



EE-585 – Space Mission Design and Operations

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Ecole Polytechnique Fédérale de Lausanne

Week 01 – 12 Sep 2025

Today's outline

Course Admin

Course outline

→ Space News

Why do we go to space?

Newton's laws, inertial frames and energy

Earth's atmosphere and magnetic field

Solar radiation on Earth and in the solar system & energy budget

Course Admin

- PhD in observational cosmology (and machine learning) at EPFL for Euclid
- Worked on CHEOPS for observation mission preparation at UNIBE & UNIGE
- Currently Space Situational Awareness expert at APCO Technologies & Swiss government
 - Satellite population monitoring
 - Orbital event analysis
 - Applied research in Space Situational Awareness

Do not hesitate to reach out: thibault.kuntzer@epfl.ch

The course...

- will cover a wide range of subjects starting the fundamental laws to advanced concepts. The goal is to give you an introduction to the most important aspects of space mission design and operations.
- is a strongly recommended prerequisite for the EPFL Minor in Space Technologies.
- is a concept-oriented course → only few mathematical demonstrations.
- will contain a news section to keep you updated with major developments in the industry.
- will have short interactive quizzes during the lectures → do participate!

The exercises

- The exercise sessions will give you the opportunity to go over the course's concepts in greater details.
- There will be 10 lectures plus 4 exercise sessions → these sessions are fully part of the course. I strongly recommend an active participation.
- Exercises will not be graded. They will be discussed during each session and presented by students or TAs, and solutions published later on Moodle.
- There will be 2 TAs for the course:
 - Jonathan Magnin, PhD student Telecommunications Circuits Laboratory
 - Oliver Pineda, PhD student Laboratory of Astrophysics

The exam...

- will be an oral session of 20 minutes (with 40 minutes preparation).
- will be based on an exercise plus a conversation around the concepts.

Guidelines on the importance of the concepts

There is an accompanying document on Moodle stating how important the different concepts are:

1. **Key concepts:** fundamental aspects of the course. You should understand these in details and be able to describe them without hesitation.
2. **Important concepts:** you should be able to describe important concept clearly, but apply with documentation. They generally are the basis for exercises.
3. **Relevant concepts:** you should be able to explain them and the larger context. They can be discussed in the exam, mostly in the second discussion part.
4. **Advanced concepts:** interesting nuggets of information or a preview of a topic not covered in the course. These will *not* be tested in the exam.

The *learning outcomes* document will be published with the slides. This not binding, but I'll stick to it the best I can.

- <http://moodle.epfl.ch> → EE-585
- Enrolling password (if needed) : `welcomeinspace`
- Course slides, learning outcomes and exercise sheets will be available on Thursdays at 12:00.
- Solutions to exercises will be available on Fridays at 16:00.
- If you have course-related questions (technical or logistical)
→ please use the forum on Moodle.

Massive open online course – MOOC

- A MOOC is available of the EE-585 course taught by astronaut Claude Nicollier until spring 2024. First instalment of this course in autumn 2024.
- Watching the MOOC is not mandatory, this course is self-sufficient.
- There are 8 units, available in self-paced mode.
- The MOOC content is similar to this course, but there are variations. Do not expect a copy/paste in the lectures here!
- (Optional) enrolment → <https://www.edx.org/learn/space/ecole-polytechnique-federale-de-lausanne-space-mission-design-and-operations>

Reference and resources

(Some) books

- *Space Mission Analysis and Design* (aka SMAD), J.R. Wertz & W. J. Larson
- *Orbital Mechanics for Engineering Students*, H. D. Curtis
- *Orbital Mechanics and Astrodynamics: Techniques and Tools for Space Missions*, G. Hintz
- *Fundamentals of Astrodynamics and Applications*, D. A. Vallado & W. D. McClain

Other resources

- *Spacecraft Dynamics and Control*, M. M. Peet, Arizona State University
- *Orbital Mechanics & Astrodynamics*, B. Weber <https://orbital-mechanics.space>
- *How GPS works*, B. Ciechanowski <https://ciechanow.ski/gps> (More focussed on GNSS, but nice visualisations of orbital mechanics)
- “Kerbal Space programme”
- Wikipedia has very good articles on most of the concepts of the course

In this course, we will study

Orbital mechanics, which is the study of motion about a center of mass, in particular the motion of spacecraft and rockets. Orbital mechanics focuses on spacecraft **trajectories**.

More generally, the field is

Celestial mechanics is the study of all objects (i.e. spacecraft + astronomical bodies), which includes black holes, dark matter, big bang and other phenomena (like tides and relativistics mechanics).

Course outline

Course outline (1/3) Subject to change

| Week | Focus | Subjects |
|-------------|---|---|
| 01 – 12 Sep | Why space?, near-Earth environment | <ul style="list-style-type: none">• Course admin• Why do we go to space?• Review of laws of mechanics and notions of energy• Earth's atmosphere and magnetic field• The radiation environment |
| 02 – 19 Sep | Orbital mechanics <i>Filming takes place</i> | <ul style="list-style-type: none">• Gravitational well• Escape velocity• Reference frames and calendars• The two body problem and Kepler's laws• Orbital motion |
| 03 – 26 Sep | Orbital classes | <ul style="list-style-type: none">• Space weather and the Sun activity cycle• Orbital regimes• Ground track• Atmospheric drag and lifetime• Non-keplerian effects and special orbits (incl Sun-Synchronous) |
| 04 – 03 Oct | Spacecraft dynamics | <ul style="list-style-type: none">• Orbital manoeuvres (Hohmann, small Δv in LEO, plane change)• Orbit determination• Launch early orbit phase, positioning and station-keeping |

Course outline (2/3) Subject to change

| Week | Focus | Subjects |
|-------------|--|--|
| 05 – 10 Oct | Exercise session | <ul style="list-style-type: none">● Exercise session 1 |
| 06 – 17 Oct | Spacecraft interaction, object population in Earth's orbit | <ul style="list-style-type: none">● Phasing● Rendezvous, proximity operations and docking (RPOD)● Relative motion● Motivations for RPOD● The resident space object population and the debris problem |
| — – 24 Oct | <i>No lectures – holidays</i> | – |
| 07 – 31 Oct | Exercise session | <ul style="list-style-type: none">● Exercise session 2 |
| 08 – 07 Nov | Interplanetary trajectories | <ul style="list-style-type: none">● The deep space environment● Sphere of influence● Interplanetary trajectories● Aerobraking |
| 09 – 14 Nov | Interplanetary trajectories, spacecraft propulsion | <ul style="list-style-type: none">● Gravity assists● Lunar trajectories● Propulsion systems● Non-impulsive manoeuvres |

Course outline (3/3) Subject to change

| Week | Focus | Subjects |
|-------------|--------------------------------------|---|
| 10 – 21 Nov | Exercise session | <ul style="list-style-type: none">● Exercise session 3 |
| 11 – 28 Nov | Critical subsystems, launch | <ul style="list-style-type: none">● Attitude control● Power generation● Launch (constraints on S/C and orbit, window)● Re-entries |
| 12 – 05 Dec | Constellations, trends in operations | <ul style="list-style-type: none">● Deploying tethers in space● New space vs old space● Satellite constellations● Major actors in the space industry● Spacecraft operations |
| 13 – 12 Dec | Human spaceflight | <ul style="list-style-type: none">● Guest lecture by astronaut Claude Nicollier |
| 14 – 19 Dec | Exercise session | <ul style="list-style-type: none">● Exercise session 4 |

→ **Space News**

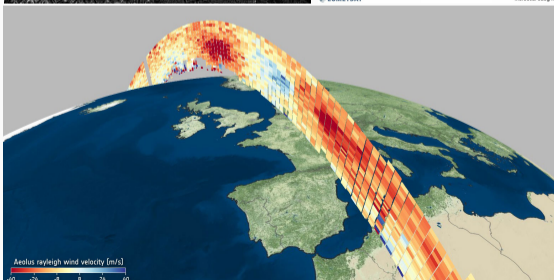
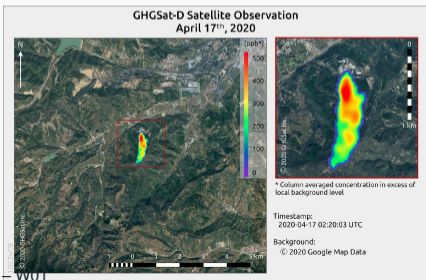
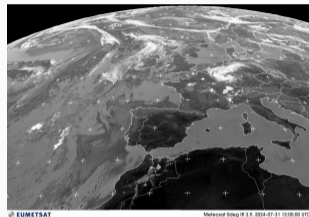
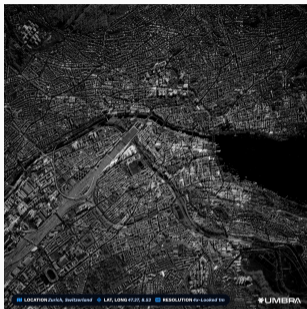
Why do we go to space?

Motivations and applications

- Earth & atmosphere observation
- Communications
- Navigation
- Science/research/exploration
- Technology demonstration
- Space race/prestige
- Tourism
- Space-oriented applications (“space for space”)

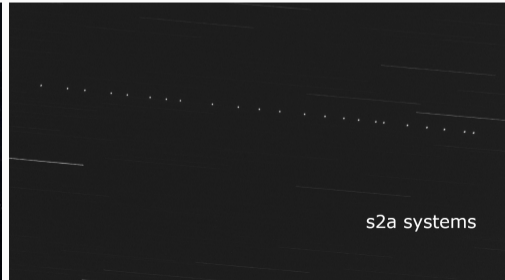
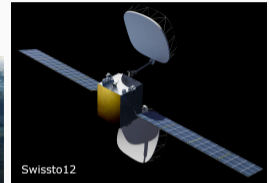
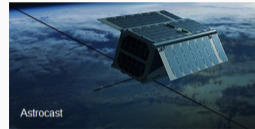
Earth & atmospheric observation

- Mapping (optical, radar, ...)
- Weather, climate
- Atmospheric content
- Ocean research
- Gravity field
- ...
- The lower altitude the better



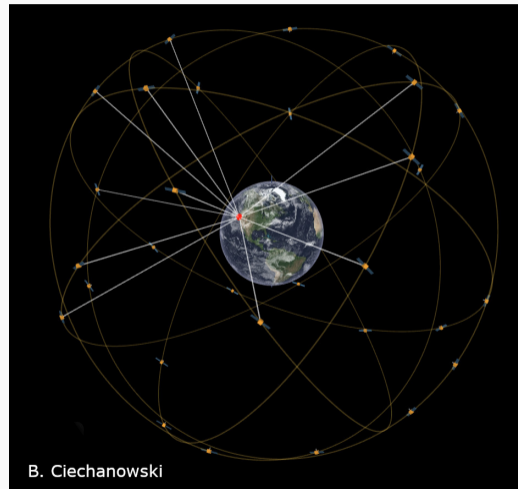
Communications

- Largest commercial motivation
- 2-way Communications: voice, IoT, data
- 1-way broadcasting: radio, TV
- Great diversity of shape, size and orbits
- Starlink: \approx 9500 satellites launched



Global navigation satellite system (GNSS)

- Precise 3D navigation (including in space)
- Critical system to many applications (transportation, agriculture, rescue, surveying, ...)
- Multiple constellations:
 - Global positioning system (GPS): USA
 - GLONASS: Russia
 - Galileo: Europe
 - BeiDou: China
 - IRNSS: India (regional)
 - QZSS: Japan (regional)

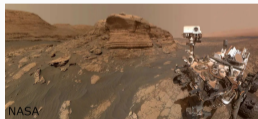
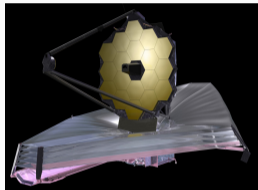
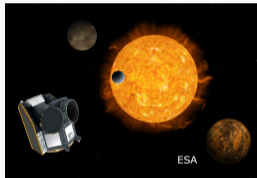


General disciplines

- Astrophysics
- Solar physics
- Space weather
- Fundamental physics
- Earth science

In addition, onboard space stations

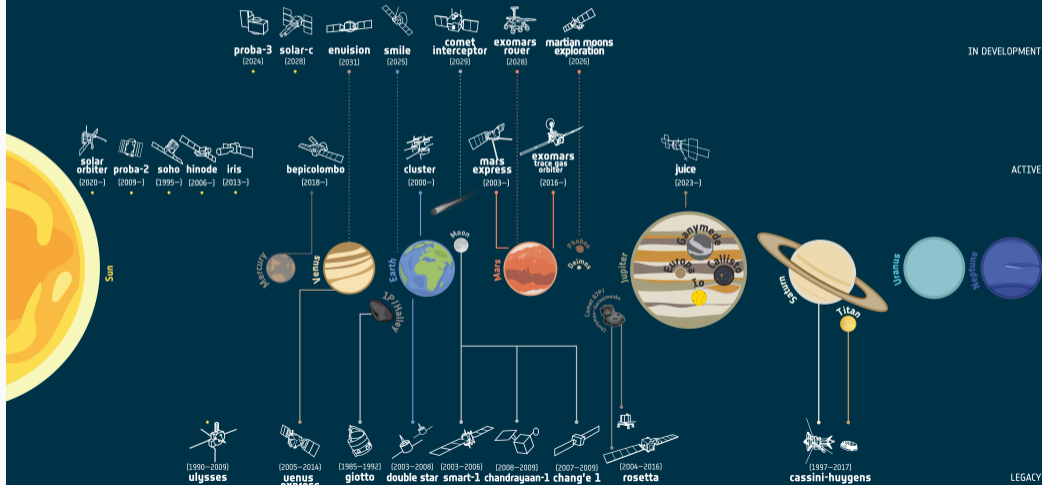
- Biology
- Plant growth
- Physiology
- Material and fluid physics



ESA's science fleet of Solar System explorers

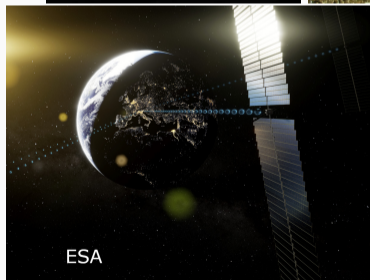
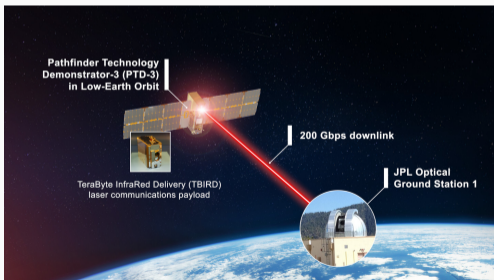
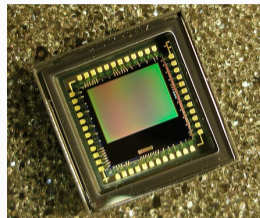


SOLAR SYSTEM EXPLORERS



Technology demonstration

- Proof of concepts
- Maturation of technologies
- ...



What a view!



Taken by astronaut William Anders on 24 Dec 1968, during the Apollo 8 mission.

“The most influential environmental photograph ever taken“ ?
G. Rowell in *100 Photographs that Changed the World*.

Space & Art: The First Artwork Created in Space



Alexei Leonov's (1st person to conduct a spacewalk) drawing depicting an orbital sunrise, 1965.

Credits: Museum of the Yuri Gagarin Cosmonaut Training Center.

Pale Blue Dot picture

"Look again at that dot. That's here. That's home. That's us. On it everyone you love, everyone you know, everyone you ever heard of, every human being who ever was, lived out their lives. The aggregate of our joy and suffering, thousands of confident religions, ideologies, and economic doctrines, every hunter and forager, every hero and coward, every creator and destroyer of civilization, every king and peasant, every young couple in love, every mother and father, hopeful child, inventor and explorer, every teacher of morals, every corrupt politician, every "superstar," every "supreme leader," every saint and sinner in the history of our species lived there – on a mote of dust suspended in a sunbeam."

- Carl Sagan, 1934-1996

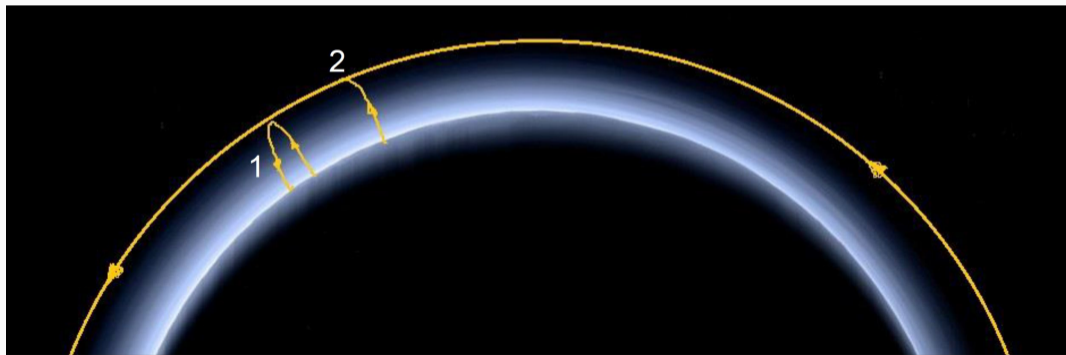


Pale Blue Dot is a photograph of Earth taken on 14 Feb 1990, by the Voyager 1 spacecraft from a distance of approximately 6 billion kilometers (40.5 AU).

Space tourism

There are two options at the moment:

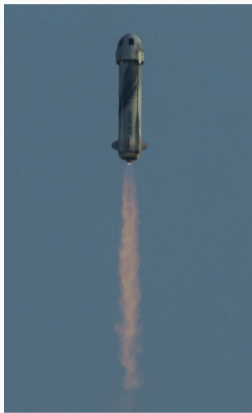
1. Suborbital less than 2 hours, “cheap”
2. Orbital days or weeks, expensive
3. (soon?) Lunar projects?



Two companies are currently offering option 1 (suborbital)



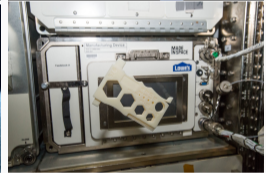
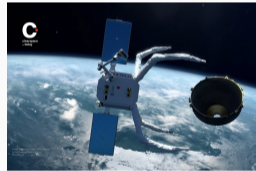
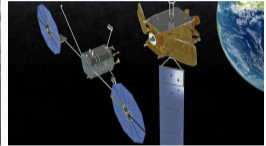
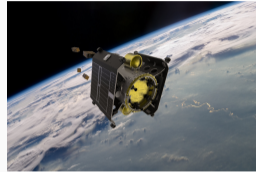
Virgin Galactic
(Richard Branson)



Blue Origin
(Jeff Bezos)

In-orbit services

- Space transportation
- Active Debris Removal (ADR)
- Refuelling/life extension
- Inspection
- In-orbit manufacturing
- ...



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Newton's laws, inertial frames and energy

Newton's laws of motion

1. In the absence of a force, a body either is at rest or moves in a straight line with constant speed (with respect to an inertial frame of reference).
2. A body experiencing a force \vec{F} will be subject to an acceleration \vec{a} such that $\vec{F} = m\vec{a} = m\ddot{\vec{r}}$, where m is the mass of the body.
3. Whenever a first body exerts a force \vec{F} on a second body, the second body exerts a force $-\vec{F}$ on the first body. The two forces are of equal magnitude and opposite in direction. (In popular culture: every action creates an equal and opposite reaction.)

Generalisation of Newton's second law

The force is equal to the time derivative of the momentum \vec{p} :

$$\vec{F} = \frac{d\vec{p}}{dt} = \dot{\vec{p}}$$

where

$$\vec{p} = m\vec{v} = m\dot{\vec{r}}$$

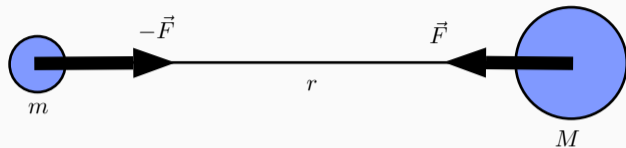
This formulation is important in case m does not remain constant (rocket equation for instance or any leaking system).

- An inertial frame is a frame with respect to which Newton's laws of motion are valid. The inertial frame should be under zero acceleration.
- A good approximation of an inertial frame has its axes fixed on distant stars with essentially zero motion on the celestial sphere.
- The centre of the inertial frame, which is an orthogonal coordinate system, is arbitrary.

Validity of Newton's laws for orbital motion

- All velocities in our context are $v < 10^{-3}c$, so Lorentz factor is essentially equal to one. (Lorentz factor = $1/\sqrt{1 - (v/c)^2}$)
 - The laws are well verified in the vicinity of the Earth and in the solar system.
 - There are a few small general relativity effects like the rotation of line of apsides (e.g. in the orbit of Mercury) and very slow orbital decay because of gravitational radiation over millennia (e.g. orbits of binary compact massive objects).
- ⇒ Newton's laws are (mostly) valid to describe the motion of celestial bodies and spacecraft.

Newton's law of universal gravitation

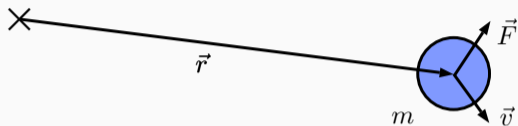


$$\vec{F} = G \frac{Mm}{\|\vec{r}\|^3} \vec{r} \implies \boxed{F = G \frac{Mm}{r^2} = \frac{\mu m}{r^2}}$$

where

- M is the mass of the largest body
- m is the mass of the spacecraft
- G is the gravitational constant, $G = 6.673 \times 10^{-11} \text{ m}^3\text{kg}^{-1}\text{s}^{-2}$
- $\mu = GM$ is the standard gravitational parameter

Newton's second law for rotations



where

- \times represents a fixed point or centre of mass of a set of point masses or of a solid body
- Torque = moment of force $\vec{T} = \vec{r} \times \vec{F}$
- Angular momentum for a single point particle $\vec{h} = \vec{r} \times \vec{p}$
- Newton's second law for rotations $\vec{T} = \frac{d\vec{h}}{dt} = \dot{\vec{h}}$

Angular momentum and moment of inertia

The angular momentum \vec{h} for a solid body with a rotation axis Δ :

$$\vec{h} = I_{\Delta} \vec{\omega}$$

where

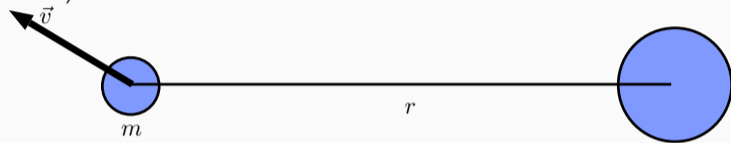
- $\vec{\omega}$ is the vector quantity of the angular velocity
- I_{Δ} is the moment of inertia

$I_{\Delta} = \sum_i m_i r_i^2$ where r_i are the distances of mass elements to the axis of rotation Δ

$I_{\Delta} = \iiint_V r^2 \rho(r) dV$ where $\rho(r)$ is the density at distance r from Δ

Potential energy of a spacecraft

Potential energy of a spacecraft of mass m in the gravitational field of a much larger mass M ($m \ll M \rightarrow$ the center of mass of the two bodies is at the centre of the large mass M)



$$E_{\text{pot}} = -GM\frac{m}{r} \quad \rightarrow \quad \boxed{E_{\text{pot}} = -\frac{\mu}{r}} \quad M$$

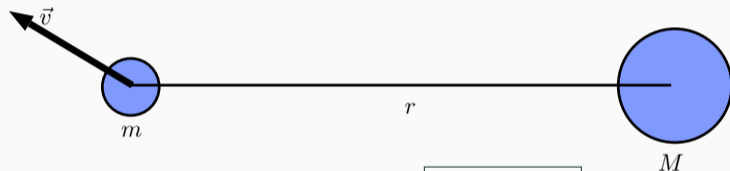
In the rest of the course, E_{pot} will always be understood per unit mass.

$\Delta E_{\text{pot}}(r_1 \rightarrow r_2)$ work done to bring a unit mass from r_1 to r_2 in the conservative gravitation field.

$$\Delta E_{\text{pot}}(r_1 \rightarrow r_2) = \int_{r_1}^{r_2} F dr = \mu \int_{r_1}^{r_2} \frac{dr}{r^2} = \mu \left(\frac{1}{r_1} - \frac{1}{r_2} \right)$$

Kinetic energy of a spacecraft

Kinetic energy of a spacecraft of mass m



$$E_{\text{kin}} = \frac{1}{2}mv^2 \quad \rightarrow \quad \boxed{E_{\text{kin}} = \frac{1}{2}v^2}$$

In the rest of the course, E_{kin} will always be understood per unit mass.

Conservation laws (i.e. invariants)

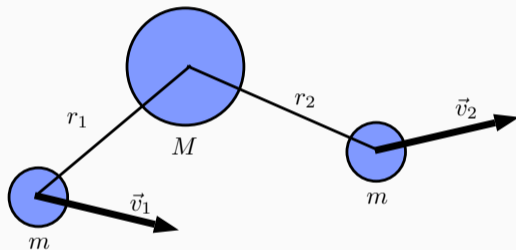
- **Conservation of momentum** for translations in an isolated system (i.e. absence of forces)
- **Conservation of angular momentum** for rotations in an isolated system (i.e. absence of torques)

$$\vec{h} = \sum_{i=1}^N \vec{r}_i \times \vec{p}_i = \sum_{i=1}^N \vec{r}_i(t) \times \dot{\vec{r}}_i(t) = \text{constant}$$

- **Conservation of mechanical energy**
Mechanical energy is the sum of potential and kinetic energies, and is conserved in a conservative force field (a gravitational force field is conservative in the absence of dissipative forces)

Conservation of mechanical energy

Conservation of mechanical energy in a gravitational field ($m \ll M$)



$$E_{\text{tot}} = \text{constant} = E_{\text{pot},1} + E_{\text{kin},1} = E_{\text{pot},2} + E_{\text{kin},2}$$

Energies are typically expressed in joules :
1 joule (J) = $1 \text{ kg m}^2\text{s}^{-2} = 2.78 \times 10^{-7} \text{ kWh}$

Example of conservation of energy

Assume that we track a satellite in Earth's at a distance from the centre of the Earth of $r_1 = 15\,000$ km at a velocity of $v_1 = 1500$ m/s. The satellite is later found at $r_2 = 10\,000$ km. Determine the velocity v_2 .

Note that $\mu_{\oplus} = 3.986 \times 10^{14} \text{ m}^3\text{s}^{-2}$

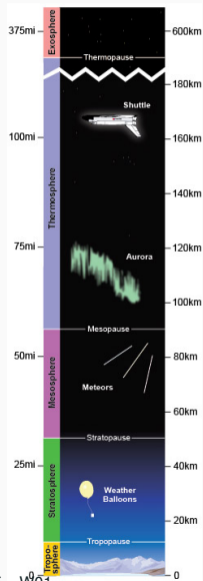
$$E_{\text{tot}} = \frac{1}{2}v_1^2 - \frac{\mu}{r_1} = \frac{1}{2}v_2^2 - \frac{\mu}{r_2} \implies v_2^2 = v_1^2 + 2\mu \left(\frac{1}{r_2} - \frac{1}{r_1} \right)$$

So, $v_2 \approx 5.4$ km/s

Careful with r ! Distance from the centre of the Earth is $r = R_{\oplus} + z$ so Earth's radius plus altitude z .

Earth's atmosphere and magnetic field

Layers of the atmosphere



- **Exosphere**, 600 – 10,000 km. Molecules are gravitationally bound to the Earth.
- **Thermosphere**, 85 – 600 km. This is the upper atmosphere. High energy ultraviolet and x-ray radiation from the sun is absorbed by the molecules causes a large temperature increase.
- **Mesosphere**, 50 – 85 km. The density is high enough to slows down passing objects.
- **Stratosphere**, 6 – 20 to 50 km. Heat is created by the absorption of the Sun's UV radiation.
- **Troposphere**, from surface to ~ 20 km at the equator and 6 km at the poles. Contains $\sim 80\%$ of the atmosphere's mass and is where weather occurs.

Image credits: NOAA

Chemical composition of the atmosphere

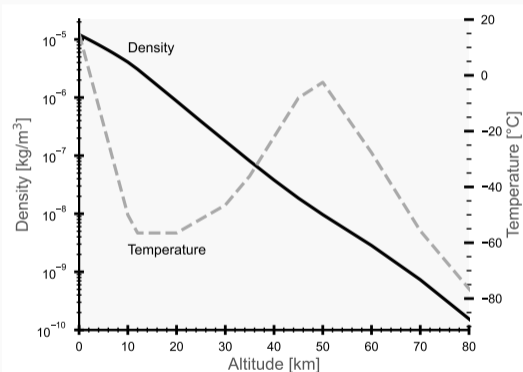
Valid at altitudes \lesssim 80-100 km:

| Gas | Symbol | Content |
|----------------------------|-----------------|---------------------|
| Nitrogen | N ₂ | 78% |
| Oxygen | O ₂ | 21% |
| Argon | Ar | 1% |
| Carbon dioxide | CO ₂ | 429 ppm (June 2025) |
| Neon, helium, methane, ... | | |

It does not include water vapour, which varies between \sim 0 to 4% of the volume. There are constant variations in the composition. Observatories are monitoring the trends (e.g. NOAA Global Monitoring Lab).

Atomic oxygen is the most abundant element between 200-500 km, which is very reactive. Beyond: helium, hydrogen.

Slow transition to vacuum



Atmosphere model: US Std Atmosphere 1976

The density goes down with the altitude: every time the altitude increases by 5.5 km, the density is approximately divided by 2.

The temperature decreases, all the way to the tropopause, to about -55 °C.

Then the temperature remains constant in value until the formation of ozone at 30-50 km altitude, where it increases.

Transparency windows in the atmosphere

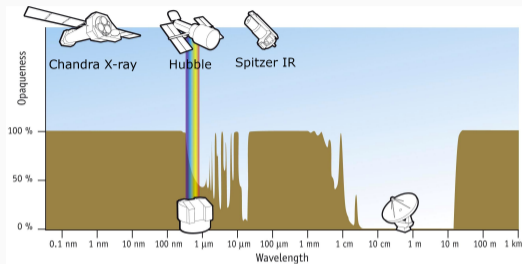


Image credits: ESA

The atmosphere is opaque to radiations except a window in the visible part of the spectrum, around 0.5 microns, or 5,000 angstroms. Telescopes on the ground observe and study objects in the sky in this visible light window.

There is also a large radio window, for radio telescopes studying objects in the large wavelength range, from about 1 cm to 10 m wavelength.

Celestial objects emitting in ultraviolet, X-ray, gamma ray and infrared can be observed only from space with facilities like the Chandra X Ray Observatory and Infrared Spitzer and Webb telescopes.

The atmosphere and the sky from Low Earth Orbit (LEO)



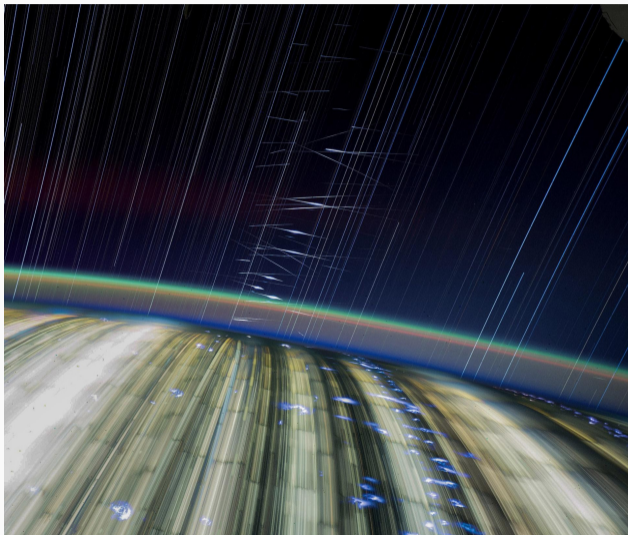
The thickness of the atmosphere corresponds to the thin golden line on the picture (credit NASA)

During the orbital day in LEO, when the Sun is above the horizon, the sky is essentially black: Some of the brightest planets and stars may be visible in the sky.

As soon as the Sun sets, within a very short time, typically ~ 20 stars and planets become visible.

The thin golden line is the airglow at about 100 km altitude. The airglow is due to photoionization of the oxygen atom and de excitation which produces a luminescence. The airglow is mainly due to sunlight exciting oxygen, somewhat also to nitrogen and radical OH.

Another view from the ISS



Same view but on a long exposure. White trails are satellites passing in front of the International Space Station (ISS). Mostly Starlinks.

Credits: D. Pettit/NASA 2025, @astro_Pettit

Microgravity in a Low earth Orbit (LEO)

Microgravity is the term used to characterize the very low acceleration level encountered inside an orbiting spacecraft in LEO (typically $10^{-6}g_0$ at 300 km altitude).

An object in microgravity is following a slightly perturbed free-fall trajectory.

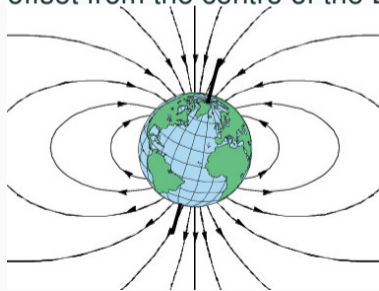
It is not zero-g or weightlessness but there are always perturbing forces acting on this object.

The largest perturbing force, when in low orbit around the Earth, is the atmospheric drag. There are other perturbing factors, like the solar radiation pressure, the flux of particles of the solar wind, that would cause a slight deviation from a pure zero-g condition, even for very high altitude.

The geomagnetic field – magnetic dipole model

The amplitude of the magnetic field is a function of the distance to the centre of the Earth and the magnetic latitude (zero degrees at the Equator, +90 at the North Magnetic Pole, and -90 at the South Magnetic Pole).

Close to the surface, the geomagnetic field is essentially a bipolar field slightly offset from the centre of the Earth.

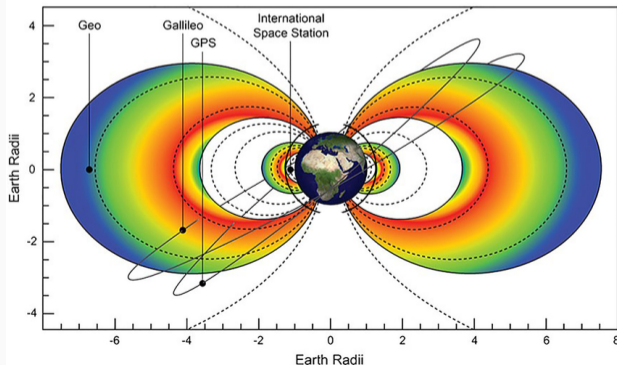


$B_0 = 0.30 \text{ gauss} = 3.12 \times 10^{-5} \text{ Tesla}$ at the surface and on the Equator.

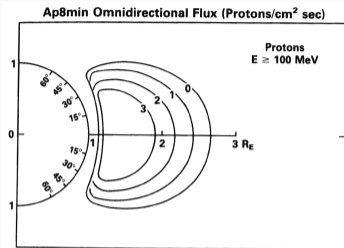
The geomagnetic field and radiations belts

The magnetic field of the Earth is creating some regions with an increased density of charged particles, mainly protons and electrons : the (respectively) inner and outer radiation belts, also known as the Van Allen belt. Charged particles are trapped in these regions.

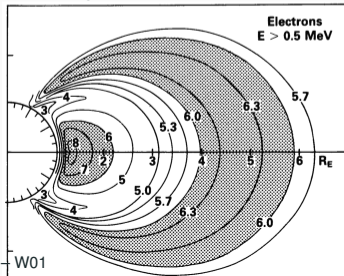
The lower boundary of the inner radiation belt is about 550 to 600 km above the Earth's surface. The International Space Station at an average altitude of 400 km is not located in the radiation belt. Highest Starlink SATCOMs are at the lower boundary of the inner radiation belt.



Radiation (or van Allen) Belts



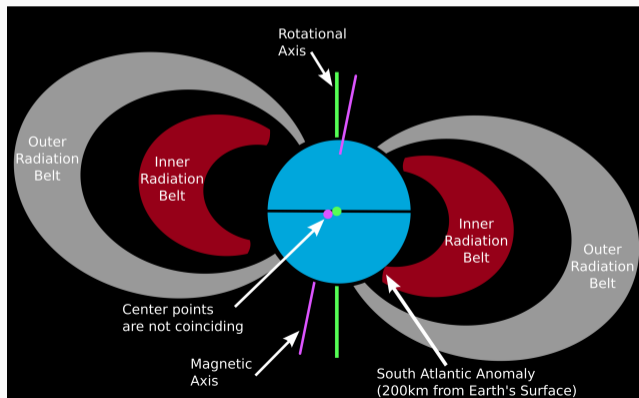
units: \log_{10} omnidirectional
particle flux/cm²s



- High energy protons and electrons trapped in two regions of the magnetosphere.
- Protons and electrons in the inner belt, electrons only in the outer belt.
- Energy of belt particles is bigger than 30 keV , up to 100 MeV.
- The outer radiation belt is not as harmful to electronic systems as the inner radiation belt.

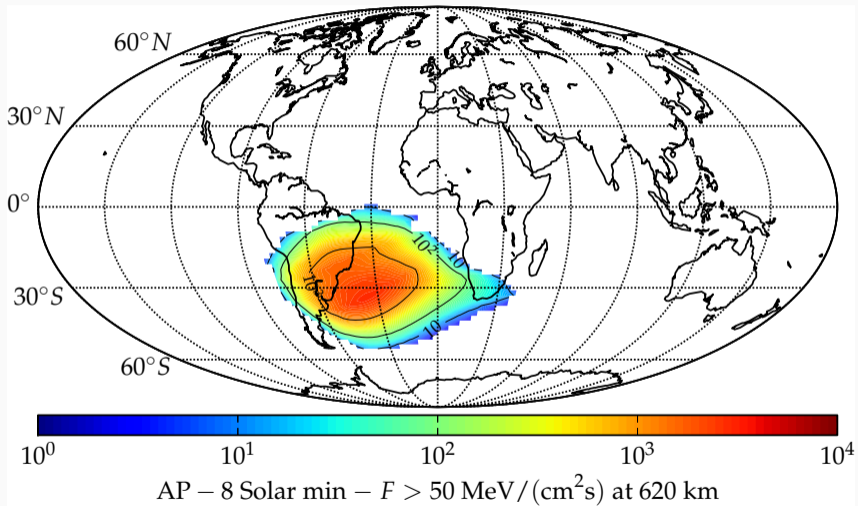
The South Atlantic Anomaly (SAA)

The SAA is a region where the inner Van Allen radiation belt reaches down to ~ 200 km altitude, posing a danger to spacecraft in LEO. Centered off the coast of Brazil, the anomaly is caused by the fact that the Earth's dipole is off-axis from its rotation axis.



Credits: Wikipedia, unknown user

Proton flux at 620 km altitude at solar minimum



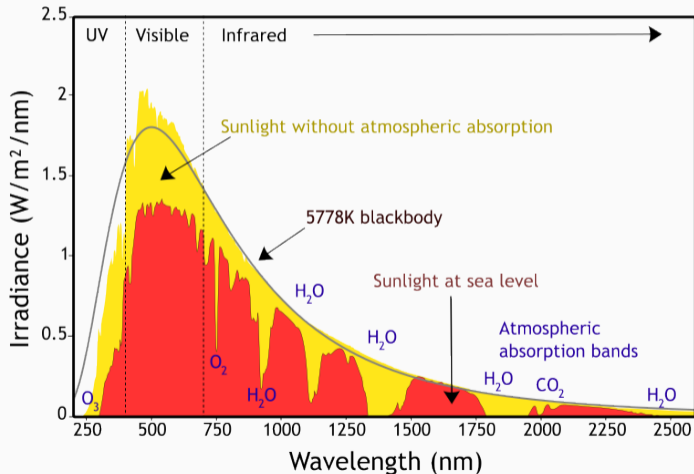
Radiation effects on spacecraft systems

- Single event effects (SEE)
 - High energy particle traveling through a semiconductor leaves an ionised track behind.
 - May cause a highly localised effect.
- Single Event Upset (SEU) is a change of state caused by one single ionizing particle → bit flip → reboot
- Single Event Latchup (SEL) is a short circuit → lost it
- Measurements taken during solar storms or passes through the SAA will have more noise → is it acceptable for the mission?

Solar radiation on Earth and in the solar system & energy budget

Solar irradiance spectrum

Spectrum of Solar Radiation (Earth)



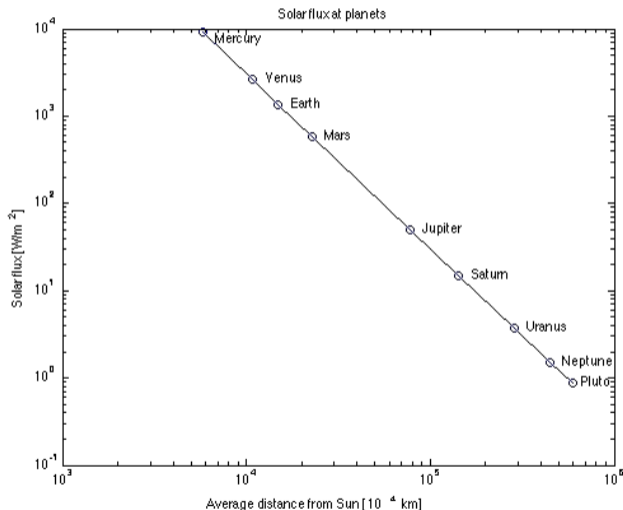
Credits: Wikipedia, prepared by Robert A. Rohde

Solar irradiance or flux in the solar system

$$\text{Solar flux} \approx 1368 \text{ W/m}^2 \frac{R_{\oplus}^2}{R_{\text{planet}}^2}$$

Remember that \oplus is the symbol for Earth.

The value of the solar irradiance at the top of the atmosphere is not constant.



Variation of the solar irradiance because of Earth's orbit

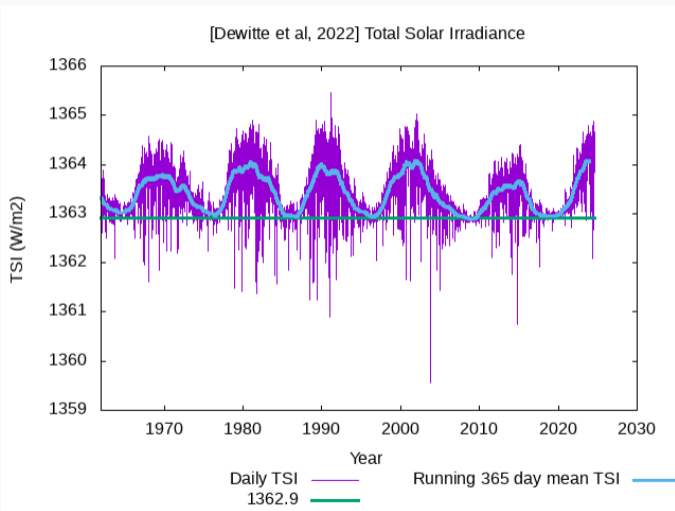
- This is not a physical constant !
- The variation of the earth-sun distance causes a $\pm 4\%$ seasonal variation because of the (small) eccentricity of Earth's orbit.

| | | |
|---------|-------------------------|-----|
| Nominal | 1367.5 W/m ² | |
| Winter | 1422.0 W/m ² | +4% |
| Summer | 1318.0 W/m ² | -4% |

Seasons for the northern hemisphere

Variation of the solar irradiance at the top of the atmosphere

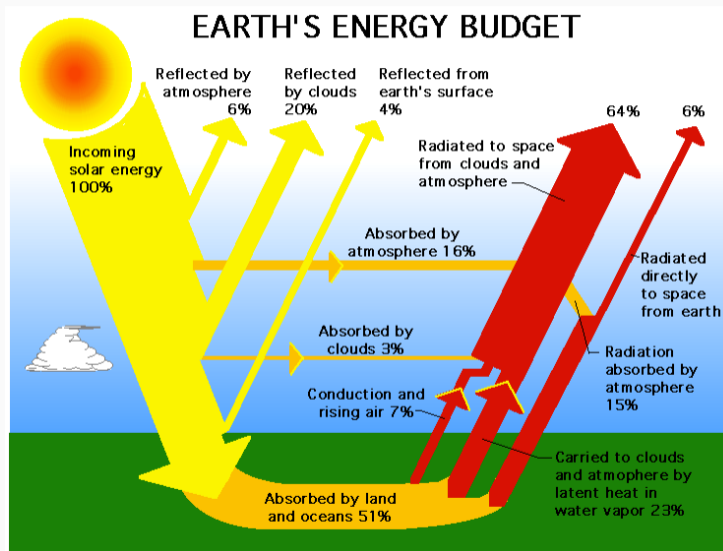
- The accuracy of the solar "constant" S is $\pm 0.5\%$
→ World Radiation Center in Davos Switzerland, the Solar uses 1362 W/m^2 (difference of $< 0.3\%$).
- Total solar irradiance normalised at $R_{\oplus} = 1 \text{ AU}$ is varying because of the effect of sunspots in magnetically active regions in the Sun.



UltraViolet (UV) light. . .

- is electromagnetic radiation with wavelength shorter than that of visible light, but longer than X-rays, in the range 10 nm to 400 nm.
- has been shown to significantly increase solar absorptivity α for some thermal control materials and coatings. For white paint α changes between 0.2 to 0.4 in ~ 3 years.
- results in a degradation of the performance of solar arrays
- causes ionization and can result in local electrical discharges

Earth's energy budget

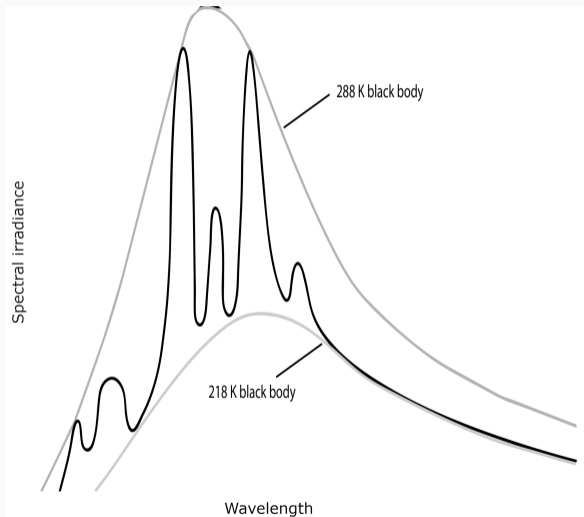


Credits: NASA

Spectral irradiance of planet Earth (general shape)

Two components of Earth's irradiance

- Irradiance from the stratosphere, approximately a blackbody radiation corresponding to a temperature of about $218\text{K} = -55^\circ\text{C}$.
- Irradiance from the Earth's surface, approximately a blackbody radiation corresponding to a temperature of about $288\text{K} = +15^\circ\text{C}$, but only visible through the wavelength bands for which the atmosphere is transparent.

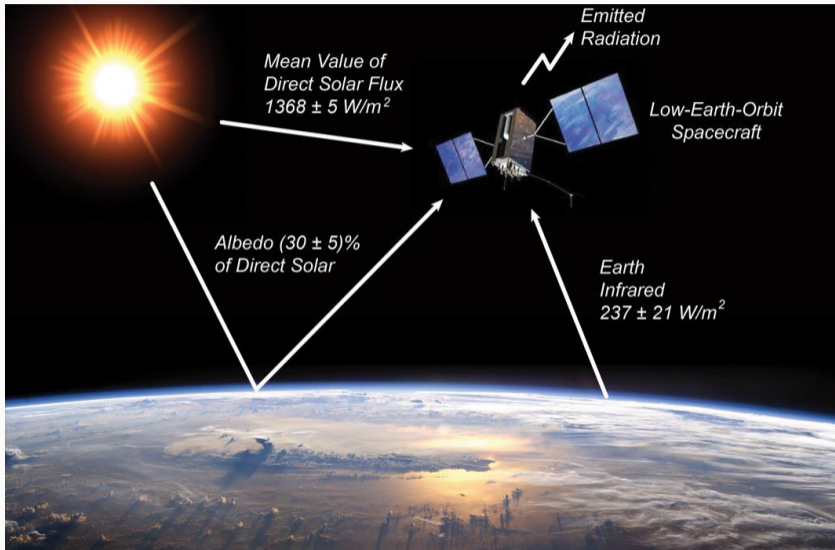


Solar flux and albedo of the planets

| Planet | Mean distance from Sun (10^6 km) | Mean Solar flux (W/m^2) | Relative mass (Earth = 1) | Planetary albedo |
|---------|-------------------------------------|------------------------------------|---------------------------|------------------|
| Mercury | 58 | 9114 | 0.055 | 0.12 |
| Venus | 108 | 2619 | 0.815 | 0.59 |
| Earth | 150 | 1368 | 1.000 | 0.30 |
| Mars | 228 | 589 | 0.107 | 0.29 |
| Jupiter | 778 | 50 | 318.0 | 0.34 |
| Saturn | 1430 | 15 | 95.1 | 0.34 |
| Uranus | 2870 | 3.7 | 14.5 | 0.34 |
| Neptune | 4500 | 1.5 | 17.2 | 0.28 |

Albedo is the diffuse reflectivity or reflecting power of a surface measured from zero for no reflecting power of a perfectly black surface, to 1 for perfect reflection.

Energy budget for a satellite in Earth's orbit



Credits: NASA

Radiation balance for a satellite or spacecraft exposed to solar and other radiation sources:

$$P_a = P_e$$

where

- P_a is the absorbed radiative power
- P_e is the emitted radiative power

Stefan-Boltzmann law

The law relates the amount of radiation emitted by a black object to its temperature:

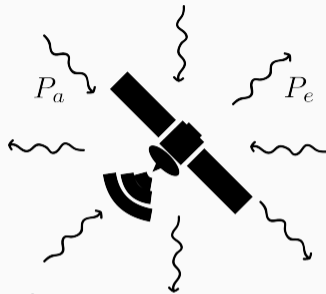
$$P_e = \sigma T^4$$

per unit surface

where

- P_e is the total amount of radiation emitted by an object per surface (W/m^2)
- $\sigma = 5.67 \times 10^{-8} \frac{\text{W}}{\text{m}^2\text{K}^4}$ is the Stefan-Boltzmann constant
- T is the temperature of the object (K)

Radiation balance with the Sun as the only incident radiation source



$$P_a = \alpha SA_n$$

$$P_e = \epsilon \sigma T^4 A_{\text{tot}}$$

where

- α is the solar absorptivity
- ϵ is the IR emissivity
- S the total irradiance of the Sun, integrated over all wavelengths (aka “solar constant”)
- A_n is the surface perpendicular to sunlight
- A_{tot} is the total surface of the object

$$\begin{aligned} T &= \left(\frac{\alpha SA_n}{\epsilon \sigma A_{\text{tot}}} \right)^{\frac{1}{4}} \\ &= \left(\frac{\alpha}{\epsilon} \right)^{\frac{1}{4}} \times \left(\frac{SA_n}{\sigma A_{\text{tot}}} \right)^{\frac{1}{4}} \end{aligned}$$

The importance of the factor $\frac{\alpha}{\epsilon}$ is clear, and its influence on the external temperature of a spacecraft has to be considered in the design.

Radiation balance for a spacecraft :

$$P_a + Q_{in} = P_e + Q_{out}$$

where

- P_a is the absorbed radiative power
- Q_{in} is the self generated power (heat loss from electric or electronic systems for instance)
- P_e is the emitted radiative power
- Q_{out} is the power of heat sinks

Properties of materials

| No. | Material | Measurement Temperature [K] | Surface condition | Solar absorptivity α | Infrared emissivity ϵ | Absorptivity /emissivity ratio | Equilibrium Temperature [°C] |
|-----|--------------------|-----------------------------|-------------------|-----------------------------|--------------------------------|--------------------------------|------------------------------|
| 1 | Aluminum (6061-T6) | 294 | As Received | 0.379 | 0.0346 | 10.95 | 443 |
| 2 | Aluminum (6061-T6) | 422 | As Received | 0.379 | 0.0393 | 9.64 | 421 |
| 3 | Aluminum (6061-T6) | 294 | Polished | 0.2 | 0.031 | 6.45 | 354 |
| 4 | Aluminum (6061-T6) | 422 | Polished | 0.2 | 0.034 | 5.88 | 340 |
| 5 | Gold | 294 | As Rolled | 0.299 | 0.023 | 13 | 475 |
| 6 | Steel (AM 350) | 294 | As Received | 0.567 | 0.267 | 2.12 | 202 |
| 7 | Steel (AM 350) | 422 | As Received | 0.567 | 0.317 | 1.79 | 182 |
| 8 | Steel (AM 350) | 611 | As Received | 0.567 | 0.353 | 1.61 | 170 |
| 9 | Steel (AM 350) | 811 | As Received | 0.567 | 0.375 | 1.51 | 163 |
| 10 | Steel (AM 350) | 294 | Polished | 0.357 | 0.095 | 3.76 | 275 |
| 11 | Steel (AM 350) | 422 | Polished | 0.357 | 0.111 | 3.22 | 254 |
| 12 | Steel (AM 350) | 611 | Polished | 0.357 | 0.135 | 2.64 | 229 |
| 13 | Steel (AM 350) | 811 | Polished | 0.357 | 0.155 | 2.30 | 212 |
| 14 | Titanium (6AL-4V) | 294 | As Received | 0.766 | 0.472 | 1.62 | 171 |
| 15 | Titanium (6AL-4V) | 422 | As Received | 0.766 | 0.513 | 1.49 | 162 |
| 16 | Titanium (6AL-4V) | 294 | Polished | 0.448 | 0.129 | 3.47 | 264 |
| 17 | Titanium (6AL-4V) | 422 | Polished | 0.448 | 0.148 | 3.03 | 246 |
| 18 | White Enamel | 294 | Al.Substrate | 0.252 | 0.853 | 0.30 | 18 |
| 19 | White Epoxy | 294 | Al.Substrate | 0.248 | 0.924 | 0.27 | 10 |
| 20 | White Epoxy | 422 | Al.Substrate | 0.248 | 0.888 | 0.28 | 13 |

Equilibrium temperature T is given per ratio of $(A_n/A_{tot})^{(1/4)}$.

Design strategies to take into account the characteristics of the space environment

- Conducting surface on the spacecraft to avoid local voltage deltas and possible resulting electrical discharges.
- Hardening of electronic components.
- Proper choice of the $\frac{\alpha}{\epsilon}$ ratio for exposed surfaces.

→ EchoPoll platform

- You can scan a QR code or go to the link
- EchoPoll is the EPFL-recommended solution
- You do not have to register, just skip entering a username and/or email address