly in Low Earth Orbit (LEO), presents a substantial and escalating threat to the sustainability of future space activities [3].

The core of this threat was conceptualized in the seminal 1978 paper by D. J. Kessler and B. G. Cour-Palais [4]. They posited that once the density of objects in LEO reaches a critical point, collisions between objects will cause a cascading effect, generating new debris exponentially. This "Kessler Syndrome" scenario, once a distant theoretical concern, is now recognized as an imminent risk, with the potential to render key orbital regimes unusable for generations. The most recent ESA Space Environment Report [1] and data from the NASA Orbital Debris Program Office [5] provide stark statistics: over 36,500 objects larger than 10 cm are tracked and cataloged. However, statistical models estimate the presence of approximately 1 million objects between 1 cm and 10 cm, and over 130 million objects between 1 mm and 1 cm [1]. Long-term models forecasting the LEO environment's evolution over the next 200 years confirm that without active remediation, the collision cascade is an inevitable outcome [6].

The primary risk to active satellites often comes from the lethal, uncatalogued population of debris in the 1 cm to 10 cm range [7]. At typical LEO orbital velocities, which can exceed 7 km/s, even a 1 cm fragment carries the kinetic energy equivalent of a hand grenade. Recent impact engineering studies confirm that fragments in this size class possess sufficient energy to cause catastrophic failure of an operational spacecraft [8]. While the IADC has issued mitigation guidelines, such as the "25-year rule" for de-orbiting, their voluntary nature and the legacy population of objects mean that mitigation alone is insufficient to stabilize the LEO environment [2].

To manage this hazard, robust Space Situational Awareness (SSA) and Space Surveillance and Tracking (SST) capabilities are paramount. A primary function of SSA is the detection, tracking, cataloging, and orbital characterization of debris to enable collision avoidance maneuvers for active satellites and to inform long-term environment models. This mission is executed by a global network of sensors, with key contributions from national and international entities like the U.S. Space Force [9] and the European Space Agency (ESA), which actively classifies and monitors objects across all orbital regimes [10].

While optical telescopes are highly effective for tracking objects in higher orbits (MEO and GEO), they are limited by weather conditions, atmospheric distortion, and daylight [11]. Consequently, RADAR (Radio Detection and Ranging) systems have become the workhorse for SSA in the LEO regime, prized for their ability to operate 24/7, under all-weather conditions, and with the sensitivity to detect small-caliber debris [12]. Modern ground-based phased-array systems, most notably the U.S. Space Fence (AN/FSY-3), are designed to detect and track objects at the centimeter level, vastly increasing the catalog's fidelity and tracking capacity [9]. Similarly, advanced systems like the EISCAT 3D radar and Europe's TIRA (Tracking and Imaging Radar) provide crucial high-resolution data for both tracking and characterization [12,13].

Despite this technological progress, the orbital environment is undergoing an unprecedented transformation. The rapid deployment of "mega-constellations" by commercial entities has dramatically increased the density, complexity, and number of conjunction (close approach) events in LEO, straining current SSA capabilities [14]. This new paradigm demands a shift from mere detection to comprehensive characterization. As argued by M. Jah et al., understanding an object's behavior, intent, and physical properties (e.g., size, shape, spin state) is critical for accurately assessing risk [15].

This has spurred significant research into advanced radar configurations and processing techniques. Bistatic and multistatic radar architectures, which separate the transmitter and receiver, are being heavily investigated, as they offer enhanced sensitivity, improved

orbital element estimation, and greater resilience [16,17]. Concurrently, advanced signal processing techniques, such as interferometric inverse synthetic aperture radar (ISAR) and sparse recovery, are being refined to extract detailed radar cross-section (RCS) signatures, enabling the reconstruction of debris shape and dynamics [18]. Furthermore, new radar-based metrics are being developed to translate raw observational data into actionable, probabilistic risk assessments, moving beyond simple collision probability to more nuanced models [19].

Ground-based systems, however, are fundamentally limited by geography. The current sensor network, concentrated in the northern hemisphere, results in significant coverage gaps, particularly over the southern oceans [20]. To achieve persistent, global surveillance, space-based SSA architectures are being proposed, often centered on space-based radar (SBR) payloads [21]. SBR offers a revolutionary vantage point, though it presents its own challenges in power, processing, and data relay [22].

The sheer volume of data from both ground- and space-based systems creates a significant data processing and orbit determination (OD) challenge. This is particularly true for collision avoidance, where orbit prediction errors, which propagate over time, remain a key limiting factor [23]. Consequently, artificial intelligence (AI) and machine learning (ML) are emerging as indispensable tools. ML is being applied to automate signal detection in noisy data and, most critically, to power next-generation collision avoidance systems by rapidly processing conjunction data and predicting high-risk events [24]. This high-fidelity data also feeds into long-term environmental models like LEGEND, which are essential for forecasting the environment's future evolution and the potential impact of mitigation policies [25].

Ultimately, enhanced SSA is not just for avoiding debris, but for removing it. Active Debris Removal (ADR) missions, such as ESA's ClearSpace-1 [26], are moving from concept to reality. These missions are entirely dependent on high-fidelity radar and optical data for locating, approaching, and capturing non-cooperative targets.

Given this dynamic, complex, and rapidly expanding research landscape, a systematic understanding of the field's intellectual structure is necessary. While numerous technical reviews exist, they are often narrative in scope. A quantitative, data-driven approach is needed to map the evolution of the "space debris radar" domain, identify its key contributors and collaborative structures, and pinpoint emerging thematic trends. Bibliometric analysis is a powerful methodology for achieving this, moving beyond subjective review to statistically analyze the scholarly literature and reveal the underlying conceptual and social networks of a scientific field [27]. This method has been successfully applied to map adjacent fields, such as active debris removal [28] and general space science [29].

Existing reviews on space-debris monitoring, radar measurements, and Space Situational Awareness have mainly focused on technical aspects, including sensor capabilities, radar architecture, tracking methods, and operational challenges. Although these studies provide valuable qualitative syntheses of specific technologies and applications, they do not systematically examine the structure and evolution of the scientific literature itself. They generally do not quantify publication growth, identify the most influential countries, institutions, journals, and authors, or map collaboration patterns, co-citation structures, keyword networks, and thematic evolution over time. Therefore, a bibliometric review focused specifically on radar-based space-debris detection is needed to complement existing technical reviews with a quantitative and longitudinal perspective of the research field.

To address this gap, this paper conducts a comprehensive bibliometric review of the scientific literature focused on radar technologies for space debris detection. The primary objectives are: (i) to quantify the growth and geographic distribution of scientific output; (ii) to identify the most prolific and impactful institutions and journals; (iii) to map the

intellectual structure of the research domain by analyzing co-citation and keyword co-occurrence networks; and (iv) to trace the thematic evolution of the field to highlight research hotspots and potential future directions.

By providing a structured overview of the research landscape, this study aims to serve as a valuable resource for researchers, funding agencies, and policymakers. It offers a clear snapshot of where the field has been, where it currently stands, and where its most significant challenges and opportunities may lie. The remainder of this paper is organized as follows: Section 2 details the bibliometric methodology, including data acquisition and analytical procedures. Section 3 presents the main results of the descriptive and network analyses. Section 4 discusses the implications of these findings, and Section 5 provides concluding remarks and suggests avenues for future research.

## 2. Materials and Methods

This review focuses on the scientific literature concerning the detection of space debris using radar technologies. A structured methodology based on bibliometric analysis was implemented to ensure analytical rigor and reproducibility. The study was organized into five interconnected modules, as shown in Figure 1: Module I, definition of the research domain and construction of the search query; module II, retrieval of bibliographic records from major scientific databases; module III, data cleaning and refinement (including deduplication and manual screening), module IV, analysis and visualization of bibliometric indicators; and module V, interpretation of results and formulation of conclusions.

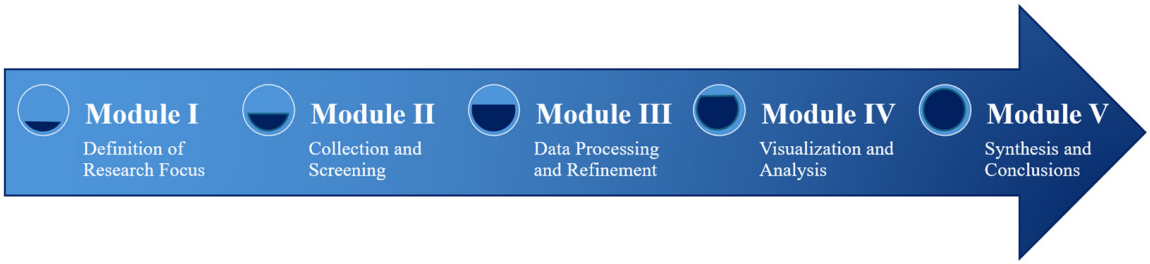



**Figure 1.** Research methodology modules.

In Module I, the research topic was precisely defined and operationalized into a Boolean search string. The goal was to delimit the scope to publications dealing with radar-based detection, monitoring, or tracking of orbital debris. To achieve this, the following search query was constructed: *TITLE-ABS-KEY (“debris” OR “wast*”) AND TITLE-ABS-KEY (“spac*” OR “orbital”) AND ALL (“radar”)*. This query was specifically designed to retrieve articles that mention debris or waste in a space or orbital context, with an explicit reference to radar technologies in any searchable field. The wildcard was used to capture different lexical variants sharing the same root and thereby improve retrieval sensitivity. For example, wast* allows the inclusion of terms such as waste and wastes, while spac* captures variants beginning with spac-, including space and spatial where applicable. This approach was intended to broaden the search without relying on less standardized or more colloquial expressions such as orbital junk, which are less consistently used in the peer-reviewed scientific literature. The query was applied to both the Scopus and Web of Science Core Collection databases, because they are the most important databases in the field [30].

In Module II, bibliographic data were collected using the aforementioned search query. The retrieval yielded a total of 2317 documents, of which 1460 were from Scopus and 827 from Web of Science. All records were exported in BibTeX format to ensure compatibility with the R-based bibliometric processing tools.

Regarding Module III, Bibliometrix from R 4.5.0 package was employed, according to previous studies [31,32]. First, the *duplicateMatching()* function from the Bibliometrix was used to automatically detect and eliminate 673 duplicate entries. Secondly, an additional manual screening excluded 18 and 2 documents due to incomplete metadata or formatting inconsistencies and out of scope reasons, respectively. Following this, a manual filtering process was applied in accordance with the PRISMA 2020 guidelines, as illustrated in Figure 2. Documents were considered eligible if they (i) were published in peer-reviewed journals, (ii) were written in English, and (iii) dealt explicitly with radar-based space debris detection. The screening steps were as follows: first, 582 conference papers and 336 proceeding papers were excluded because they did not meet the criteria of being published in peer-reviewed journals. Next, 90 non-English documents—primarily in Russian, Chinese, and Japanese—were removed to limit the review to the English-language literature only. Subsequently, 49 documents were discarded as they corresponded to review articles or book chapters. Finally, 10 records were excluded because they did not satisfy other inclusion criteria, being classified as notes, errata, reports, or short surveys.

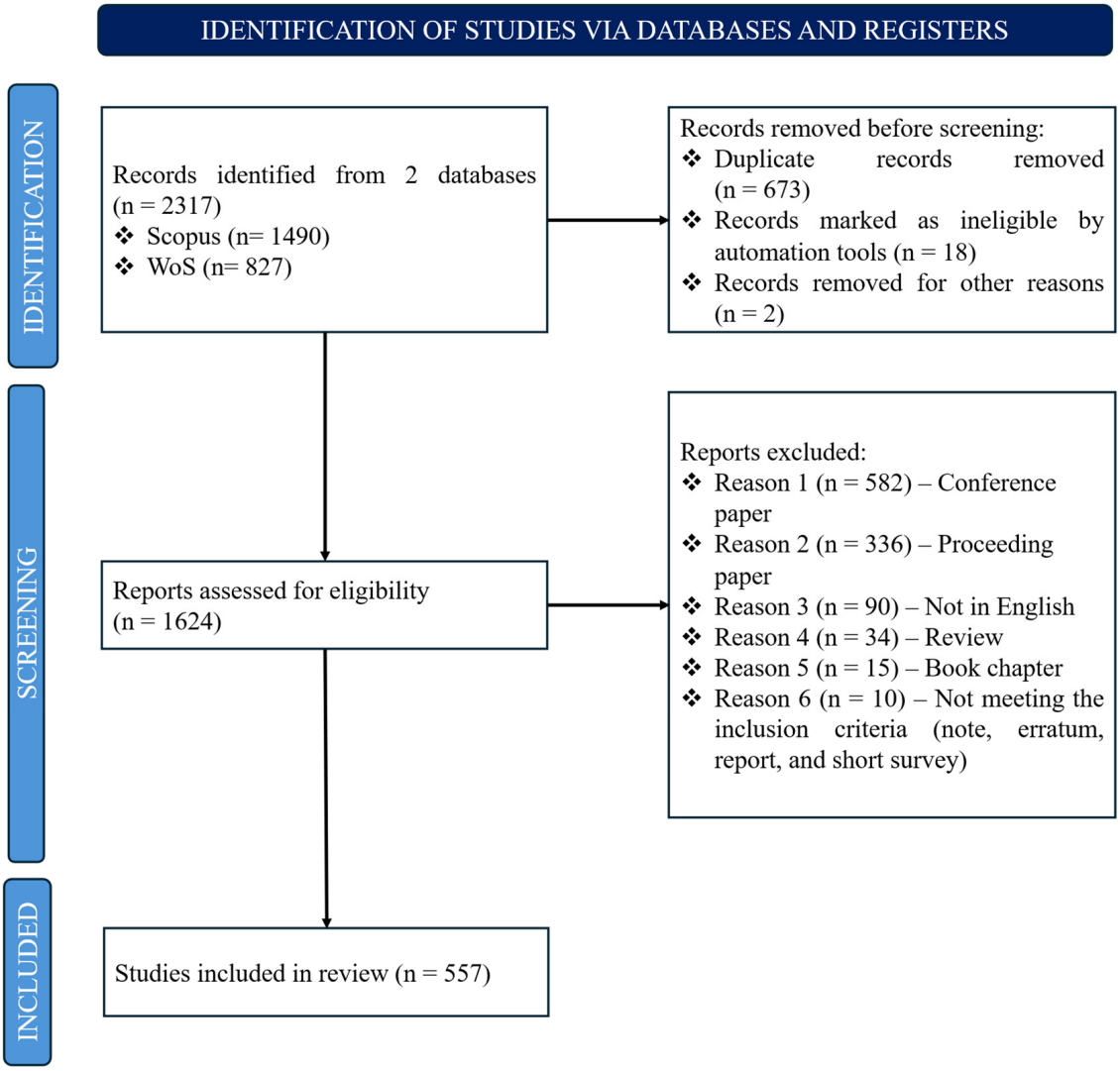



**Figure 2.** Identification of studies by following the PRISMA 2020 protocol.

The screening procedure was conducted by three independent reviewers under a triple-evaluation protocol. A pilot calibration exercise using a random subset of records enabled refinement of inclusion and exclusion criteria and harmonization of decision rules.

Each reviewer independently assessed titles and abstracts, classifying records as include, exclude, or re-evaluate in cases of uncertainty. Inter-reviewer agreement was very high (Cohen's $\kappa > 0.91$). Discrepancies were resolved through structured consensus meetings, ensuring consistent final decisions and reinforcing the methodological robustness and reliability of the bibliometric dataset in line with systematic review best practices.

In Module IV, the validated dataset underwent a quantitative bibliometric analysis. All procedures were performed using R version 4.5.0, released on 24 April 2025. This version introduced improvements in memory management and multithreaded processing, which facilitated the efficient handling of large datasets. Two primary tools were employed for the analysis. The Bibliometrix 4.2.1 package was utilized to convert and analyze the data through functions such as *convert2df()*, *biblioAnalysis()*, and *networkPlot()*. These functions enabled the extraction of key metrics related to productivity, collaboration, and conceptual trends within the research domain. Additionally, Biblioshiny, the graphical user interface for Bibliometrix, was used to generate interactive plots and dashboards. This tool allowed for the validation of trends, visualization of collaboration networks, and exploration of thematic evolution without requiring advanced programming skills.

Regarding Module V, the results obtained from the bibliometric analysis were interpreted to derive insights into the development, focal areas, and collaborative networks within the radar-based space debris detection research community. The subsequent section discusses the findings across the bibliometric dimensions of productivity, impact, collaboration, and emerging themes.

## 3. Results

### *3.1. Descriptive Analysis of the Dataset*

Table 1 provides a general overview of the bibliographic dataset analyzed in the field of radar-based space debris detection. The dataset spans from 2005 to 2025, encompassing a total of 557 documents retrieved from 211 peer-reviewed journals, as was screened according to the previous section. The annual growth rate of publications in this field is 3.76%, indicating a steady increase in scholarly interest over the last two decades. The average age of documents in the dataset is 6.84 years, which suggests a balanced mix of both foundational and recent contributions to the topic. On average, each document received 18.76 citations, reflecting a moderate level of academic impact and visibility. In terms of content, the dataset includes 2264 Keywords Plus (automatically extracted terms) and 1687 Author's Keywords, indicating a high degree of terminological diversity and thematic complexity within the domain.

With respect to authorship, the dataset includes 2055 contributing authors. Of these, only 24 are responsible for single-authored works, and a total of 26 documents were published individually. The average number of co-authors per document is 5.13, highlighting a strong collaborative trend. This is further supported by the international co-authorship rate of 19.61%, which reflects a significant level of cross-border research collaboration and represents the overall average for the complete dataset.

Figure 3 shows the annual trends in scientific output and citation impact in radar-based space debris detection from 2005 to 2025. It displays the number of documents published each year, the average citations per article, and the average citations per article per year. From the data, it is evident that the volume of publications has grown significantly over the years, especially from 2015 onwards. The year 2025 stands out, with 65 documents, the highest to date, reflecting the increasing interest in this research area. Conversely, the citation impact per article and per year shows a more fluctuating behavior. Earlier publications (2005–2012) often exhibit higher average citations due to their longer time span for impact accumulation. Peaks in citation averages can be observed around 2007

and again between 2013 and 2016. Despite the sharp increase in document output from 2017 onward, the average citation values tend to decrease slightly, a common pattern in expanding fields where newer works have not yet had time to accrue significant citation counts. This indicates a dual dynamic: while productivity has accelerated, the citation maturity of recent publications is still developing, emphasizing the need for longitudinal tracking to fully evaluate the impact of newer studies.

**Table 1.** General bibliometric data.

| Description | Results |
|---|---|
| MAIN INFORMATION ABOUT DATA | |
| Timespan | 2005:2025 |
| Sources (Journals, Books, etc.) | 211 |
| Documents | 557 |
| Annual Growth Rate % | 3.76 |
| Document Average Age | 6.84 |
| Average citations per doc | 18.76 |
| DOCUMENT CONTENTS | |
| Keywords Plus (ID) | 2264 |
| Author's Keywords (DE) | 1687 |
| AUTHORS | |
| Authors | 2055 |
| Authors of single-authored docs | 24 |
| AUTHORS COLLABORATION | |
| Single-authored docs | 26 |
| Co-Authors per Doc | 5.13 |
| International co-authorships % | 19.61 |
| DOCUMENT TYPES | |
| article | 557 |

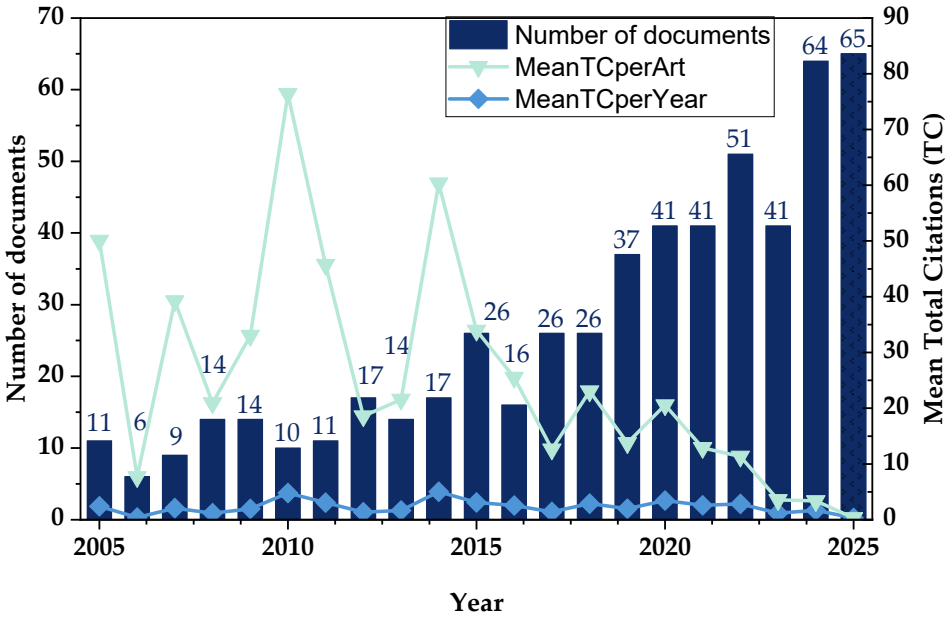



**Figure 3.** Trends in annual scientific production and citation impact in radar-based space debris detection (2005–2025): number of documents, mean citations per article, and mean citations per year.

### 3.2. Scientific Journal Production

Table 2 summarizes the bibliometric performance of the ten most influential journals in the field of radar-based space debris detection, using standard scientometric indicators: h-index, g-index, m-index, total citations (TC), number of publications (NP), and the year of first publication in the dataset (PY start). The h-index indicates the number of publications with at least h citations, combining productivity and impact. The g-index gives more weight to highly cited papers, while the m-index normalizes the h-index by the number of years since a journal's first contribution to the field. TC reflects the cumulative number of citations, NP the total number of publications, and PY start the first year of appearance in the dataset.

**Table 2.** Impact of most important scientific journals.

| Journal | h_index | g_index | m_index | TC | NP | PY Start |
|---|---|---|---|---|---|---|
| *Remote Sensing* | 14 | 23 | 1.273 | 585 | 36 | 2015 |
| *Acta Astronautica* | 13 | 22 | 0.619 | 510 | 31 | 2005 |
| *Remote Sensing of Environment* | 12 | 12 | 0.571 | 1473 | 12 | 2005 |
| *Advances in Space Research* | 8 | 17 | 0.444 | 307 | 28 | 2008 |
| *IEEE Transactions on Geoscience and Remote Sensing* | 8 | 12 | 0.471 | 265 | 12 | 2009 |
| *Geophysical Research Letters* | 7 | 8 | 0.467 | 211 | 8 | 2011 |
| *IEEE Geoscience and Remote Sensing Letters* | 7 | 11 | 0.368 | 193 | 11 | 2007 |
| *IEEE Transactions on Aerospace and Electronic Systems* | 6 | 11 | 0.545 | 135 | 11 | 2015 |
| *IET Radar Sonar and Navigation* | 6 | 8 | 0.375 | 80 | 12 | 2010 |
| *Applied Sciences-Basel* | 5 | 7 | 0.714 | 65 | 7 | 2019 |

Among the top-performing journals, *Remote Sensing* stands out with the highest h-index (14), g-index (23), and m-index (1.273), along with 36 publications and 585 citations since its first inclusion in 2015. This indicates a strong recent influence in the field. *Acta Astronautica*, despite a lower m-index (0.619), follows closely in terms of productivity and citation count, with 31 articles and 510 citations since 2005, reflecting long-term contribution and visibility. *Remote Sensing of Environment* displays the highest total citation count (TC = 1473) despite having only 12 articles, which results in a comparatively lower h-index (12) but demonstrates exceptionally high per-article impact. Similarly, *Advances in Space Research* and *IEEE Transactions on Geoscience and Remote Sensing* show sustained relevance, with 28 and 12 publications, respectively, and solid citation records. Other notable sources include *IEEE Geoscience and Remote Sensing Letters*, *Geophysical Research Letters*, and *IET Radar Sonar and Navigation*, each showing moderate levels of productivity and impact. *Applied Sciences—Basel*, although newer to the field (first appearance in 2019), already registers an m-index of 0.714, suggesting a rapid growth in influence. In general, both long-established and more recent sources play significant roles in shaping the scientific discourse on radar-based space debris detection.

### 3.3. Affiliation and Country Production

Table 3 highlights the leading institutions contributing to research. The Chinese Academy of Sciences (CAS) clearly emerges as the most prolific institution, reflecting China's growing investment and leadership in space science and technology. In fact, six out of the top ten institutions are based in China, including *Peking University*, the *National University of Defense Technology*, *Wuhan University*, *Xidian University*, and *Central South University*. This strong presence illustrates the strategic prioritization of space situational

awareness by Chinese research bodies, particularly in areas tied to national security and satellite operations.

**Table 3.** Top 10 most productive institutions.

| Institution | Country | Publications |
|---|---|---|
| *Chinese Academy of Sciences* | China | 55 |
| *National Aeronautics and Space Administration (NASA)* | United States | 41 |
| *Peking University* | China | 35 |
| *National University of Defense Technology* | China | 33 |
| *Centre National de la Recherche Scientifique (CNRS)* | France | 26 |
| *Wuhan University* | China | 21 |
| *Helmholtz Association* | Germany | 20 |
| *Xidian University* | China | 20 |
| *Istituto Nazionale di Astrofisica (INAF)* | Italy | 16 |
| *Central South University* | China | 15 |

The presence of NASA in second place confirms the United States' long-standing role in pioneering space research. NASA's significant publication output reflects its deep engagement in both observational technologies and the development of mitigation strategies for orbital debris. European institutions also maintain a solid footprint. The French CNRS, Germany's Helmholtz Association, and Italy's INAF exemplify Europe's collaborative scientific approach, often supported by multinational frameworks such as the *European Space Agency* (ESA).

This institutional distribution underscores the global nature of space debris monitoring, a field that demands both advanced technological capabilities and international cooperation. While national interests are clearly evident—particularly in countries with active space programs—the widespread involvement of academic and governmental research centers points to a shared understanding: space debris is a transboundary challenge that threatens all orbital assets, regardless of their origin.

It should be noted that two complementary bibliometric indicators are used to assess national research output. The global publication distribution considers all author affiliations associated with each document; consequently, internationally co-authored papers may be counted for more than one country. In contrast, the corresponding-author analysis assigns each publication to the country of the corresponding author, providing an indicator of national research leadership. Therefore, the values reported in these two analyses are not directly comparable, as they reflect different dimensions of scientific participation.

Table 4 shows the countries of corresponding authors in radar-based space debris detection research from 2005 to 2025. China leads with 130 articles (25.2%), mostly from national collaborations (SCP = 120), indicating a strong internal research ecosystem and limited international engagement (MCP = 7.7%). In contrast, the United States, with 112 articles (21.7%), shows a higher level of international collaboration (MCP = 17.9%), highlighting its active role in global research networks. Italy ranks third (9.5%) with moderate collaboration (MCP = 18.4%), while countries like France (MCP = 40%), the UK (38.5%), and Germany (27.6%) demonstrate stronger international ties, likely influenced by European space research programs. Australia, Spain, and Switzerland also show a balanced presence, combining modest output with notable collaboration rates.

These results suggest two distinct models: countries with high productivity and domestic focus (e.g., China), and others that enhance their impact through international partnerships (e.g., France, UK). In a global issue like space debris, strengthening collaboration could be key to shared solutions and interoperable detection systems.

**Table 4.** Corresponding Author's Countries.

| Country | Articles | Articles % | SCP | MCP |
|---|---|---|---|---|
| China | 130 | 25.2% | 120 | 10 |
| USA | 112 | 21.7% | 92 | 20 |
| Italy | 49 | 9.5% | 40 | 9 |
| Germany | 29 | 5.6% | 21 | 8 |
| France | 15 | 2.9% | 9 | 6 |
| Australia | 13 | 2.5% | 10 | 3 |
| United Kingdom | 13 | 2.5% | 8 | 5 |
| Spain | 12 | 2.3% | 9 | 3 |
| Switzerland | 11 | 2.1% | 8 | 3 |
| India | 9 | 1.7% | 8 | 1 |

SCP = Single Country Publications; MCP = Multiple Country Publications.

Figure 4 illustrates the geographical distribution of scientific publications, highlighting significant disparities in research output among countries. The United States leads with 315 articles, followed by China (269 articles) and Italy (138 articles). Other notable contributors include Germany (70), France (50), the United Kingdom (44), and Australia (45). These findings underscore the dominance of developed countries with established space programs and strong research infrastructures. In contrast, numerous regions, particularly in Africa, South America, and parts of Asia, exhibit minimal or no publication activity, indicating a lack of research capacity or prioritization in this domain.

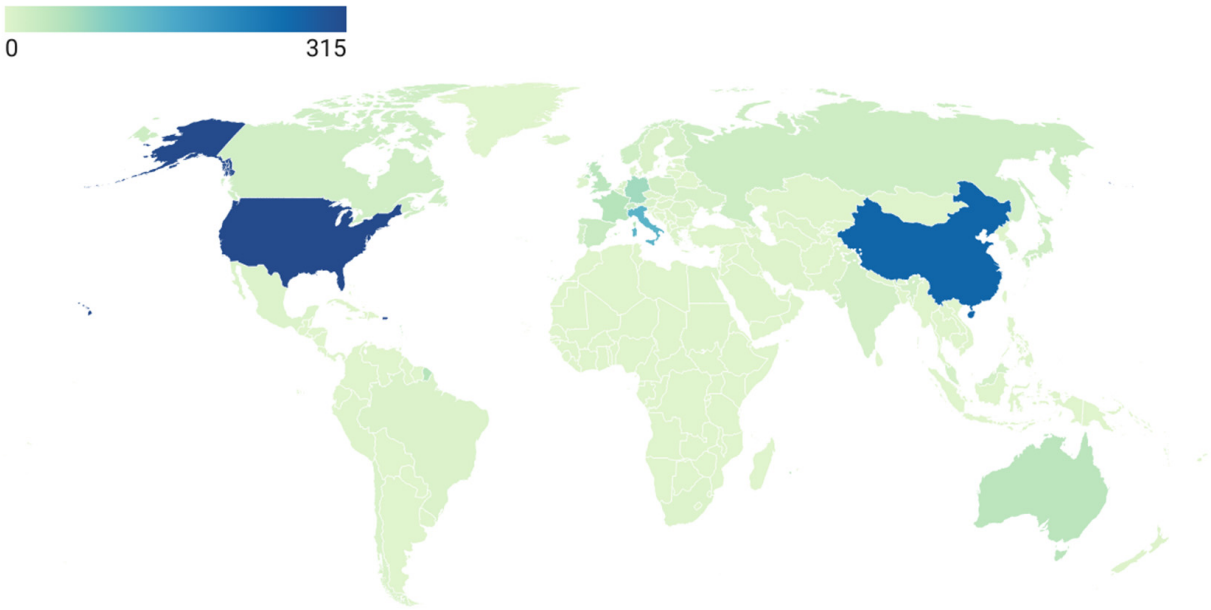



**Figure 4.** Global distribution of scientific production.

This pattern reflects the concentration of technological capabilities and resources necessary for advanced space activities and debris monitoring. Moreover, it suggests that international collaboration may be essential to engage underrepresented regions and foster more equitable contributions to space sustainability. The map emphasizes the need for global governance mechanisms that account for the uneven distribution of expertise and research output, ensuring that space debris mitigation efforts benefit from diverse regional perspectives and capacities.

### *3.4. Highly Cited Publications Across Different Periods*

To complement the overall citation analysis and provide a temporally balanced overview of influential contributions, Table 5 presents six highly cited and representative publications distributed across three consecutive periods: 2005–2010, 2011–2019, and 2020–2025. Two publications were selected for each period. In addition to total citations (TC), citations per year (TC per Year) are reported to facilitate comparison between publications with different citation windows.

**Table 5.** Highly cited and representative publications across different periods of radar-based space debris research.

| Period | Ref | Autor | Year | Journal | TC | TC per Year |
|---|---|---|---|---|---|---|
| 2005–2010 | [33] | Tommei et al. | 2007 | *Celestial Mechanics and Dynamical Astronomy* | 129 | 6.79 |
| | [34] | Bai et al. | 2009 | *IEEE Transactions on Geoscience and Remote Sensing* | 76 | 4.47 |
| 2011–2019 | [35] | Nesvorný et al. | 2011 | *The Astrophysical Journal* | 421 | 28.06 |
| | [36] | Nesvorný et al. | 2011 | *The Astrophysical Journal* | 133 | 8.87 |
| 2020–2025 | [37] | Li et al. | 2020 | *IEEE Transactions on Aerospace and Electronic Systems* | 37 | 6.17 |
| | [38] | Zhuo et al. | 2022 | *IEEE Transactions on Geoscience and Remote Sensing* | 47 | 11.75 |

## 4. Discussion

### *4.1. Qualitative Interpretation of Highly Cited Publications*

The highly cited publications identified in Table 5 provide a complementary qualitative perspective on the evolution of radar-related research associated with space debris and small-object characterization. Their scientific contributions reveal changes in the main research priorities across the three periods considered, from orbit determination and radar imaging to data-driven prediction and increasingly sophisticated three-dimensional characterization.

During the 2005–2010 period, Tommei et al. [33] and Bai et al. [33] represent two complementary methodological directions. The first work developed an admissible-region approach for preliminary orbit determination from incomplete optical or radar observations, facilitating the association and cataloguing of poorly characterized objects. The second work focused on the physical characterization of space debris through three-dimensional ISAR imaging, proposing a coherent method based on complex-valued back projection. Their results demonstrated the potential of radar techniques to move beyond detection and tracking toward high-resolution structural characterization of spinning, non-cooperative orbital targets.

The publications selected for the 2011–2019 period illustrate the importance of combining radar observations with dynamical modeling to interpret populations of small objects in the near-Earth environment. Nesvorný et al. [35], the most highly cited publication in Table 5, developed a dynamical model of the zodiacal cloud and sporadic meteors and compared the resulting particle distributions with meteor radar observations. Their results linked specific cometary sources with observed meteor populations and demonstrated how radar measurements can constrain models of particle origin, orbital evolution, and spatial distribution. Similarly, other study of Nesvorný et al. [38] investigated dust particles released from Oort Cloud comets and examined whether their dynamical evolution could explain characteristics observed in meteor radar data. The study showed that particles within size ranges can evolve toward Earth-crossing trajectories and generate observational signatures consistent with radar-detected meteors. Although these two contributions primarily concern natural dust and meteoroid populations rather than artificial orbital debris, their presence among the most highly cited records highlights the broader methodological

relationship between radar observations, orbital dynamics, and the characterization of small spaceborne objects.

The 2020–2025 period reflects a shift toward advanced computational methods and improved radar-data processing. Li et al. [37] applied machine learning to correct physics-based orbit predictions using sparse radar observations, significantly improving trajectory estimates and highlighting the potential of data-driven methods for Space Situational Awareness. Zhuo et al. [38] advanced three-dimensional imaging of spinning debris using a smoothed Lv distribution to reduce range migration, cross-terms, and sidelobes. Their method improved scattering-center estimation and image quality, illustrating the growing sophistication of radar signal-processing techniques for non-cooperative orbital targets.

To sum up, early research focused mainly on orbit determination and high-resolution radar imaging, while later studies combined radar observations with dynamical models. More recent work has introduced machine learning and advanced signal-processing techniques to improve orbit prediction and three-dimensional characterization. These developments are in line with the bibliometric trends identified in this study and reflect the growing technical capabilities of radar-based Space Situational Awareness.

### *4.2. Mapping the Intellectual Structure: Co-Occurrence Network*

Figure 5 illustrates the co-occurrence network of keywords extracted from publications on space debris. The nodes represent keywords, while the size of each node indicates the frequency of occurrence. The connecting edges reflect the strength of co-occurrence relationships, with thicker edges denoting stronger connections. The different colors represent distinct clusters or thematic areas, as identified by clustering algorithms. This network mapping technique is a cornerstone of "science mapping," as it visually represents the strength of association between concepts, allowing for the identification of a field's conceptual structure [39]. The clustering algorithm, often based on modularity, groups keywords that are frequently cited together, revealing the core research themes and their inter-relationships [40].

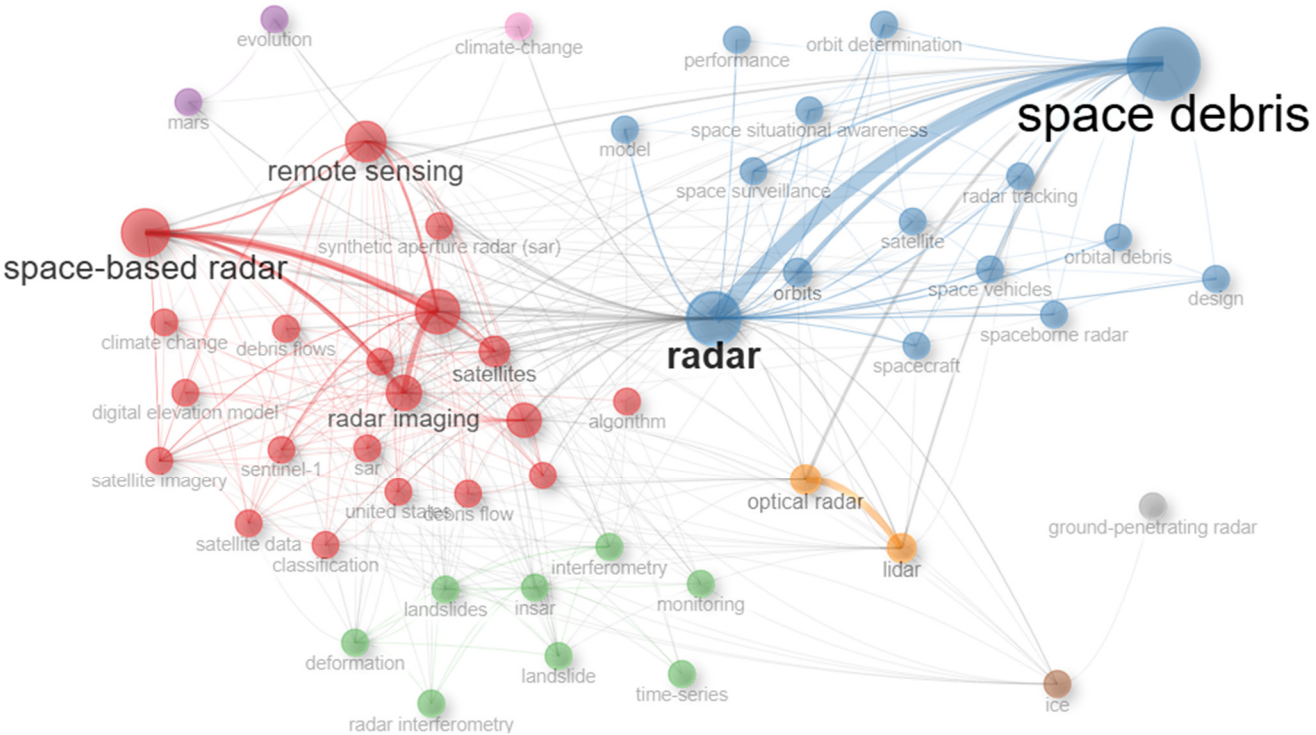



**Figure 5.** Co-occurrence network of keywords in space debris research.

A detailed examination reveals that the network is organized into several prominent clusters. The largest red cluster appears to focus on debris detection and tracking, with keywords such as radar, optical imaging, and orbit determination closely interconnected. This cluster highlights the critical role of advanced observation technologies in monitoring and cataloguing debris, which remains a foundational aspect of space situational awareness. This cluster's prominence is expected, as high-fidelity orbit determination is the fundamental prerequisite for all other SSA functions, from catalog maintenance to collision warning [41]. The strong co-occurrence of "radar" with terms like "remote sensing" and "satellites" (in the red cluster) and "optical radar" (in the orange cluster) reflects the sensor-data-fusion paradigm, where data from different phenomenologies are combined to improve orbital element accuracy and reduce uncertainty [42].

The blue cluster, which is also highly connected and prominent, centers around collision risk assessment and mitigation strategies, with terms like collision avoidance, risk analysis, and active debris removal. The thickness of the connections within this cluster suggests intensive research collaboration and frequent joint occurrence of these topics, underscoring the urgency of developing practical solutions to reduce the growing threat of orbital debris. The strong linkage between this foundational cluster and emerging themes like "active debris removal" reflects the dual strategy for managing the debris environment: short-term risk mitigation through tracking and maneuvers, and long-term environmental remediation through ADR [43]. The intensity of this cluster highlights that the field is moving from a purely observational problem to an applied engineering and risk management challenge, driven by the unsustainable growth of orbital density [44].

Smaller clusters, such as the green and orange ones, point to emerging or niche research themes. The green cluster appears related to legal and policy aspects, with terms such as space law, liability, and governance, indicating a growing recognition of the importance of regulatory frameworks and international cooperation. The orange cluster may focus on modeling and simulation tools for debris evolution and long-term forecasting, essential for designing effective mitigation measures. Isolated nodes and loosely connected terms, such as "space law" or "governance" (which do not appear to have formed a strong cluster in this visualization), suggest areas with less integration into the core technical discourse, potentially representing early-stage or parallel, non-engineering topics [45]. The focus on modeling and simulation tools for debris evolution and long-term forecasting is fundamental, as these predictive models, such as NASA's LEGEND or ESA's MASTER, are the primary tools used to justify mitigation guidelines and assess the future stability of the orbital environment [46].

This visualization demonstrates how space debris research has evolved into a multi-thematic field that integrates engineering, astronomy, policy, and risk management. It highlights the need for cross-disciplinary collaboration to address the complex and global nature of space debris challenges. Moreover, the identification of less connected clusters could guide future research efforts towards strengthening underexplored areas and fostering comprehensive solutions for sustainable space operations. This observed multi-thematic integration is characteristic of a maturing "Mode 2" knowledge production system, where research is increasingly transdisciplinary, application-oriented, and shaped by a complex set of social and economic demands [47]. Addressing the "wicked problem" of space debris inherently requires this convergence of engineering, natural science, and social science, as technical solutions cannot be implemented in a political or legal vacuum [48].

### *4.3. Thematic Evolution and Strategic Positioning*

Figure 6 illustrates the strategic diagram that maps the thematic structure of scientific research on space debris. This diagram classifies themes based on two dimensions:

centrality, which indicates the degree of interaction with other themes (relevance), and density, which reflects the theme's internal development and coherence. This analysis helps to identify the relative maturity and importance of each research theme within the field. This two-axis "strategic diagram" is a standard methodology in scientometrics, designed to visualize a research field's internal structure. Centrality ($x$-axis) measures the strength of a theme's connections to other themes, identifying it as more or less "transversal" to the field's core interests. Density ($y$-axis) measures the internal strength of the links between a theme's constituent keywords, indicating its level of conceptual development and consolidation as a specialty [49,50].

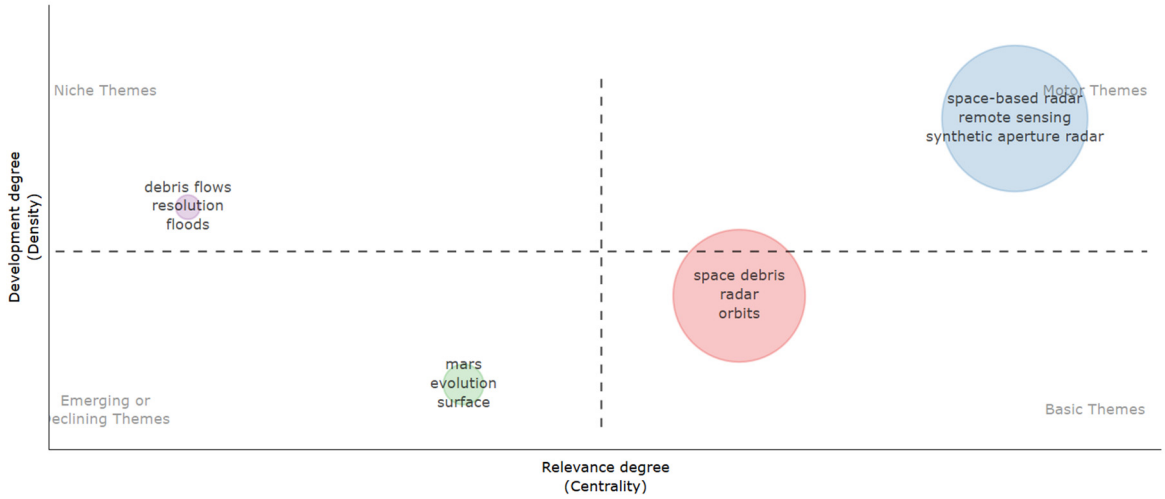



**Figure 6.** Strategic diagram of research themes in space debris studies.

In the upper right quadrant, the diagram highlights the motor themes, which are both highly developed and highly relevant. In this case, the cluster including space-based radar, remote sensing, and synthetic aperture radar represents the technological backbone of the field. These topics demonstrate strong internal links and robust connections with other themes, underlining the central role of advanced observation and monitoring technologies in tracking and managing space debris. Their prominence suggests that they drive innovation and are critical for operational and research agendas alike. Themes in this quadrant are considered the established driving forces of the research front; they are both mature and well-connected [50]. The presence of "space-based radar" and "synthetic aperture radar" (SAR) as motor themes confirms that the field's technical core is focused on developing high-resolution, persistent sensing capabilities, moving beyond traditional ground-based systems to achieve the global coverage and detailed characterization (e.g., shape and size estimation) that are deemed essential for modern SSA and future ADR missions [22,34].

The lower right quadrant corresponds to the basic themes, which are highly relevant but still relatively less mature in their internal development. Here, the cluster formed by the keywords space debris, radar, and orbits reflects the fundamental focus of the research domain. Although these topics are foundational and widely studied, their moderate density indicates that they could benefit from greater methodological diversification or interdisciplinary integration. Strengthening these connections may contribute to addressing complex challenges such as collision avoidance and orbital sustainability. Basic themes, with their high centrality, are transversal to the entire research domain and represent its conceptual foundation, but their low density shows they are not a "specialty" in themselves [49]. It is therefore logical that "space debris" and "radar" reside here; they are the fundamental

subject and primary tool of the entire field, serving as the conceptual starting point for more specialized (i.e., denser) themes, such as the motor themes.

In the upper left quadrant, the diagram shows the niche themes, which are well developed internally but exhibit lower relevance to the broader field. Terms like debris flows, resolution, and floods appear here, indicating specialized lines of research. While these topics are methodologically mature, their peripheral position suggests they are not yet fully integrated into the mainstream discourse on orbital debris. Nonetheless, these niche areas may offer valuable cross-disciplinary insights, especially considering the parallels between terrestrial geohazards and debris movement in space. Niche themes represent highly specialized topics with strong internal coherence but limited interaction with the rest of the field [50]. The presence of geophysical terms like "debris flows" and "floods"—likely introduced via automatically indexed Keywords Plus—suggests a methodological "borrowing" from the well-established field of terrestrial remote sensing for geohazards [50,51]. This cluster's isolation indicates that these specific analytical techniques have not (yet) been broadly adopted by the orbital debris community.

Finally, the lower left quadrant identifies emerging or declining themes, characterized by low density and low centrality. The cluster containing Mars, evolution, and surface falls into this category, which may indicate exploratory or nascent research directions. These themes could represent early-stage inquiries into planetary debris environments or comparative studies, but their current marginal position suggests they require further development to establish stronger ties with core research areas. This quadrant's themes are both weakly developed and peripheral, representing either fading, "legacy" topics or new, emerging concepts [49]. Given the novelty, the "Mars" cluster clearly represents a nascent research area, likely related to the very first considerations of planetary defense and debris monitoring for future missions to other planets, a concept that is only just beginning to be explored in the literature [52].

### *4.4. Unveiling the Conceptual Landscape*

To deepen the understanding of the intellectual structure of *space debris* research, a factorial analysis was conducted based on a multiple correspondence analysis of the co-occurrence matrix of the most relevant keywords. The two-dimensional map resulting from this analysis stated Figure 7 displays the spatial distribution of keywords across two main dimensions. These dimensions explain a significant share of the total variance in the dataset—76.59% for Dimension 1 and 11.53% for Dimension 2. Dimension 1 therefore captures the dominant conceptual structure of the map, whereas Dimension 2 provides a complementary secondary differentiation.

Dimension 1 serves to differentiate between keywords associated with technological applications and observational tools—such as *radar imaging*, *satellites*, *remote sensing*, and *synthetic aperture radar*—and those linked to environmental modeling and theoretical frameworks, including *evolution*, *climate change*, and *model*. This suggests a conceptual polarity between practice-oriented research and analytical or predictive studies. Accordingly, this axis can be interpreted as the main conceptual contrast between technology-oriented and modeling-oriented research.

Dimension 2, on the other hand, appears to distinguish between system-level approaches and detection-specific technologies. For instance, terms like *interferometry* and *ice* appear toward the upper section of the plot, indicating broader Earth and environmental observation contexts. In contrast, terms such as *lidar*, *optical radar*, and *space debris* are positioned toward the lower part, indicating a focus on object-level sensing and tracking. This second axis therefore provides a more specific distinction between broader observational contexts and technologies focused on the direct detection and characterization of individual

objects. The interpretation of both dimensions is based on the relative positioning of the keywords along each axis.

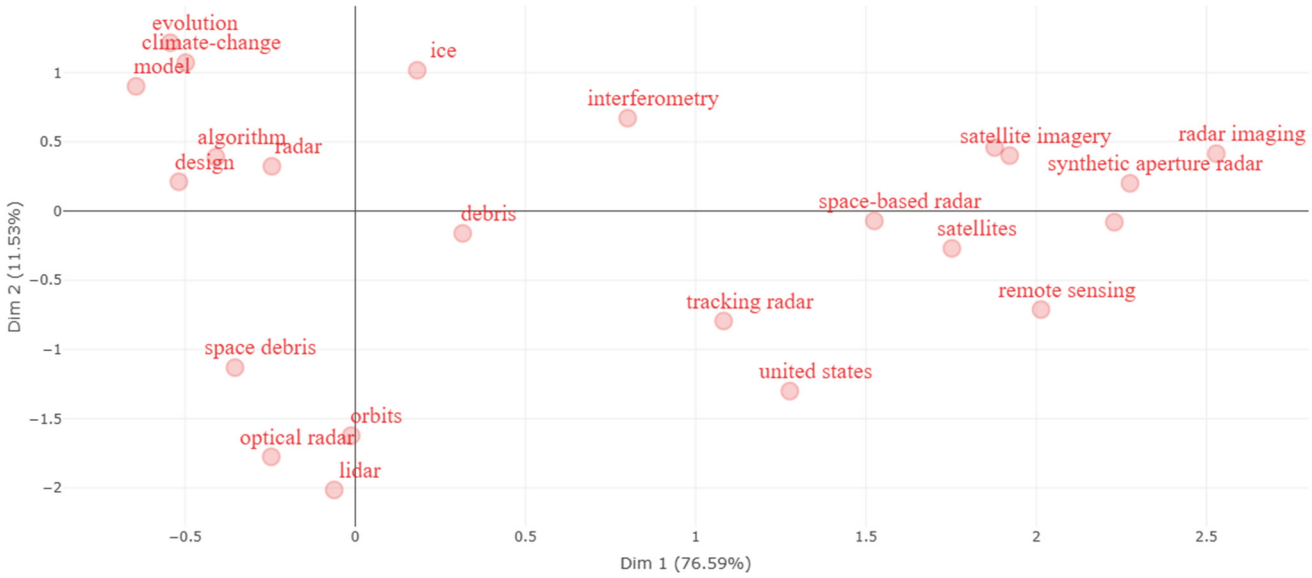



**Figure 7.** Factorial analysis of keyword co-occurrence revealing the conceptual structure of space debris research.

Three major conceptual clusters emerge from this factorial structure. The first is a technological cluster, which encompasses radar systems, satellite platforms, and advanced sensing technologies. The second is an environmental and modeling cluster, including terms that reflect long-term system evolution, environmental impact, and climate-related modeling. The third is a core conceptual cluster, centered on terms like *space debris*, *debris*, and *tracking radar*, which form the thematic heart of the literature.

### *4.5. Relationship Between International Collaboration and Research Performance*

The correlation analysis provides additional context for the collaboration patterns identified in the previous sections. As shown in Table 1, international co-authorship represents 19.61% of the publications in the dataset, confirming that cross-country collaboration is already a relevant component of research activity in this field. However, the results presented in Tables 3 and 4 and Figure 4 also reveal that scientific production remains strongly concentrated in a relatively small number of countries and institutions, particularly China and the United States.

This interpretation is supported by the correlation analysis. Collaboration intensity was not significantly associated with research output (Pearson's $r = -0.29$, $p = 0.145$), indicating that countries with a higher proportion of internationally co-authored papers do not necessarily publish more articles. This result is consistent with Table 4, where China and the United States lead the number of publications despite showing different levels of multiple-country publications. In other words, high productivity can be sustained by strong domestic research networks, particularly in countries with established space programs and substantial technological capacity.

A different pattern emerges when collaboration is compared with scientific impact. A significant positive correlation was observed between international collaboration and average citation impact (Pearson's $r = 0.63$, $p < 0.001$), and this relationship was also confirmed by Spearman's correlation ($\rho = 0.70$, $p < 0.001$). These findings suggest that international cooperation is more closely related to the visibility and influence of research than to publication volume. Collaborative studies may benefit from broader scientific

networks, complementary expertise, access to different observational infrastructures, and wider dissemination across research communities.

Taken together with the geographical distribution shown in Figure 4, these indicate that the field combines a strong concentration of research capacity with an important role for international cooperation in enhancing scientific impact. Countries with major national infrastructures can maintain high publication output independently, whereas cross-country collaboration appears to provide an additional advantage in terms of citation influence. Therefore, international cooperation may be particularly relevant for strengthening the impact of radar-based space debris research and for connecting institutions with different technical capabilities, observational resources, and expertise in Space Situational Awareness.

### *4.6. Implications and Limitations of the Review*

The results confirm a significant and accelerating growth in publication output, mostly in the last decade. This temporal trend clearly reflects the escalating urgency of the space debris problem, which has been amplified by the recent deployment of satellite mega-constellations [14] and the persistent, long-term risk of the Kessler Syndrome [4]. Geographically, the research landscape is dominated by a few key nations, with China and the United States emerging as the most prolific contributors, driven by a concentration of resources in national-level institutions like the Chinese Academy of Sciences and NASA. This institutional landscape underscores the field's deep ties to national space and security interests. However, our analysis of co-authorship patterns revealed distinct collaborative models: while the United States and European nations (notably Germany, France, and the UK) exhibit high rates of international co-authorship, China's formidable output is characterized by a primary focus on domestic collaboration. This suggests a potential for fostering greater international scientific exchange to address a problem that is, by its nature, unequivocally global.

The thematic analysis, particularly the strategic diagram, reveals a mature and well-defined intellectual core. The field's motor themes—representing topics that are both highly developed (dense) and highly central—are "space-based radar", "remote sensing", and "synthetic aperture radar". This finding is significant: it demonstrates that the research frontier has decisively moved beyond simple detection (the basic themes of "radar" and "space debris") toward advanced, high-resolution sensing and characterization. This technological focus aligns directly with the critical need identified in the literature: to detect, track, and characterize the lethal, non-cataloged population of debris in the 1–10 cm size range [7,8]. The factorial analysis further reinforced this, revealing a primary conceptual axis that separates advanced technological applications (e.g., radar imaging, satellites, interferometry) from environmental and theoretical modeling (e.g., evolution, climate change).

The temporal evolution of artificial intelligence and machine learning shows that these approaches emerged relatively recently within the analyzed literature. The first AI/ML-related records appeared in the late 2010s, with a clearer and more continuous presence from 2020 onward. Their frequency increased further in the most recent years, remarkably from 2023–2024, indicating a growing interest in data-driven methods for radar-data processing, orbit prediction, and Space Situational Awareness. This pattern supports the identification of AI/ML as an emerging research hotspot within the field.

The implications of these findings are twofold. On the one hand, for researchers and engineers, the thematic mapping identifies both consolidated technological areas and emerging research gaps. Future work may focus on refining bistatic and multistatic radar configurations [16,17], improving signal processing for interferometric ISAR [18], developing more advanced radar-based risk metrics [19], and strengthening the integration of

artificial intelligence and machine learning into radar-data processing, orbit prediction, object classification, and debris characterization. Particular attention should also be given to the validation of these emerging approaches under operational conditions and to their integration with existing Space Situational Awareness infrastructures. On the other hand, for policymakers and funding agencies, the relative scarcity of policy-related keywords suggests a gap between technological advances and the legal and regulatory frameworks required for debris mitigation and Active Debris Removal (ADR) [26]. Future policy actions should therefore encourage international data sharing, interoperable observation networks, common technical standards, and multidisciplinary research programs capable of connecting radar technologies, artificial intelligence, orbital dynamics, and debris mitigation strategies. In this way, the thematic mapping can also serve as a useful reference for directing future investment toward areas with greater scientific and operational potential.

Despite the robustness of the bibliometric methodology, this study is subject to certain limitations. Our dataset was intentionally restricted to peer-reviewed journal articles to ensure a baseline of scientific quality, as per the methodology. This, however, excludes a substantial body of work published in conference proceedings (e.g., from the International Astronautical Congress, AMOS, or IEEE Aerospace Conference), which are often the primary venue for disseminating cutting-edge engineering developments. Consequently, our analysis may underestimate the prevalence of certain nascent technologies. Furthermore, the reliance on Scopus and Web of Science, while standard, introduces a potential anglophone bias, and our findings do not represent a qualitative assessment of the technical validity or impact of the research itself.

## 5. Conclusions

This study provides a comprehensive bibliometric overview of radar-based space debris detection research, offering a systematic perspective on its scientific evolution, key contributors, and emerging thematic directions over the past two decades. The analysis demonstrates that this research field has undergone remarkable growth, transitioning from a specialized technical niche into a multidisciplinary and strategically relevant area within space science and engineering.

The bibliometric mapping revealed an increasingly mature and interconnected research landscape, driven by technological innovation, international collaboration, and the growing global concern for orbital sustainability. The intellectual structure of the field shows a clear consolidation around advanced radar sensing, remote detection, and synthetic aperture radar technologies—pillars that now define the technological frontier of space situational awareness.

At the same time, the study highlights a series of structural and methodological gaps that merit further attention. While the domain exhibits strong technological progress, there remains a need to better integrate engineering advances with policy, regulatory, and sustainability frameworks. Future research should therefore aim to strengthen cross-disciplinary collaboration, expand analyses to include conference proceedings and technical reports, and explore qualitative approaches that capture the nuances of emerging technologies and applications.

This study contributes a strategic and data-driven understanding of how radar-based debris detection research has evolved and where it is heading. By identifying the main actors, research clusters, and innovation hotspots, the study offers valuable guidance for researchers, institutions, and decision-makers seeking to advance global capabilities in orbital debris monitoring and mitigation. Continued progress in this area is not only a scientific and technological challenge but a critical step toward ensuring the long-term safety and sustainability of the near-Earth space environment.

https://doi.org/10.3390/aerospace13090770

**Author Contributions:** Conceptualization, A.d.B., D.V. and J.C.-G.; methodology, A.d.B., D.V., J.C.-G. and P.F.-A.; software, A.d.B. and P.F.-A.; validation, A.d.B., D.V., M.B.-G., F.P.-M., J.C.-G. and P.F.-A.; formal analysis, A.d.B., D.V. and P.F.-A.; investigation, A.d.B., D.V., M.B.-G., F.P.-M., J.C.-G. and P.F.-A.; resources, D.V., M.B.-G., F.P.-M. and J.C.-G.; data curation, A.d.B. and P.F.-A.; writing—original draft preparation, A.d.B. and J.C.-G.; writing—review and editing, D.V., M.B.-G., F.P.-M. and P.F.-A.; visualization, D.V. and P.F.-A.; supervision, A.d.B., D.V. and J.C.-G.; project administration, M.B.-G., F.P.-M. and J.C.-G.; funding acquisition, M.B.-G., F.P.-M. and J.C.-G. All authors have read and agreed to the published version of the manuscript.

**Funding:** This work was funded by the Spanish Agencia Estatal de Investigación MCIN/AEI/10.13039/501100011033 under grant nos. PID2021-126483OB-I00, PID2022-136869NB-C33, PDC2023-145856-I00 and PID2024-15814OB-C21. This research was supported by the Consejería de Educación, Junta de Castilla y León, under grant no. SA016G24.

**Data Availability Statement:** Dataset available on request from the authors.

**Conflicts of Interest:** The authors declare no conflicts of interest.

## References

1. ESA. Space Debris Office ESA—ESA Space Environment Report 2025. Available online: https://www.esa.int/Space_Safety/Space_Debris/ESA_Space_Environment_Report_2025 (accessed on 2 January 2026).
2. IADC. Inter-Agency Space Debris Coordination Committee, Space Debris Mitigation Guidelines. Available online: https://www.iadc-home.org/what_iadc (accessed on 2 January 2026).
3. Crowther, R. Orbital Debris: A Growing Threat to Space Operations. *Phil. Trans. R. Soc. A* **2003**, *361*, 157–168. [CrossRef]
4. Kessler, D.J.; Cour-Palais, B.G. Collision Frequency of Artificial Satellites: The Creation of a Debris Belt. *J. Geophys. Res. Space Phys.* **1978**, *83*, 2637–2646. [CrossRef]
5. Ostrom, C. ISS Maneuvers Twice to Avoid Debris. In *Orbital Debris Quarterly News*; National Aeronautics and Space Administration: Washington, DC, USA, 2025; Volume 29.
6. Anselmo, L.; Rossi, A.; Pardini, C. Updated Results on the Long-Term Evolution of the Space Debris Environment. *Adv. Space Res.* **1999**, *23*, 201–211. [CrossRef]
7. Foster, J.L.; Benbrook, J.R.; Stansbery, E.G. Detection of Small Radar Cross-Section Orbital Debris with the Haystack Radar. *Adv. Space Res.* **2005**, *35*, 1210–1213. [CrossRef]
8. Mains, D.L.; Peterson, G.E.; McVey, J.P.; Maldonado, J.C.; Sorge, M.E. Forensic Analysis of Recent Debris-Generating Events. *J. Space Saf. Eng.* **2024**, *11*, 388–394. [CrossRef]
9. Shimkus, L.K., 2nd. USSF Announces Initial Operational Capability and Operational Acceptance of Space Fence. *U.S. Space Force Public Affairs*. 27 March 2020. Available online: https://www.spaceforce.mil/News/Article/2129325/ussf-announces-initial-operational-capability-and-operational-acceptance-of-spa/ (accessed on 2 January 2026).
10. ESA Space Debris Office (SDO). *Classification of Geosynchronous Objects*; ESA: Darmstadt, Germany, 2024.
11. Schildknecht, T. Optical Surveys for Space Debris. *Astron. Astrophys. Rev.* **2007**, *14*, 41–111. [CrossRef]
12. Choi, E.J.; Cho, S.; Jo, J.H.; Park, J.H.; Chung, T.; Park, J.; Jeon, H.; Yun, A.; Lee, Y. Performance Analysis of Sensor Systems for Space Situational Awareness. *J. Astron. Space Sci.* **2017**, *34*, 303–313. [CrossRef]
13. Vierinen, J.; Markkanen, J.; Krag, H.; Siminski, J.; Mancas, A. *Use of EISCAT 3D for Observations of Space Debris*; European Space Agency (ESA): Darmstadt, Germany, 2017.
14. Boley, A.C.; Byers, M. Satellite Mega-Constellations Create Risks in Low Earth Orbit, the Atmosphere and on Earth. *Sci. Rep.* **2021**, *11*, 10642. [CrossRef]
15. Vasile, M.; Walker, L.; Campbell, A.; Marto, S.; Murray, P.; Marshall, S.; Savitski, V. Space Object Identification and Classification from Hyperspectral Material Analysis. *Sci. Rep.* **2024**, *14*, 1570. [CrossRef]
16. Cataldo, D.; Gentile, L.; Ghio, S.; Giusti, E.; Tomei, S.; Martorella, M. Multibistatic Radar for Space Surveillance and Tracking. *IEEE Aerosp. Electron. Syst. Mag.* **2020**, *35*, 14–30. [CrossRef]
17. Bianchi, G.; Naldi, G.; Fiocchi, F.; Di Lizia, P.; Bortolotti, C.; Mattana, A.; Maccaferri, A.; Magro, A.; Roma, M.; Schiaffino, M.; et al. A New Concept of Bi-Static Radar for Space Debris Detection and Monitoring. In *Proceedings of the 2021 International Conference on Electrical, Computer, Communications and Mechatronics Engineering (ICECCME), Mauritius, Mauritius, 7–8 October 2021*; IEEE: Piscataway, NJ, USA, 2021; pp. 1–6.
18. Ning, Y.; Zhou, F.; Bai, X.; Liu, L. A Method for 3-D ISAR Imaging of Space Debris. *IEEE Trans. Aerosp. Electron. Syst.* **2019**, *55*, 864–876. [CrossRef]

19. Ostrogovich, L.; Isoletta, G.; Cimmino, N.; Opromolla, R.; Fasano, G. Fragmentation Modeling and Risk Assessment for Low Earth Orbits. In *Proceedings of the 2024 AIAA DATC/IEEE 43rd Digital Avionics Systems Conference (DASC), San Diego, CA, USA, 29 September–3 October 2024*; IEEE: Piscataway, NJ, USA, 2024. [CrossRef]
20. Space Surveillance and Tracking: A Global Challenge | EU Agency for the Space Programme. Available online: https://www.euspa.europa.eu/newsroom-events/news/space-surveillance-and-tracking-global-challenge (accessed on 3 January 2026).
21. Tommila, C.D.; Jones, M.P.; Gochenaur, D.C.; de Weck, O.L.; Claypool, I.R. Resilience and Performance of Nontraditional Space Situational Awareness Sensor Architectures. *J. Spacecr. Rocket.* **2025**, *62*, 1627–1643. [CrossRef]
22. Muntoni, G.; Montisci, G.; Pisanu, T.; Andronico, P.; Valente, G. Crowded Space: A Review on Radar Measurements for Space Debris Monitoring and Tracking. *Appl. Sci.* **2021**, *11*, 1364. [CrossRef]
23. Zhang, W.; Zhang, K.; Li, X.; Huang, J. Improving LEO Short-Term Orbit Prediction Using LSTM Neural Network. *Adv. Space Res.* **2025**, *76*, 481–496. [CrossRef]
24. Ravi, P.; Zollo, A.; Kahle, R.; Fiedler, H. AI for Collision Avoidance—Go/No Go Decision-Making. In Proceedings of the International Conjunction Assessment Workshop 2023, Paris, France, 3–5 May 2023.
25. Liou, J.C.; Hall, D.T.; Krisko, P.H.; Opiela, J.N. LEGEND—A Three-Dimensional LEO-to-GEO Debris Evolutionary Model. *Adv. Space Res.* **2004**, *34*, 981–986. [CrossRef]
26. ESA—Clean Space. Available online: https://www.esa.int/Space_Safety/Clean_Space (accessed on 3 January 2026).
27. Donthu, N.; Kumar, S.; Mukherjee, D.; Pandey, N.; Lim, W.M. How to Conduct a Bibliometric Analysis: An Overview and Guidelines. *J. Bus. Res.* **2021**, *133*, 285–296. [CrossRef]
28. Mayer, M.; Dassanayake, S. Active Space Debris Removal: Feasibility and Comparative Analysis of Methods for Diverse Targets. *Res. Arch. Rising Sch.* **2025**. [CrossRef]
29. Lee, T.S.; Lee, Y.S.; Lee, J.; Chang, B.C. Analysis of the Intellectual Structure of Human Space Exploration Research Using a Bibliometric Approach: Focus on Human Related Factors. *Acta Astronaut.* **2018**, *143*, 169–182. [CrossRef]
30. del Bosque, A.; Vergara, D.; Fernández-Arias, P. An Overview of Smart Composites for the Aerospace Sector. *Appl. Sci.* **2025**, *15*, 2986. [CrossRef]
31. Aria, M.; Cuccurullo, C. Bibliometrix: An R-Tool for Comprehensive Science Mapping Analysis. *J. Informetr.* **2017**, *11*, 959–975. [CrossRef]
32. Vergara, D.; del Bosque, A.; Lampropoulos, G.; Fernández-Arias, P. Trends and Applications of Artificial Intelligence in Project Management. *Electronics* **2025**, *14*, 800. [CrossRef]
33. Tommei, G.; Milani, A.; Rossi, A. Orbit Determination of Space Debris: Admissible Regions. *Celest. Mech. Dyn. Astron.* **2007**, *97*, 289–304. [CrossRef]
34. Bai, X.; Xing, M.; Zhou, F.; Bao, Z. High-Resolution Three-Dimensional Imaging of Spinning Space Debris. *IEEE Trans. Geosci. Remote Sens.* **2009**, *47*, 2352–2362. [CrossRef]
35. Nesvorný, D.; Janches, D.; Vokrouhlick, D.; Pokorn, P.; Bottke, W.F.; Jenniskens, P. Dynamics of the Zodiacal Cloud and Sporadic Meteors. *Astrophys. J.* **2011**, *743*, 129. [CrossRef]
36. Nesvorný, D.; Vokrouhlický, D.; Pokorný, P.; Janches, D. Dynamics of Dust Particles Released from Oort Cloud Comets and Their Contribution to Radar Meteors. *Astrophys. J.* **2011**, *743*, 37. [CrossRef]
37. Li, B.; Huang, J.; Feng, Y.; Wang, F.; Sang, J. A Machine Learning-Based Approach for Improved Orbit Predictions of LEO Space Debris with Sparse Tracking Data from a Single Station. *IEEE Trans. Aerosp. Electron. Syst.* **2020**, *56*, 4253–4268. [CrossRef]
38. Zhuo, Z.; Du, L.; Lu, X.; Chen, J.; Cao, Z. Smoothed Lv Distribution Based Three-Dimensional Imaging for Spinning Space Debris. *IEEE Trans. Geosci. Remote Sens.* **2022**, *60*, 5113813. [CrossRef]
39. van Eck, N.J.; Waltman, L. Software Survey: VOSviewer, a Computer Program for Bibliometric Mapping. *Scientometrics* **2010**, *84*, 523–538. [CrossRef] [PubMed]
40. Jin, Y.; Xiao, S.; Zhang, Y.; Neri, I.; Roldán, É.; Pigolotti, S.; Iop, A.; Blondel, V.D.; Guillaume, J.-L.; Lambiotte, R.; et al. Fast Unfolding of Communities in Large Networks. *J. Stat. Mech. Theory Exp.* **2008**, *2008*, P10008. [CrossRef]
41. Farnocchia, D.; Tommei, G.; Milani, A.; Rossi, A. Innovative Methods of Correlation and Orbit Determination for Space Debris. *Celest. Mech. Dyn. Astron.* **2010**, *107*, 169–185. [CrossRef]
42. Xue, C.; Cai, H.; Gehly, S.; Jah, M.; Zhang, J. Review of Sensor Tasking Methods in Space Situational Awareness. *Prog. Aerosp. Sci.* **2024**, *147*, 101017. [CrossRef]
43. Liou, J.C. An Active Debris Removal Parametric Study for LEO Environment Remediation. *Adv. Space Res.* **2011**, *47*, 1865–1876. [CrossRef]
44. Rongzhi, Z.; Kaizhong, Y. *Spacecraft Collision Avoidance Technology*; Elsevier: Amsterdam, The Netherlands, 2020.
45. Košuda, M.; Podmajersky, M.; Kattan, N. Legal Challenges for Space Traffic Management: A Framework for Global Governance. In *Proceedings of the 2025 New Trends in Aviation Development (NTAD), Stary Smokovec, Slovakia, 27–28 November 2025*; IEEE: Piscataway, NJ, USA, 2025; pp. 186–191.

46. Flegel, S.; Gelhaus, J.; Wiedemann, C.; Vorsmann, P.; Oswald, M.; Stabroth, S.; Klinkrad, H.; Krag, H. The MASTER-2009 Space Debris Environment Model. In *Proceedings of the Fifth European Conference on Space Debris*; ESA: Darmstadt, Germany, 2009; Volume 672, pp. 1–8.
47. Gibbons, M.; Limoges, C.; Nowotny, H.; Schwartzman, S.; Scott, P.; Trow, M. *The New Production of Knowledge: The Dynamics of Science and Research in Contemporary Societies*; SAGE Publications Ltd.: London, UK, 2010.
48. Filho, W.L.; Abubakar, I.R.; Hunt, J.D.; Dinis, M.A.P. Managing Space Debris: Risks, Mitigation Measures, and Sustainability Challenges. *Sustain. Futures* **2025**, *10*, 100849. [CrossRef]
49. Callon, M.; Rip, A.; Law, J. *Mapping the Dynamics of Science and Technology: Sociology of Science in the Real World*; Palgrave Macmillan: London, UK, 1986.
50. Cobo, M.J.; López-Herrera, A.G.; Herrera-Viedma, E.; Herrera, F. SciMAT: A New Science Mapping Analysis Software Tool. *J. Am. Soc. Inf. Sci. Technol.* **2012**, *63*, 1609–1630. [CrossRef]
51. Hürlimann, M.; Coviello, V.; Bel, C.; Guo, X.; Berti, M.; Graf, C.; Hübl, J.; Miyata, S.; Smith, J.B.; Yin, H.Y. Debris-Flow Monitoring and Warning: Review and Examples. *Earth. Sci. Rev.* **2019**, *199*, 102981. [CrossRef]
52. Anilkumar, K.; Mukherjee, B.; Berend, N.; Biswas, S.K.; Buinhas, L.; Dailey, N.; Foing, B.; Rodriguez, N.F.; Hedrick, G.; Kebe, F.; et al. Moon to Mars: Challenges and Strategic Frameworks for Space Traffic Management in Cislunar and Cismartian Environments. *Acta Astronaut.* **2025**, *229*, 211–217. [CrossRef]


**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.