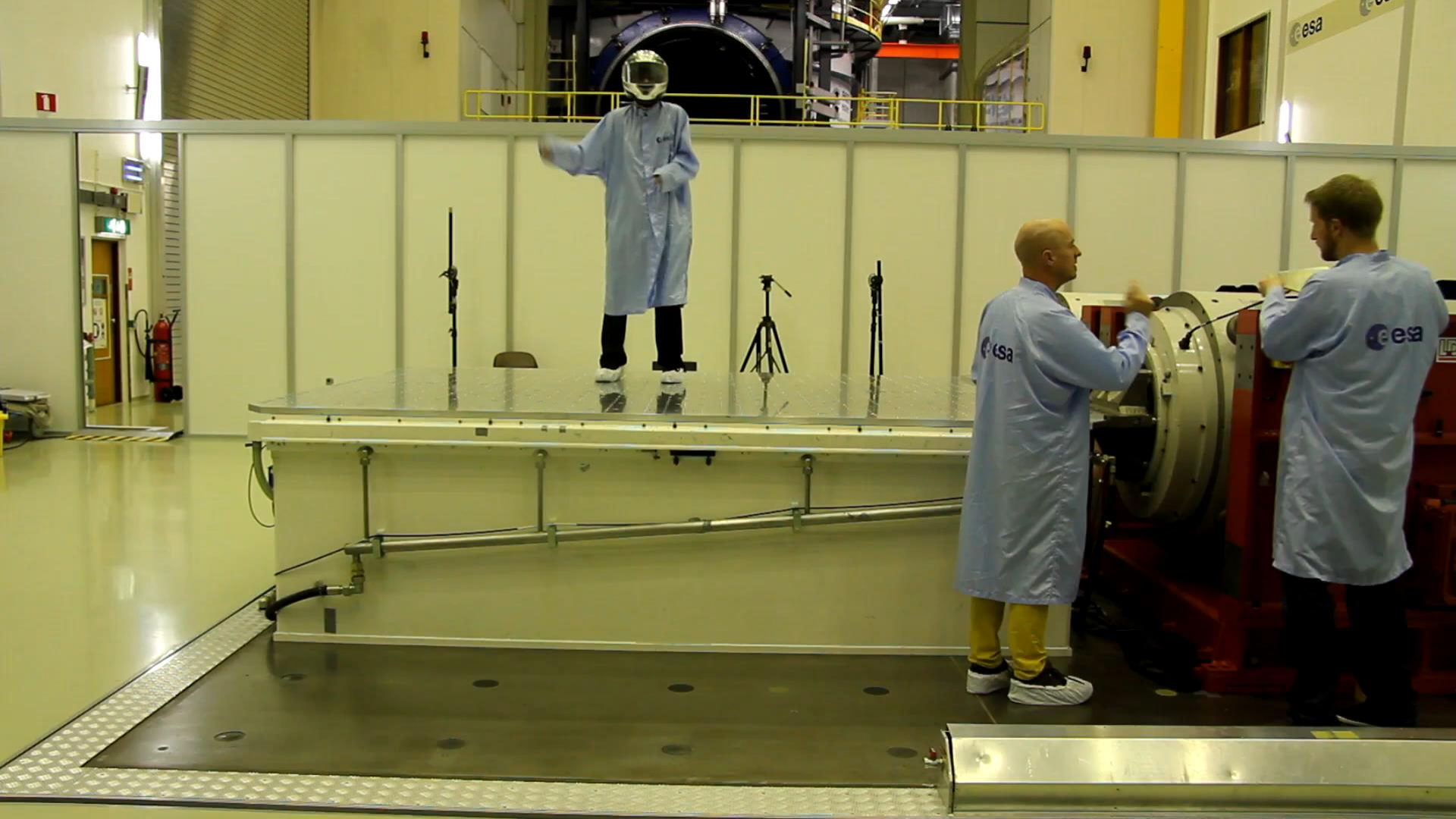




EE-584

Spacecraft Design & Systems Engineering

Space Environment & Orbital dynamics



Engineer, eSpace, EPFL Space Center

Marnix.verkammen@epfl.ch

© 2019 EPFL

- Spacecraft Environment:
 - Main spacecraft environmental factors and their attributes
 - Implications of these environmental factors on the spacecraft's design and operations
- Astrodynamics:
 - Basic concepts of orbital mechanics
 - Orbital manoeuvring and interplanetary travel
 - Basic concepts on rendez-vous
 - Re-entry

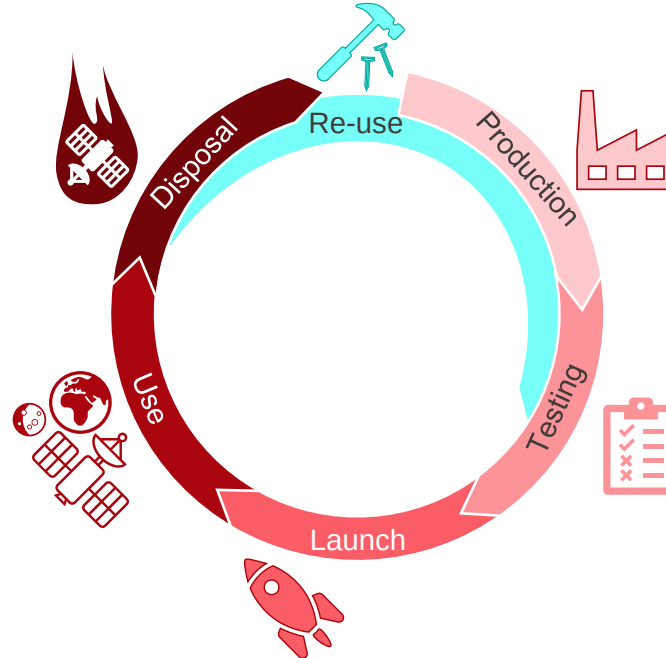


Spacecraft environment

- Main spacecraft environmental factors and their attributes
- Implications of these factors on the spacecraft's design and operations

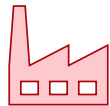
Spacecraft Environments

- Everything the spacecraft is exposed to during its complete life-cycle



Spacecraft Environments

- Everything the spacecraft is exposed to during its complete life-cycle



Production



Testing



Re-use



Launch



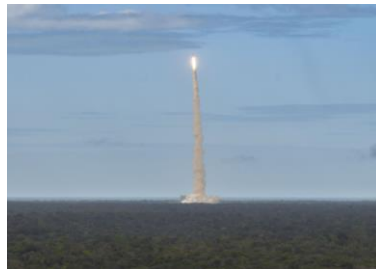
Disposal



Use



Earth
environment



Launch
environment



Atmospheric
environment



Space
environment

Spacecraft Environments -- Earth Environment

- A spacecraft remains in the terrestrial environment for a long time.
 - Design
 - Manufacturing
 - Testing
 - AIT (Assembly Integration & Testing)
 - Qualification
 - Etc.
- Small mistakes are easily made and can pile up quickly!



**Do not underestimate
the Earth Environment !**



Spacecraft Environments -- Earth Environment

- Keeping everything clean has a lot of implications.



Source of image: the European Space Agency,
[https://www.esa.int/ESA_Multimedia/Missions/Juice/\(result_type\)/images](https://www.esa.int/ESA_Multimedia/Missions/Juice/(result_type)/images)

Spacecraft Environments -- Earth Environment

- Keeping everything clean has a lot of implications.
- Environmental control!
 - Water & Humidity
 - Just right... To avoid corrosion. → 40-50%
 - Oxygen
 - Causes corrosion (with water)
 - Dust
 - Blocks mechanisms, clogs sensors, contaminates celestial bodies
 - Static Charges
 - Issue for electronics → Engineers need to be grounded (electrically)
 - Transportation
 - Vibrations, shocks, G-loads, (de-)pressurisation

Spacecraft Environments -- Earth Environment

- Keeping everything clean has a lot of implications.
- Think about the needs for a high-end clean room, or if “gray-room” is sufficient
 - Multiple ISO grades for clean room → Defines the number of particles

ISO Cleanroom Classifications

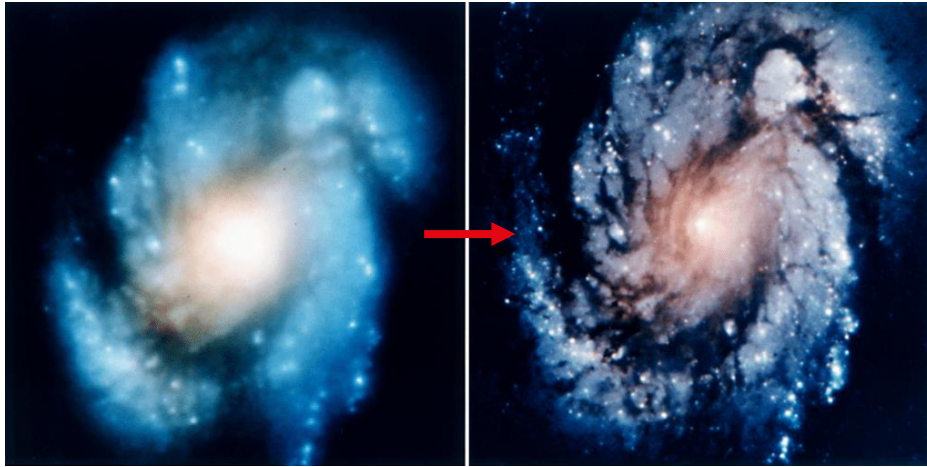
Class	FED STD 209E Equivalent	Maximum Concentration limits for particles equal to and larger than the sizes listed below					
		0.1micron	0.2micron	0.3micron	0.5micron	1micron	5micron
ISO 1		10	2				
ISO 2		100	24	10	4		
ISO 3	1	1000	237	102	35	8	
ISO 4	10	10000	2370	1020	352	83	
ISO 5	100	100000	23700	10200	3520	832	29
ISO 6	1000	1000000	237000	102000	35200	8320	293
ISO 7	10000				352000	83200	2930
ISO 8	100000				3520000	832000	29300
ISO 9						8320000	293000

IQSdirectory.com

Good video to get an impression of a high class Cleanroom: [Where does NASA keep the Moon Rocks? - Smarter Every Day 220 \(youtube.com\)](#)

Spacecraft Environments -- Earth Environment

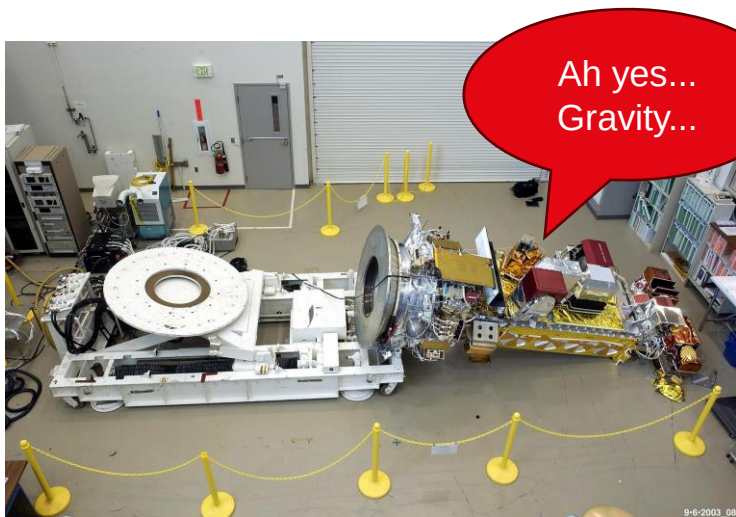
- Small mistakes are costly: Hubble



More info: <https://www.nasa.gov/content/hubbles-mirror-flaw>

Spacecraft Environments -- Earth Environment

- Small mistakes are costly: Developing **and** following procedures



More info (and source of image):
[NOAA-19 – Wikipedia](#)



[The Space Review: The cloth of doom: The weird, doomed ride of Ariane Flight 36](#)

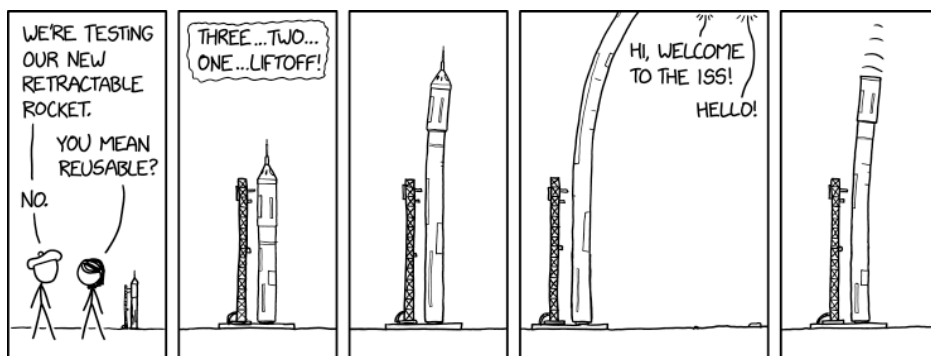
Spacecraft Environments -- Earth Environment

- Small mistakes are costly: Developing **and** following procedures



Exact Instructions Challenge - THIS is why my kids hate me. | Josh Darnit (youtube.com)

Spacecraft Environments -- Launch Environment



If only rocket launches were this gentle...

Spacecraft Environments -- Launch Environment

See
lecture 12



Rocket launches
are:

- Violent
- Brief



- Axial loading (acceleration)
 - Modest to high levels
- Lateral loads
 - Steering and wind gusts
- Vibrations: high levels
 - Mechanical & acoustic engines firing and aero buffeting
- Mechanical shocks
 - Pyrotechnics (fairing jettison, stage separation, ...)
- Air pressure changes
 - Rapid declining of ambient pressure
- Thermal changes
 - Aerodynamic heating

Spacecraft Environments -- Launch Environment

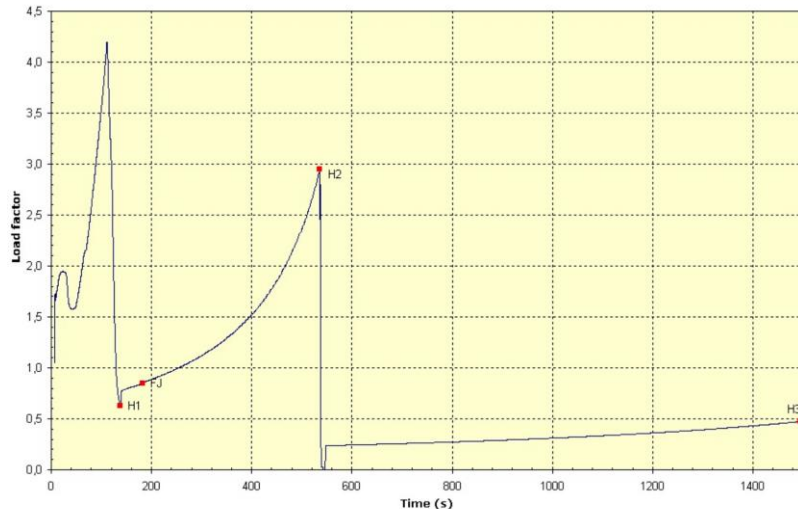


Figure 3.2.1.a – Typical longitudinal static acceleration of Ariane 5

- Axial loading (acceleration)
 - Modest to high levels
- Lateral loads
 - Steering and wind gusts
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Spacecraft Environments -- Launch Environment

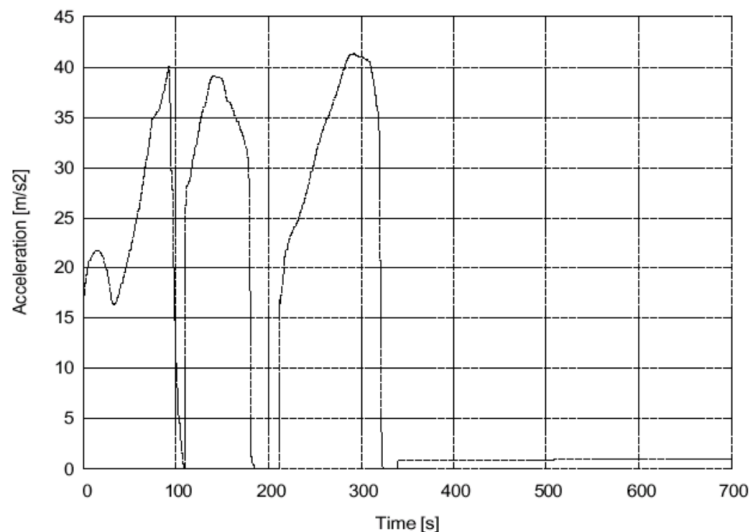


Figure 3.1 – Typical Longitudinal Steady-state Static Acceleration for the reference mission.
of the Vega Launcher

- Axial loading (acceleration)
 - Modest to high levels
- Lateral loads
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Spacecraft Environments -- Launch Environment



<https://youtu.be/4P8fKd0IVOs?t=1127>

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Spacecraft Environments -- Launch Environment



[4K: I captured a SpaceX Falcon 9 transiting the full Moon at 120fps \(youtube.com\)](#)

- Axial loading (acceleration)
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Spacecraft Environments -- Launch Environment

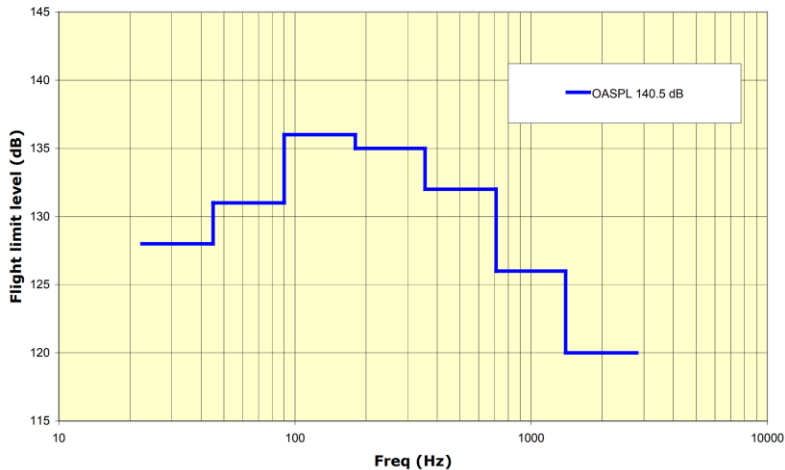


Figure 3.2.5.2.b - Acoustic noise spectrum of Ariane 5

- Axial loading (acceleration)
 - Modest to high levels
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Spacecraft Environments -- Launch Environment



<https://www.youtube.com/watch?v=GEwc6Poi4dg>

■ BepiColombo's structural & thermal model being tested

- Axial loading (acceleration)
 - Modest to high levels
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Spacecraft Environments -- Launch Environment



[Horizons mission - Soyuz: launch to orbit - YouTube](#)

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Spacecraft Environments -- Launch Environment

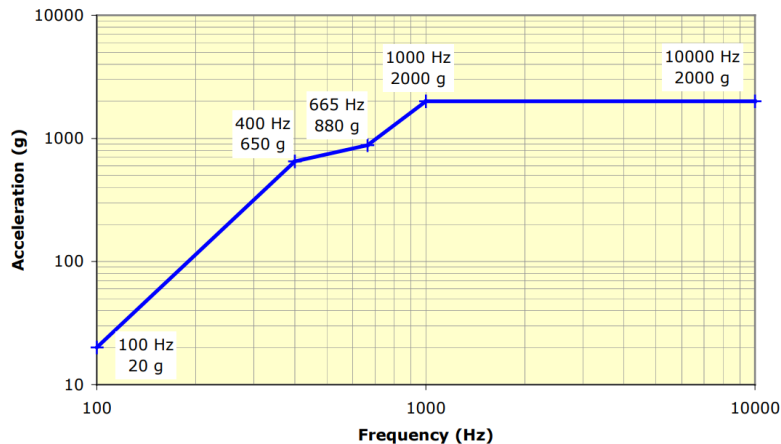


Figure 3.2.6.a – Envelope shock spectrum at spacecraft separation plane of Ariane 5

- Axial loading (acceleration)
 - Modest to high levels
- Lateral loads
 - Steering and wind gusts
- Vibrations: high levels
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- Mechanical shocks
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- Air pressure changes
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- Thermal changes
 - Aerodynamic heating

Spacecraft Environments -- Launch Environment



https://youtu.be/Pu97liO_yDI?t=585

- Axial loading (acceleration)
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Spacecraft Environments -- Launch Environment

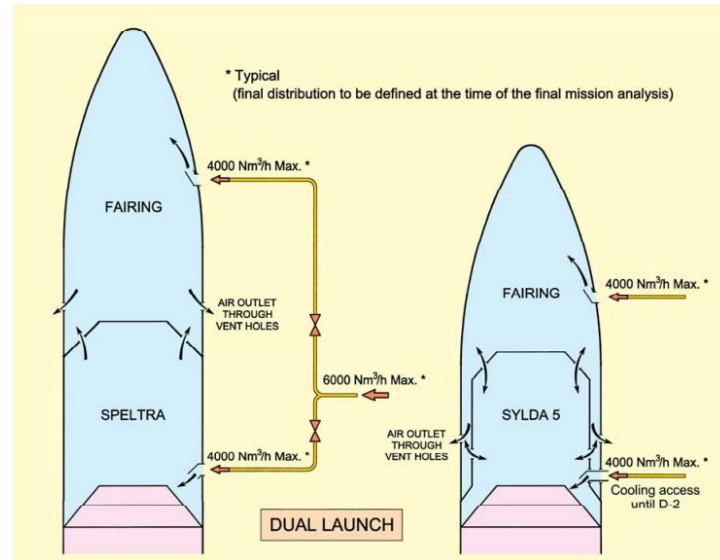


Figure 3.3.2.2.a – Configuration of ventilation within spacecraft volumes of Ariane 5

More info on the effects of venting ports:

R. C. Mehta, "[Review of Vent Systems of Space Vehicle, Spacecraft and Aircraft](#)," Scholars Journal of Engineering and Technology, 2022

- Axial loading (acceleration)
 - Modest to high levels
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Spacecraft Environments -- Launch Environment

3.3.3. Flight environment

3.3.3.1. Thermal conditions before fairing jettisoning

The mean net flux density radiated by the fairing, the SPELTRA or the SYLDA 5 does not exceed 1000 W/m^2 at any point.

This figure does not take into account any effect induced by the spacecraft dissipated power.

3.3.3.2. Aerothermal flux and thermal conditions after fairing jettisoning

This is not applicable to any passenger inside the SPELTRA or the SYLDA 5.

The nominal time for jettisoning the fairing is determined in order to not exceed the aerothermal flux of 1135 W/m^2 . This flux is calculated as a free molecular flow acting on a plane surface perpendicular to the velocity direction, and based on the atmospheric model US66, latitude 15° North.

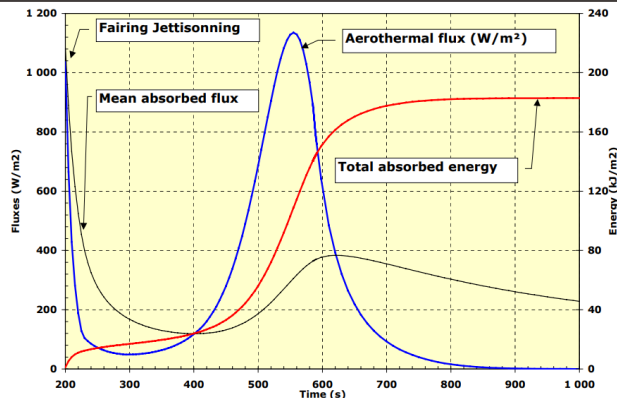


Figure 3.3.3.2.a - Aerothermal fluxes on trajectory

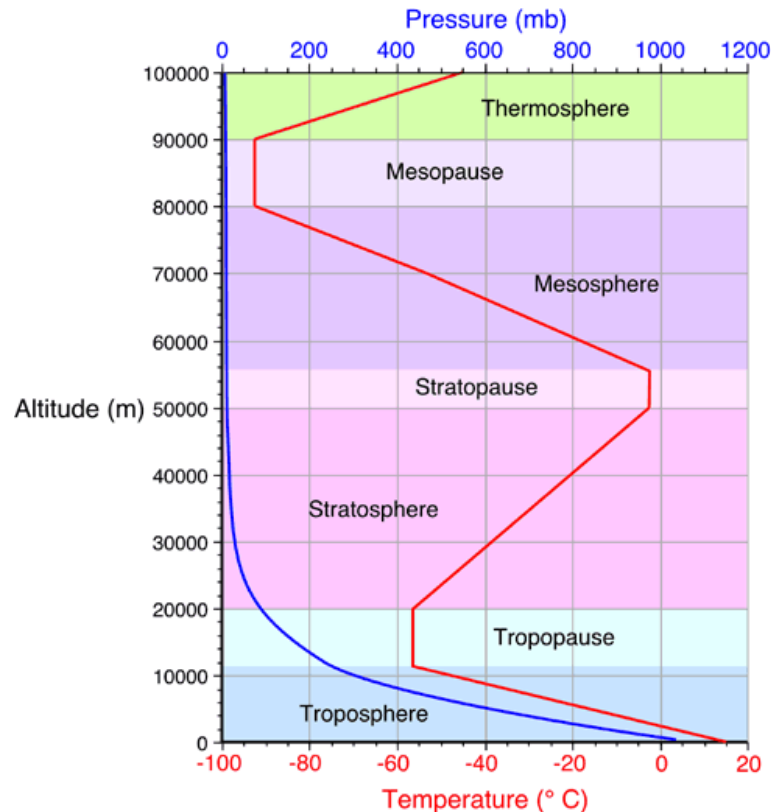
Ariane 5 equipped with storable propellant upper stage (EPS)

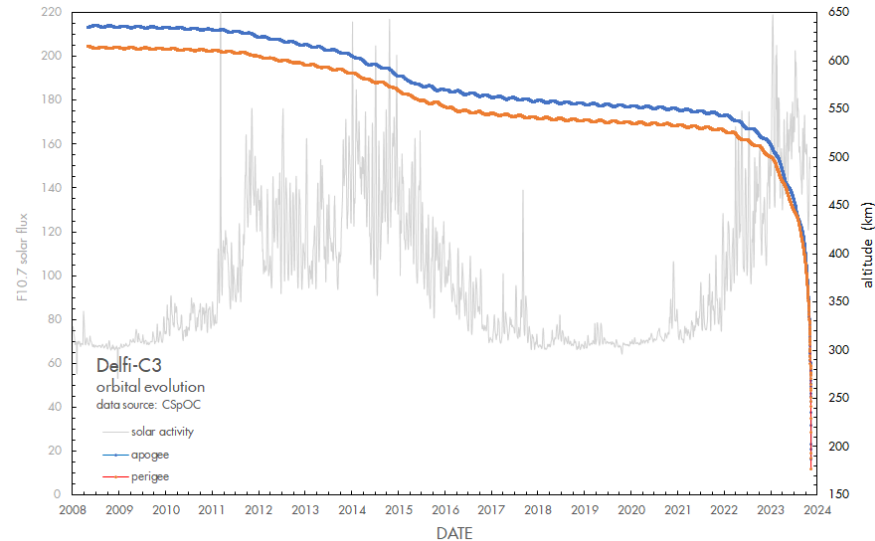
Fairing jettisoning and second flux peak constrained at 1135 W/m^2

- Axial loading (acceleration)
 - Modest to high levels
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Spacecraft Environments -- Atmospheric Environment

- Satellites are affected by the atmosphere during each phase:
 - Launch
 - Operations phase (if in Earth Orbit)
 - End-of-life
- Effects of the atmosphere vary due to:
 - Density
 - Composition





More info: [SatTrackCam Leiden \(b\)log: Delfi-C3 reentry forecast updates \(periodically updated post\)](#)

Spacecraft Environments -- Atmospheric Environment

Upper atmosphere:

- More homogenous
 - As opposed to lower atmosphere (78% nitrogen, 21% molecular oxygen, etc)
 - Photochemical process changes the composition
- Solar UV radiation → Atomic oxygen
 - Because oxygen absorbs of UV light and dissociations (O vs O₂)
 - Very powerful oxidiser → Material degradation

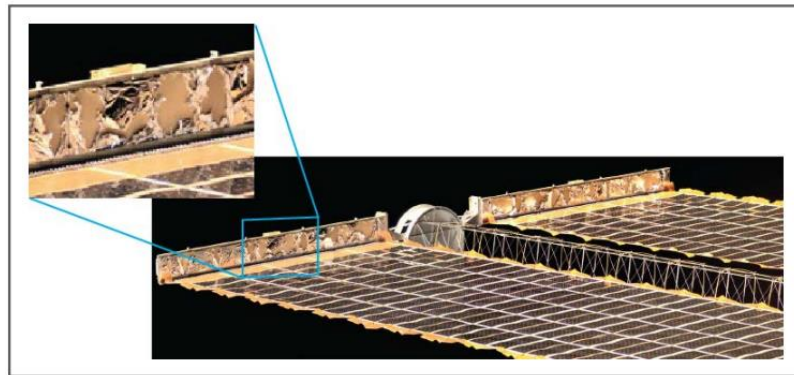


Figure 3. Image shows atomic oxygen undercutting degradation of the solar array wing blanket box cover on the International Space Station after one year of space exposure.

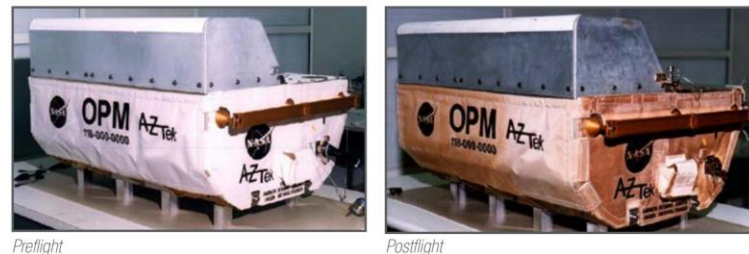


Figure 4. Preflight and postflight images of the Optical Properties Monitor shown with ultraviolet-darkened insulation after nine months of exposure on the Mir Space Station.

Spacecraft Environments -- Atmospheric Environment

Re-entry at End-of Life:

- Kinetic energy converted in heat
- Heat melts the spacecraft → Demise
 - Important to **design for demise**!
 - A lot of research is ongoing on novel materials and trajectory optimization.

Design for demise applied to spacecraft structural panels and experiments for ClearSpace One platform

Présentée le 19 avril 2024

Faculté des sciences et techniques de l'ingénieur
Laboratoire de mise en oeuvre de composites à haute performance
Programme doctoral en science et génie des matériaux

pour l'obtention du grade de Docteur ès Sciences

par

Alexandre Achille LOOTEN

Acceptée sur proposition du jury

Prof. J. Bruggen, président du jury
Prof. V. Michaud, directrice de thèse
Dr I. Sakraker Ozmen, rapporteuse
Dr U. Lallart, rapporteur
Prof. A. Vassilopoulos, rapporteur



Source: A game that every Aerospace engineer should play, namely "Kerbal Space Program".
Enjoy ;-)

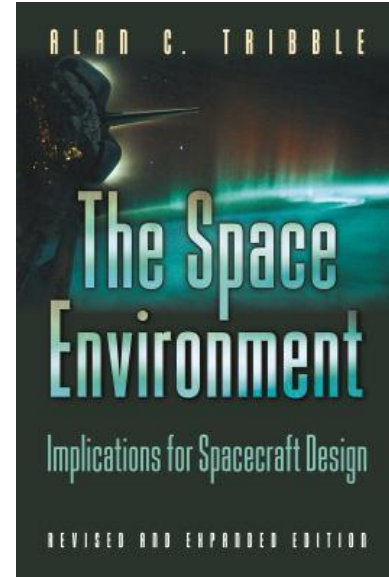
<https://infoscience.epfl.ch/entites/publication/064c9341-560d-438f-8f8e-1fe9d428e9a2>

Spacecraft Environments -- Space Environment

Vacuum

- Outgassing
 - Release of gaseous material as a result of pressure changes
 - Material may deposit back → Clouding of sensors
 - Need for a test in a Thermal Vacuum Chamber (TVAC)
 - Often for 24h, followed by weighting to see mass lost and moisture captured
 - Bake-outs might be needed
- Cold welding
 - Same kind of metal may weld together
 - Can be avoided using non-outgassing lubricants
- Heat transfer
 - Major issue: Only radiation can be used

See
lecture 7

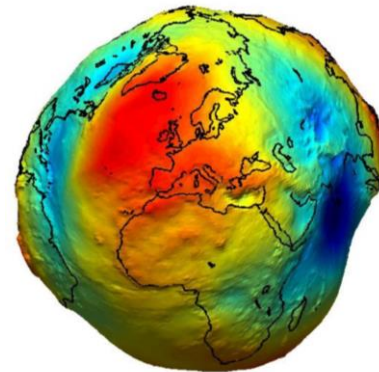


<https://doi.org/10.1515/9780691213071>

Spacecraft Environments -- Space Environment

Gravity (or lack thereof?)

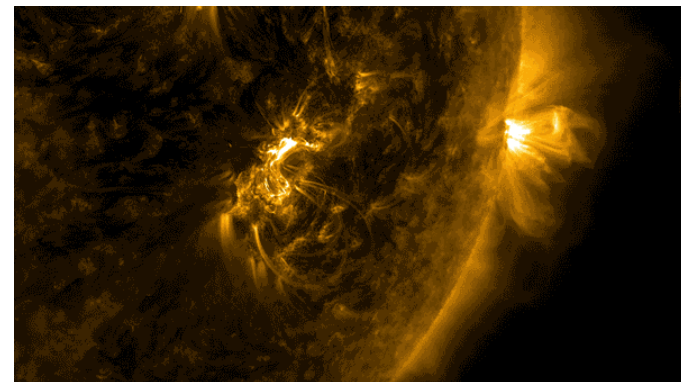
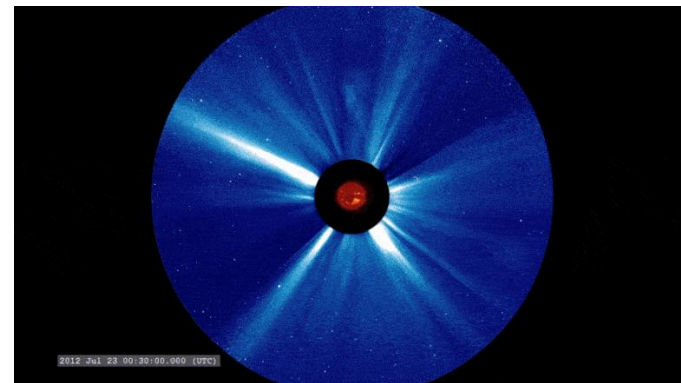
- No such thing as Zero-G !!
 - Orbits = free-falling objects, with such a speed, that they “miss” the earth constantly
- There are always some disturbances (hence the term “micro-gravity”)
 - The Earth is a potato! The Moon is even more irregular
 - Constant gravitational disturbances in the orbits
 - Atmospheric pressure
 - Solar pressure
 - Spacecraft rotation → centrifugal forces
 - Gravity gradient
 - Structural vibrations (e.g. due to uneven heating)



Spacecraft Environments -- Space Environment

Space weather

- The sun affects the space environment
 - Electromagnetic radiation
 - Non-ionizing radiation
 - a.k.a “Flares”: X-ray and energy bursts
 - Travel at the speed of light (arrive to Earth in approx. 8min)
 - Charged particles
 - Ionizing radiation
 - a.k.a “Coronal Mass Ejections”: giant clouds of particles
 - Travel more slowly (arrive at Earth in approx. 3 days)

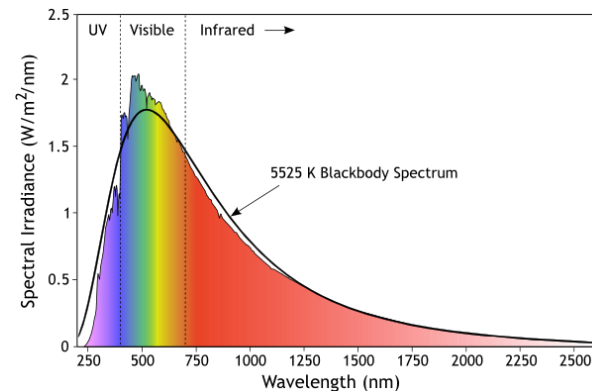


More info: <https://www.youtubeeducation.com/watch?v=TWjtYSRIOU1>

Spacecraft Environments -- Space Environment

Space weather

- Electromagnetic (EM) radiation
 - The Sun is a non-ideal blackbody at 5525K
 - 99% is emitted in UV, visible and infrared
 - Also the Earth (and on the celestial bodies) emit radiation!
 - Impacts the thermal design
 - EM radiation exerts a small pressure on surfaces
 - $\sim 5\text{N/km}^2$
 - May disturb orientation and orbits

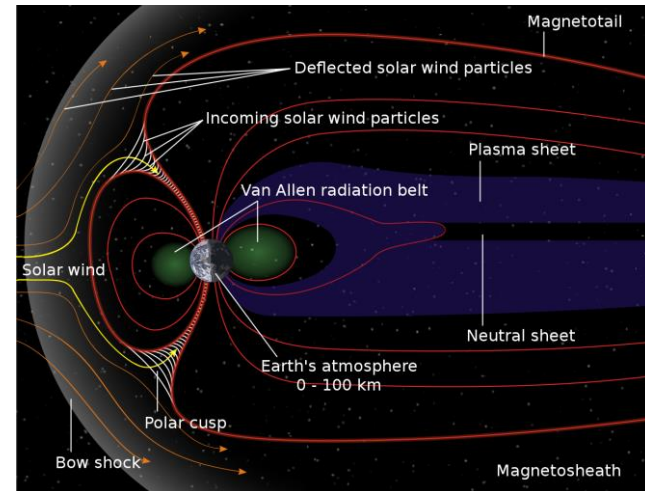


Planet	Distance (x 10^9 m)	Mean Solar Irradiance (W/m^2)
Mercury	57	9116.4
Venus	108	2611.0
Earth	150	1366.1
Mars	227	588.6
Jupiter	778	50.5
Saturn	1426	15.04
Uranus	2868	3.72
Neptune	4497	1.51
Pluto	5806	0.878

Spacecraft Environments -- Space Environment

Space weather

- Charged particles / Ionizing radiation
 - Solar winds
 - Sun cycle: 11 years approx.
 - Earth is protected by its Geomagnetic Field (GMF)
 - Van Allen radiation Belts:
 - The GMF trap energetic particles for years
 - Inner belt: 1,000 to 12,000 km from Earth centre
 - Outer belt: 13,000 to 60,000 km from Earth centre
 - Non-uniform (see [here](#)) and dynamic
 - Galactic Cosmic Rays
 - From outside the solar system
 - Substantially deflected by the GMF



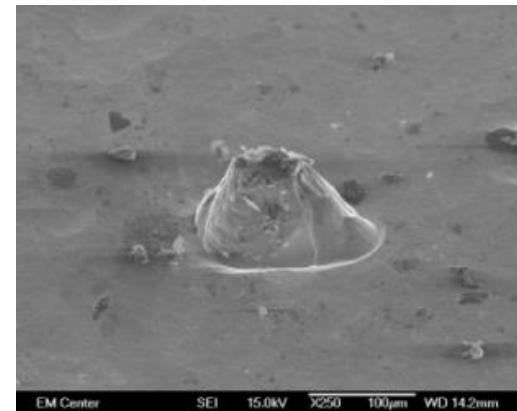
Good video on Van Allen Belts:

<https://www.youtube.com/watch?v=h9YN50xXFJY>

Spacecraft Environments -- Space Environment

Space weather

- Charged particles / Ionizing radiation
 - May damage spacecraft by:
 - Charging
 - Sputtering (high velocity impacts)
 - Single-Event Phenomena/Effects
 - Total Ionizing Dose
 - How to protect your mission?
 - Operation in “safe zone”
 - Turning off sensors
 - Shielding

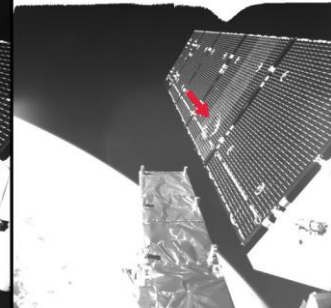
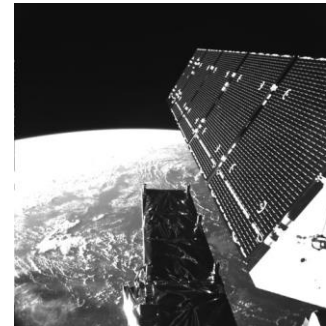
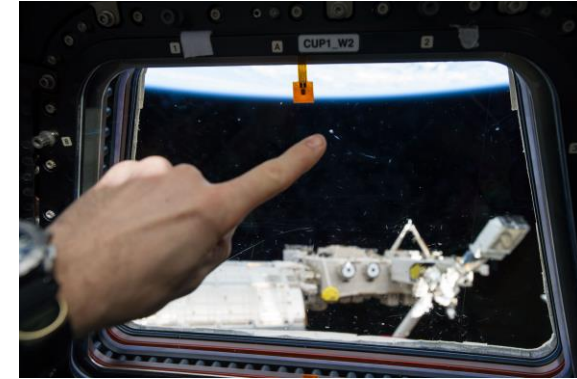
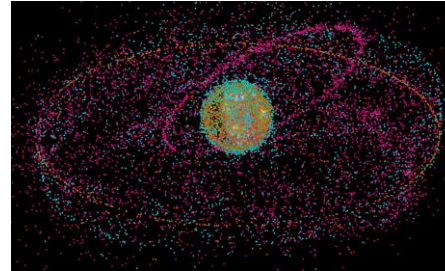
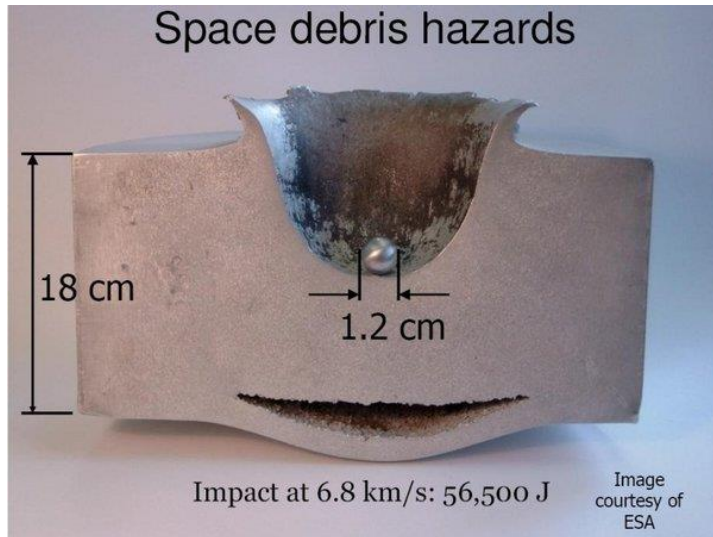


Cone formation during sputtering.

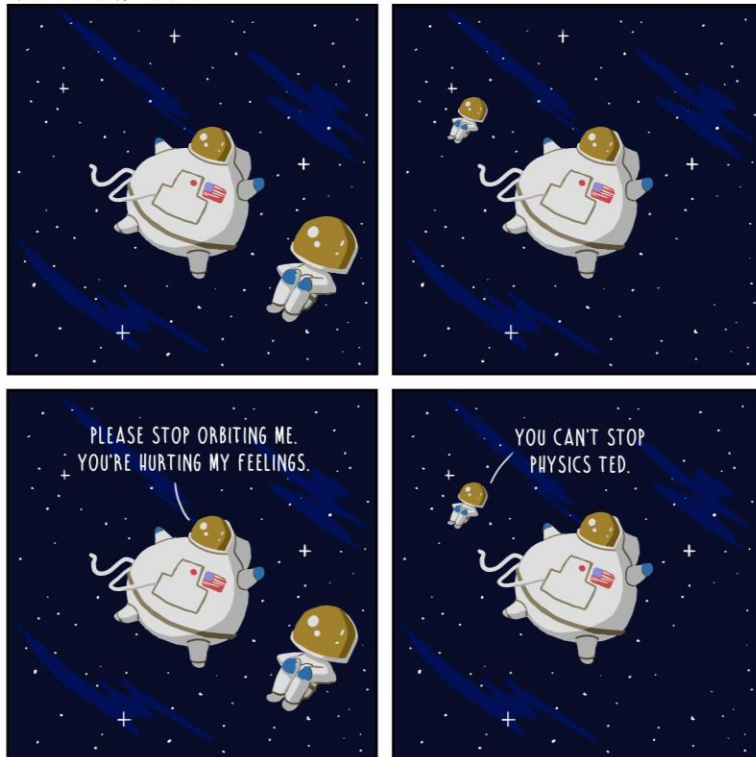
Cool interactive infographic: [Comparison of several satellite navigation system orbits \(wikimedia.org\)](#)

Spacecraft Environments -- Space Environment

Micrometeorites & orbital debris



PROLIFIC PEN COMICS "ORBITS"



INSTAGRAM@PROLIFICPENCOMICS

3-31-17

PROLIFICPENCOMICS.TUMBLR.COM

Astrodynamics

- Basic Concepts of Orbital Mechanics
- Orbital manoeuvring and interplanetary travel
- Basic concepts of rendez-vous

Details covered in class EE-585: Space mission design and operations

EPFL
STUDY PLANS

FR EN

Study plans / Minor / Space technologies minor / Space mission design and operations

Space mission design and operations

Download the coursebook (PDF)

EE-585 / 2 credits

Teacher: [Kuntzer Thibault](#) [Adrien](#)

Language: English

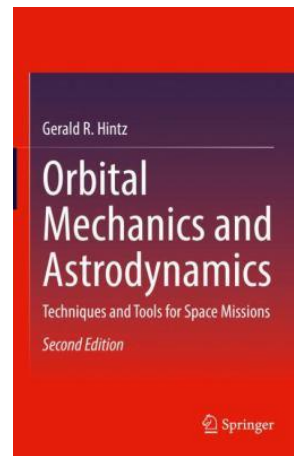
Summary

This course is a "concepts" course. It introduces a variety of concepts to design and operate a space mission. These concepts cover orbital mechanics, spacecraft operation phases and critical subsystems.

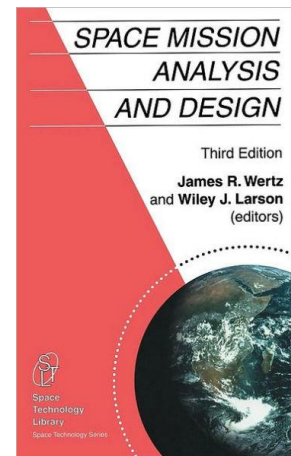
Content

- Brief review of the fundamental laws of mechanics
- Types of space missions and their objectives
- The space environment
- Applied orbital mechanics, including interplanetary trajectories
- Rendez-vous and proximity operations
- Propulsion modules
- Attitude determination and control
- Satellite and constellation operations
- Launch and early orbit phase
- Human spaceflight and extravehicular activities
- Risks of spacecraft operations & sustainability
- Future trends in spacecraft operations

Therefore, we will only go over the basics



[Orbital Mechanics and Astrodynamics: Techniques and Tools for Space Missions - EPFL \(slsp.ch\)](#)

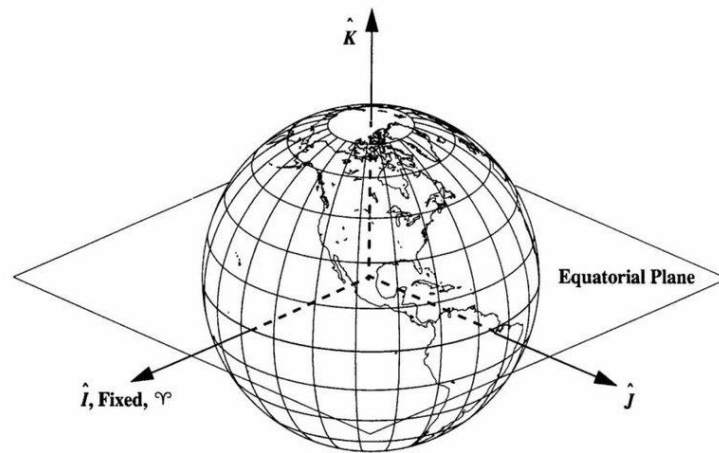


[Space mission analysis and design - EPFL \(slsp.ch\)](#)



Geocentric Equatorial Coordinate System (ECI)

- Origin: center of the Earth
- Fundamental plane: Earth's equator
- Principal direction: Vernal equinox
- Third axis: RHR



**the FPA moves about 1 deg every 70 years.

It is no longer pointing at Aries but in Pisces.

- Gravitational attraction

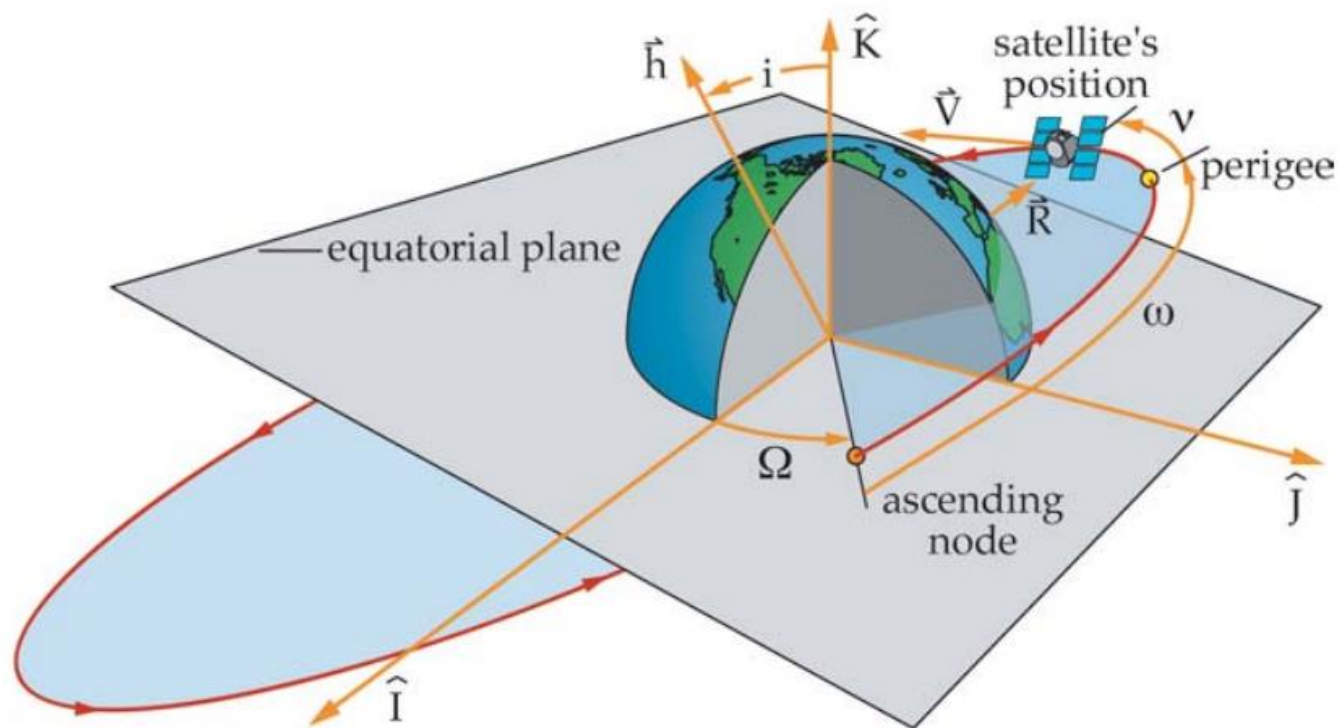
- $F = G \frac{m_1 m_2}{r^2}$

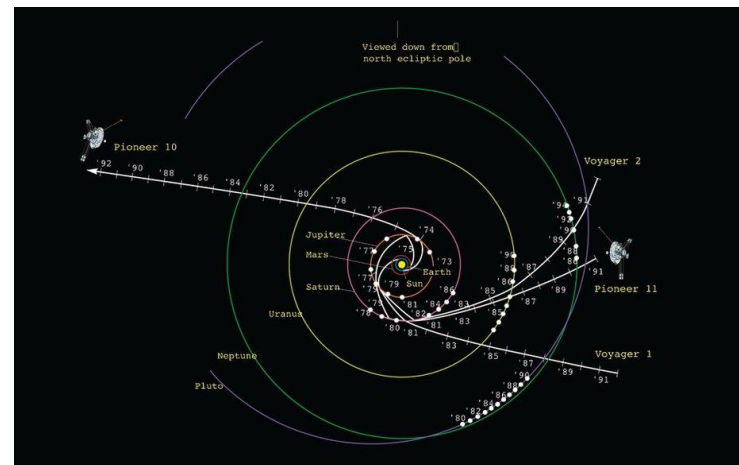
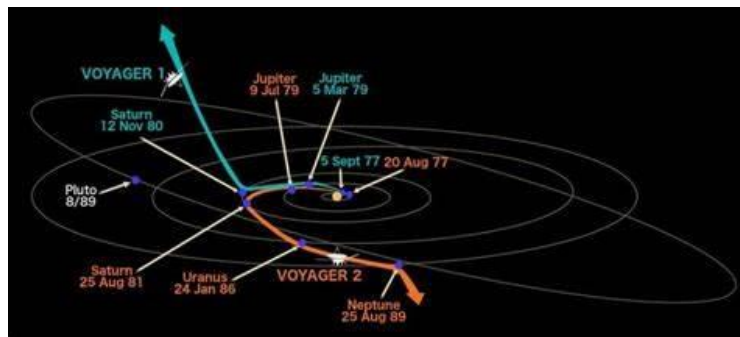
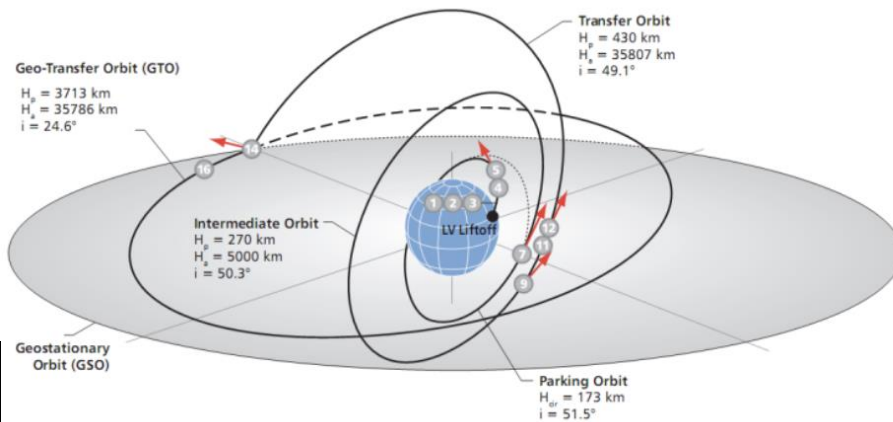
- Gravitational constant

- $G \approx 6.6730 * 10^{-11} \text{ m}^3 \text{kg}^{-1} \text{s}^{-2}$

- Tchaikovsky equation

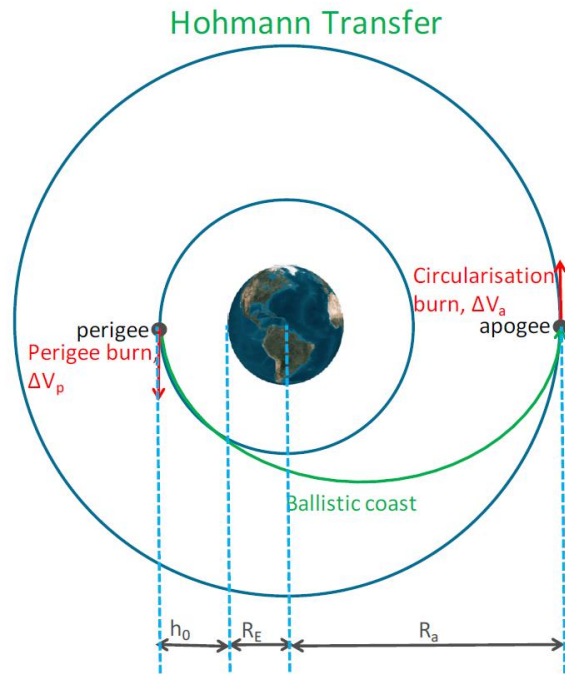
- $\Delta V = v_e \ln \left(\frac{m_0}{m_f} \right) = I_{sp} g_0 \ln \left(\frac{m_0}{m_f} \right)$





- Most energy efficient transfer between 2 circular orbits
- It requires 2 steps
 - First delta-V at perigee to put the spacecraft into an elliptical transfer orbit
 - Second delta-V at apogee to bring the spacecraft into its final orbit
 - Both delta-V's are tangential and impulsive

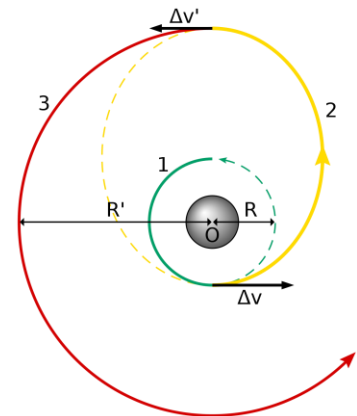
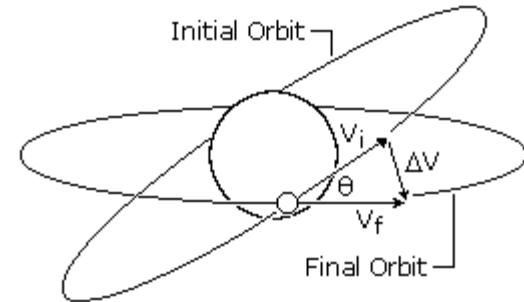
$$\Delta V_{total} = \Delta V_1 + \Delta V_2 \quad TOF = \pi \sqrt{\frac{a_t^3}{\mu}}$$



See animations: [here](#)

What if you have to change planes? → out-of-plane delta-v

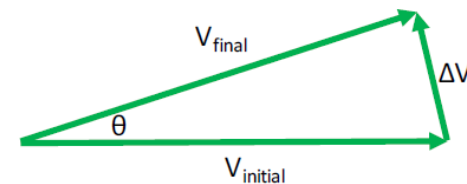
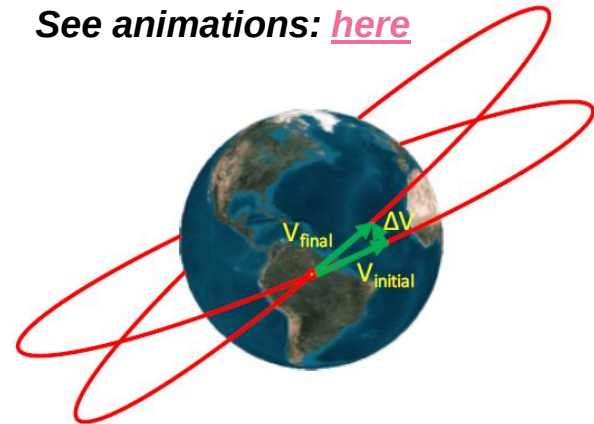
- 3 potential changes
 1. Change the inclination
 2. Change the RAAN
 3. Change the semimajor axis (“in-plane”)
- 2 scenarios
 - a. Simple plane change → we only change the direction of the velocity vector (either (1) or (2))
 - b. Combined plane change → magnitude and direction of the velocity vector changes (either (1)+(3) or (2)+(3))



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$$\Delta V_s = 2V_i \sin\left(\frac{\theta}{2}\right)$$

$$\theta = \Delta i$$

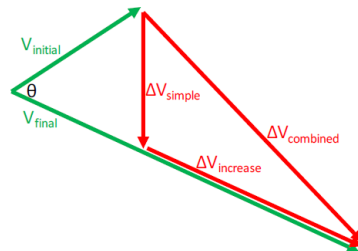
$$\theta = \Delta \Omega$$



See animations: [here](#)

What if you have to change planes? → out-of-plane delta-v

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$$\Delta V_c = \sqrt{V_i^2 + V_f^2 - 2V_iV_f\cos\theta}$$

$$\theta = \Delta i$$

Or

$$\theta = \Delta \Omega$$



- With the concept we have already seen we should be able to understand orbital maneuvering within a planet Sphere of Influence (SOI) → the same applies to interplanetary travel
- We just now move on a heliocentric coordinate system.
 - Transfer time ~ Heliocentric Hohmann Transfer → patched conic approximation
 - Planets phasing ~ Orbital rendezvous → synodic periods

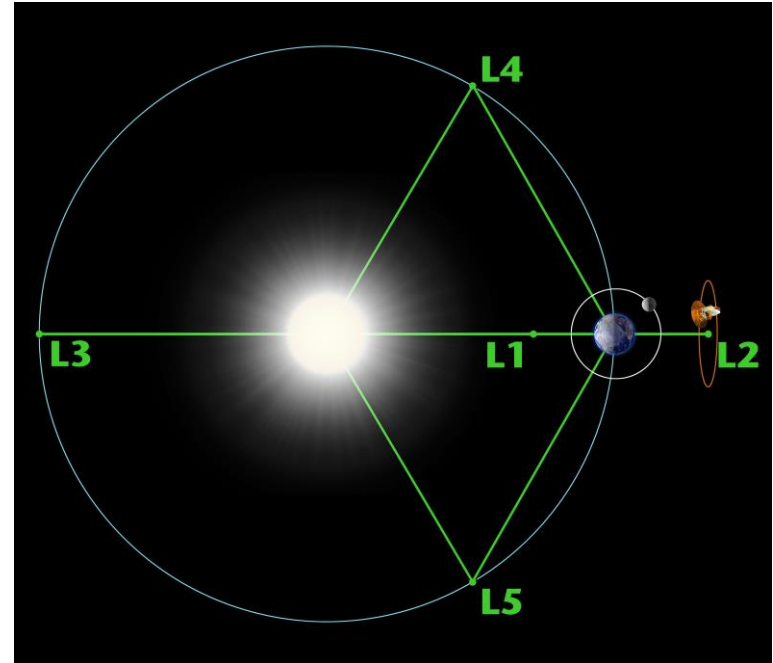


+ Gravity assists! (Save your Fuel)

https://svs.gsfc.nasa.gov/vis/a000000/a004400/a004482/orex_Outbound_GravityAssist_1080p60.webm

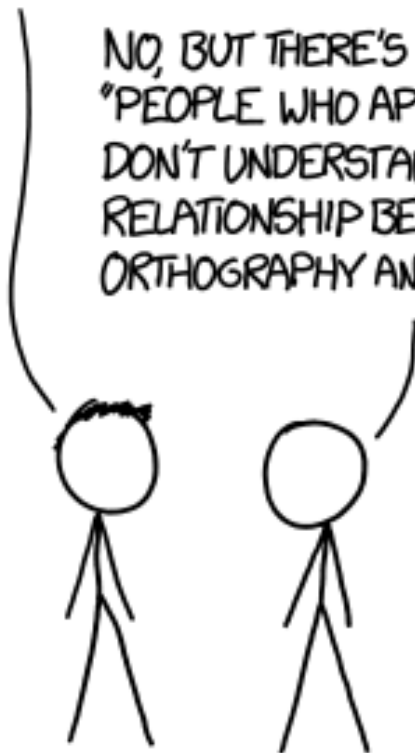
Good explanation can be found here:

[What is a Lagrange Point? - NASA Science](#)



REMEMBER, THERE'S NO "I" IN "TEAM."

NO, BUT THERE'S A "U" IN
"PEOPLE WHO APPARENTLY
DON'T UNDERSTAND THE
RELATIONSHIP BETWEEN
ORTHOGRAPHY AND MEANING."



Your turn

- You have already preliminary requirements and ConOps
- Now, dive deeper: environments, orbits, resulting constraints on space mission

■ Today's Project Work:

- By now you should have a clear idea of what your mission destination, goals, and scientific objectives are...
- You may have already defined some preliminary mission requirements and constraints.
- You have identified other mission architectures to use as a reference.
- You may already started to draft a CONOPS and top-level functions for your spacecraft.
- Today you need to start:
 - Understand the constraints from the space environment your mission will operate in.
 - Defining your **mission profile**: *how to get to (and return from) your destination?*
 - Assessing potential **launchers, launch sites**, and drafting **launch windows**
 - Calculating **required delta-Vs** and associated propellant mass for your CONOPS → don't forget the return and/or disposal of your spacecraft.
 - Defining your **propulsion subsystem** that can provide that delta-V → don't forget **margins!**
 - You can create a block diagram with number of engines, dimensions, specs, burn time, etc.