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Dirty Bits in Low-Earth Orbit: The Carbon Footprint of Launching Computers

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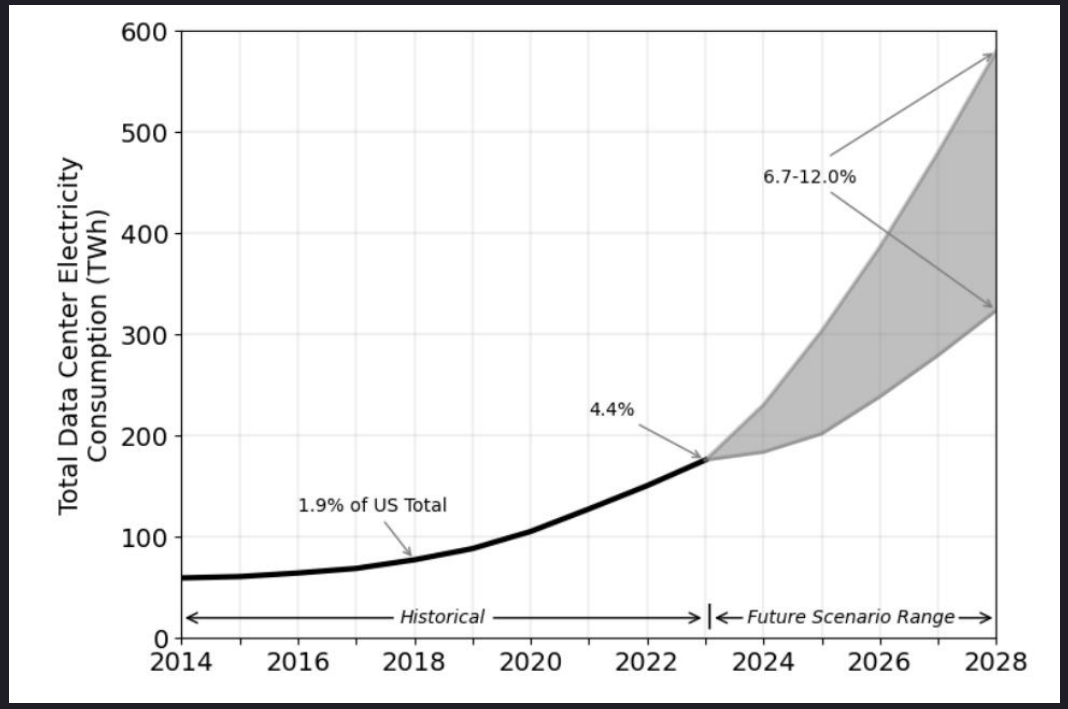
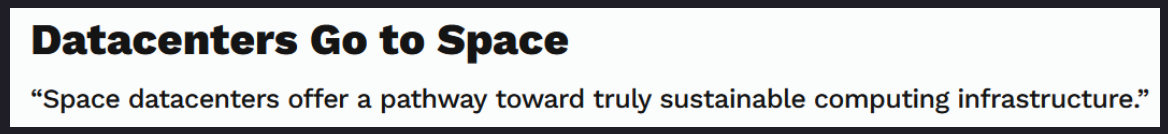
CPEC CENTER FOR PERSPICUOUS COMPUTING

Datacenters in Space

Google Datacenter [1]



Data center load [2]



ACM - data centers go to space [3]

Lumen Orbit Whitepaper [4]

Common beliefs about **Satellites:**

- Unlimited & efficient solar power.
- Can be burned in the atmosphere after EOL.
- Satellites enable global coverage.

OPERATIONAL EMISSIONS

$$O = E \cdot I$$

E : Energy consumption $[kWh]$

I : Carbon intensity $[\frac{gCO_2e}{kWh}]$

EMBODIED EMISSIONS

$$M = TE \cdot TS \cdot RS$$

TE : Total Embodied emissions $[gCO_2e]$

TS: Time share (of total lifespan)

RS: Resource share

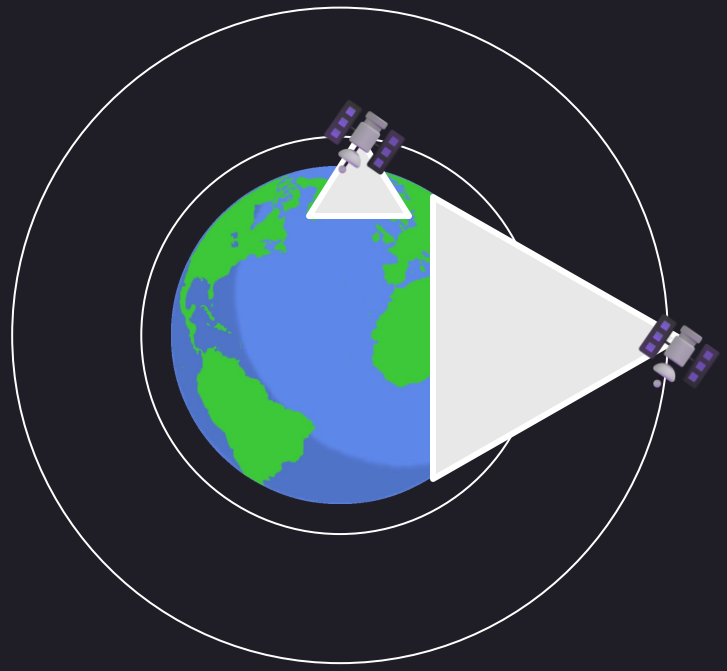
Emission tendency
according to the **beliefs**.

Different Orbit Heights

Delay to:

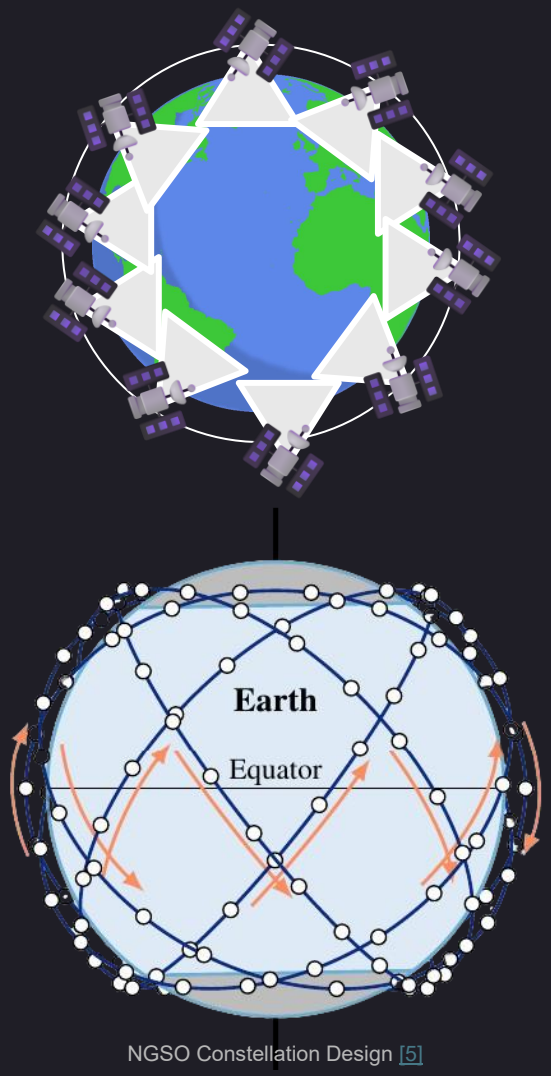
- ➔ GEO: $\frac{2 \cdot 35786\text{km}}{c} = 239\text{ms}$
- ➔ LEO: $\frac{2 \cdot 600\text{km}}{c} = 4\text{ms}$

Coverage



LEO Satellites have low visibility.

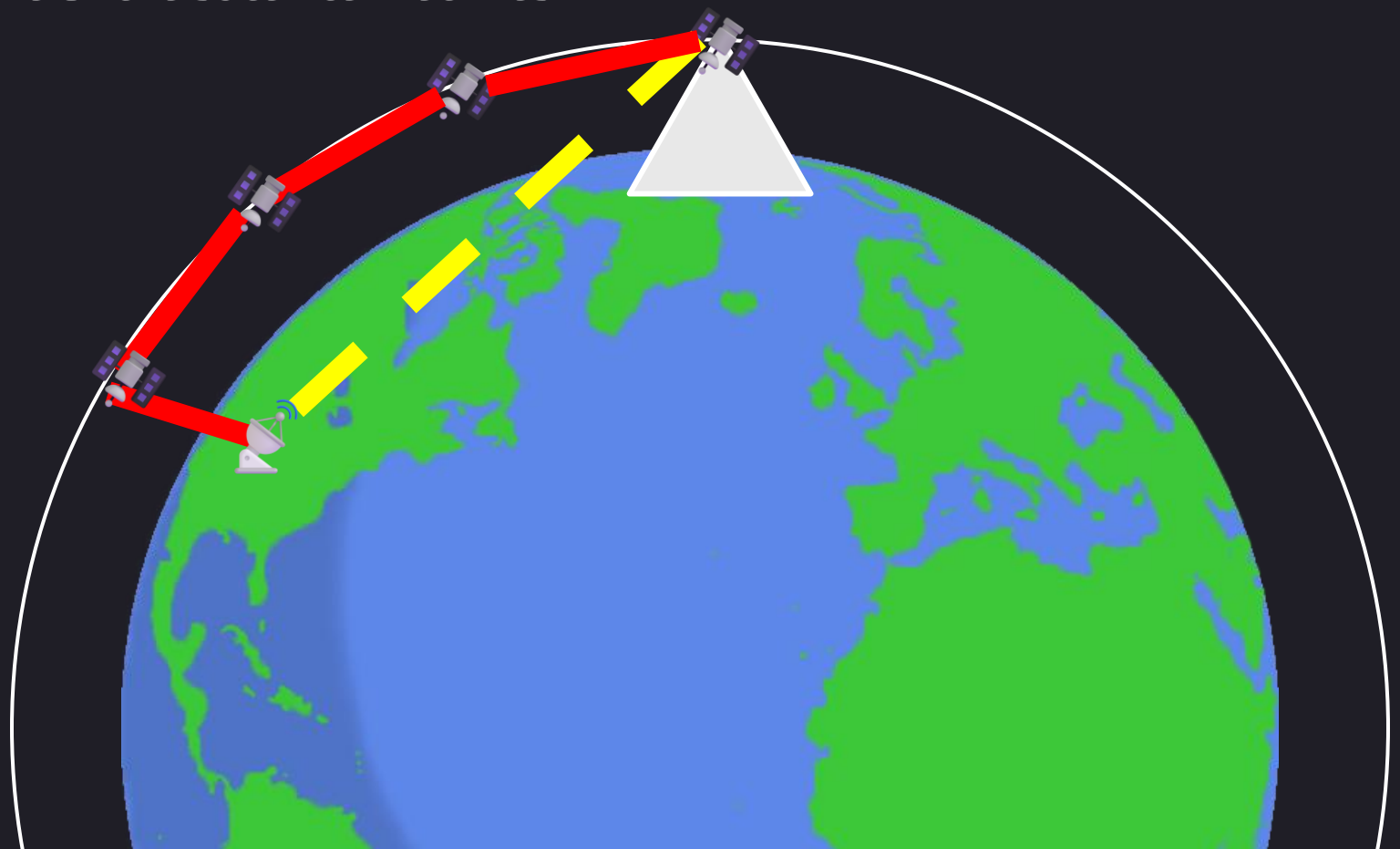
Constellations



NGSO Constellation Design [5]

Connectivity challenges

- In LEO, satellites do not always have contact to a ground station.
- Data is instead transmitted over the constellation via Inter-Satellite Links.
- This uses a share of the satellite lifetimes.



Satellite Lifecycle

Manufacturing

SES/Boeing satellite manufacturing [6]

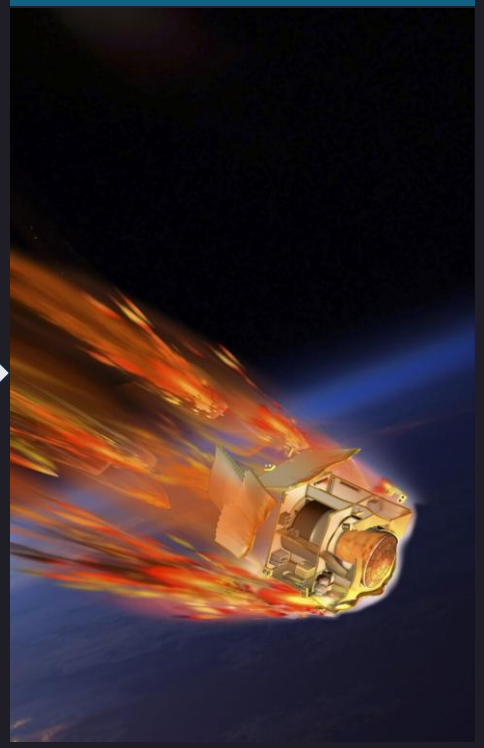
Rocket Launch

Falcon-9 rocket launch [7]

Satellite Operation

Satellite Operation [8]

Object Re-Entry



ESA project DRACO [9]

Creation of carbon equivalents.

Rocket Launch

Falcon-9 rocket launch [7]

Amplified Embodied Carbon of **Space Components**

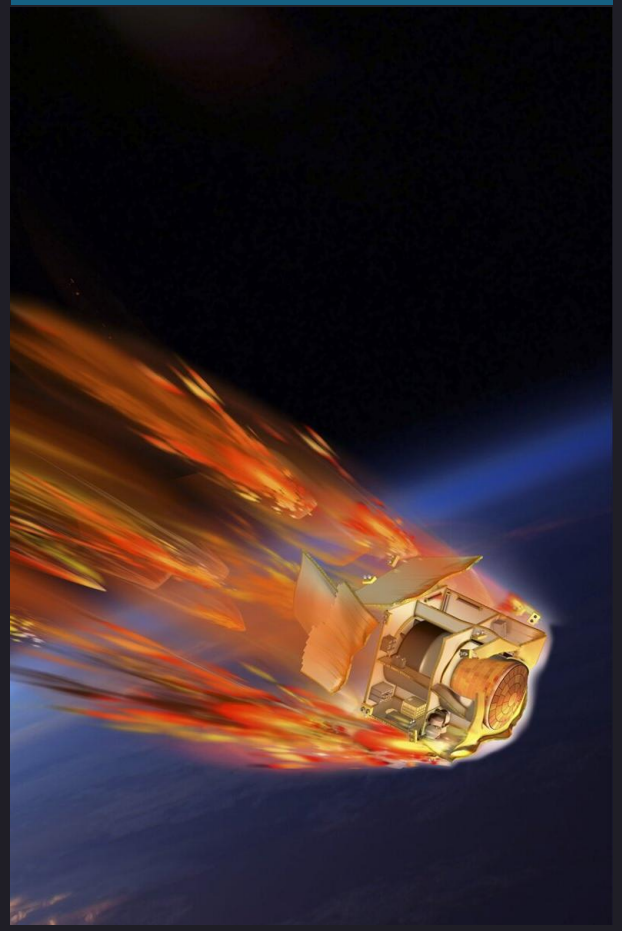
- Rocket manufacturing & launch releases large amounts of carbon.
  - Even with renewable fuel, sustainability is questionable.
- Maximum payload limit that rockets can bring to orbit.

Launch Intensity of a 2-stage Rocket system *t*:

$$C_{Launch,t}(n_1, n_2) = \frac{TE_{Prod,1st,t}}{n_1} + \frac{TE_{Prod,2nd,t}}{n_2} + TE_{Fuel,t}$$

$$I_{Launch,t}(n_1, n_2) = \frac{C_{Launch,t}(n_1,n_2)}{m_{Payl,t}}$$

Object Re-Entry



ESA project DRACO [9]

Environmental damage from objects that enter atmosphere:

- Re-enter (burn) of satellites and rockets create:
  a. nitrogen (NO_x) : depletes the protective ozone layer.
  b. alumina (Al_2O_3) : traps outgoing longwave radiation.

Re-Entry Intensity:

$$I_{Re\text{-}Entry,NO_x} = 0.4\frac{kgNO_x}{kg} = 119.2\frac{kgCO_2e}{kg}$$

$$I_{Re\text{-}Entry,Al_2O_3} = e$$

Conversion to CO_2e unclear

$$I_{Re\text{-}Entry} = 119.2\frac{kgCO_2e}{kg} + e \geq 119.2\frac{kgCO_2e}{kg}$$

Intensity calculation results:

Launch System	Fuel	Reusable?	Payload	Launch Intensity	Re-Entry Intensity	L&R Intensity
Falcon 9	RP-1	Partially (First stage)	17.5 t	21 $\frac{kgCO_2e}{kg}$	158 $\frac{kgCO_2e}{kg}$	179 $\frac{kgCO_2e}{kg}$
Starship	(green) Methane	Fully	150 t	15.8 $\frac{kgCO_2e}{kg}$	119.2 $\frac{kgCO_2e}{kg}$	135 $\frac{kgCO_2e}{kg}$

(Data approximated due to absence of official public data)

Important for us:

This is the environmental impact of putting components into orbit.

Clean Solar Energy in Orbit?

	🌍 On-Ground	🛰️ In-Orbit
- Average Solar Power in $\frac{W}{m^2}$:	400	1367
- Launch & Re-Entry Intensity: (Falcon 9)	0	$179 \frac{kgCO_2e}{kg}$
- Energy Intensity: (5-year mission)	$34 \frac{gCO_2e}{kWh}$	$165.1 \frac{gCO_2e}{kWh}$

Total Power Supply Emissions

(Production emissions Solar panels + Mass of Solar panels × L&R Intensity) + (Production emissions Battery + Mass of Battery × L&R Intensity)

÷

Total Produced Energy

Solar Panel Area × Average Solar Power × Mission Duration

Estimator implemented in Rust:

- Models launches and re-entry for launch technologies.
- Amplifies component footprints to include L&R impact.
- Format allows for future extension with new technologies.

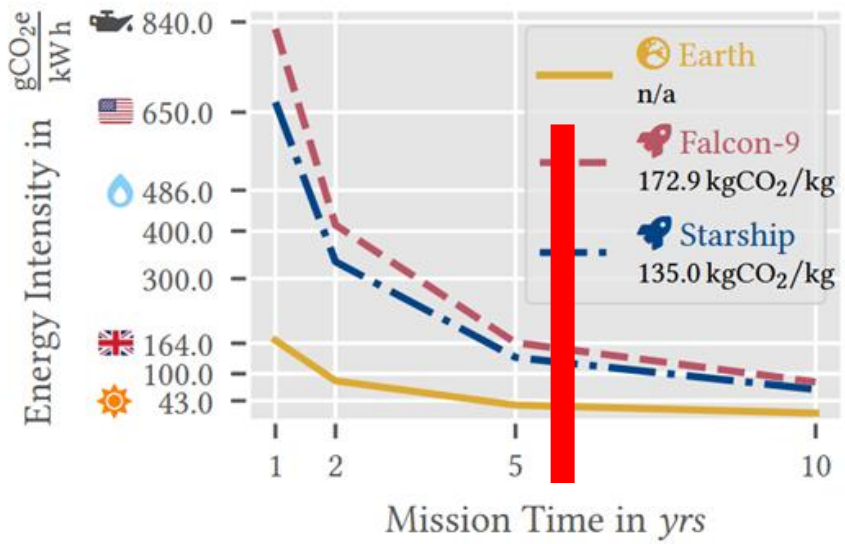
Input

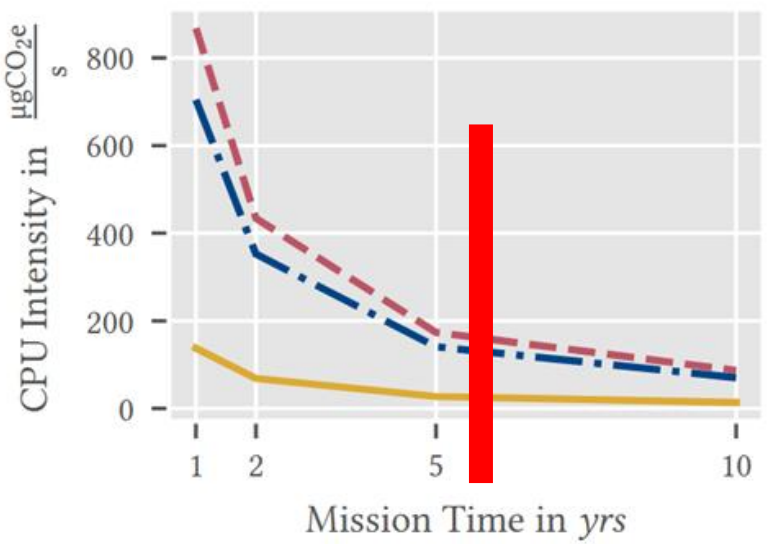
```toml
# sysX.toml (X ∈ {E, F, S})

mission_time = 5.0 # yrs
launch = "None" # or "Falcon9" or "Starship"

[solar_array]
area = 2.0 # m^2
panels = 1 # 1

[battery]
capacity = 4.0 # kWh
cycles = 5000  # 1

[transceiver]
mass = 24.5       # g
power = 1         # W
data_rate = 38.4 # Kbps

[cpu]
mass = 100          # g
area = 1137.5       # mm^2
max_power = 28.0    # W

[dram]
capacity = 16.0           # GB
power_per_memory = 0.020 # W/GB

[ssd]
capacity = 4.0       # TB
average_power = 3.0 # W
```

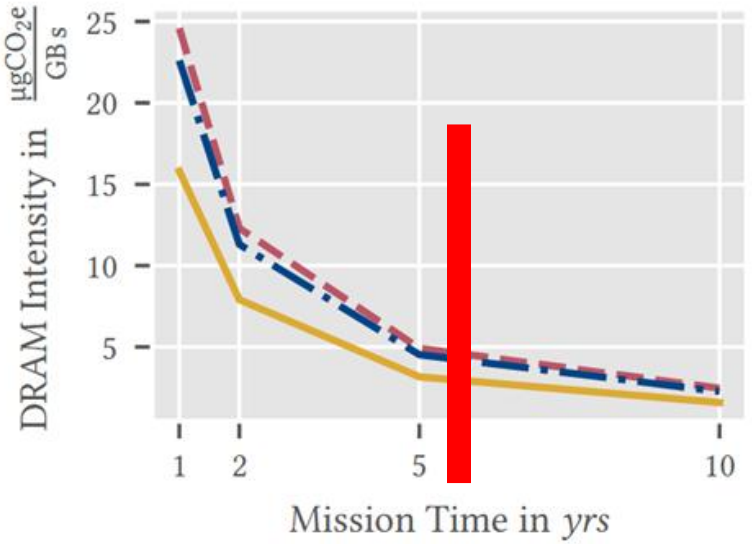
Output (5-year mission time)

Component Intensity Unit	SCI	Earth	F9	StSh
CPU	M	18.0	127.7	103.7
$\mu gCO_2e/s$	$O+M$	282.8	1412.1	1147.8
DRAM	M	3.0	4.0	3.8
$\mu gCO_2e/(GB\,s)$	$O+M$	3.2	4.9	4.5
SSD	M	0.040	0.056	0.052
$\mu gCO_2e/(GB\,s)$	$O+M$	0.047	0.090	0.080

Parameter study for different mission times:



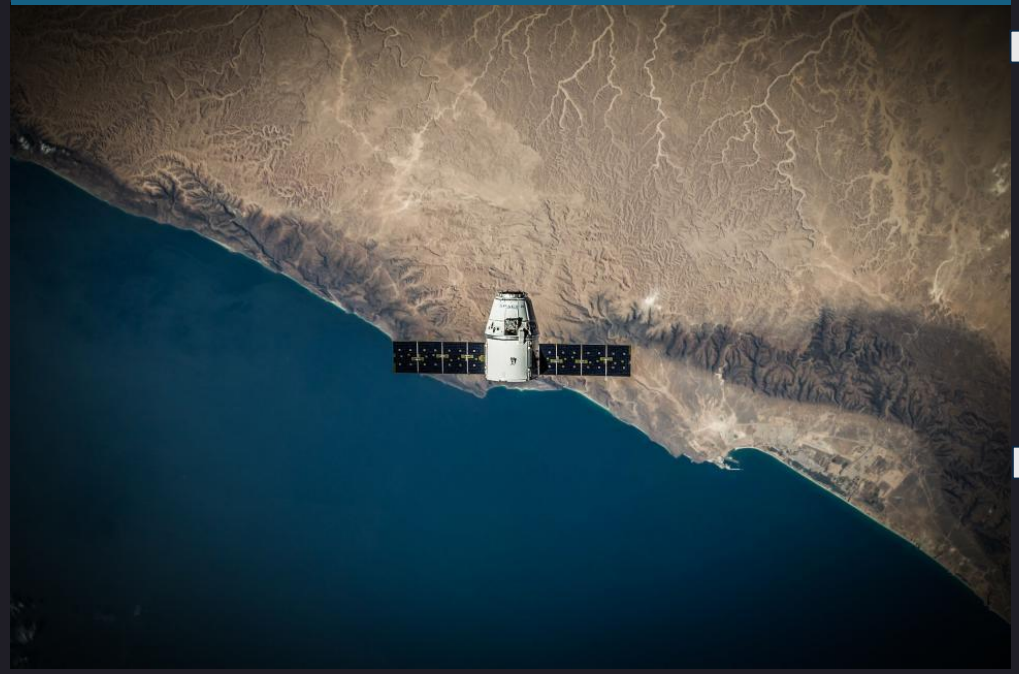




- Amplification of embodied carbon makes long mission times necessary.
  - SpaceX currently de-orbits Starlink satellites after 5-7 years.
- Systems require high reliability since physical maintenance / upgrading hardware in-orbit is (almost) impossible.

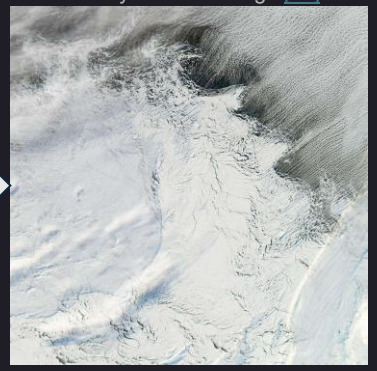
Case Study: in-orbit vs. on-ground data aggregation

Maritime Surveillance

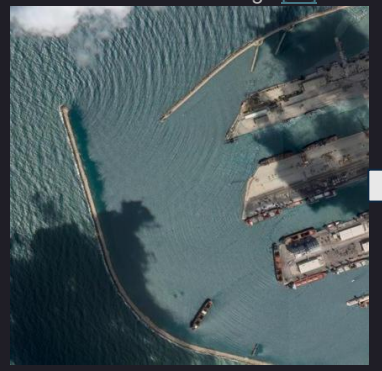


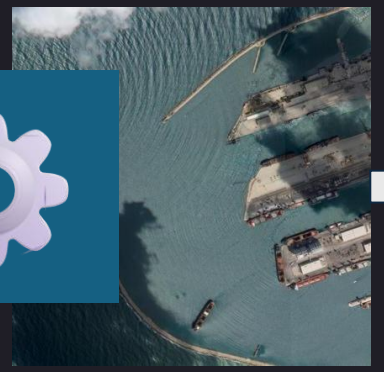
IDRS Comms Tech [10]

Cloudy Satellite Image [11]



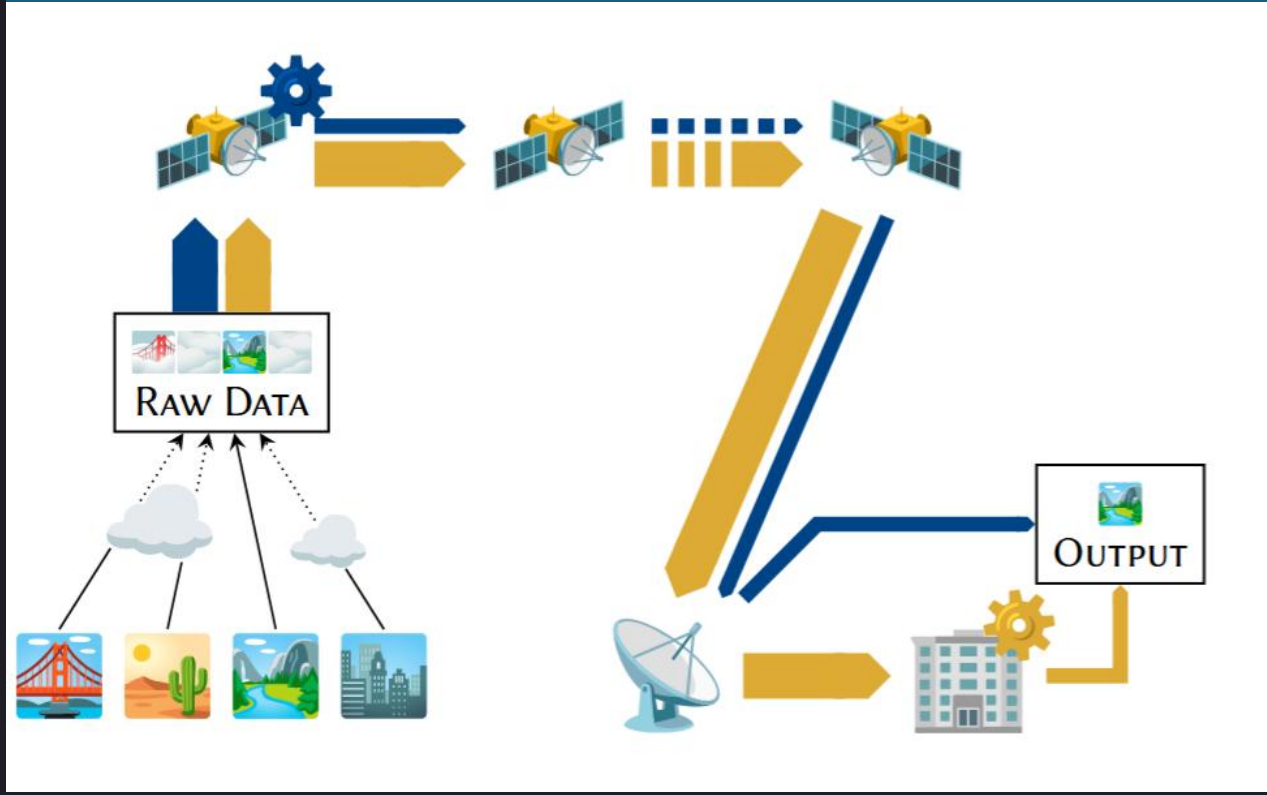
Harbor Satellite Image [12]





Case Study: in-orbit vs. on-ground data aggregation

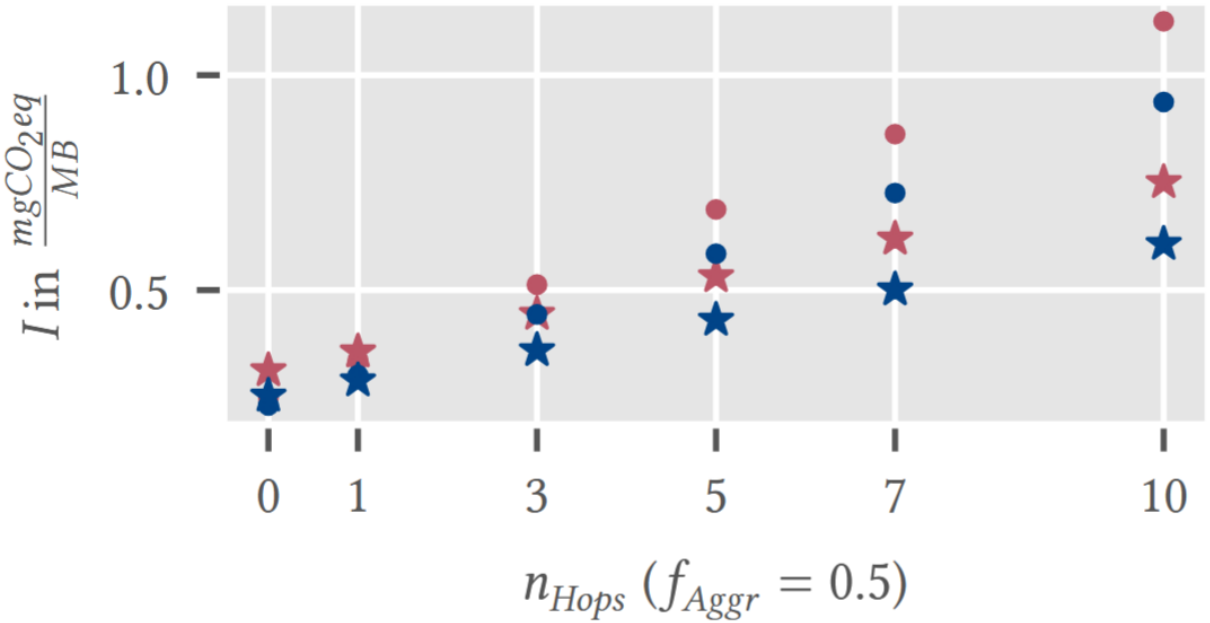
Experiment schematic



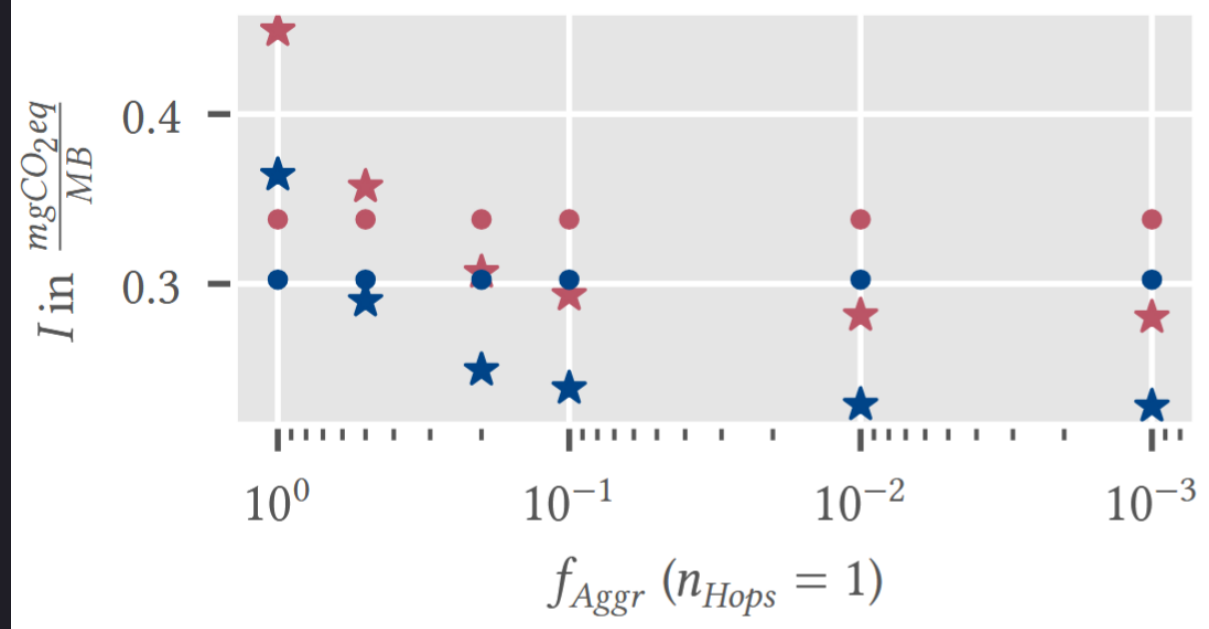
Variable params of our mission:

- Aggregation factor of processing.
  - How many pictures can be discarded?
- Number of inter-satellite links before a ground station is visible.
- Different technologies to launch constellation.
  - Falcon-9 vs. Starship

Varying number of hops (f = 0.5)



Varying aggregation factor (Single Hop)



Legend

★	In-Orbit processing
●	On-Ground processing
blue	Constellation launched with Starship
red	Constellation launched with Falcon-9

Conclusion

- Embodied emissions of components in space are amplified by launch & re-entry.
  - Especially re-entry damages the atmosphere; while often not considered.
- Solar in space is more effective, but the embodied emissions are not negligible.
  - Long mission times are required, which are unusual today in LEO.
- Newer rockets can minimize the launch and re-entry environmental impact.
- Global-coverage is only achieved with constellations; overhead is overlooked.

Reach out to us: *ohs@depend.uni-saarland.de*

Thank you!
Questions?

Credits

1. https://upload.wikimedia.org/wikipedia/commons/thumb/0/0c/Google_Data_Center%2C_Council_Bluffs_Iowa_%2849062863796%29.jpg/1280px-Google_Data_Center%2C_Council_Bluffs_Iowa_%2849062863796%29.jpg
2. https://www.uaf.edu/acep-blog/images/Data%20Center%20Load%20Growth.png
3. https://cacm.acm.org/news/datacenters-go-to-space/
4. https://www.starcloud.com/
5. https://arxiv.org/abs/2203.16597
6. https://www.ses.com/sites/default/files/styles/gallery_thumb/public/2024-05/01_SES-9_Boeing_Satellite_Systems.jpg?itok=DvPPO8Hm
7. https://commons.wikimedia.org/wiki/File:Iridium-1_Launch_%2832312419215%29.jpg
8. https://cdn12.picryl.com/photo/2016/12/31/satellite-orbit-spacex-science-technology-26e4f7-1024.jpg
9. https://www.esa.int/var/esa/storage/images/esa_multimedia/images/2022/11/esa_space_debris_project_-_draco/24584226-1-eng-GB/ESA_Space_Debris_project_-_DRACO_pillars.jpg
10. https://spacewatchafrica.com/game-changing-idrs-comms-tech-to-be-deployed-for-space-inventors-space-based-maritime-surveillance/
11. https://picryl.com/media/cloud-streets-off-the-amery-ice-shelf-image-of-the-day-8f2f8f
12. https://www.lemonde.fr/en/international/article/2022/08/16/satellite-images-show-first-grain-ship-out-of-ukraine-in-syria_5993792_4.html