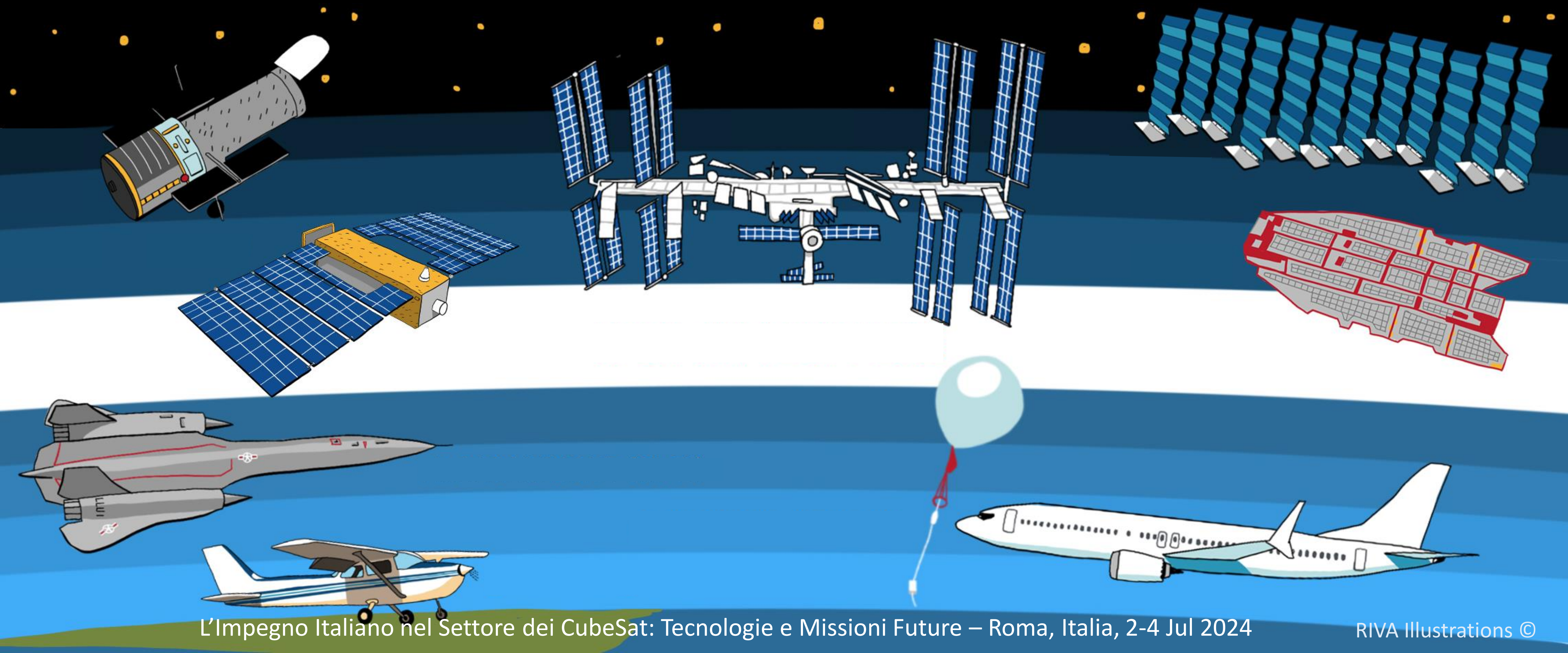
Air-breathing electric propulsion for Future Cubesat Missions in VLEO

Eugenio Ferrato, Vittorio Giannetti, Tommaso Andreussi

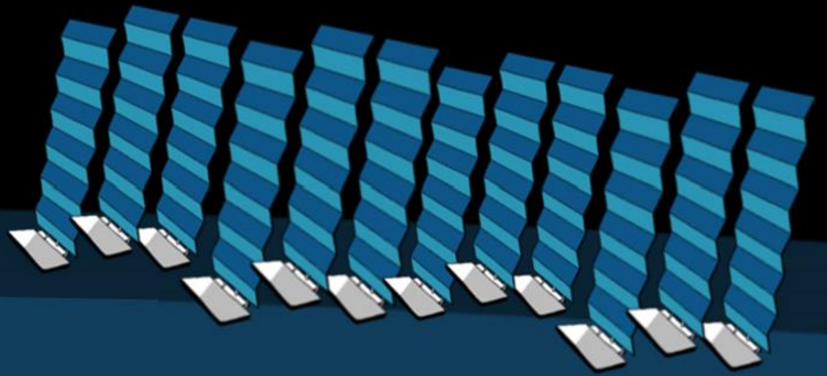


L'Impegno Italiano nel Settore dei CubeSat: Tecnologie e Missioni Future – Roma, Italia, 2-4 Jul 2024

Very-low Earth orbits

Lowering the spacecraft altitude below 350 km, in Very-low Earth orbit (VLEO), would provide significant advantages for

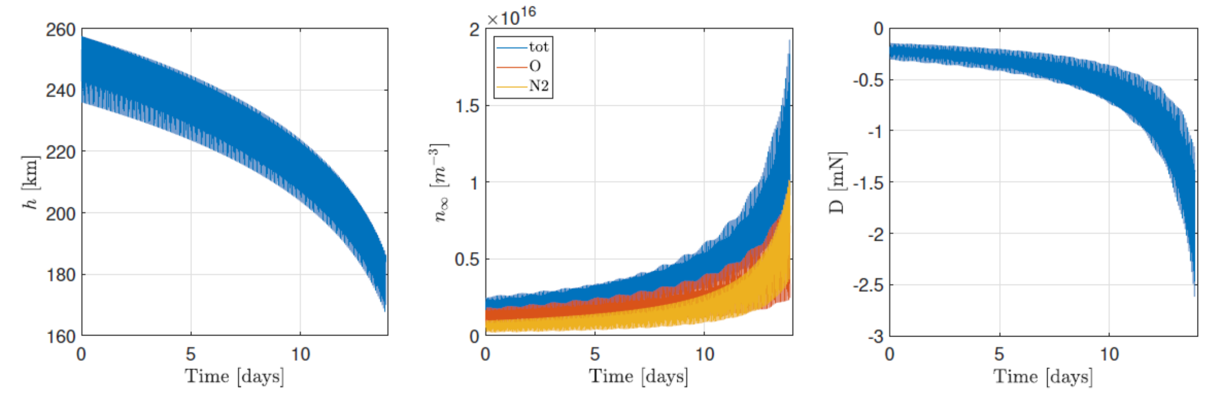
- Communication and connectivity
- Earth observation and monitoring
- Space and Earth science
- Satellite constellations



At the same time, the presence of a residual atmosphere offer

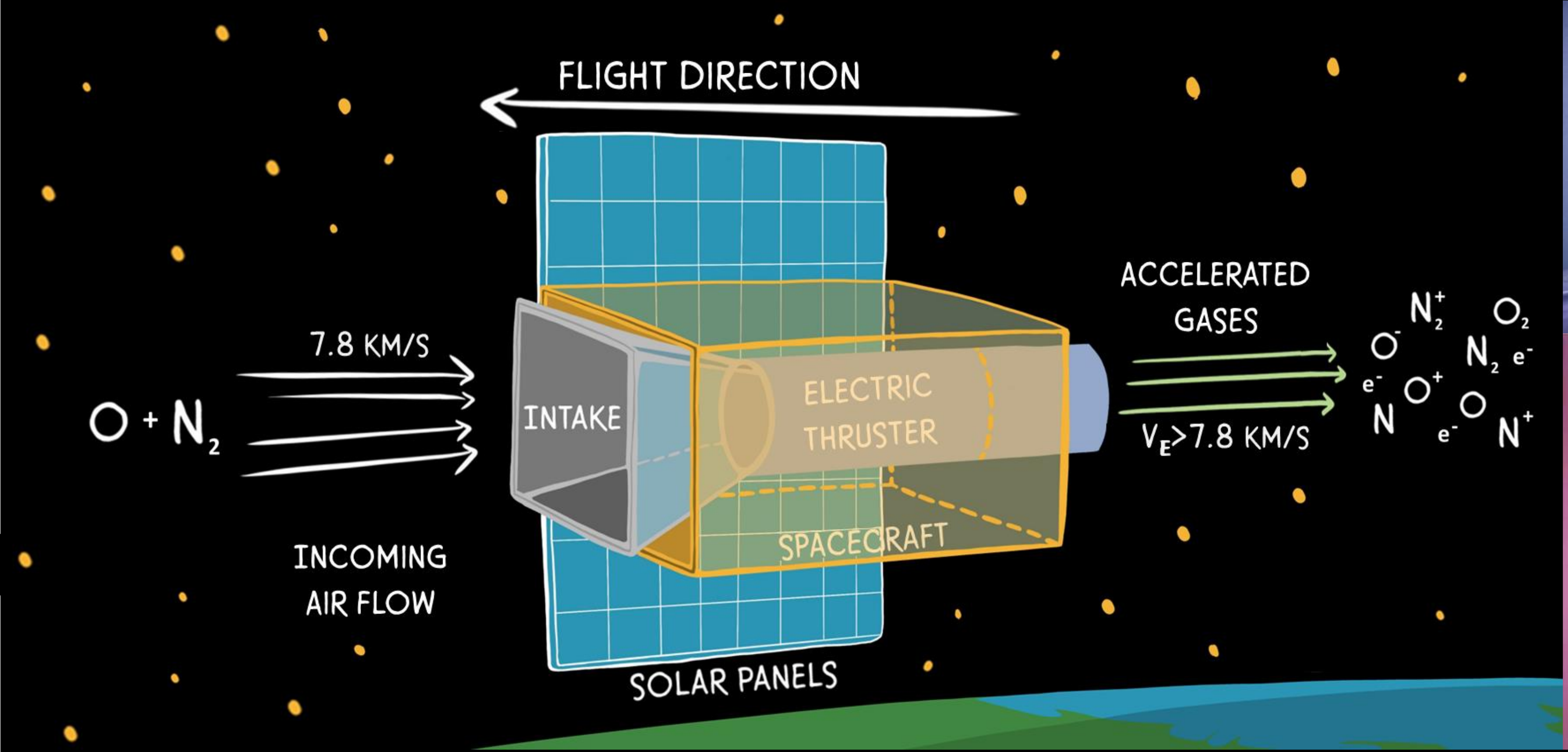
- Low radiation levels
- Rapid debris decay
- Automatic spacecraft re-entry

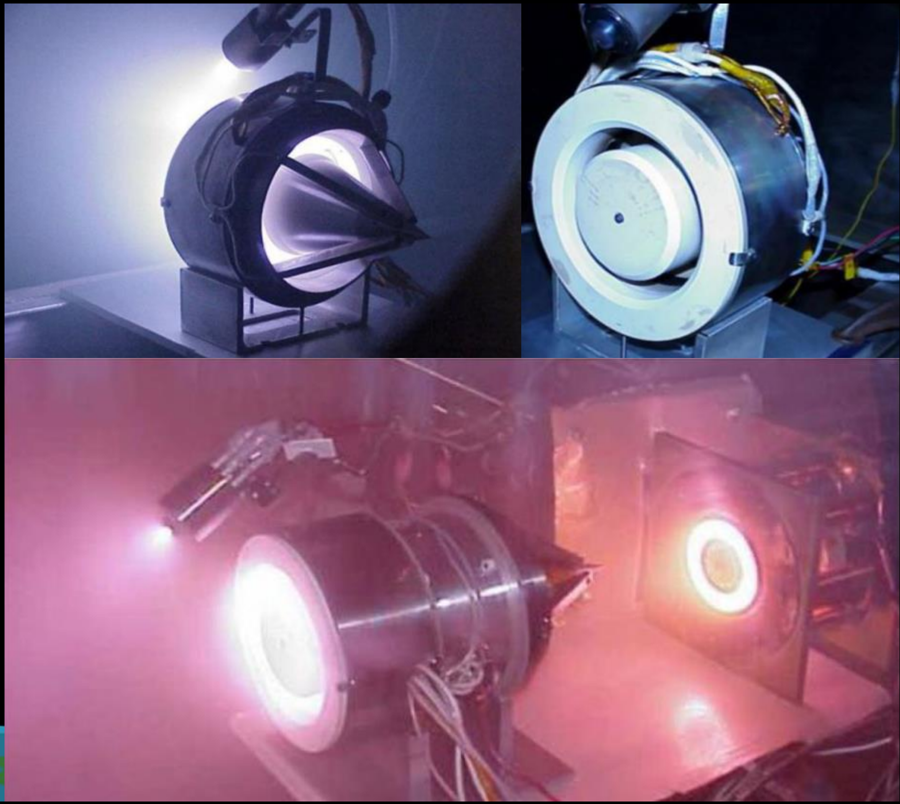
However, the presence of residual atmospheric gases translates in **drag levels in the order of 10-100 mN/m²**, resulting into fast orbit decay of unpropelled spacecraft.



On the other hand, traditional propulsion ties the mission lifetime to the amount of propellant stored on-board.

Air-breathing Electric Rocket (AER)





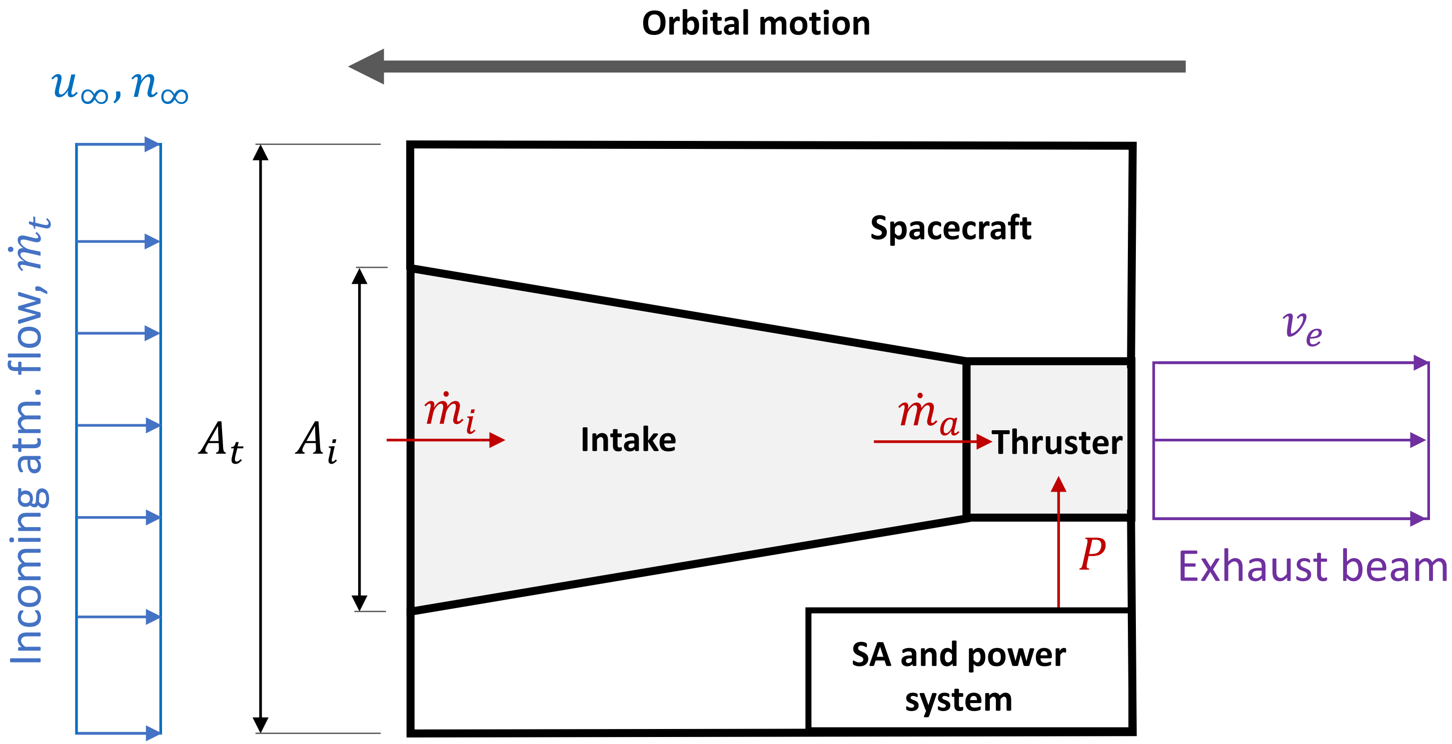
State-of-the-art: only three on-ground test campaigns* have been performed so far. Demonstrated performance still insufficient for compensating the drag of a full platform.

*Tagawa et al. (2013) J. Propuls. Power 29
Hruby et al. (2022) IEPC-2022-446
Andreussi et al. (2017) IEPC-2017-377

A single constraint

AER performance relies on:

- How efficiently we use the total (drag-inducing) frontal area to collect propellant $\eta_A = \frac{A_i}{A_t}$
- How efficiently the intake collects the propellant and transfers it to the thruster $\eta_c = \frac{\dot{m}_a}{\dot{m}_i}$
- How efficiently the thruster uses the available power to generate thrust $\eta_T = \frac{T^2}{2\dot{m}_a P}$



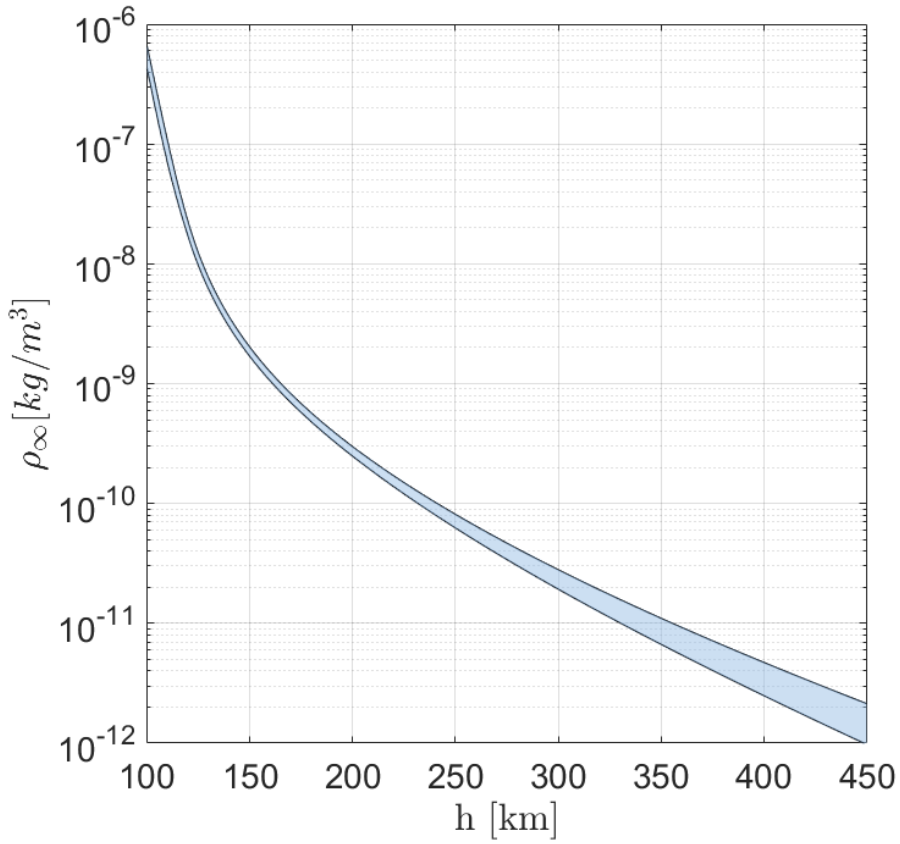
The condition $T > D$ then translates to:

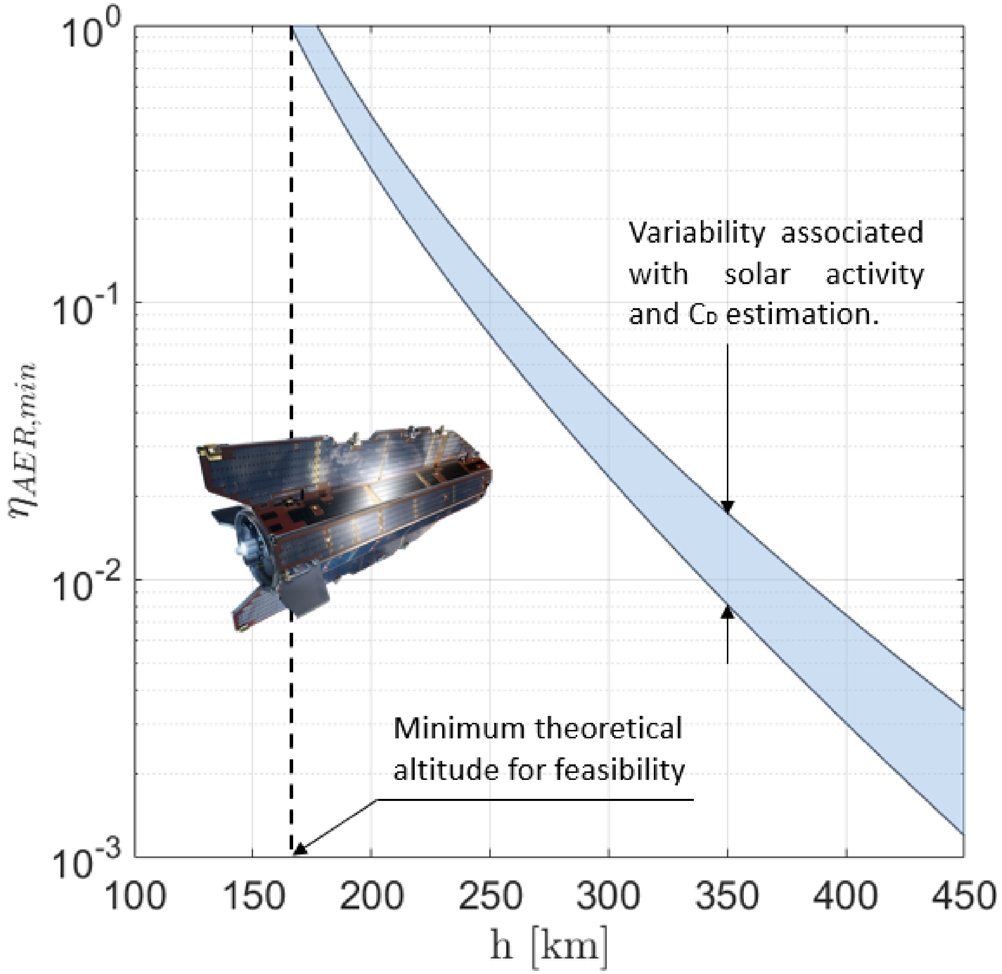
$$\sqrt{2P\eta_A\eta_c\eta_T\rho_\infty u_\infty A_t} > \frac{1}{2}C_D A_t \rho_\infty u_\infty^2$$

$$\eta_{AER} \doteq \frac{T^2}{2\dot{m}_t P} = \eta_A\eta_c\eta_T > \underbrace{\left[\frac{1}{2}\rho_\infty u_\infty^3\right]}_{O} \Big/ \underbrace{\left[\frac{4P}{C_D^2 A_t}\right]}_{S}$$

A single constraint

$$\eta_{AER} \doteq \frac{T^2}{2\dot{m}_t P} = \eta_A \eta_c \eta_T > \left[\frac{1}{2}\rho_\infty u_\infty^3\right] / \left[\frac{4P}{C_D^2 A_t}\right]$$





- **Higher altitudes** imply **lower AER feasibility requirement.**
- But lower atmospheric densities generally imply **difficulties in achieving high thruster efficiency.**

Air-breathing Cubesat Mission Analysis: Reference Platform

*Reproduced from https://terranorbital.com/spacecraft-platforms/triumph/

Item	Parameter	Symbol	Value	Unit
Full platform	mass	$M_{S/C}$	14	kg
Terrain Orbital Triumph	CoG position	$\mathbf{\Delta r_{CoG}}$	[0,0,0]	m
	$x_B x_B$ inertia	$I_{S/C,xx}$	0.466	kgm^2
	$y_B y_B$ inertia	$I_{S/C,yy}$	0.432	kgm^2
	$z_B z_B$ inertia	$I_{S/C,zz}$	0.139	kgm^2
	max. solar array power	P_{max}	100	W
4 reaction wheels	wheel inertia	I_{RW}	3e-5	kgm^2
NanoTorque GSW-600	max. torque per wheel	$\tau_{RW,sat}$	1.5e-3	Nm
in pyramidal config.	max. wheel velocity	$\omega_{RW,sat}$	6000	rpm
3-axes magnetorquers GST-600	dipole saturation per axis	$m_{MT,sat}$	0.3	Am^2
2 sun sensors NanoSense FSS	3σ accuracy	σ_{SS}	2	deg
2 star trackers arcsec Twinkle	3σ accuracy	σ_{ST}	0.03	deg
3-axes magnetometer NanoSense M315	3σ accuracy	σ_{MM}	5e-9	T
3-axes MEMS gyro	3σ noise	$\sigma_{\omega,GY}$	0.15	deg/s
InvenSense MPU-3300	3σ bias drift noise	$\sigma_{b,GY}$	0.015	deg/s^2
	bias drift time constant	$\tau_{b,GY}$	600	s
GPS Kit NovAtel OEM-719	3σ accuracy	σ_{GPS}	4.5	m

Spacecraft Dynamics, Guidance, and Navigation

Orbit Dynamics in the Earth-Centred-Inertial Frame

$$\dot{\boldsymbol{r}}_{ECI} = \boldsymbol{v}_{ECI}$$

$$\dot{\boldsymbol{v}}_{ECI} = -\mu \frac{\boldsymbol{r}_{ECI}}{|\boldsymbol{r}_{ECI}|^3} + \boldsymbol{a}_g + \boldsymbol{a}_e + \frac{\boldsymbol{D}_{ECI}}{M_{S/C}} + \frac{\boldsymbol{T}_{ECI}}{M_{S/C}},$$

Gravity harmonics

Minor perturbations

Drag acc.

ABEP acc.

Attitude Dynamics in the body frame

Gravity gradient torque

$$\dot{\mathbf{q}}_{ECI2B} = \frac{1}{2}\begin{bmatrix} 0 \\ \boldsymbol{\omega}_{ECI2B} \end{bmatrix} \circ \mathbf{q}_{ECI2B}$$

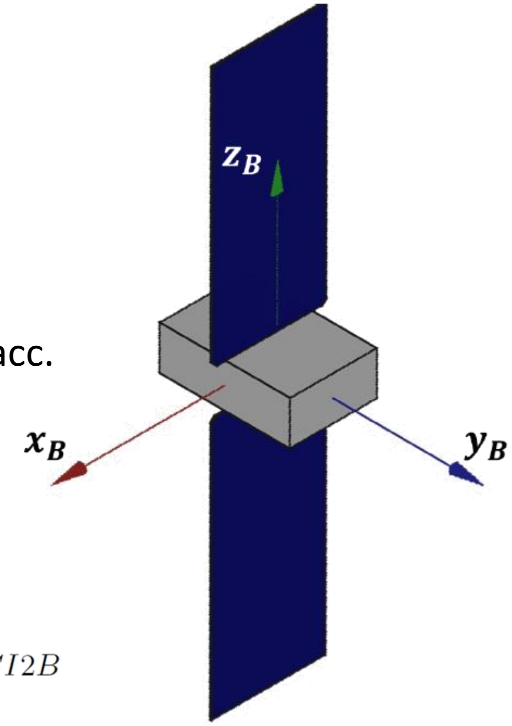
$$\dot{\boldsymbol{\omega}}_{ECI2B} = \mathbf{I}_{S/C}^{-1}(\boldsymbol{\tau}_g + \boldsymbol{\tau}_e + \boldsymbol{\tau}_D + \boldsymbol{\tau}_T + \boldsymbol{\tau}_a - \boldsymbol{\omega}_{ECI2B} \times \mathbf{I}_{S/C}\boldsymbol{\omega}_{ECI2B})$$

Minor perturbations torque

Drag torque

ABEP thrust torque

Attitude actuators torque



Guidance

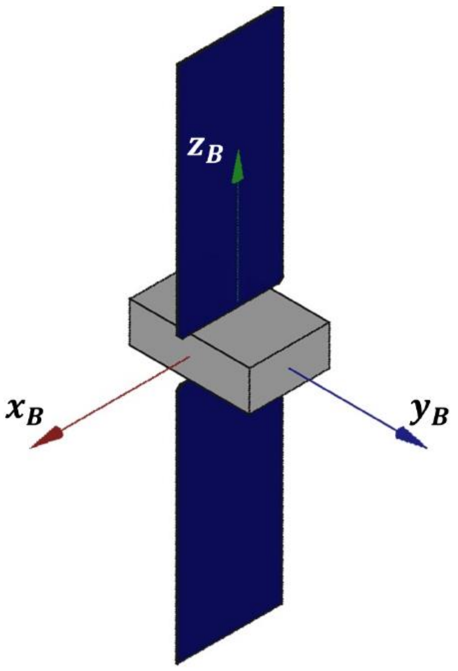
- Maintain the target dawn-dusk SSO orbit semi-major axis a and eccentricity e=0;
- Maintain the spacecraft attitude aligned with the Velocity-Normal-Binormal (VNB) frame, such as
  x_B is directed toward the orbit velocity direction
  y_B is roughly directed toward the sun
  z_b is directed towards nadir

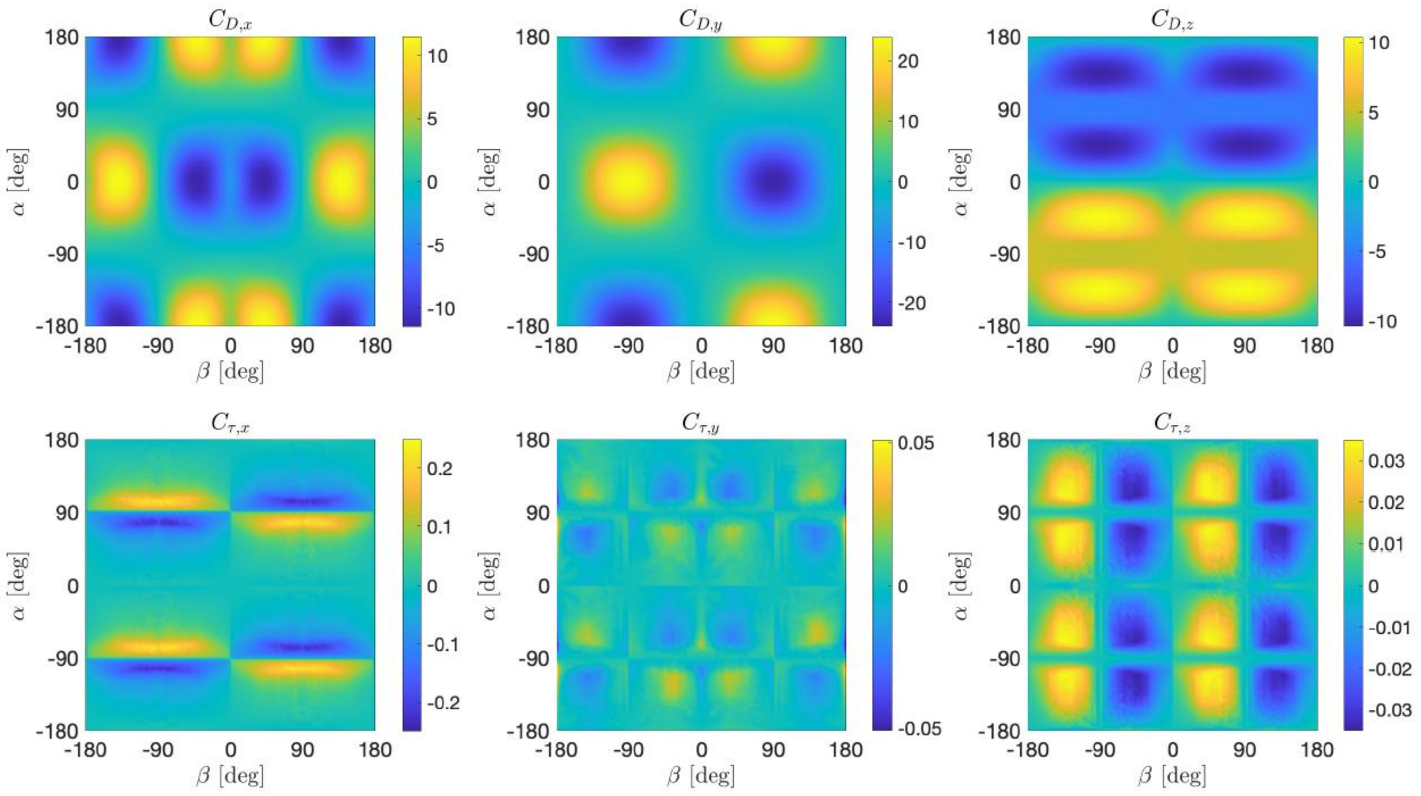
Navigation

- Autonomous control based on feedback from estimated spacecraft state
- GPS, gyro, magnetometers, sun sensors, and star trackers measurements implemented in an Extended Kalman Filter

Platform Aerodynamics

- Based on a simplified platform 3D CAD model





- Drag and Torque coefficients vs wind angles α and β estimated via the open ADBSat software*

**L. A. Sinpetru, et al, ADBSat: Methodology of a novel panel method for aerodynamic analysis of satellites, Computer Physics Communications 275 (2022).*

- Aero Drag and Torque estimated as

$$\boldsymbol{D} = \frac{1}{2}\boldsymbol{C_D}(\alpha,\beta)A_f u_\infty^2 \sum_s n_{\infty,s} M_s$$

$$\boldsymbol{\tau_D} = \frac{1}{2}\boldsymbol{C_\tau}(\alpha,\beta)A_f L_{S/C} u_\infty^2 \sum_s n_{\infty,s} M_s + \boldsymbol{\Delta r_{CoG}} \times \boldsymbol{D}$$

AER Model

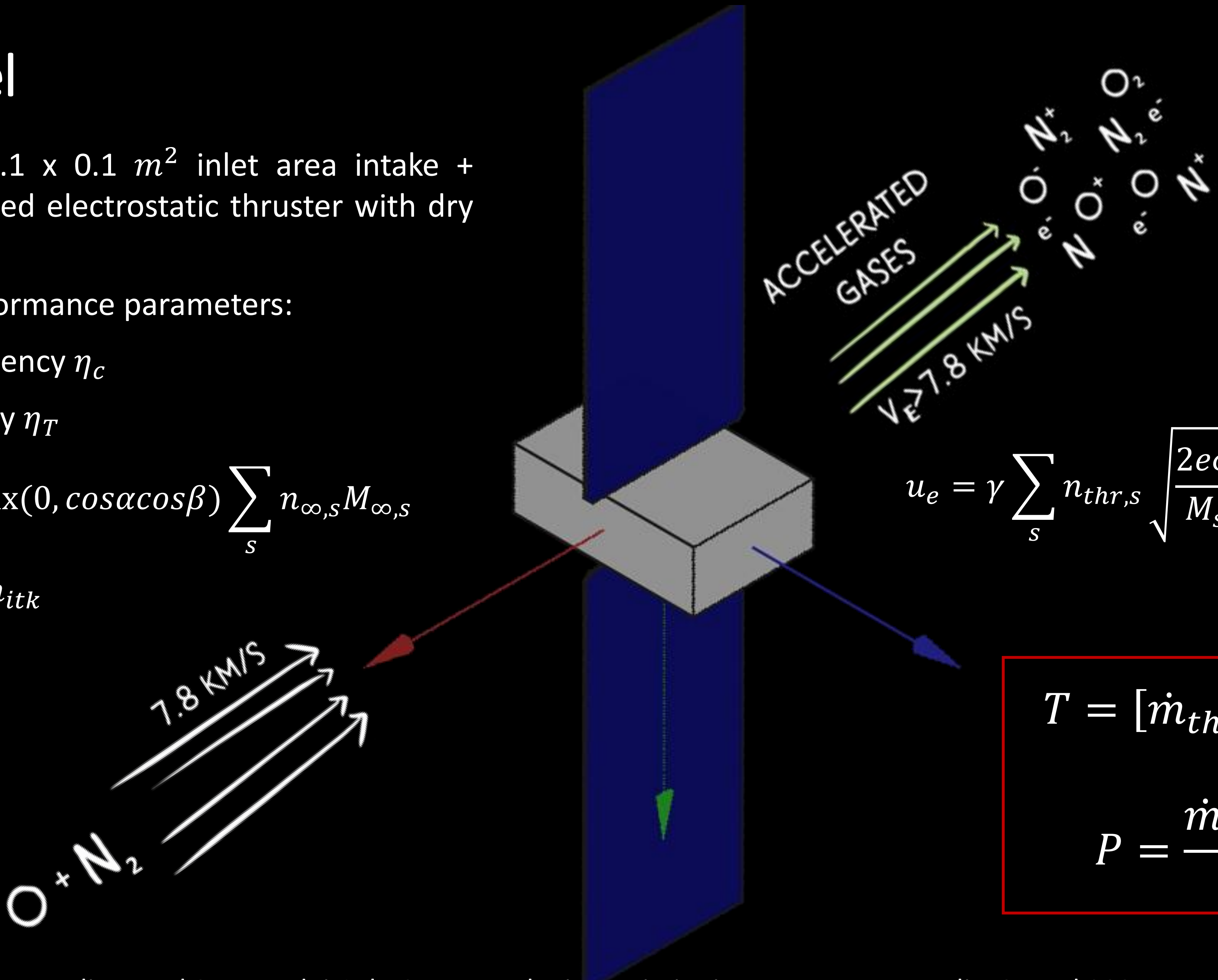
2U AER with a 0.1 x 0.1 m^2 inlet area intake + miniaturized gridded electrostatic thruster with dry neutralizer.

Fundamental performance parameters:

- Collection efficiency η_c
- Thrust efficiency η_T

$$\dot{m}_{itk} = A_{itk} u_\infty \max(0, cos\alpha cos\beta) \sum_s n_{\infty,s} M_{\infty,s}$$

$$\dot{m}_{thr} = \eta_c(\alpha, \beta) \dot{m}_{itk}$$



$$u_e = \gamma \sum_s n_{thr,s} \sqrt{\frac{2e\phi}{M_s}} / \sum_s n_{thr,s}$$

$$T = [\dot{m}_{thr} u_e, 0,0]$$

$$P = \frac{\dot{m}_{thr} u_e^2}{2\eta_T}$$

Attitude and Orbit Controllers

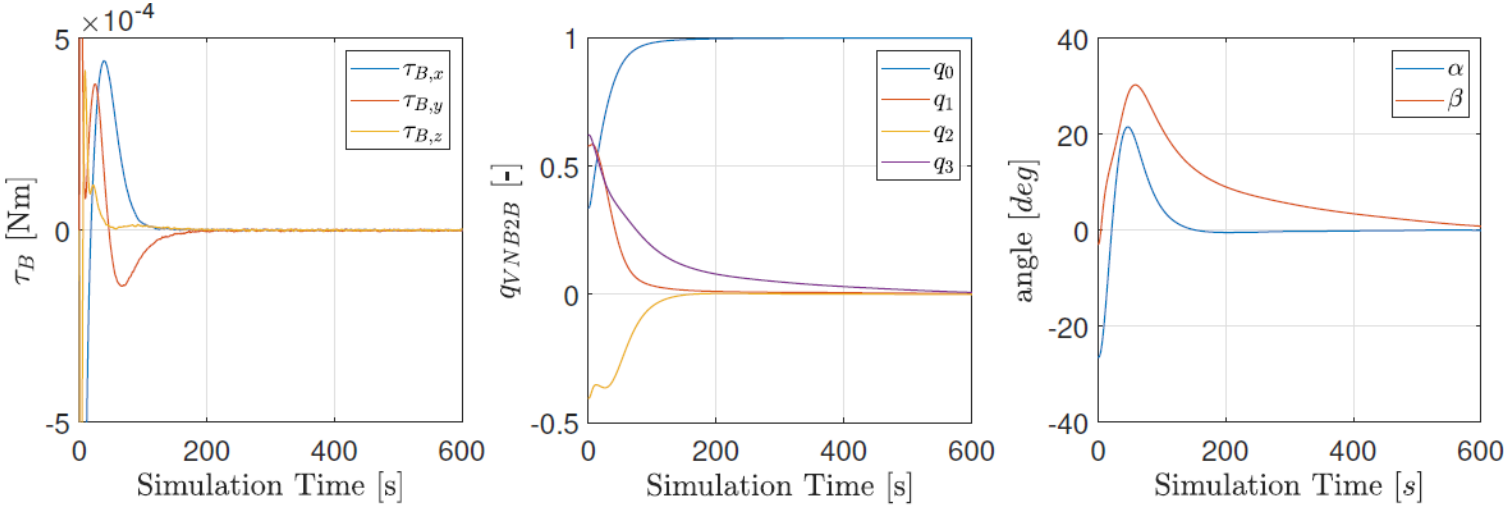
Quaternion feedback attitude control

$$\tau_{RW} = -k_{p,RW}\,\widehat{q}_0\,\widehat{\boldsymbol{q}} - k_{d,RW}\,\widehat{\omega} - \widehat{\omega}_{ECI2B} \times C_{RW}\,\widehat{\boldsymbol{h}}_{Rw}$$

Magnetorquers dipole control for RW desaturation

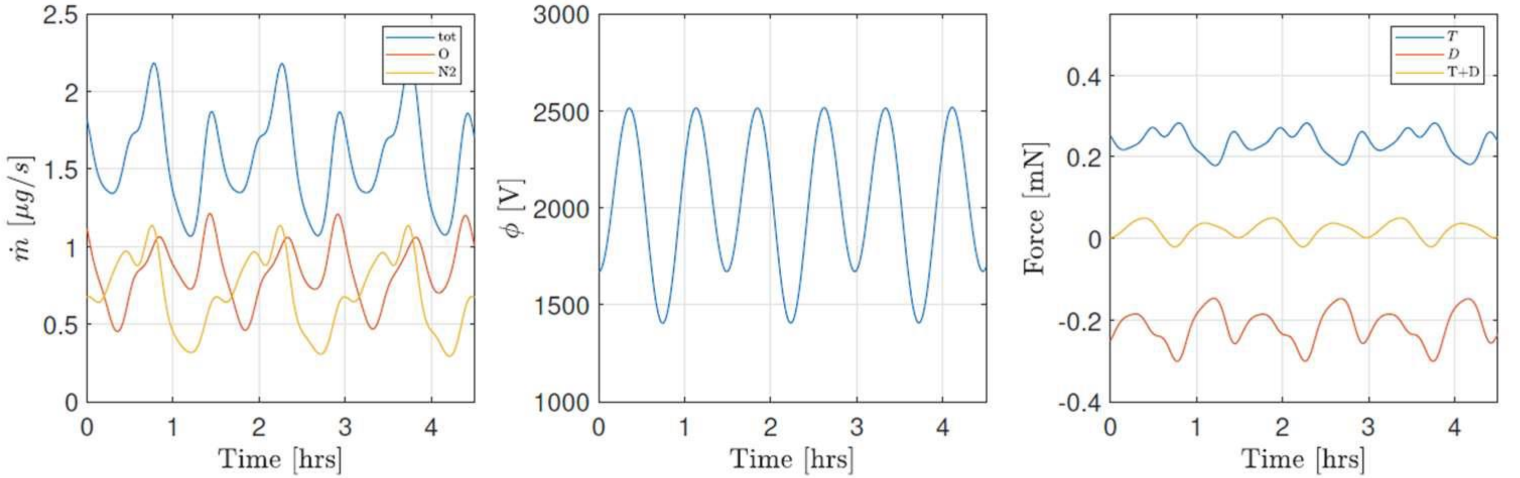
$$m_{MT} = \frac{\widehat{B}}{\left|\widehat{B}\right|^2} \times \left(-k_{MT}\,\boldsymbol{C}_{\boldsymbol{RW}}\,\widehat{\boldsymbol{h}}_{\boldsymbol{RW}}\right)$$

$$\tau_{MT} = m_{MT} \times B$$

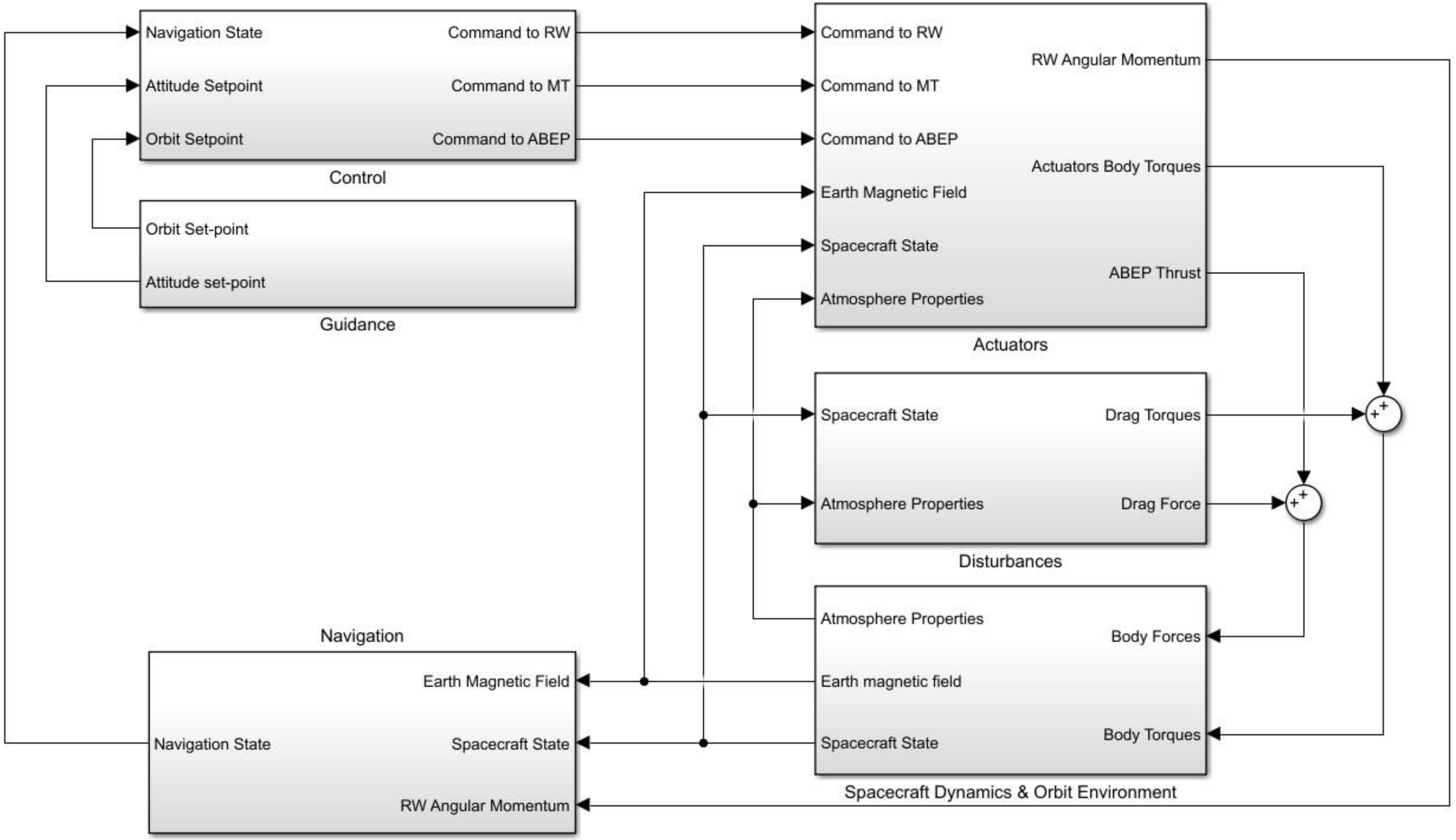


ABEP acceleration voltage control based on the estimated orbital elements:

$$\phi = \phi_0 + \sqrt{\frac{\widehat{a}}{\mu}} \begin{bmatrix} \hat{a} \\ \cos(\hat{\nu} + \widehat{\omega})\, cos\widehat{\omega} \\ \sin(\hat{\nu} + \widehat{\omega})\, sin\widehat{\omega} \end{bmatrix}^T \begin{bmatrix} k_a(\bar{a} - \hat{a}) \\ k_e(\bar{e} - \hat{e}) \\ k_e(\bar{e} - \hat{e}) \end{bmatrix} + k_i \int (\bar{a} - \hat{a})dt$$

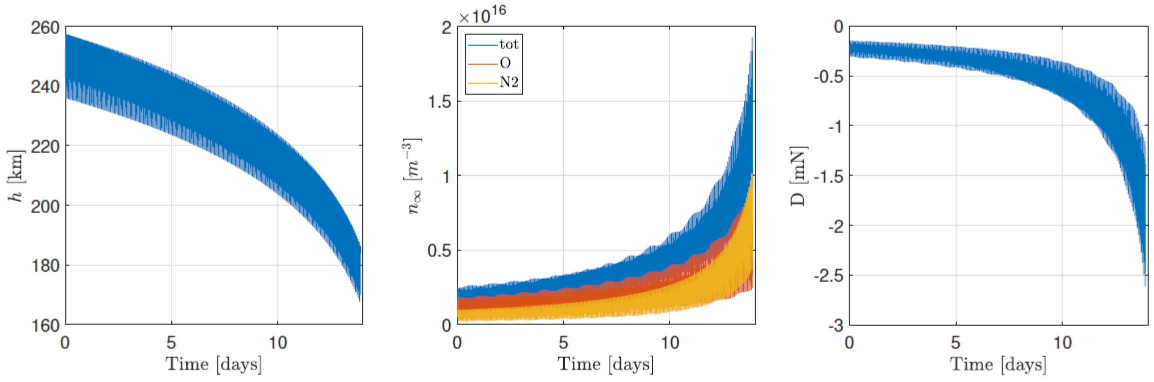


Model Implementation in Simulink

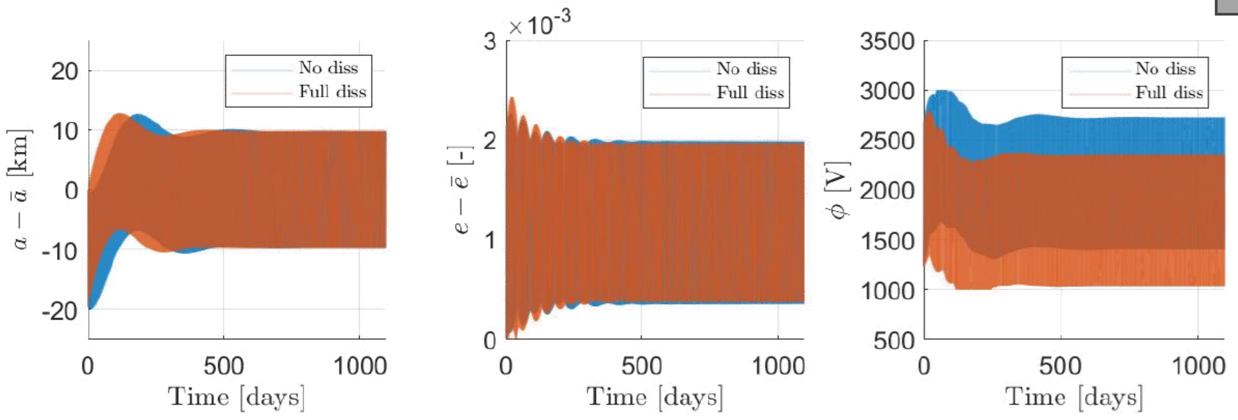


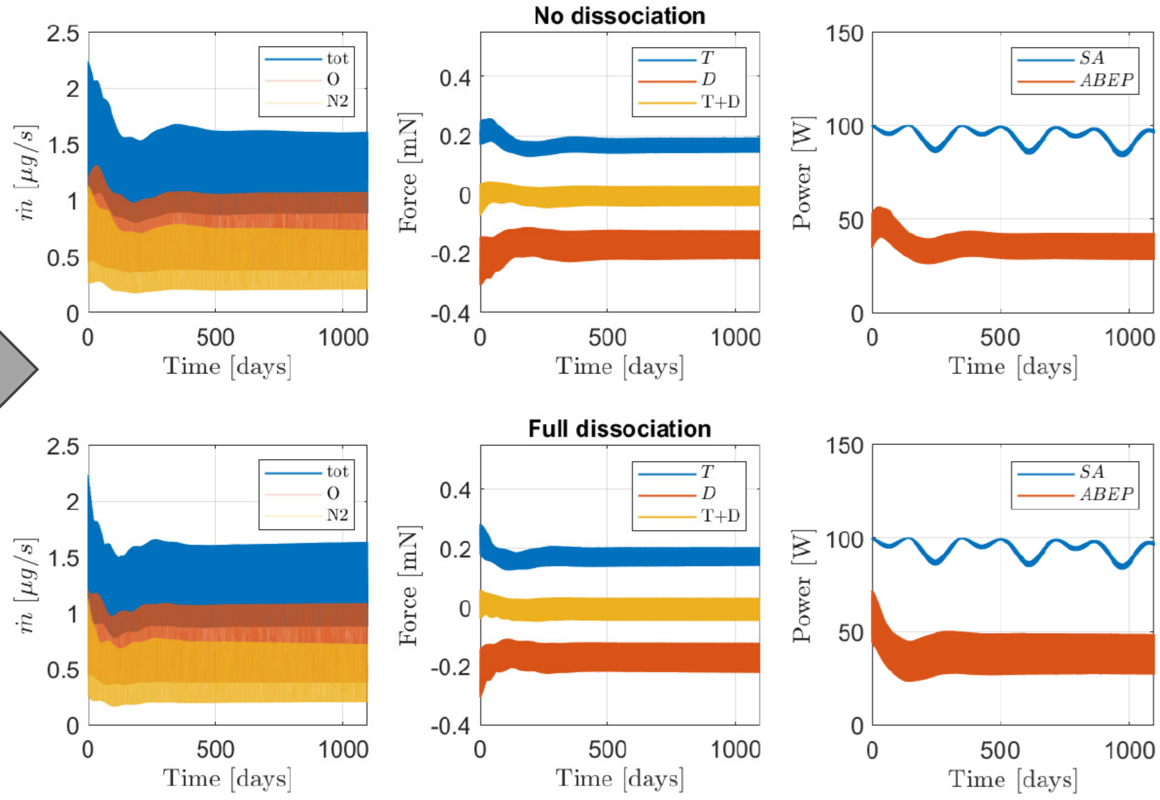
Orbit Control and Stability

14 days orbit propagation of unpropelled reference platform:

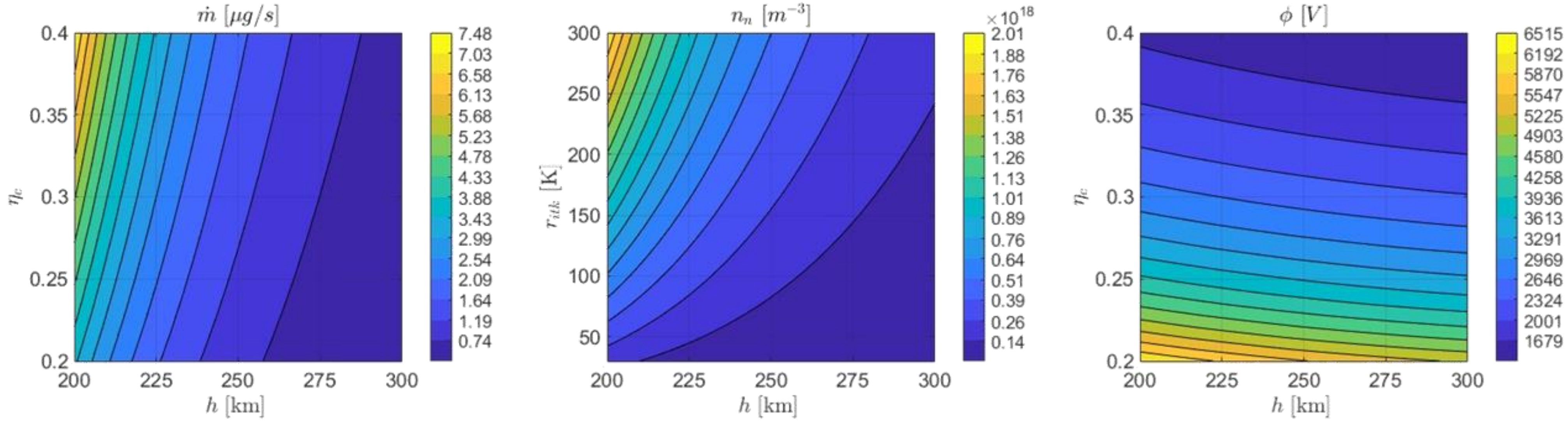


3-years orbit propagation with AER control for η_A=η_c=η_T=0.33:

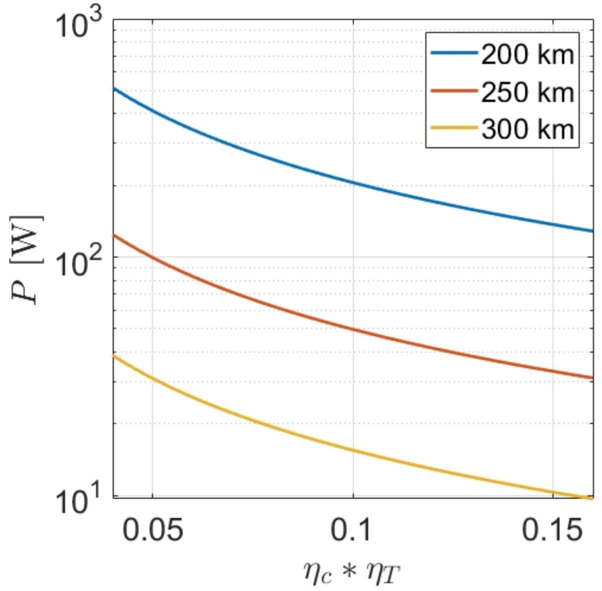




Requirements for an Air-breathing CubeSat thruster



- There always exists a critical altitude below which is never possible to compensate the drag while ensuring compliance to the platform power budget.
- Higher altitudes relax the requirement on both collection and thrust efficiency, but the lower atmospheric density make it challenging to effectively ionize the collected flow.
- Need to develop novel devices, capable of ionizing very low-density neutral flow and ensure a high flexibility in particle acceleration and thrust control.



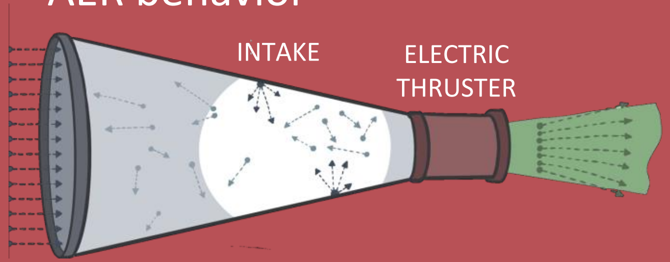
BREATHE project:

Funded by the European Research Council with a Consolidator Grant, BREATHE is a 5-year research project aimed at

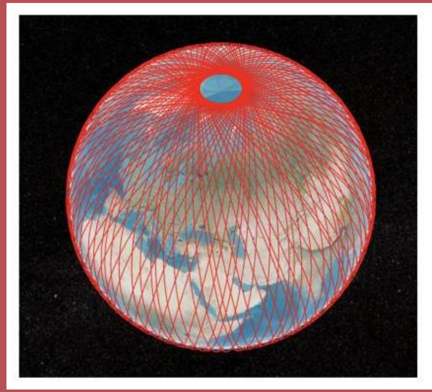
increasing the understanding of air-breathing electric propulsion to pave the way toward the in-orbit demonstration of the AER concept.

WP1 - Modelling

- A virtual laboratory to study AER behavior

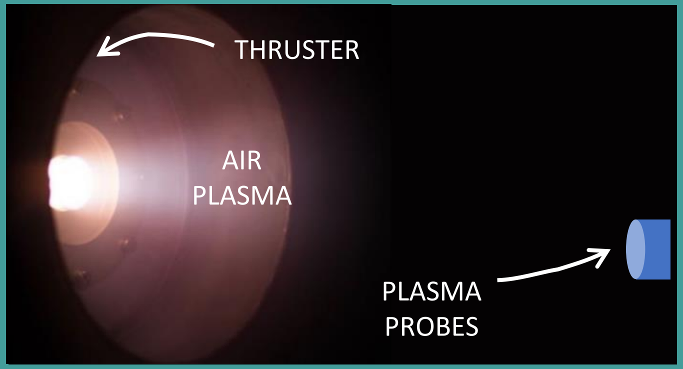


- Mission and flight environment integrated with thruster operation



WP2 - Environment

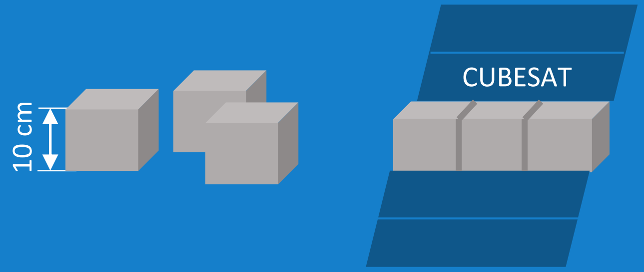
- Realization of a test facility to simulate VLEO conditions
- Setup of diagnostic system (thrust balance, plasma probes, RGA and pressure sensors)
- A mixed proof of concept



Romano (2021) PhD Thesis

WP3 - Prototypes

- Systematic investigation of different ionization (DC, RF, ECR)…
- …and acceleration strategies (grids, ExB discharges, nozzled expansion)
- Scaling down toward miniaturization and in-orbit demonstration



QUESTIONS?

This Project has received funding by EU HORIZON ERC-2022-COG
GA number: 101088694 - CUP J53C23001840006

Contacts:

eugenio.ferrato@santannapisa.it

vittorio.giannetti@santannapisa.it

tommaso.andreussi@santannapisa.it