

SPACE-BASED DATA CENTERS ROADMAP: THE CASE FOR CAUTION

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CHAPTER 2.2:

Orbital Congestion and Space Debris

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WORKING PAPER

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CHAPTER 2.2:

ORBITAL CONGESTION AND SPACE DEBRIS

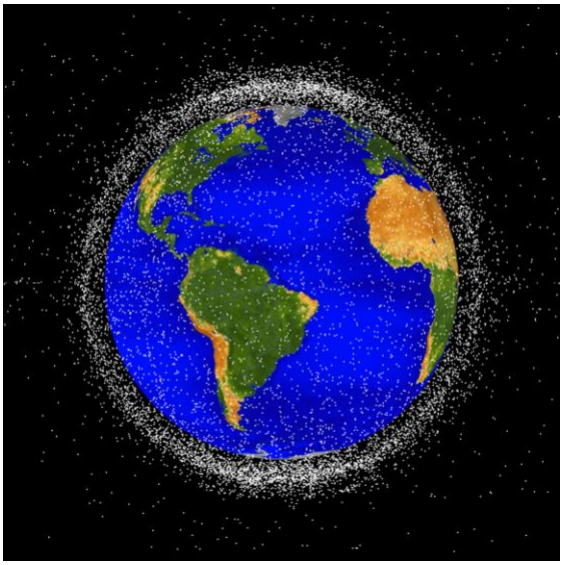
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MAIN MESSAGES

- Space-based data centers (SBDCs) would operate in an already congested orbital environment, where debris can damage spacecraft and remain in orbit for years or longer.
- Large SBDC constellations could substantially increase collision-avoidance demands and place new strain on existing space traffic-management systems.
- SBDCs could also create additional debris through collisions, failures or attacks, with risks increasing as constellation size grows.
- Reducing these risks will require reliable maneuverability, better coordination among operators and stronger international approaches to space traffic management.

A. Background

Space-based data centers (SBDCs) would operate in an already congested orbital environment. Space debris is particularly dense in low Earth orbit (LEO), where most proposed SBDCs would operate. Understanding the existing debris environment is necessary, both to assess the danger debris poses to SBDCs and to evaluate whether large SBDC constellations could worsen the problem.



Computer generation of untracked objects in low Earth orbit (LEO) (2019). Source: NASA ARES

Space debris includes defunct satellites, spent rocket bodies, fragments from collisions and breakups, debris from anti-satellite (ASAT) tests, and small objects, such as paint flecks or loose hardware. The US government has tracked more than 34,000 pieces of space debris since 1958.[1]

However, this only includes pieces of debris larger than 10 cm. Millions of smaller debris fragments cannot be tracked reliably but can still damage spacecraft at orbital velocity. This is not a hypothetical risk: a fleck of paint was suspected to have

caused a small crack in the International Space Station (ISS) cupola.[2] A 10-cm fragment can carry destructive energy comparable to several kilograms of TNT. Debris is heavily concentrated in LEO, where many SBDC concepts may operate.[1]



Impact chip in the International Space Station (ISS) Cupola window from suspected paint fleck. Source: ESA & NASA - Tim Peake

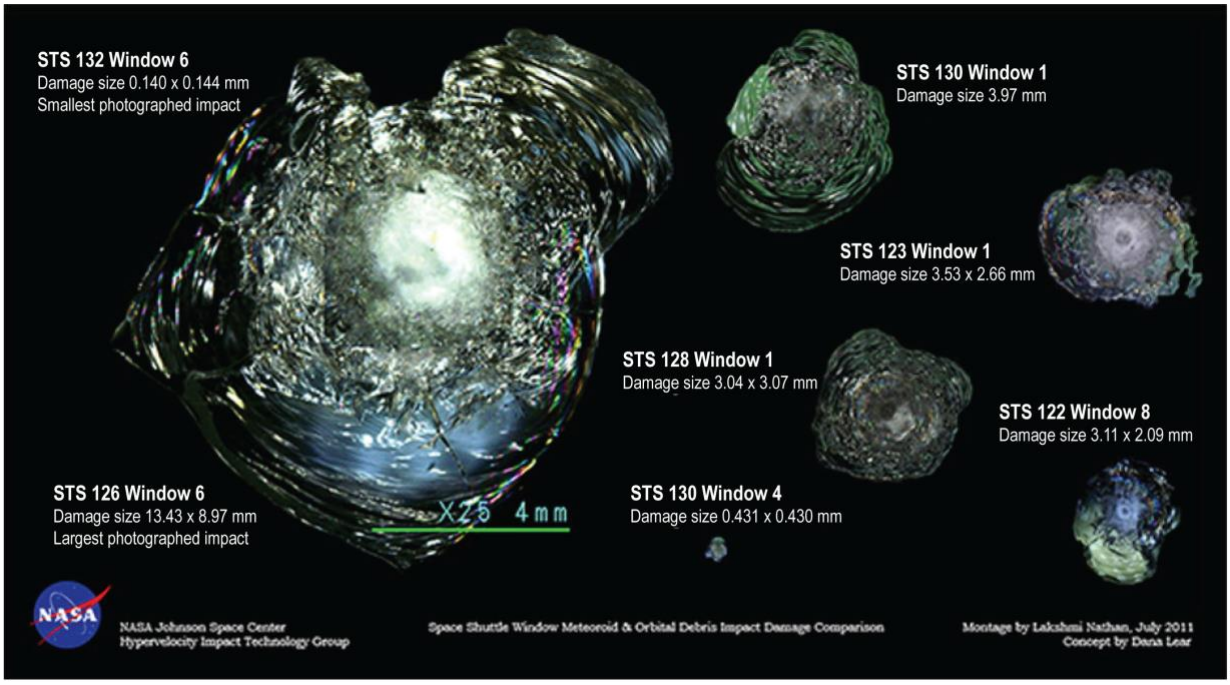
Debris lifetime varies significantly by orbit. In lower orbits, atmospheric drag can gradually slow down objects, lowering their orbits until they re-enter Earth's atmosphere and burn up. This natural process is currently the primary mechanism by which the debris population is reduced. Depending on debris altitudes, however, objects may remain hazardous for years. The average lifetime of a debris fragment in LEO is more than 15 years before drag causes re-entry.[1]

Higher-altitude debris poses a longer-lived problem. Atmospheric drag weakens exponentially with altitude, so debris in higher orbits can persist for much longer. Debris below 600 km usually falls back to Earth within several years, while debris at around 800 km may remain for centuries. Above 1000 km, debris can remain in orbit for a thousand years or more.[3] As the number of objects in space increases, so does the probability of close approaches and collisions with debris.

A satellite breakup scatters fragments across the surrounding orbital environment, threatening other missions. If these debris fragments collide with other active spacecraft, the catastrophic effects can spread. The Kessler Syndrome describes a hypothetical scenario in which debris density becomes so high that cascading collisions create debris that causes additional collisions. At worst, heavily used orbital regions like LEO could become increasingly difficult or impossible to use safely. Launching to higher orbits also becomes a challenge.

Adding tens of thousands to upward of a million objects in space means the risk of collisions with other spacecraft or space debris is more likely.[4] SBDCs would need maneuverability capabilities and extensive space-traffic-management capabilities to avoid other spacecraft and space debris.

According to Article VIII of the Outer Space Treaty, defunct satellites and their fragments are not abandoned by countries once they stop functioning.[5] A state retains jurisdiction and control over a space object carried on its registry while that object is in outer space.[6] This complicates active debris removal. An actor generally cannot remove, capture or alter a piece of debris without permission from the state that owns that object.[7] Ownership and liability issues can slow remediation, even when removal would improve the safety of the orbital environment.



Damage to space shuttle windows from space debris. Source: NASA/ARES

B. Data Center Vulnerability to Debris

SBDCs' vulnerability to debris would depend heavily on their altitude, architecture, maneuverability and level of redundancy. An individual SBDC with propulsion and substantial maneuver margins might face a workable risk. A large constellation comprising tens of thousands of spacecraft would experience greater exposure to potential collisions. Collision-avoidance operations are already a routine part of satellite operations.[8] Operators use tracking data to assess potential conjunctions and maneuver spacecraft when the predicted risk exceeds an acceptable threshold.[9] However, the system is imperfect. Tens of millions of small fragments of debris cannot be tracked reliably and maneuver decisions are complicated when multiple spacecraft respond to conjunction alerts.

These exposures are only made more threatening by a highly congested orbital environment containing tens of thousands of SBDCs in which operators have to evaluate large numbers of warnings involving both debris and other maneuverable spacecraft. Traditional collision avoidance architectures assume that building a catalog of space objects and then maneuvering around other objects as the catalog remains steady is sufficient. However, if there are thousands of satellites maneuvering regularly, then the catalog is constantly changing. Only the owners of those satellites know when the satellites will maneuver. This becomes problematic when uncertainty in satellite location grows, as many measurements are needed to converge on an answer with certainty. As a result, satellites may conduct more maneuvers making the problem worse. The maneuvers would consume fuel and reduce mission lifetimes.[8] For SBDCs that provide continuous computing or communications services, maneuvers would require changes in power use and workload allocation.

A collision involving any spacecraft, creates risks for other spacecraft. A breakup can generate debris that spreads across the surrounding orbital environment. This concern is linked to the risk of Kessler Syndrome.[10,11] At worst, heavily used orbital regions could become difficult or impossible to use safely. This would threaten SBDCs and the other missions that depend on the same orbital environment.

The 2009 collision between Iridium 33 and Cosmos 2251 shows how serious this risk can be. The collision involved an active US commercial communications satellite and a defunct Russian satellite. It was the first accidental collision between two satellites in orbit.[12] The event is the most severe accidental fragmentation on record, which is estimated to have produced more than 1800 debris fragments, each about 10 cm or larger.[1,13]



Iridium 33 satellite. Source: Wikimedia Commons. Licensed under CC BY-SA 3.0 Unported

C. Collision Prediction and Avoidance at Scale

Large SBDC constellations would need to predict and respond to conjunctions at a scale well beyond the capability of most current satellite systems. Collision-avoidance maneuvers are already routine for large constellations. SpaceX reported more than 355,000 Starlink collision-avoidance maneuvers from June 1, 2025 to May 31, 2026.[14,15] A 10,000-satellite SBDC constellation experiencing a comparable maneuver rate would conduct more than 400,000 avoidance maneuvers annually. It is also possible that scaling SBDCs is not linear. If a constellation is doubled in size, it may triple or quadruple the number of collision avoidance maneuvers required. Additionally, if two mega-constellations are not deconflicted by altitude, conjunctions could occur between the constellations, which would not scale the number of avoidance maneuvers linearly.

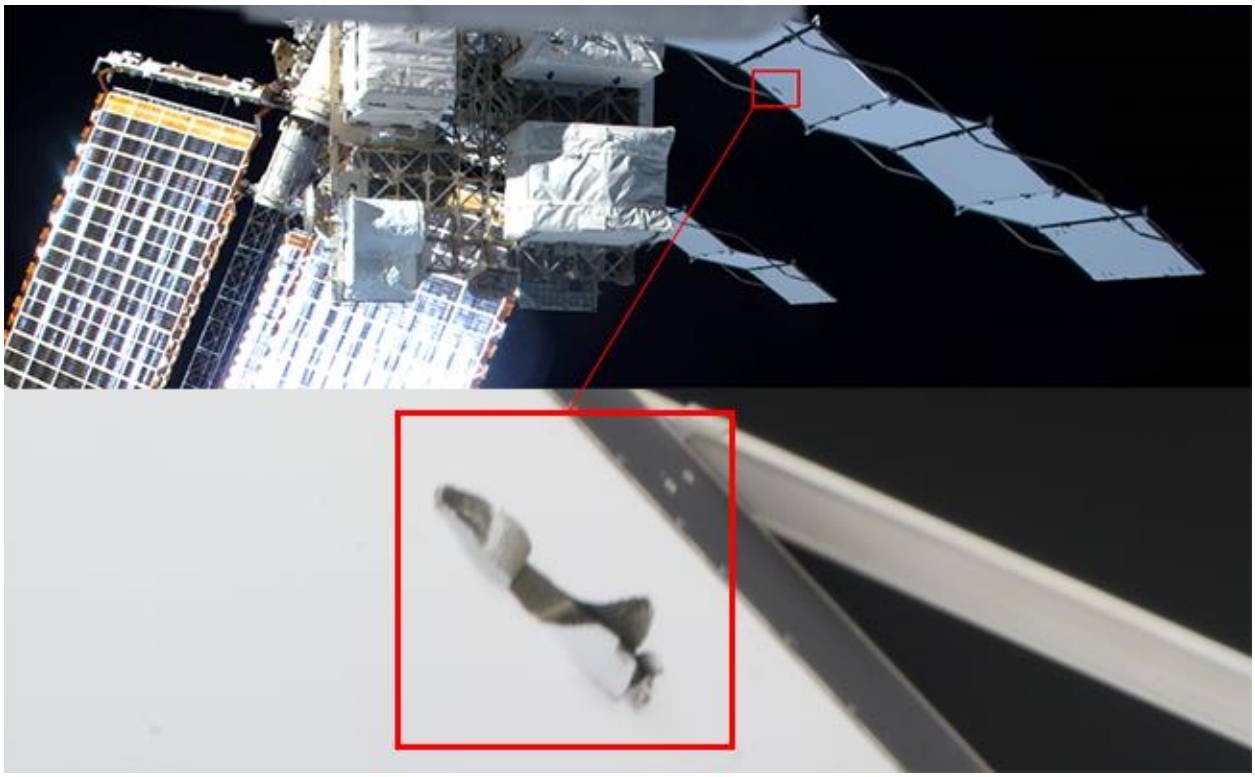
SBDC satellites could also present unusually large collision cross-sections because of the solar arrays and radiators they require to generate power and reject heat. (See Chapter 1.3-Cooling.) This makes maneuverability a basic design requirement, alongside automated systems capable of evaluating and responding to large numbers of conjunction warnings.[16]

Collision avoidance also depends on how early a threat can be predicted. For two intact, tracked objects, operators can estimate their trajectories and a time of closest approach, then maneuver before a collision occurs.[17] An unexpected collision or fragmentation event presents a harder problem. New debris clouds can pose a threat to spacecraft before tracking systems can establish fragment trajectories. Standard conjunction assessments between two tracked objects can provide days of warning for a catalogued object, but an unexpected breakup in a densely spaced constellation could require decisions within minutes. Today, it is infeasible to create these trajectories within a timeline of minutes. Maneuvering without reliable information about where the fragments are headed can also create additional conjunction risks with other satellites by moving into other collision paths.

The safety of SBDCs and other spacecraft in LEO depends on the ability to predict conjunctions. At the scale of proposed data centers, operators need rapid detection of spacecraft failures and accurate tracking to identify which satellites are threatened by debris. They would also need autonomous or highly automated maneuver capabilities able to respond within the available warning time. Constellation design can reduce this burden by maintaining sufficient separation between spacecraft so that an unexpected failure does not immediately threaten neighboring satellites.[18] However, if SBDCs need rapid data transfers between satellites in the constellation, then that required safe separation becomes a mission killer as latency may require satellites to be in close proximity to one another.[19]

D. Orbital Congestion and Space Traffic Management

Proposed SBDC deployments could significantly increase congestion in LEO even if they operate reliably and never produce debris. Multiple companies have submitted applications to the Federal Communications Commission (FCC) for constellations containing tens of thousands of orbital data-center spacecraft. Blue Origin, for example, has proposed a constellation of up to 51,600 satellites, while SpaceX has applied for authority to operate a system of up to one million satellites.[20,21] These applications do not guarantee that the systems will be built at their proposed scale. However, leading concepts involve significant proliferation of satellites from current satellite populations, with only around 18,000 active satellites currently in space.[22]



Damage to International Space Station (ISS) port-side radiator panel from space debris. Source: NASA/ARES

Deploying even a fraction of these proposed systems will create substantial space traffic-management demands.[23] Tens of thousands of additional SBDCs would also share orbital regions with communications constellations, Earth-observation satellites, scientific missions, crewed spacecraft, launch vehicles and debris. The number of potentially hazardous conjunctions can increase much faster than the number of satellites because every additional object could interact with many others. Operators need timely tracking data to distinguish serious threats from false alarms and to avoid unnecessary maneuvers that waste fuel.[10]

Effective management also requires robust and interoperable space traffic-management capabilities that allow government and commercial systems to exchange spacecraft status information.[24] Without shared procedures or knowledge of the other operator's intentions, both spacecraft could maneuver in ways that could increase the collision risk. Thus, space situational awareness and traffic management depend on cooperation and data sharing among satellite operators and tracking networks.[25]

The international nature of future SBDC development would complicate this coordination. Plans to launch SBDCs are already underway in the United States, China, India and the United Arab Emirates. (See Chapter 1.) More entities may pursue their own SBDC systems as the technology matures, producing an orbital environment in which constellations operate under different regulatory structures.[26] As is already seen in the current orbital environment, some governments or operators may be reluctant to disclose precise orbital information that they consider sensitive.

In 2025, China reportedly contacted the National Aeronautics and Space Administration (NASA) in advance of a maneuver to prevent a potential satellite collision, an encouraging but unusual instance of direct coordination.[27] A separate close approach later that year—involving a spacecraft deployed by a Chinese launch and a Starlink satellite—produced competing claims about whether sufficient coordination had occurred.[28] Cooperation is possible but shared expectations and information sharing is not yet established. These episodes illustrate both the importance and uncertainty of international coordination and the challenges of commercial deployments versus national systems, with differing barriers to international coordination.

A global SBDC ecosystem would need minimum standards for the accuracy and timeliness of orbital data, notification of planned maneuvers, communication during emergencies and the behavior of autonomous collision-avoidance systems. It would also need mechanisms for coordinating operators that cannot or will not disclose all relevant information. Without such arrangements, the proliferation of national and commercial SBDC constellations could further fragment space traffic management into dangerously non-communicative systems.

E. Risks of Additional Debris Creation



Rendering of a satellite explosion. Source: ESA

SBDCs could also become a source of debris. This risk would arise during launch and deployment, routine operations, accidental collisions, component failures, deliberate attacks and end-of-life disposal. The probability that any one spacecraft suffers a catastrophic failure may be low, but the aggregate risk increases substantially if SBDC concepts require tens of thousands to upwards of a million individual objects. Satellites have also experienced spontaneous fragmentation events caused by failures such as battery or propulsion-system malfunctions.[26,29] SBDCs are likely to carry lithium-ion batteries, which are safe except in fringe cases. However, within a million satellites, there are opportunities for many fringe cases.

The scale of some proposed SBDC architectures will challenge existing practices for space traffic management. A constellation containing hundreds of thousands of objects could generate a large number of conjunction alerts, creating substantial demands on traffic management systems and more risk of collisions.[30] SBDCs may also present additional debris concerns due to their size and complexity. Large structures could produce many fragments during a collision or breakup. Servicing, assembly and replacement missions to remediate breakups would also add traffic and create additional opportunities for accidents.

The overall risk that SBDCs create additional debris is notable for small constellations and higher for large constellations. The risk would be lower for SBDCs placed at altitudes where failed spacecraft naturally decay in Earth's atmosphere within a relatively short period of time after fragmentation. It would be substantially higher in orbital regimes where debris can persist for centuries or longer. Much would depend on whether developers can demonstrate highly reliable maneuverability, disposal, tracking and failure-management systems before deploying at scale. Risk mitigation would also depend on whether domestic and international traffic-management institutions can support safe coordination among the numerous operators that pursue SBDCs.

F. Weaponization of Debris and Debris Removal Capabilities

Space debris can also be created deliberately through ASAT tests or intentional collisions.[31] At the same time, technologies intended to address debris can introduce separate security concerns. With a kinetic weapon, a hostile actor could target an SBDC to disrupt its services and create a dangerous debris field. This would turn an attack into a broader hazard for other spacecraft in the same orbital regime—possibly threatening an entire SBDC orbital "shell."

Tools such as robotic arms, nets, harpoons, tethers and drag devices could help clean up the orbital environment.[32] The planned ClearSpace-1 mission by the European Space Agency (ESA) is a direct application of these capabilities.[33] However, similar capabilities could also be used to capture, move, damage or disable an active satellite. This creates a security dilemma.[34] Another actor may view a system designed for safety and sustainability as a potential counterspace capability. SBDCs would make this issue more important. Their size and value could make them attractive targets, while their potential debris footprint could raise the stakes of any attack or accident. At the same time, the proliferated nature of mega-constellations means they are not individually an attractive target. Depending on goals and motivations for offensive operations, non-kinetic attacks may prove more effective.



ClearSpace-1, artistic impression. Source: ©ClearSpace SA Media Library

SBDC operators might also have a strong incentive to develop or support in-space servicing and debris-removal systems capable of approaching and manipulating large objects. Even when intended for maintenance or environmental remediation, these systems could appear threatening to other states because they would possess many of the same capabilities needed to interfere with an operational spacecraft.

G. Recommendations

Several steps could limit risks related to orbital congestion and space debris.

1. National regulatory authorities should limit approvals for the launch and operation of SBDCs until risks related to orbital congestion and space debris are fully addressed.

2. Spacefaring nations should establish an International Space Traffic Management Organization (ISTMO). Such an organization could facilitate communication between launching state and satellite operators to help minimize the risks of collision and overcrowding. Eventually, such an organization could move toward standard-setting and regulating the number of satellites in LEO. A multi-stakeholder meeting at the United Nations to explore creation of an ISTMO would be a key first step.[35,36]

3. Spacefaring nations should also consider potential roles for the International Telecommunication Union (ITU) and International Civil Aviation Organization (ICAO). ITU, which coordinates radio frequencies and geostationary orbital slots, could be adapted to allocate slots and manage orbital carrying capacity in LEO.[37] The ICAO's mandate could be extended to help manage space traffic as well.[38]

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