희박 대기 효과를 활용한 초저궤도(VLEO) 위성 운용 개념 및 핵심기술

Concepts and key technologies for VLEO satellite operation utilizing rarefied atmospheric effects

명 노 신

Myong, Rho Shin

경상국립대학교 우주항공대학 교수

Aerospace Computational Modeling Laboratory (ACML)

http://acml.gnu.ac.kr/

Director, Research Center for Aircraft Core Technology (ERC)

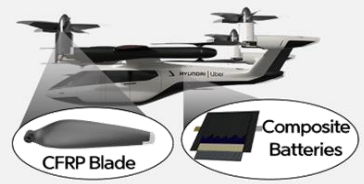
August 21st, 2025 (13:30-15:00)

Seminar at the Korea Aerospace Research Institute (KARI), Daejeon

항공우주전산모델링연구실(ACML)

미래형 항공기 기체구조 및 안전 핵심기술(ERC)

Aircraft Quality, Automotive Quantity
미래형 항공기 특성



열가소성 복합재 적용 필수

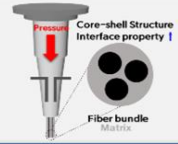
비행체 대량생산 요구

다수기체 운용, 짧은 운용주기

미래항공산업의 대응을 위한
일체형/안전 · 다기능 복합재료 혁신

일체형 대형 복합재

Core-shell 복합재 필라멘트

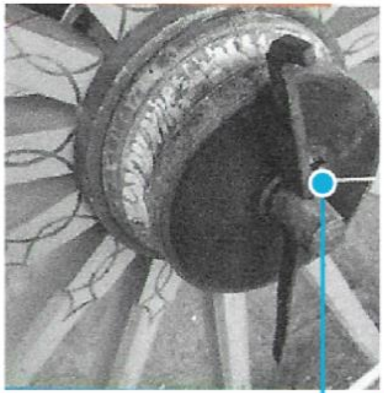


선도그룹 미국 ORNL와의 차별화

Hybrid 잔류수명 평가 기술

미래 항공기 복합재 구조

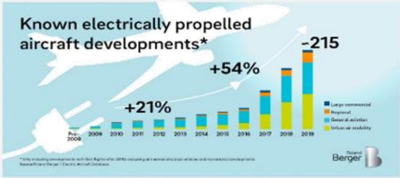
Hybrid 기반 고속 잔류수명 평가 기술



린치핀

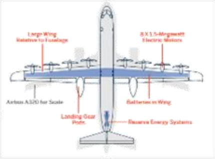
Linchpin Technology

탄소중립 달성을 위한 친환경
전기추진 항공기 수요 대응 필요



전기추진 항공기 시장 수요 급증

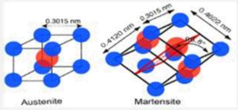
전기추진 항공기 비행 사례 (22년 9월)



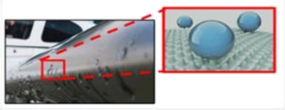
90인승 800km

미래형 항공기 적용을 위한
저비용, 고신뢰도 안전 핵심기술

형상기억합금

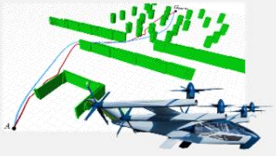


초수성 코팅 방제빙



선도그룹 캐나다 McGill 대학과의 차별화

결빙풍동시험

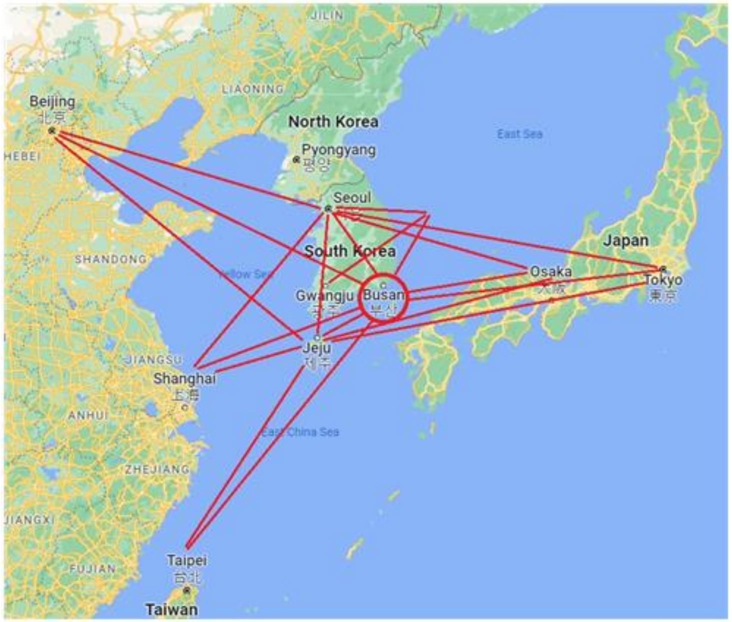


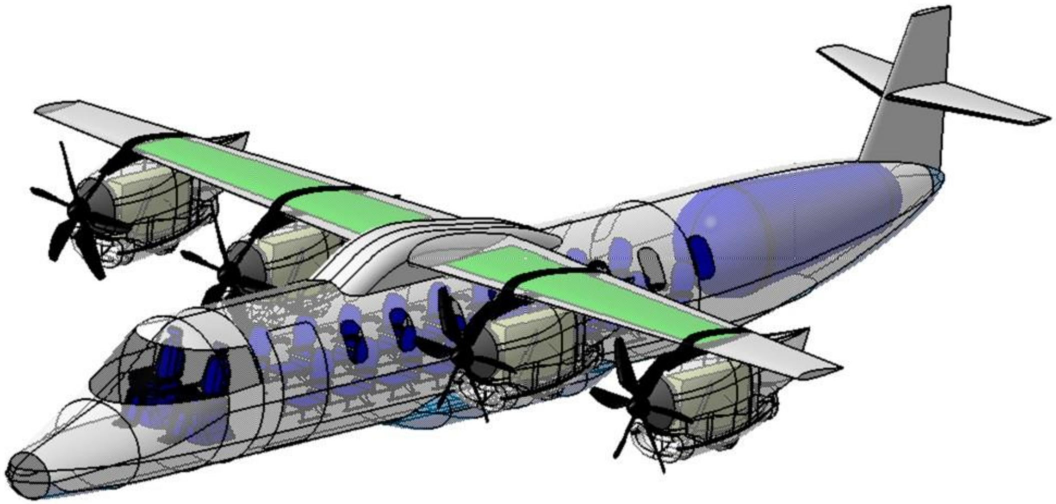
성능검증 시험평가

고신뢰도 제어기술

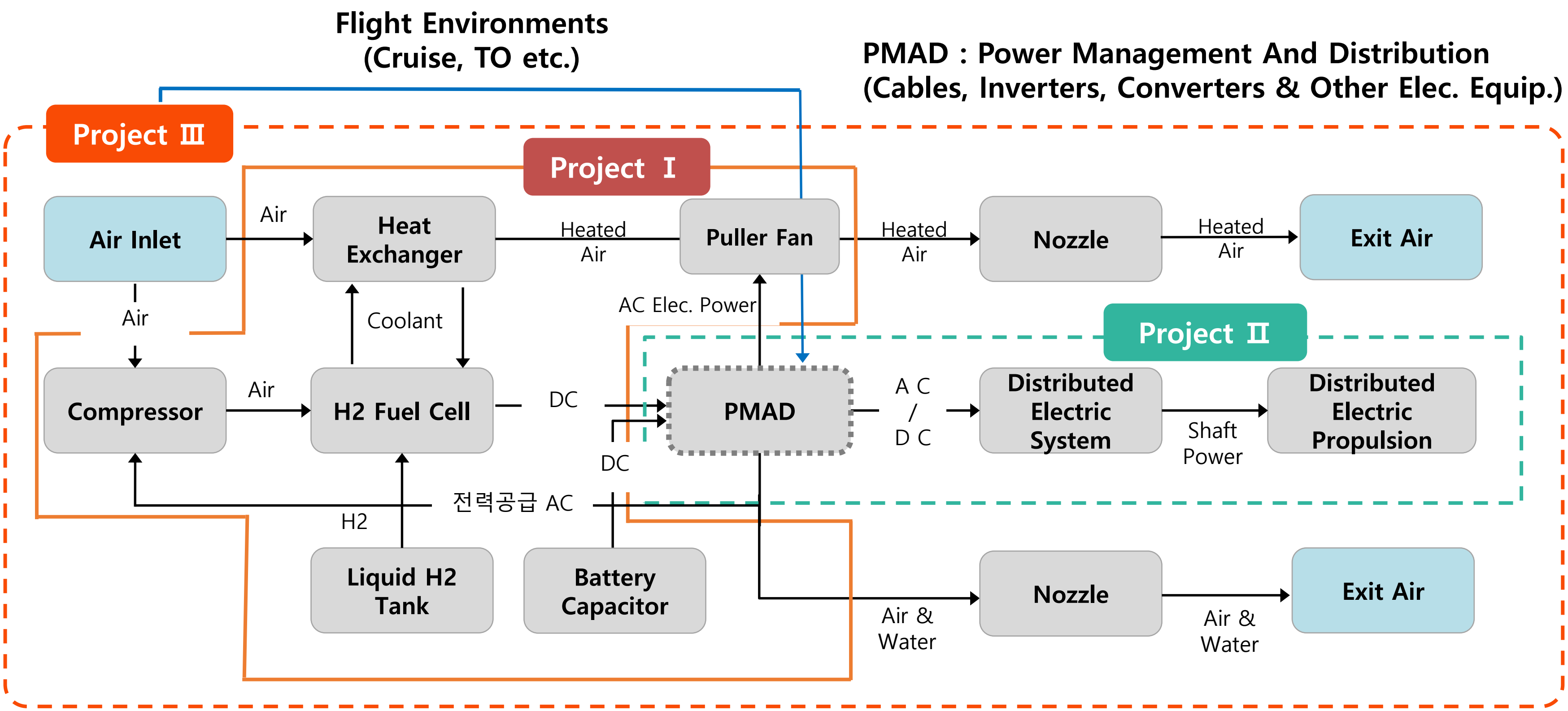
H2 Commuter Mega Project (지역혁신메가프로젝트)

Project Title	Technology for commuter-class aircraft using hydrogen-fuel-cell-powered hybrid distributed electric propulsion
Participating Organizations	10 including **GNU (Leading)**, UNIST, KERI, **KAI, Hanwha Aerospace Co.** 2 Local Government: Gyeongnam & Ulsan
Budget	**6.42 Million USD (On-going 1 Phase; 2023-25)** (Planned 2-3 Phase; 2026-2032)





Core Technology for Hydrogen Commuter Project



Requirements

19 Passenger (Part 23), Range (500~1,000 km)

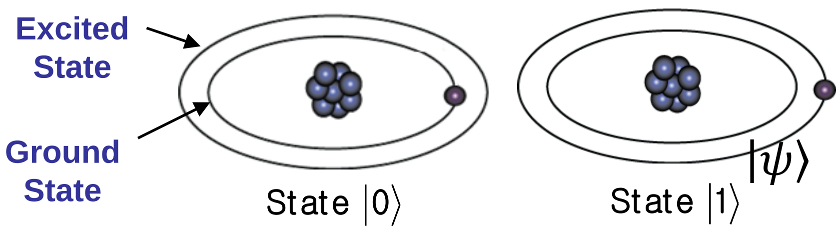
Payload (30%), TO/Landing Distance (500~800 m)

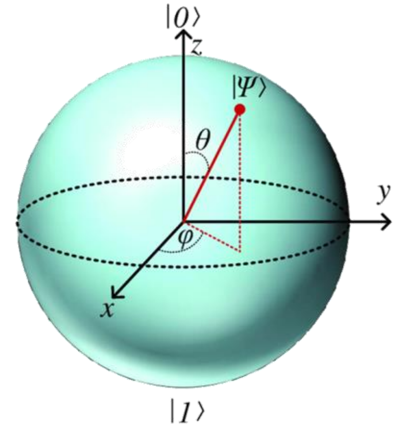
Carbon Reduction (75~90%), Low Noise (Below 75 dB)

Quantum Computing (US AFOSR)

Quantum Computing Concepts: Superposition, Entanglement, Interference, Measurement, Unitary ($UU^{\dagger}=I$) Operators

Challenges Toward QCFD: Non-linear term, Non-unitary operator, Elementwise Multiplication, Initialization, Measurement





Qubit

Bit

State Vector: $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle, \quad |\alpha|^2 + |\beta|^2 = 1$

$$|\psi\rangle = |\psi_1\rangle \otimes |\psi_2\rangle$$
$$= (\alpha_1|0\rangle + \beta_1|1\rangle) \otimes (\alpha_2|0\rangle + \beta_2|1\rangle)$$
$$= \alpha_1\alpha_2|00\rangle + \alpha_1\beta_2|01\rangle + \beta_1\alpha_2|10\rangle + \beta_1\beta_2|11\rangle$$

$$\alpha|0\rangle + \beta|1\rangle \text{ --- } \boxed{X} \text{ --- } \beta|0\rangle + \alpha|1\rangle$$

Quantum NOT gate

$$|00\rangle = |0\rangle \otimes |0\rangle = \begin{bmatrix}1\\0\end{bmatrix} \otimes \begin{bmatrix}1\\0\end{bmatrix} = [1 \quad 0 \quad 0 \quad 0]^T, \quad |01\rangle = |0\rangle \otimes |1\rangle = \begin{bmatrix}1\\0\end{bmatrix} \otimes \begin{bmatrix}0\\1\end{bmatrix} = [0 \quad 1 \quad 0 \quad 0]^T$$

$$|10\rangle = |1\rangle \otimes |0\rangle = \begin{bmatrix}0\\1\end{bmatrix} \otimes \begin{bmatrix}1\\0\end{bmatrix} = [0 \quad 0 \quad 1 \quad 0]^T, \quad |11\rangle = |1\rangle \otimes |1\rangle = \begin{bmatrix}0\\1\end{bmatrix} \otimes \begin{bmatrix}0\\1\end{bmatrix} = [0 \quad 0 \quad 0 \quad 1]^T$$

Pure Quantum Algorithm for Burgers Eqn.

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} = \mu \frac{\partial^2 u}{\partial x^2}$$

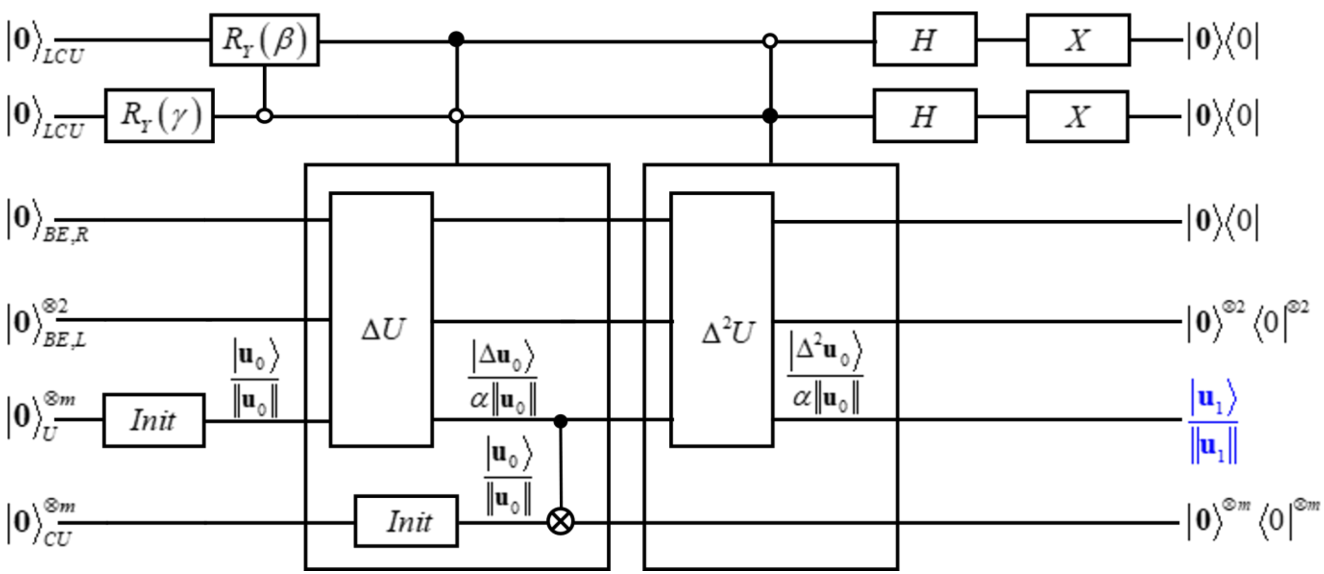
Linear combination of vectors handled by linear combination of unitaries

Velocity gradients (non-unitary transformation) using the block-encoding technique

$$\boldsymbol{u}^{n+1} = \boldsymbol{u}^n - \Delta t\left(\boldsymbol{u}^n \odot \boldsymbol{g}^n\right) + \mu\ \Delta t\left(\boldsymbol{h}^n\right)$$

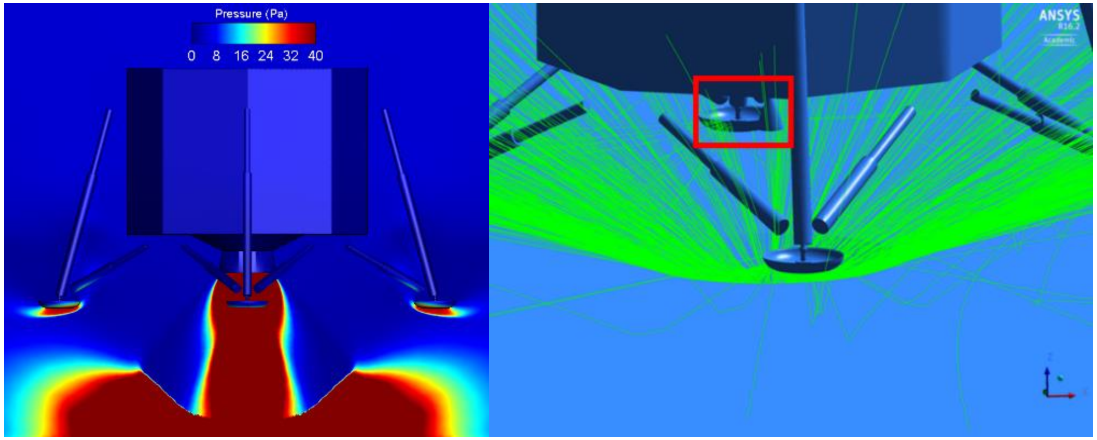
Non-linear multiplication of $\boldsymbol{u}$ and its derivative handled by employing multiple copies of $\boldsymbol{u}$

Non-unitary elementwise multiplication using quantum Hadamard product technique



Esmaeilifar, E., Ahn, D., Myong, R. S., "Quantum Algorithm for Nonlinear Burgers' Equation for High-speed Compressible Flows," *Physics of Fluids*, Vol. 36, 106110, Oct. 2024. (Desk Accept Article)

달착륙선 로켓플룸-Regolith 상호작용(우주핵심연구)

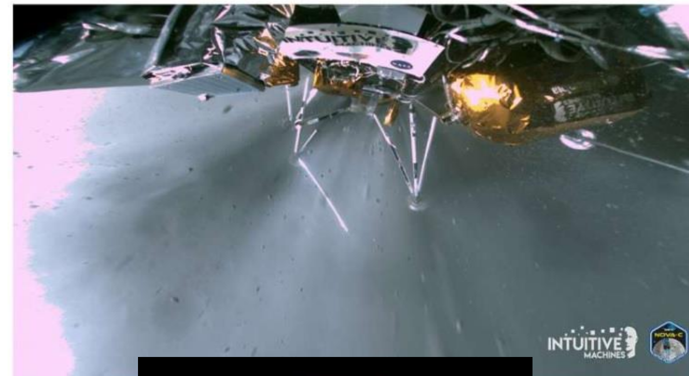


Korean Lunar Lander
(우주핵심연구 2017년)

FEBRUARY 29, 2024

Private US moon lander still working after breaking leg and falling, but not for long

by Marcia Dunn



US Intuitive Machines
(2024년 2월)

Linchpin Technology

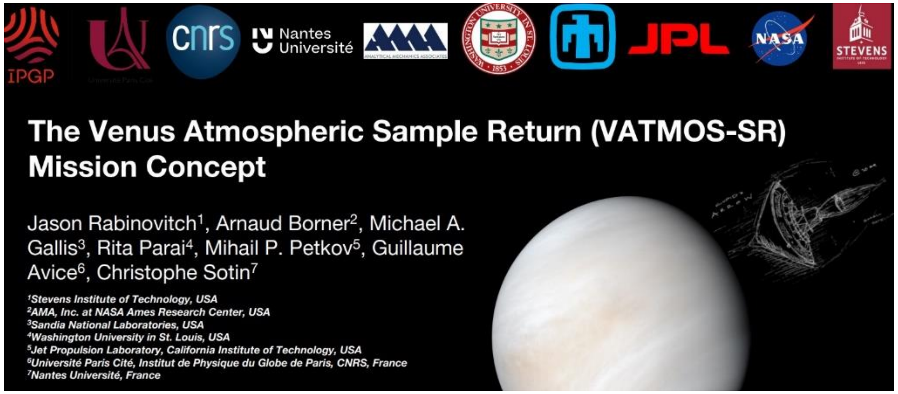
고신뢰성·저비용 저궤도 위성군 소요 위성시스템 핵심기술 연구센터(우주항공청 22-26년)

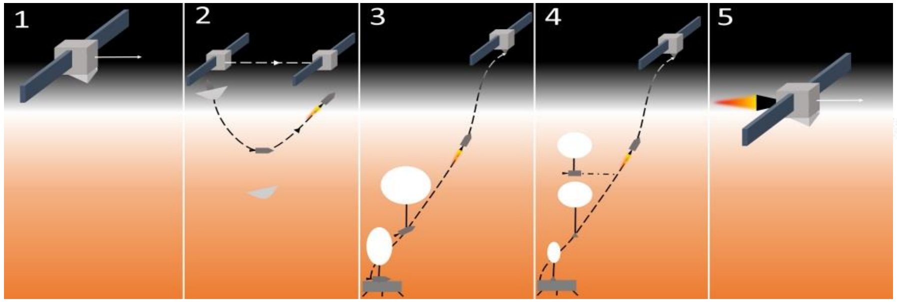
*Satellite System Core Technology Research Center

Super Low Altitude Exploration & Sample Return

Connecting the Dots

US VATMOS-SR (2020s)





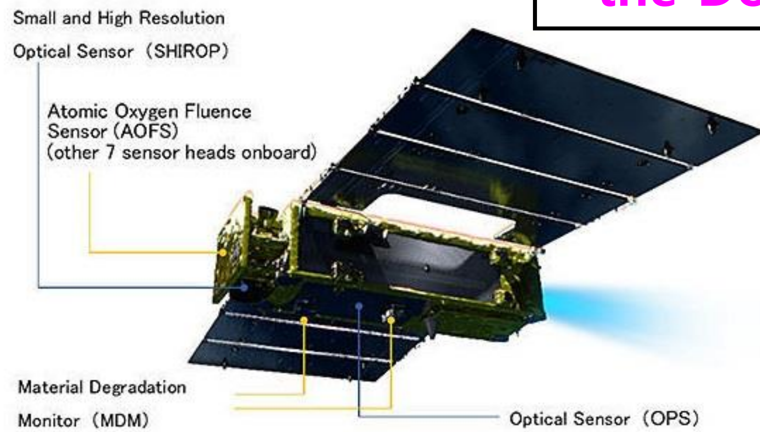
New Venus **Super Low Altitude Exploration & Sample Return (SLAESR: 2030~40)**

Preliminary mass estimates (kg) for Venus sample return missions

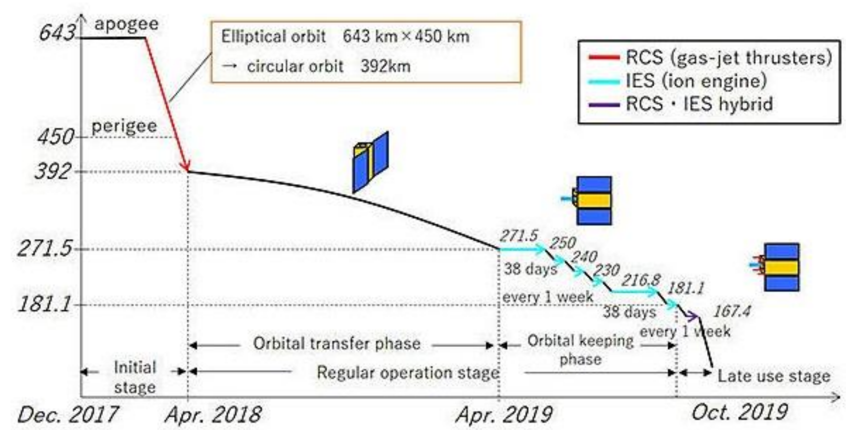
	Atmosphere skimmer	Atmosphere sample return	Surface sample return
Orbiter/return spacecraft	275	400	600
Orbiter propulsion systems and propellants	50	1300	600
Orbiter entry systems (aeroshell or ballute)	75	500	500
Venus ascent vehicle	—	1150	500
Lander and balloon systems	—	—	700
Lander entry systems (deorbit and ballute)	—	—	200
Total systems mass	400	3400	3100

1500-2000 kg

[Illustration of Tsubame in orbit]



SLATS Orbital Profile]



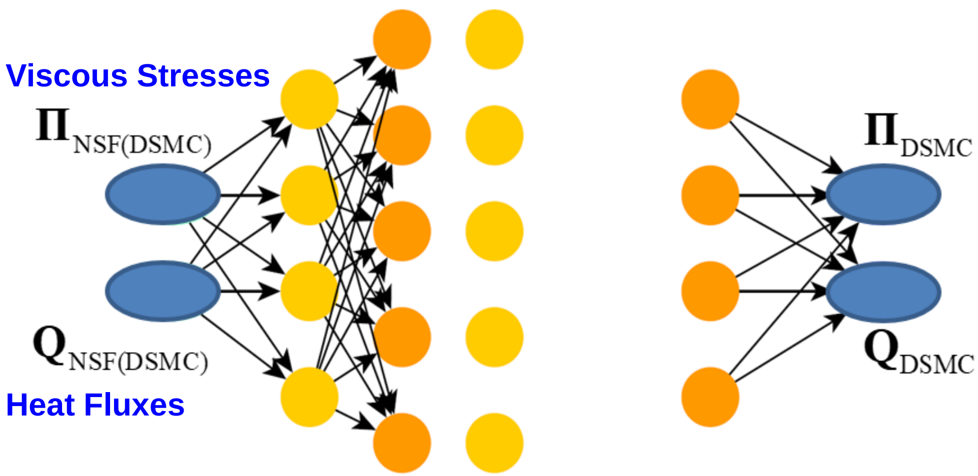
※ Orbital altitude = Average semi-major axis - Equatorial radius

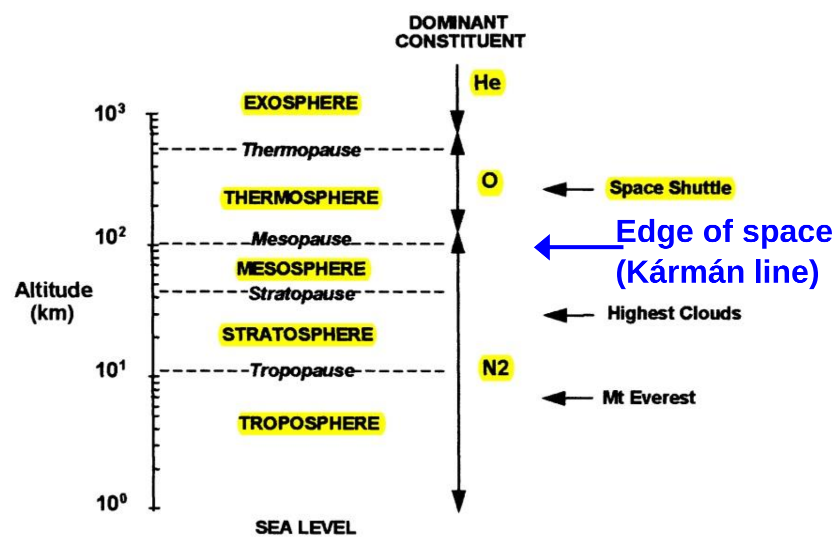
Super Low Altitude Test Satellite (JAXA, Japan, 30 Dec 2019)

위성비행체 설계용 High-fidelity 전산기법(US AFOSR)

- **US DARPA Otter Program's Orbital Drone (VLEO 90~250 km; 7.5 km/sec; 12 months; Payload 200kg; 2027; Contractor Redwire Corp.)**
- **Missions: Intelligence, surveillance, and reconnaissance (camera, IR sensors, AESA radar)**
- **Electric propulsion system (Electric Propulsion Lab., Colorado): 40 mN/kw, low drag flow-through inlet, but inlet capture efficiency classified**
- **A year-long "orbiting wind tunnel" testing; Corrosive atomic oxygen (ceramic material); Aerodynamic solar panel fins**

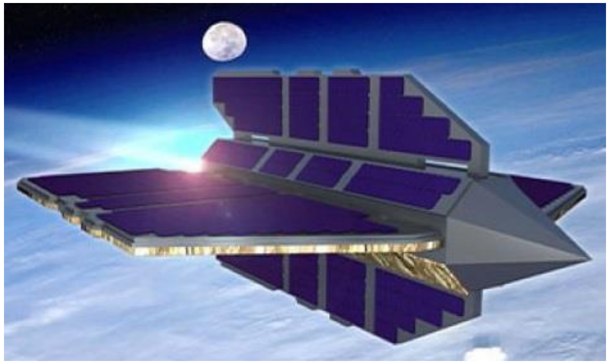
Neural Network-based Constitutive Relations
Obtained from DSMC Data

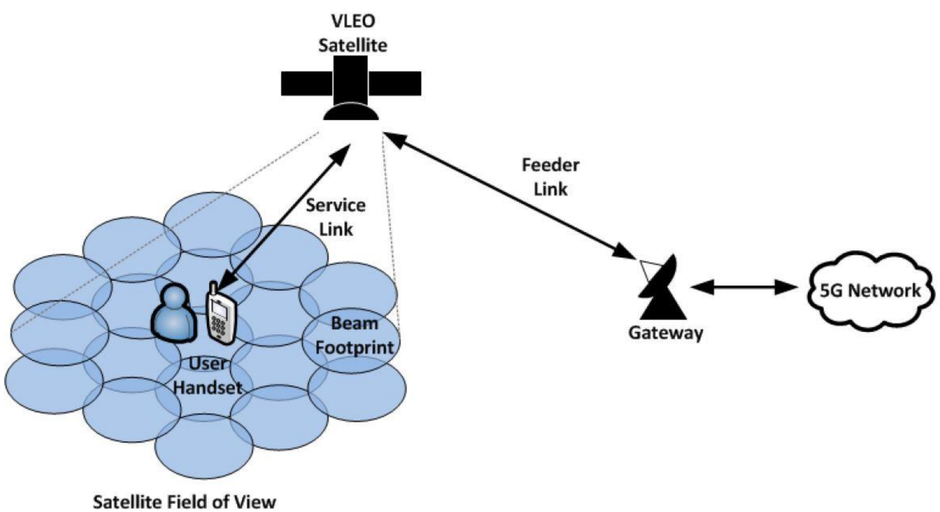


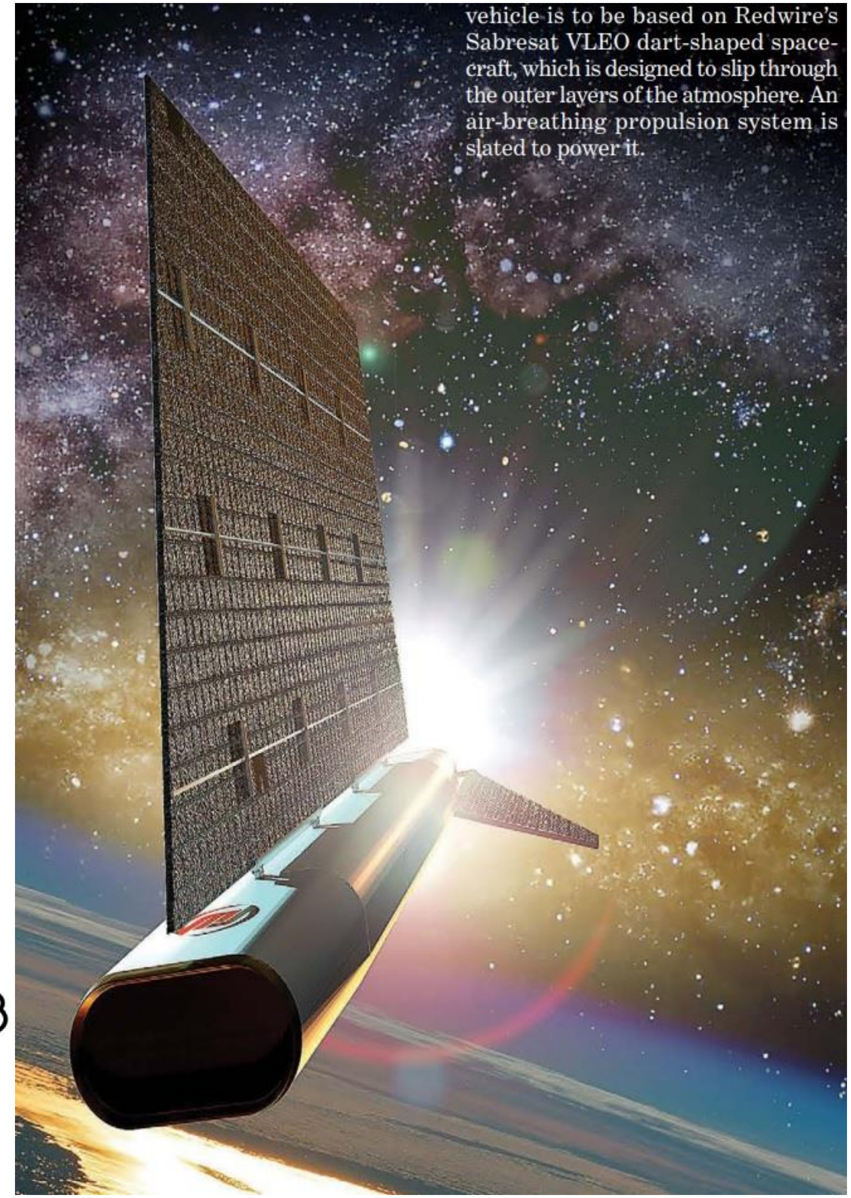


Ultra-fast NN-based FVM-DSMC Solver (Phys. Fluids, 2024 (106113) & 2025 (076105)

궤도 드론 (Orbital Drone)





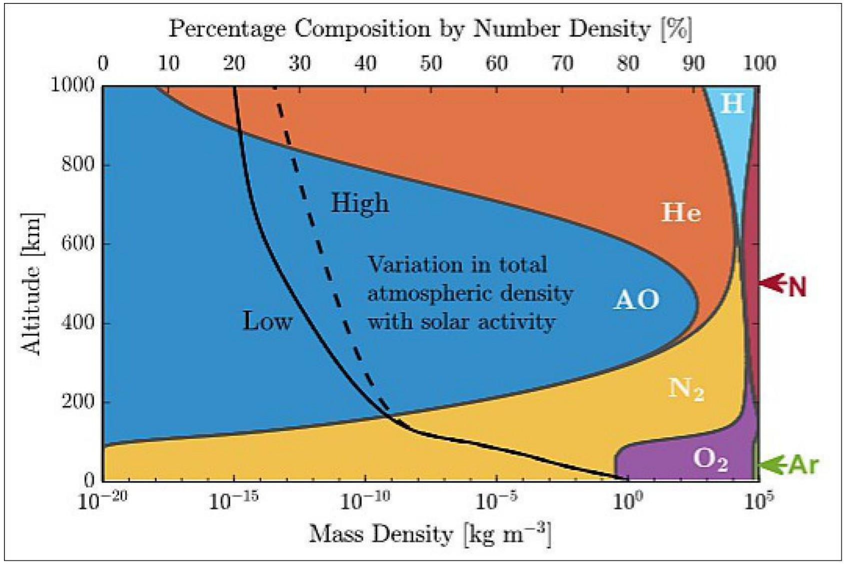


Current Trends in VLEO Satellite Missions

- **Challenging Minisatellite Payload (CHAMP; German)**: 15/07/2000 - 19/09/2010; 418 ~ 474 km; 522kg; Earth's geophysical data; atmospheric data from on-orbit data
- **Gravity Recovery and Climate Experiment (GRACE; US NASA)**: 17/03/2002 - 27/10/2017, 483 ~ 508 km; twin 487 kg; Earth's gravitational field, and its mass fluctuations; accurate geometry modelling for drag model validation and deriving atmospheric densities from accelerometer data
- **Super Low Altitude Test Satellite (SLATS; Japan JAXA)**: 23/12/2017 - 01/10/2019; 180 ~ 272 km; Earth observation at much lower orbits
- **Satellite for Orbital Aerodynamics Research (SOAR; UK)**: 14/06/2021 - 23/03/2022; 421 km & below; 3U CubeSat, flown by the University of Manchester; testing the atmospheric conditions and satellite behavior in VLEO; four fins coated with different materials, and a spectrometer on board; how the materials interact with the atmosphere; density, flow composition, and velocity measured by the spectrometer
- **Communication applications**: High-speed internet access (270 km); Mobile high-speed satellite internet access based on terrestrial access technologies (C-band, 250 km) Critical-type communications (incl. real-type messaging) (210 km)

Current Trends in VLEO Satellite Missions

Satellite for Orbital Aerodynamics Research (SOAR; UK, 2022)



1 NanoCom ANT430
2 NanoTorque GST600
3 NanoPower P31U
4 NanoPower BP4
5 NanoMind A3200 (OBC) + NanoCom AX100
6 NanoMind A3200 (ADCS) + Astrofein WDE + Novatel 719 GPS
7 NanoUtil Breakout + NanoSense M315 + Epson G370 IMU
8 Astrofein RW-1
9 Aerodynamics Payload (Steerable Fins)
10 ISIS 3U Structure
11 Atmospheric Characterisation Payload (INMS)
12 Solar Arrays
13 NanoUtil GomSpace Sensor Bus Interstages
14 NanoUtil Flight Preparation Panel
15 Launch Stow and Release System

Sinpetru, Ph.D. Thesis (2022)

VLEO 위성의 전략적 중요성 및 핵심기술

- Closer proximity to areas of interest, enabling low-latency communication and high-resolution imagery
- Avoiding congestion in traditional LEO and GEO, providing a strategic advantage for national security missions (intelligence, surveillance, reconnaissance, and communications): **Potential for a game-changer in space operations**
- **여타 임무: 차세대 통신, 우주 환경 모니터링, 저비용 우주 임무**
- **VLEO 위성 시장에 진입하기 위해서는 대기 저항 및 궤도 유지, 우주 환경에서의 내구성, 지구와의 통신 망의 효율적인 관리 및 데이터 전송 시스템 등에 관한 기술적 준비가 필요**
- **고성능 위성 개념설계, 정밀 궤도 제어 및 하강 시스템과 대기 밀도와 공기 저항에 대한 최적화 기술: 정밀 궤도 제어를 위한 추력기, 연료 관리 시스템, 항법 및 궤도 조정 시스템 기술 개발; 공기 저항을 최소화하는 설계, 실시간 대기 밀도 측정 시스템 기반으로 대기 밀도에 적응하는 궤도 관리 기술 개발**
- **초저궤도에서의 통신 및 데이터 전송 시스템 기술 개발: 지구와의 통신 거리가 가까워 빠르고 효율적인 데이터 전송이 가능하지만, 고속 데이터 전송 시스템과 안정적인 통신망 기술 개발 필요; 초저궤도에서의 빠른 통신 주파수 관리, 고속 데이터 처리 및 전송 기술, 저지연 통신을 위한 시스템 기술 개발**

VLEO 위성의 Benefits, Mission, Goals

VLEO benefits and challenges described by Josep Virgili Llop, et al. [21].

Benefits	Challenges
"Increased Resolution of Optical Payloads"	"Aerodynamic Forces"
"Increased Radiometric Performance"	"Reduced Communication Windows"
"Increased Payload Mass From Launcher"	"Atomic Oxygen Erosion"
"No De-Orbit Required"	
"Increased Geospatial Position Accuracy"	
"Increase of the Effective Surveillance Footprint Size"	
"Lower Risk of Collision with Space Debris"	

Mission Need: The United States scientific, military, and academic communities need the ability to maintain a presence within the vast gap in altitudes between where airplanes can fly and where satellites can be sustained in LEO

Goals		Objectives	
1.	Increase the time that satellites can orbit within the lowest regions of LEO	1.1	Provide drag-compensating thrust from atmospheric-ingestion EP supplemented by standard EP
		1.2	Withstand degrading effects of Atomic Oxygen fluence
		1.3	Reduce the effects of spacecraft charging events
2.	Gain scientific knowledge about the Earth's upper atmosphere and inner magnetosphere	2.1	Collect continuous, in situ measurements of the neutral density through which the satellite passes
		2.2	Collect continuous, in situ measurements of the Ionospheric plasma structures through which the satellite passes
3.	Provide worldwide coverage	3.1	Provide Earth observations that span ±60 degrees latitude (threshold), global (objective)
4.	Provide an affordable solution to the mission need	4.1	Maintain Life Cycle Cost, including 7 years of on-orbit operations to under $750M (threshold), $500M (objective)
5.	Enable unique space missions only achievable at lower LEO altitudes	5.1	Allow access to RF signals that are attenuated by the Earth's Ionosphere
		5.2	Measure the impacts to RF signal transmissions from EP exhaust plasma plumes

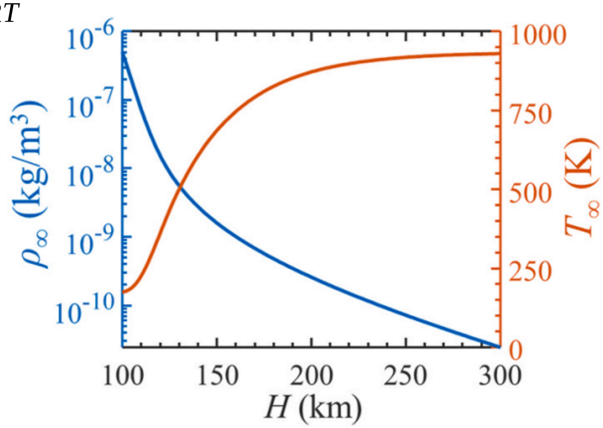
McCreary, *AST* 92 (2019) 972–989

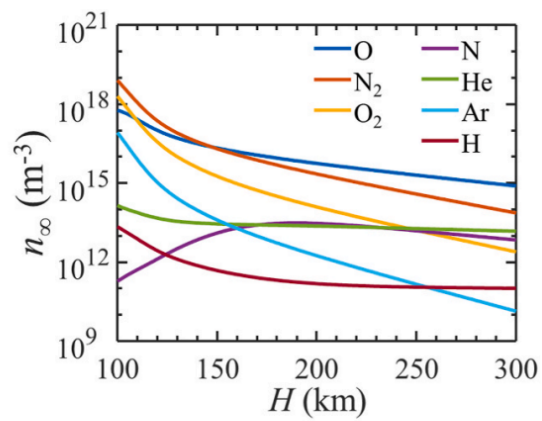
VLEO 환경

Table of orbital atmospheric parameters. Produced using the NRLMSIS 2.0 model on February 10, 2024, at 116°E longitude and 40°N latitude.

H (km)	T_∞ (K)	n_∞ (m^{-3})							Kn
		O	N_2	O_2	He	Ar	H	N	
100	174.9	6.0E+17	8.0E+18	2.0E+18	1.4E+14	8.2E+16	2.3E+13	1.9E+11	0.0241
125	434.8	7.1E+16	1.3E+17	1.8E+16	4.0E+13	5.0E+14	1.9E+12	2.1E+12	1.19
150	686.8	2.2E+16	2.0E+16	1.8E+15	2.9E+13	4.0E+13	4.9E+11	1.3E+13	5.94
175	811.3	1.0E+16	6.0E+15	4.1E+14	2.6E+13	7.3E+12	2.3E+11	2.8E+13	15.5
200	873.0	5.6E+15	2.2E+15	1.3E+14	2.4E+13	1.8E+12	1.6E+11	3.0E+13	32.3
225	903.8	3.3E+15	8.9E+14	4.4E+13	2.1E+13	4.9E+11	1.3E+11	2.3E+13	60.3
250	919.3	2.0E+15	3.8E+14	1.7E+13	1.9E+13	1.5E+11	1.1E+11	1.6E+13	104
275	927.1	1.2E+15	1.7E+14	6.4E+12	1.7E+13	4.5E+10	1.1E+11	1.1E+13	176
300	931.0	7.8E+14	7.3E+13	2.5E+12	1.5E+13	1.4E+10	1.0E+11	7.0E+12	295

$$\rho(h) = \rho_0 e^{-g_0 h/RT}$$





Knudsen number (Kn)

$$Kn_{\text{Continuum}} = \sqrt{\frac{\pi}{2}} \frac{\eta\sqrt{RT}}{pH}$$

$$Kn_{\text{DSMC}} = \frac{1}{\sqrt{2}\pi n d^2 H}$$

Xiaoqi Li et al., *Acta Astronautica* 233 (2025) 82–98

지구 전 고도에서의 대기 및 궤도 비행 동역학

$$m\frac{V^2}{r_c} = W = mg = m\frac{GM}{r_c^2}$$

↑ Orbital limit

$$m\frac{dV}{dt} = (T\cos\alpha_T - D) + W\sin\theta$$

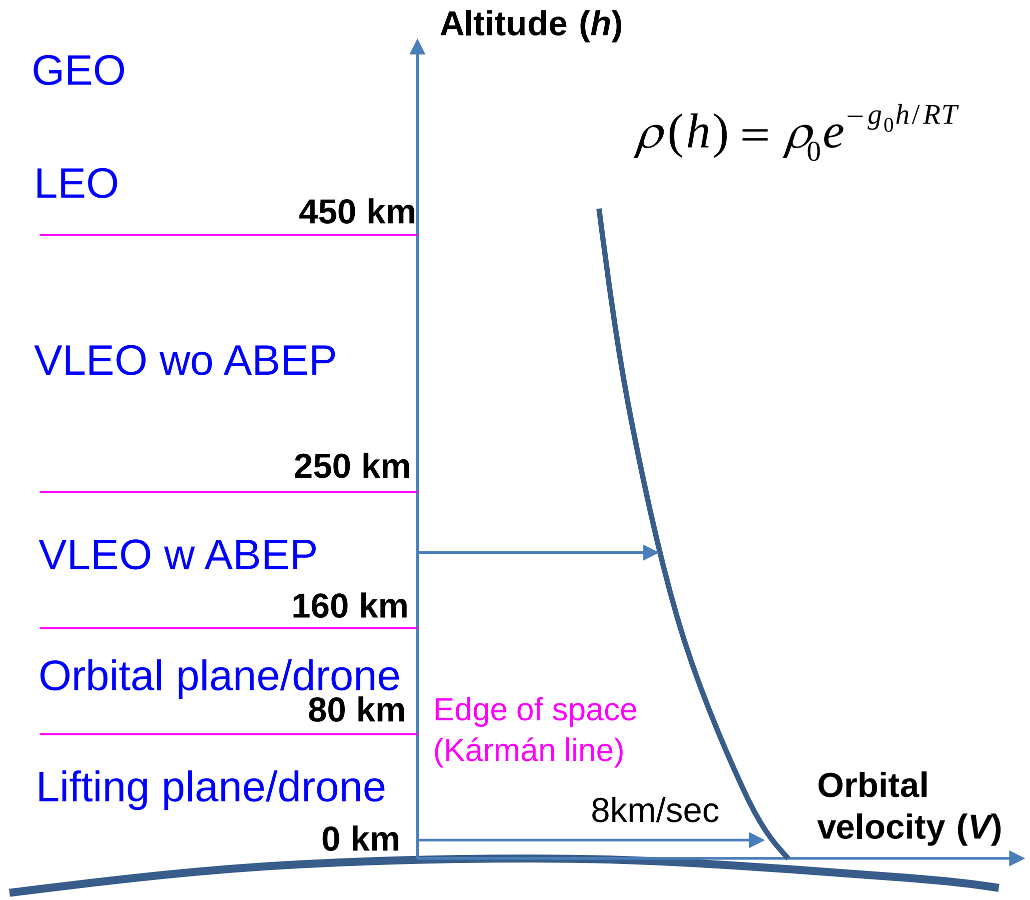
$$-m\frac{V^2}{r_c} = (T\sin\alpha_T + L) - W\cos\theta$$

$$\Rightarrow V(h), \theta(h), h(t)$$

↓ Atmospheric limit

$$T = D$$

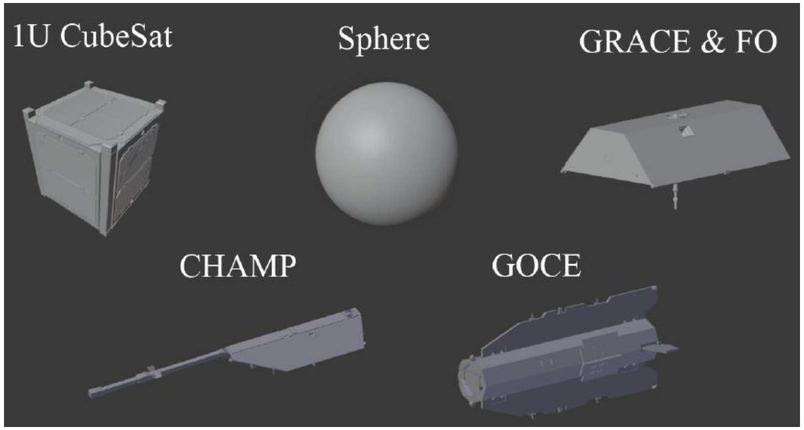
$$L = W = mg_0$$



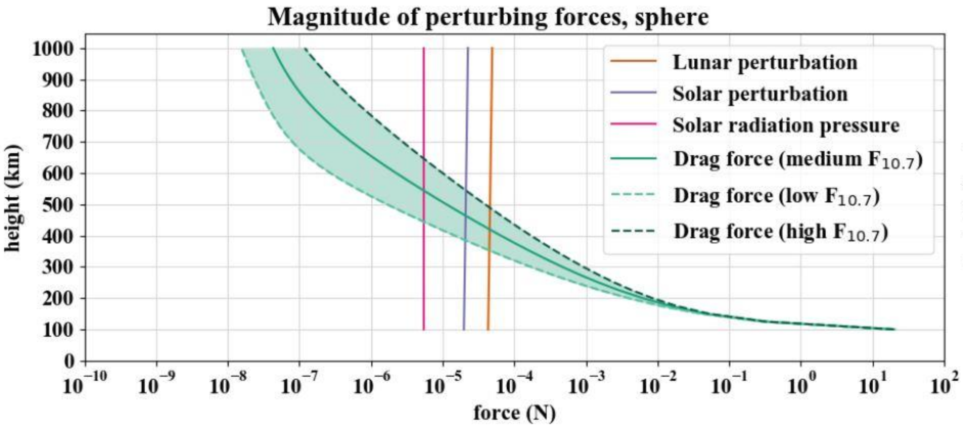
Important role of $\frac{m}{C_D S}, \frac{m}{C_L S}, \frac{C_L}{C_D}$

ABEP (Air-Breathing Electric Propulsion)

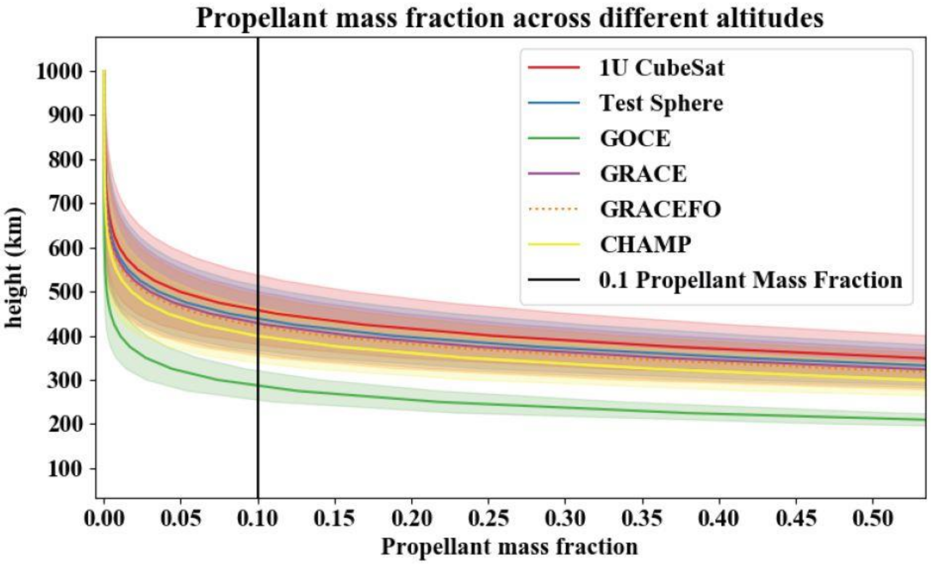
VLEO 임무 및 설계 고려 사항



Satellite	C_d	$A_{ref}\,(m^2)$	$m\,(kg)$	M_f	$I_{sp}\,(s)$	VLEO height (km)
1U CubeSat	2.2	0.01	1	-	100	458
Test Sphere	1.0	0.785	50	-	100	439
GRACE	3.9	1.0269	487	0.07	70	429
GRACE-FO	4.8	1.0269	600	0.052	70	422
CHAMP	3.6	0.8	522	0.057	70	400
GOCE	3.853	1.1	1050	0.095	500	288



Sinpetru, Ph.D. Thesis (2022)



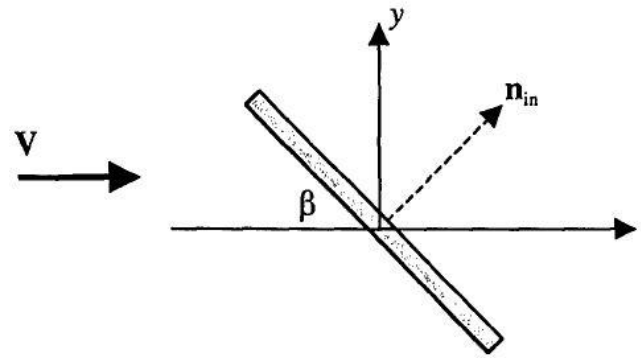
Mass fractions required for orbit-keeping maneuvers over a 5-year mission

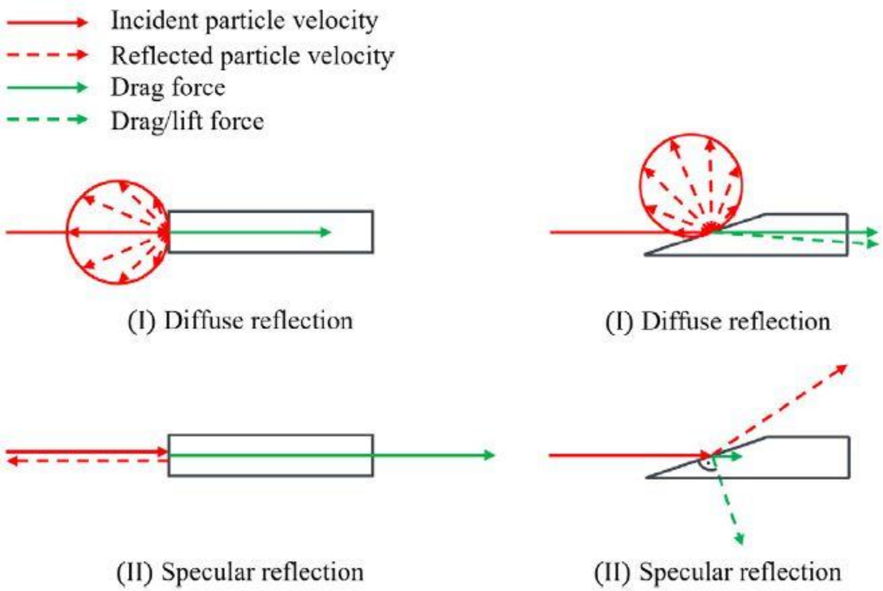
Free-molecular Aerodynamics (beyond 160 km)

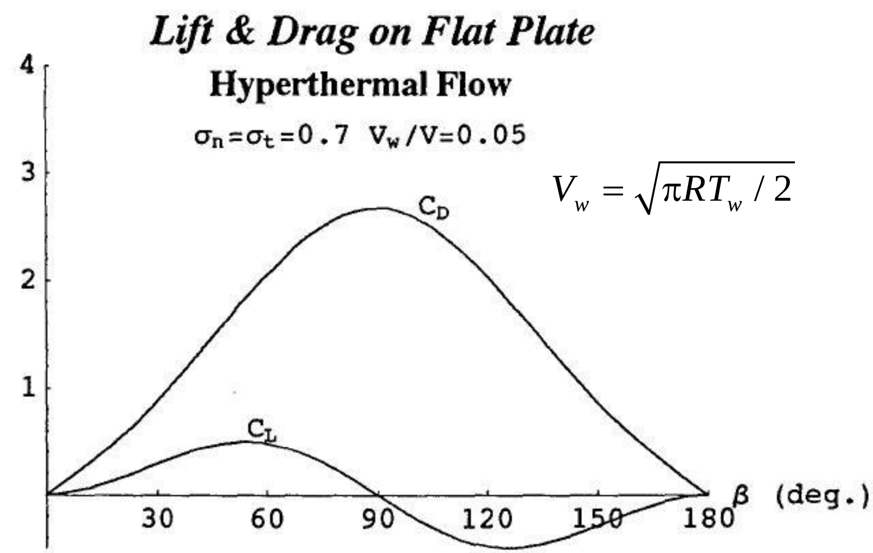
- **Large variations in dynamic pressure**

Thermospheric mass density (solar wind forcing 100% variations at the same altitude; 10~100 times variations per 100 km altitude change)

Wind velocity (10~20% at 250~500 km)





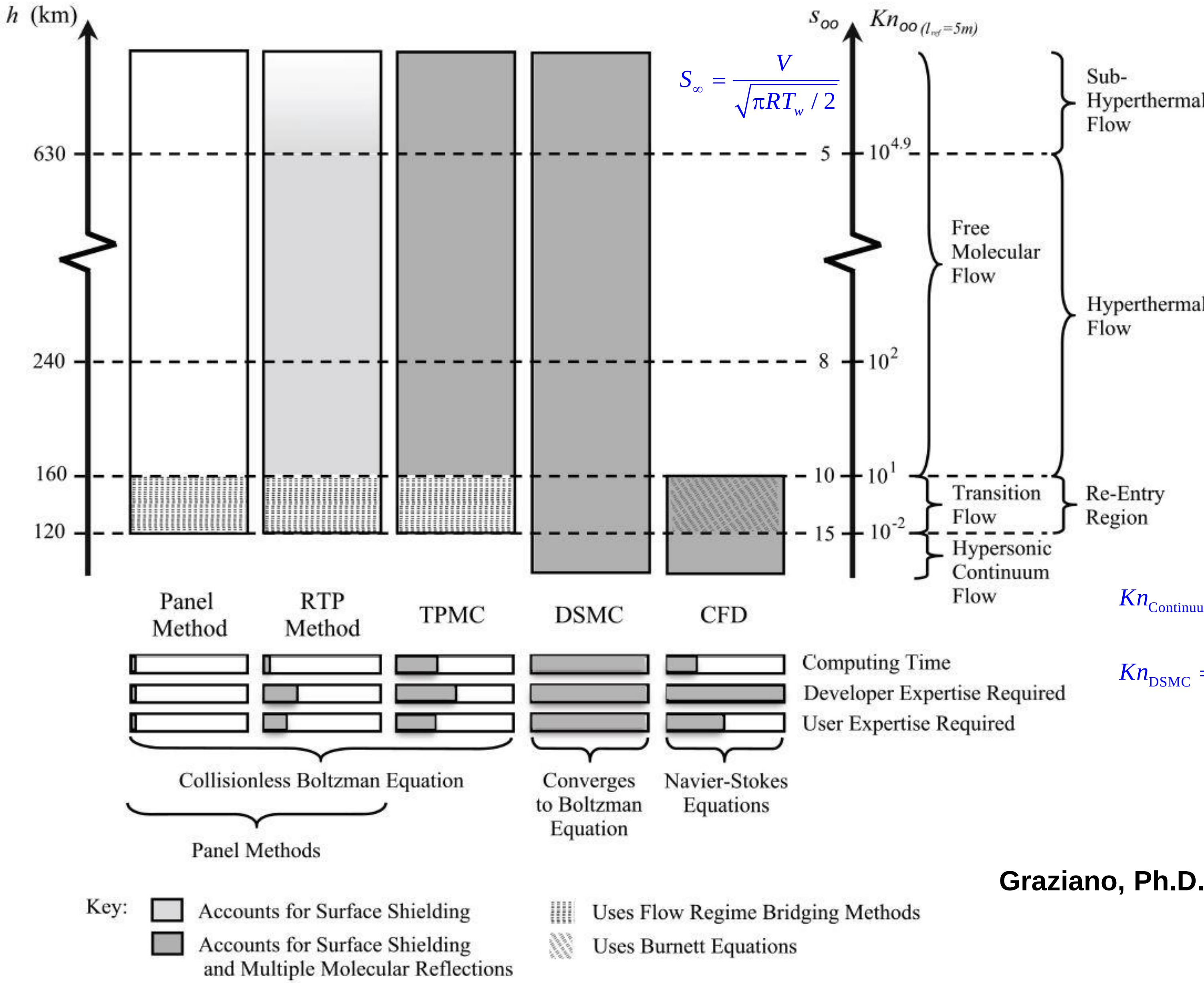


$$\sigma_n \equiv \frac{p_i - p_r}{p_i - p_w} = \begin{cases} 1 \text{ for diffusive reflection} \\ 0 \text{ for specular reflection} \end{cases}$$

$$\sigma_t \equiv \frac{\tau_i - \tau_r}{\tau_i - \tau_w} = \begin{cases} 1 \text{ for diffusive reflection} \\ 0 \text{ for specular reflection} \end{cases}$$

Storch, Aerospace Corp. (TR-2003(3397)-1)

Aerodynamic Analysis Methods



$$S_\infty = \frac{V}{\sqrt{\pi R T_w / 2}}$$

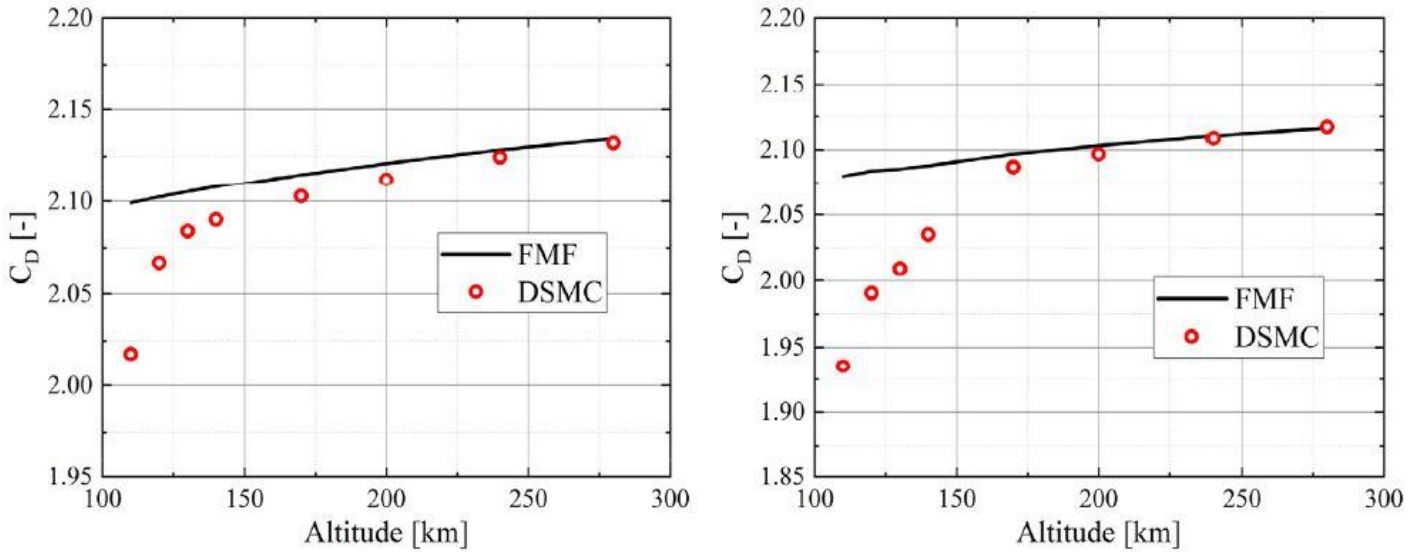
$$Kn_{\text{Continuum}} = \sqrt{\frac{\pi}{2}}\,\frac{\eta\sqrt{RT}}{pH}$$

$$Kn_{\text{DSMC}} = \frac{1}{\sqrt{2}\pi n d^2 H}$$

Graziano, Ph.D. Thesis (2007)

Aerodynamic Analysis Methods

DS1V,DS2V,DS3V	Original DSMC codes by Graeme Bird
dsmcFoam (2010) & dsmcFoam+ (2018)	OpenFoam packages developed by Scanlon et al. (C&F 39-10, pp.2078-2089, 2010) and White et al. (CPC 224, pp.22-43, 2018)
Monaco	From Iain Boyd's group at U Michigan
SMILE	From the Khristianovich Institute of Theoretical and Applied Mechanics in Russia
SPARTA	Stochastic PArallel Rarefied-gas Time-accurate Analyzer developed by Sandia National Laboratories



(a) Flat plate

(b) Cylinder

Maximization of Lift-to-Drag Ratio

- **Reduced Drag**

In VLEO, spacecraft experience substantial atmospheric drag, which can cause them to deorbit prematurely. Maximizing L/D helps minimize this drag.

- **Extended Operational Life**

By reducing drag, a higher L/D ratio can significantly extend the operational lifetime of a VLEO satellite without needing frequent orbital maintenance.

- **Reduced Fuel Consumption**

For missions requiring orbital maneuvers, a higher L/D ratio means less propellant is needed to counteract drag, leading to lower fuel consumption and potentially smaller propulsion systems.

- **Enabling New Mission Concepts**

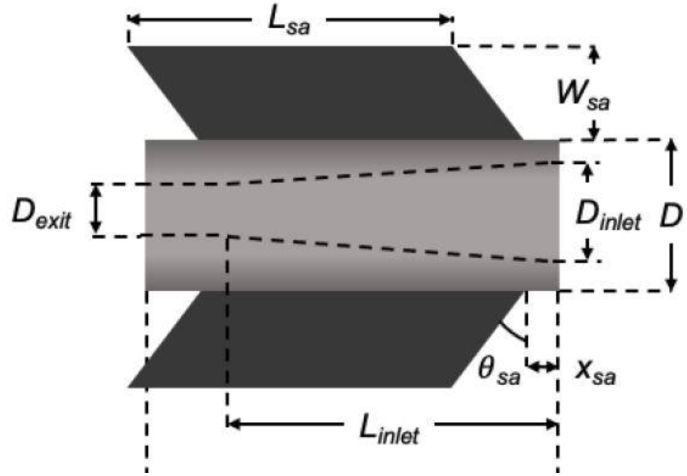
Optimizing L/D can enable new mission concepts and applications that were previously not feasible due to the challenges of operating in VLEO.

- **Methods for Maximizing L/D in VLEO**

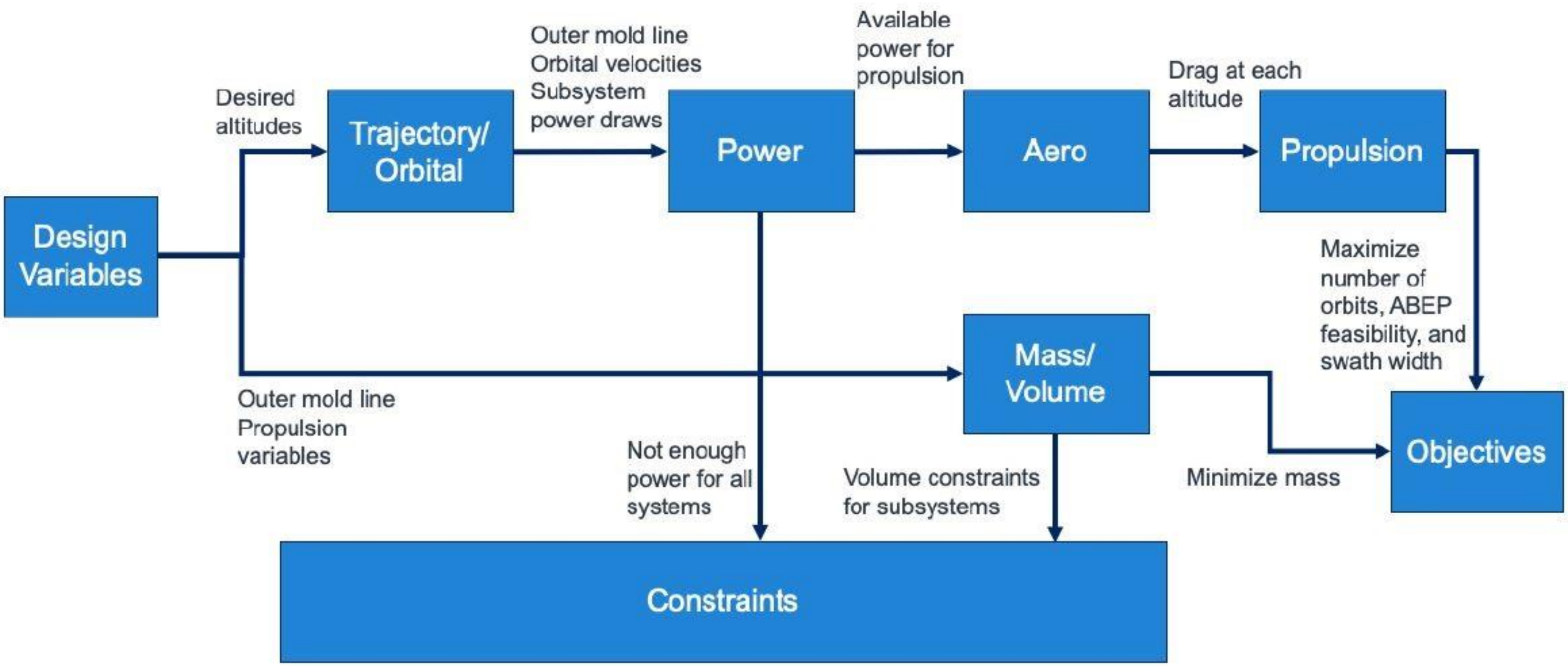
Shape Optimization: Finding the optimal shape of the spacecraft that minimizes drag and maximizes lift.

Surface Properties: Optimizing surface properties like the thermal accommodation coefficient can further enhance aerodynamic performance.

Conceptual Design and Optimization

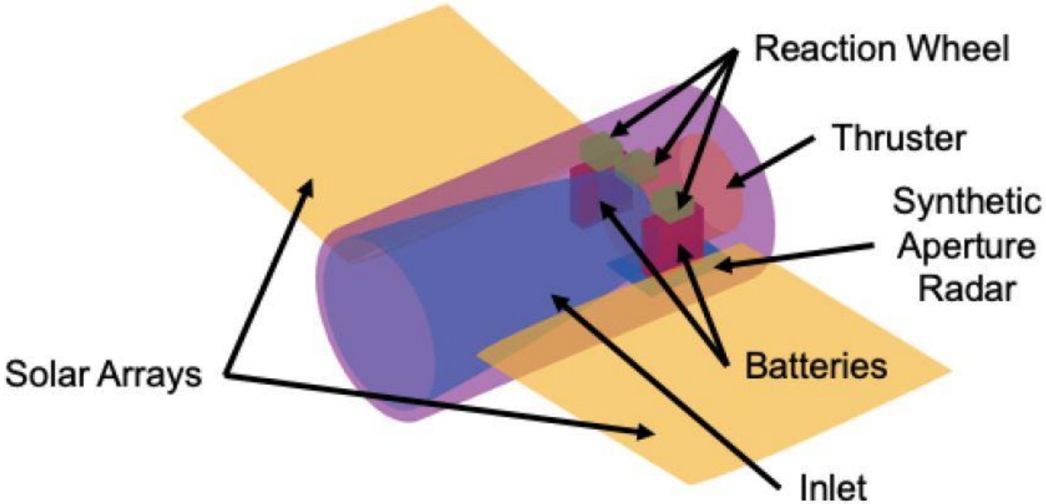


Gauntt et al., *AIAA* 2025-0552



Analysis and information flow between disciplines.

Conceptual Design and Optimization



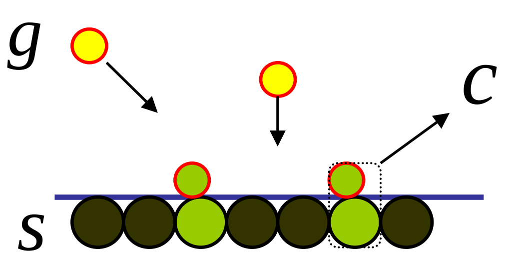
Gauntt et al., *AIAA* 2025-0552

- **Orbital analysis**: Orbital velocity, power available to offset drag
- **Atmosphere Model**: NRLMSISE-90 model
- **Drag analysis**: Drag dominant, 6 DOF in detailed analysis, free-molecular & continuum flows
- **Air-breathing electric propulsion modeling**: Inlet efficiency, thrust (specific impulse, thrust to power ratio, maximum thrust, efficiency)
- **Mass properties and packaging**: Thruster, batteries, reaction wheels, SAR
- **Synthetic aperture radar modeling:** Maximization of the SAR swath width

Other Important Issues

- **임무의 전략성, 기술적 수월성 및 축적성, 사업화**
- **Propulsion options for VLEO (micro)satellites (Leomanni, *Acta Astronautica* 133 (2017) 444-454)**
- **차기 고성능 전략적 임무 가능 VLEO (또는 SLEO) 개발을 위한 핵심기술 축적: 고성능 저비용 개념설계 및 민감도 분석, 신규 기술의 유효성 검증, 정밀 항력 측정 및 예측 기법 Validation, 항법 센서 (ADS, 광학, 관성 기반), 열관리, Corrosion 저항 재료 등**
- **Orbital Wind Tunnel: Drag (및 양력) 측정, Aerostability (stability margin, stability derivatives etc.)**
- **공력 세부 핵심기술 예: 표면의 Thermal Accommodation Coefficient의 Local 분포 최적화 (스텔스 항공기의 Hot Spot 제거 개념과 유사)**

Gaseous adsorption isotherm
(Myong, *Phys. Fluids 2004*)



$$g + s \Rightarrow c$$

$$\alpha = \frac{(1/4\omega Kn)\,p}{1 + (1/4\omega Kn)\,p}$$

$$\omega \equiv \frac{2\text{-}\sigma_v}{\sigma_v} \sim \exp\left(-\frac{D_e}{k_B T_w}\right)$$

D_e: Heat of adsorption

$[O(10^{-1} \sim 10)\ \text{kcal/mol}]$

Condense on the surface, being held by the field of force of the surface atoms, and subsequently evaporate from the surface
$\Rightarrow$ time lag $\Rightarrow$ adsorption $\Rightarrow$ slip and jump