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The political and legal landscape of space debris mitigation in emerging space nations

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ABSTRACT

The issue of space debris and its impact on space sustainability is a growing concern that requires collective action from all nations. Over the past decade, the number of spacefaring nations has increased, as evidenced by the number of satellites launched by emerging space nations and by an increase in the number of applications for United Nations Committee on the Peaceful Uses of Outer Space (UN COPUOS) membership from emerging member states. More recently, there has been an increase in emerging space nations stating their commitment to join the COPUOS Long-term Sustainability (LTS) 2.0 Working Group, as well as nations who have opted to join as signatories to initiatives such as “Net Zero Space” (e.g., Azercosmos, EgSA, GISTDA), and the Artemis Accords (e.g., Nigeria, Rwanda, and Angola). These initiatives share a common goal of promoting the sustainable and responsible use of space to ensure the long-term sustainability of space activities, including: 1) the recognition of the need for sustainable practices; 2) the importance of promoting cooperation in long-term sustainability between all nations; 3) the support of international guidelines and best practices; and 4) the recognition of the increasing role and contribution of emerging space nations.

Given the rapid diversification of the space sector, and in accordance with Part C International Cooperation, Capacity-Building and Awareness of the 2019 COPUOS Long Term Sustainability guidelines, many emerging nations continue to face challenges in implementing space debris mitigation and removal measures. The aim of this paper is threefold: 1) showcase examples of emerging space nations who are actively supporting the sustained use of space at a national, regional, and international level, which includes complying with existing binding requirements concerning space debris within national laws; 2) discuss how the Space Sustainability Rating (SSR) provides opportunities for emerging space nations to progress in their efforts to participate in seeking space sustainability; and 3) provide an analysis using the SSR for several missions launched by emerging space nations including recommended steps for increased sustainability in both the design phase and during operations. The study aims to identify potential challenges and opportunities in the adoption of the SSR by emerging space nations, and dispel the perception that sustainable design, operations, and implementation of the LTS guidelines is a barrier for emerging space nations. The selection of nations chosen for the analysis of this paper aims to ensure a representative sample of diverse space market sizes and maturity, with particular consideration given to geographic diversity.

1. Introduction

Space sustainability is a critical concern in the face of the expanding global space economy and the subsequent surge in satellite launches. With the increasing risk of collisions and the need for safe and responsible utilization of near-Earth orbits, the importance of addressing space debris is increasing. International guidelines have been established to encourage responsible space activities, but compliance is inconsistent among nations and not regulated by any international body. Concerted efforts are needed to ensure the long-term sustainability of space activities and to mitigate the risks associated with operating in a debris congested environment [1].

In response, the Space Sustainability Rating (SSR) provides a composite indicator scoring methodology of both quantitative

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Nomenclature

COLA	Collision Avoidance
COPUOS	Committee on the Peaceful Uses of Outer Space
DIT	Detectability, Identifiability, and Trackability
EPFL	École Polytechnique Fédérale de Lausanne
ESA	European Space Agency
LEO	Low Earth Orbit
LTS	Long-term sustainability
MIT	Massachusetts Institute of Technology
SPM	Space Participation Metric
SSR	Space Sustainability Rating

and qualitative modules for evaluating the sustainability of space missions, with the goal of incentivizing responsible behaviors in space. The SSR is a pioneering initiative commissioned by the World Economic Forum (WEF) through their Global Future Council on Space that evaluates a wide range of mission characteristics and operator behaviors from launch, through operations, to the spacecraft's end-of-life [2,3]. The Space Sustainability Rating was designed by an international consortium that included the European Space Agency, the Massachusetts Institute of Technology, the University of Texas at Austin, and Bryce Tech. The SSR is now operated by a non-profit association based in Switzerland called the Space Sustainability Rating. The SSR sets a precedent in defining space sustainability by proposing a way to measure it, focusing on in-space sustainability. Note that the term "space sustainability" is sometimes distinguished from "space safety" which is defined by Pelton et al. as efforts to safeguard "strategic and costly systems on orbit (i.e., satellites, international space station, and global utilities), valuable facilities on ground (e.g., launch pads), as well as the protection of the orbital space and of the Earth environment" [4]. More broadly, "space sustainability" can be defined as follows, based on the definition established by the United Nations Committee on the Peaceful Uses of Outer Space (UN COPUOS) and expanded by Wilson and Vasile:

> "*The long-term sustainability of outer space activities (on-ground and in-orbit) is defined as the ability to maintain and improve the conduct of space activities indefinitely into the future in a manner that ensures continued access to the benefits of the exploration and use of space for peaceful purposes, in order to meet the needs of the present generations while preserving both the Earth and the outer space environment for future generations. Space sustainability also requires promoting the use and environmental benefits of space data and recognising the need for the launch and in-orbit activities to be carried out in an increasingly responsible and sustainable manner.*" [5]

This study aims to explore the SSR's application as an important step towards fostering sustainable in-orbit space practices among a diverse range of space operators, focusing on specific missions from emerging space nations, and investigate potential barriers to achieving comparable ratings with more established operators from the U.S. and Europe. This paper is the second in a series of studies by the authors that examines the experiences of emerging space nations and the topic of space sustainability. The previous paper introduced examples of efforts by emerging space nations to adopt legal and technical approaches that foster space sustainability [6]. The present work adds additional technical rigor to assessing the performance of emerging space nation satellite missions using the Space Sustainability Rating. The knowledge underlying the paper is drawn from long term study of the space policies of emerging space nations and regular participation by several of the co-authors (Wood and Rathnasabapathy) as delegation members at the United Nations COPUOS meetings.

International efforts to promote space sustainability are exemplified by UN COPUOS Long-term Sustainability (LTS) Guidelines, the Artemis Accords, and the Paris Peace Forum's "Net Zero Space" initiative, the first two of which serve as examples of soft law instruments. Soft law refers to regulations that aim to guide the behavior and conduct of States through recommendations and guidelines, without enforceable sanctions for non-compliance [7]. These soft law instruments complement hard law, which refers to legally binding rules originating from formal multilateral agreements such as the Outer Space Treaty, as well as principles derived from customary international law [8]. Soft law instruments may provide additional definitions and clarifications to promote more consistent practices among States. The COPUOS LTS Working Group was established by the UN COPUOS with the goal of producing a set of best practices for long-term space sustainability. The LTS Guidelines, adopted by COPUOS in 2019, provide a global consensus on responsible and sustainable space activities [9]. In parallel, the Artemis Accords invite nations to cooperate in the peaceful exploration and utilization of outer space, emphasizing transparency, interoperability, and the utilization of space resources [10]. In Section 12 of the Artemis Accords, signatories commit to actively plan for the mitigation of orbital debris through responsible end-of-mission practices and measures to minimize the creation of new, long-lived debris during space operations. As of June 2024, there are 42 signatories including several emerging space nations. The implementation and interpretation of the Artemis Accords will be further clarified by signatories through dialog. Additionally, the "Net Zero Space" coalition brings together space actors committed to achieving net-zero space debris creation by 2030 [11]. These initiatives collectively aim to foster international cooperation, establish norms, and guide emerging and established space nations alike in promoting the sustainable and responsible use of outer space.

This study seeks to examine the political and legal challenges faced by emerging space nations in implementing space debris mitigation measures while showcasing their commitment to space sustainability; the findings build on a previous analysis of legal and technical approaches being pursued by emerging space nations to build capability in the area of space sustainability published by the authors [6]. By analyzing the SSR score for missions launched by emerging space nations, the study aims to identify potential obstacles and opportunities in the adoption of the SSR framework and other pathways for responsible behavior in space, such as orbit selection, designing for detectability, designing for collision avoidance, and committing to data sharing transparency for telemetry and mission status. Ultimately, the study dispels the perception sometimes expressed in multilateral fora such as COPUOS that adhering to sustainability guidelines hinders the progress of emerging space nations, and instead highlights steps for increased sustainability and responsible space practices within diverse space market sizes and geographic locations. This study's findings demonstrate that emerging space nations are already engaging in space missions that adhere to globally recognized best practices for space sustainability, do so without significant disadvantages compared to established space nations, and can actively enhance their sustainability practices through feasible and incremental improvements. These findings challenge concerns expressed by COPUOS delegations that emerging space nations are not equipped to significantly contribute to international discussions and the development of governance pertaining to space sustainability.

2. Activities of emerging space nations

Addressing space sustainability means reducing the risk of forming new space debris and responding to the existence of current space debris. Across every continent, new nations are investing in forming both institutional and technological capability to enhance their participation in space. The authors have previously studied examples of the formation of new national space programs in Africa, Latin America, the Middle East, and Southeast Asia via interviews, site visits, conference participation, and literature review [12–16]. Individual nations such as Angola, Rwanda, Kenya, Ghana, Mongolia, the Philippines, and Bhutan have recently formalized national space policy infrastructure or national satellite activity. There are also nations that have multiple decades of experience such as Malaysia, Thailand, Singapore, Vietnam, Indonesia, Chile, Argentina, Brazil, South Africa, Egypt, Nigeria, the United Arab Emirates and Algeria. These countries have each operated national satellites, hosted national space agencies and formulated national space regulations and policies. At the regional level, there are efforts by organizations to bring together national space activities for collaboration and knowledge exchange. The African Union has now formed the Africa Space Agency with a supportive Space Strategy and Space Policy [17]. There are efforts toward regional integration of space activity in Latin America. The Asia Pacific Regional Space Agency Forum [18] and Asia Pacific Space Cooperation Organization [19] each foster venues for regular consultation between space agencies in their geographic regions. Even though many countries around the world are increasing their national investment in space, it is still the case that a few nations or regions, especially the United States, China, Russia, India and member nations of the European Union and European Space Agency, still dominate the number of satellites launched each year [20]. A similar set of nations have also played a key role to produce much of the existing space debris that is already orbiting Earth [21]. It is possible to draw a comparison between greenhouse gas emissions in the atmosphere and space debris. A few nations are the key producers of the pollution, yet many nations need to respond to the burden of reducing future harms due to the pollution [22]. While a full legal analysis is outside the scope of this paper, author Wood has written extensively in other publications about the topic of space activity in emerging space nations, including lessons from development literature, technical motivations and strategies, international partnerships, approaches and contextual factors, strategic decision making, and issues faced in developing countries [12–16,23]. The previous paper in the present study provides further background on practical examples of legal approaches at the regional and national level to address space sustainability in emerging space nations [6].

This paper draws from a definition of emerging nations based on previous work by author Wood. In the paper by Wood and Weigel, the Space Participation Metric (SPM) is defined based on technical achievements of a national space program. Level 3 countries have Medium Space Participation because they have operations of in-space infrastructure such as satellites. Level 4 and 5 countries have programs for independent launch capability and human space flight operations as members of a space station [23]. For countries at Level 3, including those listed earlier in this section, this paper uses the term “emerging space nation” and explores what can be learned from examples of their responses to the reality that space debris and limited infrastructure for Space Traffic Management creates a threat for global space operations.

One aspect of the response of emerging space nations is that they act at the national and international level to contribute to the global effort to work toward long-term space sustainability. For this paper, such efforts include coordination to address operations beyond Earth orbit and efforts to address harmful impacts of space operations, such as the role of satellite constellations to impact dark skies and astronomical observation.

The UN COPUOS is one venue in which emerging space nations already participate actively in responding to questions around Space Sustainability, broadly defined. Examples from the 2023 meeting of the COPUOS illustrate approaches taken by emerging space nations to influence progress towards sustainability in space. One document shared in the 2023 COPUOS session was a report from the Asia-Pacific Regional Space Agency Forum National Space Legislation Initiative highlighting efforts by member nations to work on establishing or improving national space legislation, which is one approach to working toward sustainability. The following emerging nations participated, as defined by SPM Level 3: Australia, Indonesia, Malaysia, New Zealand, Philippines, Singapore, Thailand, Türkiye, and Viet Nam. In another example, Algeria, Australia, Brazil, Cuba, Ecuador, Slovak Republic, and Türkiye each contributed to a working group to help form the agenda for a conference on legal aspect of space resource utilization [24]. A report from the Legal Subcommittee of COPUOS notes that many member states reported on their efforts to adopt standards related to space debris mitigation. This includes SPM Level 3 nations such as Algeria, Argentina, Australia, Azerbaijan, Chile, Czechia, Indonesia, Laos, Mexico, Myanmar, Nigeria, Thailand, and Ukraine [25]. Emerging nations also seek ways to participate in non-United Nations multilateral fora to discuss topics related to space sustainability. In 2022, Nigeria and Rwanda became the first African countries to sign the Artemis Accords. Representatives of emerging space nations were some of the early signatories of the Washington Compact on Norms of Behavior for Commercial Space Operations led by the Hague Institute for Global Justice [26]. In another example, the country of Bermuda hosted a workshop on Space Sustainability along with the Secure World Foundation; co-author Wood was a speaker at this event and advised the government of Bermuda on their national space strategy. Each of these examples demonstrates the interest and investment by emerging space nations to help the world move in the direction of coordination and improvement of space sustainability challenges.

3. Emerging and established space nation mission descriptions

The following sections present examples of emerging space nation missions and similar missions from established space nations and perform an assessment using the Space Sustainability Rating as an illustration of the experience of the operators in adopting sustainable practices. In this section, we consider a country as an emerging space nation if they achieve a medium score (3 out of 5) on the SPM, characterized by engaging in satellites operations and owning ground stations but lacking national space launch capabilities. Participation in the International Space Station qualifies a nation as high on the SPM [23]. As seen in previous work by coauthor Wood, most emerging nations conduct their initial satellite development by working in partnership with experienced space actors such as governments or firms from foreign countries [27].

The emerging and established space nations chosen for this study represent geographic diversity as well as diverse market sizes and levels of development. Three missions from emerging space nations are compared with five missions from established space nations, covering a range of maturity including experimental endeavors, university cubesats, small constellations, and national space agency satellites. The research question driving these comparisons is whether sustainable design, operations, and implementation of long-term sustainability guidelines are barriers for emerging space nations. The results of this study show that missions from emerging nations are not disadvantaged, thereby casting doubt on the supposition that emerging space nations are not capable of playing a significant role in the international space sustainability regulatory and technical conversations. That perception is evidenced by underrepresentation and limited engagement of emerging space nations in the venues driving international consensus on space sustainability, such as the Inter-Agency Debris Coordination Committee and in major technical conferences such as AMOS and space debris conferences hosted by the International Academy of Astronautics and the European Space Agency. Mission details provided in this section are taken from publicly available sources. Some information about the missions is augmented by coauthor Wood's field work, site visits, and interviews as part of long term academic research on emerging space nation policy [13,16,27]. Unless otherwise stated, the Space Sustainability Ratings for these missions, given in subsequent sections, are calculated based on rubrics presented by Rathnasabapathy et al. and Saada et al. at the 72nd and 73rd International Astronautical Congress [2,3].

3.1. Emerging space nation missions

NigeriaSat-2 (Nigeria): Launched in 2011, NigeriaSat-2 is an Earth observation satellite within the African Resource Management constellation, providing real-time, low-cost satellite imagery to African countries. NigeriaSat-2 was developed by a collaboration between the Nigerian National Space Research and Development Agency and the firm Surrey Satellite Technology Ltd (SSTL) from the United Kingdom and was launched alongside multiple other payloads on a Russian Dnepr rocket. NigeriaSat-2's purpose was to capture high-resolution imagery for applications in mapping, agriculture, disaster management, urban planning, environmental monitoring, and security surveillance [28,29]. Table 1 gives the mission details and characteristics for NigeriaSat-2.

THEOS (Thailand): The Thailand Earth Observation System (THEOS) is an Earth observation mission launched in 2008 and developed by a collaboration between the Thai Geospatial Information and Space Technology Development Agency and the European Aeronautic Defence and Space Company (EADS) Astrium firm located in France with the goal of providing Thailand affordable access to space and fostering personnel capability growth and infrastructure development within the country. THEOS utilizes optical technology for applications in land use, agriculture, forestry, coastal monitoring, and risk management for natural disasters. It reduces reliance on foreign satellite imagery purchases and represents Thailand's first national-level remote sensing satellite project [30–32]. Table 2 gives the mission details and characteristics for THEOS.

RazakSat (Malaysia): RazakSat, also known as the Medium-sized Aperture Camera Satellite (MACSAT), was a novel Earth observation mission launched in 2009 focusing on validating experimental technologies for near-equatorial low-earth orbit (NeqO). RazakSat was built by Astronautic Technology Sdn Bhd (ATSB) in collaboration with the Satrec Initiative from South Korea. The mission's primary objectives were to demonstrate indigenous spacecraft design and provide high-resolution imagery from NeqO to developing countries. RazakSat was the first and only operational payload successfully delivered to orbit by the SpaceX Falcon 1, the first fully liquid-fueled commercially developed launch vehicle. Due to the unique NeqO orbital characteristics, RazakSat passed through the South Atlantic Anomaly several times per day, exposing it to higher levels of radiation. Ultimately the satellite was determined unusable after one year in orbit due to pointing inaccuracies, but significantly contributed to Malaysia's growing expertise in satellite technology development and operations [33,34]. Table 3 gives the mission details and characteristics for RazakSat.

3.2. Established space nation missions

GRACE (United States and Germany): The Gravity Recovery and Climate Experiment (GRACE) satellite mission was jointly conducted by the US and Germany and launched from a Russian spaceport in 2002. GRACE was operated via a collaboration between NASA and the German Aerospace Center (DLR). The mission was designed to precisely measure Earth's gravitational field variations by tracking changes in the distance between identical satellites flying in tandem. This innovative international endeavor provided ground-breaking insights into the distribution and flow of Earth's mass, ocean dynamic topography, ice sheet thinning, and other climate influencing phenomena. GRACE was planned as a five-year mission but continued in extended operations for a total lifetime of 15 years and was replaced by the GRACE Follow-on (GRACE-FO) in 2018 [35–37]. Table 4 gives the mission details and characteristics for GRACE.

Pleiades-1A/1B and Pleiades-Neo (France): The original Pleiades mission launched in 2011 by the French national space agency (CNES) included two satellites (1A and 1B) phased at 180 degrees for daily revisit rates around the globe. Primarily, the imagery collected by Pleiades is used for ice sheet and land surface topog-

Table 1
NigeriaSat-2 mission details and characteristics [28,29].

NigeriaSat-2	
Operator	National Space Research and Development Agency of Nigeria
Status	Mission completed
Date	2011-2021
Launch Vehicle	Dnepr rideshare from Dombarovsky, Russia
Mass	270-300 kg
Volume	1.0-2.0 m^3
Orbital Information	Sun-synchronous low-earth orbit, inclination 98°, 690-730 km altitude
Instruments	High and medium resolution optical imagers, imaging multi-spectral radiometers
Purpose	Earth Observation (imagery)

Table 2
THEOS mission details and characteristics [30–32].

THEOS	
Operator	Geo-Informatics and Space Technology Development Agency of Bangkok, Thailand
Status	Extended Operations
Date	2008-present
Launch Vehicle	Dnepr rocket from Dombarovsky, Russia
Mass	715-750 kg
Volume	8.0-12.0 m^3
Orbital Information	Sun-synchronous low-earth orbit, inclination 98.7°, 820-830 km altitude
Instruments	High resolution optical imagers
Purpose	Earth Observation (imagery)

Table 3
RazakSat mission details and characteristics [33,34].

RazakSat	
Operator	Astronautic Technology Sdn Bhd
Status	Mission unsuccessful
Date	2009-2010
Launch Vehicle	Falcon 1 from Kwajalein Atoll
Mass	180-200 kg
Volume	1.5-2.0 m^3
Orbital Information	Near-equatorial low-earth orbit, inclination 9°, 660-700 km altitude
Instruments	Imaging multi-spectral radiometers
Purpose	Earth Observation (imagery)

Table 4
GRACE mission details and characteristics [35–37].

GRACE	
Operator	NASA and German Aerospace Center
Status	Mission complete
Date	2002-2017
Launch Vehicle	Rokot from Plesetsk Cosmodrome
Mass	430-480 kg (each of 2 satellites)
Volume	4.0-5.0 m^3
Orbital Information	Circular polar co-planar orbit (in tandem formation), incl. 89°, 480-510 km altitude
Instruments	GPS receiver, microwave ranging
Purpose	Earth Observation (gravity variations)

Table 5
Pleiades-1A/1B mission details [38].

Pleiades-1A/1B	
Operator	French national space agency
Status	Extended Operations
Date	2011-present
Launch Vehicle	Soyuz ST-A, Guiana Space Center
Mass	940-970 kg (each of 2 satellites)
Volume	6.0-12.0 m^3
Orbital Information	Sun-synchronous low-earth orbit (180° phased), incl. 98.2°, 670-700 km altitude
Instruments	High resolution optical imagers
Purpose	Earth Observation (imagery)

Table 6
Pleiades-Neo mission details [40].

Pleiades-Neo	
Operator	Airbus
Status	Partially Operation
Date	2021-present
Launch Vehicle	Vega and Vega-C (failed launch) from the Guiana Space Center
Mass	900-920 kg (each of 4 satellites, 2 operational and 2 failed to reach orbit)
Volume	6.0-12.0 m^3
Orbital Information	Sun-synchronous low-earth orbit (90° phased), incl. 97.9°, 610-630 km altitude
Instruments	High resolution optical imagers
Purpose	Earth Observation (imagery)

raphy. The mission was designed for a five-year lifetime but is currently functioning in extended operations. As a follow-on mission to the first two Pleiades satellites, Airbus Defense and Space designed and launched four more Earth observation satellites for the Pleiades-Neo mission. The Pleiades-Neo launches utilized ESA's Small Spacecraft Mission Service (SSMS), a rideshare capability for multiple small payload deployment. Pleiades-Neo launched on Vega rockets with upper stages designed to ensure direct re-entry into Earth's atmosphere for disposal. Two Pleiades-Neo satellites launched successfully to orbit in 2021 and are operating nominally; however, the launch containing the final two satellites failed to reach orbit [38,39]. Tables 5 and 6 give the mission details for Pleiades-1A/1B and Pleiades-Neo, respectively.

MicroMAS-1 (United States): The Massachusetts Institute of Technology (MIT) designed the 3U cubesat Microwave Atmospheric Satellite (MicroMAS-1) to observe the dynamics of hurricanes from a very low-Earth orbit altitude with improved revisit rates over comparable polar orbits. The MicroMAS-1 mission is notable for its transformative architecture utilizing low-cost commercial components for operational meteorological predictive capability. MicroMAS-1 was launched to the International Space Station (ISS) on-board a re-supply mission in 2014 and deployed from the Japanese airlock eight months later. Due to the low altitude of the spacecraft and lack of orbit raising propulsive mechanisms, the satellite deorbited four months after deployment [41–43]. Table 7 gives the mission details and characteristics for MicroMAS-1.

CHESS (Switzerland): École Polytechnique Fédérale de Lausanne's (EPFL) Constellation of High-Energy Swiss Satellites (CHESS) is a student-led planned mission for a constellation of two cubesats carrying instruments from the Universities of Bern and

Table 7
MIT MicroMAS-1 mission details [41–43].

MicroMAS-1	
Operator	Massachusetts Institute of Technology (MIT)
Status	Mission Complete
Date	2014-2015
Launch Vehicle	Antares-120 from the Mid-Atlantic Regional Spaceport
Mass	4.4 kg
Volume	3U
Orbital Information	Very low-earth orbit, inclination 51.64°, 390-410 km altitude
Instruments	Multispectral passive microwave radiometer
Purpose	Earth Observation (radiometry)

Table 8
CHESS mission details [44,45].

CHESS	
Operator	École Polytechnique Fédérale de Lausanne Spacecraft Team
Status	Pre-design
Date	TBD
Launch Vehicle	TBD
Mass	3.5 kg
Volume	3U
Orbital Information	Low-earth orbit, incl. 97.59°, 550 km circular and 400-1000 km elliptical altitudes
Instruments	Mass spectrometer
Purpose	Earth Observation (atmospheric measurements)

Zurich with the intent to study Earth's exosphere and ionosphere. The satellites will be placed into one circular and one elliptical orbit to capture data from complementary viewpoints. Data collected on this mission will be used to improve Earth atmosphere models, test hypotheses about earthquake early warning signs, and investigate solutions for environmental challenges due to human-induced climate change [44,45]. CHESS represents the only formal beta-test SSR score included in this study, as opposed to the previous missions which represent estimated SSR scores. Table 8 gives the mission details and characteristics for CHESS.

4. Background on the Space Sustainability Rating

The Space Sustainability Rating (SSR) is a project initiated by the World Economic Forum's Global Future Council on Space with the aim of establishing a system that incentivizes and evaluates the long-term sustainability of space missions. The SSR quantifies the extent at which a mission contributes to debris mitigation and avoiding collisions, thus promoting safe and responsible behaviors of space operations. As the number of operational satellites in Low Earth Orbit (LEO) increases, and considering the advent of very large satellite constellations, the SSR could play a crucial role in shaping behavioral norms among satellite operators across all orbital regimes including cislunar and beyond. A consortium consisting of the Massachusetts Institute of Technology (MIT), the European Space Agency (ESA), the University of Texas at Austin, and BryceTech collaborated to develop the SSR processes and methodologies. Currently, the operational phase of the SSR is led by a Swiss non-profit association called the Space Sustainability Rating.

The SSR provides a comprehensive framework for assessing space missions with each of the SSR's six modules addressing a different aspect of mission sustainability. The six modules of the SSR are the Mission Index which calculates the Space Traffic Footprint; Collision Avoidance (COLA) Capabilities; Data Sharing; Detectability, Identifiability, and Trackability (DIT); Application of Design and Operation Standards; and External Services [3,6]. This study utilizes rating outcomes from beta-tests conducted prior to the official SSR launch. Consequently, some adjustments may have been made to the computation of ratings and arbitration of various SSR criteria between different rating instances. It is important to highlight that the overall score trends remain unaffected, as only minor adjustments were implemented during this beta testing phase.

4.1. SSR tier categories and module weights

The SSR employs a tiered scoring system to assign ratings, wherein each of the six module scores are given specific weights and aggregated to determine a final tier rating of Bronze (40-55%), Silver (56-70%), Gold (71-80%), or Platinum (>80%) as defined below. The descriptions in this section and the rubrics used in the SSR Score Optimization section are based on papers published at the 2021 and 2022 International Astronautical Congress [2,3].

Bronze: The mission meets the pre-requisite requirements to apply for an SSR. The SSR applicant demonstrates willingness to increase mission's sustainability. Current sustainable practices need to be incorporated into the mission.

Silver: The mission incorporates current sustainability practices with areas to improve upon. The SSR applicant demonstrates consideration for the orbital environment in design and operation of mission.

Gold: The SSR applicant demonstrates currently accepted best practices for sustainability in all aspects of the mission. The mission has minimal impacts on the orbital environment beyond the necessary use.

Platinum: The mission incorporates innovative methods for improving the orbital environment that go beyond common best practices. The SSR applicant demonstrates sustainable practices that enhance sustainability outcomes across all aspects of the mission.

The Space Sustainability Rating awards bonus stars for certain mission characteristics that are considered "above and beyond" and are not otherwise included in the baseline scoring. Bonus stars are awarded for behaviors such as maintaining orbital state knowledge after the end of normal operations, inclusion of external interfaces for close-proximity servicing operations, and additional forms of data sharing such as radio-frequency information, spacecraft anomaly information, and datasets to support academic and governmental research. One star (25%-50%), two stars (51%-75%), or three stars (>75%) can be awarded. The six modules are weighted by scaling factors before summing for the final score as shown in Table 9 [46].

Table 9
SSR modules, purposes, weights, and types.

Module	Purpose	Weight	Type
Mission Index	Physical interference risks based on planned design and mission operation characteristics	0.5	Quantitative
COLA Capabilities	Reduction to accidental collision risk through operator actions	0.165	Qualitative
Data Sharing	Information sharing by operators and its impact on spaceflight safety	0.165	Qualitative
DIT	Attributes influencing level of difficulty for observers to detect, identify, and track the spacecraft	0.12	Quantitative
Standards	Adoption of international standards and guidelines	0.05	Qualitative
External Services	Commitment to use of in-space servicing	0.0 (Bonus only)	Qualitative

5. Opportunities for emerging nations through the Space Sustainability Rating

The Space Sustainability Rating offers several opportunities for emerging space nations to benefit as part of ongoing work efforts to promote sustainability in their national space activity. In addition, the SSR can serve as a platform for emerging space nations to promote global efforts for space sustainability.

At the national scale, the SSR can support the process by which emerging space nations set up or improve their national space regulations. The majority of nations that have satellites operating in space have signed the Outer Space Treaty and the related international treaties that serve as the foundation for space law. These treaties provide a responsibility of a nation state to authorize and provide continuing supervision to satellites operated under their authority, both public and private. The authorization is typically done via a licensing process. In addition, nations must regulate the use of scarce radio frequency resources by following guidelines by the International Telecommunication Union and the national radio frequency management entity. The Space Sustainability Rating can be one tool that supports emerging space nations as they define what process to use for licensing and authorizing space missions. The technical information that composes the SSR modules provides examples of technical behaviors that space missions can take to reduce space debris creation and collision risk. An emerging space nation can foster sustainability either by requiring a certain SSR rating to give a license or by recommending specific actions by operators based on the SSR.

Regarding the international venue, the SSR invites any entity, including governments, to join as members. This requires a cost, but it is adjusted based on the scale of the member. Member organizations have the opportunity to participate in working groups hosted by the SSR non-profit. Through the working groups, the SSR community of members can compile or develop additional recommendations for national governments about how to foster space sustainability. One potential concern about national licensing of space missions is that a space operator may choose to pursue a license in a country with a lower technical requirement for authorization. The SSR provides an opportunity for multiple countries to adopt a common definition of sustainable behavior and agree to not license missions that do not meet the criteria.

6. SSR score comparisons and optimization

In the following sections, names and certain mission details have been obfuscated to preserve operator confidentiality. Operators are entitled to anonymity in this study since they were not asked to give permission for their SSR scores to be publicly released, and the scores calculated are not all official SSR ratings. The anonymized SSR scores for each of the missions discussed previously are shown in Fig. 1, in a random order. All scores are within the Bronze tier with the exception of two established space nation mission that scored Silver. This outcome is in line with expectations for the early years of the SSR, where achieving Gold and Platinum level ratings is challenging, especially considering that most of these missions were designed and implemented before the advent of the SSR and UN COPUOS LTS Guidelines. In particular, the documentation for space sustainability objectives were not available or published at the time these missions were designed and implemented. The fact that all studied missions attained at least a Bronze rating is significant and indicates a commendable level of compliance with current sustainability baselines. It should be noted that a Bronze rating, although considered low, does not constitute a failing grade, implying that these missions have met a significant portion of the SSR's criteria. Moreover, within the Bronze score category, there is no distinction between a “low Bronze” or a “high Bronze” rating, suggesting that missions achieving Bronze are relatively consistent in their sustainability performance, including both established and emerging space nations.

In the next section, we show options for small steps that the studied emerging space nation missions could take to improve their overall impact on space sustainability, by focusing specifically on two of the anonymized emerging space nation missions and two distinct paths for SSR score optimization methods. It is important to note that the single largest contributing factor to SSR scores is the Mission Index, which has the highest weighting at 0.5, and is an indication of the mission's overall impact on the space environment. In the optimization studies, the Mission Index is not changed from the original score. This was done in order to specifically demonstrate pathways for emerging nations to take post-launch that will significantly positively impact the sustainability of their operational behavior, and in turn be reflected in their SSR score. For pre-launch missions that are still in the design phase, the Mission Index can be changed through enhanced sustainability by choosing a less crowded orbit, including maneuver capability, and planning for de-orbit. Traditionally, smallsat missions have faced Mission Index limitations due to lacking propulsive capacity or choosing to launch on rideshare missions. However, the market for alternative smallsat propulsion such as wax, water, and iodine is gradually improving over time [47].

6.1. Verification optimization method

In addition to each module being weighted in the score calculation, the SSR also incorporates weighting based on a verification process allowing satellite mission owners to validate their response quality. Verification options include providing technical documents, official filings to regulatory bodies, documents from a third party, or evidence of an independent expert's review. A verification weighting is assigned to operator inputs, reflecting the SSR issuer's confidence in their adherence to SSR requirements and incentivizing the submission of well-verified data. The verification levels and weights are given in the Table 10 [3].

In the first optimization demonstration, only the data verification level of the SSR for the two emerging space nation missions selected for optimization is changed. For the original calculated SSR scores using online available data, the verification level assumed was “Assertion.” Increasing each verification level in the COLA, Data Sharing, and Standards modules to “Authority” results

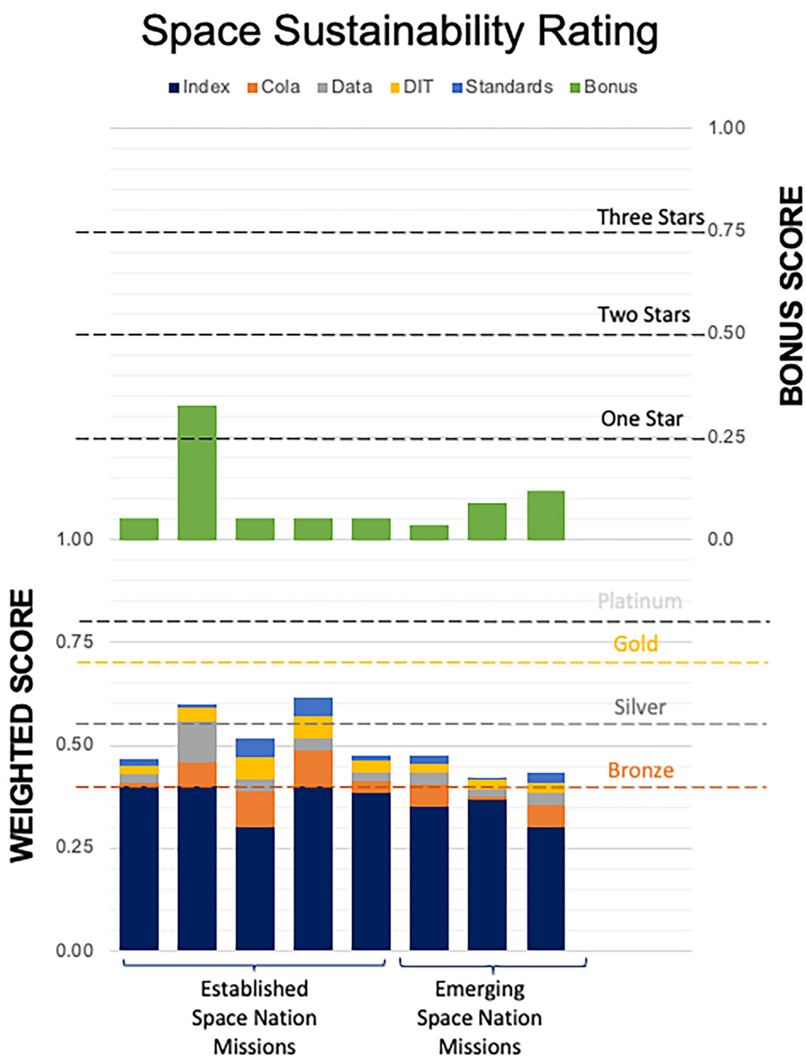

Fig. 1. SSR score comparisons prior to optimization.

Table 10
SSR verification levels and weights.

Verification level	Weight
Assertion	0.5
Technical documentation supporting assertion	0.6
Public release of technical documentation	0.8
Authority – Independent technical review	1.0

in notable score improvements for both emerging space nation missions selected for optimization, as shown in Fig. 2.

6.2. Verification plus collision avoidance and data sharing optimization method

While changes to the verification method are significant, the most noticeable score optimizations come from the combination of both behavioral changes and verification method improvements. In this second optimization method, several categories in the COLA and Data Sharing modules are improved, while maintaining the "Authority" level of verification from the previous section. Table 11 summarizes the COLA and Data Sharing changes that were made in one or both emerging space nation mission scores. Fig. 3 shows a side-by-side comparison of the scores before and after this method of optimization. Through optimization, the emerging space nation mission that started with the highest Mission Index score (which is unchanged through optimization) was able to reach the score needed to achieve a Silver rating, indicating significant improvements towards enhanced sustainability.

6.3. SSR score comparisons after optimization

Fig. 4 shows a side-by-side comparison of the Space Sustainability Ratings for each of five established space nation missions, three emerging space nation missions, and two optimized scores for each of two emerging space nation missions. The highest scoring missions in the bonus score category are two missions from emerging space nations, one established space nation mission, and the optimized mission scores. However, only one of the missions studied scored enough bonus points to earn a bonus star, even after optimization. This is because the SSR's bonus category is designed to acknowledge missions that go "above and beyond" current baseline sustainability priorities, and capture mission characteristics in preparation for the future eventuality of external servicing. There is no single module where the established space nation missions consistently out-perform the emerging space nation missions or vis versa. The findings of this research indicate that missions con-

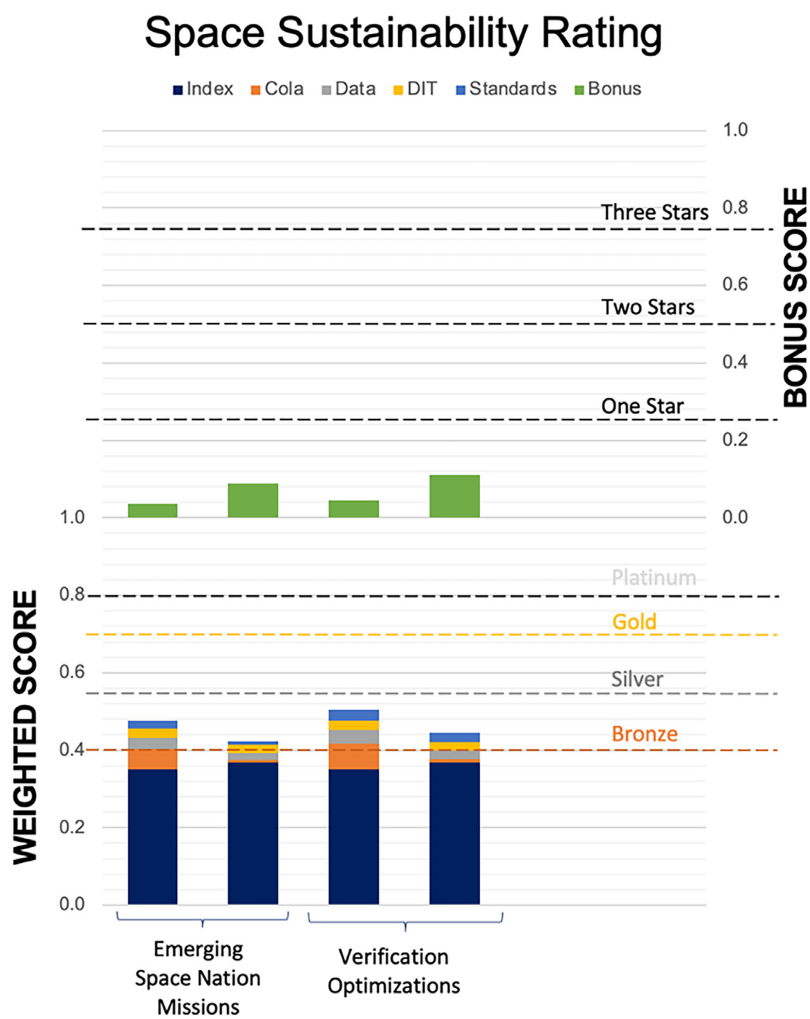

Fig. 2. SSR score comparisons for emerging space nation missions using verification optimization method.

Table 11
Optimization changes for emerging space nation missions.

Collision Avoidance: Availability to Coordinate	
Before Optimization	After Optimization
Low Able to coordinate in response to emergencies (but not necessarily on a routine basis)	Medium Able to coordinate during set hours per day
Bonus: COLA Capability During Disposal	
Before Optimization	After Optimization
None No capability during disposal	Low Maintain orbital state knowledge until spacecraft is placed into a graveyard orbit or is disposed of through atmospheric re-entry.
Collision Avoidance: Maneuver Capability	
Before Optimization	After Optimization
None Not able to maneuver or affect the spacecraft trajectory	High Able to deliver a Δv of 1 cm/s within one orbital revolution
Data Sharing: Contact Time	
Before Optimization	After Optimization
None No capability	By Request Publish and update collision avoidance contact time zone per hours of operation
Data Sharing: COLA Response Time	
Before Optimization	After Optimization
None No capability	By Request Publish and update COLA contact and coordination response time commitments

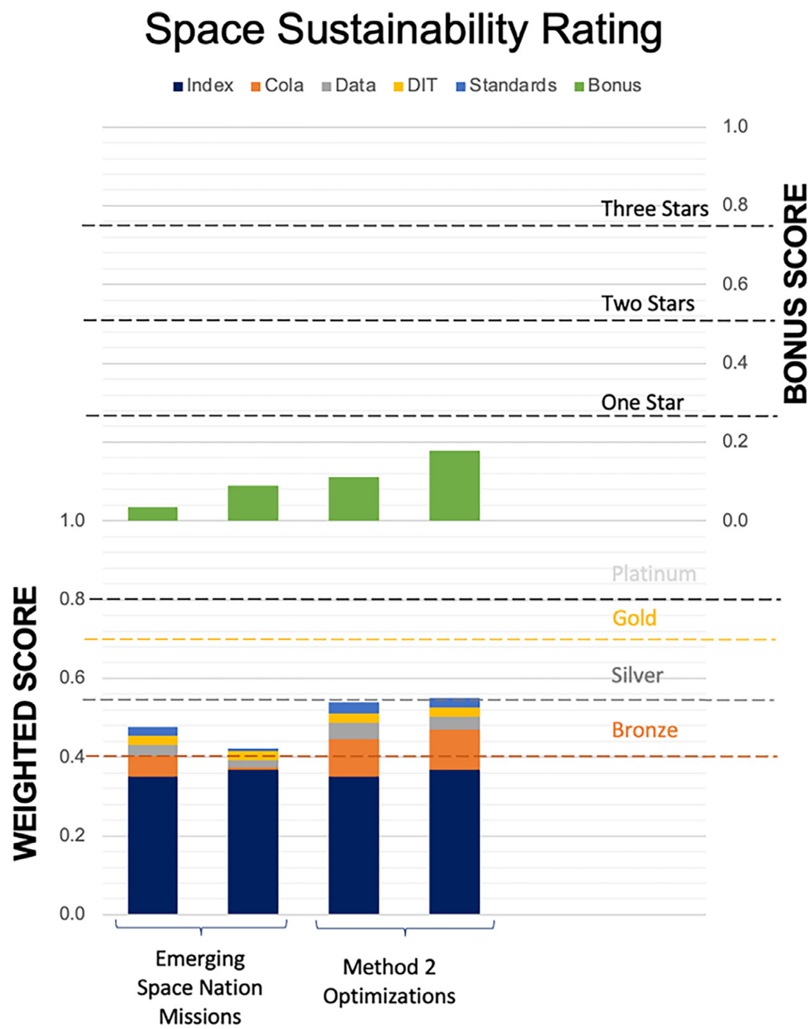

Fig. 3. SSR score comparisons for emerging space nation missions using second optimization method.

ducted by emerging space nations do not face any disadvantages on the adherence to space sustainability best practices and have several options for small steps to take to be on-par or above established space nation sustainability practices. This dispels the notion that these nations lack the capability to actively participate in important discussions regarding space sustainability regulations and technical matters.

7. Opportunities for emerging space nations through the SSR

The SSR offers several opportunities for emerging space nations to enhance their legal frameworks and regulatory practices in support of long-term space sustainability. Rathnasabapathy [6] details recent implementation of long-term sustainability design and operational guidelines in the national space strategies of several emerging space nations, and the importance given by these nations in the development of national and regional legal mechanisms to regulate the peaceful use of the space environment. By leveraging the SSR, emerging space nations can establish a clear and structured approach to space debris mitigation and sustainable space operations. This enables them to strengthen national and regional legal and regulatory frameworks, align with international norms, and actively contribute to the global effort to ensure the long-term sustainability of outer space.

Incorporation of SSR criteria into national licensing processes: Emerging space nations can integrate SSR criteria into their national space licensing and regulatory frameworks. By embedding SSR principles into their legal regimes, emerging space nations can position themselves as proactive participants in international space governance.

Adoption of international standards: By aligning national regulations with international standards and guidelines, such as those implemented in the International Standards modules of the SSR, emerging space nations can align their practices with international space sustainability standards and best practices.

Establishment of transparent reporting mechanisms: Implementing SSR recommendations can enhance transparency in sustainable space operations. Emerging space nations could establish legal requirements for operators to share data, operational plans, and end-of-life disposal strategies.

Promotion of innovative sustainability practices: Legal frameworks can be adapted to incentivize the adoption of innovative technologies and practices that improve space sustainability. For example, regulations could provide benefits or reduced fees for operators who demonstrate advanced debris mitigation techniques or commit to active deorbiting measures.

Capacity building and education: Legal reforms can also focus on building capacity and educating stakeholders about the importance of space sustainability. By promoting awareness and understanding of SSR principles among policymakers, industry players, and the public, emerging space nations can foster a culture of responsibility and sustainability in their space sectors.

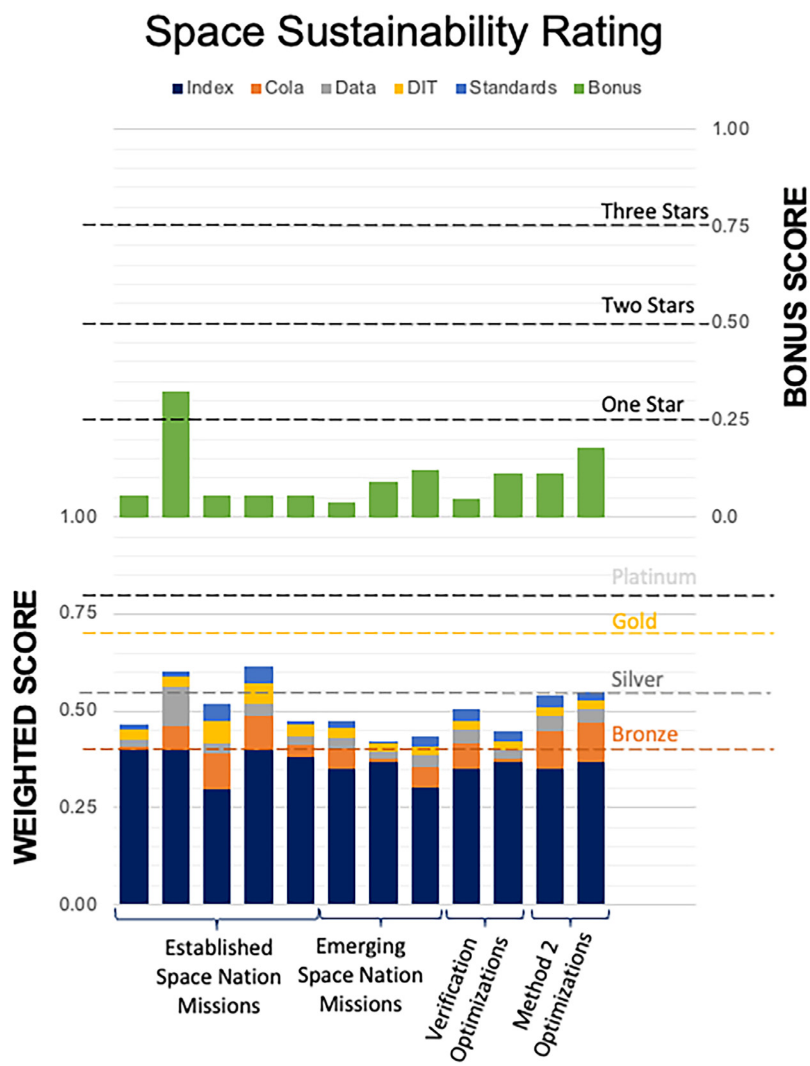

Fig. 4. SSR score comparisons after optimization.

8. Conclusion

This study has highlighted the importance of collective action from all nations to ensure the long-term sustainability of space activities. The study has shown that missions conducted by emerging space nations do not face disadvantages on the adherence to space sustainability best practices and have several options for small steps to take to be commensurate with established space nation sustainability practices. This dispels the notion that these nations lack the capability to actively participate in important discussions regarding space sustainability regulations and technical matters. One limitation of this study is that only a small selection of example missions was studied; however, related work has explored the activities of emerging space nations in more detail for other purposes [12–16,23]. Future work would benefit from an analytical exploration of a larger compilation of missions from emerging space nations, their SSR scores, their involvement with foreign partners, and covering a longer time period of study.

Within the design phase, satellite operators can significantly enhance space safety and sustainability through orbit selection and mission design, designing for detectability, and designing for collision avoidance. Opting for orbits strategically, such as those below the International Space Station, minimizes congestion and maximizes the probability of successful post-mission disposal. Deliberate material selection that balances trackability with preserving dark skies, coupled with considerations for spacecraft orientation visible to observers on Earth, enhances sustainability at a higher cost. Another design approach is the incorporation of active and passive systems, such as beacons and reflectors, to further augment trackability. Inclusion of on-orbit propulsion with emergency avoidance capability and for post-mission disposal also increases safety and sustainability.

In the operational phase, a commitment to space safety and sustainability demands a commitment to transparency and collaboration. Satellite operators can contribute to a safer space environment by openly sharing telemetry data, providing real-time information on mission location and status. Publicizing plans for orbital maneuvers, post-mission disposal, and changes in mission status not only enhances awareness but also invites collaborative collision avoidance efforts. Effective collision avoidance hinges on open communication and active coordination. Publicly sharing contact information and coordinating promptly when alerted about potential collisions are integral steps for space sustainability. Operators can also consider active deorbiting at the end of the mission or on-orbit servicing for satellite life extension.

This paper elaborated on how the SSR framework can help emerging space nations develop clear and structured approaches to space debris mitigation and sustainable space operations. By integrating SSR principles, these nations can strengthen their national and regional legal and regulatory frameworks, align with international norms, and actively contribute to the global effort to ensure the long-term sustainability of outer space. Overall, this paper emphasizes the need for continued collaboration and cooperation among all nations to ensure the long-term sustainability and equitable access of space for all humankind including future generations.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Jacqueline H. Smith: Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Minoo Rathnasabapathy:** Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Danielle Wood:** Conceptualization, Data curation, Formal analysis, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing.

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References

[1] M. Rathnasabapathy, E. David, Space Sustainability Rating in Support of the Development and Adoption of Regulatory Guidelines Related to Long-Term Sustainability, Air Space Law 48 (2023) 155–178, doi:10.54648/AILA2023036.
[2] Minoo Rathnasabapathy, Danielle Wood, Francesca Letizia, Stijn Lemmens, Moriba Jah, Simon Potter, Nikolai Khlystov, Miles Lifson, and others, Implementing the Space Sustainability Rating: An Innovative Tool to Foster Long-term Sustainability in Orbit, 72nd Int. Astronaut. Congr. IAC, 2021.
[3] Adrien Saada, Emmanuelle David, Florian Micco, Jean-Paul Kneib, Mathieu Udriot, Danielle Wood, Minoo Rathnasabapathy, and others, The Space Sustainability Rating: An operational process incentivizing operators to implement sustainable design and operation practices, 73rd Int. Astronaut. Congr. IAC, 2022.
[4] J. Pelton, T. Sgobba, M. Trujillo, Space Safety, in: K.U. Schrogl (Ed.), Handb. Space Secur., Springer International Publishing, Cham, 2020, pp. 265–298, doi:10.1007/978-3-030-23210-8_50.
[5] A.R. Wilson, M. Vasile, The space sustainability paradox, J. Clean. Prod. 423 (2023) 138869, doi:10.1016/j.jclepro.2023.138869.
[6] M. Rathnasabapathy, M. Slavin, D. Wood, Role of Emerging Nations in Ensuring Long-term Space Sustainability, Acta Astronaut. (2024).
[7] P. Martinez, The Role of Soft Law in Promoting the Sustainability and Security of Space Activities, J. Space Law 522 (2020) 522–564.
[8] Jack M. Beard, Soft law's failure on the horizon: The international code of conduct for outer space activities, Univ. Pa. J. Int. Law 38 (2016) 335–424.
[9] United Nations General Assembly Official RecordsReport of the Committee on the Peaceful Uses of Outer Space Sixty-fourth session (25 August–3 September 2021), 2021 https://www.unoosa.org/res/oosadoc/data/documents/2021/a/a7620_0_html/A_76_20E.pdf.
[10] Artemis Accords, U. S. Dep. State (n.d.). https://www.state.gov/artemis-accords/ (accessed June 5, 2024).
[11] Jérôme Barbier, María Roa-Vicens, Fostering Better and More Interoperable Norms: Comparing Existing Binding National Requirements Relating to Space Debris, (2022). https://www.netzerospaceinitiative.org/activities/2022-working-group-1.
[12] D. Wood, A. Weigel, Charting the evolution of satellite programs in developing countries – The Space Technology Ladder, Space Policy. 28 (2012) 15–24, doi:10.1016/j.spacepol.2011.11.001.
[13] Danielle Wood, Annalisa Weigel, Architectures of small satellite programs in developing countries, Acta Astronaut. 97 (2014) 109–121, doi:10.1016/j.actaastro.2013.12.015.
[14] D. Wood, A. Weigel, Building technological capability within satellite programs in developing countries, Acta Astronaut. 69 (2011) 1110–1122, doi:10.1016/j.actaastro.2011.06.008.
[15] D.R. Wood, Analysis of Technology Transfer within Satellite Programs in Developing Countries using Systems Architecture, AIAA SPACE 2013 Conf. Expo, American Institute of Aeronautics and Astronautics, San Diego, CA, 2013, doi:10.2514/6.2013-5402.
[16] D. Wood, A. Weigel, Technological learning through international collaboration: Lessons from the field, Acta Astronaut. 83 (2013) 260–272, doi:10.1016/j.actaastro.2012.09.014.
[17] African Union Commission (AUC) Department of Human Resources, Science and Technology (HRST), African Space Policy: Towards Social, Political, and Economic Integration, (n.d.).
[18] APRSAF | Asia-Pacific Regional Space Agency Forum, (n.d.). https://www.aprsaf.org/ (accessed June 27, 2024).
[19] APSCO, (n.d.). http://www.apsco.int/ (accessed June 27, 2024).
[20] BryceTech - Reports, (n.d.). https://brycetech.com/reports (accessed June 27, 2024).
[21] ESA Space Debris Office, ESA's Annual Space Environment Report, (2023).
[22] J.G.J. Olivier, J.A.H.W. Peters, Trends in global CO2 and total greenhouse gas emissions: 2020 Report, PBL Neth. Environ. Assess. Agency, 2020.
[23] D. Wood, A. Weigel, A framework for evaluating national space activity, Acta Astronaut. 73 (2012) 221–236, doi:10.1016/j.actaastro.2011.11.013.
[24] United Nations Committee on the Peaceful Uses of Outer SpaceInput to the Working Group on Legal Aspects of Space Resource Activities on Scope and Topics to be addressed at the International Conference to be held in 2024, 2023.
[25] United Nations Committee on the Peaceful Uses of Outer Space, Compendium of space debris mitigation standards adopted by States and international organizations, (2023).
[26] Marcia Smith, Compact on Norms of Behavior for Commercial Space Operations Unveiled by Hague Institute, (2023). https://spacepolicyonline.com/news/compact-on-norms-of-behavior-for-commercial-space-operations-unveiled-by-hague-institute/ (accessed June 5, 2024).
[27] Danielle Wood, Building Technological Capability within Satellite Programs in Developing Countries, Massachusetts Institute of Technology, 2012.
[28] I. Ikpaya, S. Onuh, C. Achem, F. Madalla, Quest of Nigeria into Space for Sustainable Development, in: SpaceOps 2016 Conf, American Institute of Aeronautics and Astronautics, Daejeon, Korea, 2016, doi:10.2514/6.2016-2345.
[29] NigeriaSAT –2 - National Space Research & Development Agency, 2023 https://central.nasrda.gov.ng/?page_id=2179 accessed June 13, 2024.
[30] THEOS (Thailand Earth Observation System) - eoPortal, (n.d.). https://www.eoportal.org/satellite-missions/theos (accessed June 13, 2024).
[31] M. Kaewmanee, T. Choomnoommanee, R. Fraisse, Thailand Earth Observation System: Mission and Products, in: Proc. ISPRS Comm. Symp, 2006.
[32] I.A. Federation, IAF : Geo-Informatics and Space Technology Development Agency (GISTDA), (n.d.). https://www.iafastro.org/membership/all-members/geo-informatics-and-space-technology-development-agency-(gistda).html (accessed June 13, 2024).
[33] B.J. Kim, S. Park, E.E. Kim, H.S. Chang, W. Park, J. Seon, M. Ismail, A.A. Ad-Rasheed, A. Sabirin-Arshad, MACSAT - A Mini-Satellite Approach to High Resolution Space Imaging, in: Proc. AIAAUSU Conf. Small Satell, 2003.
[34] ATSB, Introduction to RazakSAT (Malaysia's remote sensing satellite), (n.d.). https://www.aprsaf.org/newsmails_newsletters/pastnews_2009/feature_93.php (accessed June 13, 2024).
[35] www.jpl.nasa.gov, Grace - Earth Missions - NASA Jet Propulsion Laboratory, NASA Jet Propuls. Lab. JPL (n.d.). https://www.jpl.nasa.gov/missions/gravity-recovery-and-climate-experiment-grace (accessed June 13, 2024).
[36] B.D. Tapley, M.M. Watkins, F. Flechtner, C. Reigber, S. Bettadpur, M. Rodell, I. Sasgen, J.S. Famiglietti, F.W. Landerer, D.P. Chambers, J.T. Reager, A.S. Gardner, H. Save, E.R. Ivins, S.C. Swenson, C. Boening, C. Dahle, D.N. Wiese, H. Dobslaw, M.E. Tamisiea, I. Velicogna, Contributions of GRACE to understanding climate change, Nat. Clim. Change 9 (2019) 358–369, doi:10.1038/s41558-019-0456-2.
[37] B.D. Tapley, S. Bettadpur, M. Watkins, C. Reigber, The gravity recovery and climate experiment: Mission overview and early results, Geophys. Res. Lett. 31 (2004) 2004GL019920, doi:10.1029/2004GL019920.
[38] Pléiades - Earth Online, (n.d.). https://earth.esa.int/eogateway/missions/pleiades (accessed June 13, 2024).
[39] Airbus statement following Pléiades Neo 5 and 6 loss | Airbus Intelligence, (n.d.). https://intelligence.airbus.com/newsroom/news/civil-engineering-and-infrastructure/airbus-statement-following-pleiades-neo-5-6-loss/ (accessed June 13, 2024).
[40] Pleiades Neo - eoPortal, (n.d.). https://www.eoportal.org/satellite-missions/pleiades-neo#references (accessed June 13, 2024).
[41] Marinan, Anne Dorothy, From CubeSats to Constellations: Systems Design and Performance Analysis, Massachusetts Institute of Technology, Department of Aeronautics and Astronautics, 2013.
[42] W. Blackwell, G. Allen, C. Galbraith, T. Hancock, R. Leslie, I. Osaretin, L. Retherford, M. Scarito, C. Semisch, M. Shields, M. Silver, D. Toher, K. Wight, D. Miller, K. Cahoy, N. Erickson, Nanosatellites for earth environmental monitoring: The MicroMAS project, in: 2012 12th Spec. Meet. Microw. Radiom. Remote Sens. Environ. MicroRad, IEEE, Rome, Italy, 2012, pp. 1–4, doi:10.1109/MicroRad.2012.6185263.
[43] A.D. Marinan, A.G. Hein, Z.T. Lee, A.K. Carlton, K.L. Cahoy, A. Milstein, M. Shields, M. DiLiberto, W.J. Blackwell, Analysis of the Microsized Microwave Atmospheric Satellite (MicroMAS) Communications Anomaly, (n.d.).
[44] Projects - EPFL Spacecraft Team, (n.d.). https://www.epflspacecraftteam.ch/project#styling (accessed June 5, 2024).

[45] S. Perrin, EPFL moves boldly into space with its CHESS satellites, (2021). https://actu.epfl.ch/news/epfl-moves-boldly-into-space-with-its-chess-satell/ (accessed June 13, 2024).
[46] A. Saada, E. David, J.P. Kneib, M. Udriot, D. Wood, M. Slavin, S. Dorrington, F. Letizia, S. Lemmens, M. Jah, S. Potter, N. Khlystov, Promoting responsible space practices: A primer on the Space Sustainability Rating, Aerospace Europe Conference, 2023, 2023.
[47] K.J. Stober, J. Wanyiri, A. Sanchez, M. Hooper, M. Mazumder, S. Jiwani, C. Waft, C. Joseph, M. Lifson, D. Wood, An Investigation of the Centrifugal Casting of Paraffin Wax on Earth and in Microgravity, AIAA Propuls. Energy 2019 Forum, American Institute of Aeronautics and Astronautics, Indianapolis, IN, 2019, doi:10.2514/6.2019-4012.