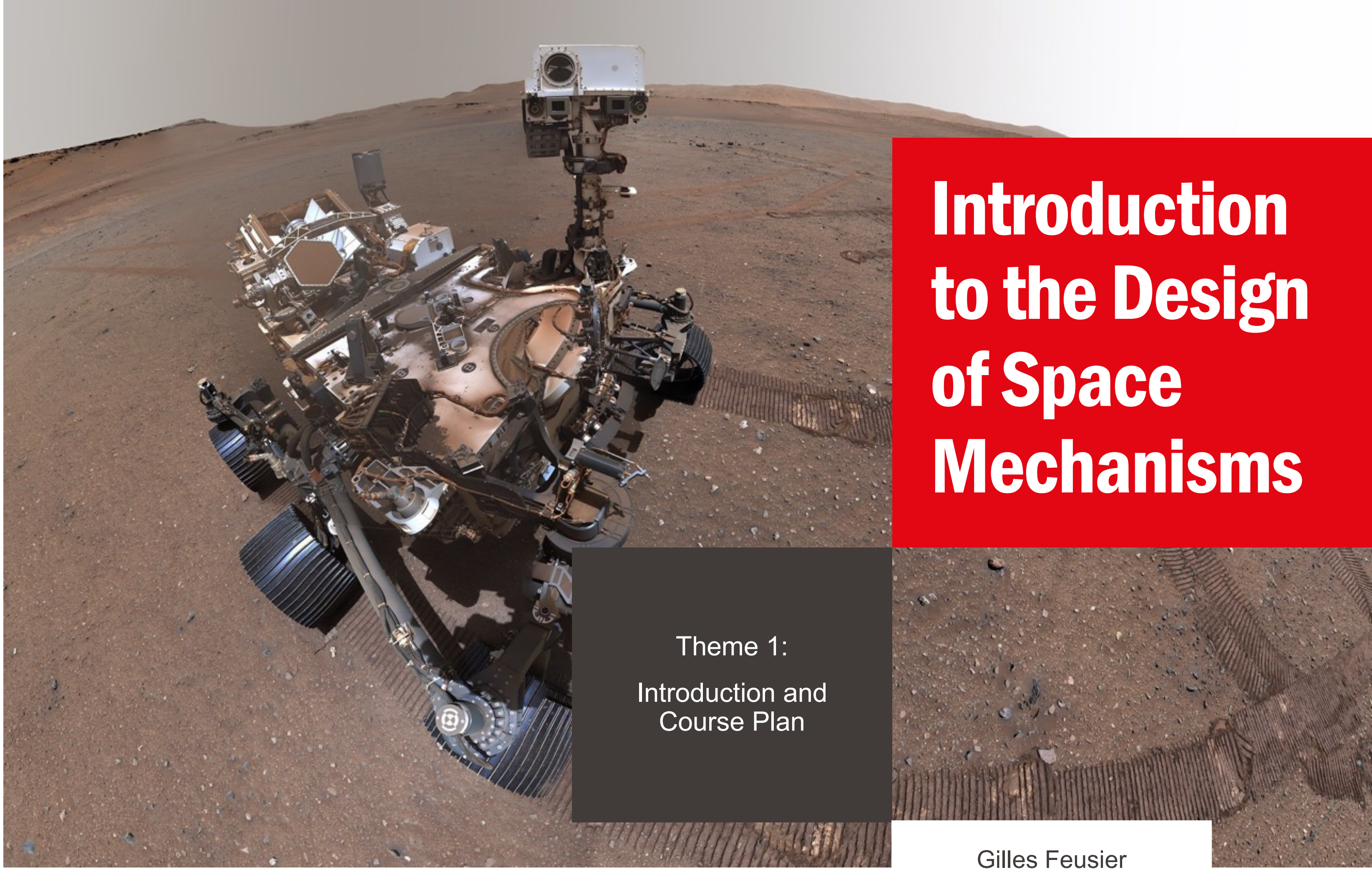
EPFL

Introduction to the Design of Space Mechanisms



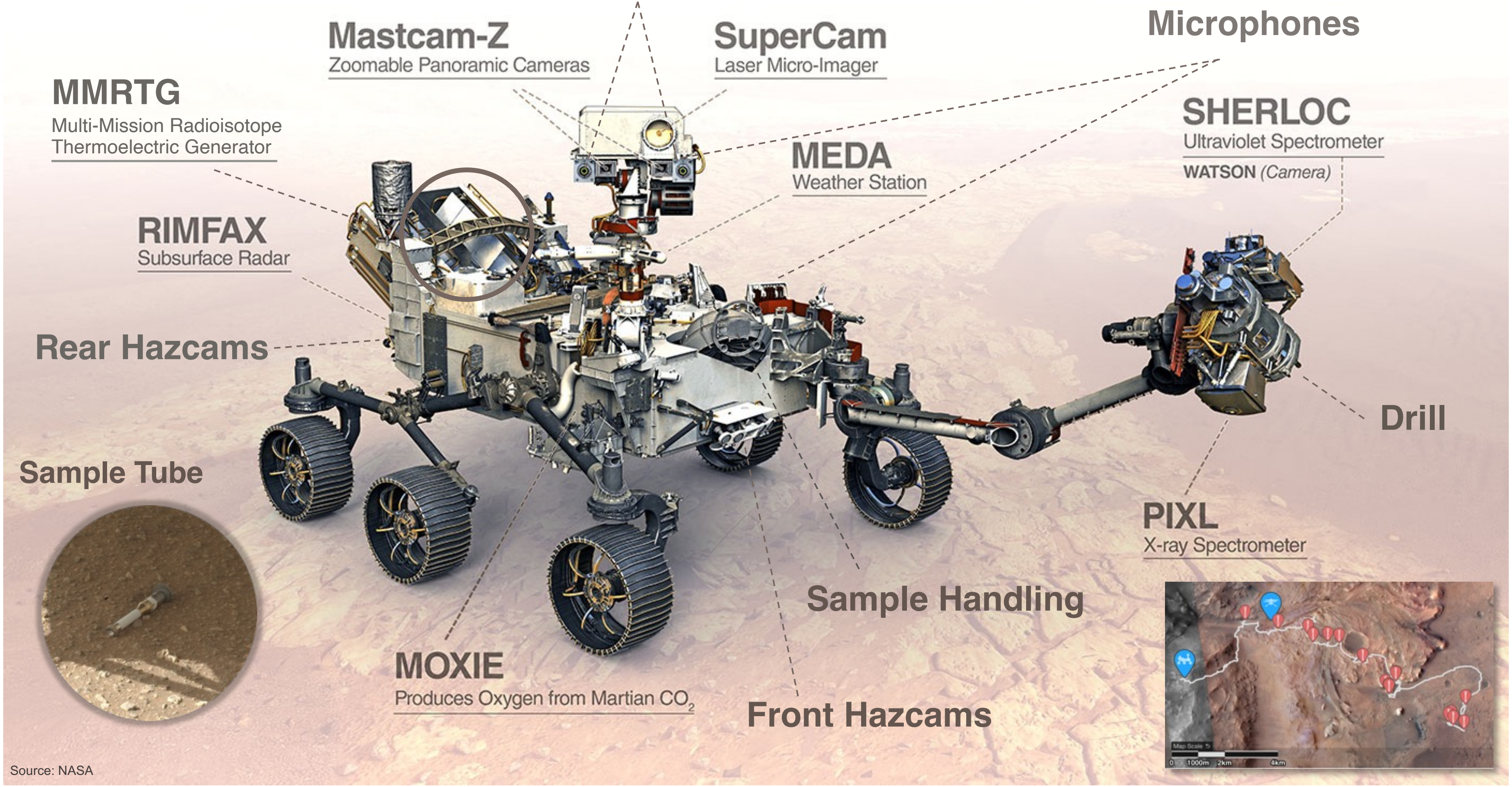
Theme 1:

Introduction and Course Plan

Gilles Feusier

Source: NASA, JPL-Caltech, Kevin M. Gill

Mars 2020 - Perseverance



Source: NASA

Class Parameters

- This class is an introduction to the **Design of Space Mechanisms**
  - It is for graduate students (1st, 2nd year of master's program).
  - It is intended to give an overall view of the specific issues related to the design of mechanisms for space. It is not another mechanical design course.
- **2 ECTS credits**.
  - Serves as one of the classes in the Minor of Space Technology
- Materials posted on http://moodle.epfl.ch/
  - Direct link: https://moodle.epfl.ch/course/view.php?id=4961

Agenda for Today

- Introductions
  - Personal Introductions
  - Course Introduction, incl. Learning Objectives
- Satellites and Spacecraft Functions
- Example of Space Mechanisms
- Space Environment – An introduction
  - Universe
  - Solar System
  - Orbits

Gilles Feusier

- Dipl. Ing. Physicist – **EPFL 1993**
- PhD in Solid State Physics – **EPFL 1997**
- Project Manager, MECANEX SA – Nyon (1997 -2001)
- Technical Director, MECANEX SA – Nyon (2001-2006)
- Head of development and innovation, RUAG AEROSPACE SA – Nyon (2007-2008)
- CTO, VOUMARD MACHINES SA – Hauterive (2008-2011)
- Product structure responsible, SCHOTT Suisse SA – Yverdon-les-bains (2011-2012)
- Member of the European Space Mechanisms and Tribology Symposium (ESMATS) committee
- Head of Technology and Science, **Space Innovation** (Swiss Space Center) – EPFL Space Center (since 2013)

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EPFL

SPACE INNOVATION

almatech

csem

esa

esmats

European Space Mechanisms and Tribology Symposium

For ESMATS 2025: esmats2025@space-innovation.ch

Learning Objectives

What I will bring you …

- To use your engineering competencies (mechanics, physics, chemistry, …) in the space environment
- Methods used for the realization of mechanisms and other objects, pieces of equipment to be used in space
- To spark your interest for participating to the space adventure
- To unleash your curiosity, imagination and creativity
- System level approach of mechanisms and space hardware

What I am expecting from you

- Active participation to the course
  - Regular attendance
  - Work through the exercises, they are part of the course
  - Ask questions (chat, oral)
- Proposed readings
  - Read it!
  - Ask questions, make comments
- Be ready to summarize the previous lecture
  - Oral summary
  - Quiz
- Succeed with your final exam

Practical Aspects

- **Lectures**
  - 13 lectures in total (2h each)
  - Thursday 11:15-13:00 (CET)
  - Room CO120
- **Documentation and communication**
  - Available through MOODLE
  - Readings: expect to read about 20-30 pages per week
- **Exercises and Mini Project**
  - To be submitted according to problem statement (information given during the lecture and on MOODLE)
  - Depending on the type of exercise, solution and correction can be done during the class or individually
  - Exercises are not graded
- **Exams**
  - Oral exam through random draw of a general question related to the course. No preparation
  - The examinee will present the subject and answer to more specific questions from the examinators, related to the content of the course
  - The subjects treated within the exercises can lead to questions during the exam

EPFL

Main functions of spacecrafts

- What are the various types and functions of spacecrafts and where are located the mechanisms if any?

1) List the type of spacecrafts (mission types)
2) Select one type of spacecraft
3) List the mechanisms needed to perform the mission
4) Briefly describe one key mechanism required for the success of the mission

- Turn out to your neighbors (3-5 people teams)
- **5 minutes**
- One team member will present the results of your discussion (i.e. outcomes of point 4) here above)

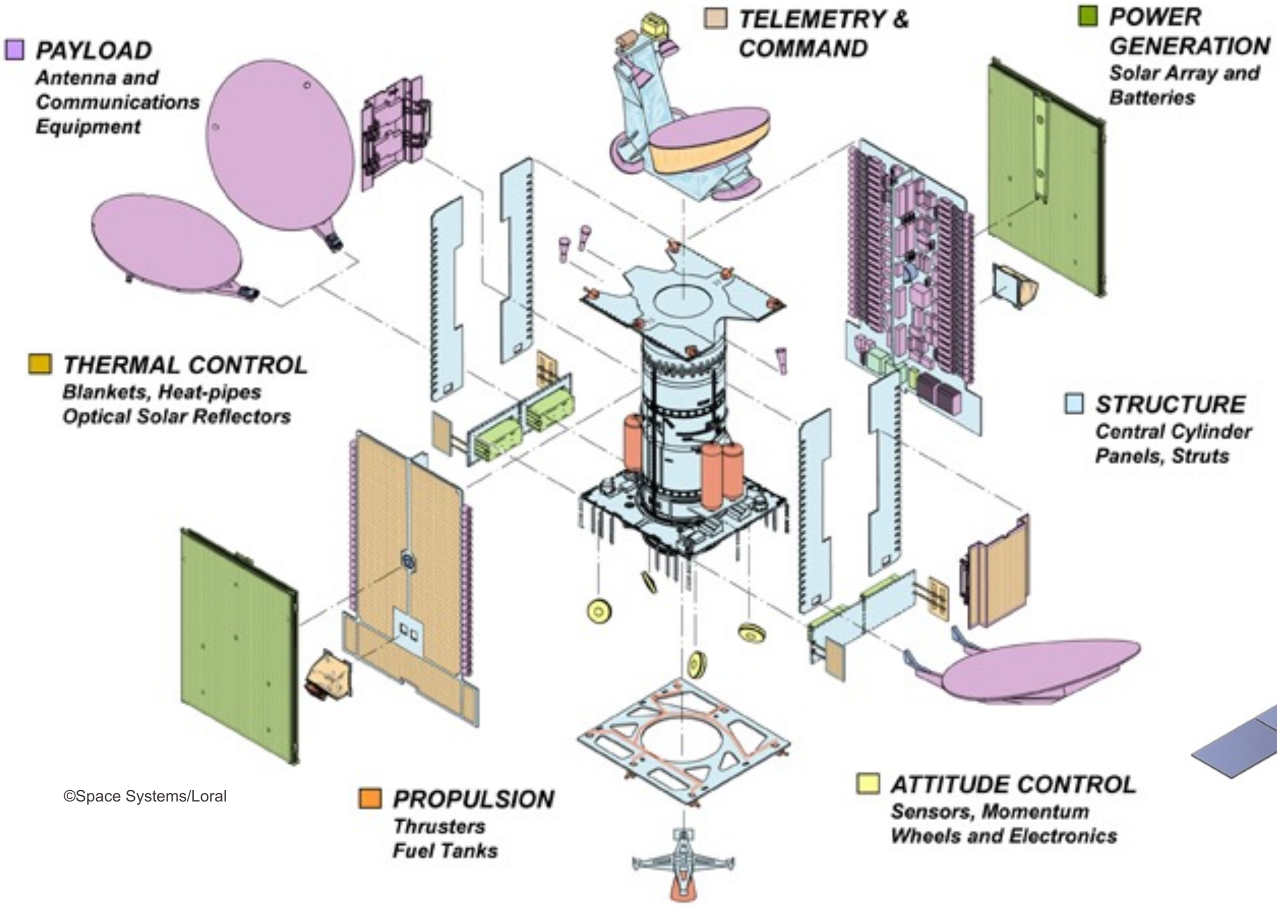
Main functions of spacecrafts

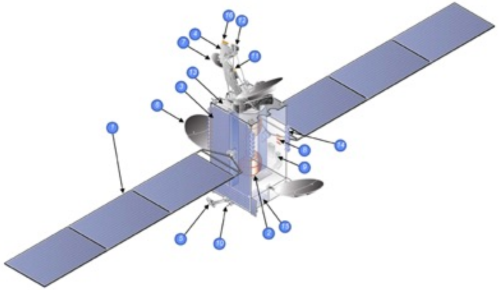
- Satellites:
  - In orbit around a planet, a moon, the sun ...
  - Functions:
    - Telecommunications
    - Positioning, Navigation and Timing (PNT, e.g. GNSS)
    - Earth Observation (EO)
      - Imagery (optical, radar, …)
      - Meteorology
    - Science mission
    - Space Station
- Space probes:
  - Interplanetary exploration missions
    - Study of the planets and their satellites, of comets, asteroids, …
  - Science missions
    - Study of the sun, of gravitational waves, …
  - Missions outside of the solar system

Space Mechanisms

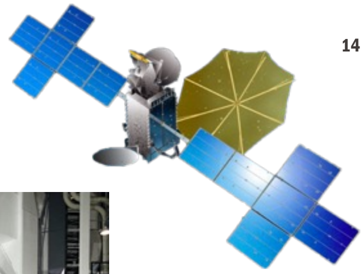
- Launch and Re-Entry Vehicles
  - Separation systems
  - Engine/propulsion regulation, gimballing devices, turbo pumps
  - Flap controls, parachute deployment systems, landing legs
- Spacecraft equipment
  - Wheels, mechanical coolers, pumps, valves, solar array drive mechanisms …
  - Hold-down/release, deployment, …
  - Pointing, …
- Science Observatories, Earth Remote Sensing, and Planetary Exploration Mechanisms, In-Orbit Maintenance
  - Mechanisms for manipulations, robots, rovers
  - Sampling systems and in-situ analysis devices, bioreactors, lab equipment
  - Mechanical devices for science and remote sensing instruments

Telecom Satellite Platform (GEO)





Deployment, release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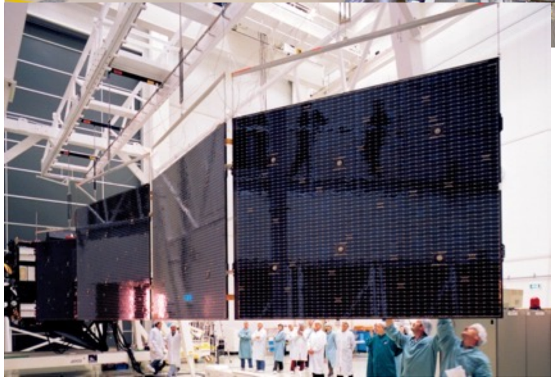
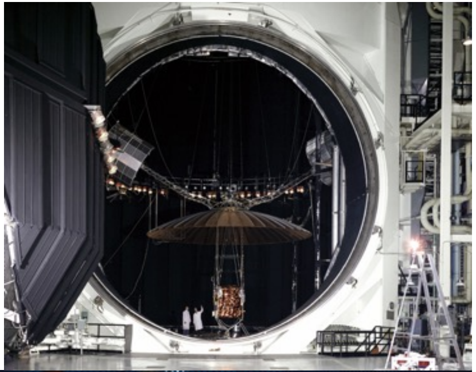
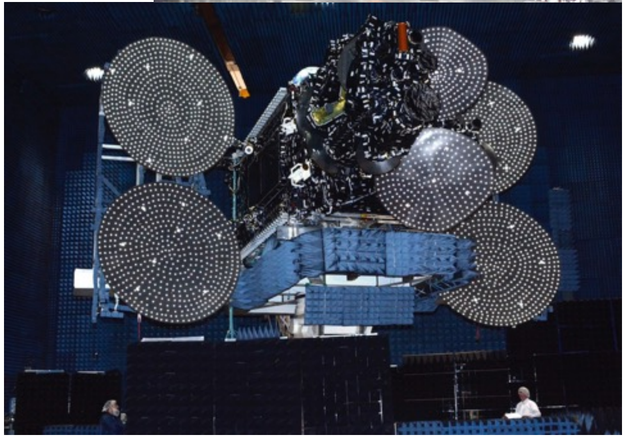
Solar arrays


Source: Lockheed Martin Corporation

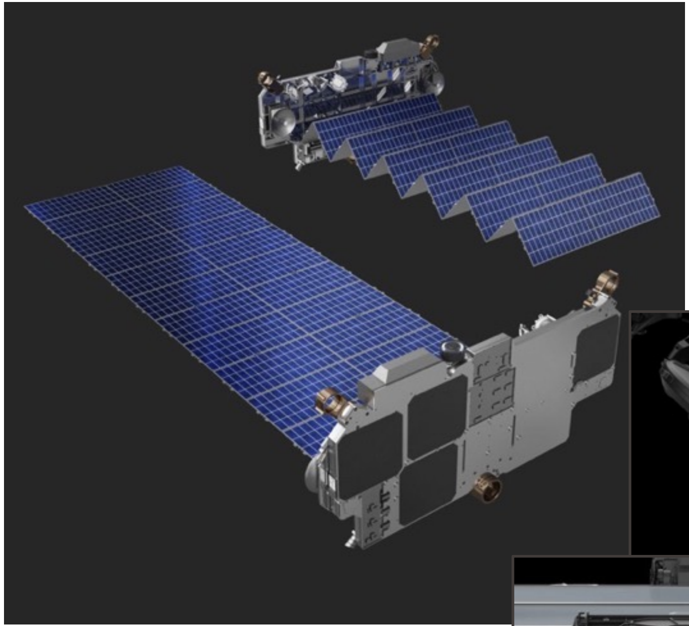

Source: ESA

Antennas


Source: NASA


Source: Space Systems/Loral

Telecom Satellite Platform (constellations, e.g. Starlink)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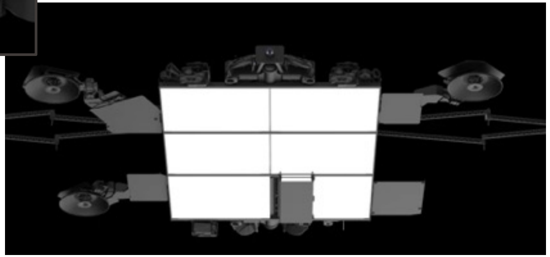
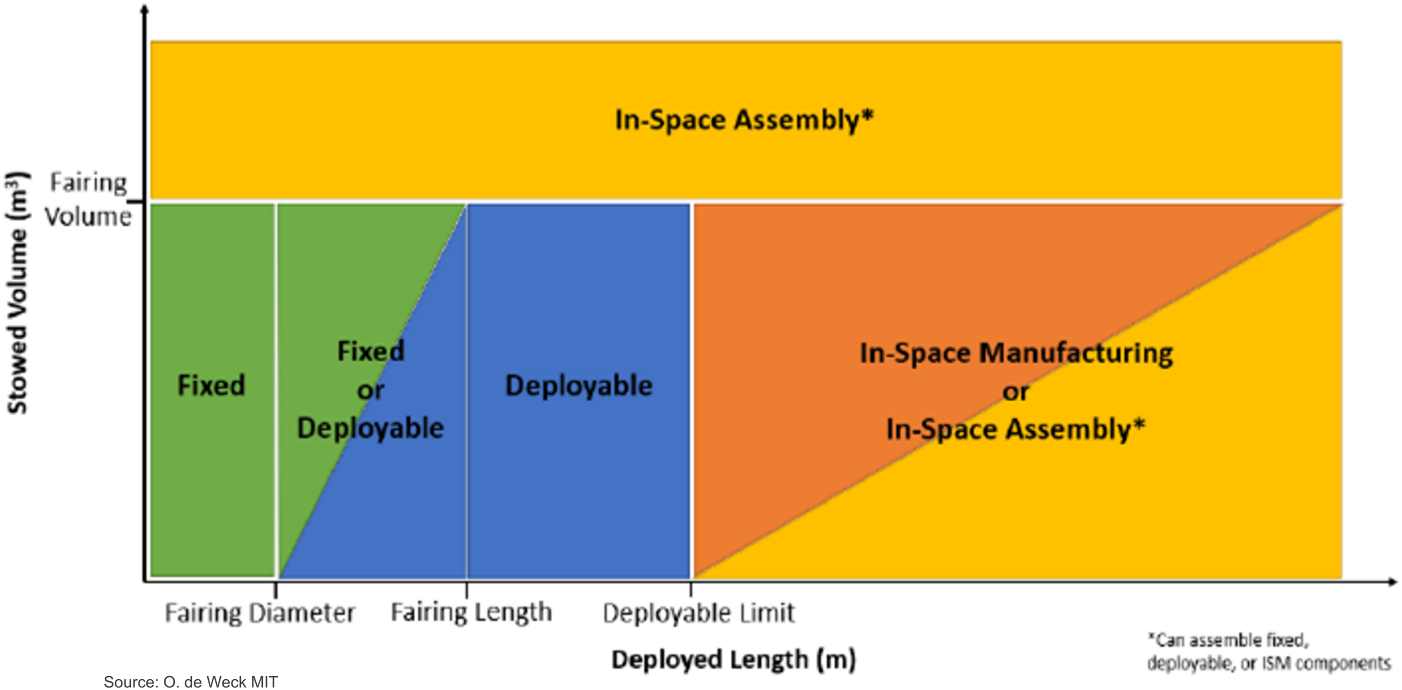


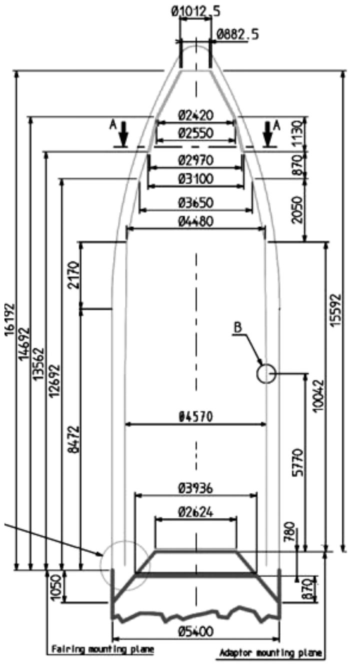
Deployment

Under what circumstances should we use each option

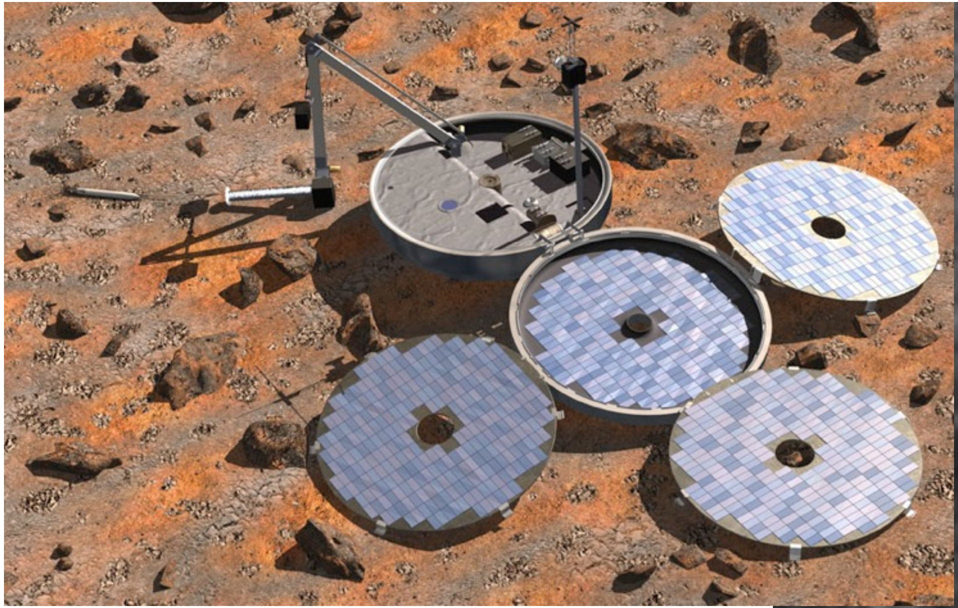


Source: O. de Weck MIT

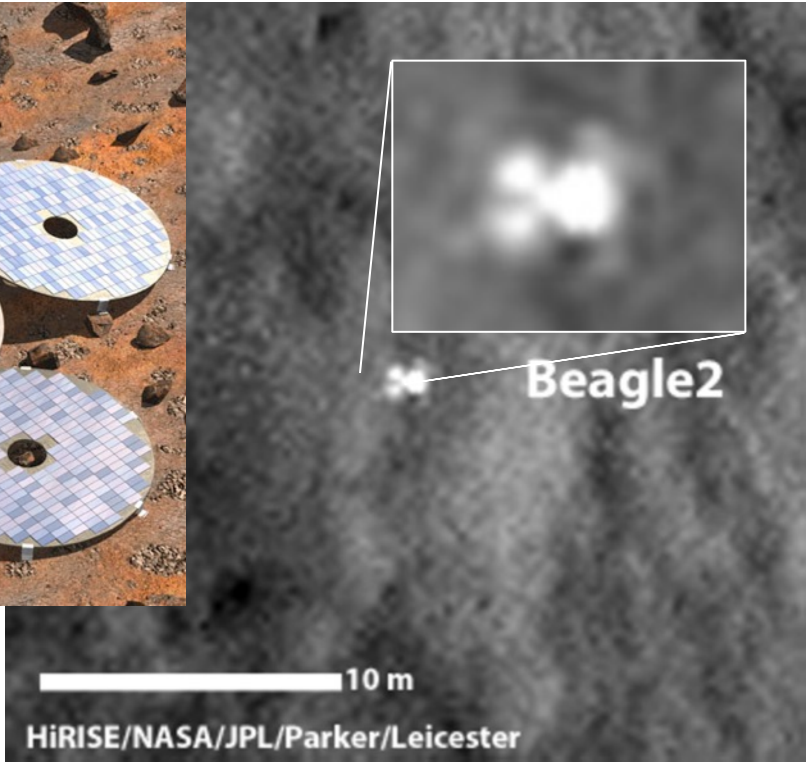
Ariane 5 Fairing Dimensions



Deployment: failure



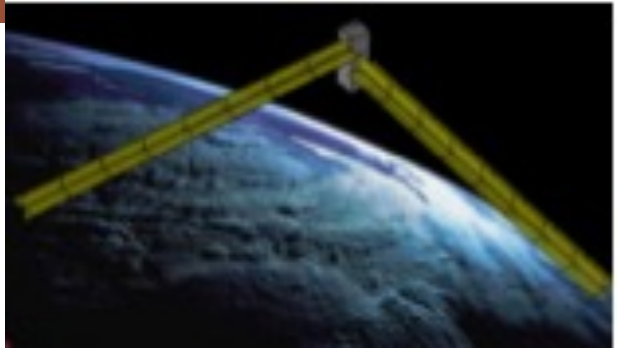
Source: ESA/Denman productions

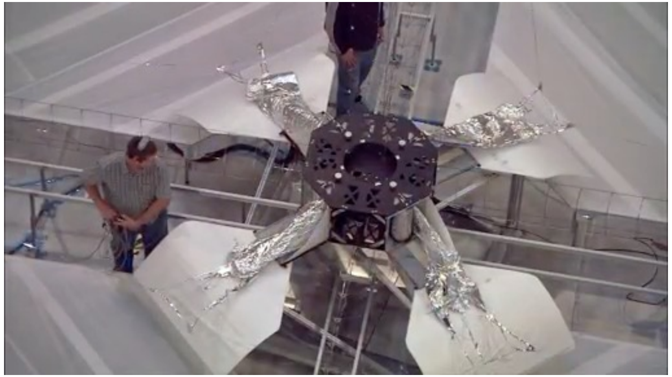


Source: NASA/JPL-Caltech/Univ. of Arizona/University of Leicester

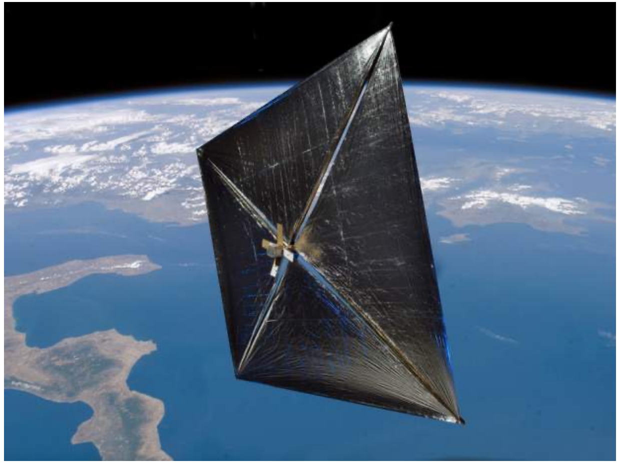
Deployment of solar sails

Source: D. Turse et al., 42nd Aerospace Mechanisms Symposium, 2014





Source: S. A. Zirbel et al., 42nd Aerospace Mechanisms Symposium, 2014
Origami-Inspired



Source: NASA. Solar Sail Demonstrator (‘Sunjammer’)

James Webb Space Telescope (JWST)


©NASA/Chris Gunn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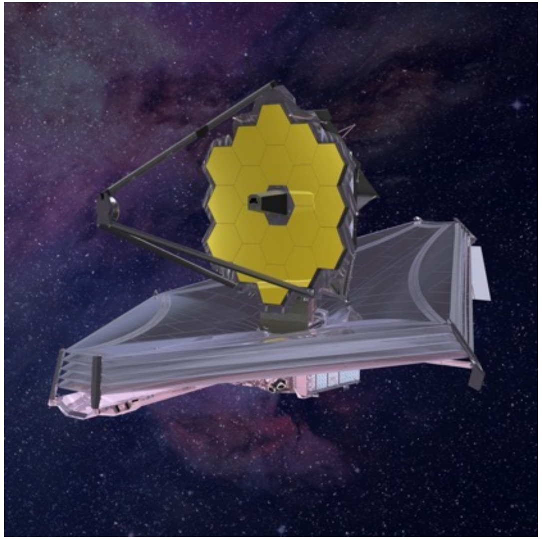
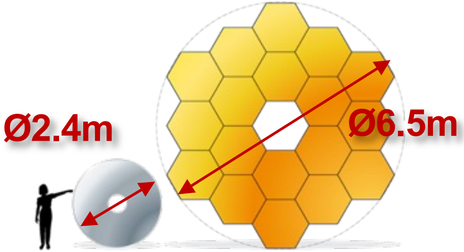

Source: Northrop Grumman



Source: Bobarino, based on NASA image

Development began in **1996**

Original launch: **2007**

Launch: **December 25th, 2021**

Budget 500 M$

↓ 20x

Budget 10 G$


ScienceCasts:
Shake, rattle, and cold: Readying the Webb Telescope for launch
Source: NASA

Drive mechanisms, power transfer

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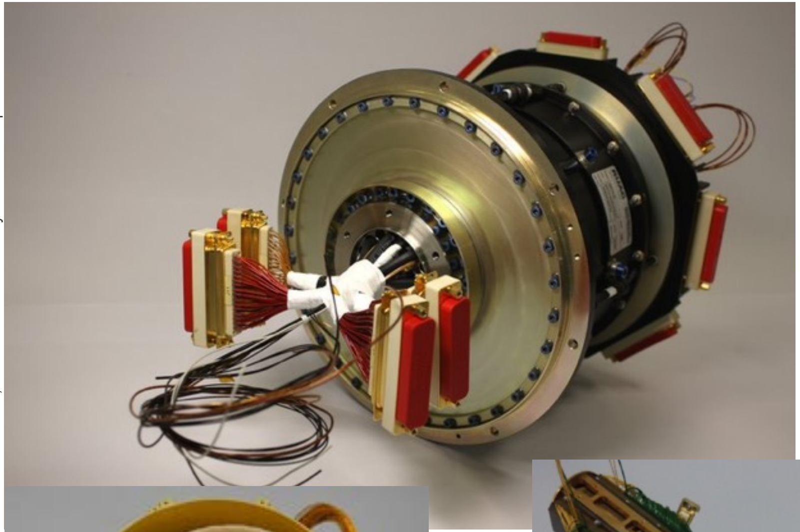
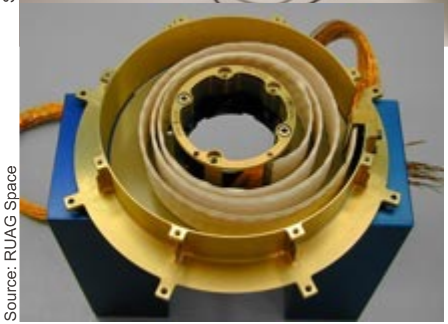
Solar Array Drive Mechanism (SADM)

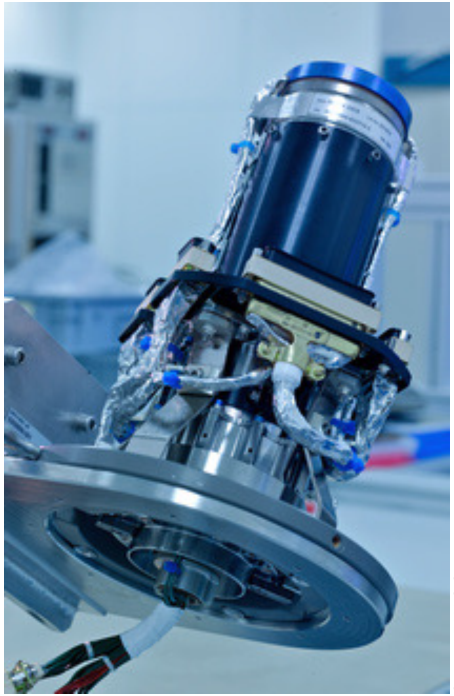


Source: ESA, SADM manufactured by RUAG Aerospace Zurich



Source: RUAG Space

Source: C. Courtois et al., 16th ESMATS

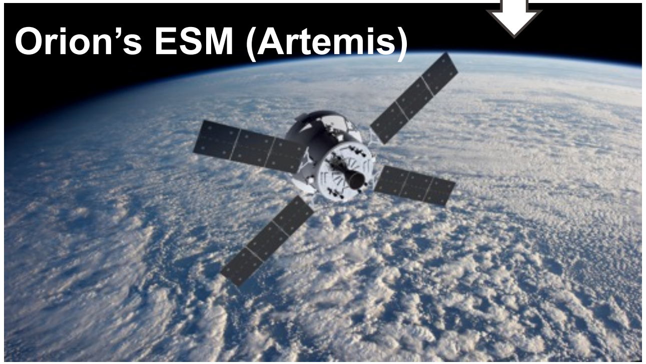


Source: RUAG Space

Drive mechanisms, power transfer

Solar Array Drive Mechanism (SADM): The Automated Transfer Vehicle (ATV) ➩ ESM

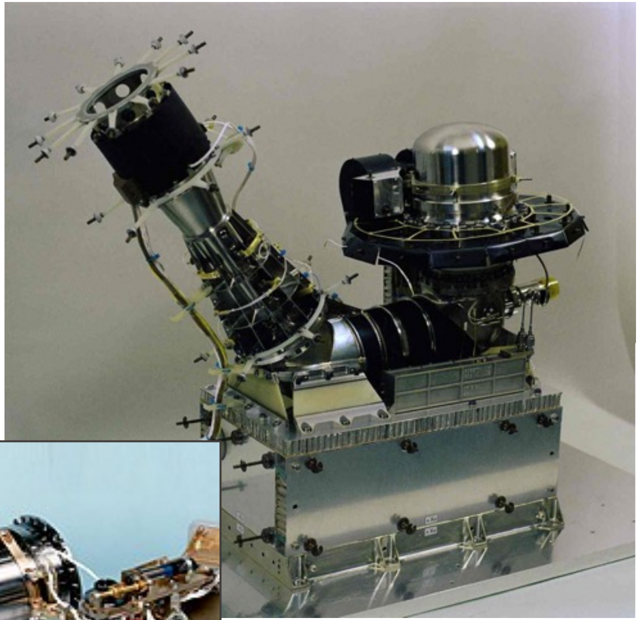
Source: ESA



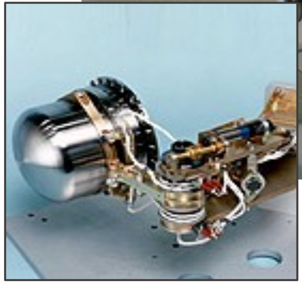
Source: ESA

Removable sensor protection

Cover mechanism, Rosetta



Source: ESA/Rosetta/ROSINA/UBern/BIRA/LATMOS/LMM/IRAP/MPS/SwRI/TUB/UMich

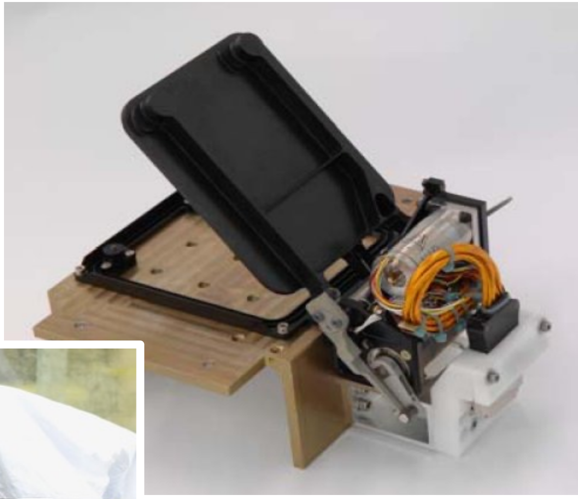


Source: Contraves

Shutter unit, Euclid

Source: APCO Technologies

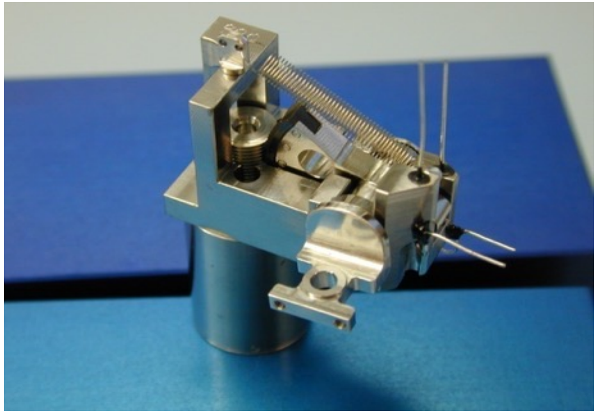
Cover mechanism, JWST



Source: RUAG Aerospace

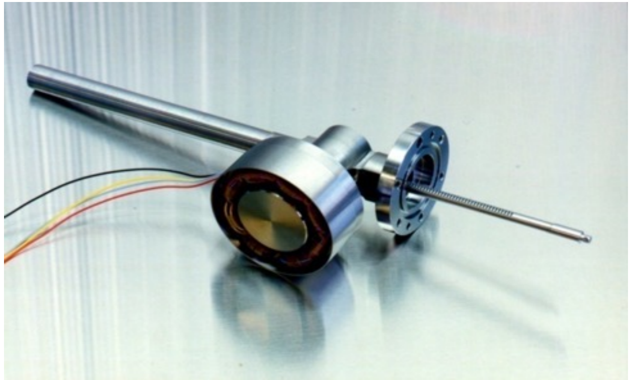
Displacement and positioning mechanisms

Grating Orientation Mechanism



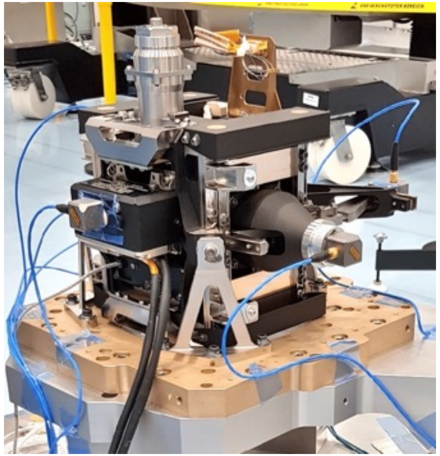
Source: RUAG Aerospace

Filter Translation Mechanism Huygens

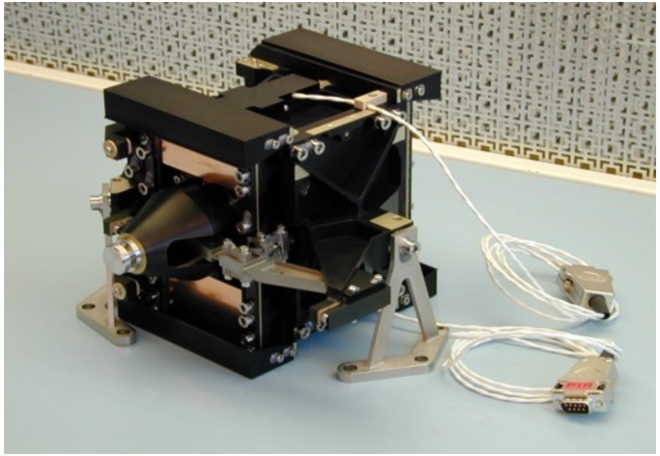


Source: RUAG Aerospace

Corner Cube Mechanism



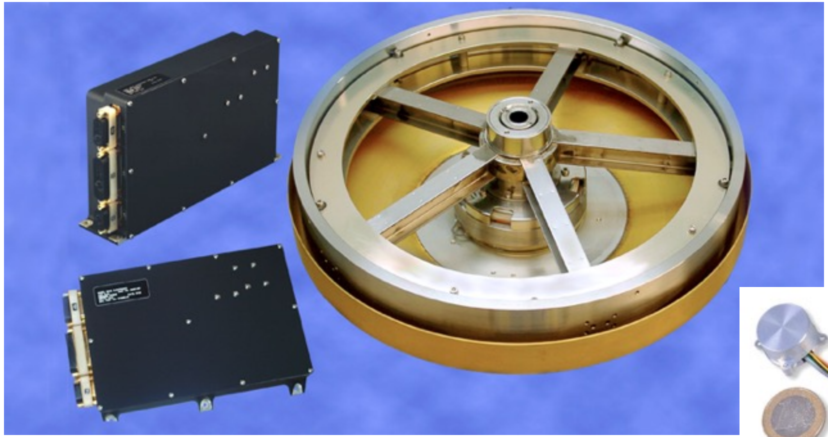
Source: CSEM



Source: RUAG Aerospace

Attitude control

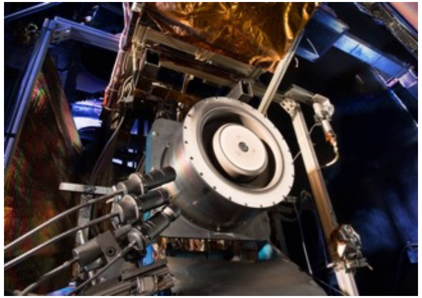
Reaction wheel



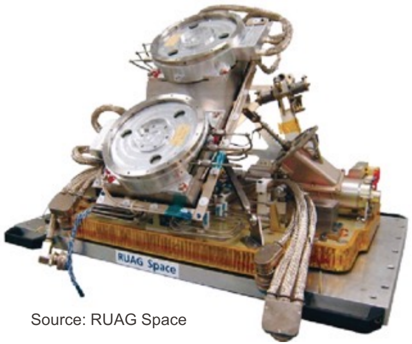
Source: Rockwell Collins

Source: Astro- und Feinwerktechnik Adlershof GmbH

Plasma thruster gimbal

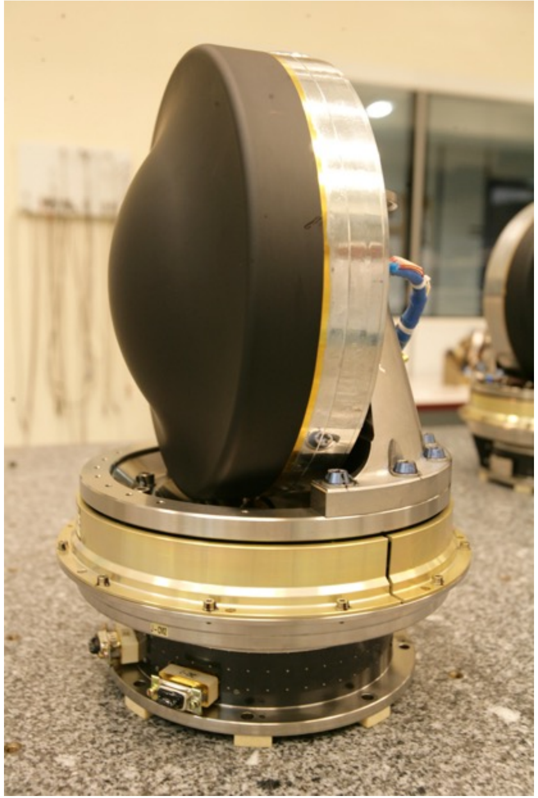


Source: NASA



Source: RUAG Space

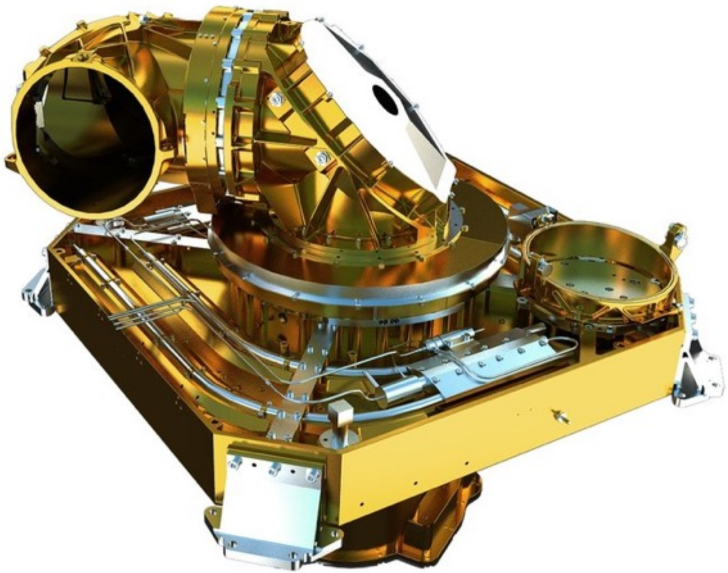
Control Moment Gyroscope (CMG)



Source: Airbus DS GmbH

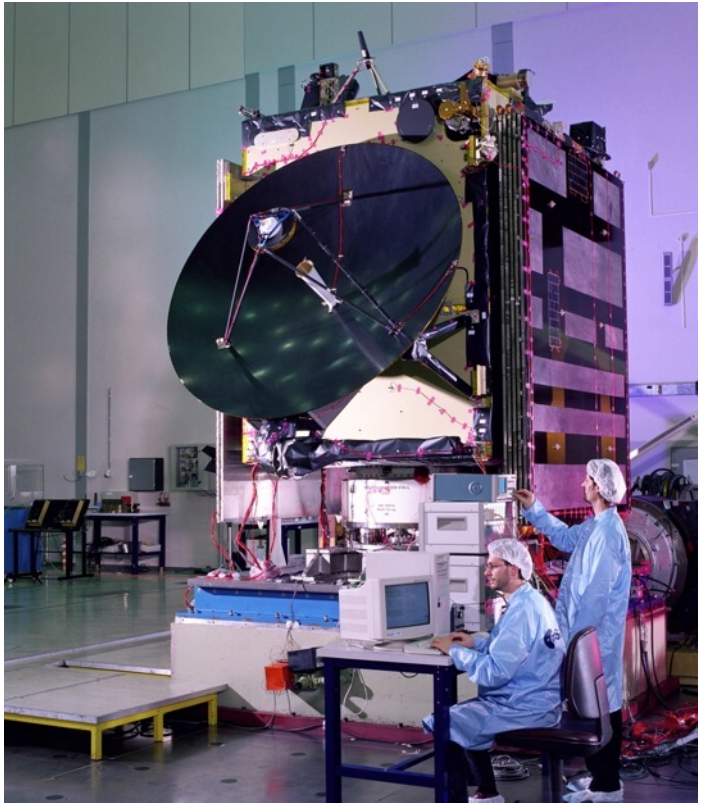
Payloads, communication

Optical



Source: TESAT, DLR

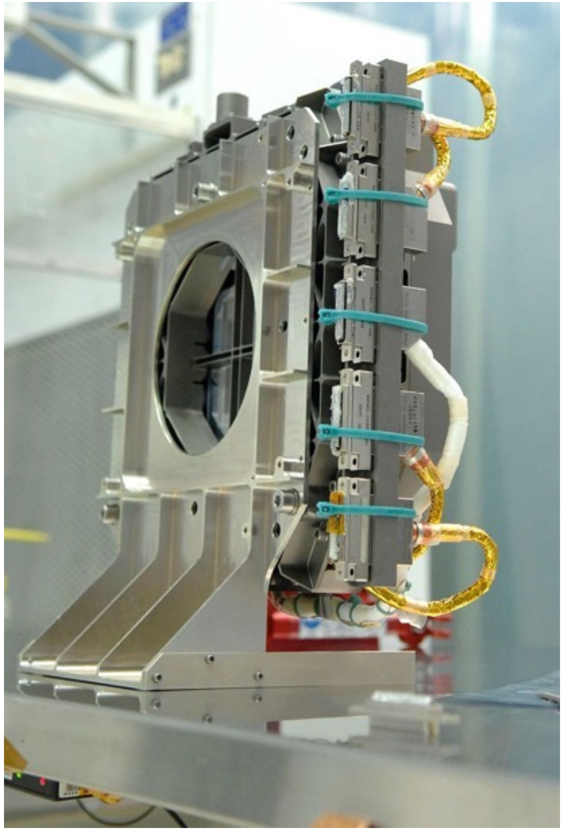
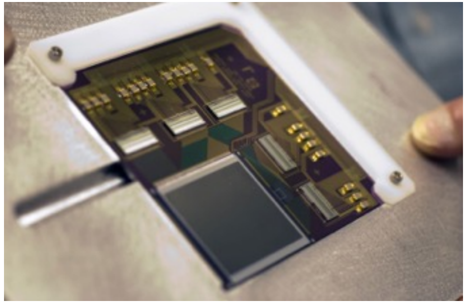
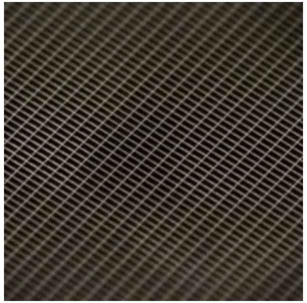
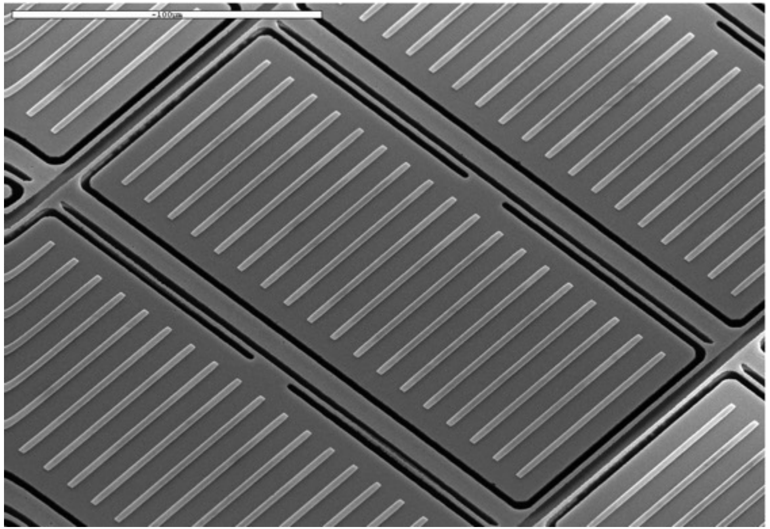
Radio Frequency (RF)



Source: ESA

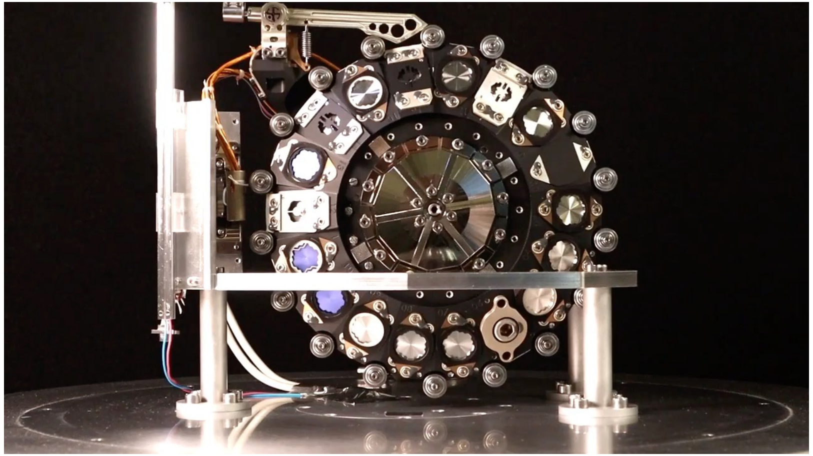
Optical payload

JWST: NIRSpec instrument microshutter (MEMS)

Optical payload – Filter assemblies

***JWST*: MIRI Filter Wheel**



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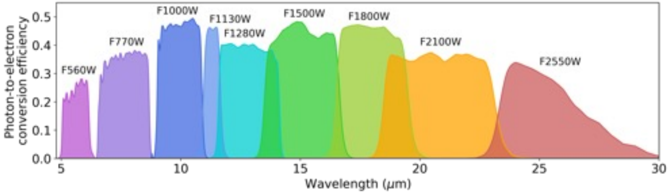
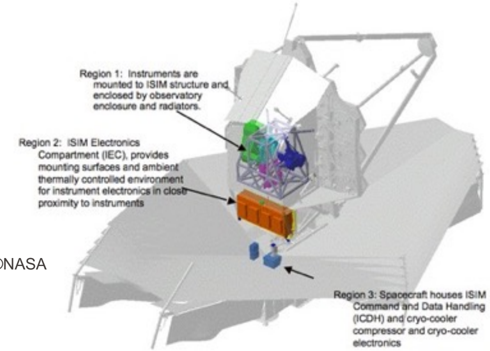


JWST User Doc



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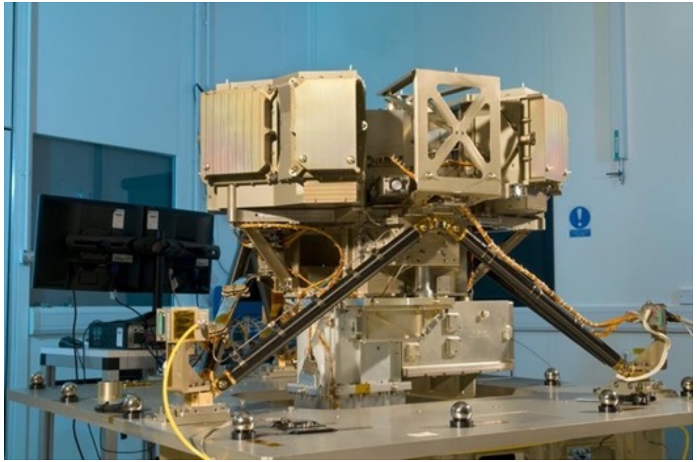

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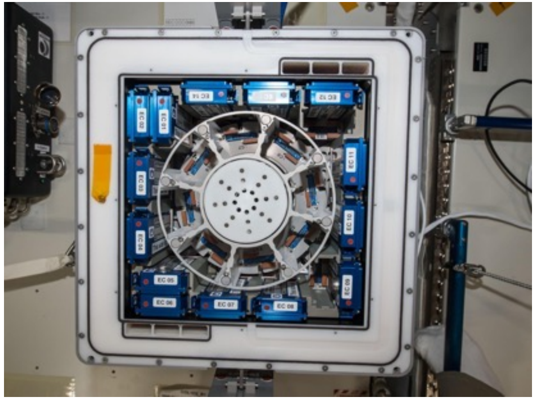
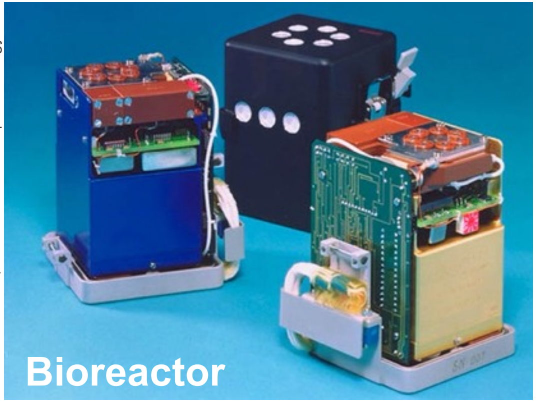
Space Laboratory



Source: NASA



Source: Mécanex, IMT and the ETH Space Biology Group

Source: ESA/NASA

Source: ESA

Source: ESA/NASA

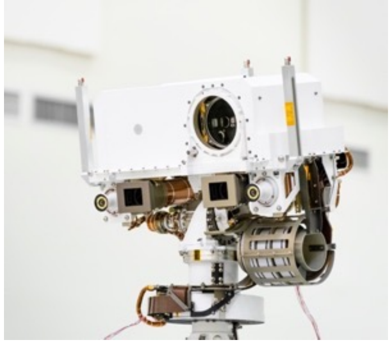
Source: NASA

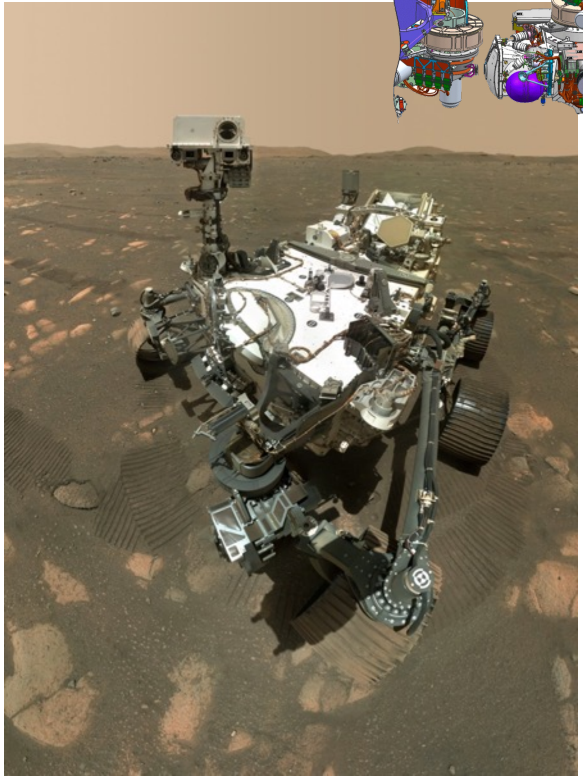
Planet exploration, robotic

Mars Sample Return

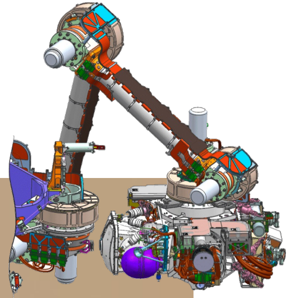
Source: P. Chu et al., 42nd Aerospace Mechanisms Symposium, 2014

Mars 2020 Perseverance





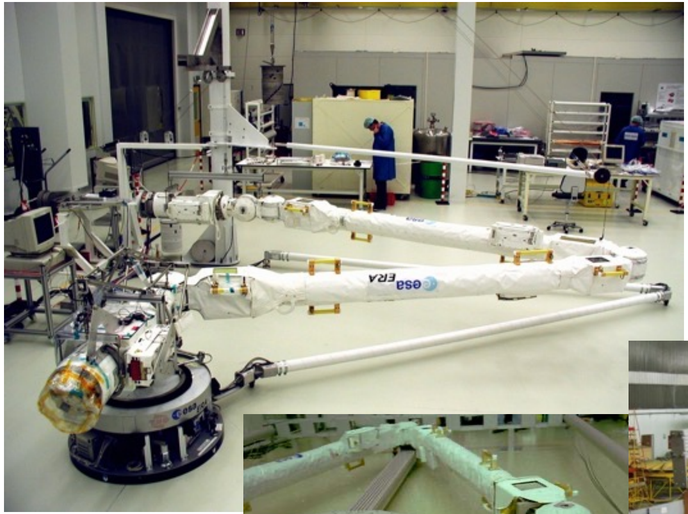
Source: NASA/JPL-Caltech/MSSS



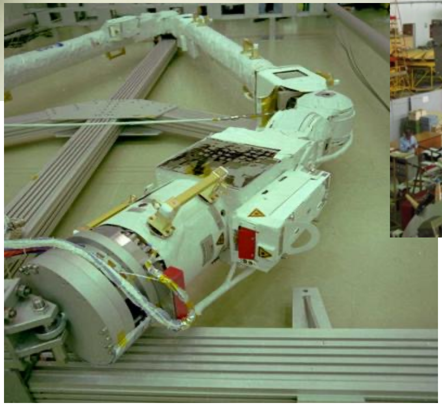
Source: Allwood et al. Space Sci Rev (2020)

Space Robotic

European Robotic Arm (ERA)



Source: Dutch Space



Source: RSC Energia

Space Station Remote Manipulator System (SSRMS) Or Canadarm2

Source: NASA

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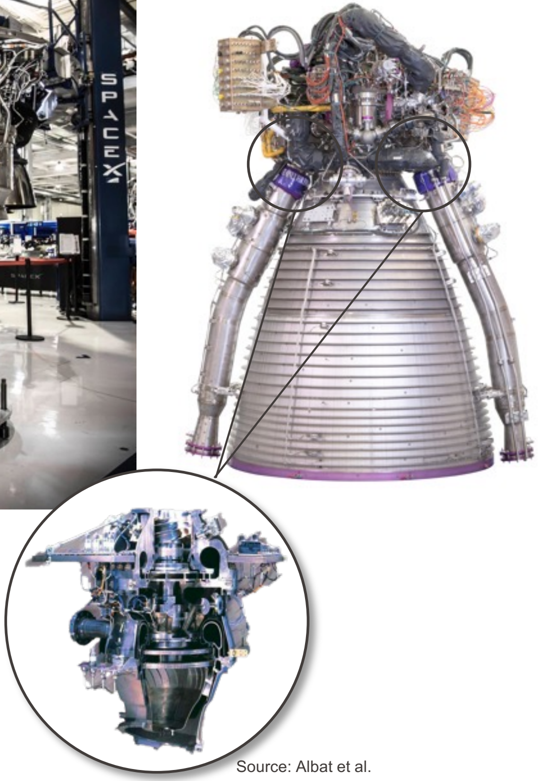
Launch Vehicles and Spacecrafts

Engine mechanisms: Thrust Vector Control, Turbopumps, Propellant Valves

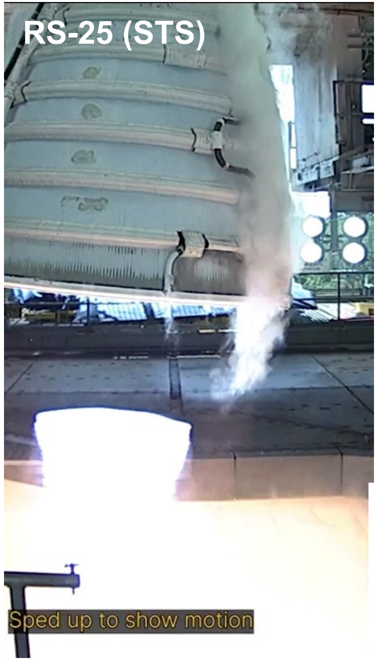
Source: SpaceX

Vulcain 2.1 (Ariane 6)

Source: ArianeGroup Holding



Source: Albat et al.



Source: NASA

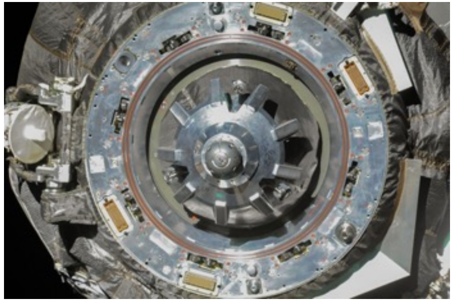
Source: Moog

Source: NASA

Launch Vehicles and Spacecrafts

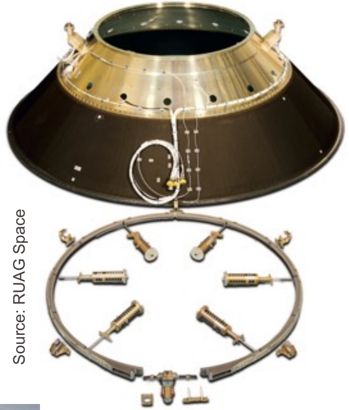
Docking and berthing mechanisms


Source: Qinetiq


Source: NASA


Source: ESA/CNES/Arianespace

Fairing and payload adapter release

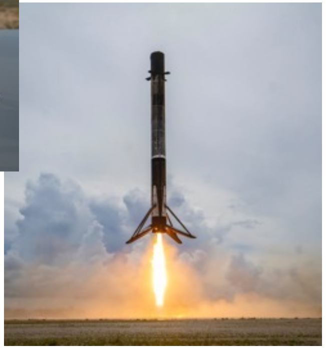

Source: RUAG Space


Source: ESA


Source: ESA–M. Pedoussaut

Landing Legs

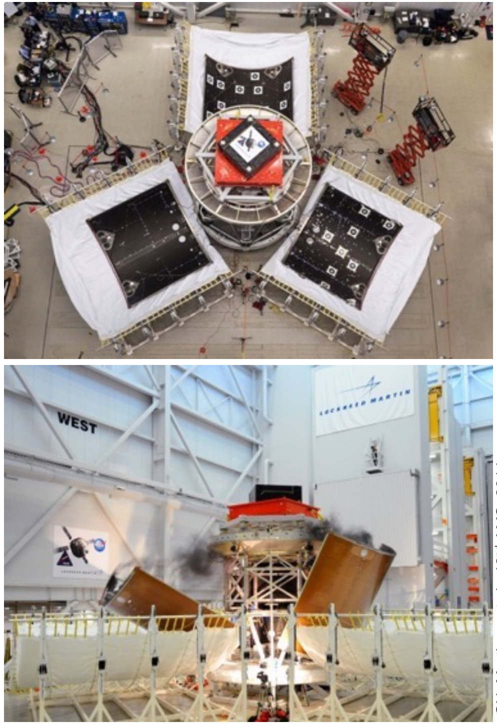

Source: Almatech


Source: SpaceX

Launch Vehicles and Spacecrafts

Fairings

Orion fairing separation test



©H. Martinez et al., 42nd AMS, 2014

Ariane 5 fairing jettisoning (Galileo)

Source: ESA

Ariane 6 fairing (1st FM)

©CNES/ESA/Arianespace-ArianeGroup/Optique Vidéo CSG/JM Guillon

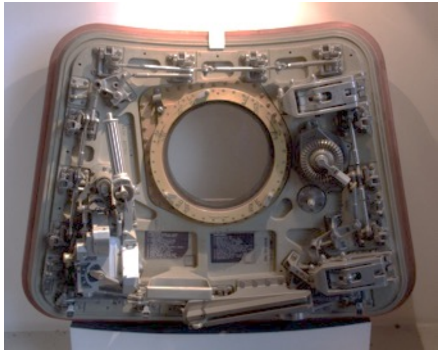
Ariane 5 fairing separation test

©RUAG-ESA

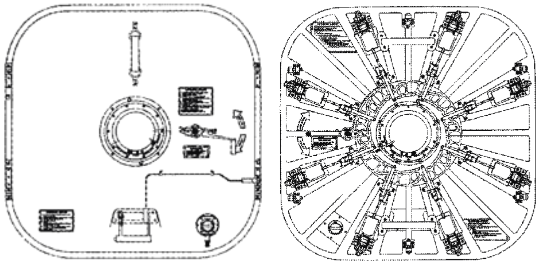
Launch Vehicles and Spacecrafts

Hatches, Nose cones, Umbilical retention and release mechanisms …

Source: NASA

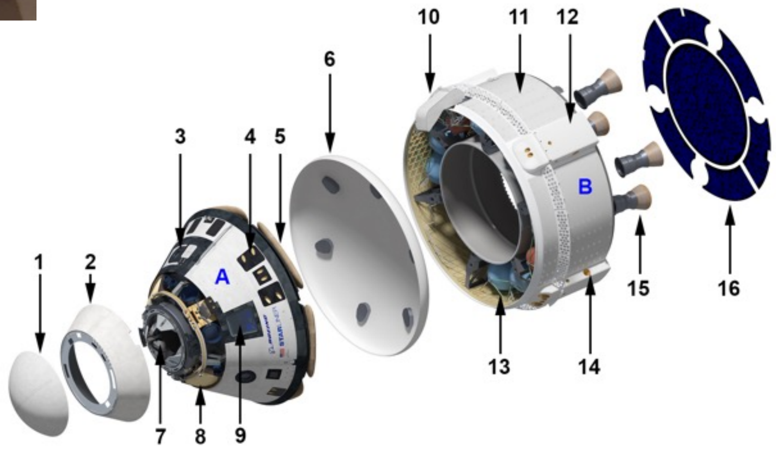


Source: Mike Pee



Source: NASA/JSC

Source: NASA/SpaceX



Source: NASA

Course Plan

- Introduction
  - Course presentation
  - Satellites and spacecraft functions
  - Example of space mechanisms
- Theme 1 - Space Environment
- Theme 2 - Environmental constraints on space mechanisms
  - Vibration and shocks
  - Thermal
  - Vacuum
  - Radiations
  - Chemical
  - …
- Theme 3 - Project management, system engineering, quality assurance
- Theme 4 - Material Properties
  - Material selection: main criteria
- Theme 5 – Structures
  - Assembly
  - Loads (static, dynamic)
  - Additive Manufacturing
- Theme 6- Components
  - Bearings and ball-bearings
  - Flexible elements
  - Motors and actuators
  - EEE components
- Theme 7 - Reliability

European Space Standards

ECSS – European Cooperation for Space Standardization: https://ecss.nl

- **ECSS-E-ST-33-01C** - Space engineering: **Mechanisms**
- ECSS-E-ST-10-04C - Space engineering: **Space environment**
- ECSS-E-ST-10-03C - Space engineering: **Testing**
- ECSS-Q-ST-70 - Space product assurance: **material, mechanical part and process**
  - ECSS-Q-ST-70-36 - Space product assurance: Material selection for controlling stress corrosion cracking
  - ECSS-Q-ST-70-37 - Space product assurance: Determination of the susceptibility of metals to stress corrosion cracking
  - ECSS-Q-ST-70-71 - Space product assurance: Data for selection of space materials and processes
- ECSS-E-ST-10C - Space engineering: **System engineering general requirements**
- ECSS-M-ST-10C - Space project management: Project planning and implementation
- …

Others (NASA, MIL, …)

+ various **handbooks** (ECSS, NASA, …)

+ papers on space mechanisms and related topics

The Universe

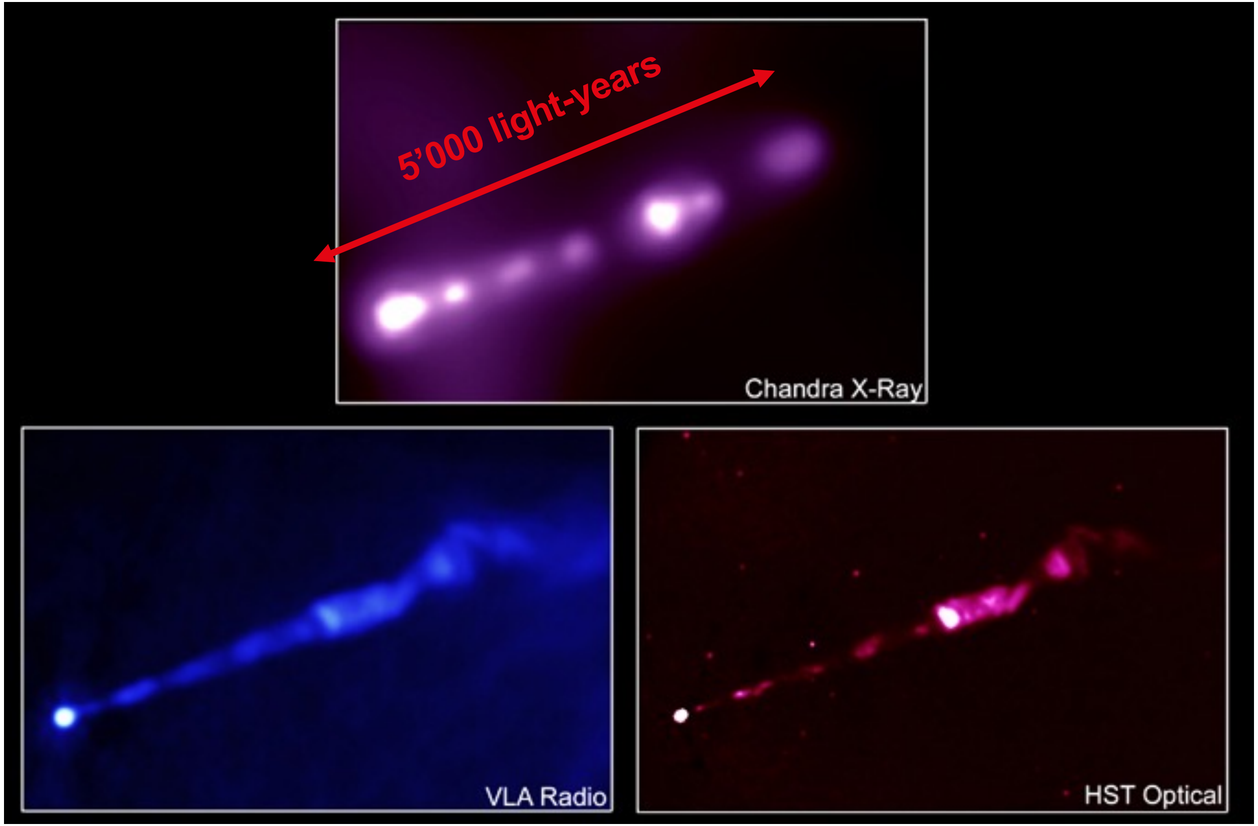
Size of the universe: https://htwins.net/scale2/

- Big bang
- Galaxies
- Stellar evolution
  - Star formation by matter condensation (mainly hydrogen)
  - Various star life cycles
    - Material factory
    - Cosmic radiation emitter
      - Emission of electromagnetic energy (radio waves, IR, Visible, UV, X, γ).
      - Emission of neutral and charged particles (α, β, electrons, …).
  - End of life of stars (explosion, condensed matter, black holes, …)
    - Stellar cataclysm
      - Emission of radiations (particles, electromagnetic)
      - Material dispersion

Giant elliptical galaxy M87's energetic jet

Galactic Cosmic Rays (GCR)

- High energy charged particles (p^+, e^-, fully ionized nuclei)
- Low flux
- Problems for electronics and humans
- Effect of solar wind and Earth magnetic field



Source:

- X-ray: H. Marshall (MIT), et al., CXC, NASA
- Radio: F. Zhou, F. Owen (NRAO), J. Biretta (STScI)
- Optical: E. Perlman (UMBC), et al., STScI, NASA

Interstellar matter and star formation

Source: NASA, ESA, and The Hubble Heritage Team

LL Ori in Orion nebula

Charged particle wind

Bow shock (interaction with stellar emission)

Source: Hubble Heritage Team (AURA / STScI), C. R. O'Dell (Vanderbilt), NASA

Source: NASA, ESA, CSA, STScI; Joseph DePasquale (STScI), Anton M. Koekemoer (STScI), Alyssa Pagan (STScI).

Pillars of Creation in the Eagle Nebula
James Webb ST Webb's
Near-Infrared Camera (NIRCam)

Solar System

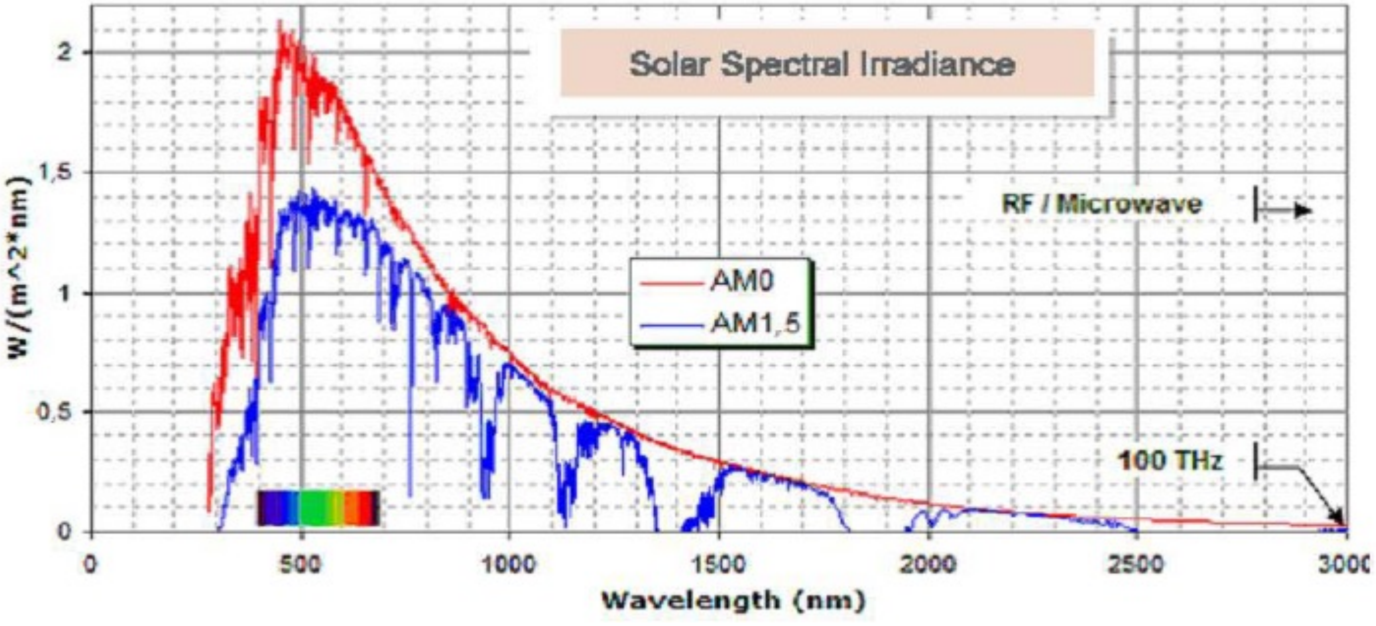
- The Sun and the planets
- Sun radiation
  - Electromagnetic
    - Sun spectrum
    - Intensity of the radiations
  - Particles (neutral and charged)
    - Intensity of the emitted particles
    - Effects of the particles
- Materials in solar orbit
  - Various bodies, fragments, dust
    - Material density and space vacuum
    - Comets
    - Asteroids
  - Planets
  - Waste/debris

For a detailed overview of the space environment, cf. **ECSS-E-ST-10-04C: Space environment**

Solar spectral irradiance

Interesting reading: [1.2] S.K. Solanki et al. Solar Irradiance Variability and Climate, Annu. Rev. Astron. Astrophys. 2013

Total Solar Irradiance (TSI):
1’362 W/m²
On terrestrial orbit, without atmosphere
(ASTM E490 / ECSS-E-ST-10-04C Rev.1)



Source: ECSS-E-ST-10-04C Rev.1, Annexe F

EPFL

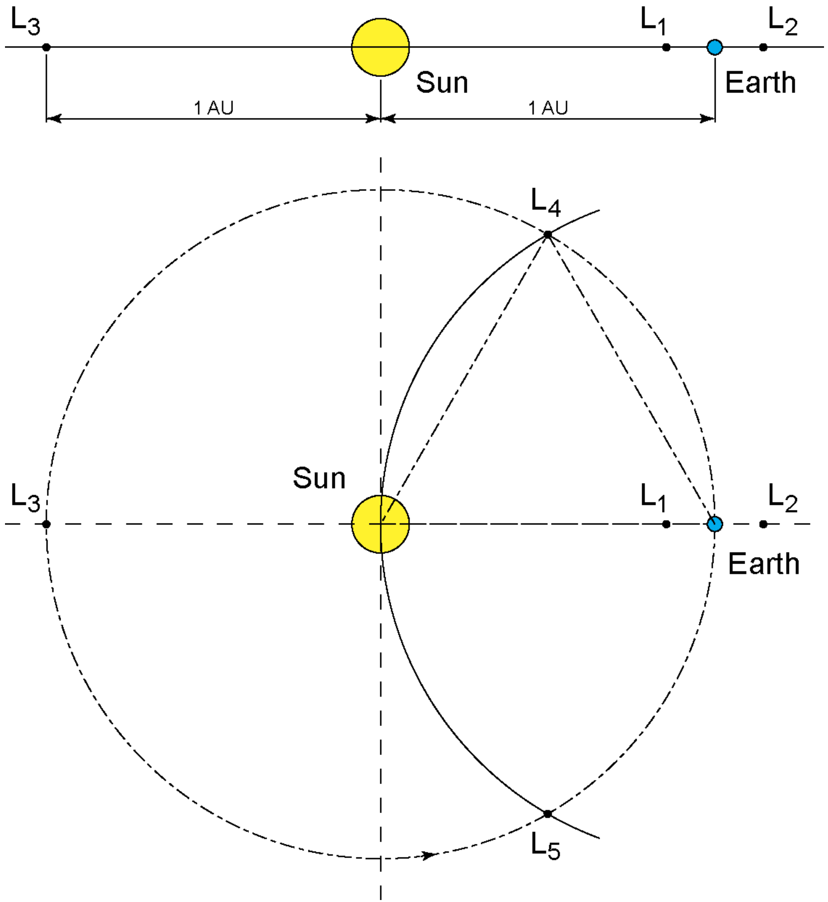
Terrestrial Orbits

Orbit	Altitude
GEO *Geostationary Earth Orbit*	36’000 km
MEO *Medium Earth Orbit*	> 10’000 km
LEO *Low Earth Orbit*	500 – 2000 km
HEO *Highly Elliptical Orbit*	Between 500 km (perigee) to 36’000 km (apogee)

Lagrange Points

Point	Distance to Earth center (km)	Examples of use
L1	1.5 x 10^6 km *Towards Sun* *Unstable position*	SOHO, LISA Pathfinder
L2	1.5 x 10^6 km *Opposite Sun* *Unstable position*	WMAP, JWST
L3	2 x Dist. (M1-M2) + ε *Towards Sun* *Unstable position*	Not occupied
L4 & L5	1 x Dist. (M1-M2) + ε *Stable orbit around L4 or L5* *(if low mass and speed)*	Telesto and Calipso *Thesis satellites, which is itself a satellite of Saturn*

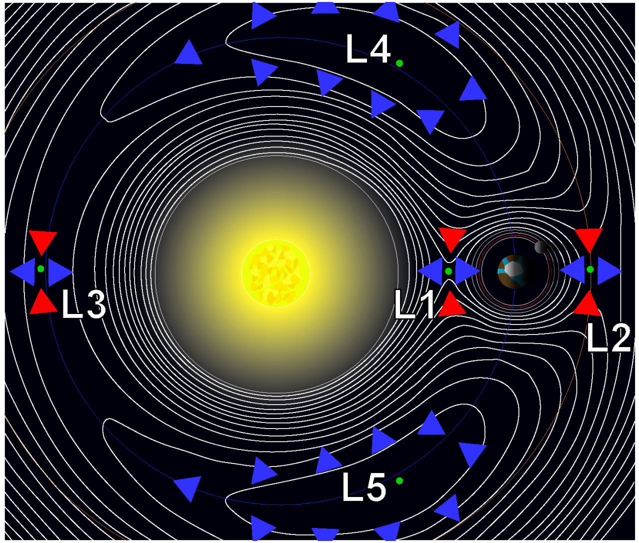
Lagrange Points



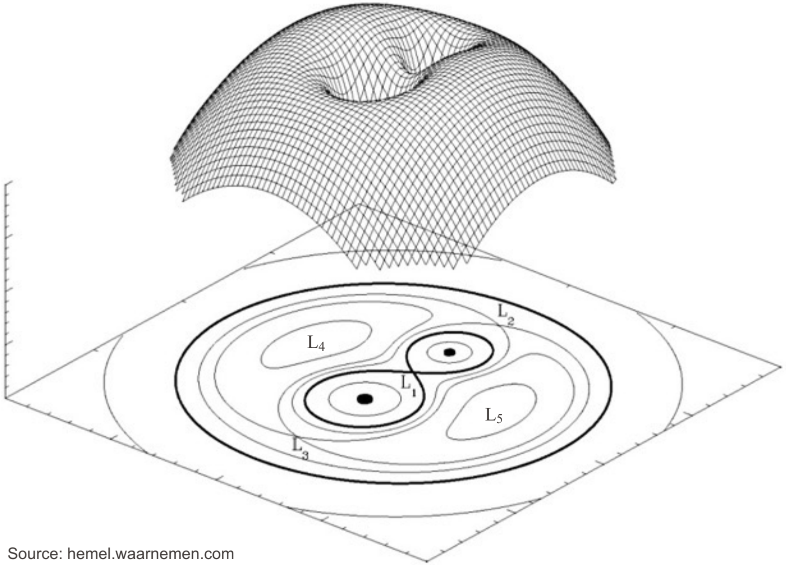
- Orbital points near two large co-orbiting bodies
- Constant-pattern solutions of the restricted three-body problem
- https://en.wikipedia.org/wiki/Lagrange_point

Lagrange Points

- Gravitational potential in rotation
  - Equilibrium between the gravitational potential and the centrifugal force + Coriolis force (linked to the rotation of the frame of reference)
- L_1, L_2, L_3: saddle point extrema: unstable
- L_4, L_5: maxima: in principle unstable, but an orbit around those points maybe stable if the mass in orbit as well as its distance to the Lagrange point are small.



Source: Wikipedia



Source: hemel.waarnemen.com

Planetary and terrestrial environment

- Planets and Natural satellites
  - Radiations
    - Thermal radiations
    - Solar wind
    - Geomagnetic storm (solar storm)
    - Earth's magnetic field and magnetosphere
      - Van Allen radiation belts (Inner: 3'500 km, protons; Outer: 20'000 km, electrons)
  - Matter
    - Gas
      - Pressure
      - Chemical nature
    - Particles
      - Dust
      - Meteoroids
      - Human-made objects

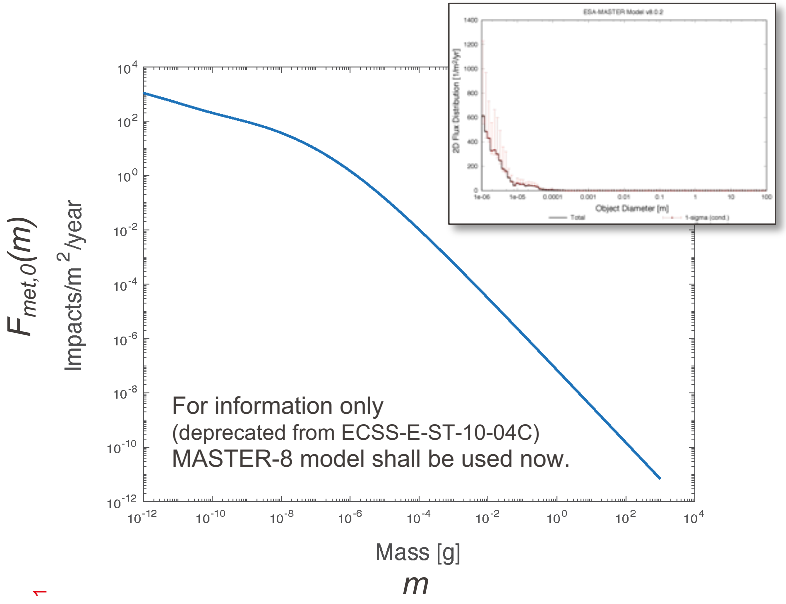
[1.1] ECSS-E-ST-10-04C Rev.1
Space engineering - Space environment

Meteoroids (from ECSS-E-ST-10-04C Rev.1)

- Particles of **natural origin**. Nearly all meteoroids originate from asteroids or comets.
- The natural meteoroid flux represents, at any instant, a total of about 200 kg of mass within 2’000 km of the Earth surface.
- **Meteoroid streams** are accumulations of meteoroids with nearly identical heliocentric orbits.
- Relative to Earth all particles of a **given meteoroid stream** have nearly **identical impact directions and velocities**. Encounters with meteoroid streams typically last from a **few hours to several days**.
- Meteoroids which do not form part of identified streams are called **sporadics**. Their **flux is fairly constant** over the year and they **do not follow any apparent pattern** with respect to incident direction or velocity.

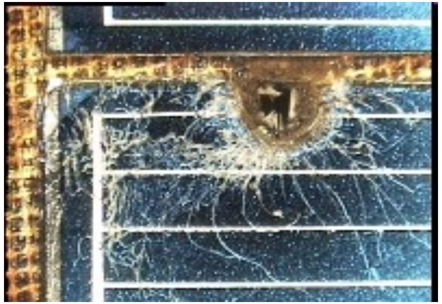
Meteoroids

Source: ECSS-E-ST-10-04C Rev.1

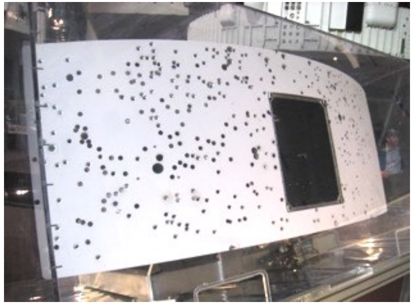


- In this example:
  - Randomly-oriented surface
  - 1 AU from the Sun
  - Nor gravitational concentration effect neither terrestrial shielding

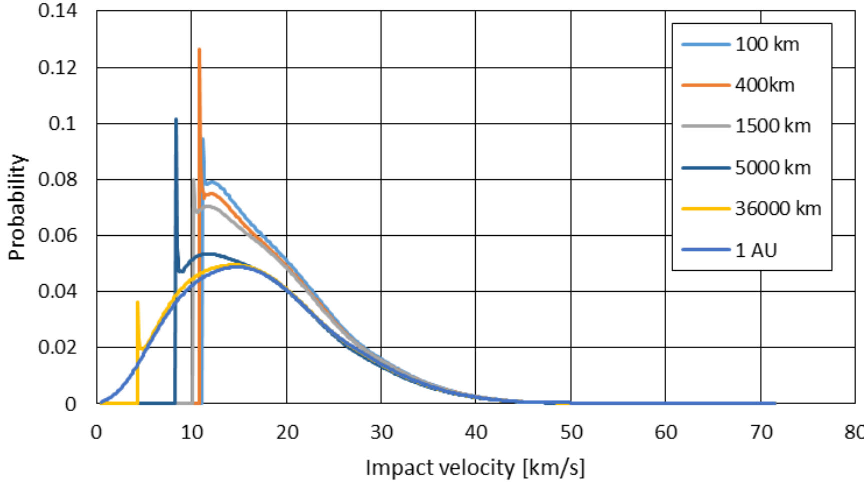
Solar panel



HST Camera radiator



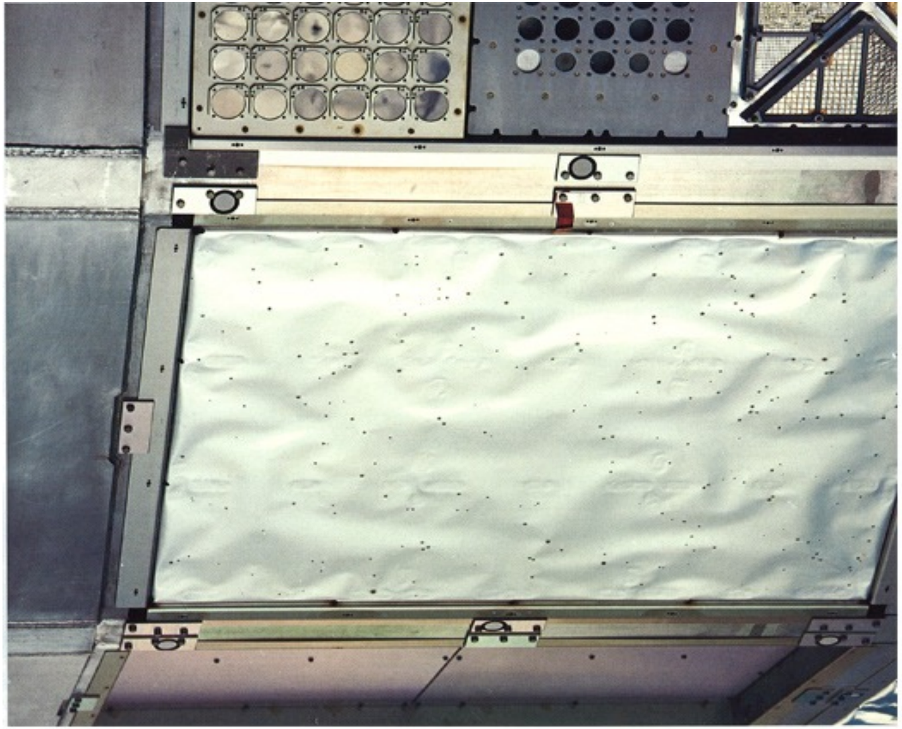
Velocity distribution for different altitudes from the Earth surface

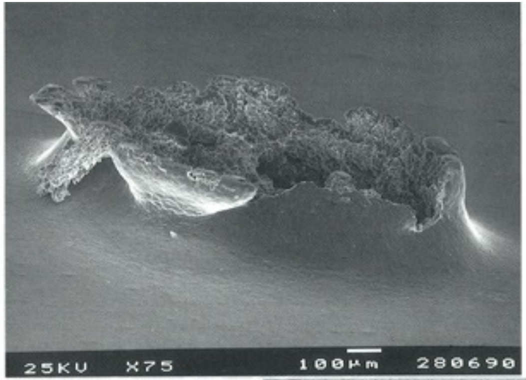


Source: ECSS-E-ST-10-04C Figure J-4

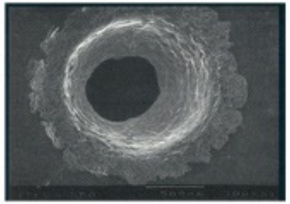
LDEF and FRECOPA

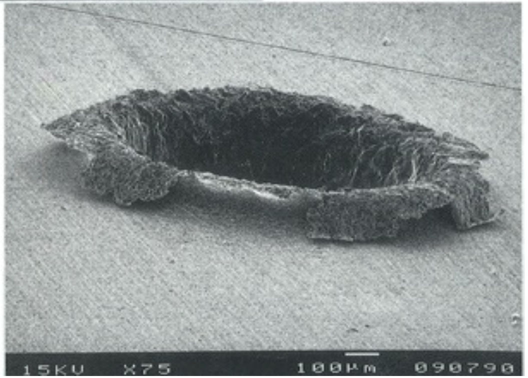
Long Duration Exposure Facility





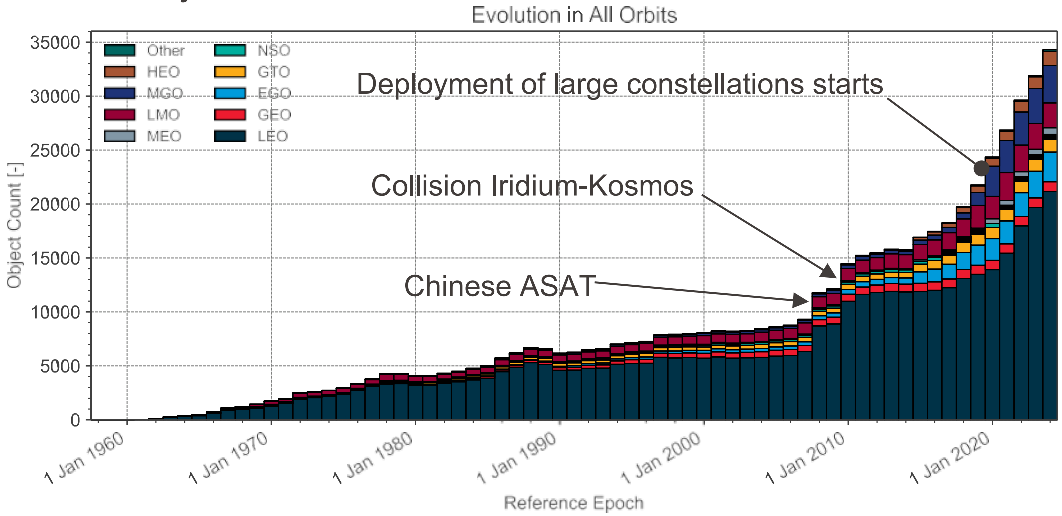
Source: NASA



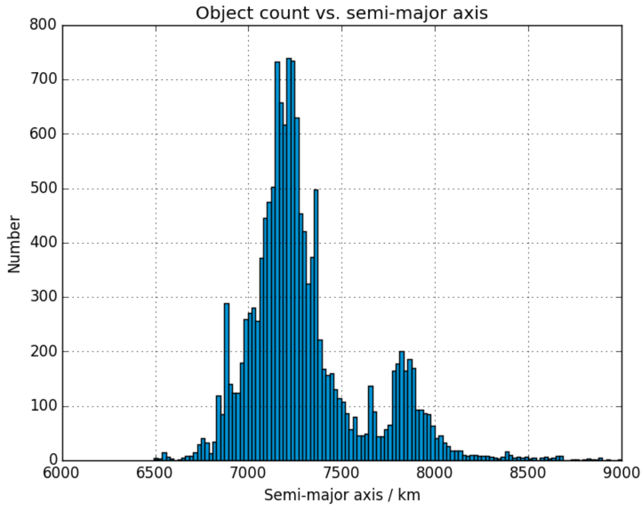


Known orbital objects

Trackable objects



Source: ESA's Annual Space Environment Report (July 2024) GEN-DB-LOG-00288-OPS-SD – Figure 2.2a



Source: ECSS-E-ST-10-04C-Rev.1 (data: May 2018)

Exercise 1.1: Energy of meteoroids

Since the beginning of the space age there have been more than 650 confirmed on-orbit fragmentation events (accidental, collision, deliberate …). Status July 19th, 2024

(source: https://sdup.esoc.esa.int/discosweb/statistics/)

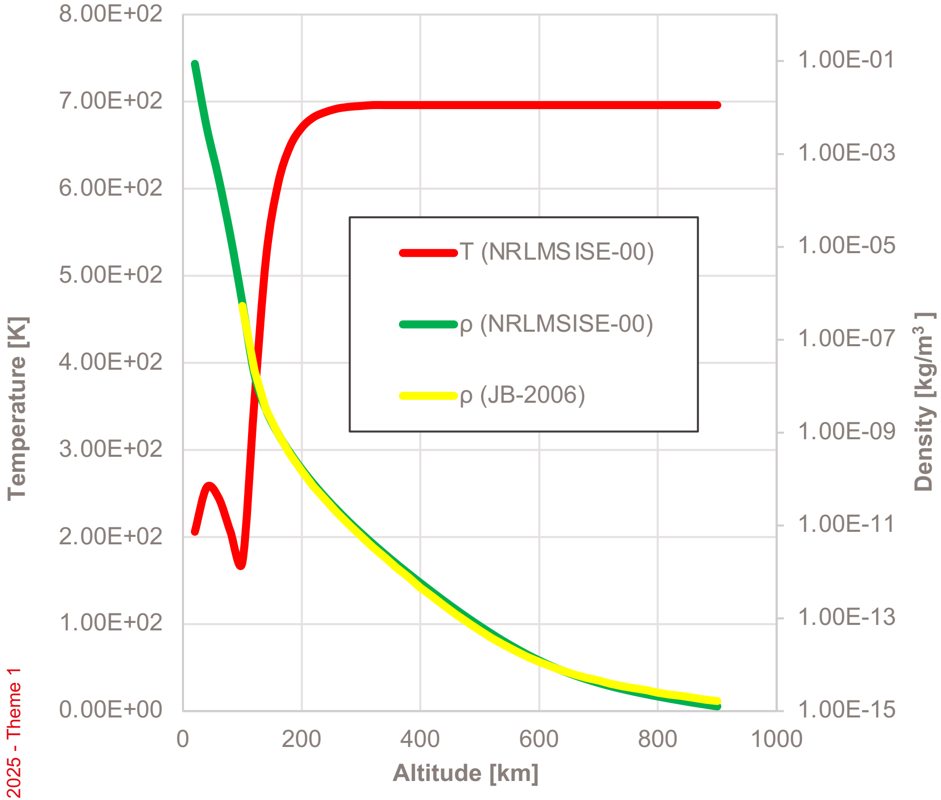
https://www.esa.int/Safety_Security/Space_Debris

https://sdup.esoc.esa.int/discosweb/statistics/

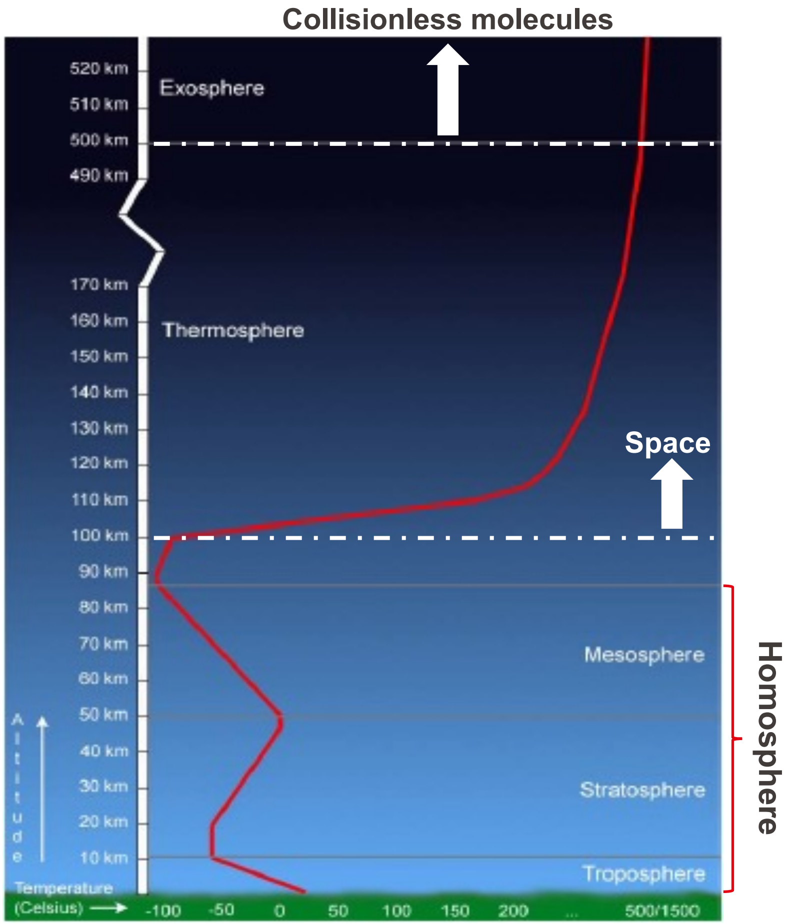
https://www.orbitaldebris.jsc.nasa.gov/reference-documents/

https://www.newyorker.com/magazine/2020/09/28/the-elusive-peril-of-space-junk

Atmospheric Profiles



Source: ECSS-E-ST-10-04C Rev.1

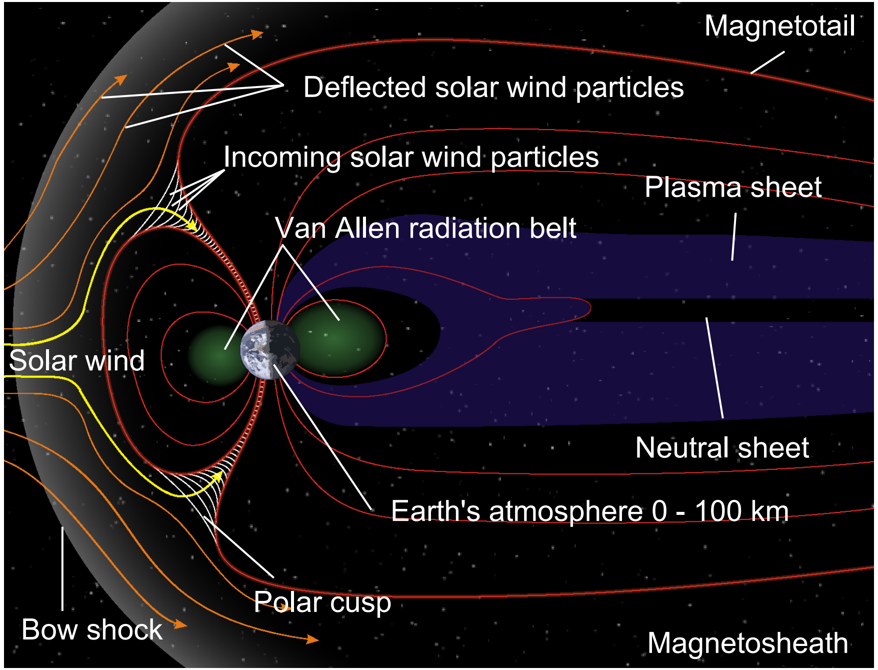


Exercise 1.2: Density of gas molecules

Chemical composition around the Earth

- Ionosphere (60 to 800 km):
  - Highly ionized gas, due to radiations (solar, cosmic, …).
    - **D layer** (60 to 90 km, 2 Pa, -76 °C) ***Polyatomic ions***
      - Ionic density varies rapidly with the Sun
    - **E layer** (90 to 120 km, 10^{-2} Pa, -50 °C) ***Oxygen ions, NO***
      - Slower ionic density variation with the Sun
    - **F layer** (120 to 500 km, 10^{-4} Pa, 1000 °C) ***O, N, H***
      - Ionization highly dependent on solar activity
- Higher layers:
  - Thermosphere (80 to ~400 km)
    - Very low orbit satellites
  - Exosphere (~400 to 800 km … / to space)
    - Earth observation satellites, space station, telecom constellations
  - Magnetosphere (> 800 km):
    - Very low gas density (< 10^{-4} Pa)
    - Geostationary satellites (36'000 km)
    - Zone of interactions between:
      - Solar particles flux
      - Terrestrial magnetic field:
        - Existence of intense plasmas
        - Complex structure
        - Van Allen radiation belt (~1'000 to 12'000 km, ~25'000 to 45'000 km)

Structure of Earth Magnetosphere



Source: NASA

Theme 1 Summary

- Mechanisms are used for many critical functions, including
  - Launch and separation
  - Deployment
  - Attitude control, navigation, exploration
  - Instruments, payload and communication
  - …
- Constrains are depending on the mission, on the spacecraft location
  - Various orbits (LEO, MEO, GEO, Lagrange Points …)
  - Space is a harsh environment
    - Radiations (electromagnetic, ionizing, non-ionizing)
    - Micro-meteoroids, debris
    - Presence of residual gazes
    - …
- Space system standards and handbooks exist (ECSS, NASA, MIL …)

Next week

- Theme 2: Environmental constrains
- Exercises 1.1 and 1.2