EE-585 – Space Mission Design and Operations

Dr Thibault Kuntzer

Ecole Polytechnique Fédérale de Lausanne

Week 01 – 13 Sep 2024

Today's outline

Course Admin

Course outline

Why do we go to space?

$\rightarrow$ Space News

Newton's laws, inertial frames and notions of energy

Earth's atmosphere and magnetic field

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

Course Admin

Your lecturer: Thibault Kuntzer

- 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
  - Event analysis
  - Space Situational Awareness Innovation
  - Technology and capability monitoring

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

Course programme 1/2

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 $\rightarrow$ there will be 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 $\rightarrow$ do participate!

Course programme 2/2

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 four 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:
    - Elisabeth Rachith, PhD student LASTRO EPFL
    - Jonathan Magnin, PhD student Telecommunications Circuits Laboratory EPFL

The exams...

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

Orbital mechanics

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 inlcudes black holes, dark matter, big bang and other phenomena (like tides and relativistics mechanics).

Moodle – Course resources

- http://moodle.epfl.ch $\rightarrow$ EE-585
- Enrolling password : welcomeinspace
- Course slides 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) $\rightarrow$ 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 last year.
- Watching the MOOC is not mandatory, this course is self-sufficient.
- There are 8 units, available in self-paced mode.
- Caution: the free version closes on 25 Sep 2024.
- The MOOC content is similar to this course, but there are variations. Do not expect a copy/paste in the lectures here!
- (Volontary) enrollement → 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

Course outline

Course outline (1/3) *Subject to changes!*

Week	Focus	Subjects
01 – 13 Sep	Why space?, near-Earth environment	• 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 – 20 Sep	Introduction to orbital mechanics	• Gravitational well • Escape velocity • Reference frames and calendars • The two body problem and Kepler's laws • Orbital motion
03 – 27 Sep	Orbital classes	• 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 – 04 Oct	Spacecraft dynamics	• Orbital manoeuvres (Hohmann, small Δv in LEO, plane change) • Complex manoeuvres & Lambert's problem • Orbit determination • Launch and early orbit phase, positioning and station-keeping

Course outline (2/3) *Subject to changes!*

Week	Focus	Subjects
05 – 11 Oct	Exercise session	• Exercise session 1
06 – 18 Oct	Spacecraft interaction, object population in Earth's orbit	• Phasing • Rendezvous, proximity operations and docking (RPOD) and relative motion • The resident space object population and the debris problem • Collision probability and avoidance manoeuvres • Active Debris Removal, intersatellite links, motivation for RPO(D)
— – 25 Oct	*No lectures – holidays*	–
07 – 01 Nov	Exercise session	• Exercise session 2
08 – 08 Nov	Interplanetary trajectories	• The deep space environment • Near Earth Objects • Sphere of influence • Interplanetary trajectories
09 – 15 Nov	Interplanetary trajectories, spacecraft propulsion	• Slingshots and aerobraking • Lunar trajectories • Propulsion systems • Non-impulsive manoeuvres

Course outline (3/3) *Subject to changes!*

Week	Focus	Subjects
10 – 22 Nov	Exercise session	• Exercise session 3
11 – 29 Nov	Launch, critical subsystems	• Attitude control • Power generation • Launch (constraints on S/C and orbit, window), re-entries • Advanced concepts (low energy trajectories, elevators, tethered deployment) (TBC)
12 – 06 Dec	Constellations, trends in operations	• Revisit time, spacecraft constellations and mega-constellations • Major governmental and commercial actors in space • In-orbit services • Spacecraft concept of operations (mission planning, execution, personnel, infrastructures, products)
13 – 13 Dec	Human spaceflight	• Guest lecture by astronaut Claude Nicollier
14 – 20 Dec	Exercise session	• Exercise session 4

Why do we go to space?

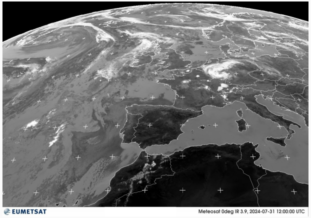
→ Space News

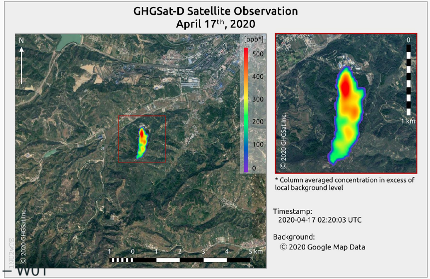
Motivations and applications

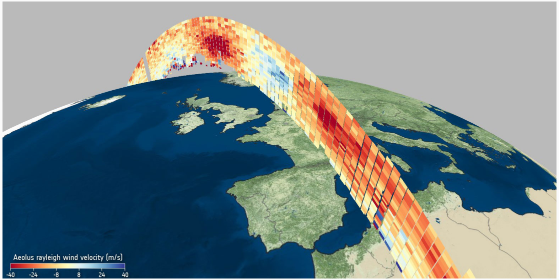
- Earth & atmosphere observation
- Communications
- Navigation
- Science/research/exploration
- Technology demonstration
- Space race/prestige
- Tourism
- Space-oriented applications (“space for space”)

Earth & atmospheric observation

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

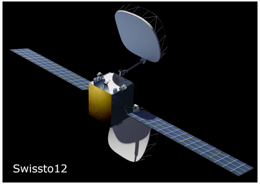


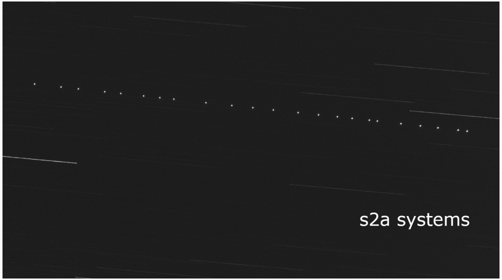




Communications

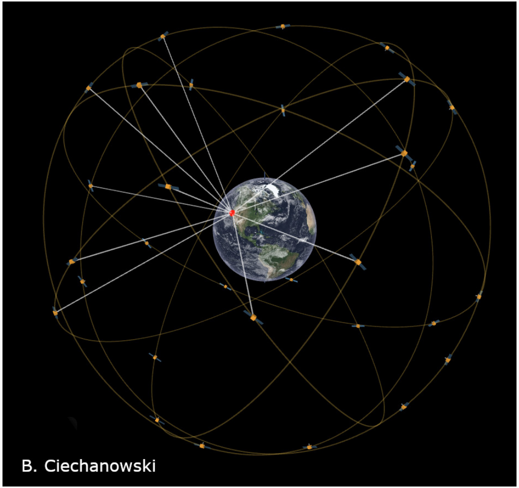
- Largest commercial motivation
- 2-way Communications: voice, IoT, data
- 1–way broadcasting: radio, TV
- Great diversity of shape, size and orbits
- Starlink: $\sim$ 7000 satellites launched





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)



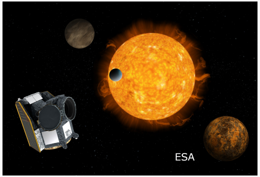
Science / research / exploration

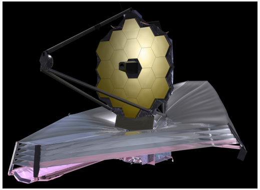
General disciplines

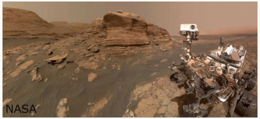
- Astrophysics
- Solar physics
- Space weather
- Fundamental physics
- Earth science

In addition, onboard space stations

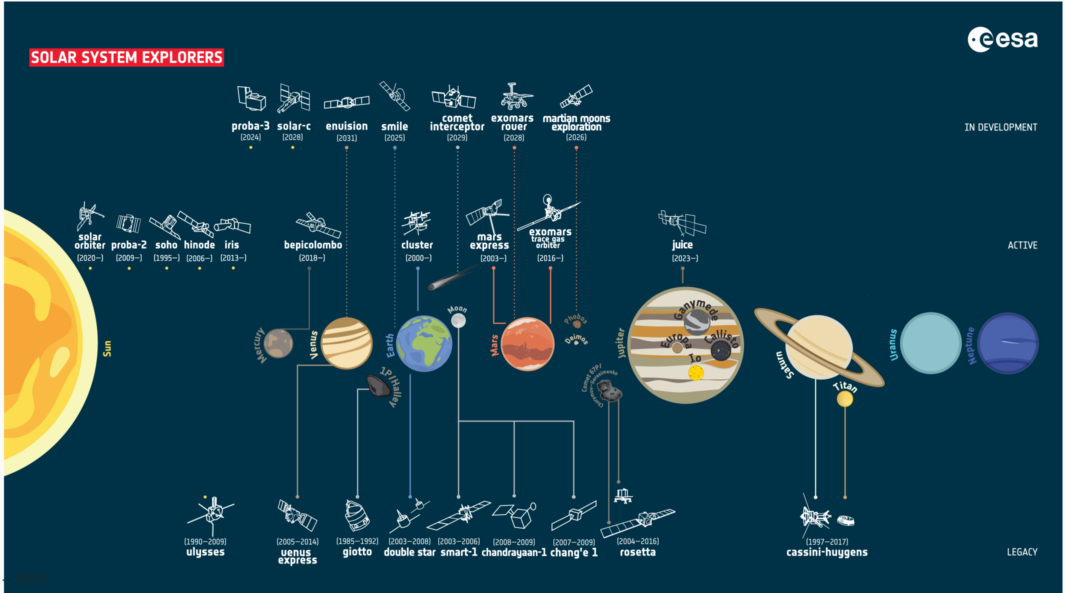
- Biology
- Plant growth
- Physiology
- Material and fluid physics





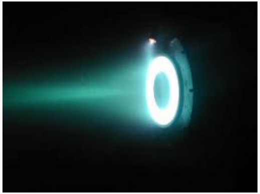


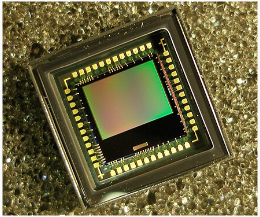
ESA's science fleet of Solar System explorers

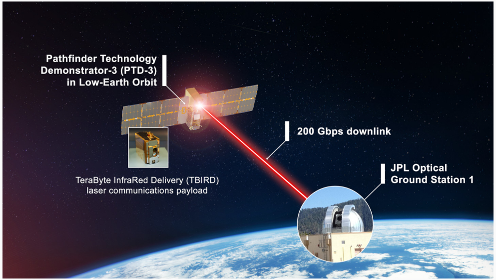


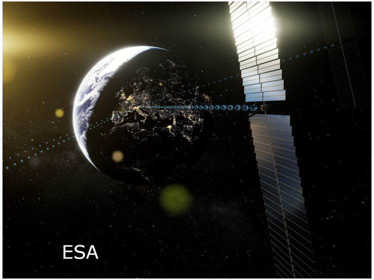
Technology demonstration

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









What a view!

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

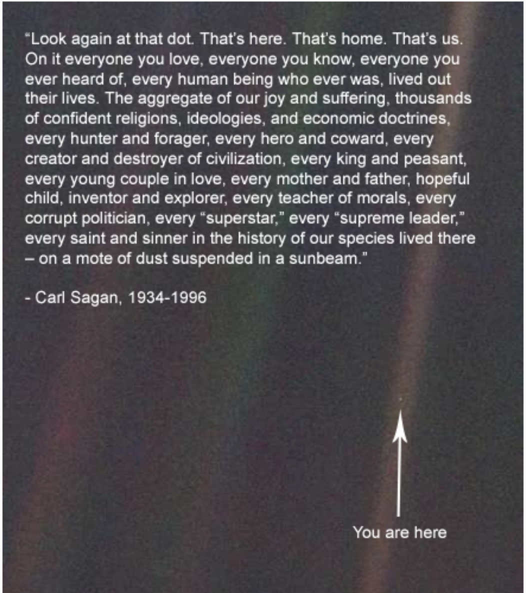
Taken by astronaut William Anders on 24 Dec 1968, during the Apollo 8 mission.

Space & Art: The First Artwork Created in Space

Credits: Museum of the Yuri Gagarin Cosmonaut Training Center.

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

Pale Blue Dot picture

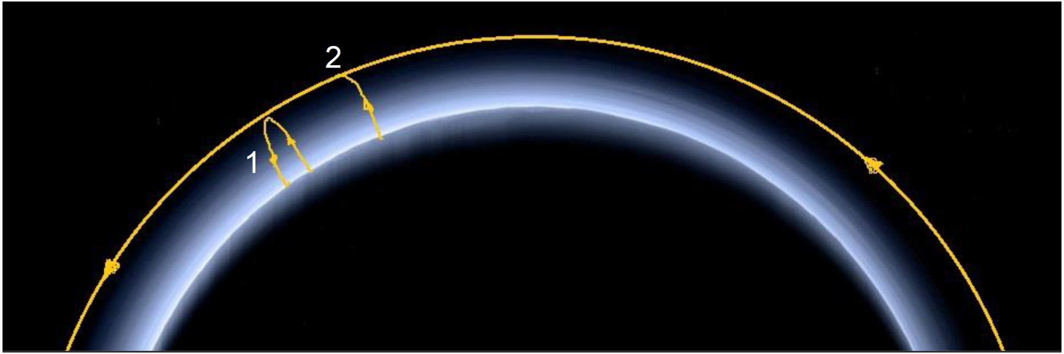


Pale Blue Dot is a photograph of Earth taken on 14 Feb 1990, by the Voyager 1 spacecraft from a distance of approximately 6 billion kilometers (40.5 AU).

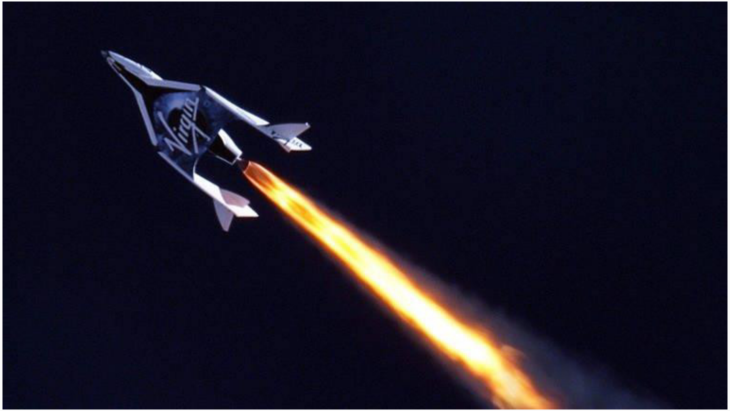
Space tourism

There are two options at the moment:

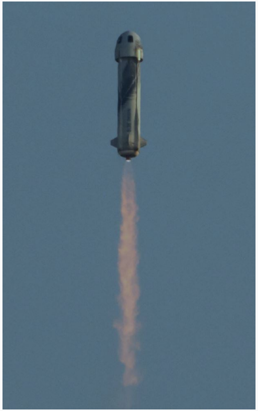
1. Suborbital less than 2 hours, “cheap”
2. Orbital days or weeks, expensive
3. (soon?) Lunar projects?



Two companies are currently offering option 1 (suborbital)



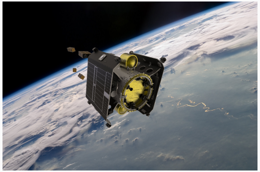
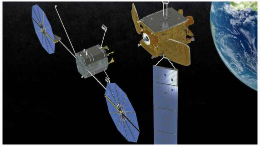
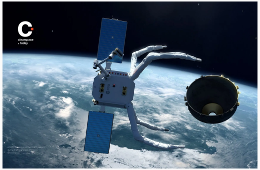
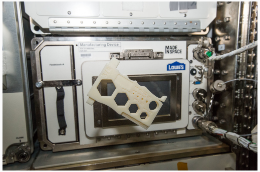
Virgin Galactic
(Richard Branson)



Blue Origin
(Jeff Bezos)

In-orbit services

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

Newton’s laws, inertial frames and notions of 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 $\vec{p}$:

$$\vec{F} = \frac{\mathrm{d}\vec{p}}{\mathrm{d}t} = \dot{p}$$

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).

Inertial frame

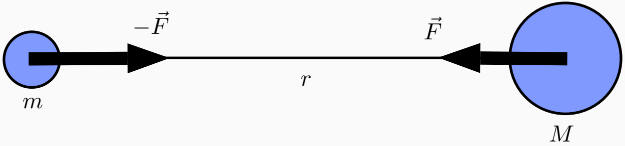
- An inertial frame is a frame with respect to which Newton's laws of motion are valid. The inertial frame should be under zero acceleration.
- A good approximation of an inertial frame has its axes fixed on distant stars with essentially zero motion on the celestial sphere.
- The centre of the inertial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

Validity of Newton's laws

- 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).

$\Longrightarrow$ Newton's laws are (mostly) valid to describe the motion of celestial bodies and spacecraft.

Newton's law of universal gravitation

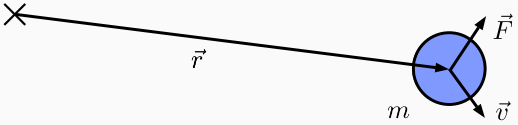


$$\vec{F} = G\frac{Mm}{||\vec{r}||^3}\vec{r} \implies \boxed{F = G\frac{Mm}{r^2} = \frac{\mu m}{r^2}}$$

where

- M is the mass of the largest body
- m is the mass of the spacecraft
- G is the gravitational constant, $G = 6.673 \times 10^{-11}\ \mathrm{m^3kg^{-1}s^{-2}}$
- $\mu = GM$ 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 $\vec{h}$ (or $\vec{L}$) for a solid body with a rotation axis Δ:

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

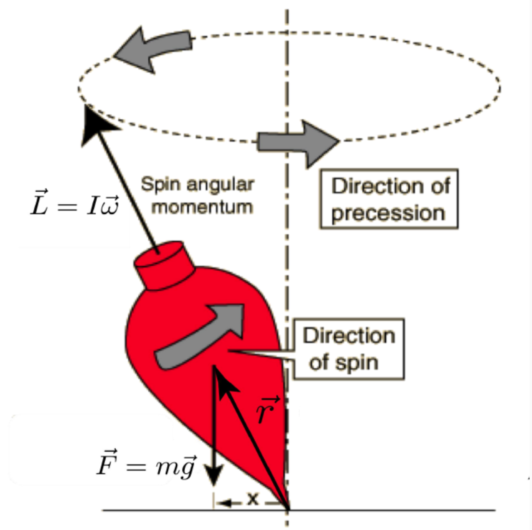
where

- $\vec{\omega}$ 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

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

Precession of a spinning top



Credits: Adapted from Georgia State University Departement of Physics and Astronomy, Hyperphysics, “Larmor precession“

Gravitational torque

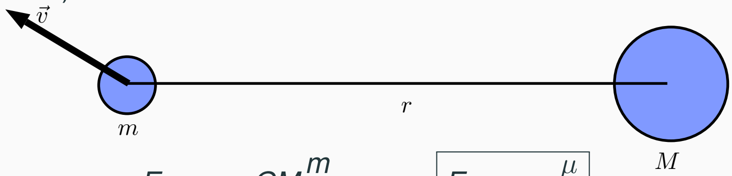
$$\vec{r} \times \vec{F}$$

produces (axial) precession and nutation.

Earth’s orientation of the rotation axis precesses with a period of ∼26,000 years.

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)



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

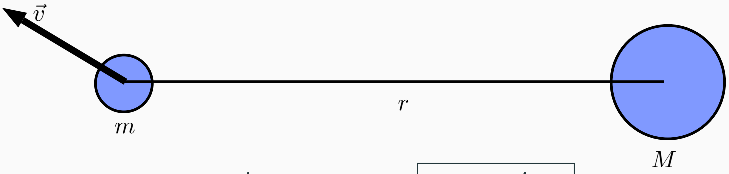
In the rest of the course, E_{pot} will always be understood per unit mass.

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

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

Kinetic energy of a spacecraft

Kinetic energy of a spacecraft of mass *m*



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

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)

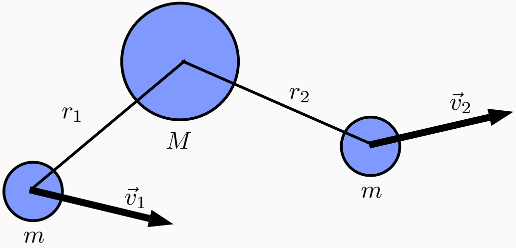
- **Conservation of angular momentum** for rotations in an isolated system (i.e. absence of torques)

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

- **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 kg $m^2 s^{-2} = 2.78 \times 10^{-7}$ 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 $\mu_\oplus = 3.986 \times 10^{14}$ m^{3}s^{-2}

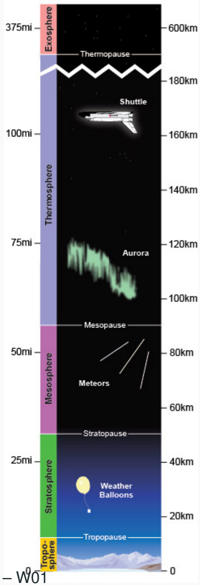
$$E_{\text{tot}} = \frac{1}{2}v_1^2 - \frac{\mu}{r_1} = \frac{1}{2}v_2^2 - \frac{\mu}{r_2} \implies v_2^2 = v_1^2 + 2\mu\left(\frac{1}{r_2} - \frac{1}{r_1}\right)$$

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 ∼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	427 ppm (June 2024)
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.

Variation in pressure and temperature with altitude

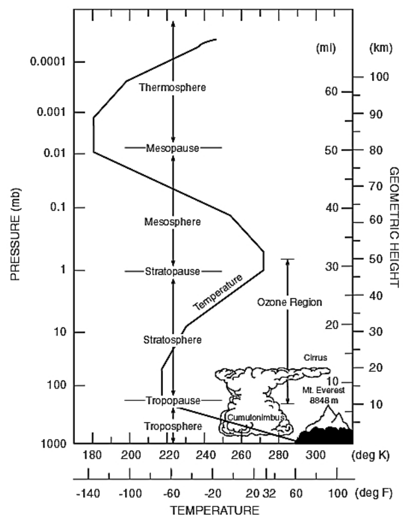


Image credits: Oxford University Press , 1999

On the ground, the standard pressure is 1013 mb (or hectopascal or hPa) with a temperature of 288 K or 15℃, which is the average temperature on the surface of the Earth.

In the first layer of the atmosphere, the troposphere, the temperature decreases with about 6.5℃ per 1000 meters elevation. At the tropopause, approximately, 9 to 15 km above the surface of the Earth, depending on the latitude, the temperature is approximately 218 K, or -55℃.

The temperature increases in the layer 40-50 km altitude due to the formation of ozone. The ozone is created by a dissociation of the oxygen molecule and combination with another oxygen atom to form ozone (O_3).

In the mesosphere, about 50 km altitude, the temperature decreases again. Above 80-90 km altitude, in the thermosphere, the temperature increases because of the ionization of mainly oxygen and some nitrogen atoms.

100 km altitude is the Kármán line, the definition of the limit to space as per the Fédération Aéronautique Internationale (FAI). $\rightarrow$ Height at which the density of the atmosphere is so low that the speed of an aircraft to achieve lift should be comparable to the orbital speed.

Slow transition to vacuum

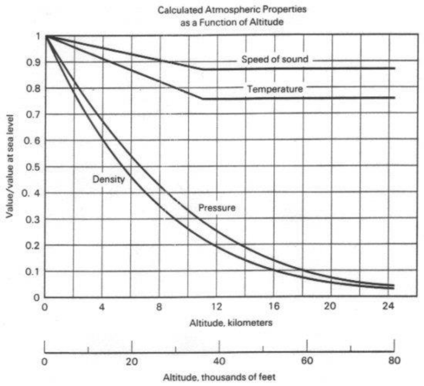


Image credits: Aerospaceweb.org

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

The pressure decreases together with the density. The temperature decreases, all the way to the tropopause, to about -55 ℃.

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

The speed of sound, being directly correlated with temperature follows the same evolution than the temperature and becomes constant when it reaches the tropopause.

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 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.

Transparency windows in the atmosphere

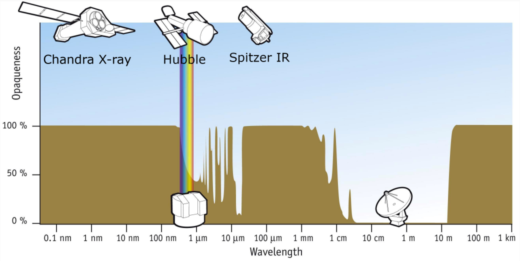


Image credits: ESA

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 20s, stars and planets become visible.

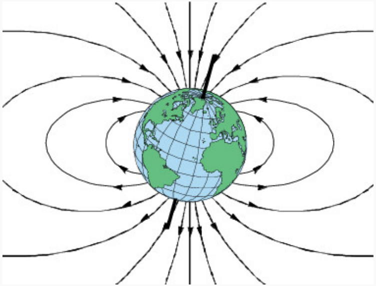
The thin golden line is the airglow at about 100 km altitude. The airglow is due to photoionization of the oxygen atom and de excitation which produces a luminescence. The airglow is mainly due to sunlight exciting oxygen, somewhat also to nitrogen and radical OH.

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.

$$B(R, \lambda) = (1 + 3\sin^2\lambda)^{\frac{1}{2}} \frac{B_0}{R^3}$$



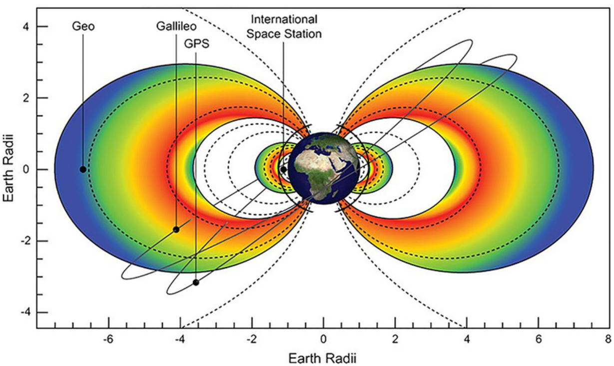
where

- B is the local magnetic field
- λ is the magnetic latitude
- R is the distance to the Earth's centre measured in Earth's radius R_E
- $B_0 = 0.30$ gauss $= 3.12 \times 10^{-5}$ Tesla at the surface and on the Equator.

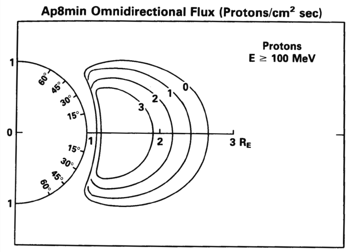
The geomagnetic field and radiations belts

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.

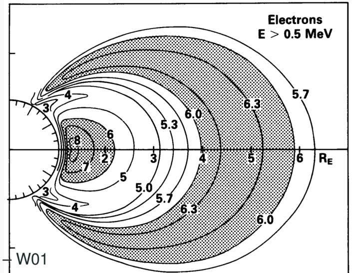
The lower boundary of the inner radiation belt is about 550 to 600 km above the Earth's surface. The International Space Station at an average altitude of 400 km is not located in the radiation belt. Highest Starlink SATCOMs are at the lower boundary of the inner radiation belt.



Radiation (or van Allen) Belts



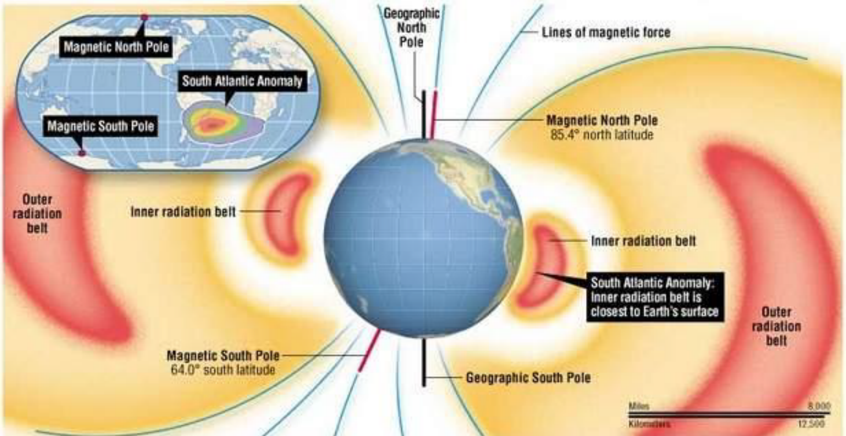
units: $\log_{10}$ omnidirectional particle flux/cm^{2}s



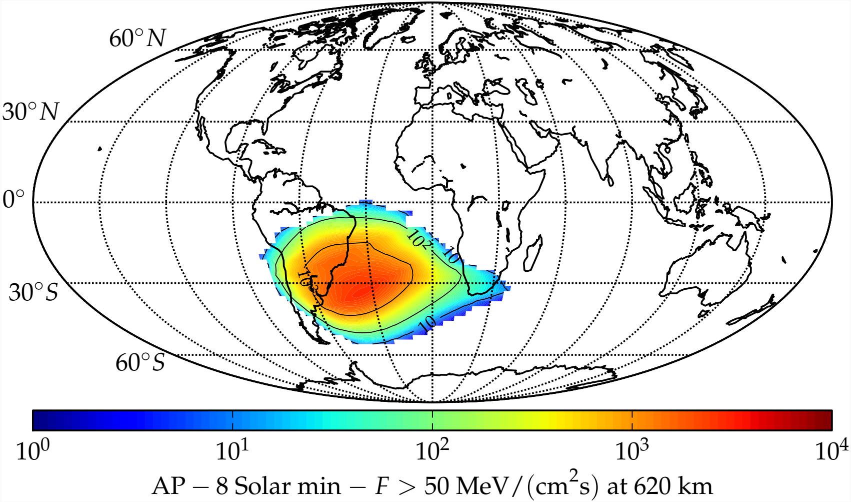
- High energy protons and electrons trapped in two regions of the magnetosphere.
- Protons and electrons in the inner belt, electrons only in the outer belt.
- Energy of belt particles is bigger than 30 keV , up to 100 MeV.
- The outer radiation belt is not as harmful to electronic systems as the inner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

The South Atlantic Anomaly (SAA)

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



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 $\rightarrow$ bit flip $\rightarrow$ reboot
- Single Event Latchup (SEL) is a short circuit $\rightarrow$ lost it
- Measurements taken during solar storms or passes through the SAA will have more noise $\rightarrow$ is it acceptable for the mission?

Physiological effect of radiation and typical doses

- RAD = Radiation Absorbed Dose = Amount of energy absorbed = 0.01 J/kg (100 erg/g)
- REM = Roentgen Equivalent Man = RAD$\times Q$
- Q = quality factor = function of type of radiation

$$
\begin{aligned}
&= 1 \text{ (x-ray, } \gamma \text{ ray, electrons, } \beta) \\
&= 2\text{-}20 \text{ (neutrons)} \\
&= 20 \text{ (alphas)} \\
&> 20 \text{ (iron ions)}
\end{aligned}
$$

- Sievert = Sv = 100 REM.

Effect	Dosage (REM)
Blood count changes	15-20
Vomiting effective threshold	100
Mortality effective threshold	150
LD_{50} with minimal care	320-360
LD_{50} with full medical care	480-540

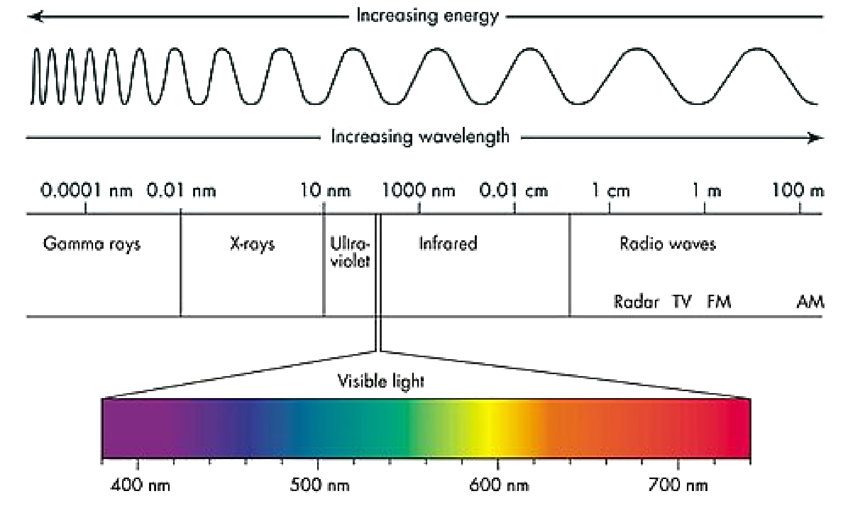
Effective threshold: Lowest dosage causing effects in at least one member of exposed population.

LD_{50}: the lethal dosage in 50% of the exposed population.

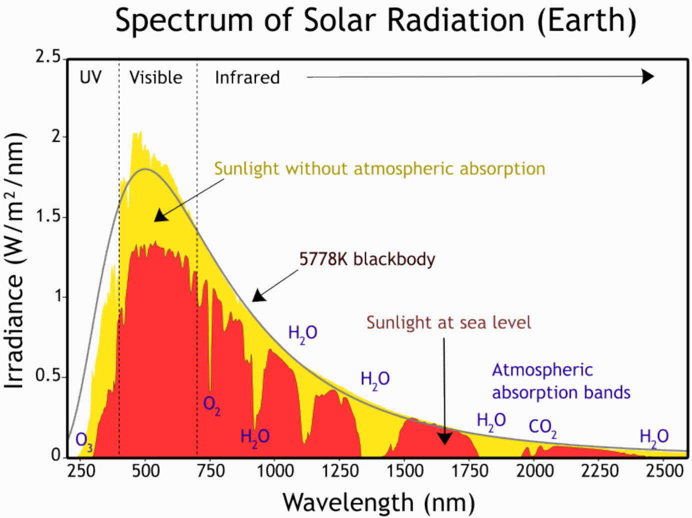
Cause	Dosage (REM)
Transcontinental roundtrip in jet	0.004
Chest X-ray (lung dose)	0.01
Leaving 1 yr in Houster (at sea level)	0.1
Leaving 1 yr in Denver (at 1600 m)	0.2
Skylab 3 for 84 days	17.85
Space shuttle mission (STS-41D)	0.65

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

Electromagnetic spectrum



Solar irradiance spectrum



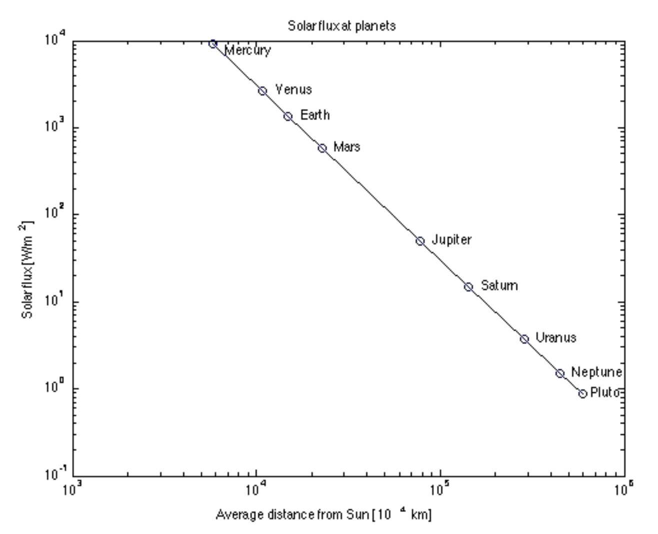
Credits: Wikipedia, prepared by Robert A. Rohde

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 at the top of the atmosphere is not constant.



Variation of the solar irradiance because of Earth's orbit

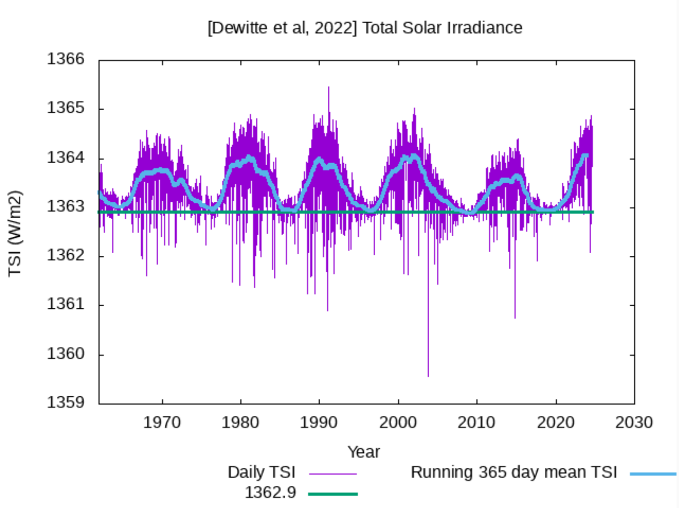
- This is not a physical constant !
- The variation of the earth-sun distance causes a ±4% seasonal variation because of the (small) eccentricity of Earth's orbit.

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

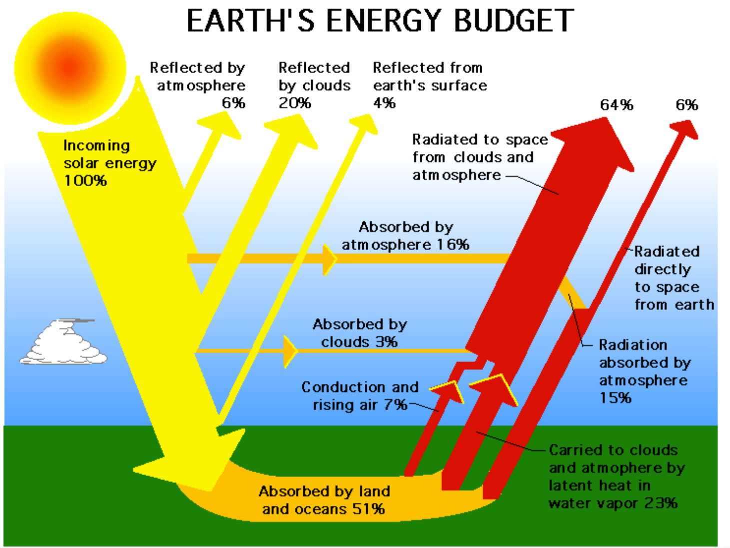


The solar UV radiation

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 $\sim$ 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

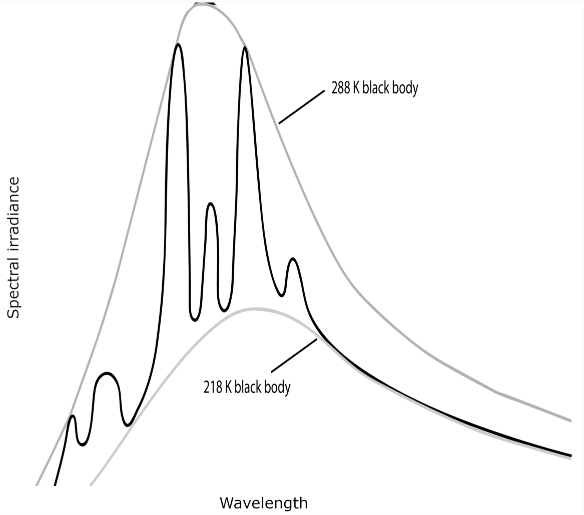


Credits: NASA

Spectral irradiance of planet Earth (general shape, no numbers)

Two components of Earth's irradiance

- Irradiance from the stratosphere, approximatively a blackbody radiation corresponding to a temperature of about 218K = -55℃.
- Irradiance from the Earth's surface, approximately a blackbody radiation corresponding to a temperature of about 288K = +15℃, but only visible through the wavelength bands for which the atmosphere is transparent.

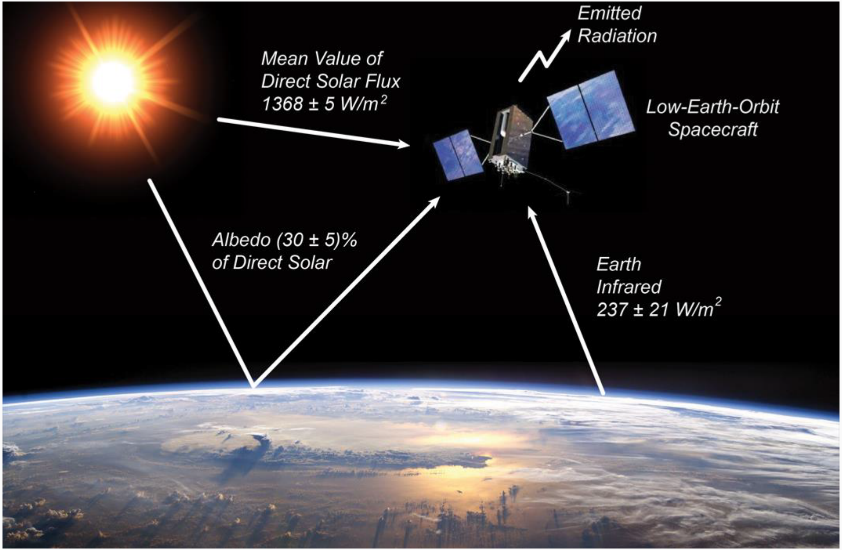


Solar flux and albedo of the planets

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.

Earth's energy budget



Credits: NASA

Radiation balance

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:

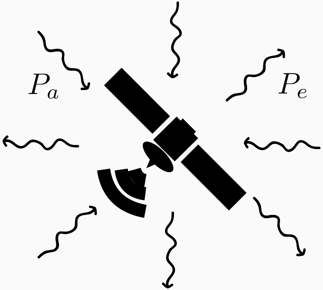
$$\boxed{P_e = \sigma T^4}$$

per unit surface

where

- P_e is the total amount of radiation emitted by an object per square meter (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



$$P_a = \alpha S A_n$$

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

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

Radiation balance and estimation of the temperature

$$T = \left(\frac{\alpha S A_n}{\epsilon \sigma A_{\text{tot}}} \right)^{\frac{1}{4}}$$

$$= \left(\frac{\alpha}{\epsilon} \right)^{\frac{1}{4}} \times \left(\frac{S A_n}{\sigma A_{\text{tot}}} \right)^{\frac{1}{4}}$$

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 with heat sources and sinks

Radiation balance for a spacecraft :

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

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 (e.g. 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 $(A_n/A_{\text{tot}})^{(1/4)}$.

Spacecraft design strategies

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.

Interactive quizz

→ 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