

LEO-NET '26 - 4TH ACM WORKSHOP ON LEO NETWORKING & COMMUNICATION

Dark Clouds Rising in Low-Earth Orbit

On environmental limits to massive orbital AI — a lifecycle carbon model (ESpaS-ODC) for orbital data centers.

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RESEARCH AREAS:

- Sustainable Computing
- Satellite Simulation
- Space Networking
- Carbon modeling

Research Question:

Can orbital data centers reduce the carbon footprint of compute workloads?

■ 01 · CONTEXT



(IEEFA)



(Starcloud)

THE SUSTAINABLE ALTERNATIVE?

- ☀ Free unlimited solar power.
- 🔧 No land usage / simpler approval procedures.
- 🌀 Easy cooling—No water consumption.
- ✋ Clean end of life.

■ 01 · CONTEXT

Suddenly everyone needs orbital data centers

Constellation-scale proposals in 2026:

COMPANY	DETAILS
SpaceX	Up to 1,000,000 LEO satellites for AI.
Google	Project Suncatcher (TPUs in Orbit)
Starcloud	Already in orbit: demonstrated H100 running inference/training.

Missing piece

➡ No proposal includes a thorough sustainability analysis.

Terrestrial vs. Orbital Data Centers

What is the competition?



(SpaceX)

✈ Data Center Satellite

Solar-powered with radiative cooling.

- Solar-powered.
- PUE of 1.1



(IEEFA)

🔥 Average Data Center

Fossil-fuel-powered average data center.

- Fossil-powered grid.
- PUE ≥ 1.54



(hanwhadatacenters)

🌿 Green Data Center

Renewable-powered with heat reuse.

- Renewable-powered grid.
- PUE of 1.2

How can we compare their carbon footprint?

METRIC TO QUANTIFY:

Carbon per GPU hour in $\frac{gCO_2e}{GPU \cdot h}$.

Reaching Orbit from a Sustainability Perspective

Case Study Falcon9 - Based on our previous work "[Dirty Bits in Low-Earth Orbit](#)".

Satellite Lifecycle

1. 🏭 Production

Assembly and manufacturing of satellites.

2. 🚀 Launch

Producing and fueling rockets.

$$\underbrace{35.5 \frac{\text{kgCO}_2\text{eq}}{\text{kg}}}_{\approx I_{Lch,F9}}$$

3. ✂️ Operation

Redundancy and spare parts.

4. 🌅 Re-entry

Re-entry burn of satellites and rocket stages.

$$\underbrace{16.2 \frac{\text{kgCO}_2\text{eq}}{\text{kg}}}_{\approx I_{Re-Entry,F9}}$$

Bringing one kilogram of payload to orbit with Falcon 9:

$$\underbrace{35.5 \frac{\text{kgCO}_2\text{eq}}{\text{kg}}}_{\approx I_{Lch,F9}} + \underbrace{16.2 \frac{\text{kgCO}_2\text{eq}}{\text{kg}}}_{\approx I_{Re-Entry,F9}} = \underbrace{51.7 \frac{\text{kgCO}_2\text{eq}}{\text{kg}}}_{\approx I_{L\&R,F9}}$$

COMPARISON



Drive ~500km with an electric car.



Run H100 for ~483 hours in a Green Data Center.

Thermal challenges in Orbit

Cooling satellites in Orbit

🖥️ Compute Units generate heat

Power consumption of compute units is proportional to heat generation.

🔥 Heat Radiation

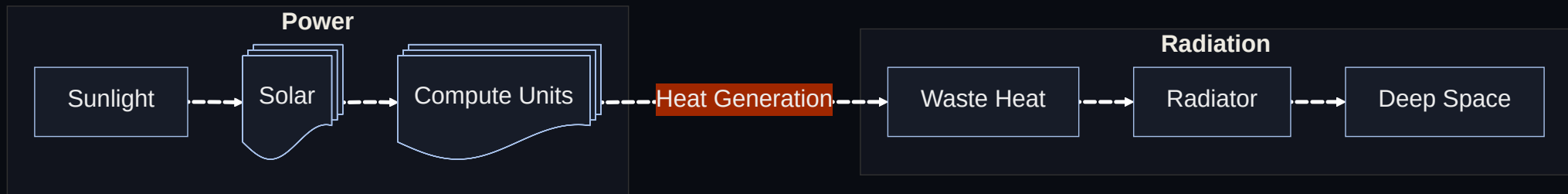
Only option for heat rejection is radiative cooling.

⇒ No Atmosphere

No convective nor conductive cooling.

≡ Radiators

Radiators must be large to be able to radiate large amounts of heat. They become heavy.



Reference node: The 1 kW-ODC

Mission Profile



NVIDIA H100

Compute Unit

-  2.4kg
-  700W

CPU

Controller Unit

-  0.2kg
-  250W

Transceiver

Communication Unit

-  0.5kg
-  50W

Σ Sum:  3.1kg and  1kW

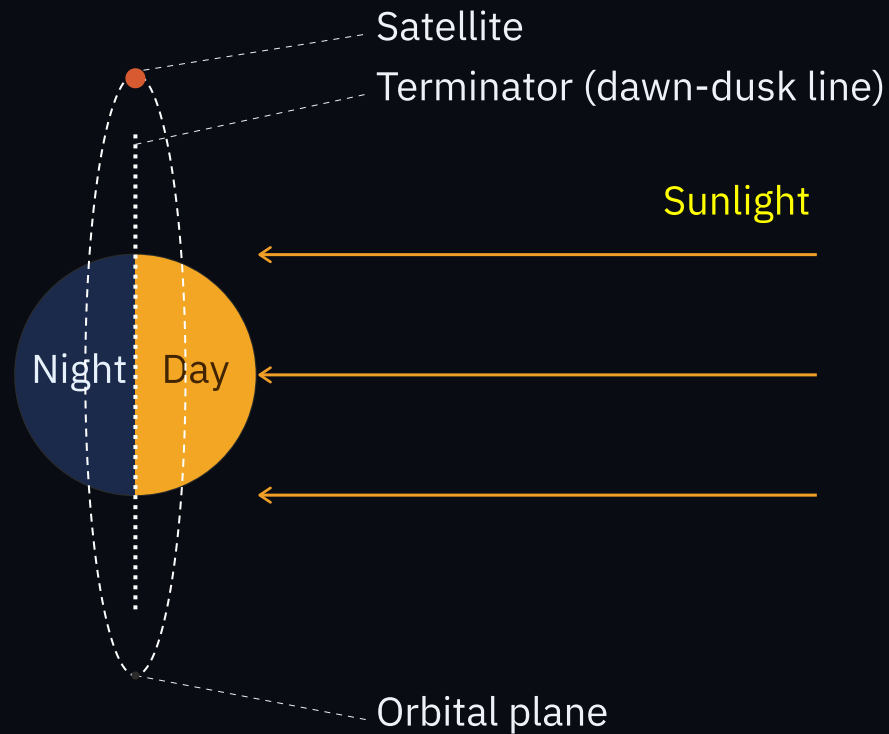
What we also need:

 Batteries,  Solar panels,  Redundancy,  Radiators

Battery-free operation in SSO

Free power with no eclipse?

SSO Orbit concept



Industry Claims

- ✓ Near-continuous solar illumination
- ✓ Minimal eclipse periods
- ✓ Elimination of large batteries
- ✓ Smaller launch mass

Solar Panel Dimensioning

Powering our 1 kW-ODC



Power Requirement

Node needs $P_C = 1$ kW.



Panel Degradation

Exponential degradation of $\delta = \frac{0.6\%}{\text{year}}$.



LEO PUE

Power Usage Effectiveness (PUE) of 1.1 for LEO ODC.

Given mission duration T and compute power P_C :

$$P_{Solar,BOL}(T, P_C) = \frac{PUE}{(1-\delta)^T} \cdot P_C$$

$$\rightarrow \frac{1.1}{0.994^5} \cdot 1kW = 1.13kW \text{ or } +13\%$$

Spare Parts - Required Redundancy

No Space Repairman

1. **No maintenance**

No physical maintenance possible in orbit. No repairman available.

2. **Rapid GPU iterations**

The next more powerful and efficient GPU generation is not far away.

Assuming a 3-year GPU lifetime:

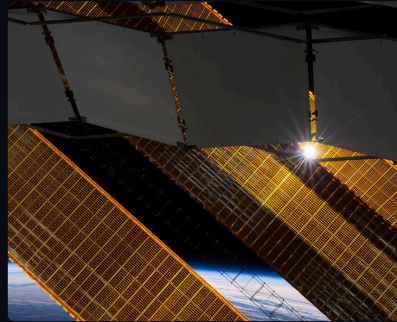
 $T_{MISSION}$	 r	Σ EFFECT
$< 3yr$	1	wasting all lifetimes
$3yr$	1	platform overhead
$> 3yr$	1	becomes unavailable
$> 3yr$	≥ 2	outdated device(s)

Modeling the radiator

The ISS active thermal control system.



Compute Units

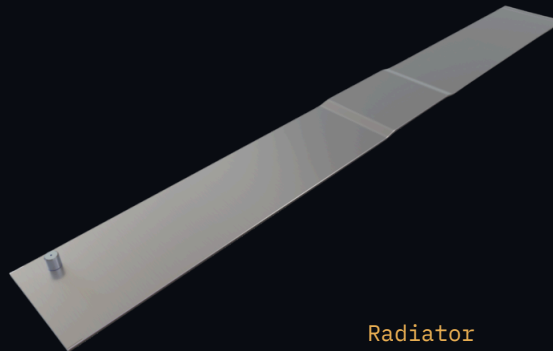


ISS Radiator

$$\sigma_{area} = 3.03 \text{ m}^2/\text{kW}$$

(Conservative calibration)

$$\sigma_{mass} = 10 \text{ kg/m}^2$$



Radiator

Launch mass

Roughly **11× the mass of the GPU** it serves — no orbit design can help.



Radiator → 68.8%

Power → 23.9%

Compute → 7.3%

How clean is terrestrial computing?

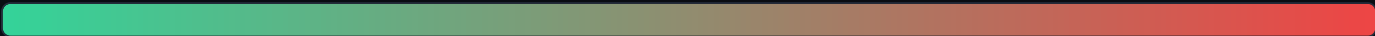
A 700W H100 Chip with 3-year chip amortization.

GLOBAL BASELINE

- Average (easy to beat) Benchmark
- Fossil Grid

GREEN BASELINE

- Aggressive Benchmark
- Green Grid (Finland)

Average Data Center  $\approx 477 \frac{gCO_2e}{GPU \cdot h}$

Green Data Center  $\approx 107 \frac{gCO_2e}{GPU \cdot h}$

How about orbital?

Orbital Data Center  TBD

How clean is orbital computing?

Sustainable Feasibility of ODCs

		Redundancy (r)				
		r=1	r=2	r=3	r=4	r=5
Mission Duration (T)	T=9	50	69	89	108	127
	T=8	56	78	100	121	143
	T=7	64	89	114	139	164
	T=6	74	103	132	162	191
	T=5	89	124	159	194	229
	T=4	111	155	198	242	286
	T=3	147	206	264	323	381
	T=2	221	308	396	484	571
	T=1	441	616	791	966	1141

Intensity of 1 GPU · hr using the 1 kW reference node — launched with a theoretical Starship.

■ ≤107 beats green DC

■ 108–477 beats global average DC

■ >477 above global average DC

dashed border = below required redundancy for mission duration T

Terrestrial vs. Orbital Computing

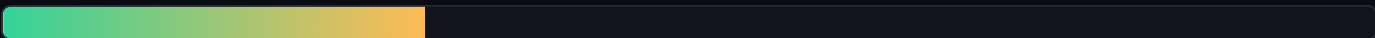
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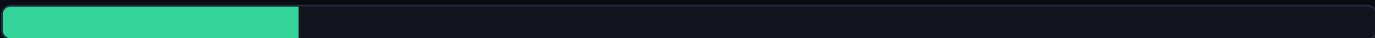
Average Data Center  $\approx 477 \frac{gCO_2e}{GPU \cdot h}$

Green Data Center  $\approx 107 \frac{gCO_2e}{GPU \cdot h}$

How about orbital?

Orbital Data Center
(T=1, R=1)  $\approx 441 \frac{gCO_2e}{GPU \cdot h}$

Orbital Data Center
(T=3, R=1)  $\approx 147 \frac{gCO_2e}{GPU \cdot h}$

Orbital Data Center
(T=6, R=2)  $\approx 103 \frac{gCO_2e}{GPU \cdot h}$

💡 We can easily beat the average. Green is the real competition.

Tensions in ODC Design

What do we need for sustainability?

Compute

- 3-yr GPU innovation cycles
- 6-yr mission runs 50% on outdated hardware

→ Replaceable GPU containers — feasibility unproven

Better Launch & Disposal

- High emissions from launch and re-entry
- burning of still working platform is wasteful

→ "Green"-fueled fully reusable rockets & new disposal technologies

Better Thermal Technologies

- Chips have thermal limits
- Radiators become more efficient with higher temperature

→ Chips that can handle higher thermal limits

Conclusion

Takeaways

01 Thermal management dominates

- radiator mass is one main constraint for sustainability

02 SSO helps to remove batteries, not cooling

- orbit selection does not remove the thermal overhead

03 Orbital AI is not greener by default

- it can outperform average data centers, the real competition are green facilities

Thank you!

