

Innovating a Sustainable Future: The Role of Small Satellites in Space Exploration and Societal Benefits

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The shift in space exploration approach during the last few decades from traditional large spacecraft to smaller, more affordable, and rapidly developed spacecraft has not only helped to revolutionize space exploration but has also increased opportunities to deliver significant global societal benefits.¹⁾ Small spacecraft as a growing part in our overall advanced space transportation portfolio have now become indispensable in advancing space exploration and addressing critical societal needs. Their affordability, flexibility, and swift development have opened access to space for a diverse range of participants, including emerging nations, governments, universities, and private industries. This paper describes how small spacecraft are contributing to reshaping space exploration, accelerating innovation, creating opportunities for international collaborations, and solving some of our societal challenges while also advancing STEM education and workforce training opportunities.

Key Words: Small Satellites, Collaborative Missions, Societal Benefits

1. Introduction

The landscape of space exploration has changed dramatically in recent decades. Traditional large spacecraft—often requiring years of development and extensive budgets—once dominated the domain. Today, the emergence of small satellites, often referred to as CubeSats, NanoSats, or microsatellites, has democratized access to space.^{1,2)} These systems, typically weighing less than 500 kilograms, are now integral components of modern space transportation architectures. Enabled by advancements in miniaturization, standardized platforms, and reduced launch costs, small spacecraft are being used by universities, space agencies, private companies, and international consortia. They are not merely budget alternatives to larger spacecraft; they enable entirely new mission concepts through swarming architectures, rapid development cycles, and agile responses to evolving scientific or societal needs. Their role extends across orbital regimes and mission types, encompassing Earth observation, communications, planetary science, and educational initiatives. This evolution is not just technical—it represents a cultural shift in how we think about space missions. No longer are space activities the exclusive domain of national space agencies. The democratization of space, enabled by small satellites, allows even high school students to participate in missions.

This grassroots participation expands public engagement in space science and fosters innovation at every level of society.

2. Small Spacecraft in Earth Observation and Societal Applications

Small satellites have revolutionized Earth observation. By enabling frequent, cost-effective imagery of our planet, they have become key contributors to monitoring climate change, supporting agriculture, and managing natural disasters. Companies like Planet Labs,³⁾ and Spire Global,⁴⁾ have deployed fleets of imaging satellites to monitor daily changes in vegetation, urbanization, and forest loss. Governments, non-profits, and academic institutions use these images to drive environmental policy and research. Small satellites provide critical real-time insights for flood detection, wildfire tracking, and coastal surveillance. Their low cost makes them accessible to developing countries and organizations previously excluded from space-based observation tools. Furthermore, the ability to deploy targeted sensors for specific regions or disaster-prone zones makes smallsats ideal for localized monitoring. This is increasingly important as climate change causes more frequent extreme weather events. Public-private partnerships are leveraging these capabilities to enhance national weather resilience

and support humanitarian logistics during crises. Private companies, including Planet Labs,³⁾ Spire Global,⁴⁾ and GHGSat,⁵⁾ are leveraging small satellites for global environmental monitoring, including greenhouse gas detection.

3. Digital Inclusion and Global Connectivity

Small satellites also address a major global issue—digital inequality. Satellite-based internet constellations now deliver broadband to remote areas, helping bridge the digital divide. In rural regions lacking fiber infrastructure, LEO constellations like OneWeb,⁶⁾ and Starlink,⁷⁾ provide tele-education, online commerce, and telemedicine access. Additionally, smallsat-based IoT systems support agriculture, infrastructure monitoring, and wildlife protection through machine-to-machine communication. Their resilience and reach make them vital for emergency communication after earthquakes, floods, or other natural disasters. Efforts are underway to integrate satellite networks with terrestrial 5G systems, allowing seamless connectivity even in mobile or maritime environments. Additionally, the compact form factor of smallsats enables the deployment of regionally focused constellations to serve specific policy or economic development goals.

4. Accelerating Innovation: Small Spacecraft as Technology Demonstrators

Small satellites serve as platforms for innovation. They allow rapid prototyping and flight testing of new technologies, such as autonomous navigation, new propulsion types, and sensor miniaturization. For example, NASA's Pathfinder and CubeSat Launch Initiative missions have validated new AI-based payload controllers, lightweight optical sensors, and deployable antenna systems. NASA's Small Spacecraft Technology Program,⁸⁾ has been instrumental in funding early-stage innovations, advancing deployable structures, propulsion systems, and AI-enabled mission architectures. Civilian use cases benefit as new capabilities are deployed faster and more affordably. This 'testbed in orbit' model has proven particularly beneficial for academia and start-ups, allowing early flight heritage at a lower barrier to entry. Many new aerospace startups use small satellites as a pathway to product maturity, often securing commercial or institutional customers after early demonstration missions. This creates a thriving innovation ecosystem that supports upstream suppliers and downstream application developers alike. Beyond their use in component testing, small spacecraft increasingly serve as platforms for validating mission concepts themselves, such as autonomous

formation flying and collaborative payload sharing. These missions act as steppingstones for more ambitious endeavors, enabling modular designs that can be adapted quickly to changing mission goals. As space missions become more commercialized and time-sensitive, the need for pre-validated, rapidly integrable technology becomes crucial—an area where small satellites excel.

5. Advancing Exploration with Constellations and Distributed Sensing

Distributed missions using small satellites have unlocked new possibilities in planetary science and Earth system studies. NASA's CYGNSS,⁹⁾ constellation, for example, collects ocean surface data for hurricane prediction. Similarly, constellations can monitor air quality, volcanic eruptions, and polar ice loss from multiple vantage points. This approach provides higher temporal and spatial resolution than traditional monolithic satellites, enhancing scientific return while improving system resilience and redundancy. Cooperative constellations also pave the way for coordinated international research, data sharing, and community science. As more distributed missions launch, standardized communication protocols and open data repositories are enabling greater interoperability among international science teams. This not only boosts discovery but also fosters transparency and reproducibility in planetary and climate sciences. This approach is also enhancing mission responsiveness, enabling rapid re-tasking and data fusion in near-real-time. Small satellite constellations can function as environmental sentinels, detecting and tracking transient phenomena like solar flares, auroras, and volcanic eruptions, and informing terrestrial systems within minutes. Future distributed systems are also being designed to conduct coordinated observations between ground-based and orbital platforms, bridging atmospheric, space domain and planetary observations.

6. SPORT Mission: A U.S.-Brazil Success in Space Weather Science

The SPORT,¹⁰⁾ mission, launched in 2022, exemplifies how small satellite missions can foster international collaboration and scientific discovery. Jointly developed by NASA, Brazil's INPE, and academic institutions, SPORT investigates equatorial ionospheric disturbances that affect satellite communications and navigation. Its compact sensor suite measures electron density, ion drift, and scintillation levels. The mission provides valuable data for civil aviation, satellite operators, and emergency services reliant on GNSS systems.

Beyond scientific outcomes, SPORT has helped build technical capacity in Brazil through workshops, internships, and joint mission operations. In addition, the mission supports educational programs and data-sharing platforms across South America, helping to standardize space weather monitoring techniques across the region. Its success has informed follow-on proposals and contributed to capacity-building strategies within the broader Latin American space community. The collaborative nature of the SPORT mission has paved the way for student-led subprojects and follow-on research in both the U.S. and Brazil. Joint data analysis activities and symposiums have contributed to professional development, expanding regional knowledge networks in ionospheric science. As a cost-effective science platform, SPORT is now being referenced in strategic frameworks as a model for building resilience against GNSS signal disruptions in the Global South.

7. ITASAT2: Operationalizing Multi-Mission

The ITASAT2 mission builds on SPORT,^{10,11)} mission by demonstrating a constellation of 16U small satellites equipped with diverse payloads: hyperspectral imagers, GNSS receivers, and software-defined radios. It focuses on environmental monitoring, atmospheric science, and maritime situational awareness. A key feature is its AI/ML-based edge processing, which allows satellites to prioritize data and reduce bandwidth use. This mission represents a modern approach to collaborative science, enabling coordinated tipping-and-cueing and shared data access across partners. NASA and Brazilian partners see it as a model for international capacity-building and sustainable operations. It also incorporates adaptive re-tasking based on mission events, which allows operational modes to shift between science and disaster response without human intervention. Such flexible payload tasking demonstrates how smallsat missions can achieve both scientific and civil protection goals within a shared infrastructure. The modular bus architecture used in ITASAT2,¹¹⁾ enables future expansion and plug-and-play integration of novel payloads, allowing iterative enhancement of mission scope over time. The mission's built-in data relay capabilities also allow it to serve as a platform for third-party scientific or humanitarian payloads, effectively functioning as a multi-agency testbed. This flexibility underscores the shift from single-purpose to service-oriented spacecraft in the smallsat domain.

8. Lunar Pathfinding: Small Spacecraft in Artemis Missions

For NASA's Artemis program includes several small satellite missions as part of its lunar campaign. CAPSTONE,¹²⁾ a CubeSat, successfully tested navigation in Near Rectilinear Halo Orbit—a future staging orbit for lunar Gateway. BioSentinel,¹³⁾ investigates radiation effects on DNA, an important precursor for long-duration human missions. Lunar IceCube and Lunar Flashlight aim to locate water ice in permanently shadowed lunar craters. These small missions reduce risk and cost for larger systems, while enabling international contributions from ESA, JAXA, and others. Small spacecraft also serve as proof-of-concept platforms for future lunar surface networks, including wireless relays, mapping tools, and robotic scouts. In addition to Artemis I companions, upcoming missions like Lunar Trailblazer and ESA's Argonaut may integrate small spacecraft for mineralogy, communications, and surface mobility scouting. This hybrid exploration model leverages both small and large systems, maximizing mission robustness and cost-efficiency. The success of small spacecraft like CAPSTONE,¹²⁾ also illustrates their role in reducing technical and programmatic risk for larger lunar initiatives. They help validate software systems, such as autonomous fault recovery and delayed command response in deep space. Additionally, these missions help establish cislunar infrastructure, including tracking networks and inter-spacecraft communication protocols, necessary for sustained lunar operations. Past missions like MarCO,¹⁴⁾ demonstrated CubeSat capabilities for deep space communication relay during the InSight Mars landing. Small spacecraft also facilitate new types of planetary science by providing short-term, mission-critical data windows at lower cost and with higher mission cadence.

9. International Collaboration and Capacity Building

International small satellite programs offer cost-effective pathways for emerging space nations to gain spaceflight experience. Projects like BIRDS,¹⁵⁾ (led by Kyutech, Japan) and QB50,¹⁶⁾ (coordinated by VKI, Belgium) have helped universities in over 30 countries develop and launch their first satellites. These missions promote global STEM engagement, local manufacturing, and international goodwill. Collaborative platforms like SPORT, and ITASAT2, also foster technical exchange, aligning with the UN's Sustainable Development Goals. Frameworks like the Artemis Accords emphasize shared exploration and transparency—values

mirrored in smallsat collaborations. These programs often serve as the first opportunity for emerging nations to participate in space research, laying the groundwork for independent national programs. They also enhance cultural exchange and promote diversity within the global space community. In addition to providing technical know-how, these collaborations help establish national space policies, regulatory frameworks, and space education curricula in emerging space nations. Workshops and virtual mission control exercises are often integrated into these programs, creating immersive learning environments that foster practical skills in systems engineering, mission design, and satellite operations. Furthermore, joint missions have been instrumental in fostering interoperability standards that ease future cooperative ventures between space agencies and private operators alike.

10. Educational Impact and Workforce Development

CubeSat programs have become central to space-related education. Students at all levels—from undergraduate to Ph.D.—participate in satellite design, assembly, testing, and mission operations. Such hands-on projects prepare graduates for careers in aerospace, systems engineering, and data science. Programs like NASA’s CubeSat Launch Initiative (CSLI), the European Space Agency’s Fly Your Satellite!¹⁷⁾ and Brazil’s ITASAT initiative illustrate how small satellites can be embedded into national workforce development strategies. Additionally, international programs such as the United Nations Office for Outer Space Affairs (UNOOSA) *Access to Space for All* Initiative,¹⁸⁾ are expanding participation by offering access opportunities to institutions from emerging and developing countries, thus broadening global workforce engagement. Universities and research labs also benefit from access to real-world datasets, fostering publications and continued research funding. As workforce needs evolve, smallsat projects are being tailored to include AI, cybersecurity, materials science, and space traffic management. This interdisciplinary approach reflects the growing complexity and relevance of the space sector to broader industrial innovation. CubeSat programs have become central to space-related education. Students at all levels—from undergraduate to Ph.D.—participate in satellite design, assembly, testing, and mission operations. Such hands-on projects prepare graduates for careers in aerospace, systems engineering, and data science.

11. Sustainability and Regulatory Frameworks

With growth comes responsibility. The proliferation of small satellites necessitates strong space traffic management, debris mitigation, and spectrum allocation policies. Guidelines such as those developed by the Inter-Agency Space Debris Coordination Committee (IADC)¹⁹⁾ provide a foundation for responsible mission planning. Operators must submit deorbit plans and coordinate frequencies with national and international bodies. Tools such as drag sails, onboard propulsion, and passive reentry mechanisms are increasingly common. Voluntary initiatives like the Space Sustainability Rating encourage best practices. Maintaining a clean orbital environment ensures continued access for scientific, educational, and commercial missions. Transparent tracking of operational status, passive end-of-life designs, and cross-agency coordination are being implemented to reduce collision risk and maintain orbital access for future generations. Policymakers are also exploring the creation of orbital 'green zones' and cooperative resource-sharing schemes for shared spectrum usage.

12. Conclusion

Small satellites have reshaped space exploration by lowering barriers and enabling distributed, rapid, and inclusive missions. Their success in areas such as Earth monitoring, lunar pathfinding, and international cooperation illustrates their versatility. Missions like SPORT,¹⁰⁾ ITASAT2,¹¹⁾ and Artemis smallsat components demonstrate how civil science, diplomacy, and education can all be served by this class of spacecraft. As launch access improves and AI technologies mature, small spacecraft will continue to support sustainable growth in both space and society on Earth. Looking ahead, their integration with emerging technologies such as quantum communication, space-based solar power, and autonomous docking systems will expand their impact even further. By fostering international cooperation and promoting peaceful use of space, small spacecraft continue to be a cornerstone of a sustainable spacefaring future. Small satellites are thus not only changing how missions are conducted but also who can participate

in space exploration. These missions serve as instruments of inclusion, opening new pathways for developing countries, underrepresented academic institutions, and startups. The growing body of missions leveraging smallsat architectures demonstrates their essential role in achieving strategic objectives for climate monitoring, sustainable development, and deep space exploration. Future directions point toward even more integrated missions where small satellites interact seamlessly with large spacecraft, rovers, and ground systems—expanding both capability and accessibility across all domains of space.

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