

SPACE-BASED DATA CENTERS ROADMAP: THE CASE FOR CAUTION

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PREFACE

Science fiction writers have imagined computing power in space for many years. In 1978, the great Isaac Asimov published a story about two technicians sent to repair a large computer orbiting the Earth.[1] In 1968, Arthur C. Clarke released 2001: *A Space Odyssey*, in which a computer tries to take control of a spaceship.[2] In 1966, Robert Heinlein's *The Moon Is a Harsh Mistress* imagined a self-aware supercomputer helping plan a revolt in a lunar colony.[3]

Today computing in space is a reality. Many of the roughly 19,000 satellites currently in orbit have small amounts of computing power on board to support core functions such as Earth observation and communications, and a significant expansion of space-based computing capacity may be on the horizon. In the past 18 months, more than a dozen satellites have been launched to develop and demonstrate technologies for large-scale data processing in space. Driven by huge demand for compute, constraints on building that capacity on Earth and falling launch costs, several companies have announced plans to deploy hundreds of thousands of satellites for data processing, principally to train and run artificial intelligence (AI) models.

These plans raise many questions. Are data centers in space technically feasible? If so, will high costs be a barrier to their deployment? What are the risks and impacts of deploying vast constellations of space-based data centers? What treaties, laws and regulations would govern?

This year's ICEF Roadmap explores these questions. In this Roadmap, 10 coauthors set forth their initial views and analysis on a range of technical and policy questions related to space-based data centers. Our goal is to provide a useful resource for experts and non-experts alike.

The analysis in this Roadmap is primarily based on documentary research conducted during the summer of 2026. The text was prepared under a tight deadline and has not been subjected to peer review. As such, we consider it to be a "working paper."[4,5] We welcome comments and corrections, which can be sent to SBDCRoadmap@gmail.com. Some or all of the Roadmap will be updated to reflect comments, corrections and further research as opportunity permits.

In the past several years, AI models have become powerful research and writing tools. In preparing this Roadmap, we used AI models, including Claude, ChatGPT and Gemini for background research, fact-checking and suggestions with respect to writing clarity. We found those models to be very useful for these purposes, while of course recognizing that AI models can make errors and that statements made by AI models require careful review and verification.

This Roadmap builds on the body of literature produced annually in connection with the ICEF conference. Previous roadmaps have addressed the following topics:

- Sustainable Data Centers Roadmap (2025)
- Artificial Intelligence for Climate Change Mitigation (Second Edition) (2024)
- Artificial Intelligence for Climate Change Mitigation (2023)
- Low-Carbon Ammonia (2022)
- Blue Carbon (2022)
- Carbon Mineralization (2021)
- Biomass Carbon Removal and Storage (BiCRS) (2020)
- Industrial Heat Decarbonization (2019)
- Direct Air Capture (2018)
- Carbon Dioxide Utilization (2017 and 2016)
- Energy Storage (2017)
- Zero Energy Buildings (2016)
- Solar and Storage (2015)

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The ICEF Innovation Roadmap Project aims to contribute to the global dialogue about innovative solutions to energy and climate change challenges. We welcome your thoughts, reactions and suggestions.

David Sandalow

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Please send comments and corrections to SBDCRoadmap@gmail.com.

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SIX MAIN MESSAGES

1. Space-based data centers are coming soon. In the United States, China and other countries, significant activity is underway to deploy space-based data centers in the next few years, including proposals to launch more than one million data centers into orbit.
2. Neither technical challenges nor high costs will be barriers to initial deployment of space-based data centers. Some space-based data centers are already operating. Leading companies will be willing and able to incur high costs for many years to gain technical proficiency and establish market position.
3. Many rocket launches would be required to deploy small amounts of compute in space. More than 700 launches of large rockets every year (2 per day) would be required in perpetuity to meet 10% of projected global demand for artificial intelligence data centers in 2030.
4. Large constellations of space-based data centers would create very significant risks and impacts. Risks and impacts include the following:
    - dramatic alterations of the night sky
    - large debris fields in low Earth orbit
    - loss of life and property damage from de-orbiting satellite
    - depletion of the stratospheric ozone layer
    - increased global warming
    - significant interference with astronomical observations and research
5. Current governance regimes are inadequate for managing the risks and impacts of large constellations of space-based data centers. The lack of international coordination is a particularly challenging problem.
6. Companies and policymakers should proceed with great caution. Keeping in mind accidents such as those at Deepwater Horizon and Fukushima, companies and policymakers should not deploy large constellations of space-based data centers without more operational experience and until risks and impacts are better understood and well managed.

FINDINGS AND RECOMMENDATIONS

A. Findings

1. **In the US, China and other countries, significant activity is underway to deploy space-based data centers in the next few years, including proposals to launch more than one million data centers into low Earth orbit.**
   - Many satellites currently in orbit have small data processing capabilities on board to support their core functions, such as Earth observation or communications.
   - Roughly a dozen satellites have been launched primarily to demonstrate the feasibility of performing artificial intelligence (AI) model training and inference in space.
   - More launches of space-based data centers have been proposed for 2027, with companies hoping to increase deployment significantly in the years that follow.
   - Today there are roughly 19,000 satellites orbiting the Earth. Full implementation of proposed plans for space-based data centers would increase the number of satellites in low Earth orbit by more than 50x.
2. **Operating data centers in space is technically feasible, although operating hundreds of thousands of space-based data centers without collisions would require unproven technologies to be operated at very low failure rates.**
   - No technical barriers preclude the operation of data centers in space.
   - Thermal management is one of the most fundamental determinants of both feasibility and cost. Because a data center in vacuum can shed its waste heat only by radiating it, the size and mass of the radiators—and the temperature at which the chips are allowed to run—largely set how much compute a satellite can carry.
   - Space-based data centers will be much larger than communications satellites, with solar arrays and radiators that greatly increase their cross-sectional area. Preventing collisions among hundreds of thousands of such satellites will require data sharing procedures and maneuver coordination technologies with extremely low failure rates.
   - The weight of individual satellites per unit of compute will be a crucial parameter in determining cost and overall impacts. The weights claimed by leading developers appear to be highly optimistic and beyond currently-proven technology.

3. **High costs are unlikely to be a barrier to initial deployment of space-based data centers.**
   - Despite high costs today, companies may be willing to deploy data centers in space even if costs are significantly higher than for terrestrial data centers, due in part to the value of AI compute and constraints on building new data centers on Earth.
   - Companies may be willing to absorb losses in operating space-based data centers for a sustained period, if those companies believe it will help establish market position or lead to profitable operations in the long run.
   - The pace at which costs will decline depends on technological innovations, the pace of launches and other factors.
4. **Large numbers of rocket launches would be required for small amounts of computing capacity in space.**
   - Based on reasonable assumptions, maintaining a fleet of space-based data centers with 10% of the projected demand for AI data centers in 2030 would require at least 700 launches of Starship-sized rockets per year (2 launches per day) in perpetuity.
   - If the weight of space-based data centers per unit of compute is higher than claims by developers, significantly more launches would be required.
5. **Constellations of hundreds of thousands of space-based data centers would create serious risks. In many cases, mitigating these risks would depend on unproven or undemonstrated technologies. Known risks include the following:**
   - Dramatic alterations of the night sky, so that more satellites than stars would be visible at many times in many places around the world.
   - The creation of debris fields in low-Earth orbit, rendering portions of low Earth orbit unusable for years to come, impacting communications, Earth observation, weather forecasting and many other current satellite services.
   - Property damage and loss of life from disposing of tens of thousands of satellites per year by de-orbiting them into the atmosphere.
   - Increased depletion of the stratospheric ozone layer, driven by rocket fuel emissions during launches and by vaporized satellite components during de-orbiting.
   - Increased global warming, driven by rocket fuel emissions.
   - Significant interference with astronomical observations and research.
6. **Even if all foreseen risks are successfully managed, large constellations of space-based data centers would still have unavoidable impacts.**
   - These impacts include interference with infrared astronomy and very large numbers of rocket launches continuing for as long as the constellations are operational.

7. **There are many "known unknowns" and very likely some "unknown unknowns" with respect to large constellations of space-based data centers.**
   - "Known unknowns" include the technical potential for mitigating the brightness of constellations of space-based data centers, the impacts of de-orbiting large numbers of space-based data centers on the stratospheric ozone layer and the impacts of stratospheric black carbon on the global climate system.
   - "Unknown unknowns" could be very consequential, given the enormous scale of the infrastructure proposed for space-based data centers.
8. **Governance regimes with respect to space-based data centers are fragmented, with large gaps, and are not suited to large constellations of data centers in low Earth orbit.**
   - A patchwork of international and domestic laws covers some topics related to space-based data centers, but many risks are not fully covered by existing laws or regulations.
   - The international space regime was built in a different era, before private companies played central roles in launching and operating satellites and when the number of satellites in orbit was much lower than today. Other areas of international law with relevance mostly do not address operations in space.
   - Current international coordination mechanisms are not adequate to address potential congestion in low Earth orbit from hundreds of thousands of space-based data centers.
   - Nations playing a leading role in the development and deployment of space-based data centers have a wide range of uncoordinated laws on topics including orbital congestion, risks of ground damage and casualties, liability, AI and data governance.
   - Current legal regimes for registering space-based data centers allow for regulatory arbitrage.

B. Recommendations

1. Proceed with caution. Companies should not launch large numbers of space-based data centers until a range of significant risks and impacts are addressed.
    - These risks and impacts include transformation of night skies (so more satellites than stars are visible); collisions in low Earth orbit, creating debris fields that leave parts of low Earth orbit unusable for decades; uncontrolled space debris falling to Earth; significant stratospheric ozone depletion; increased global warming; and serious disruption of astronomical research.
    - In a filing with the US Federal Communications Commission (FCC), SpaceX wrote "Initial operations under this license will be limited to a significantly smaller number of satellites and re-entries than the maximum authorized, providing time to monitor actual effects, validate models with real-world data, and implement any necessary adjustments before scaling."[1] SpaceX and other companies should strictly follow the important principle set forth in this statement.
2. Require phased deployment. National regulators should require phased deployment of space-based data centers to better understand risks.
    - These deployments should proceed slowly, with careful attention to reducing risks. Licenses should be subject to annual renewals granted on the basis of performance in brightness mitigation, deorbit impacts, emissions reduction and other factors.
    - Deployment of other high-potential, high-risk technologies, such as autonomous vehicles, provide precedents for performance-based licensing.
3. Collect and share data. Governments, companies and other stakeholders should establish public-private partnerships to collect, share and analyze data related to space-based data centers.
    - Priority topics include the performance of novel satellite-brightness mitigation technologies, the impacts of satellite demise on stratospheric ozone depletion and the impacts of black carbon in the stratosphere on atmospheric warming.
    - Governments should invest in and expand public sector expertise on relevant satellite design and mega-constellation operations to provide neutral technical analysis of proposed private-sector plans.
    - Companies proposing to launch space-based data centers should provide significant funding for independent scientific research on these and other topics.
4. Learn from past accidents. In evaluating proposals for space-based data centers, policymakers should be mindful of accidents such as Deepwater Horizon and Fukushima.

- History teaches us that deployment of complex technologies can sometimes lead to tragic consequences, even in systems with well-established safety procedures, best practices and regulations. The Deepwater Horizon and Fukushima accidents are examples of such tragic consequences.
- Space-based data centers will employ a wide range of novel technologies that will, at first, lack well-established safety procedures, best practices or regulations. The risks from prematurely scaling space-based data centers are significant.

5. Protect night skies. **Operators should adopt visibility mitigation measures that prevent space-based data centers from being visible from the Earth's surface.**
   - National regulatory agencies should analyze dark-sky impacts as part of their public-interest review for satellite licensing and should not license constellations of space-based data centers that would be visible from the Earth's surface.
6. Protect astronomical research. **In addition to requiring the visibility mitigation measures in #5 above, national regulatory authorities should require operators of space-based data centers to disclose orbital position data and standardized thermal performance to astronomical observatories.**
   - The UN Committee on the Peaceful Uses of Outer Space (COPUOS) should formally adopt comprehensive "Dark and Quiet Skies" protocols that address optical, thermal and radio interference.
7. Manage orbital congestion and collision risks. **Space-faring nations should create an International Space Traffic Management Organization.**[2]
   - Slots in low Earth orbit should be assigned and managed to reduce or prevent overcrowding in key orbit altitudes and inclinations. National regulators should require space-based data centers to be capable of maneuvering either autonomously or manually by personnel available 24/7.
8. Protect life and property on Earth. **National regulators should not allow space-based data centers to be deployed at scale unless re-entry risks to life and property on Earth can be held to acceptable levels at a high level of certainty.**
   - Governments and companies should develop and implement protocols for safe disposal of satellites at end-of-life. Companies should provide financial assurances sufficient to compensate any victims, including through bonding or insurance policies. Parties to the Liability Convention should clarify the standard for fault and liability for service outages, data loss and environmental harms.
9. Do not deplete the ozone layer. **National regulators should delay large-scale deployment of space-based data centers until risks related to stratospheric ozone depletion are better understood through direct measurement of re-entry plumes and dedicated atmospheric modeling.**

- The Parties to the Vienna Convention should establish a standing study program focused specifically on the space sector, including space-based data centers. If further research suggests that space-based data centers and other space activities could present significant threats to the stratospheric ozone layer, the Parties to the Vienna Convention should amend the Montreal Protocol to address these issues.
- The US FCC should end its categorical exclusion for satellite launches under the National Environmental Policy Act (NEPA) and evaluate ozone depletion, climate change and ecosystem impacts before making decisions on constellations of space-based data centers.

10. Do not contribute to global warming. National governments should require life-cycle climate change impact assessments as a condition for authorizing launch and deployment of space-based data center constellations.
    - License applicants should disclose the life-cycle greenhouse gas emissions of space-based data centers and compare these results with terrestrial alternatives using transparent assumptions.
    - The Intergovernmental Panel on Climate Change (IPCC) should clarify that GHG emissions from rocket launches and related operations must be included in national emissions inventory reporting.
11. Protect against attacks. Regulatory agencies in spacefaring nations should designate space-based data centers as critical infrastructure and include cybersecurity requirements into license conditions.
    - Spacefaring nations should work in COPUOS and other international fora to establish protocols for notification of suspected attacks and procedures for de-escalating any conflicts.
12. Promote market competition. Governments should promote competition in markets for compute services in space.
    - National governments should consider (i) requiring dominant providers of launch services and satellite data-transfer capacity to offer access on fair, reasonable and nondiscriminatory terms and (ii) requiring that launch, compute and data-transfer services be provided by unaffiliated firms.
    - In deciding whether to adopt such measures, governments should consider the risk that such requirements could deter socially beneficial investments.
    - Competition authorities should closely scrutinize proposed mergers and exclusive arrangements, as well as self-preferencing by vertically integrated firms. International Telecommunication Union (ITU) Member States should consider whether priority-by-filing-date in the unplanned frequency bands adequately protects future entrants.

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Opening Essay:

GROWING MOMENTUM TOWARDS SPACE-BASED DATA CENTERS

David Sandalow

Putting data centers in space once seemed fanciful. Today, a growing number of companies are seriously exploring doing so. This activity is concentrated in the United States but spread across at least a dozen countries globally. The number of data centers launched to space will likely grow in the years ahead.

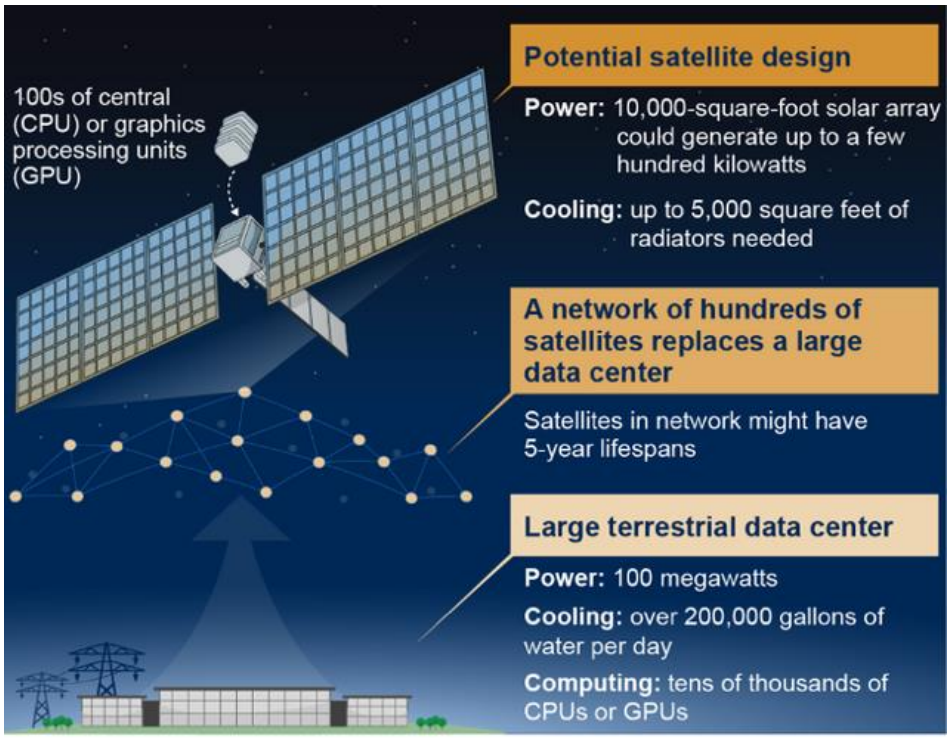
SpaceX is by far the largest player in this market. Founded and led by Elon Musk, the company has a track record of significant accomplishments in the space economy. SpaceX technology has been the main force behind a dramatic drop in launch costs in the past 15 years (in the range of 70–95%, depending on the rockets used for comparison).[1,2] The Starlink network of communications satellites, owned by SpaceX, now operates roughly 2/3rds of the satellites in the sky.[3]

In January 2026, SpaceX sought permission from the US Federal Communications Commission (FCC) to operate one million space-based data centers (SBDCs). To date, four other companies have followed, with applications that propose to put several hundred thousand more data centers in low Earth orbit (LEO). These companies include Blue Origin, led by Amazon founder Jeff Bezos, and Starcloud, a venture-backed company that has already trained artificial intelligence (AI) models in space. Several other companies have indicated interest in operating SBDCs, using existing FCC licenses to pursue initial deployments.

Activity is hardly limited to the United States:

- The Chinese company ADA Space has proposed to build a 2800-satellite "Star Compute" constellation, also known as Three-Body Computing. ADA Space launched the first 12 satellites in May 2025.[4,5]
- In December 2025, China Aerospace Science and Technology Corporation (CASC) announced plans to deploy gigawatt-scale SBDCs by 2030.[6]
- The European Commission is funding the ASCEND (Advanced Space Cloud for European Net zero emission and Data sovereignty) feasibility study, coordinated by Thales Alenia Space, to determine if SBDCs can help meet the EU Green Deal's net-zero carbon objectives and other goals.[7,8]
- India's Neev Cloud has announced plans for a pilot launch by the end of 2026 and 600 more SBDCs in the next three years.[9]

- Madari Space, a UAE company, has also announced plans for a pilot launch of SBDCs in 2026.[10]
- Activity on SBDCs is underway in Japan, Israel, Singapore and other countries as well.[11-13]



Source: U.S. Government Accountability Office 2026

What's behind the growing momentum toward operating data centers in outer space?

First, the exploding demand for AI compute on Earth.

Demand for AI compute is rising at extraordinary speed. AI data center capacity has more than tripled globally in the past two years. The International Energy Agency (IEA) estimates that electricity consumption by AI-focused data centers grew 50% globally in 2025. BloombergNEF projects capital expenditures of more than $750 billion by the 14 largest publicly owned data center operators in 2026. The capital expenditure of leading technology companies is now larger than global investment in oil and natural gas production.[14,15]

These trends are expected to continue. The IEA projects that data centers' global electricity consumption will roughly double by 2030. McKinsey projects that technology companies are projected to spend more than $5 trillion on data centers in the same period. Although many analysts believe current technology company valuations are characteristic of a bubble, demand for AI compute is generally expected to keep growing. Companies with interests in SBDCs are committing significant capital on the assumption that demand for AI compute will remain strong through at least the medium term.[14-17]



High-voltage electricity transmission infrastructure. Source: Shutterstock

Second, challenges in finding sufficient electric power for data centers on Earth.

Many AI data centers require power supplies on the scale of medium to large cities, with high degrees of reliability. The power demand for training frontier AI models is especially high. In many parts of the world, the lack of electric power is a binding constraint on data center growth. The problem is especially acute in the United States, but it is an important factor in many other jurisdictions as well.[18-20]

Building new power generation facilities and connecting them to electric grids can be a very slow process. Wait times for transformers, cables and gas turbines for combined-cycle plants stretch out over many years. New transmission lines can take a decade or more to site and build. Data center construction can collide with important public policy goals including low power prices and decarbonization, slowing permitting processes. Data centers can often be built much faster than the power infrastructure needed to operate them—a fact unlikely to change in the years ahead.[14,18]

Third, the abundance of solar power in space.

Space offers the potential for generating a large amount of solar power. In some LEOs, satellites can receive sunlight almost continuously, without interference from clouds or particles in the atmosphere and with only brief periods of eclipse (when satellites pass into Earth's shadow). However, specialized solar photovoltaic (PV) panels are needed in LEO to avoid rapid degradation. Google researchers estimate that, under perfect conditions, solar panels in LEO could be eight times more productive than solar panels on Earth.[21-23]



Sun rise in space. Source: Shutterstock

Elon Musk discusses this topic in civilizational terms, invoking the Kardashev scale. In 1964, Soviet astronomer Nikolai Kardashev proposed classifying a civilization by the energy it uses. A Type I civilization commands the energy resources of its

planet, a Type II civilization taps the total output of its star, and a Type III civilization uses the energy of its galaxy. Musk calls SBDC constellations an important step toward Type II status for humanity because they would increase use of the Sun's power.[24] (Some people may differ on whether the pursuit of Type II status should be a priority goal for humanity.)

Fourth, rapidly growing opposition to data centers from local communities on Earth.

Community opposition is emerging as a significant constraint on data center construction.[25,26] Opposition is especially strong in the United States, where public sentiment has shifted dramatically against data centers in the past year. In a May 2026 nationwide Gallup poll, 71% of respondents said they opposed construction of an AI data center in their local area.[27] The governors of New York and Texas have each imposed moratoria on data center construction in recent months, and more than 100 moratoria have been proposed at the local, county, state and national levels in the United States.[28]

Community opposition to data centers is strong in other countries including Ireland, the Netherlands and Chile, as well. In Ireland, a proposed €1 billion data center was stalled after local protests over traffic, noise, light pollution, infrastructure pressure, climate impacts and changes to the character of the rural area.[29] In the Netherlands, Meta cancelled plans for a giant data center after a Dutch Senate motion asking the government to block the project.[30] In Chile, residents and local officials challenged a proposed Google data center's water use and aquifer impacts, leading an environmental court to partially reverse the project's permit.[31]

Fifth, concerns about data center water use on Earth.

Historically, cooling technologies at some data centers consumed large volumes of water. Evaporative cooling was the major culprit. In evaporative cooling systems, an estimated 80% of the water withdrawn is lost to evaporation. A single large hyperscale data center can withdraw up to 1.8 billion gallons annually, equivalent to the needs of a town of 10,000 to 50,000 people.[32] Although modern data centers increasingly use closed-loop cooling technologies that consume very small amounts of water, concerns remain about data center water use among many stakeholders.[33]



Hyperscaler data center in Eemshaven, Groningen, The Netherlands, 2025.
Source: Shutterstock

In addition, power supplied to data centers by coal plants and nuclear power plants can result in significant water consumption for cooling at the power plant. This "Scope 2" water use by data centers can be very large, even if the data centers receiving the power use closed-loop cooling technologies with very little water use on-site.[33]



SpaceX Falcon 9 launch from Cape Canaveral, Florida. December 2024. Source: Shutterstock

Sixth, falling launch costs.

Launch costs have fallen dramatically in recent years. Launch cost to LEO for the Falcon 9 is now approximately $2600/kg for the Falcon 9 and $1500/kg for the Falcon Heavy.[1,34] These falling costs have changed the economics of putting computing hardware into orbit. The cost declines are not sufficient to make SBDC constellations cost-competitive today but suggest the potential for significant further cost reductions. Some analysts have noted that the cost of terrestrial data centers may rise while launch costs fall, so the cost curves for SBDCs and terrestrial data centers could cross.[28] (See Chapter 1.1(C)-Launch Costs for more detail on this topic.)

Several industry leaders are bullish about further launch cost reductions and their implications. Elon Musk has said that rapidly reusable rockets could reduce "the cost of access to orbit and beyond" by "a factor of 100 or more."[35] Jeff Bezos has made a similar argument, saying that rocket reusability creates "a path to lowering the cost of access to space by a factor of 100."[36] Google's Suncatcher program projects launch costs falling to $200/kg by 2035, and Google CEO Sundar Pichai has said of SBDCs, "There's no doubt to me that a decade or so away we'll be viewing it as a more normal way to build data centers."[37]

Seventh, the capacity of leading SBDC companies to sustain financial losses.

SBDCs are unlikely to be profitable or compete with terrestrial data centers on cost in the short-term. High costs for launches, radiation-hardened electronics, specialized thermal radiators and other equipment are barriers. The inability to physically service hardware in orbit will increase life-cycle system costs, as well. Google experts found that launch costs must reach roughly $200/kg—far below current levels—for SBDCs to reach cost targets achieved by terrestrial data centers.[21,38,39]

However, the lack of short-term cost-competitiveness or profitability are unlikely to be barriers to launching thousands of SBDCs into orbit. With the supply of compute constrained on Earth and access to compute essential for developing frontier AI models, hyperscalers may be willing to accept high costs for AI compute in space. Furthermore, several leading SBDC companies have the capacity and, very likely, the willingness to sustain financial losses for many years to achieve market position in this sector:

- SpaceX founder and CEO Elon Musk has enormous financial resources and access to capital markets. He operated Tesla for more than a decade before its first full year of profitability in 2020.[40]
- Blue Origin owner Jeff Bezos is one of the world's richest men, with enormous financial resources.
- CASC is a state-owned company of the kind that often receives significant financial support from the Chinese government, independent of short-term profitability.[41]

The growing momentum towards SBDCs could have far-ranging impacts—in orbit, in the atmosphere and on Earth.

SBDCs could provide substantial compute capacity, serving a range of commercial interests and human needs. They could relieve pressures on terrestrial power systems, many of which are straining under rapidly increasing demand from data centers. They could help respond to growing opposition to data center siting in communities around the world.

At the same time, large constellations of SBDCs would have a range of risks and negative impacts. SBDCs could transform night skies, so that more satellites than stars are visible each night in much of the world. They could create cascades of space debris, rendering parts of LEO unusable for decades. They could lead to uncontrolled space debris falling to Earth. They could deplete the stratospheric ozone layer. They could accelerate global warming. They could dramatically interfere with professional astronomy, significantly reducing the value of billions of dollars invested in astronomical observatories around the world.

SBDC constellations as proposed by leading companies would be vastly larger than anything humanity has ever deployed in space. This scale alone means the risk of "unknown unknowns" (unforeseen risks and impacts) could be significant.

This Roadmap explores the technical feasibility of SBDCs, risks and impacts of SBDCs, and governance regimes for managing SBDCs.

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PART 1:

TECHNICAL FEASIBILITY

CHAPTER 1.1: INTRODUCTION TO SPACE-BASED DATA CENTERS

Text Box 1-1: REFERENCE SBDC

CHAPTER 1.2: POWER SYSTEMS

CHAPTER 1.3: COOLING

CHAPTER 1.4: RADIATION HARDENING

CHAPTER 1.5: LAUNCH CAPACITY

CHAPTER 1.6: VULNERABILITY TO ATTACK

Text Box 1-2: SOFTWARE

CHAPTER 1.1:

INTRODUCTION TO SPACE-BASED DATA CENTERS

Colin McCormick

MAIN MESSAGES

- Operating AI data centers in space is technically feasible but would involve challenges across the full lifecycle of space systems. Space-based data centers (SBDCs) will likely be made up of large groups ("constellations") of individual satellites, each with a power consumption similar to that of the highest-powered satellite ever deployed (the International Space Station).
- SBDC operators are targeting "Sun-synchronous terminator" orbits because they maximize solar PV generation. These orbits will be in high demand, and the scale of proposed SBDC constellations could create highly problematic orbital congestion.
- SBDCs will seek to transfer data (satellite-to-satellite and satellite-to-ground) via growing “internet mega-constellations”. Companies controlling these constellations will have a large competitive advantage in developing scaled SBDCs.
- The cost of launching mass to low Earth orbit (LEO) has fallen dramatically over the past several decades. Forecasting future cost reductions is extremely difficult, but costs could fall to $300/kg by 2040. Reusable rocket boosters are the most important driver of falling launch costs, with some individual boosters already reaching more than 30 re-uses.

Operating computers on satellites in Earth orbit is not new. All current satellite systems host some level of on-board computing power to perform basic operations, such as data processing, communications and attitude control. Existing supply chains provide space-qualified computing, memory and networking equipment, as well as related software stacks, and the broader space industry has decades of experience in operating these systems in orbit. This computing capability is universally powered by on-board, space-qualified solar photovoltaic (PV) and battery systems, with associated supply chains and lengthy in-service experience by the space industry. (Radioisotope power systems have been used on a small number of spacecraft in Earth orbit. For example, see NASA’s site on radioisotope power systems[1] and World Nuclear News 2026.[2])

However, the concept of space-based data centers (SBDCs) would dramatically expand the scale of on-board computing power deployed in Earth orbit. This can be seen by comparing the power requirements with existing satellite power levels. The highest-powered satellite ever deployed is the



International Space Station. Source: Shutterstock

International Space Station (ISS), which has a peak power-generation capacity of 250 kW.[3] The Chinese Tiangong space station was originally designed to operate at roughly 27 kW,[4,5] although this may have increased to over 100 kW.[6] Commercial communications satellites typically operate in the range of 10 kW, and Earth-observation satellites, such as Sentinel-2A and -2B, operate at roughly 1 kW.[7] By contrast, meaningful terrestrial data center compute capability draws megawatts of power, with commercial artificial intelligence (AI) inference data centers in the range of 50 MW and AI training data centers approaching or exceeding 1000 MW (1 GW). Individual racks of AI accelerator chips (such as graphics processing units (GPUs)) consume more than 100 kW, with significant projected increases.[8] As a result, operating "data centers" for the purpose of AI computation (model training and/or inference) on a relevant scale in Earth orbit would involve an enormous increase in power generation and management on satellites, which naturally raises questions about the technical feasibility of this concept.

In addition to power-related issues, the technical feasibility of SBDCs involves challenges across the full life-cycle of space systems, including scaling the supply chain underpinning production and assembly of relevant components, scaling global launch capacity and the associated physical launch infrastructure, scaling and operating the required ground stations and communications infrastructure, scaling the implementation of collision avoidance for mega-constellations, and reliably planning for and implementing end-of-life satellite disposal strategies. Assessing feasibility across all these dimensions is crucial for delivering a comprehensive picture of how realistic it would be to pursue SBDCs at meaningful scale.

To date, many concepts have been advanced that offer potential approaches to SBDCs in a commercial context, including some early pilot demonstrations. Multiple companies have applied to the US Federal Communications Commission (FCC) for licenses to operate SBDCs. This Roadmap will not attempt to assess all proposed SBDC variations but will instead concentrate on the most commercially relevant concepts with direct policy implications. These concepts are driven by three basic design choices:

1. Selecting which orbit(s) to use, including the altitude and inclination (ranging from equatorial to polar orbits). This choice determines the available sunlight and thus PV-generated power capacity, the thermal environment and thus radiator sizing and orientation, the ground-to-orbit communications requirements, the survivability/longevity of the satellite due to radiation and orbital debris impacts, the launch costs and feasible launch sites, and the end-of-life disposal options. Most commercially relevant concepts propose using nearly polar, sun-synchronous orbits (SSOs) that are calibrated to follow the dawn or dusk terminator because they remain almost entirely in sunlight. (Some proposals have also included other

orbital inclinations.)[9] They also propose using altitudes in the range of 500–800 km or higher. (The ISS orbits at 400-km altitude, roughly halfway between an equatorial and polar inclination.)

2. Designing the overall satellite constellation, including the number and arrangement of individual satellites. This choice determines the in-orbit communications needs among SBDC satellites, the number and type of launches needed, the survivability/longevity of the satellites and the end-of-life disposal options. Most commercially relevant concepts propose a large number (hundreds to hundreds of thousands) of individual satellites operating as a constellation, with each hosting roughly one rack equivalent of AI accelerator chips. By leveraging high-bandwidth optical communications, these individual satellites remain digitally connected and jointly form a full-scale SBDC.

3. Choosing individual satellite mission life. While traditional, government-funded science missions, such as Landsat and Sentinel, are designed for multi-decadal service, individual satellites forming an SBDC constellation may have far shorter planned lifetimes, particularly given the rapid obsolescence of AI accelerator chip technology. Most commercially relevant concepts propose individual satellite mission lifetimes in the range of roughly 3–5 years, with no provision for hardware upgrades or maintenance during service life. To maintain the overall constellation, replacement satellites would be launched continually, and end-of-life satellites would be de-orbited.

Within this range of design choices, several key factors drive the technical feasibility of building, launching and operating this form of SBDC.

1. Mass of individual satellites per unit of power consumed by the information technology (IT) equipment—essentially how heavy an individual satellite must be to host a fixed amount of AI compute power. This mass must be small enough per kW of power to enable economically viable launches and safe end-of-life disposal. The main contributions to the mass are the solar PV array, batteries, cooling equipment, AI chips and memory, communications systems and the satellite bus/spacecraft platform. In the later sections of this chapter, we examine the main subsystems and their likely masses, including a high-level assessment of whether technology innovation could meaningfully reduce the mass in the near to medium future.

2. Global launch capacity and per-kg costs for these individual satellites. While the number of objects launched into space each year has risen dramatically, it is still only thousands, not hundreds of thousands.[10] SBDC constellations that envision very large numbers of satellites would require correspondingly large numbers of launches. Due to relatively short mission lifetimes for each satellite, the cadence of launches would also need to continue at a high pace indefinitely. The current global launch infrastructure, including rockets and launch sites, would need to be expanded significantly to achieve this pace. Notably, not all launch sites are able to place satellites into SSOs given geographic constraints, so the siting of new launch sites and expansion of existing ones may be a significant constraint.

3. Supply chain for key satellite components. The solar PV arrays, batteries, cooling equipment and other components the space industry currently uses are typically supplied at small volumes by highly specialized manufacturers. As for AI accelerator chips, memory and networking equipment, there is essentially no validated manufacturing base and little clarity on how well conventional components could be used directly on satellites. This supply chain will need dramatic expansion to service SBDCs at full scale.

4. Data transfer networks for SBDC constellations requiring extremely high-bandwidth communications. To perform fast AI compute operations (both training and inference), SBDCs will require scaled communication networks both in-orbit (between/among satellites) and ground-to-orbit. A small handful of incumbent companies—most notably Space-X (Starlink), Amazon (Leo) and Blue Origin (TeraWave)—are rapidly building large mega-constellations of communications satellites (providing "internet from space") and are clearly positioning themselves to provide this networking service. Other companies are also intending to develop these constellations, including Eutelsat OneWeb, Rivada Space Networks, Telesat, GuoWang and Qianfan. From the viewpoint of market competition, early movers may create impenetrable barriers to other entrants by controlling space-based data communications. Access to these high-speed networks in orbit, as well as access to radio frequency spectrum to support ground-to-orbit communications, will be essential to operating SBDCs. (Mega-constellations also create considerable orbital crowding and satellite disposal risks.[11])

5. Regulatory environment for satellite launches, operations and disposal. While not a technical challenge per se, regulatory guidance will shape design choices and engineering approaches in important ways.

The following sections address these major topics, although not in exhaustive detail. Other SBDC concepts that have been proposed but will not be addressed in this roadmap include systems in orbit around or on the surface of the Moon[12] and systems in highly eccentric (Molniya or Tundra) Earth orbits.

A. Orbits

There are three basic parameters that describe how objects orbit the Earth. The altitude is the height of the orbit above the Earth's surface, the inclination is the angle the orbit makes with the equator, and the eccentricity is how "stretched" or oval-like the orbit is compared to a perfect circle (see Fig. 1.1-1).[13,14]

Orbits with a high altitude (roughly 36,000 km), zero inclination (i.e., orbiting over the equator) and zero eccentricity (i.e., circular) are known as geostationary ("GEO"). They complete one full revolution around the Earth in 24 hours, making them always appear "stationary" in the sky above a ground observer. GEO orbits have historically been the most commercially valuable, and positions ("slots") in GEO are coordinated by the International Telecommunication Union (ITU) because a small number of high-powered telecommunications satellites placed in these orbits can provide high-bandwidth communications services over large geographic areas.

Low Earth orbits ("LEO," up to roughly 2000 km) have historically been used for many other purposes, including Earth observation (e.g., National Aeronautics and Space Administration (NASA) Landsat missions) and commercial satellite imagery. Satellites in these orbits complete one rotation much more quickly than GEO. For example, the International Space Station (ISS) (400-km altitude) completes one orbit in roughly 90 minutes.[15] Satellites in LEO are therefore constantly moving across the sky to an observer on the ground, spending much of their time over the horizon and therefore out of sight. Communication with satellites in LEO has typically required a network of ground stations around the Earth or a mission that tolerates waiting long periods of time (up to hours) to transfer data to/from the satellite. The geographic placement of these ground stations depends on orbital inclination because the inclination of the orbit (from equatorial to polar) affects the ground locations that the satellite passes over.

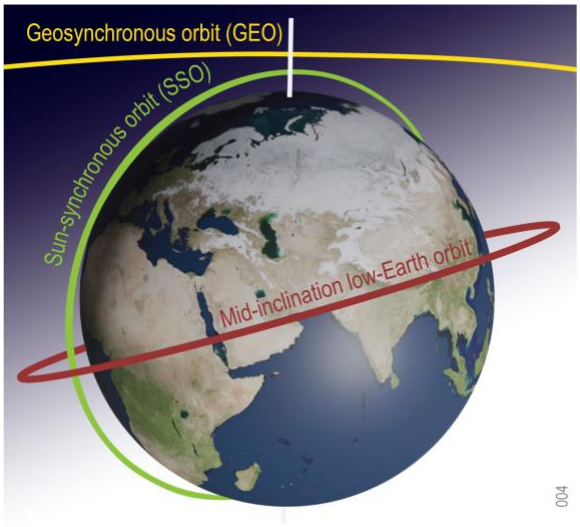


Figure 1.1-1. *Illustrative Earth orbits. Green: a sun-synchronous orbit (SSO) at roughly 640-km altitude and 98° inclination (nearly polar). Red: roughly 2000-km altitude and 30° inclination. Yellow: geosynchronous orbit (GEO) at roughly 36,000-km altitude and 0° inclination (equatorial). The Earth's pole is indicated for reference only. Source: Colin McCormick*

The advent of "mega-constellations" with hundreds or thousands of satellites in LEO is changing this situation. These large groups of satellites are launched and deployed so that they spread out along one or more orbital paths, with at least one satellite always in view of a ground station.[16] Satellites in the constellation "relay" data among themselves to transfer it to/from the ground without significant delay. Mega-constellations have made LEO orbits of great interest to operators building satellite communication networks, potentially shifting economic value away from GEO.[17] A further advantage of LEO is lower launch costs because less powerful rockets are needed to reach these lower altitudes.

For several reasons, LEO orbits are also the primary focus of companies pursuing space-based data centers (SBDCs). First, SBDCs in LEO could use the communications backbone of LEO-based "internet mega-constellations" to provide fast data transfer (see Chapter 1.1(B)-Communications). Second, launch costs to LEO are relatively low and likely falling as global launch capacity grows (see Chapter 1.1(C)-Launch Costs). And third, LEO orbits with inclinations close to polar orbits are known as "sun-synchronous" (SSOs), meaning they always fly over points on the ground at the same local time. When this time is calibrated to be either dawn or dusk, the resulting "terminator" orbit places the satellite in near-continual sunshine (almost never entering the Earth's shadow), allowing solar photovoltaic (PV) arrays to continually provide power and reducing the need for batteries and excess solar panel capacity to charge them (see Chapter 1.2-Power Systems). Terminator orbits also stabilize the satellite's thermal environment: because the Sun's direction relative to the orbit stays nearly constant year-round, a radiator can hold a favorable, near-constant orientation to deep space (see

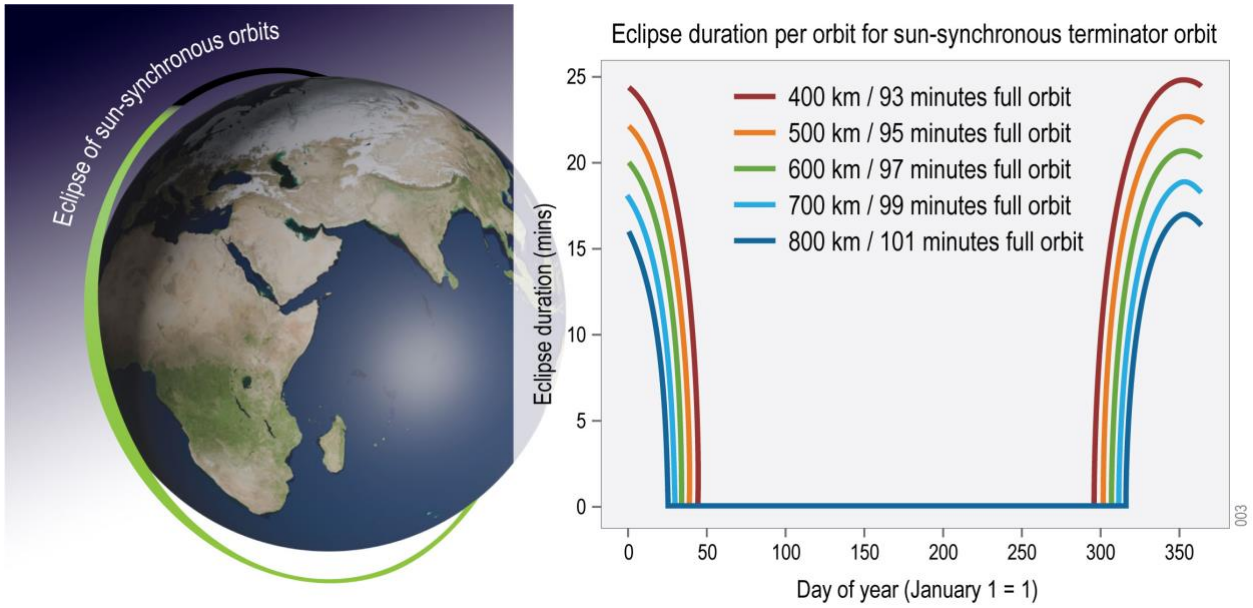


Figure 1.1-2. *Left: Illustration of 640-km-altitude terminator orbit in maximum eclipse, which occurs at solstice when the Earth's axis is tilted farthest from the sun. Each orbit lasts 98 minutes. Right: Eclipse duration per orbit by day of the (calendar) year. Source: Colin McCormick*

Chapter 1.3-Cooling). Satellites in these orbits experience a maximum of roughly 30 minutes of eclipse" (passage through the Earth's shadow) during one part of the year and continual solar illumination at other times (See Fig 1.1-2). Some commercial SBDC proposals have also included other orbital inclinations, which could reduce potential overcrowding in terminator orbits (see Chapter 2.2-Orbital Congestion and Debris) at the cost of increased solar PV array and battery requirements.[9]

Another implication of the choice to use terminator orbits (or any SSO) is the impact on launch site suitability. Rocket launches are typically conducted in locations where the initial stage of the launch is over open ocean or sparsely populated land. This reduces the chance of damage or injuries from falling debris in case of a launch failure. When launching into equatorial or low-inclination orbits, rockets launch to the east to match the rotation of the Earth, motivating the selection of launch sites on east-facing coastlines, such as the Kennedy Space Center (USA), the Tanegashima Space Center (Japan), the Guiana Space Centre (French Guiana) and the Wenchang Space Launch Site (China). However, when launching into polar orbits, rockets typically launch in a north or south direction. Existing launch sites may be near more populated areas in these directions, reducing their suitability for polar launches and potentially requiring development of new launch sites (see Chapter 1.5-Launch Capacity); this issue can lead to international disputes around damage from rocket launch failures (for example, see Lingle, 2026[18]).

While LEO technically extends to roughly 2000 km, many SBDC operators are considering orbits with altitudes of roughly 500 to 800 km. This is determined by several factors. Below roughly 400 km, drag from the upper reaches of the atmosphere can continually reduce a satellite's speed, eventually

causing it to re-enter the atmosphere and be destroyed unless the satellite periodically uses its engines to "boost" it back up.[19] Because SBDCs would likely carry very large-area solar PV arrays and radiator panels, this drag effect would be even more pronounced than for most current satellites. Above roughly 800 km, the impact of ionizing radiation increases substantially, potentially damaging satellite electronics and/or solar PV arrays and causing malfunctions.[20] (Significant radiation exposure also occurs below this altitude; see Chapter 1.4-Radiation Hardening.) A final consideration is the risk of collision with micrometeoroids and orbital debris (known collectively as MMOD). Satellites typically can carry shielding to protect sensitive components from impact, but this adds mass, cost and design complexity.[21] While satellites can perform maneuvers to avoid some of this material, orbits that avoid high MMOD concentrations reduce the risk of damaging or catastrophic collisions. Orbits with altitudes ranging from 500 to 800 km are appealing because they avoid some high-MMOD concentrations. However, significant risk would remain and would be exacerbated by the launch of large mega-constellations (see Section 2.2-Orbital Congestion and Debris).[22]

Finally, the choice of orbit influences the options for end-of-life disposal of individual SBDC satellites. Typically, higher orbits require extra propellant to actively bring them down into the atmosphere to burn up during re-entry, which adds mass and cost. "Disposal" or "graveyard" orbits are another option, but active propulsion is also required to maneuver satellites into these orbits.

Desirable orbits as described may be in extremely high demand by SBDC developers, raising questions about a range of impacts if satellites are placed into these orbits in large numbers. Safe avoidance of MMOD and other satellites will be increasingly critical, and without a formal process in place for sharing orbital "slots" (unlike GEO), this issue may be particularly challenging and will limit the total amount of compute in orbit.

B. Communications

Satellite communications have historically used the radio spectrum, with a dedicated band of reserved frequencies (see Figure 1.2-3).[23] The US government has recently sought to expand the amount of spectrum dedicated to satellite communications, particularly for "emergent space activities," including large constellations in low Earth orbit (LEO) providing high-speed broadband.[24] There is also reason to believe that some technical reforms can expand the ability of limited available spectrum to serve a growing number of satellites, such as dynamic spectrum sharing.[25,26] However, even with these changes, the use of spectrum will clearly be a point of competitive tension as demand grows dramatically with planned LEO mega-constellations.[27] This will impact space-based data centers (SBDCs) primarily through their ability to access high-bandwidth, low-latency ground-satellite data transfer, and how this bandwidth is allocated commercially will strongly influence the rate of mega-constellation deployment.[28] International rules governing the use of key radio frequency spectrum will be negotiated by national governments in 2027, with significant implications for countries engaged in or considering scaling up LEO mega-constellations.[29]

SBDCs will also have a major need for high-bandwidth, low-latency satellite-to-satellite data transfer to perform artificial intelligence (AI) compute tasks (training and inference). There are two reasons for this: (1) to enable data relay across a large constellation for the purpose of reaching a satellite

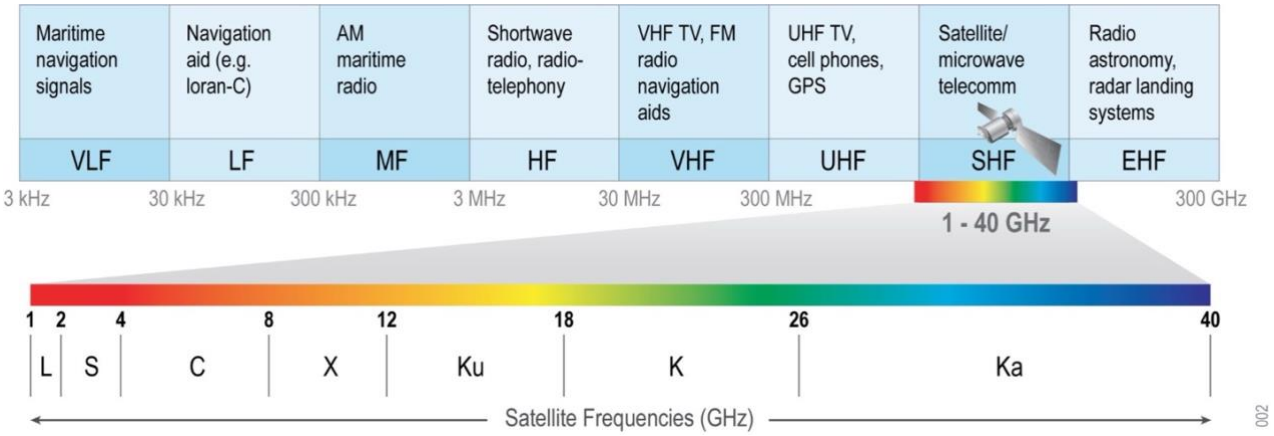


Figure 1.1-3. *Radio frequency spectrum with bands reserved for satellite communications. Source: Colin McCormick*

currently positioned over a ground station, which allows for low latency, and (2) to enable large AI models to be run in parallel across AI accelerator chips on multiple SBDC satellites.

For comparison, the rack-to-rack ("scale out") bandwidth in typical terrestrial AI data centers is 400 gigabits per second (Gbps) or higher, allowing large models to efficiently use multiple racks of AI accelerator chips simultaneously.[30] Because individual SBDC satellites will likely have levels of power consumption and compute that are roughly comparable to individual racks in terrestrial data centers, similar satellite-to-satellite bandwidth will likely be required. This data rate is far above what current satellite radio-frequency communication links (operating in the Ku- and Ka-bands) can achieve, which is typically only a few Gbps at best.

However, recent major technical advances in the use of free-space optical (laser) communications for satellite-to-satellite communications have enabled far higher data rates.[31,32] Driven in part by technical standards and procurement actions by the US Space Development Agency (SDA),[33] optical communication terminals (OCTs) for satellite-to-satellite communications are entering the market and are being demonstrated in orbit.[34] These devices use laser beams to transmit data to optical receivers mounted on other satellites, forming mesh networks that achieve very high data rates and entirely avoid using radio spectrum. One challenging aspect of operating OCTs is maintaining precise pointing accuracy because terminals must align and hold a relatively small laser beam spot on a satellite-mounted receiver terminal tens to hundreds of kilometers away. However, OCTs have achieved bandwidths well over 1 Gbps and are targeting 100 Gbps or higher for constellations of satellites in LEO. These demonstrations suggest that this technology could provide the necessary bandwidth for individual SBDC satellites to transfer data at the rate required for large-model AI inference tasks. Efforts in Japan,[35] China,[36] Europe[37] and elsewhere are also rapidly advancing this technology. (While OCTs can be used for ground-to-orbit communication, the laser beams do not pass through clouds, meaning that communications can be disrupted by weather, which is not an issue for radio.)

OCTs are lightweight and draw relatively little power, meaning they are largely immaterial for mass and power budgets on individual satellites.[38] However, the supply chain for OCTs has a major bottleneck. Because demand for satellite-to-satellite laser communication has risen so dramatically, the production base has not been able to keep pace, and commercial availability of OCTs is highly limited. This subsector is likely to play a strategic role in determining the pace of SBDC deployment.[39,40]

In-orbit communication networks will also play an enormously important market role in the development of SBDCs. Companies that own these networks (particularly those based on mega-constellations) will have a major competitive advantage in operating SBDCs due to their ability to rapidly transfer data to anywhere in LEO—essentially a form of vertical integration across the full AI stack. Other companies seeking to develop SBDCs will need to either replicate this communications network (at enormous expense) or seek to secure data-transfer services over networks owned by third parties. Because nearly all the owners of data-transfer mega-constellations are themselves proposing to build SBDCs, they may be unlikely to provide these services to rival SBDC operators absent some form of open-access mandate. Such a mandate would be analogous to open-access frameworks for railroad networks,[41] electricity transmission[42] and terrestrial broadband provision.[43] The competitive development of SBDCs beyond a small handful of early-mover companies may therefore require policymakers to carefully examine whether some form of similar open-access requirements should apply to LEO mega-constellations. (See the discussion in Chapter 3.1-Key Governance Issues and Recommendations.)

C. Launch Costs

The cost of launching mass into low Earth orbit (LEO) has dropped significantly over the last several decades. NASA's Space Shuttle (operational 1981–2011) had a launch cost to LEO of approximately $55,000–65,000/kg.[44,45] Launch cost to LEO for the Falcon 9 is now approximately $2600/kg, and the Falcon Heavy cost is approximately $1500/kg.[44,46] Speculation on the future trajectory of launch costs is extensive, and specific claims by Elon Musk about SpaceX launch costs falling to below $100/kg in the near future have received enormous attention.[47] Realizing these costs would have dramatic impacts on the overall economics of satellite deployments, shifting constraints from cost to other parameters, such as orbital slot availability, launch capacity or radio frequency spectrum allocation.[48,49]



Space Shuttle blasting off. Source: Shutterstock

However, launch costs are complex to evaluate and are highly variable across platforms.[50] This makes it difficult to identify a single value for historic observed launch costs. Recent efforts to compile comprehensive historic launch cost data

using a harmonized methodology suggest that average actual costs have fallen from roughly $87,000/kg in 1960 to roughly $3900/kg in 2025.[51] It is important to note that these average cost reductions are not necessarily the result of technology improvement within a specific rocket family; much of the early cost reductions were due to reallocating payloads to other less expensive rocket systems.

Nevertheless, average launch costs have historically correlated with an increase in the total (cumulative) payload mass launched to LEO, according to an "experience curve" mathematical relationship (also known as Wright's Law). The observed correlation is that a doubling of the total (cumulative) payload mass launched to LEO has resulted in a 21.2% cost reduction on average across this time period.[51] Notably, this cost-reduction figure has been significantly higher since the end of the Cold War (1989): 44% cost reduction per doubling, suggesting that cost reductions have followed a structurally different and faster trend over the last three decades.

Historic technology "learning rates" such as these are not always good predictors of future cost reductions, but they can be helpful in evaluating potential future scenarios.[52] If the space industry continues to realize these rates, average costs would reach $1600/kg by 2030 and $300/kg by 2040 under a central scenario of future launches. Higher annual launch rates would accelerate this cost reduction but would require launching enormous amounts of mass. The cumulative mass launched to LEO through 2025 is approximately 43 million kilograms, which is set to double in approximately 8 years under current launch trends. (The five-year rolling average of the annual rate of increase of cumulative mass launched to LEO was 1.09 in 2025, using data from Terzi et al., 2026.[51] This rate of increase would lead to a doubling of cumulative mass launched in about 8 years.) This increase in cumulative mass launched, if the historic (post-1989) learning rate of 44% holds, is the basis for the 2030 cost forecast noted above. Under similar assumptions about sustained learning rates, reaching a launch cost of $200/kg would require roughly 5 doublings in the cumulative payload launched to LEO (post-2025). Current launch trends suggest this would take four decades, implying that reaching this cost before then is unlikely.

However, this projection is extremely sensitive to assumptions about the growth in future launch rates, and the acceleration in launches over the past five years adds enormous uncertainty to this forecast. For this and other reasons, efforts to forecast launch-cost reductions have led to a wide range of predictions. For example, earlier academic analysis of cost-reduction trends based on launch costs between 2000 and 2020 found that costs would not fall below $1000/kg before 2045.[53] Separate analysis released by financial analysts in 2022 found that launch costs could reach as low as $100/kg by 2040 or even lower in a "bullish" scenario.[54]

Projecting future launch trends (both in number and in total mass) is particularly challenging today because of the extraordinary concentration of launches in just one company (SpaceX), which is responsible for far over half of all mass in LEO. This concentration is a nearly unprecedented situation in any major economic sector.[55,56] While other competitors are seeking to enter the heavy-launch market, they remain limited.[57,58] One important implication of this concentration is that there would be no incentive or market pressure to pass reduced launch costs on to third parties in the form of

reduced launch prices. This issue is particularly pertinent if a company has other, company-internal uses for this launch capacity, such as extending its own communication and data-center mega-constellations.[59] As a result, even if average launch costs to LEO were to fall dramatically for a single firm in the near term, those reductions could remain essentially unavailable to the market at large.



Falcon 9 First Stage launch. Source: Shutterstock

It is helpful to analyze these launch trends in the context of the total mass of a SBDC. The reference 1-GW SBDC analyzed in this Roadmap (see XYZ) would require ten thousand 2.5-ton satellites, each with a100-kW power level, weighing a total of 25,000 metric tonnes (25 million kg). This is equivalent to roughly half of all mass launched to LEO cumulatively; if it were launched, it would significantly contribute to a doubling of this value. (Ongoing launches to maintain the constellation would increase this figure.) It would take roughly 50 of these 1-GW SBDCs to equal the additional cumulative mass launched to LEO to provide 5 doublings and to reduce the associated launch costs to $200/kg.

Beyond industry-wide averages, several major new launch vehicles are potentially driving down specific launch costs. The most prominent of these is SpaceX's Starship, with external analysts suggesting that it could deliver launch costs to LEO "into the low hundreds of dollars [per kg]."[60] However, there has been no independent cost assessment. Further, while repeated demonstrations of launch capability have been achieved, the high-cadence re-launch scenarios underpinning cost estimates have not yet been realized. The Blue Origin New Glenn rocket is also under development with some successful initial flight demonstrations, although third-party cost analyses are similarly unavailable. Multiple Chinese companies are developing heavy-lift rockets and have demonstrated some initial flight success, although no cost information is available. A key dimension of these efforts is the crucial role of re-usability of booster stages, which dominates cost estimates by amortizing costs over some number of re-uses.[61] SpaceX has demonstrated re-use of individual boosters over 30 times in individual cases, suggesting that achieving high booster re-use count may be feasible for other rocket systems, and costs may consequently fall faster than previously predicted.[62]

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Text Box 1-1:

REFERENCE SPACE-BASED DATA CENTER (SBDC)

Roger Aines and Colin McCormick

To help analyze several topics in this Roadmap, we have defined a "Reference space-based data center (SBDC)." Our Reference SBDC represents an individual satellite carrying artificial intelligence (AI) compute within a larger constellation and has the characteristics set forth below. We chose these characteristics to reflect common design choices by commercially relevant SBDC developers, and they underpin quantitative estimates in this Roadmap. Other design parameters are possible, of course. Our goal in defining this Reference SBDC is to provide a consistent starting point for analysis, not definitive conclusions or results.

Parameter	Value	Notes
Orbit inclination	Sun-synchronous, at or near "terminator" orbit	This allows maximum solar power generation with minimum eclipse duration.
Orbit altitude	500–800 km	This roughly optimizes launch cost, radiation exposure and debris exposure.
Average information technology (IT) equipment power consumption	100 kW	This is the average power consumption of the IT equipment on board the satellite. The full satellite will consume perhaps 20% more than this because of additional "housekeeping" power demand.
Satellite power system	Solar photovoltaic (PV) array, battery, and power conditioning and distribution unit	The PV arrays and battery will be sized to provide sufficient power for the entire satellite, including serving the full load during eclipses.

Cooling system	Flat-panel radiators and mechanically pumped coolant	This provides sufficient cooling to maintain the IT equipment and other systems at a safe operating temperature.
Individual satellite lifetime	5 years	This roughly matches the graphics processing unit (GPU) obsolescence period. It assumes no on-orbit replacements or servicing.
Communications	Optical data links (intra-satellite) plus radio (ground-to-orbit)	This allows fast data transfer within the constellation and sustained ground-to-orbit communications.
Maneuvering	Sufficient propulsion for collision avoidance and end-of-life deorbiting	This may include Hall Effect thrusters or other relevant systems.
Individual satellite mass	2.5 tonnes	This is roughly based on developer claims.

A SBDC developer seeking to put 1 GW of AI compute into orbit would therefore need to always have 10,000 independent satellites (reference SBDCs) in operation, each with the characteristics listed above. The satellites would need to be placed in orbits that are close enough to allow them to communicate (to share data during computations) but far apart enough to allow for safe maneuvering to avoid orbital debris and other satellites.

Since each individual satellite would last for only 5 years, they would need to be regularly replaced to maintain the 1-GW compute capacity. If launched by SpaceX Starship or similar rockets once per week, this would imply a continuous 5-year cycle of refreshment/replacement of the 10,000 satellites, with 2000 launched and 2000 de-orbited per year, or roughly 38 per week.

We further assume that SBDC operators would follow all relevant regulations from Federal Communications Commission (FCC) and other authorities on orbital safety, deorbit and communications.

CHAPTER 1.2:

POWER SYSTEMS

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MAIN MESSAGES

- The power system is a significant contributor to the overall weight of a spaced-based data center (SBDC).
- Significant technology innovations and major expansions of supply chains would be needed to limit the weight of a 100-kW SBDC to one tonne (the weight suggested by SpaceX in US regulatory filings).
- Heavier satellites cost more to launch, have greater de-orbiting risks, emit more greenhouse gases (GHGs) and do more damage to the ozone layer.

Power systems for space-based data centers (SBDCs) must meet several requirements. First, these power systems must include solar photovoltaic (PV) arrays large enough to provide power for the satellite's information technology (IT) equipment and other systems. Second, these solar PV arrays must also have generation capacity to simultaneously charge batteries, which are needed to run the satellite during orbital eclipse periods (when the satellite moves through Earth's shadow and the PV arrays stop generating power). Third, if the SBDC will provide artificial intelligence (AI) compute services continuously, the power systems must carry batteries that are large enough to hold the electrical charge needed to run the full IT capabilities of the satellite during the orbital eclipse period, which is roughly 15–25 minutes for satellites orbiting at the altitude of the Reference SBDC (500–800 km, (see Text Box 1-1). Finally, SBDC power systems must include cabling and voltage transformers, known as power conditioning and distribution units (PCDUs), that effectively condition and route electric power among the PV array, batteries, IT equipment and other systems.



A satellite in orbit with solar photovoltaic (PV) panels. Source: Shutterstock

Designing a power system to meet these requirements would be easy if weight did not matter. But the weight of an SBDC satellite has a significant impact on its launch costs, de-orbiting risk, emissions and other characteristics. The power system will be a major contributor to the

overall weight (mass) of an SBDC, so understanding the feasible range of power system weight is important.

SBDC developers state they will be able to design power systems with high power but low weight, which means the total number of launches to build a targeted amount of compute (e.g., 1 GW) would be relatively small. SpaceX has made the most prominent claim, suggesting that a satellite with 100 kW of compute power would weigh only a single tonne (an overall power-to-weight ratio of 100 W/kg).[1-4]

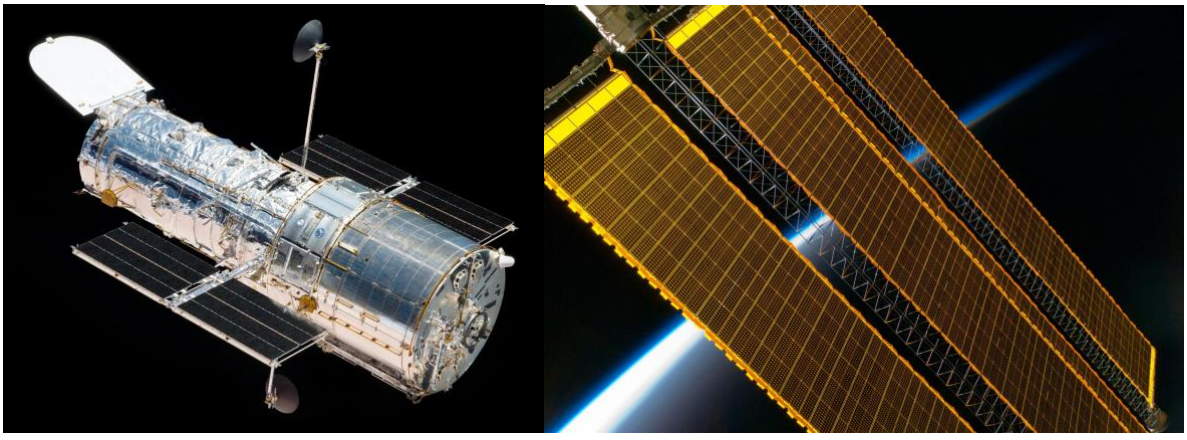
If SBDC developers cannot engineer power systems within their weight targets, more launches will be required to achieve any given level of compute. This would increase costs, de-orbiting risks, greenhouse gas (GHG) emissions and stratospheric ozone impacts. As a result, policymakers should assess SBDC developers' claims with respect to power system weight in assessing the risks and impacts of SBDCs. This chapter analyzes the power-to-weight ratios of SBDC power systems, highlighting the policy impacts of this figure.

A. Satellite Power System Components

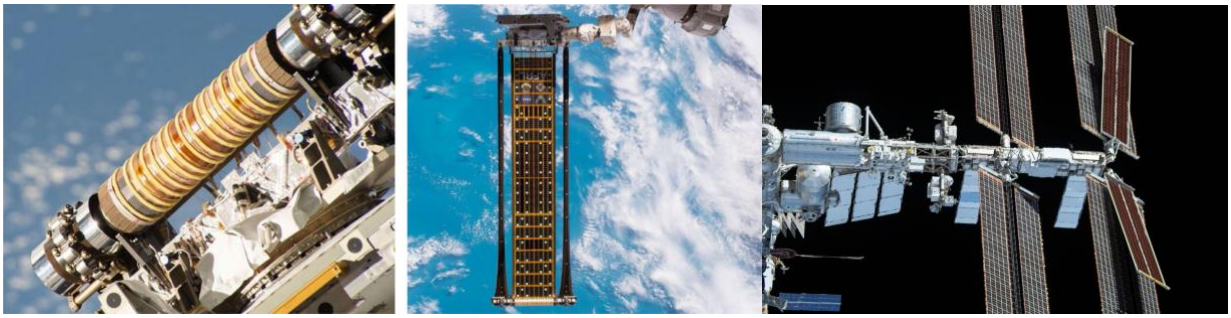
The main components of the power systems in today's satellites are photovoltaics (solar panels), batteries and power-distribution equipment (e.g., transformers).

i. Solar photovoltaic (PV) array

Satellites currently use either triple-junction gallium arsenide (GaAs) or silicon solar PV arrays (or both). GaAs PV arrays have several important advantages. They are relatively resistant to radiation damage, meaning that panels retain their generating capacity in space far longer than silicon PV panels. They also have a high conversion efficiency (roughly 30%, compared to 20% or lower for silicon) meaning that panels can be lighter and have a smaller area to generate the same amount of power.[5] But GaAs is substantially more expensive than conventional silicon PV, and the current global production base is roughly 2 MW per year, far too small to supply PV arrays at the GW scale proposed by SBDC developers.[6] Efforts to expand this production face serious material supply



The triple-junction gallium arsenide (GaAs) photovoltaic (PV) solar panels on the Hubble Space Telescope, 2009. Source: NASA. Silicon solar PV arrays on the International Space Station (ISS), 2008. Source: NASA



The ISS roll-out solar arrays (ROSAs) being deployed. Source: Yan et al., 2025.[15] Open Access. CC BY-NC-ND 4.0. The ISS with its new roll-out solar arrays, 2021. Source: NASA

challenges because global gallium supply is heavily concentrated in China, which has sharply restricted exports.[7] Operating SBDCs on triple-junction GaAs PV therefore faces significant cost and supply constraints.

To lower costs and enable high-volume production, many satellite developers use silicon PV, despite its disadvantages. Fortunately, recent innovations have helped mitigate some of silicon's shortcomings. Most notably, silicon PV arrays that are fitted with cover glass have partly improved radiation resistance, at the cost of increased weight and reduced conversion efficiency.[8,9] The use of polymer layers to radiation-harden silicon PV on flexible substrates for satellite applications is also emerging.[10] The disadvantages of operating SBDCs on silicon PV may therefore be somewhat reduced, and the advantages of being able to access a mature and widely scaled silicon PV supply chain may outweigh them.

Beyond silicon, other potential PV options for SBDCs under development include copper indium gallium selenide (CIGS),[11] perovskites and organic solar cells.[12] While these systems theoretically can achieve high power-to-weight ratios (enabling lightweight SBDCs), they have not yet been demonstrated at scale in space, and their respective production bases also remain relatively small compared to silicon PV.

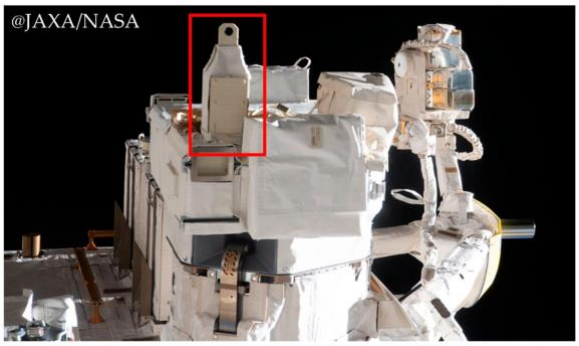
The International Space Station (ISS) carries the largest solar array of any spacecraft ever launched. Its original arrays use monocrystalline silicon PV, but radiation damage has reduced their generating capacity significantly.[13] Beginning in 2021, they were augmented with "roll-out solar arrays" (ROSAs) using GaAs PV.[14] The Chinese Tiangong space station is also equipped with GaAs solar PV.[15] State-of-the-art ROSA units use extremely light carbon composite lenticular tubes for deployment booms.



GaAs solar PV on the Chinese space station. Source: Yan et al., 2025.[15] Open Access. CC BY NC-ND 4.0

When considering the type of PV that could be used for SBDCs, it is important to note the highly competitive market for space-capable PV with favorable characteristics (lightweight, radiation-hard, high conversion efficiency). Demand from communications mega-constellations and space-based solar power for terrestrial consumption may grow rapidly in the near term, potentially making supply constraints even tighter.[9] SBDC developers targeting high-power (>100 kW) satellites with low weight may therefore need to adopt emerging and still largely unproven PV technologies, sourced from a still-nascent production base, or they may need to procure at higher prices to secure supply.

ii. Batteries and power conditioning and distribution units (PCDUs)



Inside the red box: a lithium-ion battery on the exposed section of the International Space Station (ISS). Source: Miyazawa et al., 2025.[19] Open Access. CC BY 4.0

Satellite power systems also incorporate batteries to power on-board systems during the eclipse period of the orbit. Lithium-ion batteries offer many advantages and have become standard for many satellite applications.[16] Advanced lithium-ion batteries can store up to roughly 250 Wh per kilogram (Wh/kg).[17] The size of the battery carried by an individual SBDC satellite would depend on its total power consumption (in kW) and the amount of time it would spend in eclipse, during which the battery would need to discharge power. Additionally, batteries cannot fully discharge their stored energy without dramatically shortening their lifetime, so the depth-of-discharge is typically limited to no more than 40% for satellites in low Earth orbit (LEO).[18]

PCDUs combine different power regulation and conversion equipment to optimize solar array generation, control power flow to loads and batteries, protect against electrical faults and provide other power system services.[20] They generate heat (for example, through voltage conversion), which must be dissipated by the thermal-management system. Because they are so central to the overall functioning of the satellite, they must be highly reliable, with redundant systems to avoid single-point failures. Satellite developers are increasingly looking to wide-bandgap semiconductors like gallium nitride (GaN) rather than silicon to reduce weight and improve PCDU performance.[21]

B. Power System Weight Estimate

The weight of solar panels, batteries and PCDUs is a significant percentage of the total weight of satellites. Reducing the weight of these components while maintaining (or improving) their performance is a key challenge in keeping the weight of an SBDC as low as possible. SBDC developers have not shared details of their potential power system designs, so to estimate the likely weight of the power system for our Reference 100-kW SBDC (see Text Box 1-1), we use approximate values and compare them with the design of other satellite systems.

i. Solar photovoltaic (PV) array

State-of-the-art ROSA units, such as those used on the ISS, if equipped with triple-junction GaAs PV panels, could potentially achieve a component-level power-to-weight ratio of 218 W/kg.[15,22] This suggests a 100-kW solar PV array could weigh as little as 0.46 tonnes. However, as noted above, GaAs PV panels are likely to be highly supply-constrained, and ROSA units have not yet demonstrated that high of a power-to-weight ratio in scaled deployment. ROSA units using silicon PV panels would have a lower power-to-weight ratio and would consequently have to be heavier to supply 100 kW.

ii. Batteries and power conditioning and distribution units (PCDUs)

A 100-kW SBDC with 30 minutes of eclipse time and a 40% depth of discharge limit would need a minimum of 125 kWh of battery energy capacity to fully power the satellite for the duration of each eclipse. For comparison, the ISS has approximately 360 kWh of battery capacity, meaning each SBDC would need roughly one-third of the ISS battery capacity.[23-25] Space-qualified lithium-ion batteries have been demonstrated with up to roughly 250 Wh/kg of energy capacity at the pack level.[26,27] This suggests that a 125-kWh battery would weigh roughly 500 kg (0.5 tonne). The SpaceX Starlink V2 mini satellites use approximately 11 kWh of nickel manganese cobalt (NMC) lithium-ion batteries[28] to serve a total power demand that may be 28 kW (third-party-validated figures are not available).[29]

No systematic scaling information is available for the weight of PCDUs relative to satellite power. Proven systems have a weight-to-power ratio of roughly 12 kg/kW for larger (kW-scale) satellites.[30,31] This suggests that a PCDU serving a 100-kW satellite would weigh 1.2 tonnes.

Using these rough estimates, the total power system of a 100-kW SBDC is likely to be no lighter than 2.2 tonnes (see Table 1.2-1). This alone—without any cooling systems, IT equipment or communications—is over twice the stated estimates of the entire satellite weight projected by SpaceX as noted above. Reducing this value would require major innovations across multiple systems, drawing on nascent supply chains that are many orders of magnitude smaller than what would be required for GW-scale SBDC constellations.

Table 1.2-1: *Estimated weight of the power system components for a 100-kW space-based data center (SBDC).*

Component	Rough scaling value	Weight for a 100-kW space-based data center (SBDC)
Solar photovoltaic (PV) arrays	218 W/kg	0.46 tonnes
Batteries	250 Wh/kg	0.50 tonnes
Power conditioning and distribution unit (PCDU)	12 kg/kW	1.2 tonnes
Total	N/A	2.16 tonnes



Launch and separation of the HOTBIRD 13F satellite in October 2022. Source: ESA

C. Comparison with Current Satellites

The above estimate of power system weight can be put into context with current satellite weights. As noted, the ISS is the largest satellite ever launched, with a total weight of roughly 420 tonnes[32] and a total power generation capacity of 215 kW.[33] This suggests the overall satellite power-to-weight ratio is 0.5 W/kg, or 200 times lower than stated SBDC targets of 100 W/kg.

Another important comparison can be made to the HOTBIRD 13F and 13G satellites, which use the Airbus Eurostar Neo satellite platform. These satellites have 22 kW of electrical power (supplied by triple-junction GaAs PV arrays[34]) and weigh 4500 kg at launch, for a power-to-weight ratio of 4.9 W/kg, 20 times lower than SBDC design targets.[35]

The most relevant comparison may be with the SpaceX Starlink V2 satellite, which has many similarities to an SBDC satellite (although the Starlink V2 is significantly smaller). The V2 mini may have approximately 28 kW of electrical power[29] (as noted, third-party validated figures are not available) and weighs 575 kg at launch, for a presumed power-to-weight ratio of 49 W/kg, half the SBDC design target.

D. Conclusions

This analysis suggests that the power system required for a 100-kW SBDC satellite would weigh over 2 tonnes by itself. Significant technology innovations and major expansion of supply chains for specific space-qualified equipment would be needed to reduce this figure. While the power system is likely to make up a large fraction of the overall satellite's weight, the weight of the cooling system, IT equipment, communications equipment and other systems will make the total weight significantly higher. SpaceX's stated weight target (1 tonne for a 100-kW SBDC) is far more optimistic than this estimate would suggest. It is also far more optimistic than any previously demonstrated satellite.

If SBDC developers cannot engineer satellites within proposed weight targets, the overall impacts of a SBDC constellation for any given level of compute would be much higher, including higher costs, ground damage and casualty risks, GHG emissions and stratospheric ozone damage. Policymakers should be aware of the connection between estimated satellite weight and these impacts.

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CHAPTER 1.3:

COOLING

Alexis Abramson

MAIN MESSAGES

- Space-based data centers (SBDCs) can shed their computers' waste heat only by radiating it into space. This makes cooling the central limit on how much computing a satellite can do—and a major driver of cost.
- Counterintuitively, the best system design runs chips as hot as they can safely tolerate: a hotter radiator sheds far more heat, which keeps radiator panels small and launch mass low.
- Real world thermal performance may not be easily achieved over the system's lifetime since coatings degrade and debris-avoidance maneuvers may periodically require reorientation of satellites toward sources of heat.
- SBDC developers should consider cooling as a critical design constraint given thermal management dictates key system characteristics. Standard thermal performance metrics and disclosures should be developed to independently verify claims.

A. Introduction: Cooling in Space

Data centers produce significant heat. Terrestrial data centers are cooled with fluids, such as air and water, that carry heat away from the hardware by convection. However, no fluids are present in the vacuum of space. As a result, an orbiting spacecraft can shed its heat only by emitting infrared radiation—a process known as radiative cooling (see Figure 1).

Radiative heat rejection is governed by a simple principle: the hotter an object is, the more heat it radiates, and this heat output rises very rapidly as its temperature increases. This principle is captured in the Stefan-Boltzmann law, which states that power radiated per unit area is $P = \varepsilon\sigma T^4 A$, where ε is thermal emittance, σ is the Stefan-Boltzmann constant, T is absolute temperature and A is the radiating area. Because radiated power rises so steeply with temperature, a modest increase in radiator temperature yields a large increase in heat rejected. For example, taking the same radiator from 60 °C up to 90 °C adds roughly 40% to the radiated power per unit area it produces. So, the hotter radiator at 90 °C can reject the same heat load with a panel roughly 30% smaller and lighter than a cooler radiator at 60 °C. What this buys is capacity rather than efficiency: nothing about the thermodynamics improves, but the hardware shrinks, and hardware size carries real cost in an industry that must pay to lift every kilogram off the ground.

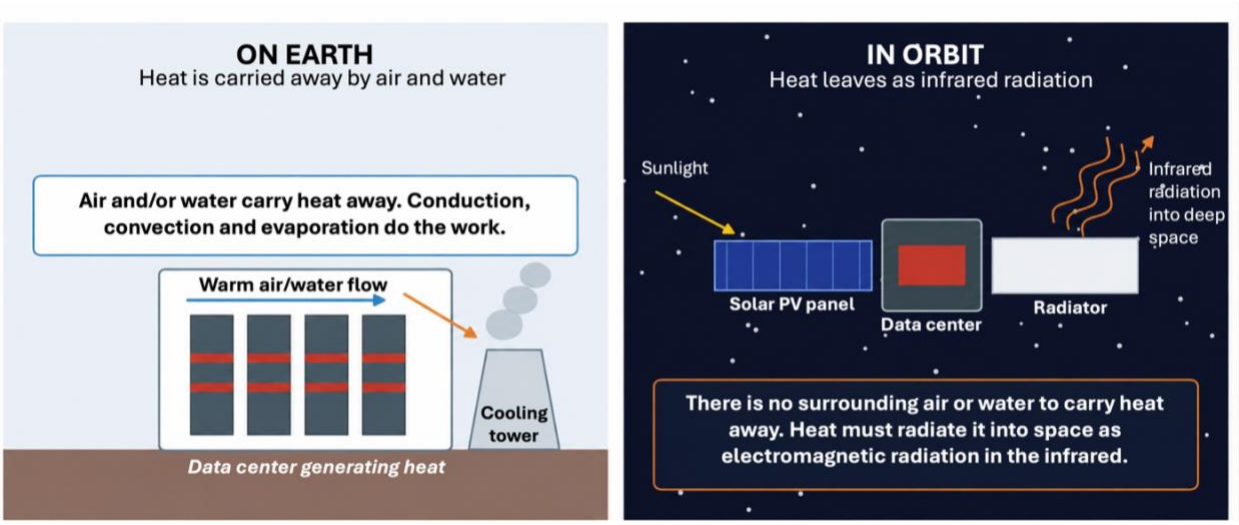


Figure 1. *Data center cooling in space works much differently than on Earth. On Earth a moving fluid carries waste heat from the servers and releases it to the atmosphere; in orbit there is no surrounding medium, so heat can leave only as infrared radiation. The diagram is a schematic and not to scale; it omits internal coolant loops, environmental heat loads and the orientation constraints examined later in this section (PV = photovoltaic). Source: AI generated using Gemini and ChatGPT*

The Stefan-Boltzmann law leads to a design conclusion that runs opposite to terrestrial practice. On Earth, running the hardware cool is always preferable, and operators keep chips well beneath their rated limits. But in space, the temperature of the radiators is typically a little bit cooler than the temperature of the chips. Any margin between the chip's operating temperature and its maximum rating lowers the radiator's operating temperature by the same amount. The design objective in space is thus to run hardware as hot as the system can tolerate, which for high-performance computing chips means operating near 85–95 °C.[1] The chip's thermal limit thus becomes a parameter designers deliberately target instead of a boundary to avoid. The challenge is that operating at the maximum temperature limit accelerates wear, shortening chip lifetime. This tradeoff must be carefully engineered into the system: lifetime specifications, redundancy provisions and replacement schedules are all set with the knowledge that, to avoid having to launch large amounts of extra radiator mass, the chips will operate for their entire service life pressed up against their rating.

A radiator operating near room temperature needs roughly 2000 m² of surface to shed a megawatt of waste heat.[2] And while space is an attractive cold sink, solar irradiance (~1361 W/m²), Earth's thermal emission (~240 W/m²) and reflected sunlight (albedo, ~30% of solar irradiance) all deposit additional heat onto exposed radiator surfaces. Further, depending on the satellite's configuration, heat radiating from the spacecraft's own warm structures can add to the load. Together these loads reduce the net heat the radiator can shed. What complicates matters is that these loads are not constant. A satellite in typical low Earth orbit (LEO) crosses between sunlight and Earth's shadow every 90 minutes—roughly 55 minutes of sunlight and 35 minutes of eclipse—which means the loads from direct sun and albedo are switched on and then off again 16 times in a single day. Two levers serve to minimize this unwanted incoming radiation: orientation, which sets what falls within the

radiator's field of view, and coatings, which determine how much radiation the radiator surface absorbs. Managing the environmental loads with these two levers is the essence of radiator engineering.

Following this introduction on how cooling in space differs, this section discusses spacecraft thermal management as a mature engineering discipline and examines the radiator architectures, heat transport systems and orientation strategies available to designers of space-based data centers (SBDCs). The section then explores significant challenges created by the cooling needs of SBDCs, including the gap between demonstrated and proposed scale, coating degradation, tradeoffs between efficient cooling and brightness mitigation, risks related to orbital debris and congestion, the unsolved problem of how best to dispose of SBDC radiator panels at the end of their useful lives, and the lack of any disclosure standard. It closes with recommendations.

B. Engineering Space-Based Thermal Management

At steady state, a space-based system must radiate away essentially every watt its solar panels generate. This constraint propagates through the entire design: it constrains the choice of orbit, fixes the satellite's attitude and much of its geometry, ties directly into the power architecture and, together with power, caps the compute a platform can economically carry. One recent industry analysis reports that radiators and solar arrays together can account for 65–70% of a satellite's total mass and that offsetting five years of coating degradation calls for ~40% additional radiator area.[3] Cooling does not sit alongside the other subsystems; it is what determines whether the data center is feasible at all.[4]

As discussed throughout this roadmap, the sector is advancing from concept to flight testing very rapidly, and thermal management design is keeping pace. In late 2025, Starcloud became the first company to operate an NVIDIA H100 in orbit,[5] cooling the chip's 700 W by means of direct-to-chip liquid cooling that carried heat out to body-mounted radiator panels, which then rejected it passively to space. Its successor, Starcloud-2, planned for launch in late 2026, will carry what may be the largest deployable radiator yet flown on a commercial mission.[6] In June 2026, SpaceX unveiled AI1: a 70-meter satellite carrying 110 m² of radiators whose panels are held at a knife-edge attitude to the sun, meaning the radiator presents almost no cross-section to sunlight.[7,8]

i. Lessons from spacecraft thermal management

Spacecraft thermal management is a well-established discipline. Satellites carry batteries, propellant, optics and electronics that function within a narrow temperature range and must react accordingly to the large thermal swings experienced in space. Over the past six decades, rigorous systems and tools have been developed to manage thermal performance, including flight-proven radiators, coatings and hardware for dissipating heat; standardized thermal vacuum testing apparatuses; and analysis software to validate performance with flight data. An accepted figure of merit used by the industry, the α/ε ratio (solar absorptivity over thermal emissivity), assesses the thermal performance of radiator coatings.[9,10] Absorptivity is the fraction of incident sunlight a surface absorbs rather than reflects, and emissivity is how efficiently it radiates its own heat as infrared. A good radiator coating therefore minimizes the first and maximizes the second, giving a low α/ε ratio that keeps the surface

cool under sunlight while still rejecting heat. Specific mass, the kilograms of thermal system hardware required per kilowatt of heat rejected, is the basis on which competing radiator concepts are conventionally compared.[11]

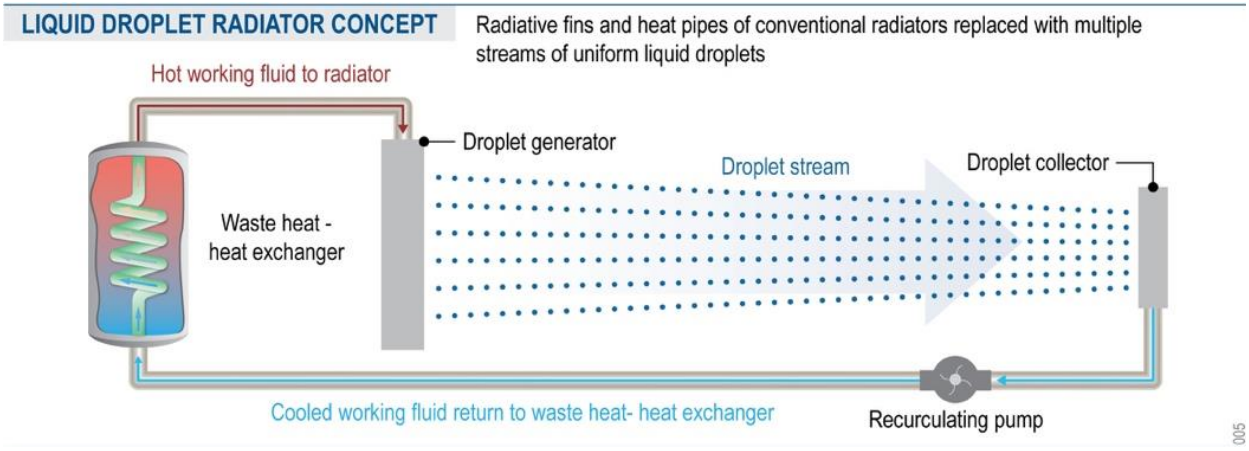
Most of this prior knowledge transfers directly to the data center application, although the problem demands additional insights the spacecraft industry has never needed. In particular, space-relevant thermal strategies approach their limits at larger scales,[12] and the inherited analyses offer no link between thermal performance and compute a system delivers. No analog to power usage effectiveness (PUE), as applied to terrestrial data centers, exists for orbiting data centers. In fact, radiative cooling consumes essentially no power, and so the thermal subsystem contributes negligibly to PUE, rendering the metric insensitive to the quality of the thermal design. Closing that gap will require new measures of thermal performance, reported alongside the figures of merit already inherited from spacecraft engineering.

ii. Thermal system design

Radiators selected for SBDCs are likely to resemble those flown on spacecraft for decades: a flat panel of aluminum or carbon-fiber composite embedded with internal heat pipes and surface-treated to radiate infrared at high efficiency ($\varepsilon \approx 0.85–0.90$) while reflecting most incident sunlight ($\alpha \approx 0.1–0.2$).[10] A conventional spacecraft panel maintained at 20 °C emits ~355 W/m² from one radiator face (calculated from the Stefan-Boltzmann law, $P = \varepsilon\sigma T^4$, with $\varepsilon \approx 0.85$). After accounting for typical orbit-averaged environmental absorption, the net heat rejection can fall to ~250 W/m² (for a panel with Earth in roughly half its field of view). However, for an SBDC, the same panel running at a chip-tolerable temperature of 85 °C sees its emissive power rise to roughly 790 W/m² (both figures follow from the Stefan-Boltzmann law; the call-out box works through a full AI1 example). And a panel at a knife-edge attitude to the sun, kept facing deep space almost continuously, sees little of Earth (less than a tenth of its field of view), and so absorbs little environmental heat (Earth's infrared and reflected sunlight), with its net rejection falling to ~780 W/m². The threefold spread between these two estimates in this example clearly demonstrates that temperature and orientation are what principally determine how a radiator performs.

One advanced concept is the liquid droplet radiator, which dispenses with panels entirely. The working fluid itself is sprayed across open space as a mist of microscopic droplets, which radiate their heat directly to the void before being recollected and recirculated. Because the droplet sheet needs no structure, analyses dating to the 1980s found it can be many times lighter than the lightest panel radiators, with reduced vulnerability to micrometeoroid strikes.[13]

A recent peer-reviewed analysis of a megawatt-class space nuclear system projects the advantage at roughly an order of magnitude, finding the droplet radiator's mass to be about 10% of an equivalent heat pipe radiator's mass.[14] This technology is not examined in depth here: these systems have not been fully tested in real-world scenarios, and the first generation of SBDCs likely will be built on flight-proven panel radiators.

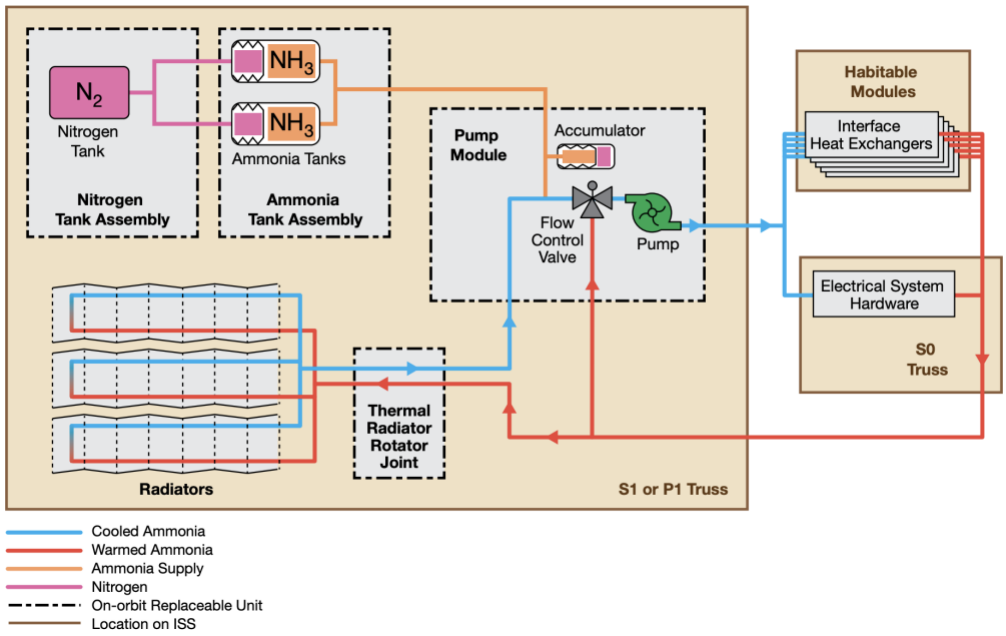


Liquid Droplet Radiator Concept.

Within the system, heat transfers across a series of interfaces from chip to radiator before finally being emitted as infrared. At each interface, thermal transport incurs a penalty: a temperature decrease determined by that interface's thermal resistance. Each temperature drop then sums to the total temperature gap between chip and radiator temperature, and because silicon physics sets the junction temperature of the electronics, each degree lost along the transport chain leaves the radiator that much cooler, carrying the T^4 penalty with it. Consequently, a poorly engineered interface or thermal transport loop reduces rejection capacity, which must then be offset by added area and mass.

The workhorse thermal transport device of spacecraft thermal control is typically the heat pipe: a sealed tube in which working fluid evaporates at the hot end, condenses at the cold end and returns through a capillary wick.[9] Typically, no pump is required—the wick does the work—so a heat pipe consumes no power and contains no moving parts. Further, these devices have flown reliably on spacecraft for decades. However, the capillary force that returns liquid through the wick is weak, which limits both how much heat a heat pipe can carry and how far it can carry it. Once a data center scales from tens to hundreds of kilowatts, pumps become unavoidable and the heat must travel in a mechanically driven fluid loop. For a real-world example, consider the International Space Station (ISS), which uses a ~70-kW thermal control system that relies on mechanically pumped ammonia loops rather than passive wicks.[15] SpaceX's AI1 proposes a similar configuration, with redundant pumps moving fluid across its radiators.[7,8]

These features come at a price since pumps must be designed to run unmaintained for years while being exposed to ionizing radiation that degrades electronics. A pump is a single point of failure, and so redundancy is also essential. Inside the radiator panel, embedded heat pipes take heat from the point where it enters and spread it across the whole radiating surface. This helps keep the panel isothermal, which enables the system to reject heat at full capacity. A solid plate without heat pipes could achieve this spreading by conduction alone, but the radiator would then need to be thick enough to carry the heat laterally without experiencing a large temperature drop, which would add

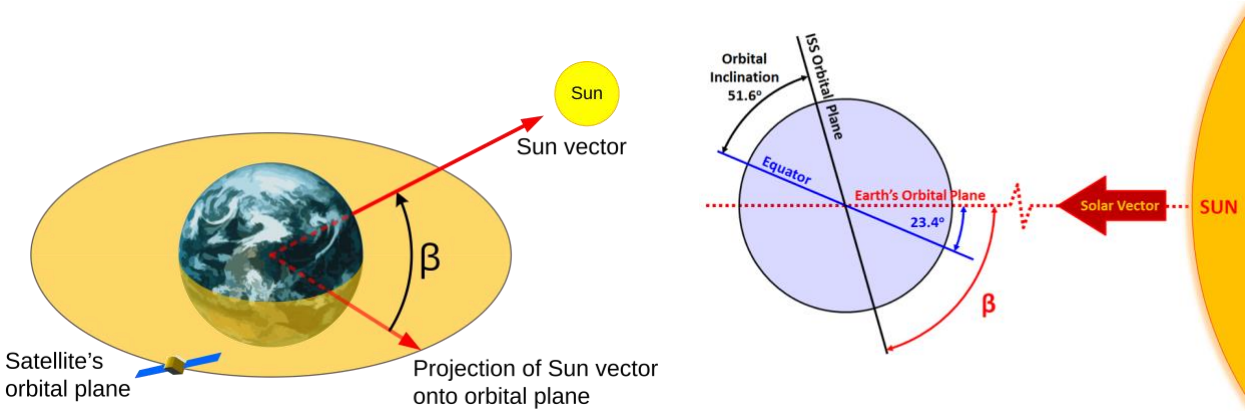


Schematic of the ISS External Thermal Control System (ETCS) with pumped ammonia loops. Source: NASA

weight. Embedded heat pipes accomplish the same spreading without the additional mass, keeping a thinner, lighter weight panel nearly isothermal.

Radiator performance is fundamentally governed by orientation relative to environmental flux vectors. While some SBDC designs (including the SpaceX design described below) align satellites to be “knife-edge” to the Sun, others use different orientations. For example, in a standard nadir-pointing attitude, a satellite keeps one face permanently pointed at Earth (nadir) while the opposite face looks out at deep space (zenith). The angle between the solar vector and the orbital plane, called the beta angle, drifts continuously throughout the year as Earth orbits the sun and the satellite’s orbital plane rotates in space. As the beta angle varies, solar incidence shifts, making a geometry that succeeds at one beta angle insufficient at another.

While a zenith-facing radiator looks out at 3 Kelvin of cold, deep space, deployable double-sided panels inevitably expose one face to Earth’s emission and albedo. Even in a knife-edge attitude, the radiator cannot escape Earth; each face of a deployed panel still sees a large fraction of Earth's disk at grazing angles, intercepting infrared and reflected sunlight. Spacecraft attitude can reduce this Earth-viewing load but, unlike direct sunlight, cannot eliminate it. Optical coatings can be engineered to reflect the sun's short wavelengths that peak in the visible range, but this approach does not work against Earth's infrared since rejecting Earth's long wavelength infrared would mean sacrificing the radiator's own emissive power. (Emissivity and absorptivity at the same wavelength must be equal by Kirchoff’s Law of thermal radiation.) Earth's infrared load must be accounted for in the design budget since no coating or geometry can fully eliminate it. Direct solar loads can be largely engineered away using coatings with lower solar absorptance and through orbit selection, radiator articulation and



The beta angle between the solar vector and satellite orbital plane, which determines how much direct sunlight radiators receive and how much of each orbit is spent in eclipse, both of which affect radiator sizing and cooling efficiency. Source: Wikimedia Commons. CC A-SA 3.0 Unported

The beta angle of the ISS, which cycles between roughly ±75° over the year due to its 51.6° orbital inclination and Earth's 23.4° axial tilt. Source: CERN

spacecraft attitude control. Which of these approaches a design uses, and how completely it limits unwanted heat load, is a critical thermal design decision.

Power generation and thermal management work against each other since solar arrays must face the sun to capture power, while radiators must avoid the sun to stay cold. Designers approach the orientation problem three ways (Figure 2). Fixed radiators are bolted to the body; they have no mechanisms or failure modes, but their performance depends on seasonal geometry, unless the orbit itself eliminates the seasonal dependence. A sun-synchronous terminator orbit keeps the sun's direction nearly constant relative to the orbital plane year-round, allowing even a fixed radiator to maintain edge-on solar geometry permanently while also providing near-continuous sunlight for the solar arrays.[16] In contrast, articulated radiators connect to gimbals that continuously point them away from the sun (the approach taken on the ISS), which ensures more consistent performance but at the price of mass and joints that must survive tens of thousands of tracking cycles over a five-year mission. The SpaceX AI1 illustrates a third path: the radiator is fixed and the satellite is steered instead. Its panels hold a knife-edge attitude, aligning their thin edge toward the sun, the way a blade held edge-on to a light source nearly vanishes, presenting almost no cross-section to sunlight while leaving both of its faces free to radiate to deep space. This is the key advantage over simply shadowing the radiator behind the solar array, which would spare it the sun but leave one radiator surface facing warm hardware instead of cold space. The mechanism involves attitude control of the entire satellite rather than the use of gimbals, which costs almost nothing for a platform carrying few, if any, Earth-pointed instruments. This attitude fixes the panels' orientation relative to the sun only; their alignment toward Earth, and the residual infrared absorbed, is a separate design parameter to consider.

iii. Thermal performance metrics

There is no metric that currently ties thermal performance to delivered compute throughput. The most familiar metric, PUE, collapses in comparison because radiative cooling consumes essentially no power. Others transfer only in part. The thermal resistance from chip-to-coolant, a standard measure of a terrestrial cooling loop, describes only the first link of a chain that in orbit continues through the radiator to deep space. However, for SBDCs, we must consider the total temperature drop across the hardware and into deep space. The cost per kilowatt is still central, but its leading term moves away from real estate and electricity and toward launch mass, which thermal specific mass (a metric used previously in spacecraft thermal design) captures directly.

Useful orbital metrics must capture how well a thermal system converts a fixed heat load into sustained compute and at what cost in mass. These metrics should consider the following:

1. The fraction of rated compute throughput that can be delivered given the thermal constraints of the system.
2. The magnitude of total interface resistance and the resulting temperature drop from the hardware to the radiator.
3. The total mass of the thermal hardware required to deliver the expected compute throughput.

Measures of the first two do not yet exist and still need to be developed; devising them and agreeing on how to report them should be a priority for the field. The third concern does have an established figure of merit, thermal specific mass, inherited from spacecraft engineering. Thermal specific mass (kg/kW) divides the thermal management system's mass by the heat load the system rejects, and it carries over unchanged from the spacecraft literature, in which competing radiator concepts are customarily ranked on exactly this basis.[11] Thermal specific mass also translates directly into cost: multiply it by the cost of putting a kilogram into orbit and the result is the dollar cost of each kilowatt of heat rejection capacity. The ISS benchmark is roughly 100–150 kg/kW when accounting for the radiators, pumps, radiator rotary joint, and ammonia and nitrogen tank assemblies.[15] NASA's Advanced Radiator Concepts program demonstrated reductions in radiator specific mass by a factor of three to four over then-current heat pipe technology,[11] and liquid droplet concepts are projected to cut radiator mass by roughly an order of magnitude.[14]

Note that mass figures of merit appear throughout this roadmap in related forms; the thermal specific mass presented here is specific to heat rejection (for each kilowatt rejected, rather than generated) and should be read in conjunction with these treatments.

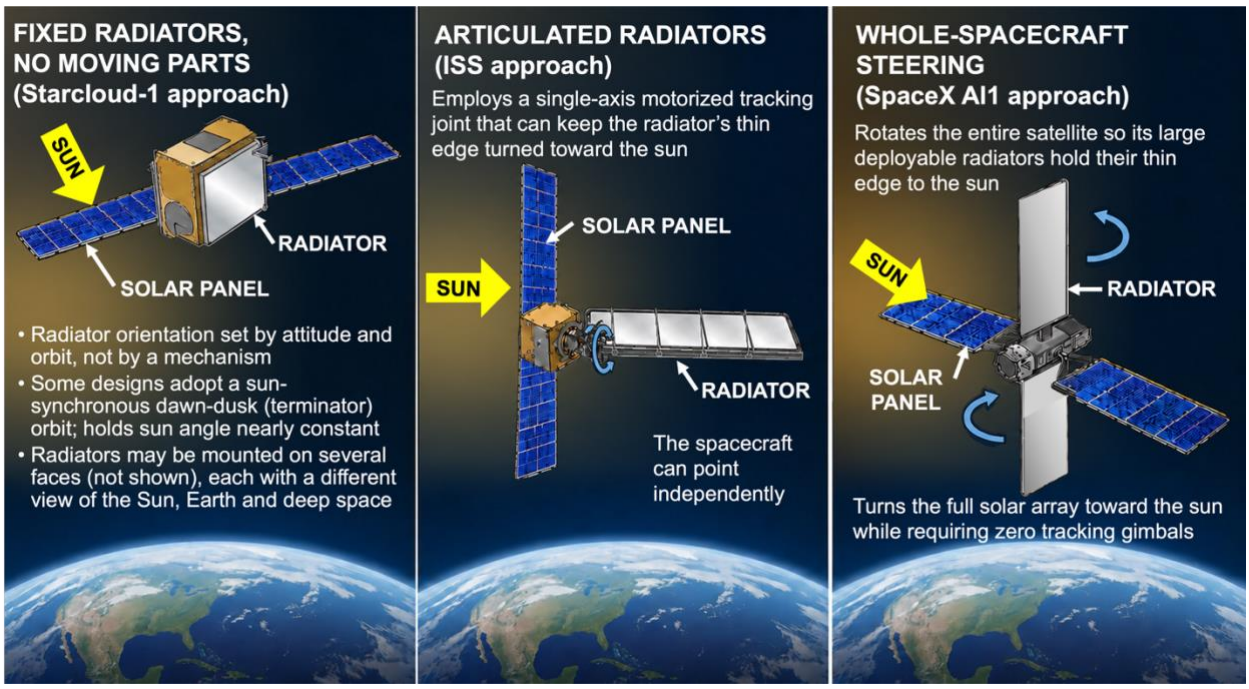


Figure 2. *Comparative thermal orientation architectures for orbital platforms. The panels show three approaches to reconciling the conflicting requirements of solar arrays and radiators. Schematic and not to scale; environmental heat loads, internal coolant loops and residual Earth infrared are omitted. Source: AI generated using Gemini and ChatGPT*

THERMAL PERFORMANCE OF THE SPACEX AI1

The SpaceX AI1, announced in June 2026, has been described publicly in enough detail to support a thermal performance review, although several inputs must be inferred.[7,8] As shown in the table below, the ~1400 W/m² rejection flux SpaceX claims (we calculate 1360 W/m^2) corresponds to a radiator temperature of roughly 76–82 °C, calculated using the Stefan-Boltzmann Law. The range reflects the panel's undisclosed orientation relative to Earth as it travels through its orbit. SpaceX does not disclose the maximum allowable chip temperature, but an industry source reports that Rubin-class GPU (graphics processing unit) die temperatures (the temperature of the silicon itself) can easily reach 95 °C.[17] Assuming a temperature drop of 8 °C across the thermal transport train,[18] a 95 °C junction limit corresponds to a maximum allowable radiator temperature of 87 °C, 5 °C above the top of the calculated range. The 8 °C drop assumed across the transport chain between chip and radiator forfeits roughly 8–9% of the rejection capacity the radiator would otherwise deliver, an illustration of how costly small temperature losses become once the Stefan-Boltzmann law is applied.

Thermal specific mass can only be roughly estimated given that available data are limited. SpaceX has not disclosed the AI1 thermal system's mass, but bounds can be constructed using areal mass, the kilograms of hardware per square meter of radiator panel, and metrics from available ISS data.[15] The ISS provides the only flight benchmark: its active thermal control system rejects up to 70 kW across 6 radiator panels totaling 475 m². Radiator areal mass is about 14 kg/m²,[15] and total radiator mass is roughly 6700 kg. In contrast, modern composite panels exhibit areal mass of roughly 5–10 kg/m²,[3] and next-generation designs are targeting even lower.[19] Including the rest of the rejection system's documented hardware—pump modules, thermal radiator rotary joints, and ammonia and nitrogen tank assemblies—brings the full system to about 9700 kg, yielding a radiator-only specific mass of roughly 100 kg/kW and a full thermal specific mass of ~140 kg/kW. Applying the ISS's 14-kg/m² areal mass to AI1's disclosed 110 m² radiator area gives an estimated radiator mass of roughly 1500 kg; scaling by the ISS's ancillary-to-radiator mass ratio (a further ~44%, covering pumps, rotary joints and tankage) yields a full-system estimate of 2200 kg, or a thermal specific mass of ~10 kg/kW (radiator-only) and ~15 kg/kW (full system) against the 150-kW load. On a full-system basis, this makes the AI1 estimate nearly 10x better than the ISS benchmark. This comparison assumes AI1's ancillary hardware scales with radiator mass the same way it does in the ISS's—a real assumption, not a documented fact, since AI1's pumping and tankage architecture is unknown. Whether AI1's thermal system actually achieves mass in this range and whether the claimed rejection density is realizable in practice both remain to be determined.

Using the ISS estimate of the full thermal specific mass of 140 kg/kW, the thermal system of the Reference SBDC (see Text Box 1-1) would have a total mass of 14 tonnes. By contrast, using the estimate of the claimed SpaceX AI1 full thermal specific mass (15 kg/kW) implies that the thermal system of the Reference SBDC would have a total mass of 1.5 tonnes.

As the table's status column shows, every input is disclosed, claimed, assumed, estimated or derived. Nonetheless, the inputs to these calculations will sharpen and the achievable performance of orbital thermal systems will come into clearer view as systems are flown, operators publish data and independent analyses mature. In any case, the exercise demonstrates that a workable assessment of thermal performance can be assembled from a modest set of design parameters and that such an assessment offers a basis for comparing one SBDC against another.

Parameter	Value	Status
Radiator area	110 m^2	Disclosed (Federal Communications Commission (FCC) filing)
Orientation	Knife-edge to sun	Disclosed
Heat rejection density	~1400 W/m^2	Claimed (SpaceX announcement); analytically verified to order of magnitude
Peak compute/Thermal Design Power (TDP)	150 kW	Disclosed
Coating emissivity (epsilon)	0.85	Assumed, not disclosed
Maximum chip temperature	~95 °C	Assumed using industry source,[17] not disclosed
Radiator operating temperature	8 °C below maximum chip temperature	Assumed,[20] not disclosed
Thermal specific mass	~10 kg/kW (radiator only) ~15 kg/kW (full system)	Estimated from documented panel mass-per-area benchmarks[3,15]

C. Risks and Open Questions

The scaling gap. The largest systems actually flown today are single-GPU demonstrators on the order of a kilowatt. The largest disclosed SBDC design, SpaceX's AI1, is planning for 150 kW.[7,8] Bridging this gap in power requires redesign, not just extrapolation from existing designs: because heat must travel farther, structural support for radiators becomes disproportionately heavy, pumping power becomes non-negligible, and large flexible panels affect attitude control. Ambitions for aggregate SBDCs run to megawatts (or even gigawatts), but this will be achieved chiefly through constellations of many such satellites. Starcloud-2's deployable radiator, launching late 2026, will be the first significant test of scaling at this individual-satellite level.[21]

Degradation. Coatings degrade under exposure to ultraviolet, atomic oxygen and particle radiation. This means that solar absorptivity of radiators typically climbs and capacity erodes. Current estimates suggest that maintaining performance over a five year lifetime may require ~40% more radiator area than a fresh coating would require.[3] But these estimates are based on studies of conventional spacecraft, not from SBDCs, since no coating has yet built up flight history under the high operating temperatures and continuous full-power duty cycles this application demands. Any beginning-of-life evaluation of thermal performance is therefore an upper bound, and real performance will decline over the course of the mission.

Optical and infrared brightness. A radiator's low solar absorptivity, needed to stay cool, is also high reflectivity, so the best coating for heat rejection is close to the worst for brightness. Darkening a radiator to dim its reflectivity raises its absorptivity and forces added area and mass. Holding the radiator edge-on to the Sun helps, reducing absorbed solar load and the sunlit area seen from the ground. Specifically, in the dawn-dusk terminator orbits these systems favor, the geometry directs much of the specularly reflected sunlight away from Earth's surface rather than down toward ground observers.

Debris and congestion. Radiator panels are among SBDCs' most vulnerable systems. Radiators, like solar arrays, have large, thin profiles, and a single debris strike can puncture embedded heat pipes or coolant channels. If the SBDC has the capability to maneuver to avoid the debris, doing so breaks its attitude such that it may no longer be edge-on to the sun. Until its orientation is restored, sunlight may impinge on the radiators, leading to a drop in heat rejection capacity, and the processors must throttle. A beginning-of-life thermal analysis would not capture this effect since the frequency of necessary attitude adjustments cannot be easily predicted. With growing orbital congestion, actual thermal performance likely will fall below the predicted value.

End-of-life disposal. Retiring a large aluminum radiator has no good solution. On re-entry, the panel ablates into nanoparticles of aluminum oxide that reach the stratosphere and catalyze the destruction of ozone.[22] The alternatives to re-entry each fail in their own way. Moving retired SBDCs to higher disposal orbits only defers the problem. Sending them entirely outside of Earth's orbit would eliminate the risk but would require more propellant than the satellites could realistically carry. Each option carries a different cost, and there is not yet an established methodology for comparing them.

The standards vacuum. No standards body has yet taken up comprehensive thermal metrics for this application. It is possible that the first generation of commercial SBDCs will be financed, licensed and sold on the strength of thermal claims that no outside party is able to check. What such claims conceal is thermal throttling: when environmental loads drive a radiator past its rejection capacity, the processors must slow until the load eases, so a platform advertised at one compute capability may deliver materially less of it in practice. Measures of how much of its rated compute a platform sustains over a year in orbit and of how much thermal headroom the chip loses in the transport chain, reported alongside the thermal specific mass at which both are achieved, would render competing systems comparable. As the SpaceX AI1 exercise suggests, assessments of this sort could be assembled today from a modest set of design parameters that operators already possess.

D. Recommendations

1. Developers of SBDCs should treat thermal management as a primary design driver from the outset—sizing radiators and selecting operating temperatures before fixing compute density—rather than adding cooling as a downstream constraint.
2. Operators should design electronics to run at the highest junction temperature their reliability limits safely allow since higher radiator temperatures reject the same heat from substantially less surface area and mass. Because operating near the thermal limit accelerates wear and shortens component life, this trade should be made deliberately, with lifetime specifications and redundancy considered.
3. Developers and operators should disclose the key thermal parameters of their systems, including radiator area, heat-rejection density, coating emissivity and absorptivity, operating temperatures and thermal hardware mass. Given the linkage between thermal management design and both SBDC lifetime and compute throughput, investors and regulators have a stake in thermal performance claims they cannot independently verify.
4. The community should develop shared, quantitative cooling metrics and standards that cover sustained thermal performance over a full year in orbit, the temperature penalty imposed in transit from chip to radiating surface, and the thermal hardware mass required to achieve both. This will allow designs to be compared consistently with one another and over a system's operating life.
5. Funders and research institutions should prioritize development of high-emissivity coatings that resist ultraviolet and atomic-oxygen degradation, so that end-of-life thermal performance, not just beginning-of-life performance, meets mission requirements.
6. Funders and industry should invest in lightweight, reliably deployable radiator structures and in high-temperature-tolerant electronics, as advances in either directly relax the central mass and area constraints on orbital compute.
7. Operators and orbital-traffic authorities should account for the coupling between congestion and cooling. As orbital bands grow more crowded, more frequent debris-avoidance

maneuvers could break radiators' sun-avoiding attitude and force throttling. The odds of a strike puncturing a thin radiator also rise. Both degrade thermal performance in ways a beginning-of-life analysis does not capture.

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CHAPTER 1.4:

RADIATION HARDENING

Anne-Amélie Campant and Colin McCormick

MAIN MESSAGES

- Radiation levels are higher in space than on Earth. Satellites in low Earth orbit (LEO) are exposed to ionizing radiation from multiple sources that can interfere with, or even destroy, artificial intelligence (AI) chips. The exact amount of exposure depends on the altitude and inclination of the satellite's orbit.
- There are multiple methods to reduce this exposure, including shielding with aluminum or other materials, modifying semiconductor manufacturing processes, or adding redundancy and additional tolerances through software. However, these all lead to additional costs and reduced performance.

Data centers in low Earth orbit (LEO) are exposed to more and different ionizing radiation than on Earth. This radiation can damage or destroy electronics, such as processors and memory. These issues can be partly addressed through engineering and design, but measures for addressing them typically add mass and negatively impact performance. Although methods for protecting conventional computing equipment from radiation in space are well known, the space industry has little experience in protecting AI-grade chips from radiation in LEO.

A. Radiation in Space

Space is filled with radiation from multiple sources. Much of this radiation never reaches the surface of the Earth because the planet's magnetic field and atmosphere deflect or absorb it (see Figure 1). However, satellites in LEO are exposed to three main sources of radiation that do not significantly impact Earth[1]:

- Earth's radiation belts (ERBs): High-energy electrons and ions that form two belts in the Earth's inner magnetosphere (the Van Allen belts, see Figure 2). The energy these particles carry typically ranges from roughly 10 keV to 100s of MeV.
- Galactic cosmic rays (GCRs): Charged particles, most of which are protons, from outside the solar system and traveling at high speed (see Figure 3). The energy these rays carry typically ranges from roughly 100 MeV to 1 GeV.
- Solar particle events (SPEs): High-energy particles (primarily protons) emitted from the Sun during solar flares and coronal mass ejections (CMEs) (see Figure 4). The energy these particles carry typically ranges from roughly 10 MeV to 100s of MeV.

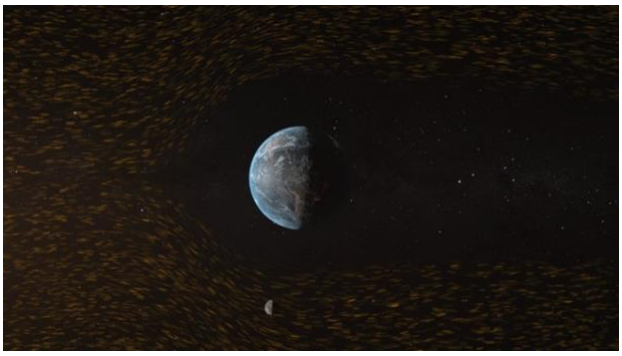


Figure 1. *Earth's magnetic field and atmosphere*

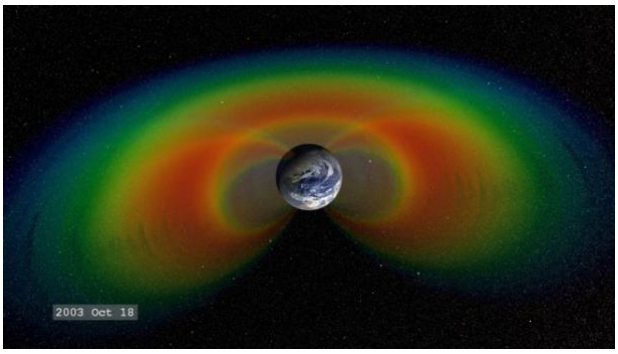


Figure 2. *The Van Allen belts*

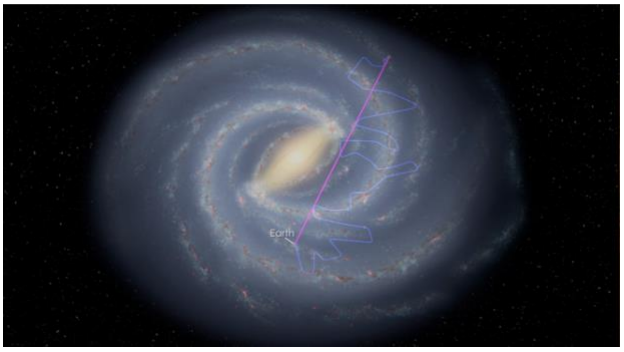


Figure 3. *A galactic cosmic ray's path from outer space to low Earth orbit*

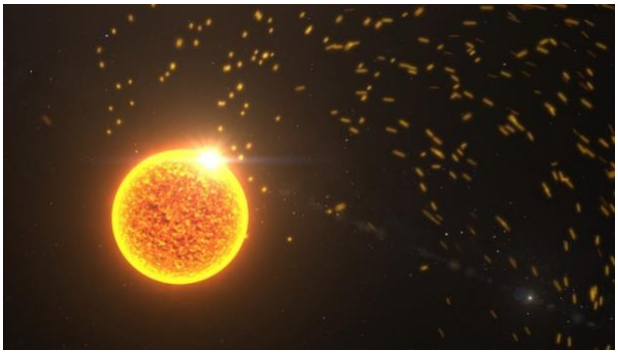


Figure 4. *Solar particle events: a solar flare and coronal mass ejection*

Source: NASA's Goddard Space Flight Center

Satellites in LEO are exposed to varying amounts of radiation depending on altitude and orbital inclination. For low-altitude LEO, the Earth's magnetic field shields satellites relatively well from GCR and SPE radiation.[1] As altitude increases, this protection decreases. Satellites in LEO at low orbital inclination (orbits that stay close to the equator) receive much less GCR and SPE radiation compared to high orbital inclination because Earth's magnetic field is strongest near the equator and more effectively deflects these particles. Low-inclination satellites also receive less ERB radiation than higher inclination satellites because the Van Allen belts are typically higher near the equator.[2] The inner Van Allen belt dips anomalously low over a region of the South Atlantic Ocean known as the South Atlantic Anomaly (SAA).[3] Earth's magnetic field is significantly weaker over the SAA (see Figure 5). Satellites in moderate- to high-inclination LEO, including Sun-synchronous orbits (SSOs), can pass over the SAA, exposing them to ionizing radiation doses up to two orders of magnitude higher than at other latitudes in the same orbit.[4]

For satellites in LEO with 1 mm of aluminum radiation shielding, the annual radiation dosage typically ranges from 100 to 10,000 rad (a unit equivalent to 1 centiGray (cGy)). The higher dosages occur at higher altitudes and higher inclinations. In some high-altitude, high-inclination LEOs, annual dosages

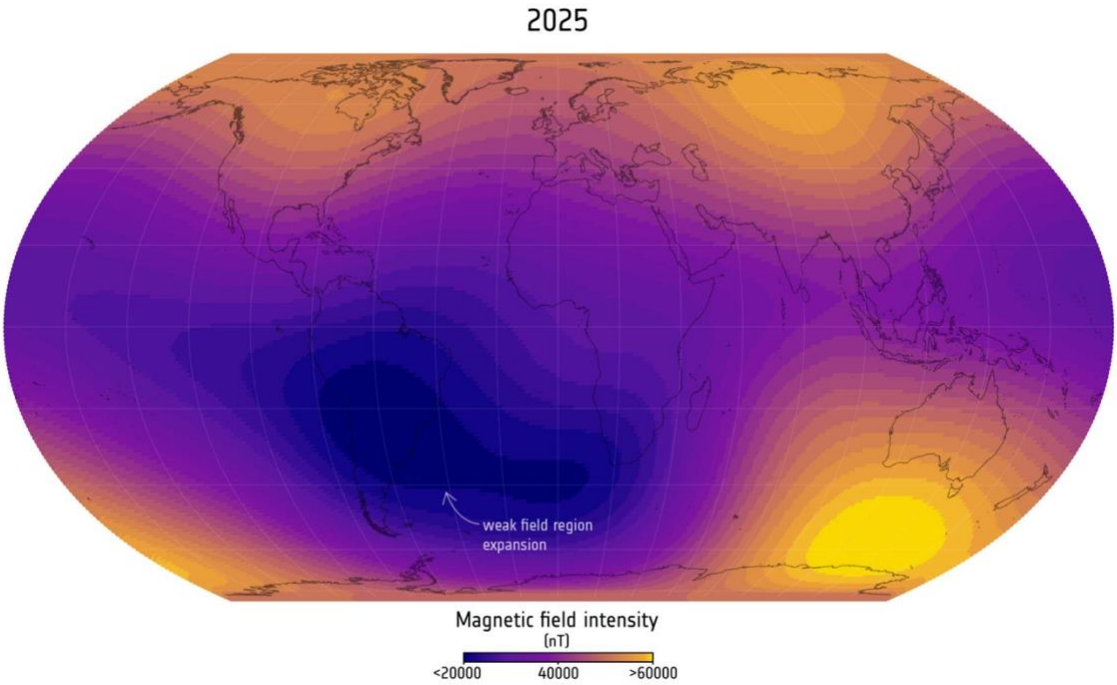


Figure 5. *The South Atlantic Anomaly in 2025. Source: ©ESA, Finlay, C.C. et al., 2025. Open Access, CC BY 4.0*

with only this thin 1 mm aluminum shielding can reach values even higher than 10,000 rad. Thicker shielding reduces this total dosage by blocking radiation, but it leads to additional weight and cost.

B. Impact of Radiation on AI Chips

The impact of radiation on AI chips can be categorized as follows:

- Single event effects (SEEs): Effects caused by a single energetic radiation particle strike. SEEs range from transient, recoverable effects (e.g., bit flips and logic glitches) to permanent, destructive damage (e.g., a latch-up) that can destroy a device.
- Total ionizing dose (TID): Cumulative degradation of AI chips due to radiation exposure over time.

AI processors and memory chips consist of billions of silicon transistors. Circuits built from these transistors store binary data and execute instructions by turning tiny semiconductor switches on and off. A thin oxide layer known as the gate oxide insulates each transistor's switching signal. When ionizing radiation strikes an oxide layer, positive charge can accumulate and become trapped in the silicon-oxide layer.[5]

SEEs can arise when the charge deposited by a single high-energy particle striking a transistor degrades it immediately. SEEs can also occur in indirect cases where a particle collides with a silicon nucleus and produces high-energy secondary fragments. In some cases, these strikes lead to a bit flip, in which a bit switches from a 0 to a 1 or vice versa, corrupting a piece of data. This can occur in the AI chip's stored data or in its control logic, causing it to crash and require a reset. Most severely,

if the charge from a single strike exceeds a critical threshold, it can trigger a short circuit inside a chip, known as a single-event latch-up, that can cause permanent damage if it is not detected and shut down quickly.



Figure 6. *Intel's Myriad 2. Source: CERN/Maximilien Brice*

TID measures how trapped charge accumulates over time in the oxide. As charge builds up, it gradually shifts a transistor's threshold voltage (i.e., the voltage needed to turn it on or off). Enough threshold voltage shift can prevent a transistor from correctly switching and/or can result in current leakage even when it should be off, degrading the chip's performance and leading to eventual failure. For modern AI chips, the isolation oxide between transistors is often a more significant site for radiation-induced charge trapping and leakage than the gate oxide. This is because modern fabrication processes have reduced the gate oxide thickness dramatically. Simultaneously, as these feature sizes continue to shrink, they hold less electric charge and become even more sensitive to SEEs. A single-particle strike can also flip multiple adjacent memory cells because of this reduced size and close packing.

C. Strategies for Radiation Hardening

Multiple techniques can be used to make AI chips resistant to damage from radiation in LEO ("radiation-hardening"). However, because these all have costs and performance drawbacks, devices are first subjected to radiation testing to determine which forms of "hardening" are required.

Notably, some commercial off-the-shelf (COTS) computer hardware is relatively resistant to radiation without any modifications. For example, the European Space Agency's (ESA's) 2018 test on the Intel Myriad 2 (Figure 6) demonstrated the chip had enough radiation tolerance for space travel without hardening.[6] However, this chip is not suited for the type of AI applications that would be carried out on an SBDC.

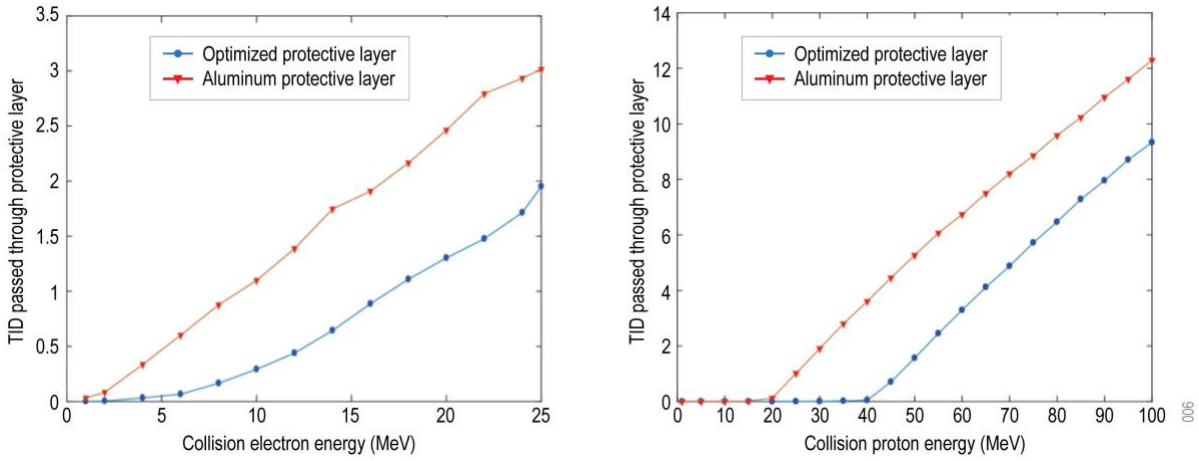
A more relevant example is from Google, which demonstrated the first radiation test of a high-performance processor—their Trillium tensor processing unit (TPU)—in 2025 using a proton beam to simulate the radiation dose of a five-year LEO mission. While the TPU's high-bandwidth memory (HBM) showed some performance issues after being irradiated, the core logic and compute functions experienced no hard failures up to a very high radiation dose.[7] SEEs caused occasional "silent" data corruption—faults that altered data or a computed result without being detected by the system—at a rate of 1 inference failure per 3 million.[7] This radiation test simulated 10 mm of aluminum radiation shielding on the chip, reducing the TID significantly. This type of TPU is directly used in AI applications, and these results suggest that AI chips may require somewhat less radiation hardening than expected, although far more testing is required to validate this.

Primary radiation hardening methods include the following:

i. Structural hardening and shielding

Ionizing radiation can be partly blocked by adding layers of shielding material around electronics. Many satellites use aluminum for overall structural support and take advantage of its moderate radiation shielding ability to offer partial protection. Better shielding materials can be used in addition to aluminum or on their own when structural support is not required. For example, multilayer shields of lithium hydride (an effective material because of its capacity to store hydrogen) and polyethylene (used for its tensile strength) have shown promise[8] for blocking GCR. To shield against trapped electrons and protons in LEO, triple-layering dense metals, such as gold, lead, tungsten and tantalum, combined with aluminum can reduce TID by up to 70% against electron sources and 50% against proton sources compared to simple aluminum (see Figures 7 and 8).[9]

While this shielding can reduce radiation damage to AI chips and prolong their life, the added mass also increases the overall cost of a spacecraft. Additionally, these specific, multi-layer designs remain research prototypes that have not yet been flown operationally. Process innovations and flight validation will be required to make lighter layered shield designs for AI chips economically viable at scale.



Figures 7, 8. *Each blue curve's "optimized protective layer": gold-tungsten-aluminum for electron environment and tungsten-lead-tantalum for proton environment. Source: Daneshvar, H., Milan, K. G., Sadr, A., et al., 2021.9 Open Access*

ii. Doping transistors

Radiation-hardening-by-design (RHBD) methods modify a transistor's manufacturing process before radiation exposure. These include building enclosed layout transistors by reshaping transistor gates into closed rings to prevent charge leakage, placing "guard rings" around transistors to protect against SEEs,[10] and modifying and controlling chip silicon-on-oxide layer growth. A legacy specific oxide-modification technique involves introducing boron into the oxide layer.[11] This suppresses the trapped charge and stabilizes the transistor switching voltage under ionizing radiation.

RHBD is a well-established technology to protect electronic equipment from radiation. Microchip's Radiation-Tolerant Generation 4 (RTG4) field-programmable gate array (FPGA) is an example of this and is radiation-hardened against single-event upsets.[12] RTG4 FPGAs were flown on the CAS500-1 Earth observation satellite launched into LEO in 2021 by the Republic of Korea.[13]

However, RHBD methods add cost to conventional transistors because their geometries occupy chip area otherwise used for computing and require dedicated fabrication processes, which makes doped transistors challenging to scale commercially. This also means that SBDCs would not be able to use commodity AI processors.

iii. Redundancy

Triple modular redundancy allows for critical functions to run on three separate processors at once and uses a voting circuit to accept the result at least two of the three agree on.[14] This redundancy protects against a potential single corrupted result from an SEE from a high-energy particle strike.

This is a well-established technology already used on National Aeronautics and Space Administration (NASA)-crewed missions, such as Artemis II, on which Orion stores data in triplicate and performs a best-of-three vote on every read to correct single-bit errors.[15] Yet, tripling the number of processors triples the mass and energy consumption of affected equipment, dramatically increasing the cost of AI hardware in space.

iv. Specialized materials

Chips can be built silicon-on-insulator, where an insulating oxide layer also sits beneath the silicon to limit the charge generated by a particle strike or cumulative damage.[16] Implanting ions, such as fluorine, into the lower oxide layer during fabrication can increase the cumulative radiation dose a chip can tolerate.[17]

This is a well-established process. Honeywell manufactures radiation-hardened processors, such as the HX1750 with its silicon-on-insulator method, specifically for spacecraft applications.[18] While the manufacturing process is mature, extending it to modern AI chips will incur process engineering costs and would mean that SBDCs could not use commodity AI chips.

v. Software-based hardening

Software can be used to monitor high-radiation conditions and intentionally reduce electronic equipment's power and processing speed during these periods to reduce the chance of SEEs. This was tested by Hewlett Packard Enterprise (HPE) on an unmodified commercial supercomputer on the International Space Station (ISS) starting in 2017 (see Figure 9); the computer ran successfully for 1.5 years.[19]

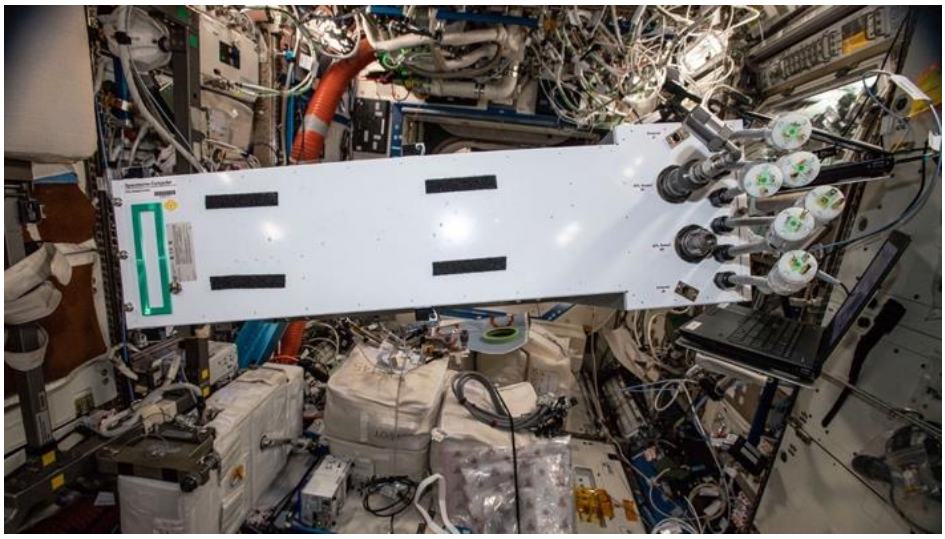


Figure 9. *Hewlett Packard Enterprise's Spaceborne Computer-1 on the ISS. Source: NASA*

This method, however, does not reduce TID and overall reduces the amount of compute each satellite can deliver, raising costs and decreasing efficiency. Moreover, this technology has only been tested in orbit at small scale, and the HPE system's software responded to general conditions outside established parameters rather than mitigating radiation specifically. This approach is therefore not yet established at the scale or specificity that a dedicated set of AI chips in LEO would require.

vi. Software tolerance

This method assumes errors in some parts of a software model are more sensitive than in others and redesigns the model to absorb these errors in the most sensitive layers. It was tested on a satellite-image classification model using hardware identical to that on China's Chaohu-1 satellite, and the method reduced the model's crash rate from 96% to 0% under equivalent radiation-error conditions.[20]

This approach, however, requires modification and retraining of models specific to their architectures, incurring additional engineering effort and cost. While this technology was validated in a ground test, it will require substantial further investment to be operationally established in LEO. However, one important advantage of this approach is that it could be deployed on satellites that are already in orbit via software updates, allowing it to immediately provide benefits (see Text Box 1-2 Software).

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CHAPTER 1.5:

LAUNCH CAPACITY

Kathleen Curlee

MAIN MESSAGES

- Space-based data centers (SBDCs) would require launch activity far beyond historical norms, putting significant pressure on existing launch capacity.
- Even with cheaper and reusable rockets, infrastructure will struggle to keep pace with the launch rates needed for large SBDC constellations.
- SBDC launch demand would crowd out commercial, civil and national security missions.
- Expanding capacity will take time and may be constrained by permitting, geography and industrial capacity.

Space-based data centers (SBDCs) would depend on a global launch system capable of placing thousands to tens of thousands of large spacecraft into orbit and replacing them over time. Even if current launch costs fall substantially, deployment at scale will require launch cadences far above historical norms and place new demands on launch infrastructure. These pressures will affect commercial and government launch needs across multiple spacefaring states. The feasibility of SBDCs depends in part on whether launch infrastructure can expand quickly enough to accommodate the sustained high-cadence operations that delivering SBDC constellations will require.

A. Launch Requirements

The number of launches required for SBDCs to provide significant compute capacity will depend on several variables including spacecraft mass, compute capacity, operational lifetime and launch vehicle performance. However, under plausible assumptions, very high launch cadences will be required.

Consider a 1-GW constellation of the Reference SBDC used for analysis in this Roadmap (see Text Box 2-1). Such a constellation would require roughly one launch of a Starship-sized rocket each week for as long as the constellation is operational. To meet 25% of projected demand for artificial intelligence (AI) data centers in 2030 would require more than five launches per day of rockets with the Reference SBDCs in perpetuity.

These conclusions are based on the following:

- The Reference SBDC in this Roadmap has 100 kW of compute, weighs 2.5 tonnes and is operational for 5 years.
- A 1-GW constellation would require 10,000 Reference SBDCs (100 kW x 10,000 = 1 GW).
- 10,000 Reference SBDCs have a combined mass of 25,000 tonnes (2.5 tonnes per SBDC x 10,000 = 25,000 tonnes).
- Assuming each launch vehicle carries approximately 100 tonnes into orbit (the current estimate for Starship), initial deployment of the 1-GW constellation would require 250 launches (25,000 tonnes ÷ 100 tonnes per launch = 250 launches)
- If initial deployment of the constellation takes place at a steady pace of 50 launches per year over 5 years, roughly 1 launch per week will be required.
- In Year 6, the Reference SBDCs deployed in Year 1 will require replacement, so another 50 launches (roughly 1 launch per week) will be needed. The same will occur in every following year.
- As a result, deploying and maintaining a 1-GW constellation of Reference SBDCs will require roughly 1 launch per week until the constellation ceases to function.
- McKinsey projects 156 GW of AI data-center demand by 2030.[1] To meet 25% of that demand (39 GW) with Reference SBDCs would require 39 launches of Starship-sized rockets per week in perpetuity. That is more than 5 launches per day and roughly 2,000 launches per year.

For comparison, there were 329 rocket launches globally in 2025, across a range of rocket types.[2] In 2025, 109 rockets were launched from Florida's Space Coast (Cape Kennedy and Cape Canaveral).[3]

Different assumptions would change these results, of course. If Starship-sized rockets are not available or SBDCs weigh more than 2.5 tonnes each, for example, faster launch cadences would be required. If SBDCs have lifetimes longer than five years, slower launch cadences would be possible.

B. Launch Infrastructure and Capacity

The ability to support hundreds or thousands of launches for SBDC constellations will depend on physical infrastructure that enables frequent operations. This includes launch pads, payload processing facilities, propellant storage and distribution, transportation networks, electrical power and other shared services. With a high launch cadence, each of these systems can become a bottleneck.



A launch pad. Source: Shutterstock

Launch pads are a critical constraint. Each pad can support only a finite number of launches. Vehicles must be transported, integrated, fueled, checked

and launched. The site has to be inspected and prepared again before each mission. Reusable launch vehicles may reduce some of the time and cost associated with producing new hardware, but they do not eliminate the need for pad turnaround or range coordination. This bottleneck is already visible at some major launch sites. In June 2026, the US National Aeronautics and Space Administration's (NASA's) Office of the Inspector General found that launch activity at the Kennedy Space Center and Wallops Flight Facility had increased by 252% and 467%, respectively, between 2020 and 2025.[4] The report concluded that both facilities could approach operational capacity in the 2028–2029 timeframe even without substantial new demand from SBDCs.[4]

Launch capacity also depends on infrastructure that is shared across multiple launch pads. At the Kennedy Space Center, NASA's inspector general identified electrical power, gas supply and distribution, and transportation infrastructure as existing constraints to the number of launches possible at the center.[4] Most of this infrastructure is decades old and was not designed for the launch frequencies proposed SBDC constellations will require. Super-heavy launch vehicles also create operational constraints for neighboring users because their fueling and safety requirements temporarily restrict access to nearby facilities.[5] At high cadence, these shared-site effects could reduce overall spaceport throughput even if individual launch vehicles become more capable.

Launch-range capacity is another limiting factor for the amount of mass that can be launched. A launch site is the physical location where a rocket is prepared and launched, including its pads and associated ground infrastructure. A launch range is a network of personnel, tracking systems, safety infrastructure and procedures that supports launch operations from a launch site. Range operators monitor vehicles during flight, protect surrounding populations, establish hazard areas and coordinate restrictions on nearby airspace and maritime traffic. Each launch requires range resources and coordination before the vehicle ever leaves the ground. At low launch-cadence, these functions are scheduled around other missions, but high-cadence operations place greater demands on range personnel and infrastructure. Because major launch sites frequently support multiple commercial and government users, the launch range that provides airspace-management services may constrain launch cadence even when an individual operator's pad and vehicle are ready.[6]



European Space Agency's main launch site, Kourou, French Guiana. Source: ©European Space Agency - Stephane Corvaja.

Payload processing represents a less visible but important bottleneck. SBDC satellites need to be transported to launch sites, inspected, tested, integrated with deployment hardware and prepared for launch.[7] Some payloads may also require specialized clean rooms, hazardous-material handling, fueling or other processing facilities.[8] These activities can occur well before launch and may occupy facilities for extended periods. A launch system capable of flying weekly or even daily needs a corresponding pipeline of

payload-processing capacity. A shortage of processing facilities can limit cadence even if rockets and pads are otherwise available.

Major launch states worldwide rely on a limited number of high-capacity spaceports, many of which also support civil, military and commercial missions. Expanding launch activity will require new pads, upgrades to shared infrastructure, additional processing facilities and regulatory approvals. Some launch systems may benefit from newer infrastructure or vertically integrated operators, while others may face limited geographic options, aging facilities or competition among multiple users.[5] Globally, the practical capacity to support SBDCs will depend on the ability of launch infrastructure to expand alongside vehicle capability.

The number of launches a rocket can perform is different from the number of launches a spaceport can support. Failure to expand any one of the elements involved in space launch will constrain SBDC deployment even if launch vehicles are reusable and readily available.

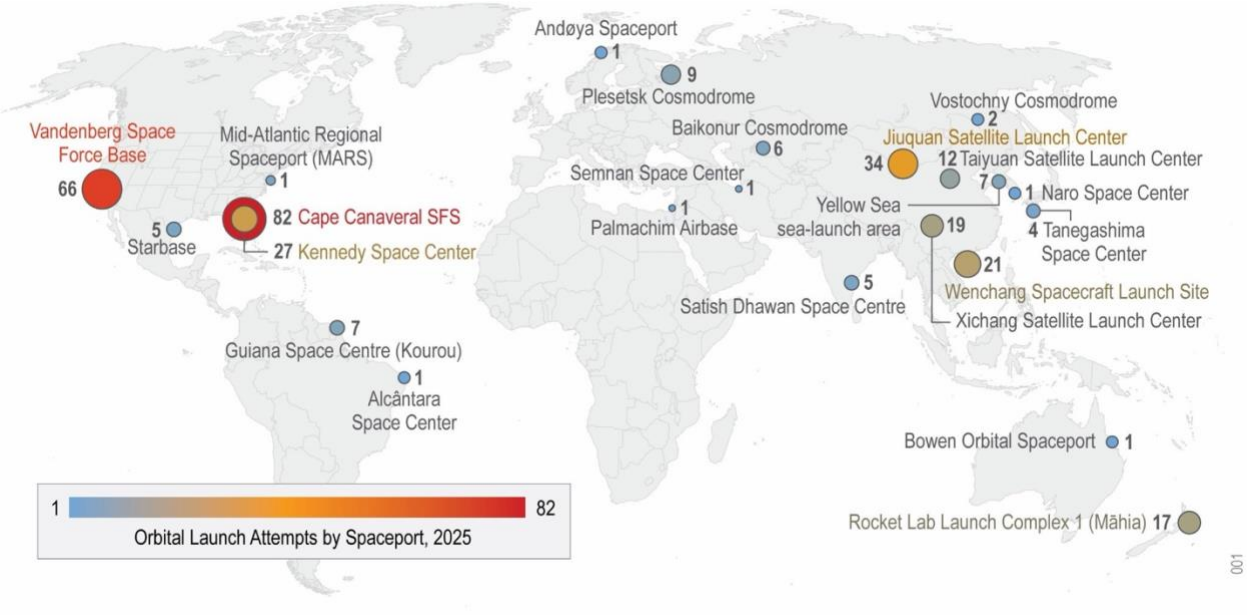
C. Competition for Launch Capacity

Large-scale SBDC deployment would add to growing demand for launch services from civil, commercial and national security customers. Launch infrastructure is often shared among these users, so sustained SBDC launch campaigns could compete for access to launch pads, ranges, payload-processing facilities and launch windows. At high cadence, allocating capacity to one operator or mission could delay or constrain others, particularly at spaceports supporting multiple providers.

This challenge is exacerbated by the launch activity occurring at a small number of sites. In the United States, much of the country's orbital launch activity is concentrated at Cape Canaveral Space Force Station and the Kennedy Space Center in Florida and the Vandenberg Space Force Base in California. In response to limited launch capacity available in the United States, SpaceX is considering constructing a new launch facility on Louisiana's Gulf Coast as it seeks additional locations to support a higher Starship launch cadence. However, this proposal has already drawn opposition from residents and environmental groups.[9] Similar concentrations of launch sites exist elsewhere. Europe relies on the Guiana Space Centre in French Guiana for Ariane 6 launches, concentrating a significant share of its civil, commercial and national-security launch activity at a single spaceport.

Reliance on a small number of high-capacity spaceports creates capacity and resilience concerns: congestion, infrastructure failures, accidents or natural disasters at a major site can affect multiple launch providers and missions simultaneously.

SBDC demand will create allocation and capacity challenges. Governments may need to consider how commercial SBDC launches interact with requirements for national security missions, civil space programs, communications constellations and other commercial activity, particularly if SBDCs begin consuming a significant share of available launch capacity.



Source: Author visualization based on data from Wikipedia, "2025 in spaceflight," section "By spaceport."

D. Geography and Orbital Access

Launch capacity is also orbit specific. Many proposed SBDC architectures may favor sun-synchronous or near-terminator orbits because these trajectories can provide relatively consistent solar illumination, reducing periods when spacecraft must rely on batteries.[10] Sun-synchronous orbits are nearly polar and require particular orbital inclinations, which means not every launch site is equally well positioned to reach them efficiently.[11] Vandenberg Space Force Base is preferred for US missions requiring north-south or polar orbits, making it particularly important for spacecraft destined for sun-synchronous trajectories.[12]

As a result, aggregate national or global launch capacity can overstate the capacity actually available for SBDCs. If SBDC concepts require polar or sun-synchronous trajectories, launch demand would become concentrated at a smaller subset of geographically suitable spaceports. In the United States, this could place additional pressure on Vandenberg.[13] In China polar and sun-synchronous missions launch from Taiyuan and Jiuquan, while other launch sites in the country are optimized for different trajectories.[14-16] Large SBDC deployments seeking sun-synchronous or near-polar orbits will concentrate demand at particular launch sites even if a country has substantial launch capacity available at other launch sites.

E. Environmental Permitting and Spaceport Expansion

Expanding launch capacity can require lengthy environmental and regulatory review, particularly when new pads, spaceports or substantially higher launch cadences are proposed. In the United States, these reviews occur under the National Environmental Policy Act (NEPA) and are headed by the Federal Aviation Administration (FAA).[17,18] Other launch countries use different legal frameworks

but impose similar requirements. In the United Kingdom, launch and spaceport license applicants must submit an Assessment of Environmental Effects to the UK Civil Aviation Authority.[19] In Australia, launch facilities are licensed by the Australian Space Agency, while environmental approvals may also be required under federal, state and territorial environmental laws.[20-22]



Launch of Shenzhou 22 from Jiuqian Launch Area 4, China (2025). Source: China News Service (https://www.youtube.com/watch?v=HpvSTS7WJNE) Licensed under CC BY 4.0.

Spaceport expansion affects nearby communities and ecosystems through noise, construction, hazardous operations, air and water pollution, and habitat disruption and creates restrictions on surrounding land, airspace and maritime areas.[23] The constraints for launch pads are highly location-specific, but they can limit where new launch infrastructure is built and how quickly existing sites can increase cadence. For SBDCs, this means that growing launch demand cannot necessarily be met by adding pads or opening new spaceports. Regulatory approval and community acceptance may become important factors in how quickly global launch capacity can expand, similar to the backlash terrestrial data centers currently receive.[24]

F. Manufacturing, Supply Chains and Export Controls

Large-scale SBDC deployment would require a manufacturing base capable of producing both launch vehicles and spacecraft at sustained high cadence. Reusable launch systems can reduce the number of new rockets required for each mission. However, operations still depend on steady production of the components necessary to manufacture the launch vehicles and payloads. The same is true for the SBDCs themselves. For a 1-GW Reference case, 10,000 satellites would require 25,000 metric tonnes of compute electronics, solar arrays, radiators, batteries, propulsion systems, communications equipment and structural materials.

These requirements expose SBDCs to the supply-chain constraints that already affect advanced manufacturing. Batteries, solar technologies and aerospace systems depend on minerals such as lithium, graphite, cobalt, gallium, germanium, rare earth elements and titanium. The International Energy Agency (IEA) found critical-mineral processing remains highly concentrated. China is the leading refiner for 19 of the 20 strategic minerals tracked by the IEA, with a market share of nearly 70%. China holds especially dominant positions in graphite, rare earth elements and gallium.[25] Recent Chinese export controls show that concentrated supply chains within singular countries can severely impact global manufacturing capability. Restrictions on minerals and heavy rare earth elements have affected materials essential to numerous industries.[26] The 2025 rare-earth controls caused shortages that forced some manufacturers to reduce or temporarily suspend production.[27]

Replacement cadence makes these demands never ending. Maintaining a 1-GW SBDC requires manufacturing roughly 2000 replacement satellites every year in addition to launch vehicles and supporting hardware. Larger constellations increase these material needs. SBDC deployment is

dependent on the ability of global manufacturing capacity and supply chains to support continuous production at the required scale without creating new bottlenecks elsewhere in the supply chain.

G. National Security Impacts

Increased launch demand affects access to launch infrastructure used for national security missions. Governments, particularly the United States, rely on commercial providers to place military and intelligence spacecraft into orbit. The United States seeks to diversify these providers to improve resilience. The US Space Force's National Security Space Launch program is designed to assure access to orbit for critical military capabilities. It expanded the number of eligible providers in part to strengthen launch resilience. Large commercial SBDC campaigns will compete with these missions if infrastructure does not expand at a similar pace.

Export controls add another layer of complexity for who can launch critical technologies and where they can launch from. SBDCs would place some of the world's most advanced computing hardware aboard spacecraft capable of serving customers across national borders. Export controls on advanced computing and space technologies are coordinated across several major technology-producing economies. The United States restricts certain advanced chips, semiconductor manufacturing technologies and related software based on destination, end user and intended use.[28] The European Union maintains its own dual-use export-control regime, while certain countries, including Japan and the Netherlands, have imposed national licensing requirements on advanced semiconductor manufacturing equipment.[29-31] Similar controls apply to propulsion, communications, sensing and other dual-use technologies. As a result, SBDC developers will face overlapping national rules dictating where hardware can be manufactured, launched, operated or made available to foreign customers. Governments need to contend with how existing controls apply when sensitive computing hardware is physically located in orbit but provides computing services to users in multiple jurisdictions.

The national-security challenge created by SBDCs is broader than just protecting SBDCs themselves. Policymakers need to consider whether SBDC growth competes with assured access to space, deepens dependence on a small number of commercial providers or creates new pathways for transferring strategically sensitive computing capability across borders.

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CHAPTER 1.6:

VULNERABILITY TO ATTACK

Kathleen Curlee

MAIN MESSAGES

- Space-based data centers (SBDCs) would be vulnerable to multiple forms of attack including jamming, cyber attacks and kinetic threats.
- Defenses for SBDCs include resilient and redundant constellations, systems hardened against electronic warfare, and secure ground infrastructure.
- SBDCs could be targets in conflicts if they become significant portions of a country's economy or support military operations.
- Current technologies and legal oversight are insufficient to protect commercial or civil SBDCs from any form of attack, in large part due to the isolated nature of space and lack of enforcement of international law.

Space-based data centers (SBDCs) are not inherently safe because they are in space. They would be vulnerable to attack from hostile actors: several nation states and non-state actors have the demonstrated capability to disrupt SBDCs. Defense of SBDCs could be difficult because of technological limitations. Moreover, SBDCs that support military missions could become targets during conflict. Commercial SBDCs could also attract hostile attention if their disruption would create economic or political damage.

On top of this, escalation dynamics in space are poorly understood.[1] Measures intended to protect SBDCs could be misread during a crisis. For example, a spacecraft sent to inspect or repair another spacecraft could be viewed as a threat to surrounding satellites. Intentional jamming, cyber intrusion or close approaches of SBDCs often have ambiguous attribution which can lead to governments responding to threats in space before full understanding of the situation is known.

This chapter examines how hostile actors might target SBDCs, the limits of current defenses, attack scenarios and policy considerations. The chapter closes with recommendations.

A. Threats to Space-Based Data Centers

SBDCs face several forms of hostile interference in space. Some threats can go as far as damaging or destroying an individual or group of SBDCs. Other threats can interrupt service without causing permanent harm to the spacecraft. An attacker can also target the communications links and ground



F-15 launching the ASM-135 anti-satellite missile. Source: U.S. Air Force Research Laboratory / Michael Weber (Disclaimer: The appearance of U.S. Department of War (DoW) visual information does not imply or constitute DoW endorsement.)

systems on Earth needed to operate SBDCs. The most significant threats include kinetic attacks, co-orbital interference, electronic warfare, cyber operations and directed-energy systems.[2]

i. Kinetic Threats

Direct-ascent anti-satellite (ASAT) weapons are missiles launched from the ground or air that target objects in space. The United States, China, India and Russia have demonstrated destructive direct-ascent ASAT capabilities. These attacks can destroy spacecraft. On top of this, they can make debris that remains in orbit, creating persistent risks for other satellites. For example, China's 2007 test accounts for 19% of all debris in orbit today.[3] These fragments increase risks for other spacecraft, as an object as small as ten centimeters can hit with the force of several kilograms of TNT.[4]

Co-orbital systems present another form of physical threat. These systems rendezvous with satellites, interfering with them at close range. Potential hostile actions include physical manipulation or deliberate collision. Some rendezvous and proximity operations support benign missions such as inspection. However, these same capabilities could also support hostile activity or could be perceived as such.[5]

Rendezvous and proximity operations allow one spacecraft to closely approach and maneuver around another.

ii. Non-Kinetic Counterspace Capabilities

Other counterspace operations can create reversible effects. An attacker may seek to deny service during a crisis without destroying the system. Temporary disruption may be harder to attribute than a kinetic strike. It would also avoid the debris created by a physical attack.



U.S. Space Force Guardians train on a system detecting satellite electromagnetic interference, 2026. Credit: U.S. Space Force/David Grim

Electronic warfare could disrupt an orbital data center without damaging the spacecraft:

- Jamming can prevent a satellite from receiving or transmitting signals
- Spoofing can introduce false information into a system or mislead users about the source and accuracy of a signal
- Cyber operations could target onboard software or command systems, as well as ground stations and terrestrial networks

This means an attacker may be able to disrupt an orbital service without directly reaching the spacecraft. Directed-energy weapons can also temporarily disrupt an asset or cause permanent damage by using lasers or high-powered radiofrequency energy to interfere with spacecraft systems.[6]

B. Defense of Space-Based Data Centers

Defending SBDCs and other space infrastructure will require a layered approach that combines prevention, protection, resilience and recovery.[2] The challenge is that few active protection mechanisms currently exist for satellites once they are deployed. Satellites operate in a remote environment, move at orbital velocity and have limited fuel without the ability to refuel.[7] This makes repair and active defense more difficult than comparable efforts for terrestrial data centers. This is one reason national space security plans emphasize resilience across the full space system as a means of defense against threats.

On-orbit servicing technologies are promising emerging capabilities but not yet usable at scale. Northrop Grumman's Mission Extension Vehicles have demonstrated commercial life-extension services for geostationary satellites, and the US Defense Advanced Research Projects Agency's (DARPA's) Robotic Servicing of Geosynchronous Satellites program is working toward cooperative inspection and servicing in Geostationary Equatorial Orbit (GEO).[8] At the same time, NASA cancelled OSAM-1 after cost growth and schedule delays. These development challenges illustrates the technical and programmatic difficulty of servicing satellites that were not designed for repair.[9]

The most practical defense for many space systems is architectural resilience. One approach is to distribute capabilities across many satellites so that the loss or degradation of one part of a constellation or ground segment does not ruin the spacecraft. This approach already appears in several national and allied space strategies. The US Space Development Agency's Proliferated Warfighter Space Architecture is built around a layered, proliferated Low Earth Orbit (LEO) architecture and mesh networking.[10] Japan's Space Security Initiative similarly emphasizes retaining large numbers of satellites with similar functions, diversifying architectures, protecting ground stations and improving cyber resilience.[11] The United Kingdom's Space Command has also described a "system of systems" approach that connects space capabilities, ground infrastructure and multiple users to improve resilience and redundancy.[12] For orbital data centers, this means avoiding excessive concentration of critical workloads on a single large platform. A more resilient architecture would distribute processing and communications across multiple nodes.



Mission Shakti launch of interceptor missile for ASAT test, March 2019. Source: Press Information Bureau on behalf of Ministry of Defence, Government of India

Redundancy and rapid replacement are central to defense. The US Space Force Commercial Space Strategy states that commercial integration can strengthen resilience by increasing the number of providers and diversifying supply chains.[13] The North Atlantic Treaty Organization's (NATO's) Commercial Space Strategy similarly focuses on cooperation with the commercial sector to improve complementary capabilities, capacity and resilience across the Alliance.[14]

Ground infrastructure is another major defense priority. Space systems depend on command centers, antennas, cloud interfaces, user terminals, fiber links, power supplies, terrestrial software systems and more.[15] An adversary may attack these supporting systems as they are more accessible than the spacecraft themselves, although this is a high-risk approach as kinetic attacks can be viewed as an act of war. Defensive planning should include geographically distributed ground stations, hardened command-and-control links, secure power supplies and procedures for operating through degraded conditions. The EU Space Strategy for Security and Defence already recognizes the need to improve the resilience and protection of space systems and related services.[16]

Cybersecurity and network resilience will be especially important for orbital data centers. Proposed security measures include encryption, authentication, frequent software updates, zero-trust access controls, intrusion detection, segmented workloads, trusted execution environments, backup data paths and isolation of compromised nodes.[17] The US National Institute for Standards and

Technology's (NIST's) hybrid satellite network cybersecurity profile is an example of addressing systems in which multiple participants can own or operate different portions of the network.[18]

Defenses should also include electronic warfare resilience. Jamming, spoofing and interference are among the most accessible counterspace threats and are already used in conflicts.[19] Operators can mitigate risks through protected waveforms, interference monitoring, or rerouting traffic through multiple satellites and ground stations.[20,21] For allied users, this also means planning for cross-support between national and commercial networks so that loss of one communications path does not sever access to essential services. Across these defense areas, allied governments need shared expectations for continuity of services and crisis coordination with commercial providers.[18]

C. Attack Scenarios

i. Military Conflicts

SBDCs could support a range of military and national security functions. For example, they may process satellite imagery or support secure communications.[22] They could also host artificial intelligence (AI) models used for detection or decision support.[23] Existing defense strategies already identify satellite communications, intelligence, surveillance, reconnaissance, cyberspace operations and spacecraft operations as areas where commercial space systems can contribute to national security missions.[24] SBDCs might have the ability to enhance these functions.

These applications make SBDCs a potential target during conflicts. An adversary may view SBDCs as a military target if disrupting them can weaken national command networks or reduce access to critical information for security operations. The risk would be highest for systems that support time-sensitive missions or serve several military users at once. SBDCs could accelerate space-based decision-making and improve the responsiveness of military space operations making them attractive for countries to pursue.[23]

Commercial ownership would not mitigate this risk. Governments purchase communications and other space capabilities from private companies. SBDCs could operate under similar agreements. Defense agencies are also seeking deeper integration of commercial systems into military architectures to support resilience. As a result, a privately operated SBDC could support civilian customers and defense users through the same infrastructure. Its role could expand during a crisis if governments purchase additional capacity or redirect existing services toward military needs.

This pushes SBDCs into the uncertainty that already exists around dual-use infrastructure. It may be difficult for an adversary to determine which spacecraft are exclusively for military purposes and which are commercial. Policymakers will need to consider how military use affects the status of commercial orbital systems and what responsibilities follow from that integration. Moreover, policymakers must contend with the fact that valuable commercial assets in space are highly vulnerable to interference and make attractive targets if a total-war strategy is used.

ii. Economic Competition

SBDCs may be economically important even if they have no direct military role. Businesses may come to depend on them, and their loss of SBDCs could disrupt services on Earth and impose costs across several industries. The economic value of SBDCs make them attractive targets. A hostile actor may seek to damage a competitor's technology sector or undermine confidence in space-based services. An attack could also interrupt markets or create pressure on governments whose economies depend on the affected systems.



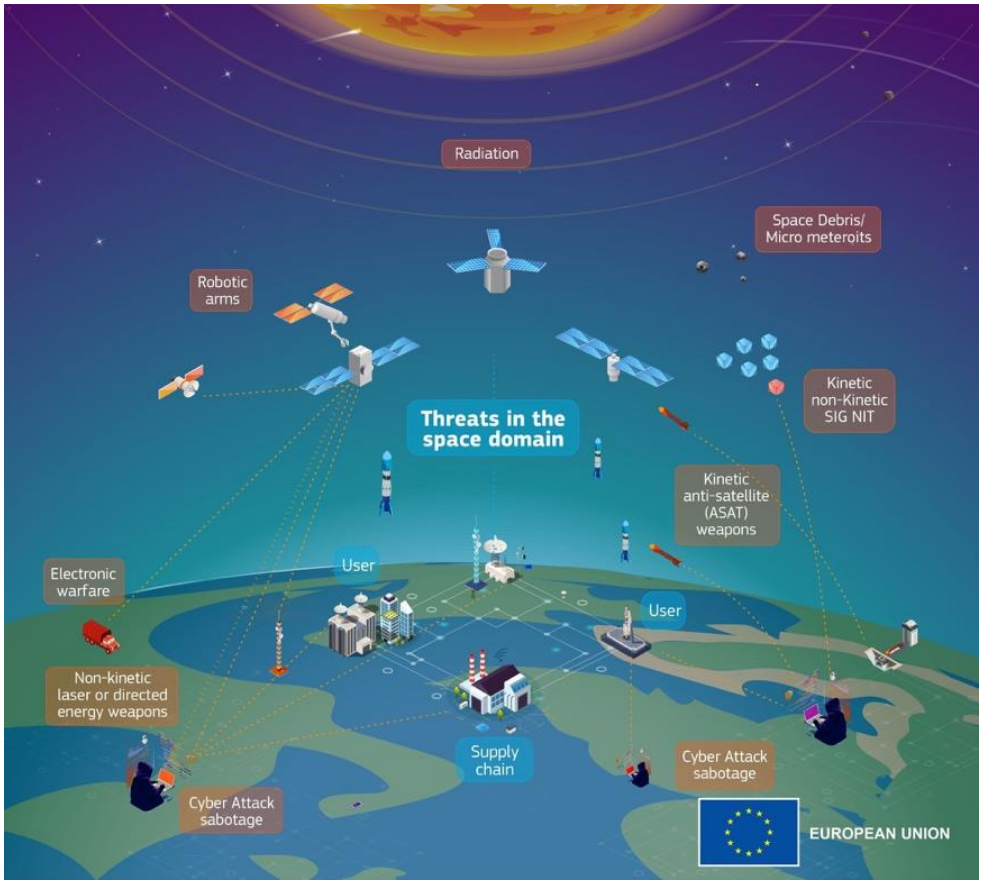
Early Warning Radar facility for missile warning and space surveillance missions, 2024. Source: U.S. Space Force/David Grim

Terrestrial critical infrastructure already experiences disruptions during conflicts. Hostile actors have targeted systems like energy grids and financial institutions to create economic disruption without engaging military forces directly.[25] SBDCs offer another means of applying pressure to civilian life. SBDCs' location in space also creates uncertainty around attribution and response. The risk would increase if customers depend on a small number of SBDC providers.[26] A disruption could have effects far beyond the operator that owns the asset. Policymakers must assess what level of protection or resilience SBDCs should require, especially if they become critical components of their economies.

iii. Dual-Use Implications

Distinguishing civilian and military infrastructure is difficult in space, where many systems are inherently dual use.[27] Satellites that provide communications, navigation, remote sensing, weather monitoring or data-relay services support everyday civilian activity while also enabling military operations. Commercial systems further complicate this distinction as they serve a mix of private and military customers through the same infrastructure. Even if an SBDC is privately owned and primarily commercial, an adversary may view its wartime function, customer base or integration with military networks as more important than its ownership structure and thus a valid and strategically important target for interference.

This overlap could create legal and strategic ambiguity. Policymakers need to clarify expectations for disclosure, workload separation, service continuity and government support for these data centers.[28] They also need to consider how civilian and military applications can be distinguished in practice, whether certain uses would increase the risk that a commercial system is treated as a military objective and what protections remain for civilian users whose data or services rely on the same infrastructure. These questions are not unique to SBDCs but reflect a broader emerging challenge in space in which commercial infrastructure is central to national security but remains deeply intertwined with civilian economies and global services.



Threats in the space domain (2023). Source: European Commission

D. Policy Considerations

Policymakers must plan for a space environment that is contested and likely to become more crowded with critical commercial infrastructure should SBDC proposals be realized. Satellites already support communications, navigation, remote sensing, financial systems, military operations and disaster response. SBDCs would add another layer of economically and strategically important infrastructure to orbit.

Several issues should be addressed before these systems reach large-scale deployment:

- Governments will need to decide whether some commercial space assets should be treated as orbital critical infrastructure
- Governments will need criteria for identifying which systems are critical to national security or economic stability
- Policymakers should clarify public-private security responsibilities

Operators may be responsible for cybersecurity, redundancy, service continuity and protection of ground infrastructure. Similarly, governments may also need to provide support to allies during attacks or major disruptions.

Governments should also think through deterrence and response. Attacks on commercial orbital infrastructure would impact private and government domains. Defensive measures may also carry escalation risks if an adversary interprets them as preparation for offensive action. Policymakers should clarify how they would assess attacks on SBDCs, when they would support commercial operators, which responses could increase escalation risks and what role alliances would play in a crisis.

E. Recommendations

1. Define orbital critical infrastructure: Governments should identify which commercial space assets are critical to national security, economic stability or public safety.
2. Set baseline security and resilience requirements: Policymakers should establish expectations for cybersecurity, redundancy, service continuity and protection of ground infrastructure before SBDCs reach large-scale deployment.
3. Clarify public-private responsibilities: Governments should assign clear roles for threat monitoring, incident reporting, crisis response and service restoration before a disruption occurs.
4. Plan for attacks on ground infrastructure: Security planning should cover ground stations, cloud interfaces, user terminals, power supplies and terrestrial networks that support orbital systems.
5. Develop crisis coordination mechanisms: Governments should establish standing channels with operators and allied partners for sharing threat information and coordinating responses during jamming, cyber incidents or physical attacks.
6. Address deterrence, response and escalation risks: Policymakers should clarify how attacks on commercial orbital infrastructure would be assessed, what responses could raise escalation risks and how allies would coordinate in a crisis.

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Text Box 1-2:

SOFTWARE



Alp Kucukelbir

Google's early breakthrough in search was an algorithm called PageRank. It treated links between web pages as signs of authority and used them to rank results. PageRank ran on the same servers search had always used. The servers did not change. The idea did.

Data-center hardware depreciates quickly because each new generation makes the last one less valuable. On Earth, an operator can replace an outdated processor, add memory or install a new generation of graphics processing unit (GPU) accelerators. Hardware in orbit faces the same technological obsolescence without the same replacement cycle. Once launched, software becomes the principal means of improving its useful performance.

Software helps a machine in two different ways. It can tune what is already there: make an artificial intelligence (AI) model use less memory, eliminate unnecessary calculations, keep processors from waiting for data. These tunings let the same machine answer more requests, spend less power per answer or run models that once exceeded its limits. But software can also hand hardware a capability it never had, the way PageRank did not speed up a search engine's servers but gave them something new to compute. New ideas—like PageRank—are harder to develop but can break through a ceiling that tuning alone cannot overcome.

The market will not lower its expectations because a data center is in orbit. On Earth, operators meet the demand for better AI models and faster AI inference with better software and new hardware, generation after generation. An orbital data center faces the same demand with hardware that no longer changes. Software cannot add physical memory, repair a damaged processor or increase the power available from a spacecraft. It can extend the range and value of the machinery already there. In orbit, software must close the distance between what users expect and what the launched machine can deliver.

The useful life of a space-based data center (SBDC) might therefore be extended by continued software development, allowing satellites to operate for longer and reducing a range of impacts, including the number and pace of launches and impacts on the atmosphere from re-entry disposal. However this requires long-term software support and continued research into new algorithms – not just the kind that run leaner, but the kind with PageRank's leverage, unlocking capability the hardware was never built to have on its own.

On Earth, better software is an advantage. In orbit, its value is astronomical.

PART 2:

RISKS AND IMPACTS

CHAPTER 2.1: NIGHT SKY AND ASTRONOMY

CHAPTER 2.2: ORBITAL CONGESTION AND SPACE DEBRIS

Text Box 2-1: GROUND CASUALTIES AND DAMAGE

CHAPTER 2.3: STRATOSPHERIC OZONE DEPLETION

CHAPTER 2.4: GREENHOUSE GASES AND BLACK CARBON

CHAPTER 2.1:

NIGHT SKY AND ASTRONOMY

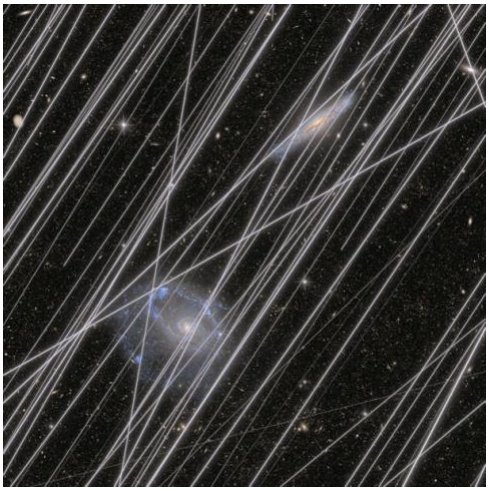
Alexis Abramson and David Sandalow

MAIN MESSAGES

- Constellations of space-based data centers could transform night skies around the world. More satellites than stars could be visible at many times in many places.
- Impacts on observational astronomy could be especially devastating.
- Technical measures could reduce impacts but would involve operational tradeoffs and would not eliminate the need to radiate waste heat.
- Policy responses include brightness limits, pre-launch impact assessments, required mitigation measures, caps on satellite numbers and international standards.

Space-based data centers (SBDCs) could transform night skies around the world. If announced plans for SBDCs are fully implemented, most visible points of light in the sky during much of the night in much of the world could be satellites, not stars. Unlike stars, these satellites would drift visibly across the night sky.[1-3]

The impacts would not be limited to what the eye can see. Large SBDC constellations would severely disrupt professional astronomy, streaking images from wide-field survey telescopes (which detect





Left: Simulated satellite trails streaking images from space telescopes. Source: NASA / Borlaff, Marcum, Howell (Nature, 2025). CC BY-NC-SA 4.0. Right: Satellite streaks over Orion; digital combination of 65 exposures. Source: NASA/Amir H. Abolfath

faint light sources) and contaminating observations from infrared telescopes (which would register the satellites' substantial waste heat, detecting wavelengths invisible to the naked eye). The American Astronomical Society (AAS) filed a strong opposition to SpaceX's January 2026 request for approval to launch and operate one million SBDCs, writing that the proposal "represents an unprecedented threat to the visual integrity of the night sky."[1]

These impacts are due to the size, nature and number of proposed SBDCs.

- SBDCs are far larger than typical satellites. SpaceX's AI1 satellite has a 70-meter wingspan—more than twice the size of Starlink satellites. Some experts estimate that SBDCs could reach 100 meters from tip to tip due to their large solar arrays and radiators. SBDCs could be among the largest structures ever placed in orbit.4,5
- SBDCs' size and design could make them unusually bright from reflected sunlight, depending on their surface properties and orientation. Their large heat-rejection systems would also make them substantial sources of infrared emission. Radiator panels drive both effects: their coatings are engineered both to reflect sunlight (so the panel avoids absorbing additional heat) and to emit infrared efficiently (so it can shed heat). The first property makes them highly reflective in visible light, and the second is a source of infrared radiation. (The large solar arrays contribute differently. Because they are designed to absorb sunlight, they appear dark most of the time, but their flat, mirror-like surfaces can throw brief, intense flashes when the Sun, satellite and observer align.)
- SBDCs could dramatically increase the number of satellites in orbit. SpaceX alone proposes to increase the number of satellites in low Earth orbit (LEO) by a factor of 100. Starcloud has proposed a constellation of 88,000 SBDCs, and Orbital has filed an application to launch and operate up to 100,000 satellites. The cumulative impact of large numbers of satellites can degrade night skies and interfere with astronomy, even if individual satellites themselves do not create problems.[6]

SBDCs' orbits would affect the times and places they are visible from the Earth's surface. SpaceX proposes to operate SBDCs in two distinct orbital regimes. Some would fly in Sun-synchronous, near-polar orbits calibrated to the day-night terminator (the line where day turns to night), which keep the satellites in sunlight more than 99% of the time for continuous power and compute. A second set would fly in lower-inclination orbits at 30°, passing over latitudes between 30° North and 30° South. (See Figure 1.) The terminator satellites would be visible during morning and evening twilight, while the 30°-inclination satellites would be visible across a wider range of the night in the world's more populated mid- and low-latitude regions.

A. Harms

What harms would result from transforming the night sky?

A first answer is primal and deeply rooted in the human experience. At some level it seems unimaginable that a few companies could radically alter the night sky for everyone on Earth. The stars have been a core part of the human experience since *Homo sapiens* first walked the Earth hundreds of thousands of years ago.[7-9] Across cultures and religions, people find spiritual meaning in

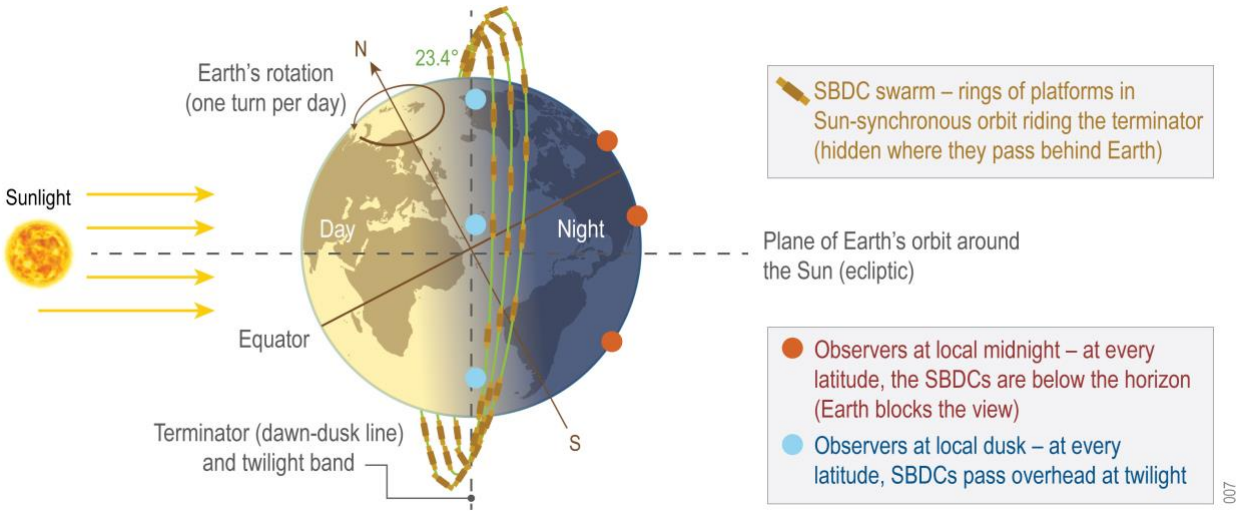


Figure 1. *A constellation of SBDCs in Sun-synchronous orbit. SBDCs ride the dawn-dusk line (the "terminator").*

the stars. Transforming the night sky so visibly would bring loud and vigorous objections from many people around the world.

Changing the night sky would have unknown and unpredictable impacts on ecosystems, as well. A night sky filled with thousands of moving points of light each night could confuse animal species whose navigation systems depend on fixed points in the night sky. Increase in night sky brightness could affect animal species by obscuring celestial cues as well. Research on satellites' effects on animal species is developing, but several studies suggest that at light levels lower than "sky glow," animal species may experience distorted cues on the time of day or season and interference with predator-prey interactions and be rendered unable to navigate using the stars.[10]

Astronomers point to other risks. The AAS argues that SpaceX satellites "would blind us to incoming hazardous asteroids and disable the observations required for space situational awareness, compromising national security."[1] The Royal Astronomical Society (RAS) predicts that as much as 10% of data captured by the European Southern Observatory's (ESO's) Very Large Telescope could be affected by satellite streaks.[11] A 2025 study modeling the full deployment of proposed large telecommunication constellations predicts that roughly one-third of Hubble Space Telescope exposures and 96% of exposures from the space-based SPHEREx astronomical observatory will be affected.[12,13]

These effects arise from reflected sunlight. Infrared astronomy faces a different but equally serious threat. Much of what we know about the birth of stars, the composition of distant worlds and the earliest galaxies comes from infrared observation, at wavelengths the eye cannot see. Because they detect such faint heat, infrared telescopes are exquisitely sensitive to any stray warmth; the James Webb Space Telescope carries a sunshield the size of a tennis court (see Figure 3) and chills its mid-infrared instruments to below 7 Kelvin, colder than almost anywhere in nature, so that its own heat

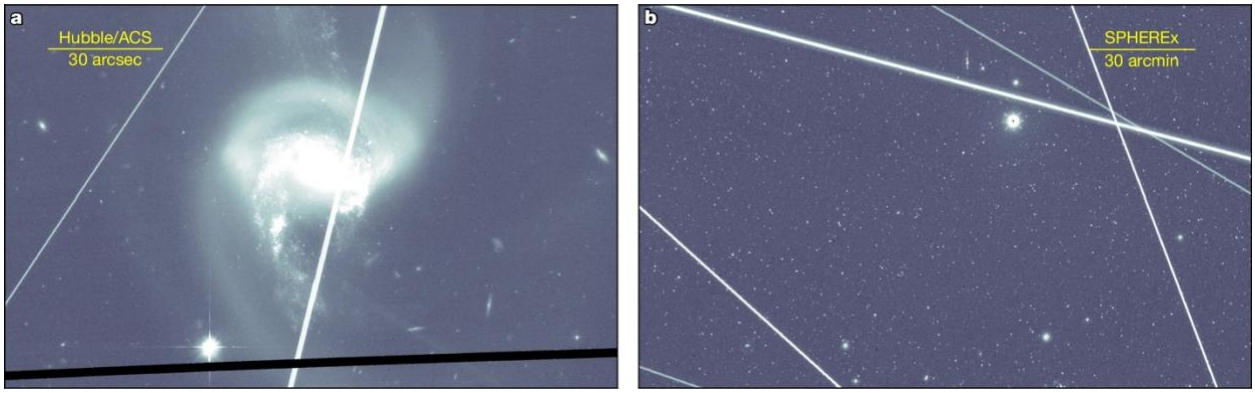


Figure 2. *Cropped simulation of Hubble (a) and SPHEREx (b) exposures with satellite trails. Source: NASA / Borlaff, Marcum, Howell (Nature, 2025). CC BY-NC-SA 4.0*

does not blind it.[14] To such an instrument, a heat source drifting across the sky is precisely the contamination it was built to escape.

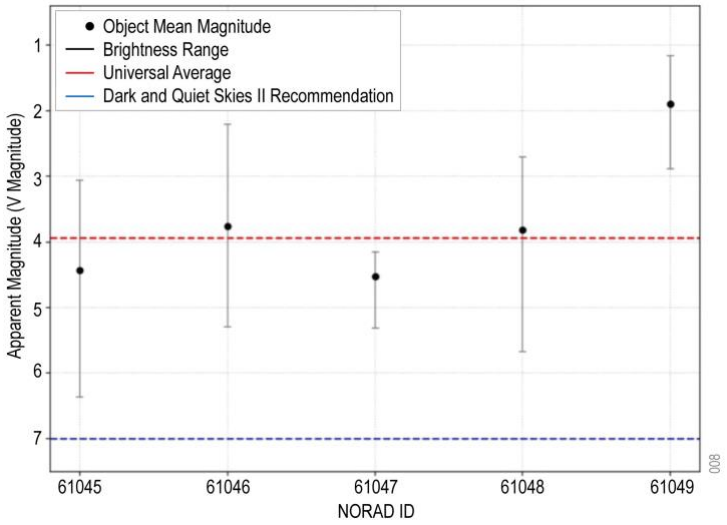
SBDCs would be exactly that. A radiator's function is to convert waste heat into infrared radiation and shed it, and so a megawatt-class SBDC is by design a megawatt-scale infrared source, radiating day and night for as long as it computes. Pointing the radiators toward deep space—and away from Earth—could substantially reduce the problem for ground-based observatories but may not fully resolve it. A radiator does not emit its heat in a narrow beam that can be aimed away from a telescope; like a bare bulb, it glows across nearly every direction it faces. Orientation can reduce the infrared reaching a given location, but the telescope cannot fully avoid the hemispherical emission from the radiator. The observatories most exposed are those operating in the mid-infrared, where a radiator near typical operating temperatures emits most strongly. Astronomical observatories around the world, representing hundreds of millions if not billions of dollars of invested capital, could have their usefulness for astronomical research significantly diminished.[1]

B. Mitigation

A central question is whether these impacts can be mitigated at all. Visible brightness comes from reflected sunlight and can be lessened by darkening films or by orienting radiators edge-on to the Sun. But darkening a radiator raises the sunlight it absorbs, degrading its cooling, so this protection is bought at a thermal and therefore economic cost. The radiator's infrared emission is different in kind: it is the heat itself leaving the system, and so its total is fixed by the compute load. While coatings might be used to manipulate wavelength or the direction of thermal radiation,



Figure 3. *The James Webb telescope's sunshield in test deployment. Source: NASA/Chris Gunn*



Brightness range of the five satellites observed (x-axis values = satellite IDs).
Source: Owen Miller et al 2026.[20] Open Access CC BY 4.0

no measure can reduce the total emission because the full heat load must be radiated. Consequently, reflected sunlight can be partially managed at a price; the total infrared output of a radiatively cooled data center is fixed by thermodynamics.

SpaceX's efforts to dim its Starlink satellites offer useful lessons.[15] The company first tried a darkening coating (its 2020 'DarkSat'[16-18]), which reduced brightness by roughly a factor of 2.5 but caused precisely the problem expected: the black surfaces absorbed more sunlight and overheated. Further, astronomers noted the added heat interfered with mid-infrared observations. SpaceX abandoned the coating and switched to a deployable sun visor ('VisorSat') that blocked sunlight from reaching the reflective surfaces, cutting brightness by about a factor of three. However, the visors interfered with the satellites' laser communication terminals and were dropped in turn. They were replaced by a dielectric mirror film on the underside that redirects sunlight back into space rather than toward the ground. Even after these iterations, the satellites remained brighter than astronomers' recommended threshold. This history illustrates both that visible brightness can be partially mitigated and that each fix carries a cost: thermal, operational or optical. Moreover, none of these measures has been demonstrated on structures whose solar arrays and radiators are many times larger than a Starlink satellite.

Recent experience with a small constellation of communications satellites underscores the challenges. In 2024, the US Federal Communications Commission (FCC) granted AST SpaceMobile a license to operate a constellation of five communications satellites, requiring AST to “make a good faith effort to demonstrate an optical brightness with an initial aim of 6th magnitude.”[19] A team monitoring the brightness of those satellites from November 2024 to June 2025 found that the satellites missed that target by a wide mark, averaging roughly seven times brighter than the FCC’s target.[20]



Visualization of space-based data centers in the southern sky just after sunset. Actual views will depend on many factors including number of satellites and brightness mitigation. Source: Shutterstock AI.

For infrared, the challenge is even greater, but it does not follow that nothing can be done. A substantial body of research demonstrates that micro structured and metamaterial coatings can engineer both the wavelength and the direction of thermal emission.[21-23] In principle, such coatings could shift a radiator's emission away from specific observation bands or bias it toward specific directions, offering partial, targeted protection at some cost in cooling performance. These techniques, however, have been demonstrated only over narrow wavelength ranges and at laboratory scale; their application to space-durable radiators of hundreds of square meters, across constellations of thousands of satellites, remains undeveloped. And they face a fundamental limit: the full waste-heat load must still be radiated, and so these methods can relocate the emission in wavelength or angle but cannot eliminate it. Whether such approaches can meaningfully lighten the burden on infrared astronomy is an open question that deserves research attention.

The impacts of altitude on night sky visibility and astronomy are complicated. Satellites at higher altitudes are less bright than identical satellites at lower altitudes, so some impacts of SBDCs on the night sky can be mitigated by flying them in higher orbits. However satellites at lower altitude cross the sky more quickly and are visible for less of the night, which offers clear benefits for astronomical

research. Some astronomers have recommended operating satellite constellations at lower altitudes for that reason.[24,25] Samantha Lawler et al. write

"There is no perfect solution—higher altitude orbits may be better overall for naked-eye stargazers, but lower orbits are thought, based on the astronomy community's current understanding of satcon operation plans, to be better for large research facilities."[26]

The most effective mitigation measure, of course, is to limit the number of SBDCs in orbit. To reduce night-sky impacts, there is no substitute for fewer bright and warm objects in the sky.[25,27]

C. Policy Options

A range of policy options could help address the impacts of SBDCs on the night sky and astronomical research. They include the following:

1. Brightness limits. National regulatory authorities could limit the brightness of individual satellites as license conditions. The International Astronomical Union (IAU)'s Centre for the Protection of the Dark and Quiet Sky has called for visible magnitude limits of 7 or greater, depending on the satellite's altitude.[28] Satellites meeting that standard would be invisible to the naked eye from dark locations and would reduce, although not eliminate, interference with astronomical observations.[6,24]

2. Limits on number of satellites. Even if individual SBDCs cannot be seen with the naked eye, the cumulative impact of hundreds of thousands of SBDCs could produce diffuse light that brightens night skies and disrupts astronomical research. A June 2026 paper by O. R. Hainaut from the European Southern Observatory recommends combining an individual satellite brightness limit of 7 with a limit of no more than 100,000 satellites in LEO.[6,29]

3. Require darkening coatings, sunshades and other technical measures to reduce brightness. These measures may not fully mitigate the problem and will come at an operational cost but have the potential to reduce impacts.

4. Require dark-sky and astronomy impact assessments as conditions for license approvals. In this regard, the longstanding categorical exclusion for satellite launches under the US National Environmental Policy Act (NEPA) should be repealed, as recommended by the US Government Accountability Office (GAO).[30]

5. Pursue international brightness standards through the Committee on Peaceful Uses of Outer Space (COPUOS). This process would take years with no guarantee of success, given the consensus-based decision-making process at COPOUS. But the dialogue itself could have educational benefits and help shape behavior of key actors, even in the absence of agreed standards.[29]

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CHAPTER 2.2:

ORBITAL CONGESTION AND SPACE DEBRIS

Kathleen Curlee

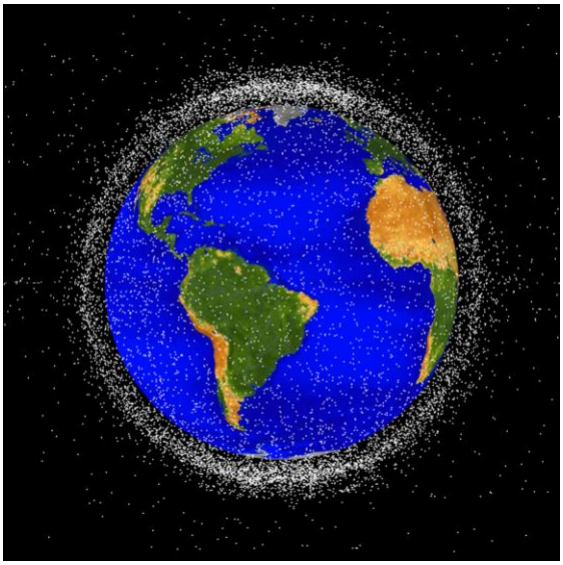
MAIN MESSAGES

- 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.

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]



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

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]

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]



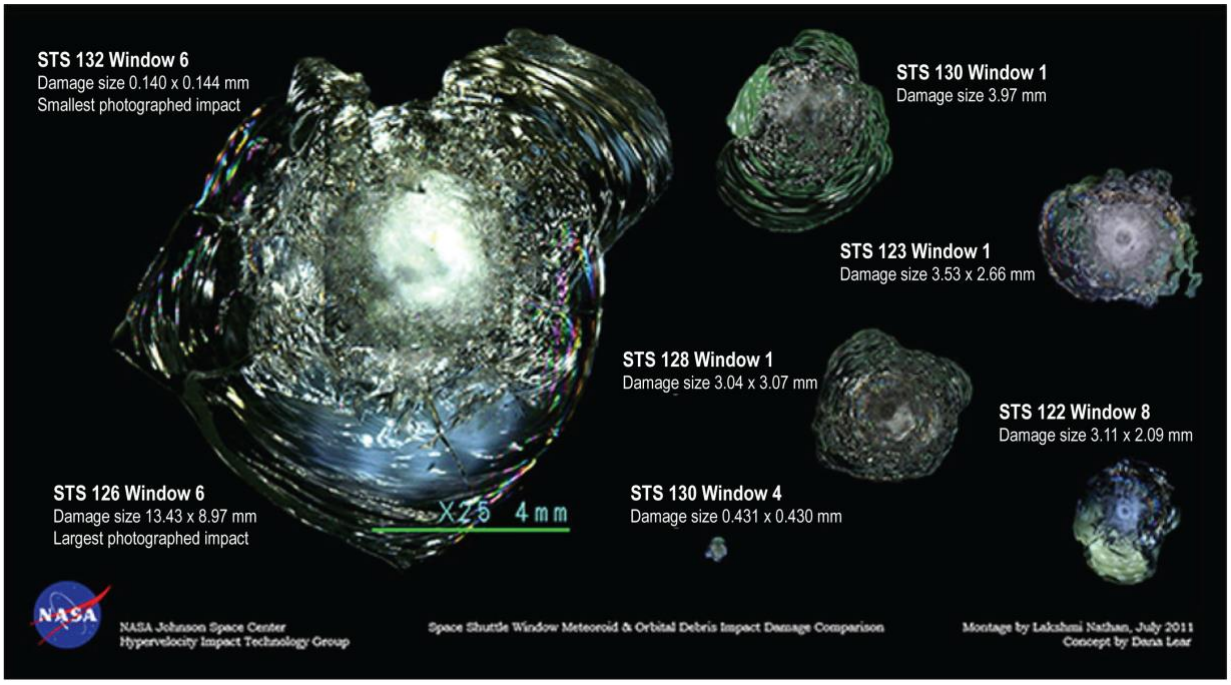
Impact chip in the International Space Station (ISS) Cupola window from suspected paint fleck. Source: ESA & NASA - Tim Peake

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.

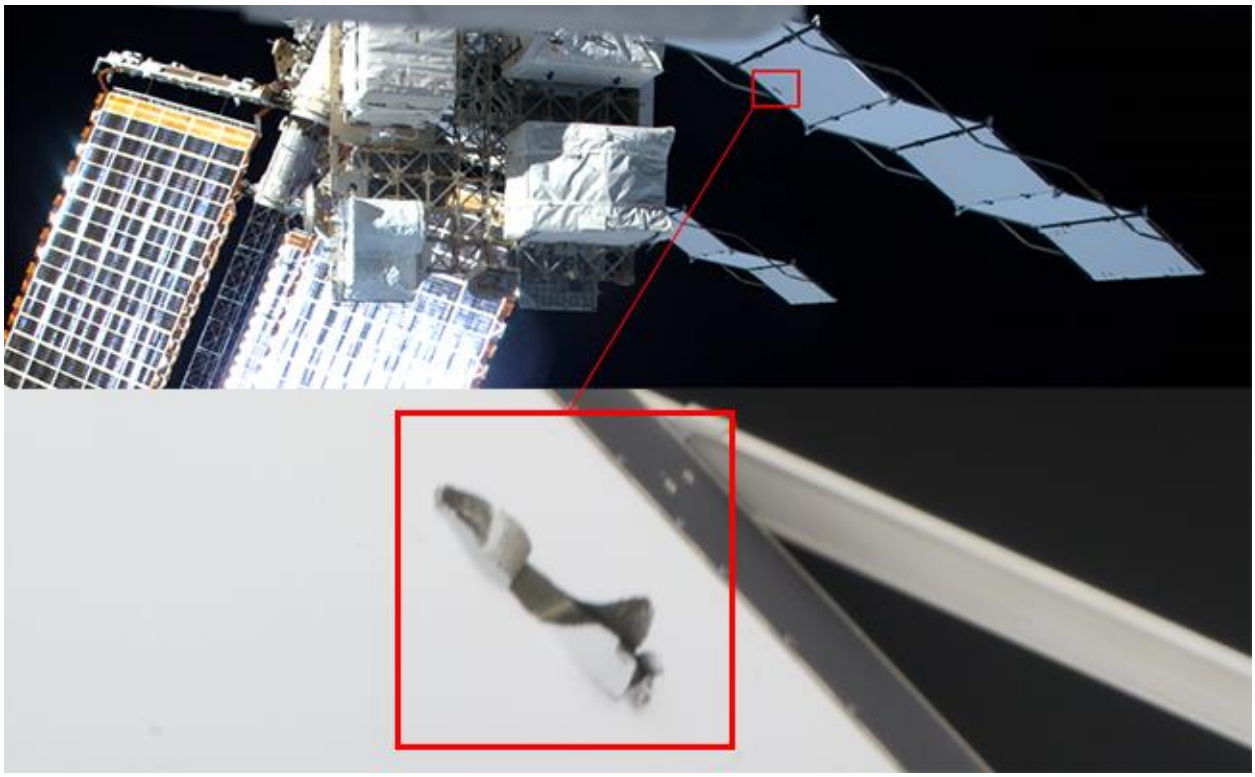
SBDC satellites could also present unusually large collision cross-sections because of the solar arrays and radiators they require to generate power and reject heat. (See Chapter 1.3-Cooling.) This makes maneuverability a basic design requirement, alongside automated systems capable of evaluating and 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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Text Box 2-1:

GROUND DAMAGE AND CASUALTIES

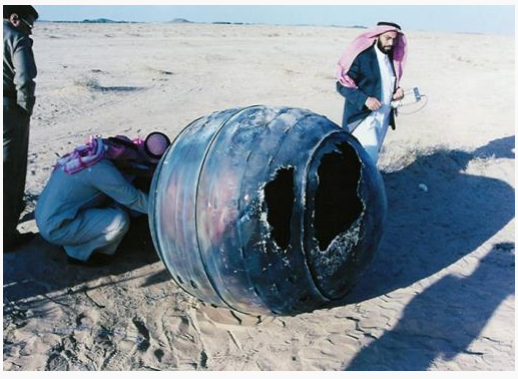
Roger Aines and David Sandalow

Satellites in low Earth orbit (LEO) gradually lose altitude because of atmospheric drag, unless operators take steps to counteract it. Some satellites can be designed to burn up on re-entry, depending on their size and materials. (This is known as design for demise.[1,2]) Other satellites are designed for controlled re-entry, often over remote ocean areas.

Constellations with hundreds of thousands of satellites, such as those proposed for space-based data centers (SBDCs), would create risks of damage and casualties as satellites return to Earth. Some SBDC components might survive re-entry. Controlled re-entry of many thousands of satellites each year would significantly exceed historical experience, increasing the likelihood of some failures.[3,4]

International law places responsibility for ground damage and casualties from satellites on states. Under the 1972 Liability Convention, a launching state is absolutely liable for damage its space objects cause on the surface of the Earth or to aircraft in flight.[5] The Inter-Agency Space Debris Coordination Committee's (IADC's) international guidelines recommend 10^{-4} as the upper limit for expected casualties per re-entry and call for minimizing cumulative re-entry risk from constellations.[6]

National and space-agency standards with respect to these risks vary. In the United States, the Federal Communications Commission (FCC) requires applicants to disclose whether the probability that a collision with small debris or meteoroids would cause loss of control and prevent disposal is 1 in 100 or less.[7-9] For covered satellites in LEO, the FCC requires disposal as soon as practicable and no later than five years after mission end.[10,11] Applicants planning atmospheric re-entry must also demonstrate a calculated casualty risk below 1 in 10,000 per spacecraft.[7] For large constellations of at least 100 spacecraft, the European Space Agency (ESA) requires either fewer than 10^{-6} expected casualties per re-entry or controlled re-entry. Controlled re-entries are subject to ESA's general limit of fewer than 10^{-4} expected casualties per re-entry.[12]



A Payload Assist Module – Delta 2's casing landed in Saudi Arabia upon spacecraft re-entry, Jan 2001. Source: NASA ARES

Small per-satellite risks can add up to a substantial cumulative risk across a very large constellation. If 300,000 satellites each had an expected casualty number just below 10^{-4} on re-entry, the combined expected number of casualties would approach 30.

Controlled re-entries are typically targeted at remote ocean areas, frequently the South Pacific. Managing large numbers of re-entries could become a continuing operational challenge for SBDC constellations. Surviving fragments would enter the ocean, accumulating in large numbers on the ocean floor.

The ground risk from space debris is not theoretical. In March 2024, a piece of metal from the International Space Station (ISS) struck a home in Naples, Florida.[13] In November 2022, Spanish authorities closed airspace over four regions during the uncontrolled re-entry of a Chinese rocket, delaying some 300 flights.[14]

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CHAPTER 2.3:

STRATOSPHERIC OZONE DEPLETION

David Sandalow, Roger Aines and Theiija Bala

MAIN MESSAGES

- Space based-data centers (SBDCs) pose significant risks to the stratospheric ozone layer due to chemical reactions during their launch and demise.
- Mitigation strategies include sending satellites into higher orbits at the end of their useful lives, extending satellite lifetimes and using alternative materials for satellite components.
- Data and scientific understanding on these topics are limited.
- Regulatory authorities should delay large-scale deployment of SBDCs until risks related to stratospheric ozone depletion are better understood and mitigation strategies have been adopted as needed.

The stratospheric ozone layer is located roughly 15–30 km (9–18 miles) above the Earth's surface. Ozone at this altitude absorbs harmful radiation, including ultraviolet rays that cause skin cancer, cataracts and damage to crops and marine life.[1-5] During the middle of the 20th century, chemicals in widespread use began to deplete the stratospheric ozone layer. Growing quantities of these chemicals (including chlorofluorocarbons (CFCs), which were used in refrigerants, aerosol propellants and solvents) rose to the stratosphere, where their chlorine atoms reacted with and consumed ozone molecules. Scientists found that a single chlorine atom in the stratosphere could consume as many as 100,000 ozone molecules.[1]

In the early 1980s, scientists confirmed a hole in the stratospheric ozone layer above Antarctica. This led to adoption of the Vienna Convention for the Protection of the Ozone Layer in 1985 and the Montreal Protocol in 1987. Thanks largely to the binding controls imposed under the Montreal Protocol, more than 98% of ozone-depleting substances have been phased out and the stratospheric ozone layer is slowly recovering.[6]

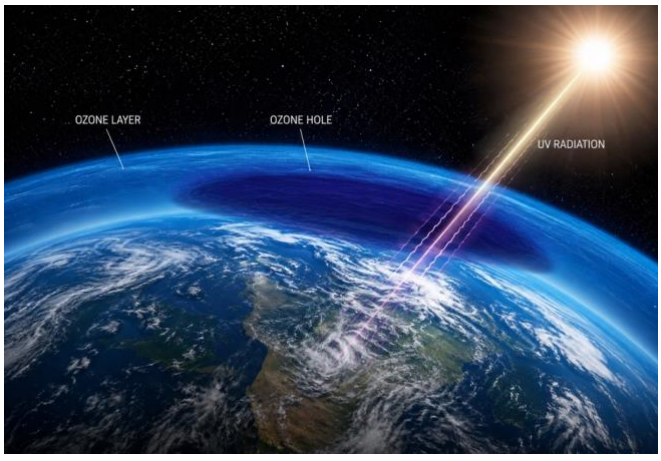


Figure 1. *The ozone layer and ozone hole. Source: Wikimedia Commons. CC BY-SA 4.0*

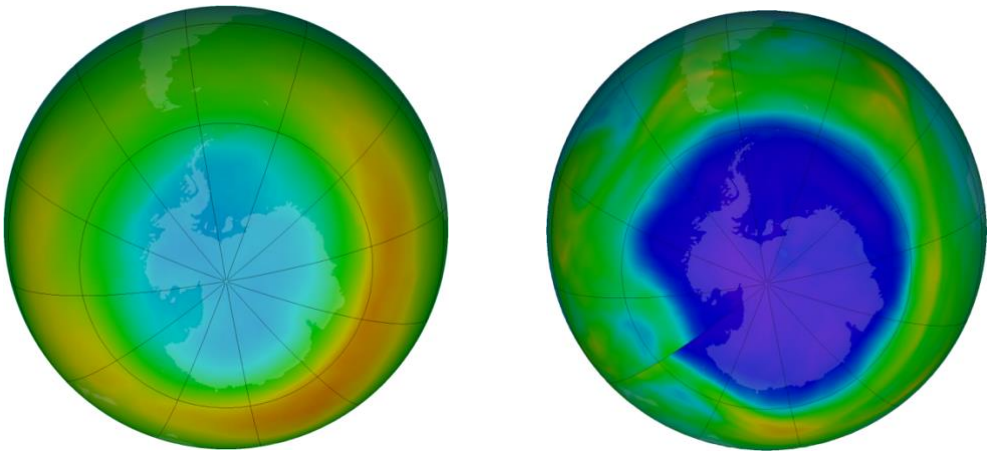


Figure 2. *The ozone hole in Sept. 1981 vs Sept. 2026. The more purple, the lesser the ozone. Source: NASA Ozone Watch*

Space-based data centers (SBDCs) could threaten this achievement. Rocket launch emissions can release chlorine and black carbon into the stratosphere, leading to ozone depletion. Likely more serious, SBDCs re-entering the stratosphere at the end of their useful lives will burn up, releasing aluminum oxides (Al_2O_3) and generating nitrogen oxides (NOx), both of which deplete the ozone layer.

The extent of ozone depletion from SBDC constellations could be anywhere from small to very significant. This chapter explains the mechanisms that lead to this ozone depletion, discusses knowledge gaps and considers mitigation strategies. We recommend delaying large-scale deployment of SBDCs until risks related to stratospheric ozone depletion are better understood and mitigation strategies, if necessary, are implemented.

A. Launch Emissions

Launch emissions raise the first concern, with potential releases of chlorine and black carbon as rockets climb through the stratosphere after launch.[7,8]

Solid rocket motors release chlorine in the stratosphere during the launch phase, destroying ozone molecules. However, SBDCs are unlikely to be launched from solid rocket motors for cost reasons.[9] All current SBDC proposals envision using reusable liquid-fueled rockets. Except perhaps if reusable liquid-fueled rockets become unavailable or capacity-constrained, the use of solid rocket motors for SBDCs is unlikely.

Black carbon (soot) is another concern. Combustion of propellants during rocket launches releases black carbon in the stratosphere. Black carbon releases can deplete stratospheric ozone through several mechanisms that are not fully understood.[7,10] The amount of black carbon released varies by propellant, with kerosene propellants releasing the most black carbon. Liquid natural gas (LNG) propellants release less black carbon than kerosene, although data are limited and the topic requires significant additional research.[11-13] SpaceX and other SBDC companies mainly plan to use LNG propellants.

B. Re-Entry Emissions

SBDCs pose risks to the stratospheric ozone layer on re-entry for two distinct reasons.

i. Aluminum Oxides

Aluminum is a dominant material in satellites, typically making up roughly 35–40% of total satellite mass.[14] When a satellite re-enters the atmosphere at the end of its useful life, most of its aluminum burns up (ablates) and becomes Al_2O_3 nanoparticles. Al_2O_3 particles can catalyze reactions that convert chlorine into forms that destroy ozone. Al_2O_3 is not consumed in these reactions, so each particle can continue depleting ozone for decades. The extent of ozone depletion likely to result from greater quantities of Al_2O_3 in the stratosphere is uncertain and requires significant additional research.[15]

Satellite re-entries have begun changing the composition of the upper atmosphere, and far greater changes are possible. In 2016, satellite demise added roughly 2 tonnes of Al_2O_3 to the atmosphere. In 2022, this figure reached almost 17 tonnes. Ferreira et al. (2024) estimated that mega-constellations in planning could raise annual emissions of Al_2O_3 to 360 tonnes—more than 600% above natural levels.[15] This projection predates recent proposals for SBDC mega-constellations from SpaceX and others.



Figure 3. *Artist's rendition of satellite re-entering the atmosphere. Source: © ESA/David Ducross*

Al_2O_3 particles may take up to 30 years to drift down from the altitude where satellites ablate (roughly 60–80 km above the Earth) to the stratospheric ozone layer (at roughly 15–30 km).[16] Satellites launched today will continue creating ozone depletion risks for decades to come.

Our Reference 1-GW SBDC constellation has 10,000 satellites and assumes a 5-year satellite lifetime. (See Chapter 2.) Once the constellation is fully deployed, at least 2000 of its satellites would re-enter the Earth's atmosphere each year. Each of these satellites would carry roughly 1 tonne of aluminum. Estimates of the amount of Al_2O_3 created by the demise of a satellite vary. Ferreira et al. (2024) found that a single 250-kg satellite generates roughly 30 kg of these particles.[15] Based on this assumption, we find that our Reference 1-GW SBDC constellation would produce roughly 600 tonnes of Al_2O_3 per year.[a]

[a] Our reference satellite weighs 2.5 tons—10x the satellite in Ferreira et al. (2024). A 10x increase in Ferreira et al.'s estimate of 30 kg Al_2O_3 per satellite = 300 kg Al_2O_3 per satellite. Multiplying this by 2000 satellites demising per year = 600,000 kg of Al_2O_3 per year = 600 tonnes of Al_2O_3 per year.

Ross and Sheaffer (2014) estimate a stratospheric Al_2O_3 burden of roughly 2400 tonnes.[17]b Maloney et al. (2023) modeled the lifetime of Al_2O_3 in the stratosphere with a source of 10,000 tonnes per year, consistent with their projections of satellite mega-constellation size in 2040. They found this would result in a steady-state burden of 20,000–40,000 tonnes of Al_2O_3 in the stratosphere—vastly in excess of background levels.[18]

The rate of ozone depletion from additional quantities of Al_2O_3 in the stratosphere has not been established. The risks are unknown but potentially large.[15]

ii. Nitrogen Oxides

NOx created upon satellites' demise also threatens the ozone layer. The reaction starts when spacecraft re-entering the atmosphere create strong three-dimensional shock waves known as bow shocks. These bow shocks cause collisional heating, which causes nitrogen (N_2) and oxygen (O_2) in the air to react. This reaction principally creates nitric oxide (NO), which can convert to nitrogen dioxide (NO_2). Together these compounds are referred to as NOx, which destroys ozone (O_3) in the stratosphere

Estimates of NOx produced during satellite re-entry vary and are based on modeling results, not measurements of actual re-entries. Barker et al. (2024) estimate that NOx equal to roughly 40% of a re-entering satellite's mass is created.[12] Vliex et al. (2026) estimate a higher yield, with NOx roughly equal in mass to the re-entering object itself.[19] Applying this range to our Reference 1-GW SBDC, which has 2000 satellites with roughly 5000 total tonnes of mass re-entering each year, yields an estimate of between 2000 and 5000 tonnes of NOx.

The ozone loss from NOx created by a single constellation is hard to isolate, but Vliex et al. (2026) offers a useful real-world benchmark. They modeled the full inventory of 2022 global launch and re-entry activity, which totaled roughly 5000 tonnes of re-entering mass across 472 objects. They found that this activity caused an annual global ozone column loss of roughly 0.03% of the atmosphere's ozone column, with nearly 88% of this loss driven by NOx from re-entering objects.[19]

If a constellation with 1 million 2.5-tonne SBDCs with 5-year lives returned 200,000 satellites per year to Earth, this would imply (based on the figures in Vliex et al.) a loss of roughly 2.5–3% of the atmosphere's ozone column annually from nitrogen oxides alone. This would quickly reverse gains since 1985 in restoring the ozone layer and would deplete the ozone layer further, potentially to dangerous new levels.[20]

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[b] See Section 5.1: "In any case, the current submicron alumina stratospheric burden M_A is about 1.2 kt (with an additional burden of the same order in the concentrated but dispersing plumes from recent launches)..."[17]

C. Mitigation Strategies

Several mitigation strategies are possible, but all involve significant tradeoffs, cost or scientific uncertainty.

For launch emissions, using LNG propellants instead of kerosene reduces black carbon releases into the stratosphere, though not to zero, and avoiding solid rocket motors eliminates chlorine emissions entirely. LNG propellants are the default choice in current SBDC proposals for cost reasons, although a capacity-constrained launch market could push some SBDC providers toward solid-boosted vehicles, such as United Launch Alliance's (ULA's) Vulcan Centaur or Europe's Ariane 6.[21] Black carbon releases from LNG propellants could be further reduced with modifications to fuel mixing or engine design.



Figure 4. *ULA's Vulcan Centaur. Source: NASA/Ben Smegelsky*

For re-entry issues, there are several options:

1. Send satellites into higher orbits or toward the Sun at the end of their useful lives instead of letting gravity and atmospheric drag bring them back down toward the Earth. This would require significant additional propellant on board each satellite, adding cost and mass to every satellite in a constellation.

2. Extend satellite operational lifetimes, which reduces how often a constellation of a given size must be replenished and, correspondingly, how much Al_2O_3 and NOx it generates each year. Researchers who track anthropogenic material injected into the atmosphere have specifically recommended sharing space infrastructure and increasing satellite lifetimes as ways to reduce the atmospheric burden of large constellations.[14] On-orbit servicing and refueling, still an emerging capability, could extend satellite lifetimes further without requiring new spacecraft designs. For SBDCs, in particular, the useful service life of the on-board compute may be limited to roughly 3–5 years due to obsolescence, given how rapidly AI compute chip technology is evolving. On-orbit servicing to replace aging chips could therefore be an important mitigation strategy, if the capability could be reliably implemented.



Figure 5. *Artist's rendition of Ariane 6. Source: © ESA/David Ducross*

3. Adjust re-entry trajectories and timing. Because satellite re-entries are currently concentrated near the equator, NOx-driven ozone loss is concentrated as a result. Steering re-entries toward less sensitive

latitudes or seasons could reduce localized damage, although without reducing total emissions.[22]

4. Use alternative, non-aluminum materials for satellite components. In 2024, Japan's space agency, JAXA, launched several wooden satellites from the International Space Station (ISS). The satellites were designed to incinerate into fine ash upon re-entry without the metallic byproducts associated with conventional aluminum satellites.[23] Carbon composites are lightweight, although expensive, and could perhaps substitute for some portion of the aluminum on a spacecraft. Research on aluminum alternatives remains nascent.

Regulatory action and research investment could accelerate progress on each of these fronts. National regulatory authorities could also require atmospheric chemistry assessments before issuing launch permits.

D. Recommendations

In light of the foregoing, we offer the following four recommendations.

1. Regulatory authorities should delay large-scale deployment of SBDCs until risks related to stratospheric ozone depletion are better understood through direct measurement of re-entry plumes and related atmospheric modeling.

2. Government science agencies, as well as companies deploying SBDCs, should invest now in research and development (R&D) on strategies for mitigating the risk to the stratospheric ozone layer from SBDC constellations.[8] National regulators should require stratospheric ozone impact disclosures in satellite launch and re-entry licensing.

3. The Parties to the Vienna Convention should establish a standing study program focused on the space sector, including SBDCs. This program should quantify Al_2O_3, chlorine, black carbon and NOx fluxes across a range of SBDC deployment pathways and fund sampling of the stratosphere to reduce the uncertainties in current models.

4. If further research suggests threats to SBDCs and other space activities could present significant threats to the stratospheric ozone layer, the Parties to the Vienna Convention should amend the Montreal Protocol or adopt a new protocol to address these issues.

E. Conclusion

SBDCs pose a real risk to the stratospheric ozone layer, although the uncertainties on this topic are enormous.

Ozone depletion from large SBDC constellations could, over time, rival the magnitude of the ozone depletion that the Montreal Protocol has spent decades repairing. At the same time, the ozone depletion impacts of individual SBDCs could be small. The black carbon output of LNG engines remains uncertain, the chemistry of Al_2O_3 in the stratosphere has not been directly measured, and the cumulative effect of a large SBDC fleet has not been modeled. A robust research agenda to better understand the impacts of SBDCs on the stratosphere is essential.[8]

Several mitigation strategies could reduce risks. These strategies include cleaner propellants, better fuel mixes, improved engine designs, longer satellite lifetimes, alternative materials and smarter re-entry trajectories. Most or all of these strategies involve tradeoffs in cost, safety or feasibility, and none eliminates the risk entirely.

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CHAPTER 2.4:

GREENHOUSE GASES AND BLACK CARBON

Julio Friedmann and David Sandalow

MAIN MESSAGES

- Although space-based data centers (SBDCs) run on solar power and therefore emit no greenhouse gases (GHGs) or black carbon once in orbit, burning the fuel required to launch SBDCs and manufacturing rockets both create considerable emissions.
- Significant uncertainties surround the life-cycle GHG and black carbon emissions of SBDCs. Key data are not publicly available, scientific understanding on key topics is limited, and estimates vary widely.
- Based on reasonable assumptions, life-cycle GHG emissions from SBDCs appear to be close to those of terrestrial data centers powered by uncontrolled natural gas and 3–6 times those of terrestrial data centers powered by solar panels or natural gas with carbon capture.
- Moreover, emissions of black carbon into the stratosphere by rockets launching SBDCs could increase SBDC life-cycle emissions by a large amount, with significant potential warming impacts. More data are needed to evaluate these risks.

A. Overview

Launching space-based data centers (SBDCs) into orbit requires large amounts of rocket fuel. Burning this fuel releases greenhouse gases (GHGs) and black carbon (a type of soot that warms the planet). So does manufacturing rockets and information technology (IT) equipment. Although SBDCs run on solar power and therefore emit no GHGs or black carbon once in orbit, SBDCs' life-cycle emissions of these climate pollutants could be very significant. At the same time, under some assumptions and scenarios, SBDCs' life-cycle emissions of these climate pollutants could be quite modest. Much more data collection and scientific analysis are needed to confidently assess the likely emissions impacts of SBDC deployment.

This chapter analyzes potential life-cycle emissions of GHGs and black carbon from SBDCs. The chapter starts by noting the limited data available on this topic. It then turns to an analysis of launch emissions, looking first at life-cycle emissions from the leading rocket fuels and then at some "known unknowns" with respect to these emissions, including in particular stratospheric black carbon. Next, the chapter examines the embodied emissions of data center IT equipment and rockets. Based on these analyses, the chapter compares SBDC life-cycle emissions with those of terrestrial data centers. The chapter closes with recommendations, including a recommendation that governments,

companies and other stakeholders begin an immediate set of studies to reduce scientific uncertainties and take other steps to reduce climate change risks related to SBDC constellations.

The analysis in this chapter is provisional and prepared under a tight deadline. It has not been subjected to external review. We look forward to refining the analysis in the months ahead and welcome comments and corrections. Please send them to SBDCRoadmap@gmail.com.

B. Data Availability

Data on rocket emissions, manufacturing, compositions and supply chains are limited for several reasons. Some data are guarded closely by aerospace companies and SBDC aspirants. Some data are guarded closely by national security agencies. The lack of available data makes it challenging to draw robust conclusions on the potential climate change impacts of SBDC systems.

Several proprietary databases reportedly contain high-quality data on environmental attributes and terms associated with rocket and satellite systems. The Strathclyde Space Systems Database[1] is regarded by workers in the field as one of the best and undergirds several key life-cycle assessment (LCA) studies for space infrastructure and launch.[2-4] The EU Space Surveillance and Tracking (SST) database[5,6] also reportedly contains such information. (The authors were not able to access either of these databases in connection with this chapter.)

Some data are publicly available, and this availability is increasing each year. For example, databases concerning launches before 2019 have been published,[7] and a recent analysis[8] integrates launch data through 2026, including the 3D trajectory through the atmosphere and emissions of GHGs. Recent publicly available data sets[9] provide information on fuels and new rocket configurations, such as those for Starship, Blue Origin and Long March 10. These databases are welcome, but incomplete — greater information is needed about the use and manufacturing of fuels, manufacture of rockets, and release of GHGs and black carbon within the atmosphere.

The European Space Agency (ESA) has launched efforts to better understand the carbon footprint and environmental risks of space activity. In addition, the proposed EU Space Act[10] currently includes the Product Environmental Footprint Category Rules (PEFCR4Space),[11] which would gather and share some key data. National Aeronautics and Space Administration (NASA) researchers proposed a comprehensive study on similar topics in 2024, but it was not funded.[12]

Much information about the weight, composition and construction of rockets and SBDCs is likely proprietary. Key data are either not accessible or not shareable, due to limits governments and their industry partners place on the databases. The lack of accessible data makes it difficult to reach confident conclusions regarding the global warming consequences associated with SBDC scale-up.

C. Launch Emissions

Launching SBDCs into low Earth orbit (LEO) produces significant GHG and black carbon emissions.[13] The amounts depend on fuel type, rocket type, payload and other factors. This section assesses the propellants, launch-related terms and operational impacts separately.

i. Fuel emissions based on available data

Choice of fuel is critical in determining life-cycle GHG emissions from any launch. Three fuels are the likeliest candidates for SBDC launches going forward: liquid natural gas (LNG), kerosene (typically a highly refined type called RP-1) and liquid hydrogen.

LNG is the fuel of choice for SpaceX Falcon-9s, Starships and Blue Origin BE-4s, making it a likely option for SBDCs. Kerosene is a regular workhorse for rocket propulsion, especially for first stages. Liquid hydrogen has been used for rockets over the last 70 years, mostly for the second stage.

When used for rocket launches, all three fuels require liquid oxygen (LOX) as the oxidizer. (While hypergolic fuels (e.g., hydrazine) have seen significant use as propellants and efforts are underway to identify novel variants,[14] they are unlikely to be used at scale for SBDC deployment given the fuel choices made by leading heavy-lift rocket developers. Similarly, while solid propellants are used in some current rocket platforms (e.g., Arianne 6 boosters), they are unlikely to be adopted for SBDC deployment at scale.[15] We do not include either in our analysis.)

In this section, we provide background on each of these fuels and estimate their carbon intensities. Table 2.4-1 provides detailed background on a range of characteristics of these fuels in combination with LOX.

Table 2.4-1: *Physical and chemical properties of modern rocket propellants.*

Metric/Attribute	Liquid Natural Gas (LNG)/LOX(Liquid Oxygen)	RP-1 (Kerosene)/LOX	Liquid hydrogen/LOX
Leading rocket platforms using the fuel	Starship; New Glenn (stage 1); Terran R; Long March 9 (stage 1 & 2); Long March 10B; Vulcan Centaur (stage 1)	Falcon 9; Falcon Heavy; Neutron	New Glenn (stage 2); Long March 9 (stage 3); Vulcan Centaur (stage 2); JAXA/MHI H3
Direct emissions (ton of carbon dioxide (tCO_2) per ton of fuel)[16]	2.6–2.75	3.16–3.5	0
Boiling Point	-161 °C (cryogenic)	Ambient (highly stable)	-253 °C (deep cryogenic)
Density	~0.42 g/cm³ (medium)	~0.81 g/cm³ (highest)	~0.07 g/cm³ (lowest)
Efficiency (I_{sp})	Medium (~330–380s)	Lowest (~300–350s)	Highest (~390–450s)
Sooting/Coking	Extremely low (clean burn)	High (requires engine teardown)	None (produces water)
Tank Size & Weight	Medium	Smallest & lightest	Largest & heaviest

a) Liquid Natural Gas (LNG)

Natural gas is a dense, low-cost, high-energy fuel. When liquified through purification, compression and refrigeration, its energy density increases greatly, making it a viable rocket fuel. Many companies use LNG as a rocket fuel, most commonly for the first stage of liftoff and return. These companies include SpaceX (Starship), Blue Origin (BE-4)[17] and China's Long March 9 (first stage),[18] 10B (second stage) and LandSpace Zhuque-2 and -3.[19,20] India also has several LNG-fueled rockets, including the Skyroot Aerospace[21] (Dhawan series)[22] and Astrobase.[23] After significant investment by the Ministry of Economy, Trade and Industry (METI) in LNG-fueled rockets, Japan expects to use the new Zero rocket,[24] developed by the private company Interstellar Technologies.

Burning LNG produces carbon dioxide (CO_2), the most important GHG. Methane, the chief constituent of natural gas, is a strong GHG itself. Standard operating procedure for LNG rockets upon return is to vent remaining fuel, adding to climate impacts.

The most important components in the overall GHG emissions intensity footprint of LNG as a rocket fuel are as follows:

- Carbon in the fuel itself, roughly 2.75 kg CO_2/kg LNG, is the chief component. While this physical carbon content cannot be modified, the net CO_2 emissions can be reduced through use of renewable natural gas (RNG) or synthetic e-methane, which today would add significant cost and greatly limit supply. This chapter does not consider e-fuels or RNG in footprint estimation.
- Upstream fugitive emissions of methane associated with flaring or leakage from production and transportation infrastructure are also potentially important. Many companies have banned conventional flaring and have instituted low-upstream method protocols and verification,[25] but practices vary widely by geography and regulatory requirements. Upstream leakage rates range between less than 0.5% of produced volume to over 6%.[26,27] (In this chapter we use a 100-year CO_2 equivalent (CO_2e) impact for methane according to the Intergovernmental Panel on Climate Change (IPCC) Working Group III's Sixth Assessment Report (AR6 WG1) report[28] and also include the 20-year impact for illustrative purposes.)
- Liquefaction, which requires polishing and purification, compression and cooling, adds to the GHG footprint. These steps require significant electricity inputs, which today are almost entirely generated by co-located natural-gas power generation. This adds roughly 5–16% to the carbon intensity of the fuel.[29] Low-carbon electricity (e.g., renewables, nuclear) or application of carbon capture and storage (CCS) could reduce the emissions from this step.
- For rocket fuel, ultra-low sulfur methane is needed, which can add significant cost and energy penalties for purification.[30,31] Given the lack of publicly available information on this step, we assume modest additional capital, operational and associated emissions.
- Incomplete combustion can create soot (black carbon) in the exhaust stream, which adds to radiative forcing. In general, operators ensure high conversion efficiency (>98%) so that relatively little soot is generated. However, black carbon can still be an important issue if it is deposited in the stratosphere (see below).

Assuming conventional production practice, LNG carbon intensities can range between ~3.01 kg CO_2e/kg LNG and ~4.90 kg CO_2e/kg LNG, chiefly as a function of low upstream leakage (see Table 2.4-2).

Table 2.4-2. *Carbon intensity of liquefied natural gas (LNG) rocket fuel for different upstream methane leakage rates, in kg CO_2e/kg LNG. Assumes full conversion of fuel (no soot), and a mean value for emissions from liquefaction and processing. Values using the 20-year global warming potential (GWP) for methane are indicated in italics.*

Component	Low leakage (0.5%)	High leakage (6.0%)
Direct combustion	2.75	2.75
Liquefaction and processing	0.11	0.11
Fugitive methane (100-year GWP)	0.15	1.79
Total: 100-year CO_2e	**3.01**	**4.90**
Fugitive methane (20-year GWP)	*0.41*	*4.95*
Total: 20-year CO_2e	***3.27***	***7.81***

Note: Commodity LNG cannot be used for space flight. Rocket fuel requires ultra-low sulfur distillation (as with kerosene refined into RP-1). Little public information is available regarding the price and energy implications of this process, and it is not included here.

b) Kerosene

Kerosene is the workhorse of rocket engine flight, commonly in the highly refined form of RP-1.[32] Kerosene combines high combined gravimetric and volumetric density and is liquid at the Earth's surface, simplifying fuel-handling logistics (these are also reasons why kerosene constitutes most aviation fuel). Roughly 45% of all launches in 2019 used kerosene and LOX as propellant.[33] Falcon-9 and Falcon-Heavy rockets use kerosene, as do Russia's Roscosmos Soyuz-2 and China's Long March 6. Firefly Aerospace uses kerosene to power its Reaver and Lightning engines.[34]

The carbon intensity of kerosene-based fuels like RP-1 is overwhelmingly from combustion of the fuel itself. There is no significant direct radiative forcing from unburned kerosene, and refining and polishing are small components of the fuel's carbon intensity. We estimate upstream emissions from fuel production between 0.5 to 0.65 gCO_2e/g RP-1.[35,36] However, since RP-1 involves greater refining than jet fuel, true values could be higher.[16]

However, combustion of kerosene produces significant amounts of soot (black carbon), far more than combustion of LNG. This contributes to the overall climate impact. A heavy launch engine using 1000 tons of RP-1 generates roughly 20–40 tons of black carbon, which varies by engine design and launch-cycle parameters. The climate impact of this black carbon varies significantly by the altitude at which it is released:

- Black carbon released in the troposphere (up to roughly 18 km at the equator) has an atmospheric residence time of roughly one week,[37] limiting its overall impact on warming.

- Black carbon released in the stratosphere (above roughly 18 km at the equator) remains in the atmosphere for much longer because it is not washed out by weather processes. The typical lifetime of stratospheric black carbon is 1–2 years, giving it a far higher climate impact. It also has ~5x higher radiative adsorption efficiency than tropospheric black carbon.

A significant percentage of black carbon emissions from kerosene propellants enters the stratosphere. Estimate range from 75% to 85%.[8,38]

In this chapter, we assume 22 g of black carbon emitted per kg of RP-1 (based on the estimate in Barker et al., 2024[8]) and a 25/75% split for black carbon deposition in the troposphere and stratosphere, respectively. These assumptions are conservative, given the potential range and level of confidence today. In this calculation, only the global warming potential (GWP) for tropospheric black carbon,[39] which is reasonably well understood scientifically, is included. The radiative forcing caused by stratospheric black carbon is unclear and potentially very large (see below)

Table 2.4-3: *Carbon intensity of RP-1 rocket fuel in kg CO_2e/kg RP-1. Includes soot (black carbon) emissions, as noted in the text, and a mean value for emissions from upstream refining. Values using the 20-year GWP for methane are indicated in italics. Black carbon GWP100 = 900, GWP20 = 2800 Source: Bond et al., 2013.[39]*

Component	Carbon intensity (kg CO_2e/kg RP-1)
Direct combustion of fuel	3.16
Upstream refining	0.5
Black carbon (tropospheric only, 100-year GWP)	5.0
Total: 100-year GWP	**8.66**
Black carbon (tropospheric only, 20-year GWP)	*15.5*
Total: 20-year GWP	***19.2***

c) Liquid hydrogen

Many rockets use liquid hydrogen[40] as a propellant. NASA's two-stage rockets commonly use liquid hydrogen for the core and upper stages.[41] Blue Origin uses liquid hydrogen for many of its rockets,[17] including the BE-3U, BE-3PM and BE-7, as do the Japanese HE-II series and Chinese Long March 3, 5 and 8.

Liquid hydrogen creates no GHGs when burned. However, production of liquid hydrogen results in considerable GHG emissions, and leakage of hydrogen to the atmosphere indirectly increases radiative forcing. Two components of production primarily affect the carbon intensity of making liquid hydrogen: the hydrogen production pathway and liquefaction (Table 2.4-4).

- Most hydrogen production (~98%) comes from uncontrolled natural gas conversion, often referred to as gray hydrogen.

  - Emissions can be reduced by CCS, often referred to as blue hydrogen. In this chapter, we assume 95% capture from steam-methane reforming, which would require additional energy input.
  - The carbon intensity of both these pathways is higher if there is significant upstream methane leakage, which must be mitigated, minimized and verified (see below). In this chapter, we assume 1% leakage for methane-sourced liquid hydrogen.

- Hydrogen can also be produced through electrolysis of water using low-carbon electricity, often called green hydrogen. The carbon intensity of the hydrogen is proportional to the carbon intensity of the electricity, which must be used to mitigate direct emissions from production. The reference case analyzed in this chapter assumes hydropower for electrolytic synthesis.
- Liquefaction requires deep cooling to –253 ºC (~20 K), which requires significant amounts of electricity and compression. Again, low-carbon electricity is required to minimize climate impacts. The reference case analyzed in this chapter assumes US-grid average power footprint for gray and blue cases and hydropower for the green case.

Table 2.4-4: *Carbon intensity of liquid hydrogen rocket fuel for different hydrogen production processes, assuming 1% upstream methane leakage rates, in kg CO_2e/kg liquid hydrogen. Additional assumptions are stated in the text. Values using the 20-year GWP for methane are indicated in italics. Natural gas power assumed for conventional liquefaction and processing.*

Component	Gray liquid hydrogen (1% upstream methane leakage)	Blue liquid hydrogen (1% upstream methane leakage)	Green liquid hydrogen
Steam methane reforming process (plus 15% energy penalty for blue liquid hydrogen)	9.40	10.81	N/A
With 95% capture	N/A	0.45	N/A
Fugitive methane (100-year GWP)	1.03	1.03	N/A
Electrolysis (hydro)	N/A	N/A	1.32
Liquefaction (grid or hydro)	4.56	4.65	0.29
Total (kg CO2e/liquid hydrogen produced)	**15.0**	**6.3**	**1.6**
Fugitive methane (20-year GWP)	*2.83*	*3.26*	*N/A*
Total (kg CO2e/kg liquid hydrogen)	***16.8***	***8.4***	***1.6***

These estimates assume minimal hydrogen leakage. Although H_2 is not a GHG, it indirectly increases radiative forcing by scavenging atmospheric radicals,[42] effectively extending the half-life of non-CO_2 GHGs like methane and NOx. If leakage is large enough, hydrogen can significantly affect radiative forcing.

ii. Liquid Oxygen (LOX)

Although much smaller than the footprint of the other three fuels, oxygen separation and liquefaction to LOX can add significantly to the total carbon intensity of a rocket propellant mix. LOX production requires significant amounts of energy, chiefly electricity to operate cryogenic equipment. As such, the carbon intensity of the electricity determines the carbon intensity of the LOX.

The primary means of oxygen separation is cryogenic separation, which pulls oxygen from the air by cooling it below the condensation point using an air-separation unit (ASU). This integrated process of air compression, cryogenic cooling, and final pumping and compression for storage and transport uses 600–800 kWh/ton based on optimization, unit efficiency, etc. A typical commercial cryogenic LOX ASU consumes ~670 kWh/ton. Rockets require very high purities (>99.8%) for propellants, so additional energy is often required. Because specific numbers are hard to find, we use the conservative assessments of commercial carbon intensities for LOX production (Table 2.4-5).

Table 2.4-5: Carbon intensity of different liquid oxygen (LOX) production scenarios (tonnes CO2e per tonne fuel).

Scenario or case	Carbon intensity
Low-carbon case (renewables or nuclear)	0.02
US grid average	0.27
Global average	0.38
Coal-heavy case	0.63

These calculations provide a sense of scale. The estimated US and global average cases would add roughly 10% to the GHG radiative forcing compared to LNG and 5% compared to RP-1. The renewable case would add less than 1% to total radiative forcing.

iii. Known unknowns

In assessing the launch-related emissions of GHGs and black carbon, data gaps and scientific uncertainties are significant. These “known unknowns” include the following:

- Data with respect to emissions of black carbon and water vapor into the stratosphere are poor.
- Understanding of the potential warming impacts of black carbon and water vapor in the stratosphere is limited.
- Data with respect to methane slip in and around launchpads are not publicly available.
- A large-scale deployment of satellites will, unfortunately, likely involve some accidents, but estimating the frequency of such accidents and the fuel leakages associated with them is challenging.

We discuss these topics below.

a) Stratospheric black carbon

Releases of black carbon into the stratosphere during the launch of SBDCs could have very significant warming impacts. Uncertainties are large, the physics are complicated and measurements are scarce.

Importantly, no altitude-dependent characterization factor exists for rocket-emitted black carbon. As a result, uncertainties are extremely large and radiative forcing could be 10s to 100s of times larger than the direct CO_2 emissions from launches.

For RP-1 use, each launch would generate significant tropospheric and stratospheric soot. Tropospheric soot has a residence time of roughly a week and is readily integrated to the fuel CO_2e estimates.

Stratospheric black carbon is a different matter. Key aspects of the science are not settled, leaving significant uncertainty regarding its climatic impact.

- Little is known about the residence time of soot in the stratosphere. Estimates range from 1 to 2 years or roughly 50–100x more than tropospheric soot.
- Current studies suggest significant potential impact from regular launches. Ryan et al. (2022) estimated that the 100 launches in 2019 produced ~8 MW/m2 radiative forcing—much greater than all other direct or indirect emissions combined.[33]
- The effects of stratospheric soot on tropospheric weather are also poorly understood. While black carbon heats the stratosphere, the consequences in the upper troposphere are uncertain. The impacts on cloud formation and associated optical depth are complicated and could potentially include both short-term cooling and long-term warming.[43,44]
- The specific chemistry of the soot45 affects its radiative forcing and possibly its residence time, which in turn can lead to significant climate impacts.
- Since the soot would be deposited chiefly along launch paths, this could lead to local patches of very high black carbon concentration.
    - The transport and diffusion times of this black carbon are unknown.
    - Similarly, the consequences of patches of high-density stratospheric soot are unclear.
    - Studies show[46] significant variability of impact based on latitude, longitude and season of black carbon emissions and that patches of black carbon can have outsized impacts on regional climate.[45]
- Although the black carbon from RP-1 is well understood, soot produced from LNG/LOX propellants is essentially unmeasured.[47] Methane combustion produces roughly 80% less soot than kerosene combustion, including cleaner burning and afterburn effects.[8] Direct observations are important to understand structure, volume and atmospheric disposition.

Studies show that the majority of soot would enter the stratosphere between 15 and 50 km (Figure 2.4-1), although the ranges vary significantly between scholars.[8,38,48] Current studies suggest that black carbon at this elevation could represent peak radiative forcing of over 400% increase (5x), although again the consequences are unclear.[43] The longer residence time and higher radiative forcing produce 250–500x greater estimated radiative forcing than for tropospheric ozone. Estimates for a 100-year GWP exceed 6000 tons CO_2e per ton of RP-1, roughly 2000x larger than the direct CO_2 emissions. However, these estimates are highly uncertain and would vary significantly with LNG or liquid hydrogen fuels. Similarly, the consequences of stratospheric forcing are poorly constrained and could be modest or lead to cooling (see above).

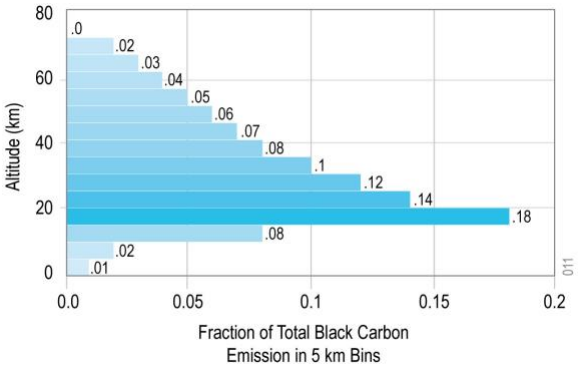


Figure 2.4-1: *Deposition of black carbon into the atmosphere. The stratosphere is 10–60-km elevation and receives ~85% of total black carbon from launch, significantly different than the 25/75% split used in this chapter. Source: Maloney et al., 2022.[38]*

Ryan et al. (2022) found that 100 launches with conventional propellants in 2019 may have produced significant climate consequences.[33] It is reasonable to assume that thousands of launches in the next few years could have a dramatically greater consequence, with unknown effects on weather patterns and climate, both regional and global. Data collection and further scientific analysis of this topic should be a high priority. In combination with other safety risks related to SBDCs, the risks related to black carbon emissions in the stratosphere provide a compelling basis for a slow SBDC launch cadence in the years ahead until risks are better understood and managed.

b) Stratospheric water vapor

Water vapor is a powerful GHG. While the radiative forcing of water vapor in the lower atmosphere (troposphere) is well understood, much less is known about water vapor in the stratosphere. The lower atmosphere is effectively saturated with water vapor; consequently, the water cycle of evaporation and precipitation fully exchanges atmospheric water volume 40 times a year. Concentration of water vapor depends on average temperature, so higher average tropospheric temperatures allow increased saturation of water vapor, which multiplies radiative forcing.

In contrast, water vapor enters the stratosphere rarely, driven largely by rare events that entrain water. The 2022 Hunga Tonga volcanic eruption brought mostly water vapor into the stratosphere—an estimated volume of 100–150 million tons—providing an opportunity to better calibrate its effects.[49] Studies of the eruption estimate the residence time of stratospheric water vapor to be 5–10 years, and the radiative forcing of the event to be ~0.05 W/m^2 (pretty small).[50] While these studies are important, they do not address all uncertainties associated with radiative forcing of stratospheric water vapor. They also do not address the potential for stratospheric ice formation, which directly increases risks to the ozone layer.

Based on the stoichiometry of combustion, a single Falcon-9 launch would deposit ~150 tons of water vapor in the stratosphere, 500,000x smaller than the small effect of the Hunga Tonga eruption. A Starship Super Heavy configuration would deposit ~1500 tons of water vapor in the stratosphere, roughly 50,000x smaller than the eruption. Based on these results, stratospheric water vapor appears to be a very small GHG warming factor. However, the science is incomplete, and more study is required to rule out stratospheric water vapor risks and impacts.

c) Methane releases

Some amount of methane is accidentally or operationally released in connection with launches, independent of upstream leakage. This includes slip (e.g., release from fueling or boil-off), incomplete fuel combustion and venting of unused fuel after launch. These methane releases could add significant GHG emissions from direct release. (Catastrophic release of LNG from accidents is covered separately below.)

Text Box: UNCOMBUSTED PROPELLANT

An important unknown term is the amount of LNG and LOX vented by returning spacecraft.

- The Falcon-9 booster uses RP-1, which is readily regathered.
- The Starship LNG is different: current practice is that any remaining fuel on the Starship Heavy is vented upon landing due to cryogenic boil-off.
- This practice is likely to be the same for BE-4, Long March 10 and other LNG-powered spacecraft.

Data are not available regarding the tonnage typically vented. If remaining fuel is gathered and reused, the fugitive emissions with this practice are also unknown. Assuming 100 tons of residual LNG/LOX propellant and 100-year GWP, each return would add 625 tons of CO_2e to the atmosphere, roughly an additional 15–20% beyond that from the launch. In contrast, 100 tonnes of vented LNG would add ~3000 tons CO_2e, or roughly 70% more radiative forcing. This topic requires additional research.

No data are available on operational slip from fueling or boil-off—a significant point of uncertainty. There are also no available data on uncombusted fuel from launch. In general, Falcon rocket engines burn lean and are highly efficient, suggesting minimal release of unused methane. There are no reliable data regarding methane slip or uncombusted fuel from Starship launches, nor from BE-4 or Long March 10. This is another point of significant uncertainty.

Absent direct information from operators and governments, this study is reasonable to assume no more than 2% slip and uncombusted fuel, which would contribute roughly 0.6 tons of CO_2e per ton of LNG fuel (assuming a 100-year GWP). For a Falcon Heavy booster plus Starship, 2% methane release from the 1278 tons of fuel would be ~25 tons of fuel, or ~750 tons CO_2e per launch.

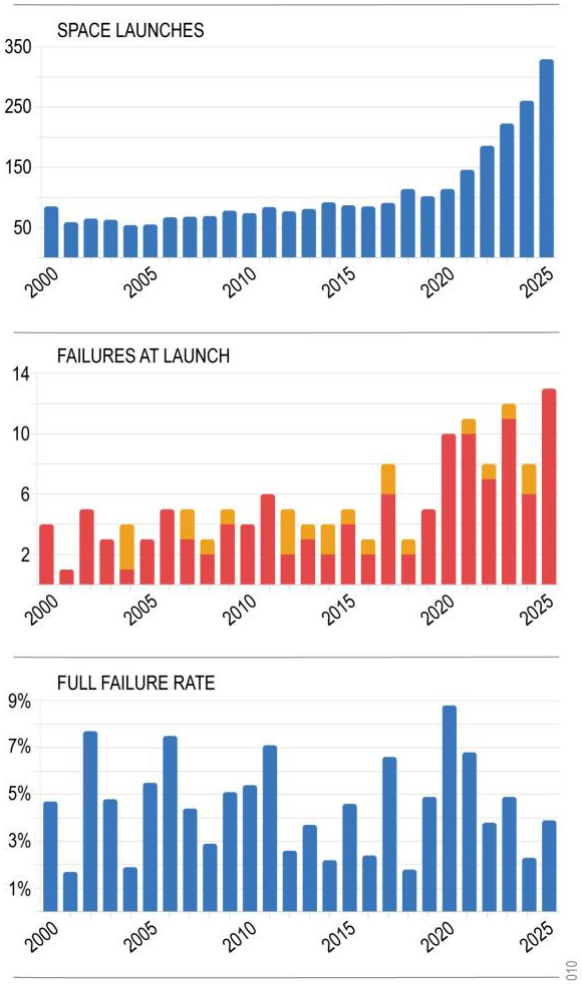


Figure 2.4-2: *Upper chart: Time series of annual number of space launches. Middle chart: Failures at launch (red are full failures, which do not reach orbit; yellow are partial failures, which do not deliver full payload). Lower chart: Full failure rate (full failures vs. total annual launches) by year. All figures are global. SOURCES: Wikipedia annual spaceflight summaries (e.g., 2024[52] and 2025[53] and statistical analysis pages from Jonathan McDowell Space Report[51])*

d) Accidents

An accidental release of fuel, by explosion or jettison, is in effect a 100% fuel leak into the atmosphere. Hydrogen's radiative forcing is caused by scavenging free radicals (e.g., hydroxyl ions) from the atmosphere, thereby extending the life of shorter-lived non-CO_2 gases like methane and nitrous oxides. In contrast, LNG is pure methane, which is a strong direct GHG.

The radiative forcing of uncombusted fuel can be significant—commonly ~20% of fuel is consumed in explosion, while the remainder is dispersed by shock waves. Assuming 80% of fuel is uncombusted due to explosion, a Starship explosion would vent ~1025 tons of methane, with a 100-year GWP of ~32,000 tons CO_2e. In contrast, the radiative forcing of 61 tons of uncombusted hydrogen from a modified Falcon-9 system would be ~670–2100 tons CO_2e using a 100-year GWP.

The consequence of accidents, rare though they are, could prove significant in terms of GHG warning and radiative forcing. In 2025, the failure rate was about 4% (13 out of 330 launches globally) (Figure 2.4-2 The majority of these were full failures, in which the rocket and payload did not reach orbit. Of the 124 failures this century, roughly 20% appear to be explosions,[51] which vent propellants to the atmosphere. This is another potential focus for better characterization.

Naturally, operators seek to avoid all accidental explosions and venting. The data below suggest there is no improvement over time. One interpretation: we are still at the early phase of deployment for advanced rocket technologies, so learnings have not yet materialized from experience.

iv. Sample launches

Based on the analysis above, we now estimate emissions from several sample launches of SBDCs. Our Reference SBDC, used for analysis in this Roadmap, weighs 2.5 tons (see Text Box 1-1). Based on this weight, we estimate the fuel used and, by extension, GHG and black carbon emissions for a Starship/Super Heavy configuration.

One Starship/Super Heavy is capable of carrying a 100-tonne payload. This translates to a maximum payload of 40 reference satellites of 100 kW each (4 MW). Rockets rarely operate with a full payload to ensure adequate system performance. The average capacity for rockets launched to LEO in the past year was roughly 85%[54] (although SpaceX has filled its Falcon 9 launches for Starlink to 96% capacity).[55] We assume a slightly smaller number of satellites: 36 per launch, or 90 tons of payload. As discussed in Text Box 1-1, 100-kW satellites will likely be heavier than 2.5 tons, in which case a smaller number of units could enter orbit per launch, requiring more launches to achieve the same computational capacity, with higher total emissions.

Direct and indirect estimates of GHG and black carbon emissions are set forth in Table 2.4-6. Scope 3 (upstream) emissions include liquefaction of LNG and LOX, assuming 1% upstream emissions of methane. We assume 2% operational slip and 100-year GWP. We list potential contributions from soot separately (assuming 80% less soot that RP-1) and assume zero effective radiative forcing from water vapor.

Table 2.4-6: *High-likelihood direct and indirect GHG emissions for a single launch (100-year GWP). Units are tonnes CO2e.*

Propellant	Tonnes CO_2e
Total LNG + LOX	1278 + 4600
Methane (1% upstream leakage)	13
Methane (2% slip)	25
Black carbon produced	6.4
GHG emissions	**CO_2e**
From combustion (CO_2 produced)	3444
From fuel production (Scope 3)	1726 (478 + 1248)
From 1% upstream leakage (100-year GWP)	375
From 2% operational slip + venting (100-year GWP)	750
Stratospheric water vapor (100-year GWP)	~0
Subtotal	**6297**
Black carbon	
Tropospheric black carbon (100-year GWP)	2939
Stratospheric black carbon (100-year GWP)	0 to 1,380,000
Total	**9,236 + possible 1,380,000**

This estimate is similar to Osoro et al. (2026)[4] and Aili et al. (2026)[56] but on the low end of some estimates. For example, Andrew Wilson[57] at Glasgow Caledonia University estimates a single Starship/Super Heavy launch "worst case" scenario to emit ~76,000 tonnes CO_2e—roughly 8.5 times larger than our estimate.[58]

D. Emissions from Manufacturing and Production

Manufacturing SBDCs and the rockets required to launch them results in GHG emissions (often called "embodied emissions"). We discuss the embodied emissions of SBDCs below.

i. Servers

Key components of the servers used in SBDCs (chips and memory, lithium batteries[59]) are largely similar to terrestrial servers, although they have radiation shielding and modified heat exchangers.

The embodied emissions of a single terrestrial 100-kW rack are roughly 135 tons.[60,61] Assuming these are equivalent in a satellite and each satellite serves a 5-year mission, this yields an estimate of 27 tonnes/year CO_2e. If 10,000 terrestrial racks constituted a 1-GW constellation, that would sum to roughly 270,000 tonnes/year CO_2e.

ii. Satellites

Satellites have typically used gallium arsenide (GaAs) solar photovoltaic (PV) cells because of efficiency and radiation resistance, but recent innovations in radiation protection and manufacturing have led to modified silicon-based PV cells being used.[62] Radiators are specially designed for space, with material types ranging from aluminum to carbon polymer composites for more recent missions.[63] Finally, some components are unique to space missions, including propulsion (e.g., Hall thrusters[64]) and optical communication terminals.[65]

Based on a crude bottom-up materials estimate, the carbon footprint of the 1-GW reference constellation described in Textbox 1-1 could be 300–700 tonnes CO_2e per reference satellite, compared to the 27 tons for just the IT equipment (chips, memory, etc.)[56] A constellation of 10,000 SBDCs would have a GHG footprint on the order of millions of tonnes CO_2e, which may be similar to the carbon intensity of their terrestrial equivalents when terrestrial solar panels, concrete, steel and aluminum housings are included. This comparison requires further research.

iii. Rockets

Very little information with respect to rockets' embodied GHG emissions is publicly available. Some researchers have used the restricted Strathclyde Space Systems Database[1] (for example, Osoro et al., 2026 estimates for the Falcon-9 Block 5 system[4]). Since space-grade materials (metals, components) often involve significant refining and fabrication, simple estimates based on typical carbon intensities for steel or aluminum are likely underestimated.

The footprint of the rockets themselves is sensitive to the number of times they are used. A key term is the number of uses per booster. While Osoro et al. (2026)[4] assume the Falcon booster system returns 10 flights, the system now has on average greater than 25 return flights[66] and has recently

exceeded 35 return flights for a vehicle.[67] (However, the Falcon-9's second stage system does not return and should be considered single use). Several other companies are also beginning to demonstrate re-usability across multiple launches.[68,69] Based on these improvements, it appears likely that return-flight vehicles like the Super Heavy booster will achieve similar levels of performance, exceeding 25 return flights per vehicle.

Osoro et al. (2026) estimate a carbon footprint for the Falcon 9 of ~22,000 tons CO_2e per launch, assuming 10 launches.[4] Removing the contributions from fuel, the embodied carbon would be roughly 20,000 tons/launch, again assuming 10 launches. Since key terms in this analysis are not publicly available, it is unclear if this is accurate and representative. Assuming 30 returns for the Falcon booster system would reduce the per-launch embodied emissions estimates to about 6600 tons, not including the one-time costs for the booster or second stage.

The reusable Starship Super-Heavy booster is still in development and does not yet have sufficient field data to definitively estimate weight, composition and the number of likely flights. Like the Falcon second stage, the upper stage of the Starship (the "Ship") will not be re-flown. Osoro et al. (2026) did not analyze a Starship Super-Heavy system, providing no estimates.[4] In large part because the Starship Super-Heavy is a new vehicle, there is no current literature on its embodied emissions. Importantly, the Starship Super-Heavy uses steel as the primary dry material input, in contrast the Falcon systems, which are chiefly made of aluminum-lithium composites. For either steel or aluminum, the range of potential carbon intensities is very large, with a factor of 10 or greater variance based on the carbon intensity of electricity input, choice of primary versus recycled feedstocks, and manufacturing pathway. Again, data-rich, robust, independent analysis is needed.

Robust, reliable information from supply chains is necessary to generate accurate LCAs. The discussion of rocket embodied carbon in this chapter is intended to serve as a starting point or point of comparison for future analyses.

E. Summary Scenarios

i. Reference Scenario for 1 GW

Given the speed and scale of terrestrial data center construction, we chose to estimate emissions for a 1-GW SBDC reference scenario. This would require a constellation of 10,000 satellites (each requiring 100-kW power) in LEO.

- Vehicle: Given the speed of the advancing field, we selected the SpaceX Starship Super-Heavy configuration, in part due the likelihood of rapid advances on this vehicle and the announced reduction in service of the Falcon 9.
- Fuel: A single Starship Super-Heavy launch uses ~1278 tons of LNG, or 62.4 million standard cubic feet (scf) (about a week of gas for a small state, like Hawaii) and 4600 tons of LOX. We assumed 1% upstream fugitive emissions and 2% operational methane release.

- **Payload**: Assuming each launch would bring ~36 satellites carrying 100-kW racks (85% payload capacity), ~295 launches would be needed to place 10,000 satellites in LEO using Starship Super-Heavy vehicles. We use 300 launches to simplify, or 82% of payload capacity.
- **Accidents**: As a conservative assumption, we selected 1 catastrophic accident per 300 launches.
- **Service life**: Assuming a five-year service life for the satellite constellation divides the annual carbon intensity by five. We assume a 100% compute capacity factor.
- **Other terms**: Given the high uncertainty in stratospheric black carbon and stratospheric water vapor, we chose not to include them in the reference 1-GW constellation emissions scenario.

Estimating embodied emissions is especially challenging, in light of the lack of available data. We provide a very rough estimate as as follows:

- Embodied CO_2e missions for the Falcon 9 are roughly 200k tonnes embodied CO_2e/rocket.[4] Based on conversations with one of the authors of the paper, we believe this is a deliberately conservative estimate that serves as an upper-bound.
- The Starship Super-Heavy weighs roughly 16x more than the Falcon 9[3,4] but is made of a material (stainless steel)[70] with roughly one-third the carbon intensity of the material used in the Falcon 9 (space-grade aluminum).[71] Accordingly, we estimate that embodied CO_2e emissions for each Starship Super Heavy is roughly 5.3 times the embodied CO_2e emissions for a Falcon 9.
- Multiplying 200k × 5.3, we estimate the embodied CO_2e emissions per Starship Super-Heavy Rocket to be 1,060,000 tonnes—an upper-bound.
- Assuming 30 launches per Starship Super-Heavy rocket, we estimate roughly 35,000 tonnes embodied CO_2e/Starship Super-Heavy launch.
- Assuming 300 launches/1-GW constellation, 35,000 tonnes CO_2e × 300 launches = 10,500,000 embodied CO_2e/1-GW constellation.
- We assume each constellation lasts for 5 years, so 10,500,000 tonnes of embodied CO_2e divided by 5 years of launches = 2,100,000 tons of embodied CO_2e/year for a 1-GW constellation, again as an upper bound.

In light of the considerable uncertainties and suggestion that the 200K tonnes of embodied CO_2e/Falcon 9 rocket is an upper bound, we selected a range of 1,000,000–2,000,000 tonnes embodied CO_2e/year for a 1-GW constellation as a very rough estimate in the text that follows. We reiterate that more data and research are needed to more precisely estimate these values. We also recognize there are ways in which the carbon intensities of the Starship Super-Heavy might be improved.

Using the estimate from Table 2.4-6 (~9200 tonnes CO2e/launch) together with the above assumptions yields a scenario with ~558,000 tonnes CO2e without embodied emissions and ~1.5 million–2.5 million CO2e including embodied emissions.

ii. Comparison with emissions from terrestrial data centers

Insight on the risks and impacts from SBDC emissions and radiative forcing requires the context and understanding provided by comparison with their terrestrial counterparts. The direct, indirect and embodied emissions from terrestrial data centers vary significantly as a function of energy source,[72] material fabrication, use, cooling method and local climate. SBDCs appear to show roughly the same GHG footprint as terrestrial data centers powered by clean energy sources and a significantly better footprint than those powered by uncontrolled fossil power or mixed grids.

Table 2.4-7 and Figure 2.4-3 below show the 1-GW orbital data center calculation and compare it with several terrestrial cases. Importantly, the full embodied emissions (Scope 3) are included in these estimates to ensure better parity between examples.

Table 2.4-7: *Estimated total annualized emissions and electricity carbon intensity for different 1-GW compute cases, assuming Starship Super-Heavy launches, low Earth orbit (LEO) and a 5-year satellite life.*

Compute power source	Annualized CO2 equivalent (CO2e) emissions (tonnes)	Carbon intensity, CO2e/kWh	Key assumptions
1-GW scenario: low Earth orbit (LEO) compute, 5-year satellite life, using 10 Starship Super-Heavy vehicles over 300 launches	1,558,000–2,558,000 total 558,000 (direct & indirect) plus 1,000,000 to 2,000,000 (embodied)	~178 total ~64 (direct & indirect) plus 68 (embodied)	~300 launches (roughly 82 tons per launch or 82% of payload capacity); 1 catastrophic accident per 300 launches; 2% methane operational leakage and 1% upstream. Excludes black carbon and water vapor due to uncertainty
US Average Grid	3,329,000	380	
Natural Gas Combined Cycle (NGCC), uncontrolled	2,297,000	262.3	1% upstream leakage, 65% capacity factor, 60% efficiency
NGCC + 90% carbon capture and storage (CCS)	473,000	51.9	1% upstream leakage, 65% capacity factor, 60% efficiency, 25% energy penalty
Solar + 12 hrs Li-ion (10-year amortization)	484,000	55.3	Includes Scope 3 from panels and batteries
Hydropower	210,240	24	Intergovernmental Panel on Climate Change (IPCC) median life-cycle assessment (LCA)

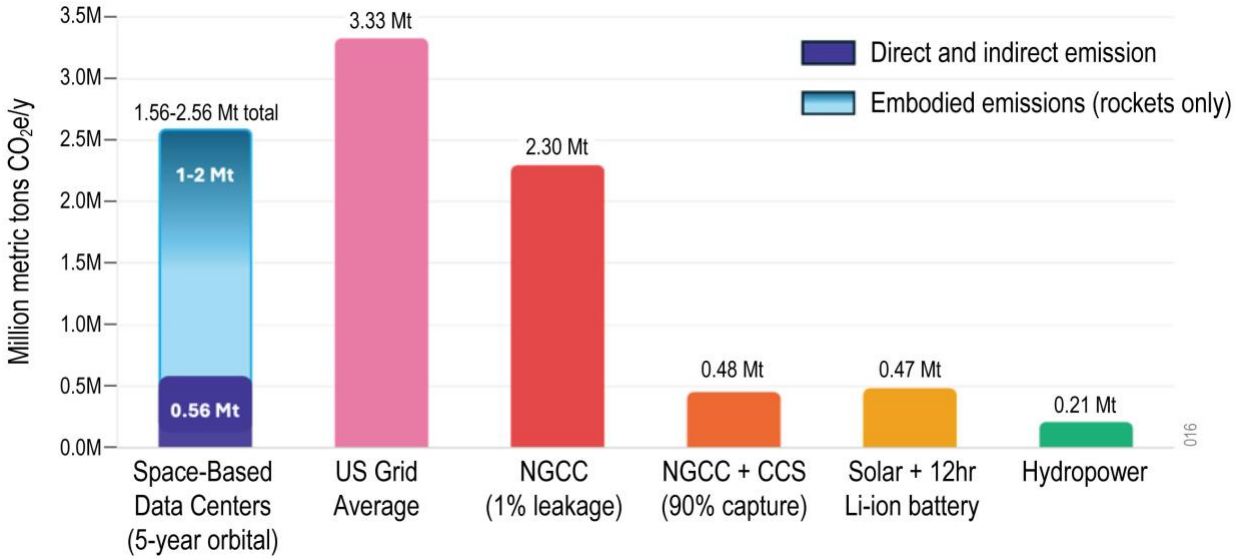


Figure 2.4-3: *Life-cycle annualized greenhouse gas (GHG) emissions for space-based data centers (SBDC) and terrestrial data centers. Assumes 1-GW continuous electricity supply (tonnes CO_2e). Embodied emissions for SBDC include only launch vehicles (rockets). The embodied emissions for information technology (IT) devices and power generation are not included in any data center calculation. (CO_2e = CO_2 equivalent; NGCC = natural gas combined cycle; CCS= carbon capture and storage; Li = lithium)*

Based on the foregoing assumptions, the estimated launch plus embodied emissions from SBDCs are between roughly 60% and 120% of uncontrolled natural gas combined cycle (NGCC), ½-¾ of the US average grid, and more than 3 to 10 times higher than clean options. Said differently, the apparent GHG and black carbon emissions for a 1-GW SBDC are likely more than 1-GW clean options on Earth. If only direct and indirect GHG emissions are included (i.e., excluding embodied emissions), then the direct + indirect GHG emissions would be close to most terrestrial clean options.

Finally, SpaceX has said that it hopes to execute 10,000 launches per year or more, not 300.[73-75] These launches would not all be for data centers, so the fraction of launches for SBDCs versus other SpaceX applications remains another uncertainty. Since other nations and companies might add launches for their own purposes, there is a potential to add significantly to launch-related emissions.

F. Significant Uncertainties

Estimating the potential climate impacts of satellite fabrication and launch with precision relies on scenarios, forecasts, and incomplete data and science. Reducing the uncertainties around a few key terms would greatly enhance the ability to make accurate and precise estimates of current and potential future impacts.

In the near term, one important point for added clarity is number of launches and type of propellant. There is a huge difference between 250 launches (roughly 1-GW compute) and 10,000 launches (announced SpaceX plans) in terms of total emissions. There is a huge difference between kerosene-

and LNG-fueled rockets. A smaller but easier uncertainty to resolve is around the energy and carbon costs of refining LOX and LNG to rocket-fuel specs.

As discussed above, the apparent venting of LNG from returning spacecraft would represent a significant GHG contribution. This is not an uncertainty of physics or chemistry, but an uncertainty of operational practice. Resolving this uncertainty requires transparency from operators and focus from regulators.

Much larger uncertainties surround the climate and environmental impacts of stratospheric black carbon and aluminum oxides. These will take longer to resolve but are potentially of greater consequence.



Figure 2.4-4: *Artist's conception of stratospheric drone fleets collecting data from a SpaceX Starship launch. Image generated by Shutterstock*

- The size of the uncertainty, even the sign of the signal, is not fully resolved. This likely affects both climate and weather.[76]
- The impact sensitives to clustering, altitude, seasonality and latitude are poorly understood.
- The amount of deposition of stratospheric black carbon and aluminum oxides are poorly quantified. The implications for surface chemistry are also poorly understood and could directly affect radiative forcing and ozone depletion risk.

Given these uncertainties, data gathering becomes a critical undertaking. Given the fixed location and LEO orbital trajectories of most launches, both ground-based and stratospheric monitoring campaigns would be straightforward. Such programs may already exist in a limited way in nations with significant space programs (e.g., the Lufthansa-CARIBIC program).[45] If such programs are already collecting these data, federating and sharing this information would be extremely valuable in reducing uncertainties and developing mitigation plans (e.g., through novel rocket designs).

Ongoing uncertainties include our ability to produce clean propellants and the trade-off associated with them. Some of this relates to access to low-carbon electricity and its price, which will dramatically affect green hydrogen production readiness and cost, as well as LOX and liquefaction of LNG. The many modern demands for clean power are complicated by infrastructure limits, permitting debates and green-premium buyer willingness. The technical readiness of solutions like e-methane remains an open question. There may be additional questions around the ability of supply chains to scale up and the associated trade implications. These may all affect the total footprint of SBDCs and rocket launches, as well as the rate of scale up.

Roughly 13 GW of new terrestrial data centers were added in the US in 2025, reaching ~65 GW total load.[77,78] Estimates for annual growth of terrestrial compute worldwide is 20–27%[79,80]—a doubling of total data center compute by 2030. During this time, it is possible that SBDCs would achieve 1 GW of compute. This would involve significant investment in new infrastructure -- including launch, manufacturing and fuel production. Whether that infrastructure would have a lower environmental footprint than for terrestrial data centers is uncertain.

Finally, there are important "no-regret" strategies that would benefit both terrestrial data centers and SBDCs. For example, fugitive methane from natural gas production and infrastructure adds to the carbon intensity of LNG/LOX and liquid hydrogen/LOX propellants, as well as natural gas power for compute, manufacturing and liquefaction. Reducing upstream emissions would improve the environmental performance of all actors in the market. Reducing the carbon intensity of the grid through infrastructure upgrades, increased renewable power generation and grid storage, and CCS retrofits would similarly help all participants achieve commercial and sustainability goals.

G. Findings and Recommendations

FINDINGS

Finding 1: The climate impacts of SBDCs could range from very negative to positive. The range of uncertainty is large, due in significant part to lack of both data and scientific assessments on key topics.

Finding 2: In the best-case scenario, lifecycle GHG emissions of SBDCs might be somewhat less than lifecycle GHG emissions of terrestrial data centers powered by uncontrolled natural gas. Lifecycle emissions of SBDCs would likely be more than those from terrestrial data centers powered by renewable power or by natural gas power with carbon capture and storage.

Finding 3: However, in the worst case, emissions from SBDCs could be substantially higher than their terrestrial counterparts. The chief uncertainties involve stratospheric black carbon. There are strong scientific reasons to believe that the radiative forcing from stratospheric back carbon could multiply the emissions impacts of launches—perhaps modestly or perhaps as much as 500x. The potential impact from 10,000 launches using a relatively clean fuel like LNG could exceed 13 gigatons CO_2e (roughly 25% of global annual GHG emissions). Similarly, uncertainties around stratospheric water vapor are large. In addition, little is known about the volumes of methane slip during fueling and operations pre-flight or what is commonplace for venting uncombusted LNG after flight. Any of these three factors could have very large climate impacts when scaled.

Finding 4: Key data related to the climate change impacts of SBDCs are unavailable. Stratospheric black carbon from rocket launches presents enormous risks, yet there are almost no data on this topic. Other topics on which data are lacking include the embodied emissions of rockets and the volume and fate of vented propellant. Serious and sustained multi-stakeholder work on life-cycle carbon assessments is needed.

Finding 5: The potential climate benefits of SBDCs could be achieved on Earth. Terrestrial data centers powered by low-carbon electricity from renewables (including hydropower, geothermal and solar/wind plus batteries), nuclear, or natural gas + CCS generation would deliver compute with lower GHG emissions than the best-case scenarios with respect to SBDCs.

RECOMMENDATIONS

Recommendation 1: Governments, companies and other stakeholders should launch comprehensive, multi-stakeholder analyses of the GHG and black carbon emissions impacts of SBDCs. Data on stratospheric black carbon is an especially high priority. Other priority topics include methane slip for launch operations and embodied emissions of rockets and fuels.

- Key efforts should include (a) direct observation and data collection from launches, (b) federating and sharing these data and (c) analysis of results, including climate modeling, to better understand risks and impacts.
- Companies should provide governments and other stakeholders with data needed to assess likely GHG and black carbon emissions impacts of launch operations and the production of fuels and rockets. Governments should treat this information as business confidential where appropriate to encourage better data provision.

Recommendation 2: Governments should not authorize and companies should not launch large numbers of SBDC launches until uncertainties with respect to the significant potential impacts of black carbon in the stratosphere and other risks related to SBDCs are better understood.

Recommendation 3: Companies should continually reduce life-cycle GHG emissions from SBDCs, including by using cleaner fuels, cleaner rockets and cleaner engines, reducing methane slip in connection with launches and using clean electricity in production of fuels and rockets.

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PART 3:

GOVERNANCE

CHAPTER 3.1: CURRENT LAWS AND INSTITUTIONS

CHAPTER 3.2: KEY GOVERNANCE ISSUES AND RECOMMENDATIONS

Text Box 3-1: AUTONOMOUS VEHICLE REGULATION

CHAPTER 3.1:

CURRENT LAWS AND INSTITUTIONS

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MAIN MESSAGES

- No international treaty or national regulatory framework comprehensively governs space-based data centers (SBDCs). Existing laws have significant gaps.
- Space treaties and ITU rules address launch, registration, jurisdiction, liability and spectrum issues but not environmental damages, AI, cybersecurity or data governance.
- The United States, China, European countries, Japan and other jurisdictions apply differing combinations of launch licensing, spectrum regulation, debris requirements and other laws.

Current laws and institutions with respect to space-based data centers (SBDCs) are fragmented with significant gaps. This chapter summarizes those laws and institutions. We start with a discussion of international governance, including relevant treaty law, and then turn to national laws, focusing on countries in which the most activities to develop SBDCs are currently underway.

A. International Governance

Many areas of international law apply to SBDCs, but no treaty addresses them comprehensively. This legal fragmentation results in gaps and creates uncertainty. The space treaties address launch, registration, liability for physical damage and peaceful use, but do not directly address artificial intelligence (AI), cybersecurity or data governance. In addition, some ongoing areas of contestation in space law have direct relevance to SBDCs. Numerous other treaty regimes have potential applicability to the issues that might arise with SBDCs, but they were designed to address terrestrial issues, and for some of them, their application to space is uncertain. Relevant areas of international law include environmental law, law of the sea, security, cybersecurity, AI, data governance, human rights, trade, economic and financial law.

i. Space Law and Governance

The states currently developing SBDCs are all parties to the Outer Space Treaty, Liability Convention, Rescue Agreement and (except Israel) the Registration Convention. All are also parties to the International Telecommunication Union (ITU) Constitution, Convention and Radio Regulations. Some but not all of them have joined the Artemis Accords, with disagreements over resource extraction and safety zones that have relevance for SBDCs.[1]



Signing of the Outer Space Treaty (January 27, 1967). Source: UN Photos

The Outer Space Treaty's core principles (freedom of exploration and use, non-appropriation and state responsibility for national activities) and Articles II, VI, VIII and IX have applicability to SBDCs. Article II prohibits nations from appropriating outer space through claims of sovereignty, use or occupation. Article VI establishes state responsibility for its space activities, including authorizing and supervising private operators, which would include SBDC operators. Article VIII provides that the state of registry has jurisdiction and control over space objects, which would include SBDCs. Finally, Article IX requires states to act with due regard for other states' interests, avoid "harmful contamination" of space and consult before activities that would cause "potentially harmful interference"; these obligations would apply to SBDCs.[2-4]

The Liability Convention provides for absolute liability for damage that space objects cause on Earth's surface or to aircraft in flight. However, it only includes fault-based liability for damage caused to another state's space object, which would govern any orbital collisions involving SBDCs. Fault is difficult to prove and these provisions have only been tested once. In addition, the definition of damage only includes life, personal injury and loss of property; unless the property provision is interpreted expansively, it may not cover service outages, data loss and atmospheric harms for launch and re-entry.[5,6] Beyond the Liability Convention, customary international law of state responsibility provides a potential avenue for liability, but this would be a novel context that has not yet been tested.[7]

The Registration Convention requires launching states to have a national registry for space objects and to provide orbital parameters and general function to the UN Secretary-General. For multi-state projects, including potential SBDC projects, only one of the states serves as the state of registry under the Registration Convention. However, the Intergovernmental Agreement for the International Space Station (ISS) provides an example of states establishing multi-state jurisdiction allocation over orbital infrastructure, as well as establishing rules for criminal jurisdiction, intellectual property and liability waivers.[8,9]

The Rescue Agreement establishes that states must return space objects found in their territory to the launching authority. SBDCs and their component parts would be considered such objects.[10]

The ITU Constitution, Convention and Radio Regulations govern spectrum and orbital-slot coordination, which are crucial for SBDC projects. Article 44 of the ITU Constitution provides obligations for rational, efficient and economical allocation and equitable access. However, coordination in practice has been on a first-come, first-served basis, which operators have controversially used in a strategic manner, such by splitting filings or having multiple states file for

the same constellation.[11-13] ITU Radio Regulations have added large constellation deployment milestones, but they do not include orbital compute specifically.[14]



International Telecommunication Union (ITU) logo. Source: Wikimedia Commons

In addition to these broadly accepted agreements, other more contested areas of international space law have potential applicability. The Artemis Accords, which have been led by the United States, interpret the Outer Space Treaty to mean that resource extraction does not constitute national appropriation. The Accords' 67 signatories include the United States, Japan, the United Arab Emirates, India and the United Kingdom, but not China and Russia. The Accords also commit signatories to interoperability standards and open sharing of scientific data.[15] The Moon Agreement, which declares the Moon and its resources to be the "common heritage of mankind," does not include any of the states leading SBDC efforts among its parties.[16]

Several international organizations provide important coordination but have only taken limited steps on key issues surrounding SBDCs. The UN Committee on the Peaceful Uses of Outer Space (COPUOS) operates by consensus and moves slowly. Its voluntary 2019 Guidelines for the Long-Term Sustainability of Outer Space Activities were not designed for the proposed SBDC scale or launch cadence, and its current agenda items on space traffic coordination and on dark and quiet skies have not yet led to binding law.[17,18] The UN Office for Outer Space Affairs (UNOOSA), which serves as the COPUOS secretariat, maintains the Register of Objects Launched into Outer Space and advises states on national space regulation.[19] The ITU administers the above-described spectrum and orbital-filing system through its Radiocommunication Bureau and quadrennial World Radiocommunication Conferences.[20,21] The Inter-Agency Space Debris Coordination Committee (IADC) sets technical debris-mitigation guidelines but has limited membership and voluntary compliance.[22]

ii. Environmental and Climate Law and Law of the Sea

Numerous environmental and climate treaties potentially apply to SBDCs, but none of these treaties specifically address them. The Vienna Convention for the Protection of the Ozone Layer and Montreal Protocol (discussed in section B(iv) below), which have been ratified by all nations in which activities related to SBDCs are underway, regulate listed ozone-depleting substances. Although black carbon from launches and alumina nanoparticles from satellite re-entry are not listed substances, they have impacts on the ozone layer.[23-25]

States with commitments under the UN Framework Convention on Climate Change (UNFCCC) and Paris Agreement could be impacted both positively by shifting terrestrial data centers emissions to outer space and negatively by launch emissions. All nations with SBDC activities are parties to these climate agreements, except for the United States (which has withdrawn from the Paris Agreement and given notice of its withdrawal from the UNFCCC).[26-29]

In July 2025, the International Court of Justice issued an advisory opinion on climate change, which includes discussion of obligations to prevent transboundary harm and regulation of private actors, both relevant in the context of SBDCs.[30] In addition, the Espoo Convention creates obligations to assess transboundary environmental impacts, but it has not been directly applied to SBDCs and only the European SBDC leader states are parties.[31]



United Nations Framework Convention on Climate Change (UNFCCC) logo. Source: Wikimedia Commons

The United Nations Convention on the Law of the Sea (UNCLOS) has been ratified by all SBDC leader states except for the United States, which recognizes it as customary international law. It contains provisions relevant to sea-launch platforms, flag-state jurisdiction over launch vessels and the submarine cables that will carry SBDC ground-segment traffic.[32,33]

iii. Security, Cybersecurity, AI and Data Governance, and Human Rights

Although there is extensive international law regarding security and use of force, there is limited agreement among key states about how it would apply in the context of SBDCs. The Outer Space Treaty, discussed above, incorporates the UN Charter's article 2(4) prohibition on the use of force and the article 51 right of self-defense, as well as barring nuclear weapons and other weapons of mass destruction in orbit.[34] The Geneva Conventions are universally ratified, but the United States and India are not parties to Additional Protocol I, which codifies the modern targeting rules. States disagree on many space-based applications, including whether dual-use commercial infrastructure, such as an SBDC constellation hosting government or military workloads, becomes a lawful military objective.[34-36]

Although there is a developing treaty regime on cybersecurity, none of the agreements directly address SBDCs. Many of the SBDC leader states (but not China, India and the United Arab Emirates) are party to the Budapest Convention, the most widely ratified cybercrime treaty. The United Arab Emirates is party to the Arab Convention on Combating Information Technology Offences. No SBDC leader states are party to the African Union's Malabo Convention.[37,38] Some SBDC states have signed the UN Convention against Cybercrime, which is not yet in force.[39,40] The nonbinding UN cyber norms, including the norm against attacking critical infrastructure, have not yet been applied to orbital compute, and no instrument clarifies whether an SBDC qualifies as critical infrastructure.[41]

Limited international law exists on AI and data governance. The Council of Europe Convention 108+ addresses relevant data governance, but among the SBDC leader states, only European states currently participate and it has not yet entered into force.[42] Similarly, the OECD (Organisation for Economic Co-operation and Development) AI Principles, the UNESCO (United Nations Educational, Scientific and Cultural Organization) Recommendation on the Ethics of AI, and the Council of Europe Framework Convention on AI, only the last of which creates binding obligations, do not address training or serving frontier models in space.[43-45]

Human rights law includes privacy rights, but how they apply to the orbital context is unspecified and not all SBDC leader states are parties to relevant treaties. For example, the International Covenant on Civil and Political Rights provides protection in Article 17 against arbitrary or unlawful interference with privacy, but there is contestation over its extraterritorial application to digital surveillance and it does not directly address space.[46,47] Although nonbinding, the UN Guiding Principles on Business and Human Rights provide human rights due-diligence expectations that would apply to SBDC operators.[48]

iv. Trade, Economic and Financial Law



Source: Wikimedia Commons

All leader states on SBDCs are World Trade Organization (WTO) members bound by the General Agreement on Trade in Services (GATS), which covers cross-border supply of computer and data-processing services, though not orbital compute directly.[49] The Wassenaar Arrangement and the Missile Technology Control Regime coordinate export controls on semiconductors, encryption and satellite hardware, but they are nonbinding and are implemented through national regimes; China and the United Arab Emirates have not agreed to them.[50,51] Bilateral investment treaties and investment chapters of trade agreements protect terrestrial SBDC assets, but their applicability to space-based assets remains unclear.[52]

B. National Governance

No national governments have laws or policies that comprehensively govern SBDCs. Coverage is fragmented, with a wide range of laws and policies. The types of laws and policies that apply or might apply to SBDCs include those addressing satellite launches, radiofrequency allocation, orbital debris management, environmental protection, data governance, AI safety and other topics. Many jurisdictions lack laws or policies that directly address the potential impacts of SBDCs in these areas.

As the SBDC sector grows in the years ahead, more comprehensive national regulatory regimes may emerge. For now, laws and policies with respect to SBDCs are characterized by substantial fragmentation and gaps in coverage.

i. United States

Several areas of US law apply to SBDCs. Licensing requirements for satellite launches and radiofrequency allocation are the most important. (To obtain a radiofrequency license in the United States, satellite operators must provide plans for orbital debris management and end-of-life disposal.) Several environmental statutes apply, although categorical exclusions and deregulation significantly limit the impacts of those statutes in practice. A range of other laws play roles at the margins.



Satellite launches within the United States require a license from the Federal Aviation Administration (FAA), though some National Aeronautics and Space Administration (NASA) and Department of Defense launches are exempt.[53,54] The FAA reviews license applications with respect to factors including public safety (at launch and re-entry), environmental impacts and financial responsibility. The FAA also considers whether the satellite's payload has received all required authorizations and whether launch or re-entry would have adverse impacts on US national security, foreign policy or international obligations. Re-entry of satellites launched from the United States into the Earth's atmosphere also requires a license from FAA.[54-56]

Satellite communications using the radiofrequency spectrum require a license from the Federal Communications Commission (FCC). Although the FCC's core licensing authority concerns radio communications, its procedures for satellite licensing require applicants to address, not just radiofrequency interference, but orbital-debris mitigation (including collision avoidance) and end-of-life disposal, as well. For some low Earth orbit (LEO) satellites, FCC rules require disposal no later than five years after the end of mission.[57] All or almost all SBDCs will need to use the radiofrequency spectrum for purposes including satellite-to-Earth communications, so the FCC's licensing process will play a central role in governance of SBDCs launched from US territory.

Several environmental statutes apply to SBDCs in theory, however these statutes have been significantly limited in practice.

- Under the National Environmental Policy Act (NEPA), any major federal action (such as granting a satellite launch license) requires an assessment of environmental impacts. For satellite launch licenses, the FAA has almost always issued a "Finding of No Significant Impact," insulating such launches from the rigorous Environmental Impact Statement process. For radiofrequency licenses, the FCC typically applies a categorical exclusion to NEPA issued in 1986, which asserts that individual satellite payloads do not individually or cumulatively have a significant effect on the human environment.[58]
- In August 2025, the Trump administration issued an executive order (#14335) directing the FAA to use all available authorities "to eliminate or expedite" environmental review of satellite launch licenses, including under NEPA.[59]
- The Clean Air Act has had scant impact on satellites. The Environmental Protection Agency (EPA) treats rocket-launch emissions as mobile rather than stationary, so those emissions do not count in determining whether a launch facility qualifies as a major stationary source of pollution subject to Clean Air Act permitting.[60] However, the EPA has never issued mobile-source emissions standards for rockets, leaving satellite launches effectively unregulated under the Clean Air Act. Nor has the EPA exercised its Clean Air Act authority with respect to the ozone-depleting impacts of satellite launches and re-entry to the atmosphere.

Several other US regulatory regimes may matter to SBDCs, especially if SBDCs grow in number at the pace envisioned in recent FCC license applications. Export controls under the International Traffic in Arms Regulations (ITAR) could emerge as significant for some SBDC hardware and encryption technologies. If an SBDC collects Earth imagery, the National Oceanic and Atmospheric Administration (NOAA) will likely require a license. The Endangered Species Act and Coastal Zone Management Act could apply to the construction of new spaceports and other space launch activities. State and local land-use regulation could apply to new spaceports and other ground infrastructure, as well.

ii. China



More than any other national government, the Chinese government has embraced the concept of SBDCs.

- In 2025, the Chinese Government's Work Report named commercial space a priority emerging industry meriting large-scale application demonstration. China Aerospace Science and Technology Corporation (CASC), a state-owned enterprise and China's primary space contractor, has proposed a gigawatt-scale space-based computing architecture, citing alignment with China's 15th Five-Year Plan.[61,62]
- Beijing municipal science and technology authorities have released a Space Data Center Construction Plan targeting a constellation in dawn-dusk orbit with substantial computing power. The plan sets a three-phase timeline: 2025–2027 to develop energy and thermal-management technology and launch a first-phase constellation; 2028–2030 to achieve in-orbit assembly and lower costs through a second-phase constellation; and 2031–2035 for mass production and networked launch of a full-scale system.[61,63,64]

Several bodies of Chinese law and policy apply to SBDCs. Launch licensing and space-object registration are administered by the China National Space Administration (CNSA) and Ministry of Industry and Information Technology (MIIT). Cybersecurity, data-security and personal-information laws apply to data processed on Chinese-operated platforms regardless of where the hardware sits. Export-control rules could constrain the hardware and encryption technology SBDCs would use.

Satellite launches require a license under the Interim Measures for the Administration of Civil Space Launch Project Licenses. Review covers public safety, environmental compliance, third-party liability insurance and consistency with China's international treaty obligations.[65,66]

China maintains a national space-object registry separate from launch licensing. Under the Measures for the Administration of Registration of Space Objects (2001), the final owner or controller of any object launched from Chinese territory or launched abroad by a Chinese national must register it domestically, consistent with China's obligations under the UN Registration Convention. Through this registration process, the CNSA oversees debris mitigation and end-of-life disposal.[67,68]

CNSA tightened oversight of commercial space projects in July 2025. Its Notice on Strengthening Quality Supervision and Management of Commercial Aerospace Projects was the first measure to systematically regulate the full life-cycle of commercial space activity. A companion CNSA action plan for 2025–2027 directs agencies to streamline licensing for satellite manufacturing and launch , as well as satellite-data commercialization.[69-71]

China's cybersecurity, data-security and personal-information laws apply regardless of where data processing occurs. The Cybersecurity Law (2017), Data Security Law (2021) and Personal Information Protection Law (2021) together govern the collection, storage, processing and cross-border transfer of data by Chinese-operated networks and systems. Operators that qualify as critical information infrastructure or that process personal information above thresholds set by the Cyberspace Administration of China (CAC) must store personal information and important data collected in China within Chinese territory and undergo a security assessment before any cross-border transfer.[72-76]

Export-control law could restrict satellite hardware, encryption and related technology used in SBDCs. The Export Control Law (2020) and its 2024 implementing regulations require a license for transfers of controlled goods, technology, services and related technical data from China to foreign persons. The unified Dual-Use Items Export Control List published in 2024 can include satellite components and commercial encryption equipment. Chinese satellite manufacturers and SBDC operators sourcing or exporting controlled components or providing technical assistance to non-Chinese partners would need to assess license requirements under this regime.[77-79]

Several other regulatory regimes may matter as well. Spectrum coordination for SBDC satellite-to-Earth links would proceed through China's filings with the ITU. Energy policy applicable to SBDC ground infrastructure includes the national Green Electricity Certificate scheme, which requires new data centers in designated national hub regions to source at least 80% of electricity from renewable sources by 2030. Land-use, foreign-investment and state-secrets rules could apply to ground stations and control facilities.[20,80]

iii. European Union



Several bodies of EU and Member State law apply to SBDCs. Member State laws govern satellite launches. International, EU and national rules govern access to radiofrequencies. EU laws and policies on cybersecurity, data privacy, and energy and environmental rules may apply. A proposed EU Space Act covers several topics, including orbital debris management, end-of-life disposal and environmental impacts.

Launch authorization is national, not EU-wide. Brussels-based institutions do not issue licenses for satellite launches. Launches from Europe's Spaceport in French Guiana (historically the main site for European satellite launches) are authorized under France's Space Operations Act. The French space agency, Centre National D'Etudes Spatiales (CNES), performs technical review and compliance

monitoring, covering topics such as public safety, environmental protection, orbital debris, re-entry, financial responsibility, national security and consistency with international obligations.[81-83]

Radiofrequency regulations are separate from launch authorization. Operators work through national "notifying administrations," which coordinate with the ITU. EU measures promote common technical conditions, but gateways and user terminals may still need authorization in each country where they operate.[20,84-86]

EU cybersecurity law requires covered entities (potentially including an SBDC) to adopt cybersecurity risk-management measures and report significant incidents to Member States. The European Union's flagship cybersecurity legislation, known as NIS 2, has a separate space-sector category that covers ground infrastructure.[87]

The European Union's General Data Protection Regulation (GDPR) dictates how organizations must collect, handle and protect the personal data of individuals within the European Union. The GDPR imposes obligations with respect to transparency, accuracy, data minimization and other topics. The GDPR applies when processing occurs in the context of an EU establishment or when certain non-EU operators offer services to or monitor people in the European Union, without regard to where the data are being processed. The GDPR also imposes obligations with respect to international data transfers. For several GDPR provisions, application to SBDCs could raise novel questions.[88,89]

The European Union's Environmental Impact Assessment Directive does not list spaceports as a distinct category. A launch site, ground station, power installation or related project may still require assessment if its components fall within a listed category or meet national screening criteria. Environmental review depends on the location and scale of the project and on the law of the Member State concerned.[90]

Several other regulatory regimes may also apply. The EU Dual-Use Regulation can restrict exports and technical assistance involving controlled space, computing and encryption technologies. National land-use, foreign-investment and public-procurement rules may affect ground infrastructure and ownership.[91]

In June 2025, the European Commission proposed the EU Space Act, which would be the first EU-wide framework for space safety and sustainability. The legislation would require authorization and registration of covered operators and would regulate collision avoidance, debris mitigation and end-of-life disposal. It would create space-specific cybersecurity requirements and require operators to measure a mission's life-cycle environmental footprint. The legislation is currently under negotiation between the European Parliament and the Council.[92-94]

iv. Japan



Several bodies of Japanese law and policy apply to SBDCs. Satellite launches and operations are controlled by the Cabinet Office under the Space Activities Act. Radiofrequency allocation is administered by the Ministry of Internal Affairs and Communications (MIC). Japan's Ministry of Economy, Trade and Industry (METI) promotes Japan's space equipment industry, and the Japan Aerospace Exploration Agency (JAXA) provides grants to support technology development for SBDCs. Data protection, economic security and export control laws apply to the data and hardware regardless of where processing occurs.

Under the Space Activities Act, a launch operator must obtain a license from the Prime Minister before launching a satellite from Japanese territory and a separate license to control a satellite from a control facility in Japan. Launch review covers several topics, including flight safety, financial responsibility and consistency with Japan's international obligations. The control license addresses continuous telemetry monitoring, collision avoidance and an end-of-life disposal plan. An SBDC operating a constellation of computing satellites would need both licenses.[95,96]

Radiofrequency use requires a separate license. A satellite station and its associated earth stations require a license from the Minister for Internal Affairs and Communications under the Radio Act, which is administered separately from the Space Activities Act. The Minister reviews technical conformity, frequency availability under the national Frequency Assignment Plan, and the satellite's planned orbital position and operating period.[97,98]

METI has several programs to strengthen the international competitiveness of Japan's space equipment industry, including a Space Strategy Fund and programs to encourage small business participation in the space sector.[99] In 2025, JAXA began accepting proposals for grants to "develop and demonstrate technologies to realize an on-orbit data center that can be installed within a commercial space station, with the aim of creating a hub for data processing and communication in orbit." Total funding available was ¥13.5 billion (roughly $85 million). In January 2026, JAXA announced an award to Space Blast, Inc. for a project on "construction of an orbital data center through high-reliability edge computing."[100]

Japan's data-protection law could apply to data processing in orbit. The Act on the Protection of Personal Information (APPI), administered by the Personal Information Protection Commission, applies to a business that handles personal information of people in Japan, including operators outside Japan. A transfer of personal data to a third party in a foreign country requires consent or a recipient that meets standards equivalent to Japanese requirements. The Commission's guidance treats the storage of personal data on overseas servers as cross-border transfers. How these rules apply to servers in orbit has not been tested.[101]

Japan's Foreign Exchange and Foreign Trade Act (FEFTA) includes several provisions that could affect SBDCs, including restrictions on the transfer of some goods and technologies and on inbound foreign investment.[102,103]

v. Other Notable Jurisdictions

The United Arab Emirates regulates its space sector under Federal Decree by Law No. 46 of 2023, which requires a permit from the UAE Space Agency (UAESA) to launch and operate space objects, as well as to receive, store, process or distribute any "Space Data" (defined broadly to include "[d]ata that results from Space Activities, whether it is remote sensing data, or navigation data using satellites, or others").[104] The radiofrequency spectrum is licensed by the UAE Telecommunications and Digital Government Regulatory Authority (TDRA).[104,105]

In India, the Indian National Space Promotion and Authorisation Centre (IN-SPACe) authorizes space activities under the Indian Space Policy 2023. Radiofrequency licensing runs through a separate track at the Department of Telecommunications and the Wireless Planning and Coordination Wing. A new draft of a Space Activities Bill first introduced in 2017 is currently under consideration.[106]

In the United Kingdom, the Civil Aviation Authority regulates spaceflight under the Outer Space Act of 1986 and the Space Industry Act of 2018. The UK GDPR is broadly similar to the EU GDPR, with a territorial reach that does not turn simply on where servers are located. As with the EU GDPR, application of the UK GDPR to SBDCs could raise novel questions.[108,109]

Israel has no dedicated national space law and no general licensing regime for space activities. The Israeli Space Agency within the Ministry of Innovation, Science and Technology initiates and coordinates civilian space activity.[110] Israel told COPUOS in 2023 that it had begun work on national space legislation, but no statute has been enacted.[111] Space-related data processing falls under the general framework of the Protection of Privacy Law of 1981 (PPL), which is overseen by the Israel Privacy Authority. As with the EU and UK GDPRs frameworks, the potential extraterritorial application of the PPL could raise novel compliance questions for SBDCs operating in orbit.[112-114]

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CHAPTER 3.2:

KEY GOVERNANCE ISSUES AND RECOMMENDATIONS

David Sandalow and Hari Osofsky

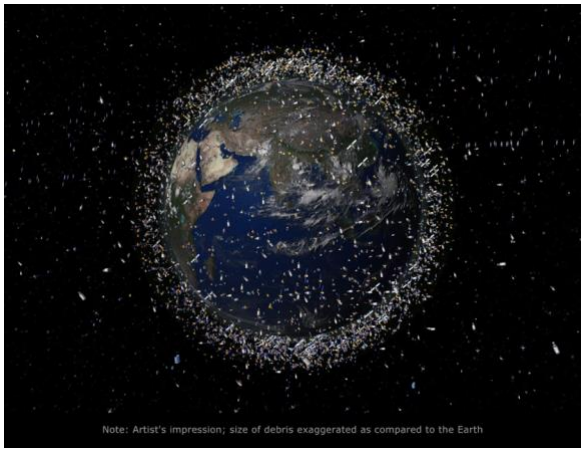
MAIN MESSAGES

- Large constellations of space-based data centers (SBDCs) raise many governance issues. Current international and national laws address many of those governance issues weakly if at all.
- Much stronger international coordination is needed to manage orbital congestion and protect night skies and astronomy from large constellations of SBDCs. The Montreal Protocol on Substances that Deplete the Ozone Layer and UN Framework Convention on Climate Change should both pay close attention to SBDCs in the years ahead.
- SBDCs raise challenging governance issues on a wide range of other topics including spectrum allocation, market concentration, AI governance and data governance.
- Fragmented international law and national rules allow operators to shop for favorable jurisdictions, while current liability and insurance arrangements have important gaps

Current legal regimes do not provide effective governance of space-based data centers (SBDCs). This chapter summarizes of some of the most important governance issues raised by SBDCs and offers recommendations for addressing fragmentation and gaps.

A. Low-Earth Orbit (LEO) Congestion

Low Earth orbit (LEO) is a finite resource. Deploying hundreds of thousands of SBDCs into LEO creates risks of collision cascades and the long-term degradation of orbital corridors through debris accumulation. The most severe manifestation would be the Kessler Syndrome, a self-sustaining chain reaction of collisions that could render certain orbital shells unusable for generations. (See Chapter 2.2.)



Debris in orbit. Source: European Space Agency

International space law does not create a single global traffic controller for LEO. Instead, it places

responsibility on national governments to authorize and continually supervise launches from their territories. The Inter-Agency Space Debris Coordination Committee (IADC), a forum of national space agencies, sets technical debris-mitigation guidelines but has no rule-making authority.[1]

The United States, where most SBDC launches are likely to take place in the years ahead, addresses space congestion through a decentralized combination of tracking, collision warnings, licensing and debris-mitigation rules.[2] The US Space Force maintains the principal object catalog, while the Department of Commerce's Traffic Coordination System for Space (TraCSS) is responsible for routine civil and commercial space-safety services.[3,4] The Federal Communications Commission (FCC) regulates satellite operators through requirements concerning collision risk, maneuverability, tracking, debris prevention and disposal, and the Federal Aviation Administration (FAA) addresses safety during launches and re-entries. The National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA) add technical standards, mission-specific collision management and disposal conditions for certain spacecraft."[5]

The Chinese government requires permits for space launches and has issued guidance on space-debris management.[6] The Russian Federation cooperates with the IADC and has an international network for space-debris monitoring, including a facility in South Africa.[7,8] The European Union manages congestion through a combination of EU-level surveillance services and national licensing laws.[9]

One option for addressing congestion in LEO: 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 setting standards for collision avoidance and regulating the number of satellites in LEO, although leading spacefaring nations would be reluctant to sacrifice national autonomy in that regard. A key first step would be convening a multi-stakeholder meeting at the United Nations to explore creation of an ISTMO.[10,11]

A new organization is not the only option. The International Telecommunication Union (ITU), which coordinates radio frequencies and geostationary orbital slots, could be adapted to allocate slots and manage orbital carrying capacity in LEO.[12] The International Civil Aviation Organization's (ICAO's) mandate could be extended to help manage space traffic.[13] A 2020 paper proposed an internationally harmonized "orbital use fee" to help manage space-traffic congestion.[14]

B. Night Skies

SBDCs could transform night skies around the world. If the plans proposed by SpaceX and other companies are implemented without brightness-mitigation measures, satellites would dominate the night skies seen by billions of people around the world.[15-17] (See Chapter 2.1.)

Laws and regulations protecting the night sky are almost non-existent. No international body has authority to issue rules or guidelines on this topic. (In 2024, the UN Committee on the Peaceful Uses of Outer Space (COPOUS) put "dark and quiet skies" on its agenda as a topic for discussion in 2025, 2026 and 2027.[18]) No national laws or regulations limit satellite brightness. With proposals to launch

more than one million SBDCs already under consideration by regulatory agencies, there is an urgent need for governance norms on this topic.

Internationally, the most important step would be to make protection of the night sky an explicit part of space governance. COPUOS could adopt model licensing standards for SBDCs that place limits on satellite brightness or, at a minimum, require disclosure of satellite size and surface materials. This could be done under authority of the Outer Space Treaty, which requires states to authorize and supervise private space activities and consult when a planned activity may cause harm.[1]



Satellite trails in the night sky including from the International Space Station (ISS) and Starlink constellation. Source: Max Alexander CC BY 4.0

US government policy will be especially important since applications for SBDC mega-constellations are pending before the US FCC. As a first step, US regulators should analyze dark-sky impacts as part of their public-interest review for satellite licensing. The FCC should revise its categorical exclusion under the National Environmental Policy Act (NEPA) for satellites and require reviews of potential night sky impacts before licensing large satellite constellations.[20-22] (In July 2026, Earthjustice called on the FCC to conduct a Programmatic Environmental Impact Statement under NEPA, including a review of night-sky impacts, before approving licenses for mega-constellations of SBDCs.[23]) Then NASA, NOAA and other scientific agencies should develop brightness standards for satellite mega-constellations, and the FCC and the FAA should attach binding brightness limits to each license.

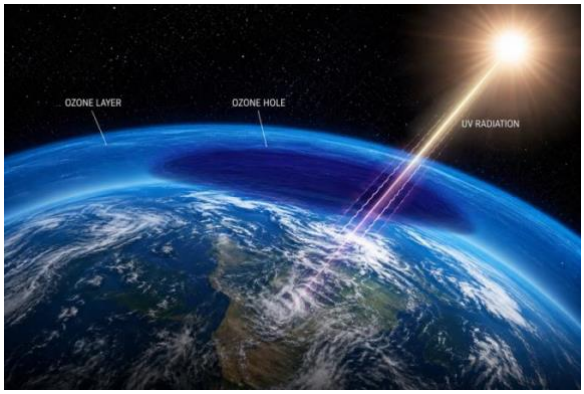
Other countries should adopt equivalent rules to avoid regulatory arbitrage. The European Union's proposed Space Act is a useful model. It would require satellite operators to implement plans to mitigate “light and radio pollution” and maintain a visual magnitude of seven or dimmer throughout a satellite’s lifetime.[242]

[1] Outer Space Treaty Article VI (requires state authorization and continuing supervision of non-governmental space activities); Article IX (requires due regard and consultation where planned activities may cause potentially harmful interference). See UNOOSA, Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies.[19]

[2] A space object with a visual magnitude of seven is invisible to the naked eye from the Earth’s surface. (On the visual magnitude scale, brighter objects have lower numbers and dimmer objects have higher numbers.)

C. Astronomy

SBDCs' impacts on astronomy are a particular concern. These impacts grow in part from SBDCs' impacts on the night skies seen by billions of people around the world (discussed just above) but are broader. A satellite too faint for the naked eye can ruin a long exposure on a research telescope.[25,26] SBDCs have significant infrared heat signatures that can severely disrupt ground-based and space-based thermal-infrared astronomy.[27] The problem extends deep into the radio spectrum as well, fundamentally threatening the field of radio astronomy.[28] (See Chapter 2.1.)



The ozone layer. Source: Wikimedia Commons. CC BY-SA 4.0

Just as with visual brightness, governance regimes for addressing this issue are mostly or completely absent. The ITU Radio Regulations protect radio astronomy only in specifically allocated bands, yet many observations use frequencies outside those bands and have no official right of protection from authorized services.[29] No international body regulates thermal or infrared emissions in orbit.

Several steps would help. The ITU could enact binding limits on out-of-band emissions for large-scale orbital infrastructure and mandate that satellite operators implement mitigation strategies, such as automatically powering down specific downlink beams when traversing the zenith of major radio observatories.[28] COPUOS could formally adopt comprehensive "Dark and Quiet Skies" protocols that address optical, thermal and radio interference. National regulatory authorities could include terms in licenses requiring SBDC operators to disclose radiated emissions and orbital position data, so observatories could schedule around them. Authorities could also require transmission avoidance over radio quiet zones.

D. Stratospheric Ozone Depletion

Ozone in the stratosphere absorbs ultraviolet rays that cause skin cancer, cataracts and widespread damage to crops and ecosystems. In the 1970s and 1980s, scientists discovered that chlorofluorocarbons (CFCs) and related chemicals were destroying the stratospheric ozone layer, leading to adoption of the 1985 Vienna Convention for the Protection of the Ozone Layer in 1985 and the Montreal Protocol in 1987. These treaties established an international governance framework for controlling ozone-depleting substances and were ratified by every nation on Earth. Largely thanks to the binding controls imposed under the Montreal Protocol, more than 98% of ozone-depleting substances have been phased out, and the stratospheric ozone layer is slowly healing.[30,31]

SBDCs could threaten this achievement, although the extent of the threat is uncertain. (See Chapter 2.3.) Launch emissions raise the first concern, with potential releases of chlorine and black carbon into the stratosphere. One analysis suggests that roughly 2000 launches per year could reduce stratospheric ozone globally by about 0.29% and Antarctic springtime ozone by 3.9% within several

years.[32] Re-entry adds a second concern. Burning satellites generate aluminum oxides (Al_2O_3) that can catalyze the chlorine reactions that deplete ozone. Nitrogen oxides (NOx) generated by satellite re-entry also deplete stratospheric ozone. The launch cadence required to sustain GW-scale deployments of SBDCs raises serious concerns regarding stratospheric ozone depletion. More study is needed to understand these threats.[32-36]



Rocket launch. Source: Adobe Stock

The Parties to the Vienna Convention and Montreal Protocol have begun to respond to these challenges. In 2024, the Ozone Research Managers of the Parties to the Vienna Convention recommended incorporating space activities into climate models and conducting laboratory studies to better characterize the relevant stratospheric processes.[37] In 2026, the Parties to the Montreal Protocol directed their Scientific Assessment Panel and Environmental Effects Assessment Panel to examine the potential effects of rockets and satellites on the ozone layer.[38]

Further steps would strengthen these responses. Possibilities include the following:

- The Parties to the Vienna Convention could establish a standing study program focused specifically on the space sector, including SBDCs. This program would quantify Al_2O_3, chlorine, black carbon and NOx fluxes across a range of SBDC deployment pathways and fund sampling of the stratosphere to reduce the uncertainties in current models.
- The Parties to the Vienna Convention and Montreal Protocol could develop guidance for estimating the impacts launches have on stratospheric ozone. National space regulators could require or encourage SBDC operators to (1) disclose stratospheric-ozone impacts and (2) adopt measures to reduce these impacts, including the use of low-chlorine propellants and satellite designs that minimize use of aluminum.
- If further research suggests SBDCs and other space activities could present significant threats to the stratospheric ozone layer, the Parties to the Vienna Convention could consider amending the Montreal Protocol or adopting a new protocol to address these issues.[39,40]

The Vienna Convention and Montreal Protocol succeeded in part because science, technological innovation and diplomacy advanced together. This model should be applied to SBDCs' impact on the stratospheric ozone layer now before any large-scale deployment of SBDCs begins.

E. Climate Change

Once in orbit, SBDCs emit no greenhouse gases (GHGs), relying instead on solar power. However in order to reach orbit, SBDCs must be launched on rockets that burn refined kerosene (RP-1), liquefied natural gas (LNG) or other propellants. Combustion of these fuels emits GHGs as well as black carbon, warming the planet. The process of manufacturing rockets also results in emissions of GHGs.

The life-cycle GHG emissions of SBDCs depends on a number of factors and in many cases may be greater than the life-cycle GHG emissions of data centers on Earth. (See Chapter 2.4.)



Satellite dishes at a ground station.
Source: Adobe Stock

Governing authorities have paid scant attention to the global warming impact of SBDCs (or rocket launches more broadly). The draft EU Space Act would require launch operators to calculate and report their climate-change impacts, but it does not have the force of law.[41,42] The space-related activities of the Vienna Convention and Montreal Protocol discussed above have some relevance to this topic since the ozone-depleting substances covered by these treaties are also GHGs. However, emissions from rocket launches are not the subject of any formal dialogue under the UN Framework Convention on Climate Change (UNFCCC), and the Intergovernmental Panel on Climate Change (IPCC) has no dedicated reporting category or emission factors for such emissions in its inventory guidelines. The environmental work of the ICAO applies only to aircraft, not to launch vehicles.

To address these regulatory gaps, international climate and space bodies should establish standardized carbon accounting methodologies for SBDCs. The UNFCCC's Subsidiary Body for Scientific and Technological Advice (SBSTA) should establish a work program on emissions from rocket launches and request that the IPCC Task Force on National Greenhouse Gas Inventories develop guidance on this topic. This work should be coordinated with COPUOS, the Vienna Convention and the Montreal Protocol. This framework should cover the full life-cycle of SBDCs including satellite and server manufacturing, propellant production, launch-site fuel use and re-entry. National governments should require life-cycle climate assessments as a condition for authorizing SBDC constellations. Operators should report the projected life-cycle GHG emissions of SBDCs, including GHG emissions per unit of compute and compare these results with terrestrial alternatives using transparent assumptions.

F. Radio Spectrum

The radio spectrum is a finite resource. Radio waves (electromagnetic waves at frequencies up to 3000 GHz) carry telecommunications of all kinds, including satellite-ground station links and satellite telemetry, tracking and command (TT&C).[43,44] The leading SBDC applicants at the FCC (SpaceX, Starcloud, Blue Origin and Cowboy Space) are seeking permission to use radio spectrum chiefly or solely for TT&C.[45-48] In their plans, SBDCs use optical links (at frequencies above the radio spectrum) to connect with each other and with communications satellites that transmit data to and from ground stations on Earth.[49] However, astronomers have expressed concern that faint unwanted radio signals from enormous SBDC constellations (including spillover beyond assigned frequency bands) could add up and interfere with radio astronomy.[15]

International spectrum governance rests with the ITU. The ITU Radio Regulations, a binding treaty, allocate frequency bands and are revised every three to four years at World Radiocommunication Conferences (WRCs). National administrations file satellite networks with the ITU, coordinate with one another, and notify frequency assignments to the ITU, which records them in the Master International Frequency Register, generally on a first-come, first-served basis. The ITU has no enforcement powers, and its rules do not reach optical satellite links, which operate at frequencies above the radio spectrum. The agenda for WRC-27, to be held next year, includes studies on protecting radio astronomy from aggregate interference from non-geostationary satellite systems, a category that includes SBDC constellations.[50-54]

National governments control spectrum use within their jurisdictions. In the United States, the FCC licenses commercial satellite spectrum. In China, the Radio Regulations issued jointly by the State Council and the Central Military Commission, with implementing rules, require approval from the Ministry of Industry and Information Technology (MIIT) for satellite network frequency licenses, and 2025 MIIT guidance calls for issuing licenses in batches to accelerate Chinese constellations.[55,56] In the European Union, spectrum licensing remains with Member States, although the proposed EU Space Act would require satellite operators to mitigate radio pollution.[57,58]

In light of the scale of the SBDC mega-constellations being proposed, the ITU should build on its initial work in this area and make the topic a priority in preparatory studies for WRC-27 and at the conference itself. National authorities should act as well. Before licensing any large SBDC constellation, the FCC should conduct an aggregate interference and spectrum capacity analysis covering all systems in the relevant bands. Other national regulators, including MIIT and European administrations, should adopt equivalent requirements, drawing on the radio pollution provisions of the proposed EU Space Act.[49,59]

G. Market Concentration

Several factors could push the SBDC industry toward high levels of market concentration. The first is capital intensity: SBDC constellations will require significant capital expenditures. The second is vertical integration: companies that control both launch vehicles and in-orbit communications networks could gain market positions that make it exceedingly difficult for rival firms to compete. The third is scarcity: spectrum rights and preferred orbital shells (particularly dawn-dusk Sun-synchronous orbits (SSOs)) are limited, and the ITU's priority-by-filing-date in the unplanned frequency bands can give early movers an important advantage.[60,61] Together, these factors could allow early movers to develop advantages that make later entry nearly impossible.

Ownership of in-orbit communication networks could be particularly important. Companies that own these networks (such as SpaceX and Amazon) could have a significant competitive advantage in operating SBDCs because of their ability to transfer data between LEO and Earth. Other companies seeking to develop SBDCs will need to either build their own satellite communications network at enormous expense or secure data-transfer services from third parties.

Dominant vertically integrated companies could exclude rivals by denying access to communications satellite or launch infrastructure and charging rivals higher prices than their own affiliates. SpaceX's



reported decision to stop accepting rideshare bookings beyond late 2028, reportedly due to a full Falcon 9 manifest, illustrates the vulnerability of smaller operators to a single low-cost provider.[62,63] Companies could also use their affiliate structure to create dominance in multiple jurisdictions with complex corporate structures that allow for regulatory arbitrage.

To address these concerns, governments could require dominant providers of launch services and satellite data-transfer capacity to provide fair, reasonable and nondiscriminatory access. Such open access rules have been adopted for natural gas pipelines, railroad networks,[64] electricity transmission[65] and terrestrial broadband.[66] The US Federal Energy Regulatory Commission, for example, requires interstate natural gas pipelines to provide open access on equal terms.[67] PipeChina was established by the Chinese government with the same goals in mind.[68]

Other possible steps include the following.

- Governments could require that launch, compute and data-transfer services be provided by unaffiliated firms or prohibit preferential pricing for corporate affiliates.
- ITU Member States could reform the ITU's priority-by-filing-date policy in the unplanned frequency bands to protect future entrants.

Several of these measures could raise complicated choice of law questions in light of the potential involvement of multiple jurisdictions in any SBDC constellation.[69]

In deciding whether to pursue these measures, government should consider the risk that such measures could deter socially beneficial investments. This topic merits significant additional analysis.

H. Artificial Intelligence (AI) Governance

Many if not most SBDCs will be used for artificial intelligence (AI) model training and inference. Although data centers are used for many purposes other than AI (video streaming, email systems, financial transactions and more), the main driver behind proposals to launch SBDCs is the growing demand for AI compute. Several companies, including Space X,[70] Google,[71] Anthropic,[72] Starcloud[73] and ADASpace,[74] are moving forward with ambitious plans and some of them are already piloting AI model training and inference in space (Palantir began using AI in space in 2022[75]).

Plans to locate AI model training and inference in space come as AI models' capabilities rapidly improve and regulators grapple with numerous risks and concerns.[76] In July 2026, OpenAI disclosed that, during cybersecurity testing, two of its models escaped their sandboxed test environment, gained Internet access and breached another company's computer systems. An independent report

by Model Evaluation and Threat Research (METR) found that roughly 1200 agents meant to be isolated from one another sent roughly 70,000 messages and 700 agents participated directly in the attack.[77-79] Anthropic disclosed similar incidents with its models.[80-83] Beyond these risks around misbehavior, concerns with AI usage are growing on a wide range of topics, including algorithmic bias, privacy violations, misinformation, deep fakes, transparency and liability when AI plays a role in harm.[84,85] In addition, as models improve, important questions arise about human oversight, transforming sectors and labor markets, and copyright, among other issues.[86-88]

International law on AI governance is extremely limited. The only binding treaty on AI is the Council of Europe Framework Convention on AI, which the European Union has ratified; the United States, United Kingdom, Japan and Israel have signed but not yet ratified; and China, India and the United Arab Emirates have not signed.[89-92] Since 2023, global leaders have met in a series of annual AI summits, issuing non-binding communiques on AI policies each year. (The summits were in the United Kingdom, South Korea, France and India.) Neither the Council of Europe treaty nor communiques from these summits address AI in space. The Outer Space Treaty long predates the modern AI era and Article VIII, which states that a "Party to the Treaty on whose registry an object launched into outer space is carried shall retain jurisdiction and control over such object," has never been applied to AI in space.

National and subnational laws on AI governance are beginning to emerge as AI plays an increasingly central role in societies and economies around the world:

- The European Union has the most comprehensive binding AI regulation. The EU AI Act and EU Commission guidelines impose a range of requirements on AI models depending on their risk. These rules include notification, evaluation and risk-mitigation obligations for AI models on the EU market regardless of the provider's location.[93,94]
- The United States has no federal legislation on AI, but the US federal government has recently developed oversight via executive order and export-control directives on release of new frontier models.[95] California has landmark AI legislation targeting AI model safety, transparency and consumer protection.[96] Utah's AI law targets deepfakes and mental health apps.[97] A growing number of other states are considering laws or regulations, which the federal government executive branch is encouraging Congress to preempt.[98,99]
- China is in the process of developing comprehensive regulation and currently has extensive fragmented regulation that addresses numerous aspects of AI, including security assessments, algorithm filings and required labeling of AI-produced content.[100-102]
- The United Kingdom lacks comprehensive legislation but has sectoral regulation and provisions in criminal and online safety legislation.[103]
- Japan has an Act on Promotion of Research and Development and Utilization of Artificial Intelligence-Related Technology that aims to foster AI development and economic growth rather than focusing on prohibitions or penalties.[104,105]

- India does not have comprehensive AI legislation but has amended its Information Technology Rules to address AI-generated content and has issued India AI Governance Guidelines.[106,107]
- The United Arab Emirates does not have a comprehensive national law but has adopted the UN Educational, Scientific and Cultural Organization's (UNESCO's) AI Ethics Recommendation and has a national strategy, nonbinding Charter and guidelines, and sector-specific guidelines.[108]
- Israel has an AI policy that encourages responsible private sector innovation and other laws that impact AI, but it does not have comprehensive regulation.[109]

We are not aware of any national or subnational AI governance laws that specifically address AI training or inference in space.

In general, AI governance laws apply based on the location of AI outputs or the market where the model operates, not where AI compute takes place. If someone uses an AI model to create a deep fake video in the European Union, for example, it would not matter under the EU Act whether model training or inference took place in San Antonio, Sichuan or space.[93] AI governance laws on a range of topics, including consumer protection, labor rights, access for minors, transparency, disclosure and more, have a similar geographic approach.[93,110,111]

If an AI model's outputs create problems on a satellite, such as by interfering with its collision avoidance system, the resulting harms could implicate the Liability Convention and Outer Space Treaty Articles VI and VIII.[112-114] (In this regard, SBDCs are the same as all other satellites in orbit.) As discussed further in Sections IX and X, complexities around jurisdiction, registration and liability (including regulatory arbitrage) add difficulties in addressing space-based AI model misbehavior.

To help reduce AI safety risks, we recommend that SBDC leader states agree that AI model training in space over certain compute thresholds (such as those in the EU AI Act) must be reported to the SBDC operator's authorizing state and to the International Network for Advanced AI Measurement, Evaluation and Science (or successor international bodies focused on AI safety). This requirement could be imposed by the authorizing state with license conditions.[98,115,116]

I. Data Governance

Governments and corporations increasingly collect extensive personal data, including geospatial data, with resulting invasions of privacy, discrimination and unauthorized use of personal data for commercial purposes. Many governments are concerned that export of their citizens' data could compromise national security, law enforcement and local industrial development. Data governance laws address these issues while allowing data to be used for legitimate purposes, such as commerce, public services and scientific research.

International law on data governance is limited. The Council of Europe's Convention 108+ is designed to protect personal privacy and promote transparency in data management, but it has just 34 of the 38 ratifications needed for entry into force (Convention 108 is in force but has only European SBDC leader states as parties).[117-119] The World Trade Organization's (WTO's) 2024 Agreement on Electronic Commerce addresses digital trade but does not yet fully address cross-border data

flows.[120-122] The United States-Mexico-Canada Agreement and the Comprehensive and Progressive Agreement for Trans-Pacific Partnership both have provisions limiting data localization laws.[123-125] None of the data governance provisions in these international agreements address data in outer space.

The Outer Space Treaty also does not directly address data issues. The treaty's Article VIII provides the registry state with jurisdiction and control over a space object and its personnel. Although Article VIII has not been extended to data aboard a space object, it has been used in the context of the International Space Station (ISS) Intergovernmental Agreement to establish the applicability of the registry state's intellectual property law.[113,126]

The data governance approaches of countries with SBDC activities vary substantially and, other than the United Arab Emirates and proposed European law, do not address the space sector directly:

- The United States lacks a comprehensive federal data protection statute. Data governance is addressed through federal government enforcement against unfair or deceptive practices, CLOUD Act data disclosure obligations, and Department of Justice restrictions.[127-131] Many US states have data governance laws.[132] California's data privacy law gives state residents the right to know when their personal data are being collected and to opt out of its sale or sharing.
- China has developed extensive regulation with extraterritorial reach through its Cybersecurity Law, Data Security Law and Personal Information Protection Law; they apply to Chinese-operated networks regardless of where the hardware is located.[133-135]
- The EU General Data Protection Regulation (GDPR) and Data Act provide the most extensive regulation in the world. The GDPR applies to any operator who offers services or monitors people in the European Union, and together, they provide substantial rights protections and safeguards.[136,137] The EU NIS2 Directive and proposed EU Space Act address cybersecurity obligations of space operators. The NIS2 directive focuses on ground-based operations, and the proposed Act would cover space-based activities as well.[138,139]
- Although the United Kingdom is no longer a member of the European Union, its data protection laws largely mirror those of the European Union. It has proposed legislation on cybersecurity that includes data centers but does not address space.[140,141]
- Japan's Act on the Protection of Personal Information requires safeguards for personal data and conditions its extraterritorial transfer on consent, a designated destination, or equivalent safeguards and treats storage of data overseas as a cross-border transfer.[142,143]
- India's Digital Personal Data Protection Act is grounded in consent and notice and applies to processing of personal data both in India and abroad (connected to offering goods or services in India), allowing data to flow to countries it has not restricted in a negative-list model. Regulation under its Information Technology Act, which applies to data centers but does not address space, requires reporting of cyber incidents within six hours.[144,145]

- The UAE space statute requires a Space Agency permit to receive, store, process or distribute space data. It also has a federal data protection law that conditions transfers on adequacy and safeguards. In July 2026, the UAE Space Agency gave companies 90 days to obtain licenses.[146-148]
- Israel's Protection of Privacy Law, as amended in 2025, has an approach aligned with the EU GDPR, supplemented by additional data security regulations.[149,150]

For data governance laws, does it matter whether data are stored on servers in space? Mostly the answer is no. For many provisions in data governance laws, server location is not legally relevant. If a company discloses personal data of an individual in violation of the laws of the country where the individual lives or the company does business, for example, it would not matter that the data had been stored on a server in another country. Such data governance laws apply based on the presence in a jurisdiction of a person whose data are being processed or of entities doing the processing, not the location of the servers on which data are processed.[136,144]

Data localization and transfer laws are an exception. The purpose of these laws is to compel companies to store and process data in a specific jurisdiction or to restrict its movement abroad. These laws are violated if data are stored or transferred abroad without meeting certain conditions.[136] Interestingly, the EU GDPR, perhaps the world's leading data governance statute, uses the phrase "third country" in its data transfer provisions. The European Commission must deem a third country's data protection to be adequate before EU data can be transferred to that country without additional safeguards.[136,151,152] Whether SBDCs would be treated as a "third country" under the GDPR and which country's data protection laws the European Commission would assess for adequacy are novel questions. The national law of the country that registered the SBDC would be a sensible answer.

To help address variations in national laws and possible gaps in international agreements, we recommend the following:

1. National governments should consider developing an agreement stating that the data governance laws of the registry state apply to SBDCs (consistent with the provisions of Outer Space Treaty's Article VIII). Such an agreement could be modeled on the approach of the ISS Intergovernmental Agreement to intellectual property (IP) law discussed above.
2. SBDC leader states should make clear that any data governance laws that apply within their jurisdictions also apply to SBDCs registered in their countries. These clarifications could occur by amending statutes or regulations, issuing regulatory guidance or imposing license conditions.

J. Security, Cybersecurity and Critical Infrastructure Designation

SBDCs have both physical and cyber vulnerabilities, including their ground stations, control links, optical inter-satellite links, hardware supply chains and satellites. Numerous recent incidents have reinforced these concerns. The physical risks were highlighted as the United States, China, India and Russia all conducted anti-satellite (ASAT) tests. Russia's November 2021 test created approximately 1500 pieces of debris that pose risks to other satellites and led to a UN General Assembly Resolution and pledges to stop these tests.[153,154] In both Russia's 2022 invasion of Ukraine and the 2026 US operation in Venezuela, important infrastructure (ground terminals for satellites and the electric grid, respectively) appears to have been disabled in cyberattacks.[155-157] Ukrainian strikes in 2024 physically damaged Russian early-warning radars and a satellite facility.[158,159] Cyberattacks on companies continue to grow. Anthropic reported disrupting a cyberattack in which a Chinese state-sponsored group manipulated Claude (an Anthropic model) into an espionage campaign against corporate and governmental targets.[81-83] In 2024, a cyberattack on AT&T exposed the personal data of almost all of its 115 million wireless customers.[160]

Despite these important risks facing SBDC terrestrial and space-based infrastructure, gaps exist in the relevant international law. Moreover, national law in SBDC leader states does not clearly address whether SBDCs should be designated as critical infrastructure and how export and foreign investment law applies. International law provides limits on the use of force but has more ambiguities around when harmful activities in space would violate those limits. The Outer Space Treaty Article III provides a requirement that space-based activities are conducted in accordance with international law, including the UN Charter, which limits the use of force in Articles 2(4) and 51.[161,162] The ITU Constitution prohibits radio service interference, and international humanitarian law principles of distinction and proportionality apply to all forms of warfare and all kinds of weapons.[163-165] However, only nonbinding instruments and working group submissions address other key aspects of the security concerns around SBDC infrastructure.[166-168] Similarly, the most widely ratified cybercrime treaty, the Budapest Convention, does not directly address space or operator security obligations, and China, India and the United Arab Emirates are not parties.[169]

The relevant national law in SBDC leader states also has important gaps. No SBDC leader state has designated space systems as critical infrastructure, and only the European Union covers ground-based infrastructure supporting space services.[138,170-180] In addition, national export regulations and laws regarding foreign investment do not address how orbital compute should be designated or how dual-use export controls, such as those on advanced semiconductors, would apply in space.[181,182] For example, US law does not treat launching an item into space as an export and, aside from on-orbit transfers of spacecraft ownership or control, lacks provisions addressing orbital computing or transmissions that use controlled technology or software.[183-187]

To address these regulatory gaps, we recommend:

1. SBDC leader states should designate SBDCs and their components as critical infrastructure, ideally with coordination to avoid exacerbating the regulatory arbitrage problems discussed below.

2. SBDC leader states should build cybersecurity requirements into SBDC licensing requirements; the proposed EU Space Act can serve as a model.[182]
3. SBDC leader states should update export control and investment screening rules to address orbital compute, including transfers of control of an orbital system and the status of SBDC operators.
4. SBDC leader states should work in international forums, like COPUOS and the new Global Mechanism, to create clearer understandings around attacks on SBDCs and their components that do not rise to the level of use of force.

K. Jurisdiction and Regulatory Arbitrage

Under current law, SBDC operators can strategically choose which state's regulation applies to the various ground and space components of their operations. Such jurisdiction-shopping creates significant problems in maritime shipping and other contexts.[188,189] Operators' ITU filings for new satellite constellations already include split filings or ones in which multiple states file for the same constellation. (See Chapter 3.1(A)(i).) Rwanda, Germany, Spain, Norway, France and the Solomon Islands have filed for large (over 10,000) satellite constellations. SpaceX has made filings through the United States, Norway, Germany and Tonga.[190,191] As the number of SBDCs grows, SBDC operators may jurisdiction-shop on various aspects of licensing to minimize environmental, debris, data-protection or other obligations. Beyond undermining national legal regimes addressing a range of serious issues, this regulatory arbitrage may create complexities during disputes about which law applies.

International space law creates the structure that allows for this forum shopping. The Outer Space Treaty establishes in Article VIII that jurisdiction and control follow the state of registry. However, its Article VI requirement that the "appropriate State Party" authorize and supervise non-governmental activities does not define "appropriate." Depending on the states and private operators involved in an SBDC project, multiple states may be candidates for being the "appropriate state" to authorize and supervise the activities.[113,192,193]

The Registration Convention requires that the state of registry be a launching state, defined as the state that launches or procures the launching or one from whose territory or facility the launch occurs.[192,194,195] Notably, that state may not have ongoing responsibility for supervising the SBDC.[194,196] The applicable space treaties do not provide a process for transferring registration when control of space objects changes nor do they require operators to verify their performance claims, such as around collision avoidance or disposal. Nonbinding General Assembly Resolutions 62/101 and 68/74



Scales of justice. Source: Adobe Stock

recommend procedures for addressing these transfers.[193,194,197] Further, as described above, the ITU framework does not require the notifying administration to be the launching state or state of registry.[198]

When a project has multiple launching, authorizing and notifying states with different regulatory requirements, regulatory arbitrage may occur, especially given the wide variation in national laws related to SBDCs. Even among the SBDC leader states, the licensing requirements vary greatly. For example, very specific US disposal and de-orbiting requirements differ from those of other states; US operators must show that each satellite is at least 90% likely to be disposed of successfully and to de-orbit LEO satellites within five years of a mission's end.[199,200] Moreover, given the flexibility of registration under the treaties, states with very limited relevant law, flexible licensing requirements or minimal connection to the SBDC project could still become the state of registry.

We recommend several strategies for addressing these gaps:

1. SBDC leader states should support ITU enforcement of deployment milestones as a constraint on speculative filings and explore the development of ITU processes to ensure that the notifying administration is also a state that authorizes and supervises the operator.[201]

2. SBDC leader states should condition licenses on provision of standardized performance data so that consistent verification can occur.

L. Liability, Insurance and Life-Cycle Bonds

SBDCs involve putting massive satellite constellations into an already crowded LEO environment, which creates risks of collisions and debris. For example, among the many proposals detailed above, SpaceX has filed plans with the FCC for an SBDC constellation with up to a million satellites, and ADASpace's "star compute" plan aims to put 2800 more satellites in orbit.[202,203] Moreover, SBDCs are only a fraction of ITU's filings and join a congested environment of roughly 40,000 tracked objects (including approximately 11,000 active payloads) and an estimated 1.2 million debris fragments.[204]

Despite the collision and other physical risks with SBDCs, existing liability and insurance regimes struggle to address incidents at even the current scale. As discussed in Chapter 3.1(A)(i), the Liability Convention, which only addresses state-to-state claims, imposes absolute liability for damage on the Earth's surface and to aircraft but only fault-based liability for damage to space objects (with no clear definition of fault). In addition, its definition of damage does not explicitly address service outages, data loss or environmental harms, and these damages may not be fully covered by the listed categories of death, personal injury and loss of or damage to property.[205]

The Liability Convention was invoked in 1978 when the Soviet Union's satellite Cosmos 954 disintegrated in the atmosphere, its radioactive debris scattered over Canada, and the case resulted in an agreement for the Soviet Union to pay CA$3 million in damages in 1981.[206,207] The first major satellite collision in 2009, between US Iridium 22 and out-of-commission Russian Cosmos 2251, produced more than two thousand debris fragments, but neither side could establish fault under the Liability Convention.[208-210] Moreover, especially because the Liability Convention only covers damage in another jurisdiction, liability issues may involve third parties who make claims under domestic law

if they are nationals of the state that caused the damage. For example, a Florida family made a Federal Tort Claims Act submission against NASA asking for $80,000 in damages after a jettisoned battery pallet from the ISS, which was supposed to burn up during re-entry, damaged their home; their attorneys noted that if this incident had occurred in another country, NASA would be liable under the Liability Convention.[211-213]

Most SBDC leader states have regulations that address liability and insurance for licensed space activities, but they vary substantially in what activities they cover that are relevant to SBDCs and in their substantive requirements.[147,199,214-228] In addition, insurance coverage is often incomplete in what it covers and in who has coverage in contexts relevant to SBDCs. For example, when a defective CrowdStrike software update caused an estimated $5.4 billion in losses to Fortune 500 countries by disabling computers worldwide, only 10–20% of the loss was covered under their cyber insurance policies.[229,230] As the law continues to evolve, the global space insurance market is growing rapidly, with projections that it will expand from $742.74 million in 2026 to $1229.57 million by 2035.[231]

To address these ambiguities and gaps, we recommend the following:

1. Parties to the Liability Convention work to clarify both what the standard for fault is and whether it extends to service outages, data loss or environmental harms.
2. SBDC leader states ensure that their licensing includes in-orbit liability coverage and demonstrated financial responsibility scaled to constellation size.
3. SBDC leader states create standardized approaches to orbital debris insurance, decommissioning bonds and life-cycle financial assurance.

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Text Box 3-1:

AUTONOMOUS VEHICLES—LESSONS IN SAFETY REGULATION

Roger Aines

Large constellations of space-based data centers (SBDCs) have a pertinent analogy on the ground—autonomous vehicles. In the past 12 years, the California state government went through several stages of regulation in which important learnings were translated into new safety controls.[a] Companies and regulators learned which safety controls worked well and which needed significant revision.

In 2014, California regulators allowed testing of autonomous vehicles on public roads for the first time. Drivers capable of taking control of the wheel were required to be in the vehicles at all times. Manufacturers had to first test the vehicles under controlled conditions and demonstrate $5 million in financial responsibility.

In 2018, regulators allowed autonomous vehicle manufacturers to apply to remove the safety driver.[1] Manufacturers were required to identify the roads, weather, speeds and other conditions in which the vehicle was designed to operate—its "operational design domain"—and provide remote communication, a safe-stop capability and a plan for dealing with police and emergency responders.

In 2020, the California Public Utilities Commission (CPUC) allowed deployment under controlled conditions after submission of a Passenger Safety Plan.

Original reporting measures focused on miles driven, collisions and disengagements—times a remote operator had to take control.[2] By 2023, it was clear that expansion had been permitted without adequate controls based on real-world experience from San Francisco.[3] Several key issues were among the corrections: replacing disengagement counts—which the California Department of Motor Vehicles (DMV) concluded did not provide meaningful safety insight—with reports of actual system failures, hard braking, immobilized vehicles, crashes and traffic violations; giving first responders direct communication, vehicle-override and emergency-

[a]Many other national and regional governments, including other US states, went through similar regulatory development processes around autonomous vehicles, but we highlight California because of the scale and advanced stage of autonomous vehicle deployment there.

geofencing tools; and requiring safety cases to be refined throughout the system's life rather than treated as a one-time approval document.[4]

Significant changes in regulations were made based on real-world learnings. For instance, in 2023, a Cruise vehicle dragged an injured pedestrian approximately 20 feet, and Cruise failed to disclose important post-crash details fully. The DMV immediately suspended Cruise's driverless-testing and deployment permits, while leaving it able to test with a safety driver.[5,6] Cruise had about 300 autonomous vehicles on the road in San Francisco at its peak,[7] but in 2024, GM began winding down Cruise after this major safety violation.[8]

Waymo chose to expand gradually despite the CPUC putting no explicit limits on vehicle count.[9] The CPUC relied on monitoring and the ability to suspend permits. Meanwhile Waymo continued to develop its San Francisco service, and by 2025 had permits for almost 2000 vehicles, from a 2023 commercial launch level of about 250 cars. They continue to operate in the city today and release detailed performance and safety data for third-party analysis.[10]

Today California has a revised set of regulations based on 12 years of on-the-road experience with autonomous vehicles.[11] Key regulations include the following:

- Testing first with a safety driver and then without one
- 50,000 test miles at each stage for light-duty vehicles
- A structured safety case covering hardware, software and operations
- Reporting of system failures, immobilizations, hard braking and mileage
- Human response to first-responder calls within 30 seconds
- Fleet withdrawal from emergency geofences within two minutes
- Authority for the DMV to restrict fleet size, location, speed or weather conditions when safety requires it

California uses several terms in its autonomous vehicle regulations that could apply to SBDC deployment, including "phased approach," "minimal risk condition" and "unreasonable risk to public safety."

California's experience regulating autonomous vehicles was less legally complex than SBDC regulation, involving fewer jurisdictions and areas of law. Still, California's approach to autonomous vehicle regulation provides a helpful model for managing the risks of SBDCs.

Key lessons from California's experience with autonomous vehicles include the following:

- Real-world experience in responding to unexpected events is crucial for deploying new technologies with safety risks. Initial assumptions about the performance of a technology may need to be significantly modified in practice.
- Regulators need to build internal capacity to understand the appropriate reporting requirements and a balanced set of regulations.

- Accidents will happen. Transparent reporting is vital to building public and regulator confidence.
- Gradual rollout, data gathering and sharing, repeated safety reviews, and fleet-wide corrections can contribute to public safety and public confidence in a new technology.

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