Masterclasses
Session 2: Benefits and Challenges of Very Low Earth Orbit

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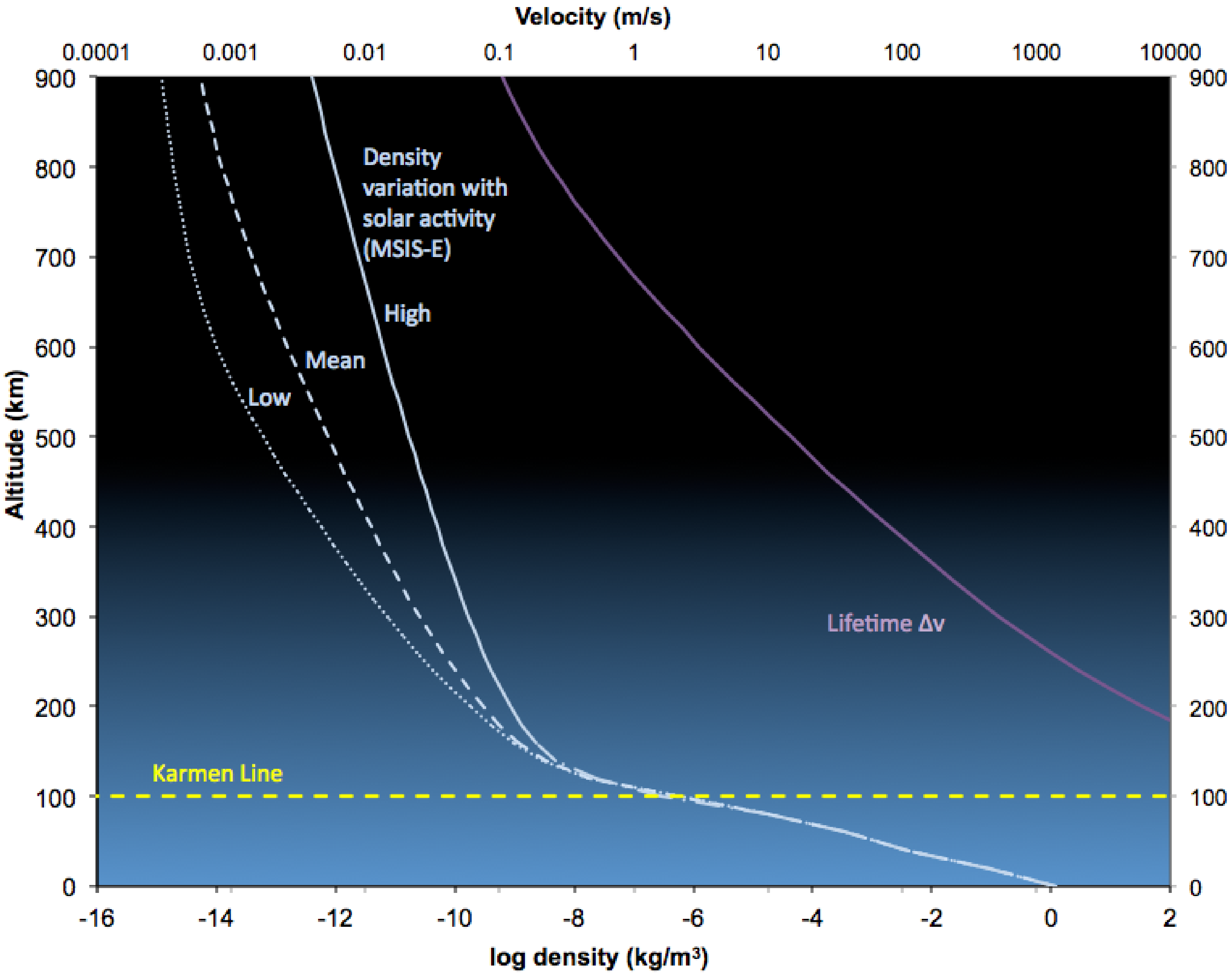
The University of Manchester

1st DISCOVERER master classes

6th – 8th December 2017, Stuttgart, Germany

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 737183.

The Environment at Lower Altitudes



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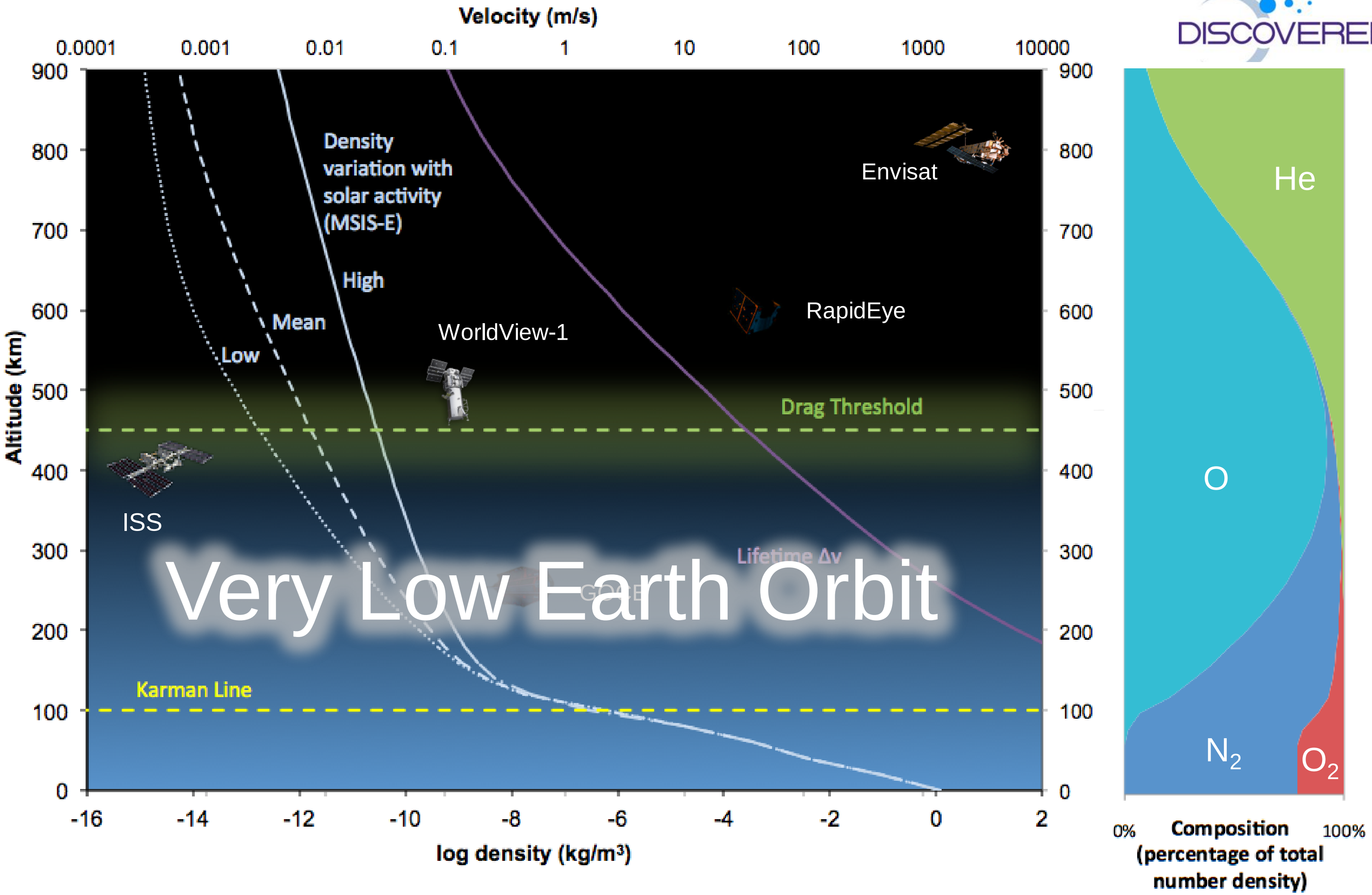
The Environment at Lower Altitudes



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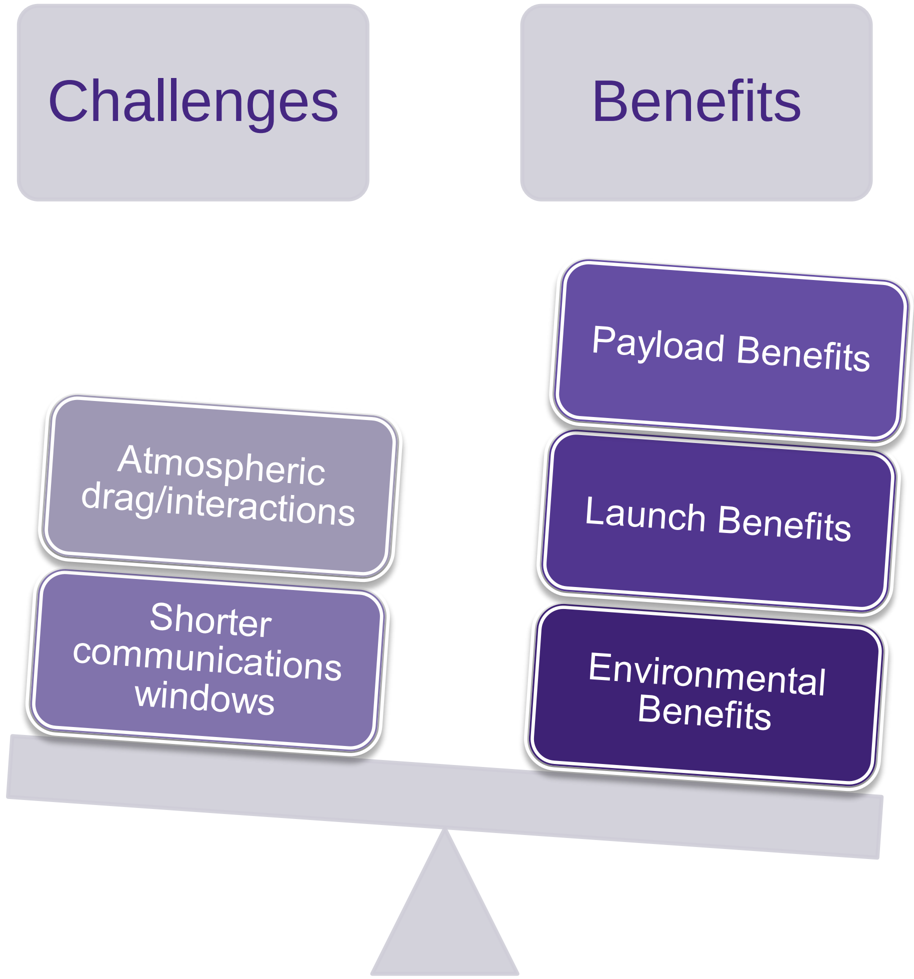
Very Low Earth Orbit
Earth Observation Platforms



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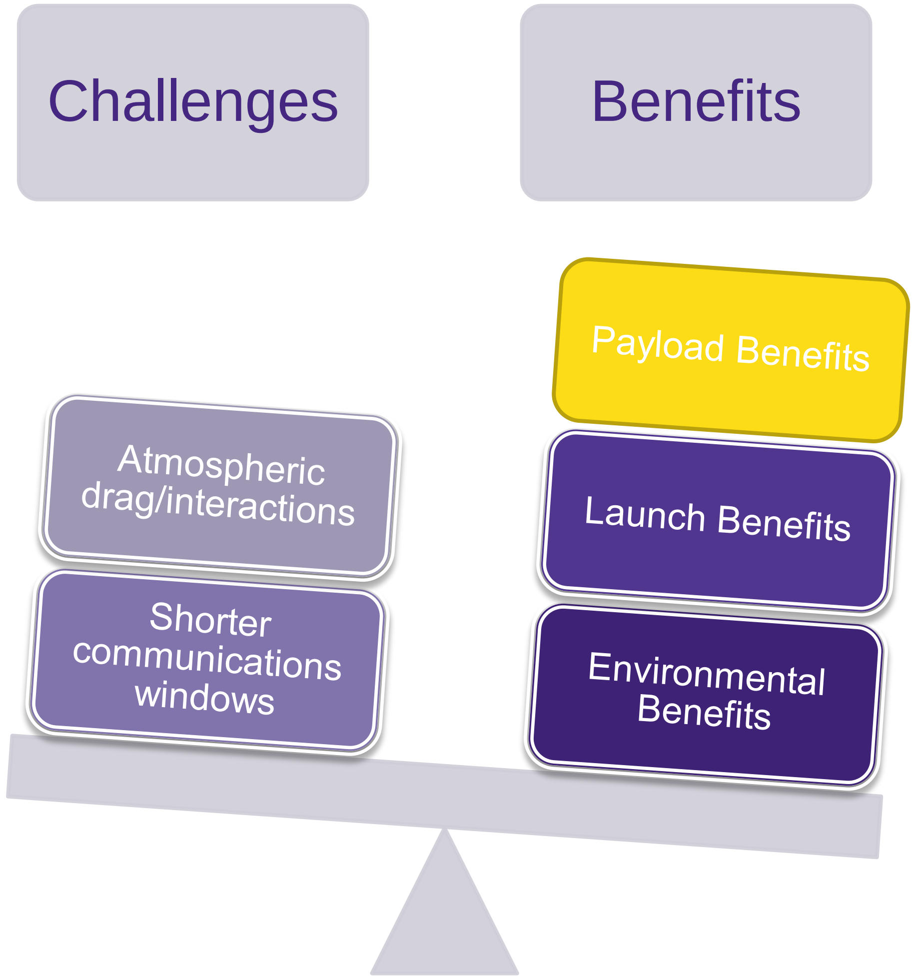

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Payload Benefits – Effect of Getting Closer to Target

Optical Payloads	Synthetic Aperture Radar Payloads	Generic Benefits
Improved diffraction limited resolution	Improved signal return	Improved geospatial position
Improved radiometric performance		Improved angular field of regard

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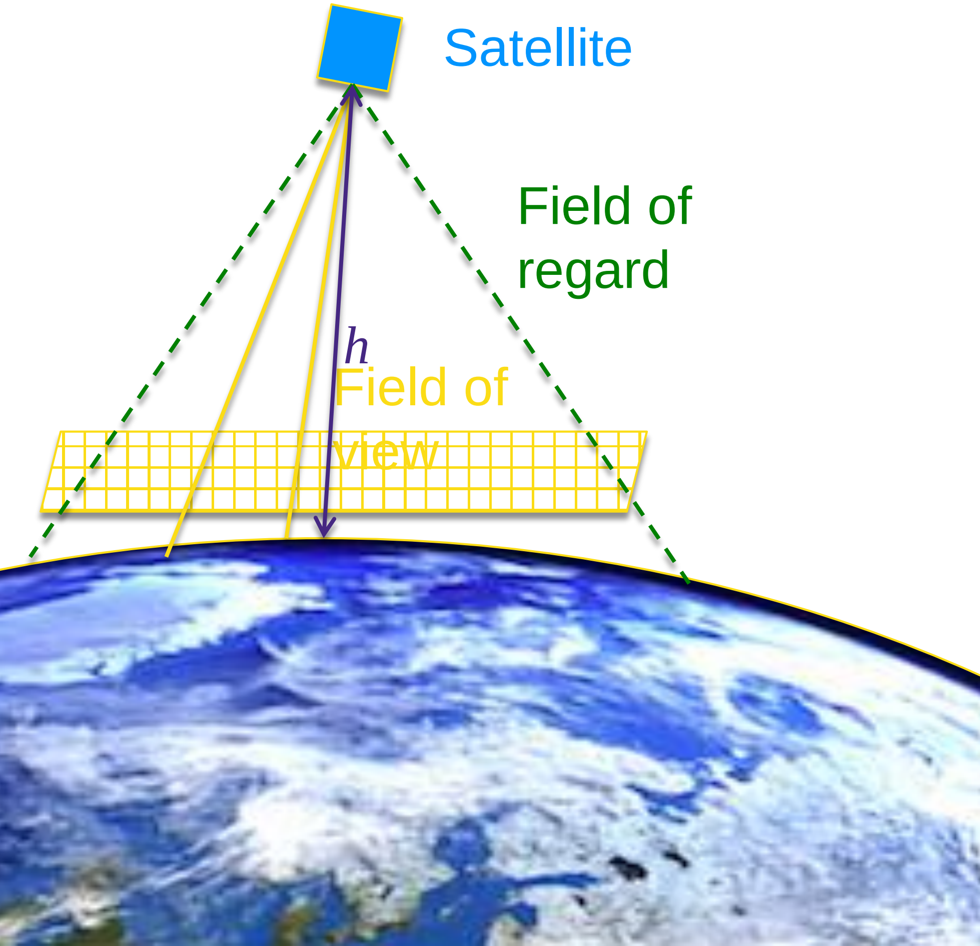
EO Principles

Best resolution limited by the Rayleigh criterion – diffraction limited nadir ground resolution

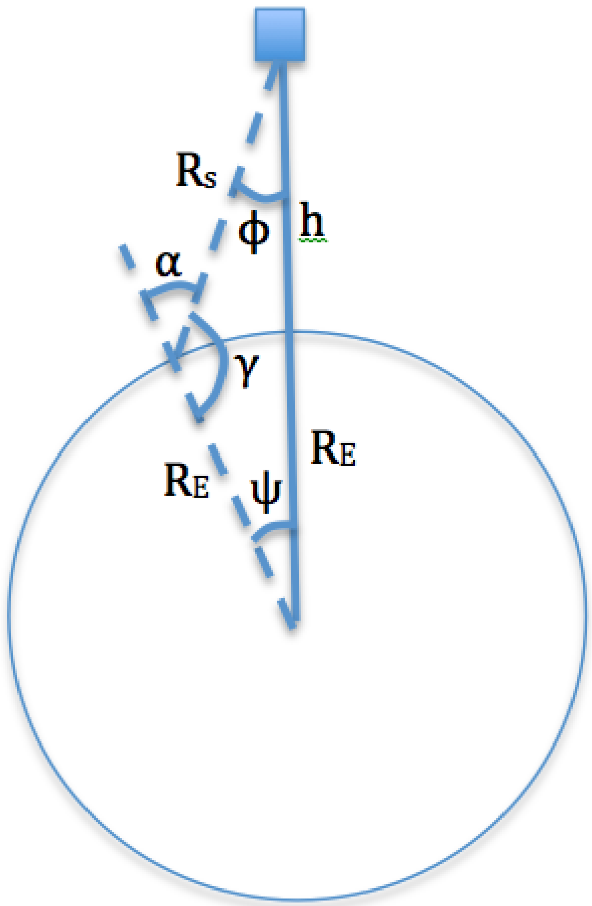
$$x_n = 1.22\frac{h\lambda}{D}$$



Optical Payloads – Improved Diffraction Ground Limited Resolution

$$x = 1.22\frac{R_s\lambda}{D}$$

- Ground resolution improves with reducing altitude
- Limiting α is also important – distorted ground features
- Angular field of regard, ϕ_{max}, for the maximum acceptable α also varies
- Radius of field of regard, $R_E\psi$, also varies – note ψ=α-ϕ



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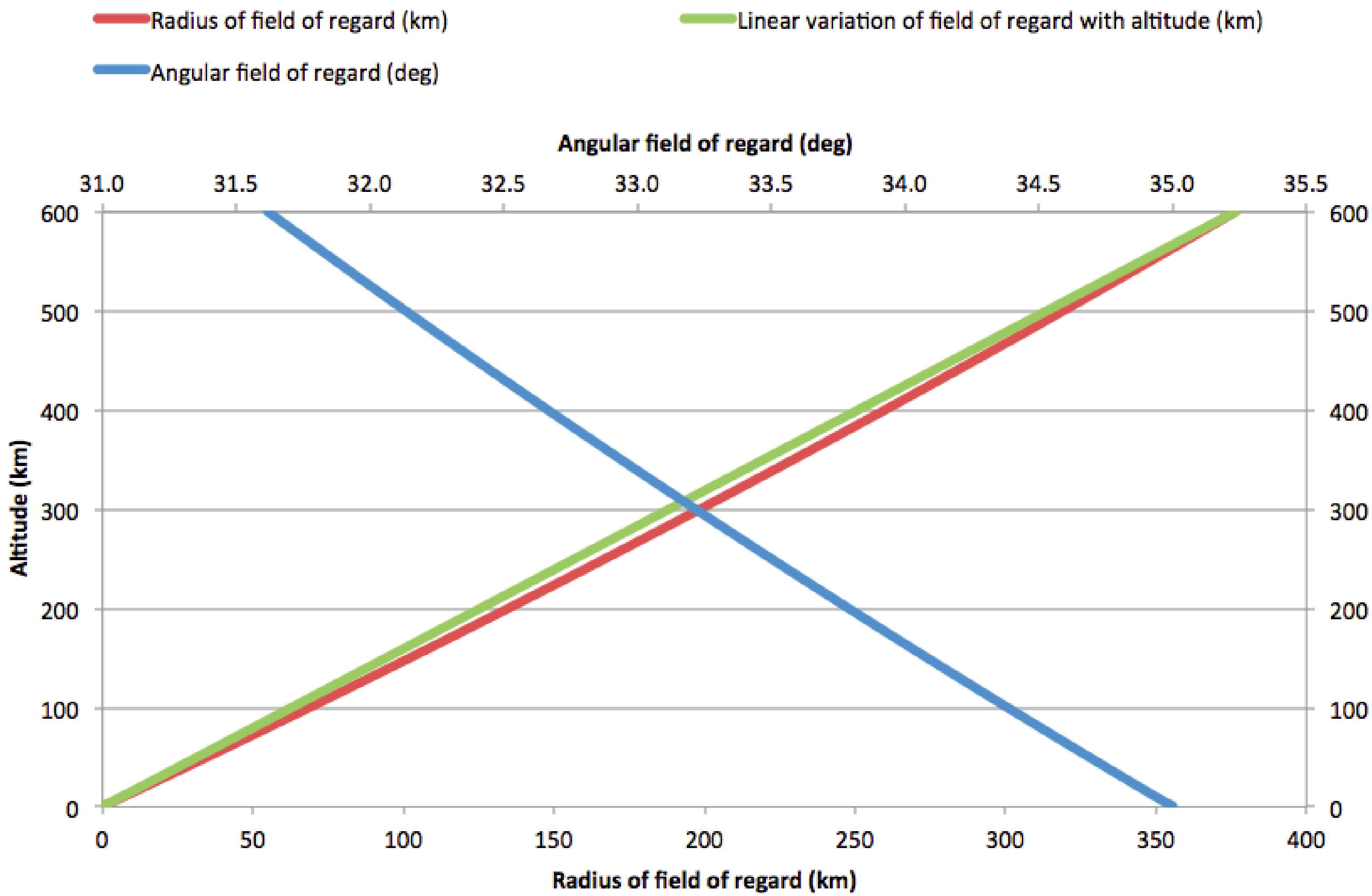
Optical Payloads – Variation of Field of Regard (α=35 deg)



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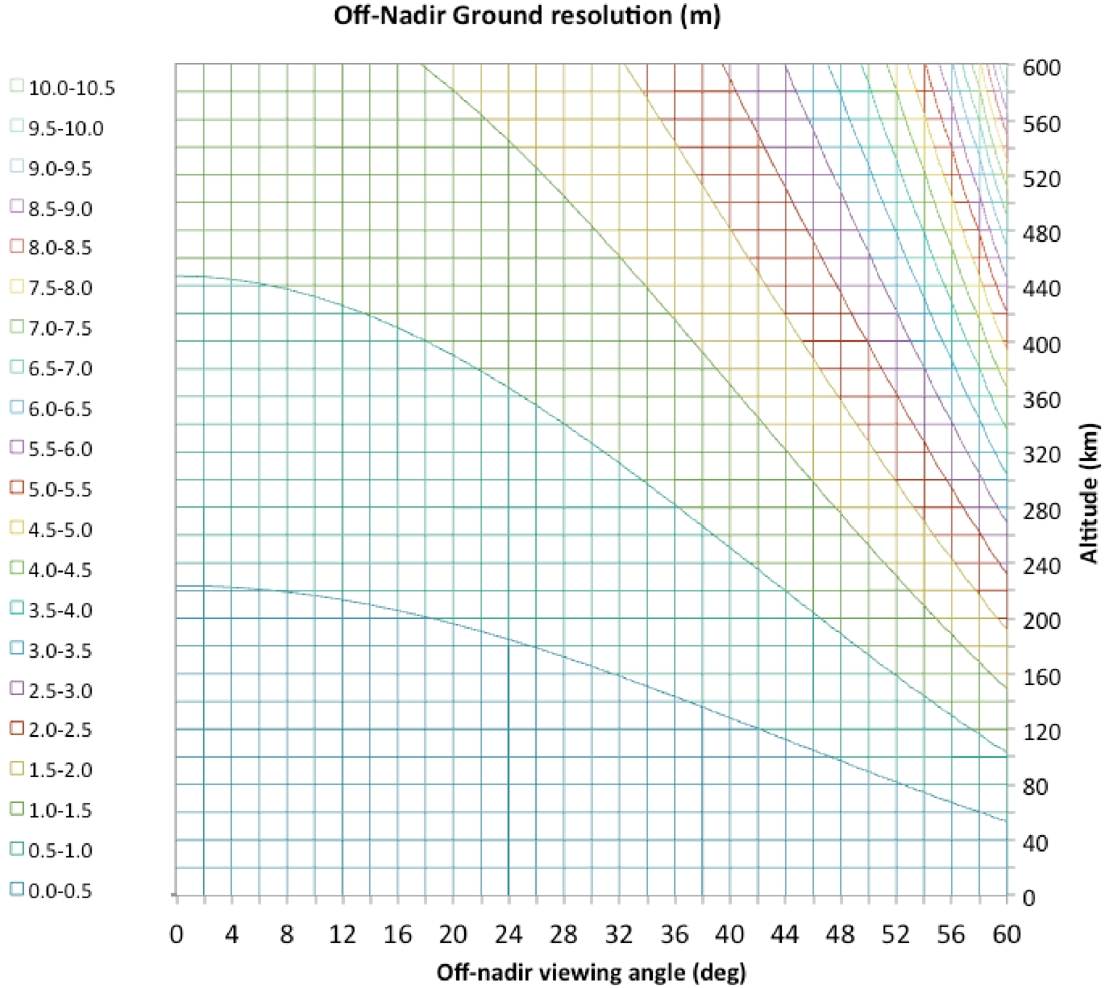
Optical Payloads – Variation in ground resolution – aperture constant (D=30 cm)



Altitude (km)	Resolution (m)	Viewing angle (deg)	Radius of field of regard (km)
600	1.5	18	196
300	1.5	46	319

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Optical Payloads – Resolution Summary

- Ground resolution improves with reducing altitude
- Radius of field of regard, acceptable ground viewing angle, and ground resolution all linked
  - Limits whilst considering reduced altitude:
    - Maintaining nadir ground resolution by reducing aperture – payload size reduced significantly but so is radius of field of regard
    - Maintaining optical aperture – increases field of regard but increases off-vertical viewing angle – no payload size benefits

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Optical Payloads – Improved Radiometric Performance - Signal to Noise

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$$SNR \propto \frac{D^2}{R_s^2}$$

- As diffusely reflected light from the surface decreases with $1/R_s^2$
- Light gathering increases with collection area, D^2
  - Limits whilst considering reduced altitude:
    - Reducing payload aperture to maintain ground resolution – SNR not affected
    - Maintaining optical aperture – SNR increases with $1/R_s^2$

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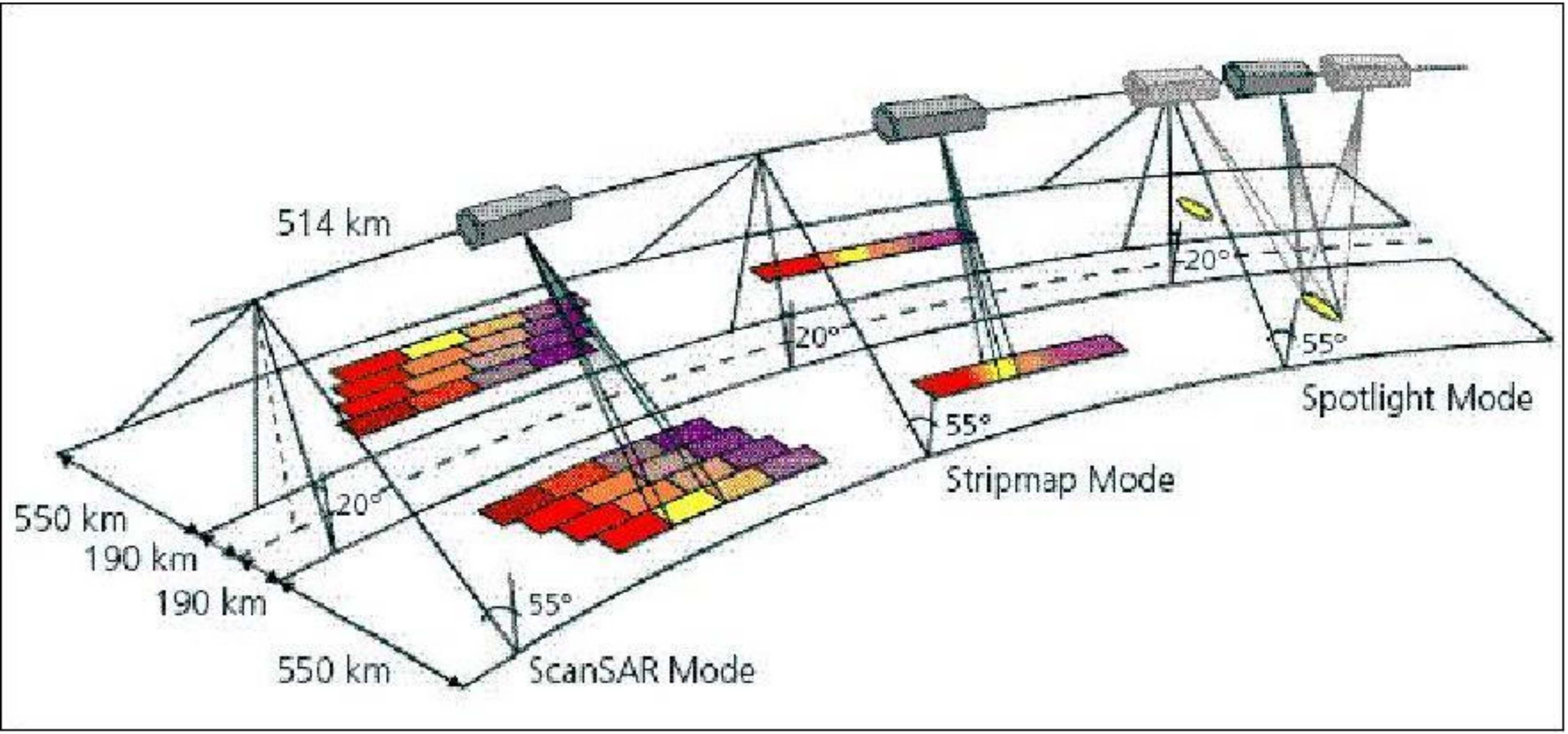
SAR Payloads – Scanning Modes



Credit: DLR – TerraSAR-X Scanning Modes

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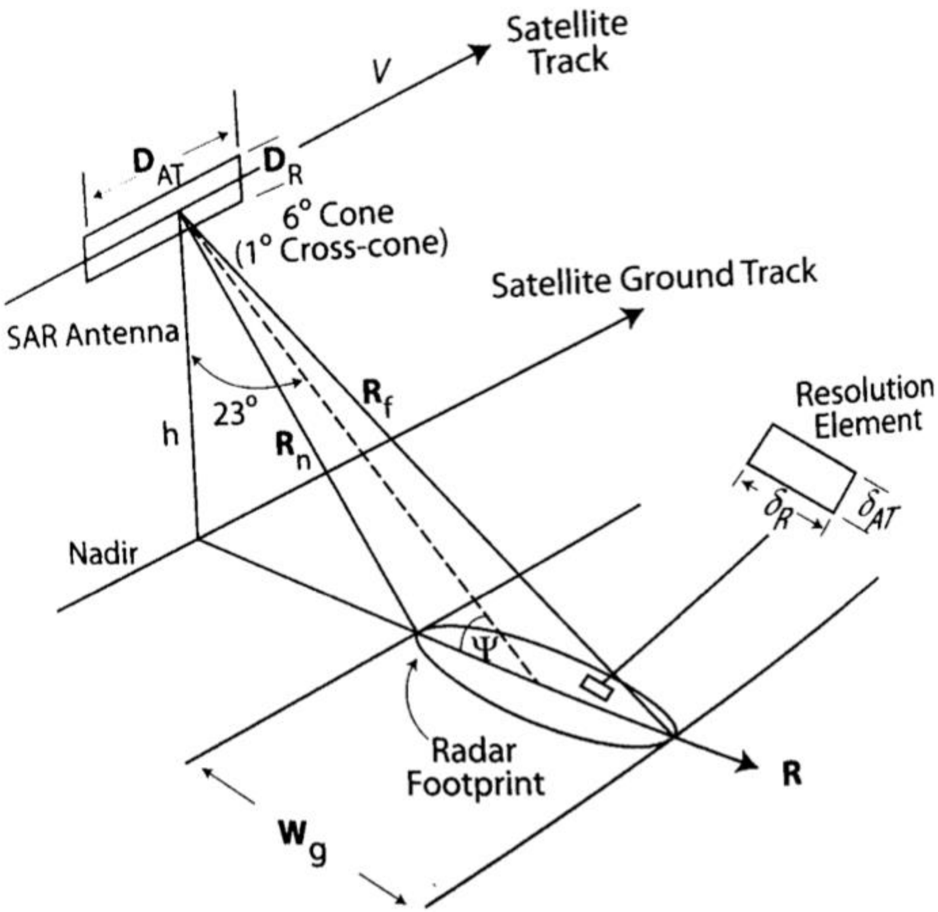
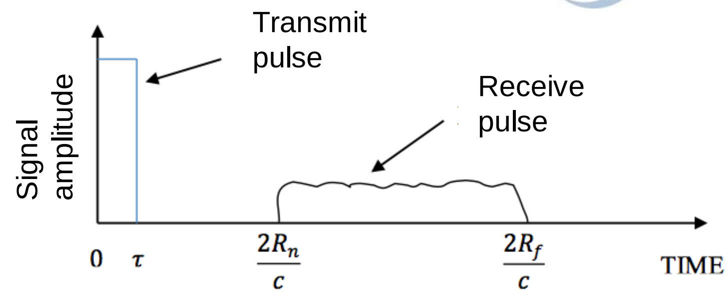
SAR Payloads - Resolution





Azimuth resolution (along track)

$$L_A = \frac{d_1}{2}$$

d_1 is the antenna length

Range resolution (cross track)

$$L_C = \frac{c\tau}{2 sin\alpha}$$

τ is the pulse duration – resolution is half the pulse length

Wertz, J. R., Everett, D.F., and Pushell J.J. (2011), Space Mission Engineering: The new SMAD, Microcosm Press, Hawthorne, CA (USA)

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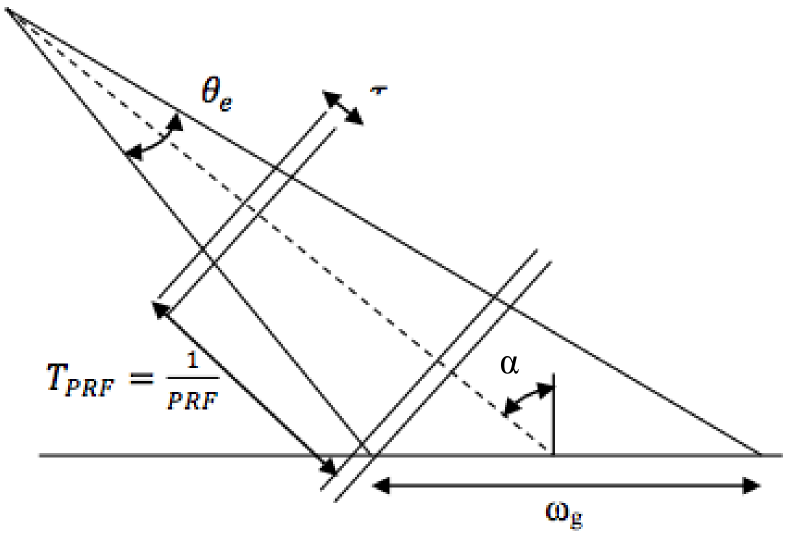
SAR Payloads – Antenna Area and Swath Width



Minimum PRF to avoid azimuth ambiguities

$$PRF > \frac{v}{L_A} = \frac{2v}{d_1}$$

Maximum PRF to avoid reflection ambiguities – one pulse on the target at any one time

$$PRF < \frac{1}{2(R_f - R_n)/c} = \frac{c}{2w_g sin\alpha} = \frac{cd_2}{2R_s \lambda tan\alpha}$$

Swath width

$$w_g = \frac{\theta_e R_s}{cos\alpha} = \frac{\lambda R_s}{d_2 cos\alpha}$$

where $\theta_e \approx \frac{\lambda}{d_2}$

$$A_{min}(\alpha, h, \lambda) = d_1 d_2 = \frac{PRF_{max}}{PRF_{min}} \frac{4v\lambda R_s tan\alpha}{c}$$

Ramio Tomas, L. (2014), Very Low Earth Orbit SAR: Feasibility and Advantages MSc Thesis, Cranfield University.

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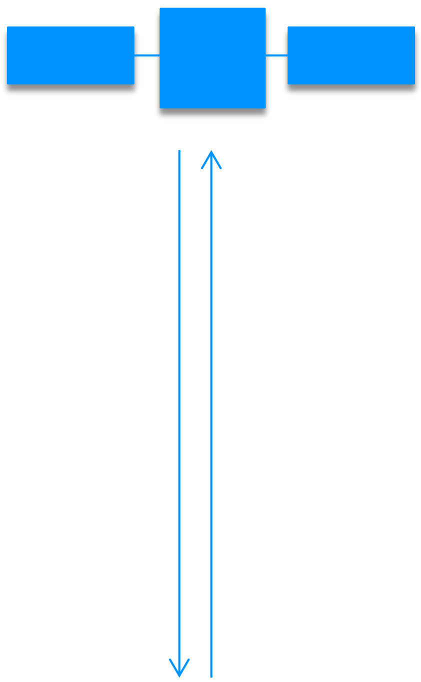
SAR Payloads – Radar Link Budget



Reflected power at a target $$P_r = \frac{G P_s \sigma}{4\pi R_s^2}$$

where σ is the radar cross-section, G the antenna gain, and Ps the power from the source

Received power at antenna $$P_e = \frac{G P_r}{4\pi R_s^2} \propto SNR$$

Antenna gain in terms of wavelength where η is the antenna efficiency $$G = \frac{4\pi A \eta}{\lambda^2}$$

Therefore

$$P_s = \frac{\lambda^4 R_s^4 P_e \sigma}{A^2 \eta^2}$$

Remembering

$$A_{min} \propto R_s \Rightarrow P_s \propto R_s^2$$

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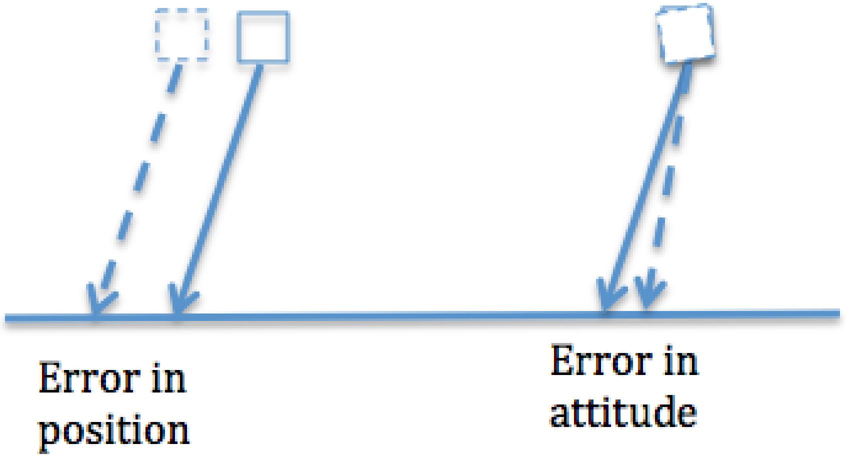
Improved Geospatial Position

- Definition: The position accuracy of an image compare to the position of the actual object
  - Optically alignment
  - Satellite position accuracy
  - Satellite attitude ($R_s\Delta\theta$)
    - $\Delta\theta$ is the attitude knowledge error



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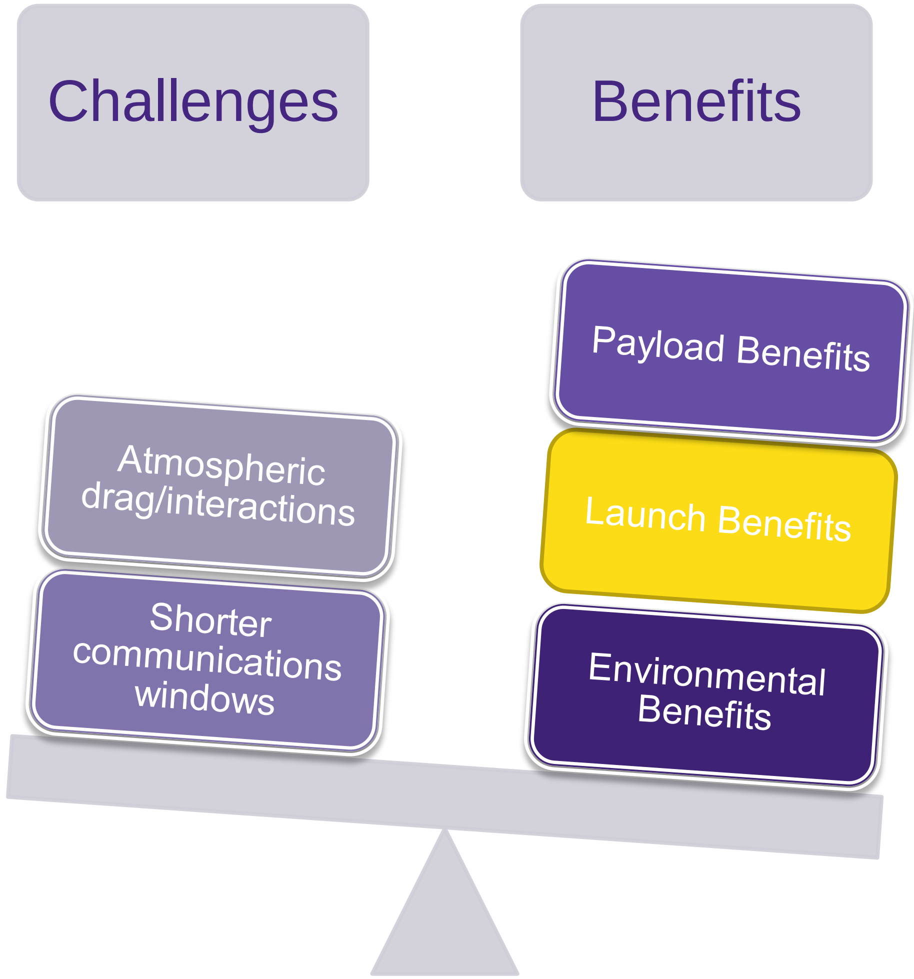
Very Low Earth Orbit
Earth Observation Platforms



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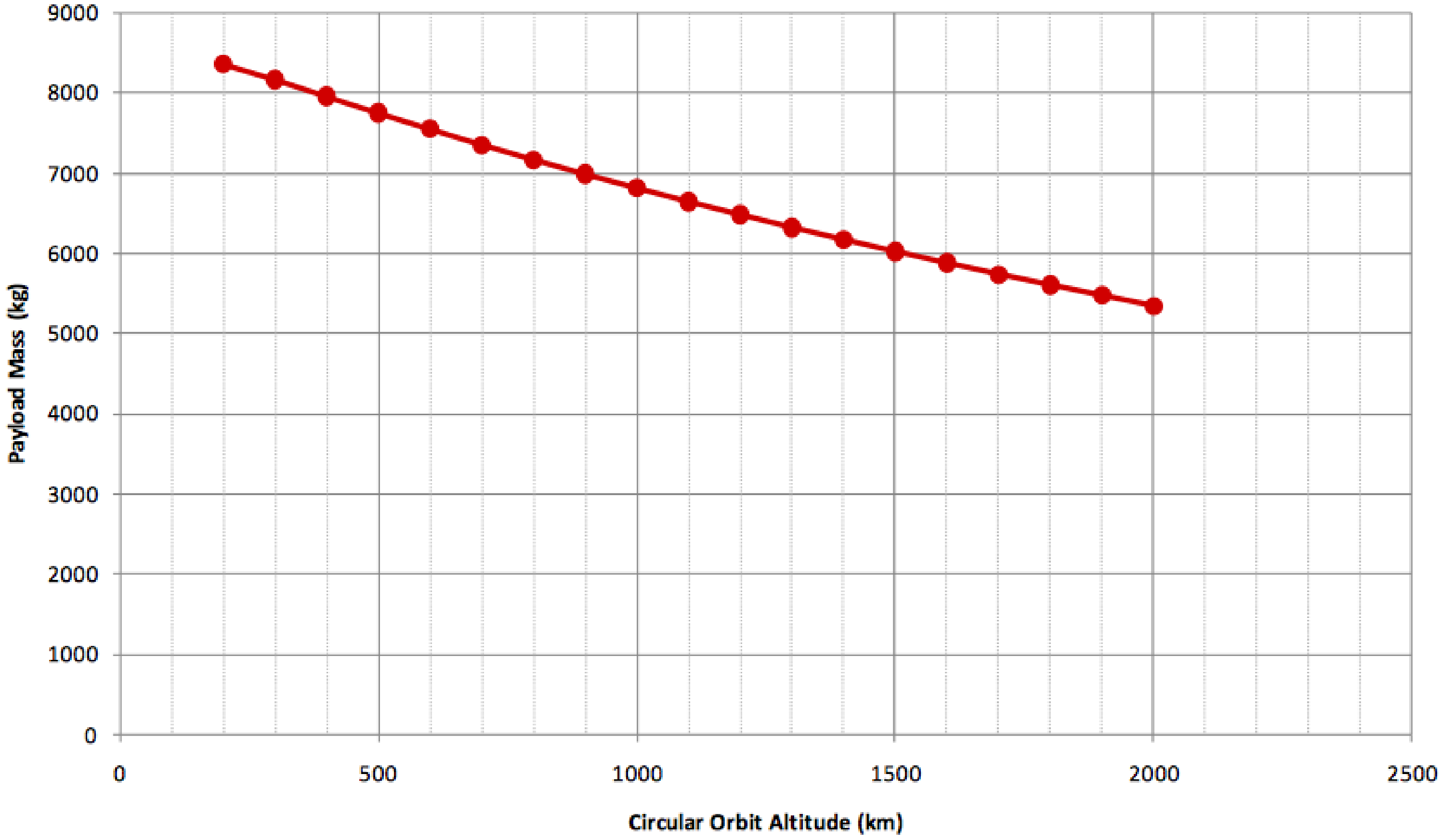
Launch Benefits – SSO – Falcon 9 (Block 2)



Falcon 9 User's Guide, Rev. 1

200 kg increase (2.6%) per
100 km altitude reduction (c.f 600 km)

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Launch Benefits – SSO – Soyuz CSG

Soyuz CSG User Manual, Issue 2

35 kg increase (0.8%) per
100 km altitude reduction (c.f 600 km)

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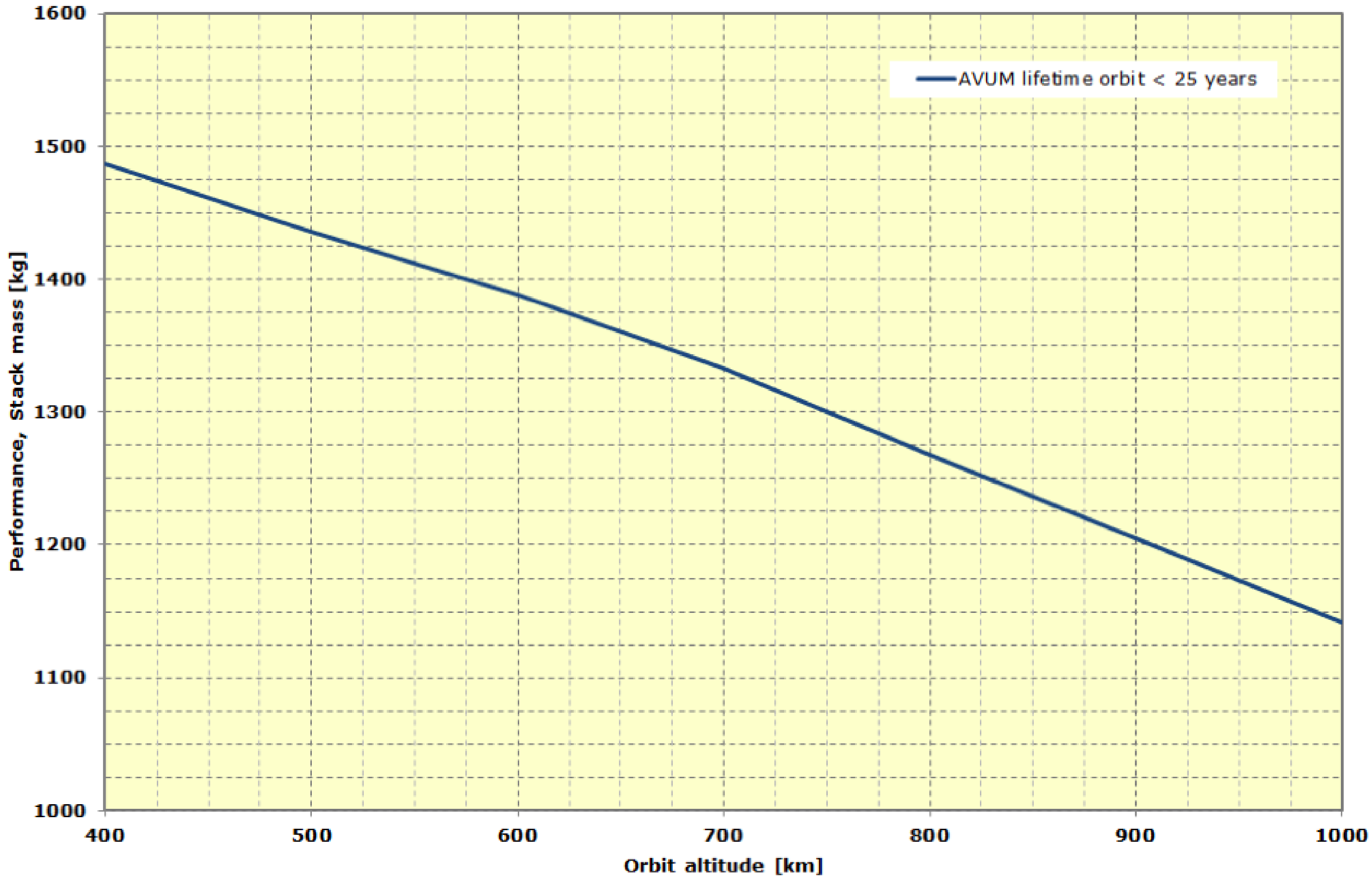
Launch Benefits – SSO - VEGA



VEGA User Manual, Issue 4

50 kg increase (3.6%) per
100 km altitude reduction (c.f 600 km)

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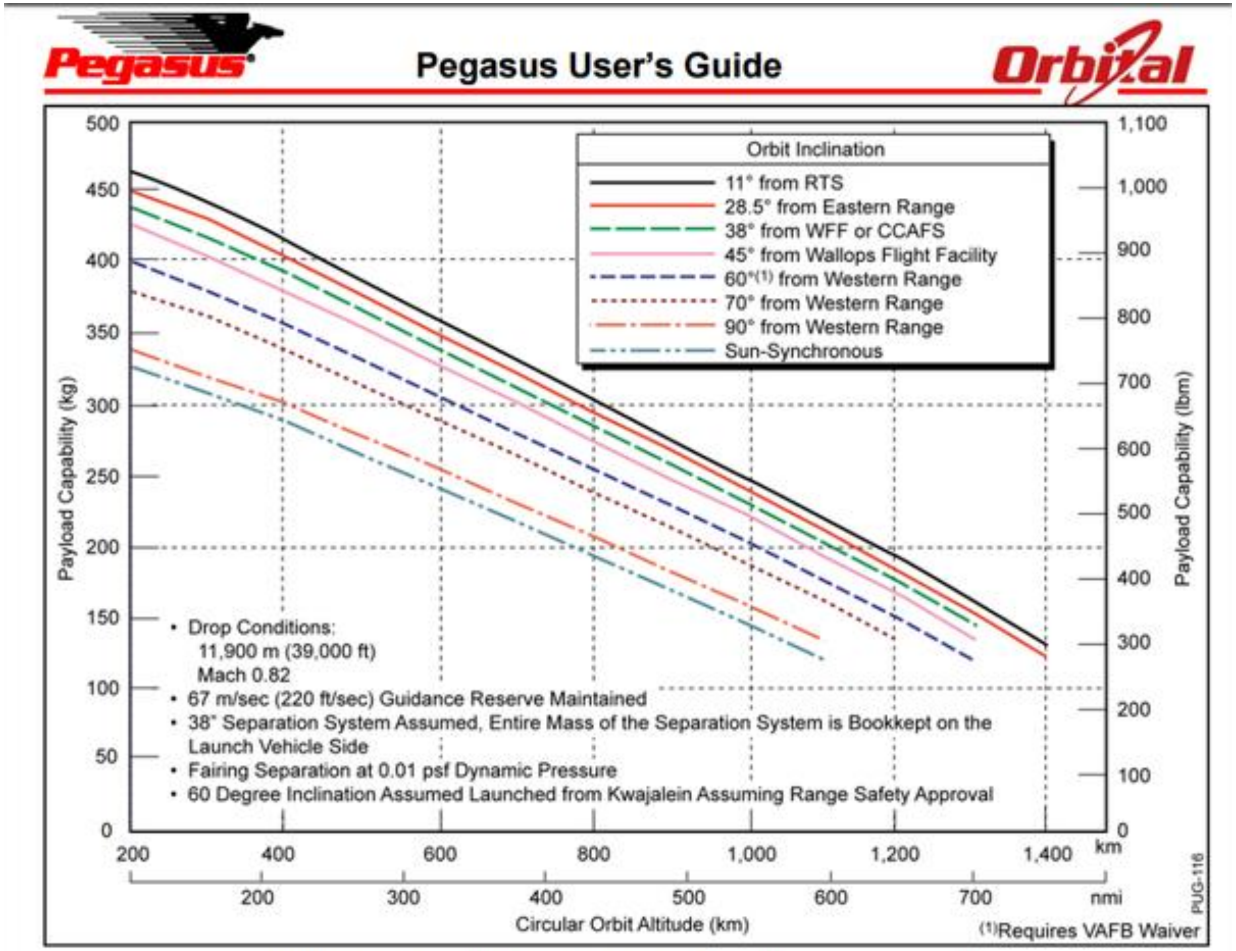
Launch Benefits – SSO - Pegasus



Pegasus User Guide

22.5 kg increase (9.4%) per
100 km altitude reduction (c.f 600 km)

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Very Low Earth Orbit
Earth Observation Platforms

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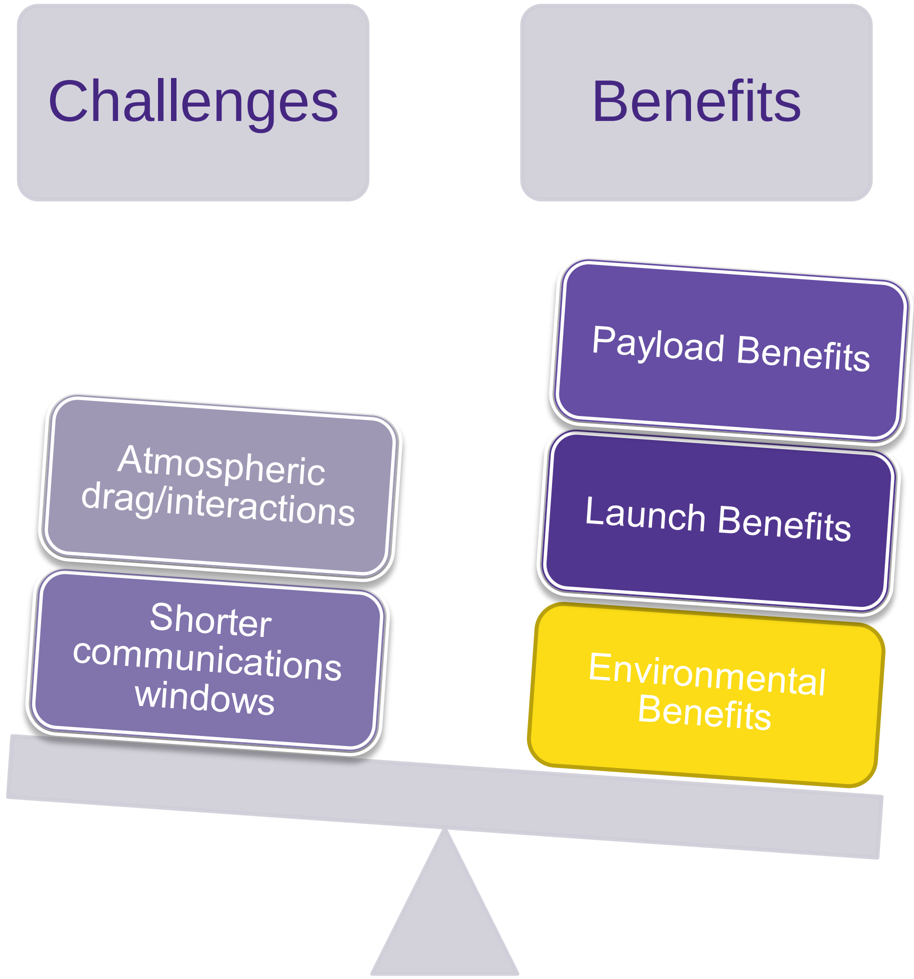

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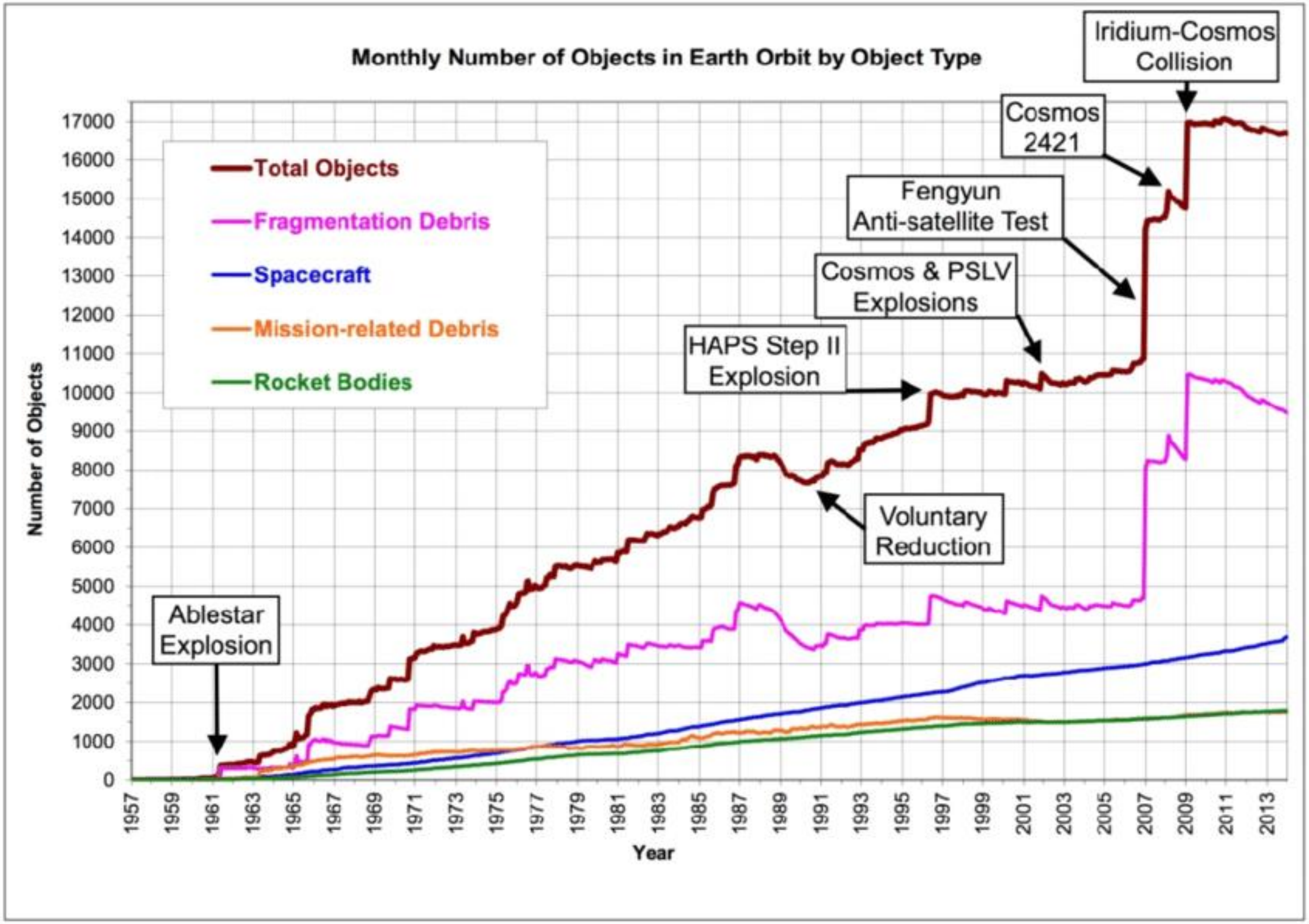
Environmental Issue – Space Debris



https://gizmodo.com/a-history-of-garbage-in-space-1572783046

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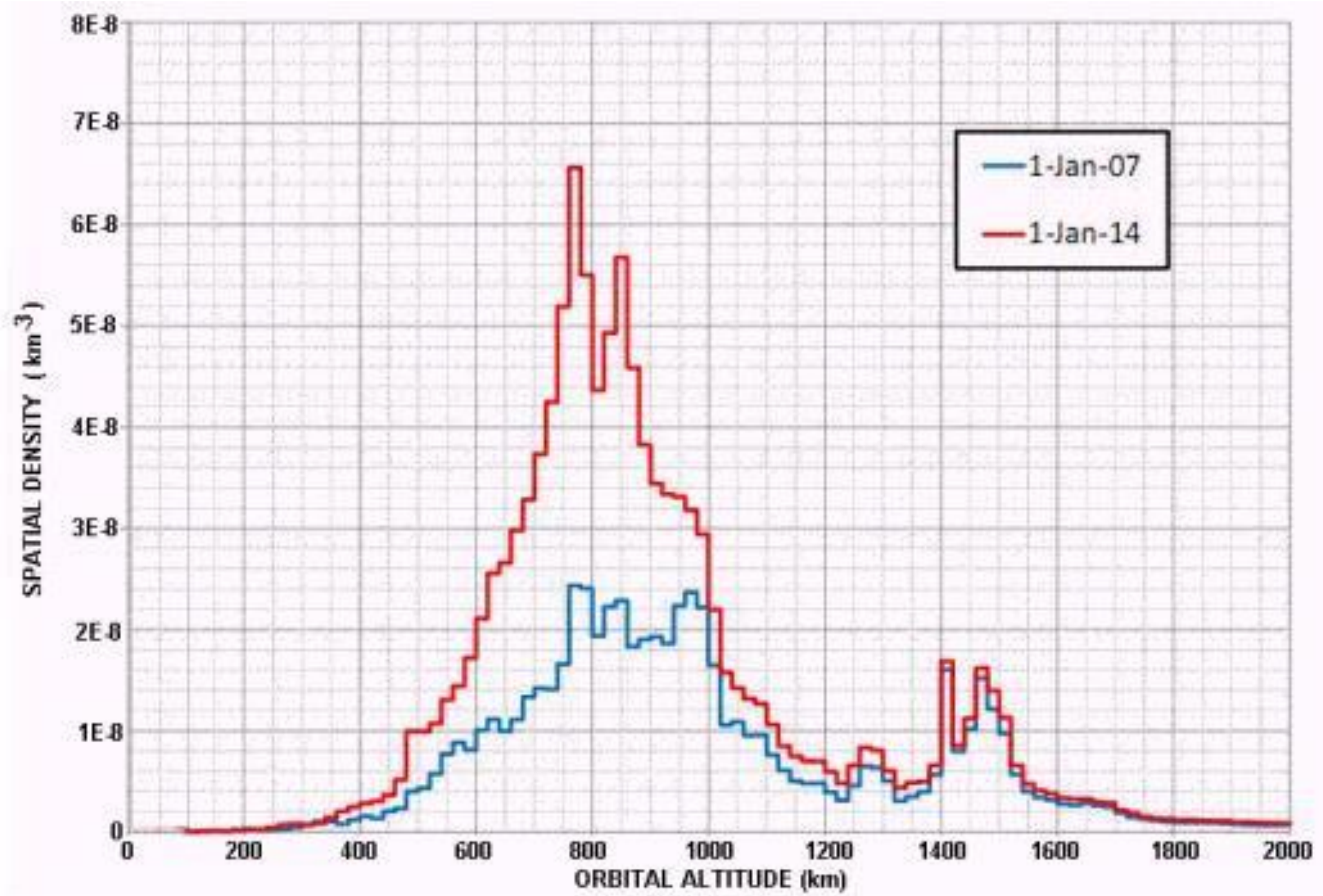
Environmental Issue – Space Debris



Credit: NASA Orbital Debris Programme Office

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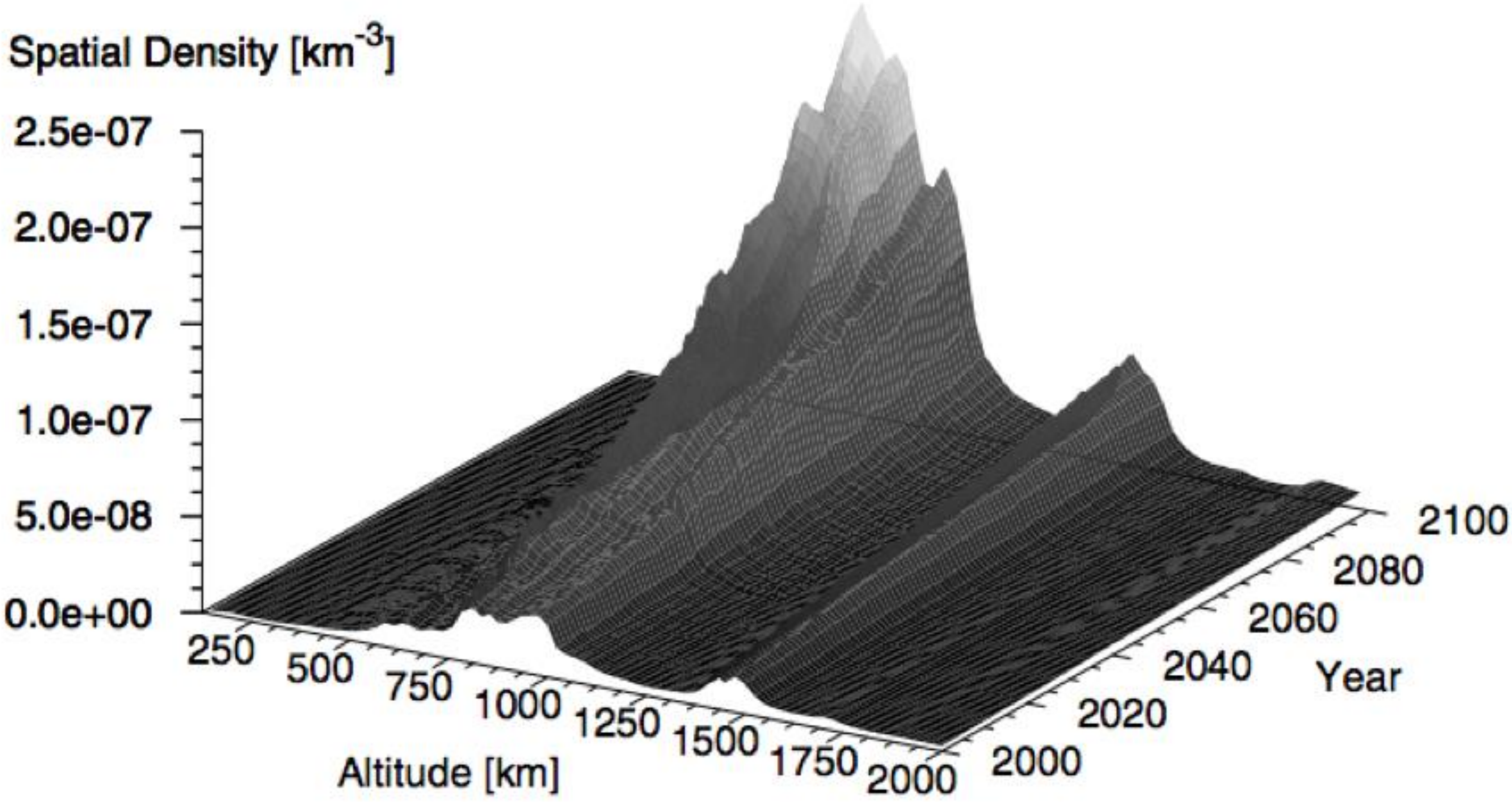
Environmental Benefits – Collision Risks



Klinkrad, H. 2006. *Space Debris – Models and Risk Analysis*. Springer.

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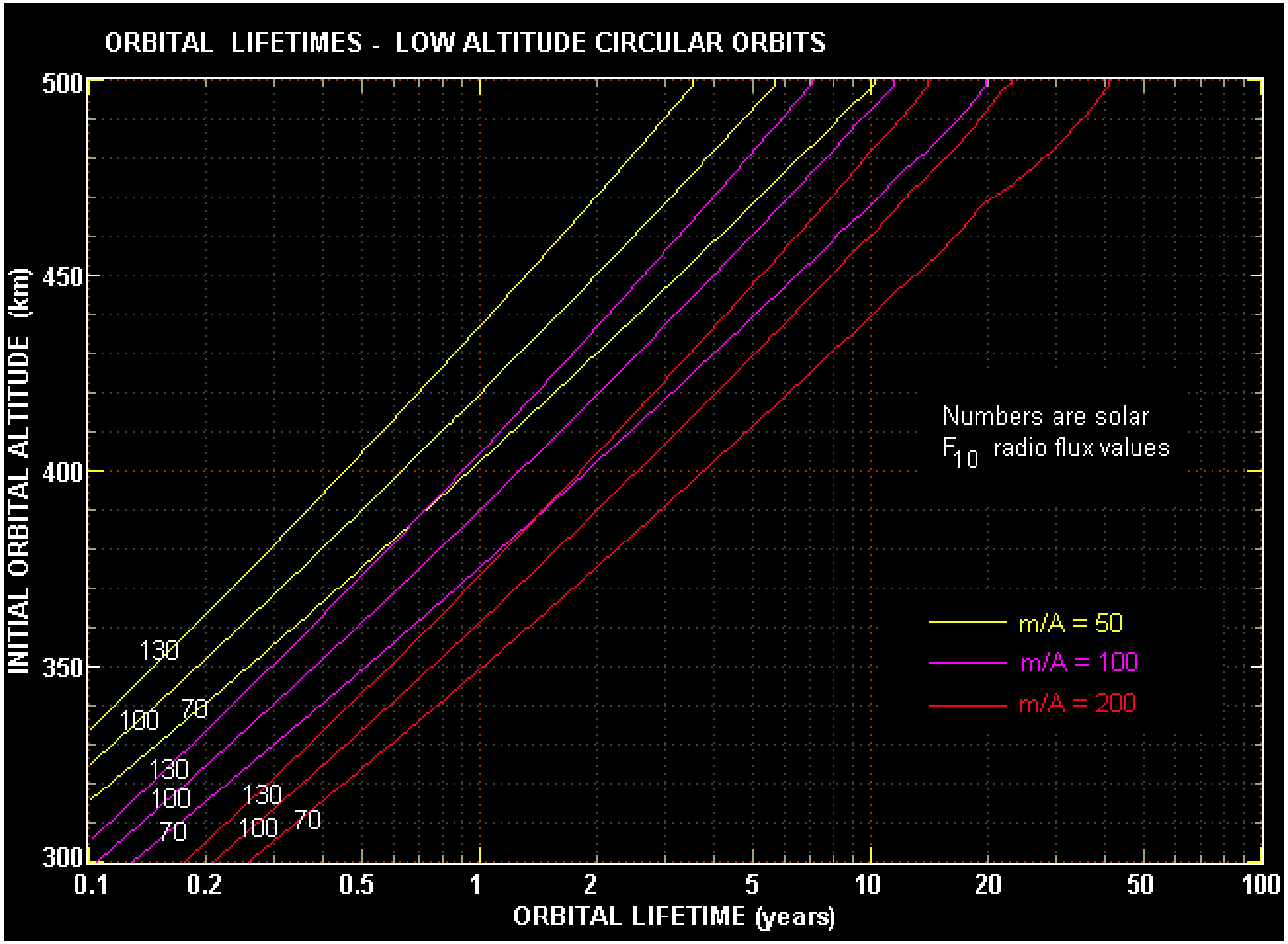
Environmental Benefits – Orbit lifetime and End-Of-Life Deorbit



http://www.spaceacademy.net.au/watch/debris/orblife.htm

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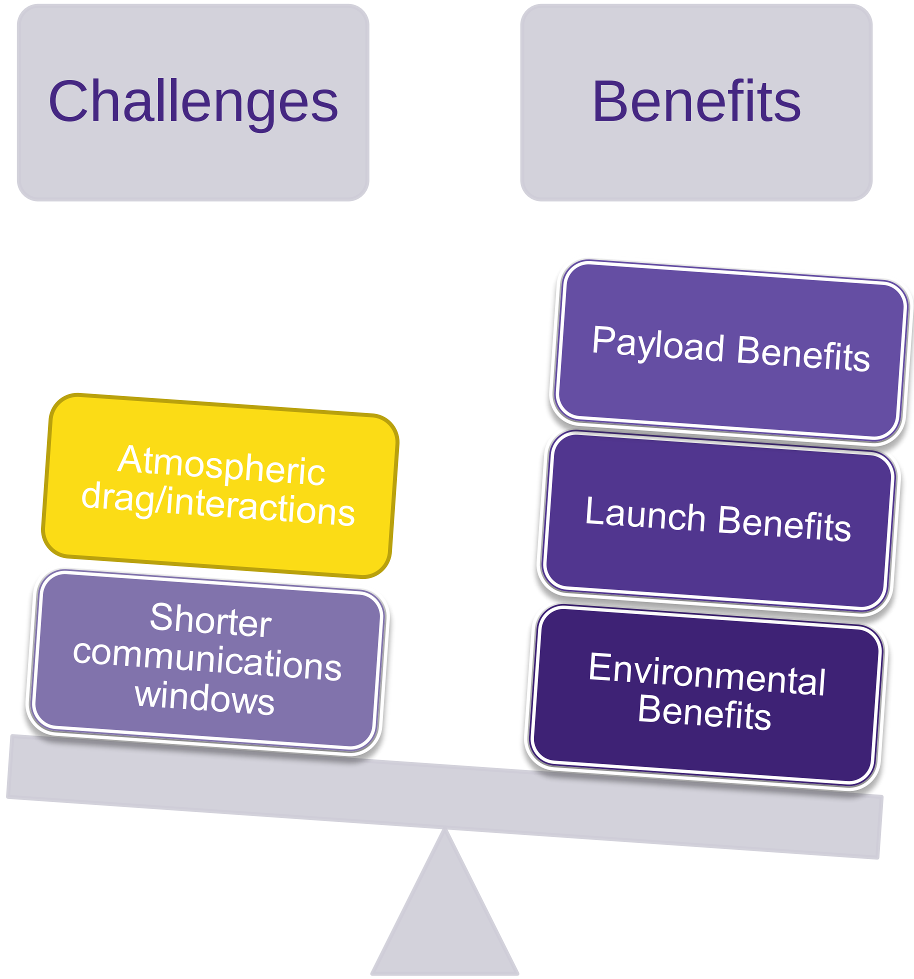
Very Low Earth Orbit Earth Observation Platforms



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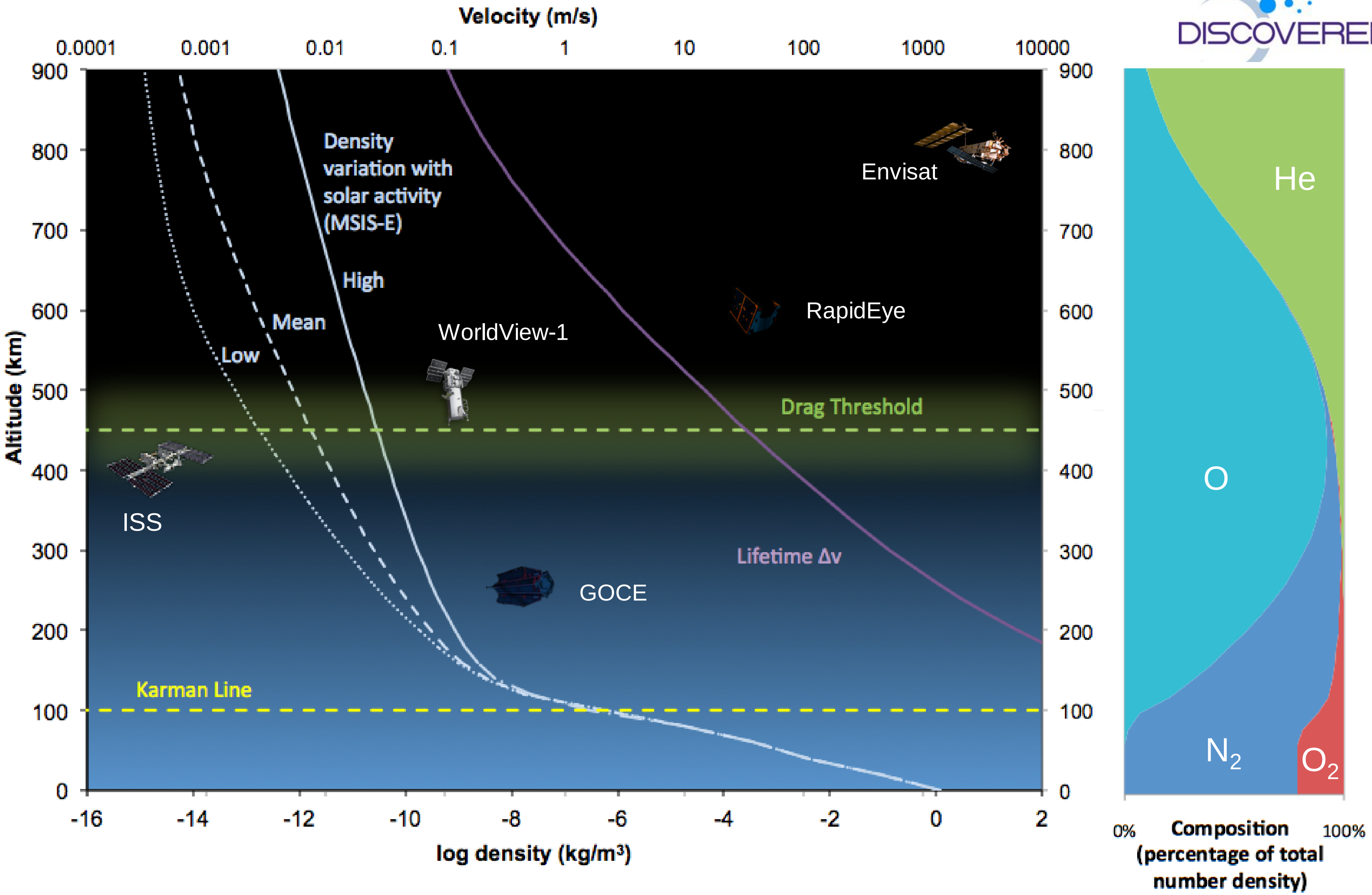
The Environment at Lower Altitudes



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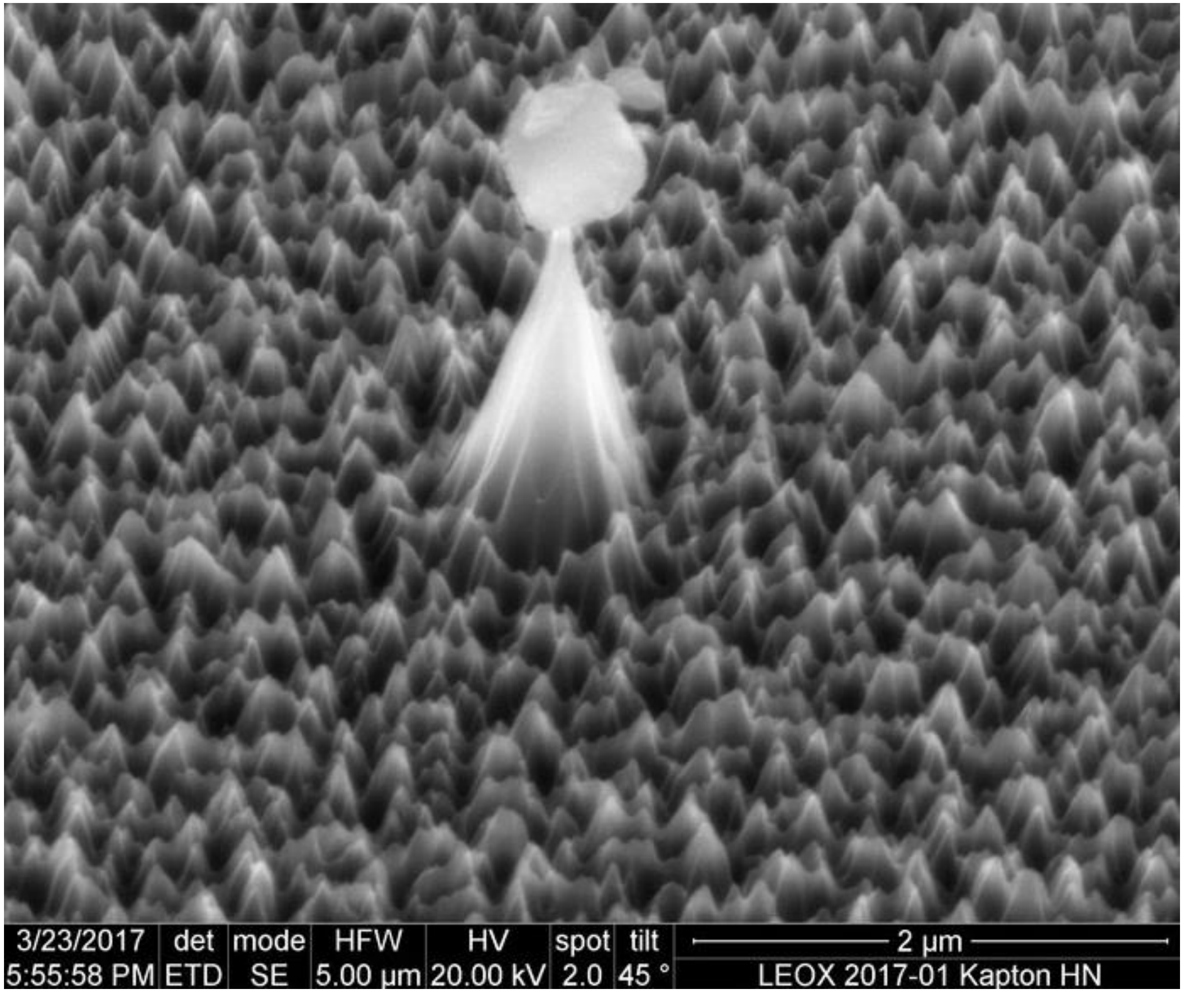
Challenges – Atmospheric Interactions Atomic Oxygen Erosion



- Erosion of Kapton with metallic contamination shielding the surface beneath
- Credit: ESA – CC BY-SA IGO 3.0

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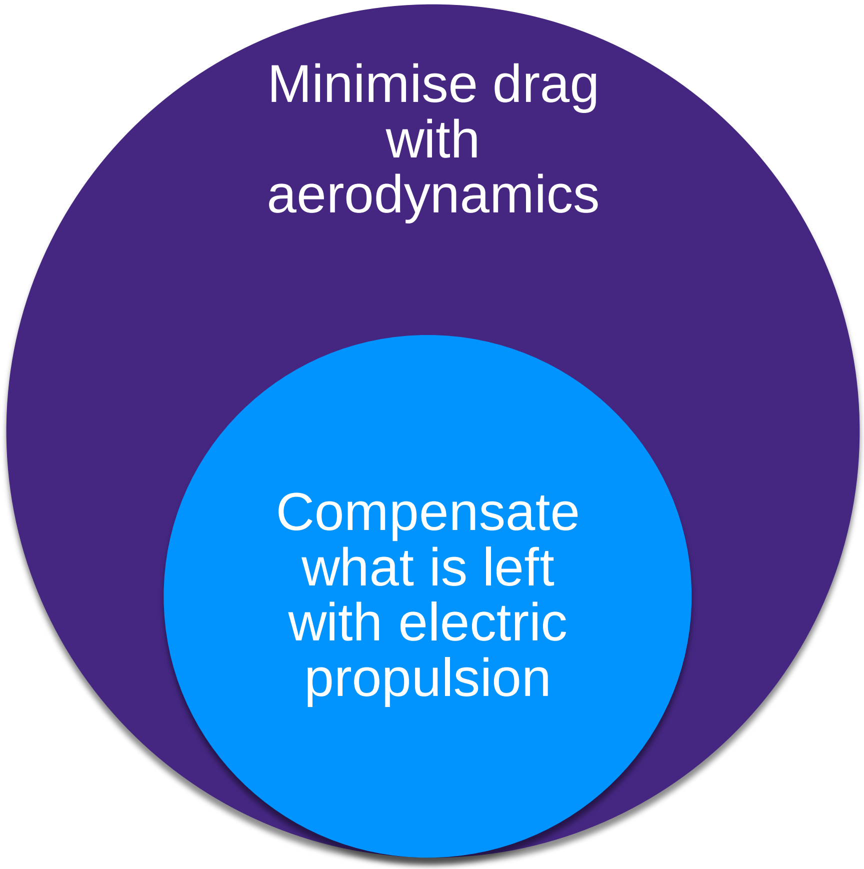
Challenges – Atmospheric Interactions
Atmospheric Drag – DISCOVERER strategy



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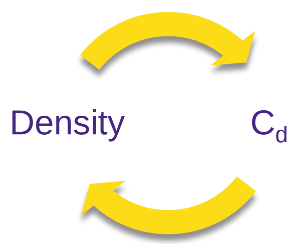
Challenges – Atmospheric Interactions
Atmospheric Drag

$$F_d = \frac{1}{2}\rho v^2 C_d A$$

Density:
Function of altitude, solar and geomagnetic activity

Velocity:
Function of altitude, atmospheric co-rotation (latitude), thermospheric winds

Specific ballistic coefficient: Dependent on geometry and gas surface interactions



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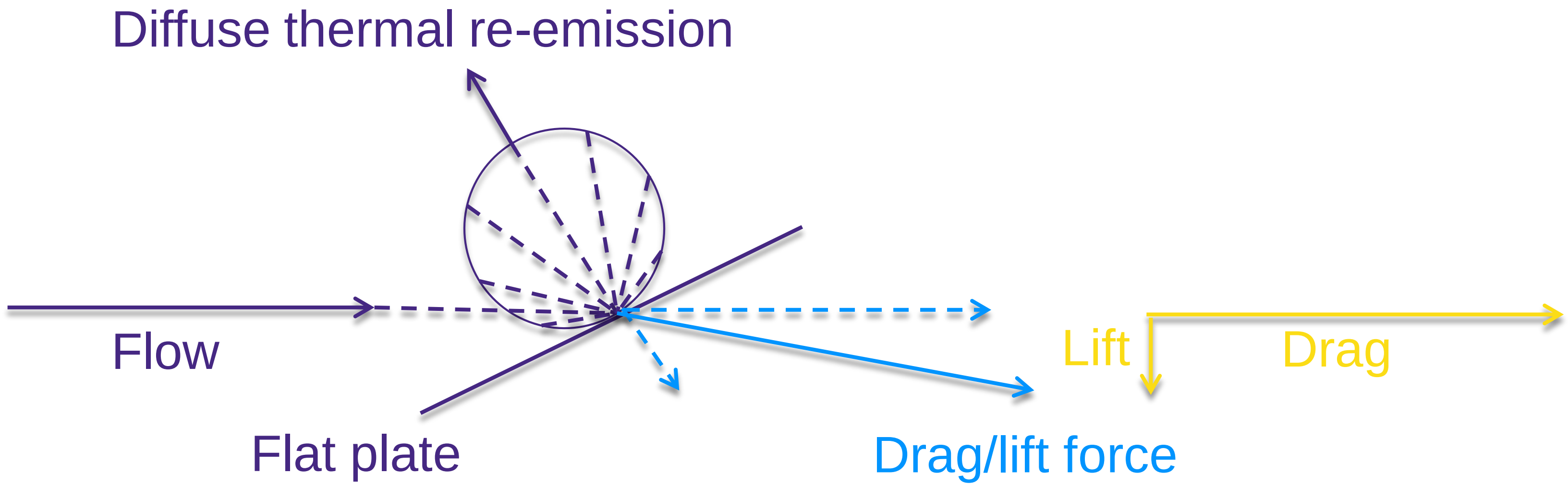
Challenges – Atmospheric Interactions
Gas Surface Interactions



- Complete accommodation
- Drag doesn't change significantly with geometry – cross-section to flow is key factor
- Approximates Newtonian flow
- Lift to drag ~1%

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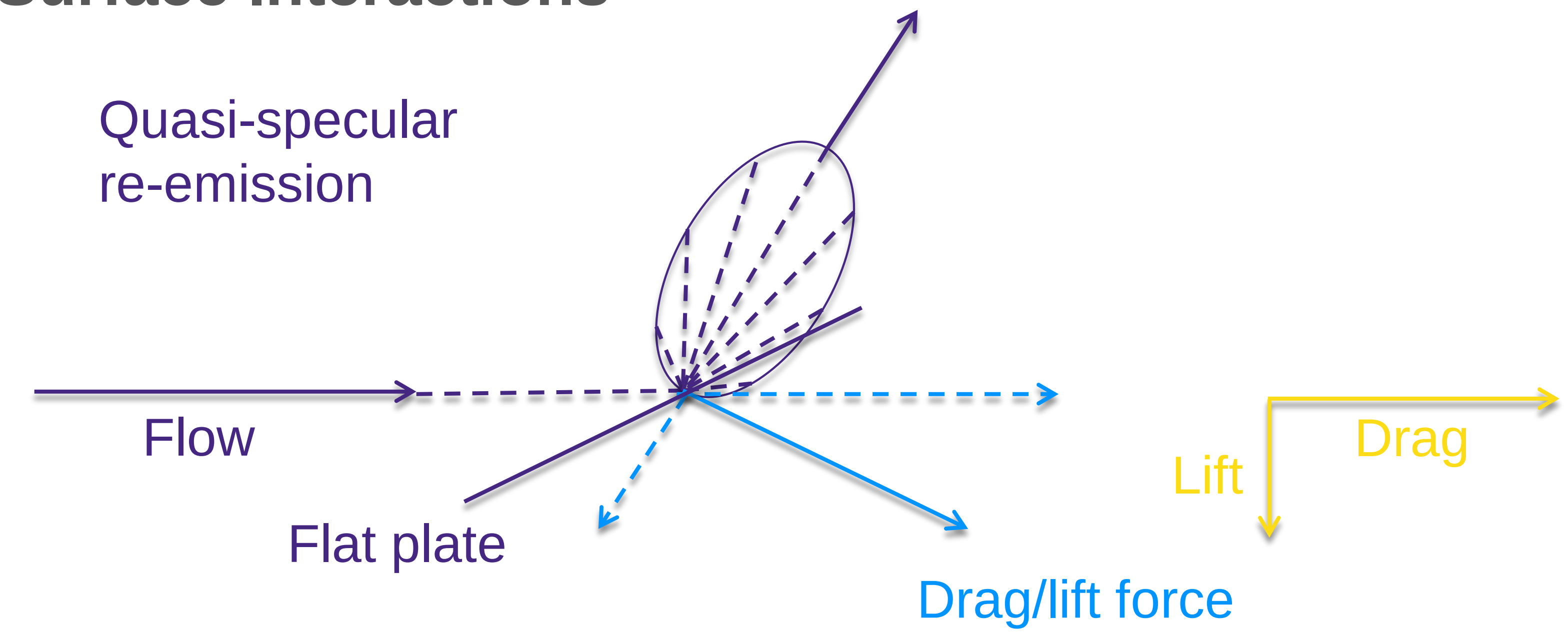
Challenges – Atmospheric Interactions
Gas Surface Interactions



- Quasi-specular re-emission- incomplete accommodation \ with partially diffuse re-emission
- Drag reduced for incidence angles greater than 45 degrees

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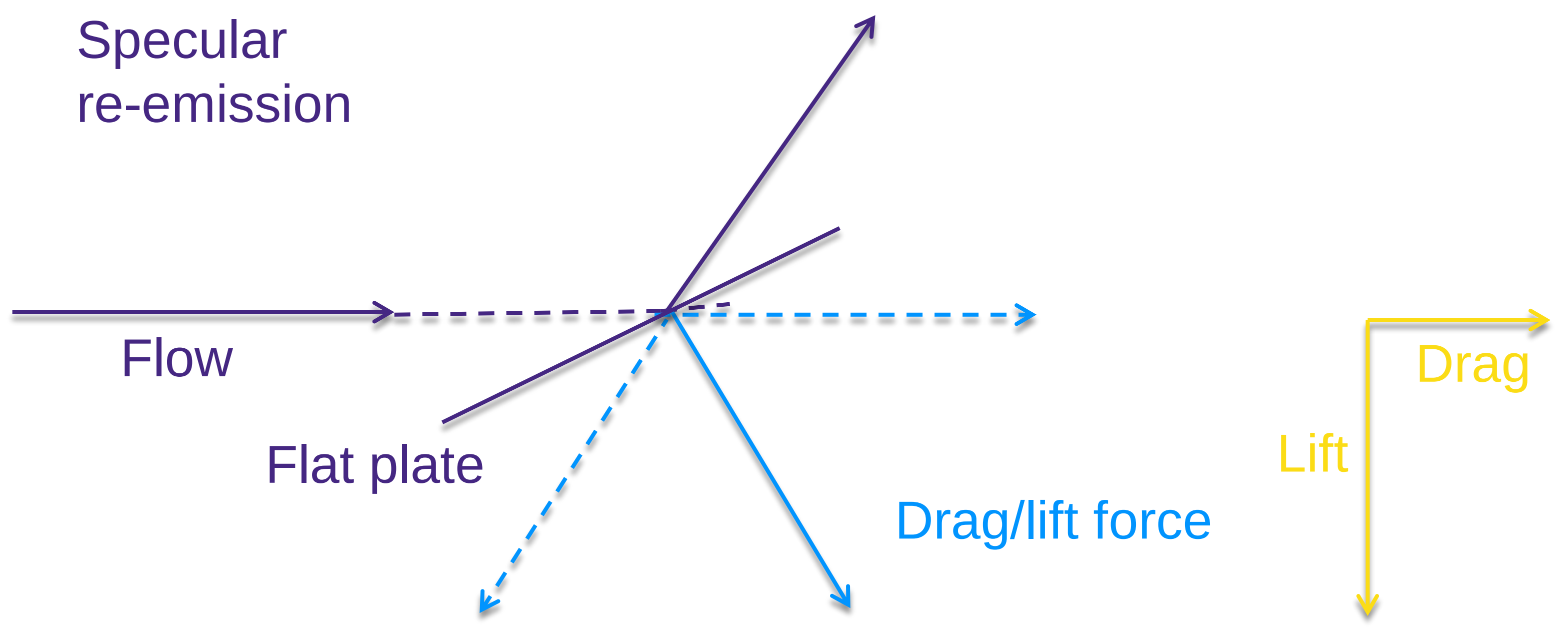
Challenges – Atmospheric Interactions
Gas Surface Interactions



- Specular – no accommodation with specular re-emission
- Drag significantly reduced for incidence angles greater than 45 degrees

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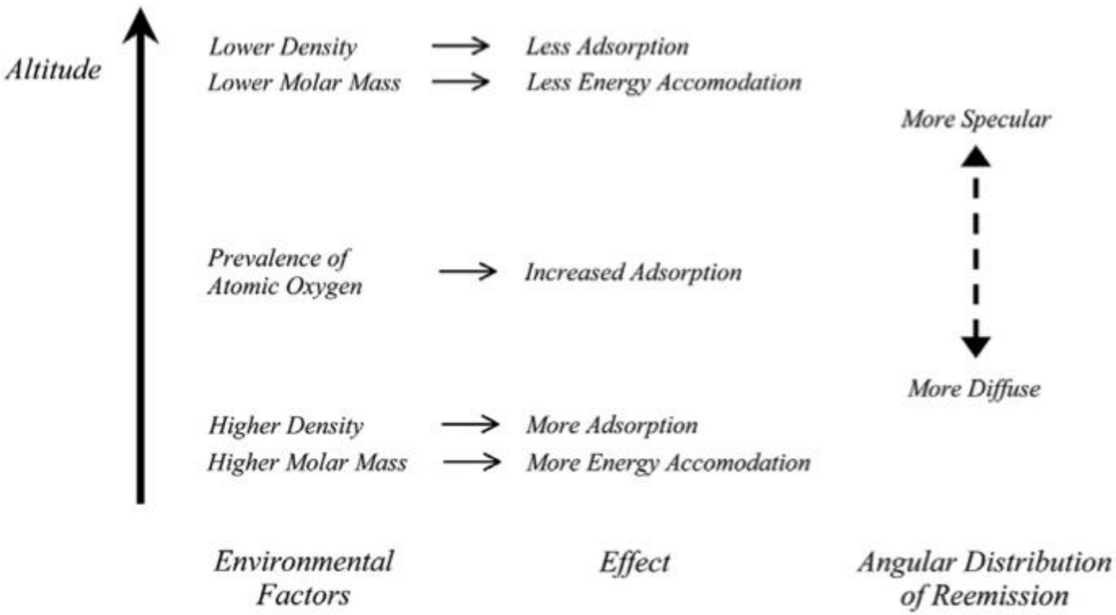
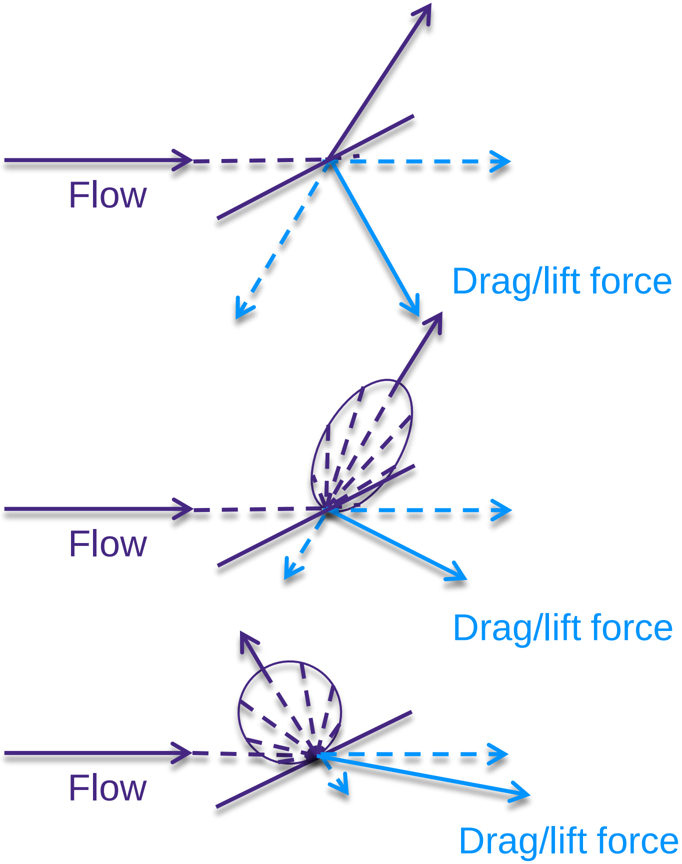
Aerodynamics Dictated By Gas Surface Interactions





Mostaza Prieto, D., Graziano, B., and Roberts, P. C. E. (2014). "Spacecraft drag modelling." Progress in Aerospace Sciences **64**: 56-65.

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Material Dependence of Gas Surface Interactions

Accommodation coefficient varies with:

- Surface roughness
- Surface molecular composition and lattice configuration
- Surface cleanliness (one example of which is atomic oxygen adsorption)
- Flow velocity
- Flow incidence angle

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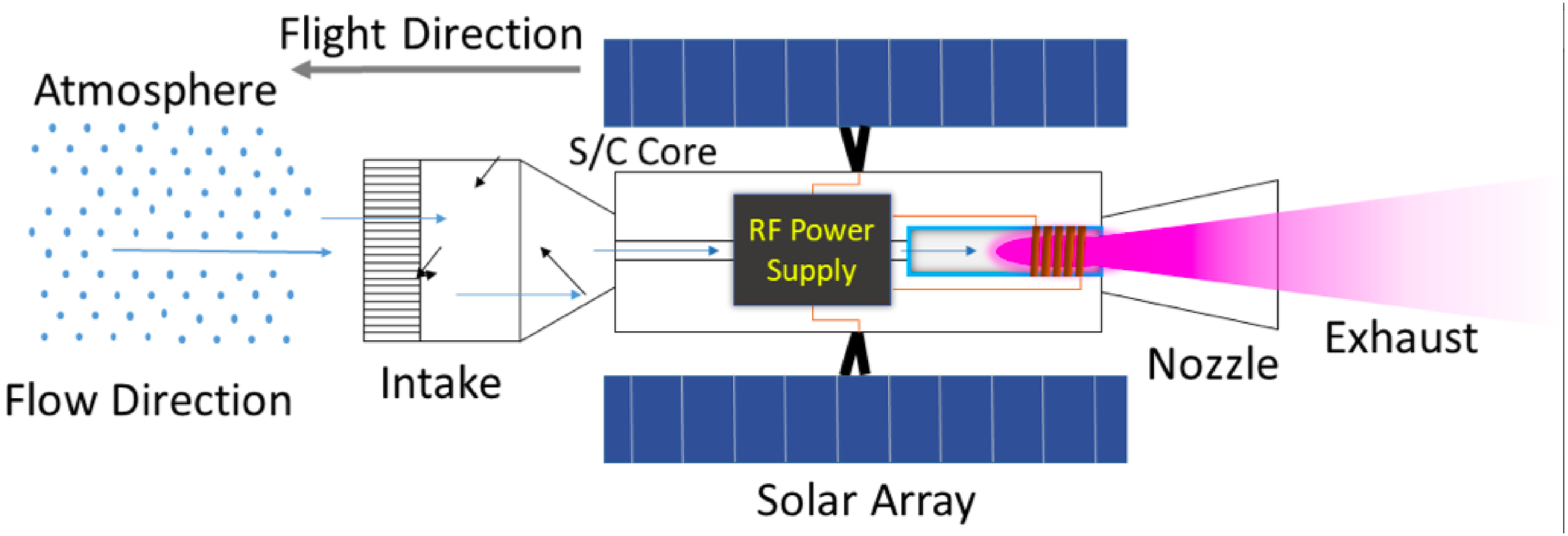
Drag compensation – Atmosphere breathing electric propulsion



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Aerodynamic Attitude Control – Opportunity? Augmentation to Traditional ACS

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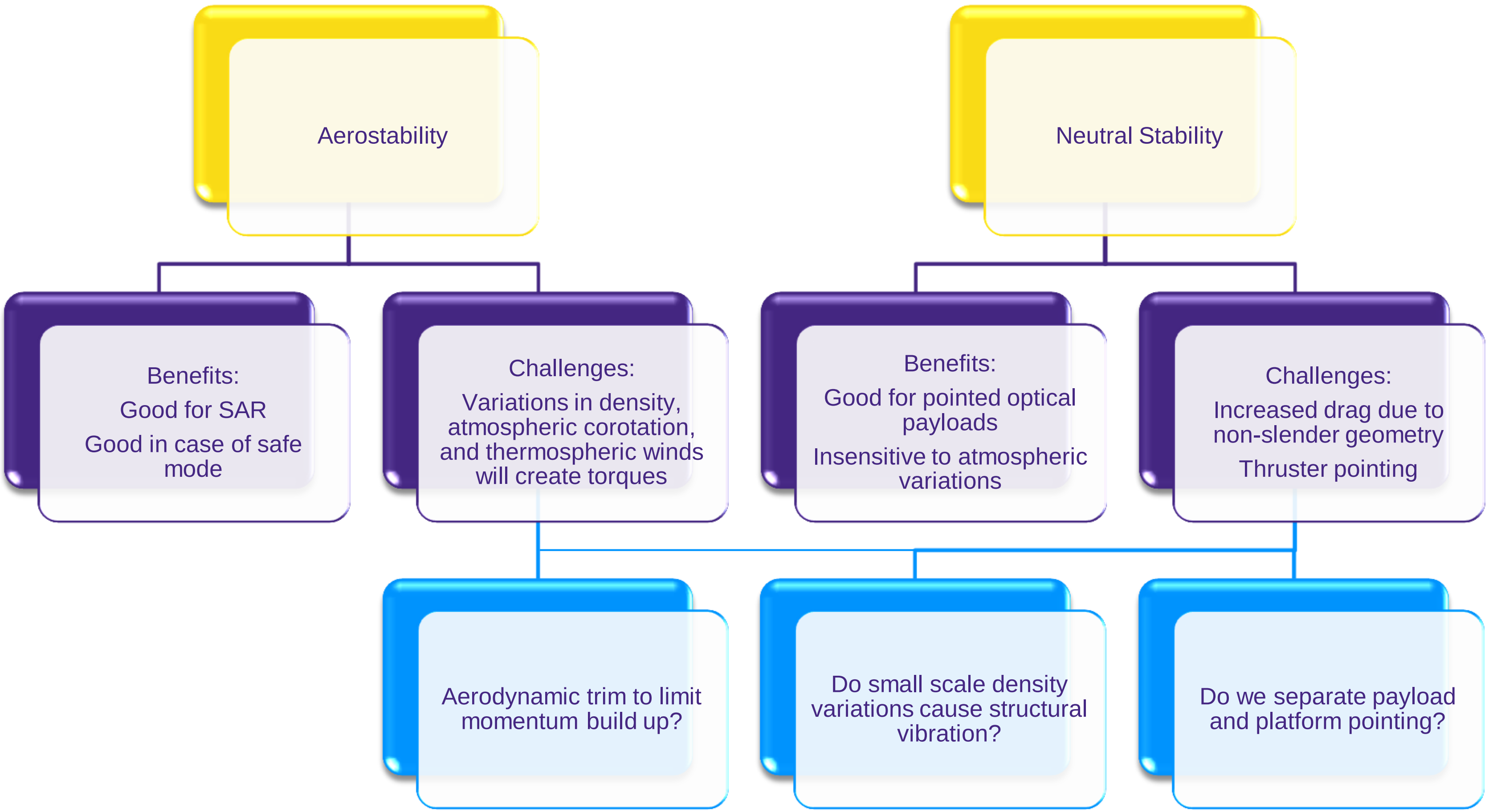

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Aerodynamic Attitude Control – Opportunity? Active Aerodynamic Control Alone?

Possible but…

- Variations in density and thermospheric winds mean actuation is variable – needs predictive control and atmospheric sensors?
- Actuation forces are small at higher VLEO altitudes (comparable to solar radiation pressure)
- Without specular reflections, actuation is limited to drag effects (pitch and yaw)

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Aerodynamic Orbit Control – Opportunity?

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- Constellation Deployment
  - Differential drag used to control orbit plane (RAAN) variations
  - With specular reflection, lift can be used to vary orbit parameters, even in aerostable state
- Targeted Reentry
  - Modulating drag can be used to target latitude and longitude of reentry point

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Conclusions

Benefits

Improved payload performance

Optical payloads have:

- Increased resolution or reduced aperture size
- Improved radiometric performance

Radar payloads have:

- Reduced antenna size
- Reduced transmission power

Improved geospatial accuracy

Improved launch vehicle payload mass

End-of-life disposal is enabled

Reduced space debris collision risk (both now and long term - orbit is resilient to space debris cascades)

Challenges

Increased atmospheric drag

Increased atomic oxygen erosion

Shorter communications windows with ground stations

Opportunities

Residual atmosphere as a propellant for drag compensation

Aerodynamic attitude and orbit control

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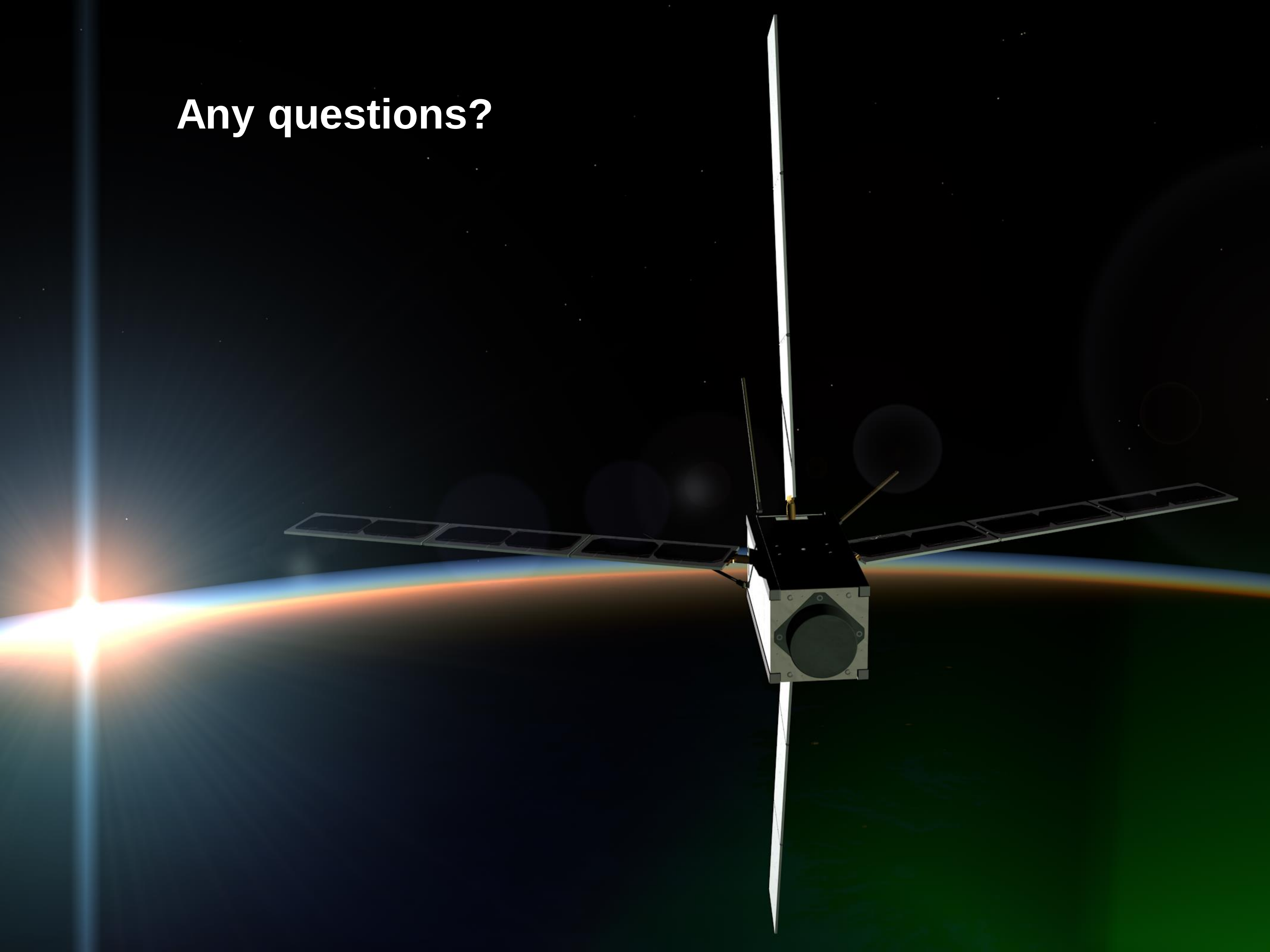
Any questions?