The Benefits and Challenges of Very Low Earth Orbits

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The benefits of very low earth orbit for earth observation missions

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ABSTRACT

Very low Earth orbits (VLEO), typically classified as orbits below approximately 450 km in altitude, have the potential to provide significant benefits to spacecraft over those that operate in higher altitude orbits. This paper provides a comprehensive review and analysis of these benefits to spacecraft operations in VLEO, with parametric investigation of those which apply specifically to Earth observation missions. The most significant benefit for optical imaging systems is that a reduction in orbital altitude improves spatial resolution for a similar payload specification. Alternatively mass and volume savings can be made whilst maintaining a given performance. Similarly, for radar and lidar systems, the signal-to-noise ratio can be improved. Additional benefits include improved geospatial position accuracy, improvements in communications link-budgets, and greater launch vehicle insertion capability. The collision risk with orbital debris and radiation environment can be shown to be improved in lower altitude orbits, whilst compliance with IADC guidelines for spacecraft post-mission lifetime and deorbit is also assisted. Finally, VLEO offers opportunities to exploit novel atmosphere-breathing electric propulsion systems and aerodynamic attitude and orbit control methods.

However, key challenges associated with our understanding of the lower thermosphere, aerodynamic drag, the requirement to provide a meaningful orbital lifetime whilst minimising spacecraft mass and complexity, and atomic oxygen erosion still require further research. Given the scope for significant commercial, societal, and environmental impact which can be realised with higher performing Earth observation platforms, renewed research efforts to address the challenges associated with VLEO operations are required.

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What are Very Low Earth Orbits?

Typically defined as orbits below 450 km in altitude

- When aerodynamic effects become significant

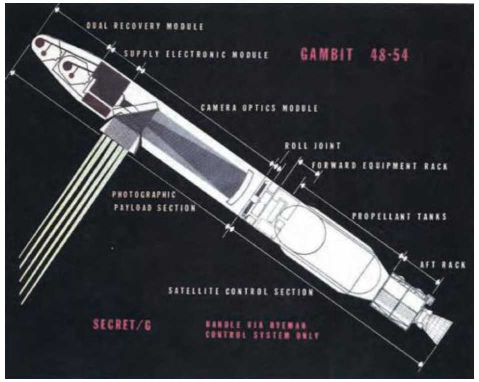
Usage over time

- Early reconnaissance
- ISS and experimental or scientific missions
- Commercial (Planet and Spire) and academic nanosatellites (CubeSats)

Why are we interested in VLEO? ▸ **Benefits**

Why hasn't VLEO been a commercial success yet? ▸ **Challenges**

What can we do? ▸ **Opportunities**



Schematic of GAMBIT-3 attached to Agena D [Image Credit: NRO]

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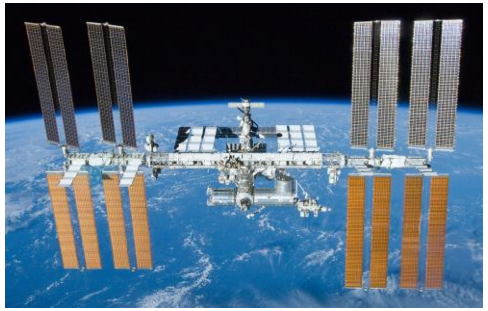
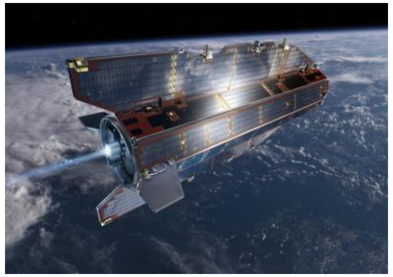
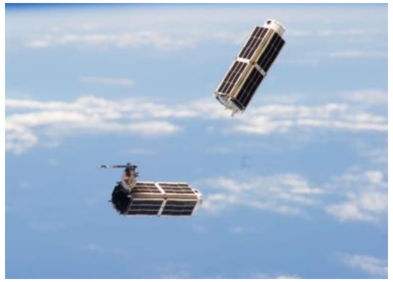


The International Space Station [Image credit: NASA]



ESA's Gravity field and steady-state Ocean Circulation Explorer (GOCE) spacecraft [Image credit: ESA–AOES-Medialab]



A pair of Planet's Dove satellites after deployment from the Space Station. [Image credit: NASA]

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The Environment in VLEO

Atmospheric Density

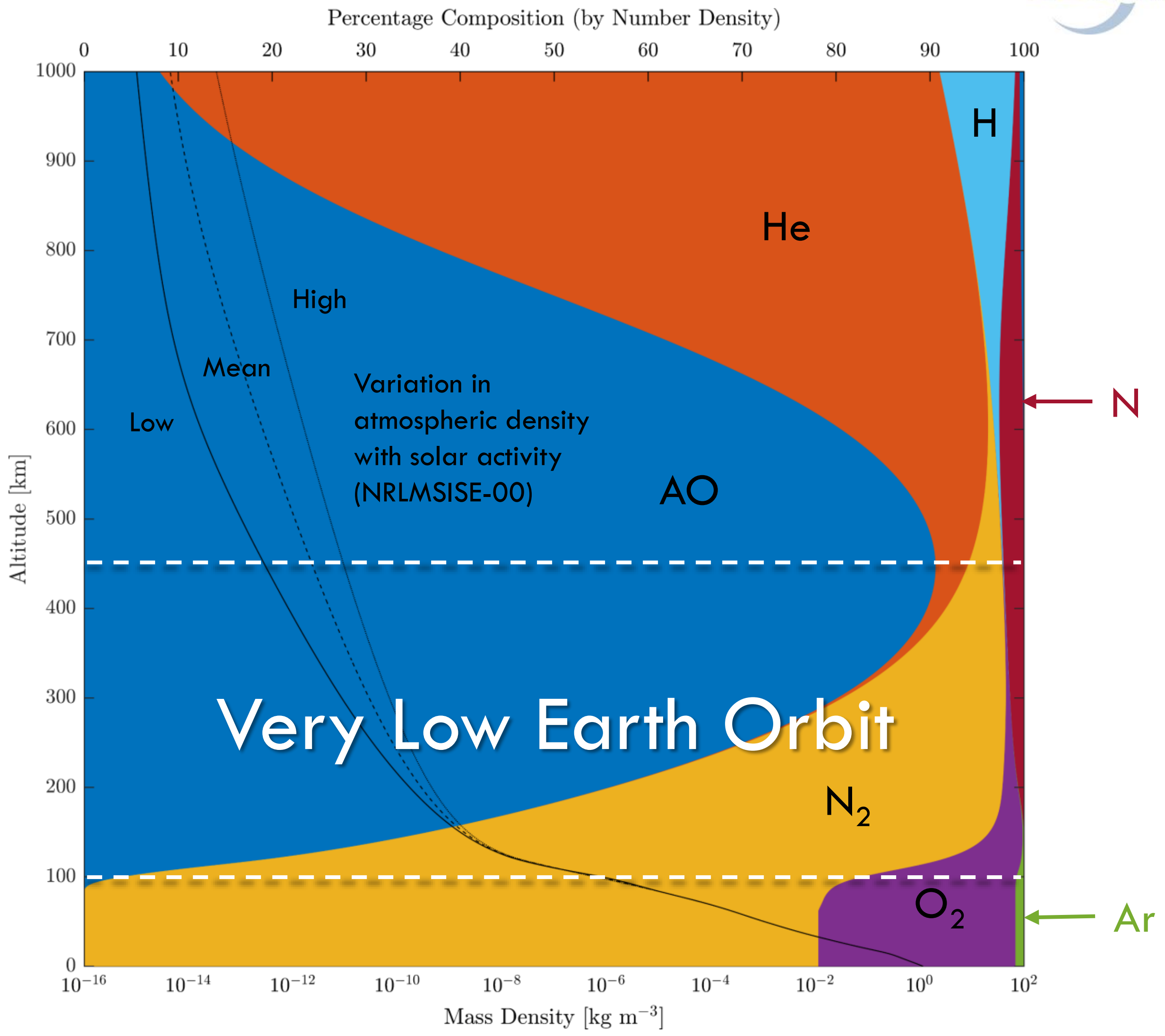
- Increases with reducing altitude
- Rarefied (free-molecular) flow

Composition

- Relative abundance of Atomic oxygen

Knowledge and Uncertainty

- Variation with solar cycle
- Incomplete models
- Thermospheric winds



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Benefit: Optical Resolution

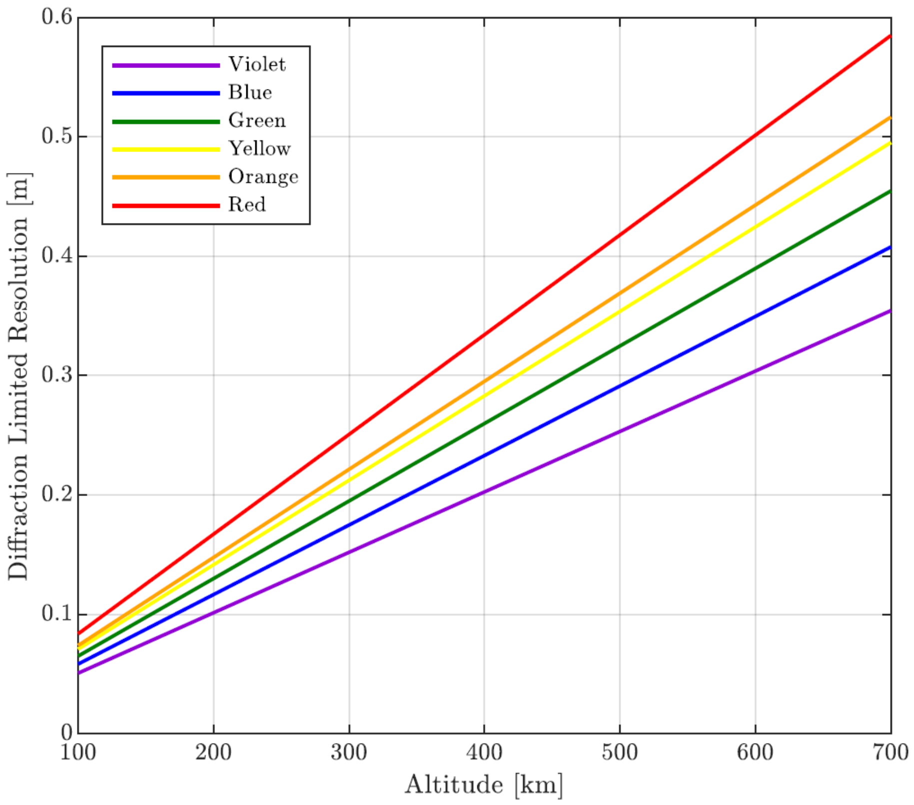
$$\text{Ground Resolution Distance [m]} = 1.22\,\frac{\lambda R}{D}$$

Wavelength [m]
Range [m]
Aperture Diameter [m]

- **Resolution increases with reducing altitude (for the same aperture diameter)**
  - e.g. 600km → 300km = $^{1}/_{2}$ spatial resolution

or

- **Aperture diameter decreases with reducing altitude (for the same resolution)**
  - e.g. 600km → 300 km = $^{1}/_{2}$ aperture diameter
  - resulting in reduction in payload mass



Nadir pointing with 1m nominal aperture diameter

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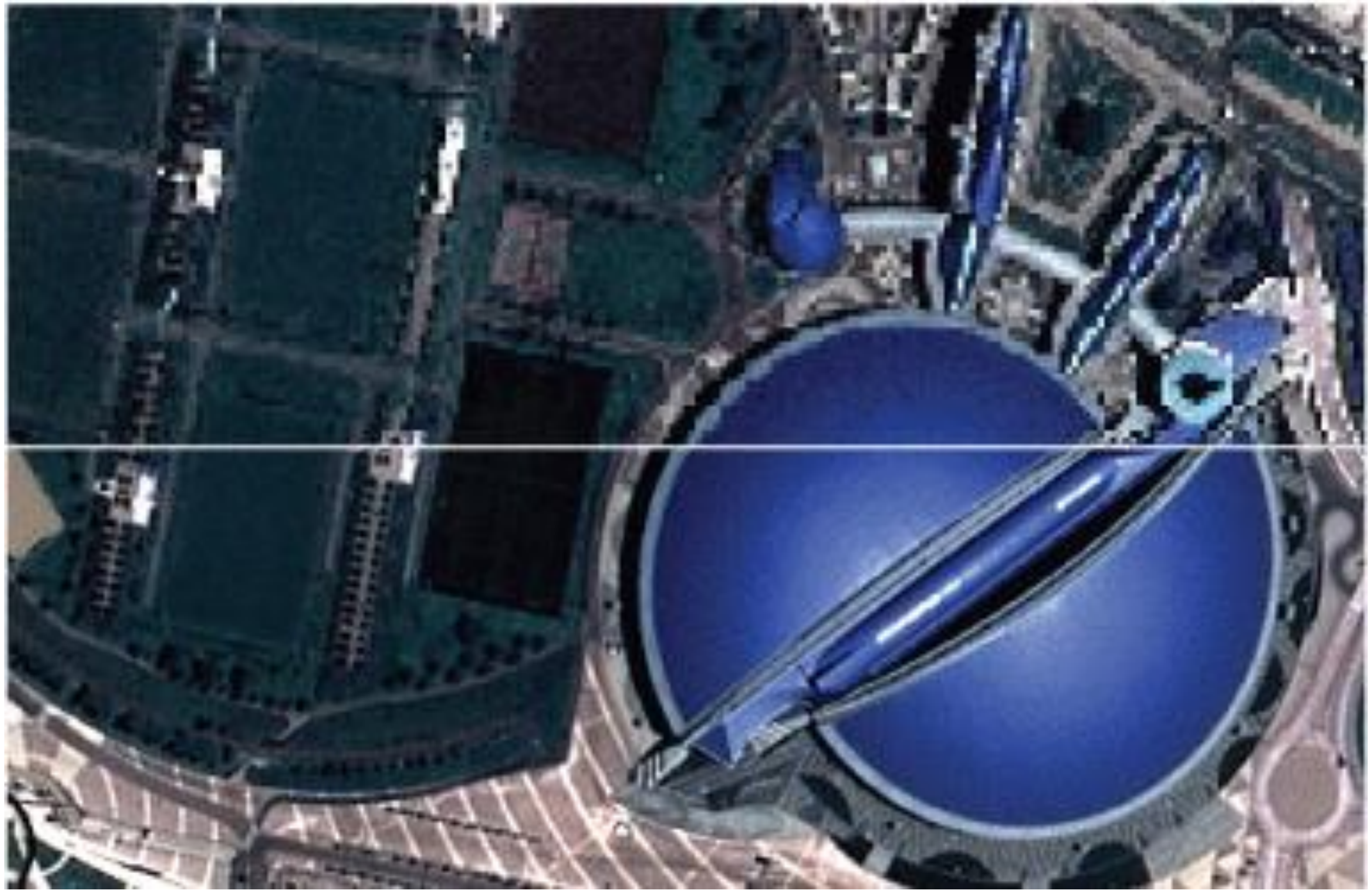
Benefit: Optical Resolution



600 km

Example of resolution increase for a fixed aperture diameter

300 km

Deimos-2 image over Qatar [Image credit: Deimos]

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Benefit: Radiometric Performance (Optical)

Received power at distance follows an inverse-square law ($^1/_{R^2}$)

Collected power increases with collection area (for a circular aperture $A = \pi D^2$)

$$\boldsymbol{P \propto \frac{D^2}{R^2}}$$

- **Signal power improves with reducing altitude or increased aperture diameter**
  - For a fixed aperture, 600km → 300km = x4 improvement in received power
  - or instrument sensitivity can be reduced at lower altitudes
  - For a fixed sensitivity, 600km → 300km = x4 reduction in aperture diameter

- **Reduction in free-space loss also applies to communications link-budgets**

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Benefit: Transmission Power and Antenna Area (Radar)

For basic radar payloads the signal is transmitted, reflected, and then received, so $P \propto R^4$

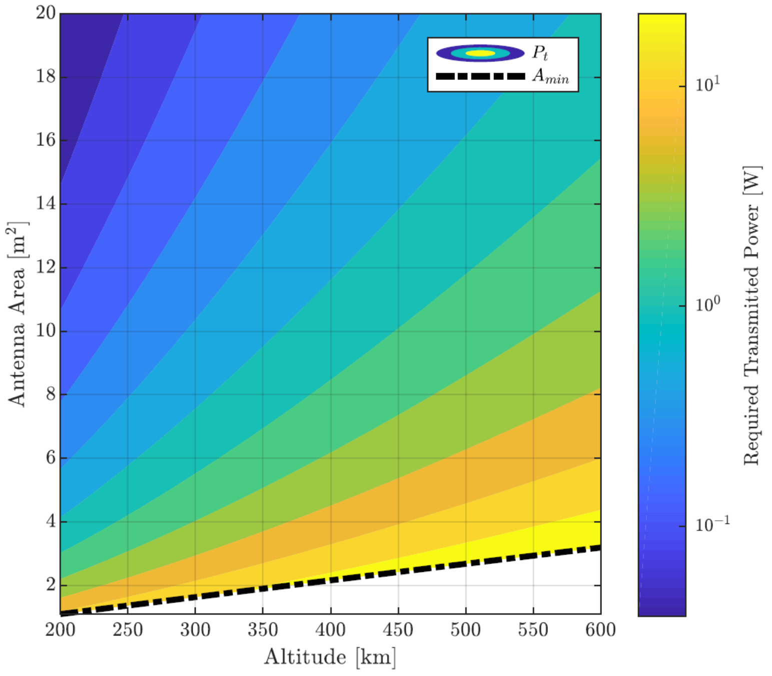
- For 600km → 300km = $^1/_{16}$ reduction in transmitted power requirement

For SAR, power, antenna area, and SNR are related to range:

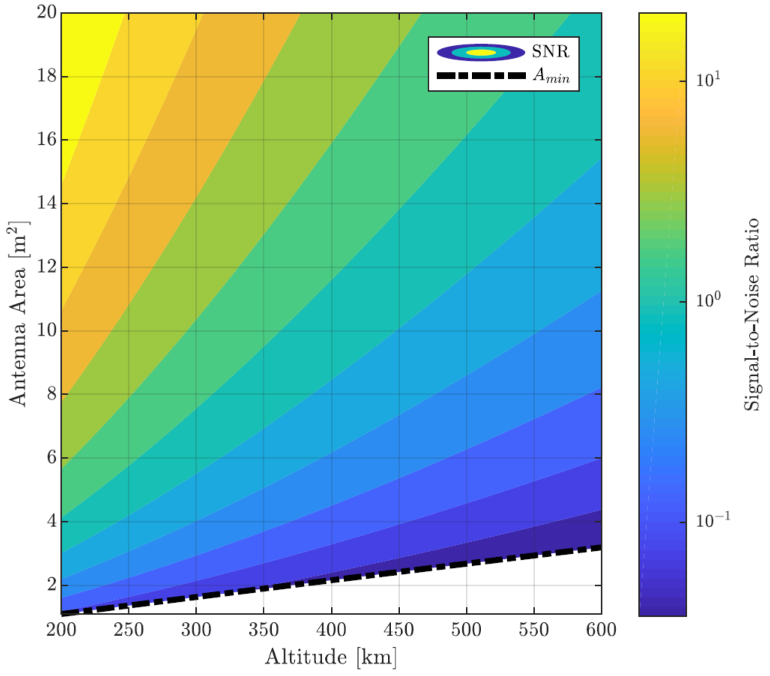
$$SNR = \frac{P_{av} A_r^2 \eta_{ant}^2 \delta_c \sigma}{8\pi T_r R^3 \overline{NF} V_a \lambda L_s}$$

For 600km → 300km (all else equal)

- $^1/_8$ reduction in transmit power
- $^1/_{2.83}$ reduction in antenna area
- x8 increase in SNR



SNR of 3, swath width of 30km, viewing angle of 45deg, PRF ratio of 1.2



Power of 5mW, swath width of 30km, viewing angle of 45deg, PRF ratio of 1.2

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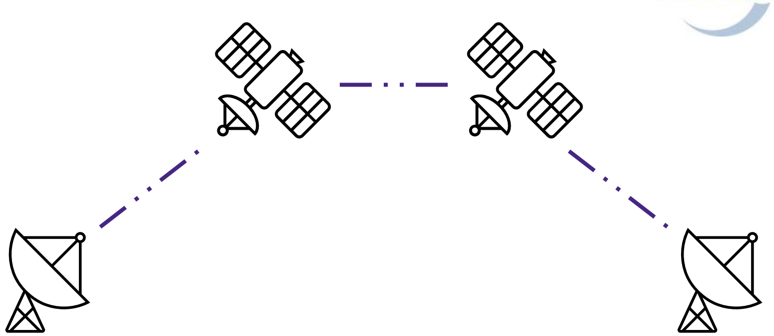
Benefit: Latency and Frequency Reuse

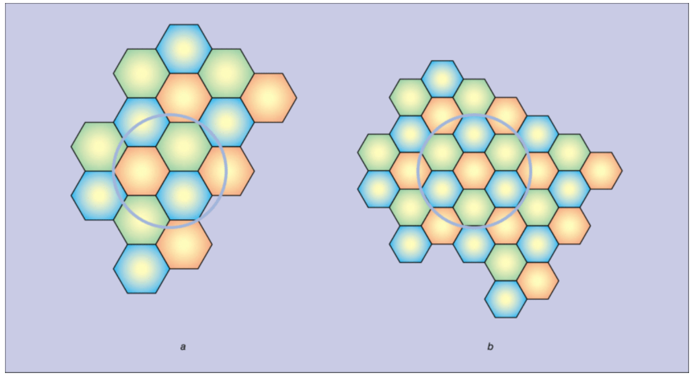


Signal propagation time is proportional to range: $t = {}^{R}/_{c}$

- Reducing altitude reduces latency
- **For 600km → 300km = $^{1}/_{2}$ time**
- Balanced by switching and processing time

For satellite communications available bandwidth is limited

- Spotbeam size (cell) decreases with reducing altitude (fixed beamwidth)
- Frequency reuse factor can therefore increase (more channels per area)
- Capacity per spotbeam remains the same (assuming available power)



B. Gavish, J. Kalvenes, The impact of satellite altitude on the performance of LEOS based communication systems, *Wireless Networks*, 4 (1998)

T.C. Tozer et al., High-altitude platforms for wireless communications, *Electronics & Communication Engineering Journal,* 13(3):127 (2001)

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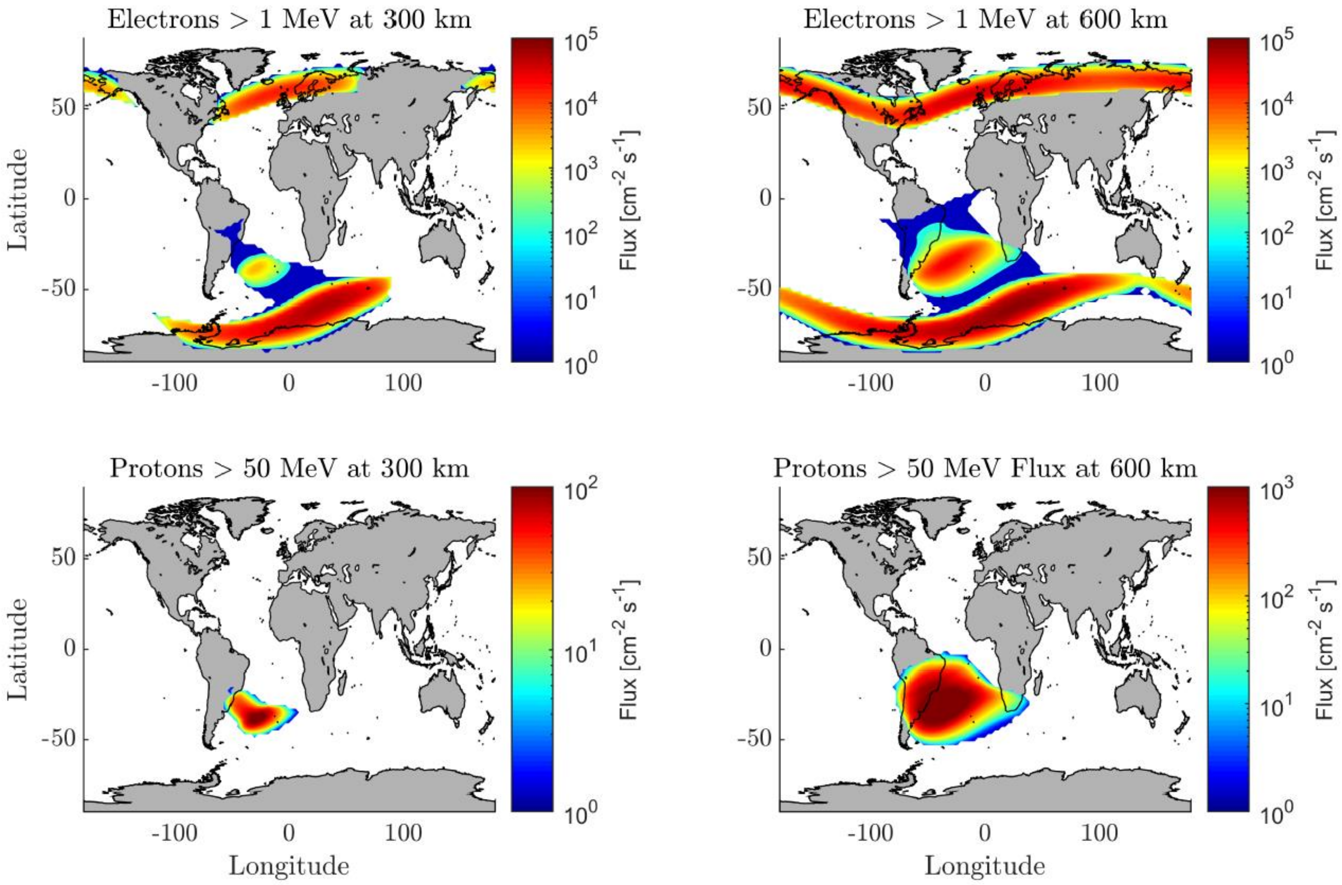
Benefit: Radiation Environment

Energetic electrons and protons trapped by the Earth's magnetic field

- Order of magnitude reduction in >50MeV proton flux
- Reduced distribution of >1MeV electron flux



Proton and electron flux maps at solar maximum conditions from ESA SPENVIS tool

- **Benefits**
  - Reduced radiation dosage to sensitive electrical components
  - Increased use of COTS and consumer components without radiation-hardening
  - Possible benefits to long-duration material performance (polymers)

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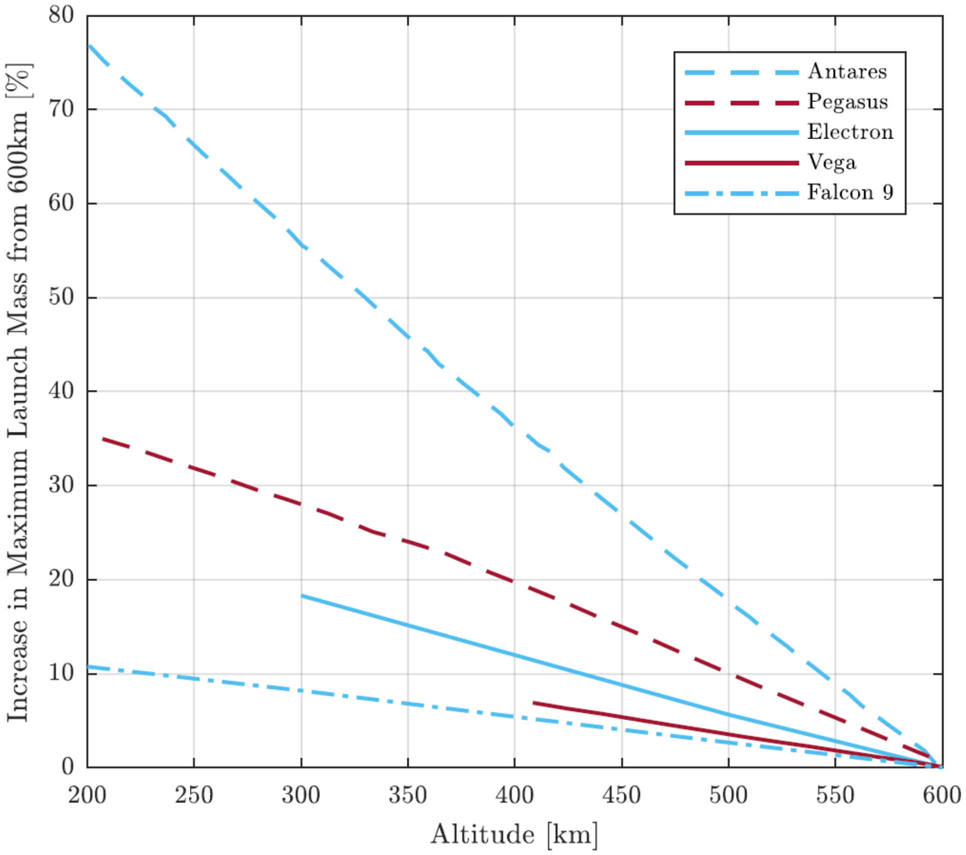
Benefit: Launch Vehicle Performance

Improved payload performance to lower orbit altitudes

- Total launch capacity increased per vehicle
- Cost per unit mass decreased
- Greater diversity in number of available launch vehicles with required capability

▸ **For 600km → 300km ≈ 10-50% improvement in capacity**



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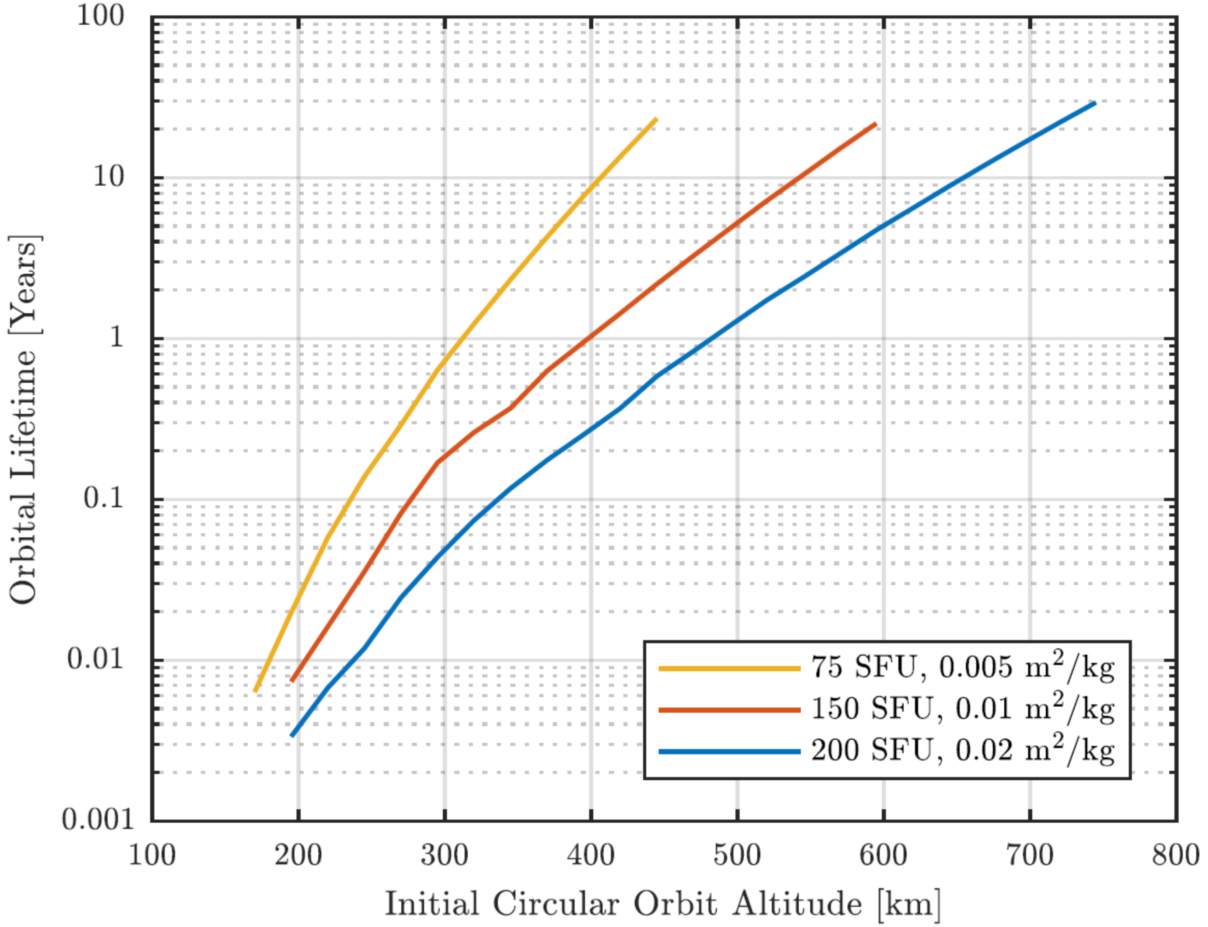
Benefit: End-of-Life Disposal

Time for natural deorbit is reduced significantly

- Due to atmospheric drag
- For 600km → 300km = $^{1}/_{100}$ time

Almost all VLEO orbits are naturally compliant with IADC guidelines on maximum lifetime after end of operations of 25 years.

- No requirement for additional deorbit hardware (drag sail, propulsion system etc)



Natural decay time for circular orbits with assumed drag coefficient of 2.2

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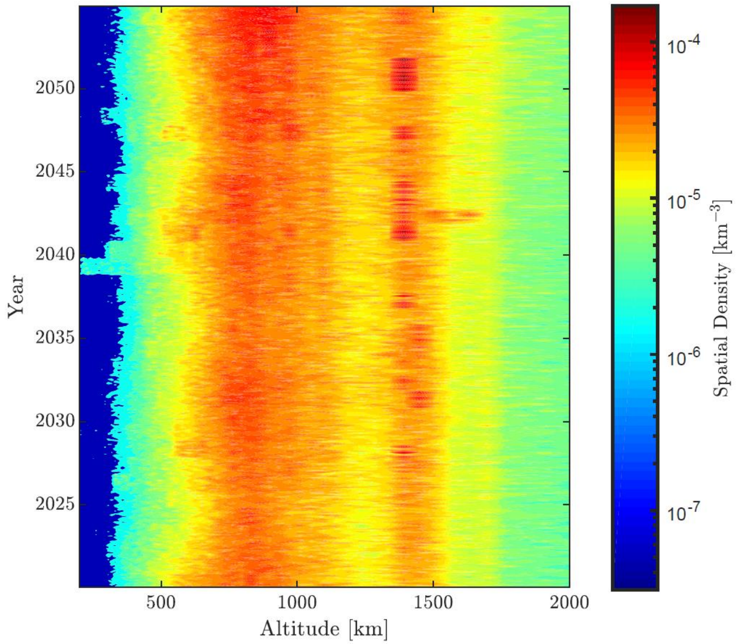
Benefit: Debris Collision Resilience



Modelled using ESA MASTER-2009 software assuming "business-as-usual" scenario and no debris mitigation actions

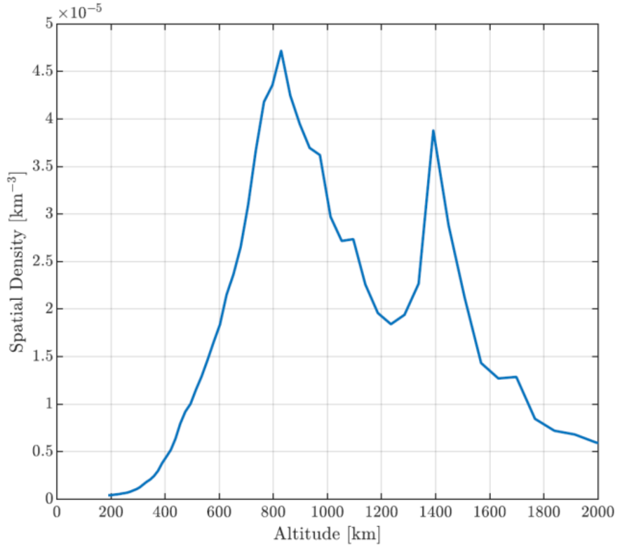
Orbital decay (due to drag) in LEO helps to clear debris

- E.g. post-mission spacecraft, launch vehicle upper stages, spacecraft fragments etc
- This is slow at higher altitudes due to reduced density
- In VLEO, any debris is quickly deorbited

Spatial density (objects per km^3) is used to illustrate the debris environment

- True collision probability requires more complex analysis
- Risk is also comprised of outcome/consequence

▸ **VLEO remains resilient to build-up in debris over time**



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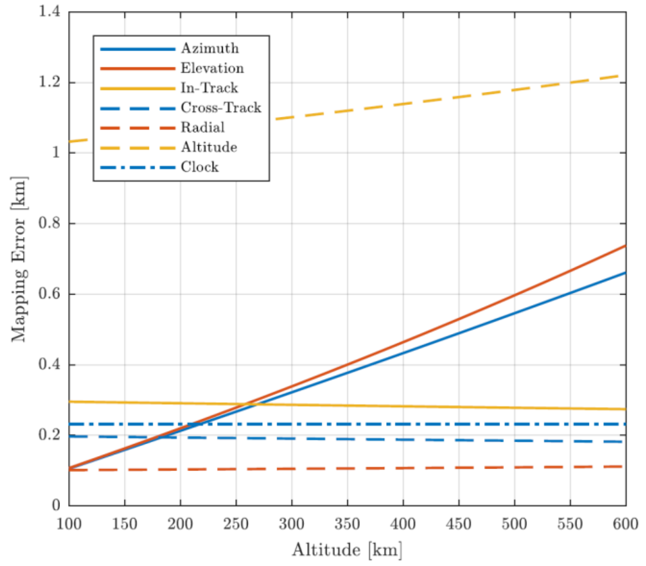
Benefit: Geospatial Accuracy

Mapping errors due to attitude (azimuth and elevation) knowledge decrease with reducing altitude

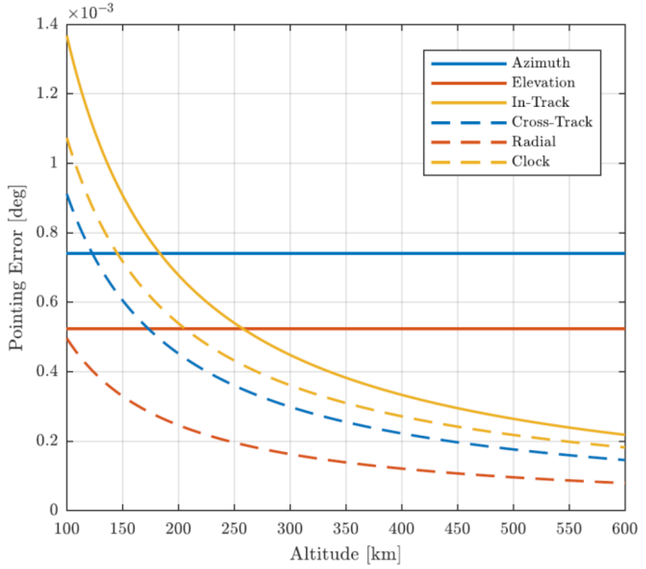
- **Reduces requirements on attitude determination and control (ADCS)**



But…

Pointing errors due to position knowledge increase with reducing altitude

- Increases requirements on orbital position knowledge (e.g. GPS or POD)



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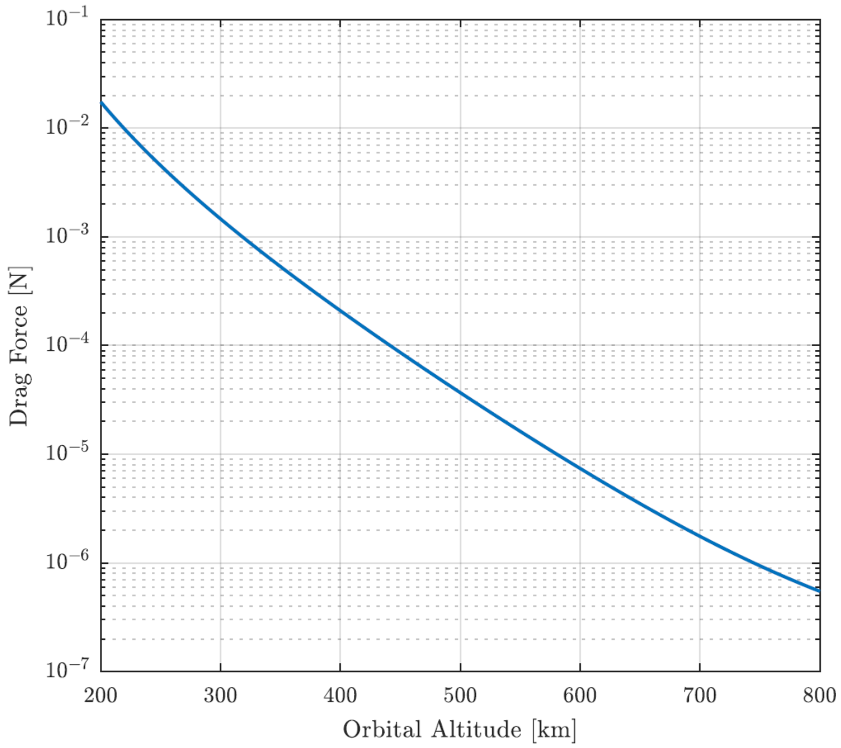
Challenge: Aerodynamic Drag

Drag force, $F_D = \frac{1}{2}\rho V^2 A_{ref} C_D$

- Increases with density and also velocity, both of which increase with reducing altitude

To maintain a given orbital altitude requires full compensation of the drag force using propulsion

Partial drag compensation or mitigation may yield useful lifetimes in orbit as the spacecraft decays slowly



Assuming 1 m^2 area, Cd = 2.2, NRLMSISE-00 atmosphere under medium solar weather conditions

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Challenge: Aerodynamic Attitude Perturbations

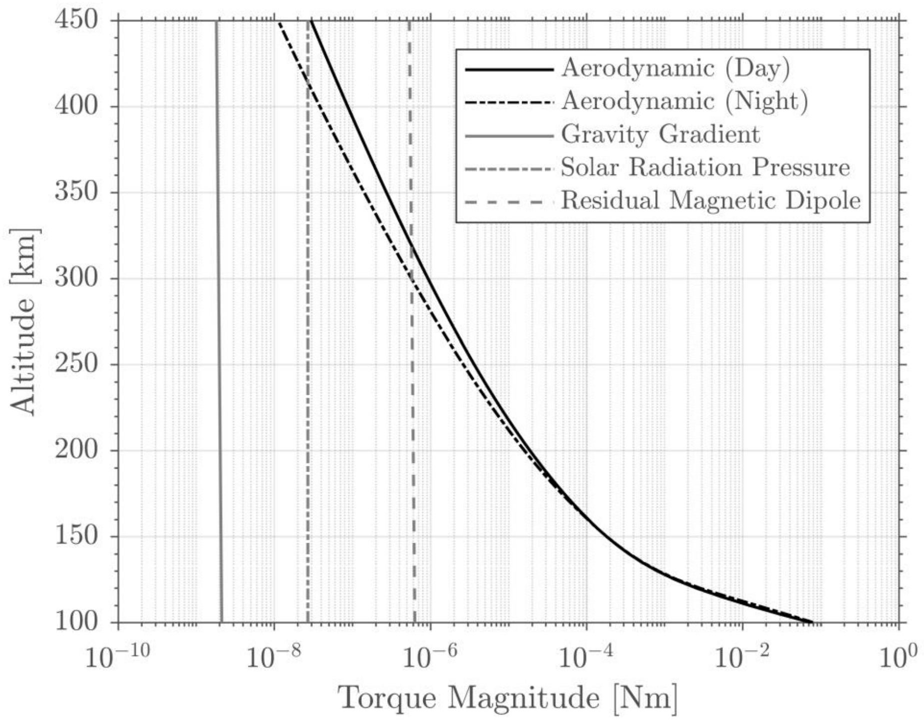
Aerodynamic Torque, $T = \frac{1}{2}\rho V^2 A_{ref} l_{ref} C_T$

Disturbing torques due to aerodynamic perturbations increase in magnitude with reducing altitude

- Atmospheric co-rotation
- Thermospheric winds
- Density variations

Aerodynamic perturbations become dominant at VLEO altitudes

- Reduced platform stability
- Increase disturbing torques when pointing
- Increased attitude control actuator requirements



Example for SOAR geometry with 30deg counter-rotation of fins and pitched at 3° to LVLH

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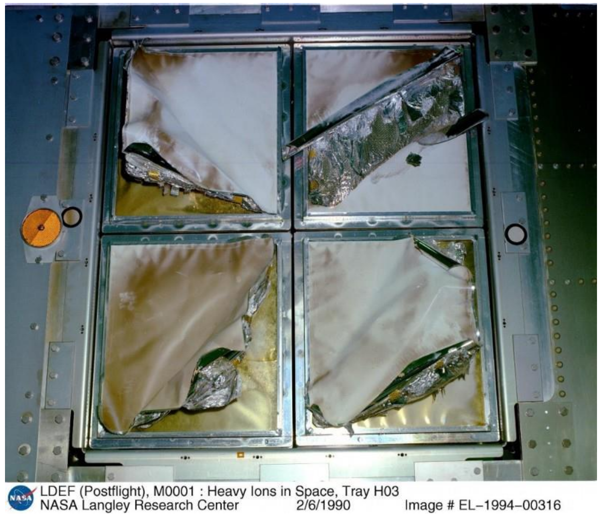
Challenge: Atomic Oxygen Erosion

AO Interactions

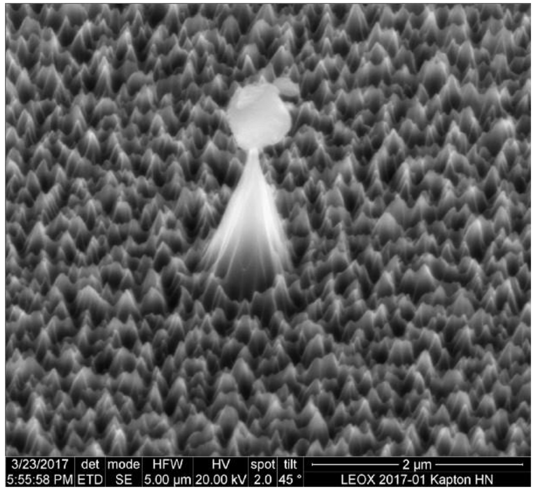
- Atomic oxygen is highly reactive
- Higher density in VLEO increases particle-surface interactions
- Orbital velocity increases collision energy
- AO interactions can therefore damage and erode surfaces (particularly flow facing)

Aerodynamic Properties

- Atomic oxygen can adsorb to surfaces
- Interaction/erosion can cause chemical and physical changes to surfaces



Combined atomic oxygen erosion and ultraviolet degradation [Image Credit: NASA Langley Research Center]



Atomic oxygen erosion (Image Credit: ESA—CC BY-SA IGO 3.0)

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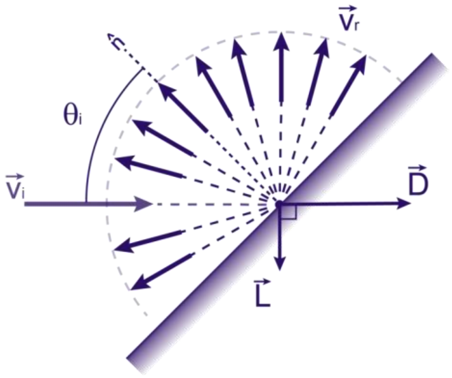
Gas-Surface Interactions in VLEO

GSIs vary with

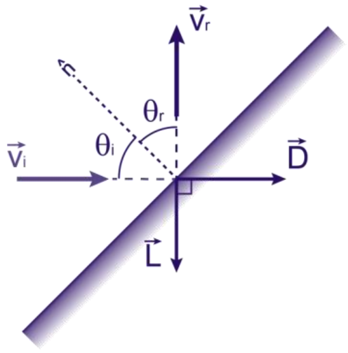
- Surface incidence with respect to oncoming flow
- Flow composition and relative velocity
- Surface composition, structure, and roughness
- Surface cleanliness and contamination
- Temperature (surface and atmospheric)

Current materials

- High AO contamination and erosion
- Generally diffuse re-emission properties



Diffuse Reemission



Specular Reflection

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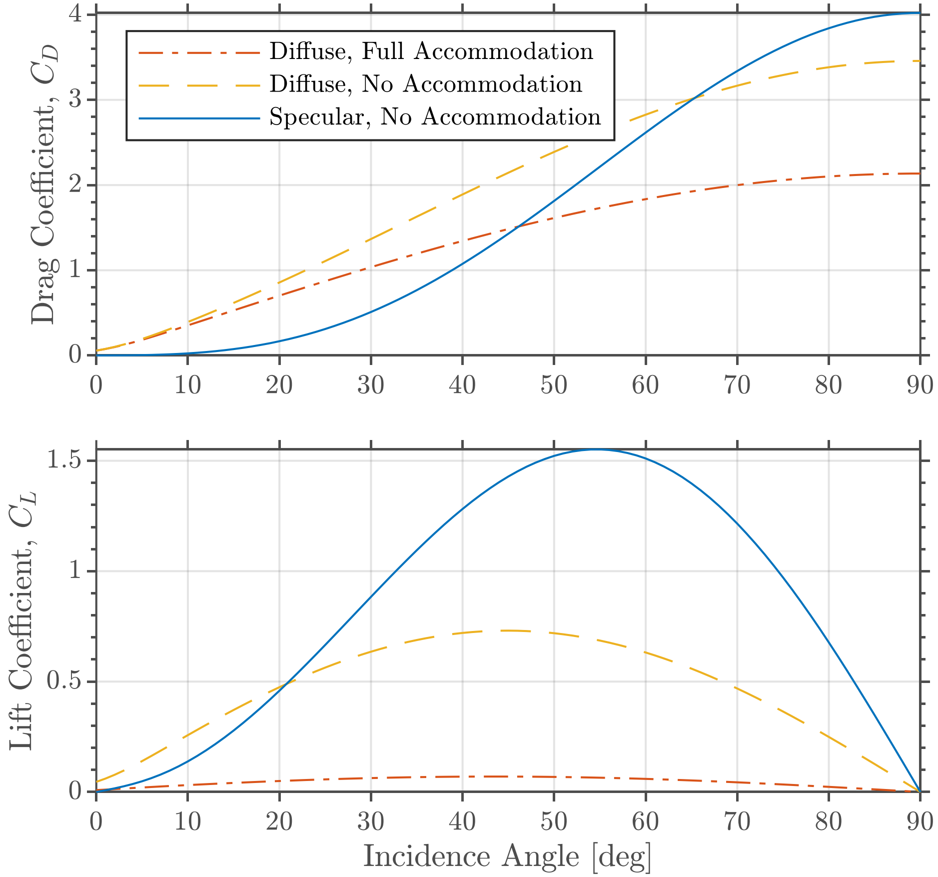
Opportunity: Novel Materials

Novel materials

- Resistant to adsorption and erosion effects of AO
- Specular or quasi-specular reflection
- Reduces drag at shallow surface incidences
- Can also promote lift force production

- **Spacecraft geometric design can mitigate drag**
- **Improvement in aerodynamic control**
- **Improved atmospheric intake performance**

- Also applications for enhanced deorbit devices (e.g. drag sails)



Diffuse re-emission using Sentman's model, specular reflection using Cercignani-Lampis-Lord model. 200km altitude, 25.8deg latitude, low solar weather conditions, NRLMSISE-00 atmosphere

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Opportunity: Aerodynamic Control

Increased density increases possible control force/torque generation in VLEO

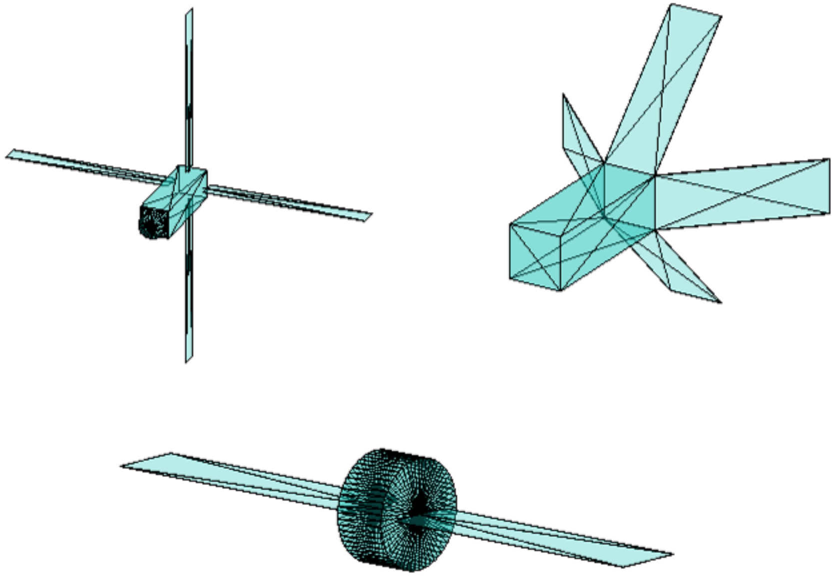
Novel materials may improve lift force generation, improving control effectiveness and efficiency

Attitude control:

- Coarse pointing control
- Aerodynamic trim (to reject aerodynamic disturbing torques)
- Momentum management

Orbit control:

- Constellation deployment and management
- Targeted re-entry



▸ **Development of new concept geometries, control methods, and implementations**

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Challenge: Spacecraft Charging

Causes:

- Electron flux is greater than ion flux, causing generally negative charging
- Electrons can also penetrate the wake more readily than ions, causing differential charging
- Photoemission biases positive charging when in sunlight, causing variation over an orbital period
- Ionised emissions (e.g. electric propulsion systems) require effective neutralisation
- Positively biased solar arrays can cause electron leakage from neutralisers
- Traversing auroral latitudes (65–70 degrees) can cause rapid differential charging

Effects:

- Discharge and damage to onboard electronics
- Interference with measurements/sensors
- Parasitic power loss on solar arrays

- **Design: encapsulation of solar cells and relative location of thrusters and solar arrays**
- **Develop: New environmental and satellite modelling and prediction methods**

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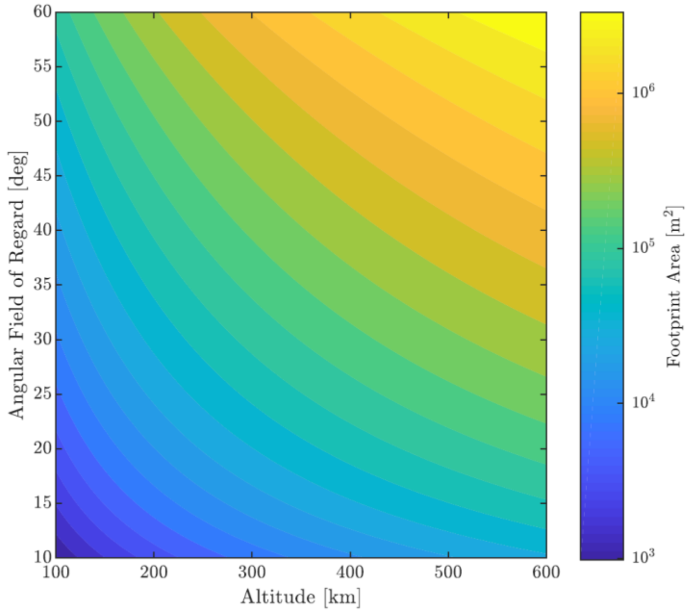
Challenge: Access, Coverage, and Revisit

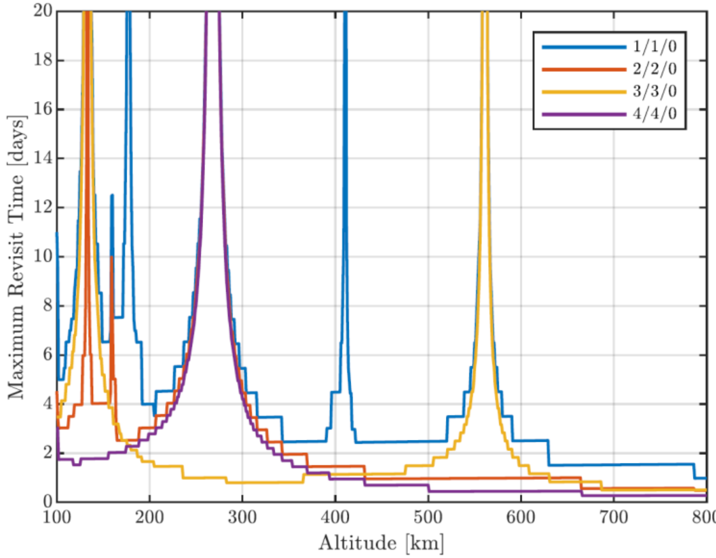
Coverage and access reduce with reducing altitude

- Due to accessible footprint area by sensor/antenna
- Elevation angle and atmospheric propagation constraints
- Reduces communication windows with ground stations
- Impact on total data up/downlink

Revisit time is also adversely affected

- Fewer low-MRT windows at lower altitudes





- Must be traded off against benefits of VLEO orbits
- Can be addressed somewhat through constellation design
- **Requires holistic systems modelling and engineering approaches**

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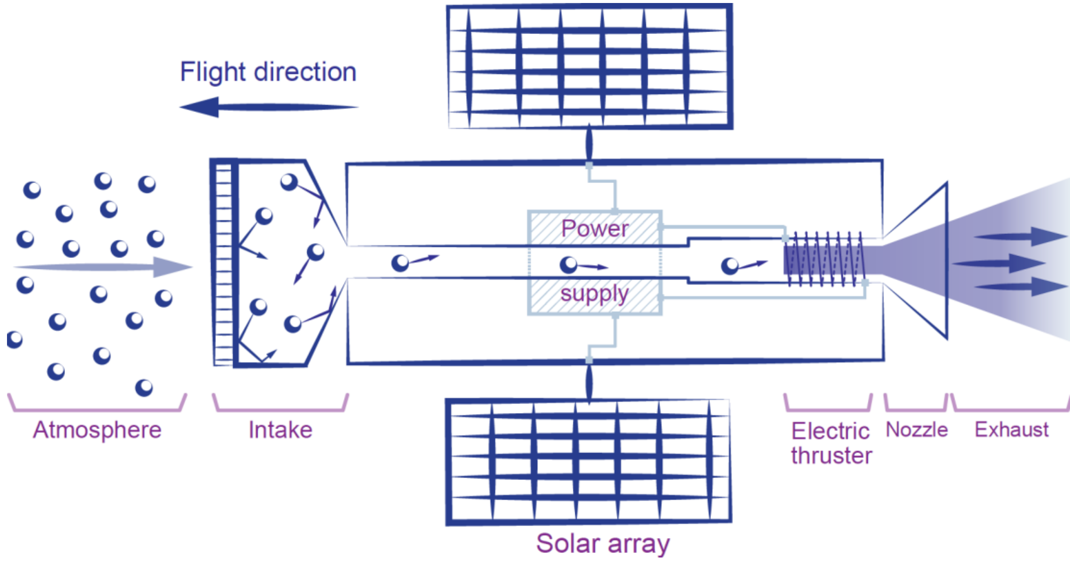
Opportunity: Atmosphere-Breathing Electric Propulsion

Collect and use residual atmosphere as propellant

- No requirement to launch with propellant
- Lifetime limited by component degradation

Novel materials can contribute to improvements in collection efficiency

- **Development of system components (intake, thruster)**
- **Systems modelling required to resolve design trades**
    - Intake geometry, drag, thrust, power, array area etc



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Summary

Benefits	Example at half altitude (e.g. 600 → 300km)
– Increased optical resolution	x2 improvement in GRD
– Reduced aperture size	x2 reduction in aperture diameter
– Improved payload radiometric performance	x4 increase in received power
– Improved communications link budget	x4 improvement in free-space loss
– Reduced radar transmitter power	> x8 reduction in power
– Reduced latency and increased frequency reuse	x2 improvement in delay
– Radiation environment	x10 reduction in peak proton flux
– Launch vehicle performance	10-50% improvement in launch mass
– End-of-life disposal	> x50 reduction in decay time
– Debris collision risk and resilience	> x10 reduction in debris (spatial density)
– Geospatial accuracy	x2 reduction in mapping error

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Summary

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Challenges

- Atmospheric drag
- Atomic oxygen effects
- Aerodynamic perturbations
- Reduced coverage and access time
- Longer revisit times
- Spacecraft charging

Opportunities & Solutions

- Aerodynamic attitude and orbit control
- Novel materials
- Atmosphere-breathing electric propulsion (ABEP)
- Holistic systems modelling and engineering

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THANK YOU!

Any Questions?

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