USC University of Southern California

Space Debris Demise in the Atmosphere
The case of Aluminum

José Pedro Ferreira

Department of Astronautical Engineering
Viterbi School of Engineering
University of Southern California

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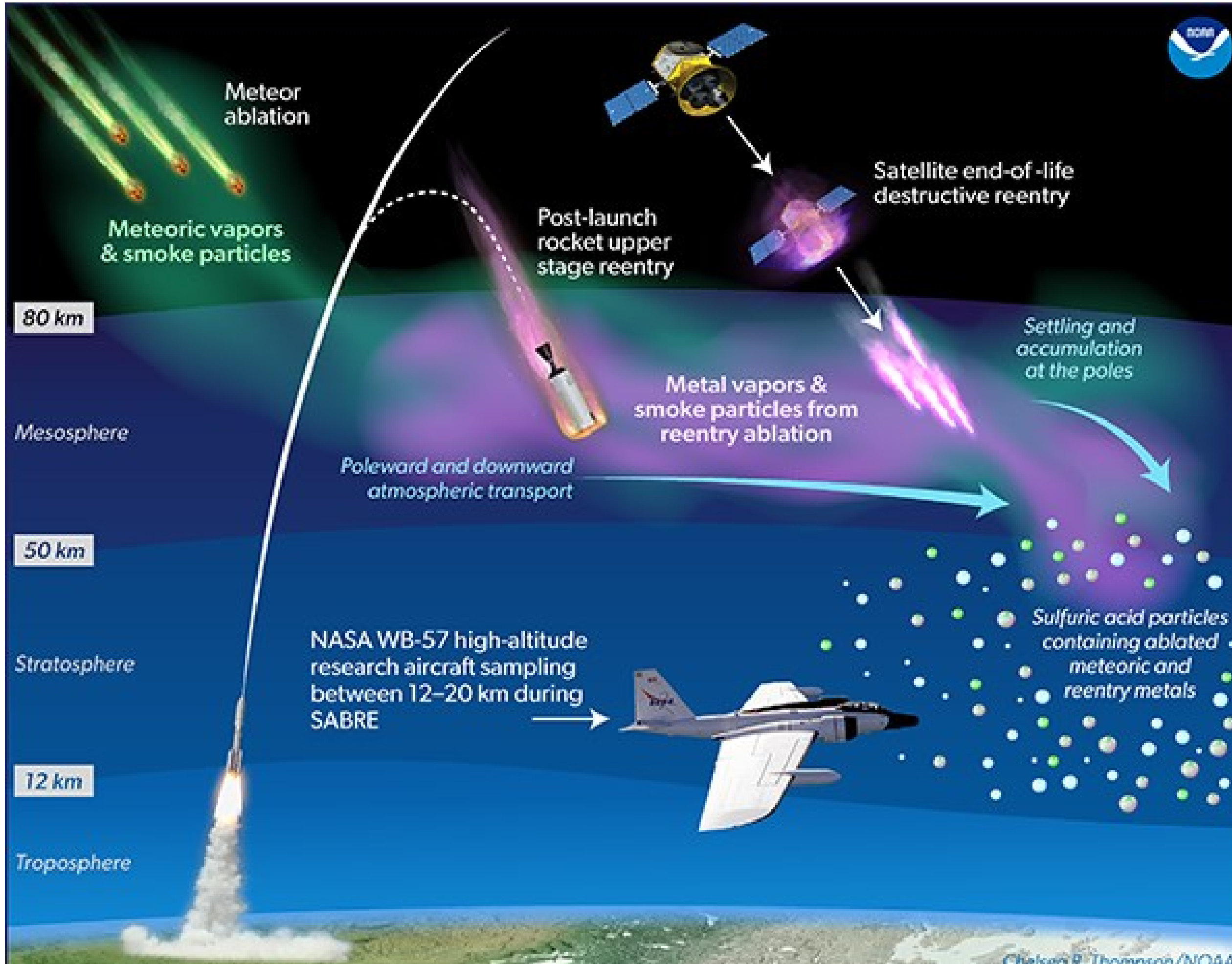
Overview

Image credit to NOAA



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Context

Concerns with mega-constellations of satellites

- Apr 2021: FCC replies to complaints filed against Starlink Gen.1 and acknowledges the "*Potential Effect on Earth's Atmosphere from Satellite Launch and Reentry*"
- Dec 2022: FCC grants approval to part of Starlink Gen.2, linking subsequent approvals the "commitment [...] to explore methods to collect observational data on formation of alumina"

Reentry polluting potential on the atmosphere

- Radiative forcing and global warming (Park et al, 2020) (Jain & Hastings, 2023)
- Ice nucleation and cloud condensation (Murphy et al, 2023)
- Stratospheric ozone concentrations (ESA, 2021) (Boley & Byers, 2021)

Legal

- **IADC Guidelines** (2021): Addresses ground environmental pollution from controlled reentry.
- **Long-Term Sustainability Guidelines** of Outer Space Activities (2021): Need to measure "risks to [...] the environment associated with the launch, in-orbit operation and re-entry of space objects" and "Promote regulations and policies that support the idea of minimizing the impacts of human activities on Earth".
- **The Pact for the Future** (2024)

Reentry Observations

ATV 1 reentry (Lips et al, 2010)
Reentry at 74 km altitude

- Air and spaceborne remote sensing from 20 km

Cygnus OA6 reentry (Löhle et al, 2017)
Reentry at 70 km altitude

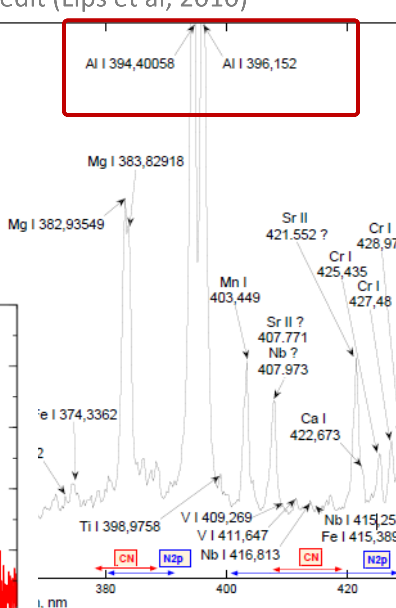
- Airborne remote sensing from 20 km altitude

Cluster II (SALSA) reentry (2024)
Reentry at 80 km altitude

Metals in the stratosphere (Murphy et al, 2023)
Aerosols at 20 km altitude

- In situ airborne measurement

Image credit (Lips et al, 2010)



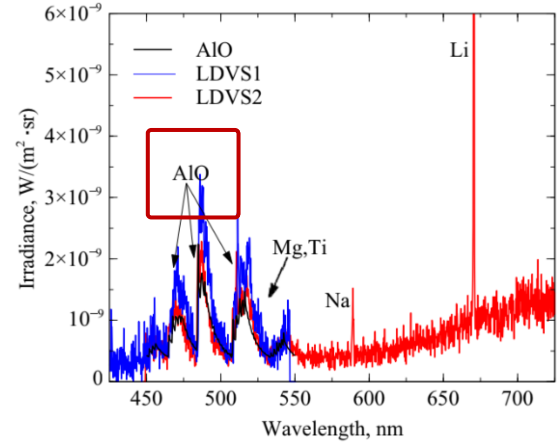


Image credit (Löhle et al, 2017)

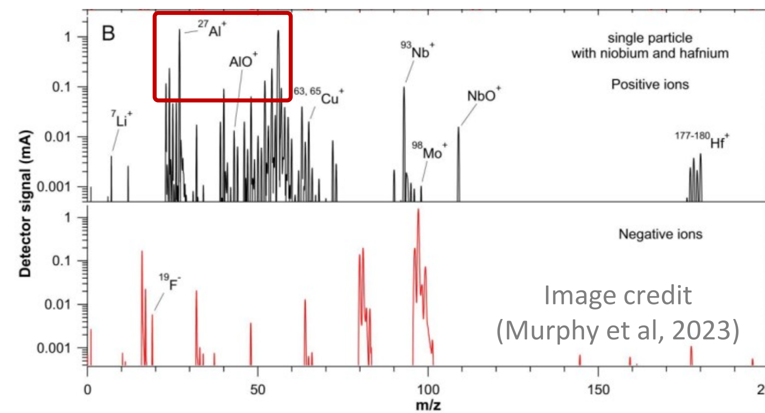
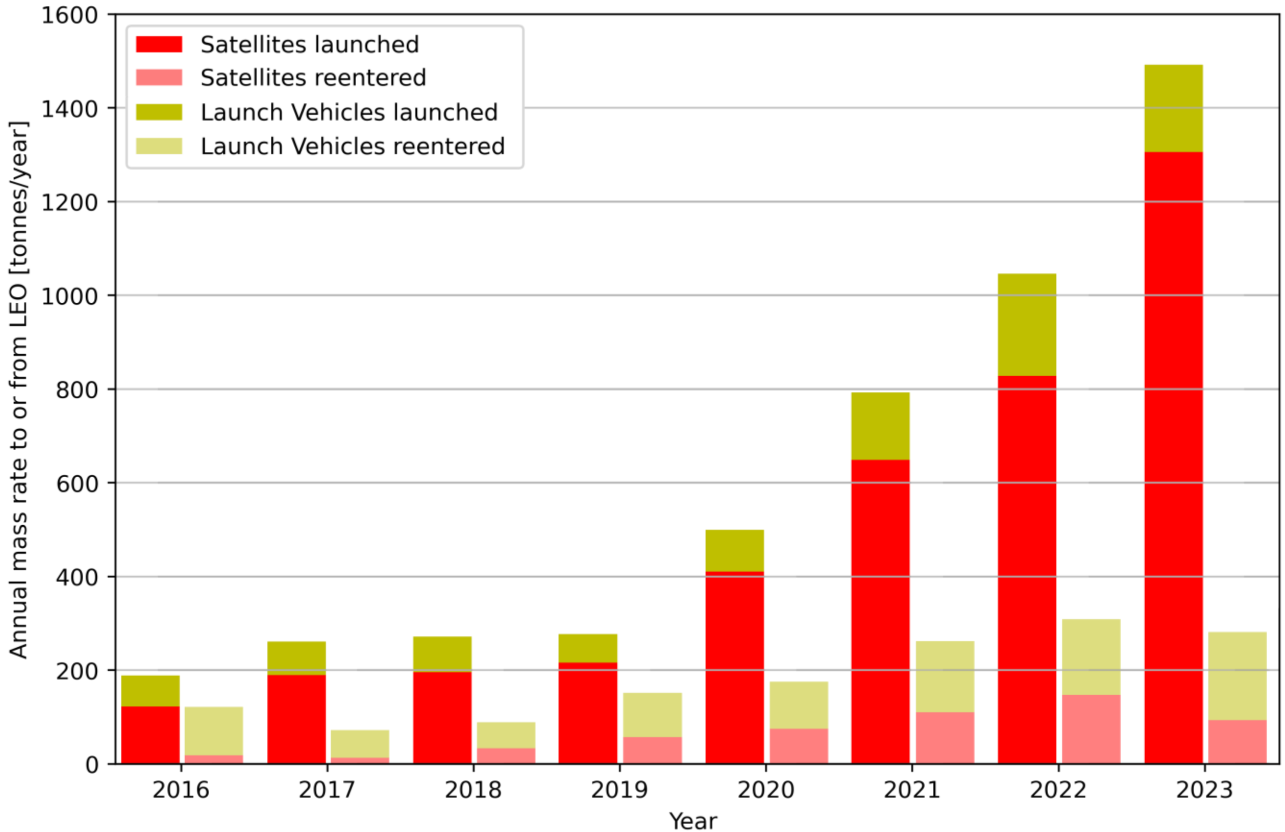


Image credit (Murphy et al, 2023)

Orbital Mass Imbalance



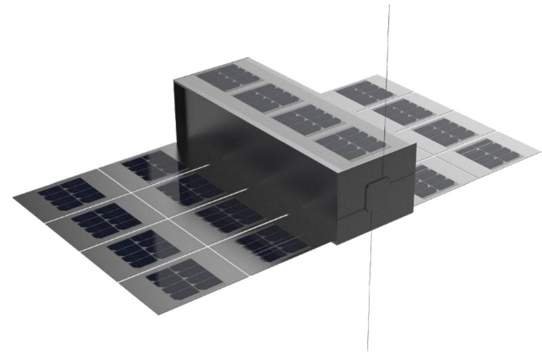
Data credit to ESA Space Environment Report (2024)

Aluminum Mass Fraction

1.2 % Al

~100 % demisability

(Schulz & Glassmeier, 2021)



30 % Al

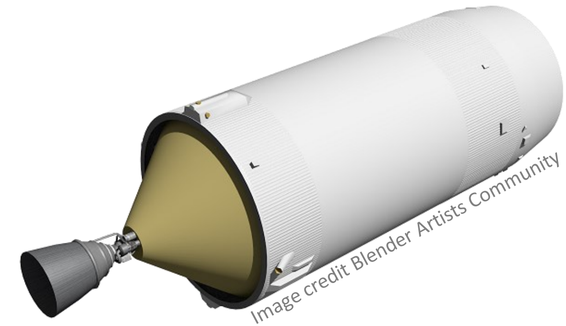
(Wertz et al, 2011)

95 % demisability

(OneWeb, 2016)

(SpaceX, 2020)

(Schulz & Glassmeier, 2021)



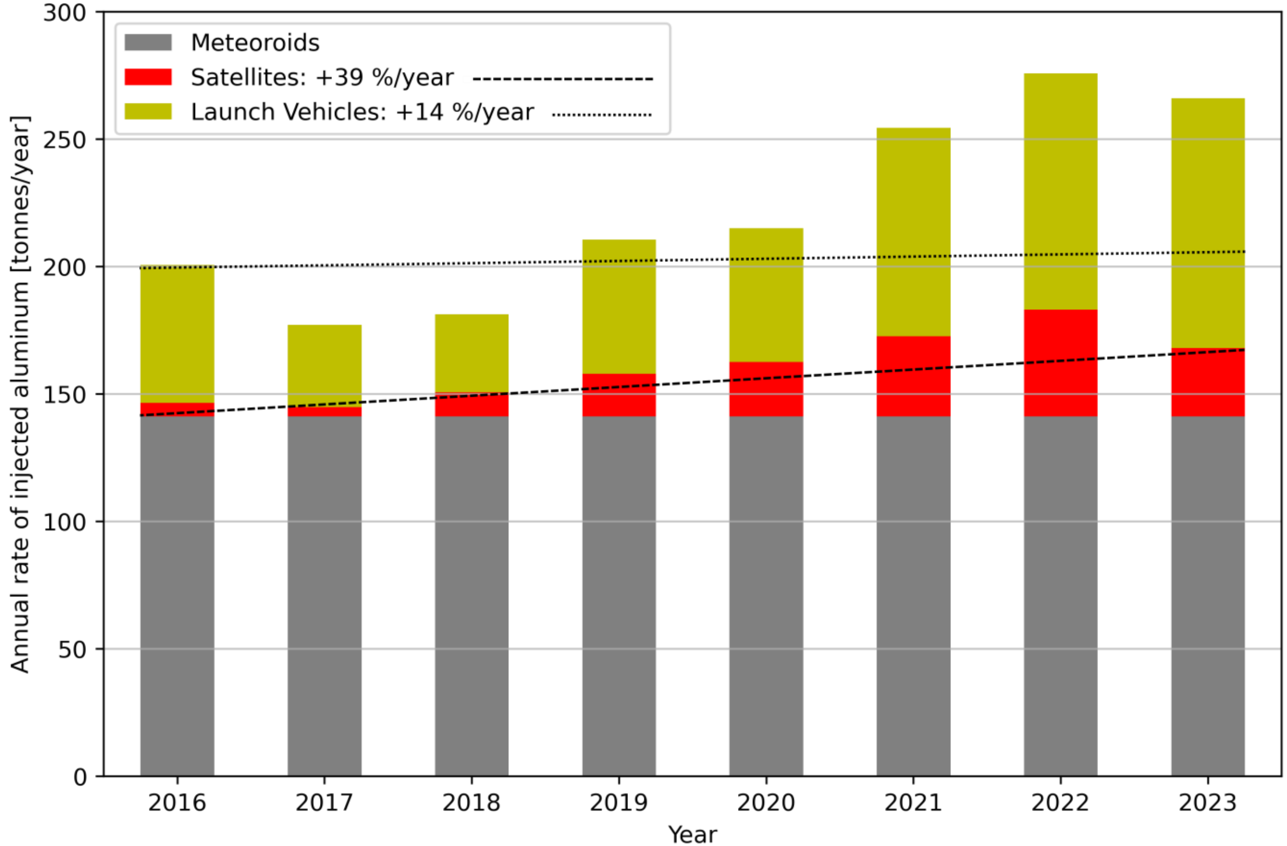
77 % Al

(Schulz & Glassmeier, 2021)

65 % demisability

(Anselmo & Pardini, 2005)

Aluminum Influx



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Reentry Byproducts

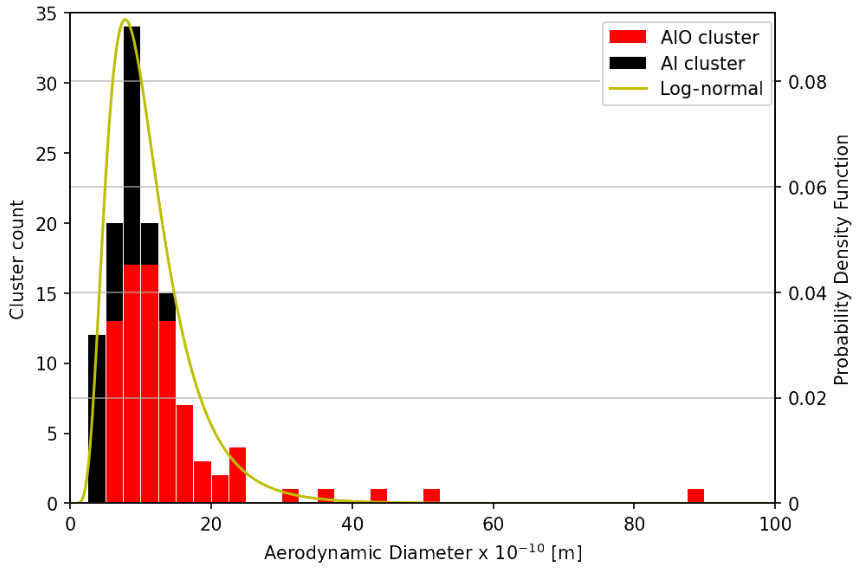
Reactive Molecular Dynamics Simulations

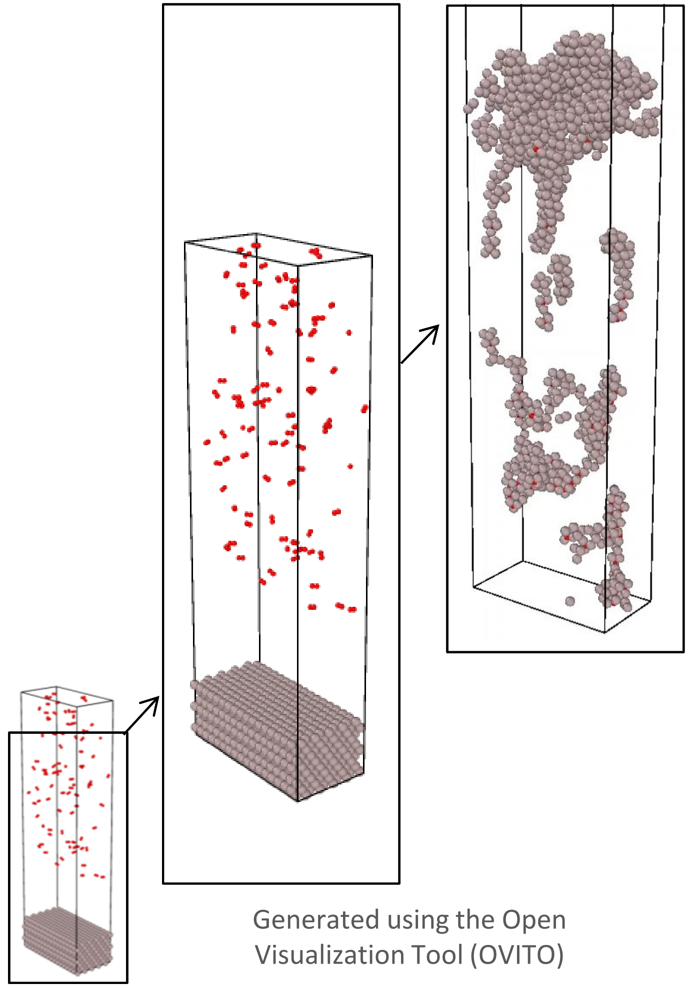
Reentry scenario from Low-Earth Orbit:

- Representative of a small satellite

Results (knowledge gap)

- Mass
- Particle size





Generated using the Open Visualization Tool (OVITO)

Long-term Extrapolation

Anthropogenic reentry numbers

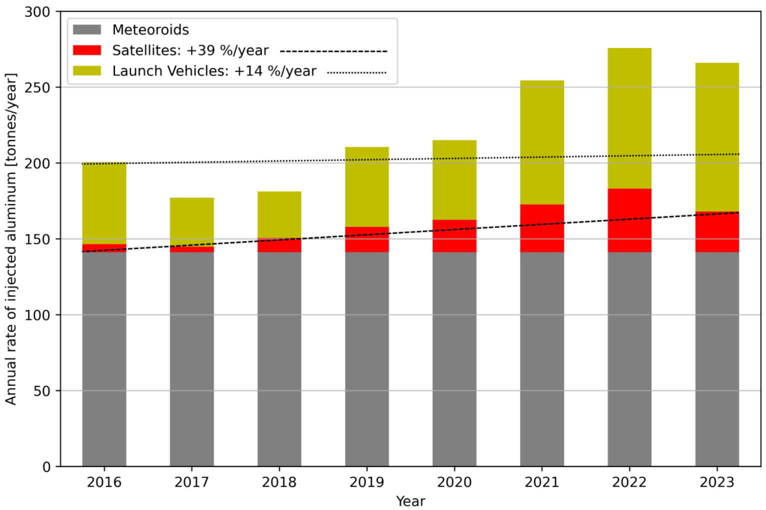
- 2023: 282 tonnes
  (ESA Space Debris Office, 2024)
- Future, worst-case scenario:
  (1800 -) 4200 tonnes/year
  (Organski et al, 2020)

Aluminum Oxide mass injected in the mesosphere from Anthropogenic objects:

- 2023: 48 tonnes
- Future, worst-case scenario:
  500+ tonnes/year

Comparing MM vs. Anthropogenic objects before reentry:

- 2023: 121 tonnes from anthropogenic objects - Excess Ratio = 86 %
- Future, worst-case scenario:
  1400 tonnes from orbital vehicles
  Excess Ratio = 1001 %



Summary

Remarks

- Anthropogenic contributions to the Aluminum influx at the top of the atmosphere > 80 % of meteoroids since 2021
- Aluminum Oxides generated from reentering debris in 2022 more than doubled that of 2016
- Size of byproducts from space debris reentering from LEO is a driver to further understand environmental impacts

Next steps

- 3D atmospheric modelling
- Experimental validation and/or in situ measurements

Takeaways

MD simulations resolve byproducts of thermal ablation at atomic scale

Provide initial conditions for further environmental assessments

Find more in

- Ferreira, J. P., Ferreira, M. (2021). APPROACHING A NEW ERA IN ORBITAL DEBRIS MITIGATION: A HOLLISTIC OVERVIEW OF ECONOMIC AND ENVIRONMENTAL FACTORS. *72nd International Astronautical Congress*. International Astronautical Federation.

- Ferreira, J. P., Nomura, K., Wang, J. (2023). PRELIMINARY ASSESSMENT OF ENVIRONMENTAL IMPACTS FROM THE DEMISE OF REENTERING SATELLITES IN THE UPPER ATMOSPHERE. *AIAA ASCEND*. American Institute of Aeronautics and Astronautics. DOI: 10.2514/6.2023-4773

- Ferreira, J. P., Nomura, K., Wang, J. (2024a). SPACE DEBRIS DEMISE UPON RE-ENTRY AS A POTENTIAL ATMOSPHERIC POLLUTANT. *IEEE Aerospace Conference*. Institute of Electrical and Electronics Engineers. DOI: 10.1109/AERO58975.2024.10521354.

- Ferreira, J. P., Huang, Z., Nomura, K., Wang, J. (2024b). POTENTIAL OZONE DEPLETION FROM SATELLITE DEMISE DURING ATMOSPHERIC RE-ENTRY IN THE ERA OF MEGA-CONSTELLATIONS. *Geophysical Research Letters, 51*, e2024GL109280. DOI: 10.1029/2024GL109280

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José Pedro Ferreira

Doctoral Researcher | Aerospace Engineer, M.Sc.

linkedin.com/josepedrodsf

jose.ferreira@usc.edu