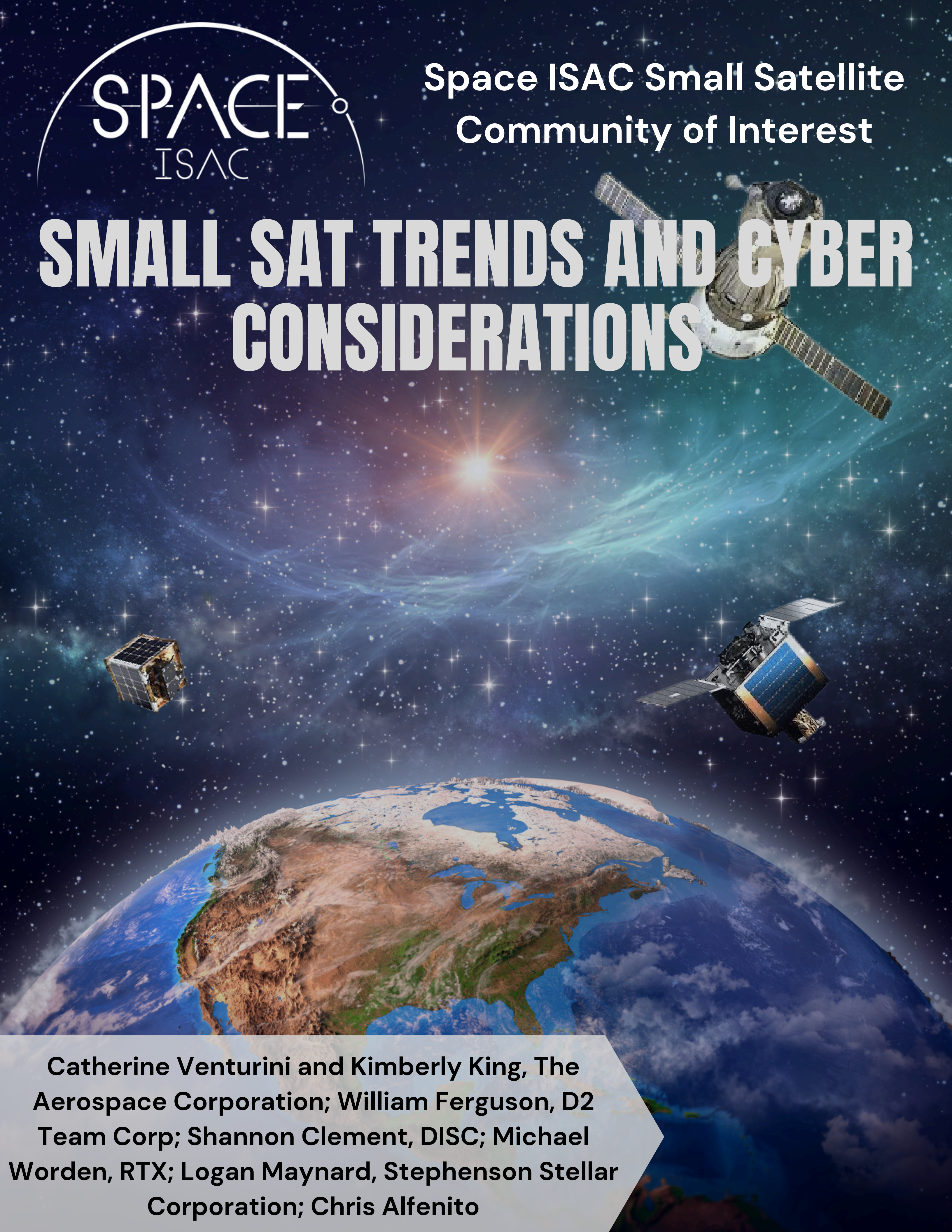

Space ISAC Small Satellite Community of Interest

SMALL SAT TRENDS AND CYBER CONSIDERATIONS

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Small Sat Trends and Cyber Considerations

Abstract:

The Space Information Sharing and Analysis Center (Space ISAC) has a steadfast commitment to fostering cooperation and measurable progress toward increasing the resiliency of systems and reducing the cyber threat exposure of current, emerging, and future small satellite technologies that support the United States and its allies.

Small satellites are prevalent in space missions, and advances in technology continue to increase their capability and usefulness as part of larger space system architectures. Small satellites are not immune from cyber and space threats. In many cases, they may be more vulnerable due to the use of standard components, production, and infrastructure. This white paper offers a historical perspective on the small satellite community, with an emphasis on current and future technology innovations and how they enhance mission capability as well as evolve small satellite resilience.

Keywords: small satellite, exposure management, resilience, cybersecurity

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Overview

This white paper aims to further our focus on informing, influencing, and measuring the progression of small satellite exposure. Throughout this white paper, we introduce several key areas of small satellite exposure themes, interspersed with cybersecurity and resilience points, as well as a central section that articulates our prioritized approach to small satellite cybersecurity and exposure management.

Our community scope for small satellite research ranges from femto satellites to mini satellites as outlined in the chart below [1].

	Mass Class Name	Kilograms
Small sats	Femto	0.01 0.09
	Pico	0.1 1
	Nano	1.1 10
	Micro	11 200
	Mini	201 600
	Small	601 1,200
	Medium	1,201 2,500
	Intermediate	2,501 4,200
	Large	4,201 5,400
	Heavy	5,401 7,000
	Extra Heavy	> 7000

The Development of Small Satellites

The CubeSat, a type of miniature satellite, has revolutionized access to space by providing a standardized, cost effective platform for scientific, educational, and commercial applications. Its development traces back to the late 1990s when Professor Jordi Puig Suari of California Polytechnic State University and Professor Bob Twiggs of Stanford University sought to create an accessible tool for student experience and experimentation in space.

Origins and Concept

The concept of the CubeSat emerged in 1999 as a solution to democratize space exploration. Puig Suari and Twiggs envisioned a small, modular satellite that adhered to a standardized design, making it easier and cheaper to develop, launch, and operate. The result was a cube shaped satellite with dimensions of 10 x 10 x 10 centimeters (about the length of the long edge of a credit card), weighing approximately 1 kilogram, and designed to fit within a deployer called the Poly Picosatellite Orbital Deployer (P POD). These specifications became the foundation of the CubeSat standard.

The primary aim was education. Universities and research institutions could utilize CubeSats to engage students in all aspects of satellite design, from conception to deployment, thereby providing hands on experience in aerospace engineering and space science.

Early Adoption and Growth

Russia's Rockot launcher facilitated a 2003 mission that launched the first CubeSats. These included several university-built satellites, demonstrating the feasibility of the CubeSat model. By 2012, launch providers had launched approximately 75 CubeSats. Between 2015 and 2024, the number of small satellites launched, including CubeSats, increased significantly, reaching 9,490 [2].

Universities around the globe began developing their own small SAT programs; however, it was the success of these early missions that ignited widespread interest.

As the appeal of these satellites expanded, private companies, government agencies, and research institutions identified a new frontier: Earth observation, communication, defense, and scientific research. Their low-cost ranging from tens of thousands to several hundred thousand dollars combined with their standardized design and the significantly reduced time to manufacture made them attractive for many initial proof of concept programs. Those successful programs laid the groundwork for the continued growth of small satellites. For the first time in history, small companies and startups can afford a space-based asset that was previously accessible only to governments.

Technological Advancements

Over the years, the capabilities of small sats have expanded dramatically due to advancements in miniaturized technologies. Initially limited to basic telemetry and low-resolution imaging, small satellites can now perform sophisticated tasks such as high-resolution Earth observation, climate monitoring, and interplanetary missions, utilizing high resolution optics, synthetic aperture radar, multispectral imaging, and elemental detection sensors. Miniaturized propulsion systems, advanced power management solutions, and compact communication systems have significantly enhanced the functionality of CubeSats.

NASA's Mars Cube One satellites, MarCO 1 and MarCO 2, were launched in 2018 as the first CubeSats to embark on an interplanetary mission. They successfully relayed data from the InSight Mars lander, demonstrating the potential of CubeSats for deep space missions [3]. The NASA DART (Dual Asteroid Redirection Test) hosted CubeSat LICIACube as part of the data gathering and transmission portions of the mission [4].

Commercial and Scientific Expansion

The commercialization of small satellites continues to be transformative. Companies like SpaceX, OneWeb, Planet Labs, Iceye, Capella Space, and Spire Global are among the growing number of organizations that have launched constellations of small satellites for Earth observation, imaging, and data collection and transfer. These satellite constellations deliver near real-time data to industries like agriculture, shipping, disaster response, and innovative city management, as well as IoT and critical infrastructure networks. Thanks to private launch services like SpaceX's rideshare programs, it's now easier than ever to get small satellites into orbit.

Scientists use small sats for everything from studying the atmosphere to monitoring space weather and testing new technologies. Agencies like NASA and ESA often incorporate them into their missions because they are flexible, efficient, and affordable.

Government and Military Applications

Small satellites have numerous applications for government-owned operators, bringing traditionally costly capabilities within reach. They can deliver secure, resilient, low-latency, high-throughput communication, as well as global Intelligence, Surveillance, and Reconnaissance (ISR).

Several proliferated low Earth constellations are in planning or early deployment. Notable examples include:

The Space Development Agency (SDA) designed the Proliferated Warfighter Space Architecture (PWSA) to provide global target tracking for warfighter support. SDA currently has 38 satellites in orbit, with more than 1000 planned in the constellation [5].

The European Space Agency (ESA) intends to launch the IRIS2 constellation, comprising hundreds of small satellites that will provide a high-speed, resilient, and secure communication network.

The Chinese government plans to launch the Qianfan ("Thousand Sails") constellation, aiming to provide global connectivity like Starlink. It currently consists of 72 space vehicles, with more than 600 scheduled for the end of 2025.

The proliferation of small satellites also raises security concerns, as addressed in the 2025 Global Counterspace Capabilities Report [7]. Operators commonly use distributed ground stations, including leased or shared resources, to manage constellations, which increases the cyber-attack surface [8]. Satellite cross-links enable attacks through on-orbit systems. Common and commodity subsystems in the system architecture and standard software expose systems to supply chain risks.

Future Prospects

The future of small sats is filled with ongoing innovations enabling more ambitious missions and data collection. Swarm constellations, interplanetary exploration, and advancements in artificial intelligence for onboard decision making are shaping the next era of small sat development. As the space industry continues to evolve, CubeSats remain at the forefront of enabling affordable and widespread access to space.

Innovation Trends Affecting Small Satellite Technology

The growing demand for fast, cost-effective, and easily deployable satellite solutions in LEO, GEO, and xGEO is accelerating the innovation and production of small satellites. This market pressure is driving emerging trends, reshaping how small satellites are designed, built, and utilized.

However, with these advancements come both industry benefits and cybersecurity challenges. This section explores key innovation trends affecting small satellite technology and their implications for cybersecurity.

Inter satellite communications (ISC)

Traditional satellite communication relies on a point-to-point model, where a fixed ground antenna communicates directly with a satellite. However, inter-satellite communications are enabled by satellite crosslinks, commonly referred to as Intersatellite Links (iSLs). They allow data to be relayed between satellites until it reaches a specific ground station. This form of communication creates a more efficient network, enabling more frequent transmission across a constellation [9].

Inter-satellite communications play a critical role for small satellites, which often have limited onboard storage and processing power. Instead of waiting for direct contact with a ground station or relying on a larger satellite that may only downlink data once per day, small satellite constellations can continuously relay data through their network, ensuring continuous and timely transmission to Earth. This capability may enhance mission efficiency, reduce latency, and improve overall operational effectiveness for applications such as Earth observation, IoT connectivity, and real-time monitoring.

However, this increased connectivity creates an increased attack surface for each space vehicle. To address this risk, CISA is advocating a Zero Trust in Space Program to provide a more secure framework for satellite design and to address and prepare for security risks as technologies mature [10].

Trend Benefit

Maturing Inter satellite links is imperative. There are key benefits, including but not limited to sustaining the data required to support distributed space service constellations, reducing on-orbit RF-related attack surface, as well as speculative use cases such as AI, QKD, and blockchain-driven solutions that may demand persistent communication across a range of constellations.

Free Space Optical (FSO) Communication

There are two types of optical communication used by small satellites, both driving a significant trend in satellite connectivity due to their ability to handle the growing demand for faster, higher-capacity data transmission:

- **Inter-satellite optical communications:** Enhances a constellation's ability to rapidly transmit data between satellites, improving network efficiency and reducing delays. This technology is particularly valuable for real-time applications, such as Earth observation and global broadband coverage.
- **Optical communication on the downlink:** Enables faster data transmission from satellites to ground stations, significantly increasing downlink speed and capacity. As data collection demands grow, engineers use optical downlinks to overcome the bandwidth limitations of traditional radio frequency (RF) communications. However, they must address several challenges with space-to-ground optical links, including atmospheric and weather conditions.

The shift toward optical communications is driven by the need to reduce latency, increase total throughput, and support data-intensive applications, making it a significant trend in modern small satellite operations [11].

Trend Benefit

These trends are critical as they represent the means to provide adequate bandwidth necessary for the small satellite technology solutions of tomorrow.

Small Satellite Technology Quantum Services

Quantum technologies encompass various quantum-related concepts. We will discuss three of them: Quantum Computing, post-quantum cryptography, and quantum key distribution.

Quantum Computing refers to a computer that works using the laws of quantum mechanics. In contrast, traditional computers are built upon the state of bits that are either zero or one. Today, quantum computers are limited in the number of qubits (the quantum equivalent of a bit) they can support and face significant multi-domain challenges to scaling [12].

The National Institute of Standards and Technology (NIST) specifies that the goal of post-quantum cryptography is to "develop cryptographic systems that are secure against both quantum and classical computers and can interoperate with existing communications protocols and networks [13]."

Quantum key distribution (QKD) provides keying material that can provide confidentiality, but it lacks authentication. "Such keying material could also be used in symmetric key cryptographic algorithms to provide integrity and authentication if one has the cryptographic assurance that the original QKD transmission comes from the desired entity (i.e. entity source authentication) [14]." In other words, QKD can be used to ensure Eve can't eavesdrop on an encrypted session from Alice, but it can't determine whether Alice is communicating with Bob, Dave, or someone else entirely.

Trend Benefit

Engineers are already using small satellites for on-orbit prototyping and experimentation in quantum key distribution (QKD). As technology matures, satellite missions will increasingly incorporate more quantum services.

Mission Operations as a Service

Not to be confused with Satellite as a Service, Mission Operations as a Service (MOaaS) is the use of cloud computing paradigms like Platform as a Service (PaaS) and Software as a Service (SaaS) for many aspects of mission operations, including mission planning and scheduling as well as satellite command and control [8].

The marketplace includes a mix of established satellite companies and standard cloud providers with MOaaS offerings (e.g., Amazon Web Services) [15].

This trend will likely ease the barrier for entry to managing new small sat systems for:

- Commercial space startups
- Universities
- Research institutions

Trend Benefit

Space operations are paramount to space, which is why MOaaS is a key element of how the future of small satellite technology platforms will be operated.

Space Debris Mitigation

Space, particularly LEO, where many small satellites operate, is increasingly congested. Collisions in space can have catastrophic impacts on both individual satellites and the entire orbital regime. The 2007 Chinese ASAT test created more than 3,000 trackable objects, with some estimates putting the total number of untrackable objects as high as 150,000 [16]. In 2009, Iridium 33 and Kosmos 2251 collided, resulting in more than 1,000 trackable objects [17]. Satellite launches and deployments release a wide range of objects, including non-operational and abandoned satellites, which contribute to space debris and pose risks to our planet. As agencies and companies launch more satellites into space, they increase the risk of collisions with other objects in orbit.

The increasing density of objects in LEO will drive the need to mitigate debris. Researchers and policymakers are developing several technologies and approaches, including regulatory requirements for satellite disposal [18-19]. Examples of technologies to address space debris include:

- **Active Debris Removal (ADR):** Robotic Arms and Nets, Harpoons, Tethers and Grippers can be used in space to actively remove space debris.

- **Laser Based Systems:** Satellites equipped with lasers could actively target debris in orbit.
- Space Surveillance and Tracking Software
- Policy and Design Measures

Trend Benefit

The need for debris mitigation is a consideration for operators, as they must meet requirements for disposal and minimization of debris that can impact flight safety. It also presents commercialization opportunities, as the commons of space must be maintained.

Autonomy

Autonomous satellites enable advanced onboard decision-making and control, decreasing dependency on ground systems and thereby reducing response time and reliance on instructions from a ground control center. Examples of autonomous operations in current satellite operations include:

- Pre-launch Programming
- In Orbit Adaptation
- Real-time Decision Making
- Anomaly Response

Leveraging autonomy, spacecraft have increased mission reliability through onboard decision-making related to fault detection, debris avoidance, power conservation, and optimized science collection.
Constellations that have inter-satellite communication will leverage autonomy to coordinate actions, collect shared data, and execute tasks to achieve complex mission objectives. Due to the complex nature of the functions, satellites that communicate in swarms will operate more effectively and efficiently, thereby reducing the overhead associated with satellites that require constant feedback [20]. As the number of satellites grows, autonomy will be essential for efficient operations, resiliency, cost reduction, and the advancement of space technology.

Trend Benefit

Spacecraft autonomy enables real time decision making, improving mission reliability, efficiency, and survivability without constant ground intervention.

Satellite Swarms and Constellations

Increased demands on satellite capabilities and performance create new challenges, and determining the need for satellite constellations or swarms pushes the boundaries, opening the doors to new possibilities. Monolith satellites once dominated the space landscape, operating independently and autonomously; over time, this evolved into constellations of satellites working together under ground control. While important and relevant for some applications, these constellations do not communicate with each other. For example, each satellite has a set role, such as GPS. On the other hand, smaller teams of satellites, known as “swarms,” are entering the space scene, working in harmony to achieve their goals [21].

These sophisticated “swarms” work in coordination to achieve objectives. These teams of satellites offer resilience as they adapt in an orchestrated manner, collecting data, collaborating on decision-making, protecting space intelligence, and providing a new approach to meeting the demanding needs of satellite capabilities [22]. Satellite swarms are entering the space landscape, offering coordinated capabilities that have never before been realized [23]. The ability to autonomously communicate, perform, and orchestrate tasks makes swarms an exciting addition to space.

Trend Benefit

The benefits of swarms and constellations include the ability to orchestrate tasks through inter-satellite communication, leveraging autonomous coordination to share data, execute tasks, and adapt dynamically to complex mission objectives, resulting in greater efficiency, reduced operational overhead, and improved mission performance.

Summary

Satellite engineers have historically prioritized environmental resilience and flight safety in the design of their flight systems. Engineers and space agencies will shift the paradigm as they deploy more complex, connected, and automated satellite systems. By extension, standards and regulatory requirements for satellite cybersecurity are still in their infancy.

Attacks against space systems will no longer originate from the relatively small attack surface of dedicated ground systems. The expanding use of leased command and control architecture for small sats provides an increased attack surface. In the future, adversaries may launch attacks not from the ground but through connected assets already in orbit [24].

Innovation trends affecting small satellite technology, such as inter-satellite communications, optical links, and autonomy, are expanding system capabilities while introducing new cybersecurity challenges. Increased connectivity and real-time data exchange across space and ground segments create a broader attack surface, exposing critical vulnerabilities. As quantum technologies and on-orbit networking become more integrated, the imperative is clear: cybersecurity must be treated as a core engineering discipline, not a compliance afterthought, to ensure the survivability of next-generation space systems.

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Appendices

- **Mini Satellites:**
  - **Mass**: Around 201 600kg
  - **Examples**: Certain Earth observation or technology demonstration satellites.
- **Micro Satellites (μsats)**
  - **Mass**: Around 11 200kg

    - **Examples**: University built science missions, smaller remote sensing platforms.
- **Nano Satellites (nanosats)**
    - **Mass**: Around 1.1 10kg
    - **Examples**: Many CubeSats (especially 1U through 6U configurations).
- **Pico Satellites (picosats)**
    - **Mass**: Around 0.1 1kg
    - **Examples**: Some very small CubeSat variants (e.g., PocketQubes) or custom build technology demos.
- **Femto Satellites (femtosats)**
    - **Mass**: < 0.1kg
    - **Examples**: Experimental “chip satellites” or “satellites on a board,” generally used in research.