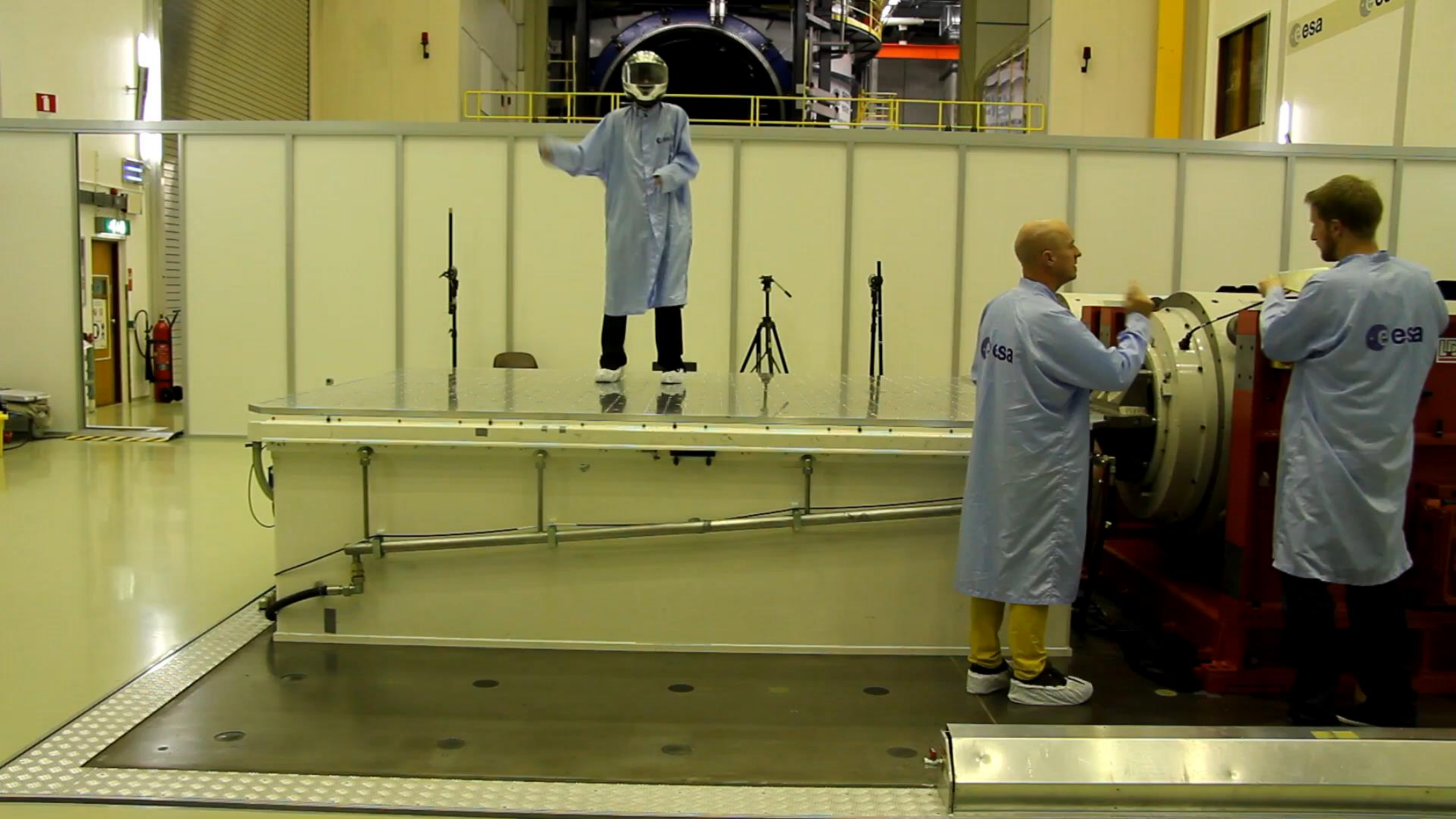

esa
esa
esa

EPFL

EE-584
Spacecraft Design & Systems Engineering

Space Environment & Orbital dynamics

Engineer, eSpace, EPFL Space Center
Marnix.verkammen@epfl.ch

EPFL

Who am I ?

TU Delft
Aerospace Engineering
BSc + MSc

EPFL Space Center eSpace

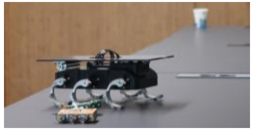
EcoΔV
Spinoff from the EPFL Space Center
www.ecodeltav.com

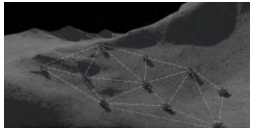
TU Delft **Impact Contest**
Launch your start-up idea

LUNAR ZEBRO subsulto aude ad

www.zebro.space

https://www.youtube.com/watch?v=w_BUfLucM8g





Learning outcomes

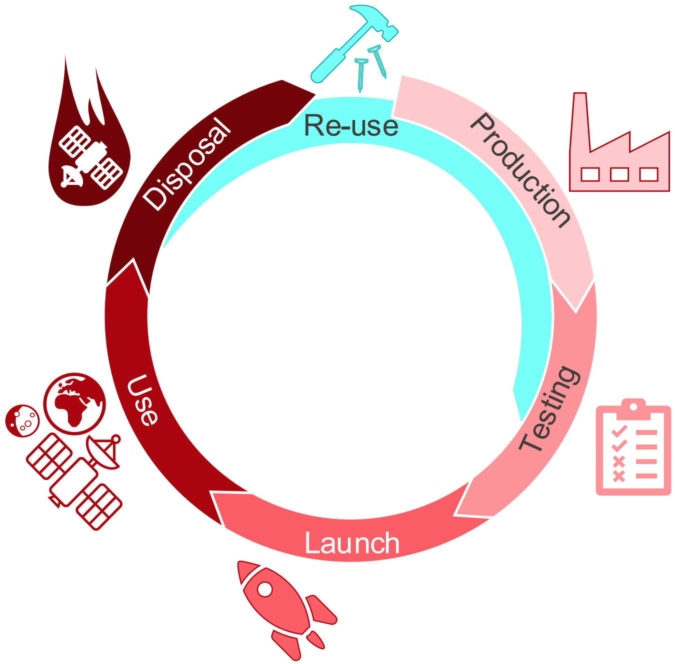
- Spacecraft Environment:
  - Main spacecraft environmental factors and their attributes
  - Implications of these environmental factors on the spacecraft’s design and operations
- Astrodynamics:
  - Basic concepts of orbital mechanics
  - Orbital manoeuvring and interplanetary travel
  - Basic concepts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

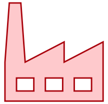
Spacecraft Environments

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



Spacecraft Environments

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

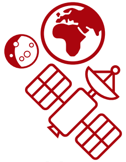

Production


Testing


Re-use


Launch


Disposal


Use

Earth environment


Launch environment


Atmospheric environment


Space environment

Source of image: ESA and NASA

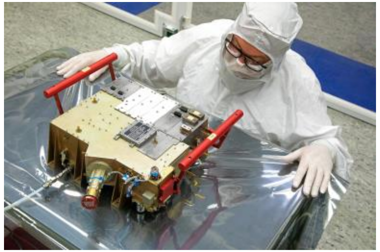
Spacecraft Environments -- Earth Environment

- 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

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

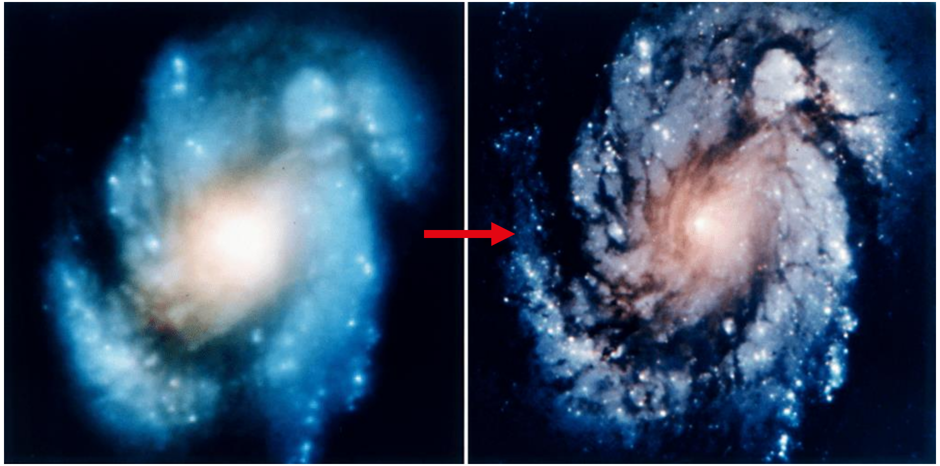
Class	FED STD 209E Equivalent	Maximum Concentration limits for particles equal to and larger than the sizes listed below					
		0.1micron	0.2micron	0.3micron	0.5micron	1micron	5micron
ISO 1		10	2				
ISO 2		100	24	10	4		
ISO 3	1	1000	237	102	35	8	
ISO 4	10	10000	2370	1020	352	83	
ISO 5	100	100000	23700	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

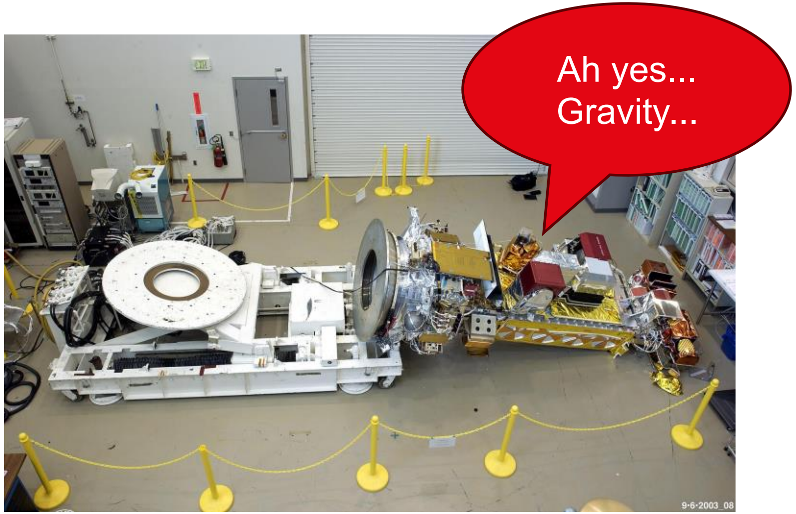
- Small mistakes are costly: Hubble



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

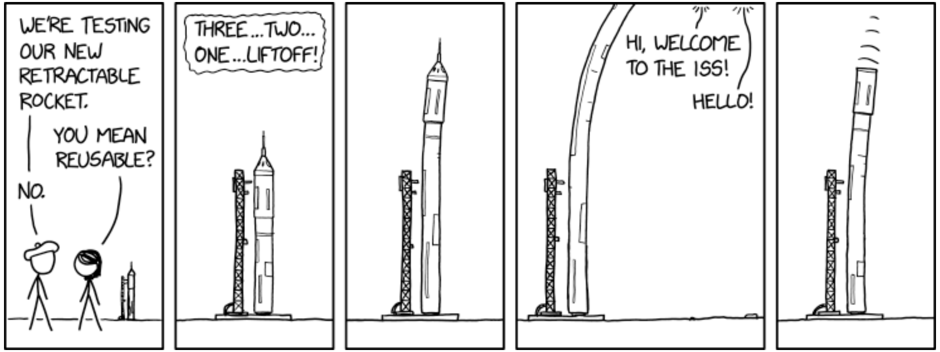
The Space Review: The cloth of doom: The weird, doomed ride of Ariane Flight 36

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...

Source of image: https://xkcd.com/2534

Spacecraft Environments -- Launch Environment

See lecture on Launch Vehicles and Launch Operations

> 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

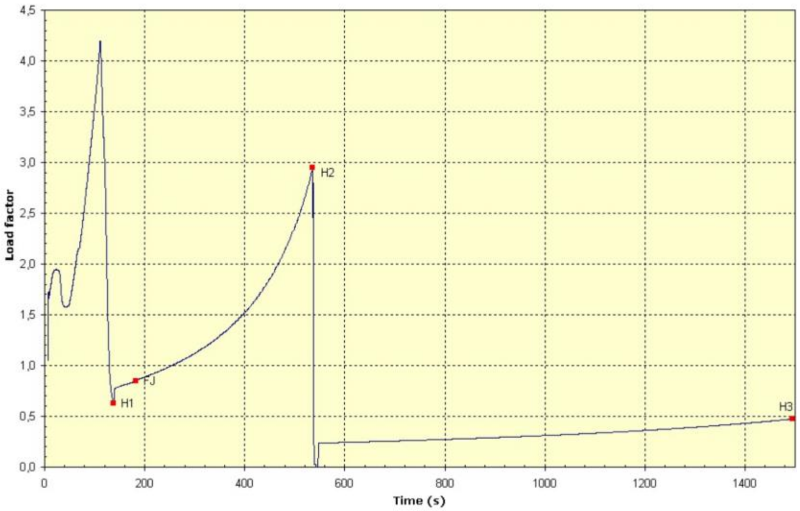


Figure 3.2.1.a – Typical longitudinal static acceleration of Ariane 5

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

Source of image: Ariane 5 User Manual, Issue 4, 2004

Spacecraft Environments -- Launch Environment

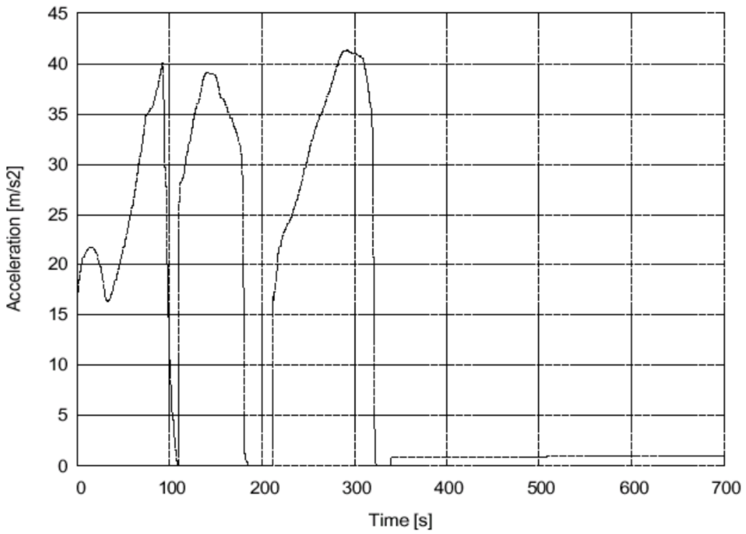


Figure 3.1 – Typical Longitudinal Steady-state Static Acceleration for the reference mission.
of the Vega Launcher

- Axial loading (acceleration)
  - Modest to high levels
- Lateral loads
  - 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

Source of image: Vega User Manual, Issue 3, 2006

Spacecraft Environments -- Launch Environment

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

- 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

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

- 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

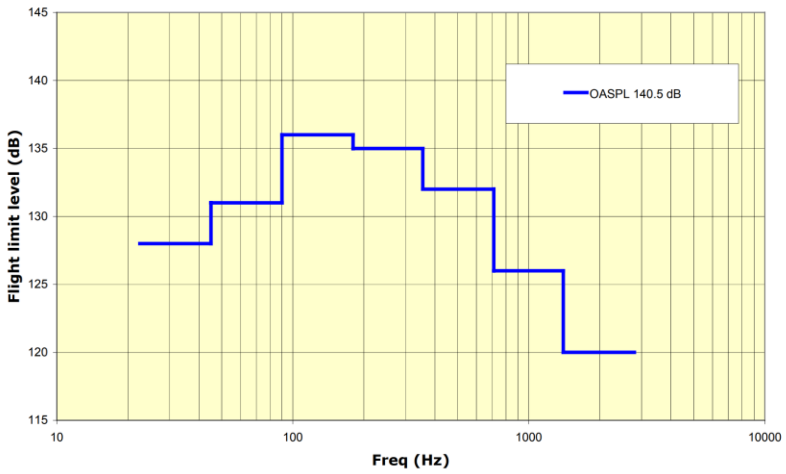


Figure 3.2.5.2.b - Acoustic noise spectrum of Ariane 5

- 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

Source of image: Ariane 5 User Manual, Issue 4, 2004

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
- 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

[Horizons mission - Soyuz: launch to orbit - YouTube]

- 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
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Spacecraft Environments -- Launch Environment

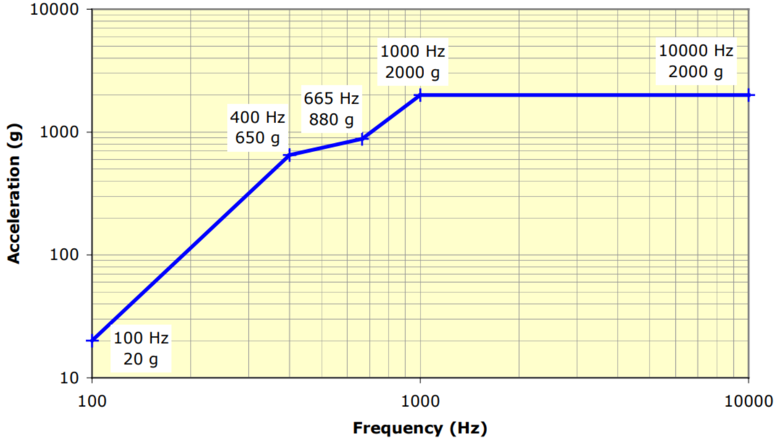


Figure 3.2.6.a – Envelope shock spectrum at spacecraft separation plane of Ariane 5

- Axial loading (acceleration)
  - Modest to high levels
- Lateral loads
  - Steering and wind gusts
- Vibrations: high levels
  - 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

Source of image: Ariane 5 User Manual, Issue 4, 2004

Spacecraft Environments -- Launch Environment

https://youtu.be/Pu97IiO_yDI?t=585

- 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

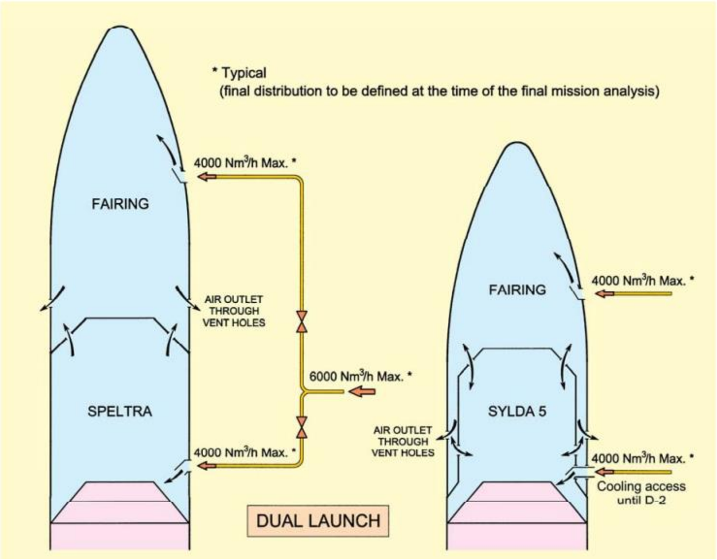


Figure 3.3.2.2.a – Configuration of ventilation within spacecraft volumes of Ariane 5

- 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

- 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

Source of image: Ariane 5 User Manual, Issue 4, 2004f

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.

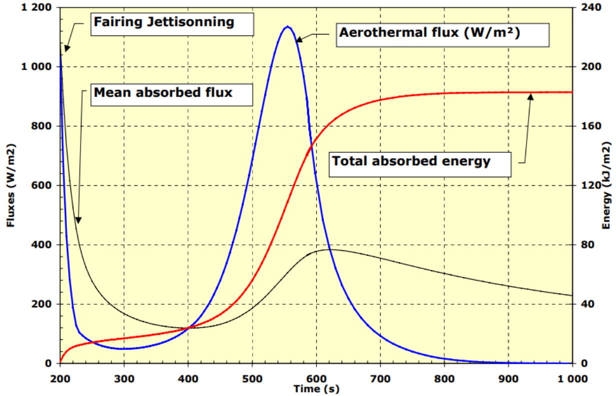


Figure 3.3.3.2.a – Aerothermal fluxes on trajectory

Ariane 5 equipped with storable propellant upper stage (EPS)

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

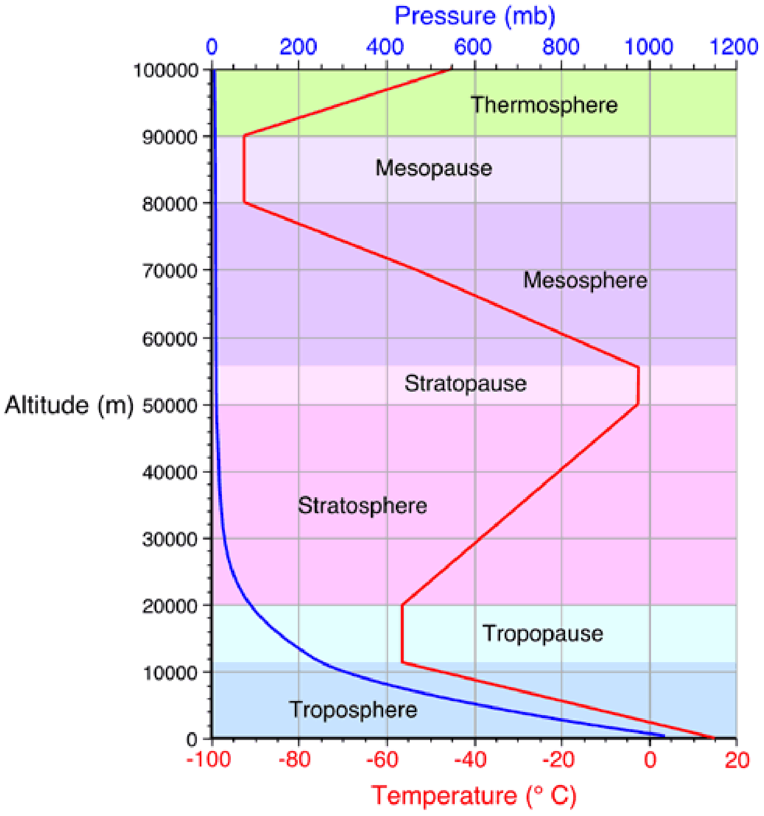
- Axial loading (acceleration)
  - Modest to high levels
- Lateral loads
  - Steering and wind gusts
- Vibrations: high levels
  - Mechanical & acoustic engines firing and aero buffeting
- Mechanical shocks
  - Pyrotechnics (fairing jettison, stage separation, ...)
- Air pressure changes
  - Rapid declining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

Source of images: Ariane 5 User Manual, Issue 4, 2004

Spacecraft Environments -- Atmospheric Environment

- Satellites are affect by the atmosphere during each phase:
  - Launch
  - Operations phase (if in Earth Orbit)
  - End-of-life

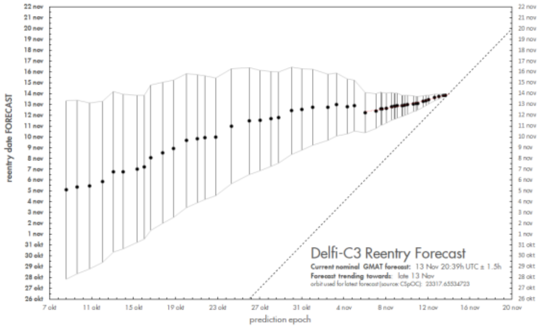
- Effects of the atmosphere vary due to:
  - Density
  - Composition

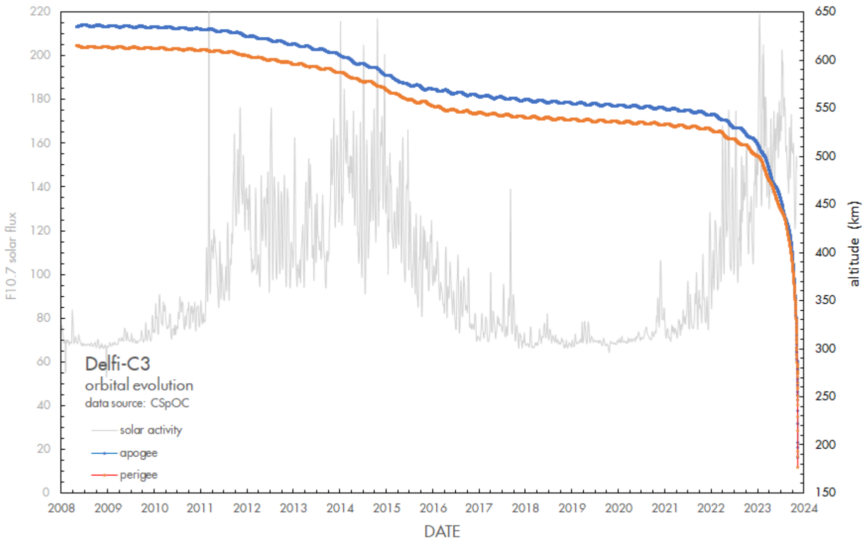


Spacecraft Environments -- Atmospheric Environment

In space

- Atmospheric drag:
  - ≤ 130 km - rapid re-entry.
  - 130-600 km - loss of altitude over months or years - strongly influenced by solar heating.
  - ≥ 600 km - very little effect.
- Effect of solar winds!





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

EPFL

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

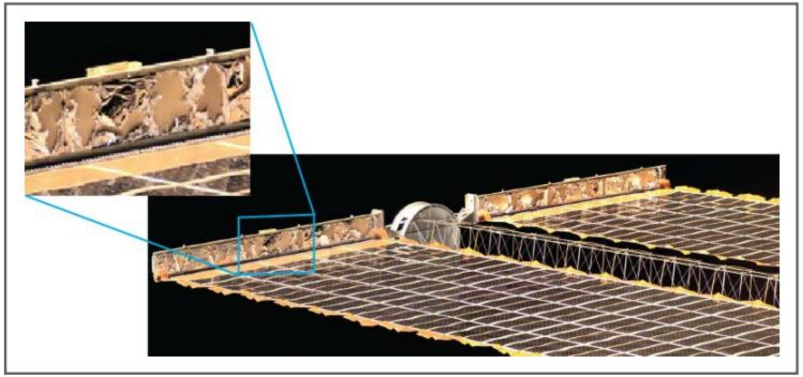
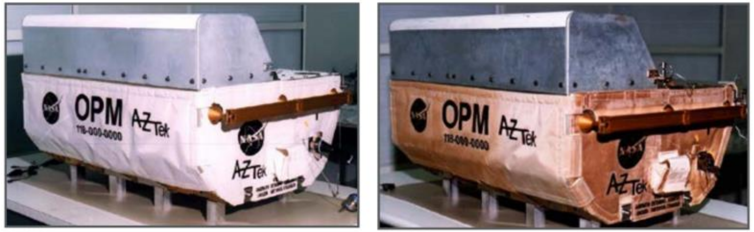


Figure 3. Image shows atomic oxygen undercutting degradation of the solar array wing blanket box cover on the International Space Station after one year of space exposure.



Preflight *Postflight*

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.

Source: The International Space Station (ISS) Researcher's Guide to Space Environmental effects, 2015 (rev. 2020), [A Researcher's Guide to Space Environmental Effects (nasa.gov)]

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.

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

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

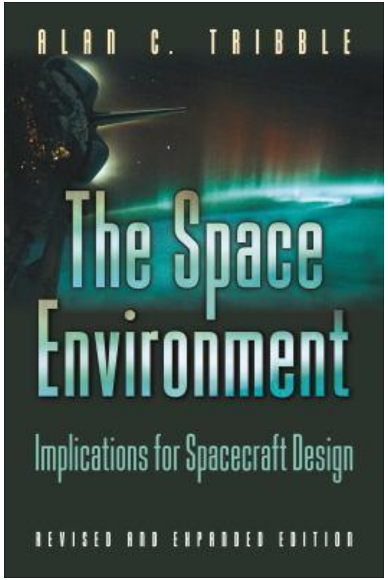
https://infoscience.epfl.ch/entities/publication/064c9341-560d-438f-8f8e-1fe9d428e9a2

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

Hands-on insights during the (non-mandatory) practicals

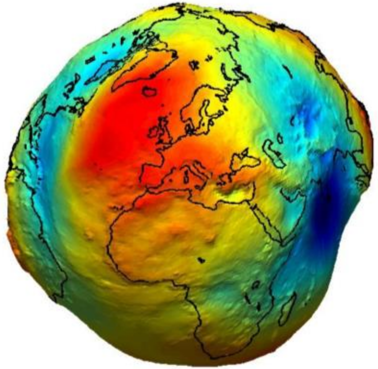


https://doi.org/10.1515/9780691213071

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)

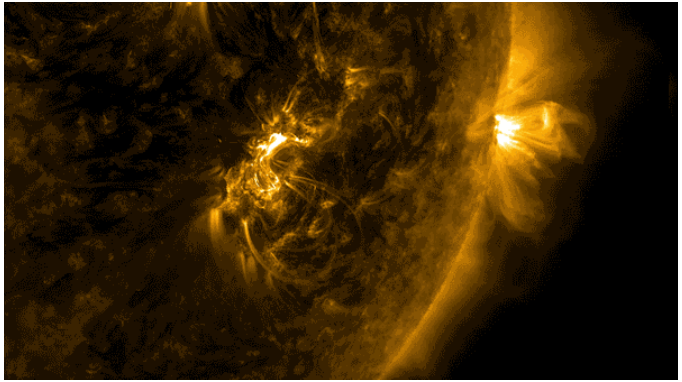


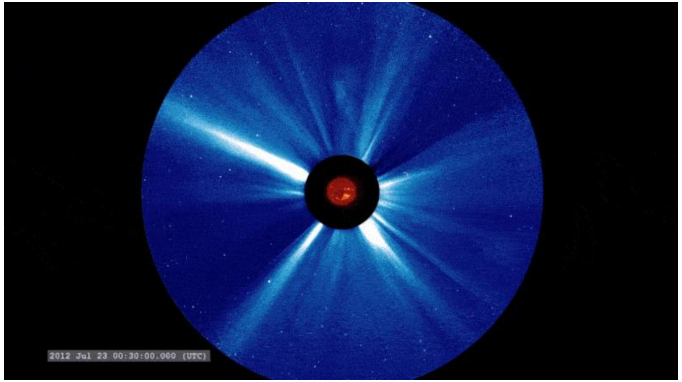
Source of image: ESA, ESA - The Earth's gravity field (geoid)

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)



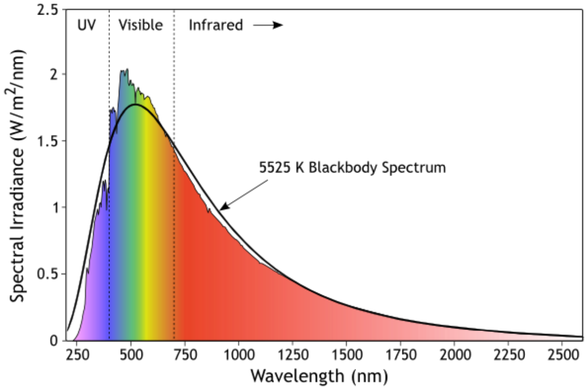


More info: NASA | The Difference Between CMEs and Solar Flares

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
    - ~ 5N/km2
    - May disturb orientation and orbits

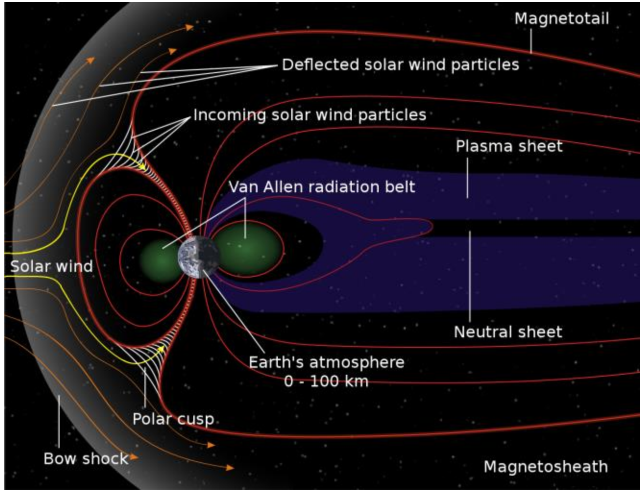


Planet	Distance (x 10^9 m)	Mean Solar Irradiance (W/m^2)
Mercury	57	9116.4
Venus	108	2611.0
Earth	150	1366.1
Mars	227	588.6
Jupiter	778	50.5
Saturn	1426	15.04
Uranus	2868	3.72
Neptune	4497	1.51
Pluto	5806	0.878

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

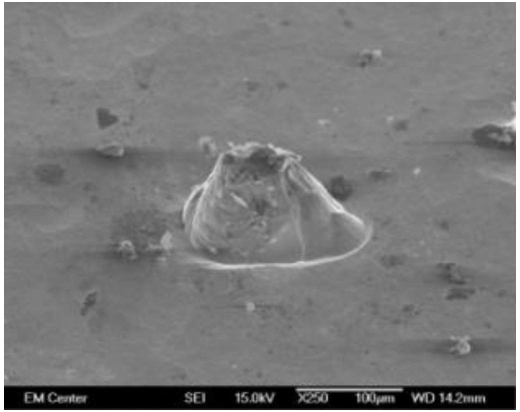


Good video on Van Allen Belts: https://www.youtube.com/watch?v=h9YN50xXFJY

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

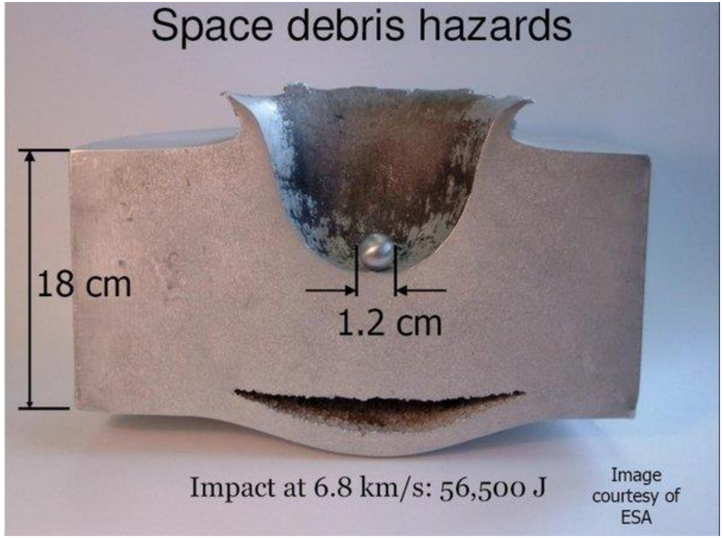


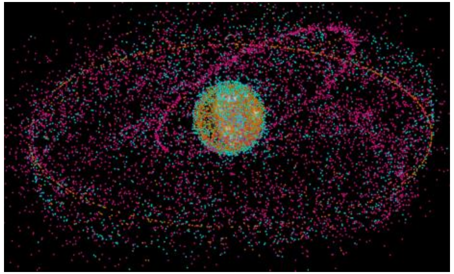
[Cone formation during sputtering.]

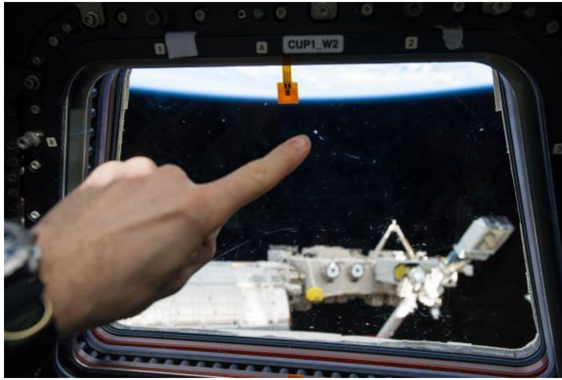
Cool interactive infographic: [Comparison of several satellite navigation system orbits (wikimedia.org)]

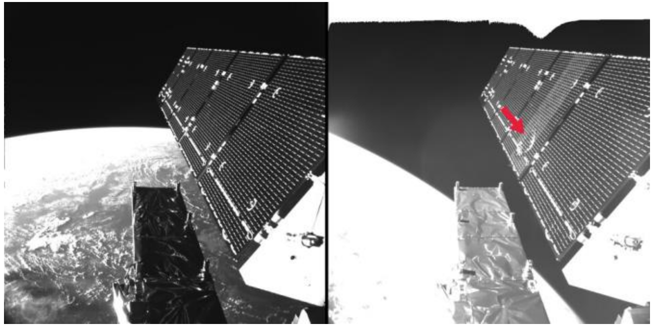
Spacecraft Environments -- Space Environment

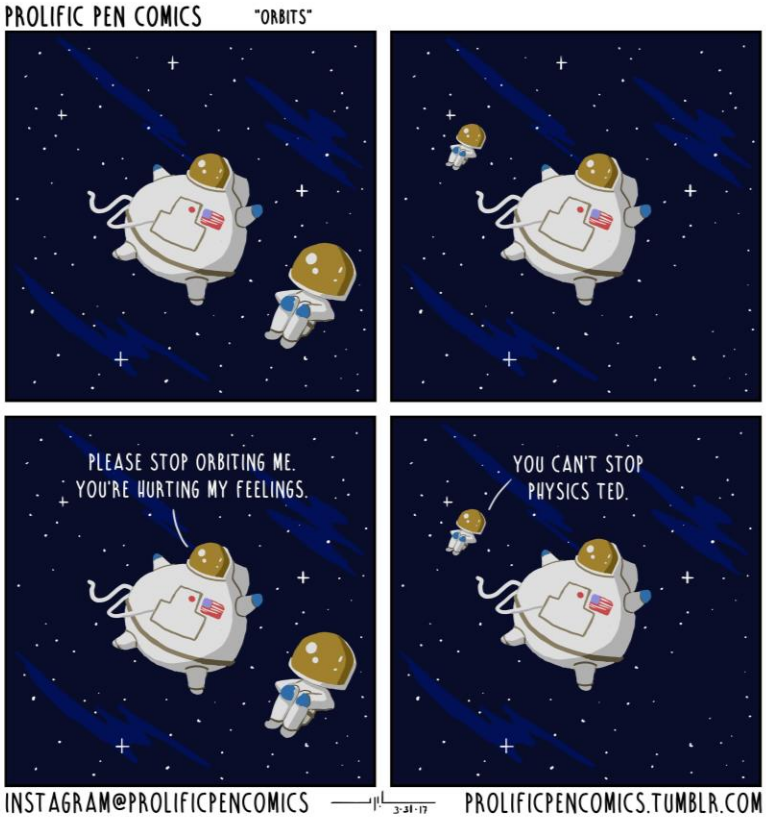
Micrometeorites & orbital debris











Astrodynamics

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

EPFL

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

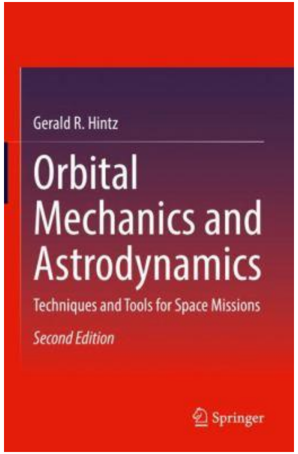
Summary

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.

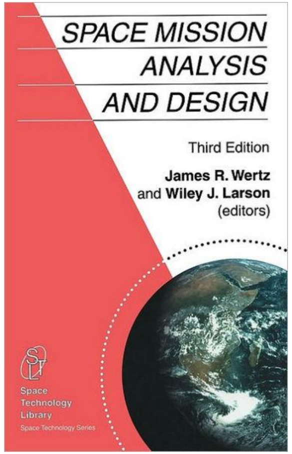
Content

- 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)

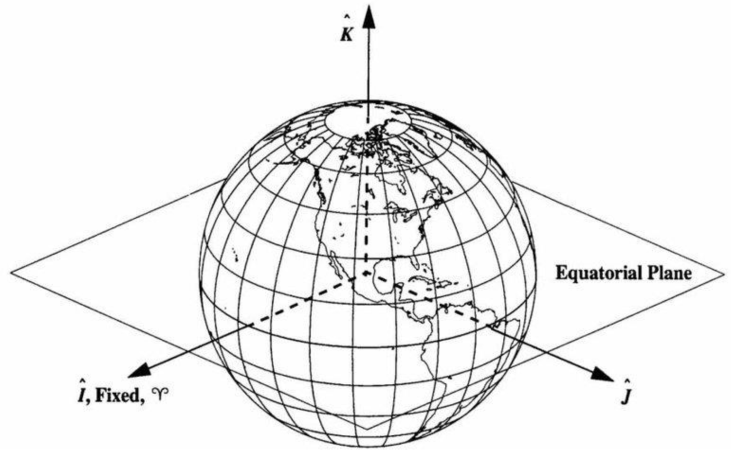


Space mission analysis and design - EPFL (slsp.ch)

Coordinate systems

<u>Geocentric Equatorial Coordinate System (ECI)</u>

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



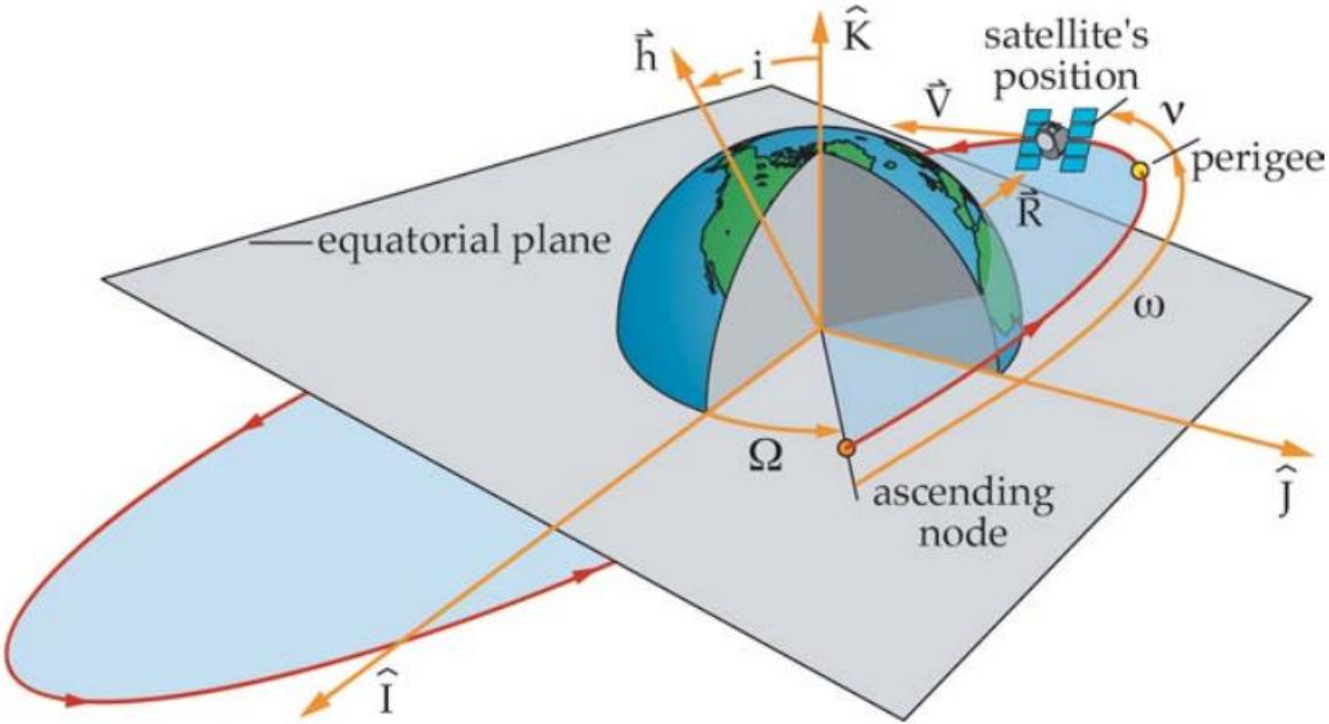
**the FPA moves about 1 deg every 70 years.

It is no longer pointing at Aries but in Pisces.

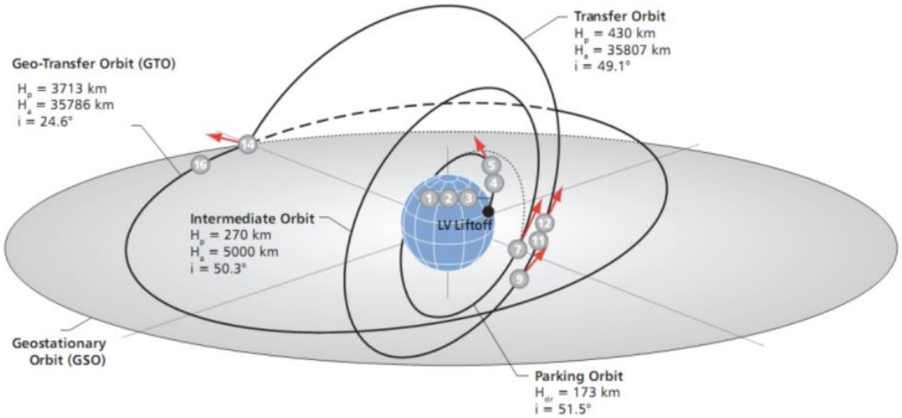
Key equations

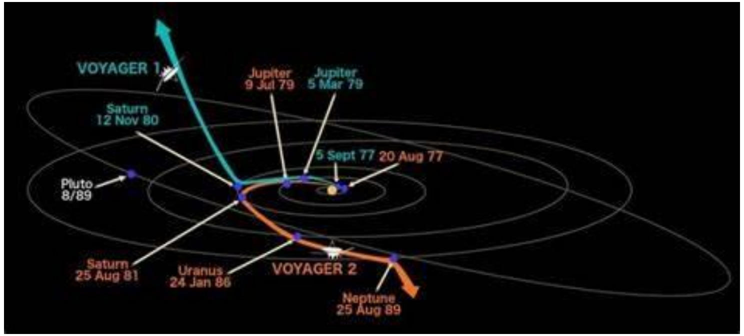
- Gravitational attraction
  - $F = G\frac{m_1 m_2}{r^2}$
- Gravitational constant
  - $G \approx 6.6730 * 10^{-11}\ m^3 kg^{-1} s^{-2}$
- Tchaikovsky equation
  - $\Delta V = v_e \ln\left(\frac{m_0}{m_f}\right) = I_{sp} g_0 \ln(\frac{m_0}{m_f})$

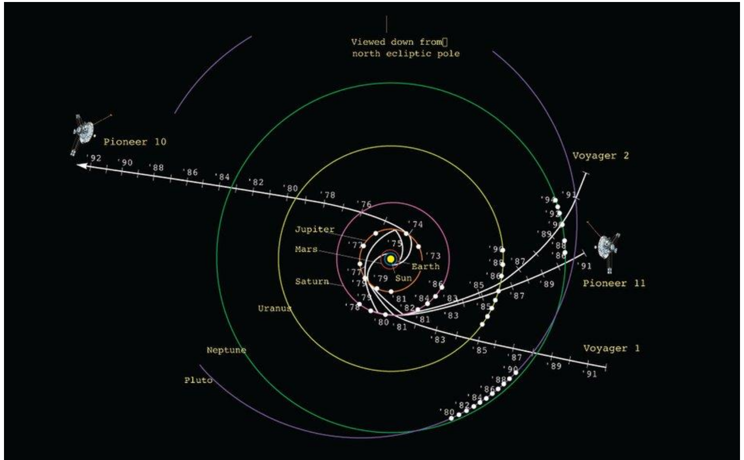
Orbital Elements



Manoeuvring



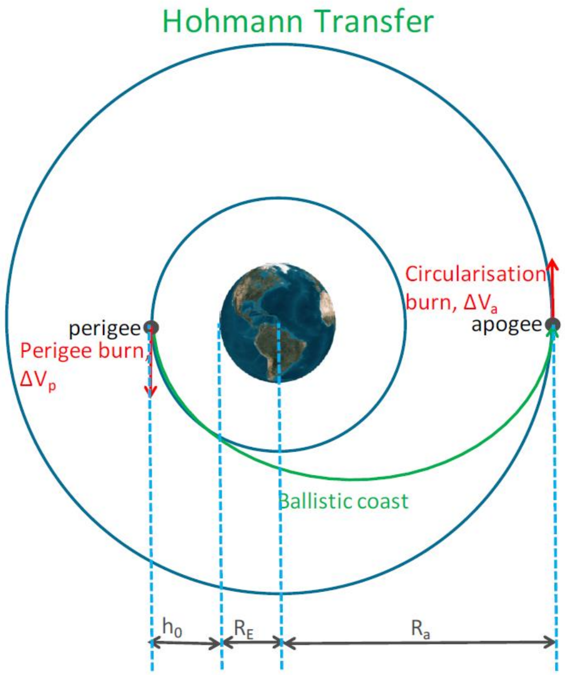




Hohman Transfer

- 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

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

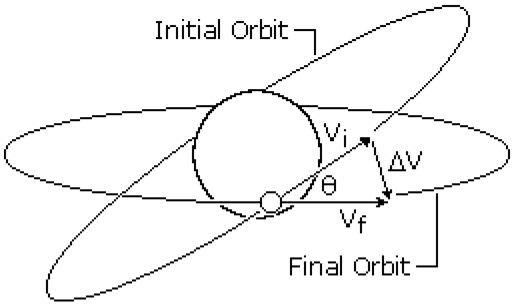


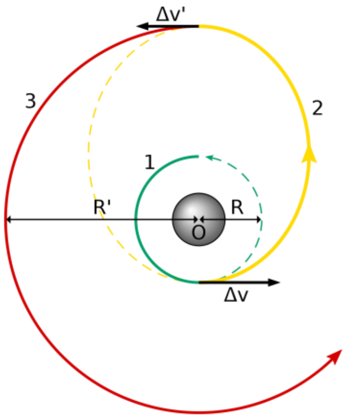
Orbital plane changes

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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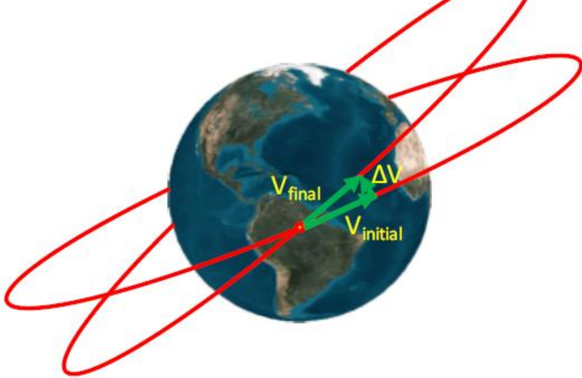

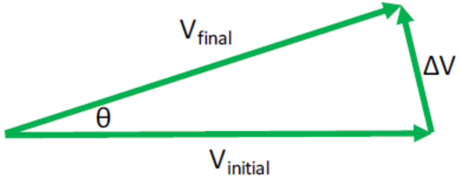

$$\Delta V_s = 2V_i \sin\left(\frac{\theta}{2}\right)$$

$$\theta = \Delta i$$

$$\theta = \Delta\Omega$$

Orbital plane changes

***See animations:* [*here*]**

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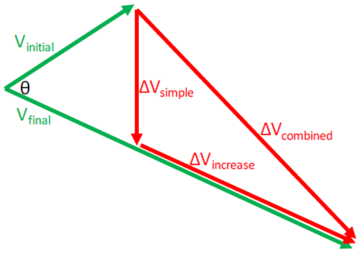


$$\Delta V_c = \sqrt{V_i^2 + V_f^2 - 2V_iV_f cos\theta}$$

$$\theta = \Delta i$$

Or

$$\theta = \Delta\Omega$$

Interplanetary travel

- 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

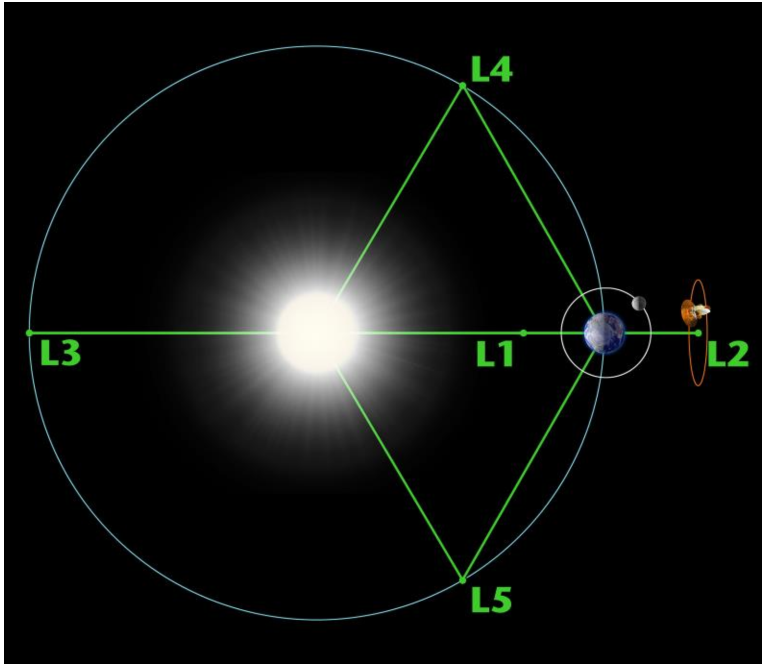
+ Gravity assists! (Save your Fuel)

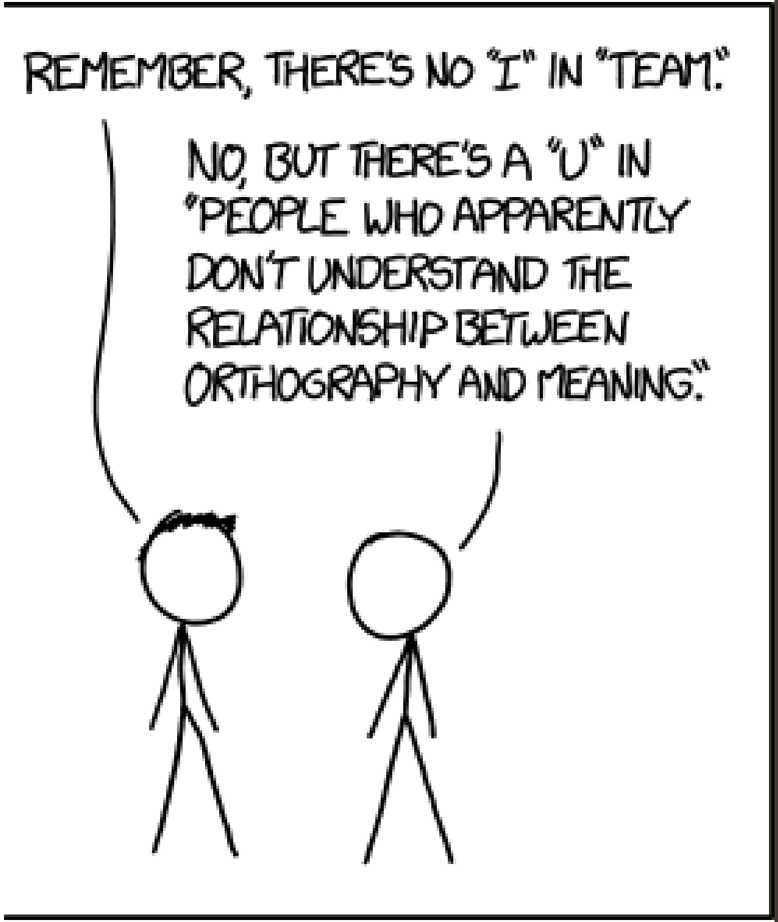
https://svs.gsfc.nasa.gov/vis/a000000/a004400/a004482/orex_Outbound_GravityAssist_1080p60.webm

Lagrange points

Good explanation can be found here:

[What is a Lagrange Point? - NASA Science]





Your turn

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

Now it is your turn

- **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 oyur 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 you **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.